Higgs Physics – Lecture 4

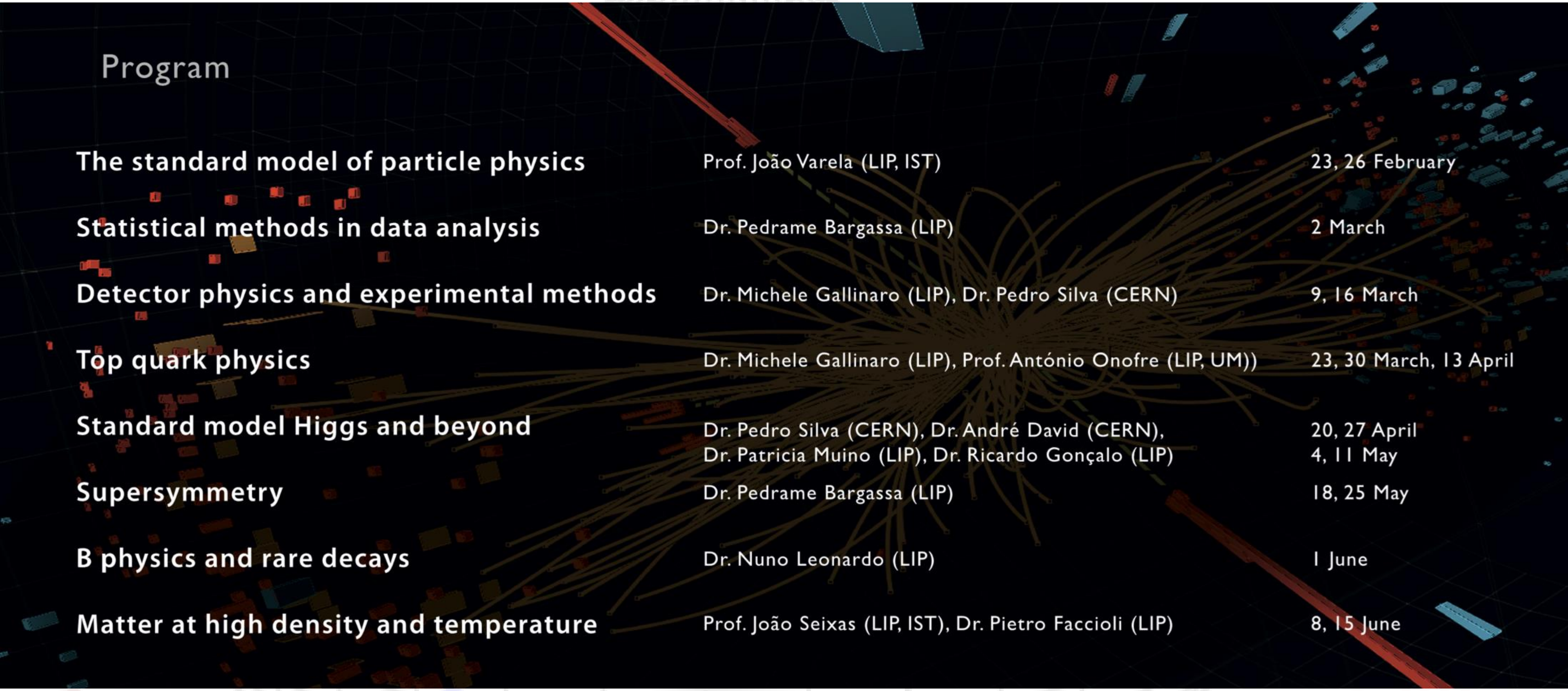
Higgs Physics at the LHC – suppressed and exotic channels, future directions

Ricardo Gonçalo – LIP

Course on Physics at the LHC – LIP, 11 May 2015

FCOMP-01-0124-FEDER-041830.

Outlook

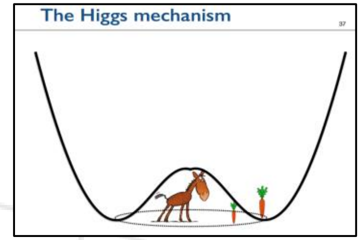


Program

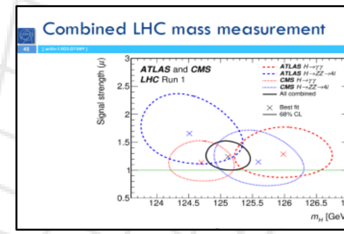
The standard model of particle physics	Prof. João Varela (LIP, IST)	23, 26 February
Statistical methods in data analysis	Dr. Pedrame Bargassa (LIP)	2 March
Detector physics and experimental methods	Dr. Michele Gallinaro (LIP), Dr. Pedro Silva (CERN)	9, 16 March
Top quark physics	Dr. Michele Gallinaro (LIP), Prof. António Onofre (LIP, UM))	23, 30 March, 13 April
Standard model Higgs and beyond	Dr. Pedro Silva (CERN), Dr. André David (CERN), Dr. Patricia Muino (LIP), Dr. Ricardo Gonçalo (LIP)	20, 27 April 4, 11 May
Supersymmetry	Dr. Pedrame Bargassa (LIP)	18, 25 May
B physics and rare decays	Dr. Nuno Leonardo (LIP)	1 June
Matter at high density and temperature	Prof. João Seixas (LIP, IST), Dr. Pietro Faccioli (LIP)	8, 15 June

Higgs lectures so far…

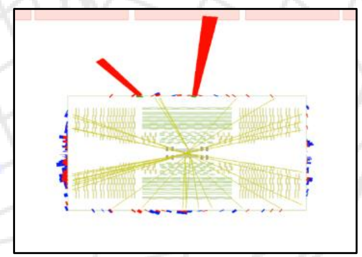
- Lecture 1
  - Higgs & EWSB introduction



- Lecture 2
  - Higgs boson properties



- Lecture 3
  - Detailed experimental searches

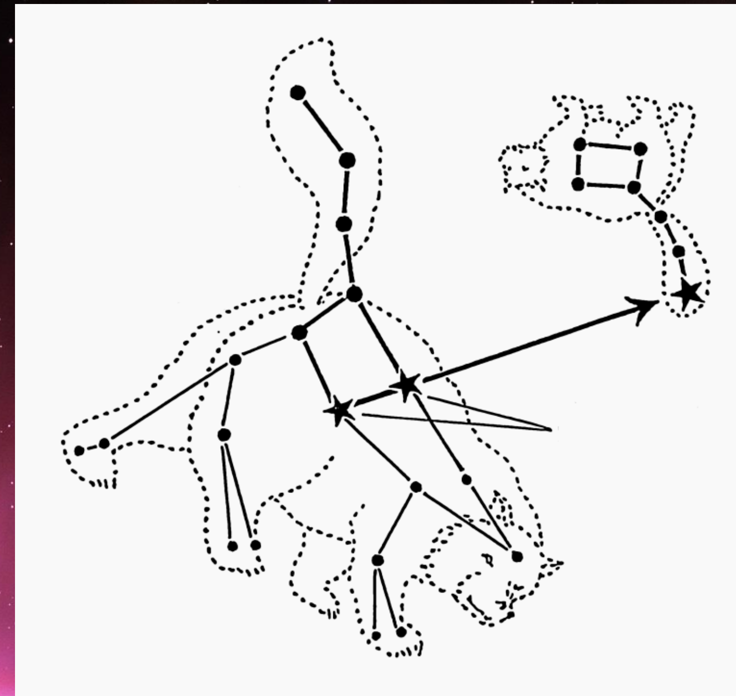


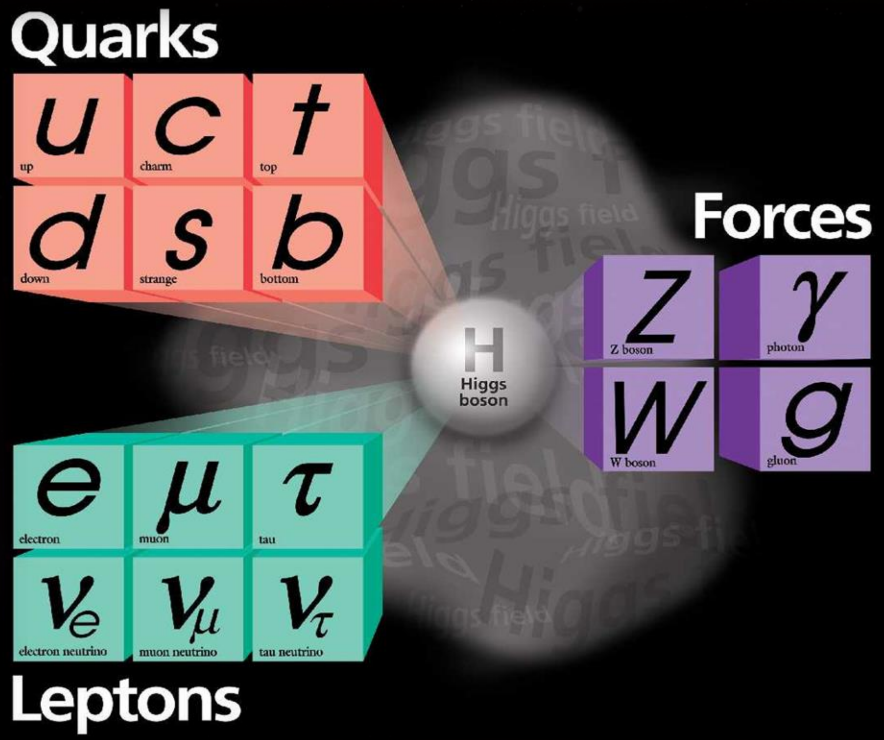
- This lecture
  - Missing channels and the future…

This lecture

- Recapitulation of previous Higgs lectures
  - Higgs mechanism
  - The state of the art
- Beyond the Standard Model Higgs
  - Constraints from Higgs couplings – 2HDM
  - Exotic channels: invisible Higgs
  - Rare channels: Higgs decay to J/Ψ plus γ
- Future of Higgs physics at the LHC
  - Higher luminosity and higher energy
  - Precision and new measurements

Recap of previous lectures



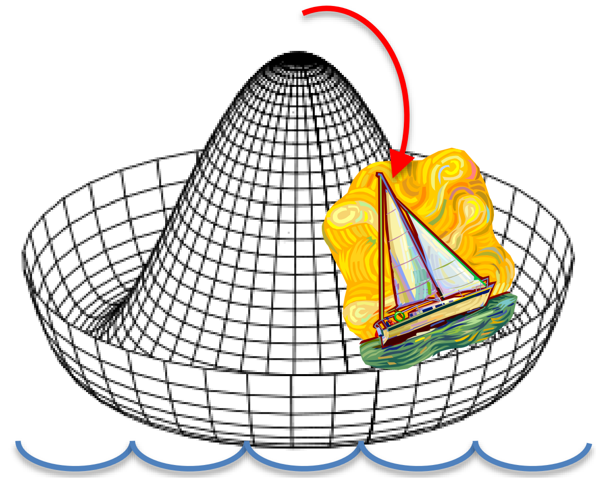

Quarks
u
up
c
charm
t
top
d
down
s
strange
b
bottom
Higgs field
H
Higgs boson
Forces
Z
Z boson
γ
photon
W
W boson
g
gluon
e
electron
μ
muon
τ
tau
ν_e
electron neutrino
ν_μ
muon neutrino
ν_τ
tau neutrino
Leptons

The Standard Model Higgs Mechanism

- In the Standard Model with no Higgs mechanism, interactions are symmetric and particles do not have mass

- The symmetry between the electromagnetic and the week interactions is broken:
  - Photon does not have mass
  - W, Z have a large mass

- Higgs mechanism:
  - mass of W and Z results from the Higgs mechanism



$$\phi = \begin{pmatrix} \dfrac{\phi_1 + i\phi_2}{\sqrt{2}} \\ \dfrac{\phi_3 + i\phi_4}{\sqrt{2}} \end{pmatrix}$$

see J.Varela's lecture

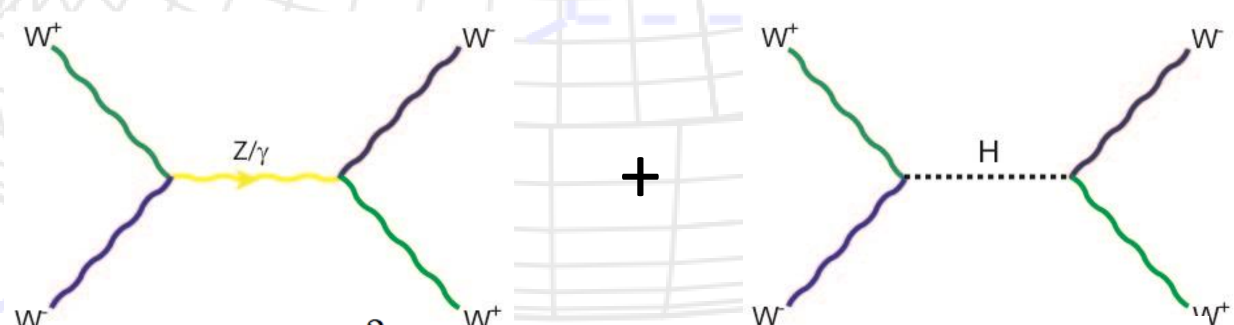
Added bonus

Non-zero average value of the Higgs field can also give masses to the quarks, electrons and muons – to all point-like particles.

Old theoretical problem affecting the quantum theory of the weak force :

> the probability of two W's interacting becomes larger than 1 at high energies (> 1 TeV).

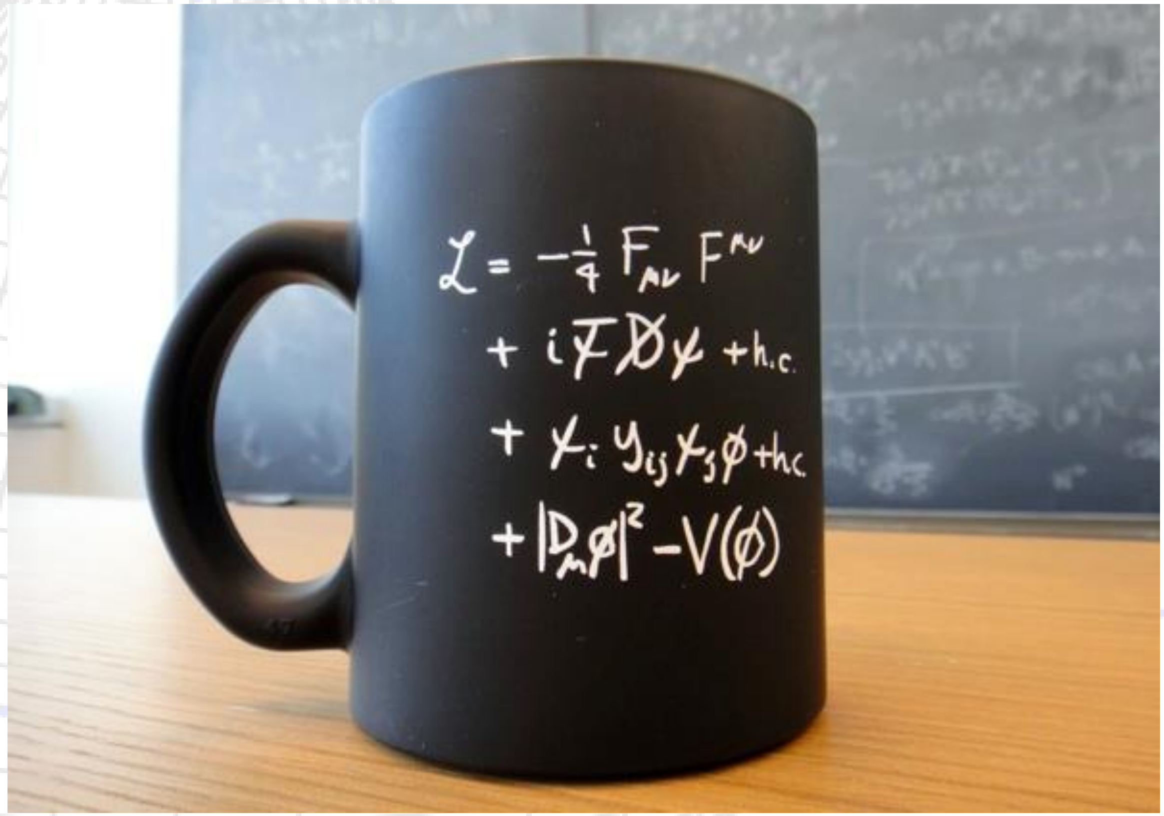
Solved by the Higgs field!



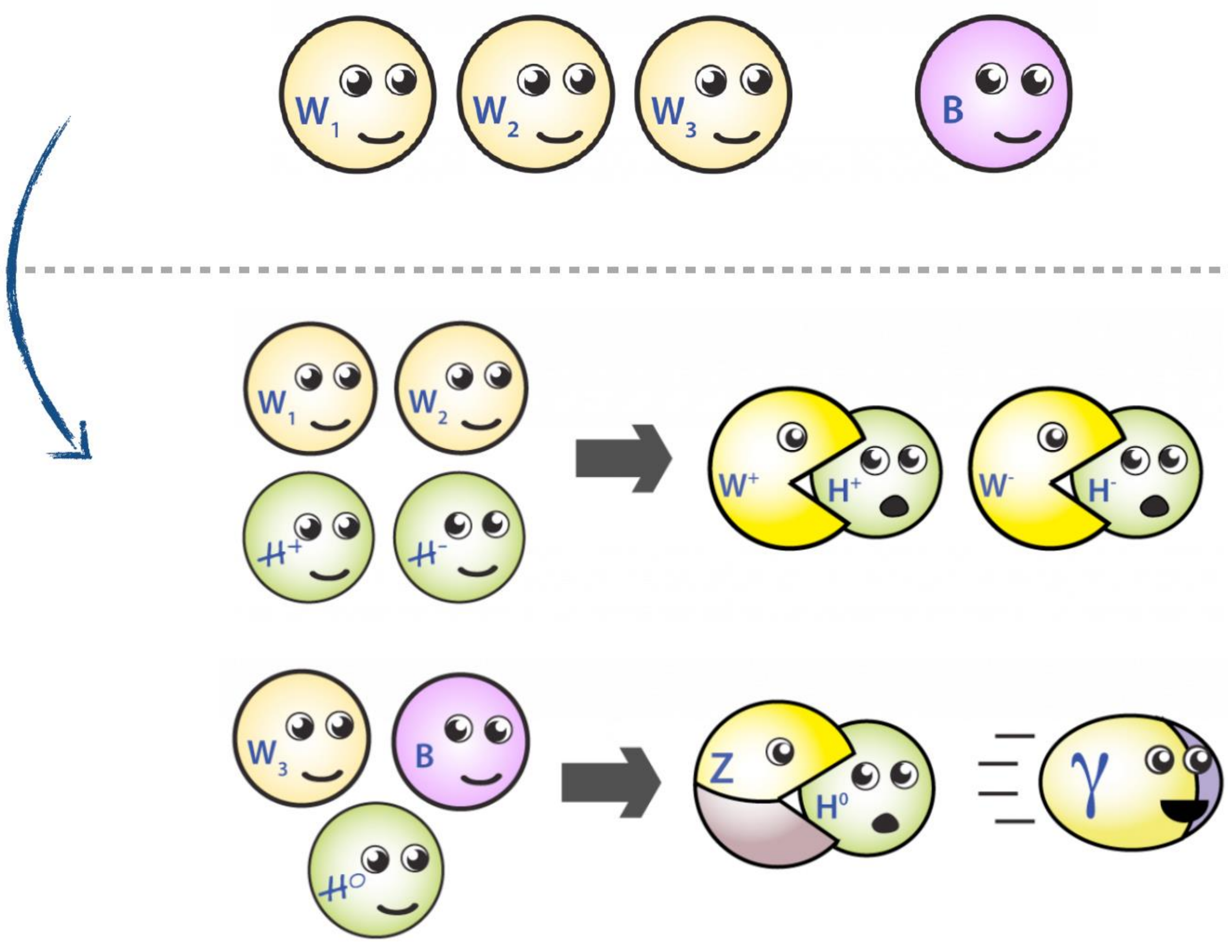
$$\lim_{E\to\infty} \mathcal{A} \propto E^2 \qquad\qquad \lim_{E\to\infty} \mathcal{A} \propto \text{const.}$$

Lagrangians and coffee mugs

- Throughout history, we have been looking mostly at the second line
- Interactions between fermion matter particles transmitted by force carriers
- I.e. all of chemistry and most of physics
- Disclamer: gravity not on the mug



Electroweak symmetry breaking

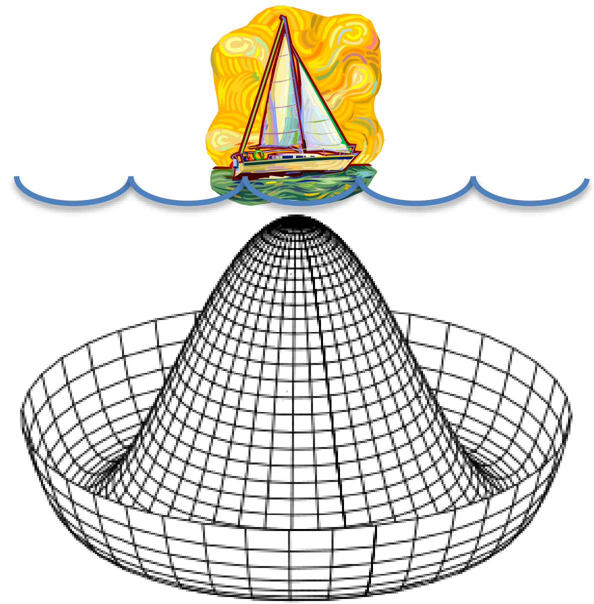


see P.Silva's lecture

Wikipedia wisdom

Electroweak Lagrangian before spontaneous symmetry breaking

$$\mathcal{L}_{EW} = \mathcal{L}_g + \mathcal{L}_f + \mathcal{L}_h + \mathcal{L}_y.$$



Electroweak gauge bosons: B^0 W^0 $W^\pm$

$$\mathcal{L}_g = -\frac{1}{4}W^{a\mu\nu}W^a_{\mu\nu} - \frac{1}{4}B^{\mu\nu}B_{\mu\nu}$$

