Higgs properties at CMS

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On behalf of the CMS
Collaboration

La Thuile, 28/02/1014

CMS
Compact Muon Solenoid

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dépasser les frontières

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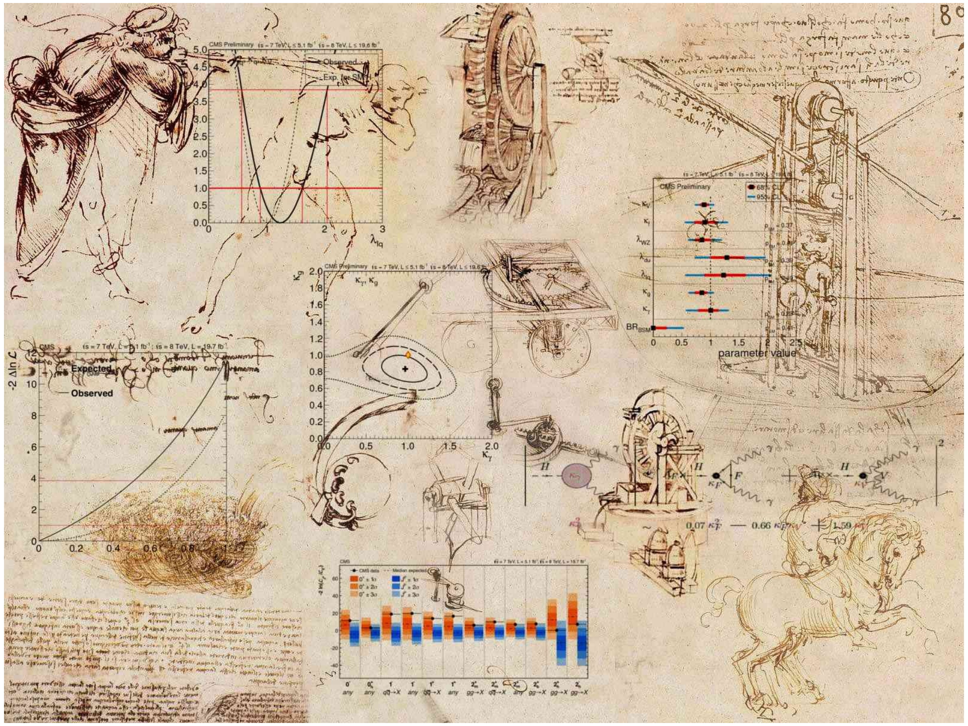
Presented results

- Higgs combination (does not contain the latest results from individual channels*)
  - ↳ April 2013 **[CMS-PAS-HIG-13-005]**
- Properties from H→γγ
  - ↳ July 2013 **[CMS-PAS-HIG-13-016]**
- Properties from H→WW **(NEW)**
  - ↳ December 2013 **[JHEP01(2014)096]**
- Properties from H→ZZ→4l **(NEW)**
  - ↳ December 2013 **[arXiv:1312.5353, Submitted to Phys. Rev. D]**

(*) no Run-1 legacy H→ZZ, WW, ττ, no $t\bar{t}H$→multileptons, ...

Why and how studying Higgs properties?

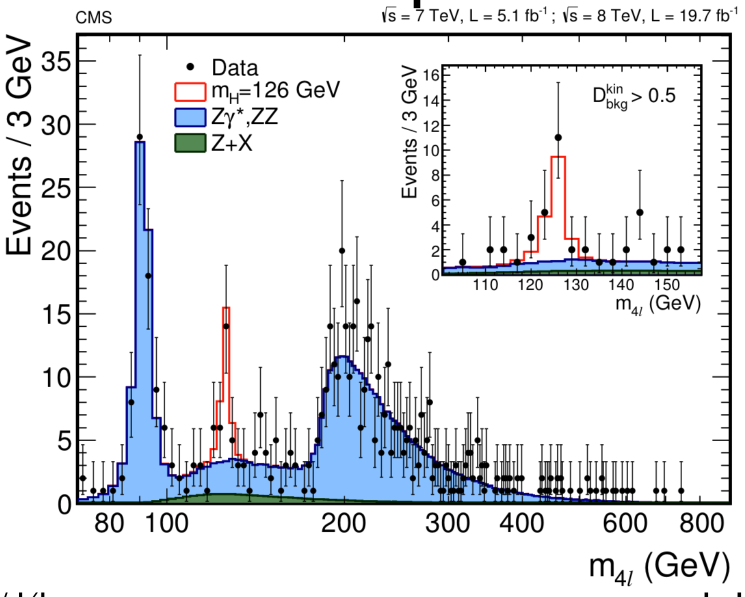
- The discovery of the Higgs-like boson is a discovery of new physics and therefore opened a completely unexplored area
- The nature of the electroweak symmetry breaking mechanism can be probed in an unprecedented manner
  - ↳ Precision measurements in the new scalar sector may open a sensitivity to additional new physics
- Different tools are already available to sketch the Higgs sector
  - ↳ Mass and width
  - ↳ Coupling strengths
    - – Assuming SM coupling structure
  - ↳ Spin-parity and coupling structure
    - – Based on kinematic alone



Observation

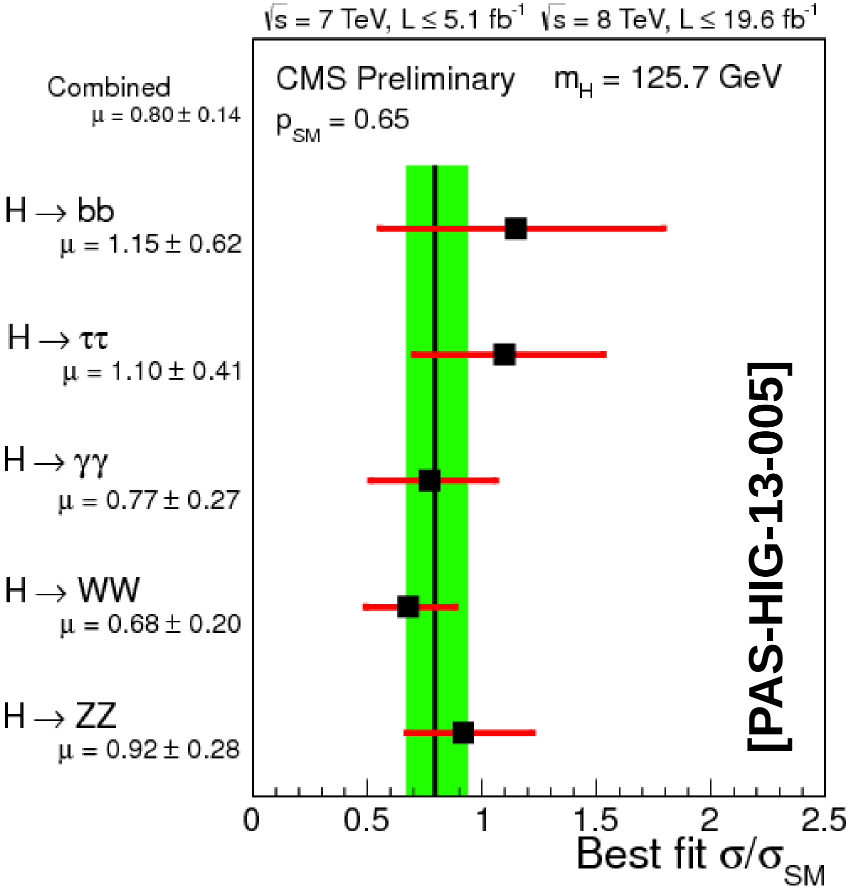
- The Higgs-like particle has been observed in different channels
- Bosonic channels (H → γγ, WW, ZZ) are the most significant
  - ↳ With a standalone discovery in the ZZ → 4l final state
- And strong evidence of fermionic decays
  - ↳ See CMS talk by J. Swanson
- Rates are in agreement with a SM Higgs
  - ↳ … within current (large) uncertainties
- Starting point for property studies

4l mass spectrum



[arXiv:1312.5353]

Signal strengths

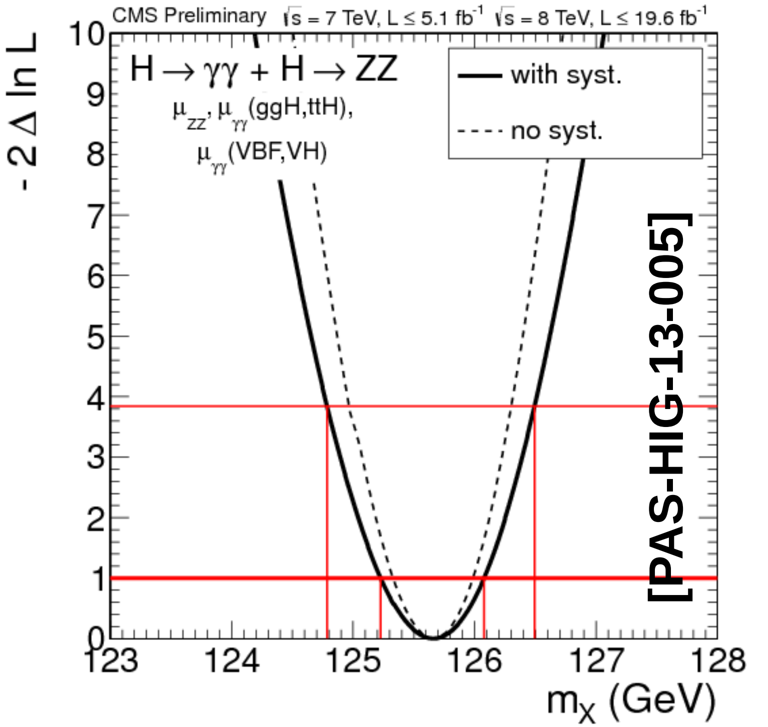


[PAS-HIG-13-005]

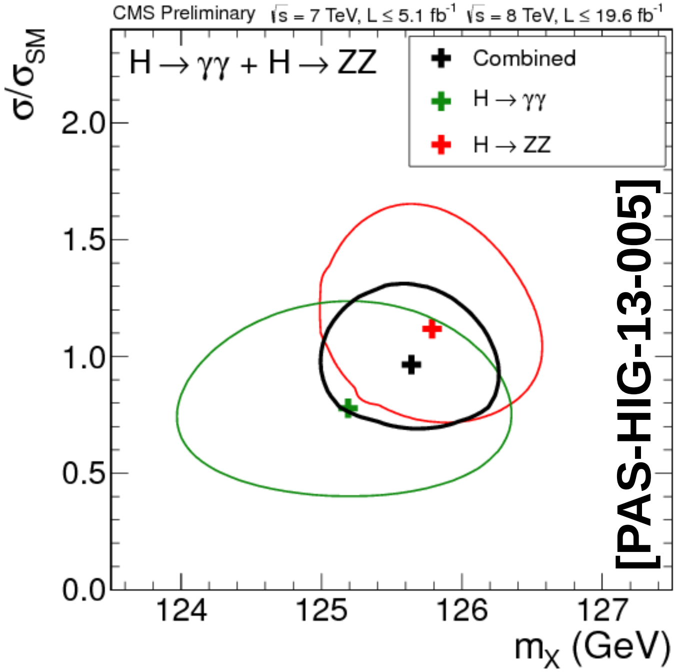
Mass

- With high resolution channels (γγ and ZZ→4l)
  - Assuming it is the same particle
- Combined mass measurement
  - 125.7 ± 0.3(stat) ± 0.3(sys) GeV
  - Good compatibility between γγ and ZZ→4l masses before combination
    - <u>γγ</u>: 125.4 ± 0.5(stat.) ± 0.6(syst.) GeV
    - <u>ZZ→4l</u>: 125.8 ± 0.5(stat.) ± 0.2(syst.) GeV
- To be compared with the latest ZZ→4l measurement **[arXiv:1312.5353]**
  - 125.6 ± 0.4 (stat.) ± 0.2 (syst.) GeV

Combined mass



[PAS-HIG-13-005]

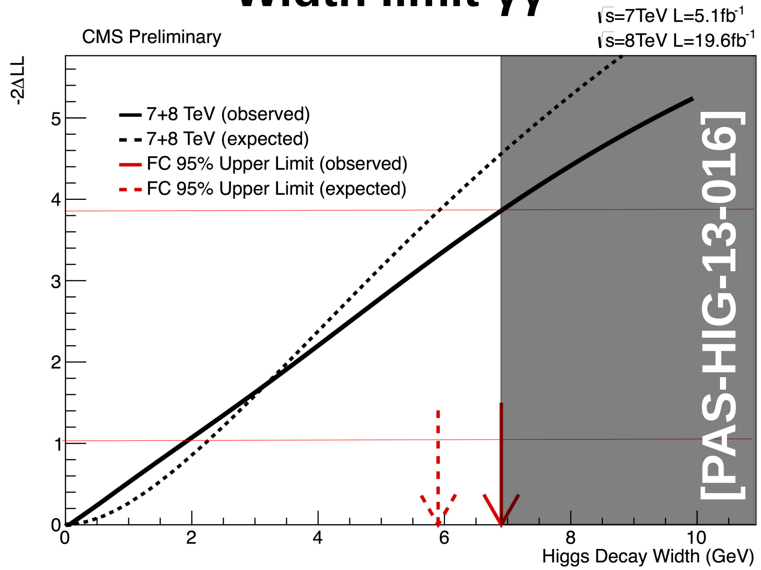


[PAS-HIG-13-005]

