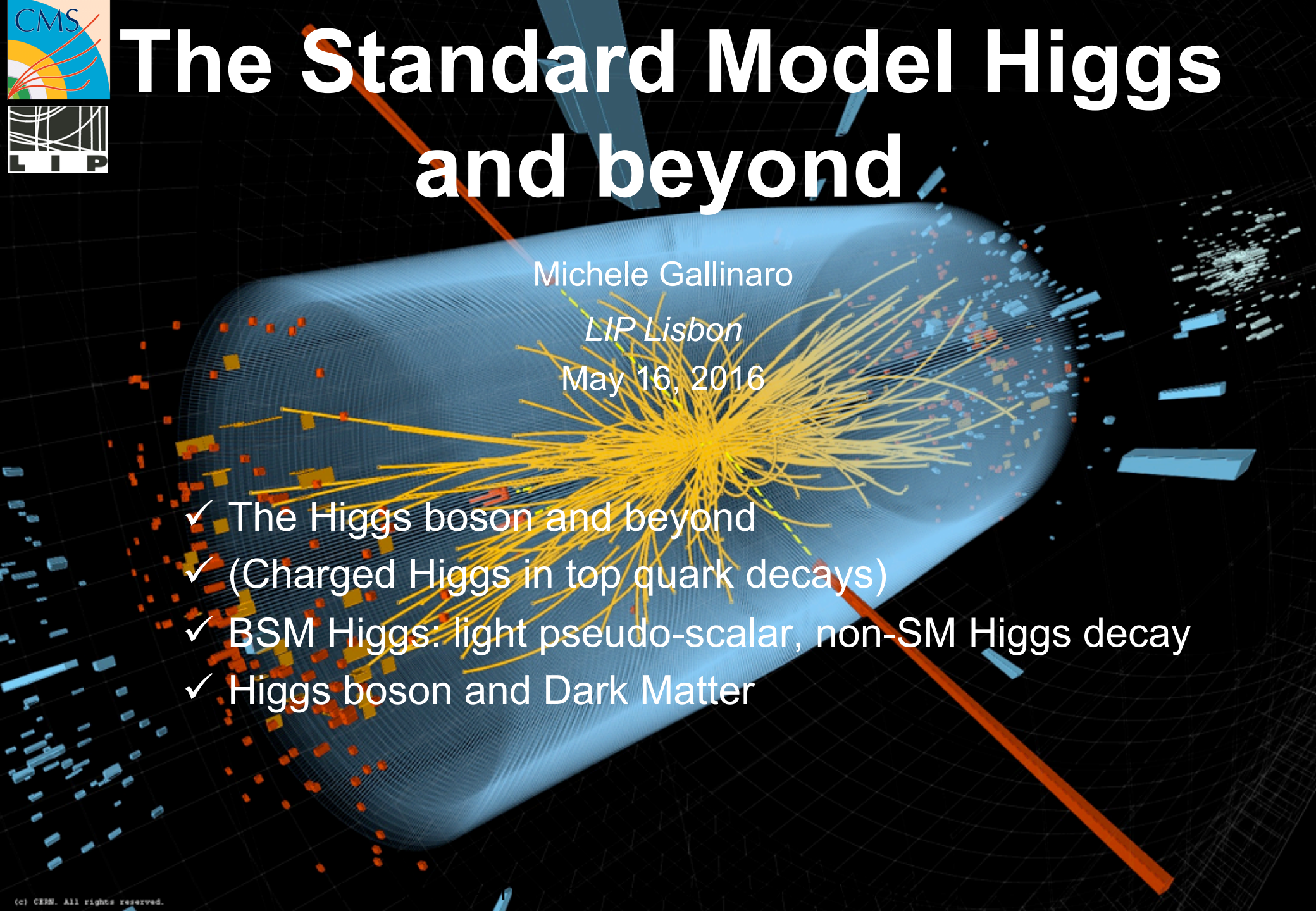


# The Standard Model Higgs and beyond

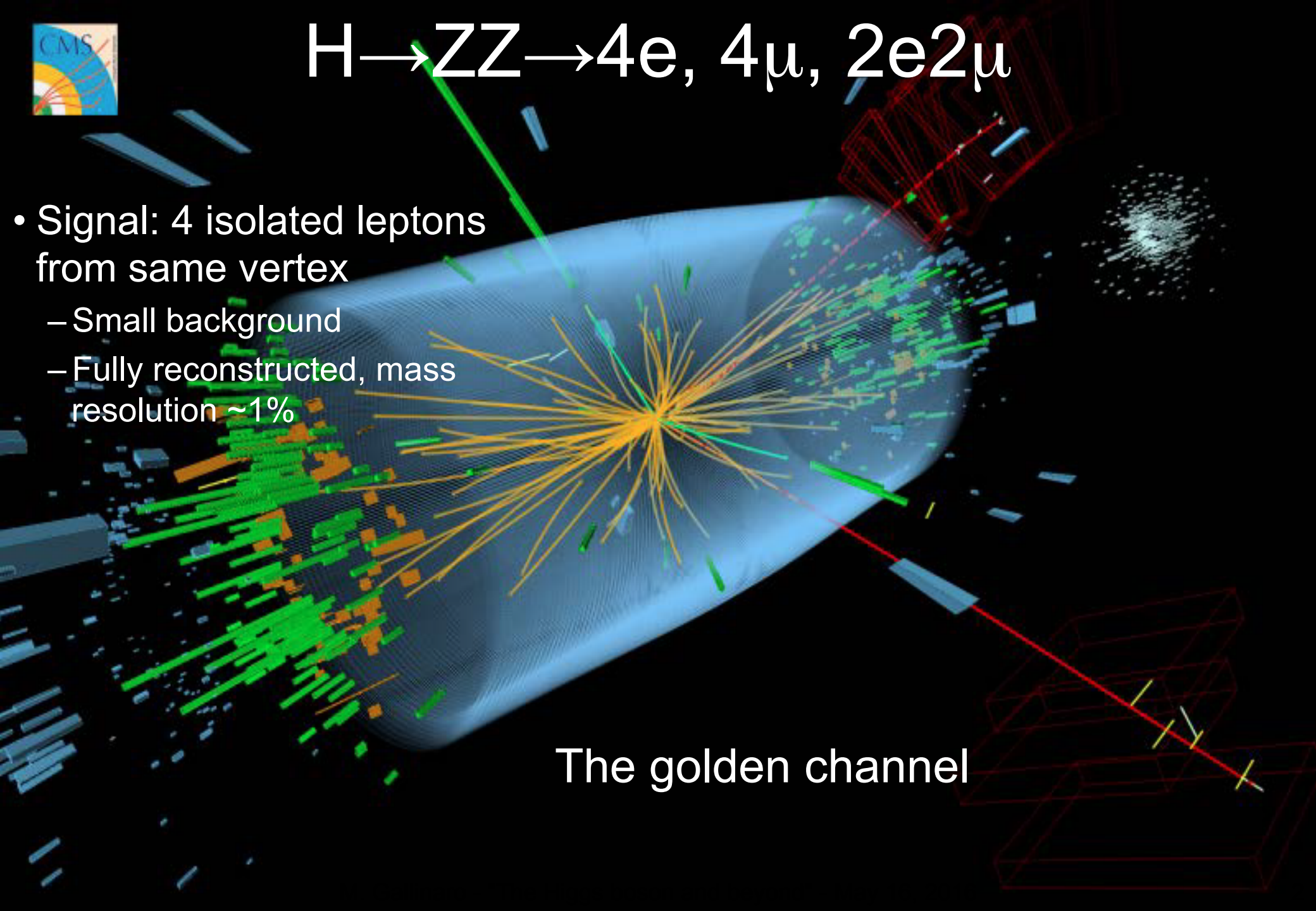
Michele Gallinaro

*LIP Lisbon*

May 16, 2016

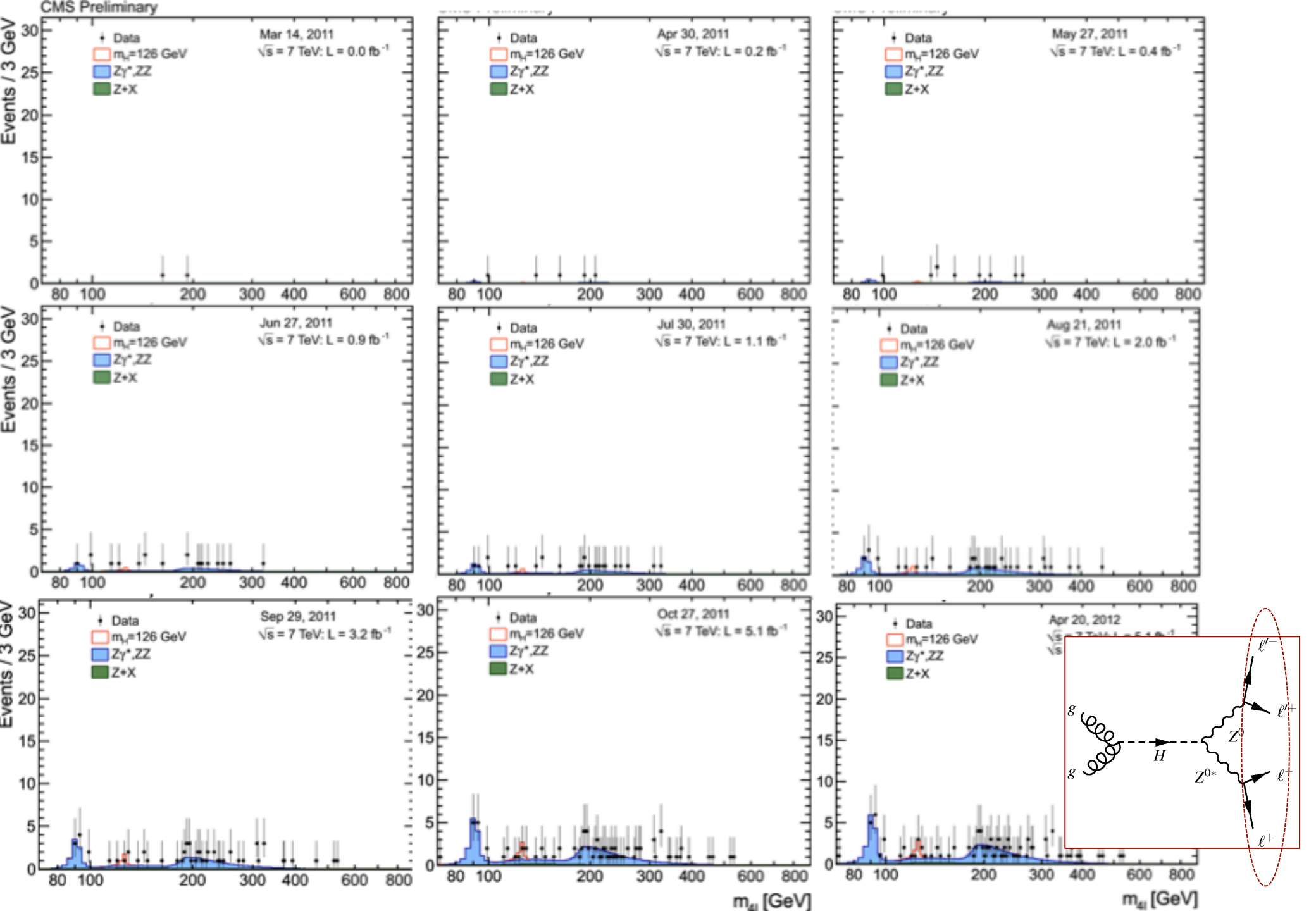
- ✓ The Higgs boson and beyond
- ✓ (Charged Higgs in top quark decays)
- ✓ BSM Higgs: light pseudo-scalar, non-SM Higgs decay
- ✓ Higgs boson and Dark Matter

# H→ZZ→4e, 4μ, 2e2μ

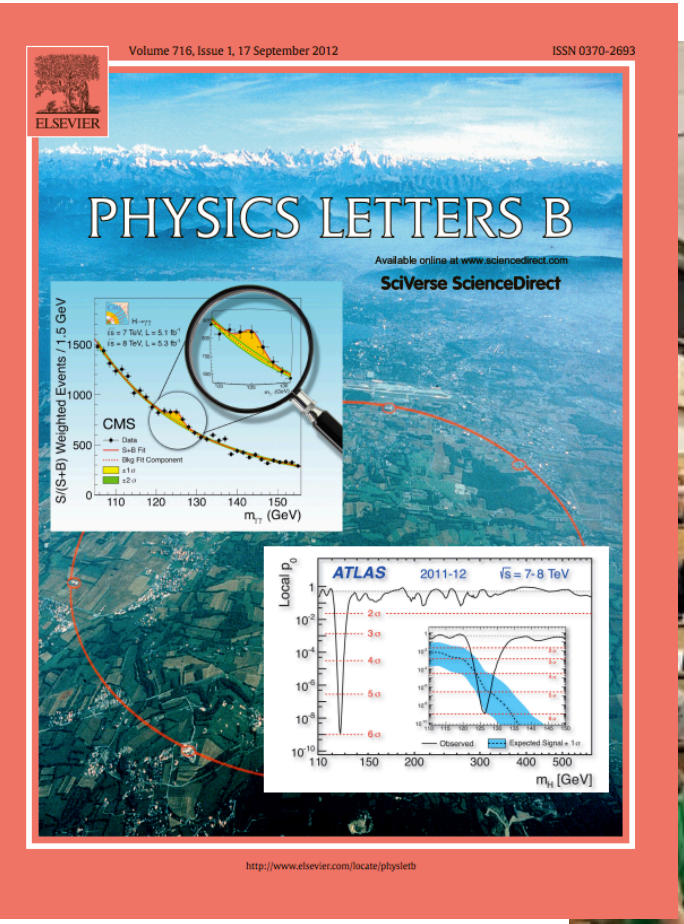


- Signal: 4 isolated leptons from same vertex
  - Small background
  - Fully reconstructed, mass resolution ~1%

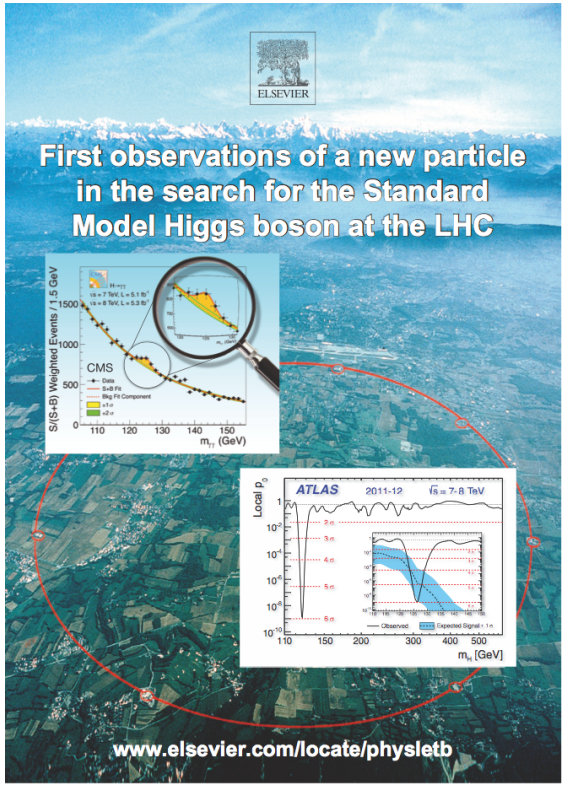
The golden channel

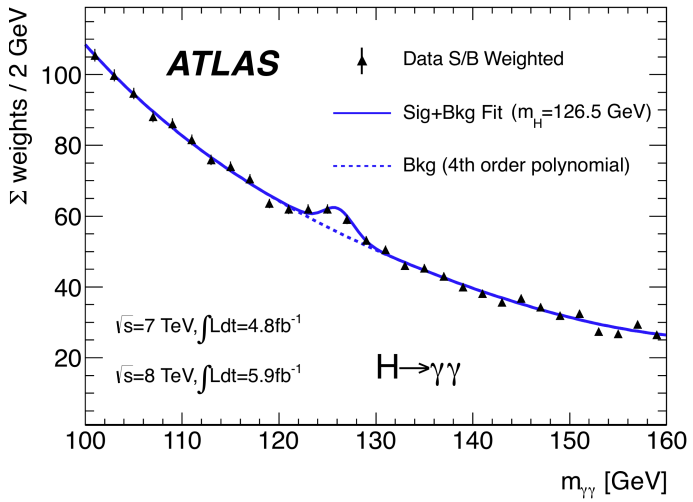

CMS Preliminary
Data
m_H=126 GeV
Zγ*,ZZ
Z+X
Mar 14, 2011
√s = 7 TeV: L = 0.0 fb⁻¹
Apr 30, 2011
√s = 7 TeV: L = 0.2 fb⁻¹
May 27, 2011
√s = 7 TeV: L = 0.4 fb⁻¹
Jun 27, 2011
√s = 7 TeV: L = 0.9 fb⁻¹
Jul 30, 2011
√s = 7 TeV: L = 1.1 fb⁻¹
Aug 21, 2011
√s = 7 TeV: L = 2.0 fb⁻¹
Sep 29, 2011
√s = 7 TeV: L = 3.2 fb⁻¹
Oct 27, 2011
√s = 7 TeV: L = 5.1 fb⁻¹
Apr 20, 2012
Events / 3 GeV
m_4l [GeV]
g
g
H
Z⁰
Z⁰*
ℓ⁻
ℓ⁺
ℓ⁻
ℓ⁺

