





PROPERTIES OF THE HIGGS BOSON WE CANNOT "UNSEE"

André David (CERN)

The experimental method



falsifying theories since the dawn of reason

2



Evolutions & revolutions of the elements

2

CÉRN

[Plot courtesy of Jim Virdee]



The Standard Model of Particle Physics



CERN



Higgs in CMS – ca. 2008

[http://cern.ch/go/dJf7] [http://cern.ch/go/Sx8m]



Higgs boson – the field's massive radial excitation, tacit to Brout and Englert, massless via approximations in Guralnik et al., and explicitly mentioned by Higgs (1964).

• Viability – photons and massive weak bosons can coexist was shown by Kibble (1967).

A tribute to those doing SM calculations

6

"Yesterday's discovery is today's calibration, and tomorrow's background." - V. L. Telegdi





LHC Higgs Cross Section WG

[http://xkcd.com/888/]

Experimentalists and theorists.

- Together since 2010.
- Produce the best pieces for a common Higgs puzzle.





How SM Higgses are born

8

[http://cern.ch/go/cWH8][http://cern.ch/go/SnJ8]



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LHC Physics 2015



How SM Higgses die

9

[http://cern.ch/go/qkh6][arXiv:1208.1993][arXiv:1408.0827]

 Couplings and kinematics drive BR (bb, WW, ττ, ZZ).
 Decays with photons (γγ, Zγ) through loops.







["Lawrence of Arabia" idea from C. Grojean]

We first saw that we could not exclude a narrow range.





["Lawrence of Arabia" idea from C. Grojean]

We first saw that we could not exclude a narrow range.





In 2012 some theorists speculated...

[http://goo.gl/CVm6s]

After Moriond 2012, new fits disfavor the SM and motivate for New Physics

> red = no Higgs boson green = SM



P. Giardino, K. Kannike, M. Raidal, A. Strumia, 1203.4254



In 2012 some theorists speculated...

[http://goo.gl/CVm6s]



P. Giardino, K. Kannike, M. Raidal, A. Strumia, 1203.4254



In 2012 some theorists speculated...

[http://goo.gl/CVm6s]





["Lawrence of Arabia" idea from C. Grojean]

□ We discovered a peak rising from the background.



July 4, 2012 Looking up to a new boson

[http://cern.ch/go/q8jx]

16







Higgsdependence day recap

[http://cern.ch/go/q8jx]



	TIME Person of the Vear		f 🎐 g+ t あ Apr
Magazine Video LIFE Person of the Yo	ear FCISULUI ULLE FCA		
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As always, TIME's editors will choose the Person of the Year Cast your vote for the person you think most influenced the i om on Dec. 12 and the winner will be appounced on Dec.	r, but that doesn't mean readers shouldn't have their say. news this year for better or worse. Voting closes at 11:59 14	The Candidates Video	
Like 1.5k Tweet 536 Q +1 20 In Sha		Poll Results	
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By Jeffrey Kluger Monday, Nov. 26, 2012		n 🔁 🔫 🕯	
	What do you think?	(e) 2 (c) 4	
	Should The Higgs Boson be TIME's Person of the Year 2012?	2011: The Protester	2010: Facebook's Mark Zuckerberg
	Take a moment to thank this little particle for all the		
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	universe. It was in the 1960s that Scottish physicist Peter Higgs first posited the existence of a particle	Most Read Mo	st
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SSPL/GETTY IMAGES

Simulation of a Higgs-Boson decaying into four muons, CERN, 1990.

18

Photos: Step inside the Large Hadron Collider.

more-fundamental particles, but the scientists would surely be happy to collect any honors or

awards in its stead.

3 Nativity-Scene Battles: Score One for the Atheists

4 The \$7 Cup of Starbucks: A Logical Extension of the

Coffee Chain's Long-Term Strategy





SSPL/GETTY IMAGES

Simulation of a Higgs-Boson decaying into four muons, CERN, 1990.

20

Take a moment to thank this little particle for all the work it does, because without it, you'd be just inchoate energy without so much as a bit of mass. What's more, the same would be true for the entire universe. It was in the 1960s that Scottish physicist Peter Higgs first posited the existence of a particle that causes energy to make the jump to matter. But it was not until last summer that a team of researchers at Europe's Large Hadron Collider - Rolf Heuer, Joseph Incandela and Fabiola Gianotti - at last sealed the deal and in so doing finally fully confirmed Einstein's general theory of relativity. The Higgs - as particles do - immediately decayed to more-fundamental particles, but the scientists would surely be happy to collect any honors or awards in its stead.

Photos: Step inside the Large Hadron Collider.

Most Emailed

2008: Barack Obama

2009: Ben Bernanke

Most Read

- Who Should Be TIME's Person of the Year 2012?
- 2 LIFE Behind the Picture: The Photo That Changed the Face of AIDS

3 Nativity-Scene Battles: Score One for the Atheists

4 The \$7 Cup of Starbucks: A Logical Extension of the Coffee Chain's Long-Term Strategy



The LHC Run 1: a bountiful harvest

[http://cern.ch/go/K8Tj] [http://cern.ch/go/ZW9S]

□ LHC delivered \sim 30 fb⁻¹.

Challenge: precision physics with ~20 simultaneous proton-proton collisions.

Data included from 2010-03-30 11:21 to 2012-12-16 20:49 UTC 25 25 **2010, 7 TeV, 44.2** pb^{-1} Total Integrated Luminosity (${ m I\!D}^{-1}$) 5 0 5 5 0 **2011, 7 TeV, 6.1** fb^{-1} **2012, 8 TeV, 23.3** fb⁻¹ 20 15 10 × 100 2 Jun 2 Jul 1 May 2 NOV 1 Apr 1 AUG 1 Sep 1 Oct 1 Dec Date (UTC)

Event with 78 reconstructed vertices along \sim 10 cm.

a.david@cern.ch LHC Physics 2015

CMS Integrated Luminosity, pp

On the shoulders of giants



22

detector makers & theory calculators

"Yesterday's discovery is today's calibration, and tomorrow's background." – V. L. Telegdi [http://cern.ch/go/lf9C][http://cern.ch/go/KD8D]





["Lawrence of Arabia" idea from C. Grojean]

□ By early 2013 a clear Higgs-like picture emerged.



(self-inflicted) Mission: impossible

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Present a coherent view of present-day results of Higgs couplings from the LHC (and Tevatron) experiments.
 Any mistake is the speaker's fault (send email).



Oversimplified big picture

T – Tevatron;	A - ATLAS;	C – CMS;	combination	drivers	in	red.
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★ "seen" ★ "tried" 'impossible"	н	→b	b	H-	$ ightarrow extsf{ au}$	τ	H-	→W	w	н	>Z	Z	H-	$ ightarrow \gamma$	γ	H-	→Z	γ	H	—→in	١٧.	H-	→ µ	μ	н Н	l→c →H	c H
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□ Still much to explore on the rarer ends.

(to the right and to the bottom) (and outside this picture 🗮)



VH, $H \rightarrow b\overline{b}$ vignettes

[PRD 89 (2014) 012003]



PRD 89 (2014) 012003







H→ττ vignettes

[JHEP 05 (2014) 104]



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LHC Physics 2015



Fermion decay combination vignette

[Nature Physics 10 (2014) 557]





[JHEP 01 (2014) 096]

29



$H \rightarrow ZZ \rightarrow 4\ell$ vignettes

[PRD 89 (2014) 092007]

30



a.david@cern.ch LHC Physics 2015

best fit μ



[EPJC 74 (2014) 3076]

31



LHC discovery

Birth of a Higgs boson

Results from ATLAS and CMS now provide enough evidence to identify the new particle of 2012 as 'a Higgs boson'.

In the history of particle physics, July 2012 will feature prominently as the date when the ATLAS and CMS collaborations announced that they had discovered a new particle with a mass near 125 GeV in studies of proton-proton collisions at the LHC. The discovery followed just over a year of dedicated searches for the Higgs boson, the particle linked to the Brout-Englert-Higgs mechanism that endows elementary particles with mass. At this early stage, the phrase "Higgs-like boson" was the recognized shorthand for a boson whose properties were yet to be fully investigated (*CERN Courier* September 2012 p43 and p49). The outstanding performance of the LHC in the second half of 2012 delivered four times as much data at 8 TeV in the centre of mass as were used in the "discovery" analyses. Thus equipped, the experiments were able to present new results at the 2013 Rencontres de Moriond in March, giving the particle-physics community enough evidence to

March, giving the particle-physics community enough evidence to name this new boson "a Higgs boson".

results that further elucidate the nature of the particle discovered just eight months earlier. The collaborations find that the new particle is looking more and more like a Higgs boson. However, it remains an open question whether this is *the* Higgs boson of the Standard Model of particle physics, or one of several such bosons predicted in theories that go beyond the Standard Model. Finding the answer to this question will require more time and data.