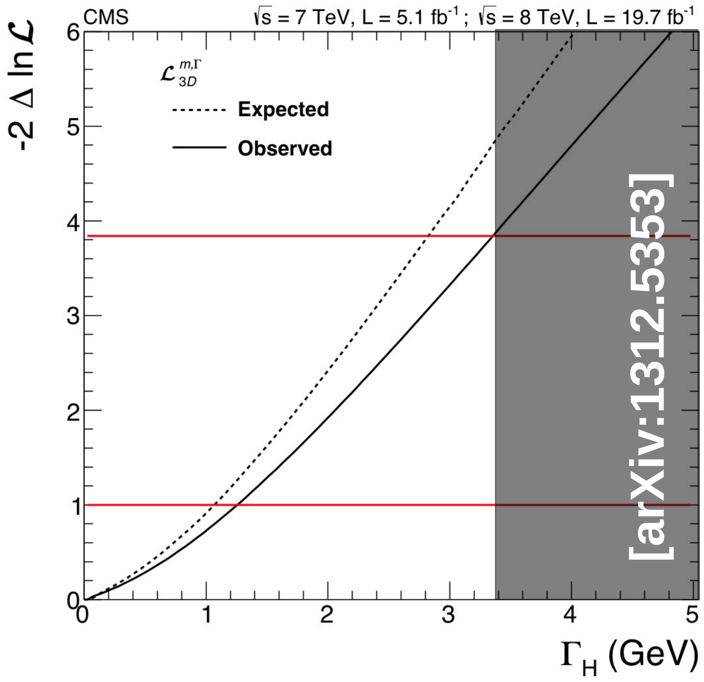
Width

- Measured separately in γγ and ZZ→4l channels using the peak width
  - Driven by detector resolutions
  - Only limits far from the SM Higgs width can be set
    - ZZ→4l: < 3.4 GeV @95% CL
    - γγ: < 6.9 GeV @95% CL
  - Much improved width sensitivity is expected from off-shell production measurement in the H*→ZZ channels
    - CMS result coming soon!

Width limit γγ



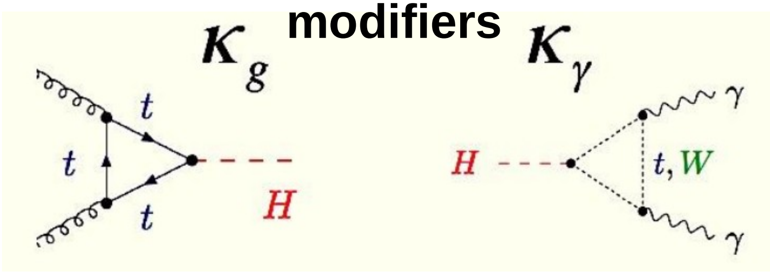
Width limit ZZ→4l



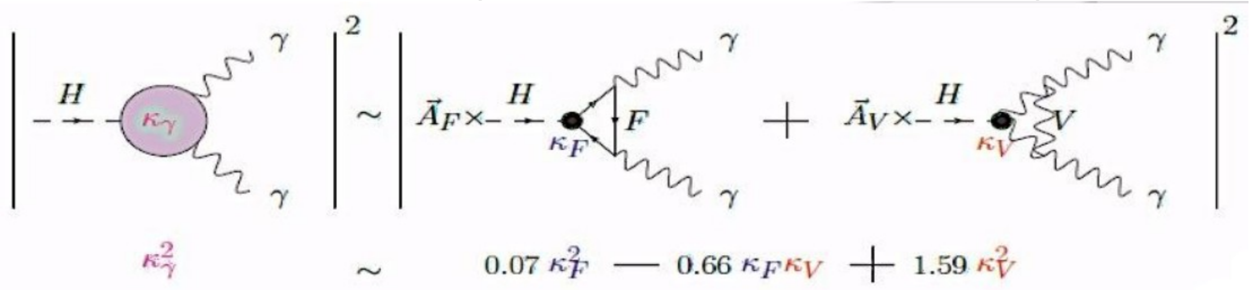
Coupling strength measurements

- SM tensor structure ($J^{CP} = 0^{++}$)
  - ↳ Only allow modifications of coupling strengths
- Narrow resonance approximation
  - ↳ Production and decay factorize: $\sigma \cdot BR(xx \to H \to yy) = \sigma(xx) \cdot \Gamma_{yy} / \Gamma_{tot}$
- Deviations from SM predictions are assessed by parameterizing σ and Γ in terms of multiplicative modifiers κ (or their ratios λ)
  - ↳ Parameterizations are LO in κ around the state of the art SM prediction
- Different benchmark parameterizations are used to test for possible BSM scenarios **[arXiv:1209.0040, LHC Higgs XS WG YR3]**
  - ↳ With assumptions on some modifiers
  - ↳ Possible to use effective couplings for loop-induced couplings, or derive them based on tree-level couplings

Effective loop-induced coupling modifiers



Hγγ coupling from tree-level couplings

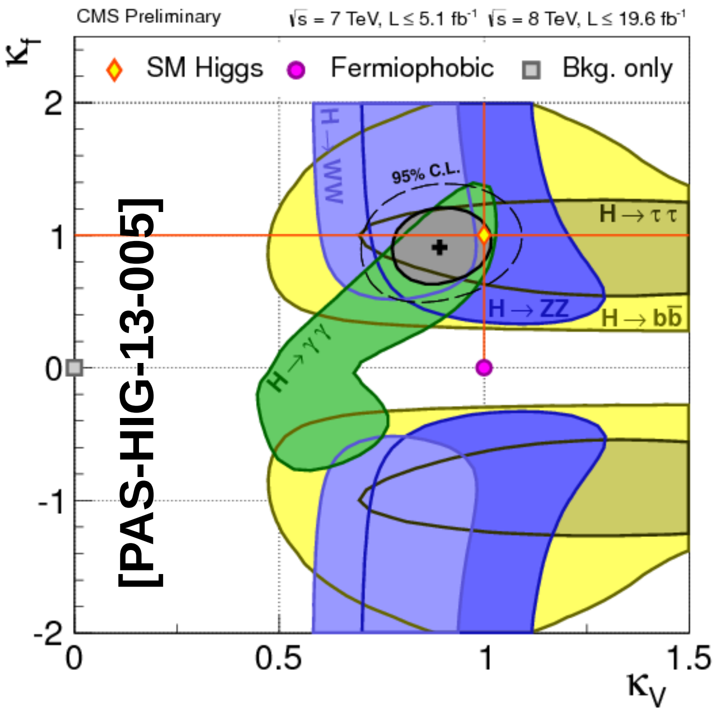


$$\left| \kappa_\gamma \right|^2 \sim \left| \vec{A}_F \times \kappa_F + \vec{A}_V \times \kappa_V \right|^2$$

$$\kappa_\gamma^2 \sim 0.07\,\kappa_F^2 - 0.66\,\kappa_F \kappa_V + 1.59\,\kappa_V^2$$

Fermion and boson couplings

- Higgs couplings to fermions and bosons come from two distinct parts of the Higgs sector
- The simplest benchmark model introduces two universal modifiers for these couplings
  - ggH and Hγγ loop-induced couplings are interpreted in terms of tree level couplings
  - Assume no BSM contributions in loops and decays
  - The relative sign of κ_V and κ_f can be assessed from interference between quark and W loops in Hγγ
- κ_V more constrained than κ_f
  - Bosonic channels more significant
- Positive couplings are preferred, with a good compatibility with SM

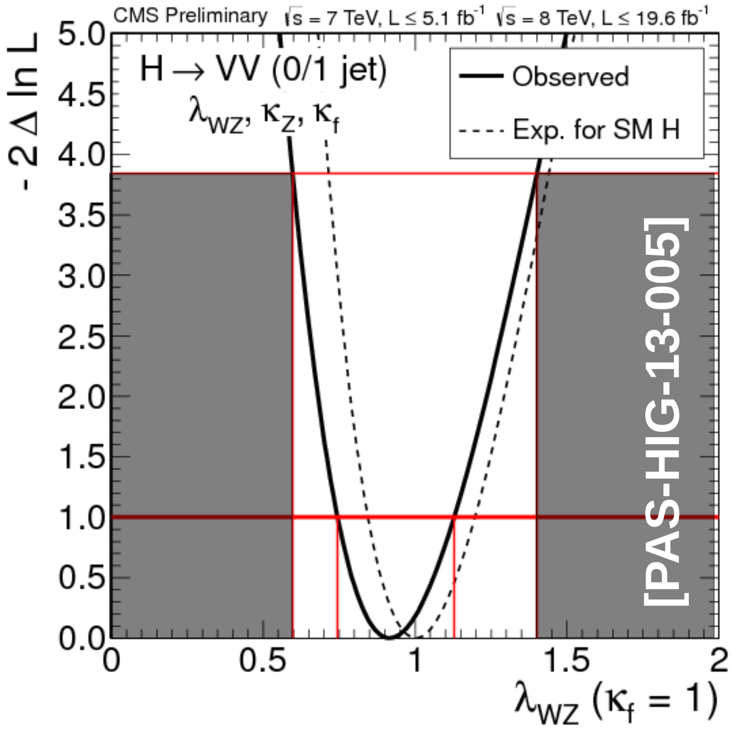


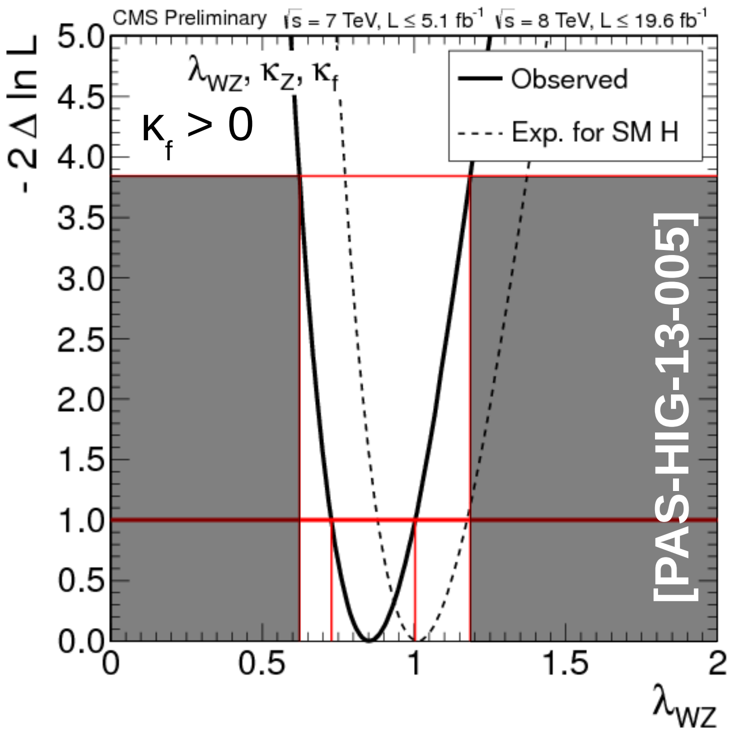
[PAS-HIG-13-005]

Custodial symmetry

- Custodial symmetry fixes the ratio between the W and Z couplings to the SM one
- It has been tested in two ways, looking at $\lambda_{WZ} = \kappa_W / \kappa_Z$
  - ↳ Directly from BR(H→WW) / BR(H→ZZ) = λ_{WZ}^2 in 0/1 jet categories
    - [0.60,1.40] @95% CL
  - ↳ From a combined fit of the couplings (including information from VBF, VH, Hγγ)
    - [0.62, 1.19] @95% CL

