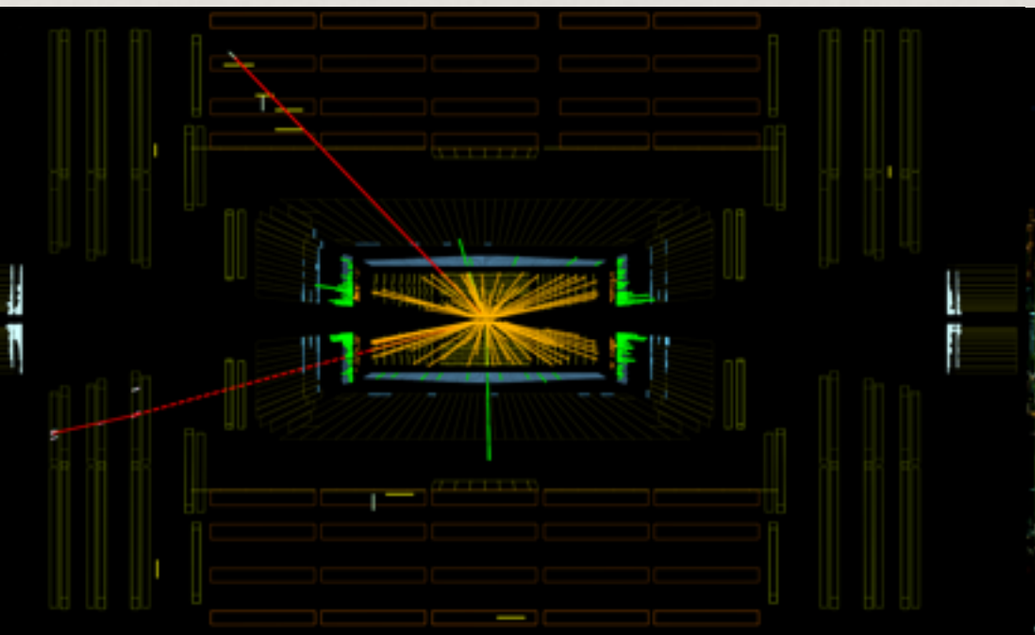
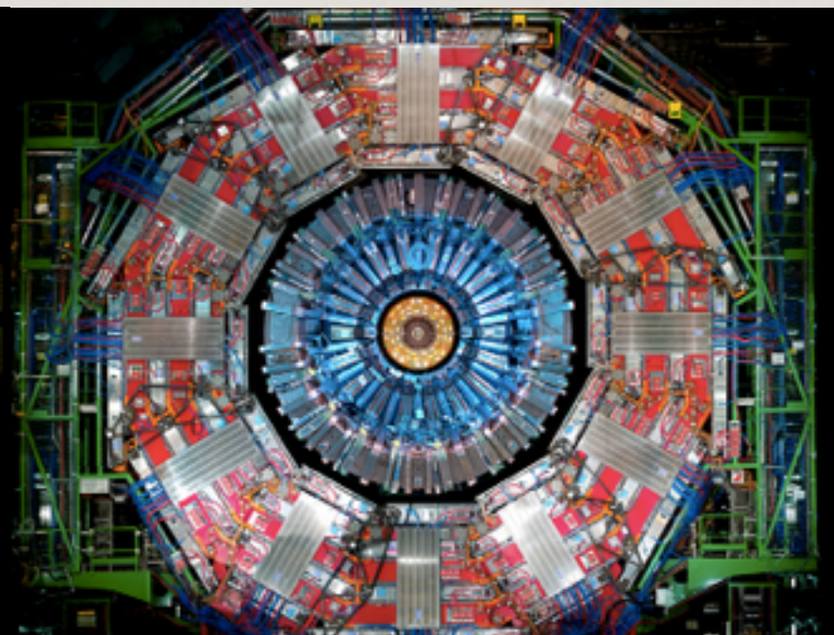
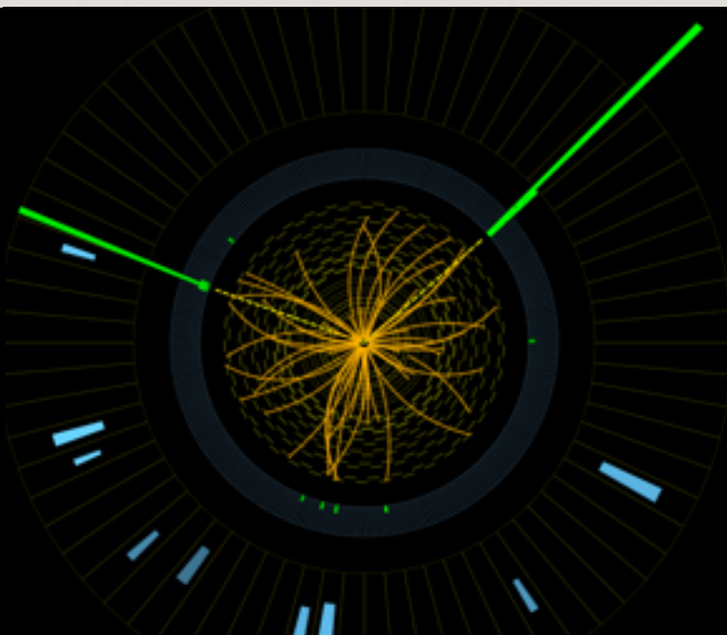
Standard Model Higgs Results from CMS

Markus Klute (MIT) on behalf
of the CMS Collaboration

LHCP 2014
Columbia University New York
June 2nd - 7th, 2014

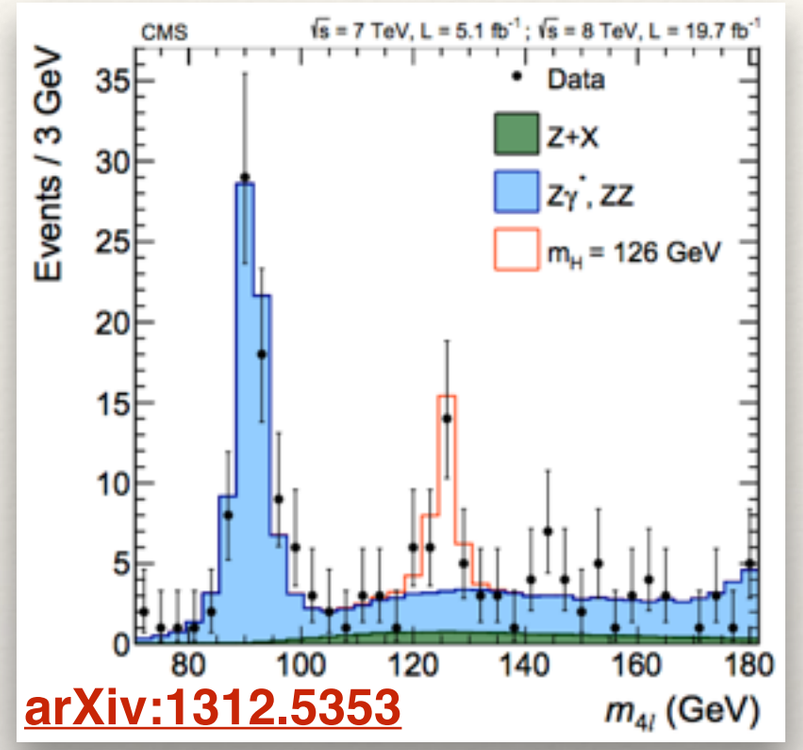




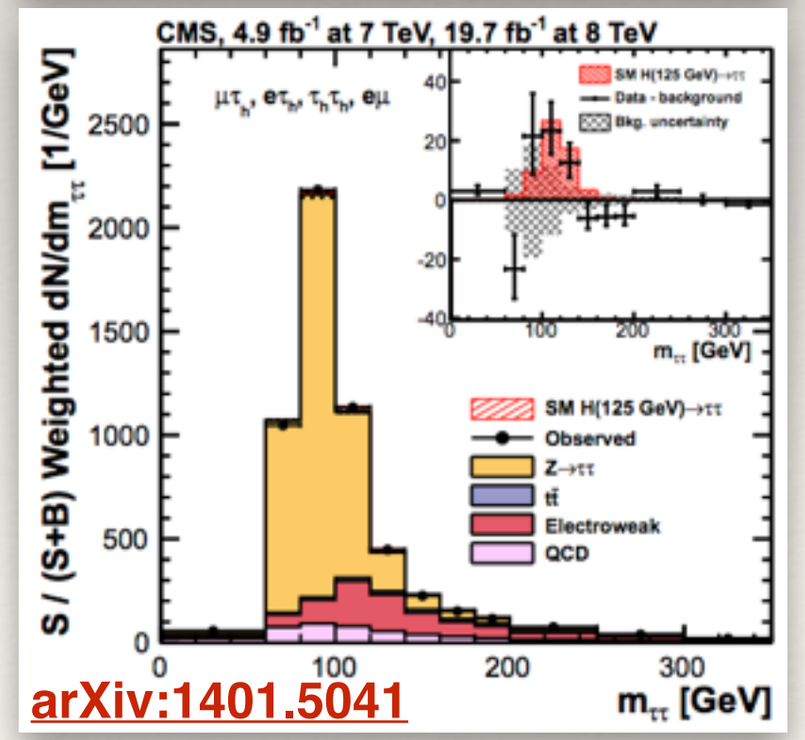


Introduction

- **Fantastic progress since the discovery July 2012**
  - Observation in three boson channels
  - Evidence for fermion couplings
  - Precision mass measurements ~125 GeV
  - Spin/parity determined
- **New particle looks more and more like the SM Higgs boson**
  - No evidence for non-SM decays
  - No evidence for additional Higgs bosons
- **CMS is finalizing Run I publications**



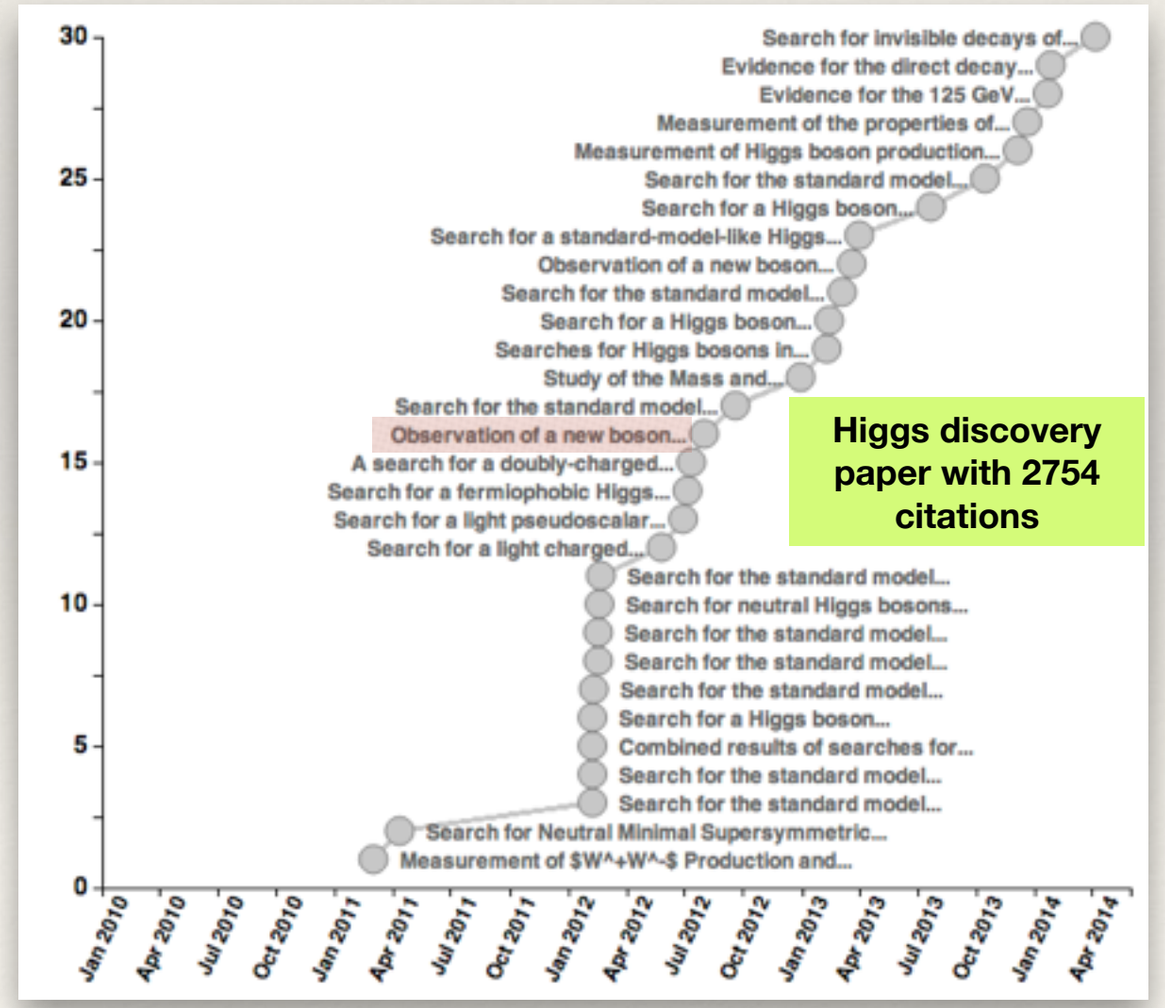
arXiv:1312.5353



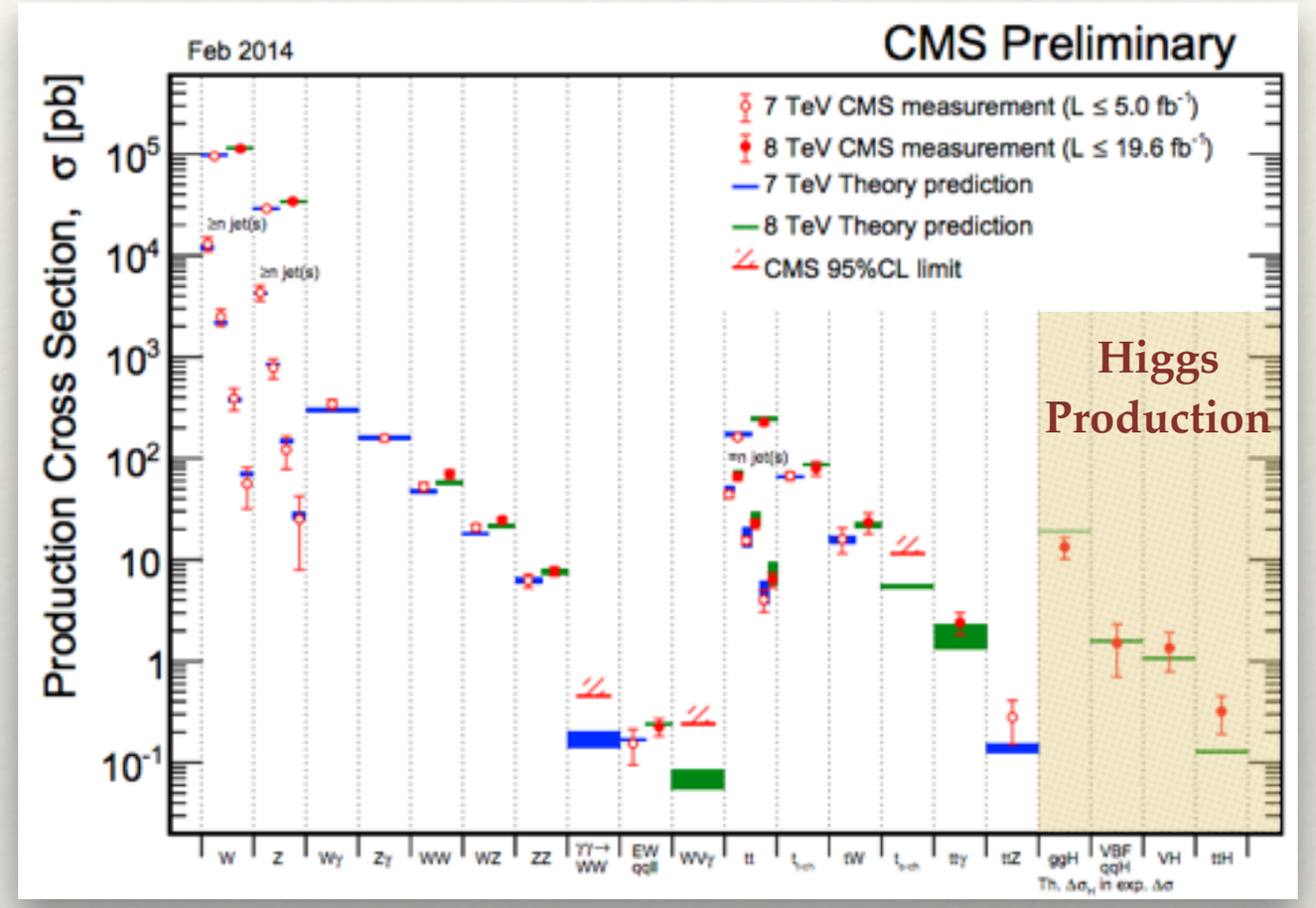
arXiv:1401.5041

Introduction

- **CMS exploiting Run I data on pp, pPb, and PbPb**
  - O(300) results published
  - Many more to come



Higgs discovery paper with 2754 citations



- This presentation shows **highlights of 31 publications** and numerous preliminary results

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIG

Introduction

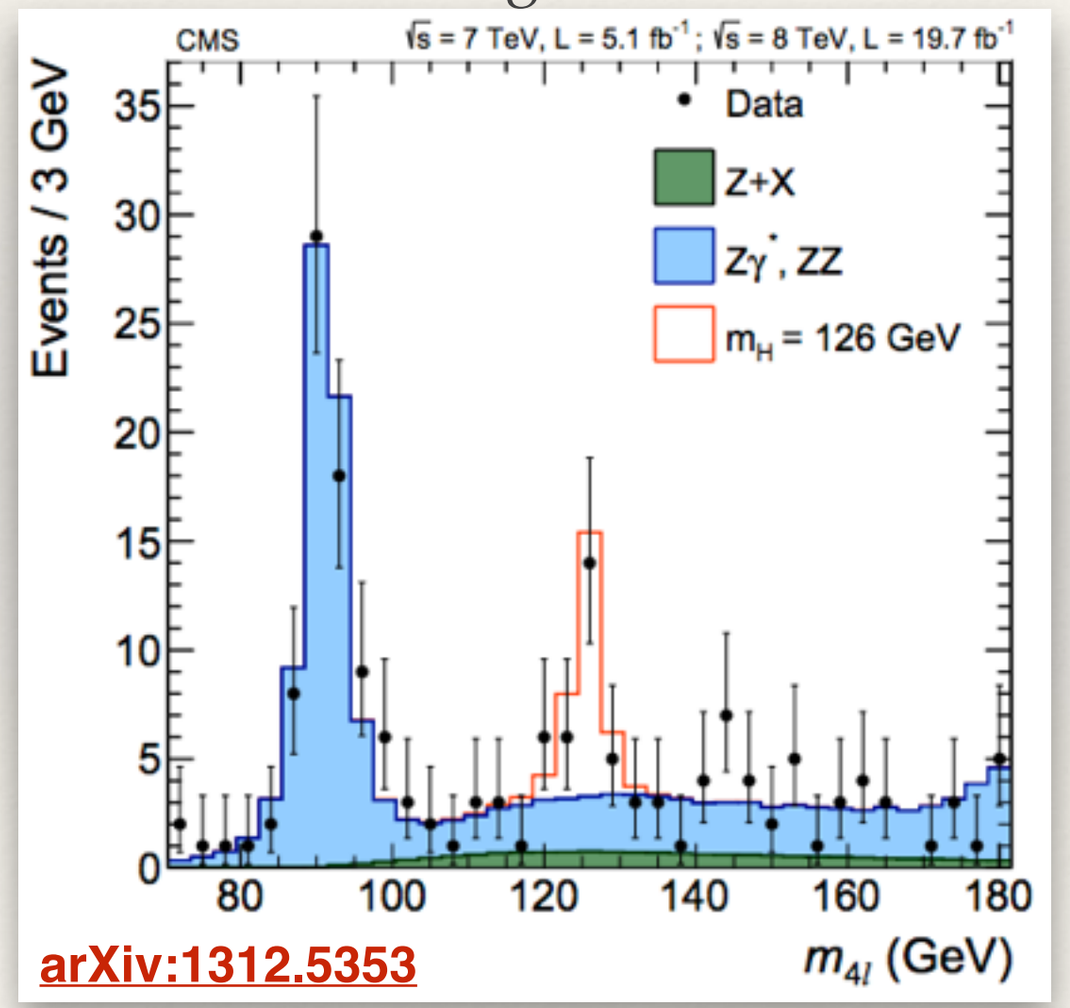
- **CMS Higgs Talks at LHCP**
  - **High highlight and prospect: Jim Virdee (Plenary, ATLAS & CMS)**
  - **BSM Higgs: Will Davey (Plenary, ATLAS & CMS)**
  - **Prospects: Susan Shotkin (Plenary, ATLAS & CMS)**
  - **Bosonic decays: Xavier Janssen (Higgs 1)**
  - **Fermionic decays: Jacobo Konigsberg (Higgs 1)**
  - **BSM Higgs: Mario Pelliccioni (Higgs 2)**
  - **Combination and properties: Predrag Milenovic (Higgs 3)**
  - **Prospects: Miguel Vidal Marono (Higgs 3)**

Overview of Key SM Higgs Measurements

Channel	CMS Lumi [1/fb]	Specialty	Inclusive signature	σ Obs. (Exp.)	mass [GeV]	Signal Strength μ	Spin/ Parity
H → ZZ → 4l	5.1+19.6 arXiv: 1312.5353	mass, discovery, spin/parity	4 leptons	6.8 (6.7)	125.6 ±0.4 (stat) ±0.2 (sys)	0.93+0.29-0.25	√
H → WW → 2l2v	4.9+19.5 arXiv: 1312.1129	cross section, coupling	2 leptons, MET	4.3 (5.8)	125 ± 4	0.72+0.20-0.18	√
H → γγ	5.1+19.6 CMS-PAS-HIG-13-001	mass, discovery, couplings	two photons	3.2 (4.2)	125.4 ±0.5 (stat) ±0.6 (sys)	0.78+0.28-0.26	√
H → bb	5.0+18.9 arXiv: 1310.3687	total width, coupling to fermions	two b-jets	2.1 (2.1)	consistent	1.0 ± 0.5	-
H → ττ	4.9+19.4 arXiv: 1401.5041	couplings to leptons	hadronic taus, leptons, MET	3.4 (3.6)	122 ± 7	0.78 ± 0.27	-