This brief summary provides an update of the measurements

Obse comp	erved CL_s ared with $P^P = 0^+$	0 ⁻ (gg) pseudo- scalar	2 ⁺ _m (gg) minimal couplings	2 ⁺ (qq̄) minimal couplings	1 ⁻ (qq̄) exotic vector	1+ (qq̄) exotic pseudo-vector
ZZ(*)	ATLAS	2.2%	6.8%	16.8%	6.0%	0.2%
10/10/(*	ATLAS	0.10%	5.1%	<0.1%	<0.1%	-
~~~~	CMS	-	14%	-	-	-
ŶΫ	ATLAS	-	0.7%	12.4%	-	-

Table 1. Summary of preliminary results of the hypothesis tests compared with the Standard Model hypothesis of no spin, positive parity ( $J^P=0^+$ ). All alternatives are disfavoured using the CL_s ratio of probabilities that takes into account how the observation relates to both the Standard Model and the alternative hypotheses.



## Entry in the PDG

#### $H^0$ (Higgs Boson)

The observed signal is called a Higgs Boson in the following, although its detailed properties and in particular the role that the new particle plays in the context of electroweak symmetry breaking need to be further clarified. The signal was discovered in searches for a Standard Model (SM)-like Higgs. See the following section for mass limits obtained from those searches.

### $H^0$ MASS

**INSPIRE** search

Value (GeV)	Document ID		TECN	Comment					
125.9 ±0.4	OUR AVERAGE								
$125.8 \pm 0.4 \pm 0.4$	CHATRCHYAN ¹	2013J	CMS	pp , 7 and 8 TeV					
$126.0 \pm 0.4 \pm 0.4$	AAD ²	2012AI	ATLS	pp , 7 and 8 TeV					
*** We do not use the following data for averages, fits, limits, etc ***									
$126.2 \pm 0.6 \pm 0.2$	CHATRCHYAN ³	2013J	CMS	pp , 7 and 8 TeV					
$125.3 \pm 0.4 \pm 0.5$	CHATRCHYAN ⁴	2012N	CMS	pp , 7 and 8 TeV					
¹ Combined value from ZZ and $\gamma\gamma$ final states.									
² AAD 2012AI obtain results based on 4.6 – 4.8 fb ⁻¹ of $pp$ collisions at $E_{cm}$ = 7 TeV and 5.8 – 5.9 fb ⁻¹ at $E_{cm}$ = 8 TeV. An excess of events over background with a local significance of 5.9 $\sigma$ is observed at $m_{H^0}$ = 126 GeV. See also AAD 2012DA.									
³ Result based on final states in 5.1 fb ⁻¹ of $pp$ collisions at $E_{\rm cm}$ = 7 TeV and 12.2 fb ⁻¹ at $E_{\rm cm}$ = 8 TeV.									
$\frac{1}{2}$ CHATRCHVAN 2012N obtain results based on 4.0 5.1 fb ⁻¹ of an collisions of E = 7. To V and 5.1 5.2 fb ⁻¹ of E = 9.									

⁴ CHATRCHYAN 2012N obtain results based on 4.9 - 5.1 fb⁻¹ of pp collisions at  $E_{cm} = 7$  TeV and 5.1 - 5.3 fb⁻¹ at  $E_{cm} = 8$  TeV. An excess of events over background with a local significance of 5.0  $\sigma$  is observed at about  $m_{H^0} = 125$  GeV. See also CHATRCHYAN 2012BY.

#### References

Document Id		Journal Name
CHATRCHYAN	2013J	PRL 110 081803
AAD	2012AI	PL B716 1
CHATRCHYAN	2012N	PL B716 30

NB: the mass measurement alone "cleared up" a huge chunk of BSM space.



### 2013: "killer" news

["Lawrence of Arabia" idea from C. Grojean]

### SM-like: the Swedish academy shot the prize at Englert and Higgs.







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## The Nobel Prize in Physics 2013



Photo: A. Mahmoud François Englert Prize share: 1/2



Photo: A. Mahmoud Peter W. Higgs Prize share: 1/2

The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs "for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"

### ...and knighthoods.

36



by Deborah Evanson, Colin Smith, Gail Wilson 16 June 2014



Two of Imperial's physicists, best known for predicting and finding the Higgs boson, have been knighted in this year's Queen's Birthday honours list.
# The fate/character of the Universe

[ JHEP 08 (2012) 098 ]

37



The SM vacuum stability depends crucially on the masses of the top quark and Higgs boson.

## Mass peaks: mass measurements

0.0



## Mass peaks: mass measurements

39



## Mass measurement

[ arXiv:1406.3827 ][ arXiv:1412.8662 ]



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40



[ arXiv:1406.3827 ][ arXiv:1412.8662

41

-2lnA



□ Slight difference in ATLAS results:

- m_H^{γ γ}-m_H^{ZZ} = 1.47 ±0.67(stat.) ±0.28(syst.) GeV
- **1.97**σ (p=4.9%).
- Using more conservative energy scale uncertainties: 1.8σ (p=7.5%).



- In CMS, less significant and with opposite sign:
  - □  $m_{H}^{\gamma \gamma} m_{H}^{ZZ} = -0.9 \pm 0.6 \text{ GeV}$ □ 1.6σ.

[ arXiv:1503.07589 ]

42



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43

## **Combined LHC mass measurement**

[ arXiv:1503.07589 ]



#### [ arXiv:1503.07589 ]

44



45



46





# $m_{H} = 125.09 \pm 0.21 ~(stat)$

Uncertainty is mostly statistical

Scale uncertainties dominate systematic

→ But we can expect that to improve with more data!

 $\pm 0.11 \text{ (scale)} \\ \pm 0.02 \text{ (other)} \\ \pm 0.01 \text{ (theory}^*$ 

GeV



48



















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50



51









## Deviations of H(125)

## Heavy New Physics

- Concern of LHC HXSWG WG2
- Decoupling of heavy d.o.f.
- Indirect effects, loops, dim-6 operators, etc.

## Light New Physics

- Benchmarks from LHC HXSWG WG3
- Other states, degenerate states, etc.



- Exp. Uncertainties
- **SM** consistency:  $(m_H, m_W, m_{top})$

Spin

Are we happy now?

🗆 Charge

Zero. (That was easy.)

Parity

Amplitude decomposition  $\rightarrow$  EFT

Scalar couplings

 $\square \ \mathcal{K} \longrightarrow \ \mathcal{K} \ (q) \longrightarrow f(q) \longrightarrow EFT$ 

## An actual measurement





#### Mass

Exp. Uncertainties

**S**M consistency:  $(m_{H'}, m_{W'}, m_{top})$ 

🗆 Spin

#### Are we happy now?

□ Charge

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Are we happy now?

Charge

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Parity

## 

Scalar couplings

 $\blacksquare \ \mathcal{K} \longrightarrow \ \mathcal{K} (q) \longrightarrow f(q) \longrightarrow EFT$ 

$$\begin{split} A(X_{J=0} \to V_1 V_2) &\sim v^{-1} \left( \left[ a_1 - e^{i\phi_{\Lambda_1}} \frac{q_{Z_1}^2 + q_{Z_2}^2}{(\Lambda_1)^2} \right] m_z^2 \epsilon_{Z_1}^* \epsilon_{Z_2}^* \right. \\ &+ a_2 f_{\mu\nu}^{*(Z_1)} f^{*(Z_2),\mu\nu} + a_3 f_{\mu\nu}^{*(Z_1)} \tilde{f}^{*(Z_2),\mu\nu} \\ &+ a_2^{Z\gamma} f_{\mu\nu}^{*(Z)} f^{*(\gamma),\mu\nu} + a_3^{Z\gamma} f_{\mu\nu}^{*(Z)} \tilde{f}^{*(\gamma),\mu\nu} \\ &+ a_2^{\gamma\gamma} f_{\mu\nu}^{*(\gamma_1)} f^{*(\gamma_2),\mu\nu} + a_3^{\gamma\gamma} f_{\mu\nu}^{*(\gamma_1)} \tilde{f}^{*(\gamma_2),\mu\nu} \right) \end{split}$$



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#### Mass

- Exp. Uncertainties
- SM consistency:  $(m_H, m_W, m_{top})$

□ Spin

- Are we happy now?
- Charge
  - Zero. (That was easy.)
- Parity

Amplitude decomposition  $\rightarrow$  EFT

- Scalar couplings
  - $\square \ \mathcal{K} \longrightarrow \ \mathcal{K} \ (\mathbf{q}) \longrightarrow \mathbf{f}(\mathbf{q}) \longrightarrow \mathsf{EFT}$



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## Oversimplified big picture

T – Tevatron;	A – ATLAS;	C – CMS;	combination	drivers	in	red.
---------------	------------	----------	-------------	---------	----	------

★ "seen" ★ "tried" 'impossible"	H→bb			$H \rightarrow \tau \tau$			H→WW		H→ZZ		$H \rightarrow \gamma \gamma$			$H \rightarrow Z \gamma$			H—inv.			$H \rightarrow \mu \mu$			H→cc H→HH				
1	Т	А	С	T	А	С	т	А	С	T	А	С	Т	А	С	Т	А	С	Т	А	С	Т	А	С	Т	А	С
ggH	-	-	-	☆	*	*	☆	*	*	☆	*	*	☆	*	*	-	☆	☆				-	☆	☆	-		
VBF			☆	☆	*	*		*	*		*	☆		*	☆	-		☆			☆	-		☆	-		
VH	*	☆	*	☆		☆	☆	☆	☆		☆	☆		☆	☆	-				☆	☆	-			-		
ttH		☆	☆	☆		☆	☆							☆	☆	-						-			-		

## □ Still much to explore on the rarer ends.

(to the right and to the bottom) (and outside this picture 🗮)

## Relative signal strengths

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60

#### [ arXiv:1303.6346 ][ ATLAS-CONF-2015-007 ][ arXiv:1412.8662 ]



# What's in a "signal strength"?



 $\mu = \frac{(\sigma \cdot BR)_{\text{observed}}}{(\sigma \cdot BR)_{\text{expected}}}$ 

 Deviations are searched relative to SM expectation.
Conclusions are only as good as the accuracy and precision of the numerator and denominator.



62



Deviations are searched relative to SM expectation.

 Conclusions are only as good as the accuracy and precision of the numerator and denominator.



$$\mu = \frac{(\sigma \cdot BR)_{\text{observed}}}{(\sigma \cdot BR)_{\text{expected}}}$$

 Deviations are searched relative to SM expectation.
Conclusions are only as good as the accuracy and precision of the numerator and denominator.



## Anatomy of deviations

$$\mu = \frac{(\sigma \cdot BR)_{\text{observed}}}{(\sigma \cdot BR)_{\text{expected Standard Model}}}$$

 Deviations are searched relative to SM expectation.
Conclusions are only as good as the accuracy and precision of the numerator and denominator.





#### $\square$ $\mu = 1$ means that the data match the SM.

- **D** Uncertainty on  $\mu$  quantifies the compatibility with the SM:
  - μ = 1.3 ±1.2 is inconclusive and "more data is needed", but
  - $\mu = 2.0 \pm 0.2$  could mean New Physics (or a systematic effect).





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- $\square$   $\mu$  = 1 means that the data match the SM.
  - **D** Uncertainty on  $\mu$  quantifies the compatibility with the SM:
    - $\mu = 3 \pm 5$  usually means "more data needed", but
    - $\mu = 2.0 \pm 0.2$  could mean New Physics (or a systematic effect).



- $\square$   $\mu$  = 1 means that the data match the SM.
  - $\blacksquare$  Uncertainty on  $\mu$  quantifies the compatibility with the SM:
    - $\mu = 3 \pm 5$  usually means "more data needed", but
    - $\mu = 2.0 \pm 0.2$  could mean New Physics (or a systematic effect).

Imprecise measurement compatible with anything. Inconclusive, "more data or better theory needed".

Precise measurement **compatible** with the SM. Large deviations excluded!

Precise measurement **incompatible** with the SM! Evidence of a deviation **or exp./theory bias**.

> "New Physics ⇒ Deviation" but "Deviation ⇒ New Physics" See, e.g., http://cern.ch/go/W8wW

Theory contributes as much to the conclusions as experiments !

## Relative signal strengths

70

#### [ arXiv:1303.6346 ][ ATLAS-CONF-2015-007 ][ arXiv:1412.8662 ]



## So small that you need a pipette

# Particles smaller than the Higgs boson exist?

By PTI | 23 Mar, 2014, 01.52PM IST

#### 1 comments | Post a Comment

#### READ MORE ON » settlement option | net worth | Insurability

LONDON: There are unknown particles floating around the universe that may be even smaller than the Higgs boson, the 'God particle' discovered in 2012, scientists say.

The so-called techni-quarks can be the yet unseen particles, smaller than the Higgs particle that will form a natural extension of the Standard Model which includes three generations of quarks and leptons.

These particles together with the



Ryttov referred to the theories that have been put forward over the last five years for the existence of particles in the universe that are smaller than the Higgs particle.

## The Standard Model of Particle Physics



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### Scalar coupling structure

73



### Scalar coupling structure

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74



### Scalar coupling structure

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75



















## Scalar coupling deviations framework

#### [arXiv:1307.1347]

80



- □ Single state, spin 0, and CP-even.
- □ Narrow-width approximation: ( $\sigma \times BR$ ) = $\sigma \cdot \Gamma / \Gamma_H$

### Scalar coupling deviations framework

#### [arXiv:1307.1347]



Loops resolved at NLO QCD and LO EWK accuracy.
 Peg the as-of-yet unmeasured to "closest of kin".

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81

### Scalar coupling deviations framework

#### [arXiv:1307.1347]



Total width as dependent function of all K_i.
 Total width scaled as free parameter: K_H.

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82

## Weak bosons and fermions

83

#### [ arXiv:1303.6346 ][ ATLAS-CONF-2015-007 ][ arXiv:1412.8662 ]



	Tevatron	ATLAS	CMS
p(SM)	-	41%	< 1 <i>o</i>

### Weak bosons and fermions

#### [ ATLAS-CONF-2015-007 ][ arXiv:1412.8662 ]

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84



### The deviations that we do not (yet) see

85

#### [ ATLAS-CONF-2015-007 ][ arXiv:1412.8662 ]





### The deviations that we do not (yet) see

[ATLAS-CONF-2015-007 ][ arXiv:1412.8662 ]



## **Resolving SM contributions**

[ ATLAS-CONF-2015-007 ][ arXiv:1412.8662 ]

87



# Coupling deviations summaries

[ ATLAS-CONF-2015-007 ][ arXiv:1412.8662 ][ arxiv:1207.1693 ][ arxiv:1303.3570 ]

88



## A very long way to go...

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89

#### Decay Modes

	Mode	Fraction ( $\Gamma_i / \Gamma$ )	Scale Factor/ Confidence Level	P (MeV/c)		
	$H^0 \rightarrow WW^*$	seen				
	$H^0 \rightarrow ZZ^*$	seen				
3	$H^0  ightarrow \gamma\gamma$	seen				
,	$H^0  o b\overline{b}$	possibly seen				
	$H^0  ightarrow  au^+  au^-$	possibly seen				
nbine	d Final States	1.07 ±0.26	(S = 1.4)			
W* Fir	nal State	$0.88 \pm 0.33$	(S = 1.1)			
$ZZ^*$ Final State $\gamma\gamma$ Final State $b\overline{b}$ Final State		$0.89 \substack{+0.30 \\ -0.25}$				
		$1.65 \pm 0.33$				
		0.5 +0.8 -0.7 Decay Modes				ļ
$^+ au^-$ Fi	nal State	$0.1 \pm 0.7$	$\Gamma_i$	Mode	Fraction $(\Gamma_i / \Gamma)$	
			$\Gamma_1$	$Z \rightarrow e^+e^-$	$3.363 \pm 0.004 \%$	
				$Z \to \mu^+ \mu$ $Z \to \tau^+ \tau^-$	$3.366 \pm 0.007 \%$ $3.370 \pm 0.008 \%$	
			$\Gamma_4$	$Z \to \ell^+ \ell^-$	3.3658 ±0.0023 %	
			$\Gamma_5$	$Z \to \ell^+ \ell^- \ell^+ \ell^-$	$(4.2 \substack{+0.9 \\ -0.8}) \times 10^{-6}$	
			$\Gamma_6$	Z  ightarrow invisible	$(2.000 \pm .006) \times 10^{-1}$	
			$\Gamma_7$	Z  ightarrow hadrons	$(6.991 \pm .006)$ ×10 ⁻¹	
			$\Gamma_8$	$Z \rightarrow (u\overline{u} + c\overline{c})/2$	.116 ±.006	
			$\Gamma_9$	$Z \rightarrow (dd + s\overline{s} + b\overline{b})/3$	$.156 \pm .004$	
			$\Gamma_{10}$	$Z \rightarrow c\overline{c}$	$(1.203 \pm .021)$ $\times 10^{-1}$	
			E.,	7 . 10	$(1.512 \pm .005)$	

 $\Gamma_{12}$ 

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 $(3.6 \pm 1.3) \times 10^{-4}$ 

 $Z \rightarrow b\overline{b}b\overline{b}$ 



### Dark matter: invisible Higgs decay search

[ EPJC 74 (2014) 2980 ]

VBF and ZH topologies combined;  $Z \rightarrow \ell \ell$  and  $Z \rightarrow bb$ .  $BR(H \rightarrow inv.) < 0.58 (0.44 exp.) at 95\% CL$ 



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# Invisible Higgs search combination

#### [ EPJC 74 (2014) 2980 ]

□ Combination of VBF, Z(ll)H, and Z(bb)H searches: BR(H→inv) < 0.58 (0.44 exp.) at 95% CL.</p>





# Invisible Higgs search combination

#### [ EPJC 74 (2014) 2980 ]

- Combination of VBF, Z(ℓℓ)H, and Z(bb)H searches: BR(H→inv) < 0.58 (0.44 exp.) at 95% CL.</p>
- Competitive limits for low mass DM in "Higgs portal" models.







### Lepton flavor violation: search for $H{\rightarrow}\mu\tau$

[CMS-PAS-HIG-14-005]

- $\Box$   $\tau$  lepton flavor violation not as well constrained as  $\mu e$  (MEG).
- □ Based on SM  $H \rightarrow \tau \tau$  analysis. Different kinematics allows good SM H rejection.
  - **BR(H\rightarrowµ\tau) < 1.57% at 95%CL (expected limit of 0.75%)**



# Search for $H \rightarrow \mu \tau$

[CMS-PAS-HIG-14-005]

94



# Search for $H \rightarrow \mu \tau$

[CMS-PAS-HIG-14-005]



95





["Lawrence of Arabia" idea from C. Grojean]

- □ We must examine this Higgs to the fullest extent !
  - It may be the only clue to leave the SM oasis and cross the desert.



## The many facets of HVV





Decay	γ	γ*/Z*	Z
γ	1	1	1
γ*/Z*		? (∨BF)	✔ (VH)
Z			✓ (H*)



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[ arXiv:1407.4222 ][ arXiv:1408.3226 ][ arXiv:1504.05833 ]

- Differential picture directly touches fundamental aspects:
  - The loop structure where new particles may be running (p_T shape).
  - The QCD structure of the calculations (N_{iets}).
- □ ATLAS H→ Y Y and ZZ results and the adventure of unfolding.
   □ Illustrates the power of having more statistics (signal-like excess).



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(CÉRN) 100

[ arXiv:1407.4222 ][ arXiv:1408.3226 ][ arXiv:1504.05833 ]

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101

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### From deviations to EFTs

[ http://cern.ch/go/W96V ]

102

- Today we talk about deviations from the SMH.
  - arXiv:1209.0040 or equivalent.
  - Draw/exclude your own theory.
- One (single) nice feature: K =1 recovers best SMH calculations.
  - But that's it: we can find deviations, but only roughly fathom their meaning.





### Deviations are on a diet





104

# Effective field theory (EFT): the idea

#### [ NPB 268 (1986) 621 ]

- Instead of an experimentally-driven basis of parameters use a basis of QFT operators that may be more aligned with the BSM physics.
- EFT allows to perform accurate calculations.
  - NLO EWK effects, etc.
  - More sensitive interpretation.
- 59 dim-6 operators already mapped out in 1986.
  - Which operators to keep?
  - What about dim-8?
  - What about loop processes?





# Delayed unitarization: until when?

[ http://cern.ch/go/q8Gq ]

- Assume that WW scattering is δ^{-1/2} that of SM.
- Things can look like the SM for a long time.
  - **Time** ~ Energy.



### Things you can't "unsee"

106 [http://cern.ch/go/Dxh7]



### Things you can't "unsee"

107 [http://cern.ch/go/Dxh7]





### Things you can't "unsee"

108 [http://cern.ch/go/Dxh7]




### The future is in precision and accuracy





### Outlook



- □ LHC13: last chance before a "BSM desert".
  - Tevatron: Run I → top discovery, Run II → SM precision.
  - LHC 2010: early SUSY and EXO exclusions.

### Higgs, one way out of the "SM oasis":

- From O(10%) to differential.
- From "seen" to O(%) measurements.
- From limits on rare things to observations.
- From conjectures on weird things, to putting limits on them.
- From ad-hoc  $\kappa$  fits to global EWK EFT fits.
- □ We have a long way to go.
   All it takes is one deviation.





## "...and references therein."

- Experiments' pages on Higgs results:
  - ATLAS: <u>http://cern.ch/go/7IDT</u>
  - CMS: <u>http://cern.ch/go/6qmZ</u>
  - Tevatron: <u>http://cern.ch/go/h9jX</u>
    - CDF: <u>http://cern.ch/go/q8NV</u>
    - D0: <u>http://cern.ch/go/9Djq</u>
- Partial list of conferences and workshops:
  - Higgs Days 2013: <u>http://cern.ch/go/6zBp</u>
  - ECFA HL-LHC workshop: <u>http://cern.ch/go/SFW6</u>
  - Higgs EFT 2013: <u>http://cern.ch/go/bR7w</u>
  - Higgs Couplings 2013: <u>http://cern.ch/go/THp9</u>
  - Moriond 2014: <u>http://cern.ch/go/k8FP</u>
  - Bernasque 2014: <u>http://cern.ch/go/Pz7I</u>
  - ICHEP 2014: <u>http://cern.ch/go/8Btf</u>
  - Rencontres du Vietnam 2014: <u>http://cern.ch/go/9ZJJ</u>
  - Zuoz Summer School 2014: <u>http://cern.ch/go/9SHw</u>
  - Higgs Days 2014: <u>http://cern.ch/go/lfP6</u>
  - Higgs Couplings 2014: <u>http://cern.ch/go/HMm6</u>



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### From the other side of the pond

**114** [ arXiv:1207.6436 ]



**2.8**  $\sigma$  local significance at m_H=125 GeV.

# 115 The Future

### Looking ahead

116 [ arXiv:1307.7135 ][ CMS-PAS-HIG-13-007 ]

- □ 300 fb⁻¹ at 14 TeV:
  - Vast improvement over present datasets.
  - Room for theory improvements.



## Looking ahead

arXiv:1307.7135 ][ CMS-PAS-HIG-13-007 ]

- □ 300 fb⁻¹ at 14 TeV:
  - Vast improvement over present datasets.
  - Room for theory improvements.

self-coupling?



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**CMS** Projection

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# $X \rightarrow HH \rightarrow b \overline{b} \gamma \gamma$ and the future

### [ CMS-PAS-HIG-13-032 ]

 First step towards two-Higgs measurements at the HL-LHC.

For now setting limits on radion production from warped extra dimensions.





### Off-shell – involved processes







[PLB 736 (2014) 64 ][ JHEP 08 (2012) 116 ][ PRD 88 (2013) 054024 ][ arXiv:1311.3589

Define  $r = \Gamma_{\rm H} / \Gamma_{\rm H}^{\rm SM}$ 

121

On-mass-shell we have

# $\sigma_{gg \to H \to ZZ}^{on-peak} = \frac{\kappa_g^2 \kappa_Z^2}{r} (\sigma \cdot \mathcal{B})_{SM}$

Off-mass-shell there is no r:  $\frac{d\sigma_{\rm gg \to H \to ZZ}^{\rm off-peak}}{dm_{ZZ}} = \frac{\kappa_{\rm g}^2 \kappa_{\rm g}^2}{\kappa_{\rm g}^2 \kappa_{\rm g}^2}$  $\frac{d\sigma_{\rm gg \rightarrow H \rightarrow ZZ}^{\rm off-peak,SM}}{dm_{ZZ}}$ 

### Can make inference on *r* from on-and off-shell assuming:

■ 
$$\mu_{on-shell} = \mu_{off-shell}$$
  
■ Only SM processes → ZZ:  
■  $gg \rightarrow H^*$   
■  $gg = |gg \rightarrow H^* + gg \rightarrow non-H|^2$   
■  $|gg \rightarrow H^*|^2 + |gg \rightarrow non-H|^2$   
■  $Total = gg + qq$ 



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## $H^*$ – off-shell decay to ZZ

### [ PLB 736 (2014) 64 ]

- Two channels exploited:
  - □ ZZ→4Q
    - 2D: m_{4l} and gg vs. qq discriminant.
  - ZZ→2Q2v
    - Jet-inclusive  $m_T$  shape.

### Observed limit lower than expected.



Obs. (exp.)	42	222v		Combined	
Г _Н /Г _Н SM ( <b>9</b> 5% CL)	< 8.0 (10.1)	< 8.1 (10.6)		< 5.4 (8.0)	
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[http://cern.ch/go/W96V]

Shifts to tree-level couplings due to mixing with heavier Higgs

$$c_{V} = \sin(\beta - \alpha) \qquad c_{t} = \frac{\cos \alpha}{\sin \beta} \qquad c_{b} = -\frac{\sin \alpha}{\cos \beta} \qquad \qquad \begin{pmatrix} h^{0} \\ H^{0} \end{pmatrix} = \begin{pmatrix} \cos \alpha & -\sin \alpha \\ \sin \alpha & \cos \alpha \end{pmatrix} \begin{pmatrix} \operatorname{Re} H^{0}_{u} \\ \operatorname{Re} H^{0}_{d} \end{pmatrix}$$

$$\operatorname{tan} \beta = \frac{v_{u}}{v_{d}}$$

Only two regions in the  $(c_t, c_b)$  plane accessible in a generic Type-II 2HDM

Down-Suppressed region almost not accessible in the MSSM for  $\tan \beta > 1$ 

see: Azatov, Chang, Craig, Galloway PRD 86 (2012) 075033





128

129 [ http:/

#### [http://cern.ch/go/W96V]



### For the impatient ones here is a theorist's combination of ATLAS+CMS+Tevatron:

from: Azatov, Galloway Int. J. Mod. Phys. A28 (2013) 1330004

the current fit by CMS seems to favor the MSSM region, though errors are large

It would be nice to see the same plot by ATLAS and even nicer to see plot in the plane  $(\kappa_u, \kappa_d)$ 



)

[http://cern.ch/go/W96V]

130

Shifts to loop-induced couplings due to squarks



[ http://cern.ch/go/W96V ]

131

Implications on the masses of the heavier Higgses

In the decoupling limit:  $\alpha 
ightarrow \beta$ 

$$\alpha o \beta - \pi/2$$

$$c_{V} = 1 - \Delta^{2} \frac{1}{\tan^{2}\beta} + O(\Delta^{3}) \qquad c_{t} = 1 - \Delta \frac{1}{\tan^{2}\beta} + O(\Delta^{2}) \qquad \Delta = O\left(\frac{m_{Z}^{2}}{m_{H}^{2}}\right)$$
starts at  $O(m_{H}^{-4})$ 

$$c_{b} \text{ most sensitive probe of spectrum of Heavy Higgses} \qquad \frac{\delta c_{b}}{c_{b}} > 0.1 \qquad \longrightarrow \qquad m_{H} > 300 - 400 \text{ GeV}$$

### Notice:

masses of Heavy Higgses are not linked to naturalness of m_h anyway

Lighter masses (up to  $m_H \sim 200 \text{ GeV}$ ) however simple to obtain in explicit models (ex: NMSSM) with mild tuning of  $\Delta$ 

see for example: Barbieri et al. arXiv:1304.3670

# The case for the SMH (R.Contino)

### [http://cern.ch/go/W96V]

### If one assumes that

- 1. The new boson is part of an  $SU(2)_L$  doublet
- 2. There is a gap between the NP scale and  $m_{\rm H}$

### then it must follow:

- h has spin 0
- h is (mostly) CP=+ ✓
- There exists a correlation among processes with 0,1,2 Higgs bosons
  - Ex: custodial symmetry

 $\frac{m_W}{m_Z \cos \theta_W} = 1 \quad \Longrightarrow \quad \lambda_{WZ} = \frac{c_W}{c_Z} = 1$ 

 There are no new light states to which the Higgs boson can decay