From H→VV



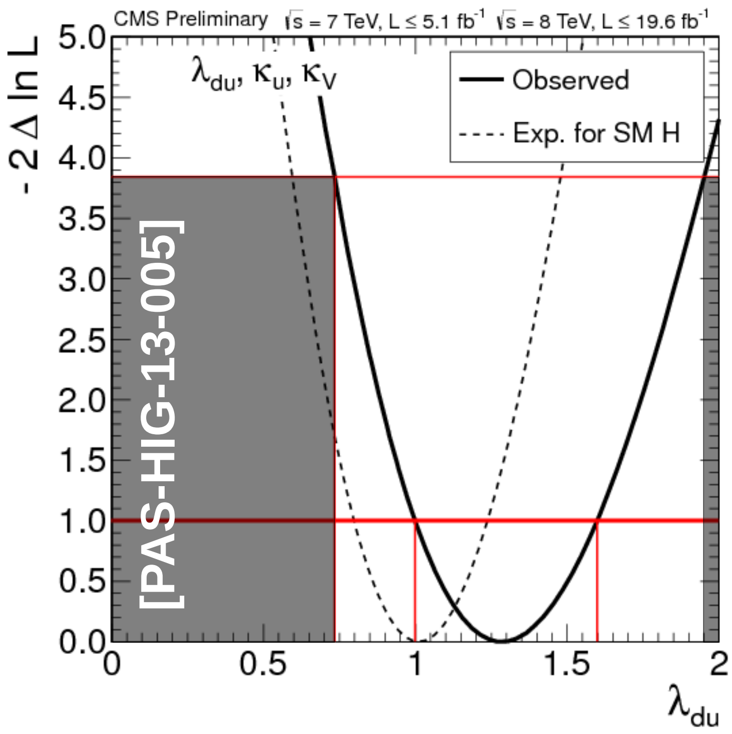


From all channels

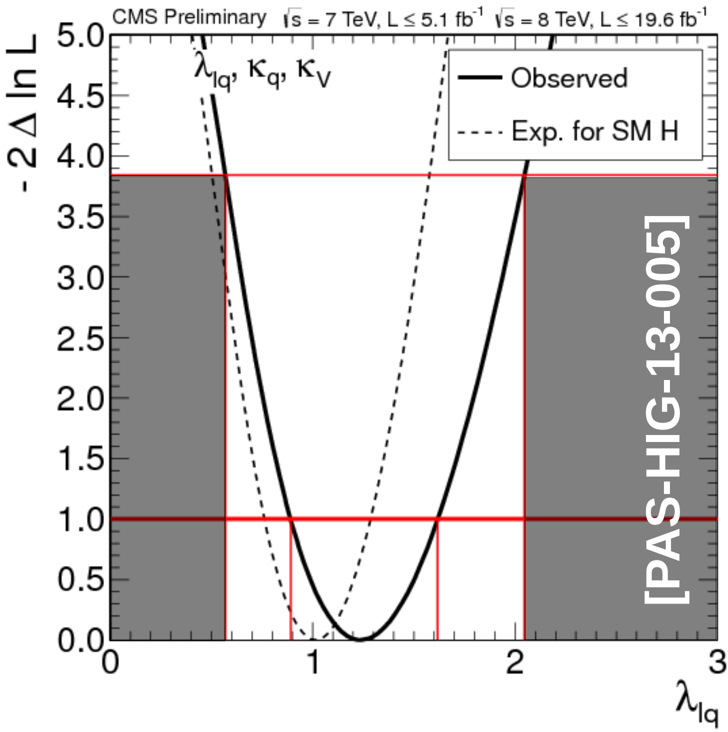
Fermion non-universality

- Some BSM theories predict Yukawa couplings modifiers that depend on the fermion type (e.g., 2HDM)
  - ↳ Differences between up-type and down-type fermions
  - ↳ Differences between leptons and quarks
- Measured modifier ratios (constrained to be positive) are in agreement with SM
  - ↳ $\lambda_{du} = \kappa_d / \kappa_u \in [0.74,1.95]$ @95% CL
  - ↳ $\lambda_{lq} = \kappa_l / \kappa_q \in [0.57,2.05]$ @95% CL

up-down



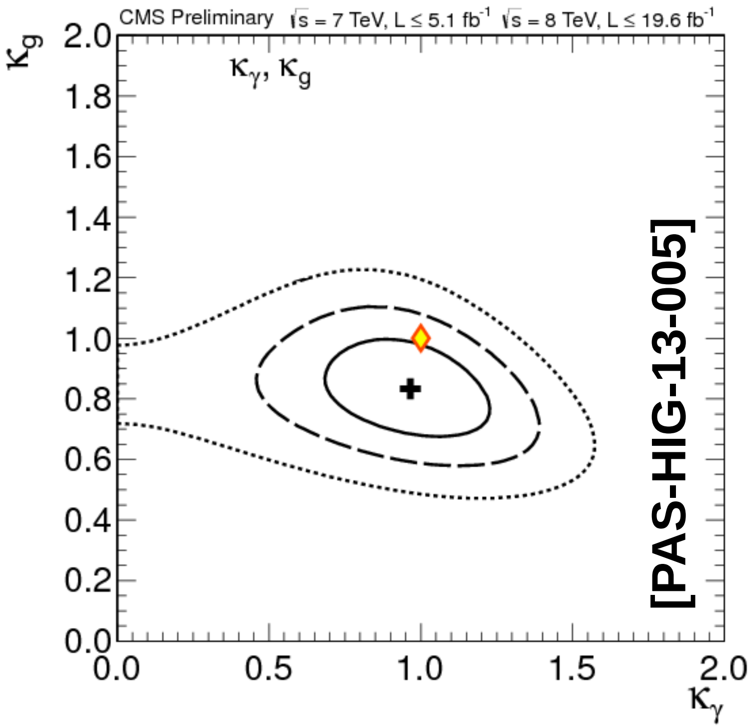
Lepton-quark



BSM in loops

- Loop-induced couplings are particularly sensitive to the presence of new particles
  - ↳ Effective gluon and photon couplings are considered free in the fit
  - ↳ With the assumption of SM tree-level couplings
- $\kappa_\gamma \in [0.59, 1.30]$ @95%CL
- $\kappa_g \in [0.63, 1.05]$ @95%CL

Effective loop-induced couplings

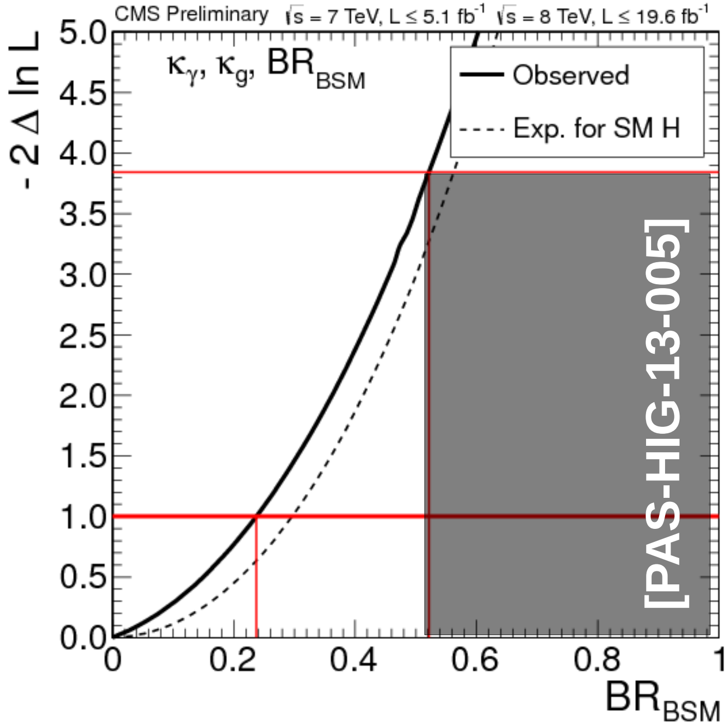


[PAS-HIG-13-005]

BSM in decay

- BSM effects can also appear in decays to non-SM states
  - ↳ Width parameterized with additional Γ(BSM)
    - – Taking into account both invisible and undetectable decays
  - ↳ Fixed SM tree-level couplings and free loop-induced couplings
- $BR_{BSM} < 0.52$ @95% CL
- To be compared with direct searches (of invisible decays)
  - ↳ VBF, H→inv: $BR_{BSM} < 0.69$ @95% CL
  - ↳ VH, H→inv : $BR_{BSM} < 0.75$ @95% CL

BSM in decay

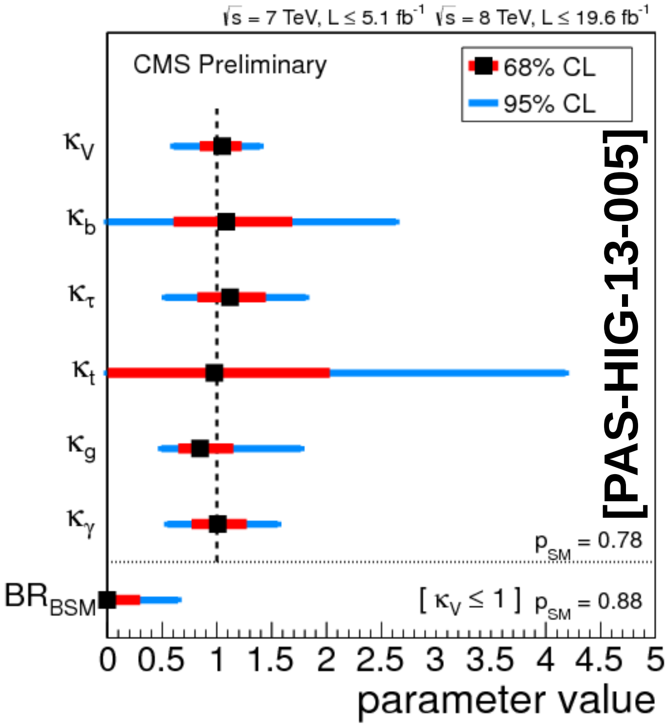


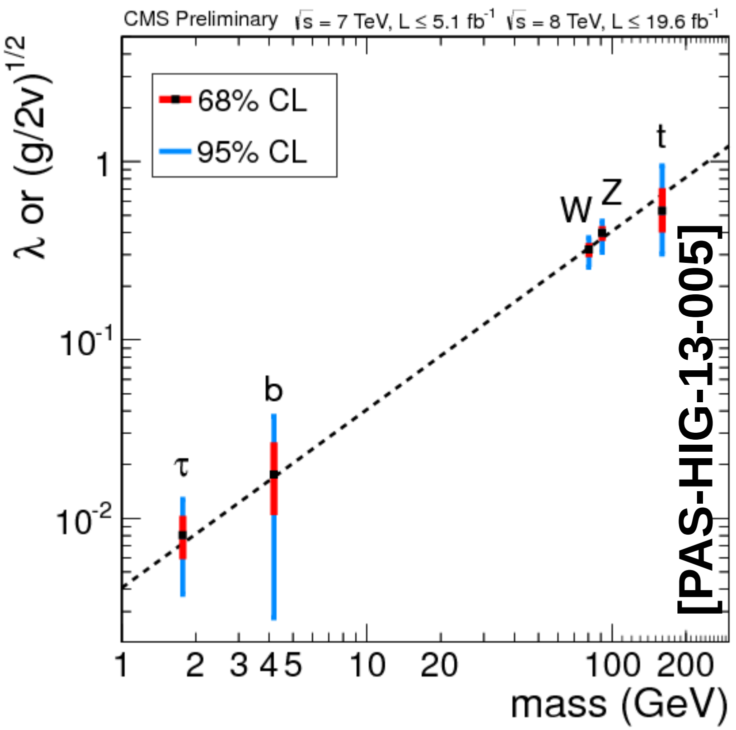
[PAS-HIG-13-005]

More general (less constrained) fits

- 6 parameters
  - ↳ Assuming custodial symmetry
  - ↳ Couplings to 3rd generation fermions are scaled independently
    - – κ_t obtained from $t\bar{t}H$
  - ↳ Effective couplings to gluons and photons

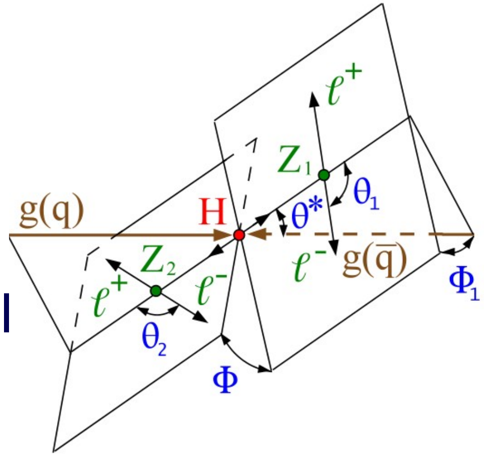
- 5 parameters
  - ↳ Assuming just SM particles in loops
  - ↳ Top coupling from ggH