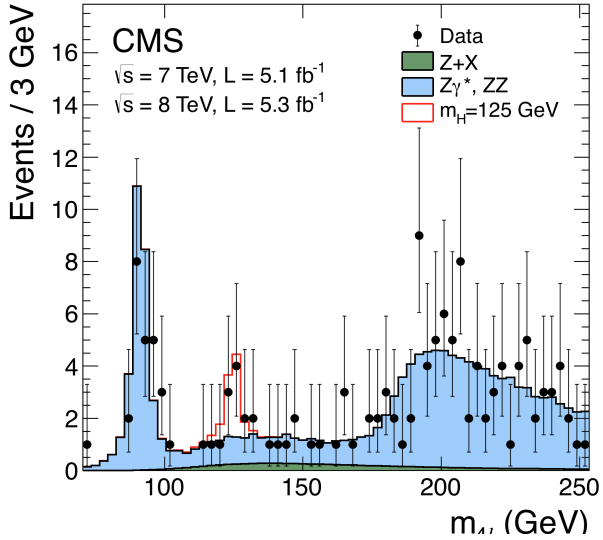
# 2012: A new boson discovery

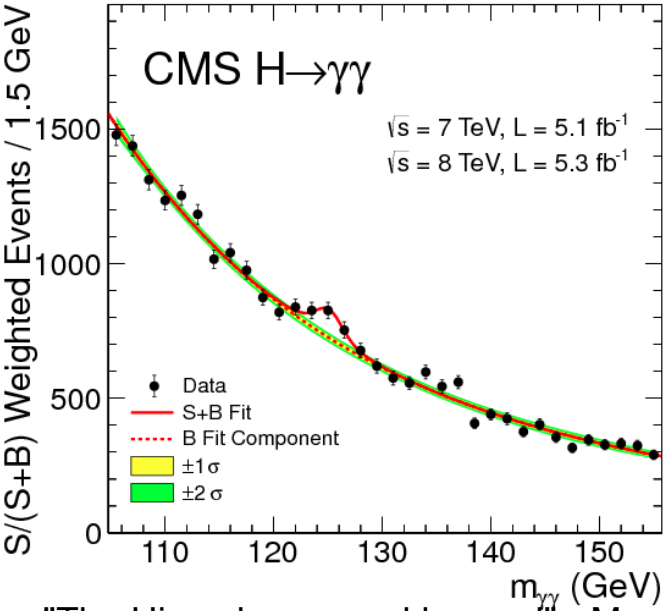


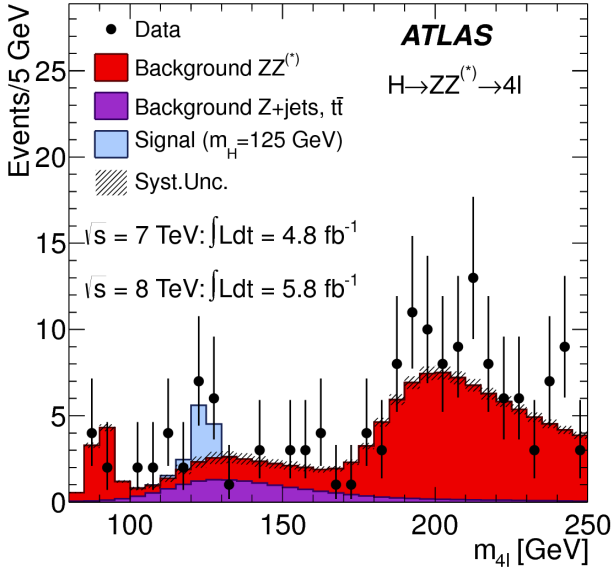

# July 4th, 2012: A Higgs boson

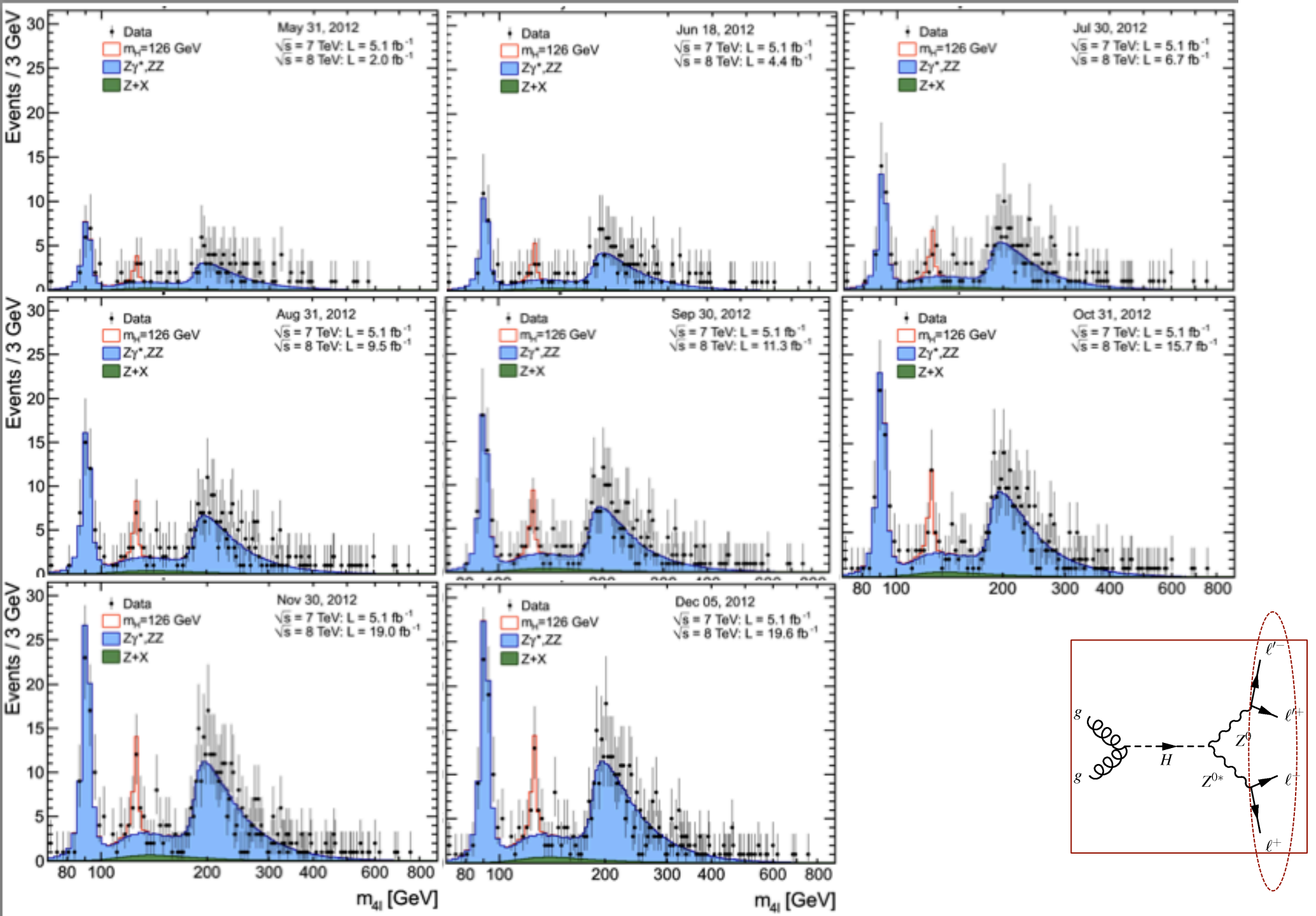


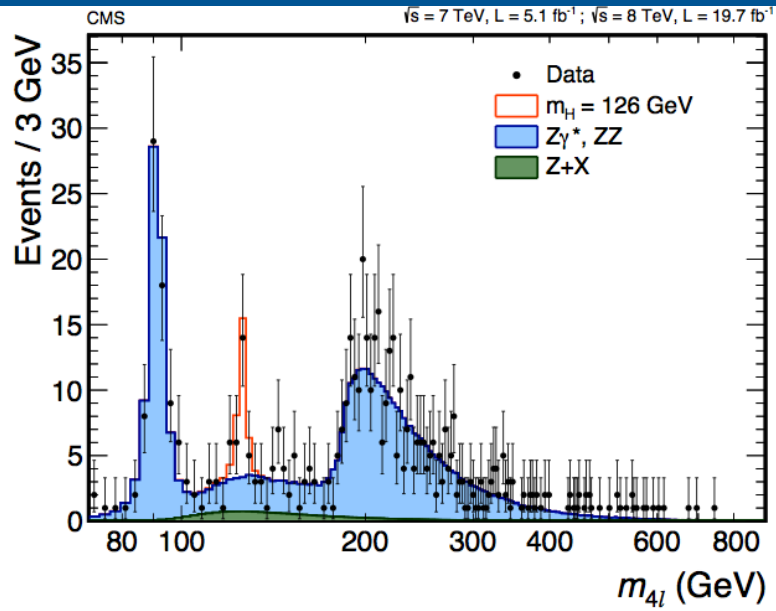



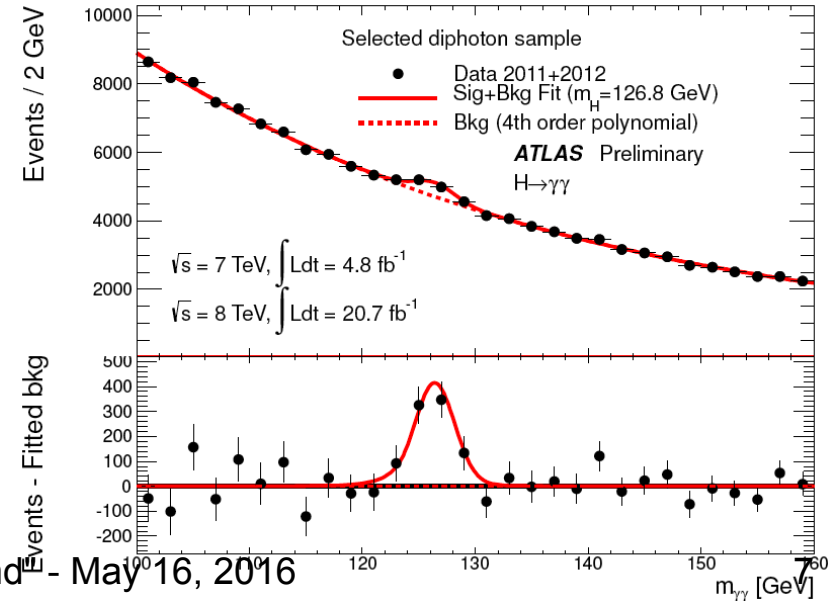

Data
$m_H$=126 GeV
Zγ*,ZZ
Z+X
May 31, 2012
√s = 7 TeV: L = 5.1 fb$^{-1}$
√s = 8 TeV: L = 2.0 fb$^{-1}$
Jun 18, 2012
√s = 7 TeV: L = 5.1 fb$^{-1}$
√s = 8 TeV: L = 4.4 fb$^{-1}$
Jul 30, 2012
√s = 7 TeV: L = 5.1 fb$^{-1}$
√s = 8 TeV: L = 6.7 fb$^{-1}$
Aug 31, 2012
√s = 7 TeV: L = 5.1 fb$^{-1}$
√s = 8 TeV: L = 9.5 fb$^{-1}$
Sep 30, 2012
√s = 7 TeV: L = 5.1 fb$^{-1}$
√s = 8 TeV: L = 11.3 fb$^{-1}$
Oct 31, 2012
√s = 7 TeV: L = 5.1 fb$^{-1}$
√s = 8 TeV: L = 15.7 fb$^{-1}$
Nov 30, 2012
√s = 7 TeV: L = 5.1 fb$^{-1}$
√s = 8 TeV: L = 19.0 fb$^{-1}$
Dec 05, 2012
√s = 7 TeV: L = 5.1 fb$^{-1}$
√s = 8 TeV: L = 19.6 fb$^{-1}$
Events / 3 GeV
0
5
10
15
20
25
30
80
100
200
300
400
600
800
$m_{4l}$ [GeV]
g
g
H
$Z^0$
$Z^{0*}$
$\ell^-$
$\ell^+$
$\ell^-$
$\ell^+$

# Higgs boson

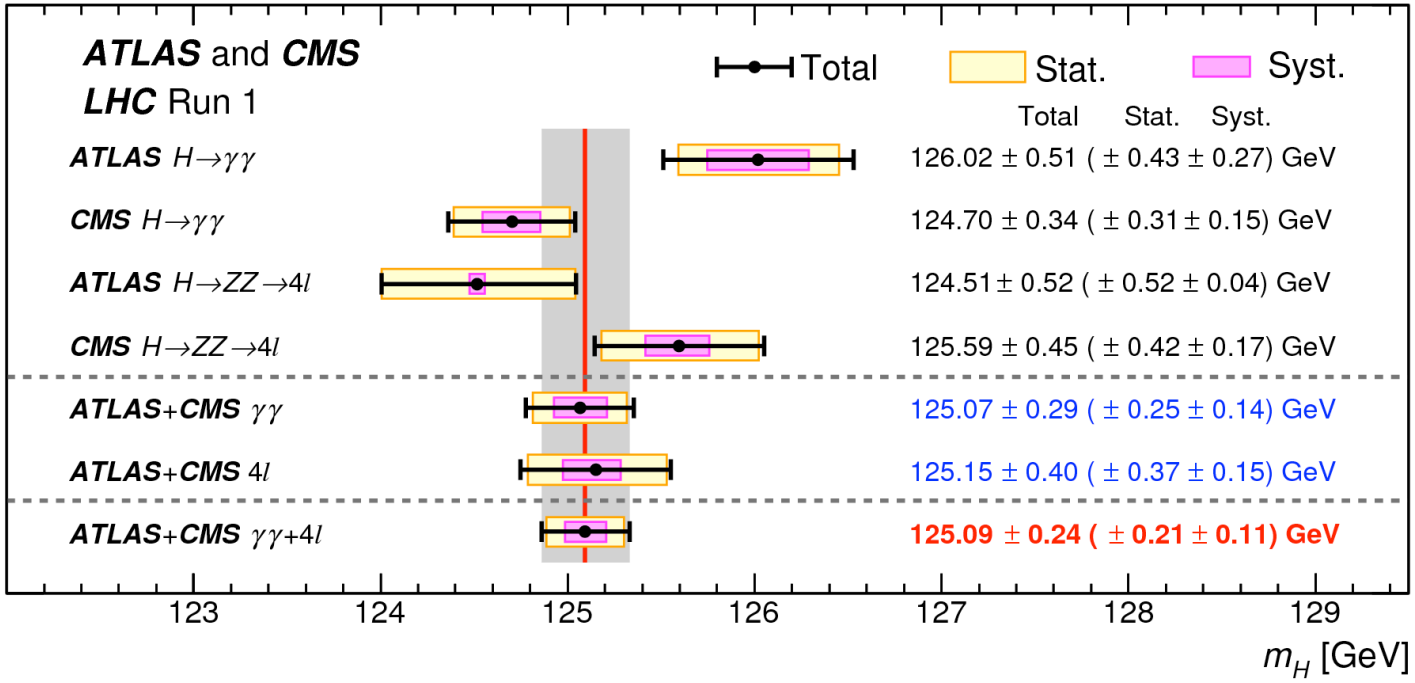
PRD 89 (2014) 092007, PLB726(2013)088

- Progress since Higgs discovery (July 2012)
  - Observation in boson channels
  - Evidence for fermion couplings
  - Precision mass measurement (~125 GeV)
  - Spin determined
- It looks more like SM Higgs boson



# Mass in the individual channels

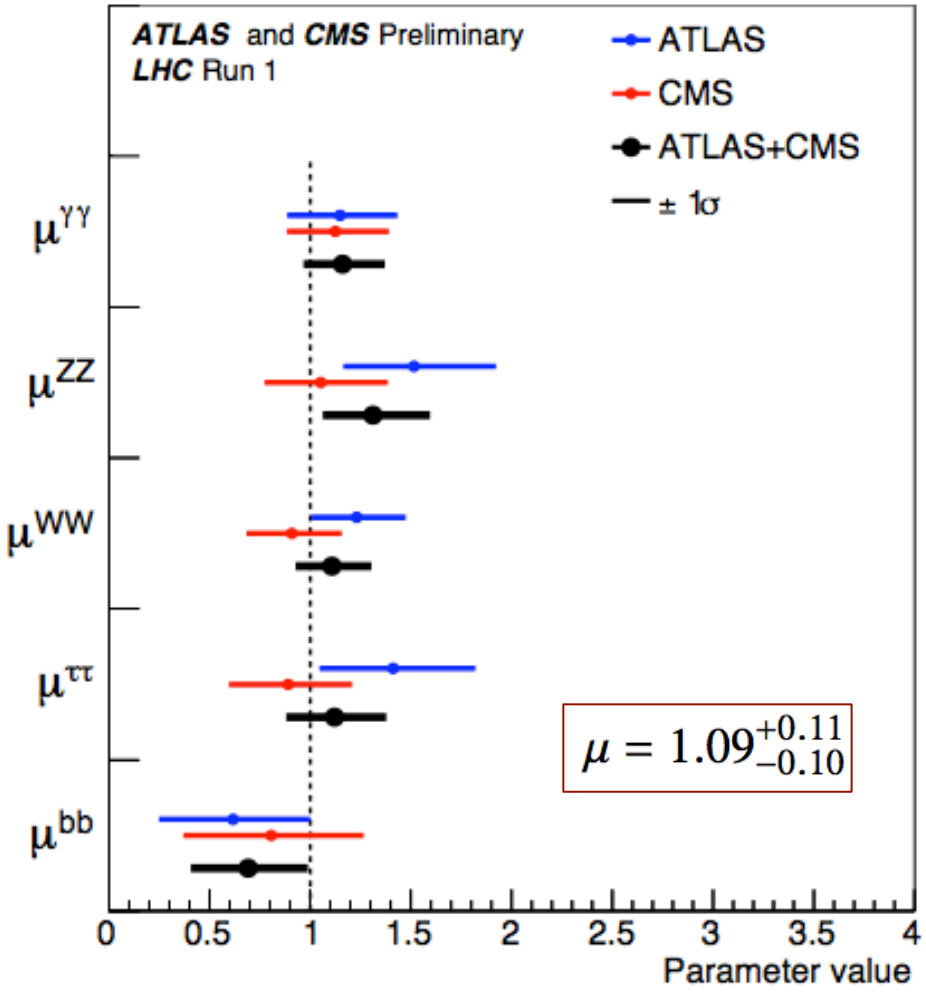



- Most accurate measurement in the $\gamma\gamma$ and 4l channels
- Some “tension” between the four measurements (p-value ~10%)

# Couplings: individual channels

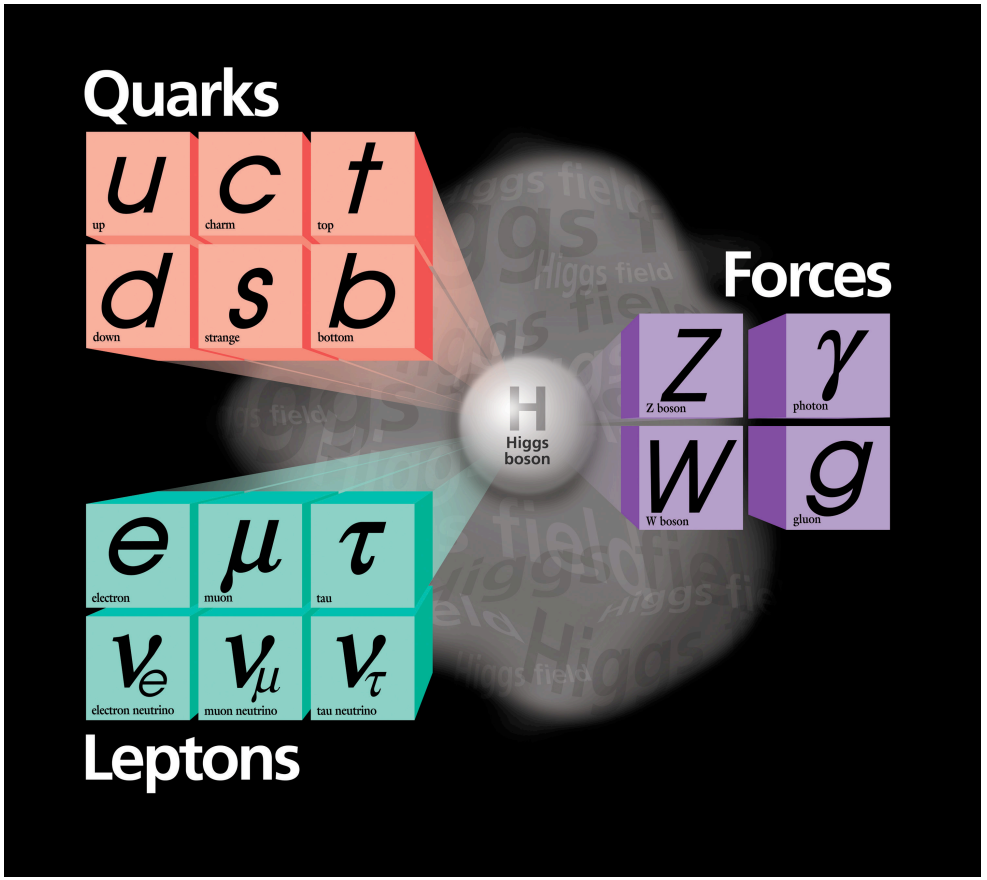
EPJC 75(2015)212, arXiv:1507.04548

Results based on the full Run 1 data samples



# Standard Model theory of everything?

- Discovery of the Higgs boson marks the triumph of the SM
- However, even with the inclusion of the Higgs boson, SM is an incomplete theory



# Beyond the Standard Model

The Standard Model answers many of the questions about the structure of matter. But the Standard Model is not complete; there are still many unanswered questions:

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

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

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

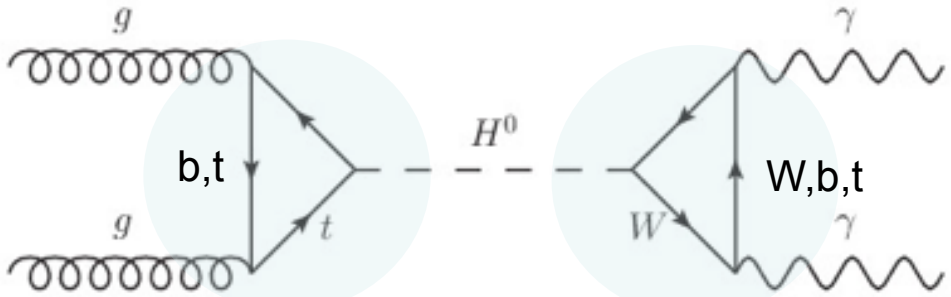
d) Why are there three generations of quarks and leptons? What is the explanation for the observed pattern for particle masses?

e) How does gravity fit into all of this?

# Higgs and BSM

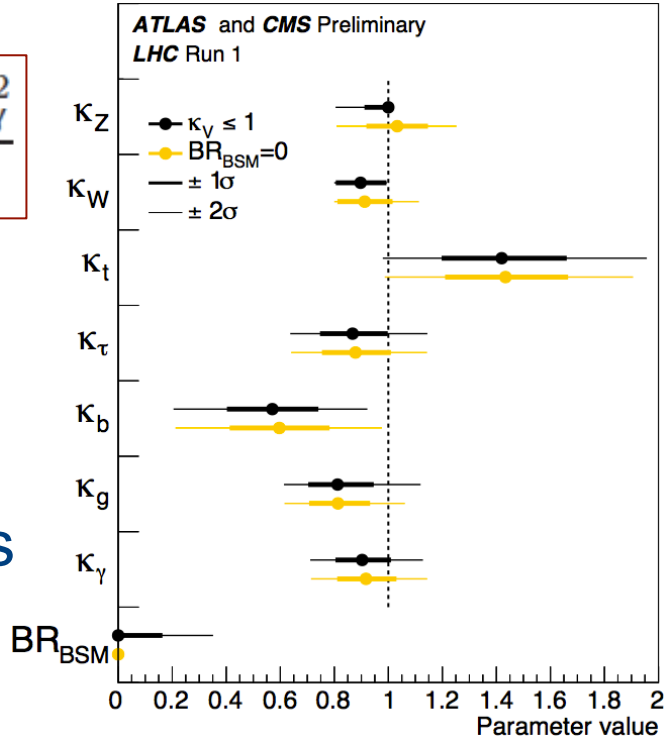
ATLAS-CONF-2015-044, CMS-HIG-15-002

- Is there BSM physics hidden in the "Higgs sector"?




$$(\sigma \cdot \mathrm{BR})\,(gg \to H \to \gamma\gamma) \;=\; \sigma_{SM}(gg \to H) \cdot \mathrm{BR}_{SM}(H \to \gamma\gamma) \cdot \frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_H^2}$$

Strategy: parametrize deviations wrt SM in production and decay
⇒ loops are sensitive to BSM physics



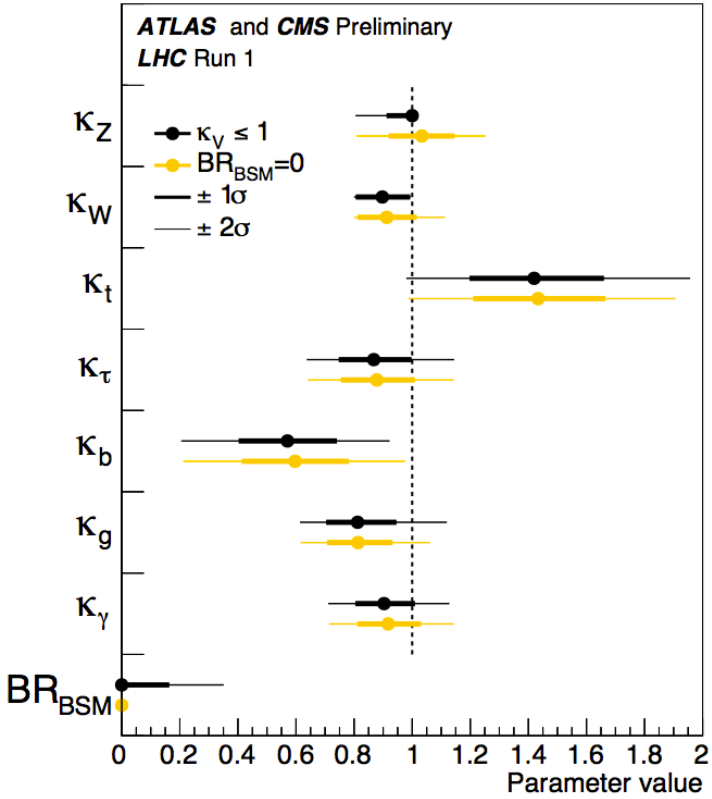

## Experimental approach

- Measure H(125) properties
- Search for additional Higgs bosons
- Search for BSM in signatures with Higgs bosons
- Search for BSM Higgs decays