Fermion kinetic terms

$$\mathcal{L}_f = \overline{Q}_i i\not{D} Q_i + \overline{u}_i i\not{D} u_i + \overline{d}_i i\not{D} d_i + \overline{L}_i i\not{D} L_i + \overline{e}_i i\not{D} e_i$$

$$\mathcal{L}_h = |D_\mu h|^2 - \lambda\left(|h|^2 - \frac{v^2}{2}\right)^2$$

Higgs term (note: vacuum expectation value zero before symmetry breaking)

$$\mathcal{L}_y = -y_{u\,ij}\epsilon^{ab}\,h_b^\dagger\,\overline{Q}_{ia}u_j^c - y_{d\,ij}\,h\,\overline{Q}_i d_j^c - y_{e\,ij}\,h\,\overline{L}_i e_j^c + h.c.$$

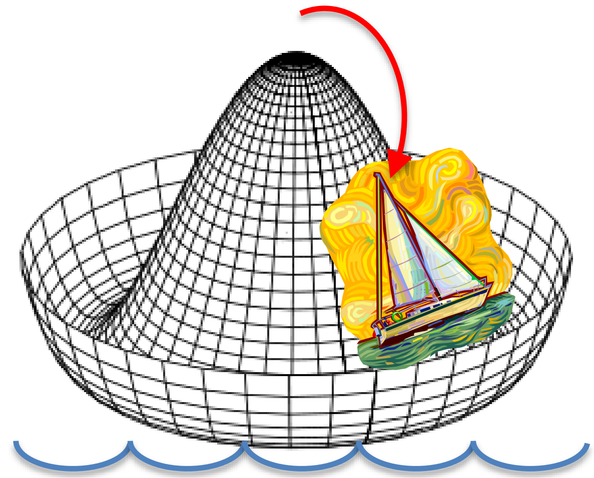
Yukawa interaction term between Higgs field and fermions

Wikipedia wisdom

After electroweak symmetry breaking

$$\mathcal{L}_{EW} = \mathcal{L}_K + \mathcal{L}_N + \mathcal{L}_C + \mathcal{L}_H + \mathcal{L}_{HV} + \mathcal{L}_{WWV} + \mathcal{L}_{WWVV} + \mathcal{L}_Y$$

Spontaneous symmetry breaking:
New bosons γ and Z^0 from W^0 and B^0



$$\begin{pmatrix} \gamma \\ Z^0 \end{pmatrix} = \begin{pmatrix} \cos\theta_W & \sin\theta_W \\ -\sin\theta_W & \cos\theta_W \end{pmatrix} \begin{pmatrix} B^0 \\ W^0 \end{pmatrix}$$

Kinetic terms: **notice boson masses** for Z^0,$W^\pm$, H

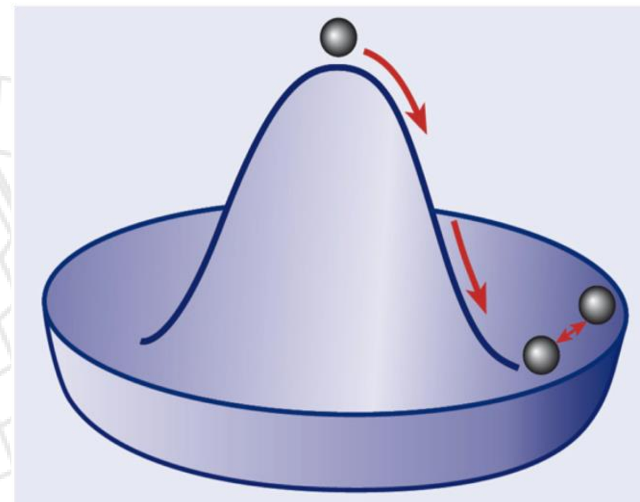
$$\mathcal{L}_K = \sum_f \overline{f}(i\partial\!\!\!/ - m_f)f - \frac{1}{4}A_{\mu\nu}A^{\mu\nu} - \frac{1}{2}W^+_{\mu\nu}W^{-\mu\nu} + \boxed{m_W^2 W^+_\mu W^{-\mu}}$$
$$-\frac{1}{4}Z_{\mu\nu}Z^{\mu\nu} + \boxed{\frac{1}{2}m_Z^2 Z_\mu Z^\mu} + \frac{1}{2}(\partial^\mu H)(\partial_\mu H) - \boxed{\frac{1}{2}m_H^2 H^2}$$

Wikipedia wisdom

Higgs boson mass: transverse oscillation modes

Higgs boson 3- and 4-point self-interaction

$$\mathcal{L}_H = -\frac{g m_H^2}{4 m_W} H^3 - \frac{g^2 m_H^2}{32 m_W^2} H^4$$

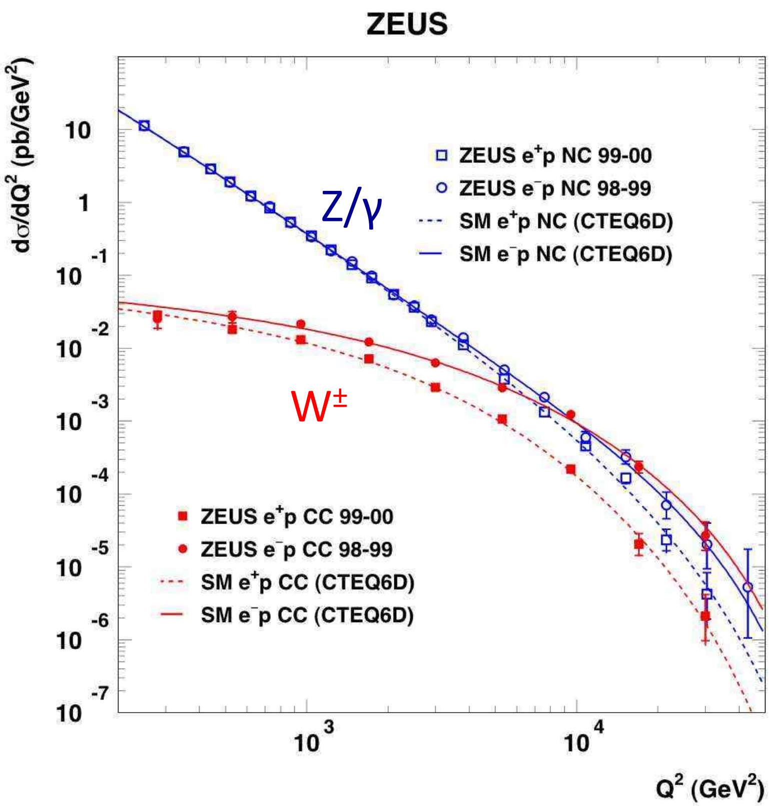


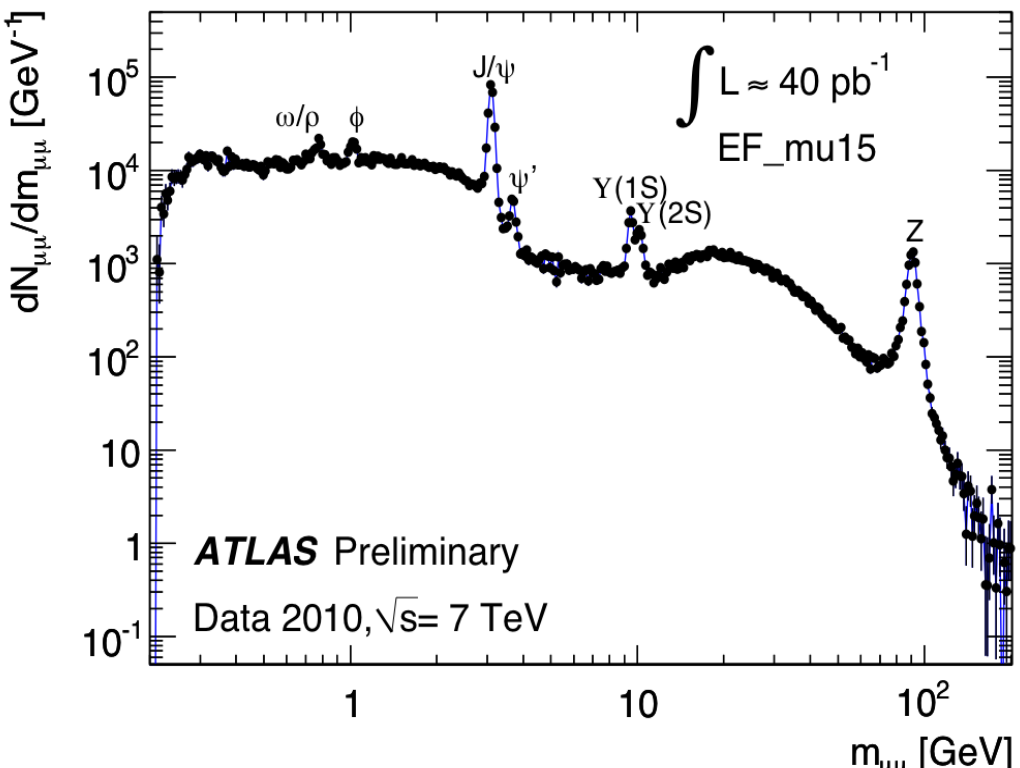
Yukawa interactions between Higgs and fermions:
note fermion masses!

$$\mathcal{L}_Y = -\sum_f \frac{g m_f}{2 m_W} \bar{f} f H$$

Why does it matter?

- Because it's real!
  - Data shows Higgs mechanism (or something like it) needed in the theory
- Because it may lead us to new discoveries and a new understanding of Nature!
  - "There is nothing so practical as a good theory" (Kurt Lewin)





Repubblica.it
Cern, scoperta la "particella di Dio"
« PRECEDENTE
Foto 1 di 19
SUCCESSIVO
Higgs boson-like particle discovery claimed at LHC
THANH NIÊN ONLINE
DIỄN ĐÀN CỦA HỘI LIÊN HIỆP THANH NIÊN VIỆT NAM
Chính trị - Xã hội
Quốc phòng
Thế giới trẻ
Kinh tế
Thế giới
Văn nghệ
Giáo dục
Công nghệ
Khoa học
Chủ nhật, 08/07/2012, 10:35:36 GMT+7
RSS
Newsletter
Quảng cáo
Đường dây nóng
Đặt làm
Khoa học
Sân bóng của các hạt nhân
Ngày 4.7 tại Geneva, Thụy Sĩ, Viện Nghiên cứ
mới được cho là tương ứng với hạt Higgs - c
5 thập niên qua. Nếu thông tin này hoàn toàn
tương đương với việc Christophe Columbus
SAY GOD PARTICLE
ONE MORE GODDAMN TIME
http://www.ne
The New York Times
U.S.
N.Y. / REGION
BUSINESS
Le boson d
99,9999 %
Le Monde.fr | 04.07.2012
ero
Physicists Find Elusive Particle Seen as
PHYSIK
Haarscharf am gottverdammten Teilchen vorbei
Die Belege scheinen überwältigend: Forscher könnten
ein neues Teilchen gefunden haben. Unklar ist, ob es
das Higgs-Boson ist, der letzte Baustein im Weltbild
der Physik.
theguardian
News
Sport
Comment
Culture
Business
Money
London 2
Comment is free
The Higgs boson discovery is another giant leap for humankind
The Cern discovery of the Higgs particle is up there with putting man on the moon – something all humanity can be proud of
Scientists in Geneva on Wednesday applauded the discovery of a

Going beyond the standard model

But the Standard Model is not complete; there are still many unanswered questions.

Why do we observe matter and almost no antimatter if we believe there is a symmetry between the two in the universe?

What is this "dark matter" that we can't see that has visible gravitational effects in the cosmos?

Are quarks and leptons actually fundamental, or made up of even more fundamental particles?

Why are there exactly three generations of quarks and leptons? What is the explanation for the observed pattern for particle masses?

How does gravity fit into all of this?

Many possible theories

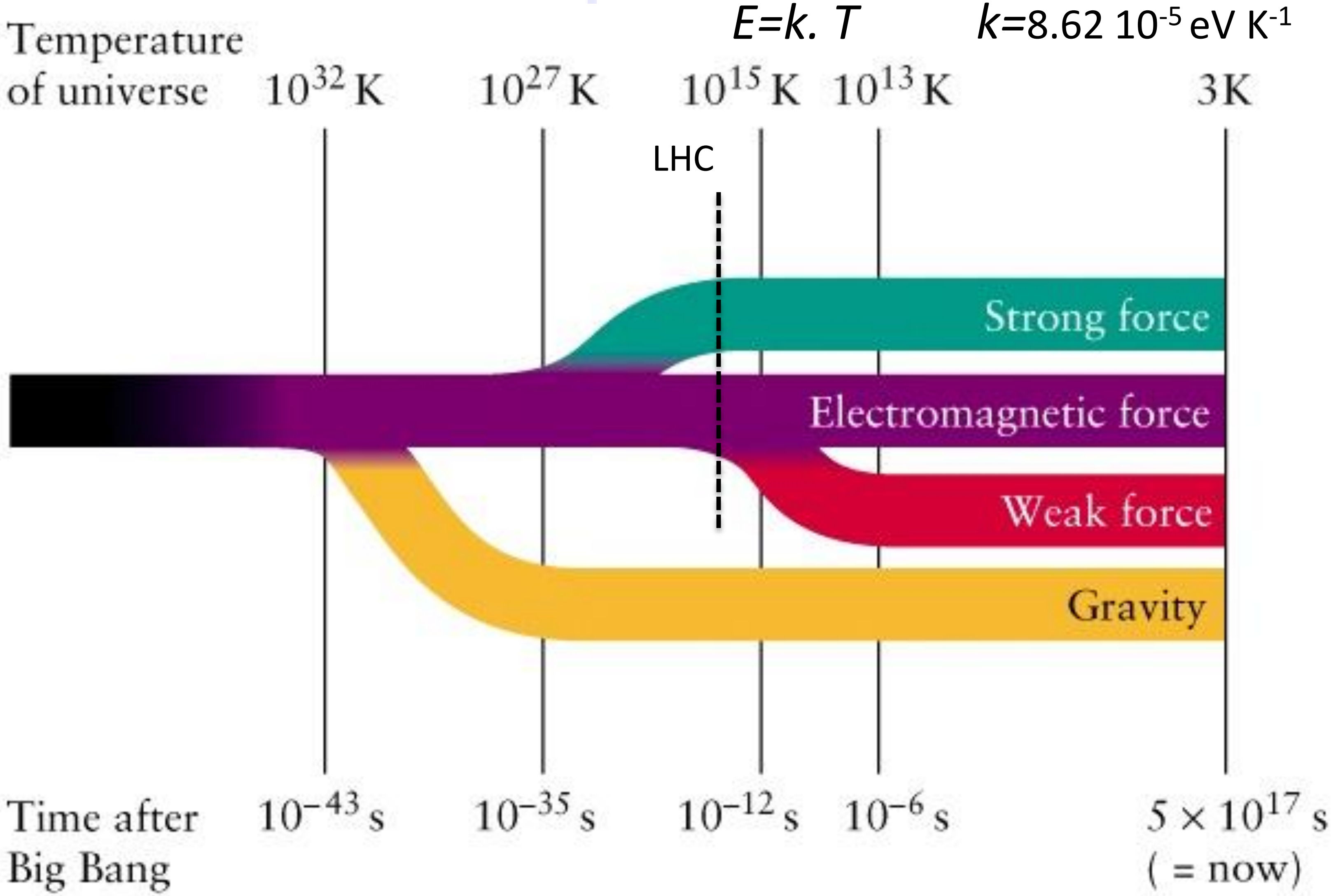
There are a large number of models which predict new physics at the TeV scale accessible at the LHC:

- Supersymmetry (SUSY)
- Extra dimensions
- Extended Higgs Sector e.g. in SUSY Models
- Grand Unified Theories (SU(5), O(10), E6, …)
- Leptoquarks
- New Heavy Gauge Bosons
- Technicolour
- Compositeness

Any of this could still be found at the LHC

Forces and expansion of the Universe

$E = k.\,T \qquad k = 8.62\ 10^{-5}\ \mathrm{eV\ K^{-1}}$

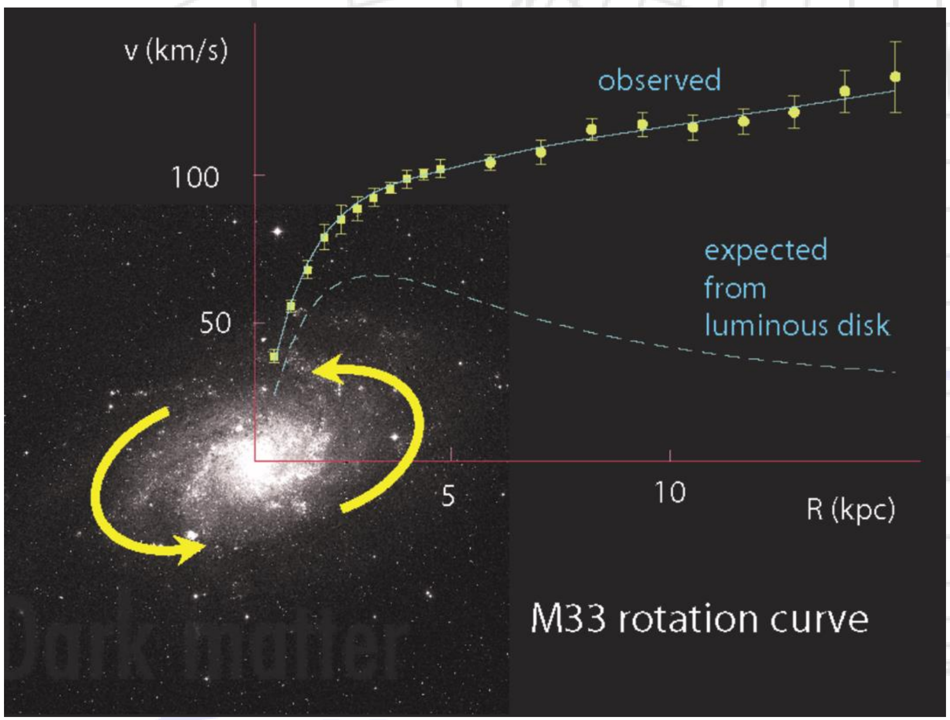


The dark side of the Universe

Long standing problem:

We know that ordinary matter is only ~4% of the matter-energy in the Universe.

What is the remaining 96%?



The LHC may help to solve this problem, discovering **dark matter**

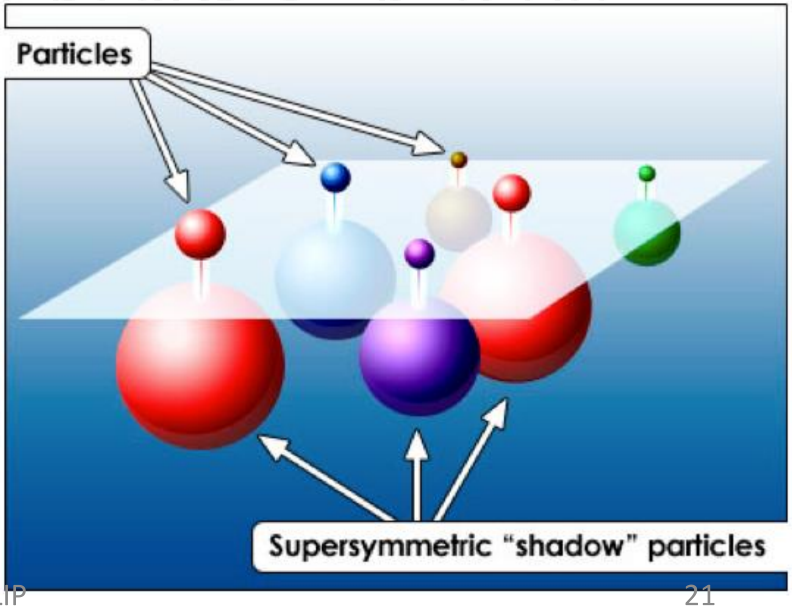
Supersymmetry

Some physicists attempting to unify gravity with the other fundamental forces have proposed a new fundamental symmetry:

- Every fermion should have a massive "shadow" boson
- and boson should have a massive "shadow" fermion.

This relationship between fermions and bosons is called supersymmetry (SUSY)

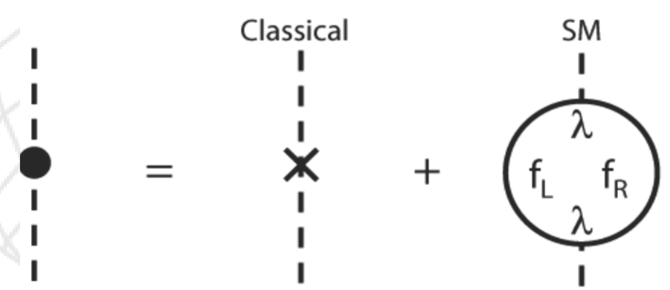
No supersymmetric particle has yet been found, but we will now explore a much bigger kinematic region … more news soon!



