Rencontres du Vietnam

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WINDOWS ON THE UNIVERSE

2013

Measurement of Higgs boson properties at the LHC

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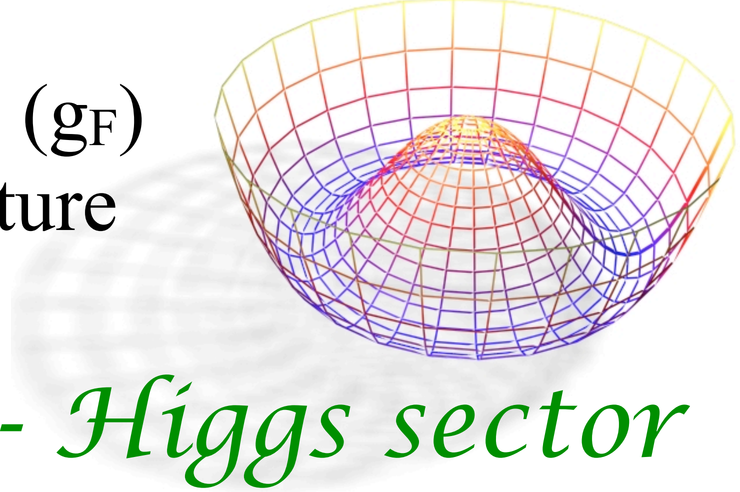
on behalf of ATLAS and CMS collaborations

August 13, 2013
ICISE, Quy Nhon, Vietnam

ATLAS EXPERIMENT
CMS
LABORATOIRE DE L'ACCÉLÉRATEUR LINÉAIRE
cnrs IN2P3 Les deux infinis

Higgs Boson Property Measurements

1. Higgs boson mass (M_H) & decay width (Γ_H)
2. Higgs couplings to gauge bosons (g_V) and fermions (g_F)
3. Higgs boson quantum numbers J^{PC} and tensor structure
4. Higgs potential - Higgs self-coupling (λ)



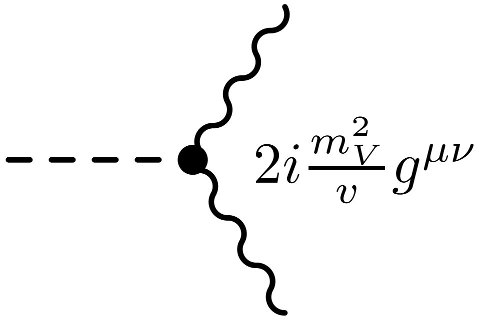
K. Cranmer

The Standard Model Lagrangian - Higgs sector

$$\mathcal{L}_{SM} = D_\mu H^\dagger D_\mu H + \mu^2 H^\dagger H - \frac{\lambda}{2}\left(H^\dagger H\right)^2 - \left(y_{ij} H \bar{\psi}_i \psi_j + \text{h.c.}\right)$$

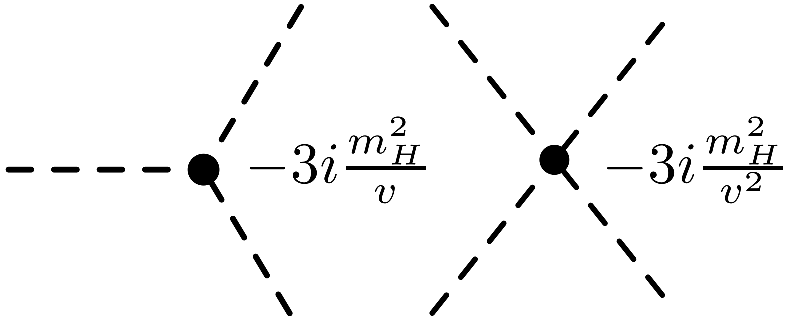
Couplings to EW gauge bosons

$$\left[m_W^2 W^{\mu+} W_\mu^- + \frac{1}{2} m_Z^2 Z^{\mu 0} Z_\mu^0\right] \cdot \left(1 + \frac{h}{v}\right)^2$$