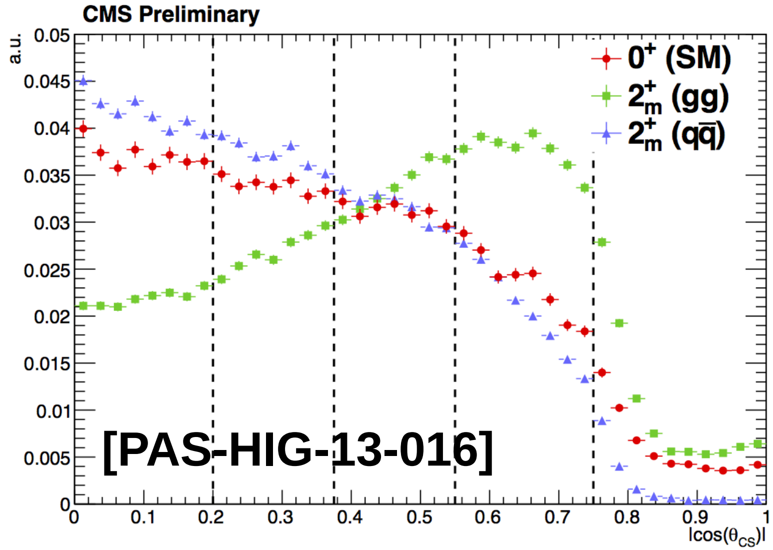


Spin and parity

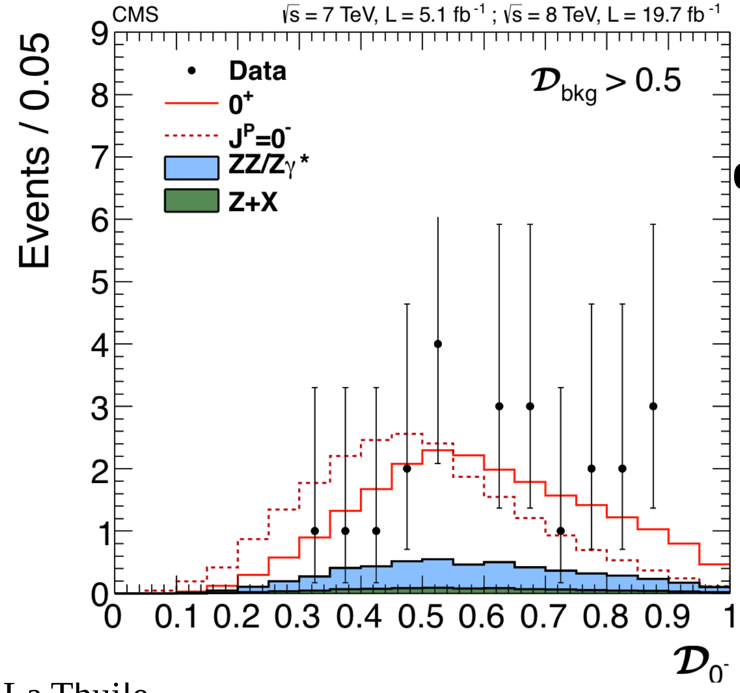
- Spin-parity state and tensor structure have been probed with kinematic information
  - ↳ cos(θ*) for H→γγ
  - ↳ m_T and m_{ll} for H→WW
  - ↳ Discriminants based on angles and masses for H→ZZ→4l
- Decay to photons is forbidden for spin 1
  - ↳ Nervertheless, spin 1 hypotheses are also tested in ZZ→4l (assuming different resonances)



H→γγ cos(θ*)



[PAS-HIG-13-016]

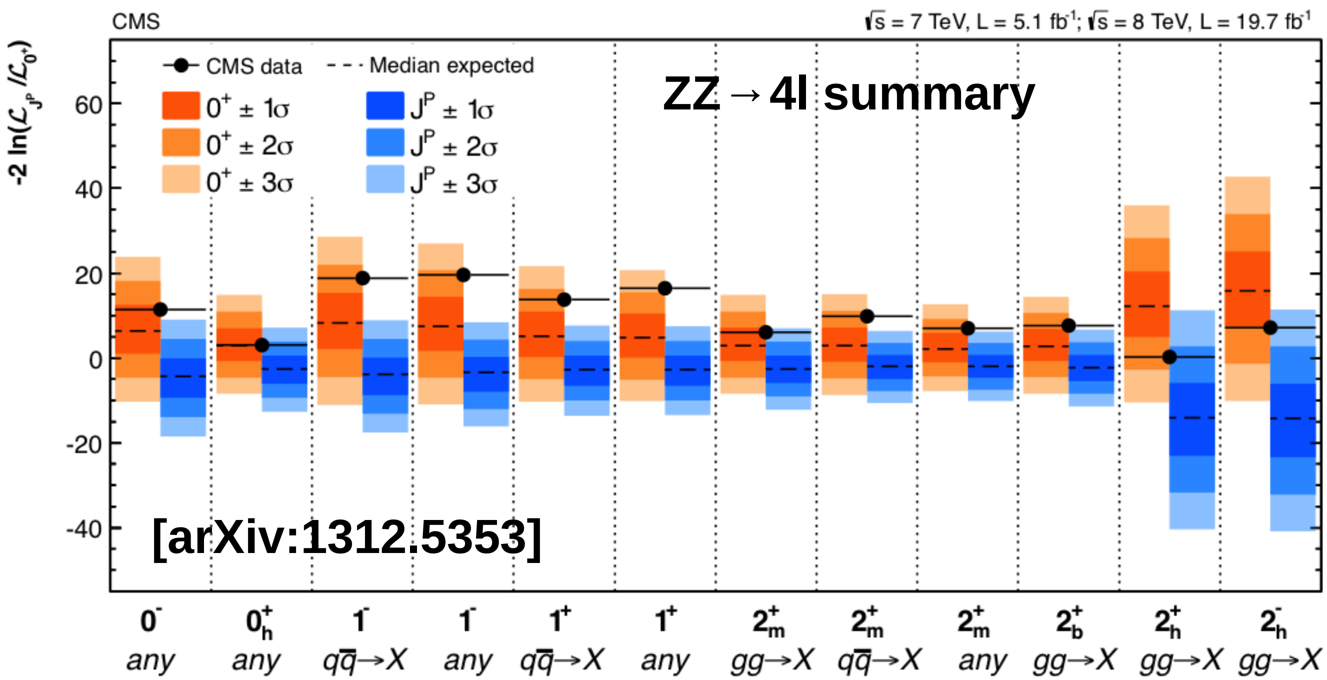


ZZ→4l 0- discriminant

[arXiv:1312.5353]

Spin and parity pure states

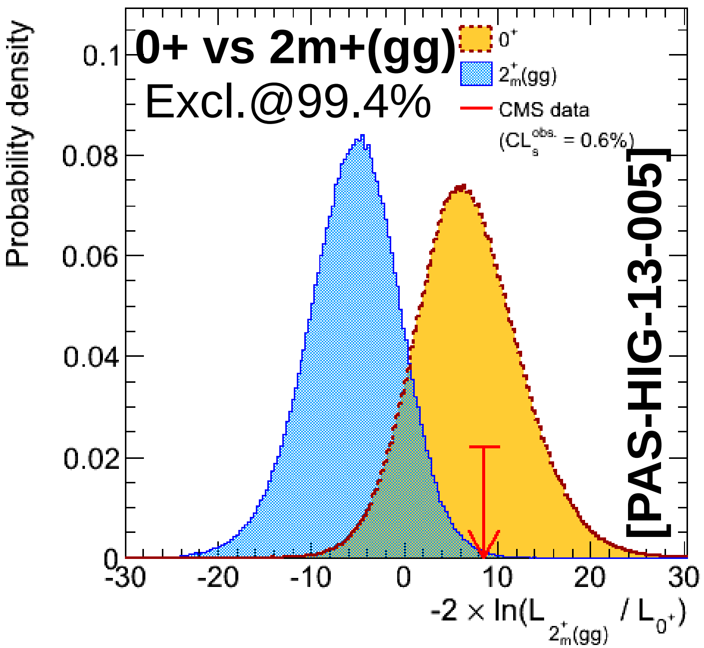
- H → ZZ → 4l is a well-suited channel for probing J^P
  - ↳ Kinematic fully reconstructed (with 5 angles and 2 masses)
  - ↳ High signal over background ratio
- Various spin 0, 1, 2 hypotheses have been tested (production dependent and independent)
  - ↳ All hypotheses are excluded at more than 95% CL, except 2_h^+, 0_h^+
- Also the 2_m^+(gg) model has been tested in the April 2013 combination



ZZ→4l summary

[arXiv:1312.5353]

Combination



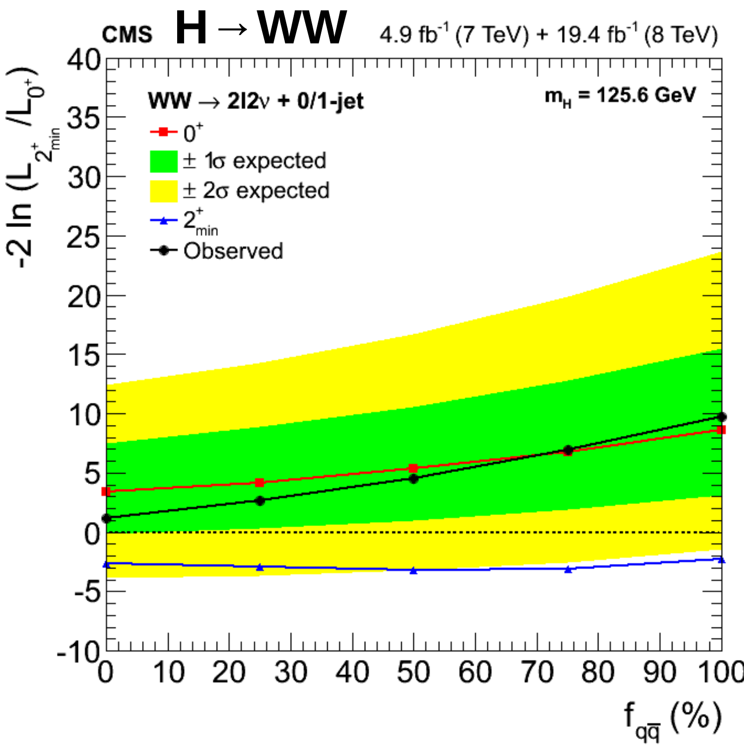
0+ vs 2m+(gg)

Excl.@99.4%

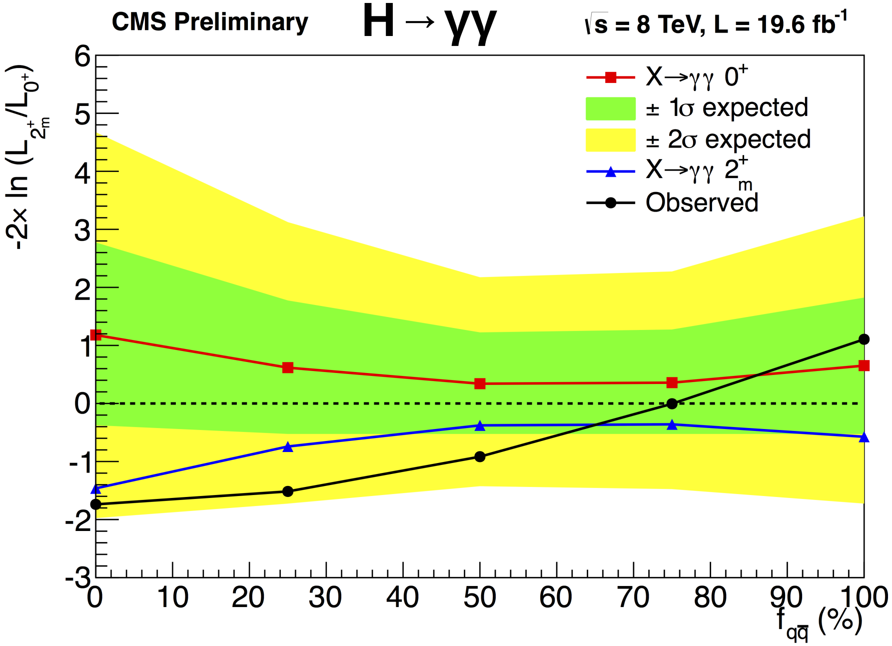
[PAS-HIG-13-005]

2_m^+ exclusion vs $q\bar{q} \to X$ fraction

- The relative 2^+ production via $q\bar{q}$ or gg is unknown
  - ↳ 2^+ hypotheses can be tested in a production independent way (as in ZZ→4l)
  - ↳ Or different production hypotheses can been tested
- Tested in the γγ and WW channels
  - ↳ 100% $q\bar{q}$ rejected in WW @ >99% CL
  - ↳ Separation power in γγ still too weak to make any statement



[JHEP01(2014)096]

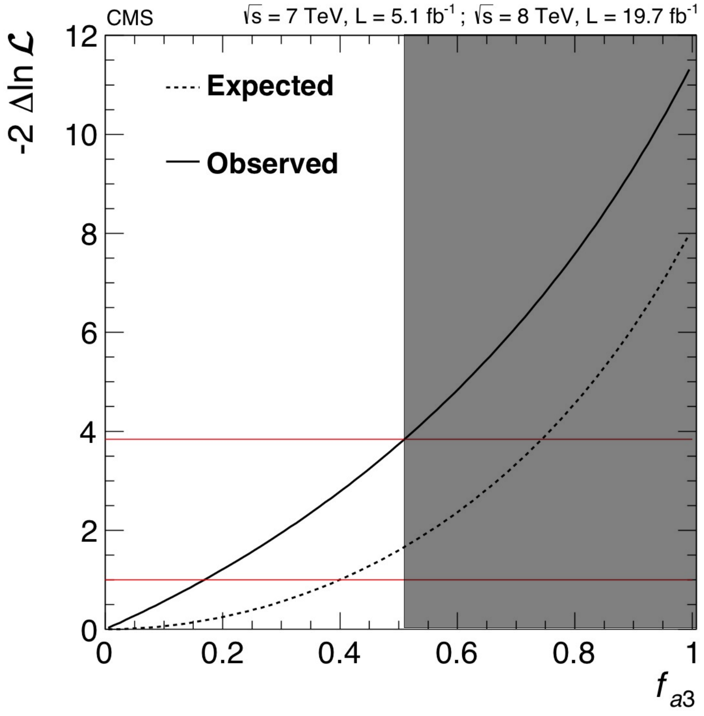


[PAS-HIG-13-016]