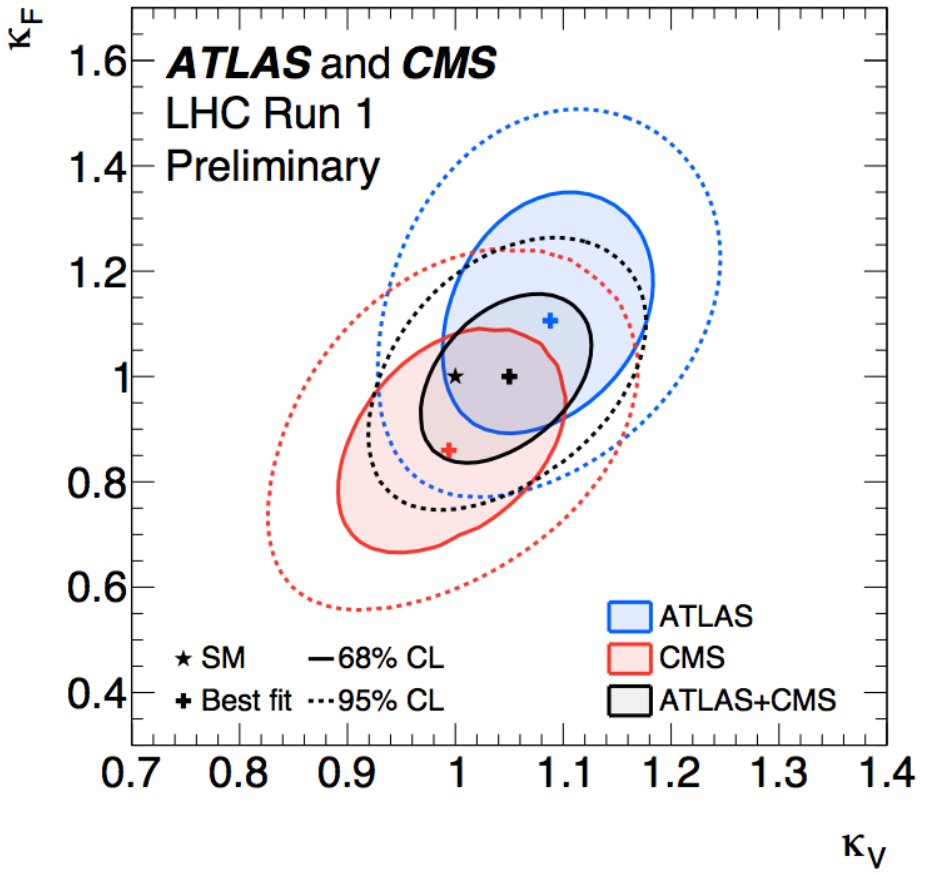
# Couplings: decays

ATLAS-CONF-2015-044, CMS-HIG-15-002

## BSM physics in the loop




## Vector and fermion couplings




$BR_{BSM}$ can be measured

$BR_{BSM}$ < 0.34 at 95% C.L. (assuming $\kappa_V \leq 1$)

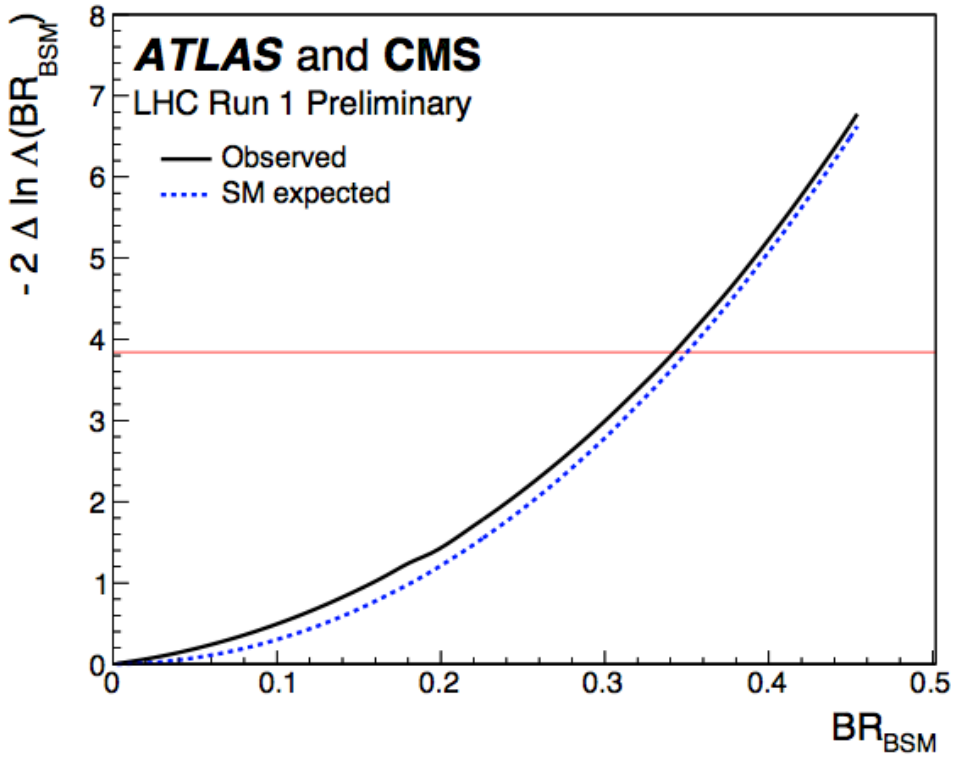
$BR_{BSM}$ includes non standard decays, visible or invisible

⇒Results in agreement with SM ($k_V$=$k_F$=1) within 1$\sigma$

# Looking for new particles

ATLAS-CONF-2015-044, CMS-HIG-15-002

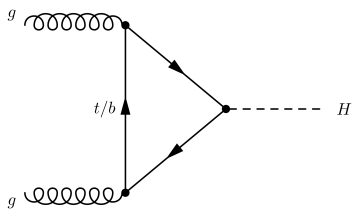
- Constrain $BR_{BSM}$ in a scenario with free parameters
- $\Gamma_{tot}=\Gamma_{WW}+\Gamma_{ZZ}+\Gamma_{bb}+\ldots +\Gamma_{BSM}$
- Likelihood scan vs $BR_{BSM}$
- Assuming couplings bound by SM expectations ($k_V<1$)
- $0\leq BR_{BSM}\leq 0.34$ at 95%CL



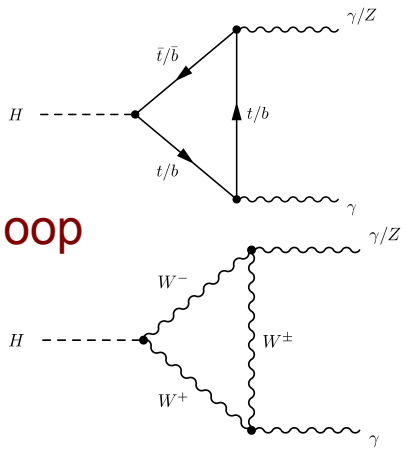
# Couplings: production

- Assuming tree level couplings as in the SM and only allow modifications in the ggF and H→γγ loops

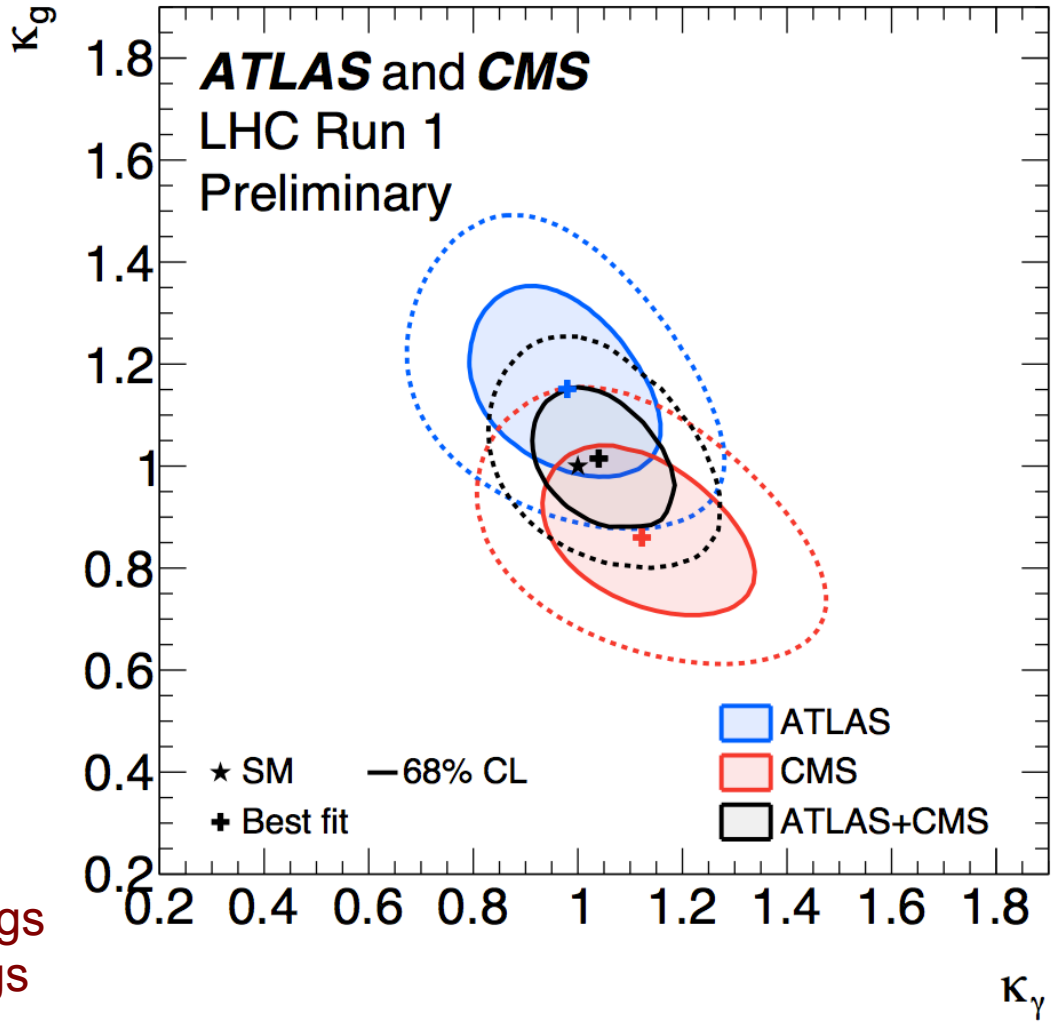
ggF loop




H→γγ loop




Additional heavy fermions or charged Higgs boson would modify the effective couplings



# Constraining Higgs width

PLB 736(2014)64

obs.(exp.) @95%CL:
$\Gamma_H < 5.4(8.0)\Gamma_H^{SM}$
$\Gamma_H < 22(33)$MeV

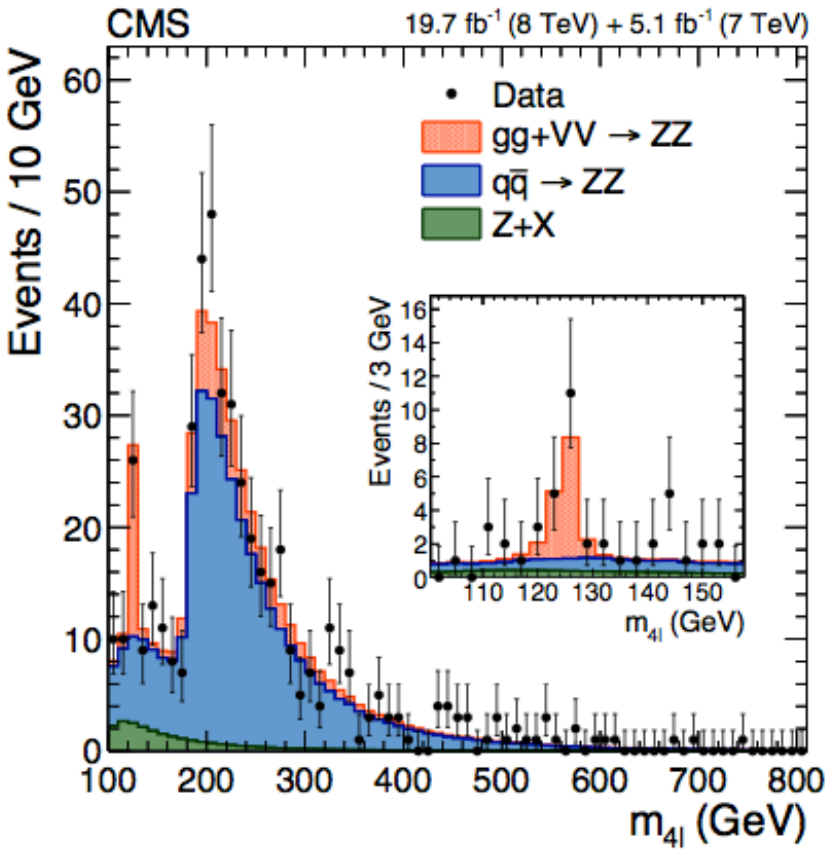
- couplings and width sensitive probes to BSM
- indirectly constrained in coupling fits
- off-peak to on-peak ratio proportional to $\Gamma_H$
- constrain Higgs boson width by using off-shell production/decay
- measure ratio of $\sigma^{\text{off-peak}}$ to $\sigma^{\text{on-peak}}$

$$\sigma^{\text{on-peak}}_{gg\to H\to ZZ} \propto \frac{g^2_{ggH} g^2_{HZZ}}{\Gamma_H}, \qquad \sigma^{\text{off-peak}}_{gg\to H\to ZZ} \propto g^2_{ggH} g^2_{HZZ}$$

F. Caola, K. Melnikov PRD88(2013)054024
J. Campbell et al. arXiv:1311.3589

– $g_{ggH}$ and $g_{HZZ}$: couplings to gluons and bosons

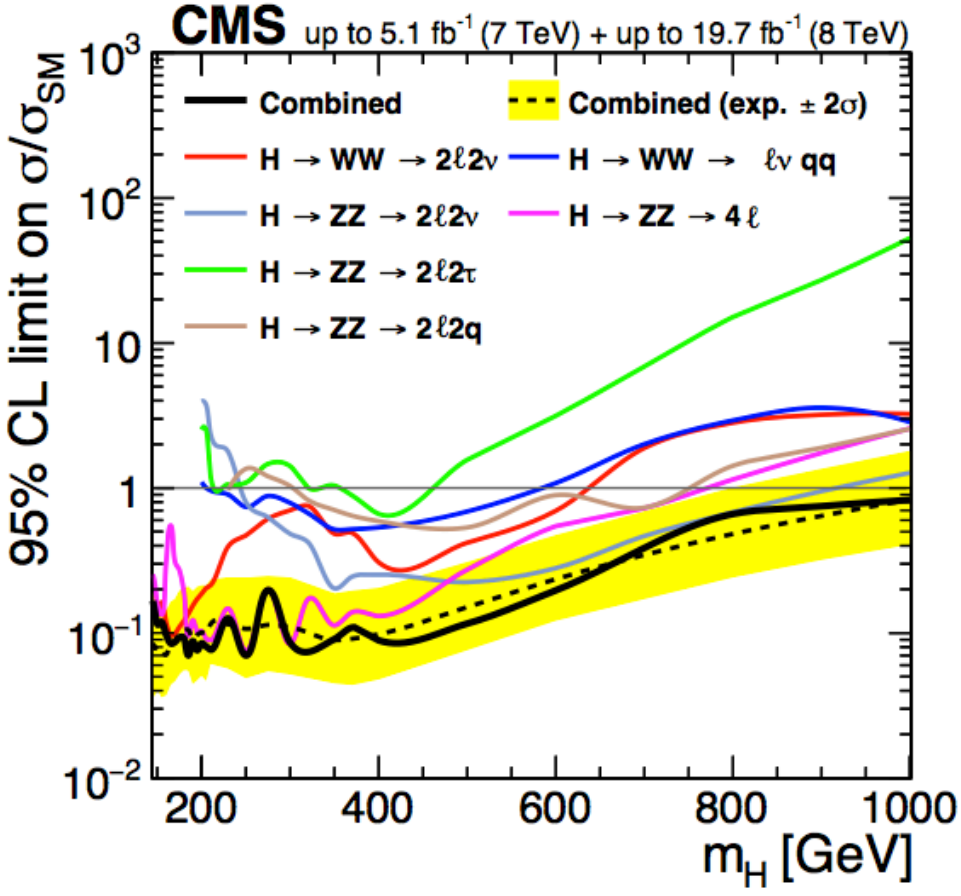
- measurement of $\Gamma_H$



# High mass: H→ WW/ZZ

JHEP 10(2015)144

- Search for a heavy Higgs boson
  - H→ZZ→4ℓ, 2ℓ2ν, 2ℓqq
  - H→WW→2ℓ2ν, 2ℓqq
- optimized separately for VBF and gluon fusion production processes
- SM-like Higgs boson excluded in 4ℓ and 2ℓ2ν/ℓνqq channels at 95%CL in mass ranges up to 1000 GeV
- Search interpreted in BSM scenario (heavy Higgs, heavy EWK singlet state)
  - evolution of signal strength of the singlet state with modified couplings/width wrt SM.
  - assume new scalar does not decay to any new particle



# Extending searches

- Minimal Supersymmetric SM (MSSM)
  - Neutral Higgs: $\phi \to \tau\tau/bb/\mu\mu$
  - Charged Higgs
- Next-to-MSSM
  - Light pseudoscalar: $h \to aa$
  - Non-SM decays: $h \to 2a \to 4\tau/4\mu$
  - Heavy Higgs: $H \to h_{125}h_{125}$ or $A \to Zh_{125}$
- FCNC: $t \to cH$

# Higgs sector in the MSSM

Higgs sector in SUSY contains two scalar doublets:

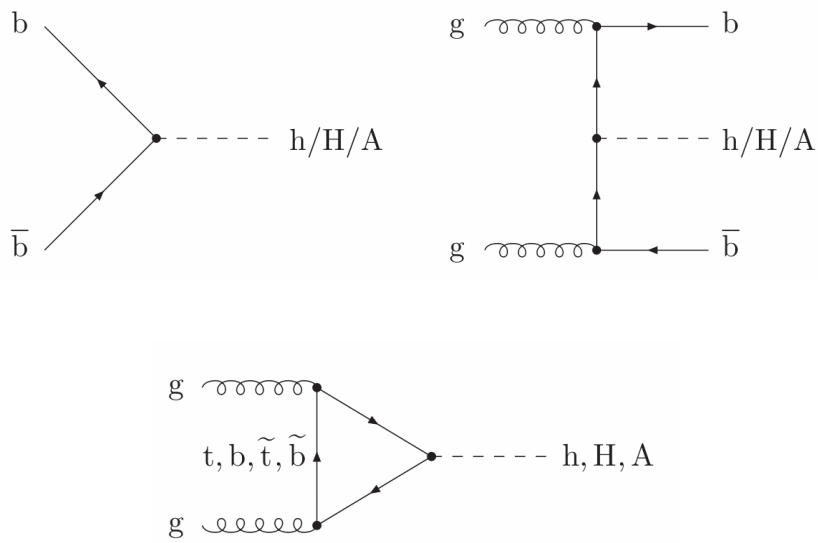
- 5 physical Higgs bosons
  - 3 neutral: CP-even $\phi$=h,H CP-odd A
  - 2 charged $H^{\pm}$
- SM-like Higgs boson: h

Neutral Higgs $\phi$ decay modes:

- BR($\phi \rightarrow$bbar)~90%
- BR($\phi \rightarrow \tau\tau$)~10%
- BR($\phi \rightarrow \mu\mu$)~0.1%

Two main production modes:

- gg$\rightarrow$H
- $b\bar{b}$H

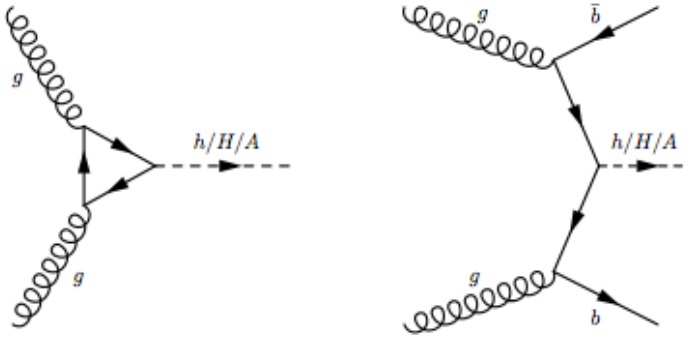


# Neutral MSSM Higgs

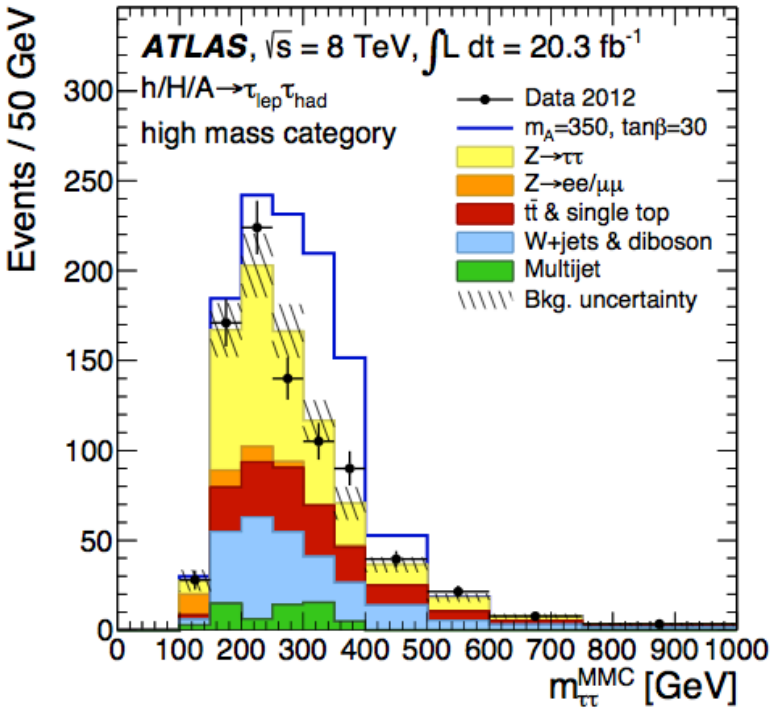
JHEP 10(2014)212, arXiv:1409.6064

- Enhanced couplings of MSSM Higgs to down-type fermions (large tanβ)

⇒increased BR to τ leptons and b-quarks




- Search for neutral MSSM Higgs boson
- 5 final states used: $\mu\tau_h$, $e\tau_h$, $\tau_h\tau_h$, $e\mu$, $\mu\mu$
  - Reconstruct tau-pair invariant mass
  - Split in b-tag/no b-tag categories to enhance sensitivity
- Main backgrounds: $Z\rightarrow\tau\tau$, QCD/W+jets, DY,ttbar, dibosons