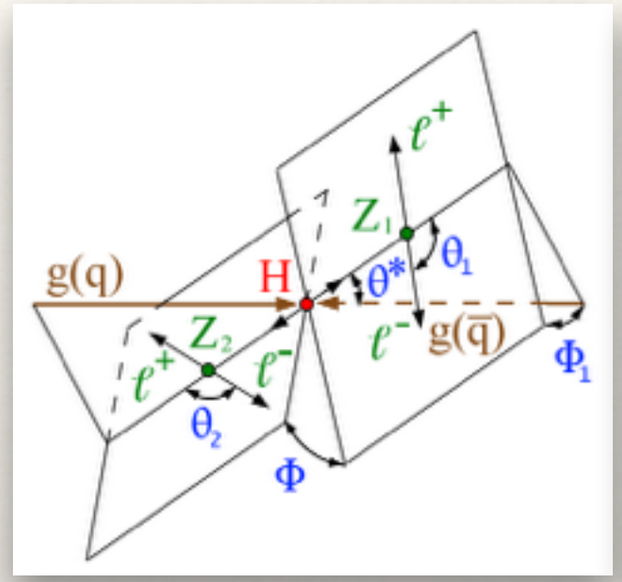
$H \rightarrow ZZ \rightarrow 4l$

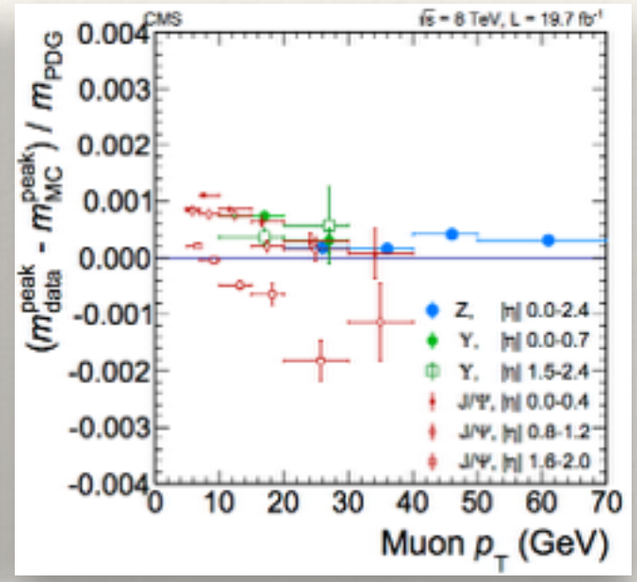
- Search for narrow resonance
- Clean channel to probe the Higgs boson
- Low number of signal events



arXiv:1312.5353

Observation in $H \rightarrow ZZ^* \rightarrow 4l$ (6.8σ)





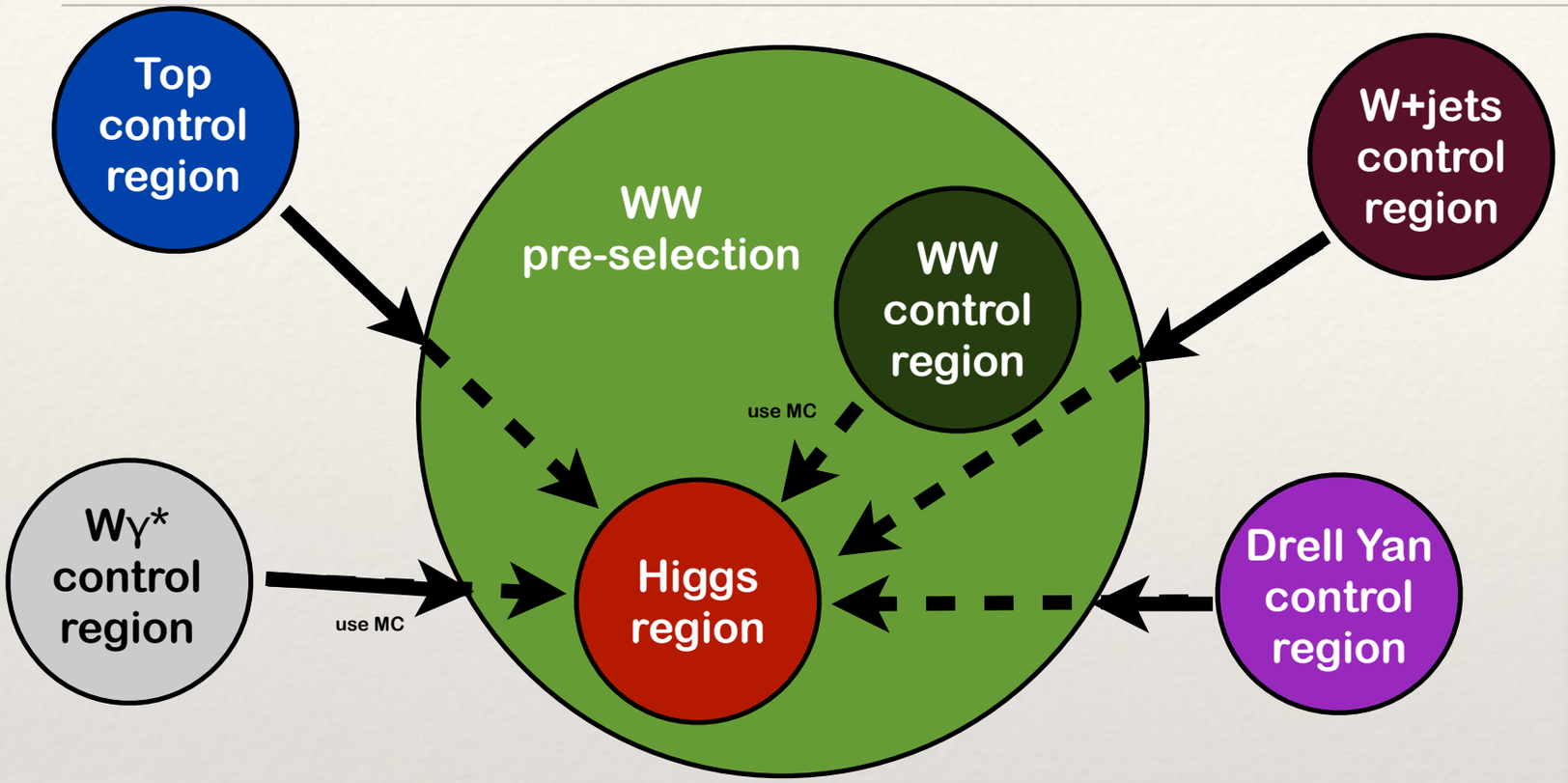
$m_{4\ell} > 100$ GeV

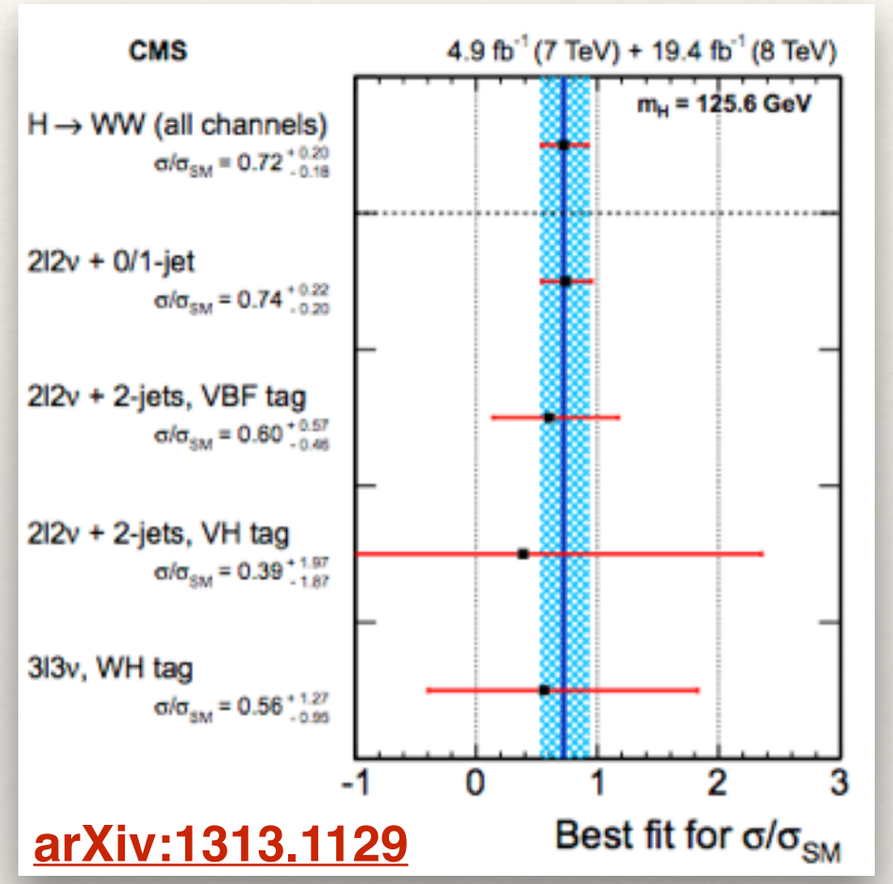
Channel	4e	2e2μ	4μ	4ℓ
ZZ background	77 ± 10	191 ± 25	119 ± 15	387 ± 31
Z + X background	7.4 ± 1.5	11.5 ± 2.9	3.6 ± 1.5	22.6 ± 3.6
All backgrounds	85 ± 11	202 ± 25	123 ± 15	410 ± 31
$m_H = 500$ GeV	5.2 ± 0.6	12.2 ± 1.4	7.1 ± 0.8	24.5 ± 1.7
$m_H = 800$ GeV	0.7 ± 0.1	1.6 ± 0.2	0.9 ± 0.1	3.1 ± 0.2
Observed	89	247	134	470

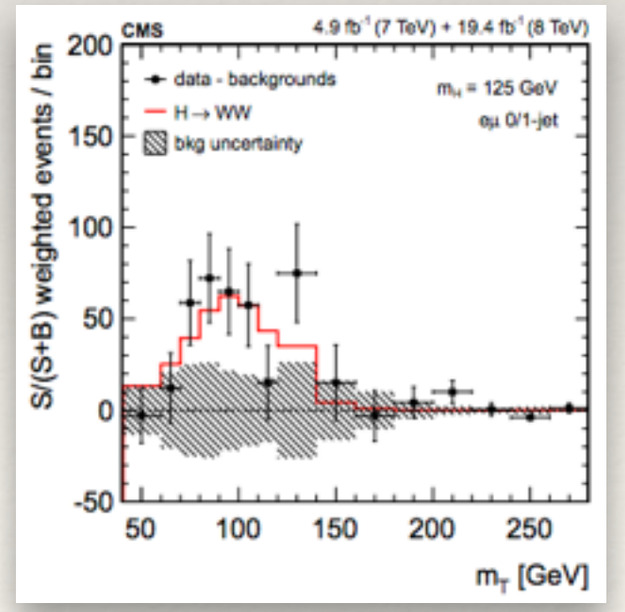
121.5 GeV $< m_{4\ell} <$ 130.5 GeV

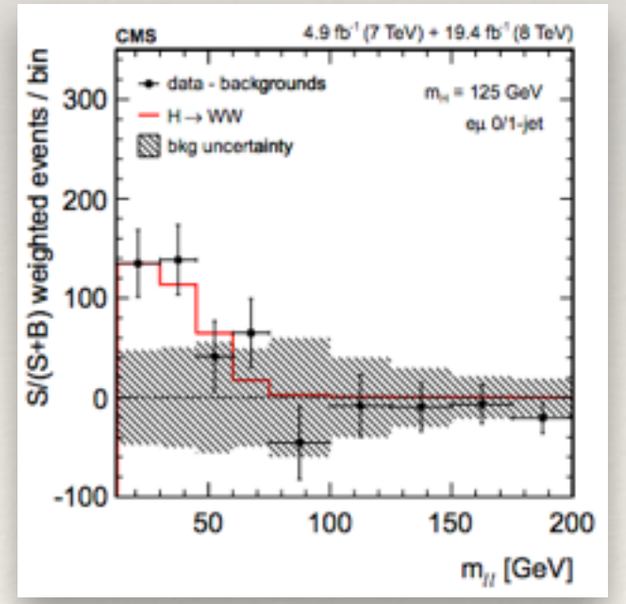
Channel	4e	2e2μ	4μ	4ℓ
ZZ background	1.1 ± 0.1	3.2 ± 0.2	2.5 ± 0.2	6.8 ± 0.3
Z + X background	0.8 ± 0.2	1.3 ± 0.3	0.4 ± 0.2	2.6 ± 0.4
All backgrounds	1.9 ± 0.2	4.6 ± 0.4	2.9 ± 0.2	9.4 ± 0.5
$m_H = 125$ GeV	3.0 ± 0.4	7.9 ± 1.0	6.4 ± 0.7	17.3 ± 1.3
$m_H = 126$ GeV	3.4 ± 0.5	9.0 ± 1.1	7.2 ± 0.8	19.6 ± 1.5
Observed	4	13	8	25

H → WW → 2l2ν





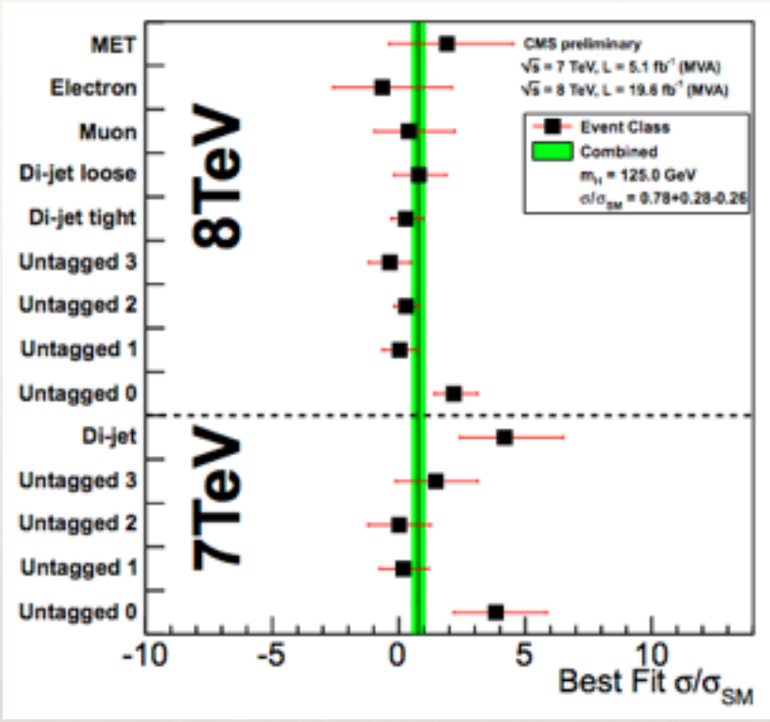


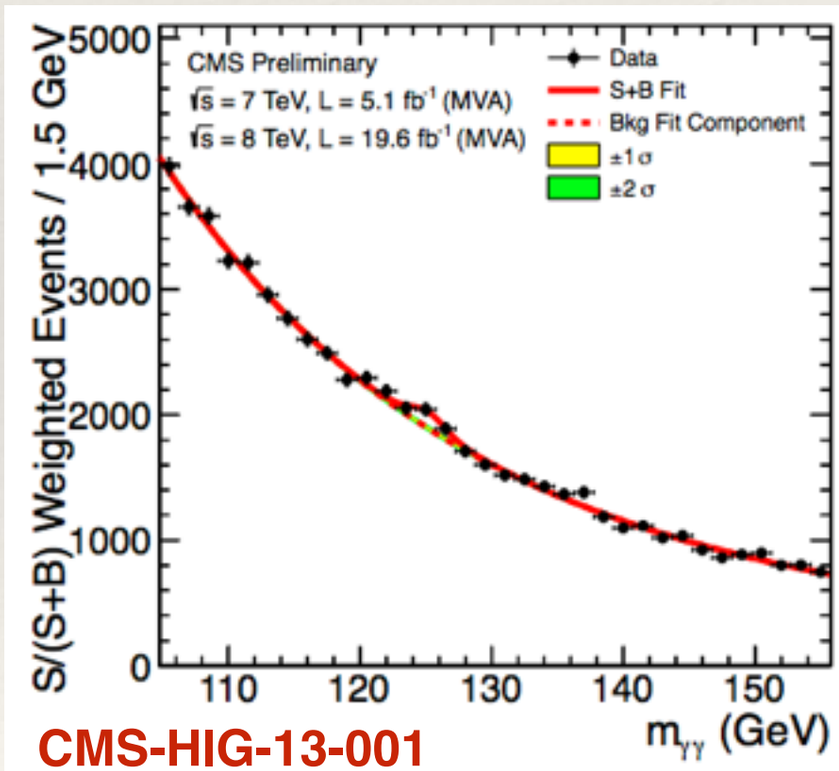


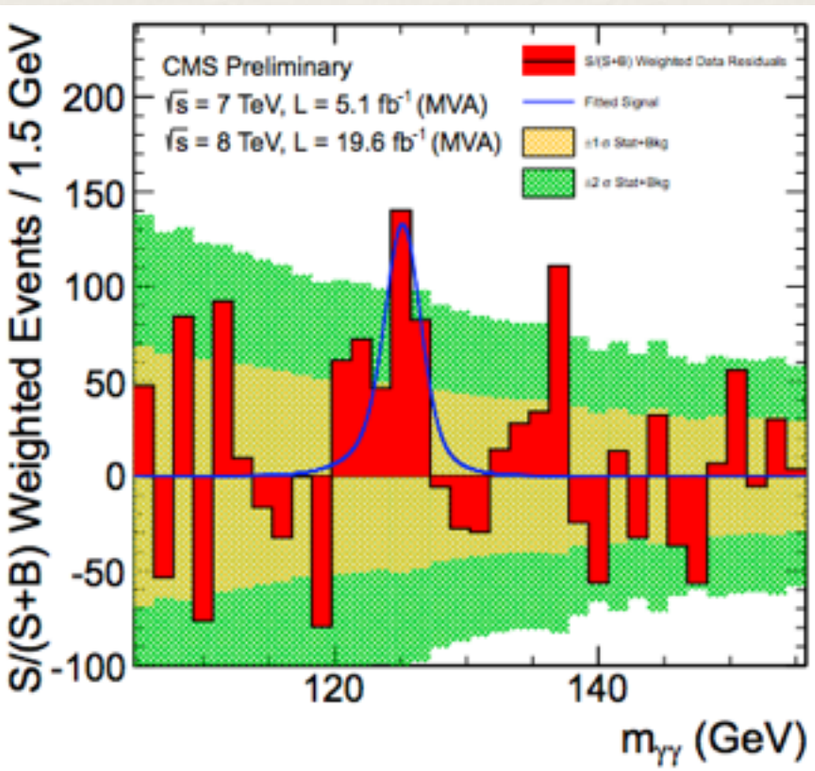
Evidence for H →WW → 2l2ν (4.3σ)

$H \rightarrow \gamma\gamma$

- Search for narrow resonance
- Categorize di-photon events by S/B and mass resolution
- Signal extraction from fit to di-photon mass distributions
- **Publication with final results available soon**







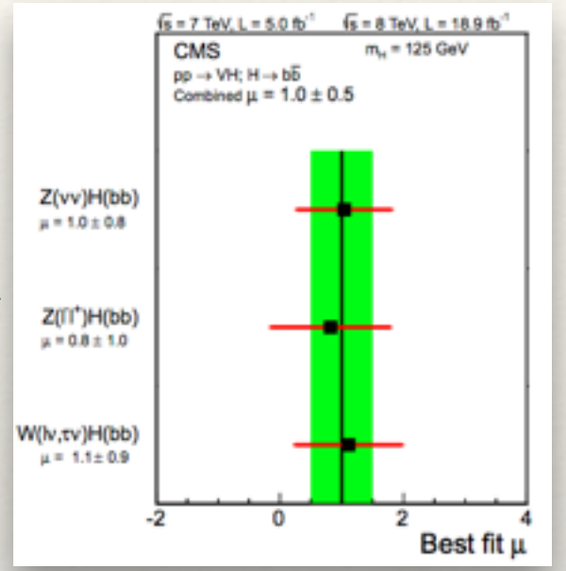
CMS-HIG-13-001

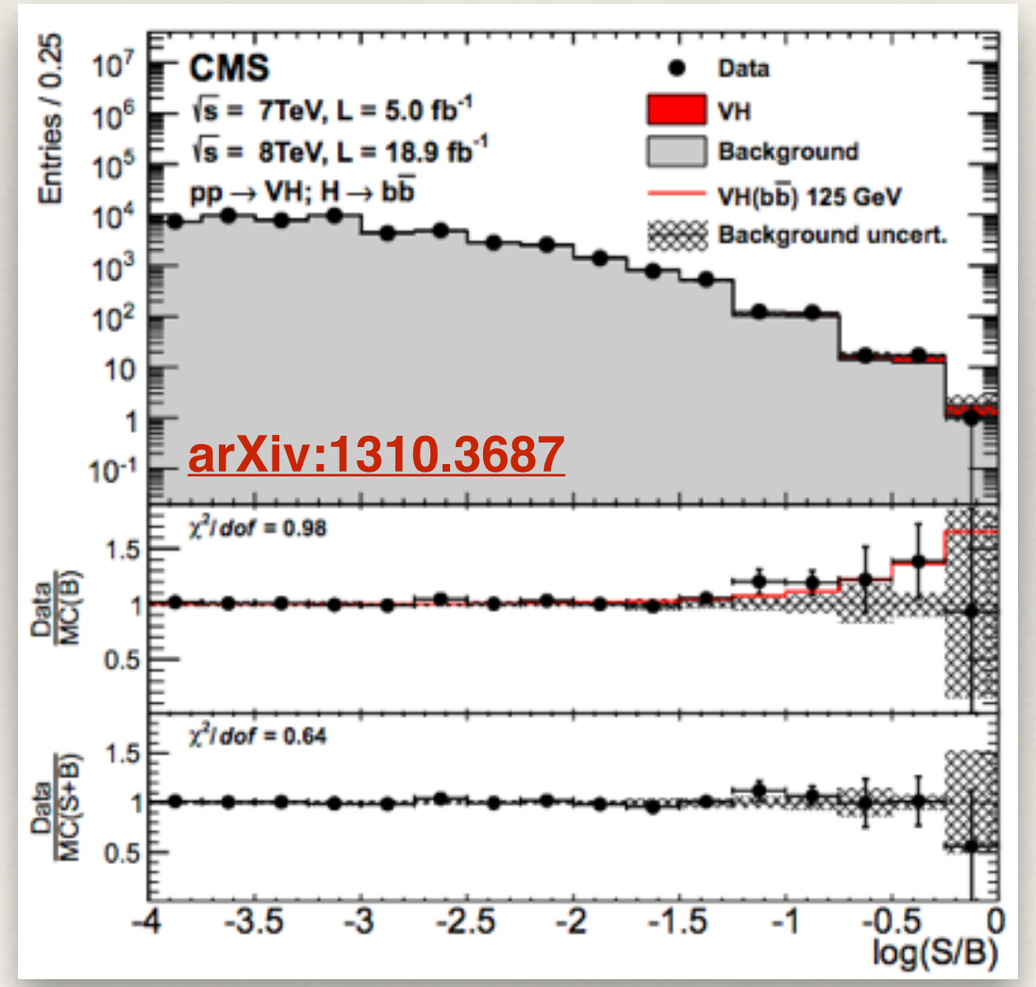
	mass-fit-MVA (at $m_H = 125\,\text{GeV}$)
7 TeV	$1.69^{+0.65}_{-0.59}$
8 TeV	$0.55^{+0.29}_{-0.27}$
7 + 8 TeV	$0.78^{+0.28}_{-0.26}$