```
Ex: Invisible width=0
```



All these independent tests important to confirm the picture but their success comes less of a surprise given the fits on couplings

- 20 30 (L₀. / L₀.)
- Ex: there's no reason why a J^P=0⁻ boson should have SM coupling strength

$$D_{\mu}H|^2$$
 vs  $rac{ ilde{c}_{WW}}{M^2}W_{\mu
u} ilde{W}^{\mu
u}H^{\dagger}H$ 





134

### To loop or not to loop

### **Generic coupling fit**

- Assume custodial symmetry ( K v = K w = K z).
- Loops treated
   effectively (κ_γ, κ_g).
- □ Option to allow BSM decays, forcing  $K_V \le 1$ .

### **Resolved coupling fit**

- Keep W and Z separate.
- Loops assuming SM structure:
  - $\bullet \ \mathcal{K}_{g} (\mathcal{K}_{b}, \mathcal{K}_{t}).$
  - $\overset{\bullet}{} \quad \mathcal{K}_{\gamma} (\mathcal{K}_{W}, \mathcal{K}_{b}, \mathcal{K}_{t}, \mathcal{K}_{t}).$
- Only SM-like decays.



[ arXiv:1412.8662 ]



135

# 136 More on scalar couplings



[ arXiv:1412.8662 ]

137

# $1.00 \pm 0.09 \text{ (stat.)}^{+0.08}_{-0.07} \text{ (theo.)} \pm 0.07 \text{ (syst.)}$

- Grouped by dominant decay:
  - $\chi^2/dof = 1.0/5$
  - p-value = 0.96 (asymptotic)





[ arXiv:1412.8662 ]

138

# $1.00 \pm 0.09 \text{ (stat.)}^{+0.08}_{-0.07} \text{ (theo.)} \pm 0.07 \text{ (syst.)}$

□ Grouped by productionCom<br/>μtag:Untage□  $\chi^2/dof = 5.5/4$ Untage□ p-value = 0.24VBF ta<br/>μ =(asymptotic)VH tag<br/>μ =ttH-tagged 2.00 abovettH tag<br/>μ =





139

# $1.00 \pm 0.09 \text{ (stat.)}^{+0.08}_{-0.07} \text{ (theo.)} \pm 0.07 \text{ (syst.)}$

- Grouped by production tag and dominant decay:
  - $\chi^2/dof = 10.5/16$
  - p-value = 0.84 (asymptotic)
- ttH-tagged 2.0σ above
   SM.
  - Driven by one channel.



### Scalar coupling deviations framework

### [ arXiv:1307.1347 ]

140



- □ Single state, spin 0, and CP-even.
- □ Narrow-width approximation: ( $\sigma \times BR$ ) = $\sigma \cdot \Gamma / \Gamma_H$

### Scalar coupling deviations framework

[ arXiv:1307.1347 ]

141



Loops resolved at NLO QCD and LO EWK accuracy.
 Peg the as-of-yet unmeasured to "closest of kin".

### Scalar coupling deviations framework

### [ arXiv:1307.1347 ]

142



- $\Box$  Total width as dependent function of all  $\kappa_i$ .
- Total width scaled as free parameter: K_H. (invisible decays) a.david@cern.ch LHC Physics 2015



### [ arXiv:1307.1347 ]



## Probing custodial symmetry

#### **144** [ arXiv:1307.1347 ]

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	Probing custodial symmetry assuming no invisible or undetectable widths							
2	Free parameters: $\kappa_Z$ , $\lambda_{WZ}(=\kappa_W/\kappa_Z)$ , $\kappa_f(=\kappa_t = \kappa_b = \kappa_\tau)$ .							
2		$ m H  ightarrow \gamma\gamma$	$\mathrm{H} \to \mathrm{ZZ}^{(*)}$	${ m H}  ightarrow { m WW}^{(*)}$	$H \rightarrow b\overline{b}$ $H \rightarrow \tau^{-}\tau^{+}$			
	ggH ++H	$\frac{\kappa_{\rm f}^2 \cdot \kappa_{\gamma}^2(\kappa_{\rm f},\kappa_{\rm f},\kappa_{\rm f},\kappa_{\rm Z}\lambda_{\rm WZ})}{\kappa_{\rm r}^2(\kappa_{\rm i})}$	$\frac{\kappa_{\rm f}^2 \cdot \kappa_{\rm Z}^2}{\kappa_{\rm f}^2 \cdot (\kappa_{\rm i})}$	$\frac{\kappa_{\rm f}^2 \cdot (\kappa_{\rm Z} \lambda_{\rm WZ})^2}{\kappa_{\rm r}^2 (\kappa_{\rm i})}$	$\frac{\kappa_{f}^{2} \cdot \kappa_{f}^{2}}{\kappa_{r}^{2}(\kappa_{i})}$			
	VBF	$\frac{\kappa_{\rm WBF}^2(\kappa_{\rm Z},\kappa_{\rm Z}\lambda_{\rm WZ})\cdot\kappa_{\gamma}^2(\kappa_{\rm f},\kappa_{\rm f},\kappa_{\rm f},\kappa_{\rm Z}\lambda_{\rm WZ})}{2}$	$\frac{\kappa_{\rm WBF}^2(\kappa_{\rm Z},\kappa_{\rm Z}\lambda_{\rm WZ})\cdot\kappa_{\rm Z}^2}{2}$	$\frac{\kappa_{\rm VBF}^2(\kappa_Z,\kappa_Z\lambda_{\rm WZ})\cdot(\kappa_Z\lambda_{\rm WZ})^2}{2}$	$\frac{\kappa_{\rm VBF}^2(\kappa_{\rm Z},\kappa_{\rm Z}\lambda_{\rm WZ})\cdot\kappa_{\rm f}^2}{\kappa_{\rm VBF}^2(\kappa_{\rm Z},\kappa_{\rm Z}\lambda_{\rm WZ})\cdot\kappa_{\rm f}^2}$			
	WH	$\frac{\kappa_{\rm H}^{\rm c}(\kappa_i)}{(\kappa_{\rm Z}\lambda_{\rm WZ})^2\cdot\kappa_{\gamma}^2(\kappa_{\rm f},\kappa_{\rm f},\kappa_{\rm f},\kappa_{\rm Z}\lambda_{\rm WZ})}$	$\frac{\kappa_{\rm H}(\kappa_i)}{(\kappa_{\rm Z}\lambda_{\rm WZ})^2\cdot\kappa_{\rm Z}^2}$	$\frac{\kappa_{\rm H}^{\kappa}(\kappa_i)}{(\kappa_{\rm Z}\lambda_{\rm WZ})^2 \cdot (\kappa_{\rm Z}\lambda_{\rm WZ})^2} \frac{\kappa_{\rm H}^{\kappa}(\kappa_i)}{(\kappa_{\rm Z}\lambda_{\rm WZ})^2 \cdot \kappa_{\rm f}^2}$				
	** 11	$\kappa_{\rm H}^2(\kappa_i)$	$\kappa_{\rm H}^2(\kappa_i)$	$\kappa_{\rm H}^2(\kappa_i)$	$\kappa_{\rm H}^2(\kappa_i)$			
	$\mathbf{ZH}$	$rac{\kappa_{ m Z}^2\cdot\kappa_{ m \gamma}^2\left(\kappa_{ m f},\kappa_{ m f},\kappa_{ m Z}\lambda_{ m WZ} ight)}{\kappa_{ m H}^2(\kappa_i)}$	$rac{\kappa_Z^2 \cdot \kappa_Z^2}{\kappa_H^2(\kappa_i)}$	$\frac{\frac{\kappa_{\rm Z}^2 \cdot (\kappa_{\rm Z} \lambda_{\rm WZ})^2}{\kappa_{\rm H}^2(\kappa_i)}}$	$rac{\kappa_Z^2\cdot\kappa_{ m f}^2}{\kappa_{ m H}^2(\kappa_i)}$			
	Probing custodial symmetry without assumptions on the total width							
	Free par	The parameters: $\kappa_{ZZ}(=\kappa_Z \cdot \kappa_Z/\kappa_H), \lambda_{WZ}(=\kappa_W/\kappa_Z), \lambda_{FZ}(=\kappa_f/\kappa_Z).$						
TLAS		${ m H}  ightarrow \gamma\gamma$	$\mathrm{H} \to \mathrm{ZZ}^{(*)}$	${ m H}  ightarrow { m WW}^{(*)}$	$H \rightarrow b\overline{b}$ $H \rightarrow \tau^{-}\tau^{+}$			
	$_{ m ggH}^{ m ggH}$	$\kappa_{\mathrm{ZZ}}^2 \lambda_{FZ}^2 \cdot \kappa_{\mathrm{Y}}^2 (\lambda_{FZ}, \lambda_{FZ}, \lambda_{FZ}, \lambda_{\mathrm{WZ}})$	$\kappa^2_{ZZ}\lambda^2_{FZ}$	$\kappa_{\rm ZZ}^2\lambda_{\rm FZ}^2\cdot\lambda_{\rm WZ}^2$	$\kappa_{ZZ}^2\lambda_{FZ}^2\cdot\lambda_{FZ}^2$			
	VBF	$\kappa_{\mathrm{ZZ}}^2\kappa_{\mathrm{VBF}}^2(1,\lambda_{\mathrm{WZ}}^2)\cdot\kappa_{\gamma}^2(\lambda_{FZ},\lambda_{FZ},\lambda_{FZ},\lambda_{\mathrm{WZ}})$	$\kappa^2_{\mathrm{ZZ}}\kappa^2_{\mathrm{VBF}}(1,\lambda^2_{\mathrm{WZ}})$	$\kappa^2_{\mathrm{ZZ}}\kappa^2_{\mathrm{VBF}}(1,\lambda^2_{\mathrm{WZ}})\cdot\lambda^2_{\mathrm{WZ}}$	$\kappa_{ m ZZ}^2\kappa_{ m VBF}^2(1,\lambda_{ m WZ}^2)\cdot\lambda_{FZ}^2$			
	WH	$\kappa^2_{\mathrm{ZZ}} \lambda^2_{\mathrm{WZ}} \cdot \kappa^2_{\gamma}(\lambda_{FZ},\lambda_{FZ},\lambda_{FZ},\lambda_{\mathrm{WZ}})$	$\kappa^2_{ m ZZ}\cdot\lambda^2_{ m WZ}$	$\kappa^2_{ m ZZ}\lambda^2_{ m WZ}\cdot\lambda^2_{ m WZ}$	$\kappa^2_{ m ZZ} \lambda^2_{ m WZ} \cdot \lambda^2_{FZ}$			
	ZH	$\kappa_{\mathrm{ZZ}}^2 \cdot \kappa_{\gamma}^2(\lambda_{FZ},\lambda_{FZ},\lambda_{FZ},\lambda_{\mathrm{WZ}})$	$\kappa_{\rm ZZ}^2$	$\kappa^2_{ m ZZ}\cdot\lambda^2_{ m WZ}$	$\kappa^2_{ZZ}\cdot\lambda^2_{FZ}$			
# Probing custodial symmetry



## [ arXiv:1303.6346 ][ ATLAS-CONF-2015-007 ][ arXiv:1412.8662 ]



# Looking for new particles

### **146** [ arXiv:1307.1347 ]



# Looking for new particles in loops





# Looking for new particles

148 [ ATLAS-CONF-2015-007 ][ arXiv:1412.8662 ]





# A further take on loops

## [ ATLAS-CONF-2015-007 ]

Effective  $H \rightarrow \gamma \gamma$ ,  $H \rightarrow Z \gamma$ , and ggH loops.

 Waiting for more data.





# Probing the fermion sector

#### 150 [ arXiv:1307.1347 ]

		u-type	d-type	lepton	
	Ι	$rac{\cos lpha}{\sin eta}$	$rac{\cos lpha}{\sin eta}$	$rac{\cos lpha}{\sin eta}$	SM-like
ХQ	I'	$\frac{\cos \alpha}{\sin \beta}$	$\frac{\cos \alpha}{\sin \beta}$	$\frac{-\sin\alpha}{\cos\beta}$	
2HI	II	$\frac{\cos \alpha}{\sin \beta}$	$\frac{-\sin\alpha}{\cos\beta}$	$\frac{-\sin\alpha}{\cos\beta}$	
	II'	$\frac{\cos \alpha}{\sin \beta}$	$\left(\frac{-\sin\alpha}{\cos\beta}\right)$	$\frac{\cos\alpha}{\sin\beta}$	Probing

	Pro	bingu	p-type and down-type fermion sym	metry assuming no invisible	e or undetectable widths
IS/	/ Free	paramete	ers: $\kappa_{\rm V}(=\kappa_{\rm Z}=\kappa_{\rm W}), \lambda_{\rm du}(=\kappa_{\rm d}/\kappa_{\rm u}), \kappa_{\rm u}(=$	<b>κ</b> _t ).	
$\bigcirc$		Probi	ng up-type and down-type fermion s	ymmetry without assumption	s on the total width
$\checkmark$	6	🔿 ee pa	rameters: $\kappa_{uu}(=\kappa_u\cdot\kappa_u/\kappa_H), \lambda_{du}(=\kappa_d/\kappa_u),$	$\lambda_{ m Vu}(=\kappa_{ m V}/\kappa_{ m u}).$	
		$\mathcal{I}$	$\mathrm{H} \to \gamma\gamma$	$H \to ZZ^{(*)}$ $H \to WW^{(*)}$	$H \rightarrow b\overline{b}$ $H \rightarrow \tau^{-}\tau^{+}$
		γH	$\kappa_{uu}^2\kappa_g^2(\lambda_{du},1)\cdot\kappa_{\gamma}^2(\lambda_{du},1,\lambda_{du},\lambda_{Vu})$	$\kappa_{\mathrm{uu}}^2\kappa_{\mathrm{g}}^2(\lambda_{\mathrm{du}},1)\cdot\lambda_{\mathrm{Vu}}^2$	$\kappa_{\mathrm{uu}}^2\kappa_{\mathrm{g}}^2(\lambda_{\mathrm{du}},1)\cdot\lambda_{\mathrm{du}}^2$
		AS tH	$\kappa_{\mathrm{uu}}^2 \cdot \kappa_{\gamma}^2(\lambda_{\mathrm{du}}, 1, \lambda_{\mathrm{du}}, \lambda_{\mathrm{Vu}})$	$\kappa_{ m uu}^2\cdot\lambda_{ m Vu}^2$	$\kappa_{\mathrm{uu}}^2\cdot\lambda_{\mathrm{du}}^2$
	wi	VBF			
	71	WH	$\kappa_{\mathrm{uu}}^2\lambda_{\mathrm{Vu}}^2\cdot\kappa_{\mathrm{y}}^2(\lambda_{\mathrm{du}},1,\lambda_{\mathrm{du}},\lambda_{\mathrm{Vu}})$	$\kappa_{uu}^2 \lambda_{Vu}^2 \cdot \lambda_{Vu}^2$	$\kappa_{\mathrm{uu}}^2 \lambda_{\mathrm{Vu}}^2 \cdot \lambda_{\mathrm{du}}^2$

	Pro	bingq	uark and lepton fermion s	ymmetry ass	uming no invisi	ble or und	etectable widths	
CMS	/ Free	paramet	ers: $\kappa_{\rm V}(=\kappa_{\rm Z}=\kappa_{\rm W}), \lambda_{\rm lq}(=\kappa_{\rm l}/\kappa_{\rm r})$	$\kappa_{\rm q}$ ), $\kappa_{\rm q}$ (= $\kappa_{\rm t}$ = $\kappa$	сь).			
	Probing quark and lepton fermion symmetry without assumptions on the total width							
	K	> ee pa	rameters: $\kappa_{\rm qq} (= \kappa_{\rm q} \cdot \kappa_{\rm q} / \kappa_{\rm H}), \lambda_{\rm lq} (=$	$=\kappa_{ m l}/\kappa_{ m q}),\lambda_{ m Vq}(=$	$\kappa_{ m V}/\kappa_{ m q}).$			
-	- 6		$\mathrm{H} \to \gamma\gamma$	$H \rightarrow ZZ^{(*)}$	$\mathrm{H} \rightarrow \mathrm{WW}^{(*)}$	$\mathrm{H} \to \mathrm{b} \overline{\mathrm{b}}$	${\rm H} \to \tau^- \tau^+$	
ATLAS gH		gH tH	$\kappa_{qq}^2\cdot\kappa_{\gamma}^2(1,1,\lambda_{lq},\lambda_{Vq})$	$\kappa_{qq}^2\cdot\lambda_{Vq}^2$		$\kappa_{ m qq}^2$	$\kappa_{qq}^2\cdot\lambda_{lq}^2$	
L		VBF	2 . 2 2/1 1	2 . 2		2 . 2	2 . 2 . 2	
		WH	$\kappa_{\rm qq}^2 \lambda_{\rm Vq}^2 \cdot \kappa_{\gamma}^2 (1, 1, \lambda_{\rm lq}, \lambda_{\rm Vq})$	$\kappa_{qq}^2 \lambda_V^2$	$\lambda_{\rm Q} \cdot \lambda_{\rm Vq}^2$	$\kappa_{qq}^2 \cdot \lambda_{Vq}^2$	$\kappa_{ m qq}^2 \lambda_{ m Vq}^2 \cdot \lambda_{ m lq}^2$	
		ZH			-			

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 $\mathbf{ZH}$ 

 $\mathbf{Z}$ 

# Probing the fermion sector

## **151** [ arXiv:1412.8662 ]

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# Probing the fermion sector

[ ATLAS-CONF-NOTE-2015-007 ]

152



# **Resolving SM contributions**

## [ arXiv:1412.8662 ][ arxiv:1303.3570 ]

153

- Individual coupling scaling factors:
  - $\square K_{W'} K_{Z'} K_{b'} K_{t'} K_{\tau}.$
  - All loops resolved:
    - κ_γ(κ_W, κ_t)
    - κ_g(κ_t, κ_b)
  - SMH width scaled.
- "Reduced" couplings as function of "mass":
   λ_f = κ_f (m_f/vev)
  - $(g_{v}/2vev)^{1/2} = \kappa_{v}^{1/2}$   $(m_{v}/vev)$





## [ arXiv:1412.8662 ][ arxiv:1207.1693 ]

154



# ¹⁵⁵ More on the CMS combination

# Bringing it all together in CMS

## **156** [ arXiv:1412.8662 ]



## Also include further ttH searches:

- JHEP 05(2013)145 ttH, H→bb (7 TeV).
- arXiv:1408.1682 (subm. to JHEP) ttH,  $H \rightarrow b\overline{b}$ ,  $H \rightarrow \tau\tau$ , and H decaying to multiple leptons (8 TeV).

# Bringing it all together in CMS

#### 7 [ arXiv:1412.8662 ]



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# Bringing it all together in CMS

**158** [ arXiv:1412.8662 ]

# > 200 channels > 2'500 floating parameters

## H→WW

JHEP 01(2014) 096

PRD 89 (2014) 092007

H→ZZ→4l

PRD 89 (2014) 012003

JHEP 05 (2014) 104

arXiv:1407.0558 (subm. to EPJC)

## Also include further ttH searches:

- JHEP 05(2013)145 ttH, H→bb (7 TeV).
- arXiv:1408.1682 (subm. to JHEP) ttH,  $H \rightarrow b\overline{b}$ ,  $H \rightarrow \tau\tau$ , and H decaying to multiple leptons (8 TeV).

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Η→ττ



# The challenge of combining

- Include five main decays and searches for ttH production.
- 207 channels.
- 2519 parameters.
  - 219 H→γγ background
    - parameters.

			$\sigma_{m_{\rm H}}/m_{\rm H}$	Luminosity $(fb^{-1})$	
Decay tag and production	ag Expected signal composition			No. of	categori
				7 TeV	8 TeV
$H \rightarrow \gamma \gamma$ [20], Section 2.1				5.1	19.7
	Untagged	76–93% ggH	0.8-2.1%	4	5