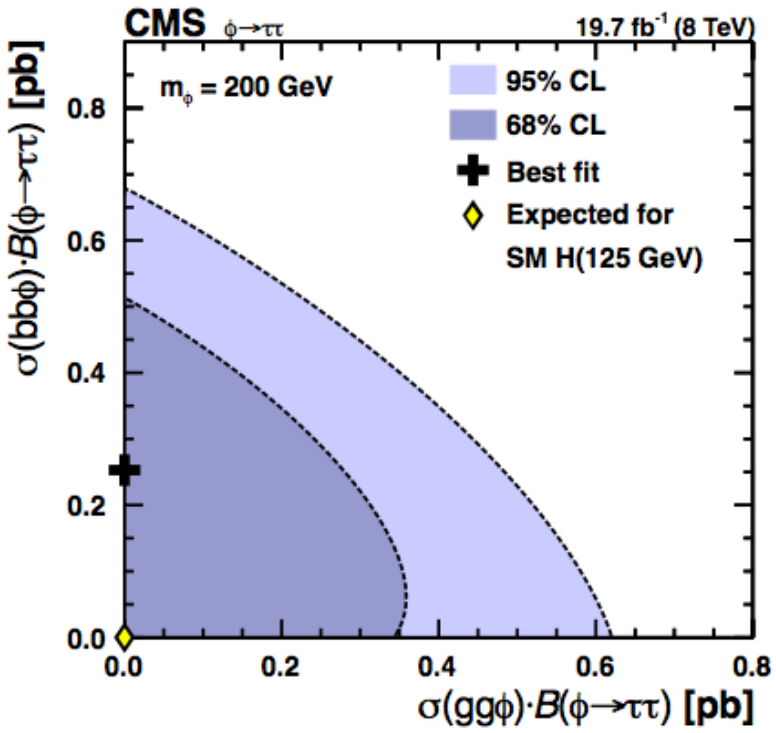


# Neutral MSSM Higgs: $\phi \to \tau\tau$

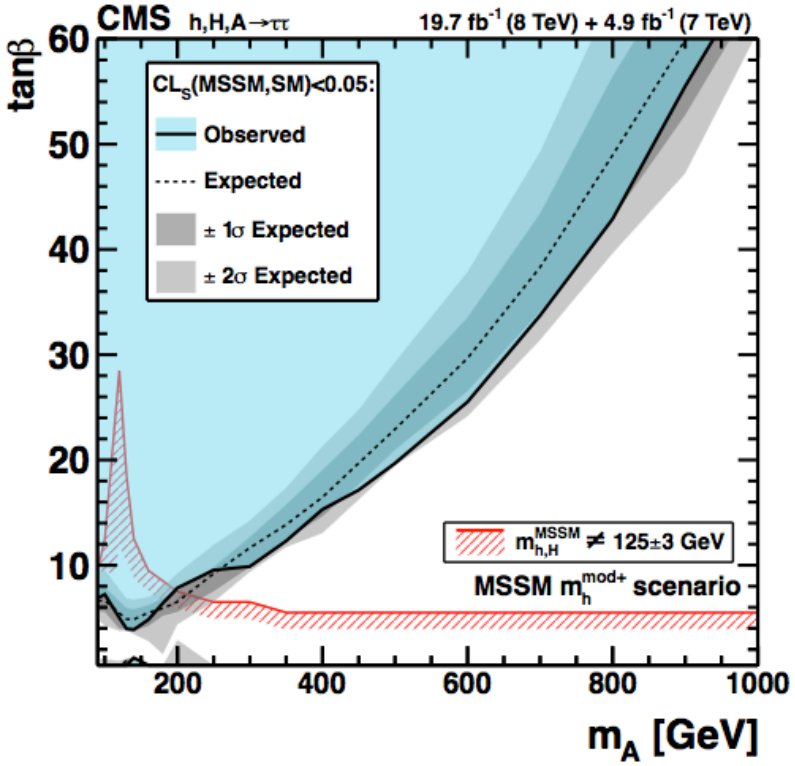
JHEP 10(2014)160, arXiv:1409.6064

- Direct search: inclusive and b-tagged
- $\tau$ in both leptonic and hadronic decays

$\tan\beta$ vs $m_A$ window becoming smaller




Model-independent limits by separating production modes

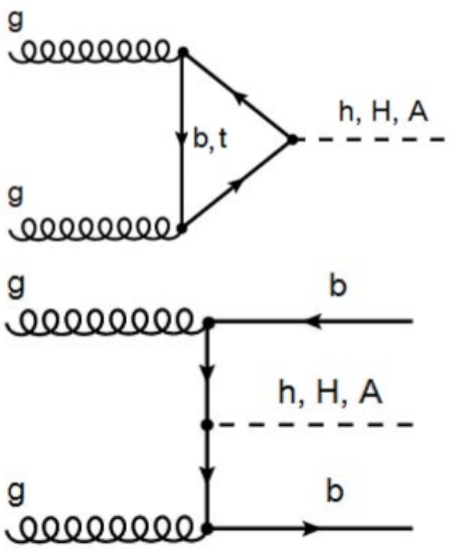


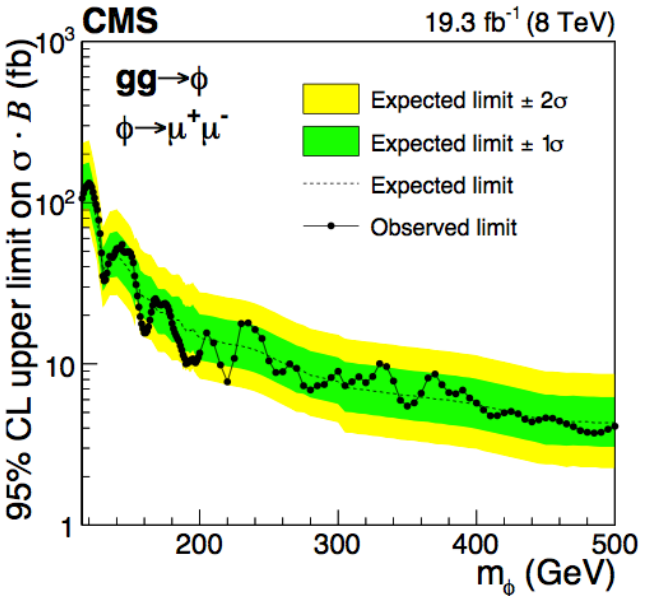

No significant excess over bkg expectations

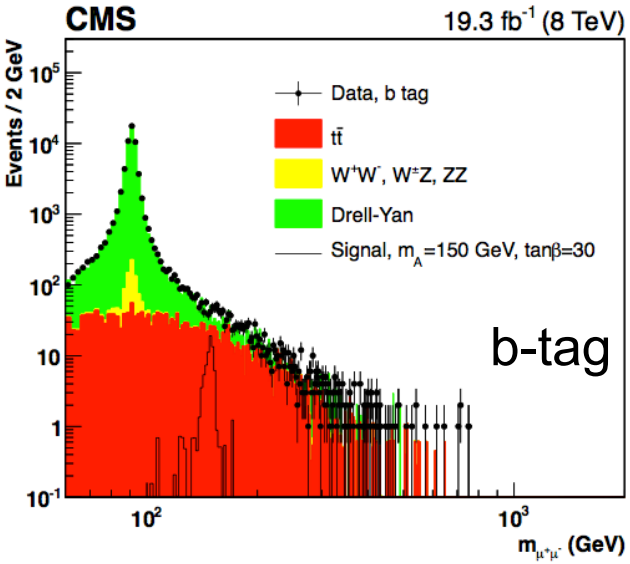
# Neutral MSSM Higgs: $\phi \rightarrow \mu\mu$

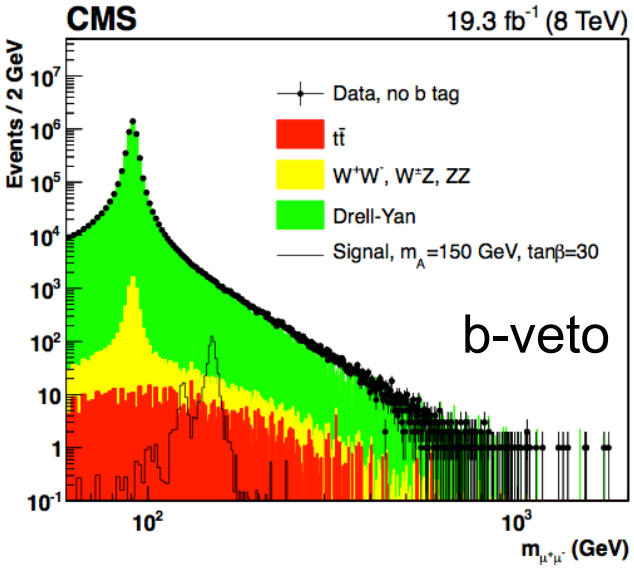
arXiv:1508.01437, ATLAS-CONF-2012-094

- Search for a $\mu\mu$ mass resonance
  - Model-independent
  - associated production, gluon fusion
- Good mass resolution
  - full and clean reconstructed final state
- Split in b-tagged and non b-tagged categories to be sensitive to $gg \rightarrow \phi$ and $bb\phi$ production modes
- Main backgrounds: DY, VV, ttbar



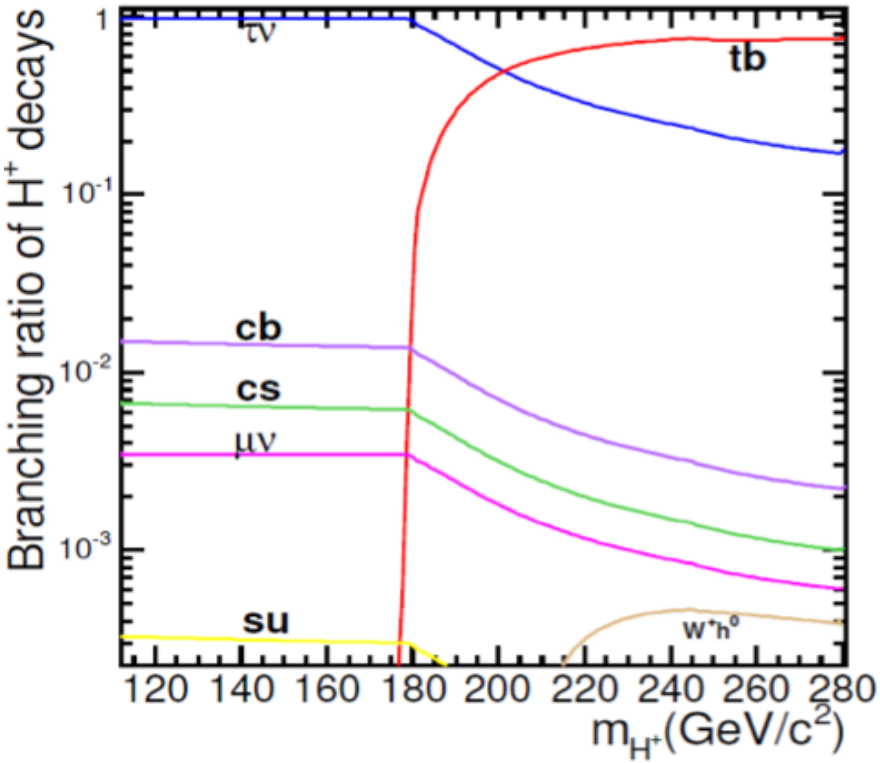



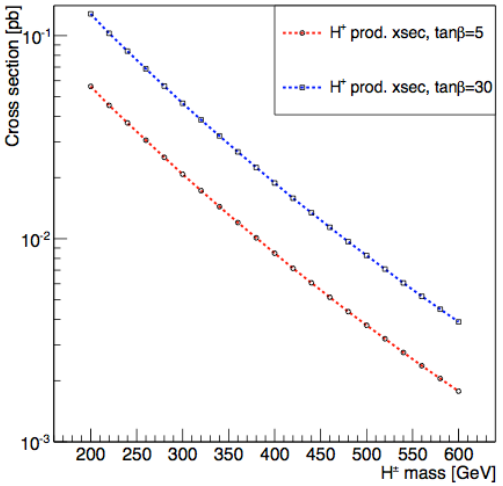
# Charged Higgs

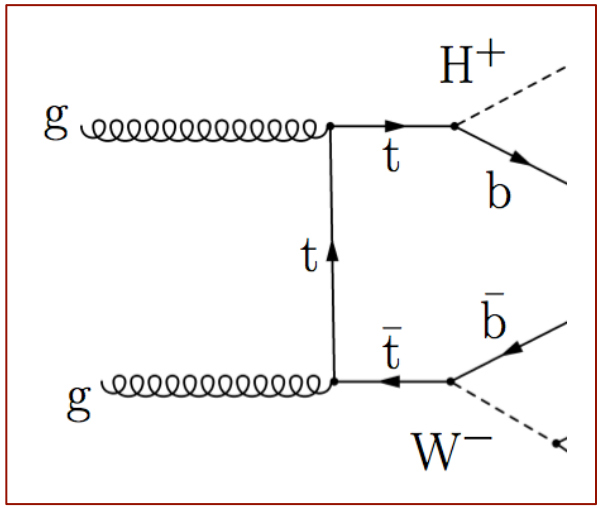
- If found, a clear indication of BSM
- Study non-SM Higgs in two mass regimes:
- $m_H < m_{top}$
  - Mostly produced in top quark decays
  - Large tanβ: $H^{\pm} \rightarrow \tau^{+}\nu$
  - Small tanβ (<1): $H^{+} \rightarrow c\bar{s}$
- $m_H > m_{top}$
  - Produced in gluon-gluon fusion
  - Main decays: $H^{+} \rightarrow tb$, $H^{+} \rightarrow \tau^{+}\nu$
- Main backgrounds: ttbar, W+jets



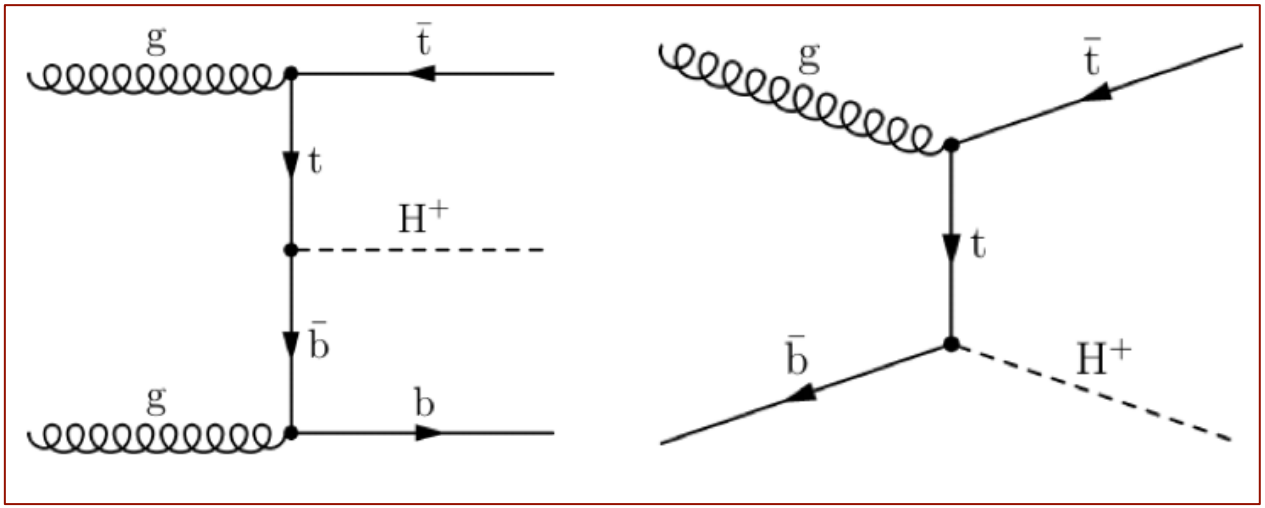
# Charged Higgs (cont.)

- Different strategies for low- and high-mass searches
- tau+lepton, lep+jets, and eμ final states
- b-tagged jet categorization
- limited by statistics at high-mass




$m_H < m_{top}$

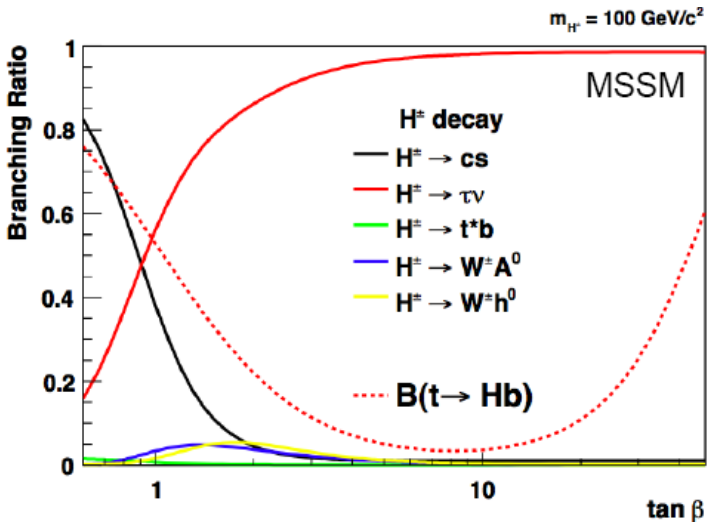



$m_H > m_{top}$

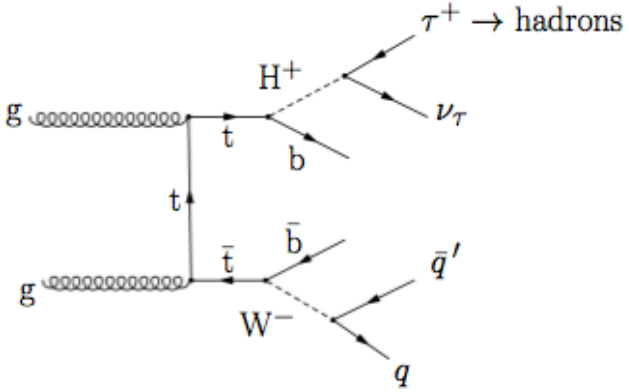
# Charged Higgs and top quark decays

JHEP 07(2012)143, arXiv:1508.07774

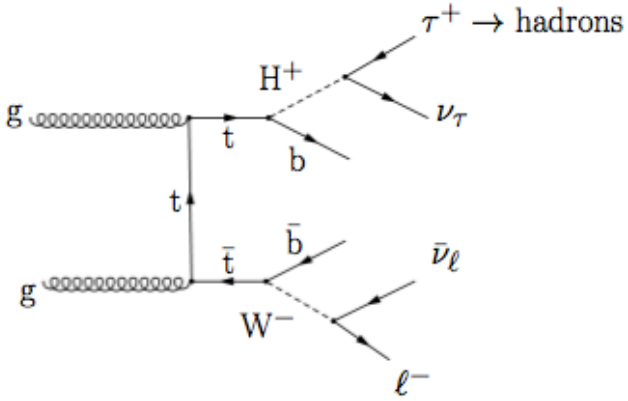
- Look for charged Higgs in four final states:
  - Tau+lepton (electron or muon)
  - Dilepton (tau decays leptonically)
  - lepton+jets
  - Fully hadronic: tau+jets



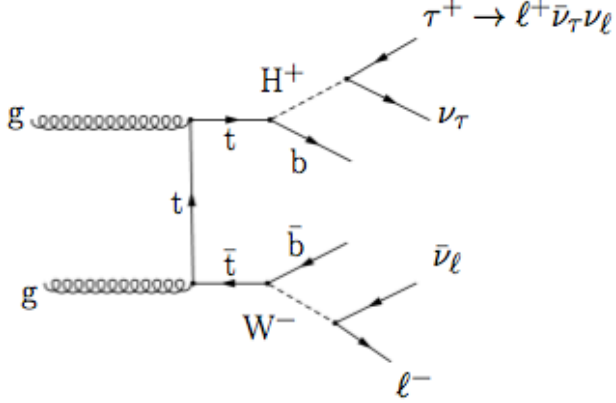

$\tau_h$+jets



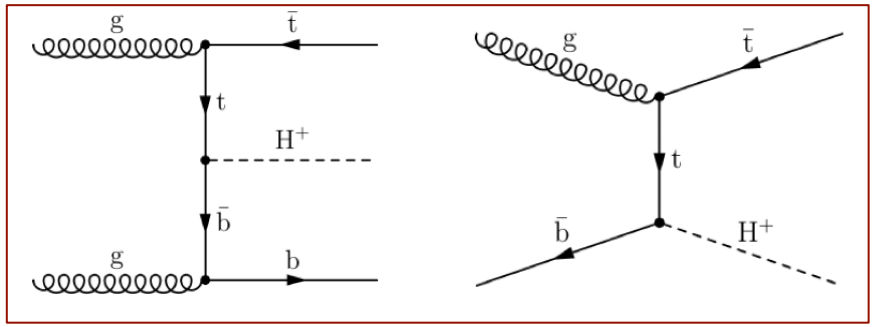

$\tau_h$+lepton (e/μ)



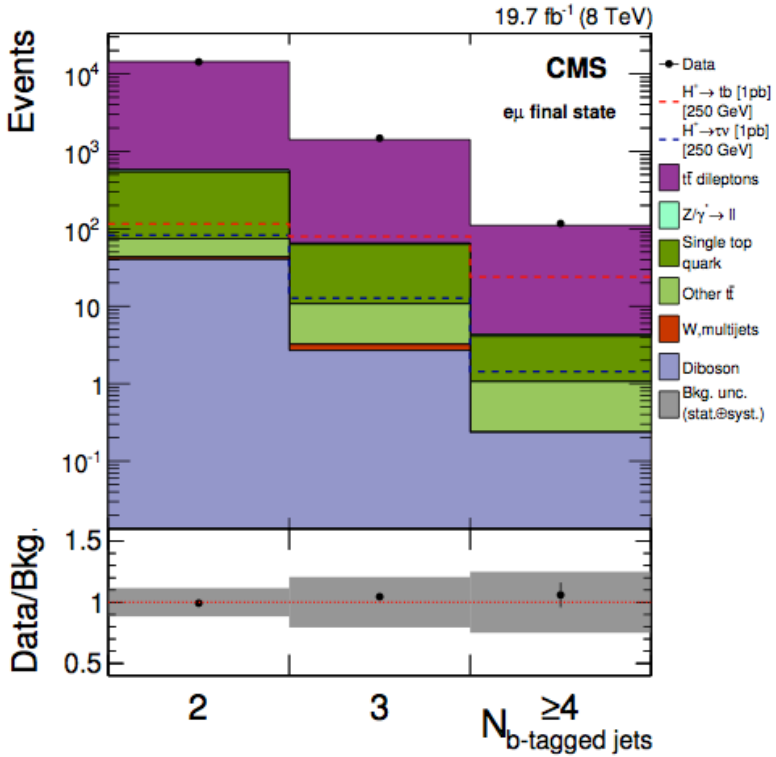

di-lepton (eμ)