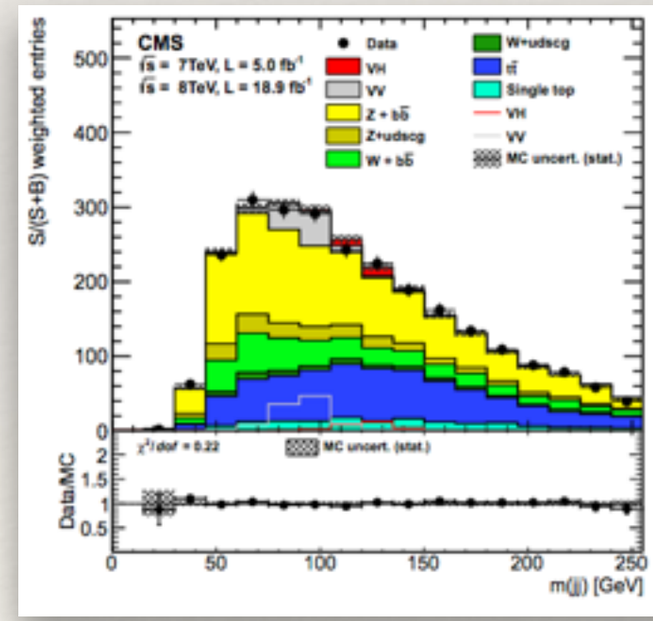
Evidence for $H \rightarrow \gamma\,\gamma$ (3.2σ)

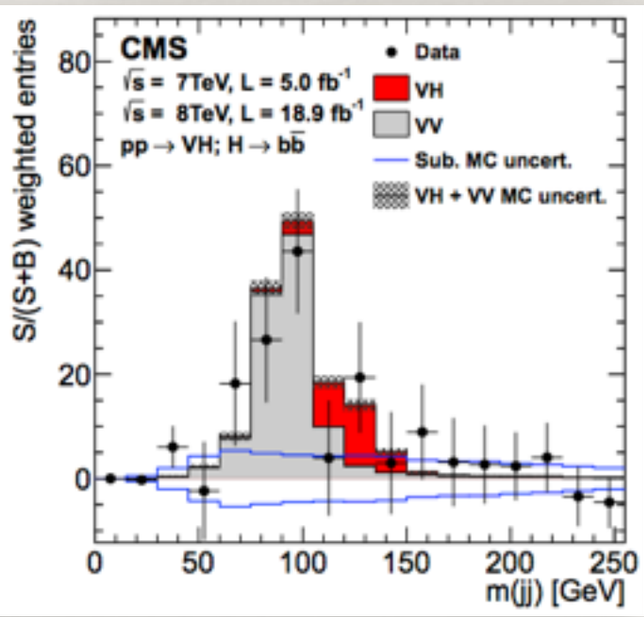
H → bb

- Search using associated production with W or Z bosons
- Backgrounds from single boson, di-boson and top production
- Multivariate analysis (BDT) discriminant used for signal extraction







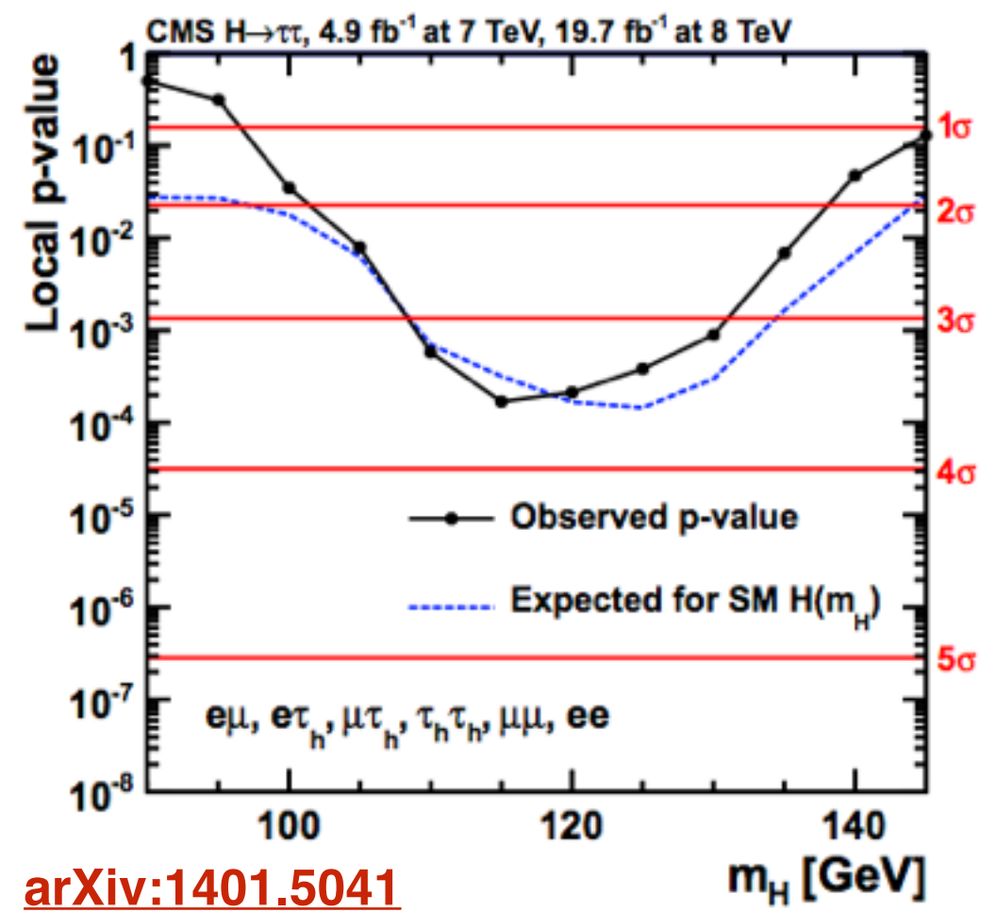


Cross check analysis

No evidence for H → bb yet (2.1σ)

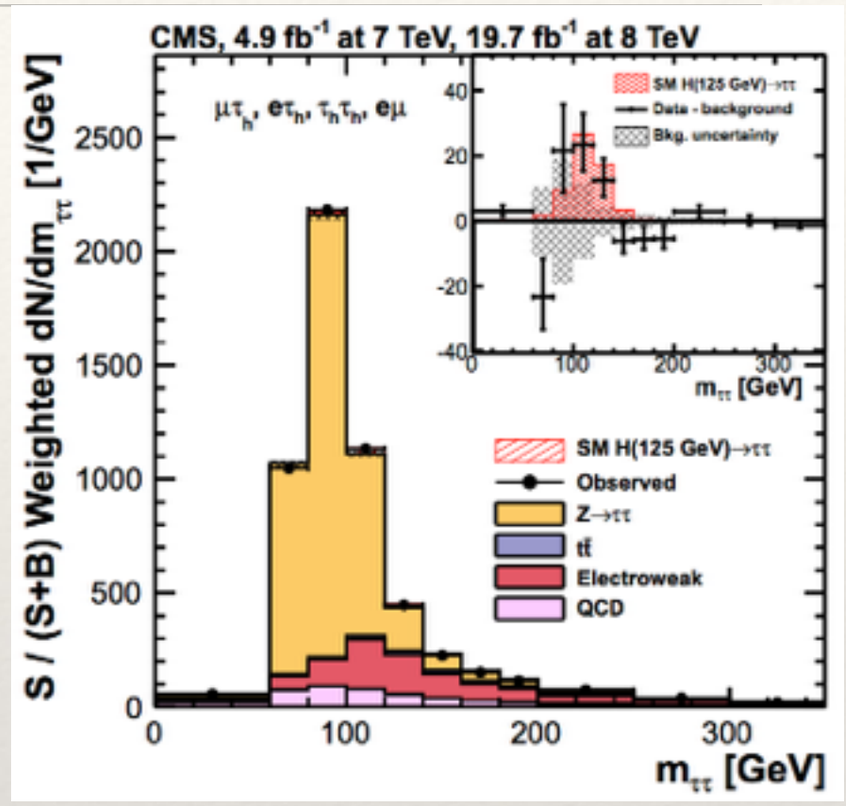
$H \rightarrow \tau\tau$

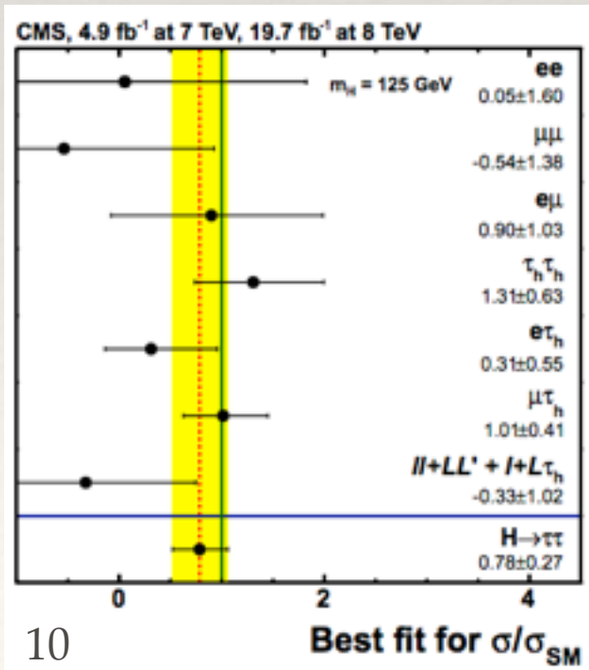
- Search in di-tau mass distribution
- Search in all possible di-tau decay modes
- Categorize di-tau events by S/B and mass resolution

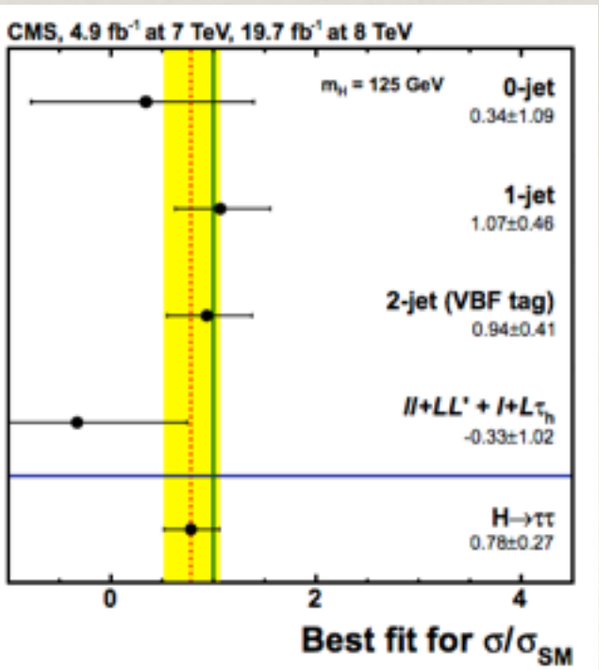


arXiv:1401.5041

Evidence for $H \rightarrow \tau\tau$ (3.4σ)

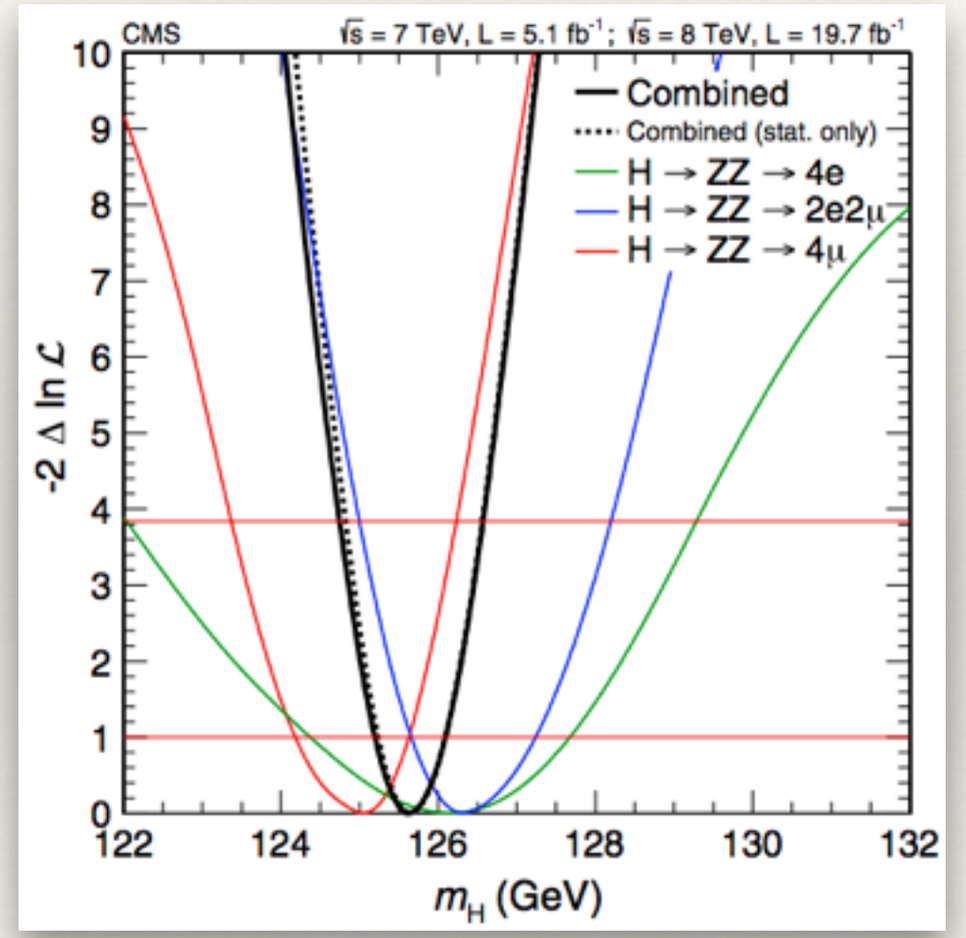




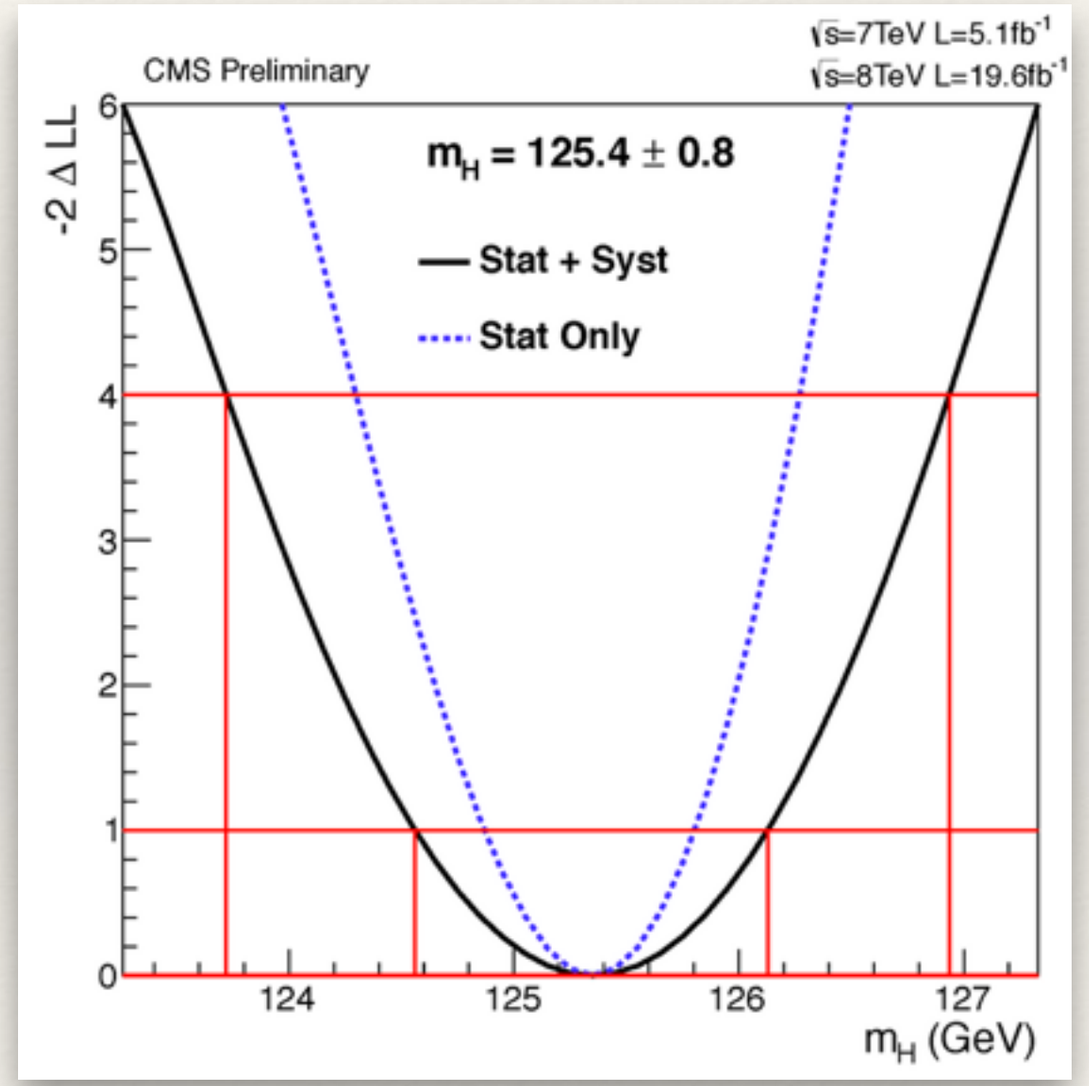


Higgs Mass Measurement

- Precision mass measurement from $H \rightarrow ZZ^* \rightarrow 4l$ and $H \rightarrow \gamma\gamma$
- Consistent measurements across channels



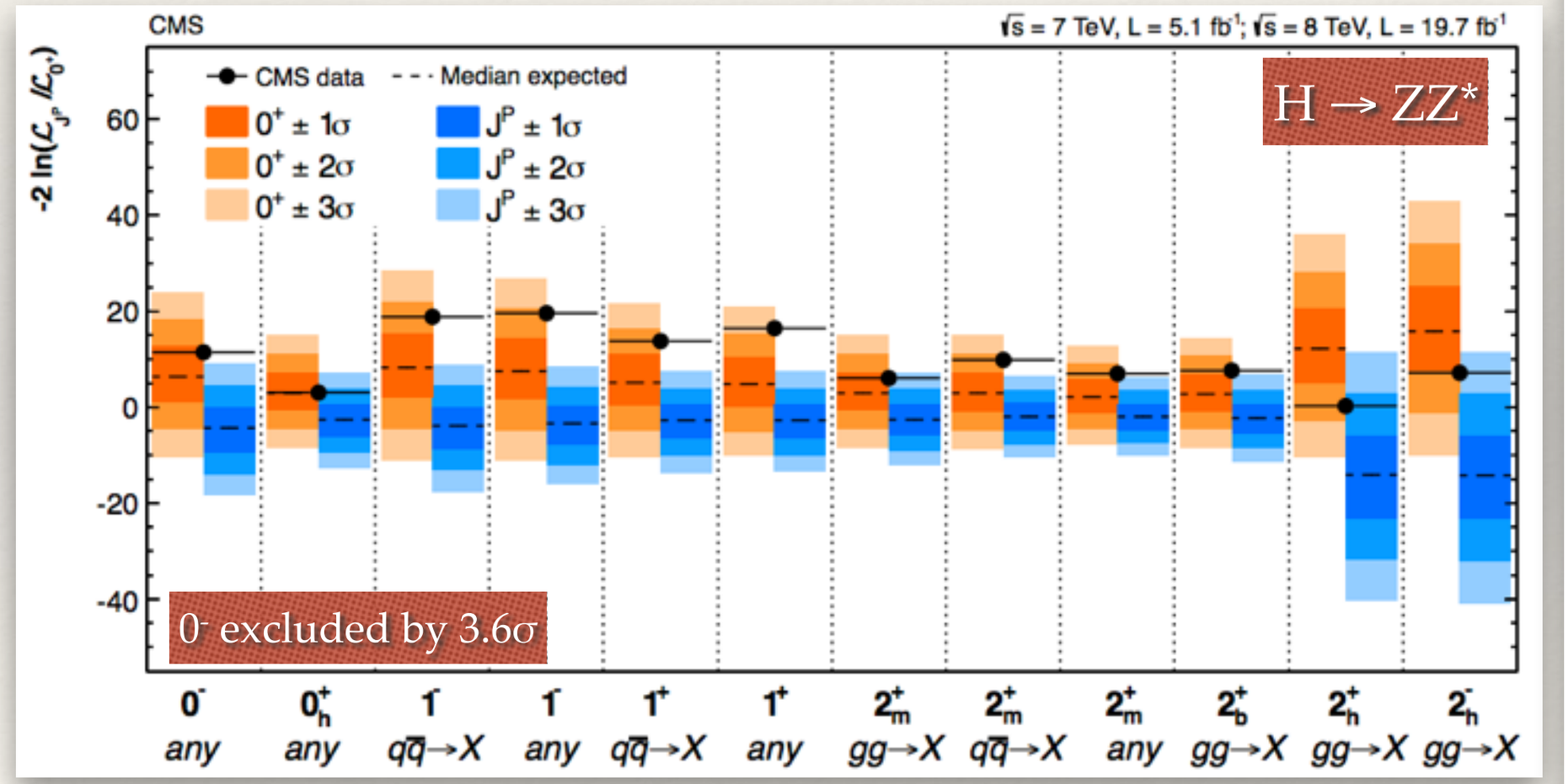
Channel	Measured mass (GeV)
$4e$	$126.2^{+1.5}_{-1.8}$
$2e2\mu$	$126.3^{+0.9}_{-0.7}$
4μ	$125.1^{+0.6}_{-0.9}$
4ℓ	$125.6 \pm 0.4(\text{stat}) \pm 0.2(\text{syst})$