	2-jet VBF	50-80% VBF	1.0-1.3%	2	3
$\gamma\gamma$	Leptonic VH	$\approx$ 95% VH (WH/ZH $\approx$ 5)	1.3%	2	2
	E ^{miss} VH	$70-80\%$ VH (WH/ZH $\approx 1$ )	1.3%	1	1
	2-iet VH	$\approx 65\%$ VH (WH/ZH $\approx 5$ )	1.0-1.3%	1	1
	Leptonic t <del>T</del> H	≈95% tīH	1.1%		1
	Multijet t <del>Ī</del> H	>90% #H	1.1%	1 ⁺	1
$H \rightarrow ZZ^{(*)} \rightarrow 4\ell$ [18]. Section 2.2		,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,		5.1	19.7
	2-iet	42% VBF + VH		3	3
$4\mu$ , $2e2\mu$ , $4e$	Other	≈90% ggH	1.3, 1.8, 2.2%‡	3	3
$H \rightarrow WW^{(*)} \rightarrow lulu$ [17] Section 2.3	oulei	~5070 6611		19	19 /
$\Pi \rightarrow WW \rightarrow evev [\Pi], Section 2.5$	0-iot	06 08% ccH	oru 16% ‡	1.5	15.4
	0-jet	90-90% ggn	eµ: 10% ⁺	2	2
$ee + \mu\mu$ , $e\mu$	1-jet	82-84% ggri	eμ: 17 %*	2	2
	2-jet VBF	78-86% VBF		2	2
	2-jet VH	31–40% VH			2
3 <i>ℓ</i> 3 <i>ν</i> WH	SF-SS, SF-OS	$\approx 100\%$ WH, up to 20% $\tau\tau$		2	2
$\ell\ell + \ell'\nu jj ZH$	еее, ееµ, µµµ, µµе	≈100% ZH		4	4
$H \rightarrow \tau \tau$ [19], Section 2.4				4.9	19.7
	0-jet	≈98% ggH	11-14%	4	4
$e\tau_{h}, \mu\tau_{h}$	1-jet	70–80% ggH	12-16%	5	5
	2-jet VBF	75–83% VBF	13–16%	2	4
7.7	1-jet	67–70% ggH	10-12%	-	2
th th	2-jet VBF	80% VBF	11%	-	1
	0-jet	≈98% ggH, 23–30% WW	16-20%	2	2
eµ	1-jet	75–80% ggH, 31–38% WW	18-19%	2	2
	2-jet VBF	79–94% VBF, 37–45% WW	14–19%	1	2
	0-jet	88–98% ggH		4	4
ee, <i>µµ</i>	1-jet	74–78% ggH, ≈17% WW *		4	4
	2-jet CIV	≈50% VBF, ≈45% ggH, 17–	24% WW *	2	2
$\ell\ell + LL' \operatorname{ZH}$	$LL' = \tau_h \tau_{h,\ell} \tau_{h,eu}$	$\approx 15\%$ (70%) WW for $LL' =$	$\ell \tau_{\rm b} (eu)$	8	8
$\ell + \tau_{\rm b} \tau_{\rm b} WH$		$\approx 96\%$ VH, ZH/WH $\approx 0.1$		2	2
$\ell + \ell' \tau_{\rm b} WH$		$ZH/WH \approx 5\%$ , 9–11% WW	r	2	4
VH with H $\rightarrow$ bb [16]. Section 2.5		,		5.1	18.9
$W(\ell v)bb$	$p_{\rm T}({\rm V})$ bins	≈100% VH. 96–98% WH		4	6
$W(\pi y)$ bb	F1(*) 0110	93% WH		-	1
$Z(\ell\ell)$ bb	$n_{\rm T}({\rm V})$ bins	≈100% <b>7</b> H	$\approx 10\%$	4	4
Z(uv)bb	$n_{\rm r}({\rm V})$ bins	~100% VH 62_76% 7H		2	2
$t\bar{t}H$ with $H \rightarrow hadrons [14, 28]$ Section 2.6	P1(*) 0115	~100/0 11,02-70/0 2.11		5.0	10 2
$111$ while $11 \rightarrow$ flattons [14, 20], 3ection 2.6	tī loptop Liets	$\sim 00\%$ bb but $\sim 24\%$ W/W in	>6i + 2b	5.0	15.5
${ m H}  ightarrow { m bb}$	ti tepton+jets	~70 /0 DD DUT ~24 /0 WW IN	$\geq 0$ $j + 2D$	2	
<b>II</b>	ti unepton	43-05% DD, 8-35% WW, 4-1	470 TT	2	
$H \rightarrow \tau_h \tau_h$	tt lepton+jets	00-00% TT, 13-22% WW, 5-	-13% DD	-	6
ttH with H $\rightarrow$ leptons [29], Section 2.6				-	19.6
2 <i>ℓ</i> -SS		WW/ $\tau\tau \approx 3$		-	6
$3\ell$		WW/ $\tau\tau \approx 3$		-	2
10		MIMI			4

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## Combined m_H measurement

**160** [ arXiv:1412.8662 ]



# Extra Higgs sensitivity in $H \rightarrow \tau \tau$ analysis

[ JHEP 05 (2014) 104 ][ arXiv:1412.8662 ]

161



# $H \rightarrow VV$ results in combination

[ JHEP 01 (2014) 096 ][ PRD 89 (2014) 092007 ][ arXiv:1412.8662 ]

## What changed?

- **BR(H** $\rightarrow$ **VV) changes by 4 5%.** 
  - H→WW and H→ZZ paper results evaluated at H→ZZ m_H result: m_H = 125.6 GeV.
  - Combined mass slightly lower: m_H = 125.0 GeV.
- □ In the combination  $H \rightarrow WW$  includes the ttH, H

decaying to multi-lepton result:  $\sigma/\sigma_{SM} = 3.7 \pm 1.5$ .

σ/σ _{sm}	Individual publication	Combination
H→ZZ	0.93	1.00
H→WW	0.72	0.83



# ttH multi-leptons

163

[CMS-PAS-HIG-13-020][http://cern.ch/go/FKr9]

# Very extensive cross-checks performed:







164

# Significance of excesses

[ arXiv:1412.8662 ]

Channel grouping	Significance ( $\sigma$ )		
Charmer grouping	Observed	Expected	
$H \rightarrow ZZ$ tagged	6.5	6.3	
$H \rightarrow \gamma \gamma$ tagged	5.6	5.3	
$H \rightarrow WW$ tagged	4.7	5.4	
Grouped as in Ref. [22]	4.3	5.4	
$H \rightarrow \tau \tau$ tagged	3.8	3.9	
Grouped as in Ref. [23]	3.9	3.9	
$H \rightarrow bb tagged$	2.0	2.6	
Grouped as in Ref. [21]	2.1	2.5	
$H \rightarrow \mu \mu$ tagged	< 0.1	0.4	



# **Combined production measurement**

165



# Production mode scaling



# assuming SM BR structure

166

$$\square \mu_{ggH} = 0.85 ^{+0.11}_{-0.09} \text{ (stat.)} ^{+0.11}_{-0.08} \text{ (theo.)} ^{+0.10}_{-0.09} \text{ (syst.)}$$



# Coupling deviations summaries

[ arXiv:1412.8662 ][ arXiv:1307.1347 ]

167

Visible searches can constrain BR_{BSM}=BR_{inv}+Br_{undet}.
 Combine with H(inv) searches, assuming BR_{undet}=0.
 Can then scan BR_{inv} vs. BR_{undet}.



# Coupling



# deviations

8 [ arXiv:1412.8662 ][ arXiv:1307.1347 ]

Model memory store	Table in	Damamatan	Best-fit result		Comment
Model parameters	Ref. [169]	1 arameter	68% CL	95% CL	Comment
$\kappa_Z$ , $\lambda_{WZ}$ ( $\kappa_f$ =1)	_	$\lambda_{WZ}$	$0.94\substack{+0.22\\-0.18}$	[0.61, 1.45]	$\lambda_{WZ} = \kappa_W / \kappa_Z$ from ZZ and 0/1-jet WW channels.
$\kappa_Z, \lambda_{WZ}, \kappa_f$	44 (top)	$\lambda_{WZ}$	$0.92\substack{+0.14\\-0.12}$	[0.71, 1.24]	$\lambda_{WZ} = \kappa_W / \kappa_Z$ from full combination.
κ _V , κ _f	43 (top)	$\kappa_{ m V}$	$1.01\substack{+0.07 \\ -0.07}$	[0.87, 1.14]	$\kappa_{\rm V}$ scales couplings to W and Z bosons.
	(10)	$\kappa_{ m f}$	$0.87\substack{+0.14 \\ -0.13}$	[0.63, 1.15]	$\kappa_{\rm f}$ scales couplings to all fermions.
κ _V , λ _{du} , κ _u	46 (top)	$\lambda_{ m du}$	$0.99\substack{+0.19 \\ -0.18}$	[0.65, 1.39]	$\lambda_{du} = \kappa_u / \kappa_d$ , relates up-type and down-type fermions.
$\kappa_{ m V}, \lambda_{\ell  m q}, \kappa_{ m q}$	47 (top)	$\lambda_{\ell q}$	$1.03\substack{+0.23 \\ -0.21}$	[0.62, 1.50]	$\lambda_{\ell q} = \kappa_{\ell} / \kappa_{q}$ , relates leptons and quarks.
		$\kappa_{ m W}$	$0.95 \ ^{+0.14}_{-0.13}$	[0.68, 1.23]	
10-1- 10- 10-		$\kappa_Z$	$1.05 \ ^{+0.16}_{-0.16}$	[0.72, 1.35]	
κ _W , κ _Z , κ _t ,	Extends	$\kappa_{\mathrm{t}}$	$0.81 \ ^{+0.19}_{-0.15}$	[0.53, 1.20]	Up-type quarks (via t).
16 16 16	51	$\kappa_{ m b}$	$0.74 \ ^{+0.33}_{-0.29}$	[0.09, 1.44]	Down-type quarks (via b).
$\kappa_b, \kappa_\tau, \kappa_\mu$		$\kappa_{ au}$	$0.84 \ ^{+0.19}_{-0.18}$	[0.50, 1.24]	Electron and tau lepton (via $\tau$ ).
		$\kappa_{\mu}$	$0.49 \ ^{+1.38}_{-0.49}$	[0.00, 2.77]	$\kappa_{\mu}$ scales the coupling to muons.
Ma	B-6 [202]	M (GeV)	$245\pm15$	[217, 279]	$\kappa_{\rm f} = v \frac{m_{\rm f}^{e}}{M^{1+e}}$ and $\kappa_{\rm V} = v \frac{m_{\rm V}^{2e}}{M^{1+2e}}$
Μ, ε	Kei. [202]	$\epsilon$	$0.014\substack{+0.041\\-0.036}$	[-0.054, 0.100]	(Section 7.4)
	48	κ _g	$0.89^{+0.11}_{-0.10}$	[0.69, 1.11]	Effective couplings to
κ _g , κ _γ	(top)	κγ	$1.14_{-0.13}^{+0.12}$	[0.89, 1.40]	gluons (g) and photons ( $\gamma$ ).
					111 ( 2017)
$\kappa_{\rm g}, \kappa_{\gamma}, {\rm BR}_{\rm BSM}$	48 (middle)	BR _{BSM}	$\leq 0.14$	[0.00, 0.32]	Allows for BSM decays.
$\kappa_{g}, \kappa_{\gamma}, BR_{BSM}$ with H(inv) searches	48 (middle)	BR _{BSM} BR _{inv}	$rac{\leq 0.14}{0.03  {}^{+0.15}_{-0.03}}$	[0.00, 0.32]	Allows for BSM decays. H(inv) use implies BR _{undet} =0.
$\frac{\kappa_{\rm g}, \kappa_{\gamma}, {\rm BR}_{\rm BSM}}{{\rm with } {\rm H}({\rm inv}) {\rm  searches}}$ with H(inv) and $\kappa_i = 1$	48 (middle) — —	BR _{BSM} BR _{inv} BR _{inv}	${\leq 0.14} \over 0.03  {}^{+0.15}_{-0.03} \over 0.06  {}^{+0.11}_{-0.06}$	[0.00, 0.32] [0.00, 0.32] [0.00, 0.27]	Allows for BSM decays. $H(inv)$ use implies $BR_{undet} = 0$ . Assumes $\kappa_i = 1$ and uses $H(inv)$ .
$ \begin{array}{c} \kappa_{\rm g}, \kappa_{\gamma}, {\rm BR}_{\rm BSM} \\ \hline \\ {\rm with} \ {\rm H}({\rm inv}) \ {\rm searches} \\ \hline \\ \hline \\ {\rm with} \ {\rm H}({\rm inv}) \ {\rm and} \ \kappa_i = 1 \\ \hline \end{array} $	48 (middle) — —	$\frac{BR_{BSM}}{BR_{inv}}$ $\frac{BR_{inv}}{\kappa_{gZ}}$	$\leq 0.14 \ 0.03 \ {}^{+0.15}_{-0.03} \ 0.06 \ {}^{+0.11}_{-0.06} \ 0.98 \ {}^{+0.14}_{-0.13}$	[0.00, 0.32] [0.00, 0.32] [0.00, 0.27] [0.73, 1.27]	Allows for BSM decays. $H(inv)$ use implies $BR_{undet} = 0$ . Assumes $\kappa_i = 1$ and uses $H(inv)$ . $\kappa_{gZ} = \kappa_g \kappa_Z / \kappa_H$ , i.e. floating $\kappa_H$ .
$\frac{\kappa_{g}, \kappa_{\gamma}, BR_{BSM}}{\text{with } H(\text{inv}) \text{ searches}}$ with H(inv) and $\kappa_i = 1$ $\kappa_{gZ},$	48 (middle) 	$\frac{BR_{BSM}}{BR_{inv}}$ $\frac{BR_{inv}}{\kappa_{gZ}}$ $\lambda_{WZ}$	$\frac{\leq 0.14}{0.03 + 0.15 - 0.03}$ $\frac{0.06 + 0.11}{-0.06}$ $0.98 + 0.14 - 0.13 \\0.87 + 0.15 - 0.13$	[0.00, 0.32] [0.00, 0.32] [0.73, 1.27] [0.63, 1.19]	Allows for BSM decays. H(inv) use implies BR _{undet} =0. Assumes $\kappa_i = 1$ and uses H(inv). $\kappa_{gZ} = \kappa_g \kappa_Z / \kappa_H$ , i.e. floating $\kappa_H$ . $\lambda_{WZ} = \kappa_W / \kappa_Z$ .
$\frac{\kappa_{g}, \kappa_{\gamma}, BR_{BSM}}{\text{with } H(\text{inv}) \text{ searches}}$ $\frac{\text{with } H(\text{inv}) \text{ and } \kappa_{i} = 1}{\kappa_{gZ}}$	48 (middle) 	$\frac{BR_{BSM}}{BR_{inv}}$ $\frac{BR_{inv}}{\kappa_{gZ}}$ $\frac{\kappa_{gZ}}{\lambda_{WZ}}$ $\lambda_{Zg}$	$\begin{array}{c} \leq 0.14 \\ 0.03 \ {}^{+0.15}_{-0.03} \\ 0.06 \ {}^{+0.11}_{-0.06} \\ 0.98 \ {}^{+0.14}_{-0.13} \\ 0.87 \ {}^{+0.15}_{-0.13} \\ 1.39 \ {}^{+0.36}_{-0.28} \end{array}$	[0.00, 0.32] [0.00, 0.32] [0.00, 0.27] [0.73, 1.27] [0.63, 1.19] [0.87, 2.18]	Allows for BSM decays. H(inv) use implies BR _{undet} =0. Assumes $\kappa_i = 1$ and uses H(inv). $\kappa_{gZ} = \kappa_g \kappa_Z / \kappa_H$ , i.e. floating $\kappa_H$ . $\lambda_{WZ} = \kappa_W / \kappa_Z$ . $\lambda_{Zg} = \kappa_Z / \kappa_g$ .
$ \begin{array}{c} \kappa_{\rm g}, \kappa_{\gamma}, {\rm BR}_{\rm BSM} \\ \hline \\ {\rm with} \ {\rm H}({\rm inv}) \ {\rm searches} \\ \hline \\ \hline \\ {\rm with} \ {\rm H}({\rm inv}) \ {\rm and} \ \kappa_i = 1 \\ \hline \\ \hline \\ \kappa_{\rm gZ}, \\ \hline \\ \lambda_{\rm WZ}, \ \lambda_{\rm Zg}, \ \lambda_{\rm bZ}, \end{array} $	48 (middle) 	$\frac{\text{BR}_{\text{BSM}}}{\text{BR}_{\text{inv}}}$ $\frac{\text{BR}_{\text{inv}}}{\kappa_{gZ}}$ $\lambda_{WZ}$ $\lambda_{Zg}$ $\lambda_{bZ}$	$ \leq 0.14 \\ 0.03 + 0.15 \\ -0.03 \\ 0.06 + 0.11 \\ -0.06 \\ -0.06 \\ -0.13 \\ 0.87 + 0.15 \\ -0.13 \\ 0.87 + 0.15 \\ -0.13 \\ 1.39 + 0.36 \\ -0.28 \\ 0.59 + 0.22 \\ 0.59 + 0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ -0.23 \\ $		Allows for BSM decays. H(inv) use implies BR _{undet} =0. Assumes $\kappa_i = 1$ and uses H(inv). $\kappa_{gZ} = \kappa_g \kappa_Z / \kappa_H$ , i.e. floating $\kappa_H$ . $\lambda_{WZ} = \kappa_W / \kappa_Z$ . $\lambda_{Zg} = \kappa_Z / \kappa_g$ . $\lambda_{bZ} = \kappa_b / \kappa_Z$ .
$\begin{aligned} \kappa_{\rm g}, \kappa_{\gamma}, {\rm BR}_{\rm BSM} \\ \text{with } {\rm H}({\rm inv}) \text{ searches} \\ \hline \\ \hline \\ {\rm with } {\rm H}({\rm inv}) \text{ and } \kappa_i = 1 \\ \hline \\ \\ \kappa_{\rm gZ}, \\ \lambda_{\rm WZ}, \lambda_{\rm Zg}, \lambda_{\rm bZ}, \end{aligned}$	48 (middle) — — 50 (bottom)	$\frac{\text{BR}_{\text{BSM}}}{\text{BR}_{\text{inv}}}$ $\frac{\text{BR}_{\text{inv}}}{\kappa_{gZ}}$ $\frac{\kappa_{gZ}}{\lambda_{WZ}}$ $\frac{\lambda_{Zg}}{\lambda_{bZ}}$ $\frac{\lambda_{\gamma Z}}{\lambda_{\gamma Z}}$	$ \leq 0.14 \\ 0.03 + 0.15 \\ -0.03 \\ 0.06 + 0.11 \\ -0.06 \\ -0.13 \\ 0.87 + 0.15 \\ -0.13 \\ 1.39 + 0.36 \\ -0.28 \\ 0.59 + 0.22 \\ 0.59 + 0.23 \\ 0.93 + 0.17 \\ 0.14 $		Allows for BSM decays. H(inv) use implies BR _{undet} =0. Assumes $\kappa_i = 1$ and uses H(inv). $\kappa_{gZ} = \kappa_g \kappa_Z / \kappa_H$ , i.e. floating $\kappa_H$ . $\lambda_{WZ} = \kappa_W / \kappa_Z$ . $\lambda_{Zg} = \kappa_Z / \kappa_g$ . $\lambda_{bZ} = \kappa_b / \kappa_Z$ . $\lambda_{\gamma Z} = \kappa_{\gamma} / \kappa_Z$ .
$\begin{aligned} \kappa_{\rm g}, \kappa_{\gamma}, {\rm BR}_{\rm BSM} \\ \text{with } {\rm H}({\rm inv}) \text{ searches} \\ \hline \\ \hline \\ \hline \\ \hline \\ \\ \hline \\ \\ \\ \\ \\ \\ \\ \\ $	48 (middle) — — 50 (bottom)	$\frac{\text{BR}_{\text{BSM}}}{\text{BR}_{\text{inv}}}$ $\frac{\text{BR}_{\text{inv}}}{\kappa_{gZ}}$ $\lambda_{WZ}$ $\lambda_{Zg}$ $\lambda_{bZ}$ $\lambda_{\gamma Z}$ $\lambda_{\tau Z}$	$ \leq 0.14 \\ 0.03 + 0.15 \\ -0.03 \\ 0.06 + 0.11 \\ 0.98 + 0.14 \\ -0.13 \\ 0.87 + 0.15 \\ -0.13 \\ 1.39 + 0.36 \\ -0.28 \\ 0.59 + 0.22 \\ -0.23 \\ 0.93 + 0.17 \\ 0.79 + 0.19 \\ 0.79 + 0.17 \\ 0.79 + 0.17 \\ 0.79 \\ -0.17 \\ 0.14 \\ 0.79 + 0.17 \\ 0.14 \\ 0.79 + 0.17 \\ 0.17 \\ 0.14 \\ 0.79 + 0.17 \\ 0.17 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 \\ 0.11 $		Allows for BSM decays. H(inv) use implies BR _{undet} =0. Assumes $\kappa_i = 1$ and uses H(inv). $\kappa_{gZ} = \kappa_g \kappa_Z / \kappa_H$ , i.e. floating $\kappa_H$ . $\lambda_{WZ} = \kappa_W / \kappa_Z$ . $\lambda_{Zg} = \kappa_Z / \kappa_g$ . $\lambda_{bZ} = \kappa_b / \kappa_Z$ . $\lambda_{\gamma Z} = \kappa_{\gamma} / \kappa_Z$ . $\lambda_{\tau Z} = \kappa_{\tau} / \kappa_Z$ .