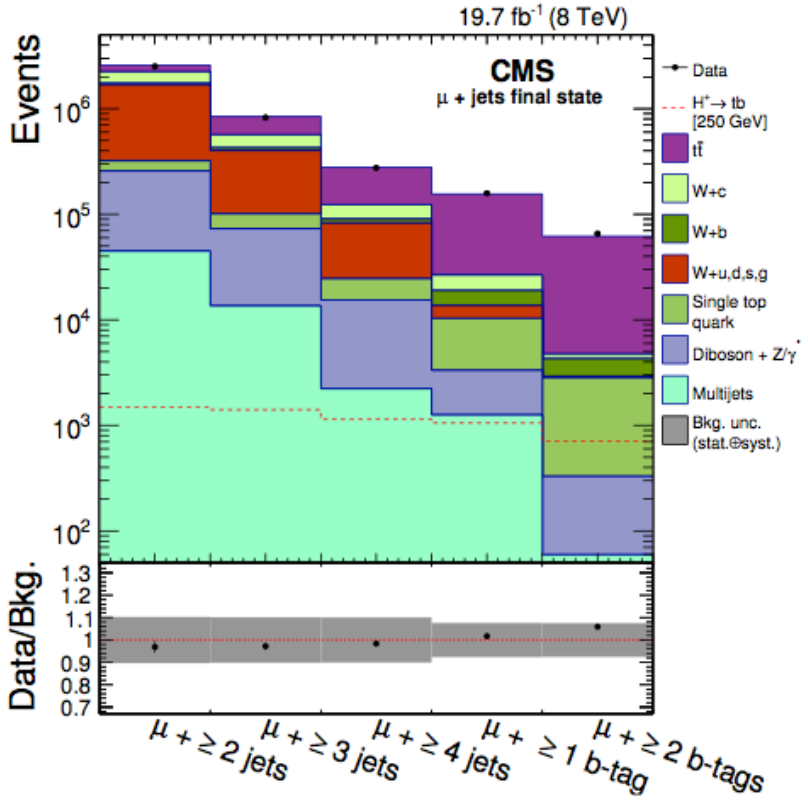


# Number of b-tagged jets




High-mass $H^+$ search:
look at b-tag multiplicity



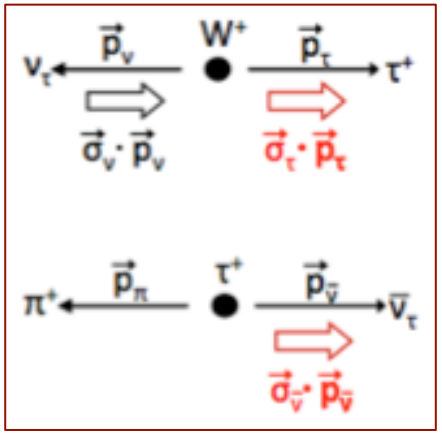



# Looking at tau decays

CMS-HIG-12-052

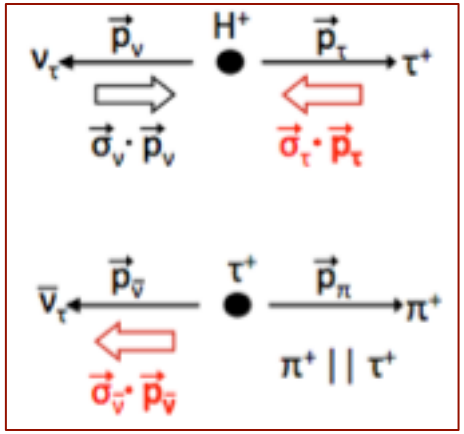
- Use R variable in the limit extraction: binned maximum-likelihood fit
- Tau fake component is data-driven, includes uncertainties

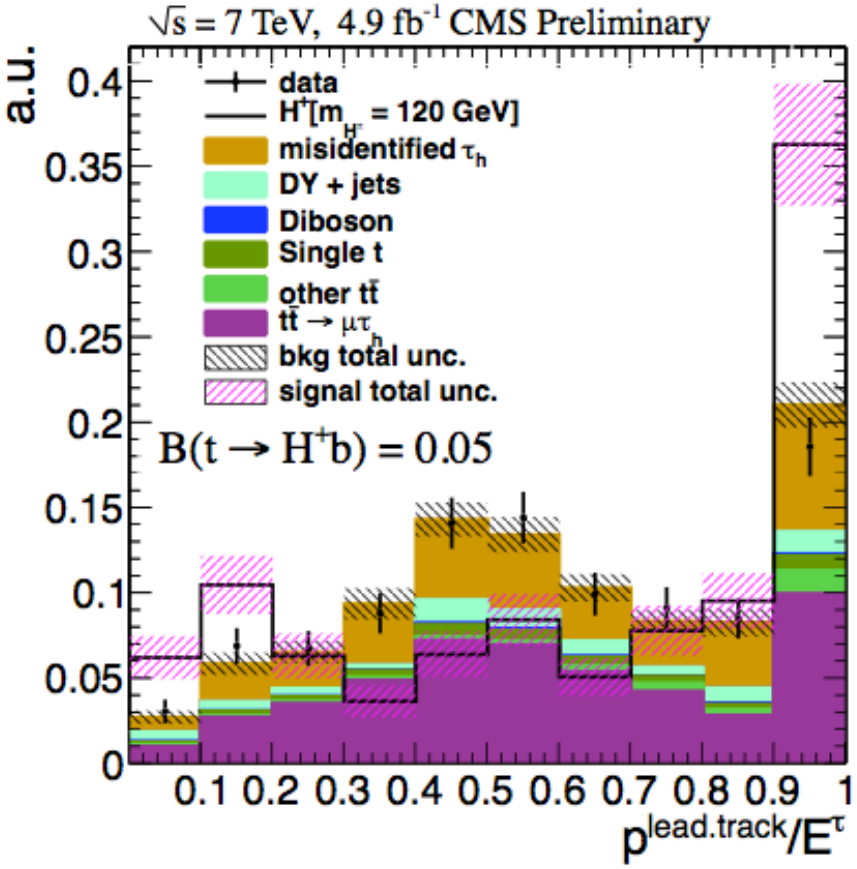
SM




vs

BSM



# Is there a charged Higgs?

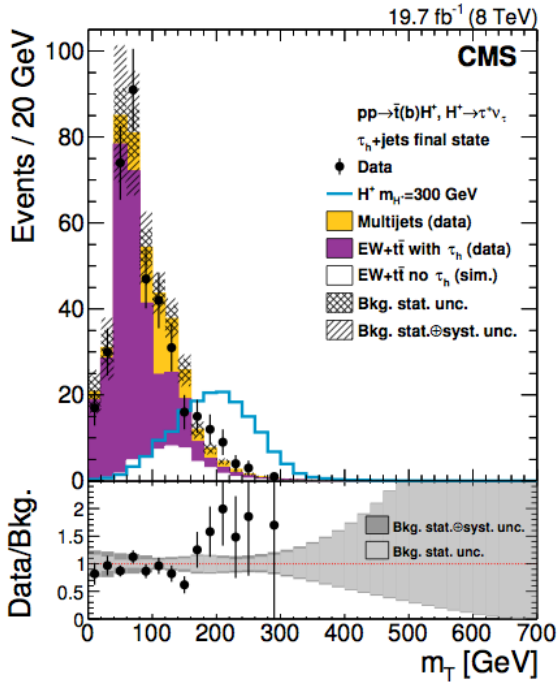
JHEP 07(2012)143, CMS-HIG-12-052, arXiv:1508.07774

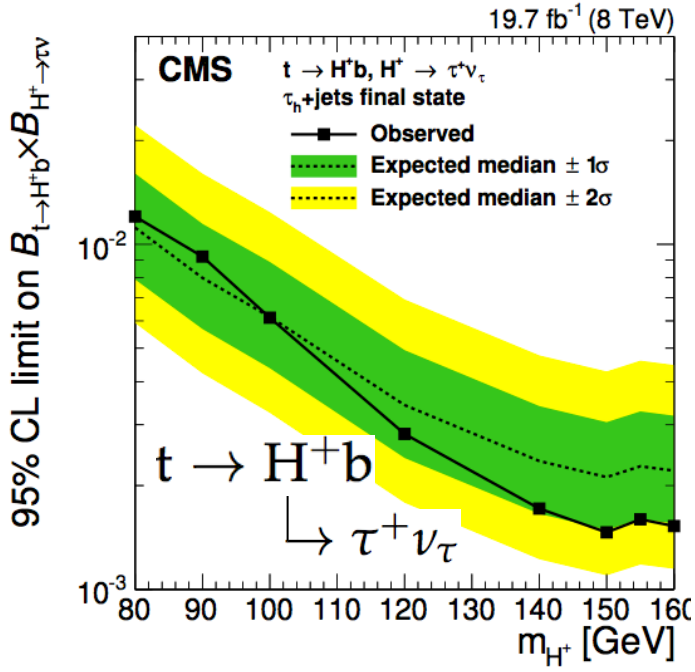
- If anomalous tau/lepton production in ttbar decays there may be contribution from $H^+$

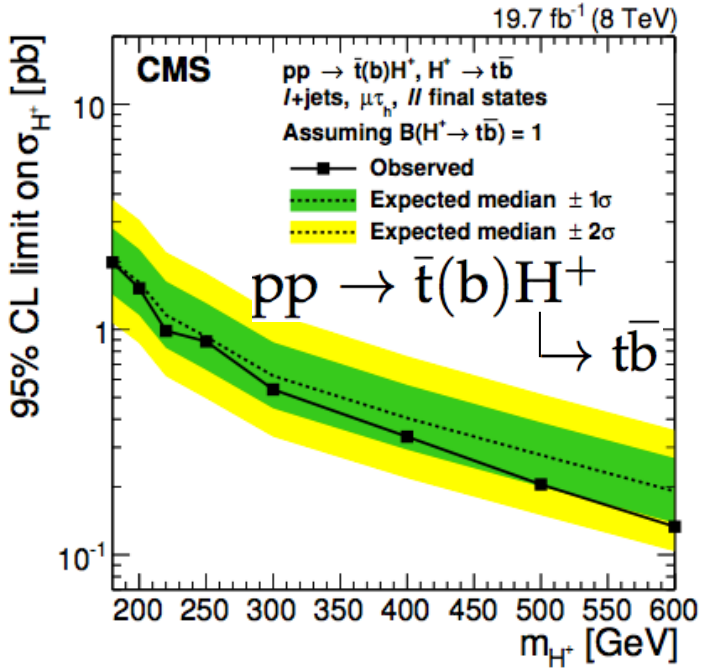
  Yields in agreement with expectations ⇒ set limits

$m_H$: 80-160 GeV $\quad \mathcal{B}(t \to bH^+) < 1.2\text{-}0.3\%$

200-600 GeV $\quad \sigma(pp \to \bar{t}(b)H^+) < 2.0\text{-}0.2$ pb



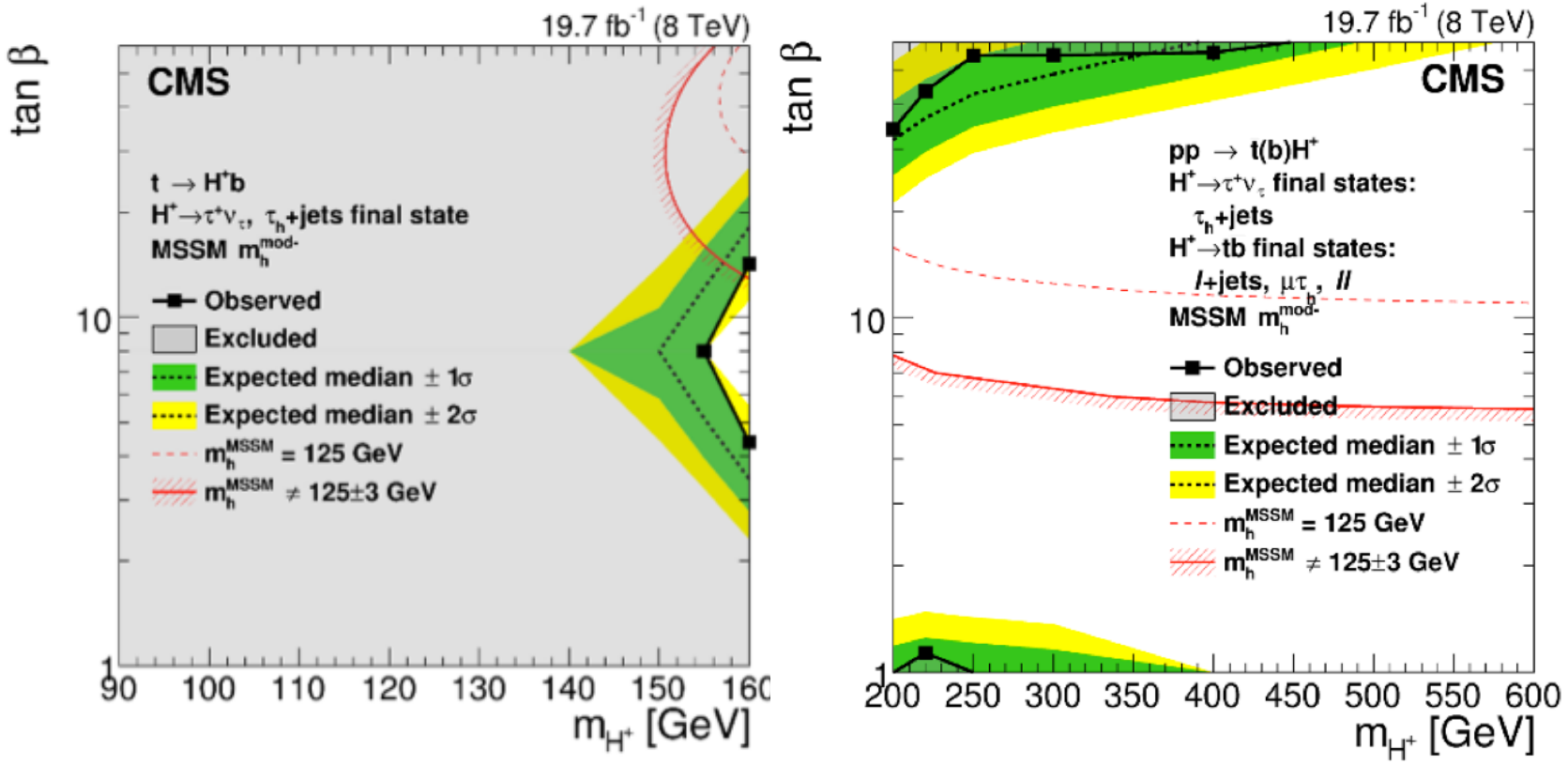

At 13TeV, expect improvement with 5-10/fb for $m_{H+}$>300GeV ⇒

- ttbar xsection increases x3.3
- signal increases x6(x7) for $m_{H+}$=500(600)GeV

# Still hope for MSSM?

JHEP 07(2012)143, CMS-HIG-12-052, arXiv:1508.07774

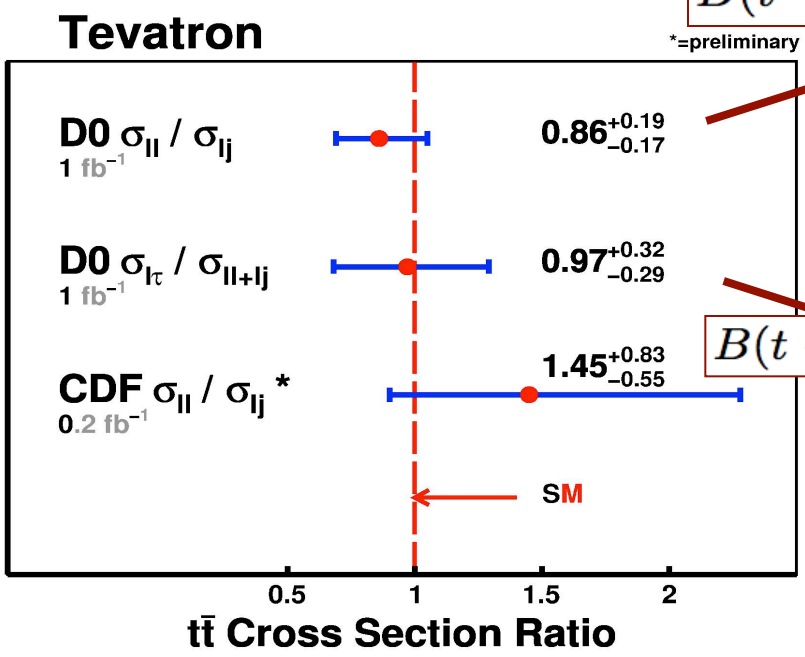
- A new modified MSSM scenario: $m_h^{mod}$ (arXiv:1302.7033)
- Reduce amount of mixing in the stop sector ($X_t/M_{SUSY}$)
- A/H decays to chargino/neutralinos allowed (arXiv:0709.1029)
- Allows for reduction of decays into $\tau\tau$ and bb



# Cross section ratios

PRD 80(2009) 071102

Many systematic unc. cancel in the ratio
Study of cross section ratios
⇨sensitive to BSM
1. BR(l+jets)/BR(ll)
2. BR(l+tau)/BR(ll)

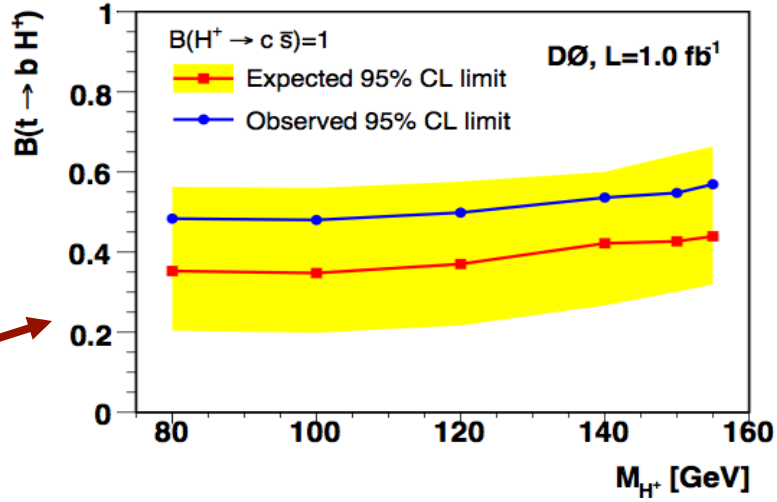


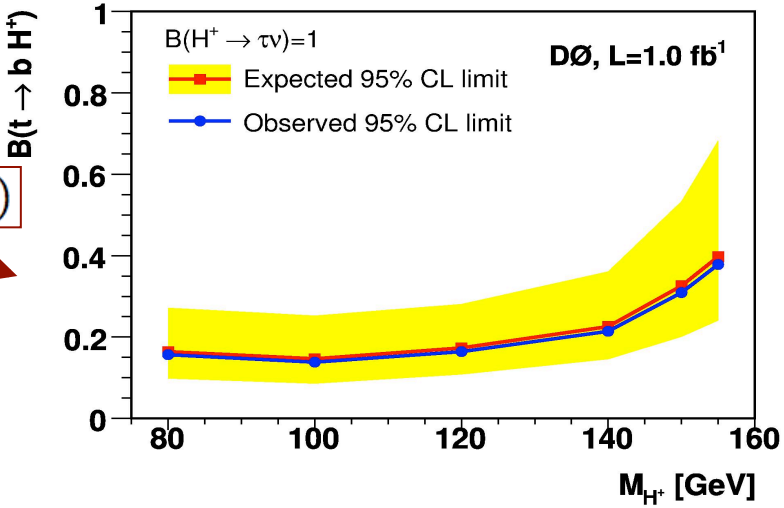

$B(t \to H^+ b \to c\bar{s}b)$

lept.+jets

$B(t \to H^+ b \to \tau^+ \nu b)$

tau leptons

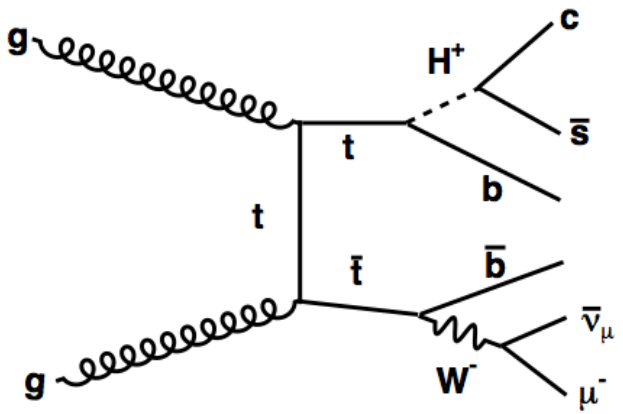


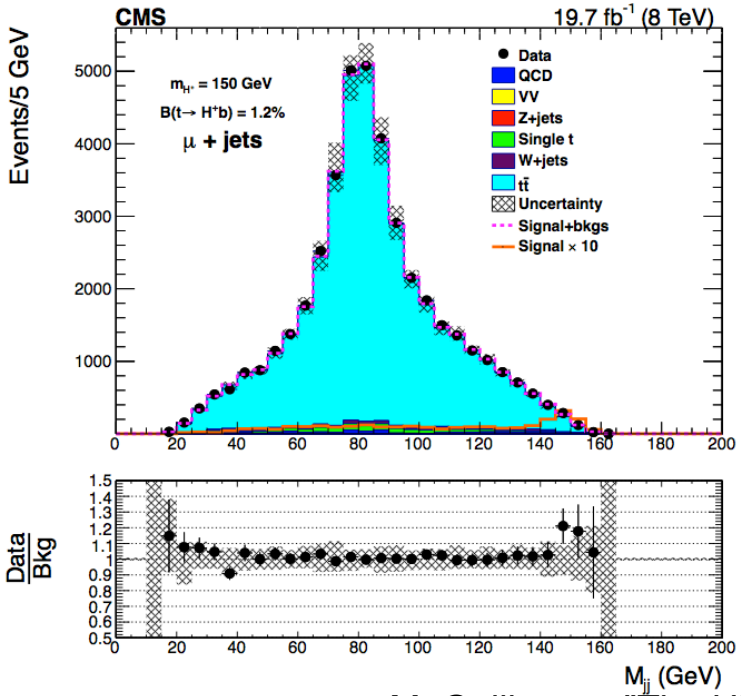



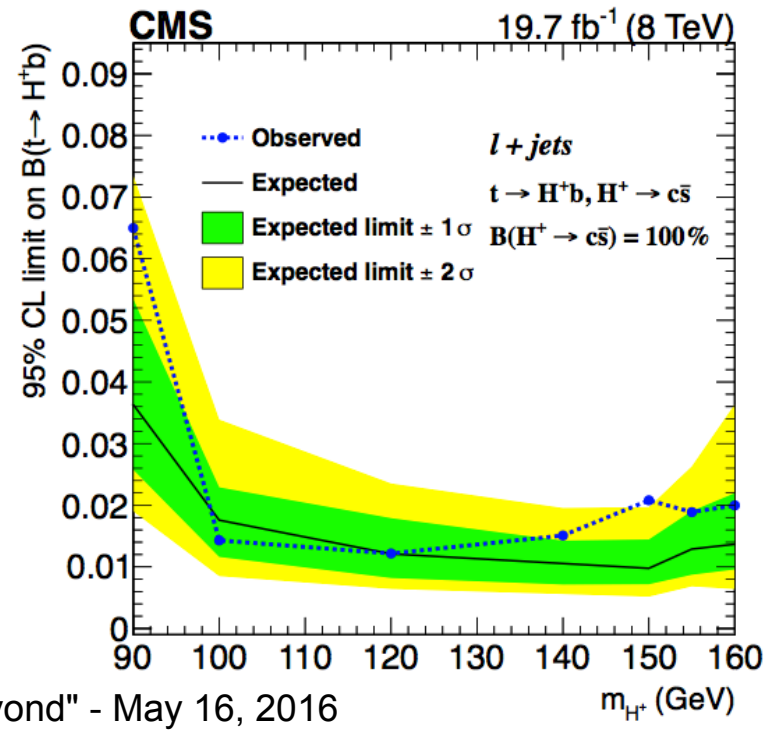
# Light charged Higgs: csbar

JHEP 12(2015)1, arXiv:1510.04252

- H→csbar decay
  - dominant in low tanβ region
- Lepton+jet final states
- Dominant bkg from ttbar
- Kinematic fit to reconstruct W/H mass
- Set model-independent limits on BR(t→H⁺b)~2-7%