HZZ spin-0 tensor structure

$$A(\mathrm{H}\to\mathrm{ZZ}) = v^{-1}\left(a_1 m_Z^2 \epsilon_1^* \epsilon_2^* + \cancel{a_2 f_{\mu\nu}^{*(1)}} f^{*(2),\mu\nu} + \boxed{a_3 f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}}\right)$$

- Possible CP-odd contribution (a_3), higher order CP-even contributions (a_2)
- Here only CP-odd – CP-even mixture has been probed, with a_2=0, and without phase determination
  - $f_{a3} = \frac{|a_3|^2 \sigma_3}{|a_1|^2 \sigma_1 + |a_3|^2 \sigma_3}$
  - $f_{a3} = 0$ → 0+
  - $f_{a3} = 1$ → 0-
  - $0 < f_{a3} < 1$ → CP violation



[arXiv:1312.5353]

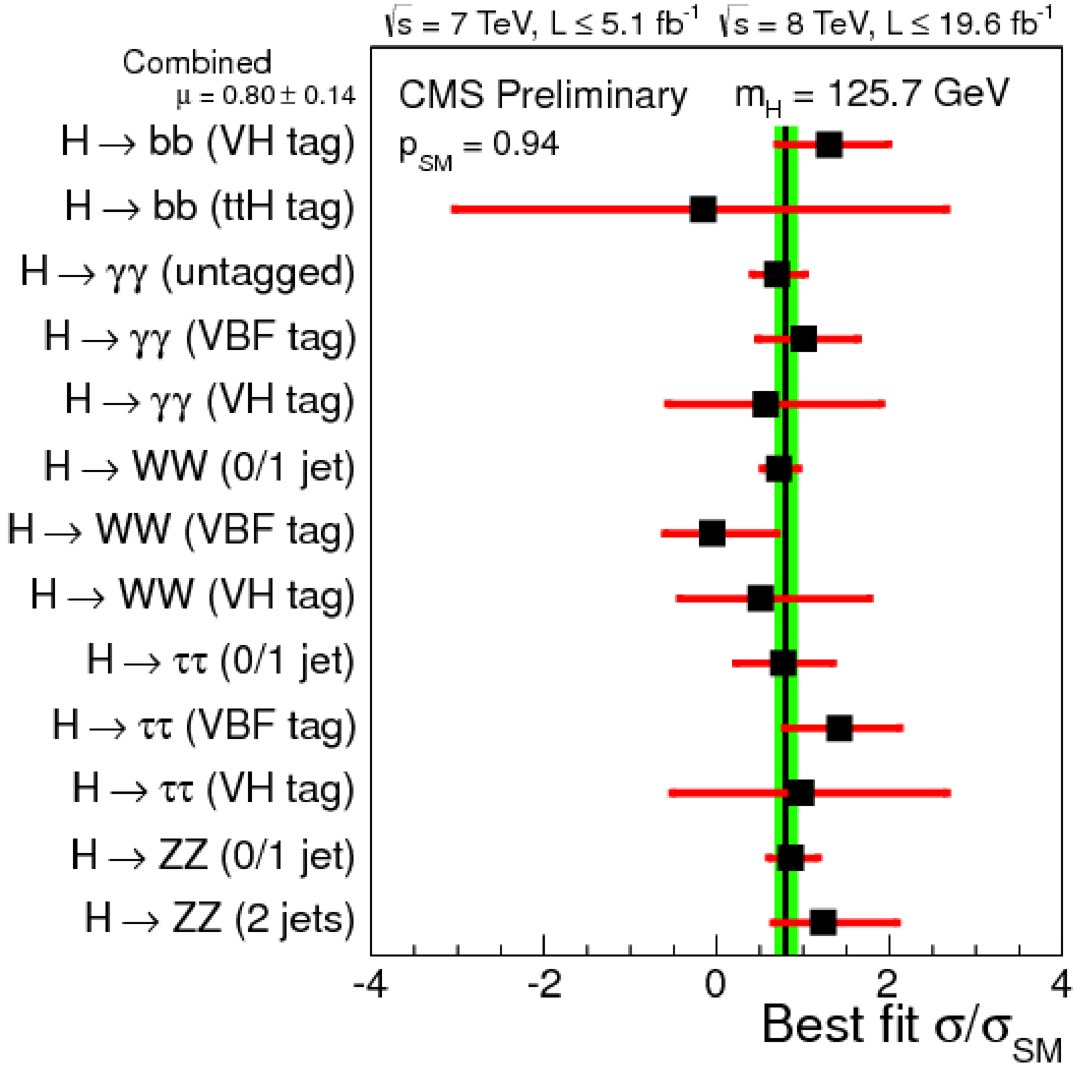
- $\boxed{f_{a3} < 0.51 \text{ @95\% CL}}$
  - Consistent with 0, expected for SM
- Limit of 0.13 (0.04) expected with 300 fb^{-1} (3000 fb^{-1})
  - Such measurements will become very important in the next runs of the LHC

Conclusion

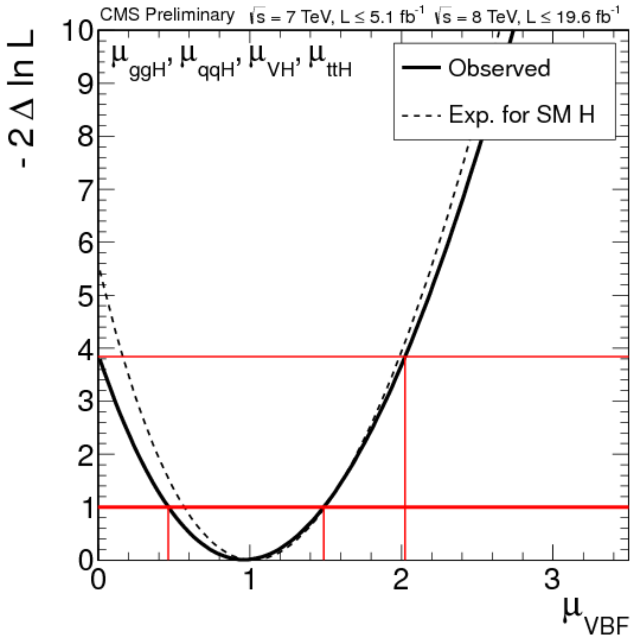
- No significant deviations from the SM predictions have been observed so far in Run-1 data
  - ↳ Both in the coupling strengths and in spin-parity studies
- But it is only the beginning of the story
  - ↳ More production and decay modes will become accessible in the next run of the LHC
  - ↳ … and in parallel we'll have more data in already well-established channels
  - ↳ Which will give a much more precise picture of the Higgs couplings (strengths and structure)
- And many new physics scenarios can have a Higgs boson with properties close to the SM one.

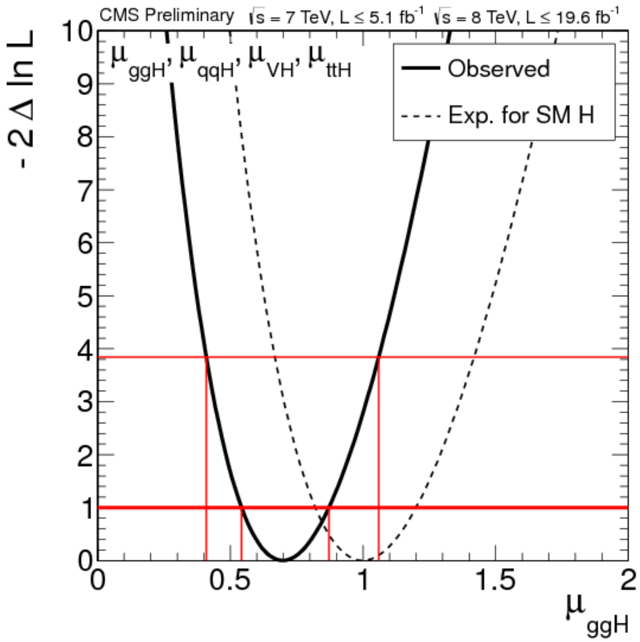
Backup

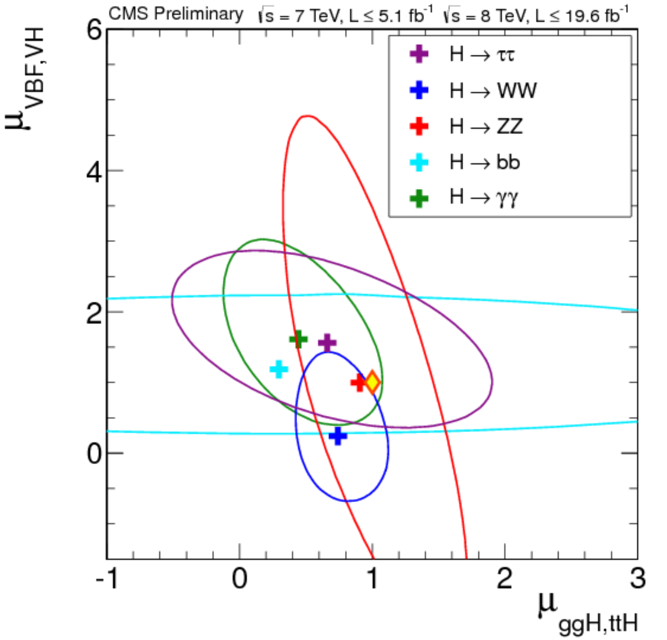
Combination signal strengths

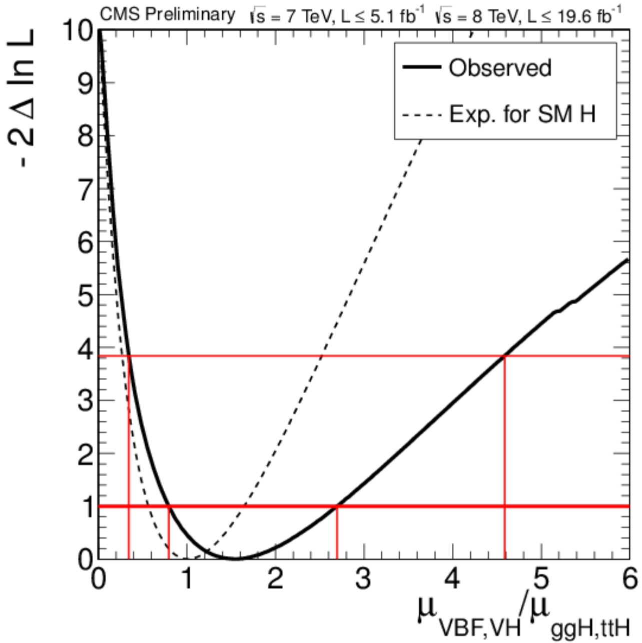


Combination: ggH, VBF

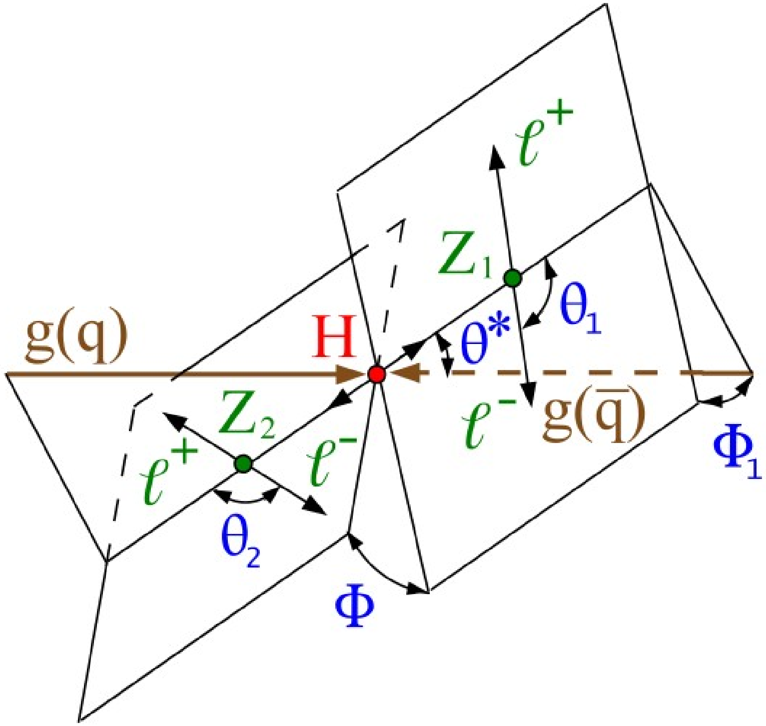








HZZ: probabilities



$$\mathcal{P}_{\mathrm{bkg}} = \mathcal{P}^{\mathrm{kin}}_{\mathrm{bkg}}(m_{Z_1}, m_{Z_2}, \vec{\Omega} | m_{4\ell}) \times \mathcal{P}^{\mathrm{mass}}_{\mathrm{bkg}}(m_{4\ell}),$$

$$\mathcal{P}_{J^P} = \mathcal{P}^{\mathrm{kin}}_{J^P}(m_{Z_1}, m_{Z_2}, \vec{\Omega} | m_{4\ell}) \times \mathcal{P}^{\mathrm{mass}}_{\mathrm{sig}}(m_{4\ell} | m_{\mathrm{H}}),$$