$\begin{aligned} \kappa_{\rm g}, \kappa_{\gamma}, {\rm BR}_{\rm BSM} \\ & \text{with } {\rm H}({\rm inv}) \text{ searches} \\ \hline \\ \hline \\ \hline \\ \hline \\ \\ \hline \\ \\ \\ \\ \\ \\ \\ \\ $	48 (middle)  50 (bottom)	$\frac{\text{BR}_{\text{BSM}}}{\text{BR}_{\text{inv}}}$ $\frac{\text{BR}_{\text{inv}}}{\kappa_{\text{gZ}}}$ $\lambda_{\text{WZ}}$ $\lambda_{\text{Zg}}$ $\lambda_{\text{bZ}}$ $\lambda_{\gamma Z}$ $\lambda_{\tau Z}$ $\lambda_{\text{tg}}$	$ \leq 0.14 \\ 0.03 + 0.15 \\ -0.03 \\ 0.06 + 0.11 \\ 0.98 + 0.14 \\ -0.13 \\ 0.87 + 0.15 \\ -0.13 \\ 1.39 + 0.36 \\ -0.28 \\ 0.59 + 0.22 \\ -0.23 \\ 0.93 + 0.17 \\ -0.14 \\ 0.79 + 0.19 \\ -0.17 \\ 2.18 + 0.54 \\ -0.46 \\ \end{array} $		Allows for BSM decays. H(inv) use implies BR _{undet} =0. Assumes $\kappa_i = 1$ and uses H(inv). $\kappa_{gZ} = \kappa_g \kappa_Z / \kappa_H$ , i.e. floating $\kappa_H$ . $\lambda_{WZ} = \kappa_W / \kappa_Z$ . $\lambda_{Zg} = \kappa_Z / \kappa_g$ . $\lambda_{bZ} = \kappa_b / \kappa_Z$ . $\lambda_{\gamma Z} = \kappa_{\gamma} / \kappa_Z$ . $\lambda_{\tau Z} = \kappa_{\tau} / \kappa_Z$ . $\lambda_{tg} = \kappa_t / \kappa_g$ .
$\begin{aligned} \kappa_{\rm g}, \kappa_{\gamma}, \text{BR}_{\rm BSM} \\ \text{with } H(\text{inv}) \text{ searches} \\ \hline \\ \hline \\ \hline \\ \\ \hline \\ \\ \\ \\ \\ \\ \\ \\ \\ \\ $	48 (middle) — — 50 (bottom)	$\frac{\text{BR}_{\text{BSM}}}{\text{BR}_{\text{inv}}}$ $\frac{\text{BR}_{\text{inv}}}{\kappa_{\text{gZ}}}$ $\lambda_{\text{WZ}}$ $\lambda_{\text{Zg}}$ $\lambda_{\text{bZ}}$ $\lambda_{\gamma Z}$ $\lambda_{\tau Z}$ $\lambda_{\text{tg}}$ $\frac{\kappa_{\text{V}}}{\kappa_{\text{V}}}$	$ \leq 0.14 \\ 0.03 + 0.15 \\ -0.03 \\ 0.06 + 0.11 \\ -0.06 \\ 0.98 + 0.14 \\ -0.13 \\ 0.87 + 0.15 \\ -0.13 \\ 1.39 + 0.36 \\ -0.28 \\ 0.59 + 0.22 \\ -0.23 \\ 0.59 + 0.22 \\ -0.23 \\ 0.93 + 0.17 \\ 0.93 + 0.17 \\ 0.93 + 0.17 \\ -0.17 \\ 2.18 + 0.54 \\ -0.46 \\ 0.96 + 0.14 \\ 0.96 + 0.15 \\ \end{array} $		Allows for BSM decays. H(inv) use implies BR _{undet} =0. Assumes $\kappa_i = 1$ and uses H(inv). $\kappa_{gZ} = \kappa_g \kappa_Z / \kappa_H$ , i.e. floating $\kappa_H$ . $\lambda_{WZ} = \kappa_W / \kappa_Z$ . $\lambda_{Zg} = \kappa_Z / \kappa_g$ . $\lambda_{bZ} = \kappa_b / \kappa_Z$ . $\lambda_{\gamma Z} = \kappa_{\gamma} / \kappa_Z$ . $\lambda_{\tau Z} = \kappa_{\tau} / \kappa_Z$ . $\lambda_{tg} = \kappa_t / \kappa_g$ .
$\kappa_{g}, \kappa_{\gamma}, BR_{BSM}$ with H(inv) searches with H(inv) and $\kappa_{i} = 1$ $\kappa_{gZ},$ $\lambda_{WZ}, \lambda_{Zg}, \lambda_{bZ},$ $\lambda_{\gamma Z}, \lambda_{\tau Z}, \lambda_{tg}$	48 (middle)  50 (bottom)	$\begin{array}{c c} & & & & & \\ \hline & & & & & \\ \hline & & & & & \\ \hline & & & &$	$ \leq 0.14 \\ 0.03 + 0.15 \\ -0.03 \\ 0.06 + 0.11 \\ 0.98 + 0.14 \\ -0.13 \\ 0.87 + 0.15 \\ -0.13 \\ 0.87 + 0.15 \\ -0.13 \\ 0.87 + 0.15 \\ -0.28 \\ 0.59 + 0.22 \\ 0.23 \\ -0.14 \\ 0.79 + 0.17 \\ -0.17 \\ 2.18 + 0.54 \\ -0.46 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.05 + 0.15 \\ 0.64 + 0.28 \\ 0.29 \\ -0.15 \\ 0.64 + 0.28 \\ 0.29 \\ -0.15 \\ 0.64 + 0.28 \\ 0.29 \\ -0.15 \\ 0.64 + 0.28 \\ 0.29 \\ -0.15 \\ 0.64 + 0.28 \\ 0.29 \\ -0.15 \\ 0.64 + 0.28 \\ 0.29 \\ -0.15 \\ 0.64 + 0.28 \\ 0.29 \\ -0.15 \\ 0.64 + 0.28 \\ 0.29 \\ -0.15 \\ 0.64 + 0.28 \\ 0.29 \\ -0.15 \\ 0.64 + 0.28 \\ 0.29 \\ -0.15 \\ 0.64 + 0.28 \\ 0.29 \\ -0.15 \\ 0.28 \\ -0.15 \\ 0.28 \\ -0.15 \\ 0.28 \\ -0.15 \\ 0.28 \\ -0.15 \\ 0.28 \\ -0.15 \\ 0.28 \\ -0.15 \\ 0.28 \\ -0.15 \\ 0.28 \\ -0.28 \\ -0.15 \\ 0.28 \\ -0.15 \\ -0.28 \\ -0.15 \\ -0.28 \\ -0.15 \\ -0.28 \\ -0.15 \\ -0.28 \\ -0.15 \\ -0.28 \\ -0.15 \\ -0.15 \\ -0.28 \\ -0.15 \\ -0.15 \\ -0.28 \\ -0.15 \\ -0.15 \\ -0.28 \\ -0.15 \\ -0.15 \\ -0.15 \\ -0.15 \\ -0.15 \\ -0.15 \\ -0.15 \\ -0.15 \\ -0.15 \\ -0.15 \\ -0.15 \\ -0.28 \\ -0.15 \\ -0.15 \\ -0.15 \\ -0.28 \\ -0.15 \\ -0.15 \\ -0.15 \\ -0.15 \\ -0.28 \\ -0.15 \\ -0.28 \\ -0.15 \\ -0.28 \\ -0.15 \\ -0.28 \\ -0.15 \\ -0.28 \\ -0.15 \\ -0.28 \\ -0.15 \\ -0.28 \\ -0.15 \\ -0.28 \\ -0.15 \\ -0.28 \\ -0.15 \\ -0.28 \\ -0.15 \\ -0.28 \\ -0.15 \\ -0.28 \\ -0.15 \\ -0.28 \\ -0.15 \\ -0.28 \\ -0.15 \\ -0.28 \\ -0.28 \\ -0.15 \\ -0.28 \\ -0.28 \\ -0.28 \\ -0.28 \\ -0.28 \\ -0.28 \\ -0.28 \\ -0.28 \\ -0.28 \\ -0.28 \\ -0.28 \\ -0.28 \\ -0.28 \\ -0.28 \\ -0.28 \\ -0.28 \\ -0.28 \\ -0.28 \\ -0.28 \\ -0.28 \\ -0.28 \\ -0.28 \\ -0.28 \\ -0.28 \\ -0.28 \\ -0.28 \\ -0.28 \\ -0.28 \\ -0.28 \\ -0.28 \\ -0.28 \\ -0.28 \\ -0.28 \\ -0.28 \\ -0.28 \\ -0.28 \\ -0.28 \\ -0.28 \\ -0.28 \\ -0.28 \\ -0.28 \\ -0.28 \\ -0.28 \\ -0.28 \\ -0.28 \\ -0.28 \\ -0.28 \\ -0.28 \\ -0.28 \\ -0.28 \\ -0.28 \\ -0.28 \\ -0.28 \\ -0.28 \\ -0.28 \\ -0.28 \\ -0.28 \\ -0.28 \\ -0.28 \\ -0.28 \\ -0.28 \\ -0.28 \\ -0.28 \\ -0.28 \\ -0.28 \\ -0.28 \\ -0.28 \\ -0.28 \\ -0.28 \\ -0.28 \\ -0.28 \\ -0.28 \\ -0.28 \\ -0.28 \\ -0.28 \\ -0.28 \\ -0.28 \\ -0.28 \\ -0.28 \\ -0.28 \\ -0.28 \\ -0.28 \\ -0.28 \\ -0.28 \\ -0.28 \\ -0.28 \\ -0.28 \\ -0.28 \\ -0.28 \\ -0.28 \\ -0.28 \\ -0.28 \\ -0.28 \\ -0.28 \\ -0.28 \\ -0.28 \\ -0.28 \\ -0.28$		Allows for BSM decays. H(inv) use implies BR _{undet} =0. Assumes $\kappa_i = 1$ and uses H(inv). $\kappa_{gZ} = \kappa_g \kappa_Z / \kappa_H$ , i.e. floating $\kappa_H$ . $\lambda_{WZ} = \kappa_W / \kappa_Z$ . $\lambda_{Zg} = \kappa_Z / \kappa_g$ . $\lambda_{bZ} = \kappa_b / \kappa_Z$ . $\lambda_{\gamma Z} = \kappa_{\gamma} / \kappa_Z$ . $\lambda_{\tau Z} = \kappa_{\tau} / \kappa_Z$ . $\lambda_{tg} = \kappa_t / \kappa_g$ . Down-type quarks (via b).
$\kappa_{g}, \kappa_{\gamma}, BR_{BSM}$ with H(inv) searches with H(inv) and $\kappa_{i} = 1$ $\kappa_{gZ},$ $\lambda_{WZ}, \lambda_{Zg}, \lambda_{bZ},$ $\lambda_{\gamma Z}, \lambda_{\tau Z}, \lambda_{tg}$ $\kappa_{V}, \kappa_{b}, \kappa_{\tau},$	48 (middle) 	$\begin{array}{c c} & BR_{BSM} \\ \hline BR_{inv} \\ \hline BR_{inv} \\ \hline \\ & \kappa_{gZ} \\ & \lambda_{WZ} \\ & \lambda_{Zg} \\ & \lambda_{bZ} \\ & \lambda_{\rho Z} \\ & \lambda_{\rho Z} \\ & \lambda_{\tau Z} \\ & \lambda_{tg} \\ \hline \\ & \kappa_{V} \\ & \kappa_{b} \\ & \kappa_{\tau} \end{array}$	$ \leq 0.14 \\ 0.03 + 0.15 \\ -0.03 \\ 0.06 + 0.11 \\ 0.98 + 0.14 \\ -0.13 \\ 0.87 + 0.15 \\ -0.13 \\ 1.39 + 0.36 \\ -0.28 \\ 0.59 + 0.22 \\ 0.59 + 0.22 \\ 0.59 + 0.22 \\ 0.93 + 0.17 \\ 0.79 + 0.19 \\ -0.17 \\ 2.18 + 0.54 \\ -0.46 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.18 \\ 0.64 + 0.28 \\ 0.82 + 0.18 \\ 0.82 + 0.18 \\ 0.82 + 0.18 \\ 0.82 + 0.18 \\ 0.82 + 0.18 \\ 0.82 + 0.18 \\ 0.82 + 0.18 \\ 0.82 + 0.18 \\ 0.82 + 0.18 \\ 0.82 + 0.18 \\ 0.82 + 0.18 \\ 0.82 + 0.18 \\ 0.82 + 0.18 \\ 0.82 + 0.18 \\ 0.82 + 0.18 \\ 0.82 + 0.18 \\ 0.82 + 0.18 \\ 0.82 + 0.18 \\ 0.82 + 0.18 \\ 0.82 + 0.18 \\ 0.82 + 0.18 \\ 0.82 + 0.18 \\ 0.82 + 0.18 \\ 0.82 + 0.18 \\ 0.82 + 0.18 \\ 0.82 + 0.18 \\ 0.82 + 0.18 \\ 0.82 + 0.18 \\ 0.82 + 0.18 \\ 0.82 + 0.18 \\ 0.82 + 0.18 \\ 0.82 + 0.18 \\ 0.82 + 0.18 \\ 0.82 + 0.18 \\ 0.82 + 0.18 \\ 0.82 + 0.18 \\ 0.82 + 0.18 \\ 0.82 + 0.18 \\ 0.82 + 0.18 \\ 0.82 + 0.18 \\ 0.82 + 0.18 \\ 0.82 + 0.18 \\ 0.82 + 0.18 \\ 0.82 + 0.18 \\ 0.82 + 0.18 \\ 0.82 + 0.18 \\ 0.82 + 0.18 \\ 0.82 + 0.18 \\ 0.82 + 0.18 \\ 0.82 + 0.18 \\ 0.82 + 0.18 \\ 0.82 + 0.18 \\ 0.82 + 0.18 \\ 0.82 + 0.18 \\ 0.82 + 0.18 \\ 0.82 + 0.18 \\ 0.82 + 0.18 \\ 0.82 + 0.18 \\ 0.82 + 0.18 \\ 0.82 + 0.18 \\ 0.82 + 0.18 \\ 0.82 + 0.18 \\ 0.82 + 0.18 \\ 0.82 + 0.18 \\ 0.82 + 0.18 \\ 0.82 + 0.18 \\ 0.82 + 0.18 \\ 0.82 + 0.18 \\ 0.82 + 0.18 \\ 0.82 + 0.18 \\ 0.82 + 0.18 \\ 0.82 + 0.18 \\ 0.82 + 0.18 \\ 0.82 + 0.18 \\ 0.82 + 0.18 \\ 0.82 + 0.18 \\ 0.82 + 0.18 \\ 0.82 + 0.18 \\ 0.82 + 0.18 \\ 0.82 + 0.18 \\ 0.82 + 0.18 \\ 0.82 + 0.18 \\ 0.82 + 0.18 \\ 0.82 + 0.18 \\ 0.82 + 0.18 \\ 0.82 + 0.18 \\ 0.82 + 0.18 \\ 0.82 + 0.18 \\ 0.82 + 0.18 \\ 0.82 + 0.18 \\ 0.82 + 0.18 \\ 0.82 + 0.18 \\ 0.82 + 0.18 \\ 0.82 + 0.18 \\ 0.82 + 0.18 \\ 0.82 + 0.18 \\ 0.82 + 0.18 \\ 0.82 + 0.18 \\ 0.82 + 0.18 \\ 0.82 + 0.18 \\ 0.82 + 0.18 \\ 0.82 + 0.18 \\ 0.82 + 0.18 \\ 0.82 + 0.18 \\ 0.82 + 0.18 \\ 0.82 + 0.18 \\ 0.82 + 0.18 \\ 0.82 + 0.18 \\ 0.82 + 0.18 \\ 0.82 + 0.18 \\ 0.82 + 0.18 \\ 0.82 + 0.18 \\ 0.82 + 0.18 \\ 0.82 + 0.18 \\ 0.82 + 0.18 \\ 0.82 + 0.18 \\ 0.82 + 0.18 \\ 0.82 + 0.18 \\ 0.82 + 0.18 \\ 0.82 + 0.18 \\ 0.82 + 0.18 \\ 0.82 + 0.18 \\ 0.82 + 0.18 \\ 0.82 + 0.18 \\ 0.82 + 0.18 $		Allows for BSM decays. H(inv) use implies BR _{undet} =0. Assumes $\kappa_i = 1$ and uses H(inv). $\kappa_{gZ} = \kappa_g \kappa_Z / \kappa_H$ , i.e. floating $\kappa_H$ . $\lambda_{WZ} = \kappa_W / \kappa_Z$ . $\lambda_{Zg} = \kappa_Z / \kappa_g$ . $\lambda_{bZ} = \kappa_b / \kappa_Z$ . $\lambda_{\gamma Z} = \kappa_{\gamma} / \kappa_Z$ . $\lambda_{\tau Z} = \kappa_{\tau} / \kappa_Z$ . $\lambda_{tg} = \kappa_t / \kappa_g$ . Down-type quarks (via b). Charged leptons (via $\tau$ ).
$\kappa_{g}, \kappa_{\gamma}, BR_{BSM}$ with H(inv) searches with H(inv) and $\kappa_{i} = 1$ $\kappa_{gZ},$ $\lambda_{WZ}, \lambda_{Zg}, \lambda_{bZ},$ $\lambda_{\gamma Z}, \lambda_{\tau Z}, \lambda_{tg}$ $\kappa_{V}, \kappa_{b}, \kappa_{\tau},$	48 (middle) — 50 (bottom) Similar to 50 (top)	$\begin{array}{c c} & BR_{BSM} \\ \hline BR_{inv} \\ \hline BR_{inv} \\ \hline \\ \kappa_{gZ} \\ \lambda_{WZ} \\ \lambda_{Zg} \\ \lambda_{bZ} \\ \lambda_{\rho Z} \\ \lambda_{\gamma Z} \\ \lambda_{\tau Z} \\ \lambda_{tg} \\ \hline \\ \kappa_{V} \\ \kappa_{b} \\ \kappa_{\tau} \\ \kappa_{t} \\ \hline \end{array}$	$ \leq 0.14 \\ 0.03 + 0.15 \\ -0.03 \\ 0.06 + 0.11 \\ 0.98 + 0.14 \\ -0.13 \\ 0.87 + 0.15 \\ -0.13 \\ 0.87 + 0.15 \\ -0.23 \\ 0.59 + 0.22 \\ 0.59 + 0.22 \\ 0.59 + 0.22 \\ 0.93 + 0.17 \\ 0.79 + 0.19 \\ 0.79 + 0.19 \\ 0.17 \\ 2.18 + 0.54 \\ -0.46 \\ 0.96 + 0.14 \\ 0.96 + 0.15 \\ 0.64 + 0.28 \\ 0.82 + 0.18 \\ 1.60 + 0.34 \\ 1.60 + 0.34 \\ 0.32 \\ 0.32 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\ 0.33 \\$		Allows for BSM decays. H(inv) use implies BR _{undet} =0. Assumes $\kappa_i = 1$ and uses H(inv). $\kappa_{gZ} = \kappa_g \kappa_Z / \kappa_H$ , i.e. floating $\kappa_H$ . $\lambda_{WZ} = \kappa_W / \kappa_Z$ . $\lambda_{Zg} = \kappa_Z / \kappa_g$ . $\lambda_{bZ} = \kappa_b / \kappa_Z$ . $\lambda_{\gamma Z} = \kappa_{\gamma} / \kappa_Z$ . $\lambda_{\tau Z} = \kappa_{\tau} / \kappa_Z$ . $\lambda_{tg} = \kappa_t / \kappa_g$ . Down-type quarks (via b). Charged leptons (via $\tau$ ). Up-type quarks (via t).
$\kappa_{g}, \kappa_{\gamma}, BR_{BSM}$ with H(inv) searches with H(inv) and $\kappa_{i} = 1$ $\kappa_{gZ},$ $\lambda_{WZ}, \lambda_{Zg}, \lambda_{bZ},$ $\lambda_{\gamma Z}, \lambda_{\tau Z}, \lambda_{tg}$ $\kappa_{V}, \kappa_{b}, \kappa_{\tau},$ $\kappa_{t}, \kappa_{g}, \kappa_{\gamma}$	48 (middle) — 50 (bottom) Similar to 50 (top)	$\begin{array}{c c} & BR_{BSM} \\ \hline BR_{inv} \\ \hline BR_{inv} \\ \hline \\ \kappa_{gZ} \\ \lambda_{WZ} \\ \lambda_{Zg} \\ \lambda_{bZ} \\ \lambda_{\rhoZ} \\ \lambda_{\gamma Z} \\ \lambda_{\tau Z} \\ \lambda_{tg} \\ \hline \\ \kappa_{V} \\ \kappa_{b} \\ \kappa_{\tau} \\ \kappa_{t} \\ \kappa_{g} \\ \end{array}$	$ \leq 0.14 \\ 0.03 + 0.15 \\ -0.03 \\ 0.06 + 0.11 \\ 0.98 + 0.14 \\ -0.13 \\ 0.87 + 0.15 \\ -0.13 \\ 0.87 + 0.15 \\ -0.13 \\ 0.87 + 0.15 \\ -0.28 \\ 0.59 + 0.22 \\ -0.23 \\ 0.59 + 0.27 \\ -0.23 \\ 0.93 + 0.17 \\ 0.93 + 0.17 \\ 0.93 + 0.17 \\ 0.93 + 0.17 \\ 0.93 + 0.17 \\ 0.17 \\ -0.18 \\ -0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.$		Allows for BSM decays. H(inv) use implies BR _{undet} =0. Assumes $\kappa_i = 1$ and uses H(inv). $\kappa_{gZ} = \kappa_g \kappa_Z / \kappa_H$ , i.e. floating $\kappa_H$ . $\lambda_{WZ} = \kappa_W / \kappa_Z$ . $\lambda_{Zg} = \kappa_Z / \kappa_g$ . $\lambda_{bZ} = \kappa_b / \kappa_Z$ . $\lambda_{\gamma Z} = \kappa_{\gamma} / \kappa_Z$ . $\lambda_{\tau Z} = \kappa_{\tau} / \kappa_Z$ . $\lambda_{tg} = \kappa_t / \kappa_g$ . Down-type quarks (via b). Charged leptons (via $\tau$ ). Up-type quarks (via t).