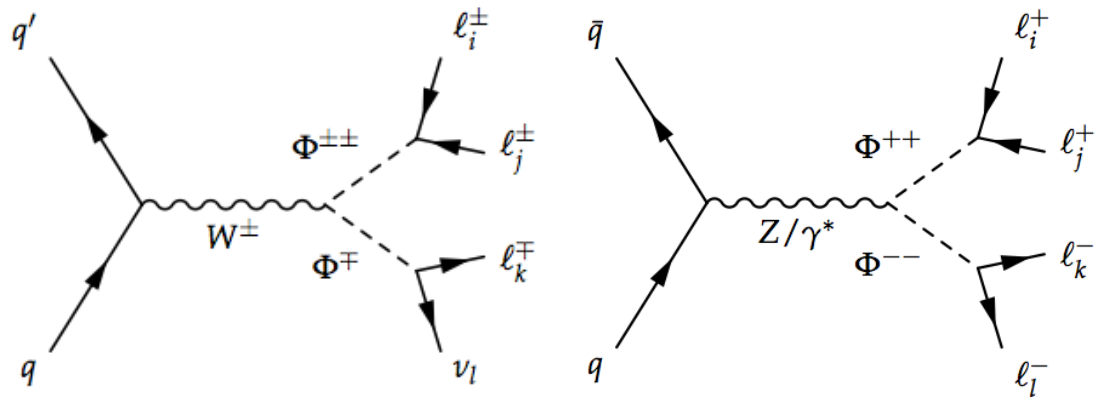


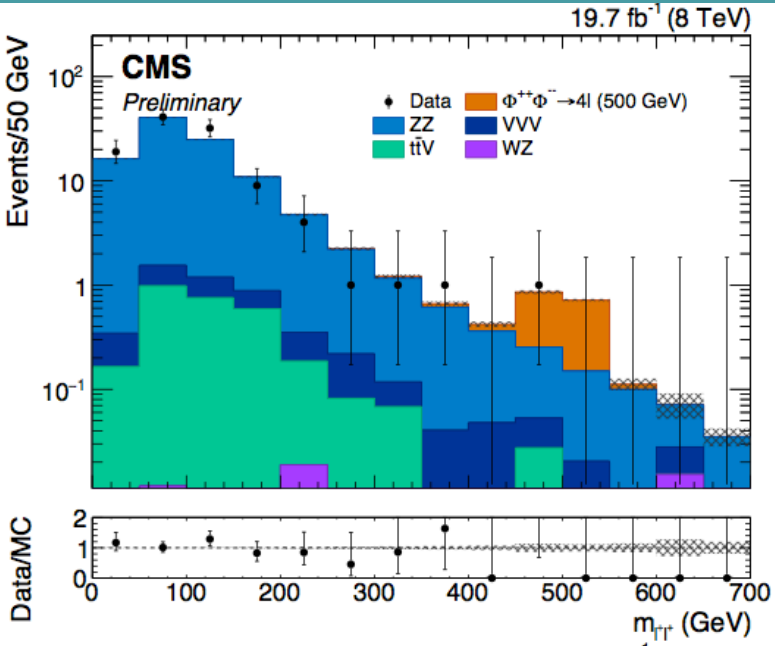



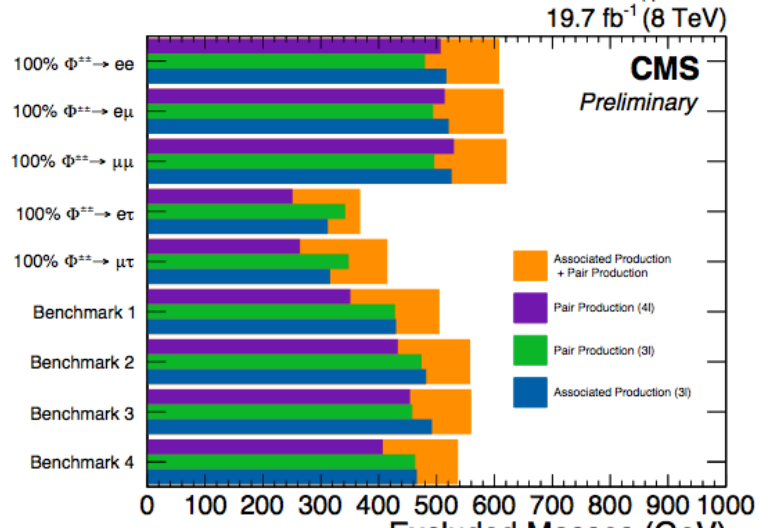
# Doubly charged Higgs

EPJC 72 (2012) 2189, CMS-HIG-14-039




- Model
  - SM extended with scalar triplet ($\Phi^{++}$, $\Phi^{+}$, $\Phi^{o}$)
  - Triplet responsible for neutrino masses
  - Search for doubly- and singly-charged
  - DY pair production is most common
  - SS lepton pair of any flavor combination
- Search with ≥3 leptons of any flavor
  - Search for excess of events in one or more flavor combinations of SS lepton pairs
- Dilepton invariant mass as discriminant

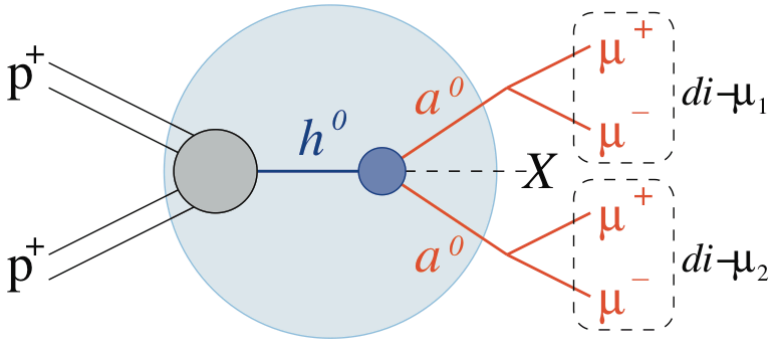


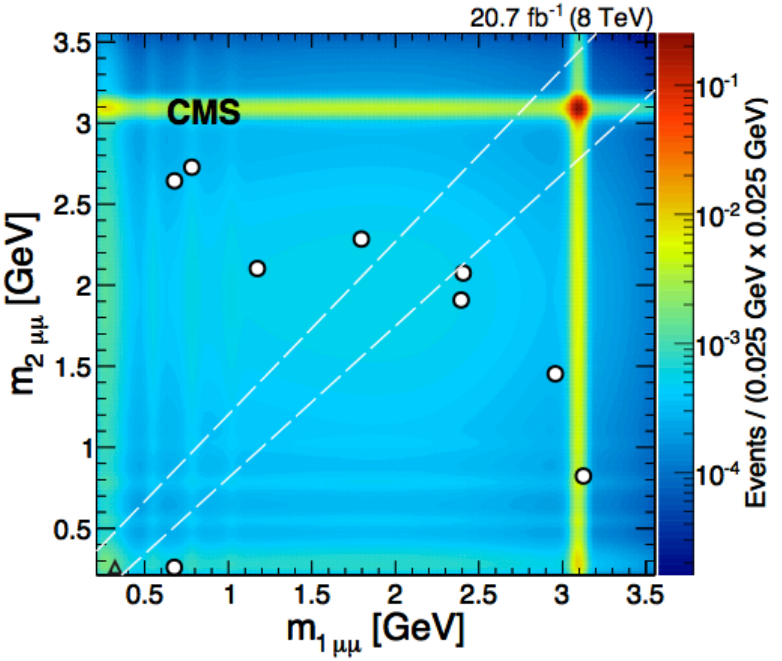



# non-SM Higgs decay: h→2a→4μ

PLB 726(2013)564, arXiv:1506.00424

- Explore non-SM decays of a Higgs boson (h)
  - Higgs boson (h) can be SM or not
  - include production of two new light boson ($a^0$)
- Search for generic Higgs decays: h→2a+X→4μ+X
- Selection: minimize sensitivity to model details
  - Find low mass muon pairs ("dimuons")
  - Require each event to have two dimuons
  - Require two dimuon masses to be consistent
- Results
  - Observe 9 events in off-diagonal region, consistent with bkg expectations
  - Signal region: 1 event (2.2±0.7 bkg)
  - Limits on production rates, benchmark models



# NMSSM and Dark SUSY Limits

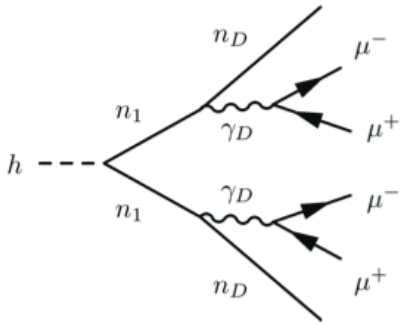
PLB 726(2013)564, arXiv:1506.00424

Results interpreted in NMSSM and dark SUSY

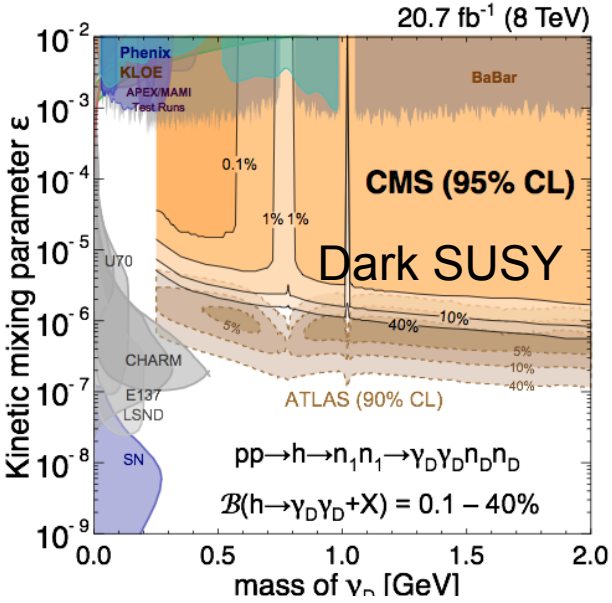
- Dark SUSY: h decay to pair of neutralinos ($n_1$): LSP

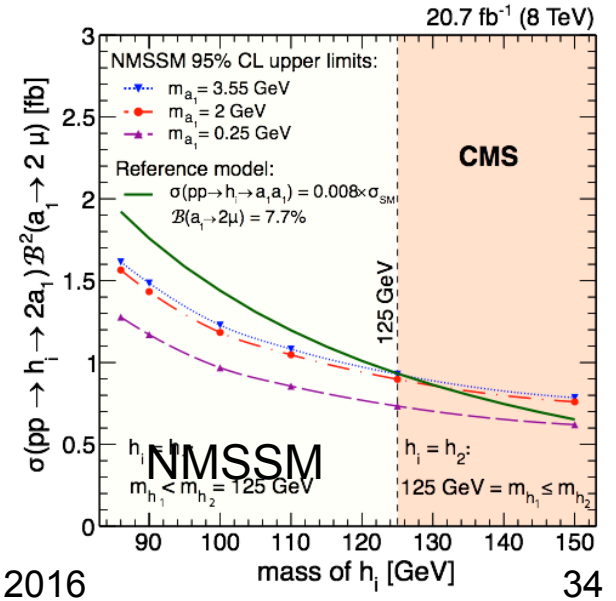
$n_1 \rightarrow n_D \gamma_D$ decays

- $\mu\mu$
- invisible




- NMSSM: Extend MSSM by adding a complex singlet field (1 CP-even+1 CP-odd boson)
- NMSSM: $h_{1,2} \rightarrow 2a_1$; $a_1 \rightarrow 2\mu$
- Compare to SM Higgs cross section

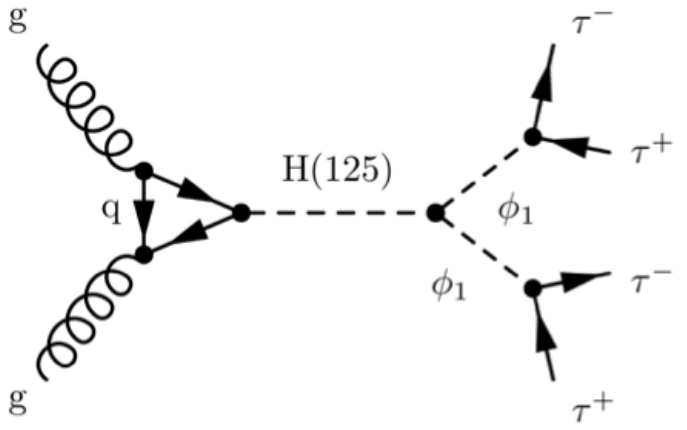


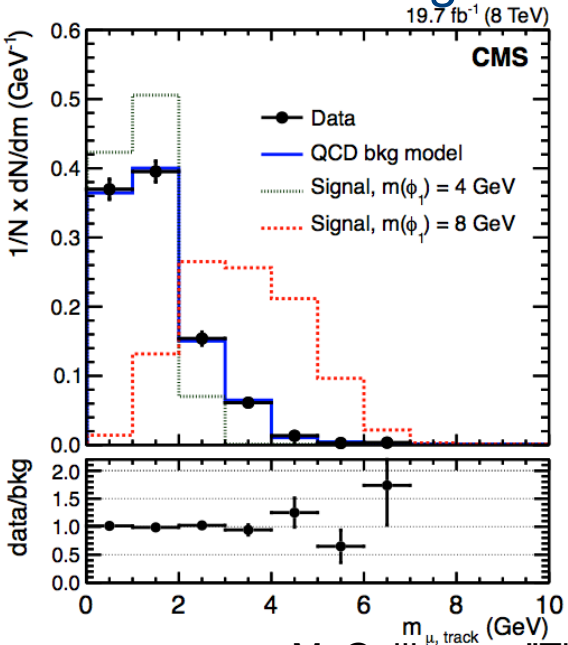



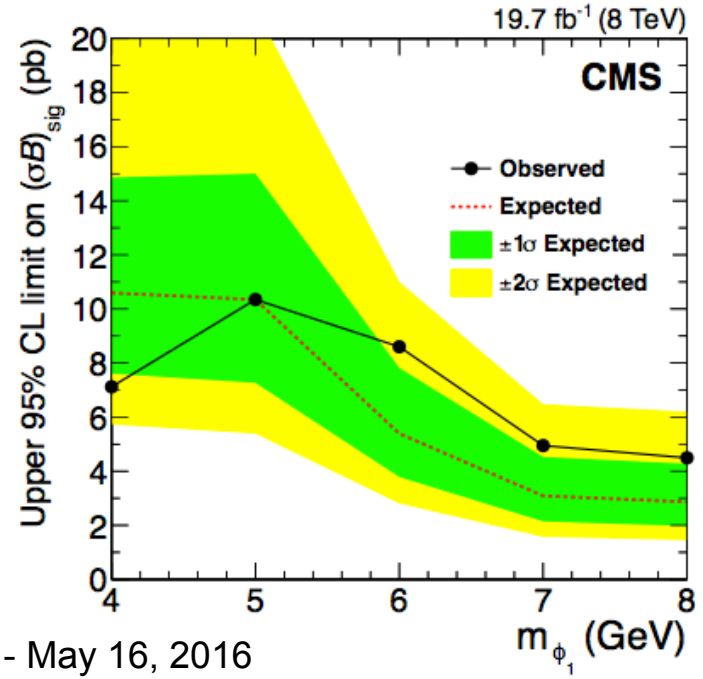
# non-SM Higgs decay: $H_{125} \rightarrow 2h(a) \rightarrow 4\tau$

arXiv:1510.06534

- Search for very light Higgs in NMSSM
  - $h_{1,2}$ (CP-even), $a_{1,2}$ (CP-odd) to a pair of $\tau$ leptons
  - $H(125) \rightarrow h_1 h_2 (a_1 a_2) \rightarrow 4\tau$
- Reconstruct $\mu$-track invar. mass ($m_1$,$m_2$)
  - SS dimuon sample (removes DY)
  - bin in 2-dim distribution, fit signal and bkg
  - QCD bkg from control region
- No excess over SM backgrounds



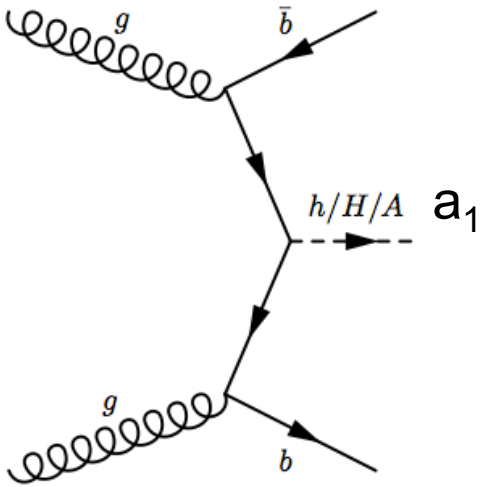



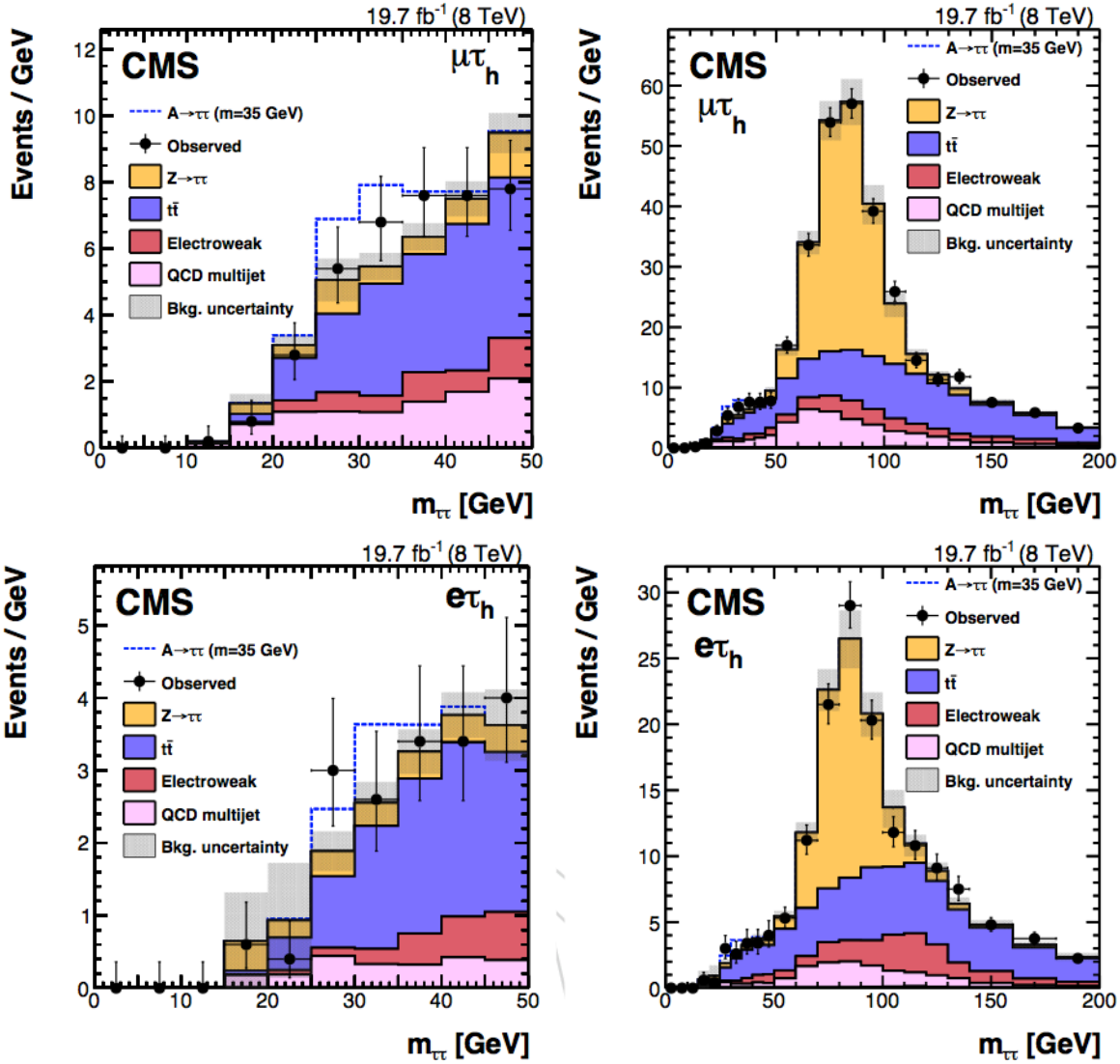



# Low mass Higgs: a(→ττ)bb

arXiv:1511.03610

- Low mass Higgs in the NMSSM
- Low mass pseudo-scalar ($a_1 \to \tau\tau$) in association with bbar: $a_1 bb \to \tau\tau\, bb$
- Similar strategy to $H \to \tau\tau$
- Search for $a_1$ masses below Z mass
- No evidence for signal
- Set limits: $\sigma \times B$~9-39 pb