Higgs and hierarchy problem

In the SM the Higgs mass is a huge problem:

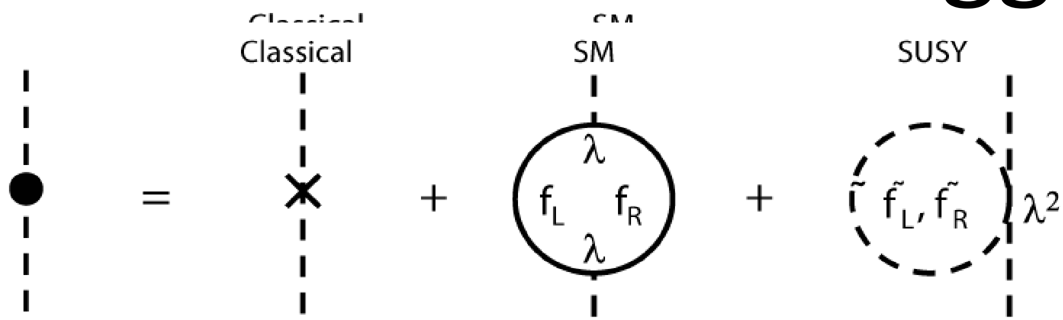
- Virtual particles in quantum loops contribute to the Higgs mass
- Contributions grow with Λ (upper scale of validity of the SM)
- Λ could be huge – e.g. the Plank scale (10^{19} GeV)
- Miraculous cancelations are needed to keep the Higgs mass < 1 TeV



$$m_h^2 = (m_h^2)_0 - \frac{1}{16\pi^2}\lambda^2\Lambda^2 + \dots ,$$

This is known as the hierarchy problem

SUSY and the Higgs mass



$$m_h^2 = (m_h^2)_0 - \frac{1}{16\pi^2}\lambda^2\Lambda^2 + \dots ,$$

Higgs mass:

- correction has quadratic divergence!
  - Λ a cut-off scale – e.g. Planck scale

Cancellation

$$\begin{aligned} m_h^2 &= (m_h^2)_0 \boxed{- \frac{1}{16\pi^2}\lambda^2\Lambda^2 + \frac{1}{16\pi^2}\lambda^2\Lambda^2} + \dots \\ &\approx (m_h^2)_0 + \boxed{\frac{1}{16\pi^2}(m_{\tilde{f}}^2 - m_f^2)\ln(\Lambda/m_{\tilde{f}})} , \end{aligned}$$

Superpartners fix this:

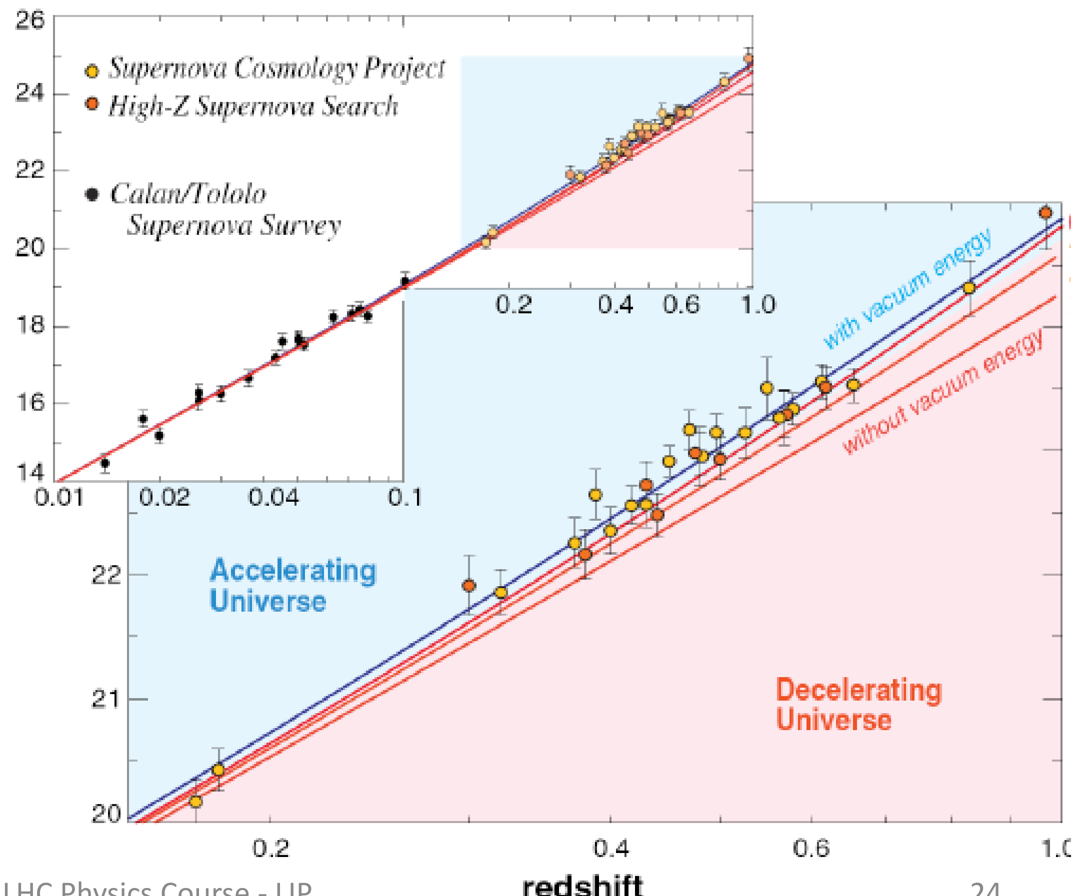
- Need superpartners at mass ~1-2 TeV
  - Otherwise the logarithmic term becomes too large, which would require more fine-tuning.

The Universe expansion is accelerating

In 1998, two groups used distant Supernovae to measure the expansion rate of the universe: Perlmutter et al. (Supernova Cosmology Project), and Schmidt et al. (High-z Supernova Team)

They got the same result:
The Universe expansion is accelerating

Some form of energy (dark energy) fills space



Vacuum energy density

Dark energy responsible for acceleration of expansion is very small

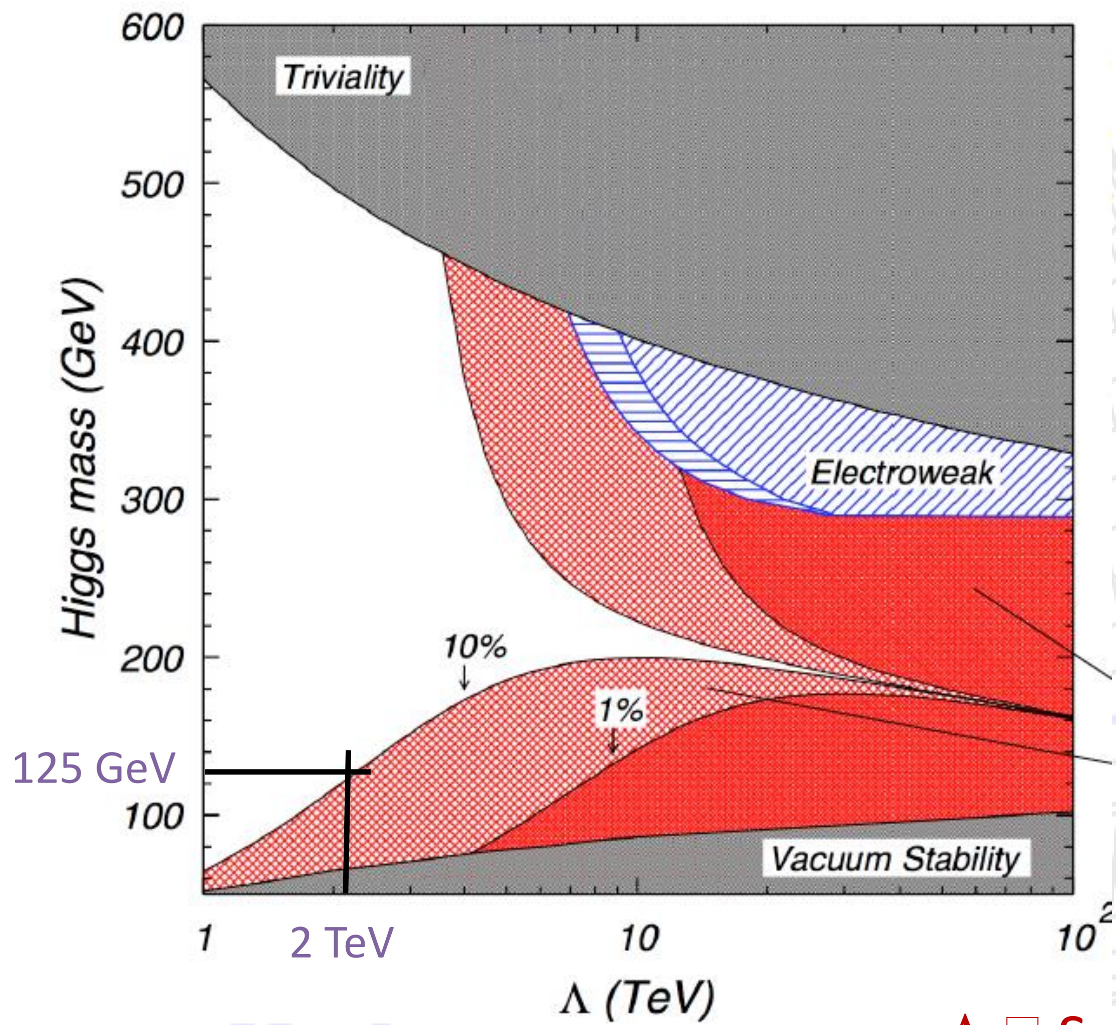
From particle physics we know that Vacuum has energy:

- potential energy of scalar fields
- energy of quantum fluctuations as predicted by quantum mechanics

This vacuum energy is 100 orders of magnitude larger than dark energy!

This huge discrepancy is known as the vacuum catastrophe.

New physics at a few TeV?

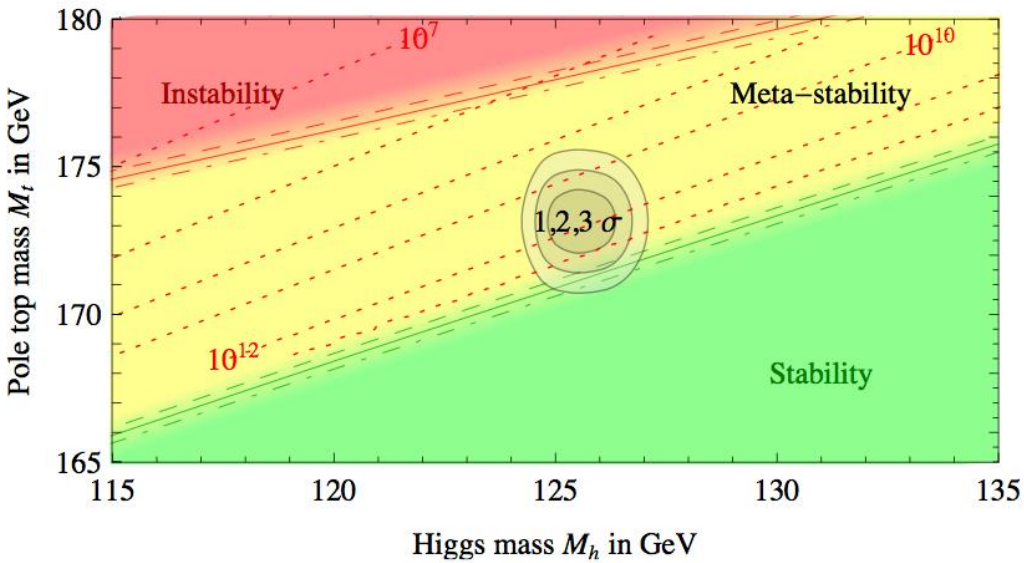


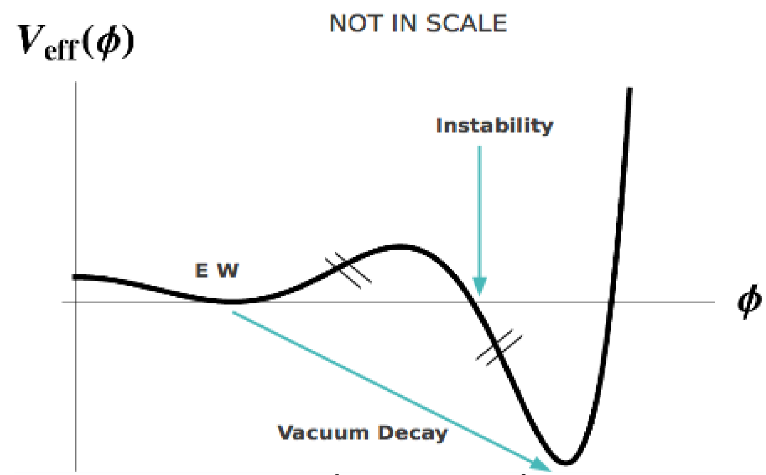
Naturalness implies Supersymmetry or another 'New Physics' below ~ 2 TeV

Excluded to avoid fine-tuning

Λ □ Scale of New Physics

A bit of fun…





RG-improved potential

- What if…
  - At higher orders, Higgs potential doesn't have to be stable
  - Depending on m_t and m_H second minimum can be lower than EW minimum ⇒ tunneling between EW vacuum and true vacuum?!
- "For a narrow band of values of the top quark and Higgs boson masses, the Standard Model Higgs potential develops a shallow local minimum at energies of about 10^{16} GeV, where primordial inflation could have started in a cold metastable state", I. Masina, arXiv:1403.5244 [astro-ph.CO]
  - See also: V. Brachina, Moriond 2014 (Phys.Rev.Lett.111, 241801 (2013)), G. Degrassi et al, arXiv:1205.6497v2; R.Contino, Workshop sulla fisica p-p a LHC, 2013

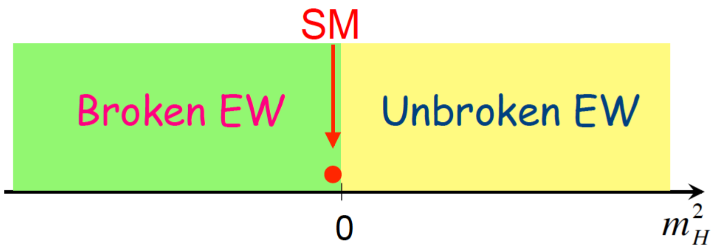
The universe seems to live near a critical condition

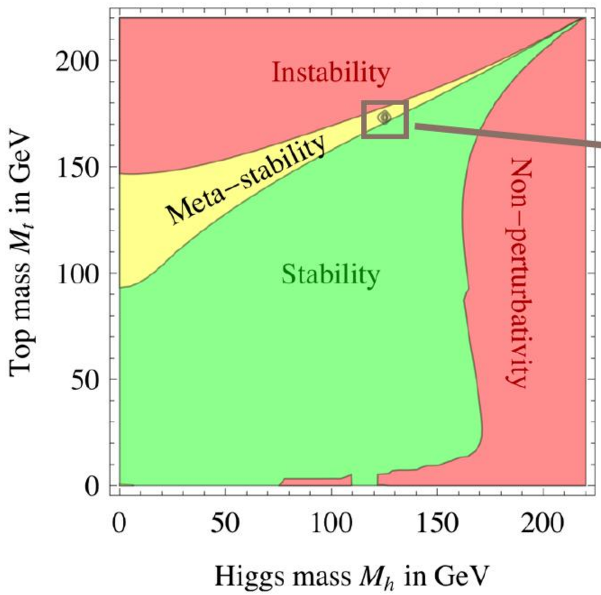
JHEP 1208 (2012) 098

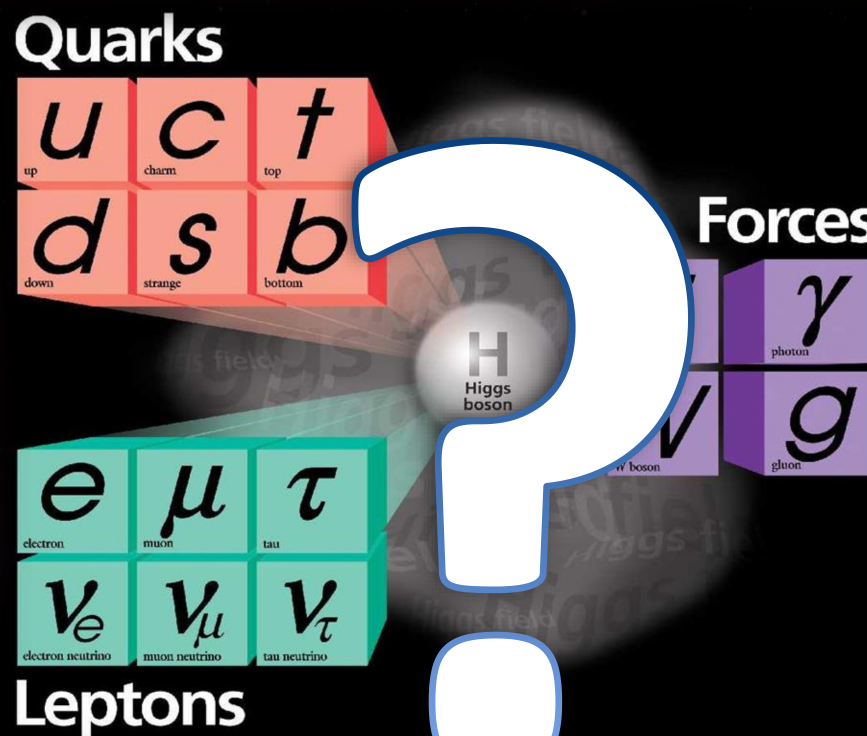
Why?!

Explained by underlying theory?

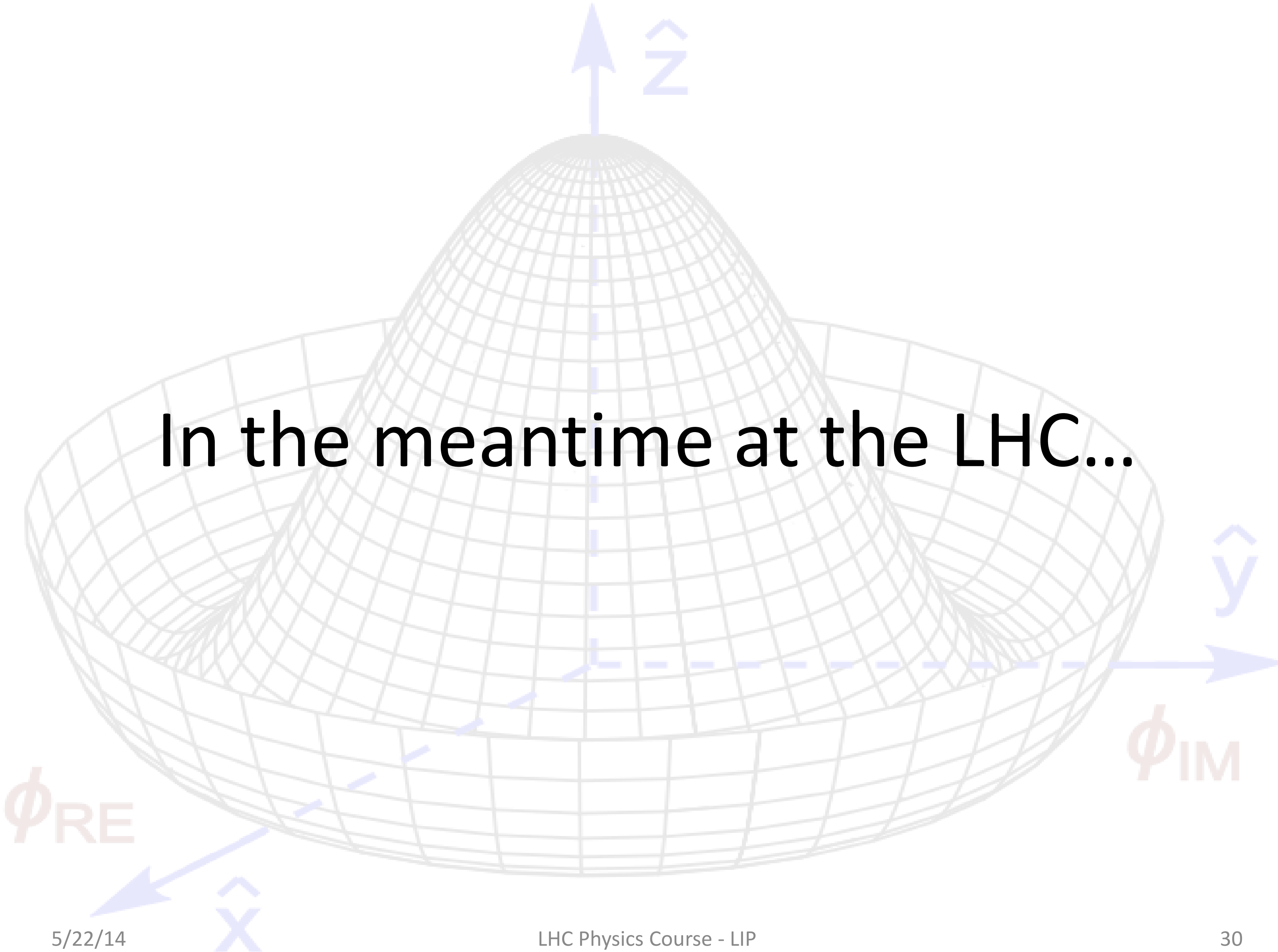
Anthropic principle?





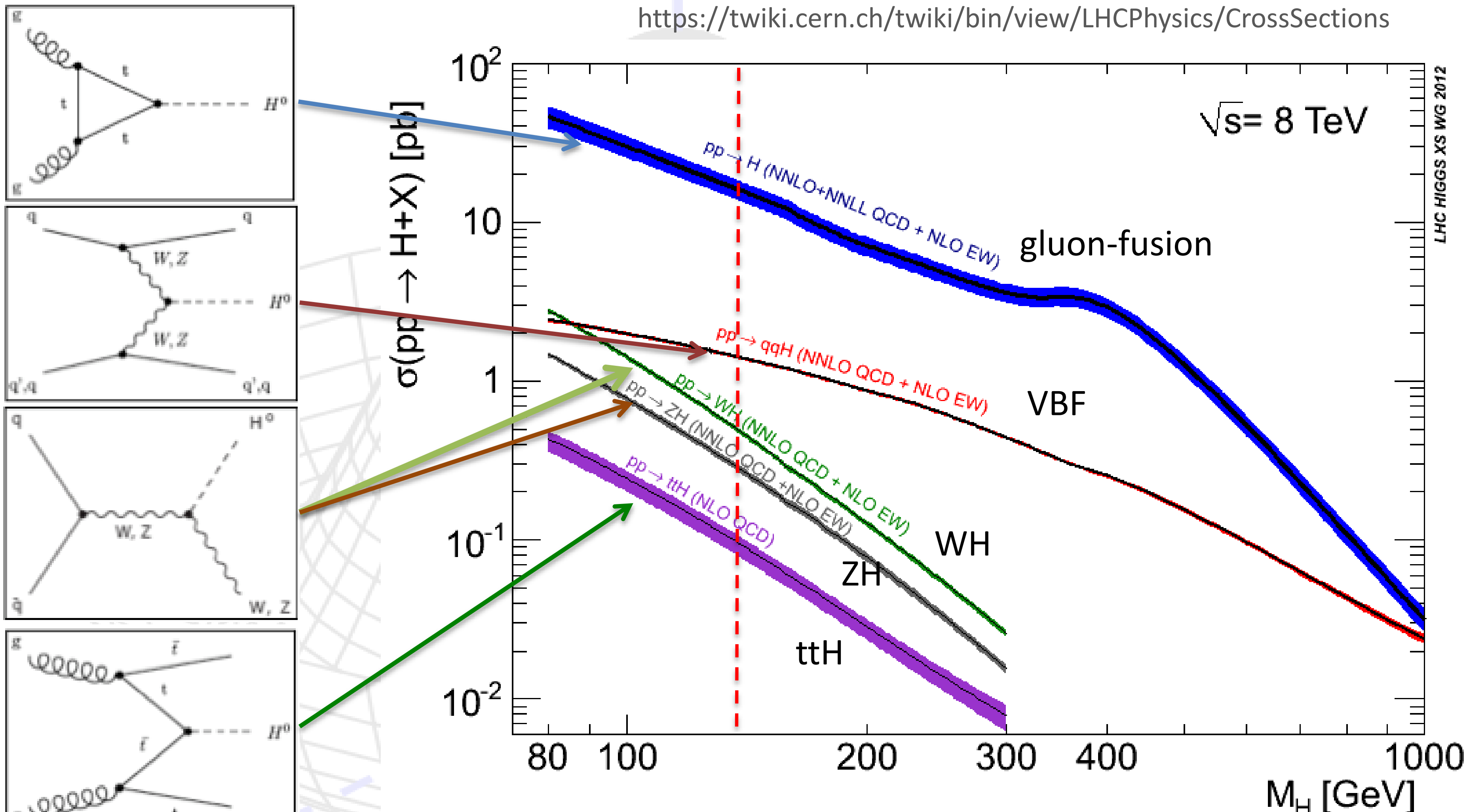


Back to the big questions!!