$\begin{aligned} \kappa_{\rm g}, \kappa_{\gamma}, {\rm BR}_{\rm BSM} \\ \text{with } {\rm H}({\rm inv}) \text{ searches} \\ \hline \\ \kappa_{\rm gZ}, \\ & \lambda_{\rm WZ}, \lambda_{\rm Zg}, \lambda_{\rm bZ}, \\ & \lambda_{\gamma Z}, \lambda_{\tau Z}, \lambda_{\rm tg} \\ \hline \\ \hline \\ \kappa_{\rm V}, \kappa_{\rm b}, \kappa_{\tau}, \\ & \kappa_{\rm t}, \kappa_{\rm g}, \kappa_{\gamma} \end{aligned}$	48 (middle) — 50 (bottom) Similar to 50 (top)	$\begin{array}{c c} & BR_{BSM} \\ \hline BR_{inv} \\ \hline BR_{inv} \\ \hline \\ \kappa_{gZ} \\ \lambda_{WZ} \\ \lambda_{Zg} \\ \lambda_{bZ} \\ \lambda_{\rho Z} \\ \lambda_{\gamma Z} \\ \lambda_{\tau Z} \\ \lambda_{tg} \\ \hline \\ \kappa_{V} \\ \kappa_{b} \\ \kappa_{\tau} \\ \kappa_{t} \\ \kappa_{g} \\ \kappa_{\gamma} \\ \end{array}$	$ \leq 0.14 \\ 0.03 + 0.15 \\ -0.03 \\ 0.06 + 0.11 \\ 0.98 + 0.04 \\ -0.13 \\ 0.87 + 0.15 \\ -0.13 \\ 0.87 + 0.15 \\ -0.13 \\ 0.87 + 0.15 \\ -0.28 \\ 0.59 + 0.22 \\ -0.23 \\ 0.93 + 0.17 \\ 0.93 + 0.17 \\ 0.93 + 0.17 \\ 0.93 + 0.17 \\ 0.93 + 0.17 \\ 0.11 \\ 0.79 + 0.19 \\ -0.11 \\ 0.79 + 0.19 \\ -0.11 \\ 0.94 + 0.12 \\ 0.11 \\ 0.94 + 0.12 \\ 0.11 \\ 0.94 + 0.12 \\ 0.11 \\ 0.94 + 0.12 \\ 0.11 \\ 0.98 + 0.11 \\ 0.98 + 0.11 \\ 0.98 + 0.11 \\ 0.98 + 0.11 \\ 0.98 + 0.11 \\ 0.98 + 0.11 \\ 0.98 + 0.11 \\ 0.98 + 0.11 \\ 0.98 + 0.11 \\ 0.98 + 0.11 \\ 0.98 + 0.11 \\ 0.98 + 0.11 \\ 0.98 + 0.11 \\ 0.98 + 0.11 \\ 0.98 + 0.11 \\ 0.98 + 0.11 \\ 0.98 + 0.11 \\ 0.98 + 0.11 \\ 0.98 + 0.11 \\ 0.98 + 0.11 \\ 0.98 + 0.11 \\ 0.98 + 0.11 \\ 0.98 + 0.11 \\ 0.98 + 0.11 \\ 0.98 + 0.11 \\ 0.98 + 0.11 \\ 0.98 + 0.11 \\ 0.98 + 0.11 \\ 0.98 + 0.11 \\ 0.98 + 0.11 \\ 0.98 + 0.11 \\ 0.98 + 0.11 \\ 0.98 + 0.11 \\ 0.98 + 0.11 \\ 0.98 + 0.11 \\ 0.98 + 0.11 \\ 0.98 + 0.11 \\ 0.98 + 0.11 \\ 0.98 + 0.11 \\ 0.98 + 0.11 \\ 0.98 + 0.11 \\ 0.98 + 0.11 \\ 0.98 + 0.11 \\ 0.98 + 0.11 \\ 0.98 + 0.11 \\ 0.98 + 0.11 \\ 0.98 + 0.11 \\ 0.98 + 0.11 \\ 0.98 + 0.11 \\ 0.98 + 0.11 \\ 0.98 + 0.11 \\ 0.98 + 0.11 \\ 0.98 + 0.11 \\ 0.98 + 0.11 \\ 0.98 + 0.11 \\ 0.98 + 0.11 \\ 0.98 + 0.11 \\ 0.98 + 0.11 \\ 0.98 + 0.11 \\ 0.98 + 0.11 \\ 0.98 + 0.11 \\ 0.98 + 0.11 \\ 0.98 + 0.11 \\ 0.98 + 0.11 \\ 0.98 + 0.11 \\ 0.98 + 0.11 \\ 0.98 + 0.11 \\ 0.98 + 0.11 \\ 0.98 + 0.11 \\ 0.98 + 0.11 \\ 0.98 + 0.11 \\ 0.98 + 0.11 \\ 0.98 + 0.11 \\ 0.98 + 0.11 \\ 0.98 + 0.11 \\ 0.98 + 0.11 \\ 0.98 + 0.11 \\ 0.98 + 0.11 \\ 0.98 + 0.11 \\ 0.98 + 0.11 \\ 0.98 + 0.11 \\ 0.98 + 0.11 \\ 0.98 + 0.11 \\ 0.98 + 0.11 \\ 0.98 + 0.11 \\ 0.98 + 0.11 \\ 0.98 + 0.11 \\ 0.98 + 0.11 \\ 0.98 + 0.11 \\ 0.98 + 0.11 \\ 0.98 + 0.11 \\ 0.98 + 0.11 \\ 0.98 + 0.11 \\ 0.98 + 0.11 \\ 0.98 + 0.11 \\ 0.98 + 0.11 \\ 0.98 + 0.11 \\ 0.98 + 0.11 \\ 0.98 + 0.11 \\ 0.98 + 0.11 \\ 0.98 + 0.11 \\ 0.98 + 0.11 \\ 0.98 + 0.11 \\ 0.98 + 0.11 \\ 0.98 + 0.11 \\ 0.98 + 0.11 \\ 0.98 + 0.11 \\ 0.98 + 0.11 \\ 0.98 + 0.11 \\ 0.98 + 0.11 \\ 0.98 + 0.11 \\ 0.98 + 0.11 \\ 0.98 + 0.11 \\ 0.98 + 0.11 \\ 0.98 + 0.11 \\ 0.98 + 0.11 \\ 0.98 + 0.11 \\ 0.98 + 0.11 \\ 0.98 + 0.11 \\ 0.98 + 0.11 \\ 0.9$		Allows for BSM decays. H(inv) use implies BR _{undet} =0. Assumes $\kappa_i = 1$ and uses H(inv). $\kappa_{gZ} = \kappa_g \kappa_Z / \kappa_H$ , i.e. floating $\kappa_H$ . $\lambda_{WZ} = \kappa_W / \kappa_Z$ . $\lambda_{Zg} = \kappa_Z / \kappa_g$ . $\lambda_{bZ} = \kappa_b / \kappa_Z$ . $\lambda_{\gamma Z} = \kappa_{\gamma} / \kappa_Z$ . $\lambda_{\tau Z} = \kappa_{\tau} / \kappa_Z$ . $\lambda_{tg} = \kappa_t / \kappa_g$ . Down-type quarks (via b). Charged leptons (via $\tau$ ). Up-type quarks (via t).
$\begin{array}{c} \kappa_{\rm g}, \kappa_{\gamma}, {\rm BR}_{\rm BSM} \\ \hline \\ {\rm with} \ {\rm H}({\rm inv}) \ {\rm searches} \\ \hline \\ \hline \\ {\rm with} \ {\rm H}({\rm inv}) \ {\rm and} \ \kappa_i = 1 \\ \hline \\ \hline \\ \kappa_{\rm gZ}, \\ \hline \\ \lambda_{\rm WZ}, \lambda_{\rm Zg}, \lambda_{\rm bZ}, \\ \hline \\ \lambda_{\gamma Z}, \lambda_{\tau Z}, \lambda_{\rm tg} \\ \hline \\ \kappa_{\rm V}, \kappa_{\rm b}, \kappa_{\tau}, \\ \hline \\ \kappa_{\rm t}, \kappa_{\rm g}, \kappa_{\gamma} \\ \hline \\ {\rm with} \ \kappa_{\rm V} \leq 1 \ {\rm and} \ {\rm BR}_{\rm BSM} \end{array}$	48 (middle) 	$\frac{\mathrm{BR}_{\mathrm{BSM}}}{\mathrm{BR}_{\mathrm{inv}}}$ $\frac{\mathrm{BR}_{\mathrm{inv}}}{\kappa_{\mathrm{gZ}}}$ $\frac{\kappa_{\mathrm{gZ}}}{\lambda_{\mathrm{WZ}}}$ $\frac{\lambda_{\mathrm{Zg}}}{\lambda_{\mathrm{bZ}}}$ $\frac{\lambda_{\gamma Z}}{\lambda_{\tau Z}}$ $\frac{\lambda_{\tau Z}}{\lambda_{\mathrm{tg}}}$ $\frac{\kappa_{\mathrm{V}}}{\kappa_{\mathrm{b}}}$ $\kappa_{\tau}$ $\kappa_{\mathrm{t}}$ $\kappa_{\mathrm{g}}$ $\kappa_{\gamma}$ $\mathrm{BR}_{\mathrm{BSM}}$	$ \leq 0.14 \\ 0.03 + 0.15 \\ -0.03 \\ 0.06 + 0.11 \\ 0.98 + 0.14 \\ -0.13 \\ 0.87 + 0.15 \\ -0.13 \\ 0.87 + 0.15 \\ -0.13 \\ 0.87 + 0.15 \\ -0.28 \\ 0.59 + 0.22 \\ -0.23 \\ 0.93 + 0.17 \\ -0.14 \\ 0.79 + 0.19 \\ -0.17 \\ 2.18 + 0.54 \\ -0.17 \\ 2.18 + 0.54 \\ -0.15 \\ 0.64 + 0.28 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.15 \\ 0.64 + 0.28 \\ 0.82 + 0.18 \\ 0.82 + 0.18 \\ 0.82 + 0.18 \\ 0.84 + 0.28 \\ 0.84 + 0.17 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0$		Allows for BSM decays. H(inv) use implies BR _{undet} =0. Assumes $\kappa_i = 1$ and uses H(inv). $\kappa_{gZ} = \kappa_g \kappa_Z / \kappa_H$ , i.e. floating $\kappa_H$ . $\lambda_{WZ} = \kappa_W / \kappa_Z$ . $\lambda_{Zg} = \kappa_Z / \kappa_g$ . $\lambda_{DZ} = \kappa_b / \kappa_Z$ . $\lambda_{\gamma Z} = \kappa_{\gamma} / \kappa_Z$ . $\lambda_{\tau Z} = \kappa_{\tau} / \kappa_Z$ . $\lambda_{tg} = \kappa_t / \kappa_g$ . Down-type quarks (via b). Charged leptons (via $\tau$ ). Up-type quarks (via t). Allows for BSM decays.
$\begin{array}{c} \kappa_{\rm g}, \kappa_{\gamma}, {\rm BR}_{\rm BSM} \\ \hline \\ {\rm with} \ {\rm H}({\rm inv}) \ {\rm searches} \\ \hline \\ \hline \\ {\rm with} \ {\rm H}({\rm inv}) \ {\rm and} \ \kappa_i = 1 \\ \hline \\ \hline \\ \kappa_{\rm gZ}, \\ \hline \\ \lambda_{\rm WZ}, \lambda_{\rm Zg}, \lambda_{\rm bZ}, \\ \hline \\ \lambda_{\rm WZ}, \lambda_{\rm Zg}, \lambda_{\rm bZ}, \\ \hline \\ \lambda_{\rm \gamma Z}, \lambda_{\rm \tau Z}, \lambda_{\rm tg} \\ \hline \\ \kappa_{\rm V}, \kappa_{\rm b}, \kappa_{\tau}, \\ \hline \\ \kappa_{\rm V}, \kappa_{\rm b}, \kappa_{\tau}, \\ \hline \\ \kappa_{\rm t}, \kappa_{\rm g}, \kappa_{\gamma} \\ \hline \\ \\ {\rm with} \ \kappa_{\rm V} \leq 1 \ {\rm and} \ {\rm BR}_{\rm BSM} \\ {\rm with} \ \kappa_{\rm V} \leq 1 \ {\rm and} \ {\rm H}({\rm inv}) \end{array}$	48 (middle) 	$\begin{array}{ c c c c c c } & BR_{BSM} \\ \hline BR_{inv} \\ \hline BR_{inv} \\ \hline \\ & \kappa_{gZ} \\ & \lambda_{VZ} \\ & \lambda_{Zg} \\ & \lambda_{bZ} \\ & \lambda_{\gamma Z} \\ & \lambda_{\gamma Z} \\ & \lambda_{\gamma Z} \\ & \lambda_{\tau Z} \\ & \lambda_{\tau Z} \\ & \lambda_{\tau Z} \\ & \kappa_{V} \\ \hline \\ & \kappa_{K} \\ & \kappa_{K} \\ & \kappa_{K} \\ & \kappa_{g} \\ & \kappa_{\gamma} \\ \hline \\ & BR_{BSM} \\ \hline \\ & BR_{inv} \end{array}$	$\begin{array}{r} \leq 0.14 \\ 0.03 + 0.15 \\ 0.03 + 0.03 \\ 0.06 + 0.11 \\ 0.98 + 0.14 \\ -0.13 \\ 0.87 + 0.15 \\ -0.13 \\ 0.87 + 0.15 \\ -0.13 \\ 0.87 + 0.15 \\ 0.93 + 0.17 \\ 0.93 + 0.17 \\ 0.93 + 0.17 \\ 0.93 + 0.17 \\ 0.17 \pm 0.17 \\ 2.18 + 0.54 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.15 \\ 0.64 + 0.29 \\ 0.82 + 0.18 \\ 0.64 + 0.29 \\ 0.82 + 0.18 \\ 1.60 + 0.34 \\ 0.75 + 0.15 \\ 0.98 + 0.17 \\ 0.98 + 0.17 \\ 0.98 + 0.17 \\ 0.94 + 0.17 \\ 0.94 + 0.17 \\ 0.94 + 0.17 \\ 0.17 \pm 0.17 \\ \end{array}$		Allows for BSM decays. H(inv) use implies BR _{undet} =0. Assumes $\kappa_i = 1$ and uses H(inv). $\kappa_{gZ} = \kappa_g \kappa_Z / \kappa_H$ , i.e. floating $\kappa_H$ . $\lambda_{WZ} = \kappa_W / \kappa_Z$ . $\lambda_{Zg} = \kappa_Z / \kappa_g$ . $\lambda_{Zg} = \kappa_p / \kappa_Z$ . $\lambda_{\gamma Z} = \kappa_{\gamma} / \kappa_Z$ . $\lambda_{\tau Z} = \kappa_{\tau} / \kappa_Z$ . $\lambda_{tg} = \kappa_t / \kappa_g$ . Down-type quarks (via b). Charged leptons (via $\tau$ ). Up-type quarks (via t). Allows for BSM decays. H(inv) use implies BR _{undet} = 0.
$\begin{array}{c} \kappa_{\rm g}, \kappa_{\gamma}, {\rm BR}_{\rm BSM} \\ \hline \\ {\rm with} \ {\rm H}({\rm inv}) \ {\rm searches} \\ \hline \\ \hline \\ {\rm with} \ {\rm H}({\rm inv}) \ {\rm and} \ \kappa_i = 1 \\ \hline \\ \hline \\ \kappa_{\rm gZ}, \\ \hline \\ \lambda_{\rm WZ}, \lambda_{\rm Zg}, \lambda_{\rm bZ}, \\ \hline \\ \lambda_{\gamma Z}, \lambda_{\tau Z}, \lambda_{\rm tg} \\ \hline \\ \kappa_{\rm V}, \kappa_{\rm b}, \kappa_{\tau}, \\ \hline \\ \kappa_{\rm t}, \kappa_{\rm g}, \kappa_{\gamma} \\ \hline \\ \\ {\rm with} \ \kappa_{\rm V} \leq 1 \ {\rm and} \ {\rm BR}_{\rm BSM} \\ {\rm with} \ \kappa_{\rm V} \leq 1 \ {\rm and} \ {\rm H}({\rm inv}) \\ \\ {\rm with} \ \kappa_{\rm V} \leq 1 \ {\rm and} \ {\rm H}({\rm inv}) \\ \\ {\rm with} \ \kappa_{\rm V} \leq 1, \ {\rm H}({\rm inv}), \end{array}$	48 (middle) 	$\frac{\text{BR}_{\text{BSM}}}{\text{BR}_{\text{inv}}}$ $\frac{\text{BR}_{\text{inv}}}{\text{KgZ}}$ $\frac{\lambda_{\text{gZ}}}{\lambda_{\text{WZ}}}$ $\frac{\lambda_{\text{Zg}}}{\lambda_{\text{bZ}}}$ $\frac{\lambda_{\gamma Z}}{\lambda_{\tau Z}}$ $\frac{\lambda_{\tau Z}}{\lambda_{\text{tg}}}$ $\frac{\kappa_{\text{V}}}{\kappa_{\text{b}}}$ $\frac{\kappa_{\tau}}{\kappa_{\text{t}}}$ $\frac{\kappa_{g}}{\kappa_{\gamma}}$ $\frac{\text{BR}_{\text{BSM}}}{\text{BR}_{\text{inv}}}$ $\frac{\text{BR}_{\text{inv}}}{\text{BR}_{\text{inv}}}$	$\begin{array}{r} \leq 0.14 \\ 0.03 + 0.15 \\ 0.03 + 0.03 \\ 0.06 + 0.11 \\ 0.98 + 0.14 \\ - 0.13 \\ 0.87 + 0.15 \\ - 0.13 \\ 0.87 + 0.15 \\ - 0.13 \\ 0.87 + 0.17 \\ 0.93 + 0.17 \\ 0.93 + 0.17 \\ 0.93 + 0.17 \\ 0.93 + 0.17 \\ 0.94 + 0.19 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.96 + 0.14 \\ 0.17 \pm 0.17 \\ 0.17 \pm 0.17 \\ 0.17 \pm 0.17 \\ \end{array}$		Allows for BSM decays. H(inv) use implies BR _{undet} =0. Assumes $\kappa_i = 1$ and uses H(inv). $\kappa_{gZ} = \kappa_g \kappa_Z / \kappa_H$ , i.e. floating $\kappa_H$ . $\lambda_{WZ} = \kappa_W / \kappa_Z$ . $\lambda_{Zg} = \kappa_Z / \kappa_g$ . $\lambda_{Zg} = \kappa_p / \kappa_Z$ . $\lambda_{\tau Z} = \kappa_{\tau} / \kappa_Z$ . $\lambda_{\tau Z} = \kappa_{\tau} / \kappa_Z$ . $\lambda_{tg} = \kappa_t / \kappa_g$ . Down-type quarks (via b). Charged leptons (via $\tau$ ). Up-type quarks (via t). Allows for BSM decays. H(inv) use implies BR _{undet} = 0. Separates BR _{inv} from BR _{undet} ,

**169** [ arXiv:1411.3441 ]

Parameterization in terms of cross-section fractions:

$$\begin{split} f_{a3} &= \frac{|a_{3}|^{2}\sigma_{3}}{|a_{1}|^{2}\sigma_{1} + |a_{2}|^{2}\sigma_{2} + |a_{3}|^{2}\sigma_{3} + \tilde{\sigma}_{\Lambda_{1}}/(\Lambda_{1})^{4}} \qquad \phi_{a3} = \arg\left(\frac{a_{3}}{a_{1}}\right) \\ f_{a2} &= \frac{|a_{2}|^{2}\sigma_{2}}{|a_{1}|^{2}\sigma_{1} + |a_{2}|^{2}\sigma_{2} + |a_{3}|^{2}\sigma_{3} + \tilde{\sigma}_{\Lambda_{1}}/(\Lambda_{1})^{4}} \qquad \phi_{a2} = \arg\left(\frac{a_{2}}{a_{1}}\right) \\ f_{\Lambda 1} &= \frac{\tilde{\sigma}_{\Lambda_{1}}/(\Lambda_{1})^{4}}{|a_{1}|^{2}\sigma_{1} + |a_{2}|^{2}\sigma_{2} + |a_{3}|^{2}\sigma_{3} + \tilde{\sigma}_{\Lambda_{1}}/(\Lambda_{1})^{4}} \qquad \phi_{\Lambda 1}, \end{split}$$

# Spin zero amplitude in $H \rightarrow ZZ \rightarrow 4\ell$

## **170** [ arXiv:1411.3441 ]

 $g(\overline{q})$ 

g(q)

- Full final state available:
  - **Kinematic discriminants** reducing to 2D or 3D.
  - **BD likelihood** fit.
- 2D scans of anomalous coupling fractions (real phases).
  - But also done profiling over the phases.

## No significant deviations from SM found.



17

- Anomalous couplings formalism:
  - $\square$  a₁ is the SM amplitude.
  - $\square$   $\Lambda_1$  is a higher-term of an expansion in momentum.
  - a₂ and a₃ control the CP-even and CP-odd amplitudes.
- □ Parameterized using fractions of cross-sections:  $f_{a1}$ ,  $f_{a2}$ ,  $f_{a3}$ ,  $f_{\Lambda 1}$ .

$$\begin{split} A(X_{J=0} \to V_1 V_2) &\sim v^{-1} \left( \left[ a_1 - e^{i\phi_{\Lambda_1}} \frac{q_{Z_1}^2 + q_{Z_2}^2}{(\Lambda_1)^2} \right] m_Z^2 \epsilon_{Z_1}^* \epsilon_{Z_2}^* \right. \\ &+ a_2 f_{\mu\nu}^{*(Z_1)} f^{*(Z_2),\mu\nu} + a_3 f_{\mu\nu}^{*(Z_1)} \tilde{f}^{*(Z_2),\mu\nu} \\ &+ a_2^{Z\gamma} f_{\mu\nu}^{*(Z)} f^{*(\gamma),\mu\nu} + a_3^{Z\gamma} f_{\mu\nu}^{*(Z)} \tilde{f}^{*(\gamma),\mu\nu} \\ &+ a_2^{\gamma\gamma} f_{\mu\nu}^{*(\gamma_1)} f^{*(\gamma_2),\mu\nu} + a_3^{\gamma\gamma} f_{\mu\nu}^{*(\gamma_1)} \tilde{f}^{*(\gamma_2),\mu\nu} \right) \end{split}$$

## [ arXiv:1411.3441 ]

172

- □ Anomalous couplings formalism:
  - $\square$  a₁ is the SM amplitude.