HZZ: discriminants

Discriminant signal-background

$$\mathcal{D}_{\mathrm{bkg}}^{\mathrm{kin}} = \frac{\mathcal{P}_{0^+}^{\mathrm{kin}}}{\mathcal{P}_{0^+}^{\mathrm{kin}} + \mathcal{P}_{\mathrm{bkg}}^{\mathrm{kin}}} = \left[1 + \frac{\mathcal{P}_{\mathrm{bkg}}^{\mathrm{kin}}(m_{Z_1}, m_{Z_2}, \vec{\Omega}|m_{4\ell})}{\mathcal{P}_{0^+}^{\mathrm{kin}}(m_{Z_1}, m_{Z_2}, \vec{\Omega}|m_{4\ell})}\right]^{-1}$$

Discriminant signal-background including mass probabilities

$$\mathcal{D}_{\mathrm{bkg}} = \left[1 + \frac{\mathcal{P}_{\mathrm{bkg}}^{\mathrm{kin}}(m_{Z_1}, m_{Z_2}, \vec{\Omega}|m_{4\ell}) \times \mathcal{P}_{\mathrm{bkg}}^{\mathrm{mass}}(m_{4\ell})}{\mathcal{P}_{0^+}^{\mathrm{kin}}(m_{Z_1}, m_{Z_2}, \vec{\Omega}|m_{4\ell}) \times \mathcal{P}_{\mathrm{sig}}^{\mathrm{mass}}(m_{4\ell}|m_{0^+})}\right]^{-1}$$

Discriminant spin hypotheses

$$\mathcal{D}_{J^P} = \left[1 + \frac{\mathcal{P}_{J^P}^{\mathrm{kin}}(m_{Z_1}, m_{Z_2}, \vec{\Omega}|m_{4\ell})}{\mathcal{P}_{0^+}^{\mathrm{kin}}(m_{Z_1}, m_{Z_2}, \vec{\Omega}|m_{4\ell})}\right]^{-1}$$

Production independent discriminants

$$\mathcal{D}_{\mathrm{bkg}}^{\mathrm{dec}} = \left[1 + \frac{\frac{1}{4\pi}\int \mathrm{d}\Phi_1 \mathrm{d}\cos\theta^* \mathcal{P}_{\mathrm{bkg}}^{\mathrm{kin}}(m_{Z_1}, m_{Z_2}, \vec{\Omega}|m_{4\ell}) \times \mathcal{P}_{\mathrm{bkg}}^{\mathrm{mass}}(m_{4\ell})}{\mathcal{P}_{0^+}^{\mathrm{kin}}(m_{Z_1}, m_{Z_2}, \vec{\Omega}|m_{4\ell}) \times \mathcal{P}_{\mathrm{sig}}^{\mathrm{mass}}(m_{4\ell}|m_{0^+})}\right]^{-1},$$

$$\mathcal{D}_{J^P}^{\mathrm{dec}} = \left[1 + \frac{\frac{1}{4\pi}\int \mathrm{d}\Phi_1\, \mathrm{d}\cos\theta^* \mathcal{P}_{J^P}^{\mathrm{kin}}(m_{Z_1}, m_{Z_2}, \vec{\Omega}|m_{4\ell})}{\mathcal{P}_{0^+}^{\mathrm{kin}}(m_{Z_1}, m_{Z_2}, \vec{\Omega}|m_{4\ell})}\right]^{-1}.$$

HZZ: likelihoods

Limits and p-values

$$\mathcal{L}^{\mu}_{3D} \equiv \mathcal{L}^{\mu,0/1\text{-jet}}_{3D}(m_{4\ell}, \mathcal{D}^{\text{kin}}_{\text{bkg}}, p^{4\ell}_{\text{T}}) = \mathcal{P}(m_{4\ell}|m_{\text{H}}, \Gamma)\mathcal{P}(\mathcal{D}^{\text{kin}}_{\text{bkg}}|m_{4\ell}) \times \mathcal{P}(p^{4\ell}_{\text{T}}|m_{4\ell}),$$

$$\mathcal{L}^{\mu}_{3D} \equiv \mathcal{L}^{\mu,\text{dijet}}_{3D}(m_{4\ell}, \mathcal{D}^{\text{kin}}_{\text{bkg}}, \mathcal{D}_{\text{jet}}) = \mathcal{P}(m_{4\ell}|m_{\text{H}}, \Gamma)\mathcal{P}(\mathcal{D}^{\text{kin}}_{\text{bkg}}|m_{4\ell}) \times \mathcal{P}(\mathcal{D}_{\text{jet}}|m_{4\ell}).$$

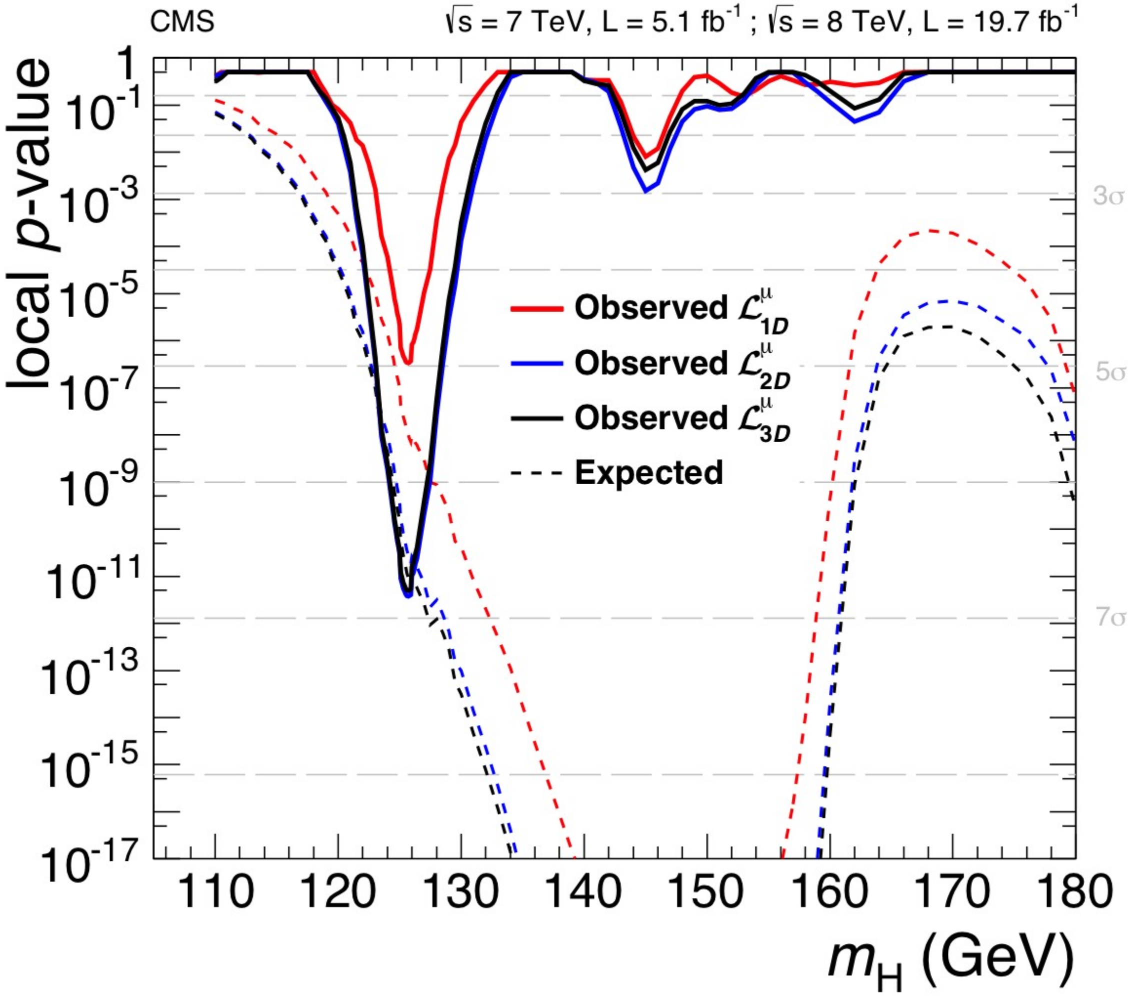
Mass and width

$$\mathcal{L}^{m,\Gamma}_{3D} \equiv \mathcal{L}^{m,\Gamma}_{3D}(m_{4\ell}, \mathcal{D}_{\text{m}}, \mathcal{D}^{\text{kin}}_{\text{bkg}}) = \mathcal{P}(m_{4\ell}|m_{\text{H}}, \Gamma, \mathcal{D}_{\text{m}})\mathcal{P}(\mathcal{D}_{\text{m}}|m_{4\ell}) \times \mathcal{P}(\mathcal{D}^{\text{kin}}_{\text{bkg}}|m_{4\ell}).$$

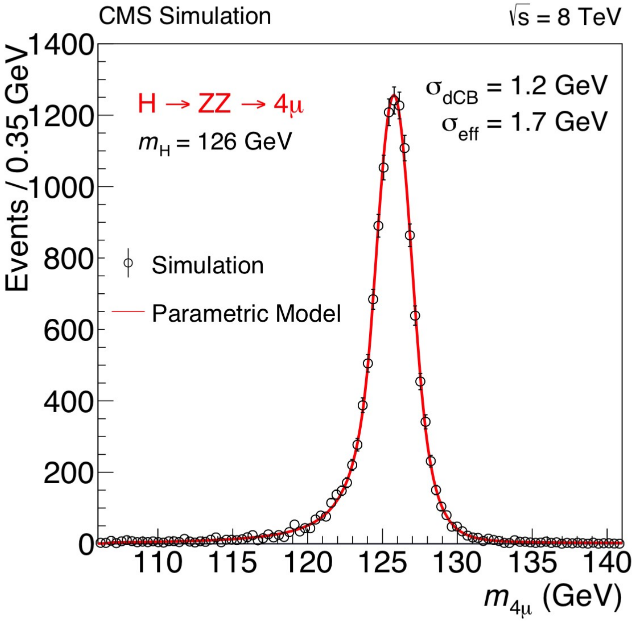
Spin-parity

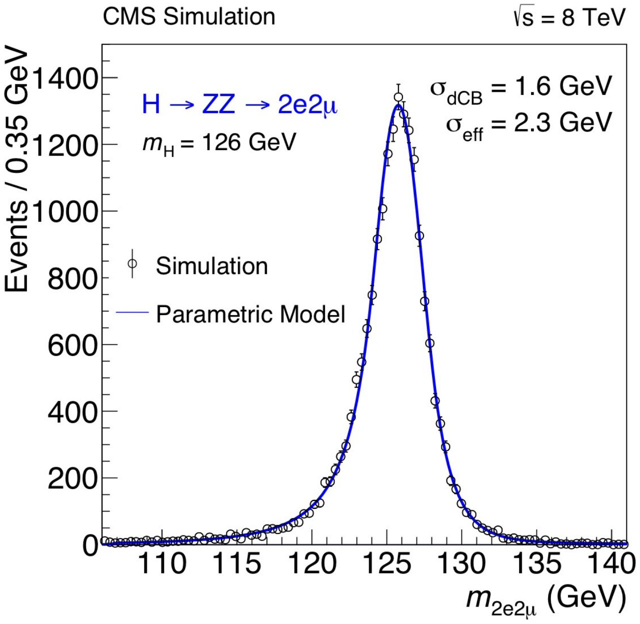
$$\mathcal{L}^{J^P}_{2D} \equiv \mathcal{L}^{J^P}_{2D}(\mathcal{D}_{\text{bkg}}, \mathcal{D}_{J^P}).$$

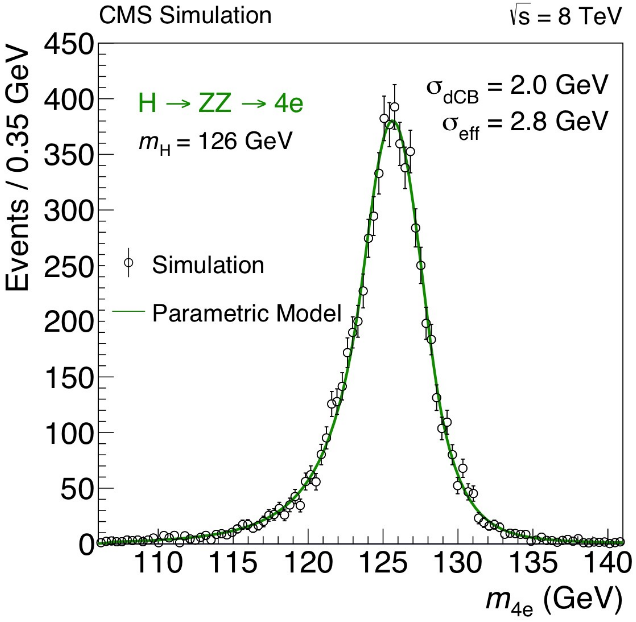
HZZ: p-value


CMS
$\sqrt{s}$ = 7 TeV, L = 5.1 fb^{-1} ; $\sqrt{s}$ = 8 TeV, L = 19.7 fb^{-1}
local p-value
1
10^{-1}
10^{-3}
10^{-5}
10^{-7}
10^{-9}
10^{-11}
10^{-13}
10^{-15}
10^{-17}
3σ
5σ
7σ
Observed $\mathcal{L}^{\mu}_{1D}$
Observed $\mathcal{L}^{\mu}_{2D}$
Observed $\mathcal{L}^{\mu}_{3D}$
Expected
110
120
130
140
150
160
170
180
m_H (GeV)