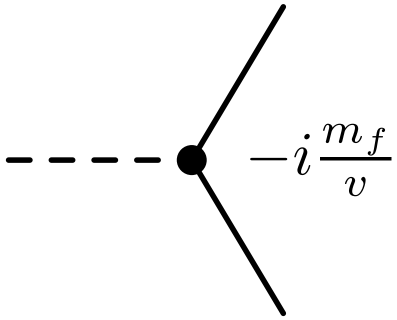
Higgs self-couplings

$$-\mu^2 h^2 - \frac{\lambda}{2} v h^3 - \frac{1}{8}\lambda h^4$$



Couplings to fermions

$$-\sum_f m_f \bar{f} f \left(1 + \frac{h}{v}\right)$$

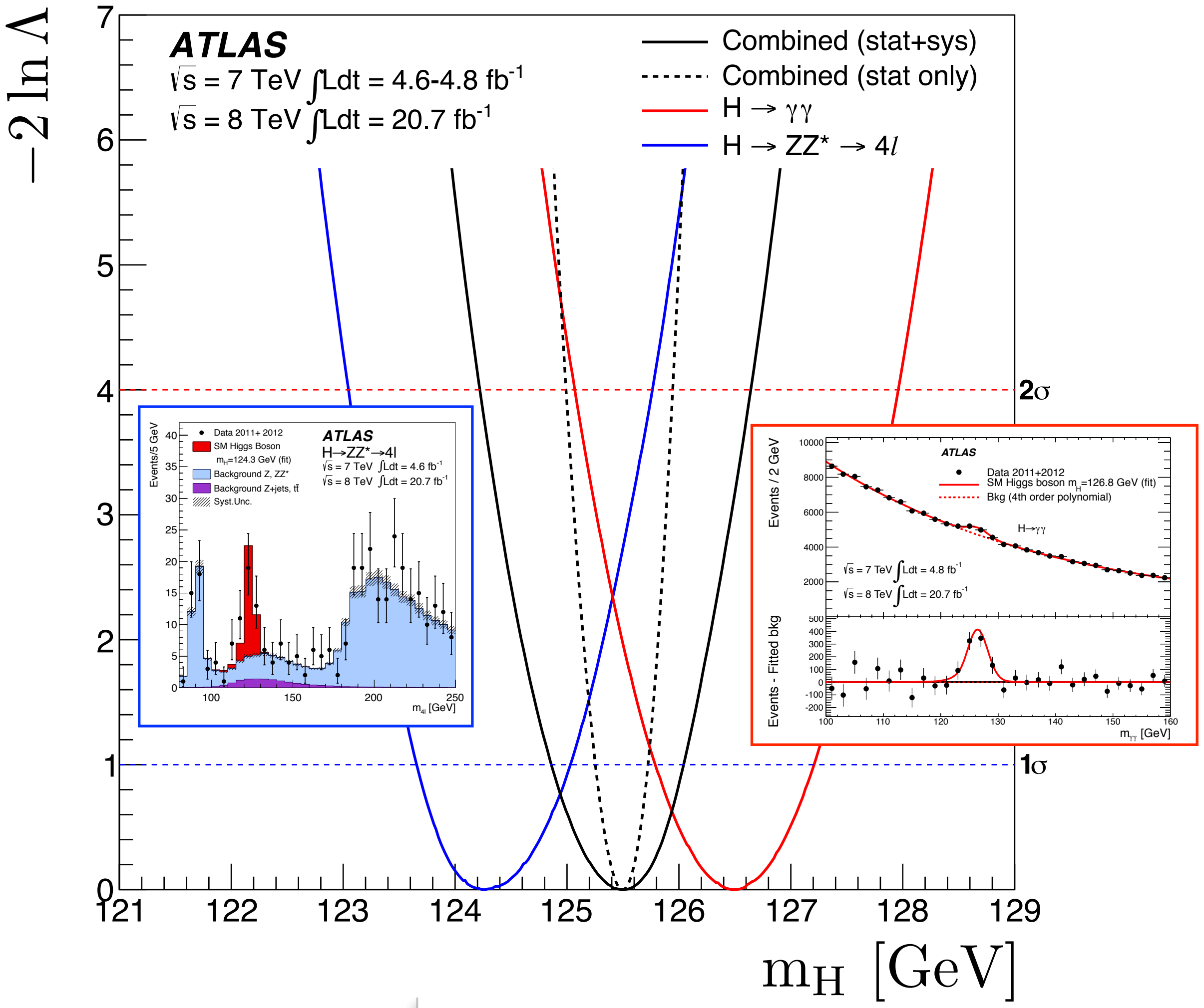


$$m_H = \sqrt{2}\mu = \sqrt{\lambda}v \ (v = \text{vacuum expectation value})$$

The ultimate goal of particle physics of today is to fix the Standard Model (SM) Lagrangian and find the physics beyond the Standard Model (BSM).