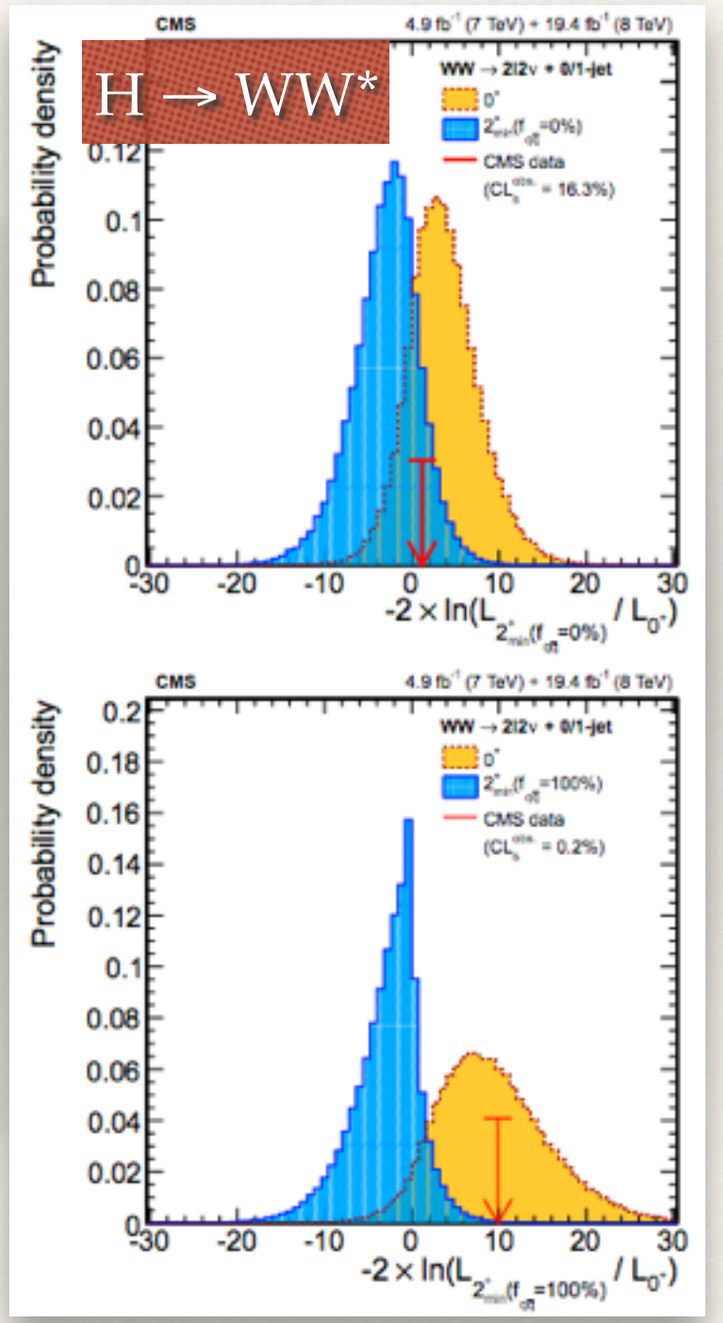


$H \rightarrow \gamma\gamma$: $m_H = 125.4 \pm 0.5\ (\text{stat.}) \pm 0.6\ (\text{syst.})$ GeV

Spin-Parity Measurements

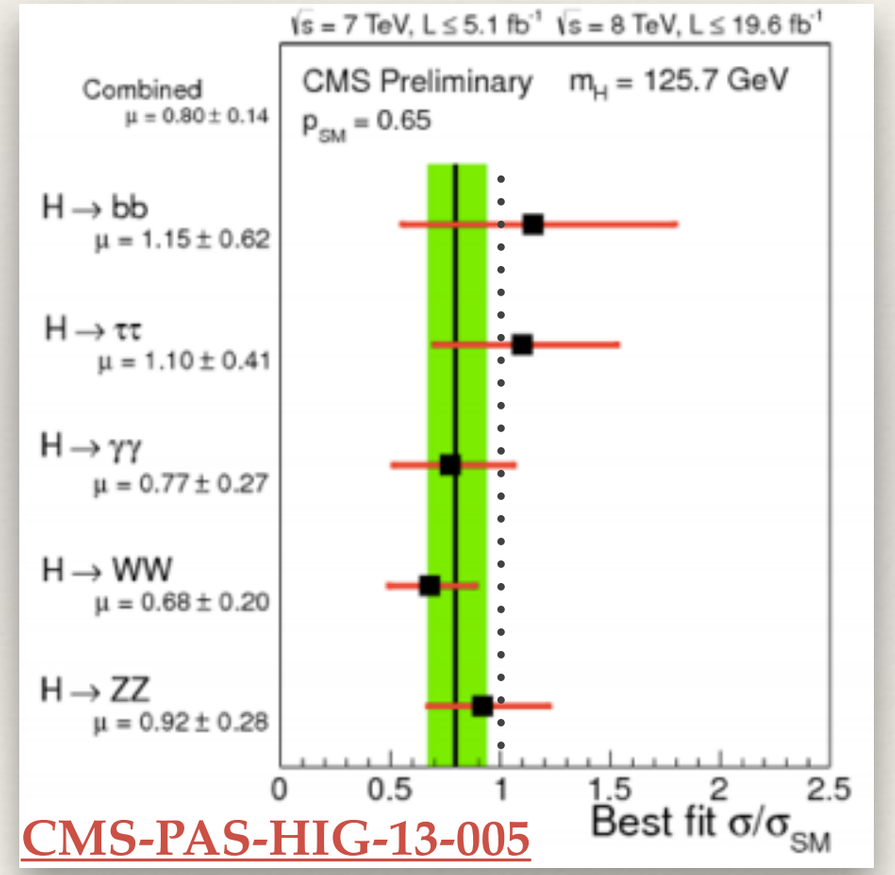
- Measurement from $H \to ZZ^* \to 4l$, $H \to WW^* \to 2l2\nu$, and $H \to \gamma\gamma$
- $J^P = 0^+$ strongly favored by measurements





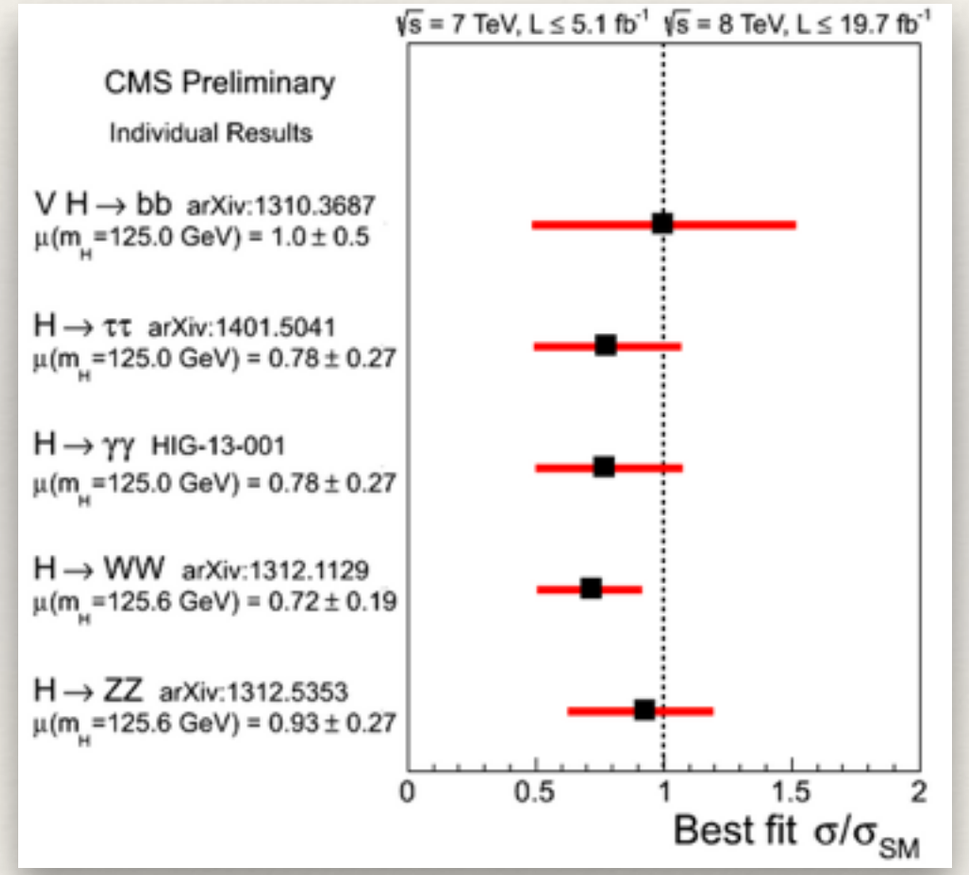
Higgs Couplings

- CMS coupling fits are based on preliminary results released Spring 2013.
- Updated individual measurements are available and consistent with preliminary results.



CMS-PAS-HIG-13-005

Spring 2013



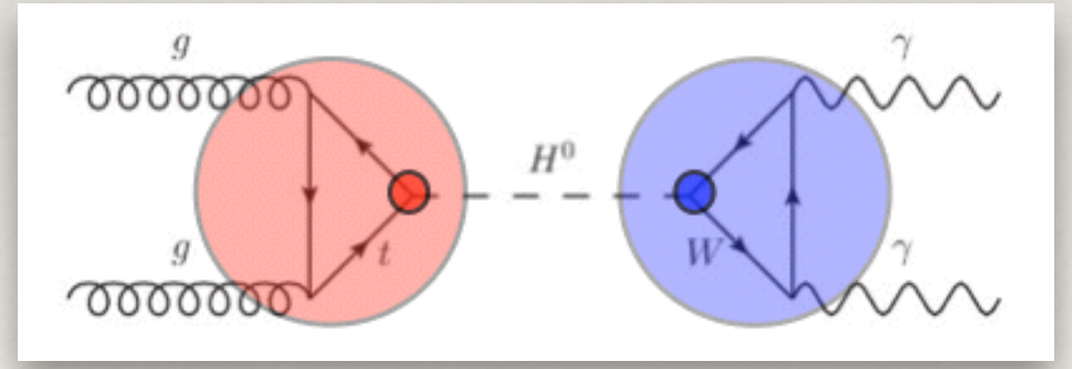
Spring 2014

Higgs Coupling Measurements

- **Strategy:** narrow width approximation

$$(\sigma \cdot \mathrm{BR})\,(ii \to \mathrm{H} \to ff) = \frac{\sigma_{ii} \cdot \Gamma_{ff}}{\Gamma_{\mathrm{H}}}$$

- **Measurement:** parametrize deviations wrt SM in production, decay, and total width
- Implies precise knowledge of the SM prediction
- BSM acceptance effects are not considered



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

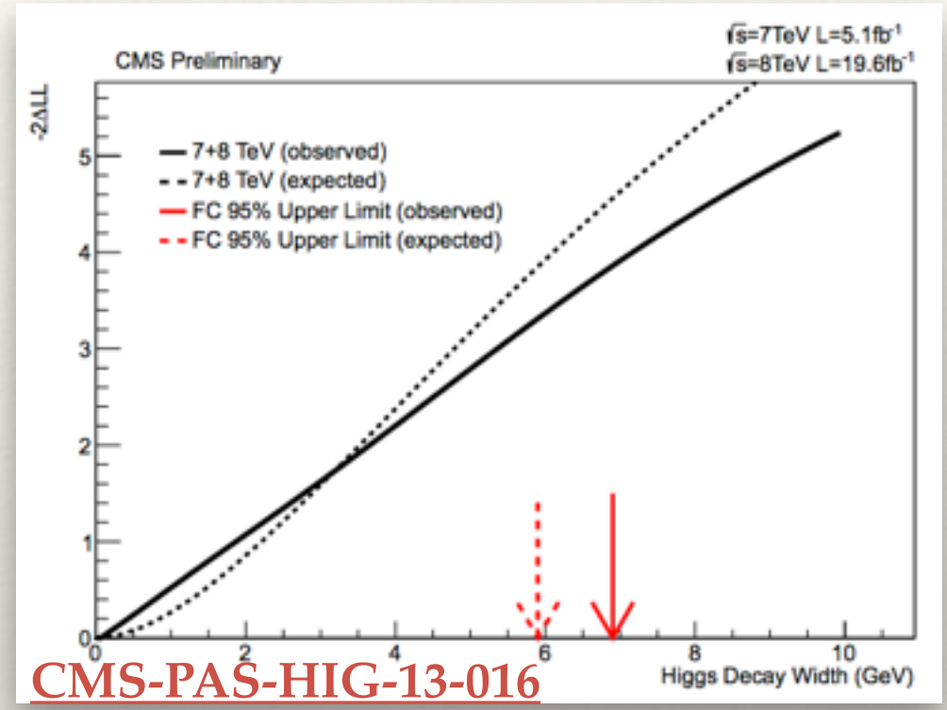
$$\kappa_x \equiv \frac{g_x}{g_x^{\mathrm{SM}}}$$

Total Width Measurements

- SM Higgs total width 4.2 MeV
- Indirect constraints in coupling fits require assumptions

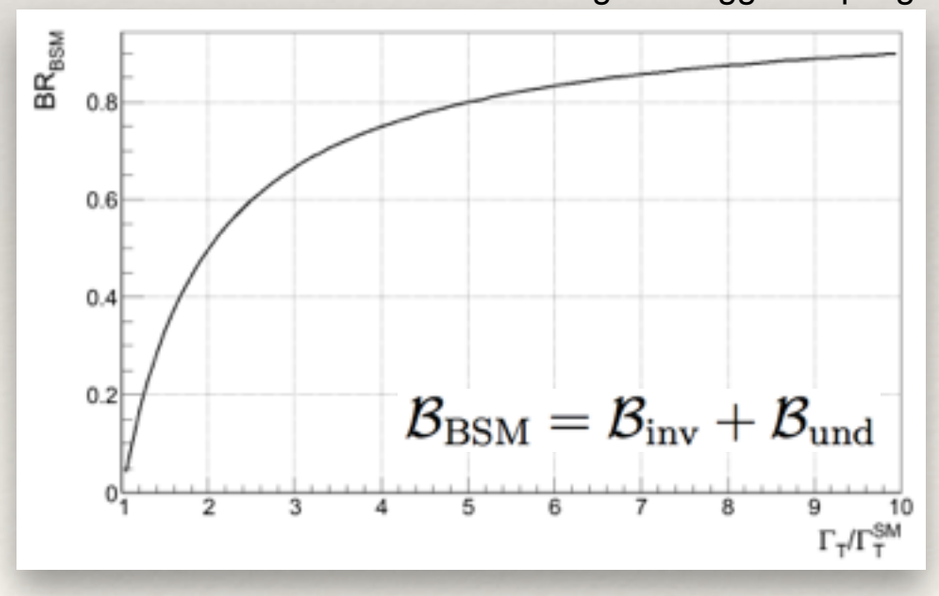
$$\kappa_H^2 \equiv \frac{\Gamma_H}{\Gamma_H^{SM}} \qquad \kappa_H^2 = \sum_f \kappa_f^2 \frac{\mathcal{B}_{\rm SM}(H\to ff)}{1-\mathcal{B}_{\rm BSM}}$$

- Measurements at the LHC
  - interference between $gg \to H \to \gamma\gamma$ and $gg \to \gamma\gamma$ continuum results in Higgs mass shift
  - off-shell H* production



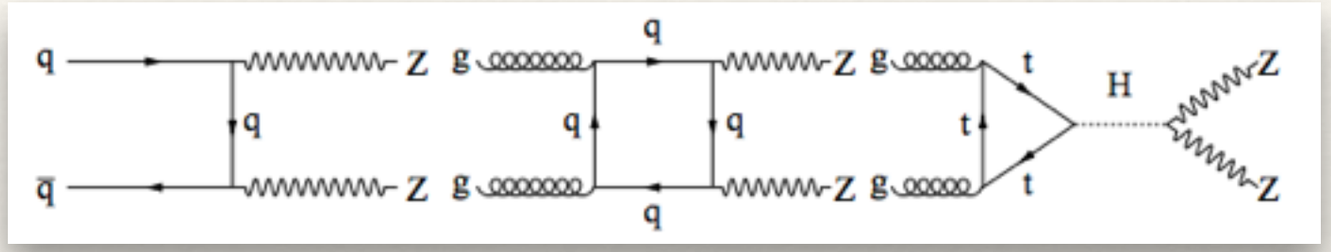
CMS-PAS-HIG-13-016

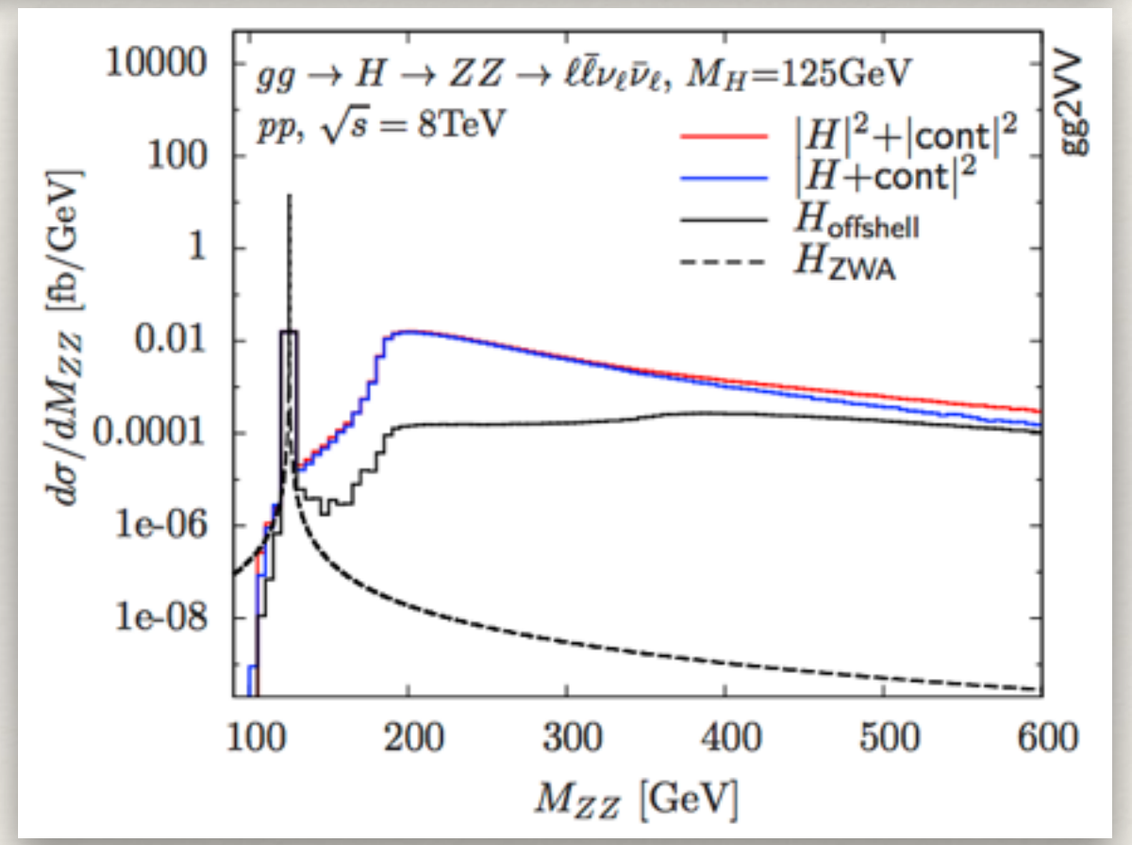
assuming SM Higgs coupling



Total Width Measurements

- Enhancement of cross section at high mass due to Higgs boson. ~8 % in ZZ final state
- Can be used to constrain total width





$$r = \Gamma_H/\Gamma_H^{SM}$$

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

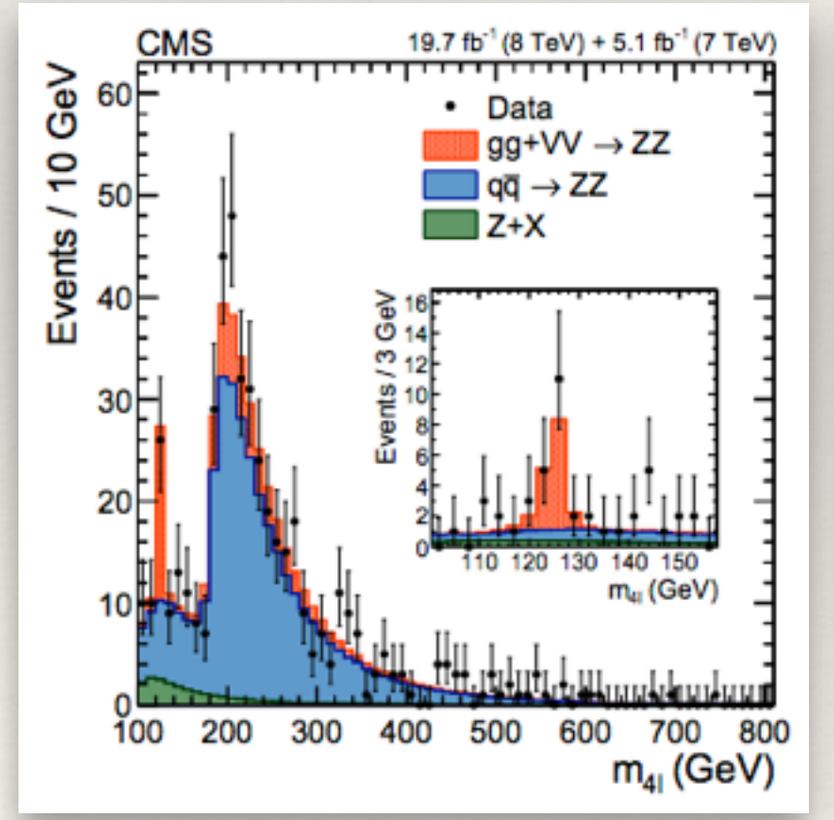
$$\frac{d\sigma_{gg\to H\to ZZ}}{dm^2_{ZZ}} \propto g^2_{ggH}g^2_{HZZ}\frac{F(m_{ZZ})}{(m^2_{ZZ}-m^2_H)^2+m^2_H\Gamma^2_H}$$