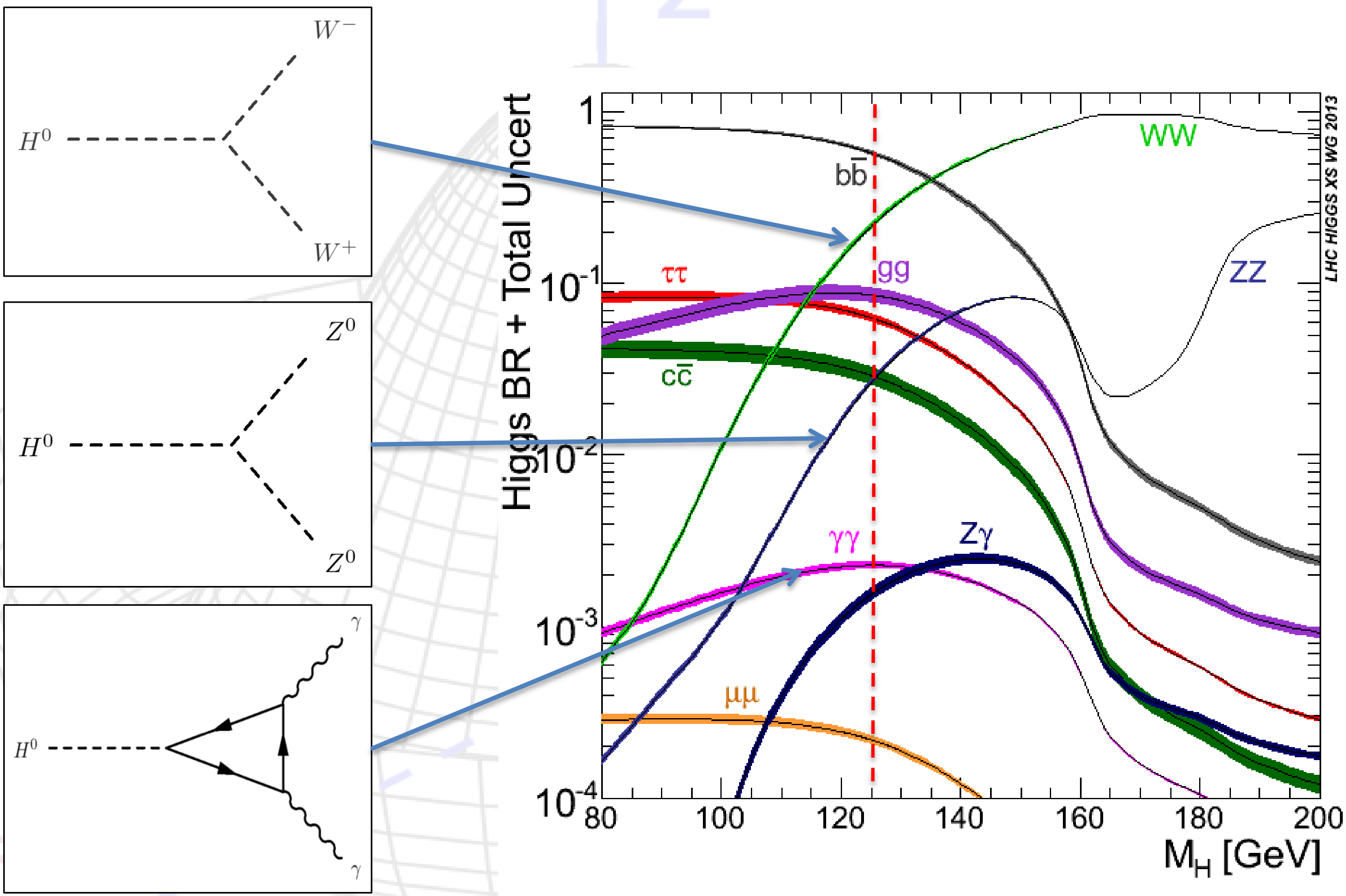


In the meantime at the LHC…

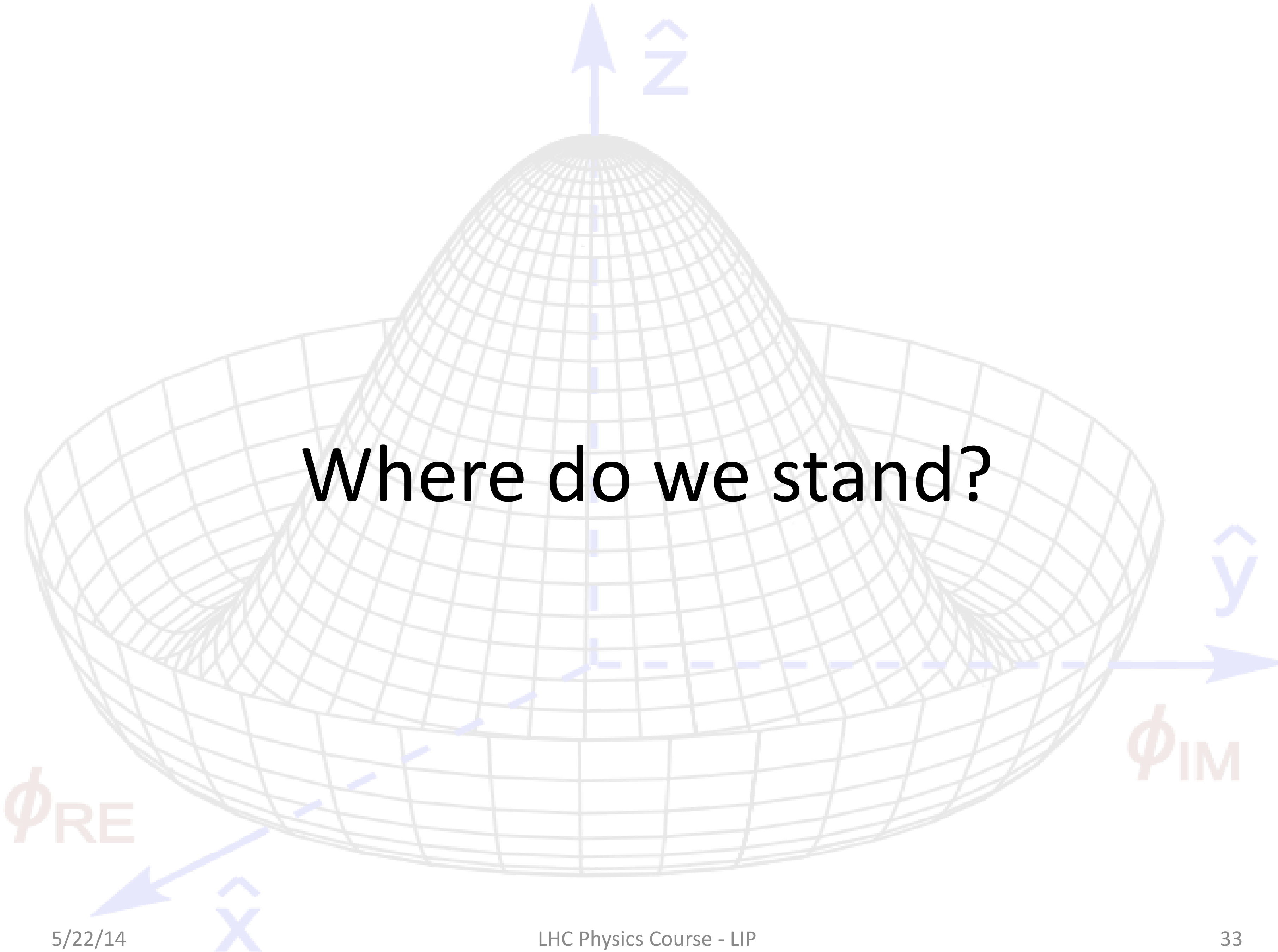
https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CrossSections



See previous lectures


H^0
W^-
W^+
H^0
Z^0
Z^0
H^0
γ
γ
Higgs BR + Total Uncert
M_H [GeV]
LHC HIGGS XS WG 2013
WW
$b\bar{b}$
$\tau\tau$
gg
ZZ
$c\bar{c}$
$\gamma\gamma$
$Z\gamma$
$\mu\mu$
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
80
100
120
140
160
180
200

Where do we stand?



- Most modes available with current lumi explored
- Precision: obvious signal in bosonic decays
  - Mass around 125GeV
  - Signal strength consistent with SM – some questions
  - Main alternatives to $J^P = 0^+$ discarded – questions remain
- Fermion couplings seen in $H \rightarrow \tau\tau$ (4σ)
- Evidence for VBF production (3σ)
- Mainly indirect sensitivity to ttH coupling through loops
- Many direct searches for other Higgses turned out nothing (yet)

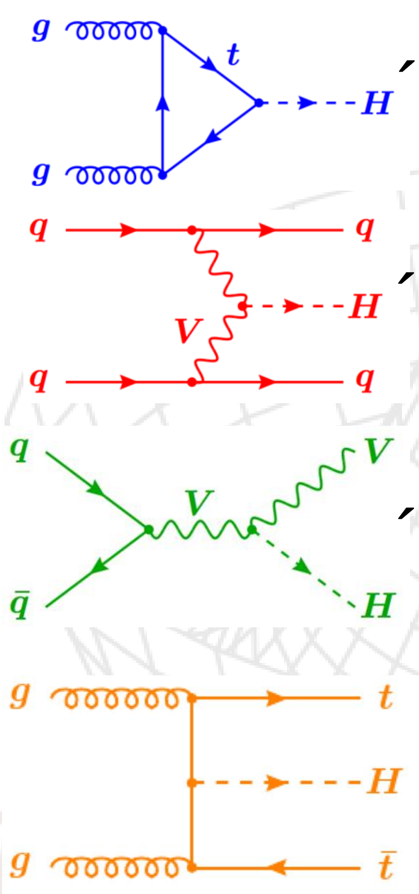
T – Tevatron; A – ATLAS; C – CMS; combination drivers in red.

★ "seen" ☆ "tried" - "impossible"	$H\rightarrow b\bar{b}$			$H\rightarrow\tau\tau$			$H\rightarrow WW$			$H\rightarrow ZZ$			$H\rightarrow\gamma\gamma$			$H\rightarrow Z\gamma$			$H\rightarrow$inv.			$H\rightarrow\mu\mu$			$H\rightarrow c\bar{c}$ $H\rightarrow HH$		
	T	A	C	T	A	C	T	A	C	T	A	C	T	A	C	T	A	C	T	A	C	T	A	C	T	A	C
ggH	-	-	-	☆	★	★	☆	★	★	☆	★	★	☆	★	★	-	☆	☆				-	☆	☆	-		
VBF			☆	☆	★	★		★	★		★	☆		★	☆	-		☆			☆	-		☆	-		
VH	★	☆	★	☆		☆	☆	☆	☆		☆	☆		☆	☆	-				☆	☆	-			-		
ttH		☆	☆	☆		☆	☆							☆	☆	-						-			-		

See A.David and P.Conde's lectures

Combining Higgs Channels

Production



´ k_g^2

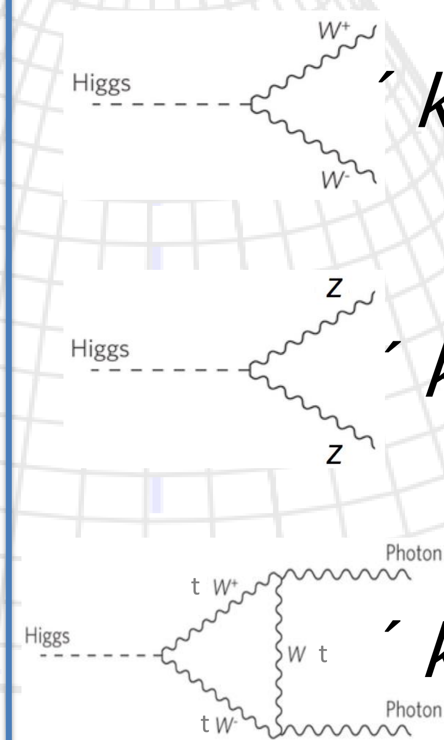
´ $k_{W/Z}^2$

´ $k_{W/Z}^2$

´ k_t^2

×

Decay



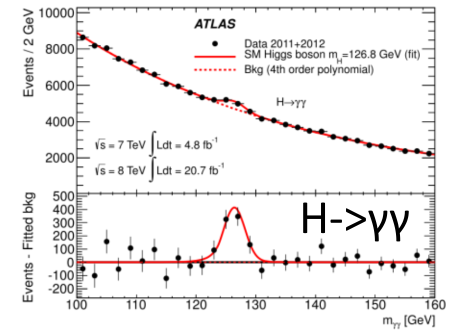
´ k_W^2

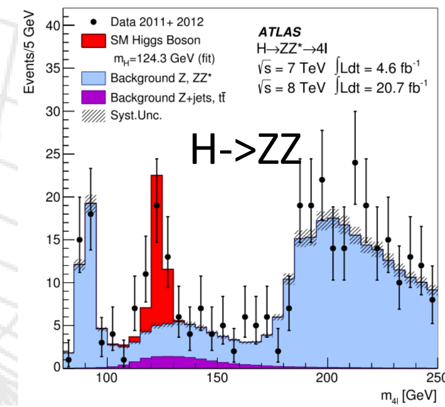
´ k_Z^2

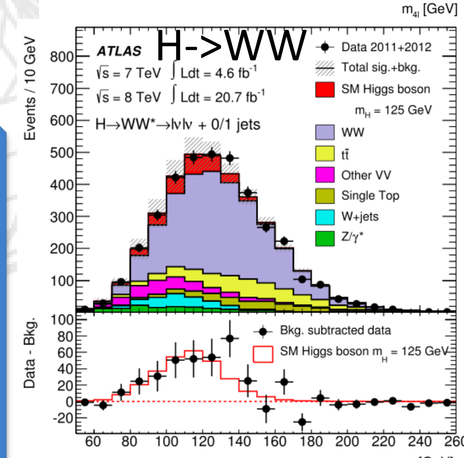
´ k_g^2

FIT

Backgrounds +







See A.David's lecture

A bit more technically

- **Assumptions:**
  - Single resonance (at m_H = 125.5GeV)
  - No modification of tensor structure of SM Lagrangian:
    - i.e. H has $J^P = 0^+$
  - Narrow width approximation holds
    - i.e. rate for process i ➔ H ➔ f is: $\sigma \times BR = \frac{\sigma_{i\to H} \times \Gamma_{H\to f}}{\Gamma_H}$
- **Free parameters** in framework:
  - Coupling scale factors: κ_j^2
  - Total Higgs width: κ_H^2

$$\sigma_i = k_i^2 \times \sigma_i^{SM}; \Gamma_f = k_f^2 \times \Gamma_f^{SM}; \Gamma_H = k_H^2 \times \Gamma_H^{SM}$$

  - Or ratios of coupling scale factors: $\lambda_{ij} = \kappa_i / \kappa_j$
- Tree-level motivated framework
  - Useful for **studying deviations** in data with respect to expectations
    - E.g. extract coupling scale factor to weak bosons κ_V by setting $\kappa_W = \kappa_Z = \kappa_V$
  - Not same thing as fitting a new model to the data

Higgs boson mass

- **Mass:** around 125GeV
  - Used to be the only unknown SM-Higgs parameter, remember? ☺
- ATLAS: arXiv:1307.1427
  - $m_H^{H\to 4l} = 124.3 \pm 0.6(\text{stat}) \pm 0.5(\text{sys})$
  - $m_H^{H\to\gamma\gamma} = 126.8 \pm 0.2(\text{stat}) \pm 0.7(\text{sys})$
  - Assuming single resonance:

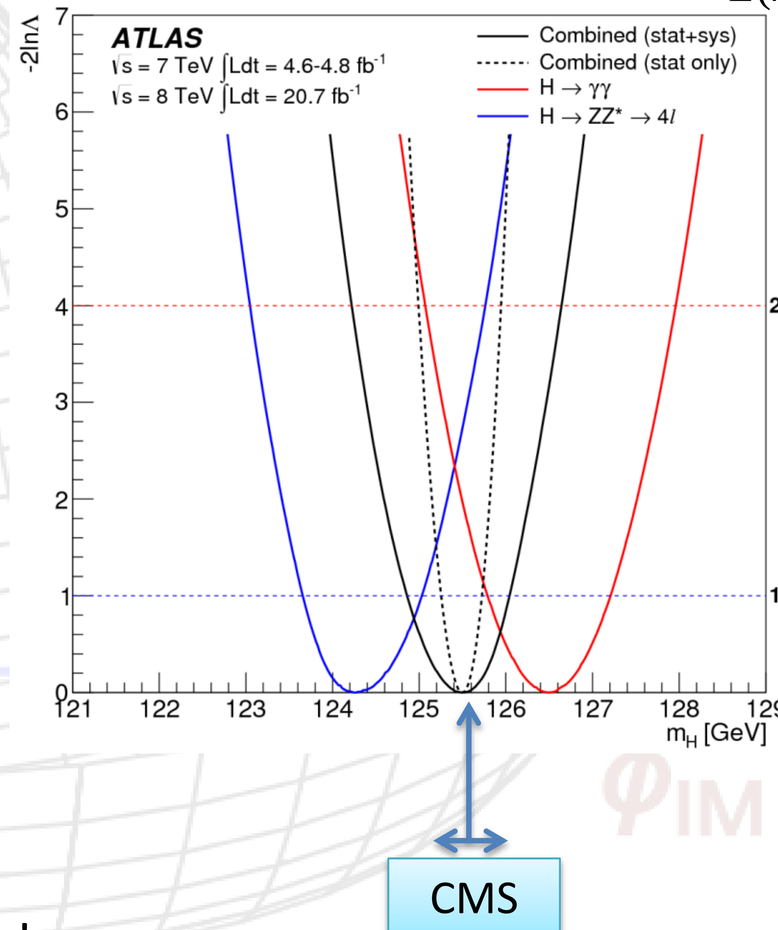
    $m_H = 125.5 \pm 0.2(\text{stat})\ ^{+0.5}_{-0.6}(\text{sys})$
- Tension between channels!
  - Compatibility P=1.5% (2.4σ)
  - Rises to 8% with square syst.prior

BUT:

- CMS: arXiv:1312.5353
  - $m_H^{H\to 4l} = 125.6 \pm 0.4(\text{stat}) \pm 0.6(\text{sys})$
- CMS: CMS-PAS-HIG-13-005
  - $m_H^{H\to\gamma\gamma} = 125.4 \pm 0.5(\text{stat}) \pm 0.6(\text{sys})$
- Doesn't look like two different resonances!...

ATLAS: arXiv:1307.1427

$$\mathrm{L} = \frac{L(m_H)}{L(\hat{m}_H)}$$

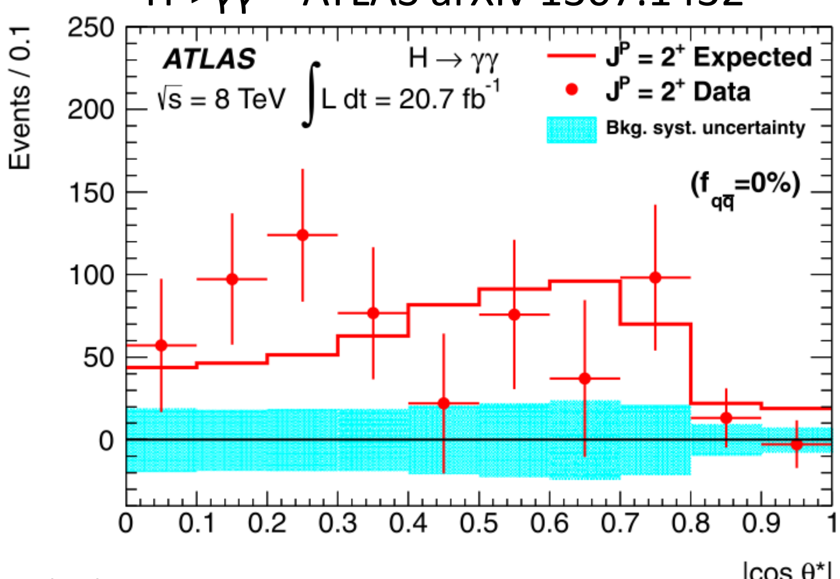


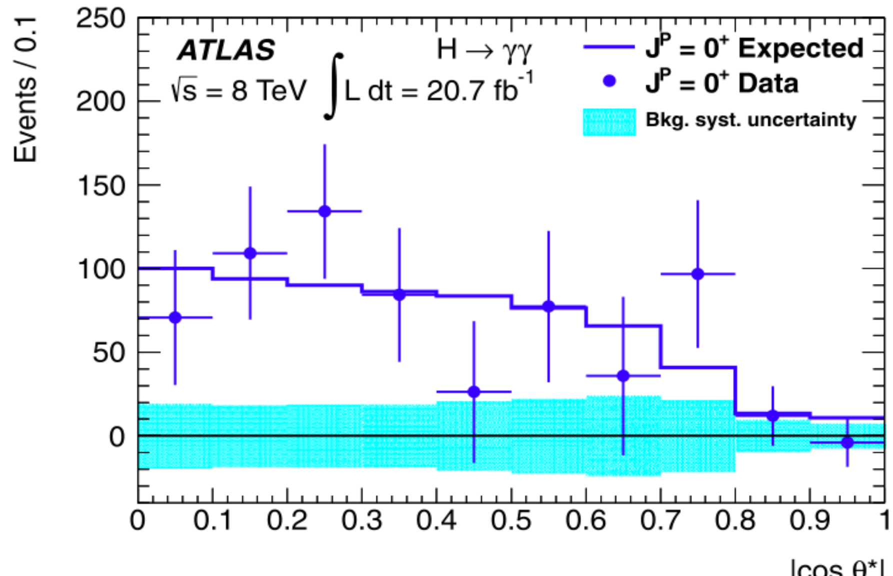
Spin and Parity

- Pure $J^P = 0^-, 1^+, 1^-$, and 2^+ excluded with 97.8, 99.97, 99.7, and 99.9% Confidence Level (ATLAS arXiv 1307.1432)
- But note: Higgs could have CP-violating component!

$$|\cos\theta^*| = \frac{|\sinh(\Delta\eta^{\gamma\gamma})|}{\sqrt{1+(p_T^{\gamma\gamma}/m_{\gamma\gamma})^2}}\frac{2p_T^{\gamma 1}p_T^{\gamma 2}}{m_{\gamma\gamma}^2}$$

H->γγ – ATLAS arXiv 1307.1432





Direct Evidence of Fermion Couplings

- **Challenging** channels at the LHC!
  - Huge backgrounds (H->bb,H->ττ)
  - Or low rate: H->μμ

- ATLAS:

  4.1σ evidence of H->ττ decay 3.2σ exp.