1. Higgs Boson Mass

- M_H - the only parameter not fixed in the Standard Model ➪ Fixes $\lambda = \frac{M_H^2}{v^2}$.
- Most precisely determined with H→γγ and 4 lepton channels.
- δM_H precision at 0.3% level (PDG2013: δM_W 187ppm, δM_Z 23ppm, δM_{top} 0.5%).



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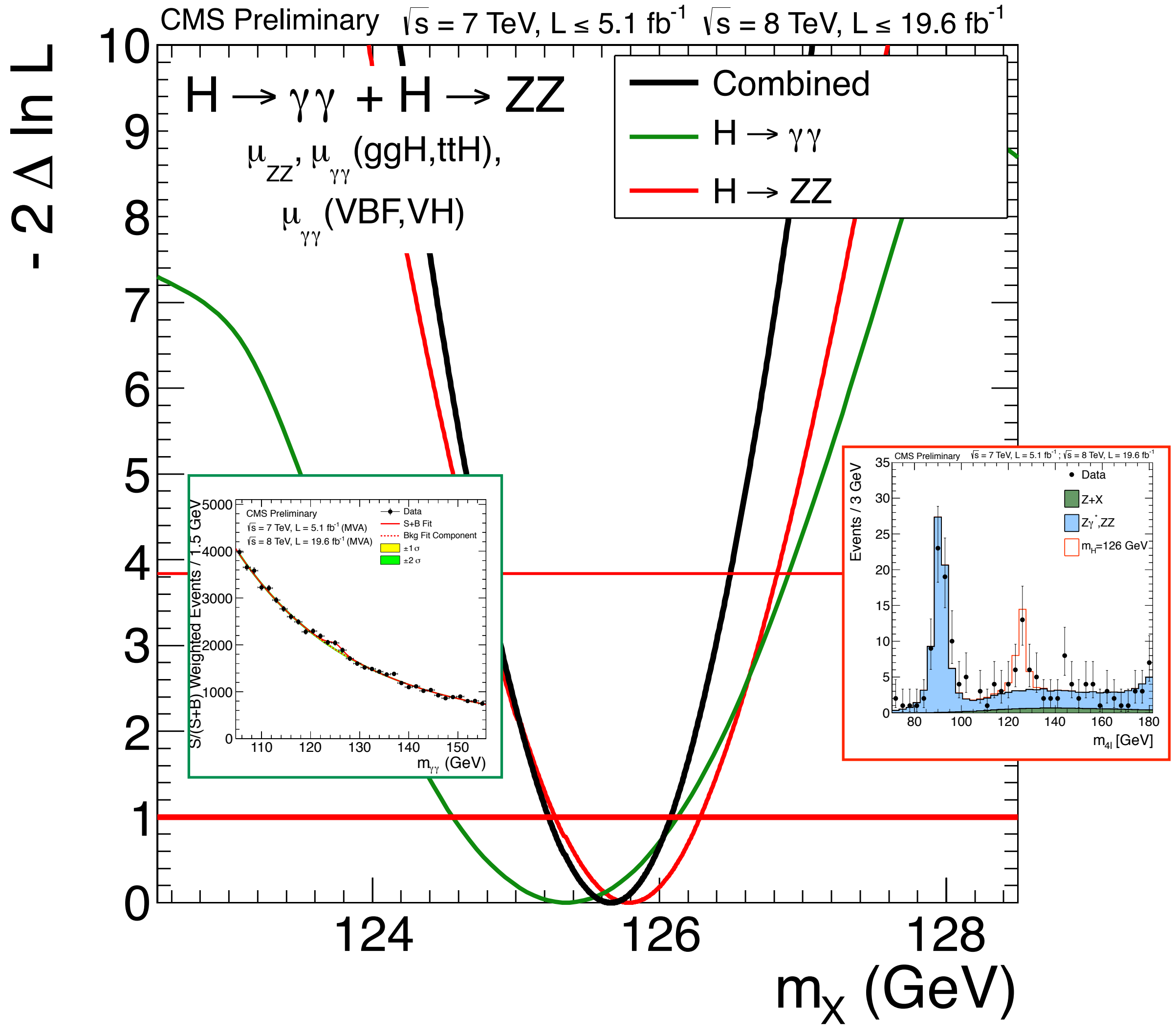