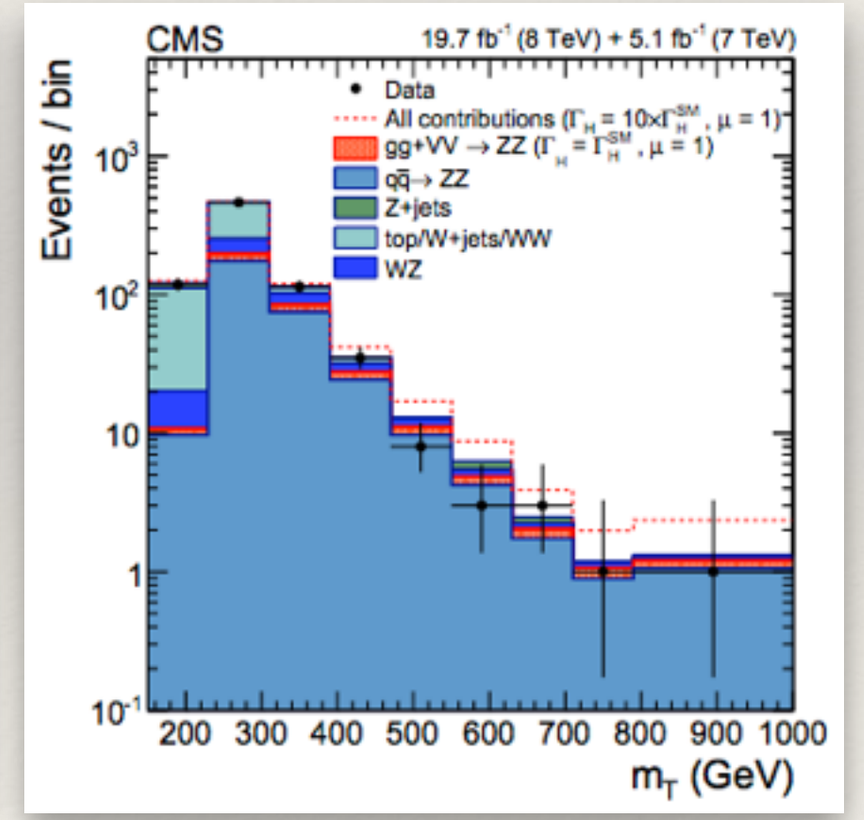
$$\frac{d\sigma^{\text{off-peak}}_{gg\to H\to ZZ}}{dm_{ZZ}} = \kappa_g^2\kappa_Z^2\cdot\frac{d\sigma^{\text{off-peak,SM}}_{gg\to H\to ZZ}}{dm_{ZZ}} = \mu r\frac{d\sigma^{\text{off-peak,SM}}_{gg\to H\to ZZ}}{dm_{ZZ}}$$

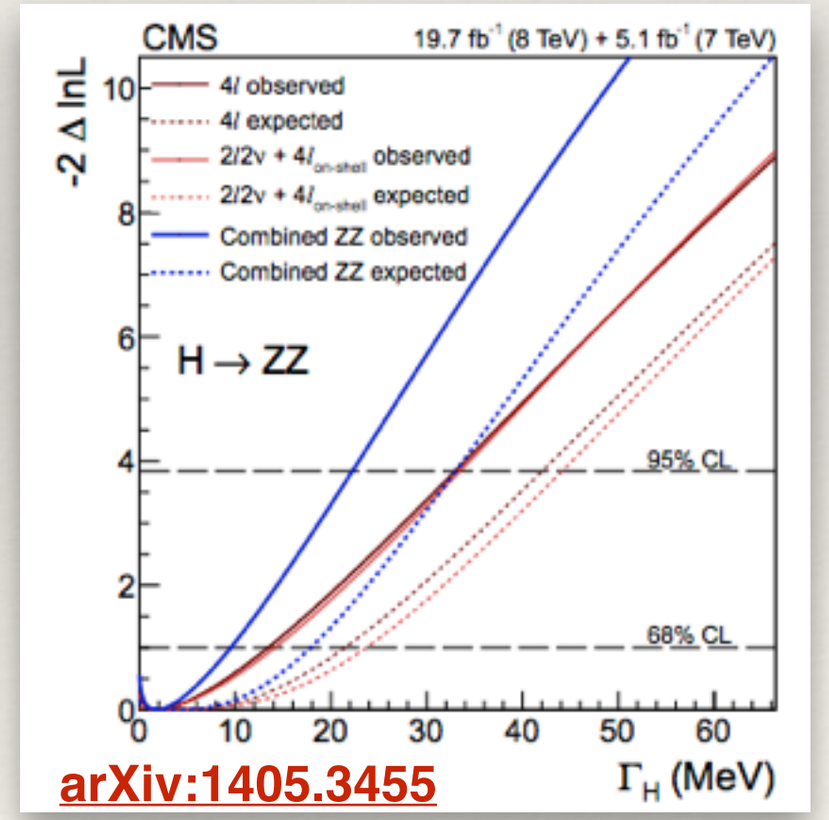
N. Kauer, G. Passarino, JHEP 08 (2012) 116
F. Koala, K. Melnikov, Phys. Rev. D88 (2013), 054024
J. Cambell et al, arXiv:1311.3589

Total Width Measurements

- Experimental constrain on total width using $H^* \rightarrow ZZ$
- Combination of 4l and 2l2v final states
- Results: **$r < 5.4$** (8.0 expected) or **$\Gamma_H < 22$ MeV** (33 MeV expected) @ 95%CL

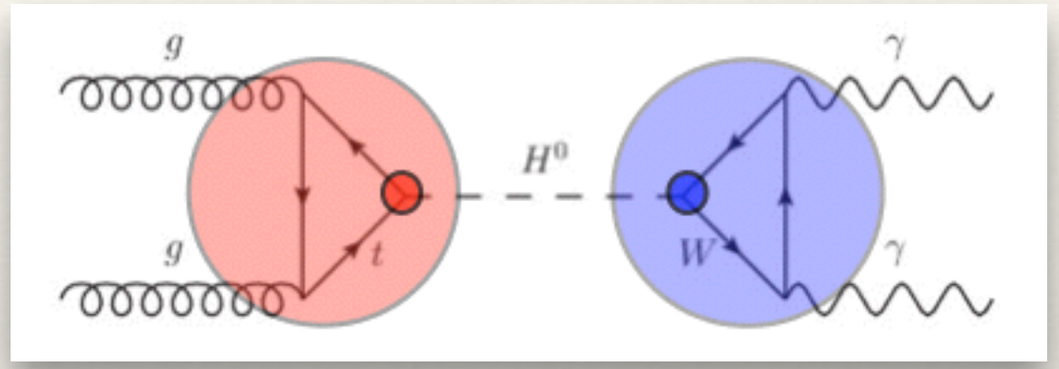






Higgs Couplings

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



- **Probing beyond the SM physics**
- Simultaneous fit of all couplings with assumption on total width
- Searches for new physics in loops: κ_g, κ_γ, BR_{BSM}
- Fermion versus vector boson couplings: κ_V, κ_f
- Probing asymmetries: λ_{WZ}, λ_{du}, λ_{lq}

$$\lambda_{xy} \equiv \frac{\kappa_x}{\kappa_y}$$

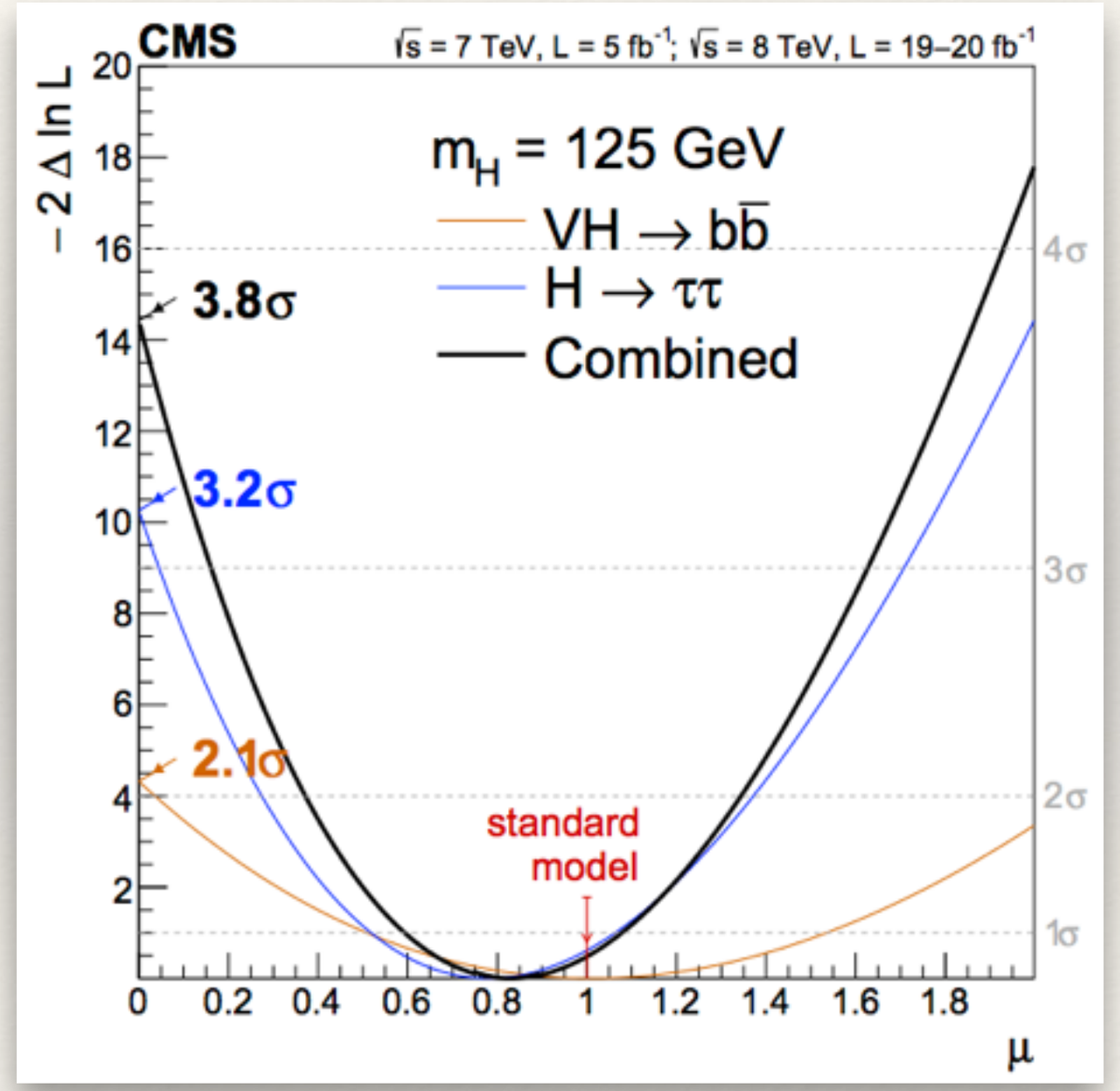
- Overall scaling of signal strength: μ

Fermion Couplings

- Does the Higgs boson coupling to fermions?
- Direct evidence for decays to fermions. Combination H → $\tau\tau$ and H → bb channels

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

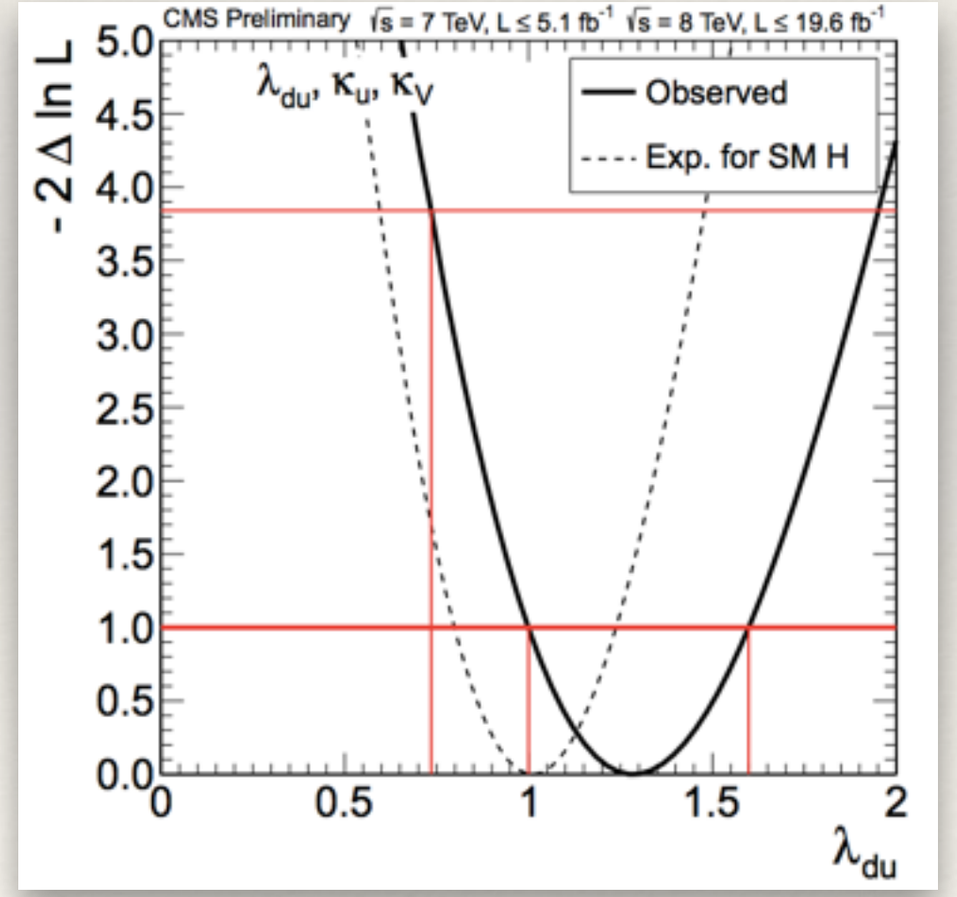
arXiv:1401.6527

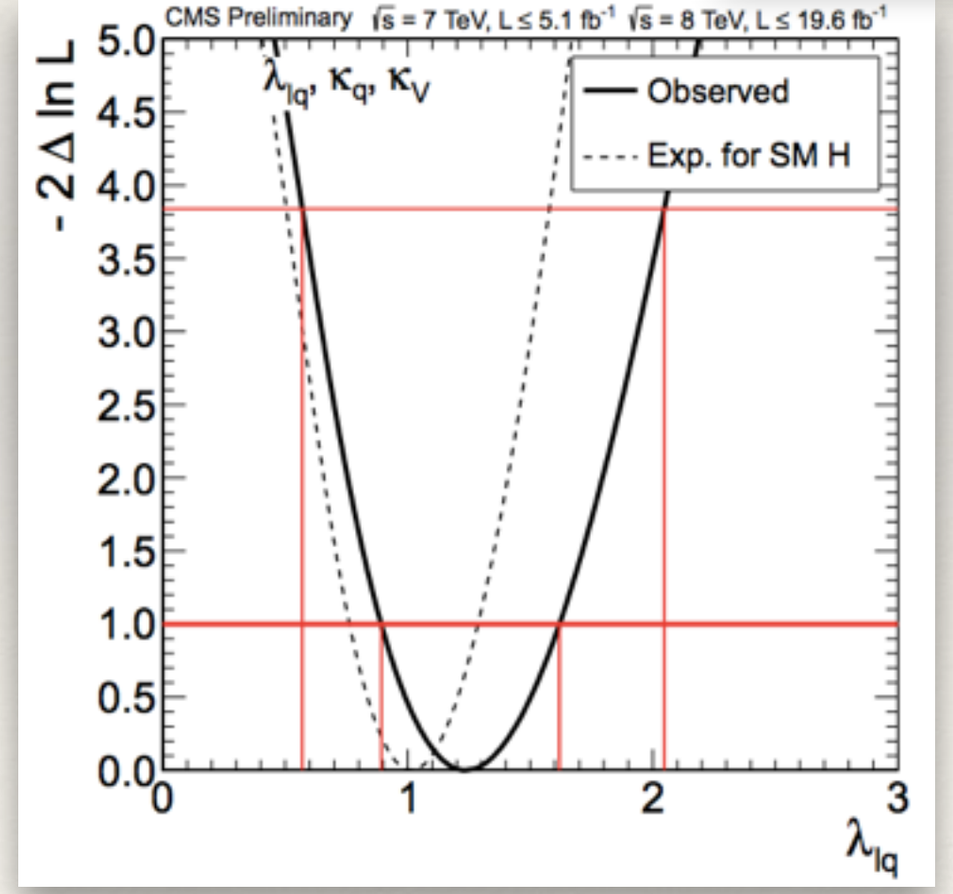


Fermion Coupling Asymmetry

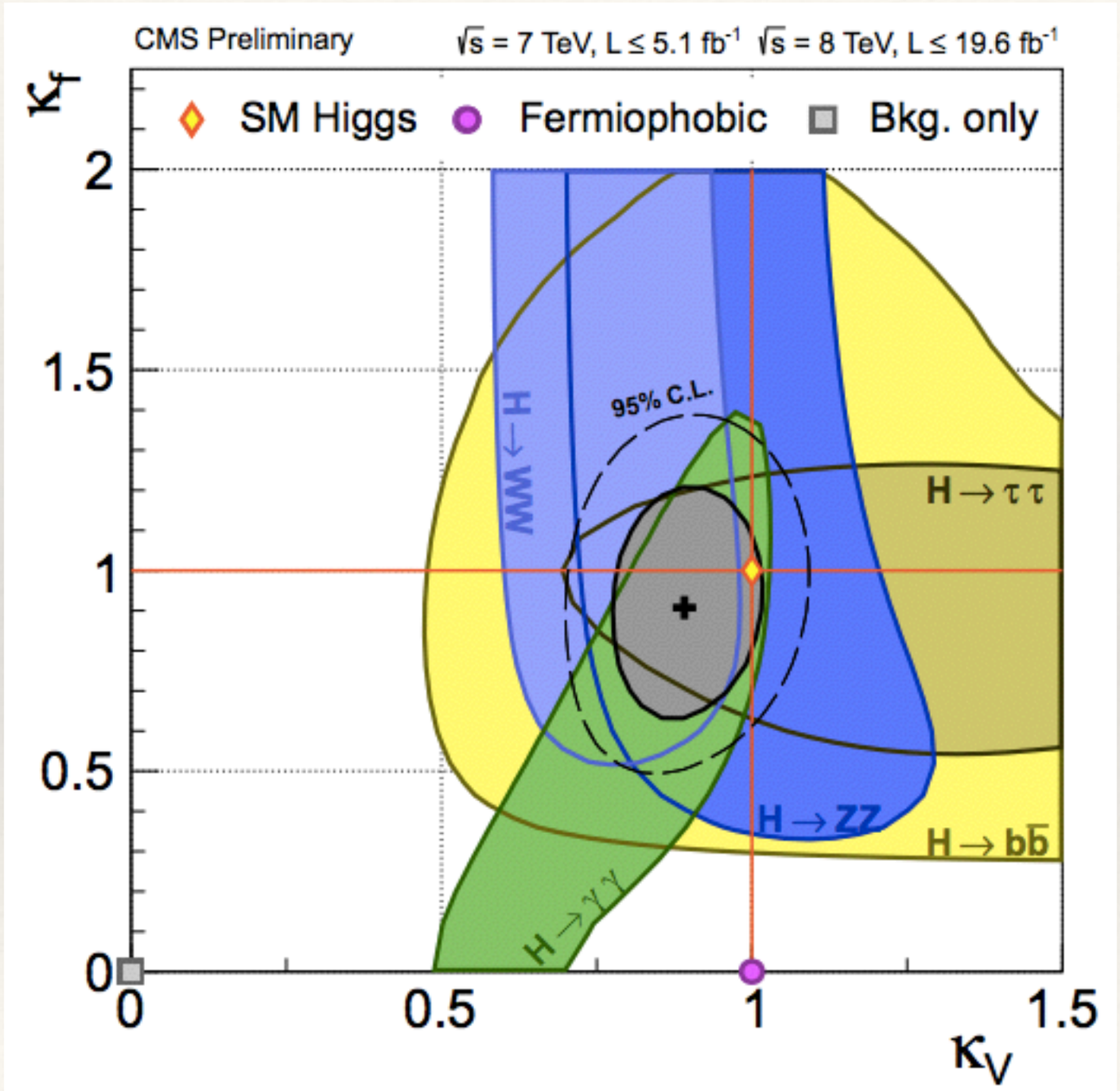
- BSM models (e.g. 2HDM) show asymmetries between up and down type or lepton and quark couplings
- Explored in three parameter fits
- Down-type fermion coupling established ~4σ