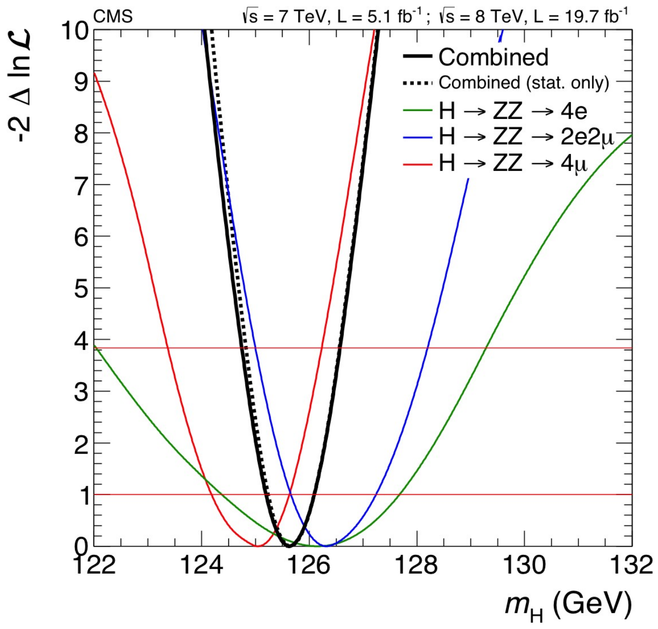
HZZ: resolutions

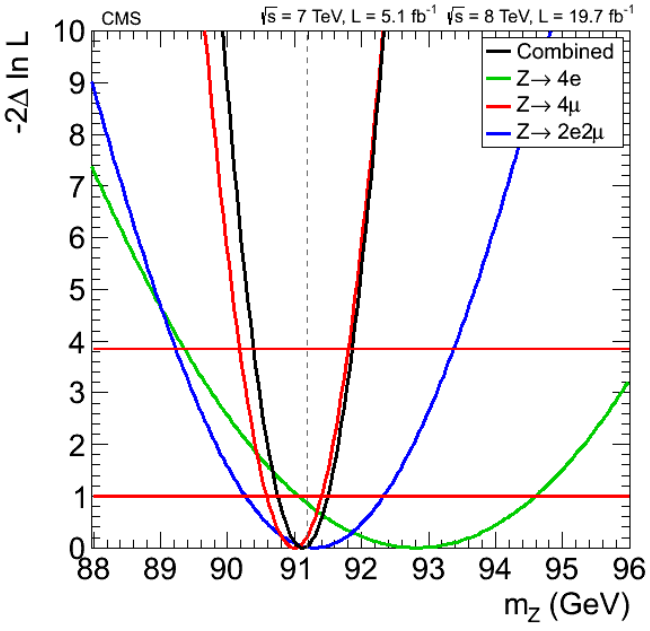


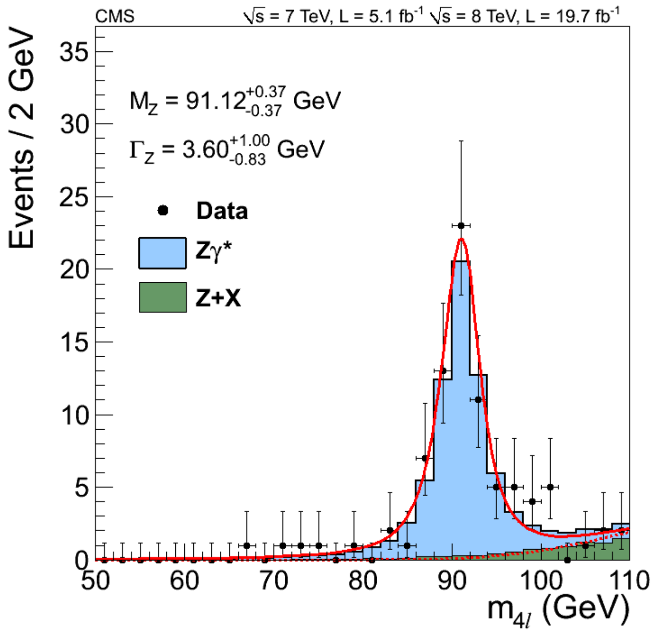




HZZ: mass compatibility





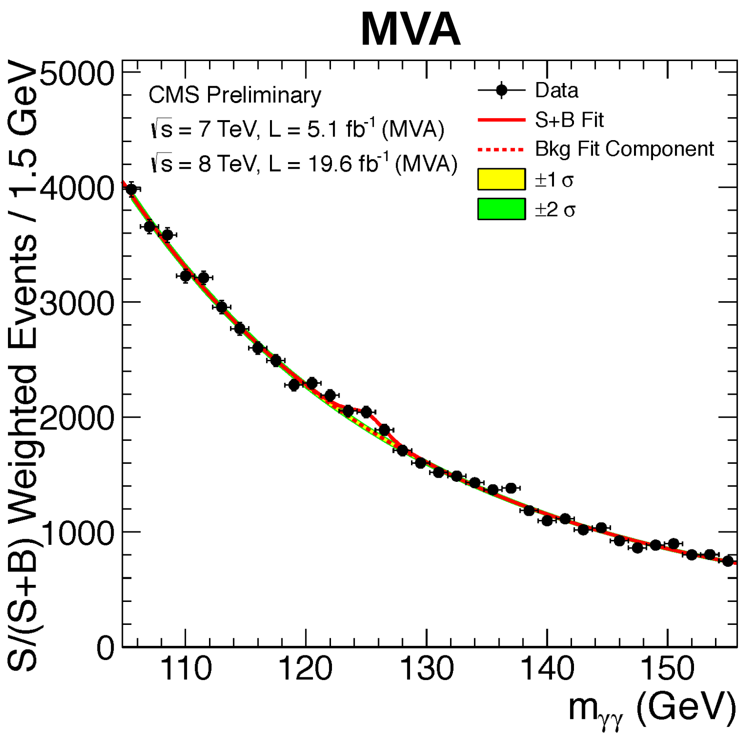


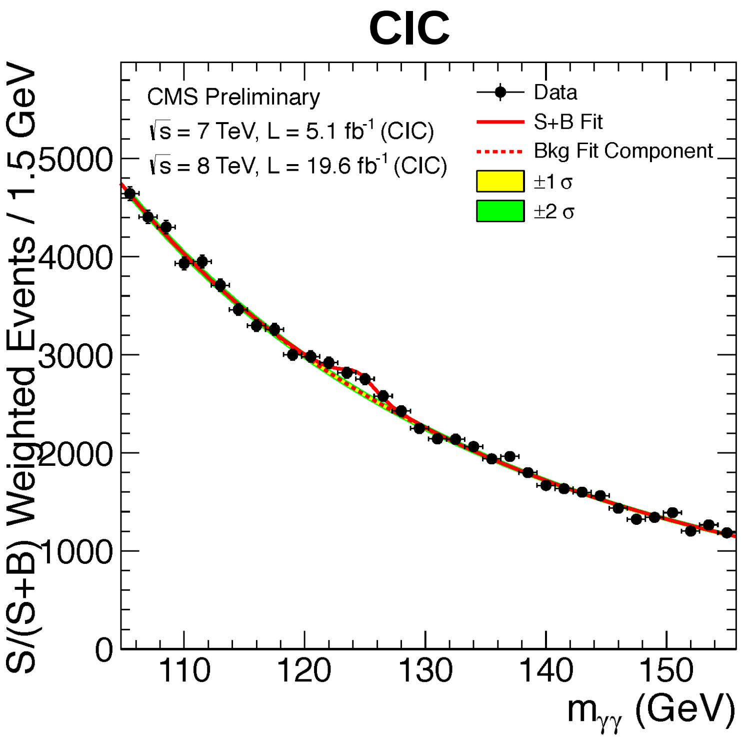
Spin 2 tested models

$$
\begin{aligned}
A(X\to V_1V_2)=\Lambda^{-1}\Big[& \boxed{2g_1^{(2)}} t_{\mu\nu} f^{*(1)\mu\alpha} f^{*(2)\nu\alpha} + 2g_2^{(2)} t_{\mu\nu} \frac{q_\alpha q_\beta}{\Lambda^2} f^{*(1)\mu\alpha} f^{*(2)\nu\beta} + g_3^{(2)} \frac{\tilde{q}^\beta \tilde{q}^\alpha}{\Lambda^2} t_{\beta\nu} (f^{*(1)\mu\nu} f^{*(2)}_{\mu\alpha} + f^{*(2)\mu\nu} f^{*(1)}_{\mu\alpha}) \\
& + \boxed{g_4^{(2)}} \frac{\tilde{q}^\nu \tilde{q}^\mu}{\Lambda^2} t_{\mu\nu} f^{*(1)\alpha\beta} f^{*(2)}_{\alpha\beta} + m_V^2 \Big(\boxed{2g_5^{(2)}} t_{\mu\nu} \epsilon_1^{*\mu} \epsilon_2^{*\nu} + 2g_6^{(2)} \frac{\tilde{q}^\mu q_\alpha}{\Lambda^2} t_{\mu\nu} (\epsilon_1^{*\nu} \epsilon_2^{*\alpha} - \epsilon_1^{*\alpha} \epsilon_2^{*\nu}) + g_7^{(2)} \frac{\tilde{q}^\mu \tilde{q}^\nu}{\Lambda^2} t_{\mu\nu} \epsilon_1^* \epsilon_2^* \Big) \\
& + \boxed{g_8^{(2)}} \frac{\tilde{q}_\mu \tilde{q}_\nu}{\Lambda^2} t_{\mu\nu} f^{*(1)\alpha\beta} \tilde{f}^{*(2)}_{\alpha\beta} + m_V^2 \Big(g_9^{(2)} \frac{t_{\mu\alpha} \tilde{q}^\alpha}{\Lambda^2} \epsilon_{\mu\nu\rho\sigma} \epsilon_1^{*\nu} \epsilon_2^{*\rho} q^\sigma + \frac{g_{10}^{(2)} t_{\mu\alpha} \tilde{q}^\alpha}{\Lambda^4} \epsilon_{\mu\nu\rho\sigma} q^\rho \tilde{q}^\sigma (\epsilon_1^{*\nu} (q\epsilon_2^*) + \epsilon_2^{*\nu} (q\epsilon_1^*)) \Big) \Big]
\end{aligned}
$$

- 2_m^+: KK Graviton-like with minimal couplings (gg → X or $q\bar{q}$ → X)
  - ↳ g1 = g5 ≠ 0
- 2_b^+: KK Graviton-like with SM in the bulk (gg → X)
  - ↳ g5 ≠ 0 for X → ZZ and g1 ≠ 0 for gg → X
- 2_h^+: BSM tensor with higher dimension operators (gg → X)
  - ↳ g4 ≠ 0
- 2_h^-: BSM pseudo-tensor with higher dimension operators (gg → X)
  - ↳ g8 ≠ 0