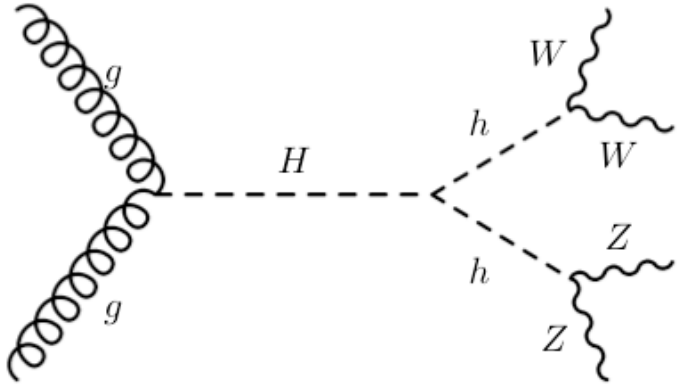



# Heavy Higgs: $H \to h_{125}h_{125}$, $A \to Zh_{125}$

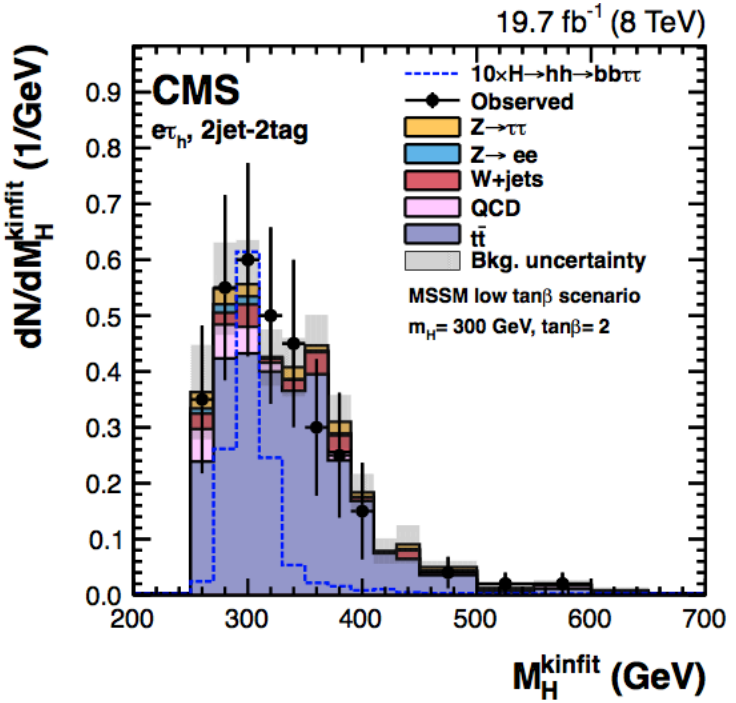
arXiv:1410.2751, arXiv:1510.01181

- MSSM: Heavy Higgs searches
  - Search for $A \to Zh_{125}$ and $H \to hh$
- Exclusive search in multilepton and diphoton +lepton channels
  - Also bbττ (hh), or llττ (Zh)
  - exclusive channels (leptons, taus, photons, $N_{btags}$, etc)

⇒No excess in data, set limits




| Process | SM | QS | 2HDM-III | FC-2HDM | MSSM |
|---|---|---|---|---|---|
| $t \to u\gamma$ | $3.7 \cdot 10^{-16}$ | $7.5 \cdot 10^{-9}$ | — | — | $2 \cdot 10^{-6}$ |
| $t \to uZ$ | $8 \cdot 10^{-17}$ | $1.1 \cdot 10^{-4}$ | — | — | $2 \cdot 10^{-6}$ |
| $t \to uH$ | $2 \cdot 10^{-17}$ | $4.1 \cdot 10^{-5}$ | $5.5 \cdot 10^{-6}$ | — | $10^{-5}$ |
| $t \to c\gamma$ | $4.6 \cdot 10^{-14}$ | $7.5 \cdot 10^{-9}$ | $\sim 10^{-6}$ | $\sim 10^{-9}$ | $2 \cdot 10^{-6}$ |
| $t \to cZ$ | $1 \cdot 10^{-14}$ | $1.1 \cdot 10^{-4}$ | $\sim 10^{-7}$ | $\sim 10^{-10}$ | $2 \cdot 10^{-6}$ |
| $t \to cH$ | $3 \cdot 10^{-15}$ | $4.1 \cdot 10^{-5}$ | $1.5 \cdot 10^{-3}$ | $\sim 10^{-5}$ | $10^{-5}$ |



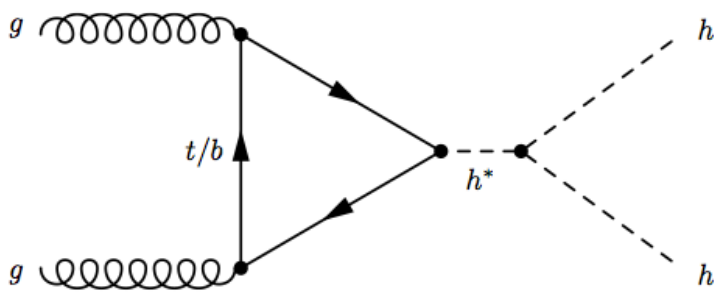

FCNC decays

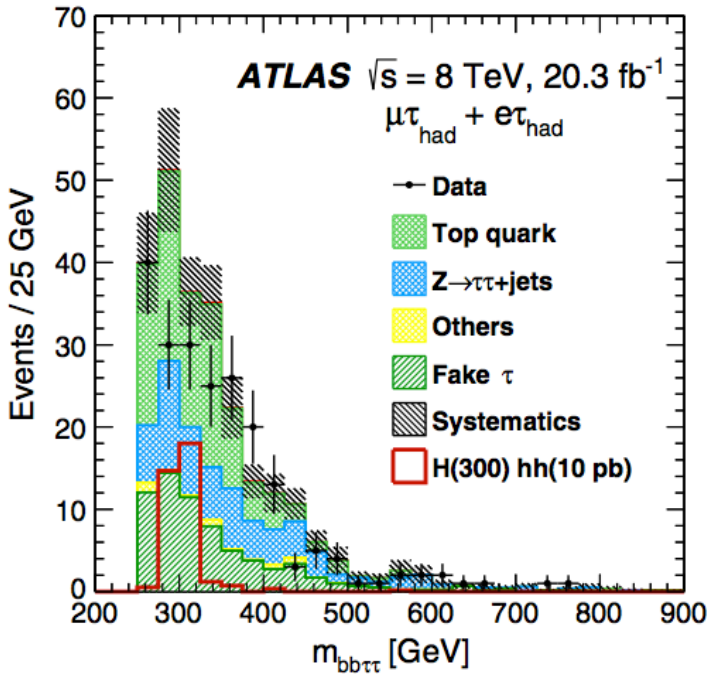
- Also search for tt→(bW)(ch)
  - Not forbidden but highly suppressed
  - enhanced w/some parameter models
- BR(t→cH)<0.56% (0.65%) @95%CL

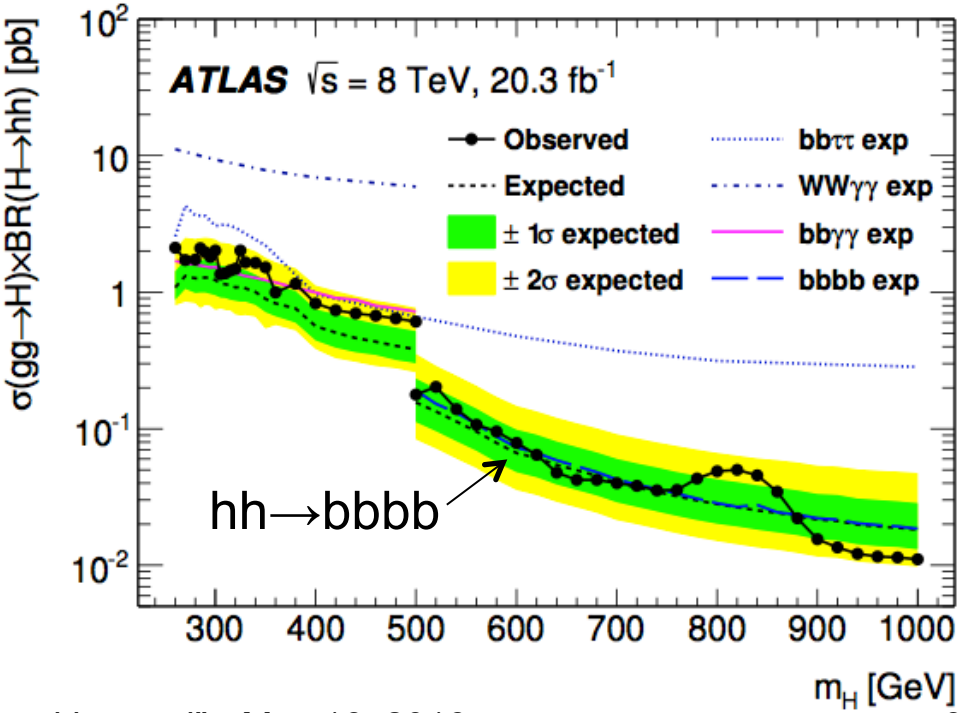
# Heavy Higgs to $h_{125}h_{125}$

arXiv:1509.04670, PRD 92(2015)092004

- Searches for resonant and non-resonant Higgs pair production
- Neutral heavy Higgs: $H \to h_{125}h_{125}$
- $H \to h_{125}h_{125} \to bb\tau\tau$, $\gamma\gamma WW$, 4b, $\gamma\gamma bb$
- No significant excess is observed over SM bkg

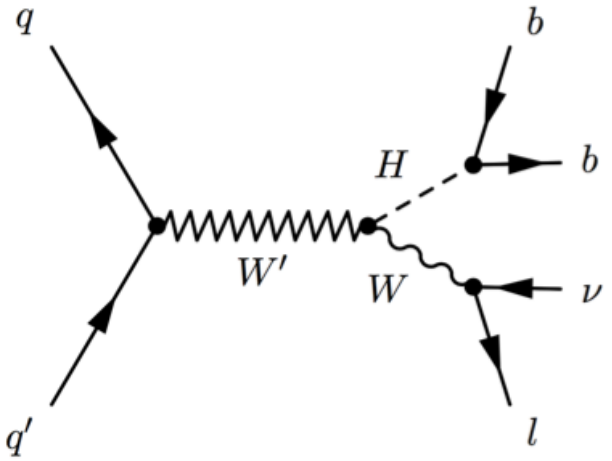


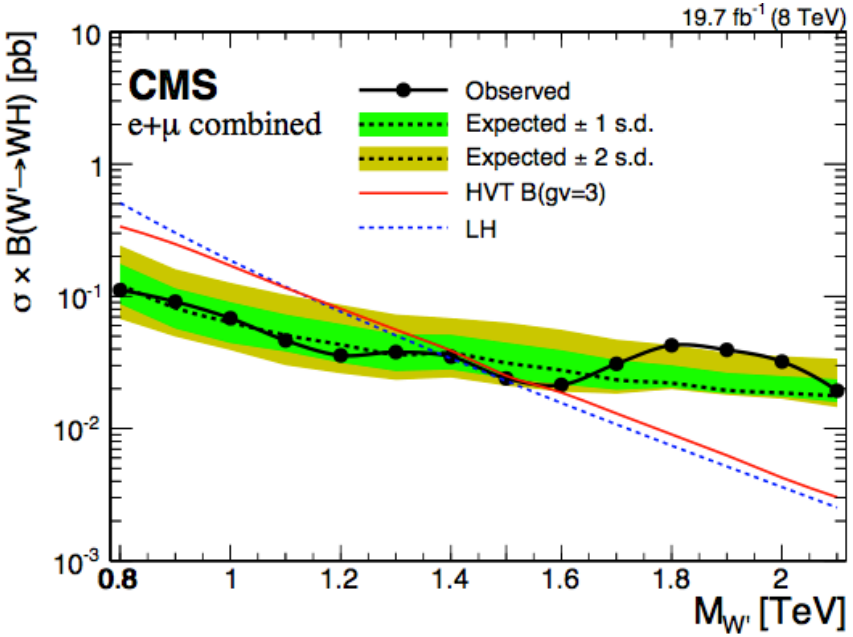



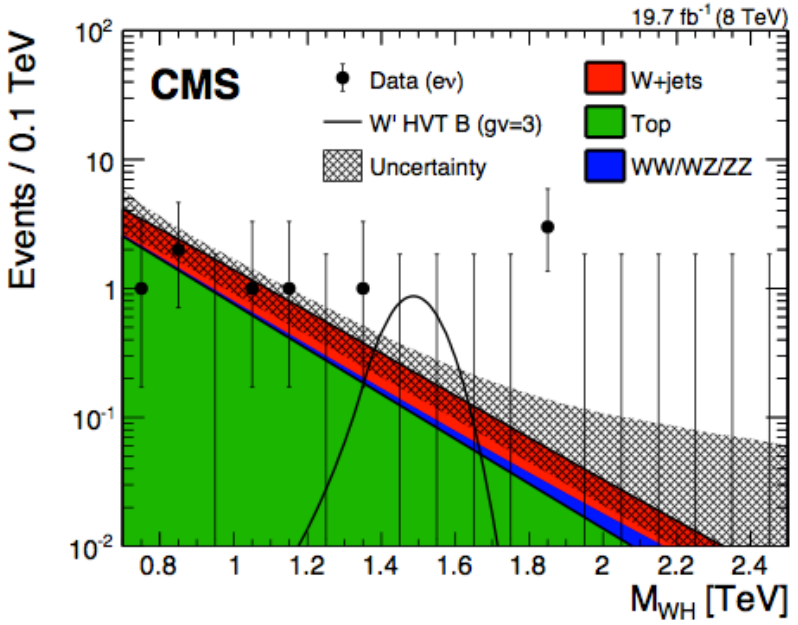



# Heavy resonance: WH final state

- Search for massive resonance W'→WH
- Distinctive features of BSM models, i.e. composite/little Higgs, technicolor, etc.
- Lepton+jet final state
- Use jet substructure/btag for H→bb
- 2.2$\sigma$ highest local significance at 1.8TeV

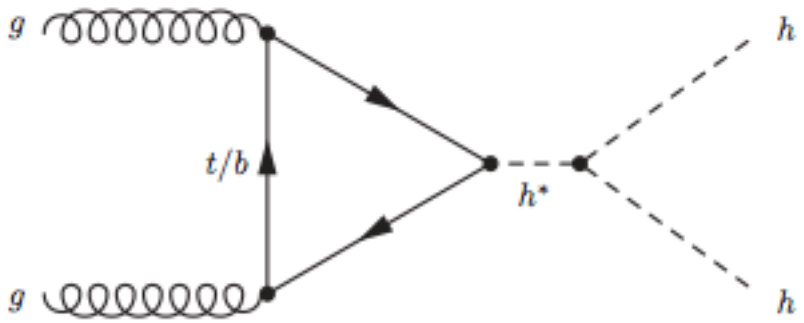


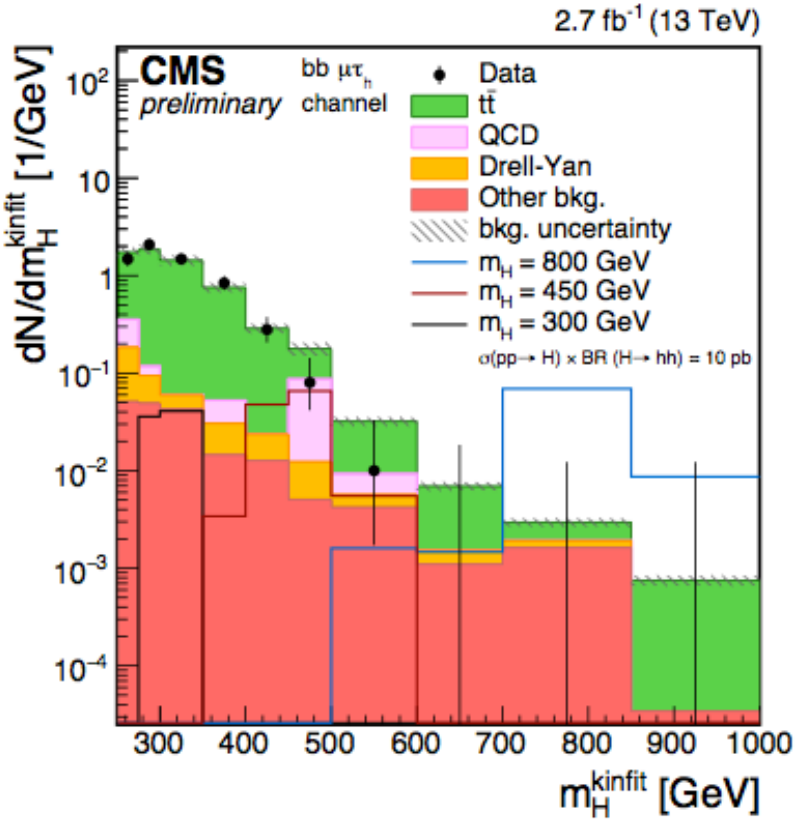



# Heavy Higgs to $h_{125}h_{125} \rightarrow \tau\tau bb$

CMS-EXO-15-008, CMS-HIG-16-012, CMS-HIG-16-013



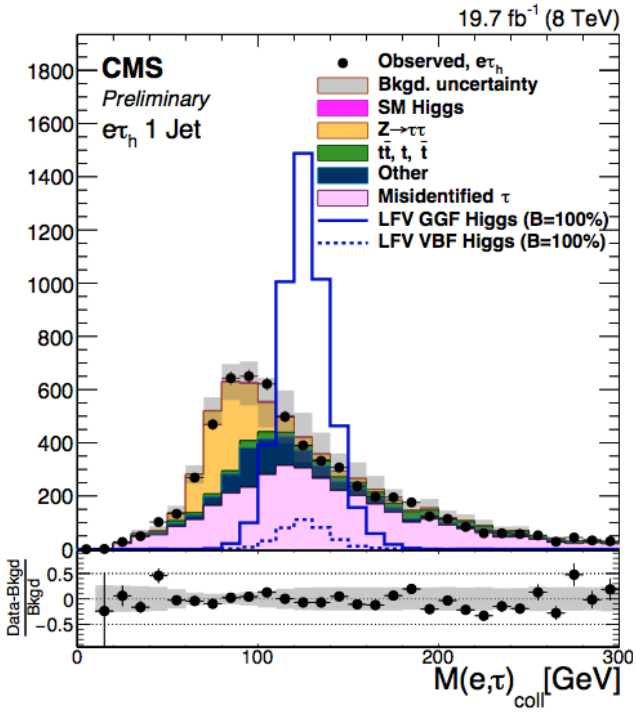

- Resonant and non-resonant production
- High-mass resonant production
  - $H \rightarrow h_{125}h_{125} \rightarrow bb\tau\tau$
- $h_{125}$ decay products nearly collinear
- boosted "single" merged jet ($\rightarrow bb$)
- use $\tau_e\tau_h$, $\tau_\mu\tau_h$, and $\tau_h\tau_h$ final states
- sidebands/inverted isolation to determine bkg
- set limits on spin-0 resonance at 850-30fb for $M_X$=0.8-2.5 TeV

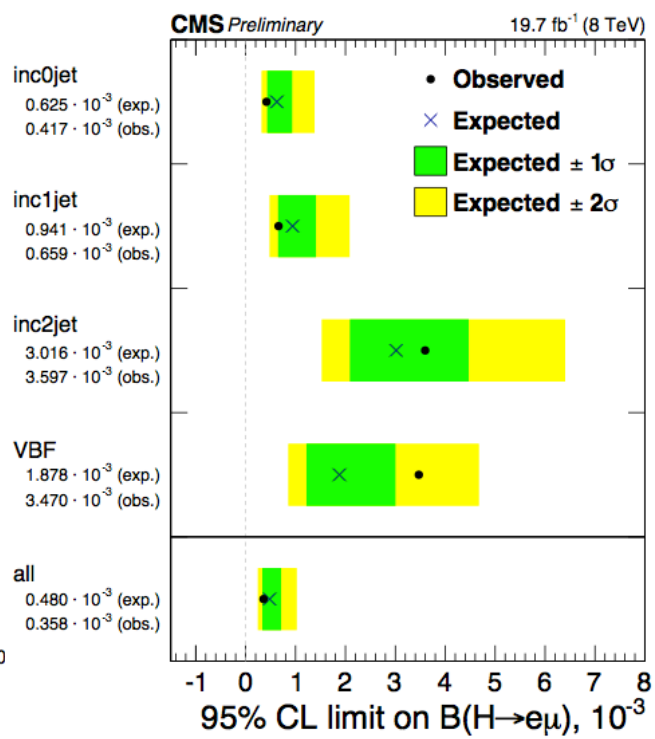


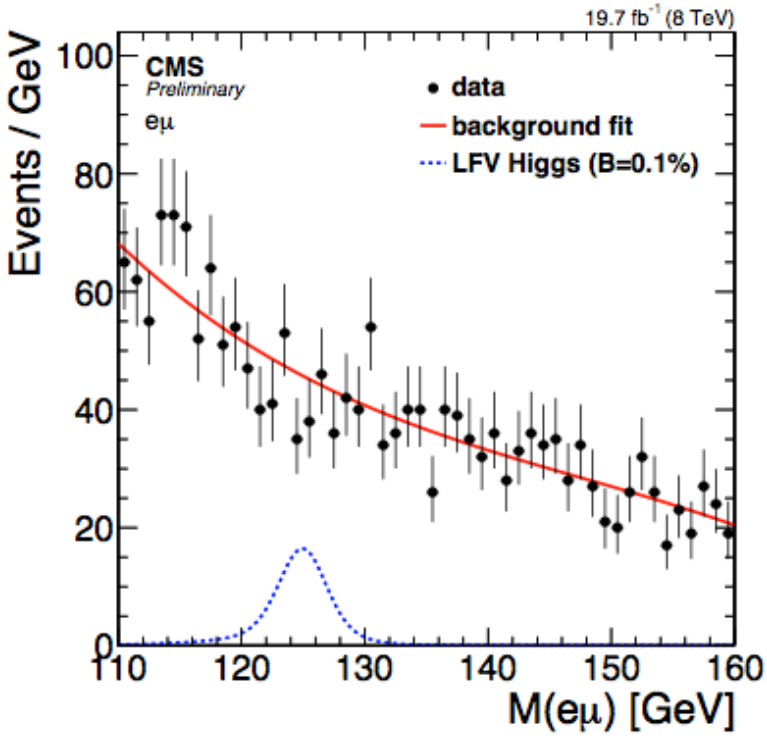
# LFV Higgs decays

CMS-HIG-14-040

- Study eτ, eμ final states
- Categories: $N_{jet}$, lepton kinematics
- VBF with jets
- Main background from DY, ttbar, WW
- Upper limits on B(H→eτ)<0.7% and B(H→eμ)<0.036% @95%CL