  $\mu = \boldsymbol{\sigma_{obs.}/\sigma_{SM}} = 1.4 \pm 0.3(\text{stat}) \pm 0.4(\text{sys})$

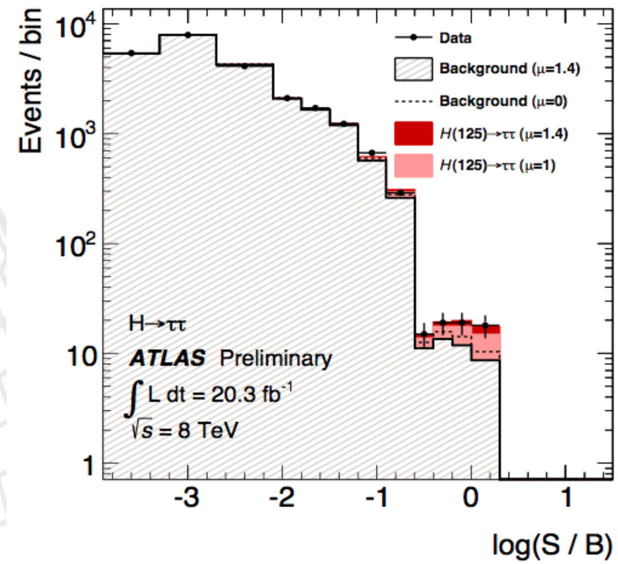
- CMS:
  - Combination of H->bb and H->ττ:

  3.8σ evidence (obs.) 4.4σ (expected)

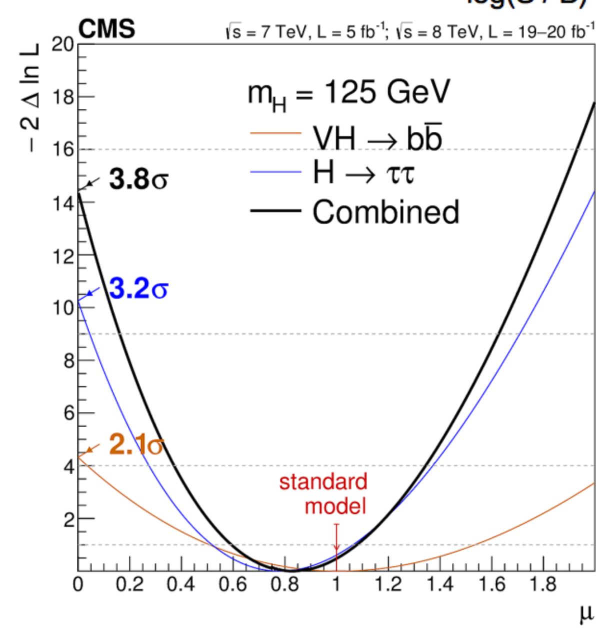
  $\mu = \boldsymbol{\sigma_{obs.}/\sigma_{SM}} = 0.83 \pm 0.24$

CMS 1401.6527

Channel ($m_H = 125\,\mathrm{GeV}$)	Significance (σ) Expected	Significance (σ) Observed	Best-fit μ
$\mathrm{VH} \to \mathrm{b\bar{b}}$	2.3	2.1	1.0 ± 0.5
$\mathrm{H} \to \tau\tau$	3.7	3.2	0.78 ± 0.27
Combined	4.4	3.8	0.83 ± 0.24



ATLAS-CONF-2013-108



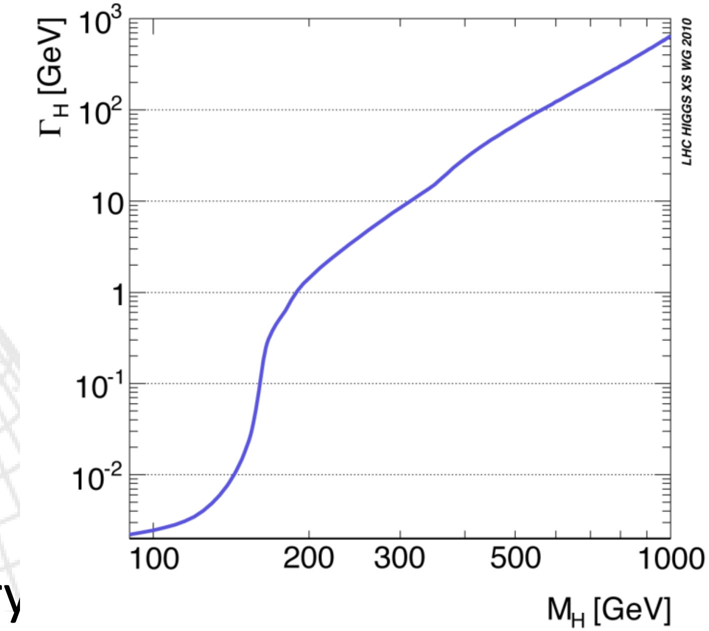
CMS 1401.6527

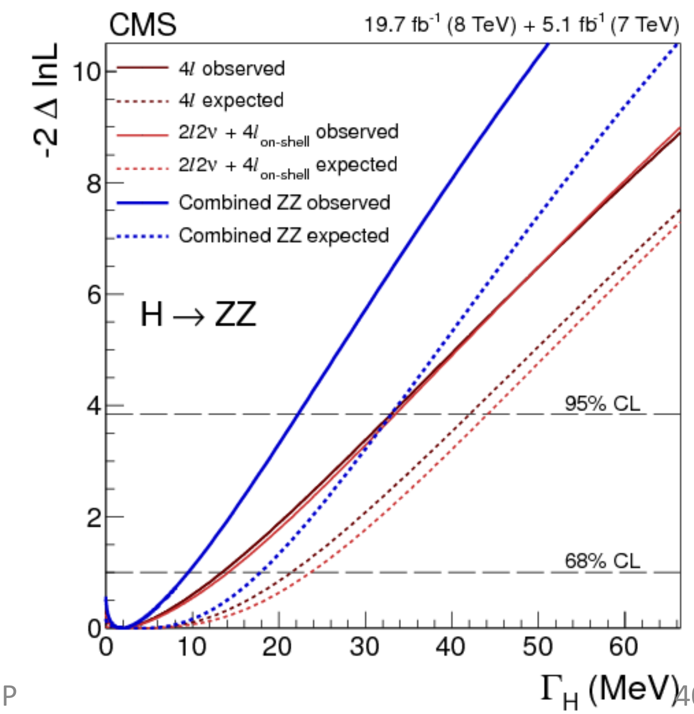
Higgs Width

- Total width not measurable at the LHC
  - Hadronic decays invisible in huge jet background
- Sensitivity can be achieved through "interferometric" measurement
  - **Use gg→H→ZZ with H on- or off-shell**
- Proof of principle done, although still very far from theoretically expected value (4MeV)
  - **Γ_H < 22 MeV at 95% CL**

$$\sigma^{\text{on-shell}}_{gg\to H\to ZZ} \sim \frac{g^2_{ggH}g^2_{HZZ}}{m_H\Gamma_H}$$

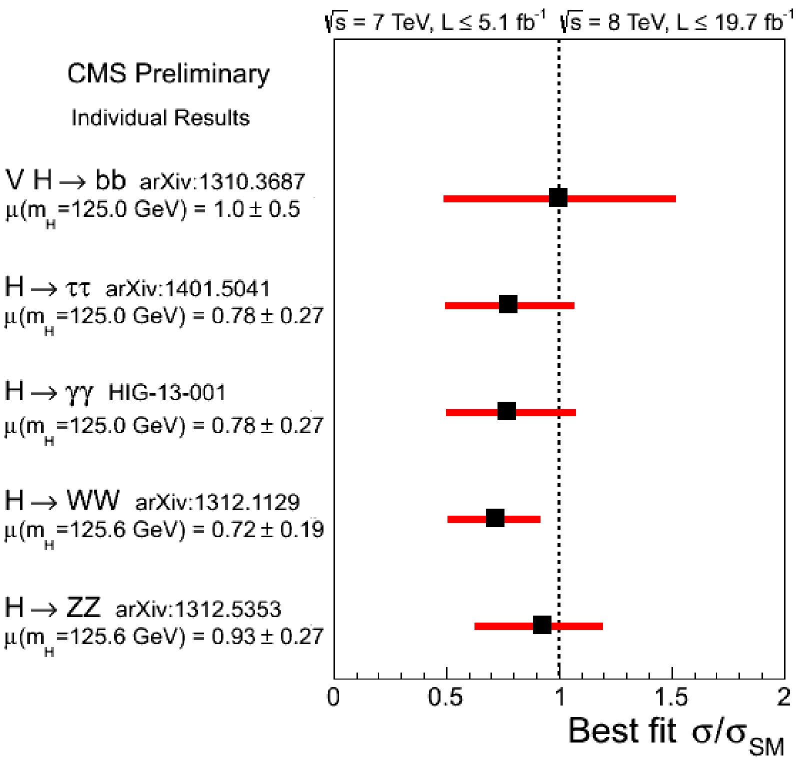
$$\sigma^{\text{off-shell}}_{gg\to H\to ZZ} \sim \frac{g^2_{ggH}g^2_{HZZ}}{(2m_Z)^2}$$

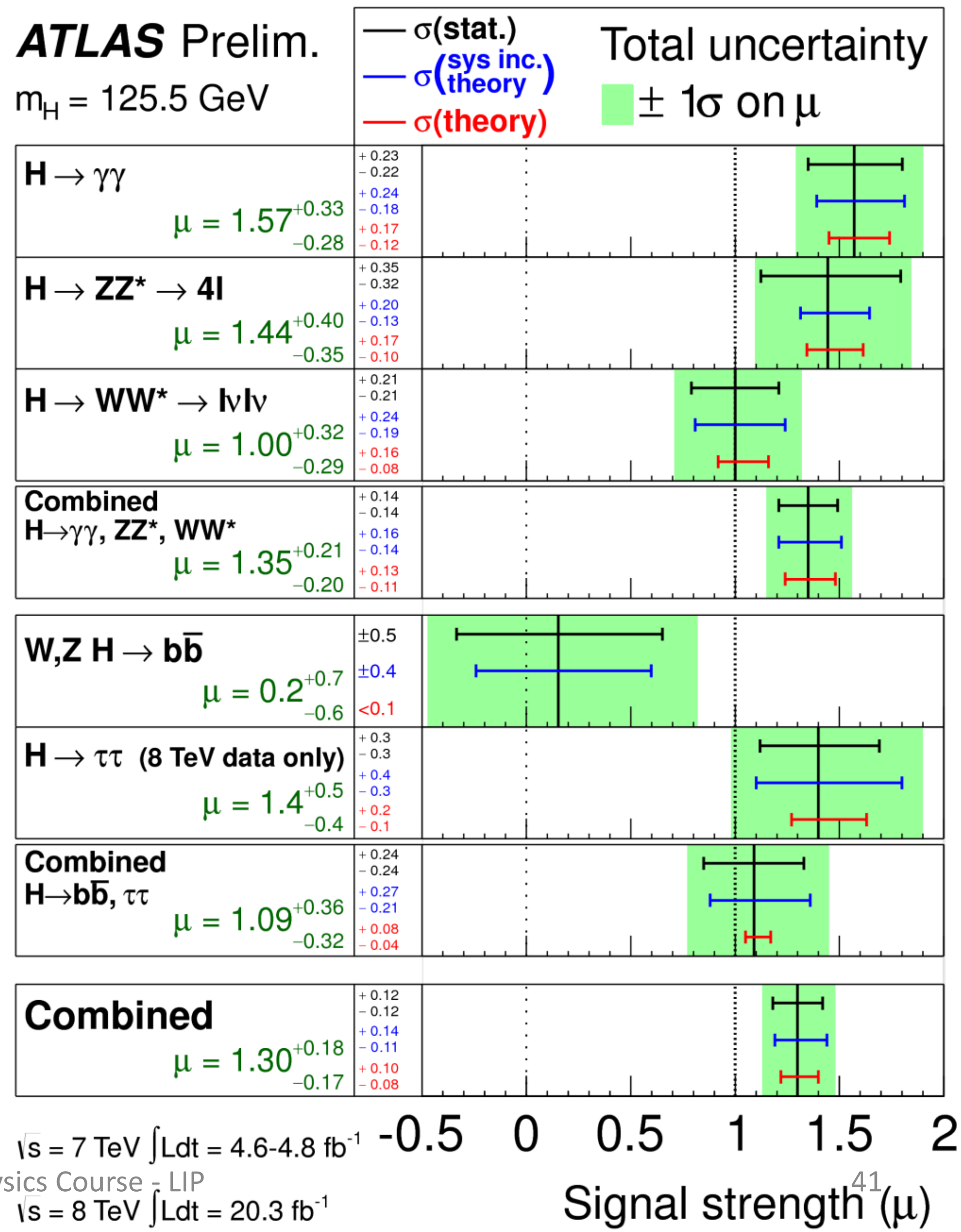




http://arxiv.org/pdf/1405.3455.pdf

Signal strength





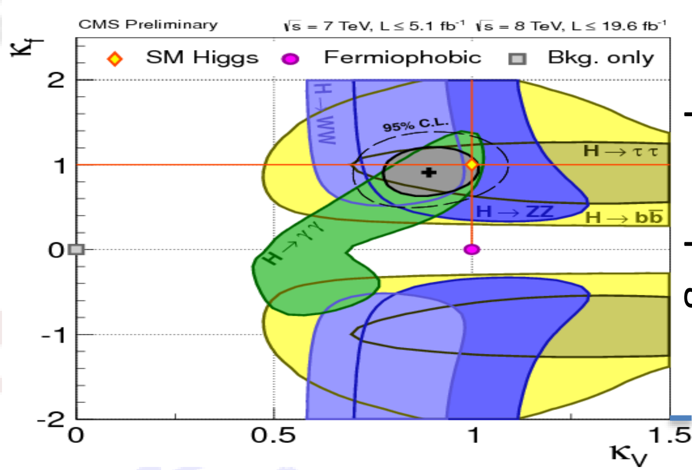
$$m = \frac{s_{meas}}{s_{SM}}$$

Take-home messages:

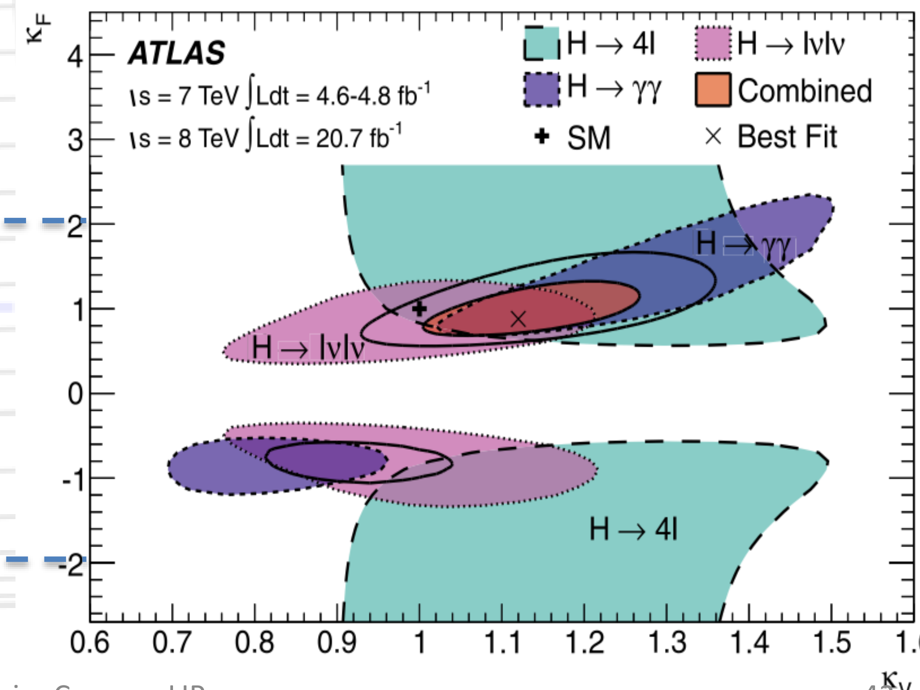
- Need more data!
- **Always run two experiments!**

Fermion and Boson couplings from fit

- Set one scale factor for all fermions (**κ_F** = κ_t = κ_b= κ_τ =…) and one for all vector bosons (**κ_V** = κ_Z = κ_W)
- Assume **no new physics**
- Strongest constraint to κ_F comes form gg->H loop
- ATLAS and CMS fits within 1-2σ of SM expectation (compatibility P=12%)
- Note ATLAS and CMS κ_V different – see signal strength below

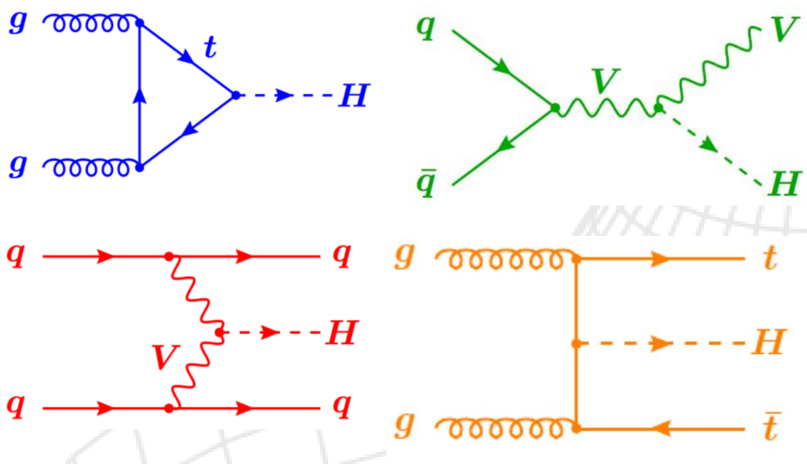


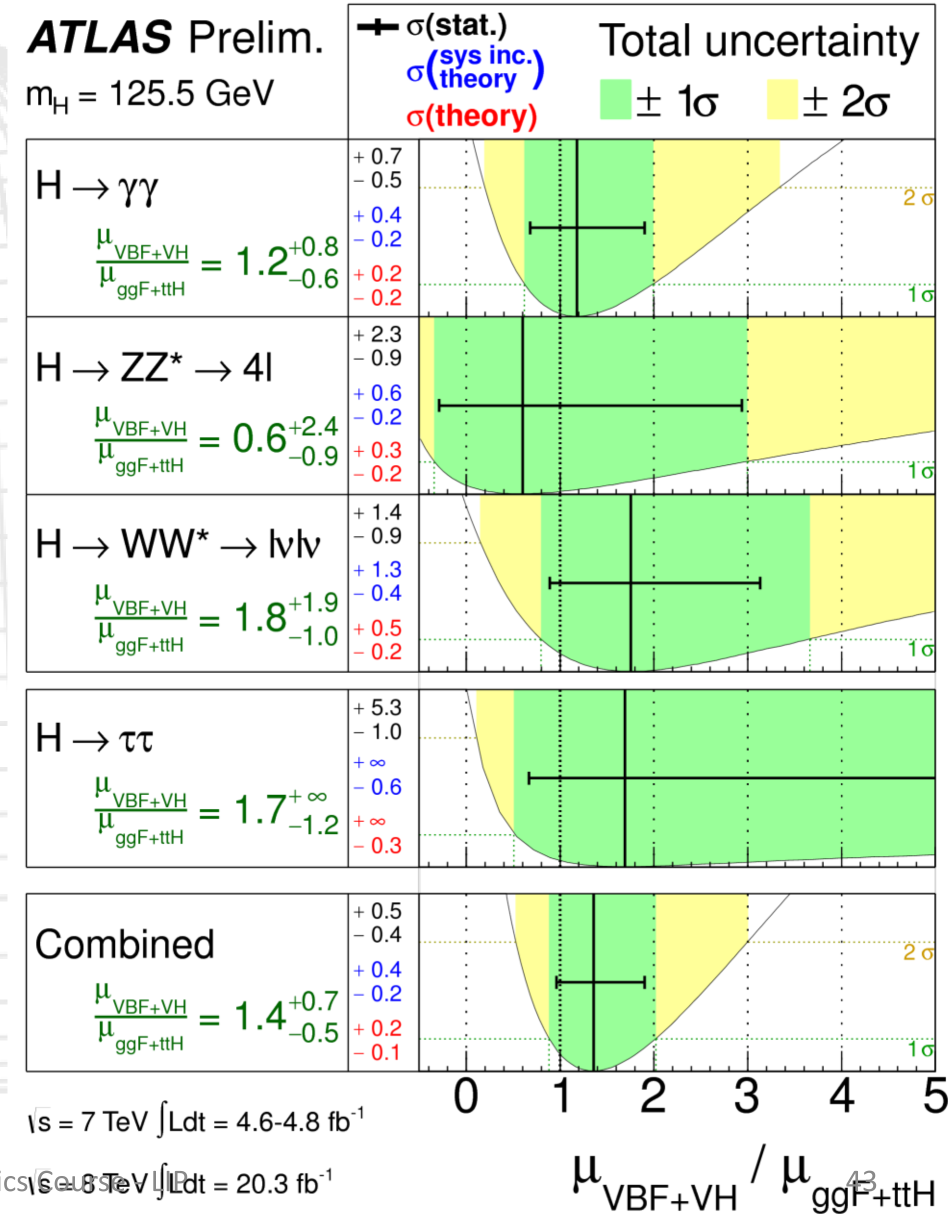
CMS public page



ATLAS 1307.1427

Production Modes

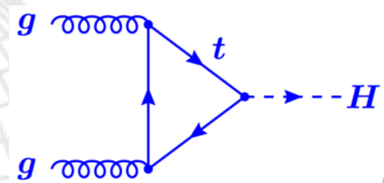


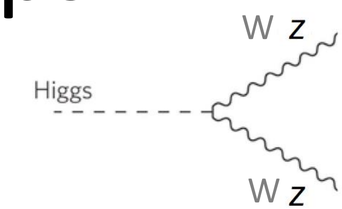


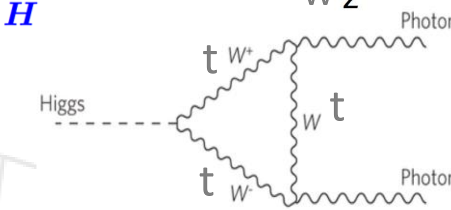
- Combination of channels allows consistency checks
- Evidence for VBF production (3σ)
- Sensitivity to top Yukawa coupling only through loops so far

New Physics in the Loops?