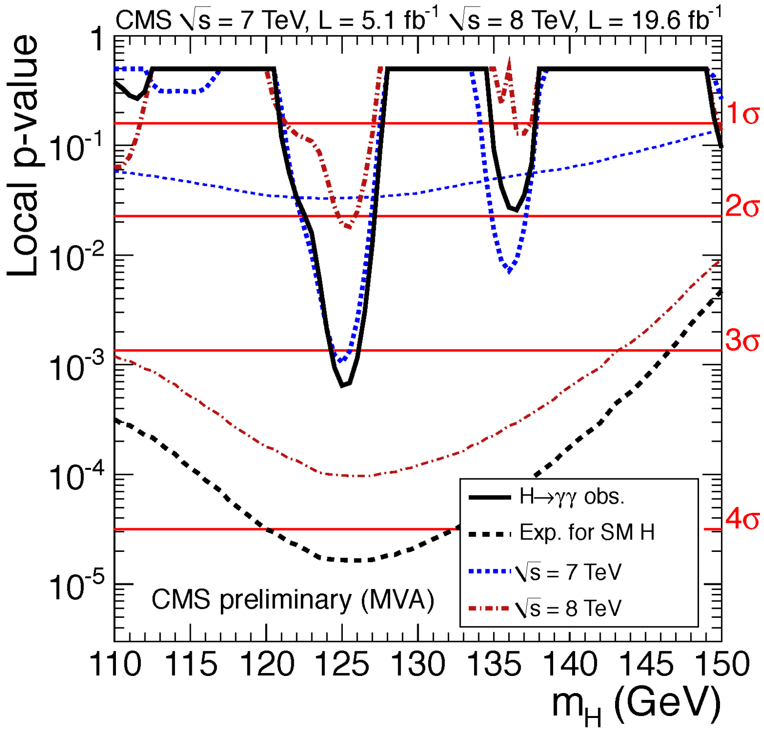
Hγγ: mass spectrum


MVA

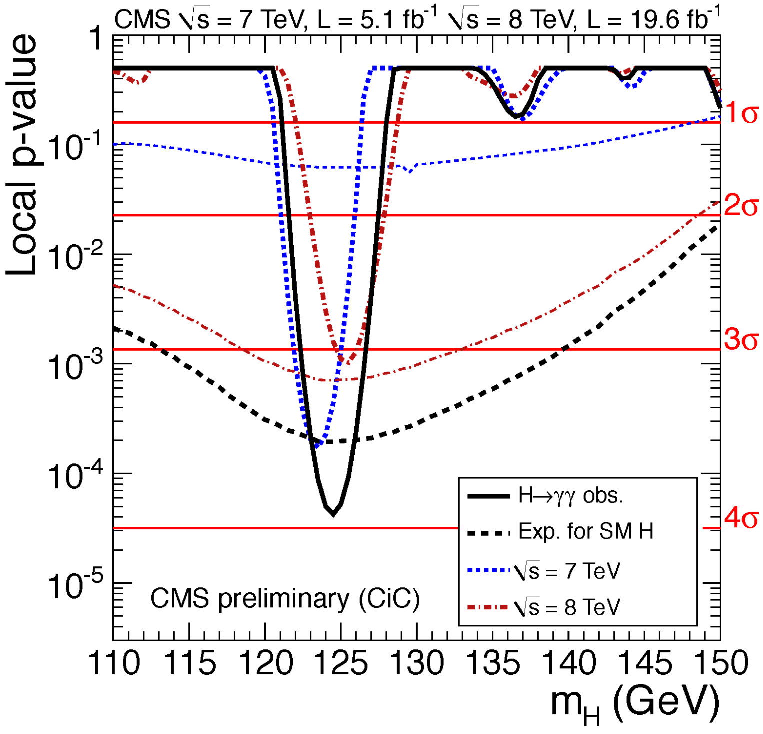

CIC

Hγγ: p-value

MVA

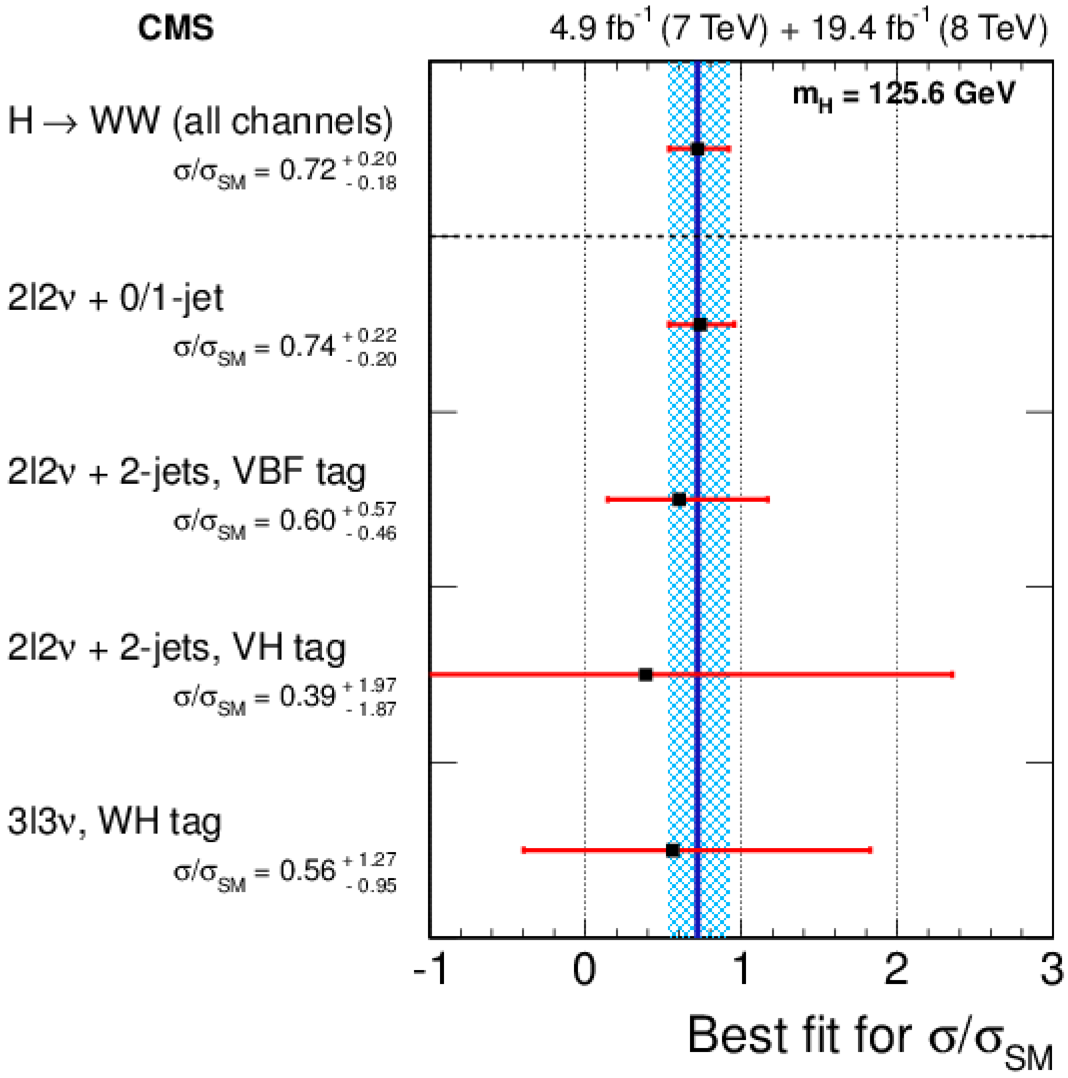


CIC

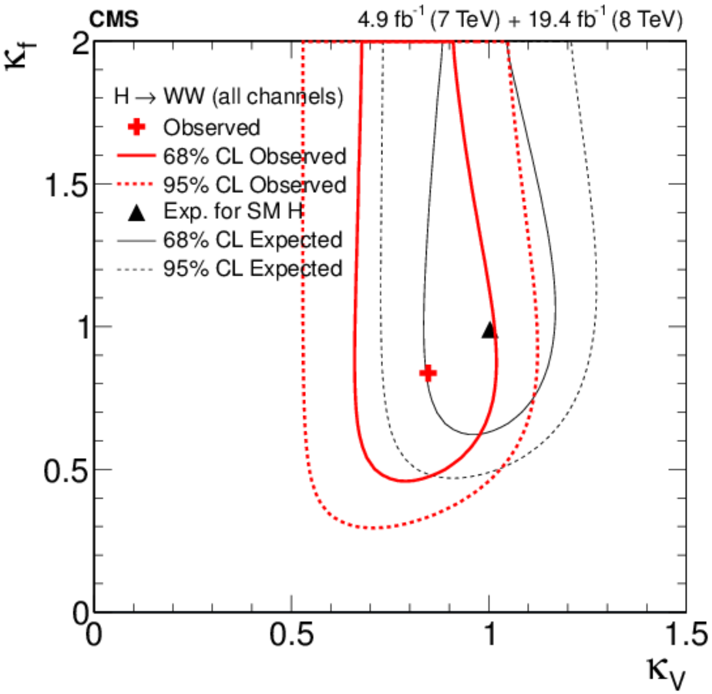


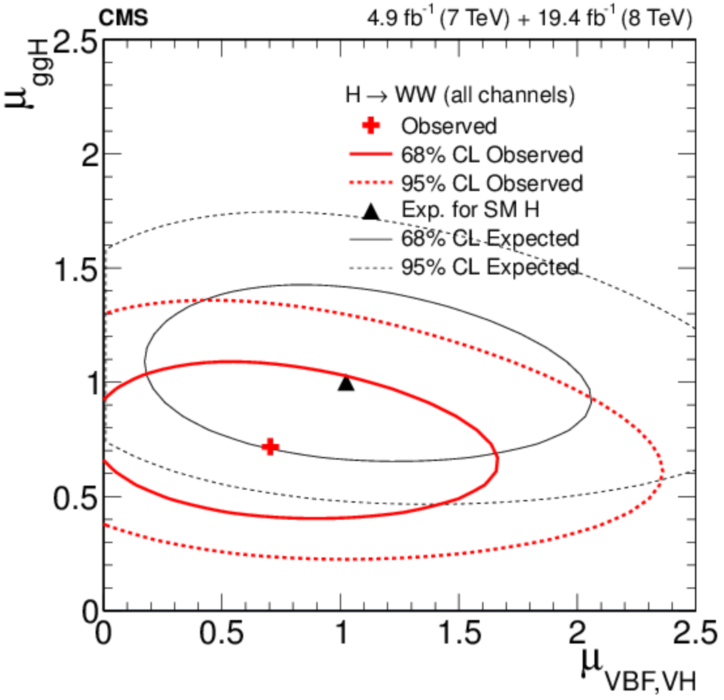
HWW: signal strength

- Five exclusive categories
  - ↳ 2l2υ + 0/1 jet → ggH production
  - ↳ 2l2υ + 2 jets → VBF production
  - ↳ 2l2υ + 2 jets → VH production
  - ↳ 3l3υ → WH production
  - ↳ 3lυ + 2 jets → ZH production (hadronic W)

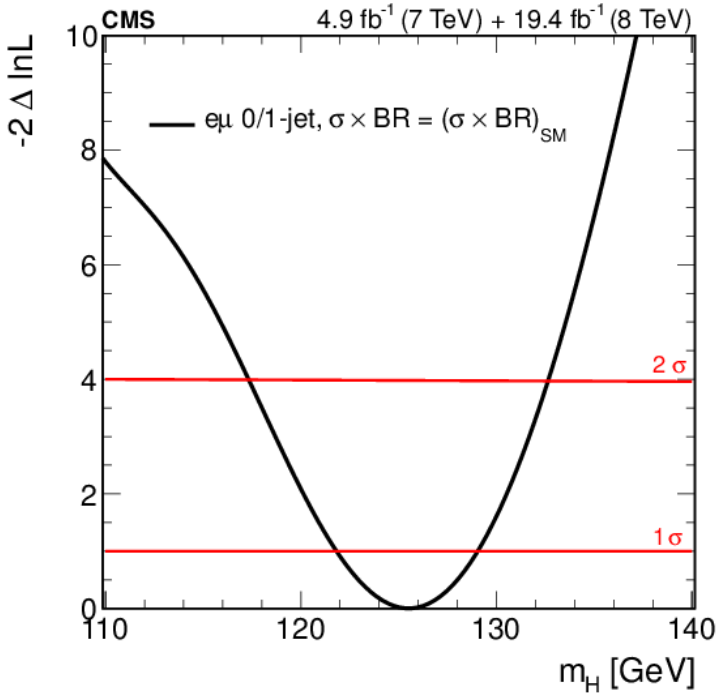


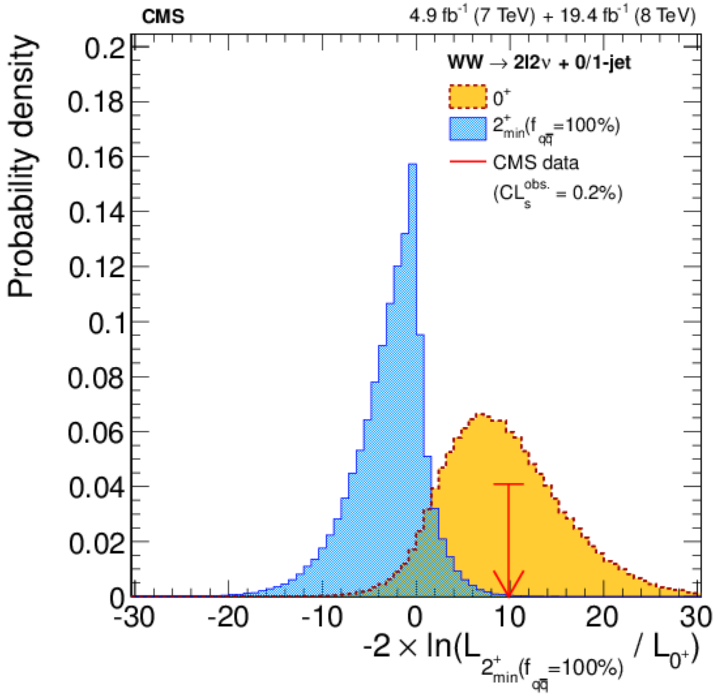
HWW: production and couplings





HWW: mass and spin





HWW: spin templates