CMS PAS HIG-13-005

ATLAS: M_H = 125.5 ± 0.2 (stat.) ± 0.6 (syst.) GeV
CMS: M_H = 125.7 ± 0.3 (stat.) ± 0.3 (syst.) GeV

2. The signal strength

$$\mu = \frac{\sigma \cdot \mathrm{BR}}{(\sigma \cdot \mathrm{BR})_{\mathrm{SM}}}$$

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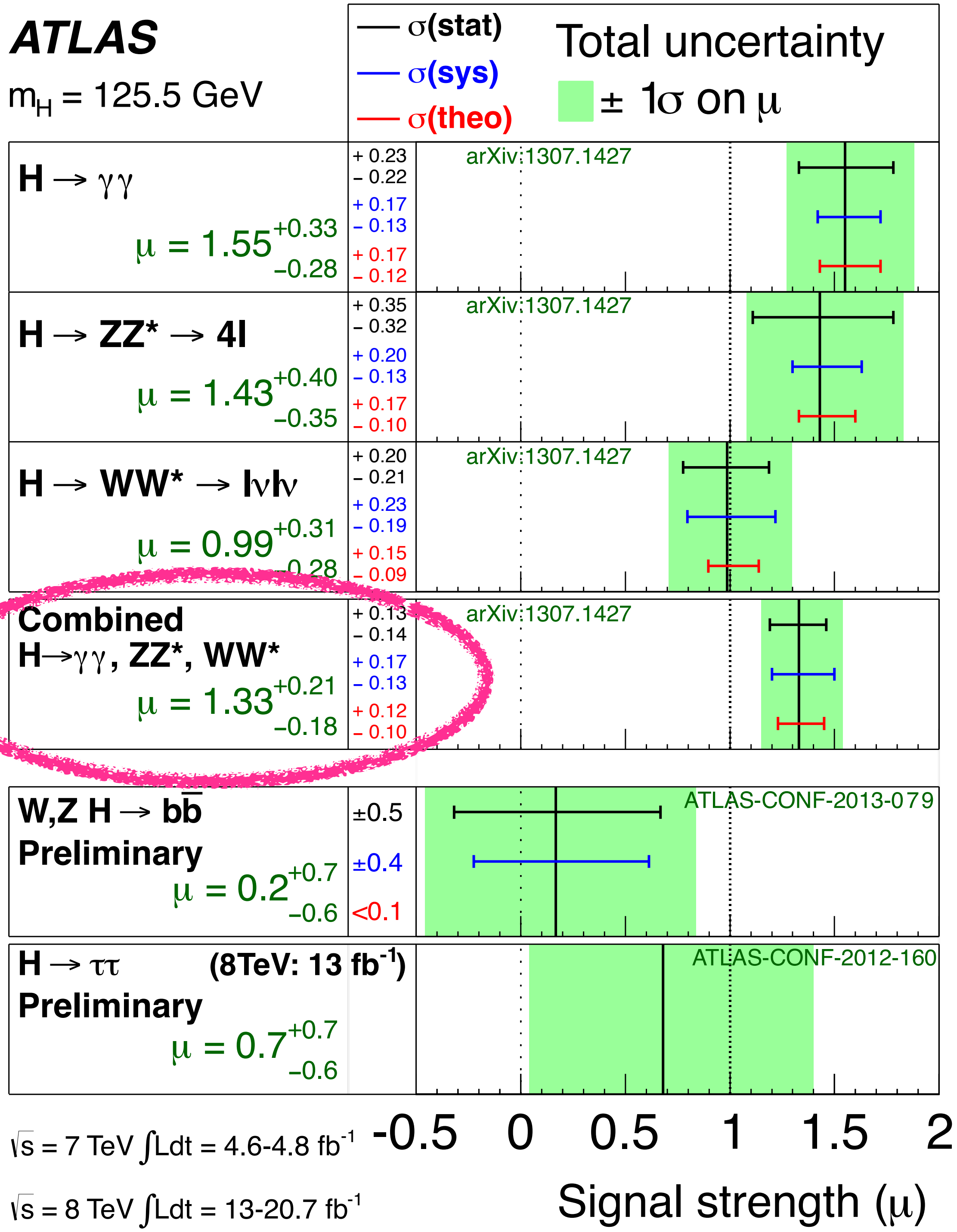
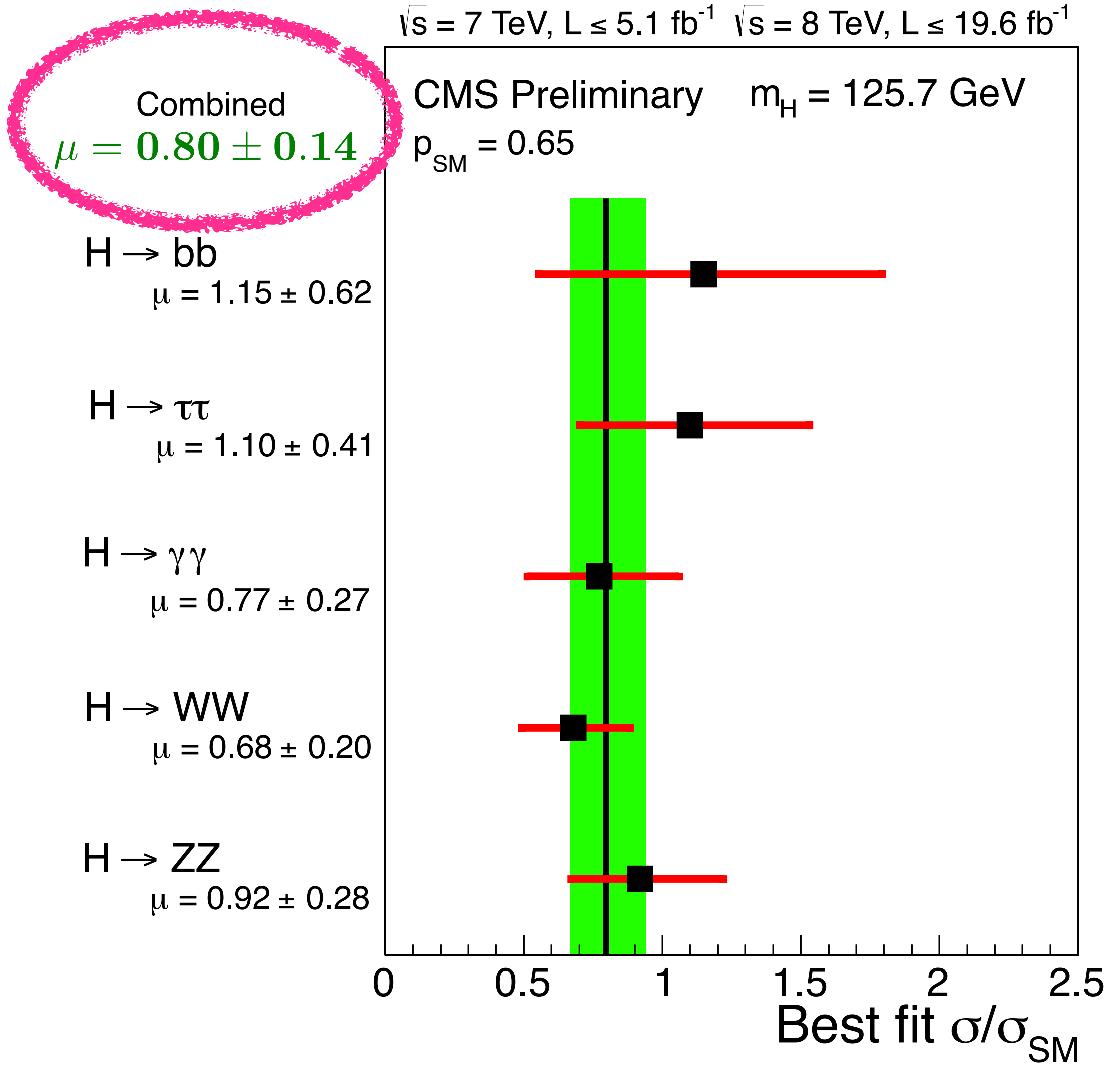