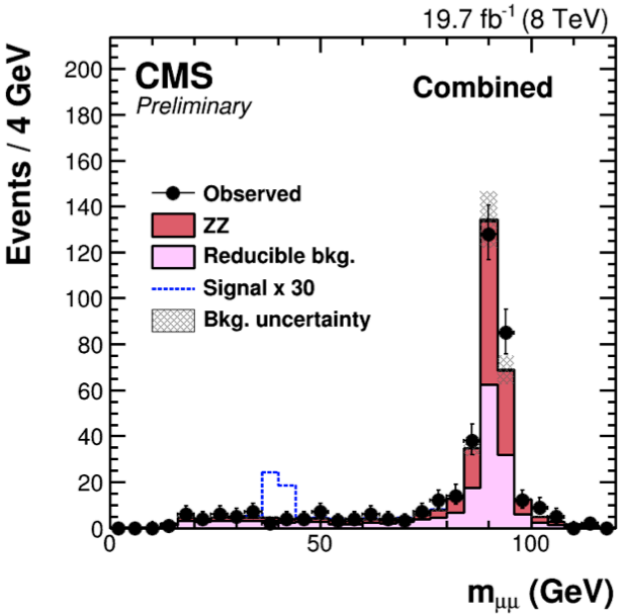



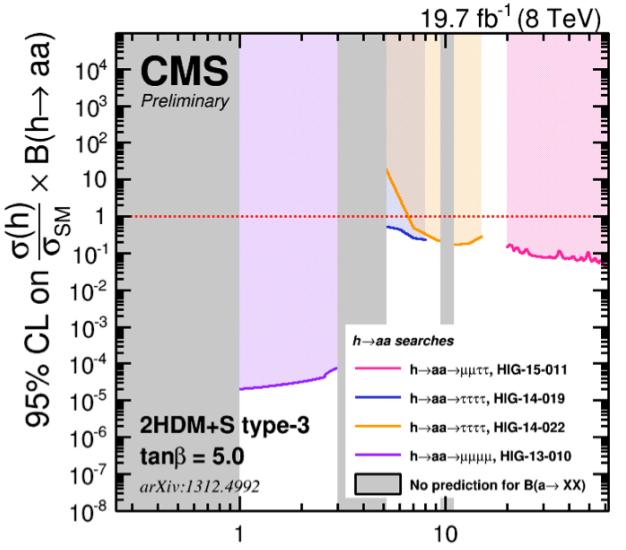



# Exotic Higgs decays: h→aa→μμττ

CMS-HIG-15-011

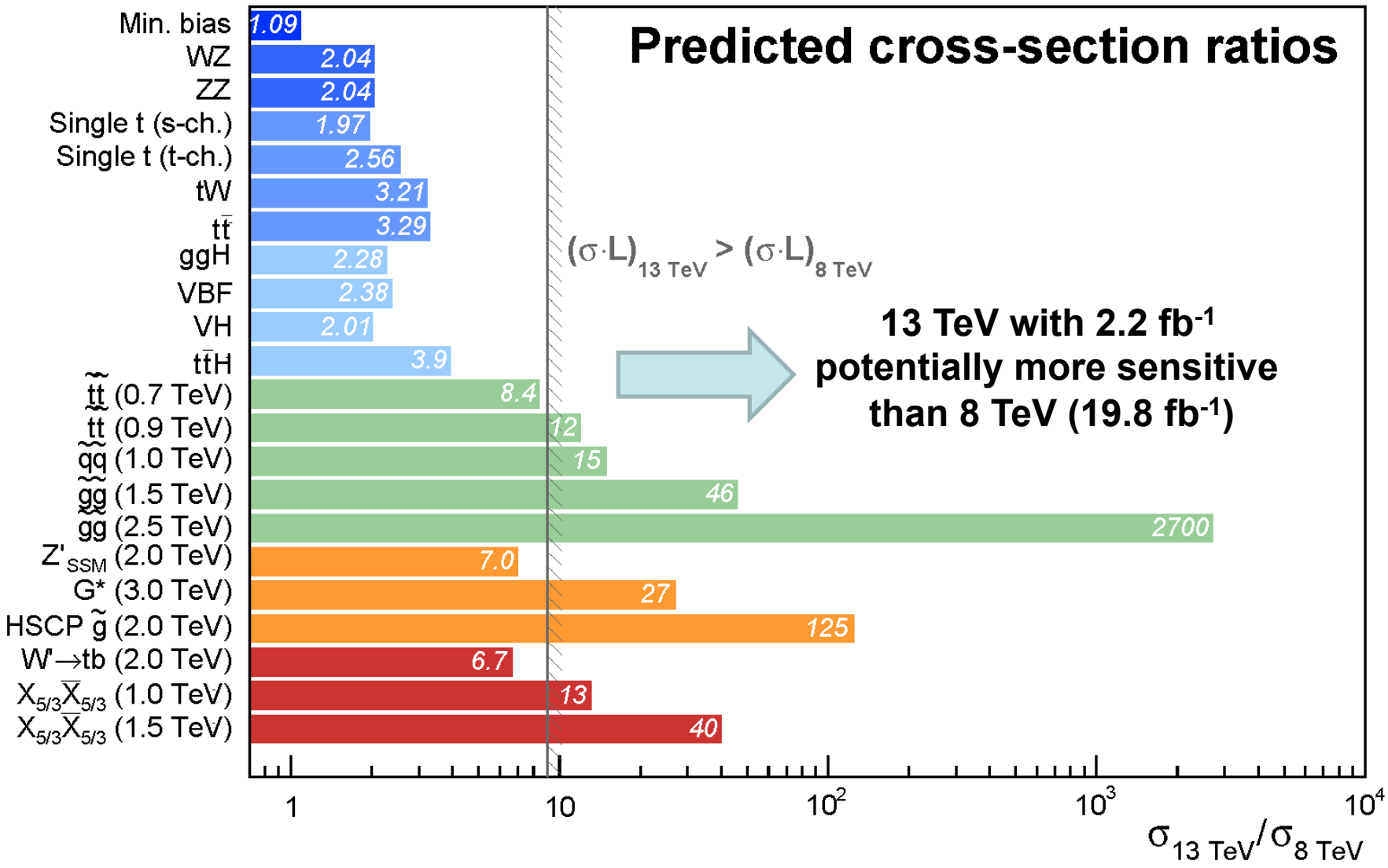
- $h_{125}$: small width compared to its mass
- Exotic decays with large BR possible
- Study h→aa→μμττ final state
  - enhancement decays to down/up-type fermions for low/high tanβ
  - larger BR to taus than to muons
- excellent μμ mass resolution
- Unbinned shape of $m_{\mu\mu}$ distr.
- (non-) irreducible background: ZZ→4l, Z/W+jets, etc.




| | Signal | | Backgrounds | | | Obs. |
|---|---|---|---|---|---|---|
| | $m_a$ = 20 GeV | $m_a$ = 60 GeV | ZZ | Reducible | Total | |
| $\mu\mu\tau_e\tau_e$ | 0.20±0.02 | 0.58±0.06 | 4.64±0.39 | 2.49±1.03 | 7.13±1.10 | 8 |
| $\mu\mu\tau_e\tau_\mu$ | 0.58±0.08 | 1.42±0.16 | 0.10±0.01 | 1.70±0.74 | 1.80±0.74 | 2 |
| $\mu\mu\tau_e\tau_h$ | 0.74±0.08 | 2.02±0.20 | 0.16±0.02 | 5.65±1.77 | 5.81±1.77 | 5 |
| $\mu\mu\tau_\mu\tau_h$ | 0.96±0.10 | 2.30±0.22 | 0.13±0.02 | 0.99±0.31 | 1.12±0.31 | 1 |
| $\mu\mu\tau_h\tau_h$ | 0.60±0.06 | 1.90±0.18 | 0.06±0.01 | 4.64±0.98 | 4.70±0.98 | 3 |
| Combined | 3.08±0.31 | 8.22±0.82 | 5.09±0.39 | 15.47±2.41 | 20.56±2.44 | 19 |

# Increased reach at 13 TeV



# Summary

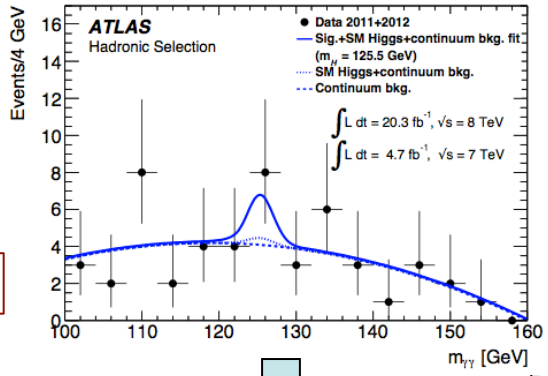
- Excellent consistency of SM but SM is incomplete
- Extensions foresee existence of additional bosons
- Searches for BSM bosons natural companion to precision SM Higgs boson measurements
  - Charged Higgs searches with top quark decays
  - Other BSM searches show no indication of deviations
- Searches provide no hints for BSM yet

# backup

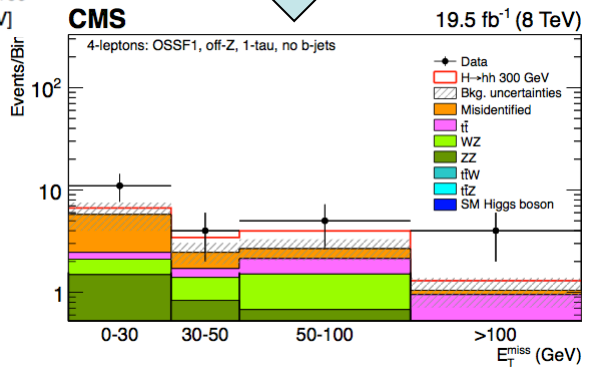
# FCNC decays: t→cH

arXiv:1410.2751, arXiv:1403.6293

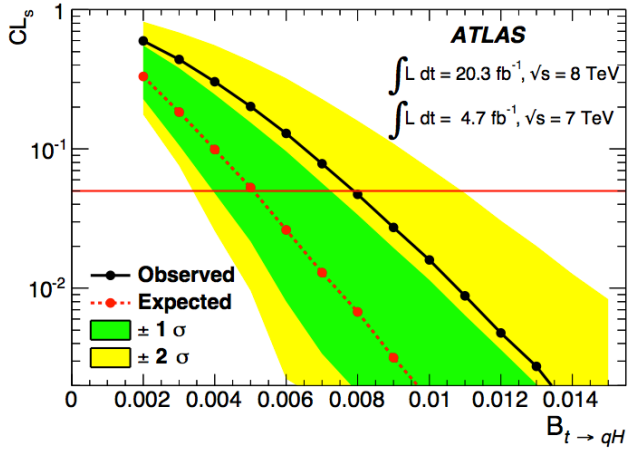
| Process | SM | QS | 2HDM-III | FC-2HDM | MSSM |
|---|---|---|---|---|---|
| $t \to u\gamma$ | $3.7 \cdot 10^{-16}$ | $7.5 \cdot 10^{-9}$ | — | — | $2 \cdot 10^{-6}$ |
| $t \to uZ$ | $8 \cdot 10^{-17}$ | $1.1 \cdot 10^{-4}$ | — | — | $2 \cdot 10^{-6}$ |
| $t \to uH$ | $2 \cdot 10^{-17}$ | $4.1 \cdot 10^{-5}$ | $5.5 \cdot 10^{-6}$ | — | $10^{-5}$ |
| $t \to c\gamma$ | $4.6 \cdot 10^{-14}$ | $7.5 \cdot 10^{-9}$ | $\sim 10^{-6}$ | $\sim 10^{-9}$ | $2 \cdot 10^{-6}$ |
| $t \to cZ$ | $1 \cdot 10^{-14}$ | $1.1 \cdot 10^{-4}$ | $\sim 10^{-7}$ | $\sim 10^{-10}$ | $2 \cdot 10^{-6}$ |
| $t \to cH$ | $3 \cdot 10^{-15}$ | $4.1 \cdot 10^{-5}$ | $1.5 \cdot 10^{-3}$ | $\sim 10^{-5}$ | $10^{-5}$ |




- $H \to WW^* \to \ell\nu\ell\nu$,
- $H \to \tau\tau$,
- $H \to ZZ^* \to jj\ell\ell, \nu\nu\ell\ell, \ell\ell\ell\ell$,
- $H \to \gamma\gamma$.




- Not forbidden but highly suppressed
  - enhanced w/some parameter models
- Tree-level in BSM
- SM Higgs now a background
  - ATLAS: H→γγ
  - CMS: H→γγ and multileptons
- b-tag provides bkg suppression



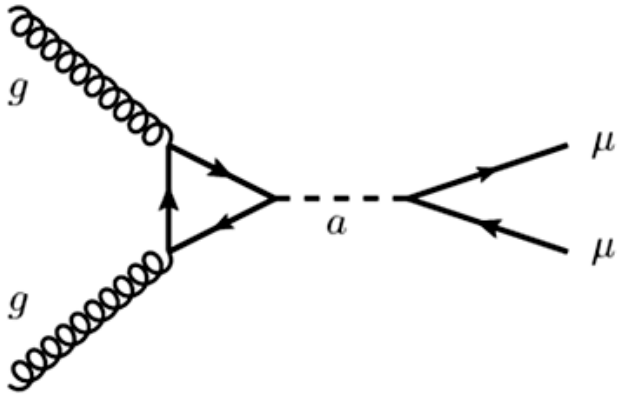

| Higgs boson decay mode | Upper limits on $\mathcal{B}(t \to ch)$ | | |
|---|---|---|---|
| | Obs. | Exp. | 68% CL range |
| $\mathcal{B}(h \to WW^*)$ = 23.1% | 1.58% | 1.57% | (1.02–2.22)% |
| $\mathcal{B}(h \to \tau\tau)$ = 6.15% | 7.01% | 4.99% | (3.53–7.74)% |
| $\mathcal{B}(h \to ZZ^*)$ = 2.89% | 5.31% | 4.11% | (2.85–6.45)% |
| Combined multileptons (WW*, ττ, ZZ*) | 1.28% | 1.17% | (0.85–1.73)% |
| $\mathcal{B}(h \to \gamma\gamma)$ = 0.23% | 0.69% | 0.81% | (0.60–1.17)% |
| Combined multileptons + diphotons | 0.56% | 0.65% | (0.46–0.94)% |

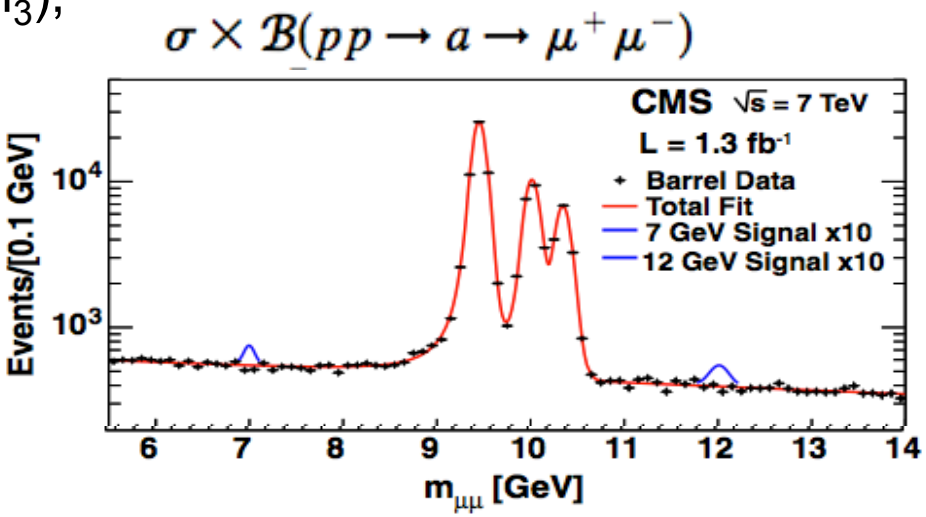
| | ATLAS obs(exp) | CMS |
|---|---|---|
| BR(t→cH) (95%CL) | <0.79% (0.51%) | <0.56% (0.65%) |

# Light pseudo-scalar: $a \rightarrow \mu^+\mu^-$

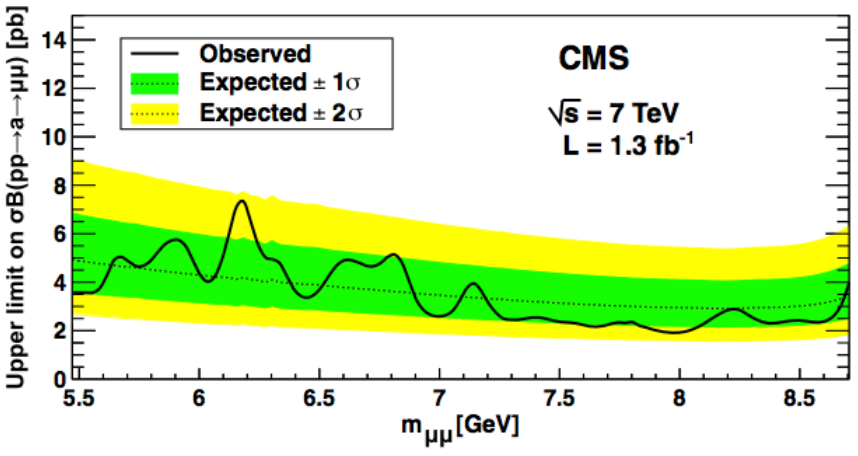
PRL 109,121801(2012)

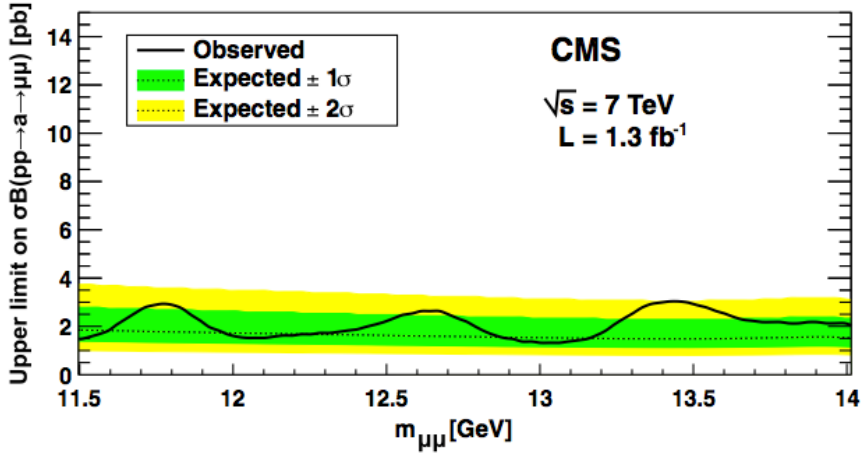
- Low-energy SUSY
  - solution to hierarchy problem
  - provides DM candidate
  - provides unification of gauge couplings
- Predicted in NMSSM
  - Expands MSSM: 3 CP-even scalars ($h_1$, $h_2$, $h_3$), 2 CP-odd ($a_1$, $a_2$), 2 charged ($H^{\pm}$)
  - Add scalar singlet to MSSM family
- Large cross section: $gg \rightarrow a \rightarrow \mu^+\mu^-$
- Search for general light pseudo-scalar Higgs (a) near Y resonance



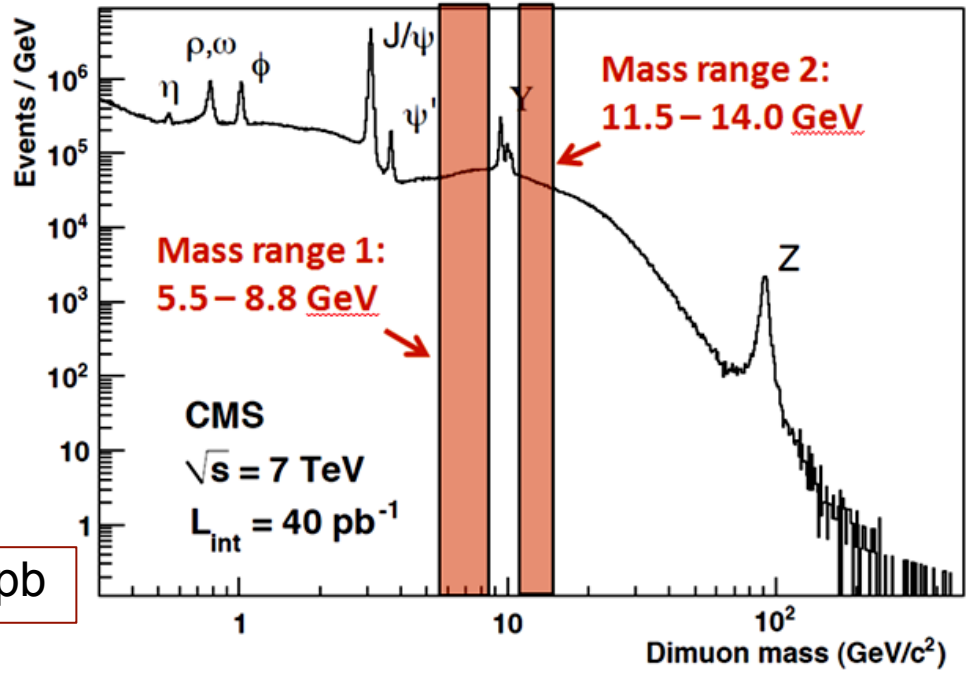



# Constraints on $a \to \mu^+\mu^-$ production




- Search below and above the Y family
- Set limits:
  - No excess found above background expectations

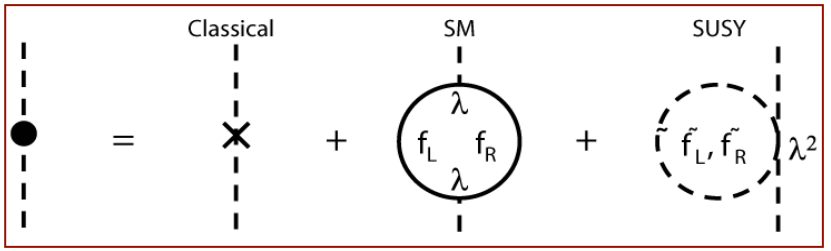



$\sigma \times \mathcal{B}(pp \to a \to \mu^+\mu^-)$ ~1.5-7.5 pb

# Higgs and the SM

- SM is a successful theory
- Nothing prevents the SM to survive up to the Planck scale. However, it is unnatural.
- Virtual particles in quantum loops contribute to the Higgs mechanism
  - Contributions grow with $\Lambda$ (upper scale validity of the SM)
  - Higgs mass depends quadratically on $\Lambda$: $m^2 = m_0^2 + g^2\Lambda^2$
- Miraculous cancellations are needed to keep $m_H$<1TeV
- Is there a symmetry that protects the Higgs mass from receiving large corrections?

cancelation?



# Higgs and the SM (cont.)

- SUSY postulates a new symmetry between fermions and bosons
  - Loops of particles and their SUSY partners have the ability to cancel the quadratic divergences in the Higgs field self-couplings, solving the naturalness problem
  - SUSY foresees unification of couplings at large energy scales ~$10^{15}$ GeV
  - Provides DM candidates (LSP)
- It suggests many options, but the LHC may not be able to find it
- # of experimental scenarios is large