  - $\square$   $\Lambda_1$  is a higher-term of an expansion in momentum.
  - $a_2$  and  $a_3$  control the CP-even and CP-odd amplitudes.
- □ Parameterized using fractions of cross-sections:  $f_{a1}$ ,  $f_{a2}$ ,  $f_{a3}$ ,  $f_{\Lambda 1}$ .

$$\begin{aligned} A(X_{J=0} \to V_1 V_2) &\sim v^{-1} \left( \begin{bmatrix} a_1 - e^{i\phi_{\Lambda_1}} \frac{q_{Z_1}^2 + q_{Z_2}^2}{(\Lambda_1)^2} \end{bmatrix} m_Z^2 \epsilon_{Z_1}^* \epsilon_{Z_2}^* \\ &+ a_2 f_{\mu\nu}^{*(Z_1)} f^{*(Z_2),\mu\nu} + a_3 f_{\mu\nu}^{*(Z_1)} \tilde{f}^{*(Z_2),\mu\nu} \\ &+ a_2^{Z\gamma} f_{\mu\nu}^{*(Z)} f^{*(\gamma),\mu\nu} + a_3^{Z\gamma} f_{\mu\nu}^{*(Z)} \tilde{f}^{*(\gamma),\mu\nu} \\ &+ a_2^{\gamma\gamma} f_{\mu\nu}^{*(\gamma_1)} f^{*(\gamma_2),\mu\nu} + a_3^{\gamma\gamma} f_{\mu\nu}^{*(\gamma_1)} \tilde{f}^{*(\gamma_2),\mu\nu} \end{pmatrix} \end{aligned}$$

- □ Anomalous couplings formalism:
  - a₁ is the SM amplitude.
  - **\square**  $\Lambda_1$  is a higher-term of an expansion in momentum.
  - a₂ and a₃ control the CP-even and CP-odd amplitudes.
- □ Parameterized using fractions of cross-sections:  $f_{a1}$ ,  $f_{a2}$ ,  $f_{a3}$ ,  $f_{\Lambda 1}$ .

$$\begin{split} A(X_{J=0} \to V_1 V_2) &\sim v^{-1} \left( \begin{bmatrix} a_1 - e^{i\phi_{\Lambda_1}} \frac{q_{Z_1}^2 + q_{Z_2}^2}{(\Lambda_1)^2} \end{bmatrix} m_Z^2 \epsilon_{Z_1}^* \epsilon_{Z_2}^* \\ &+ a_2 f_{\mu\nu}^{*(Z_1)} f^{*(Z_2),\mu\nu} + a_3 f_{\mu\nu}^{*(Z_1)} \tilde{f}^{*(Z_2),\mu\nu} \\ &+ a_2^{Z\gamma} f_{\mu\nu}^{*(Z)} f^{*(\gamma),\mu\nu} + a_3^{Z\gamma} f_{\mu\nu}^{*(Z)} \tilde{f}^{*(\gamma),\mu\nu} \\ &+ a_2^{\gamma\gamma} f_{\mu\nu}^{*(\gamma_1)} f^{*(\gamma_2),\mu\nu} + a_3^{\gamma\gamma} f_{\mu\nu}^{*(\gamma_1)} \tilde{f}^{*(\gamma_2),\mu\nu} \end{pmatrix} \end{split}$$

- □ Anomalous couplings formalism:
  - a₁ is the SM amplitude.
  - **\square**  $\Lambda_1$  is a higher-term of an expansion in momentum.
  - a₂ and a₃ control the CP-even and CP-odd amplitudes.
- □ Parameterized using fractions of cross-sections:  $f_{a1}$ ,  $f_{a2}$ ,  $f_{a3}$ ,  $f_{A1}$ .

$$\begin{split} A(X_{J=0} \to V_{1}V_{2}) &\sim v^{-1} \left( \begin{bmatrix} a_{1} - e^{i\phi_{\Lambda_{1}}} \frac{q_{Z_{1}}^{2} + q_{Z_{2}}^{2}}{(\Lambda_{1})^{2}} \end{bmatrix} m_{Z}^{2} \epsilon_{Z_{1}}^{*} \epsilon_{Z_{2}}^{*} \\ &+ a_{2} f_{\mu\nu}^{*(Z_{1})} f^{*(Z_{2}),\mu\nu} + a_{3} f_{\mu\nu}^{*(Z_{1})} \tilde{f}^{*(Z_{2}),\mu\nu} \\ &+ a_{2}^{Z\gamma} f_{\mu\nu}^{*(Z)} f^{*(\gamma),\mu\nu} + a_{3}^{Z\gamma} f_{\mu\nu}^{*(Z)} \tilde{f}^{*(\gamma),\mu\nu} \\ &+ a_{2}^{\gamma\gamma} f_{\mu\nu}^{*(\gamma_{1})} f^{*(\gamma_{2}),\mu\nu} + a_{3}^{\gamma\gamma} f_{\mu\nu}^{*(\gamma_{1})} \tilde{f}^{*(\gamma_{2}),\mu\nu} \right) \\ &= a_{2} \text{ terms} \\ \text{CP-even (scalar)} \\ &= a_{2} \text{ david@cern.ch} \quad \text{LHC Physics 2015} \end{split}$$

- □ Anomalous couplings formalism:
  - a₁ is the SM amplitude.
  - **\square**  $\Lambda_1$  is a higher-term of an expansion in momentum.
  - a₂ and a₃ control the CP-even and CP-odd amplitudes.
- □ Parameterized using fractions of cross-sections:  $f_{a1}$ ,  $f_{a2}$ ,  $f_{a3}$ ,  $f_{A1}$ .

$$\begin{split} A(X_{J=0} \to V_{1}V_{2}) &\sim v^{-1} \left( \begin{bmatrix} a_{1} - e^{i\phi_{\Lambda_{1}}} \frac{q_{Z_{1}}^{2} + q_{Z_{2}}^{2}}{(\Lambda_{1})^{2}} \end{bmatrix} m_{Z}^{2} \epsilon_{Z_{1}}^{*} \epsilon_{Z_{2}}^{*} \\ &+ a_{2} f_{\mu\nu}^{*(Z_{1})} f^{*(Z_{2}),\mu\nu} + a_{3} f_{\mu\nu}^{*(Z_{1})} \tilde{f}^{*(Z_{2}),\mu\nu} \\ &+ a_{2}^{Z\gamma} f_{\mu\nu}^{*(Z)} f^{*(\gamma),\mu\nu} + a_{3}^{Z\gamma} f_{\mu\nu}^{*(Z)} \tilde{f}^{*(\gamma),\mu\nu} \\ &+ a_{2}^{\gamma\gamma} f_{\mu\nu}^{*(\gamma_{1})} f^{*(\gamma_{2}),\mu\nu} + a_{3}^{\gamma\gamma} f_{\mu\nu}^{*(\gamma_{1})} \tilde{f}^{*(\gamma_{2}),\mu\nu} \\ &+ a_{2}^{\gamma\gamma} f_{\mu\nu}^{*(\gamma_{1})} f^{*(\gamma_{2}),\mu\nu} + a_{3}^{\gamma\gamma} f_{\mu\nu}^{*(\gamma_{1})} \tilde{f}^{*(\gamma_{2}),\mu\nu} \\ &+ a_{2}^{\gamma\gamma} f_{\mu\nu}^{*(\gamma_{1})} f^{*(\gamma_{2}),\mu\nu} + a_{3}^{\gamma\gamma} f_{\mu\nu}^{*(\gamma_{1})} \tilde{f}^{*(\gamma_{2}),\mu\nu} \\ &+ a_{2}^{\gamma\gamma} f_{\mu\nu}^{*(\gamma_{1})} f^{*(\gamma_{2}),\mu\nu} + a_{3}^{\gamma\gamma} f_{\mu\nu}^{*(\gamma_{1})} \tilde{f}^{*(\gamma_{2}),\mu\nu} \\ &+ a_{2}^{\gamma} f_{\mu\nu}^{*(\gamma_{1})} f^{*(\gamma_{2}),\mu\nu} + a_{3}^{\gamma\gamma} f_{\mu\nu}^{*(\gamma_{1})} \tilde{f}^{*(\gamma_{2}),\mu\nu} \\ &+ a_{2}^{\gamma} f_{\mu\nu}^{*(\gamma_{1})} f^{*(\gamma_{2}),\mu\nu} + a_{3}^{\gamma\gamma} f_{\mu\nu}^{*(\gamma_{1})} \tilde{f}^{*(\gamma_{2}),\mu\nu} \\ &+ a_{2}^{\gamma} f_{\mu\nu}^{*(\gamma_{1})} f^{*(\gamma_{2}),\mu\nu} + a_{3}^{\gamma\gamma} f_{\mu\nu}^{*(\gamma_{1})} \tilde{f}^{*(\gamma_{2}),\mu\nu} \\ &+ a_{2}^{\gamma} f_{\mu\nu}^{*(\gamma_{1})} f^{*(\gamma_{2}),\mu\nu} + a_{3}^{\gamma\gamma} f_{\mu\nu}^{*(\gamma_{1})} \tilde{f}^{*(\gamma_{2}),\mu\nu} \\ &+ a_{2}^{\gamma} f_{\mu\nu}^{*(\gamma_{1})} f^{*(\gamma_{2}),\mu\nu} + a_{3}^{\gamma\gamma} f_{\mu\nu}^{*(\gamma_{1})} \tilde{f}^{*(\gamma_{2}),\mu\nu} \\ &+ a_{3}^{\gamma} f_{\mu\nu}^{*(\gamma_{2}),\mu\nu} \\ &+ a_{3}^{\gamma} f_{\mu\nu}^{*(\gamma_{1})} \tilde{f}^{*(\gamma_{2}),\mu\nu} \\ &+ a_{3}^{\gamma} f_{\mu\nu}^{*(\gamma_{1})} \tilde{f}^{*(\gamma_{1})} \tilde{f}^{*(\gamma_{1$$

- □ Anomalous couplings formalism:
  - a₁ is the SM amplitude.
  - **\square**  $\Lambda_1$  is a higher-term of an expansion in momentum.
  - **a**  $a_2$  and  $a_3$  control the CP-even and CP-odd amplitudes.
- □ Parameterized using fractions of cross-sections:  $f_{a1}$ ,  $f_{a2}$ ,  $f_{a3}$ ,  $f_{\Lambda 1}$ .

$$\begin{array}{rcl} A(X_{J=0} \rightarrow V_{1}V_{2}) &\sim & v^{-1} \left( \begin{bmatrix} a_{1} - e^{i\phi_{\Lambda_{1}}} \frac{q_{Z_{1}}^{2} + q_{Z_{2}}^{2}}{(\Lambda_{1})^{2}} \end{bmatrix} m_{Z}^{2} \epsilon_{Z_{1}}^{*} \epsilon_{Z_{2}}^{*} \\ & ZZ, WW &+ & a_{2} f_{\mu\nu}^{*(Z_{1})} f^{*(Z_{2}),\mu\nu} + a_{3} f_{\mu\nu}^{*(Z_{1})} \tilde{f}^{*(Z_{2}),\mu\nu} \\ & Z\gamma^{*} &+ & a_{2}^{2\gamma} f_{\mu\nu}^{*(Z)} f^{*(\gamma),\mu\nu} + a_{3}^{2\gamma} f_{\mu\nu}^{*(Z)} \tilde{f}^{*(\gamma),\mu\nu} \\ & \gamma^{*}\gamma^{*} &+ & a_{2}^{\gamma\gamma} f_{\mu\nu}^{*(\gamma_{1})} f^{*(\gamma_{2}),\mu\nu} + a_{3}^{\gamma\gamma} f_{\mu\nu}^{*(\gamma_{1})} \tilde{f}^{*(\gamma_{2}),\mu\nu} \\ & & a_{2} \text{ terms} \\ & CP\text{-odd} \\ & \text{(pseudoscalar)} \\ & a.david@cern.ch & LHC Physics 2015 \end{array}$$

# Spin zero amplitude in $H \rightarrow ZZ \rightarrow 4\ell$

## [ arXiv:1411.3441 ]

 $g(\overline{q})$ 

177

g(q)

- Full final state available:
  - **Kinematic discriminants** reduce 8D to 2D or 3D.
- □ 2D scans of anomalous coupling fractions.
  - Assuming real phases and floating the phases.





## **178** [ arXiv:1411.3441 ]

# Broad range of hypothesis tests based on the observables optimized for each case.





## [ CMS-PAS-HIG-14-012 ]

179

# Broad range of hypothesis tests based on the observables used for the SM measurements.





[CMS-PAS-HIG-14-012][arXiv:1411.3441]

180

## □ Combination of $H \rightarrow WW \rightarrow 2\ell 2\nu$ and $H \rightarrow ZZ \rightarrow 4\ell$ .




[CMS-PAS-HIG-14-012][arXiv:1411.3441]

181

- □ Combination of  $H \rightarrow WW \rightarrow 2\ell 2\nu$  and  $H \rightarrow ZZ \rightarrow 4\ell$ .
- □ All tested hypotheses excluded at more than 99.9% CL_s.







[ http://cern.ch/go/r8kv ]



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183



184 [http://cern.ch/go/r8kv]







[ http://cern.ch/go/r8kv ]

185





186

# High-mass diphoton searches

[ CMS-PAS-HIG-14-006 ]

- Simplified cut-based selection.
- □ Signal model: double Crystal-Ball ⊗ Breit-Wigner.
  - Signal width and mean scale appropriately with m_{H.}
- **Limits on \sigma \times BR as a function of Γ_x and m_x.**



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19.7 fb⁻¹ (8 TeV) All Categories Combined

γ²/NDF: 2.064

Data

γ + jet γ + γ Bkg Err

Events/10.00

 $10^{4}$ 

 $10^{3}$ 

10²

10

CMS

Prelimina

## $H^+ \rightarrow cs$ in decays of $t \rightarrow H^+ + b$

#### [ CMS-PAS-HIG-13-035 ]

187



- lepton and MET.
- Mass reconstructed using m_W and m_t constraints and likelihood fit.



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188

# Search for MSSM $\Phi \rightarrow \tau \tau$

#### [ CMS-PAS-HIG-13-021 ]

Not shown: model-independent limits on  $gg \rightarrow \Phi$  and  $gg \rightarrow \Phi b\overline{b}$ .



**189** [CMS-PAS-HIG-14-005]

- $\Box$   $\tau$  lepton flavor violation not as well constrained as  $\mu e$  (MEG).
- **D** Based on SM  $H \rightarrow \tau \tau$  analysis. **Different kinematics allows good SM H rejection**.
  - **BR(H→** $\mu$ τ) < 1.57% at 95%CL (expected limit of 0.75%)



**190** [CMS-PAS-HIG-14-005]

- $\Box$   $\tau$  lepton flavor violation not as well constrained as  $\mu e$  (MEG).
- □ Based on SM  $H \rightarrow \tau \tau$  analysis. Different kinematics allows good SM H rejection.
  - **BR(H→** $\mu$ τ) < 1.57% at 95%CL (expected limit of 0.75%)



**191** [CMS-PAS-HIG-14-005]

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- $\Box$   $\tau$  lepton flavor violation not as well constrained as  $\mu e$  (MEG).
- **D** Based on SM  $H \rightarrow \tau \tau$  analysis. **Different kinematics allows good SM H rejection**.
  - **BR**( $H \rightarrow \mu \tau$ ) < 1.57% at 95%CL (expected limit of 0.75%)



[CMS-PAS-HIG-14-005]

192



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193

## Search for $H \rightarrow \mu \tau$

[ CMS-PAS-HIG-14-005 ]



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μτ

[ CMS-PAS-HIG-14-005 ]

194



195 [ CMS-PAS-HIG-14-005 ]



# New search for ttH with $H \rightarrow b\overline{b}$

[CMS-PAS-HIG-14-010]

196

- Improved performance:
  - Event probability (P_{s/b}) based on matrix element probabilities.
  - Single lepton (SL) and di-lepton (DL) topologies.
    - Best with identified  $W \rightarrow jj$  (**SL Cat-1**).
  - Reduced dependency on tt+HF modeling.

#### Clearly a hot topic for Run 2.



# New search for ttH with $H \rightarrow b\overline{b}$

[CMS-PAS-HIG-14-010]

197

- Improved performance:
  - Event probability (P_{s/b}) based on matrix element probabilities.
  - □ Single lepton (SL) and di-lepton (DL) topologies.
    - Best with identified  $W \rightarrow jj$  (SL Cat-1).
  - Reduced dependency on tt+HF modeling.



# New search for ttH with $H \rightarrow b\overline{b}$

[ CMS-PAS-HIG-14-010 ]

198

- Improved performance:
  - Event probability  $(P_{s/b})$  based on matrix element probabilities.
  - Single lepton (SL) and di-lepton (DL) topologies.
    - Best with identified  $W \rightarrow jj$  (**SL Cat-1**).







### Statistics interlude

200 [ATL-PHYS-PUB-2011-11, CMS NOTE-2011/005]

	Test statistic	Profiled?	Test statistic sampling
LEP	$q_{\mu} = -2 \ln rac{\mathcal{L}(data \mu,  ilde{ heta})}{\mathcal{L}(data 0,  ilde{ heta})}$	no	Bayesian-frequentist hybrid
Tevatron	$q_{\mu} \;=\; -2\lnrac{\mathcal{L}(data \mu,\hat{ heta}_{\mu})}{\mathcal{L}(data 0,\hat{ heta}_{0})}$	yes	Bayesian-frequentist hybrid
LHC	$\widetilde{q}_{\mu} \;=\; -2\lnrac{\mathcal{L}(data \mu,\hat{ heta}_{\mu})}{\mathcal{L}(data \hat{\mu},\hat{ heta})}$	$yes (0 \le \hat{\mu} \le \mu)$	frequentist

- **LEP:** nuisances parameters ( $\theta$ ) kept at nominal values ( $\sim$ ).
- Tevatron: maximise likelihood against nuisances ([^]).
  - Denominator considers background-only hypothesis (µ=0).
- □ **LHC**: frequentist profiled likelihood.
  - Denominator considers global best-fit likelihood with floating signal strength.
  - Nice asymptotic properties, savings in computational power.

## Breaking down uncertainties

Nuisances grouped into stat, theo, other.

- **stat** includes  $H \rightarrow \gamma \gamma$  background parameters.
- **theo** includes QCD scales, PDF+ $\alpha_s$ , UEPS, and BR.
- **u** syst = theo  $\cup$  other.
- Procedures:

201

For (stat)+(syst):

- σ_{all} from scan floating all nuisances.
- σ_{stat} from scan floating stat group only.

$$\bullet \sigma_{syst} = \sigma_{all} \ominus \sigma_{stat}.$$

#### For (stat)+(theo)+(other)

- σ_{all} from scan floating all nuisances.
- σ_{stat} from scan floating stat group only.
- $\bullet$   $\sigma_{stat+other}$  from scan floating stat and other.

• 