- New heavy particles may show up in **loops**
  - Dominant **gluon-fusion** through a (mostly) top loop production for H->ZZ, H->WW and H->γγ
  - **H->γγ decay** through top and W loops (and interference)



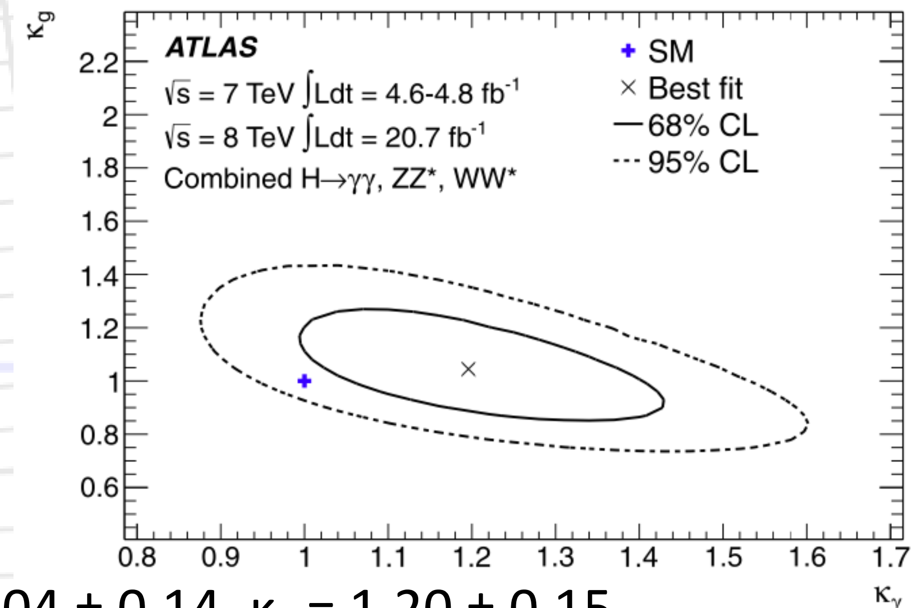




ATLAS 1307.1427

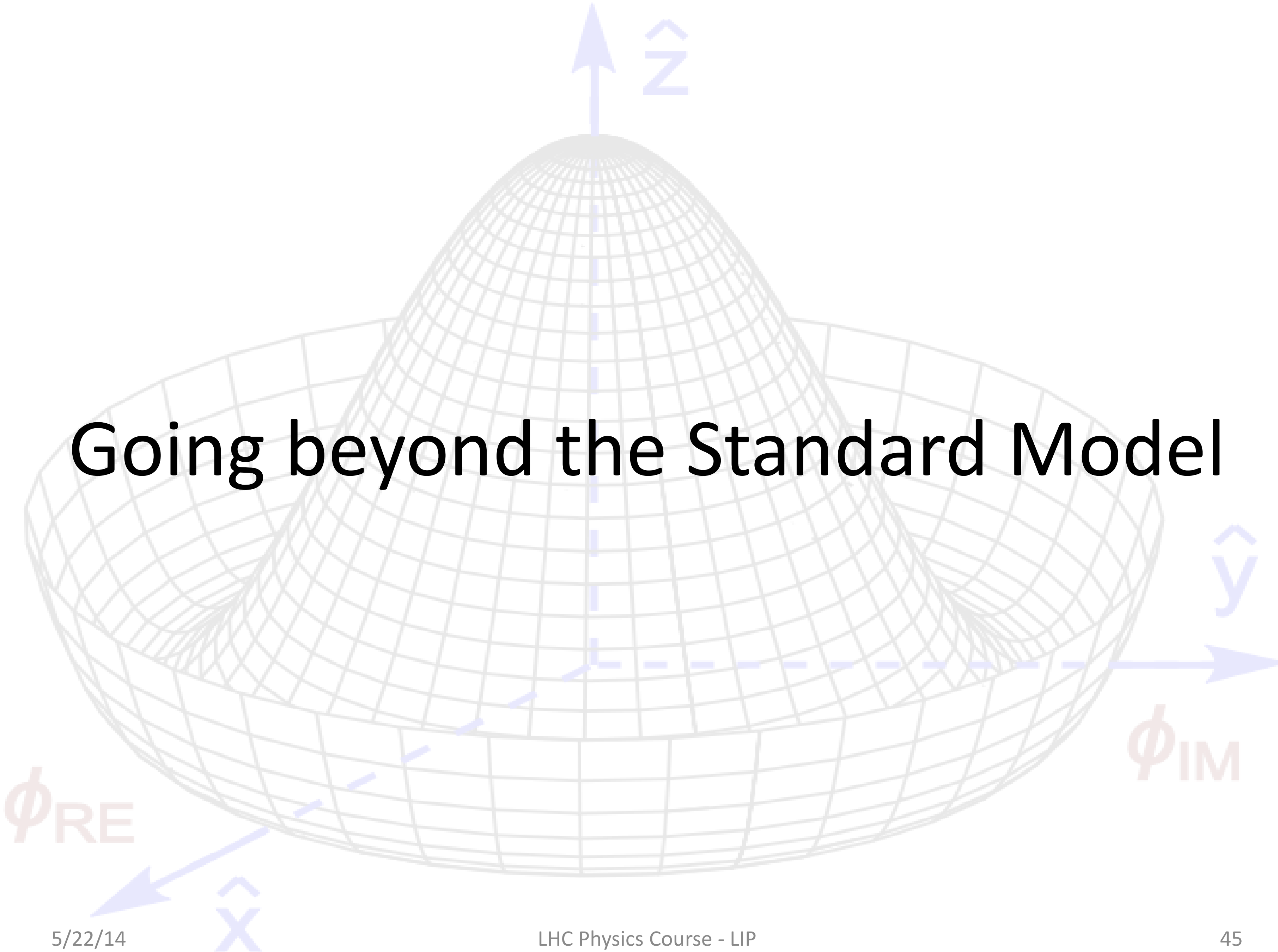
- Assume no change in Higgs width and SM couplings to known particles

- Introduce effective coupling scale factors:
  - κ_g and κ_γ for ggH and Hγγ loops



- Best fit values: $\kappa_g = 1.04 \pm 0.14$, $\kappa_\gamma = 1.20 \pm 0.15$
- Fit within 2σ of SM (compatibility P=14%)

Going beyond the Standard Model



Two Higgs Doublet Model (2HDM)

- No reason for simplest Higgs sector scenario to be true!
- One of the simplest alternatives: 2 Higgs doublets

$$\Phi_j = \begin{pmatrix} \phi_j^+ \\ (v_j + \rho_j + i\eta_j)/\sqrt{2} \end{pmatrix}$$

- Leads to 5 different Higgs bosons:
  - CP even (scalar): h, H
  - CP odd (pseudoscalar): A
  - charged: H^+, H^-
- Two doublets => two vacuum expectation values (mean field strength in the vacuum) – $\boldsymbol{v_1}$ **and** $\boldsymbol{v_2}$

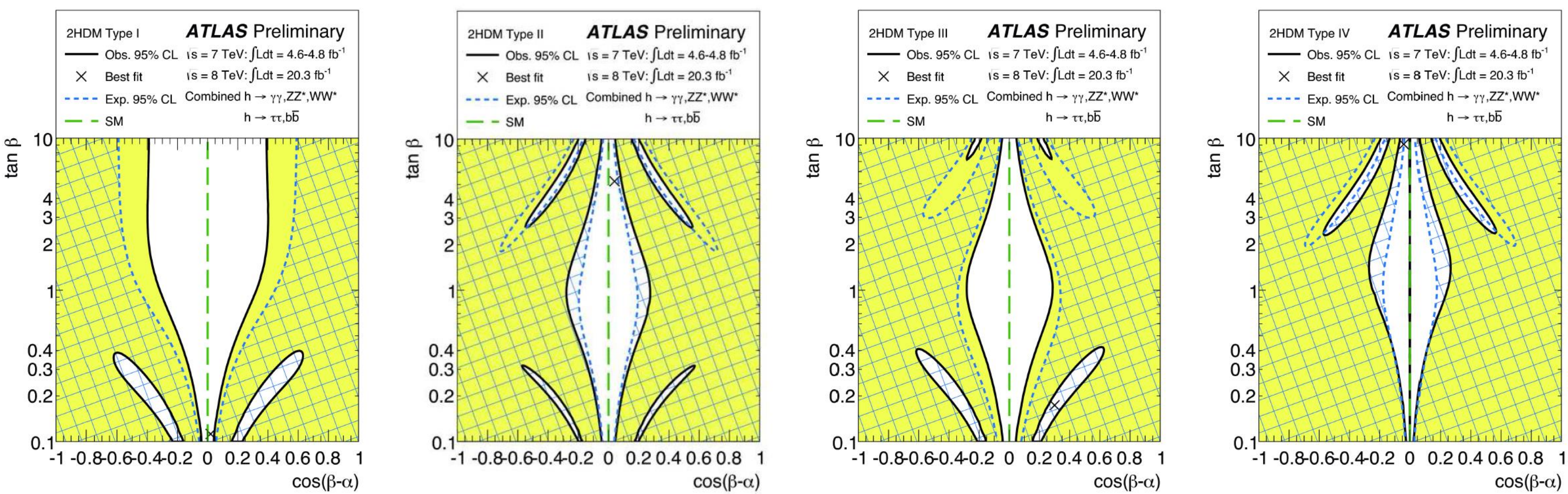
Two Higgs Doublet Model (2HDM)

- Free parameters:
  - 4 masses (Do we know one? Assume it's m_h)
  - $\tan\beta = v_1/v_2$ ratio of v.e.v.'s
  - Mixing angle of h and H: α
- 4 possible Yukawa coupling arrangements ("types")
- Most common SUSY benchmark (MSSM) is based on Type II
- If $\cos(\beta-\alpha) = 0$, h = Standard Model H^0

	Type I	Type II	Lepton Specific	Flipped
κ_V	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$
κ_u	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$
κ_d	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$
κ_l	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$\cos(\alpha)/\sin(\beta)$

Constraints from SM channels

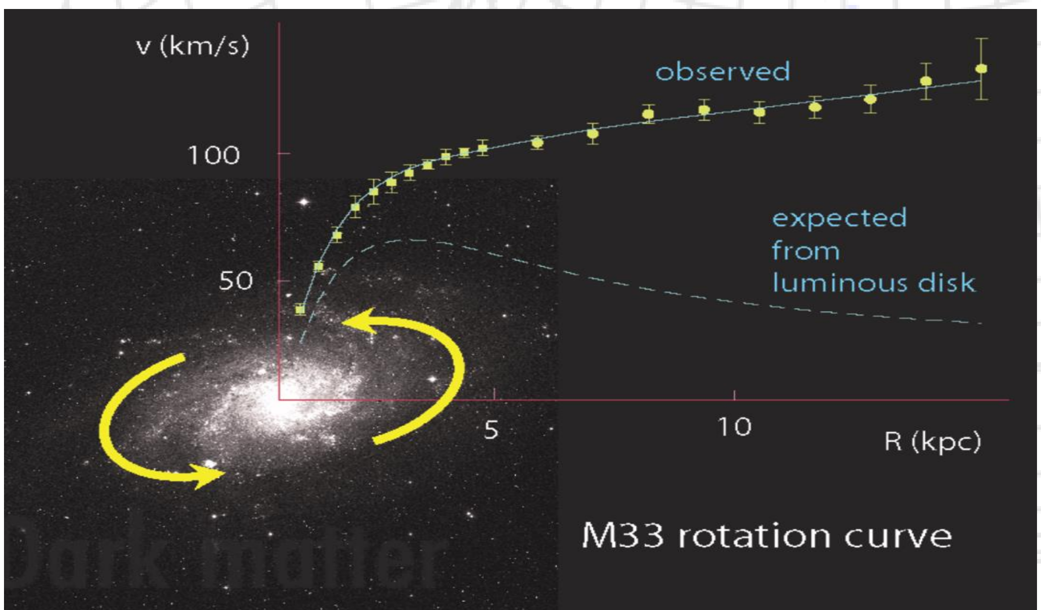
- What can our data already say about the 2HDM?
  - If it exists in Nature, then some of the measured rates (signal strength) are modified
  - Existing measurements can already rule out many possibilities
  - Used final states γγ, ZZ, WW, bb, ττ

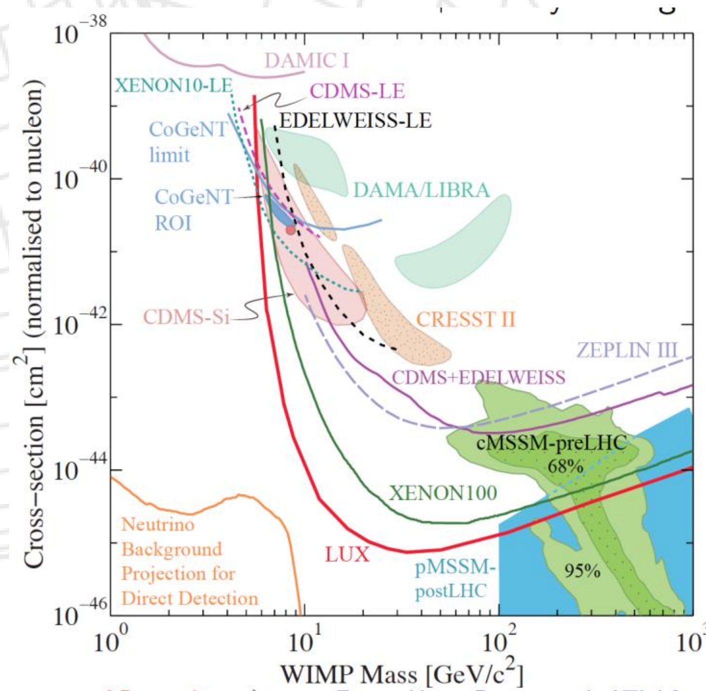


ATLAS-CONF-2014-010

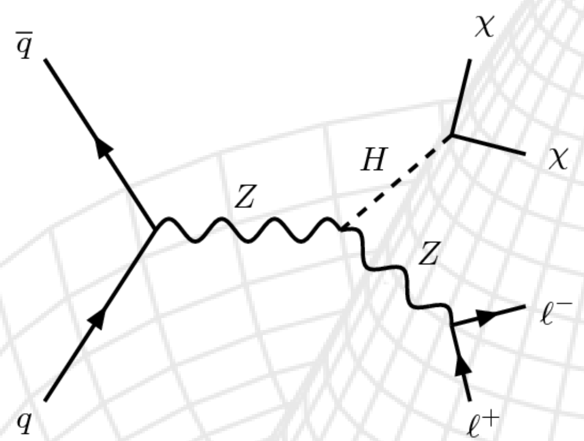
Invisible Higgs

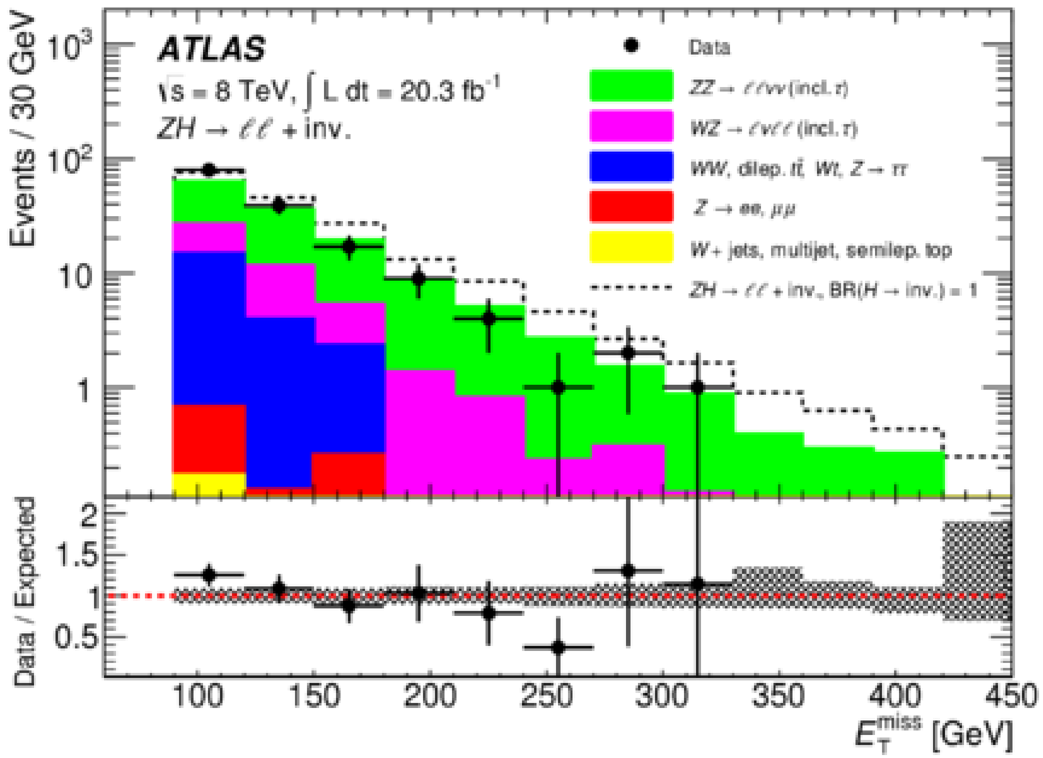
- Direct searches for Dark Matter usually hidden in deep caverns for low noise. But there is another way…
  - Dark matter has mass! Should couple to the Higgs. Do we see it?
  - Weakly interacting particles would leave no trace in detector – "Invisible" Higgs decays
  - Could be e.g. neutralinos in SUSY scenario
  - Would contribute to total Higgs width





Invisible Higgs





Require dileptons from Z

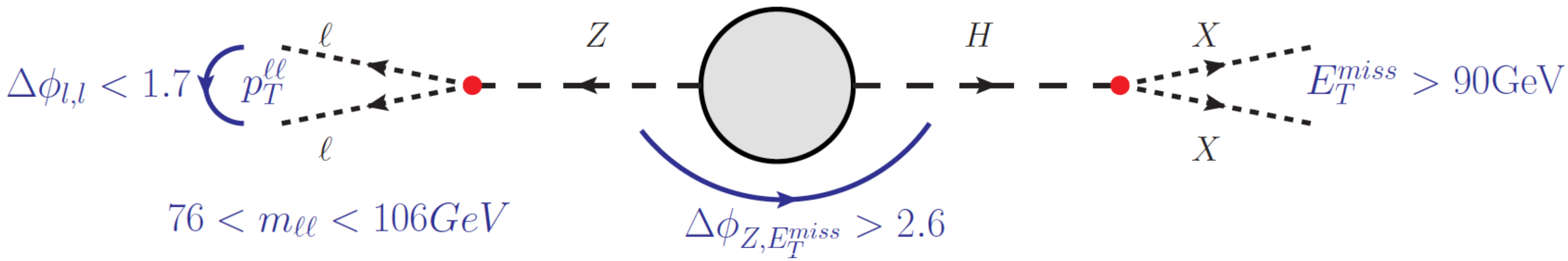
Back to back with Missing E_T and $p_T(\ell\ell)$

No jets

Main backgrounds ZZ, WZ

Claire Shepherd-Themistocleous - 26th Rencontres de Blois 2014

Z(H -> Invisible): Analysis Strategy

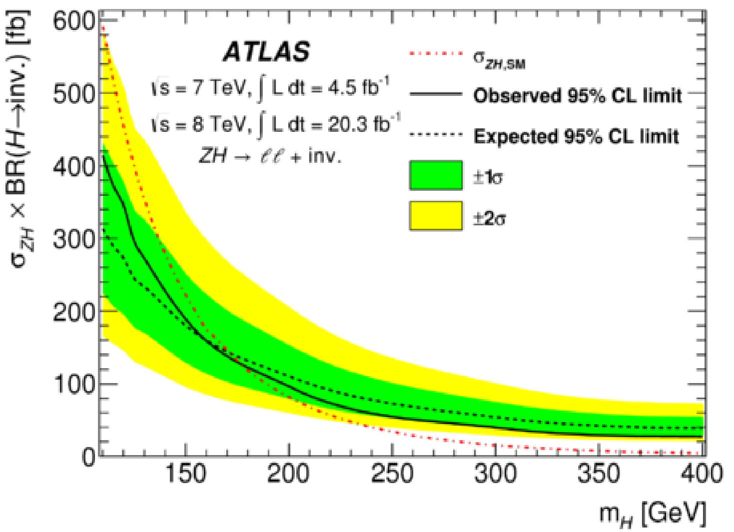


- Analysis cuts designed around the idea that the Z ($\ell\ell$ system) recoils off of the H (E_T^{miss}) for signal
- Most important background is Drell-Yan (Z) production with fake E_T^{miss} from mismeasured jets which is hard to estimate from MC
  - Estimated by 2 dimensional sideband fit of events failing one or both ❄