$$\lambda_{xy} \equiv \frac{\kappa_x}{\kappa_y}$$



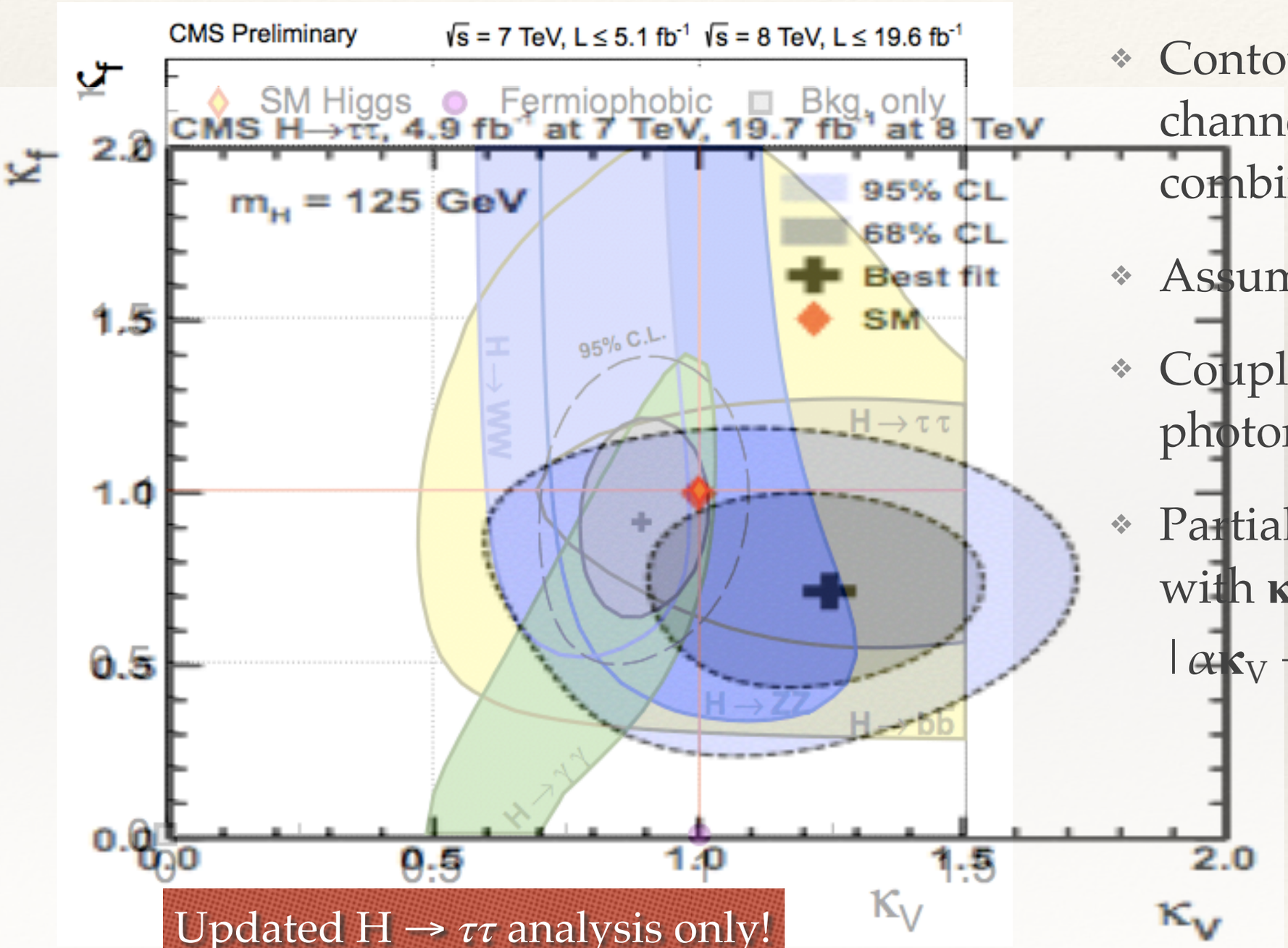


Fermion vs Vector Boson Couplings



- Contours for individual channels and overall combination
- Assume $\Gamma_{BSM} = 0$
- Coupling to gluons and photons resolved
- Partial width scales either with $\boldsymbol{\kappa}_V^2$ or $\boldsymbol{\kappa}_f^2$, except $\Gamma_{\gamma\gamma} = |\alpha\boldsymbol{\kappa}_V + \beta\boldsymbol{\kappa}_f|^2$

Fermion vs Vector Boson Couplings



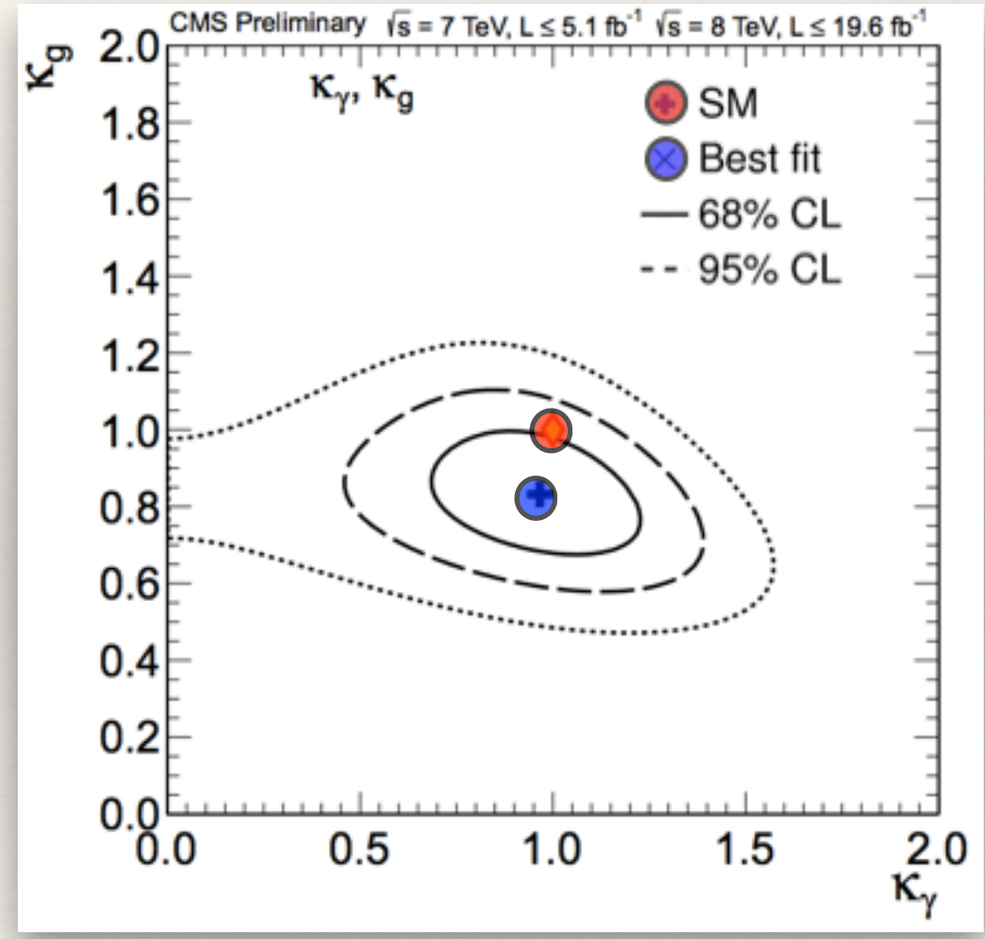
Updated H → $\tau\tau$ analysis only!

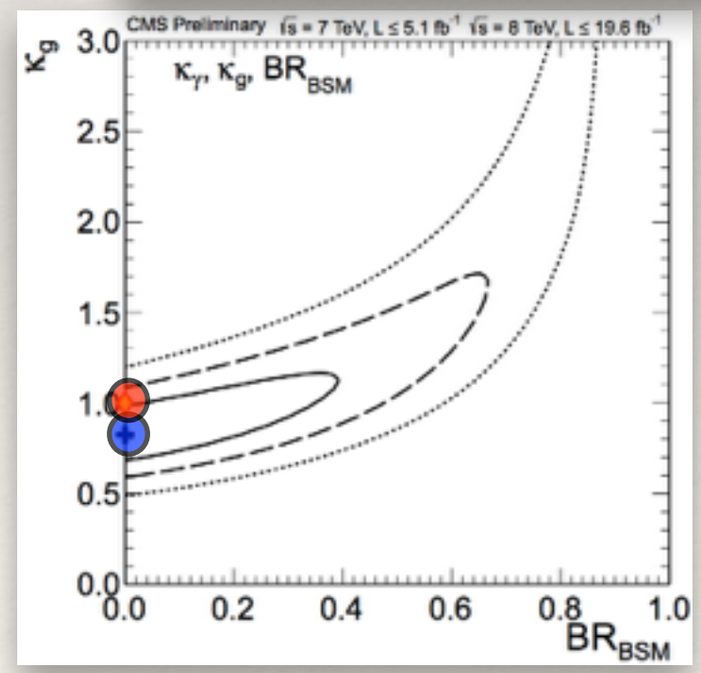
- Contours for individual channels and overall combination
- Assume $\Gamma_{BSM} = 0$
- Coupling to gluons and photons resolved
- Partial width scales either with κ_V^2 or κ_f^2, except $\Gamma_{\gamma\gamma} = |\alpha\kappa_V + \beta\kappa_f|^2$

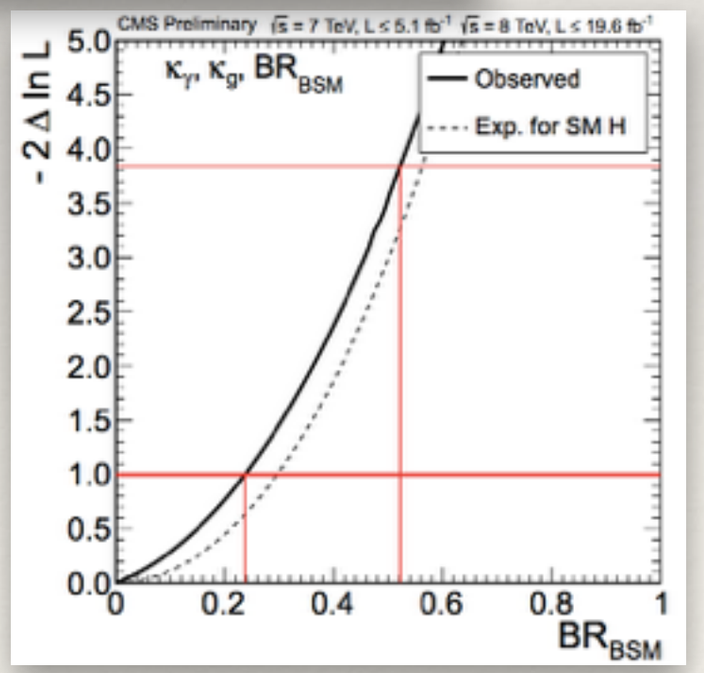
Probing BSM in Loops

- Study effective coupling to gluons and photons
- Constrain total width assuming SM Higgs tree -level couplings
- Degeneracy of BR_{BSM} with gluon coupling from ($gg \rightarrow H$)
- Direct search for invisible Higgs decays or total width measurements not included

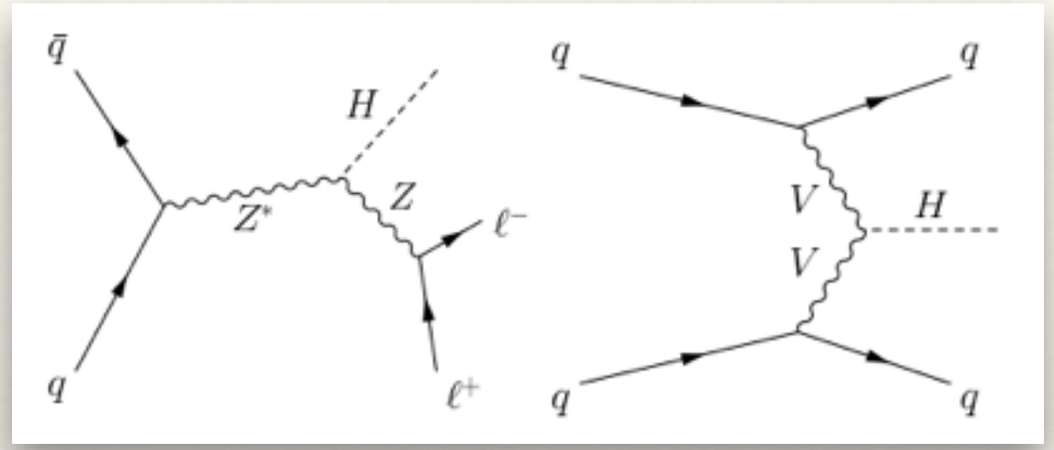
CMS: $\mathcal{B}_{\mathrm{BSM}} < 0.52$ (0.58 expected) at 95% CL





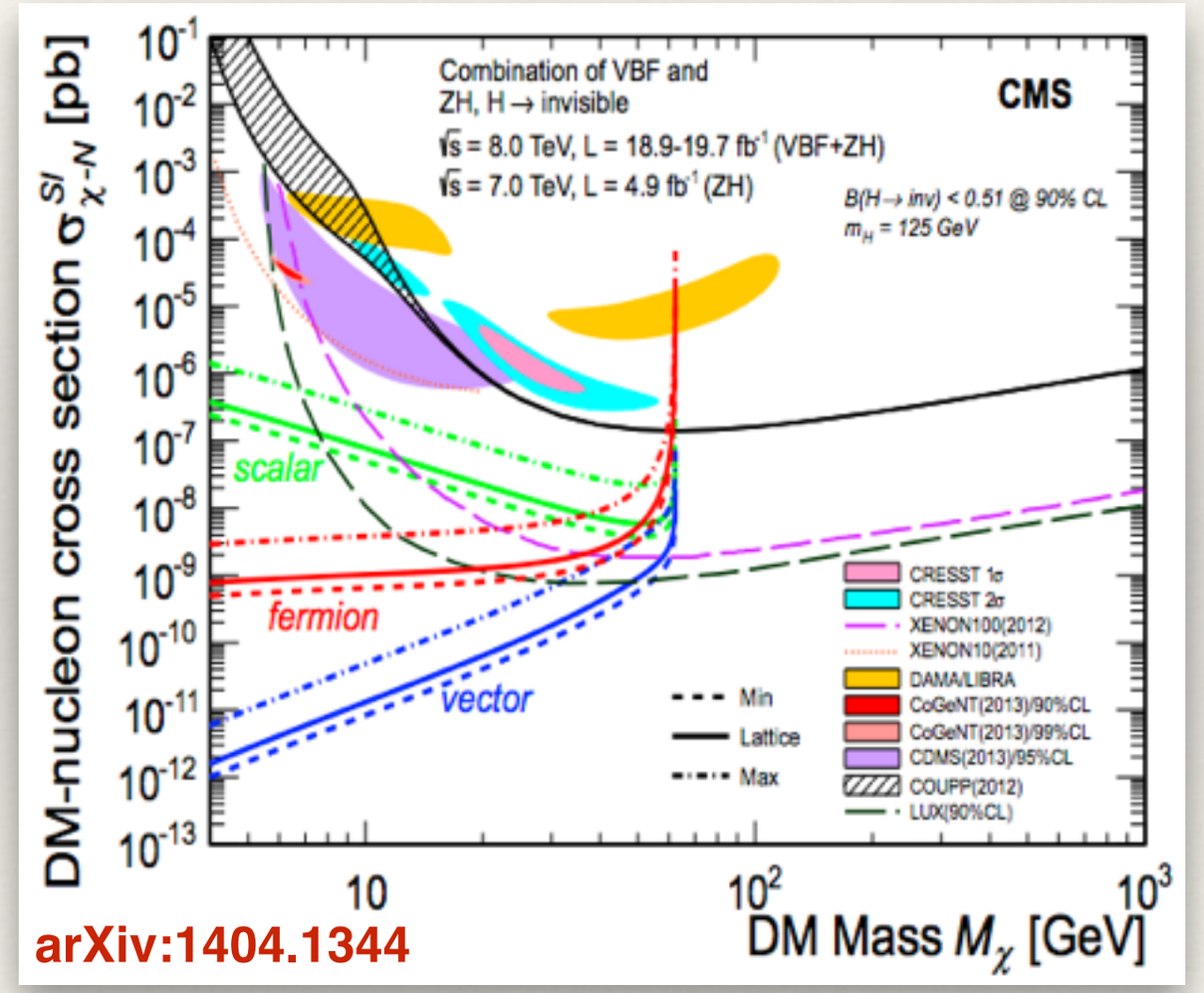


Invisible Decays

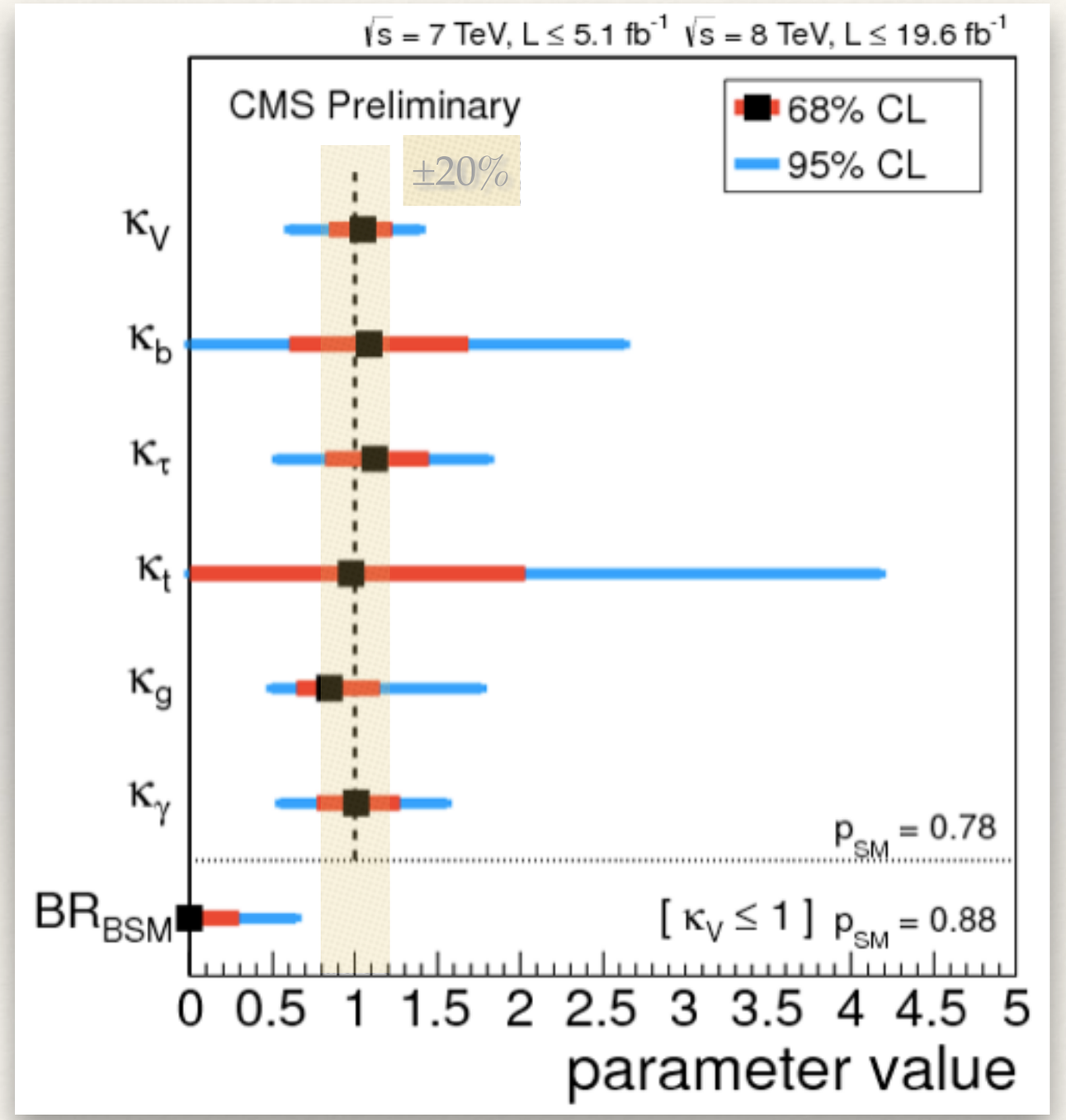


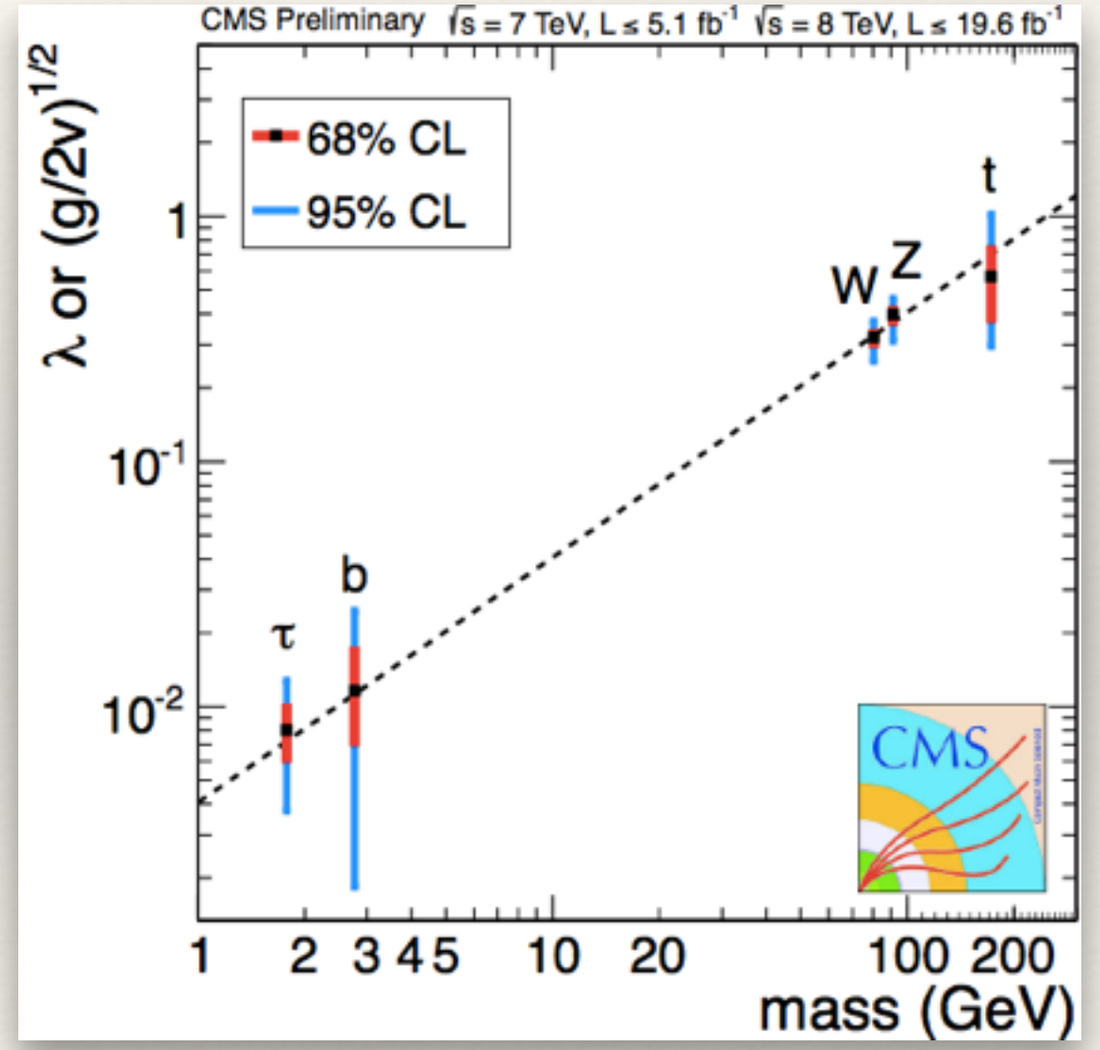
- Direct search for invisible Higgs decays
- VBF and ZH production used to tag events
- DM interpretation complementary to direct searches