$$\sigma_{\text{theo}} = \sigma_{\text{all}} \ominus \sigma_{\text{stat+other}}$$
.

• 
$$\sigma_{\text{other}} = \sigma_{\text{all}} \ominus \sigma_{\text{stat}} \ominus \sigma_{\text{theo}}$$
.



## A 2012 hit

203

#### [http://goo.gl/ShJJG]



#### Breakthrough of the Year, 2012

Every year, crowning one scientific achievement as Breakthrough of the Year is no easy task, and 2012 was no exception. The year saw leaps and bounds in physics, along with significant advances in genetics, engineering, and many other areas. In keeping with tradition, *Science*'s editors and staff have selected a winner and nine runners-up, as well as highlighting the year's top news stories and areas to watch in 2013.



#### FREE ACCESS The Discovery of the Higgs Boson

A. Cho

Exotic particles made headlines again and again in 2012, making it no surprise that the breakthrough of the year is a big physics finding: confirmation of the existence of the Higgs boson. Hypothesized more than 40 years ago, the elusive particle completes the standard model of physics, and is arguably the key to the explanation of how other fundamental particles obtain mass. The only mystery that remains is whether its discovery marks a new dawn for particle physics or the final stretch of a field that has run its course.

Read more about the Higgs boson from the research teams at CERN.

#### Runners-Up FREE WITH REGISTRATION

This year's runners-up for Breakthrough of the Year underscore feats in engineering, genetics, and other fields that promise to change the course of science.





#### Oct 2013: boson becomes Nobel

204



# CERN

205

## Theory uncertainties: a tale of PDFs

[http://cern.ch/go/V8xJ]

 Long-standing difference in d/u ratio between MSTW and others.

- Neatly resolved by CMS
   W asymmetry measurements.
- MSWT made parameterization more flexible: case closed.





#### Theory uncertainties

- Bottom-line for Run2:
  - Consider measurements that constrain PDF fits.
  - For higher orders, more than precision, also a matter of accuracy.
    - Need to work with theorists to get these right, also differentially.
- Or you can try to dodge them with p_T ratios...
   ...but end up needing a lot of data.

### A Rosetta stone for Higgs EFT







#### First steps in YR3

**Table 52:** Dimension-6 operators involving Higgs doublet fields or gauge-boson fields. For all  $\psi^2 \Phi^3$ ,  $\psi^2 X \Phi$  operators and for  $\mathcal{O}_{\Phi ud}$  the hermitian conjugates must be included as well.

$\Phi^6$ and $\Phi^4 D^2$	$\psi^2 \Phi^3$	X ³
$\mathcal{O}_{\Phi} = (\Phi^{\dagger}\Phi)^3$	$\mathcal{O}_{\mathrm{e}\Phi} = (\Phi^{\dagger}\Phi)(\overline{1}\Gamma_{\mathrm{e}}\mathrm{e}\Phi)$	$\mathcal{O}_G = f^{ABC} G^{A\nu}_\mu G^{B\rho}_\nu G^{C\mu}_\rho$
$\mathcal{O}_{\Phi\Box} = (\Phi^{\dagger}\Phi)\Box(\Phi^{\dagger}\Phi)$	$\mathcal{O}_{u\Phi} = (\Phi^\dagger \Phi) (\bar{q}\Gamma_u u \widetilde{\Phi})$	$\mathcal{O}_{\widetilde{G}} = f^{ABC} \widetilde{G}^{A\nu}_{\mu} G^{B\rho}_{\nu} G^{C\mu}_{\rho}$
$\mathcal{O}_{\Phi D} = (\Phi^{\dagger} D^{\mu} \Phi)^* (\Phi^{\dagger} D_{\mu} \Phi)$	${\cal O}_{d\Phi} = (\Phi^\dagger \Phi) (\bar q  \Gamma_d d\Phi)$	$\mathcal{O}_{\mathrm{W}} = \varepsilon^{IJK} \mathrm{W}^{I\nu}_{\mu} \mathrm{W}^{J\rho}_{\nu} \mathrm{W}^{K\mu}_{\rho}$
		$\mathcal{O}_{\widetilde{\mathbf{W}}} = \varepsilon^{IJK} \widetilde{\mathbf{W}}_{\mu}^{I\nu} \mathbf{W}_{\nu}^{J\rho} \mathbf{W}_{\rho}^{K\mu}$
$X^2 \Phi^2$	$\psi^2 \mathrm{X} \Phi$	$\psi^2 \Phi^2 D$
$\mathcal{O}_{\Phi G} = (\Phi^{\dagger} \Phi) G^A_{\mu\nu} G^{A\mu\nu}$	$\mathcal{O}_{\mathrm{u}G} = (\bar{\mathrm{q}}\sigma^{\mu\nu}\frac{\lambda^{A}}{2}\Gamma_{\mathrm{u}}\mathrm{u}\widetilde{\Phi})G^{A}_{\mu\nu}$	$\mathcal{O}_{\Phi l}^{(1)} = (\Phi^{\dagger} i \overset{\leftrightarrow}{D}_{\mu} \Phi) (\bar{l} \gamma^{\mu} l)$
$\mathcal{O}_{\Phi\widetilde{G}}=(\Phi^{\dagger}\Phi)\widetilde{G}^{A}_{\mu\nu}G^{A\mu\nu}$	$\mathcal{O}_{\mathrm{d}G} = (\bar{\mathrm{q}}\sigma^{\mu\nu}\frac{\lambda^A}{2}\Gamma_{\mathrm{d}}\mathrm{d}\Phi)G^A_{\mu\nu}$	$\mathcal{O}_{\Phi \mathrm{l}}^{(3)} = (\Phi^{\dagger} \mathrm{i} \overset{\leftrightarrow}{D}{}^{I}_{\mu} \Phi) (\bar{\mathrm{l}} \gamma^{\mu} \tau^{I} \mathrm{l})$
$\mathcal{O}_{\Phi \mathrm{W}} = (\Phi^{\dagger} \Phi) \mathrm{W}^{I}_{\mu  u} \mathrm{W}^{I \mu  u}$	$\mathcal{O}_{\mathrm{eW}} = (\bar{\mathrm{l}}\sigma^{\mu\nu}\Gamma_{\mathrm{e}}\mathrm{e}\tau^{I}\Phi)\mathrm{W}^{I}_{\mu\nu}$	$\mathcal{O}_{\Phi \mathrm{e}} = (\Phi^\dagger \mathrm{i} \stackrel{\leftrightarrow}{D}_\mu \Phi) (ar{\mathrm{e}} \gamma^\mu \mathrm{e})$
$\mathcal{O}_{\Phi \widetilde{\mathbf{W}}} = (\Phi^{\dagger} \Phi) \widetilde{\mathbf{W}}_{\mu \nu}^{I} \mathbf{W}^{I \mu \nu}$	$\mathcal{O}_{\mathrm{uW}} = (\bar{\mathrm{q}}\sigma^{\mu\nu}\Gamma_{\mathrm{u}}\mathrm{u}\tau^{I}\widetilde{\Phi})\mathrm{W}^{I}_{\mu\nu}$	$\mathcal{O}^{(1)}_{\Phi \mathrm{q}} = (\Phi^\dagger \mathrm{i} \overset{\leftrightarrow}{D}_\mu \Phi) (\bar{\mathrm{q}} \gamma^\mu \mathrm{q})$
$\mathcal{O}_{\Phi B} = (\Phi^{\dagger} \Phi) B_{\mu\nu} B^{\mu\nu}$	$\mathcal{O}_{\rm dW} = (\bar{\mathbf{q}} \sigma^{\mu\nu} \Gamma_{\rm d} \mathbf{d} \tau^I \Phi) \mathbf{W}^I_{\mu\nu}$	$\mathcal{O}_{\Phi \mathbf{q}}^{(3)} = (\Phi^{\dagger} \mathbf{i} \overset{\leftrightarrow}{D}{}^{I}_{\mu} \Phi)(\bar{\mathbf{q}} \gamma^{\mu} \tau^{I} \mathbf{q})$
$\mathcal{O}_{\Phi\widetilde{\mathbf{B}}}=(\Phi^{\dagger}\Phi)\widetilde{\mathbf{B}}_{\mu\nu}\mathbf{B}^{\mu\nu}$	$\mathcal{O}_{eB} = (\bar{l}\sigma^{\mu\nu}\Gamma_{e}e\Phi)B_{\mu\nu}$	$\mathcal{O}_{\Phi\mathrm{u}} = (\Phi^\dagger \mathrm{i} \overleftrightarrow{D}_\mu \Phi) (\bar{\mathrm{u}} \gamma^\mu \mathrm{u})$
$\mathcal{O}_{\Phi WB} = (\Phi^{\dagger} \tau^{I} \Phi) W^{I}_{\underline{\mu}\nu} B^{\mu\nu}$	$\mathcal{O}_{uB} = (\bar{q}\sigma^{\mu\nu}\Gamma_{u}u\widetilde{\Phi})B_{\mu\nu}$	$\mathcal{O}_{\Phi \mathrm{d}} = (\Phi^{\dagger} \mathrm{i} \overset{\leftrightarrow}{D}_{\mu} \Phi) (\bar{\mathrm{d}} \gamma^{\mu} \mathrm{d})$
$\mathcal{O}_{\Phi \widetilde{\mathbf{W}} \mathbf{B}} = (\Phi^{\dagger} \tau^{I} \Phi) \widetilde{\mathbf{W}}_{\mu \nu}^{I} \mathbf{B}^{\mu \nu}$	$\mathcal{O}_{dB} = (\bar{q}\sigma^{\mu\nu}\Gamma_{d}d\Phi)B_{\mu\nu}$	$\mathcal{O}_{\Phi \mathrm{ud}} = \mathrm{i}(\widetilde{\Phi}^{\dagger} D_{\mu} \Phi)(\bar{\mathrm{u}} \gamma^{\mu} \Gamma_{\mathrm{ud}} \mathrm{d})$

Table 53: Alternative basis of dimension-6 operators involving Higgs doublet fields or gauge-boson fields.

$\Phi^6$ and $\Phi^4 D^2$	$\psi^2 \Phi^3$	X ³				
$\mathcal{O}_6' = (\Phi^\dagger \Phi)^3$	$\mathcal{O}_{e\Phi}' = (\Phi^{\dagger}\Phi)(\overline{l}\Gamma_{e}e\Phi)$	$\mathcal{O}_G' = f^{ABC} G^{A\nu}_\mu G^{B\rho}_\nu G^{C\mu}_\rho$				
$\mathcal{O}'_{\Phi} = \partial_{\mu}(\Phi^{\dagger}\Phi)\partial^{\mu}(\Phi^{\dagger}\Phi)$	$\mathcal{O}_{\mathrm{u}\Phi}^{\prime}=(\Phi^{\dagger}\Phi)(\bar{q}\Gamma_{\mathrm{u}}\mathrm{u}\widetilde{\Phi})$	$\mathcal{O}_{\widetilde{G}}' = f^{ABC} \widetilde{G}^{A\nu}_{\mu} G^{B\rho}_{\nu} G^{C\mu}_{\rho}$				
$\mathcal{O}_{\mathrm{T}}' = (\Phi^{\dagger} \stackrel{\leftrightarrow}{D_{\mu}} \Phi) (\Phi^{\dagger} \stackrel{\leftrightarrow}{D^{\mu}} \Phi)$	$\mathcal{O}_{\mathrm{d}\Phi}^{\prime} = (\Phi^{\dagger}\Phi)(\bar{\mathrm{q}}\Gamma_{d}d\Phi)$	$\mathcal{O}'_{\mathrm{W}} = \varepsilon^{IJK} \mathrm{W}^{I\nu}_{\mu} \mathrm{W}^{J\rho}_{\nu} \mathrm{W}^{K\mu}_{\rho}$				
		$\mathcal{O}'_{\widetilde{\mathbf{W}}} = \varepsilon^{IJK} \widetilde{\mathbf{W}}_{\mu}^{I\nu} \mathbf{W}_{\nu}^{J\rho} \mathbf{W}_{\rho}^{K\mu}$				
$X^2 \Phi^2$	$\psi^2 X \Phi$	$\psi^2 \Phi^2 D$				
$\mathcal{O}_{\mathrm{D}W}^{\prime} = \left( \Phi^{\dagger} \tau^{I} \mathrm{i} \overleftrightarrow{D^{\mu}} \Phi \right) \left( D^{\nu} \mathrm{W}_{\mu\nu} \right)^{I}$	$\mathcal{O}'_{\mathrm{u}G} = (\bar{\mathrm{q}}\sigma^{\mu\nu}\frac{\lambda^A}{2}\Gamma_{\mathrm{u}}\mathrm{u}\widetilde{\Phi})G^A_{\mu\nu}$	$\mathcal{O}_{\Phi \mathbf{l}}^{\prime(1)} = (\Phi^{\dagger} \mathbf{i} \stackrel{\leftrightarrow}{D}_{\mu} \Phi)(\bar{\mathbf{l}} \gamma^{\mu} \mathbf{l})$				
$\mathcal{O}_{D\mathrm{B}}^{\prime} = \left( \Phi^{\dagger} \mathrm{i} \overleftrightarrow{D^{\mu}} \Phi \right) \left( \partial^{\nu} \mathrm{B}_{\mu\nu} \right)$	$\mathcal{O}'_{\mathrm{d}G} = (\bar{\mathrm{q}}\sigma^{\mu\nu}\frac{\lambda^A}{2}\Gamma_{\mathrm{d}}\mathrm{d}\Phi)G^A_{\mu\nu}$	$\mathcal{O}_{\Phi \mathbf{l}}^{\prime(3)} = (\Phi^{\dagger} \mathbf{i} \overset{\leftrightarrow}{D}{}^{I}_{\mu} \Phi)(\bar{\mathbf{l}} \gamma^{\mu} \tau^{I} \mathbf{l})$				
$\mathcal{O}_{D\Phi\mathbf{W}}^{\prime} = \mathbf{i} (D^{\mu} \Phi)^{\dagger} \tau^{I} (D^{\nu} \Phi) \mathbf{W}_{\mu\nu}^{I}$	$\mathcal{O}_{\rm eW}^{\prime} = (\bar{\mathbf{l}}\sigma^{\mu\nu}\Gamma_{\rm e}\mathbf{e}\tau^{I}\Phi)\mathbf{W}_{\mu\nu}^{I}$	$\mathcal{O}'_{\Phi \mathrm{e}} = (\Phi^{\dagger} \mathrm{i} \overset{\leftrightarrow}{D}_{\mu} \Phi) (\bar{\mathrm{e}} \gamma^{\mu} \mathrm{e})$				
$\mathcal{O}_{D\Phi\widetilde{W}}' = \mathrm{i}(D^{\mu}\Phi)^{\dagger}\tau^{I}(D^{\nu}\Phi)\widetilde{W}_{\mu\nu}^{I}$	$\mathcal{O}'_{\mathrm{uW}} = (\bar{\mathbf{q}} \sigma^{\mu\nu} \Gamma_{\mathrm{u}} \mathbf{u} \tau^{I} \widetilde{\Phi}) \mathbf{W}^{I}_{\mu\nu}$	$\mathcal{O}_{\Phi \mathbf{q}}^{\prime(1)} = (\Phi^{\dagger} \mathbf{i} \overset{\leftrightarrow}{D}_{\mu} \Phi)(\bar{\mathbf{q}} \gamma^{\mu} \mathbf{q})$				
$\mathcal{O}_{D\Phi\mathbf{B}}^{\prime}=\mathbf{i}(D^{\mu}\Phi)^{\dagger}(D^{\nu}\Phi)\mathbf{B}_{\mu\nu}$	$\mathcal{O}_{\mathrm{dW}}^{\prime} = (\bar{\mathbf{q}} \sigma^{\mu\nu} \Gamma_{\mathrm{d}} \mathbf{d} \tau^{I} \Phi) \mathbf{W}_{\mu\nu}^{I}$	$\mathcal{O}_{\Phi \mathbf{q}}^{\prime(3)} = (\Phi^{\dagger} \mathbf{i} \overset{\leftrightarrow}{D}{}^{I}_{\mu} \Phi)(\bar{\mathbf{q}} \gamma^{\mu} \tau^{I} \mathbf{q})$				
$\mathcal{O}_{D\Phi\widetilde{\mathbf{B}}}^{\prime}=\mathbf{i}(D^{\mu}\Phi)^{\dagger}(D^{\nu}\Phi)\widetilde{\mathbf{B}}_{\mu\nu}$	$\mathcal{O}_{\rm eB}' = (\bar{l}\sigma^{\mu\nu}\Gamma_{\rm e}{\rm e}\Phi)B_{\mu\nu}$	$\mathcal{O}'_{\Phi \mathbf{u}} = (\Phi^{\dagger} \mathbf{i} \overleftrightarrow{D}_{\mu} \Phi)(\bar{\mathbf{u}} \gamma^{\mu} \mathbf{u})$				
$\mathcal{O}_{\Phi \mathrm{B}}^{\prime} = (\Phi^{\dagger} \Phi) B_{\mu\nu} \mathrm{B}^{\mu\nu}$	$\mathcal{O}'_{uB} = (\bar{q}\sigma^{\mu\nu}\Gamma_u u\widetilde{\Phi})B_{\mu\nu}$	$\mathcal{O}'_{\Phi \mathrm{d}} = (\Phi^{\dagger} \mathrm{i} \overset{\leftrightarrow}{D}_{\mu} \Phi) (\bar{\mathrm{d}} \gamma^{\mu} \mathrm{d})$				
$\mathcal{O}_{\Phi\widetilde{\mathbf{B}}}^{\prime}=(\Phi^{\dagger}\Phi)\mathbf{B}_{\mu\nu}\widetilde{\mathbf{B}}^{\mu\nu}$	$\mathcal{O}_{dB}^{\prime}=(\bar{q}\sigma^{\mu\nu}\Gamma_{d}d\Phi)B_{\mu\nu}$	$\mathcal{O}'_{\Phi \mathrm{ud}} = \mathrm{i}(\widetilde{\Phi}^{\dagger} D_{\mu} \Phi)(\bar{\mathrm{u}} \gamma^{\mu} \Gamma_{\mathrm{ud}} \mathrm{d})$				
$\mathcal{O}_{\Phi G}^{\prime}=\Phi^{\dagger}\Phi G^{A}_{\mu\nu}G^{A\mu\nu}$						
$\mathcal{O}'_{\Phi \widetilde{G}} = \Phi^{\dagger} \Phi G^A_{\mu \nu} \widetilde{G}^{A \mu \nu}$						

### Rare decays: full Dalitz analysis

[arXiv:1308.0422]

209

- Υ Υ and Z Υ loops sensitive to different physics because of V-A structure for Z.
- More information from full m_{QQ} spectrum.
  - Need to clearly define the phase-space used in analysis.



 $\blacksquare H \longrightarrow \gamma^* \gamma \longrightarrow \varrho \varrho \gamma$ 

[CMS-PAS-HIG-14-003]

210

 $m_{\mu\mu}$  < 20 GeV.  $\Box$  Veto out J/ $\psi$  and Y.

Requirement	Observed event	Expected number
	yield	of signal events
		for $m_{\rm H} = 125~{ m GeV}$
Trigger, photon selection, $p_T^{\gamma} > 25 \text{ GeV}$	0.6M	6.2
Muon selection, $p_T^{\mu 1} > 23$ GeV and $p_T^{\mu 2} > 4$ GeV	55836	4.7
$110 \text{ GeV} < m_{\mu\mu\gamma} < 170 \text{ GeV}$	7800	4.7
$m_{\mu\mu} < 20  { m GeV}$	1142	3.9
$\Delta \mathrm{R}(\gamma,\mu) > 1$	1138	3.9
Removal of resonances	1020	3.7
$p_T^\gamma/m_{\mu\mu\gamma}>0.3~{ m and}~p_T^{\mu\mu}/m_{\mu\mu\gamma}>0.3$	665	3.3
$122 \text{ GeV} < m_{\mu\mu\gamma} < 128 \text{ GeV}$	99	2.9



 $\mu$  at 125 GeV (95% CL)

Obs. (exp.)

#### < 11 (8)

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211 [http://cern.ch/go/X6rC]

#### Fiat 505





212 [http://cern.ch/go/X6rC]





213

#### [http://cern.ch/go/X6rC]

#### Fiat 850





214 [http://cern.ch/go/X6rC]





215 [ http://cern.ch/go/X6rC ]