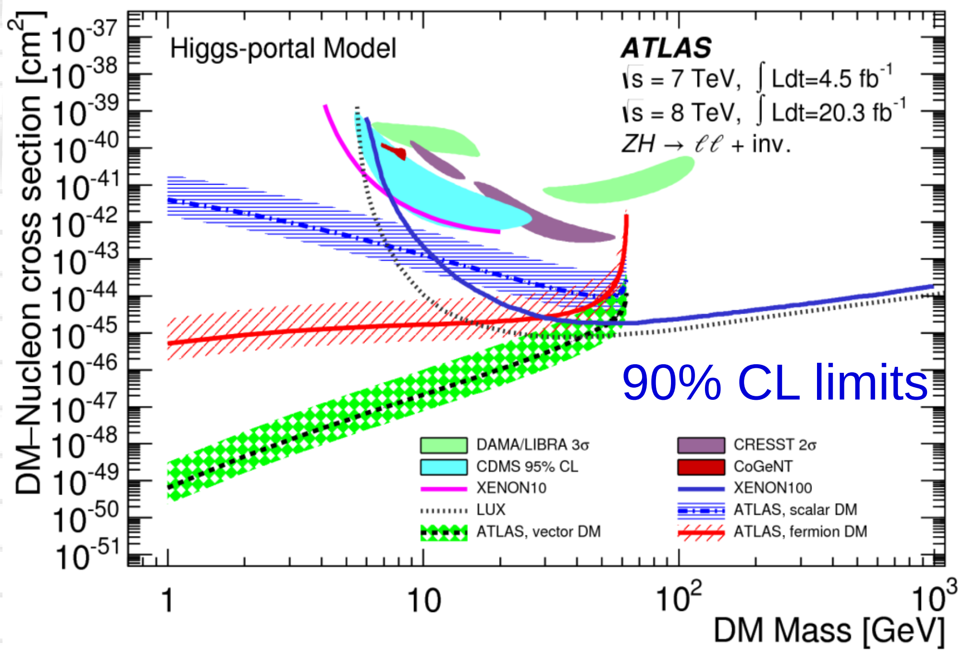
Requirement	Justification
$76 < m_{\ell\ell} < 106\text{GeV}$	Dilepton system consistent with $Z \to \ell\ell$
$E_T^{miss} > 90\text{GeV}$	Requiring the H to have p_T forces the Z to also have p_T
E_T^{miss} Cleaning Cuts	
$\Delta\phi_{\ell,\ell} < 1.7$	Boosted Z has leptons close together
$\Delta\phi_{Z,E_T^{miss}} > 2.6$	Z and H should be back-to-back
$\Delta\phi(E_T^{miss}, E_T^{miss,track}) < 0.2$	E_T^{miss} not correlated for background (E_T^{miss} from mismeasured jets) ❄
$\lvert E_T^{miss} - p_T^{\ell\ell}\rvert / p_T^{\ell\ell} < 0.2$	Balance of Z and H momentum ❄
Central Jet Veto	Drell-Yan background tends to have one or more jets

R.Vanguri, Lake Louise Winter Institute 2015

Invisible Higgs



Upper limit Br to inv. 75%

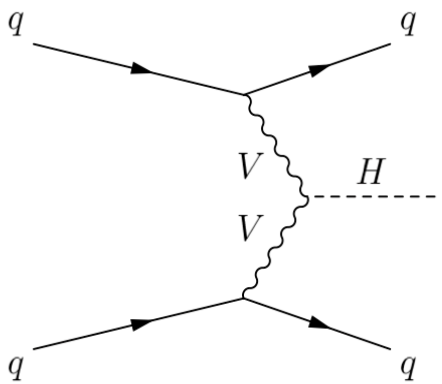


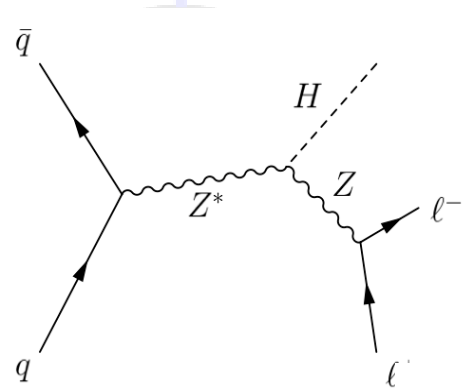
Upper limit interpreted as limit on DM-nucleon scattering cross section
Fox et al. Phys. Rev. D 85 050611

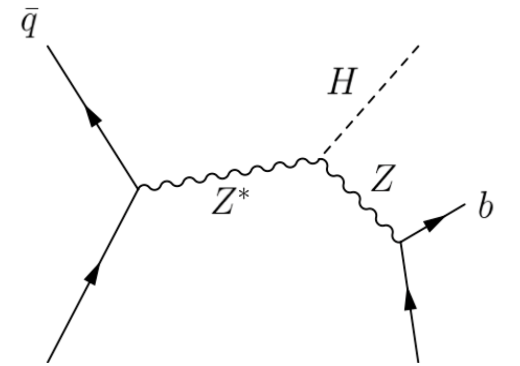
DM scenarios scalar, vector or Majorana fermion

Higgs-nucleon coupling 0.33 $^{+0.30}_{-0.07}$ Djouadi et al. Phys. Lett. B 709 65 (2012)

Invisible Higgs





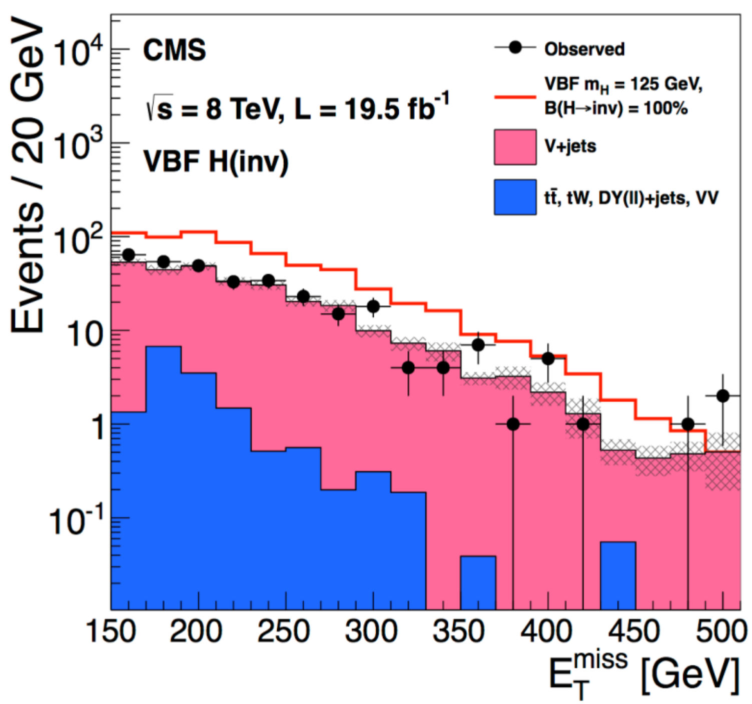


Other search channels:
Search in VBF and ZH , Z → ll and bb

VBF mode requires 2 jets in forward region
($\Delta\eta_{jj} > 4.2$) , $E_t^{miss} > 130$ GeV

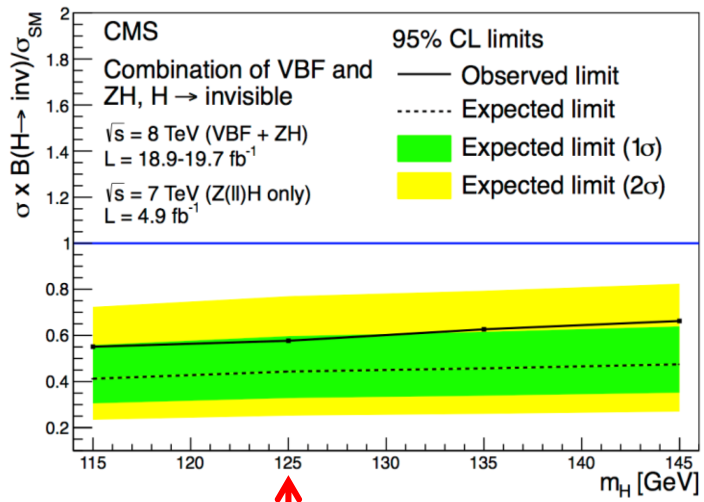
Central jet veto on any jet $p_T > 30$ GeV.

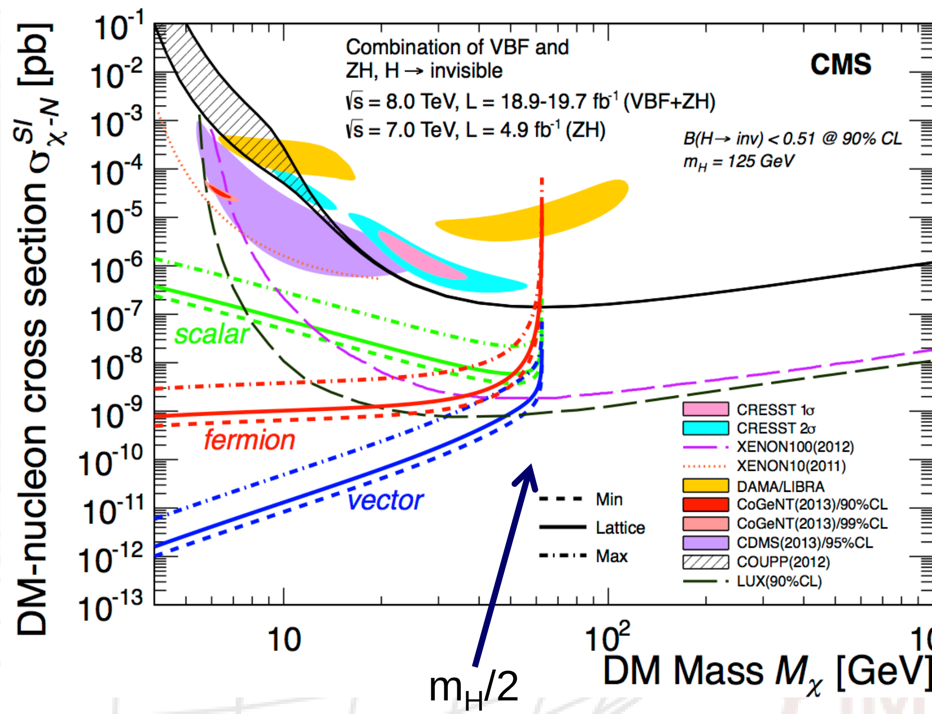
Dominant backgrounds
$Z(\nu\nu)$ + jets, $W(l\nu)$ + jets



Invisible Higgs

7 TeV 4.9 fb^{-1} 8 TeV ~ 19 fb^{-1}





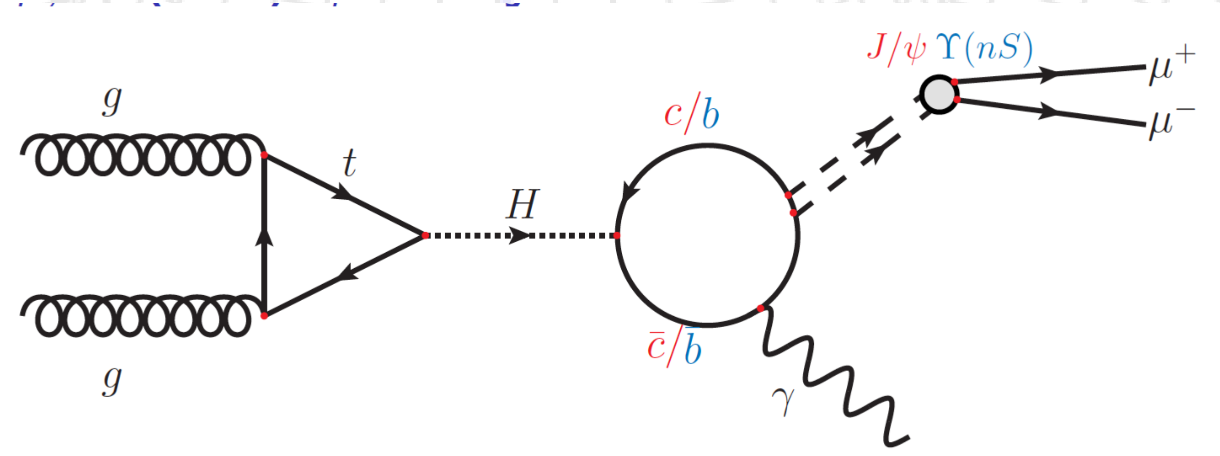
Upper limit on Br to invisible
0.58 for Higgs mass 125 GeV

Higgs nucleon coupling 0.33 (range 0.26 - 0.63)

DM scenarios scalar, vector or Majorana fermio

Rare decays

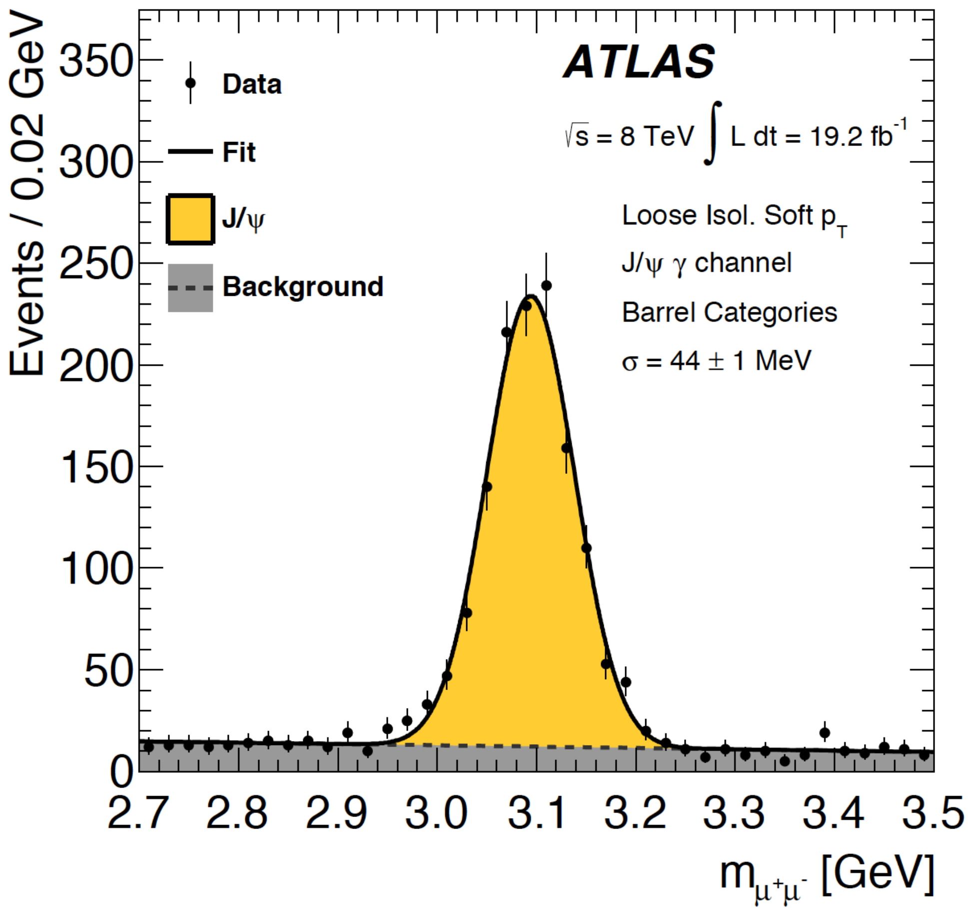
- Only way to probe Higgs decays to charm – charm Yukawa coupling – at LHC
- Deviations in coupling from SM value can lead to increase in branching fraction
- Analysis also probes Z decays to J/Ψ or ϒ(nS) plus γ – improved LEP limits by 2



Backgrounds

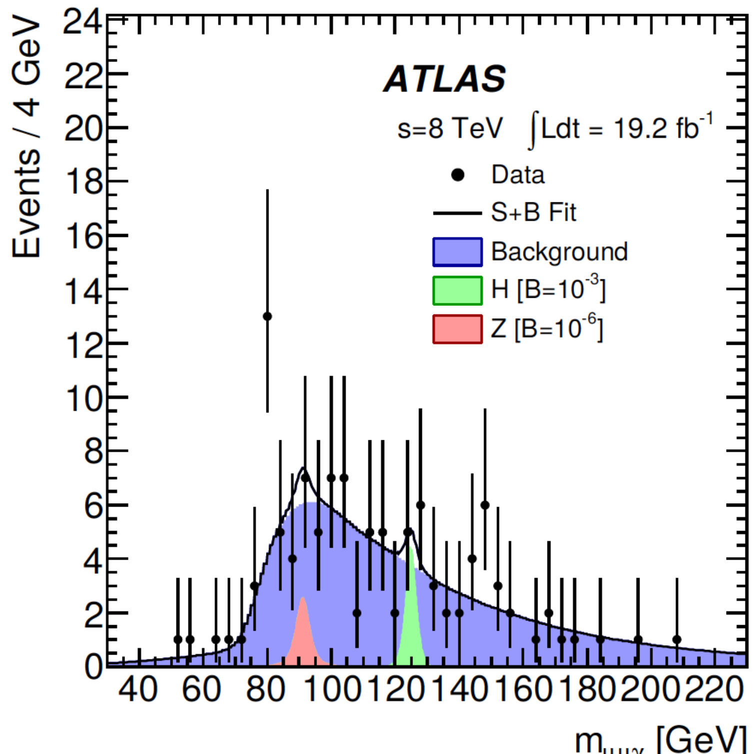
Dominant Backgrounds

- 56% Prompt J/ψ: Peaks in $m_{\mu\mu}$
  - $gg \to J/\psi g$ where g (jet) is misidentified as a γ
  - Suppressed by requiring γ be isolated since there is usually hadronic activity around a jet
- 41% Non-resonant: Smooth in $m_{\mu\mu}$
  - Production of a di-muon pair with invariant mass close to J/ψ



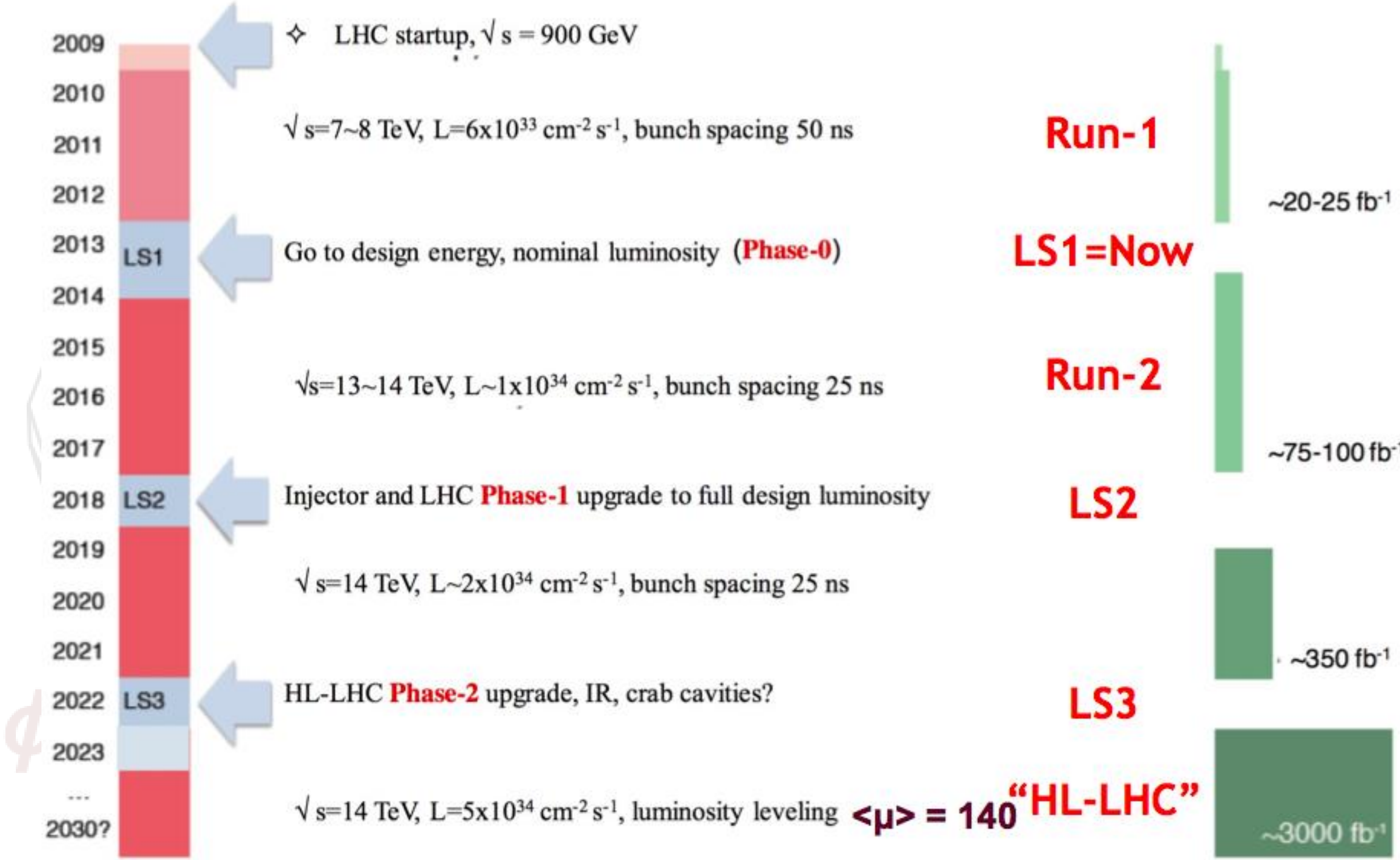
Results

- Upper limit set on branching fraction of H decay to J/Ψ plus γ at 95% confidence:
- Br (J/Ψ γ) < 1.5 x 10^{-3} (expected $1.2^{+0.6}_{-0.3}$ x 10^{-3})
- 540 ≈ SM Expectation



Looking into the future

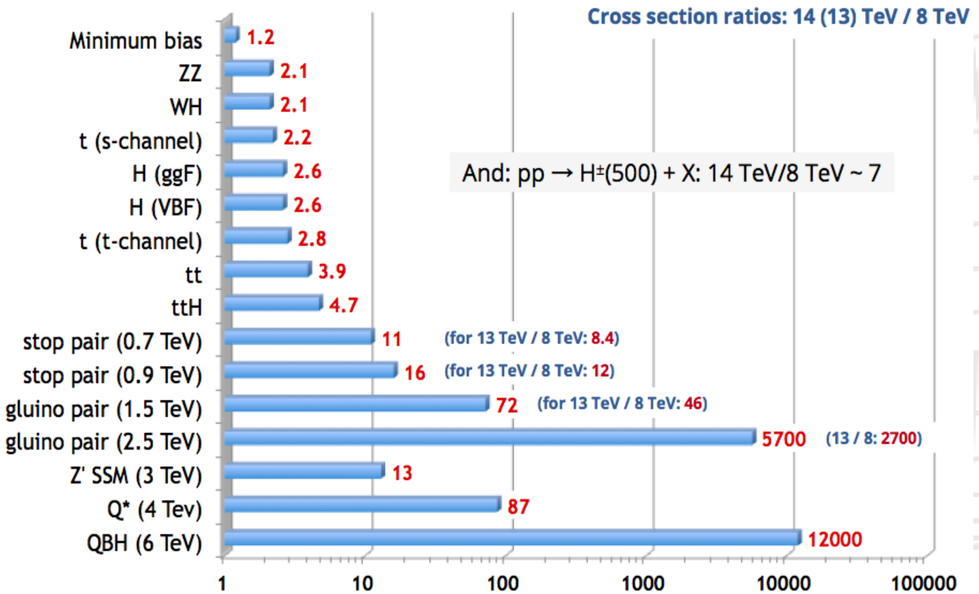
Future LHC Running

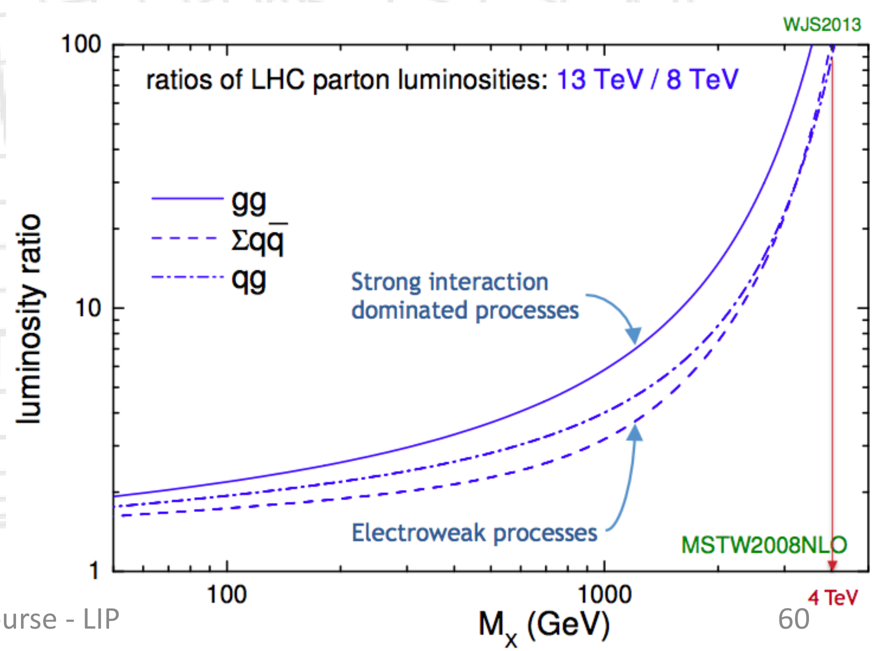


Not only more luminosity

- Higher centre of mass energy gives access to higher masses
- Hugely improves potential for discovery of heavy particles
- Increases cross sections limited by phase space
  - E.g. ttH increases faster than background (factor 4)
- But may make life harder for light states
  - E.g. only factor 2 increase for WH/ZH, H→bb and more pileup
  - Could be compensated by use of boosted jet techniques (jet substructure)

http://www.hep.ph.ic.ac.uk/~wstirlin/plots/plots.html





Run II/High-Lumi LHC Programme

Precision AND searches!