CMS ($H \rightarrow$ invisible): $\mathcal{B}_{\text{inv}} < 0.58$ (0.44 expected) at 95% CL



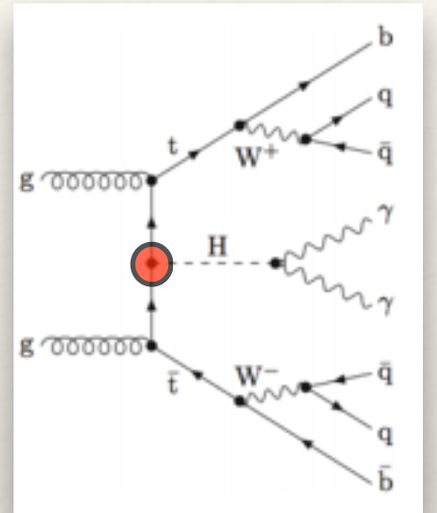
Generic Coupling Fits

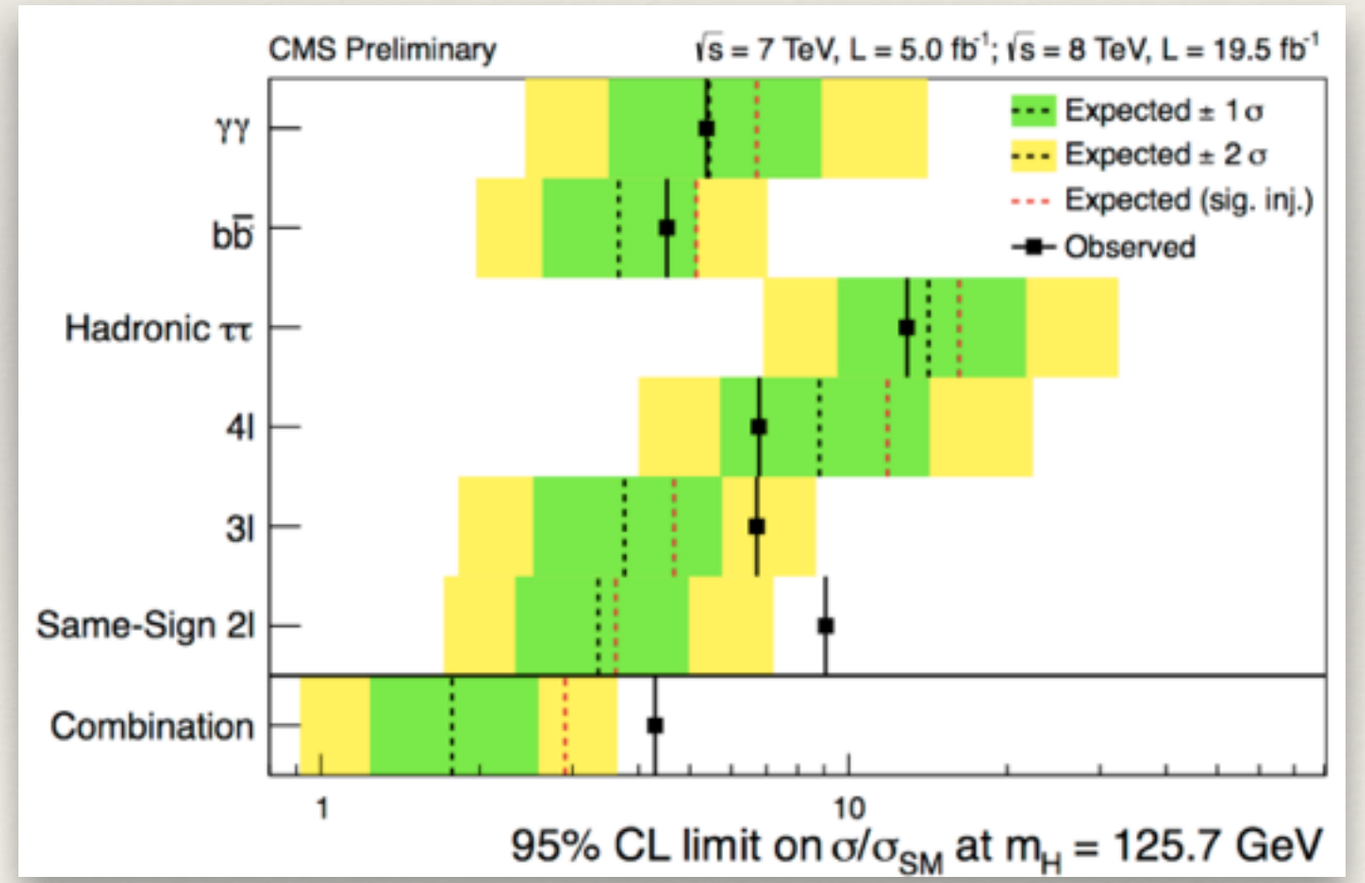




ttH Measurements

- Direct study of top Yukawa coupling
- Exploring all accessible Higgs decay modes
- Approaching SM sensitivity in 8 TeV data

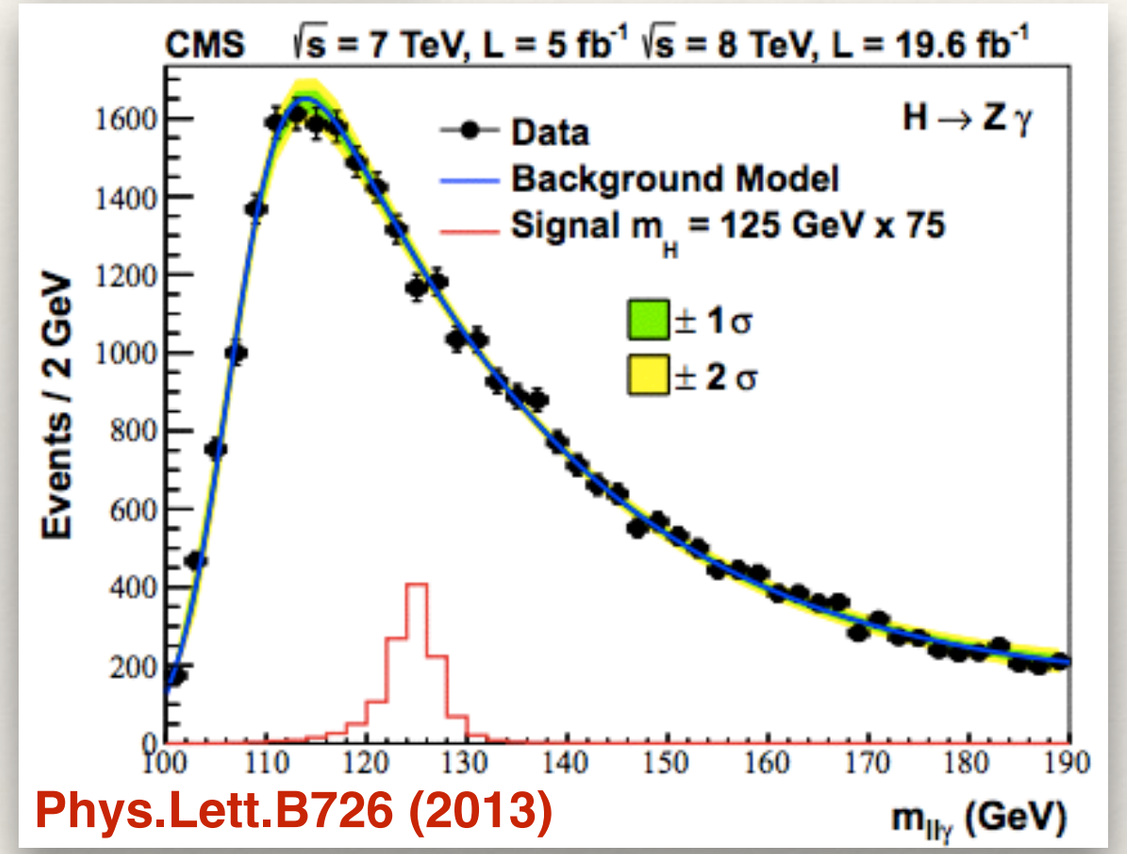




ttH Channel	$\mu = \sigma/\sigma_{SM}$ ($m_H = 125.7$ GeV)
$\gamma\gamma$	$-0.2^{+2.4}_{-1.9}$
$b\bar{b}$	$+1.0^{+1.9}_{-2.0}$
$\tau\tau$	$-1.4^{+6.3}_{-5.5}$
4l	$-4.8^{+5.0}_{-1.2}$
3l	$+2.7^{+2.2}_{-1.8}$
Same-sign 2l	$+5.3^{+2.2}_{-1.8}$
Combined	$+2.5^{+1.1}_{-1.0}$

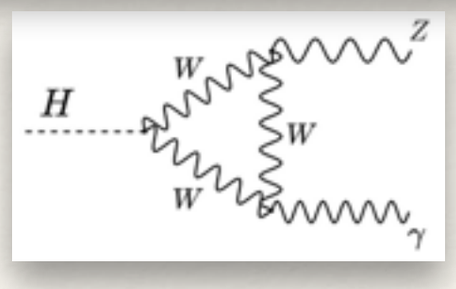
Rare Decays

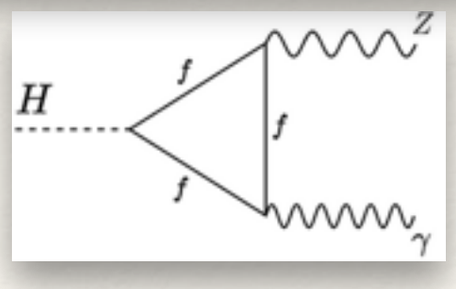
$$H \to Z\gamma$$



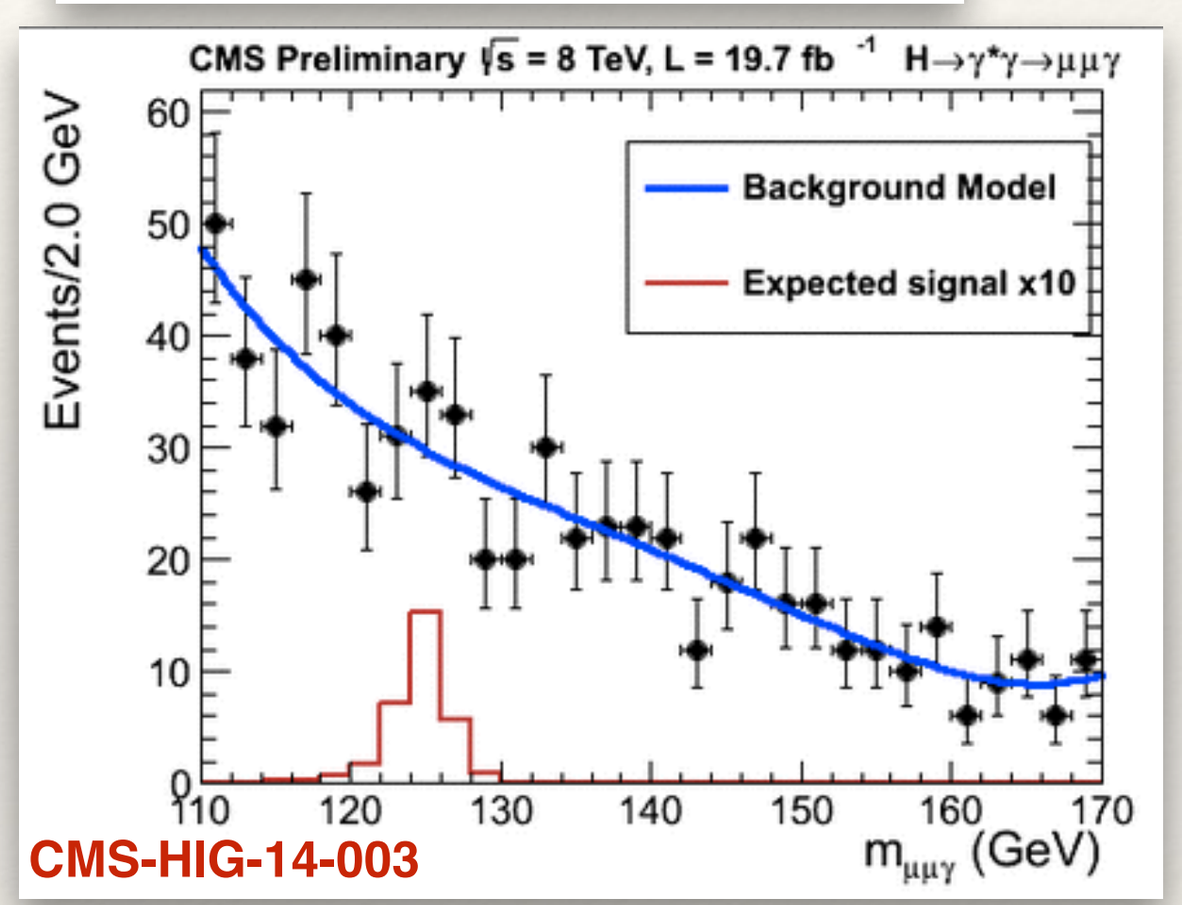
Phys.Lett.B726 (2013)

CMS ($H \to Z\gamma$): $\mu < 9$ (9 expected) at 95% CL





$$H \to \gamma^*\gamma \to \mu^+\mu^-\gamma$$



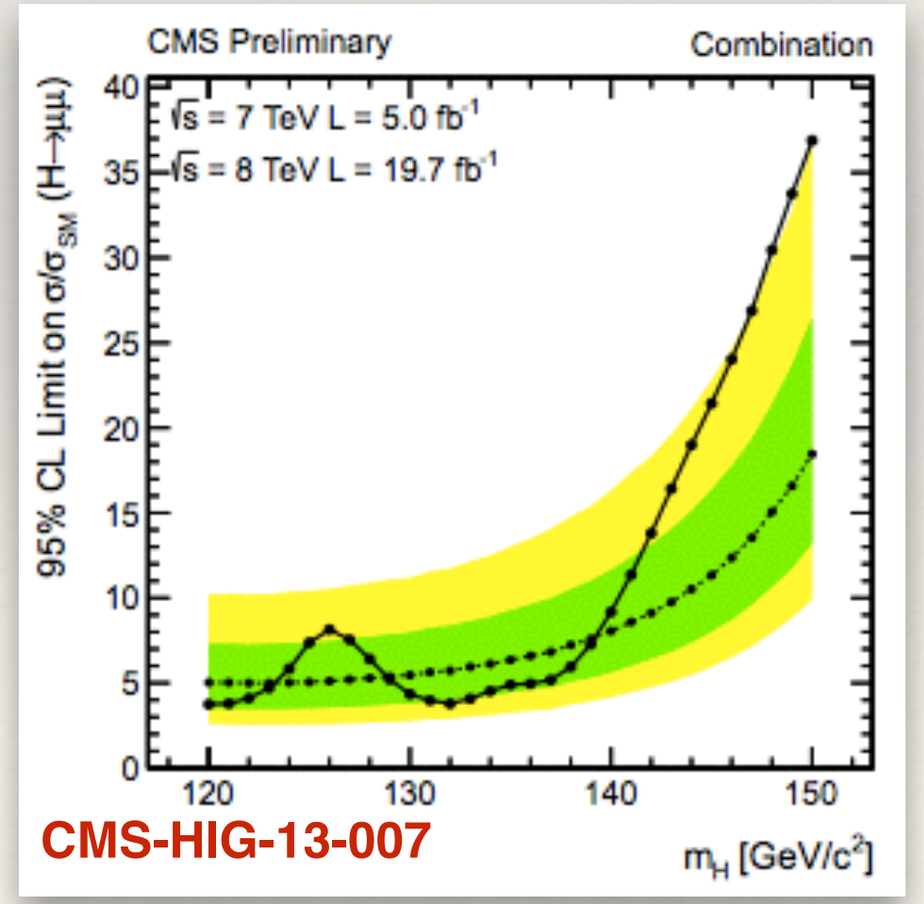
CMS-HIG-14-003

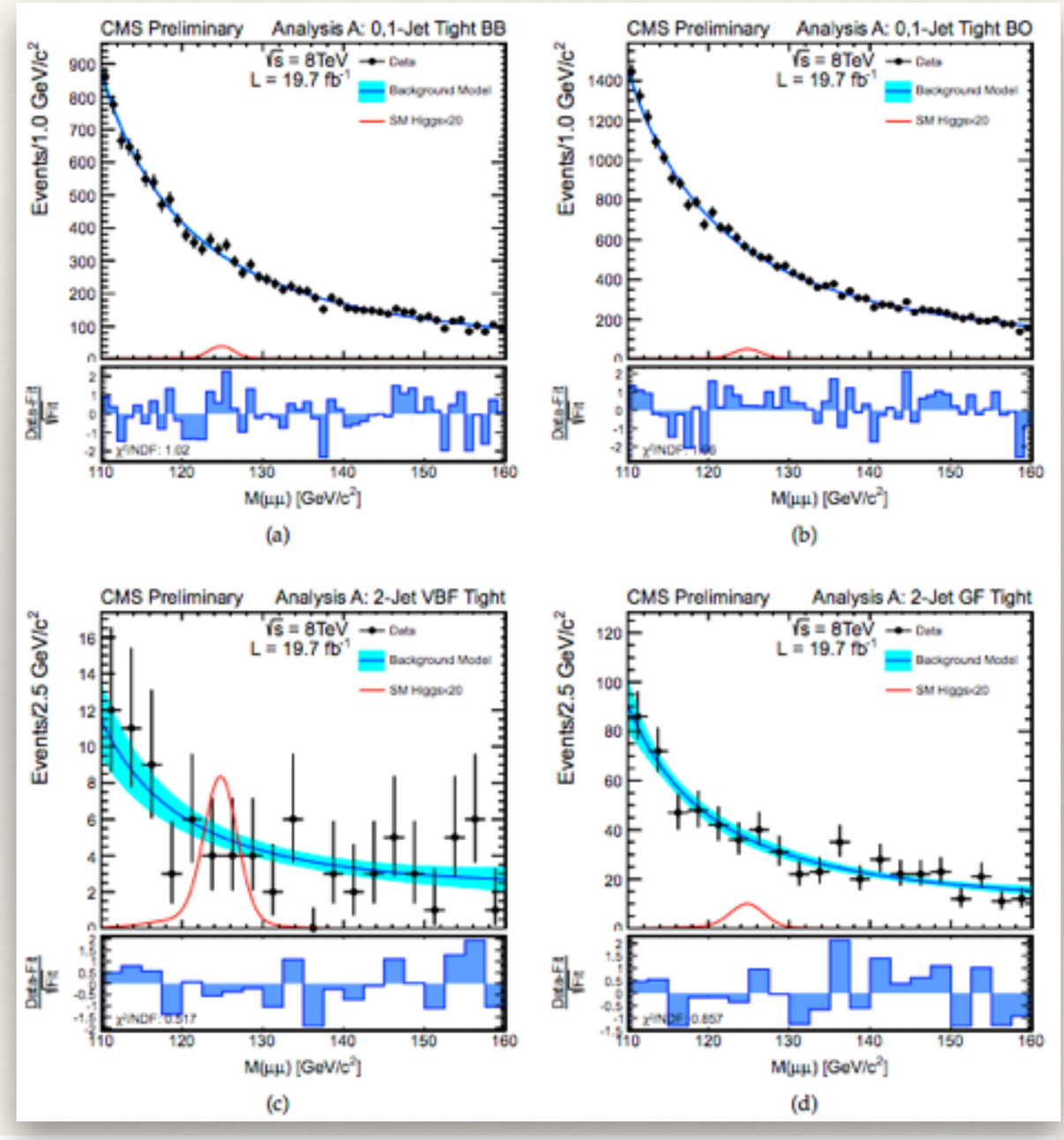
CMS ($H \to \gamma^*\gamma \to \mu^+\mu^-\gamma$): $\mu < 12$ (8 expected) at 95% CL