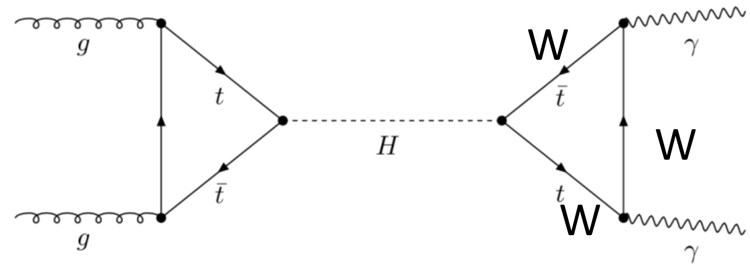
- Precision:
  - Continue to look for deviations wrt Standard Model
- Differential cross sections:
  - New physics in loops could modify event kinematics
- Complete measurement of properties:
  - E.g. CP quantum numbers:
  - Sensitivity in H→ZZ and VBF
  - Search for CP violation in Higgs sector
- Search for rare decay modes:
  - H→HH to access self coupling (long term!)
- Search for additional Higgs bosons:
  - E.g. 2-Higgs Doublet Model is a natural extension and predicted in SUSY

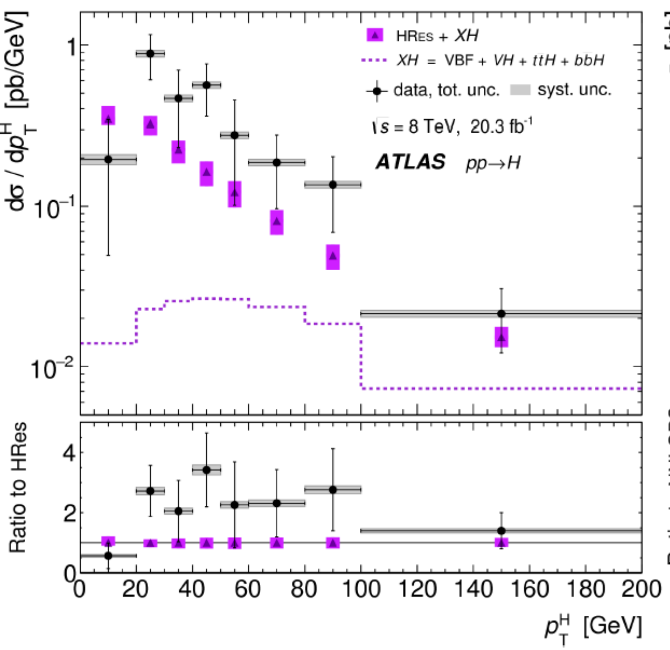
Luminosity	$H \to Z\gamma$	$H \to \mu\mu$	$H \to$ Invisible
300fb^{-1}	2.3 σ	2.3 σ	$Br < 23\%$
3000fb^{-1} HL-LHC	3.9 σ	7.0 σ	$Br < 8\%$

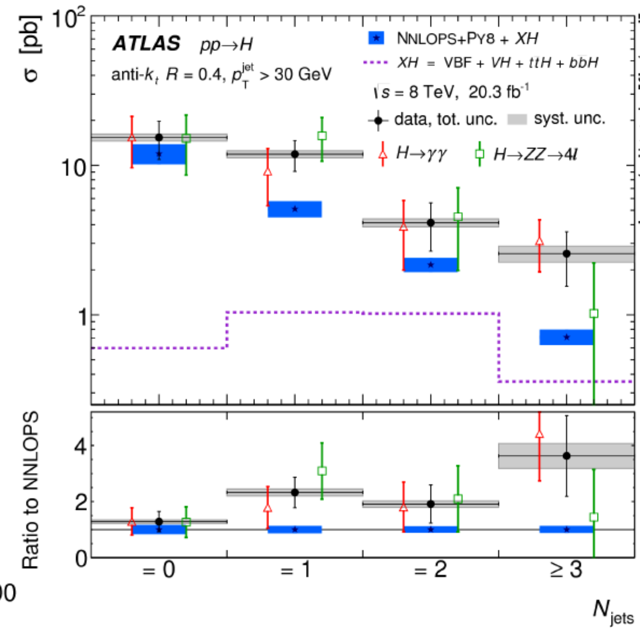
ATL-PHYS-PUB-2014-006 ATL-PHYS-PUB-2013-014 ATL-PHYS-PUB-2013-014

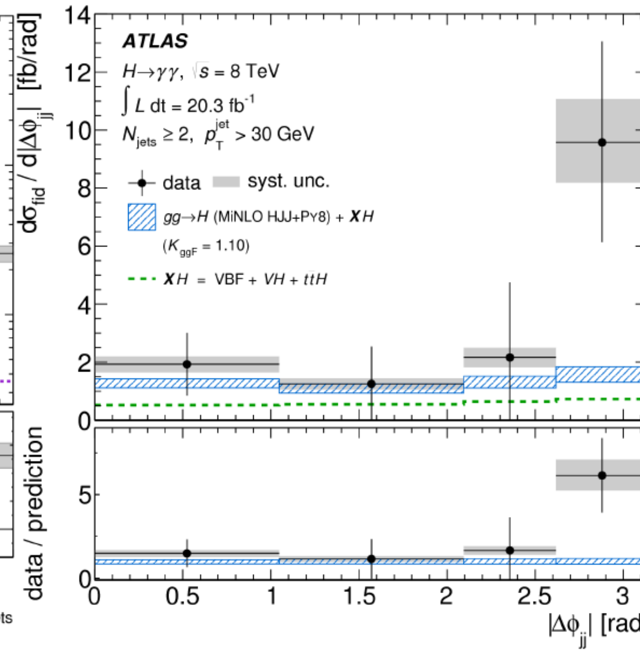
Higgs differential cross sections

- Get access to the loop structure where there may be new physics
- ATLAS H→γγ and ZZ so far – more to come in run 2



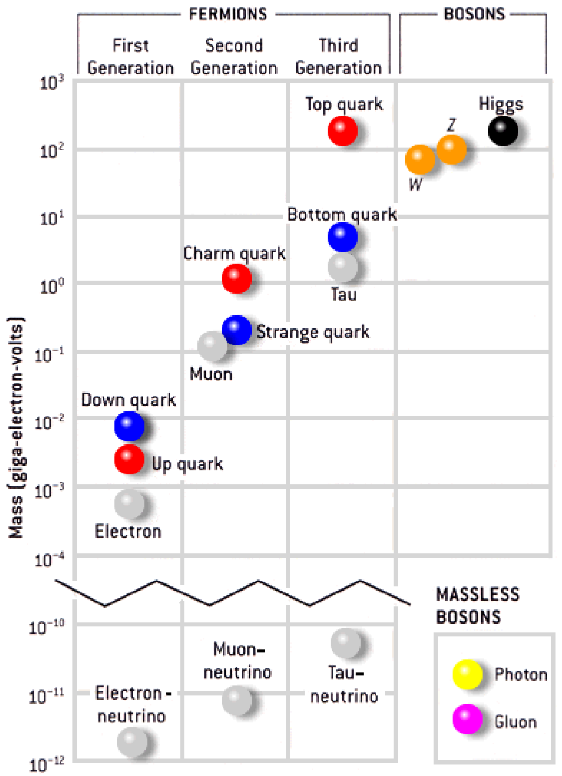


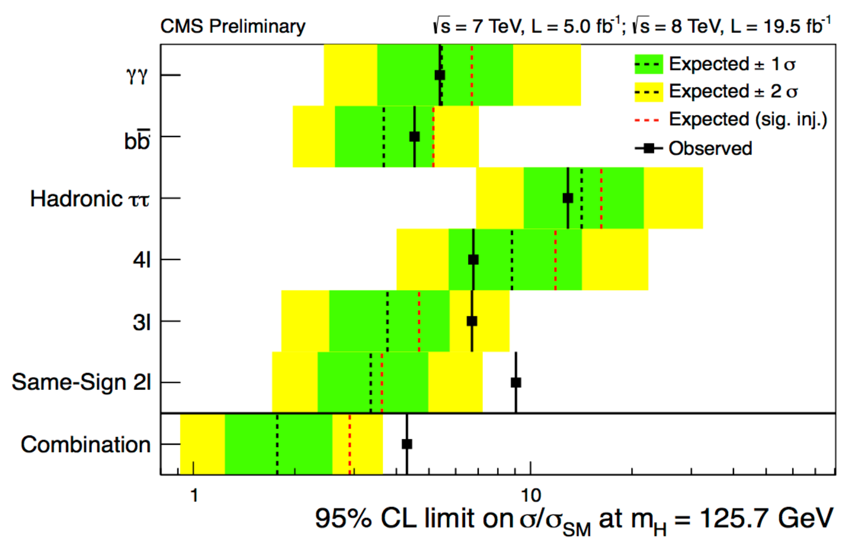


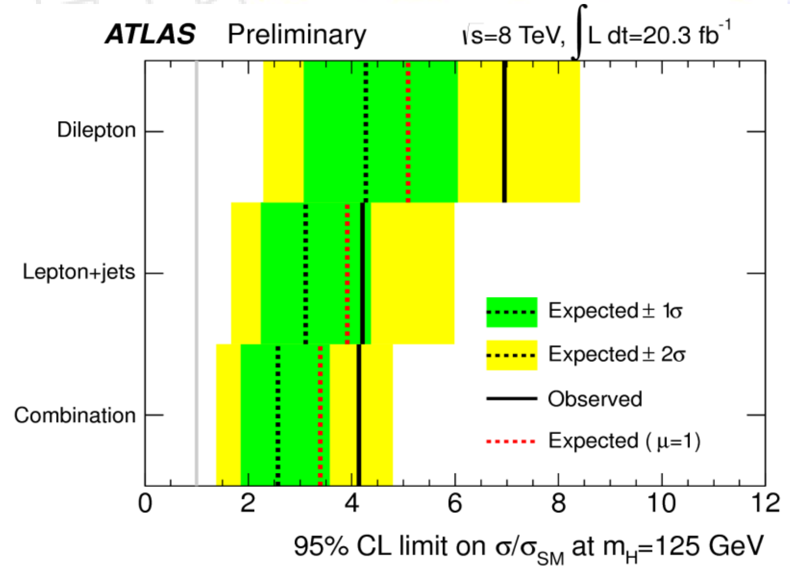


Another example: ttH

- Indirect constraints on top-Higgs Yukawa coupling from loops in ggH and ttH vertices
  - Assumes no new particles contribute to loops
- Top-Higgs Yukawa coupling can be measured directly
  - Allows probing for New Physics contributions in the ggH and γγH vertices
- Top Yukawa coupling $Y_t = \sqrt{2}M_t/vev = 0.996 \pm 0.005$
  - Does this mean top plays a special role in EWSB?

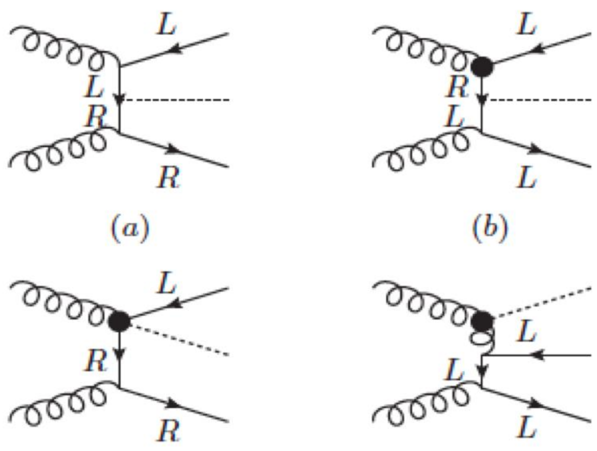




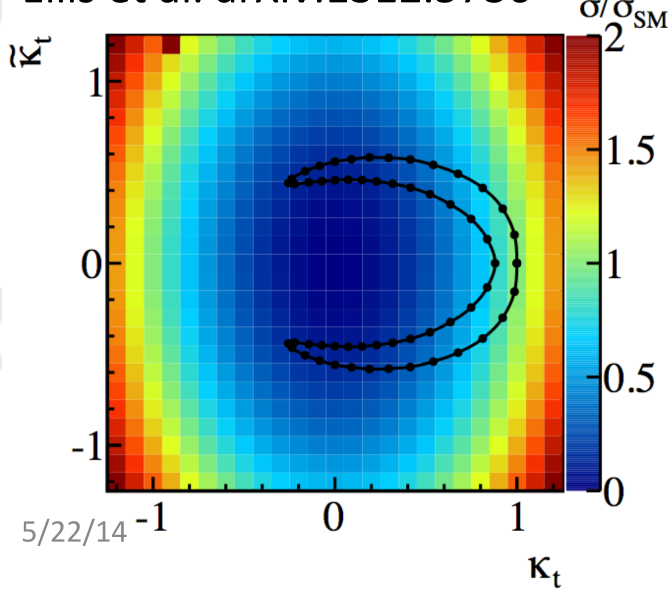


Sensitivity to New Physics

Degrande et al. arXiv:1205.1065



Ellis et al. arXiv:1312.5736



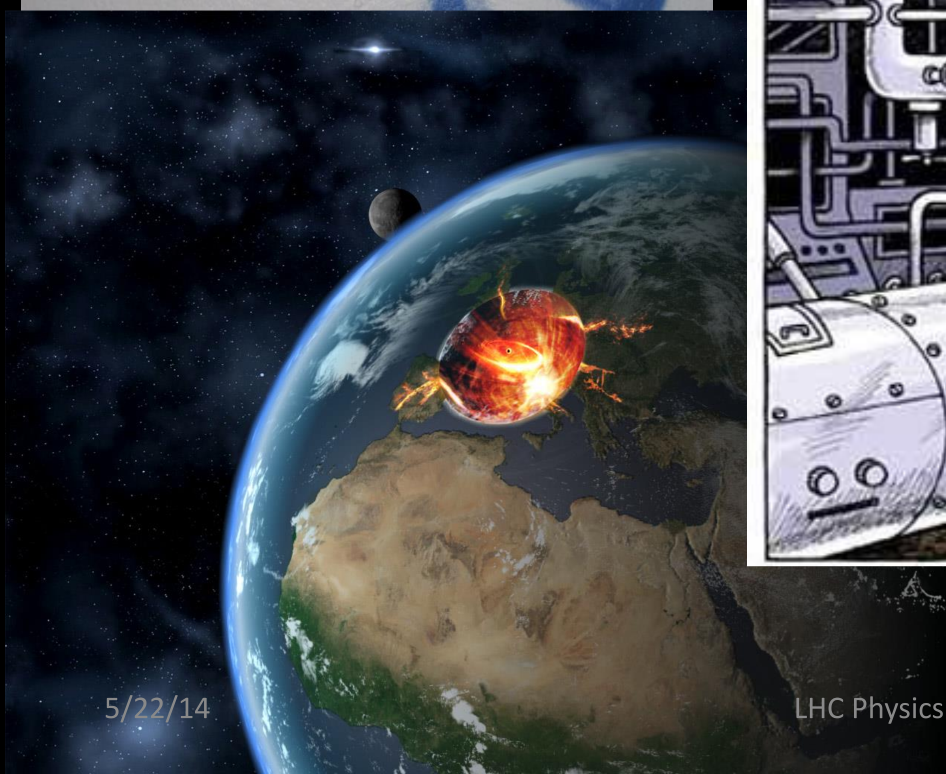
- Effective top-Higgs Yukawa coupling may deviate from SM due to new higher-dimension operators
  - Change **event kinematics –** go differential!
- ttH sensitive new physics: little Higgs, composite Higgs, Extra Dimensions,…
- In the presence of CP violation, Higgs-top coupling have scalar (κ_t)and pseudoscalar ($\tilde{\kappa}_t$)components
  - Strong dependence on ttH cross section
  - Note: Indirect constraints from electron electric dipole moment not taken into account (give $|\tilde{\kappa}_t| < 0.01$)

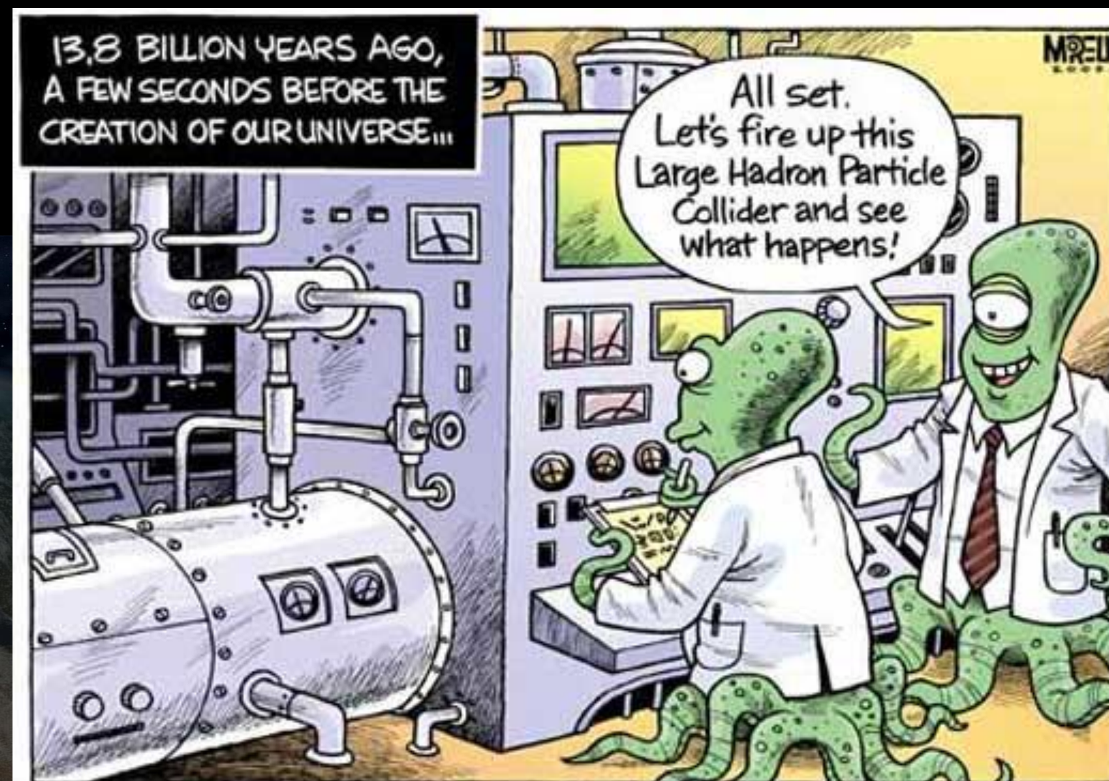
Summary

- Recapitulation:
  - Electroweak symmetry breaking
  - Higgs boson in Electroweak Lagrangian
  - Higgs boson production and decay at the LHC
  - The landscape at the end of LHC run I
- The Higgs sector beyond the Standard Model
  - Constraints from current data
  - Examples of rare and exotic channels
- Future Higgs measurements at LHC and beyond
  - Fundamental questions at the end of run I
  - Future LHC running – luminosity, energy, and physics reach
  - Higgs physics in future LHC analyses – Precision and Searches
  - An example: associated production with top-quark pair – SM and BSM

The End


QUI A PEUR
DU
TROU NOIR




13.8 BILLION YEARS AGO, A FEW SECONDS BEFORE THE CREATION OF OUR UNIVERSE...
All set. Let's fire up this Large Hadron Particle Collider and see what happens!