Rare Decays

$H \to \mu\mu$

- $BR_{SM}\ (H \to \mu\mu) = 2.2 \times 10^{-4}$
- Excellent mass resolutions, tiny signal, huge DY background
- Testing Higgs coupling to 2nd generation





CMS $(H \to \mu\mu)$: $\mu < 7.4$ (5.1 expected) at 95% CL

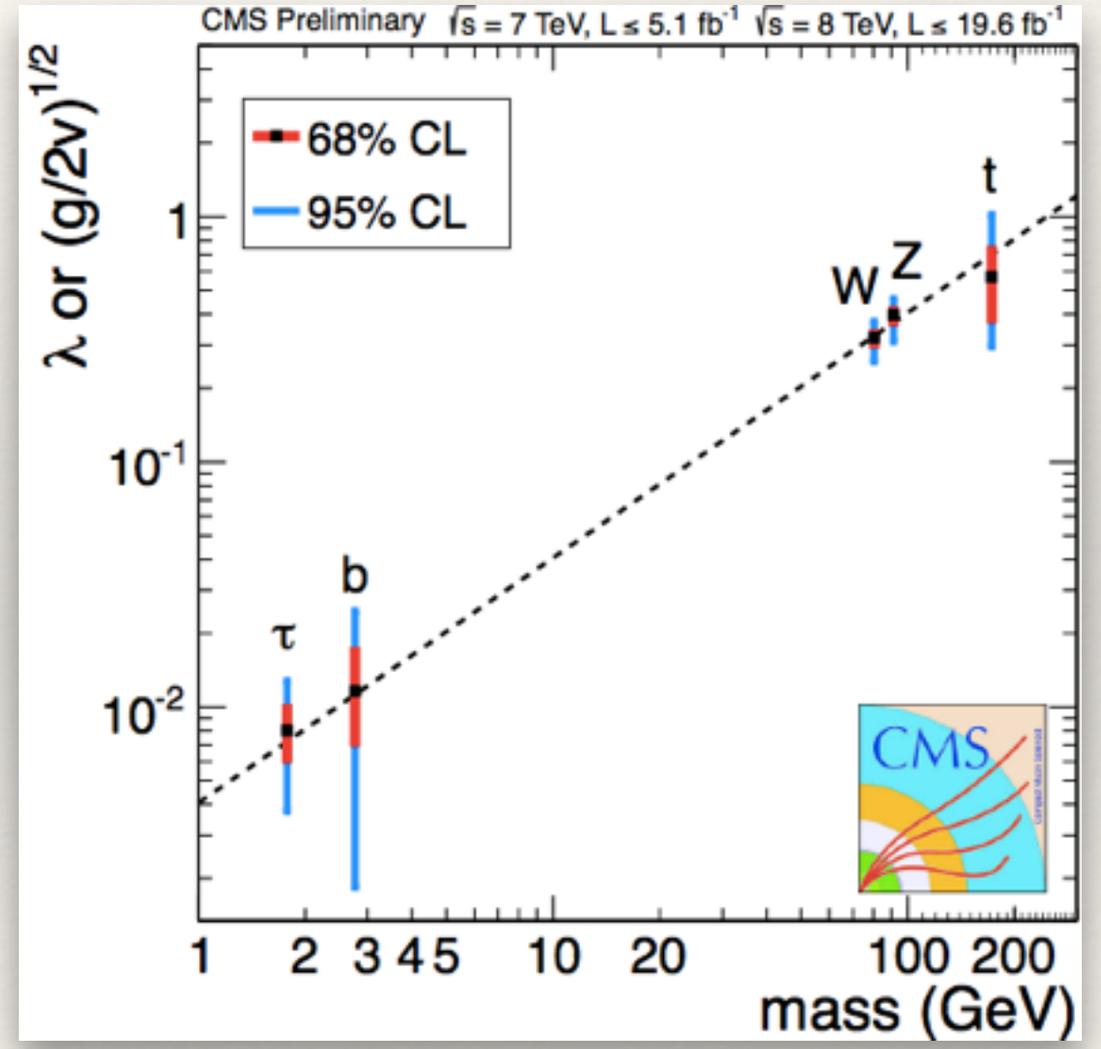
BSM in Higgs Sector

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

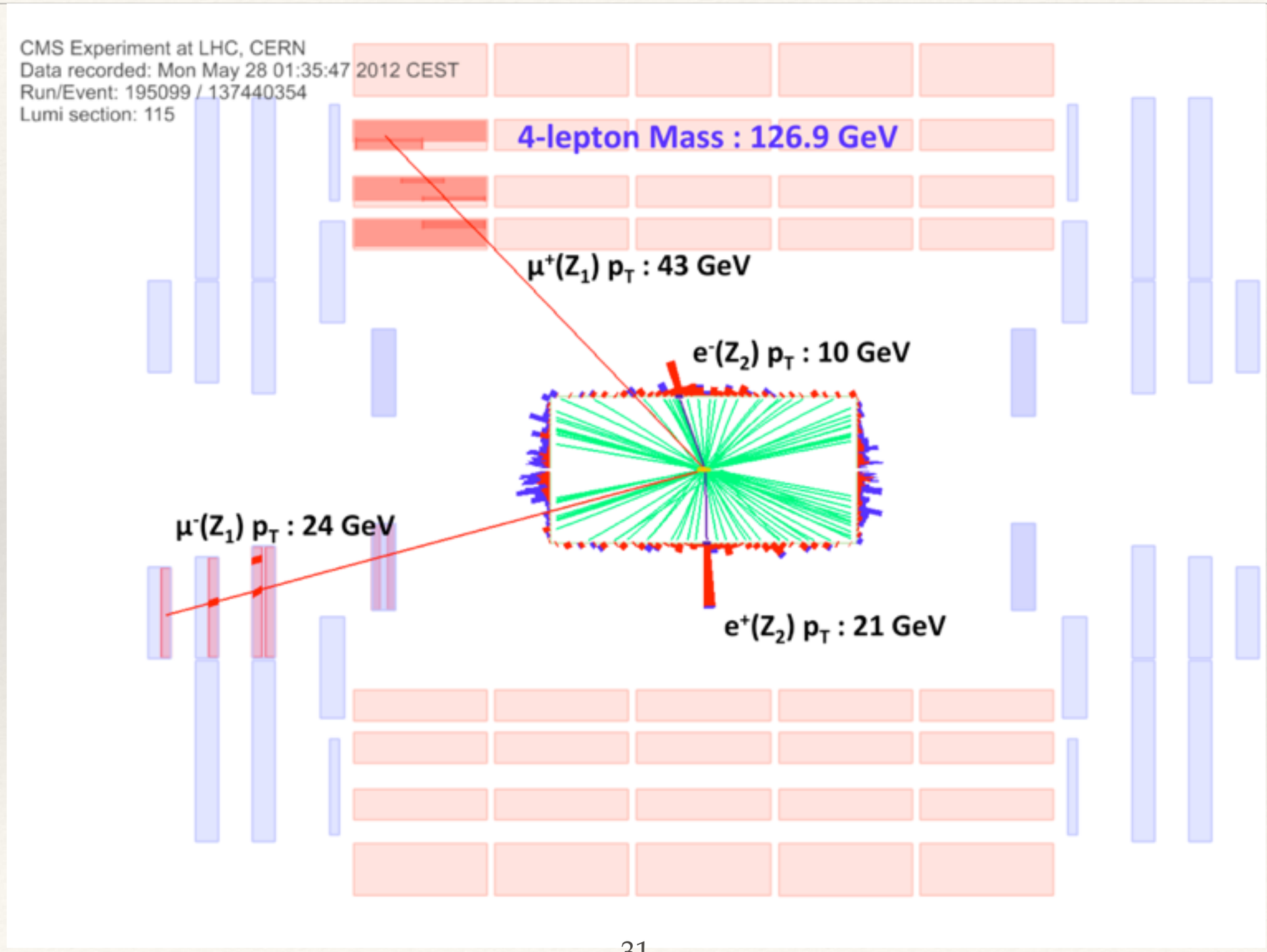
- **Experimental post-discovery approach**
  - **Measure (126 GeV) Higgs properties**
  - Search for additional Higgs bosons
  - Search for BSM in signatures with Higgs bosons
  - Search for BSM Higgs Higgs decays

Conclusion

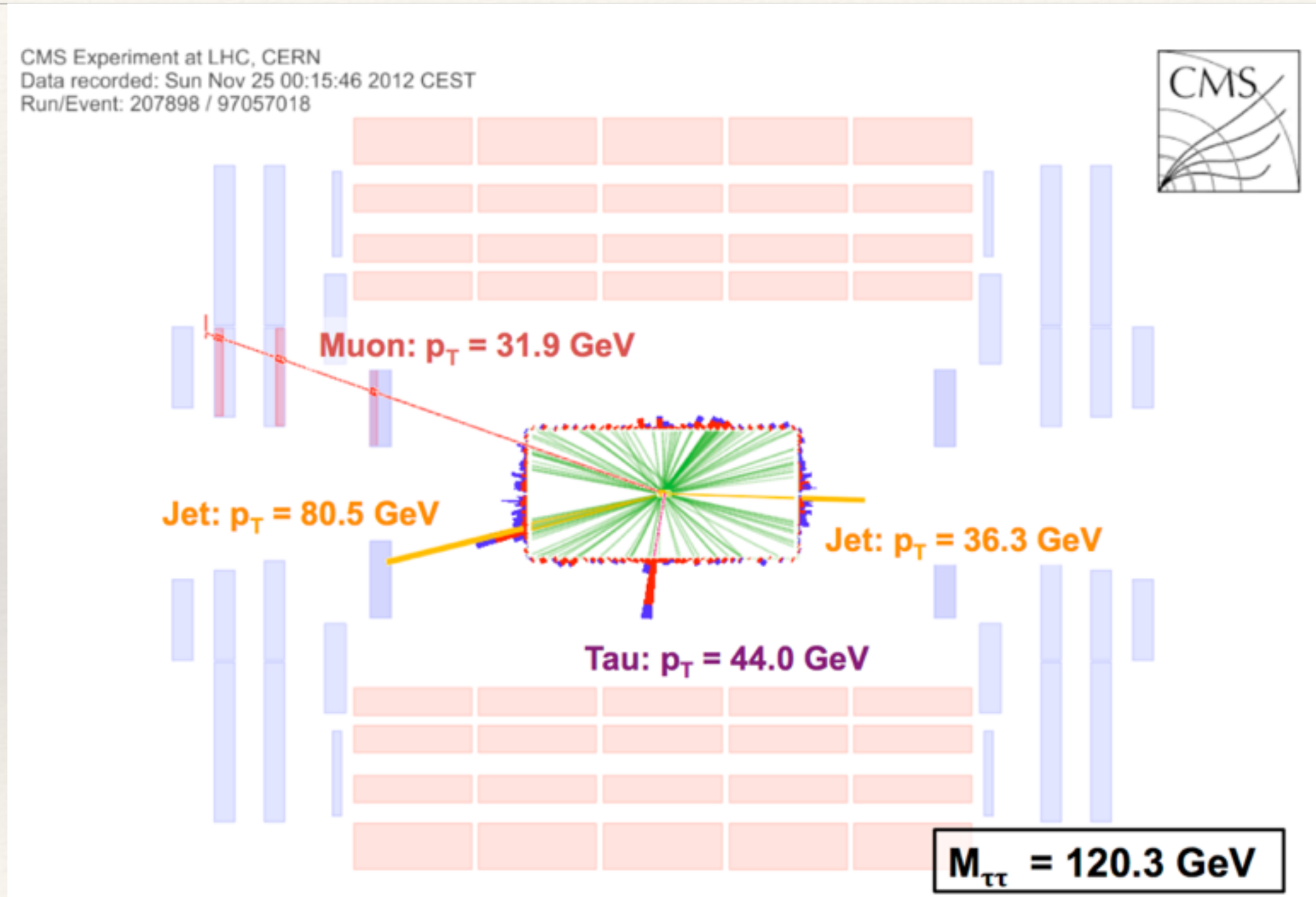
- **Wide range of Higgs production and decay channels studied in CMS**
- **Signatures of the Higgs boson compatible with the Standard Model**
  - Interpretations in numerous BSM models possible
  - Future precision measurements can unveil its true nature
- **Finalizing Run I Higgs results**
- **Preparing for Run II and beyond**



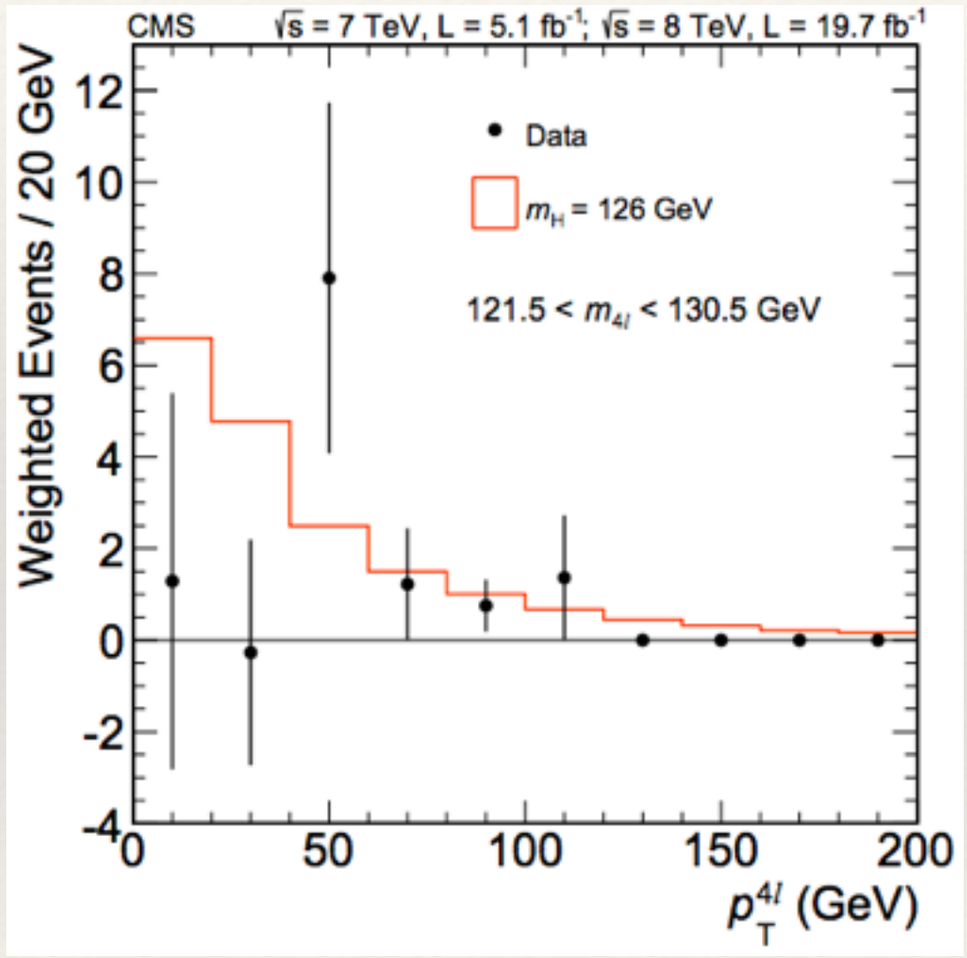
Higgs to Bosonic Decays



Higgs to Fermion Decays



Backup on Production Kinematic



Backup on ATLAS vs. CMS Higgs Summary

Channel	ATLAS Lumi [1/fb]	CMS Lumi [1/fb]	Specialty	Inclusive signature	σ Obs. (Exp.)	mass [GeV]	Signal Strength μ	Spin/ Parity
H → ZZ → 4l	4.6+20.7 ATLAS-CONF-2013-012	5.1+19.6 arXiv: 1312.5353	mass, discovery, spin/parity	4 leptons	6.6 (4.4) 6.8 (6.7)	124.5 ± 0.5 125.6 ±0.4 (stat) ±0.2 (sys)	1.7+0.5-0.4 0.93+0.29-0.25	√ √
H → WW → 2l2v	4.6+20.7 ATLAS-CONF-2013-030	4.9+19.5 arXiv: 1312.1129	cross section, coupling	2 leptons, MET	3.8 (3.7) 4.3 (5.8)	consistent 125 ± 4	1.01 ± 0.31 0.72+0.20-0.18	√ √
H → γγ	4.8+20.7 ATLAS-CONF-2013-012	5.1+19.6 CMS-PAS-HIG-13-001	mass, discovery, couplings	two photons	7.4 (4.3) 3.2 (4.2)	126.0 ± 0.5 125.4 ±0.5 (stat) ±0.6 (sys)	1.65+0.33-0.28 0.78+0.28-0.26	√ √
H → bb	4.7+20.3 ATLAS-CONF-2013-079	5.0+18.9 arXiv: 1310.3687	total width, coupling to fermions	two b-jets	- 2.1 (2.1)	consistent consistent	0.2 ± 0.7 1.0 ± 0.5	- -
H → ττ	20.3 ATLAS-CONF-2013-108	4.9+19.4 arXiv: 1401.5041	couplings to leptons	hadronic taus, leptons, MET	4.1 (3.2) 3.4 (3.6)	- 122 ± 7	1.4 + 0.5 - 0.4 0.78 ± 0.27	- -

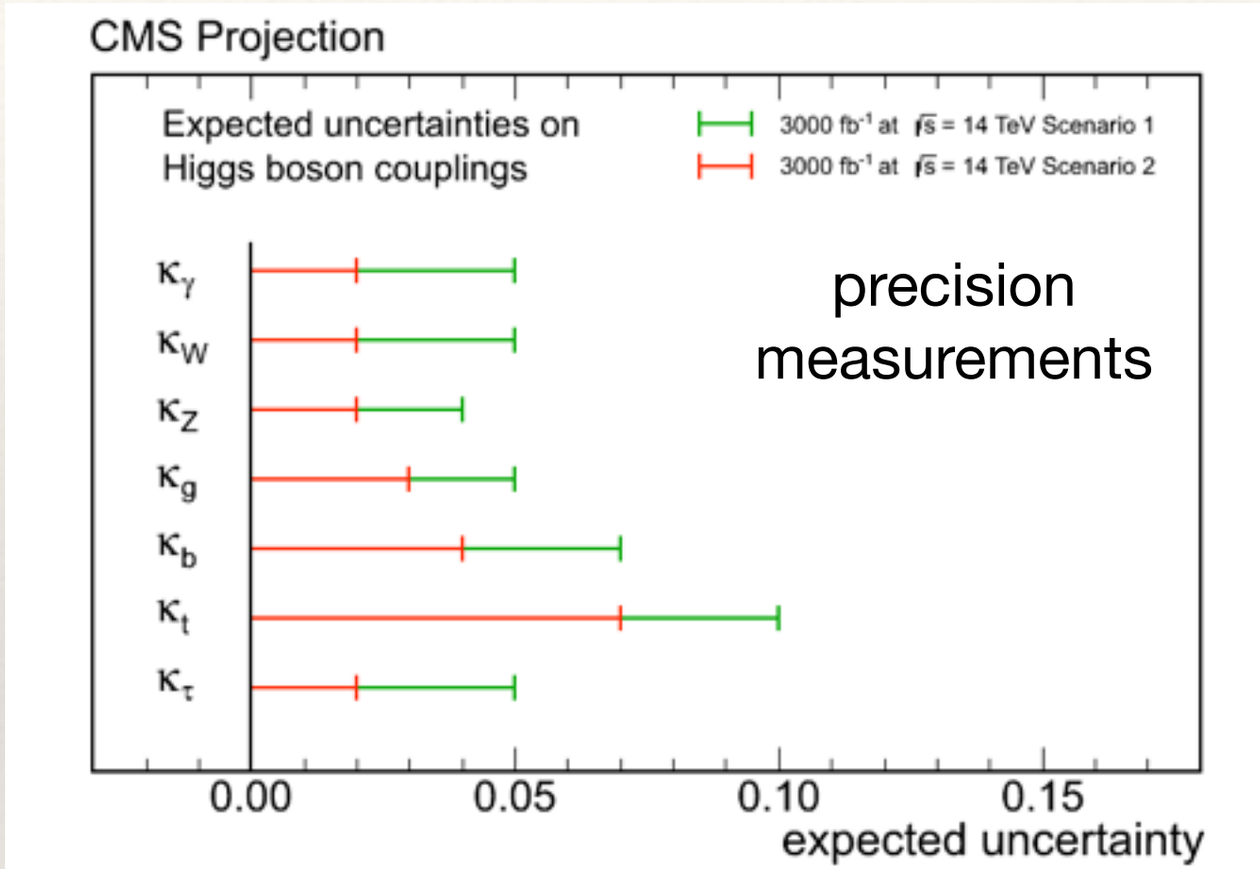
ATLAS masses updated

Backup on Prospects on Couplings

κ_g, κ_γ, $\kappa_{Z\gamma}$: loop diagrams ➜ allow potential new physics
κ_W, κ_Z: vector bosons
κ_t, κ_b: up- and down-type quarks
κ_τ, κ_μ: charged leptons
total width from sum of partial widths

Assumptions on systematic uncertainties
Scenario 1: no change
Scenario 2: Δ theory / 2, rest ∝ 1/√L

coupling precision 2-10 %
factor of ~2 improvement from HL-LHC



L (fb^{-1})	κ_γ	κ_W	κ_Z	κ_g	κ_b	κ_t	κ_τ	$\kappa_{Z\gamma}$	κ_μ
300	[5,7]	[4,6]	[4,6]	[6,8]	[10,13]	[14,15]	[6,8]	[41,41]	[23,23]
3000	[2,5]	[2,5]	[2,4]	[3,5]	[4,7]	[7,10]	[2,5]	[10,12]	[8,8]