CMS PAS HIG-13-005



- Consistent with the SM prediction for both ATLAS and CMS with precision about 15% level.
- Theory uncertainty (QCD scale ±8%@NNLO and PDF+α_s ±8%) is comparable to experimental and statistical uncertainties on the combined signal strength.

↪ A. de Roeck, H. Gray : plenary talks

T. Lenz, P. Bruckman de Renstrom : parallel talks

Evidence for vector-boson-fusion process

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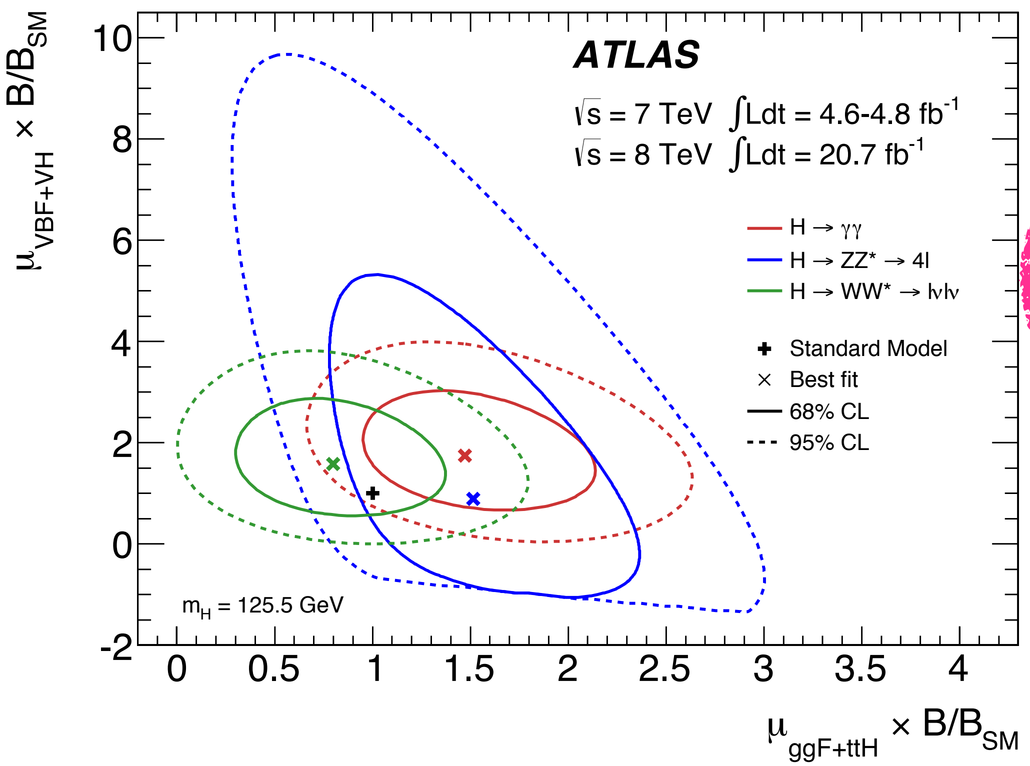
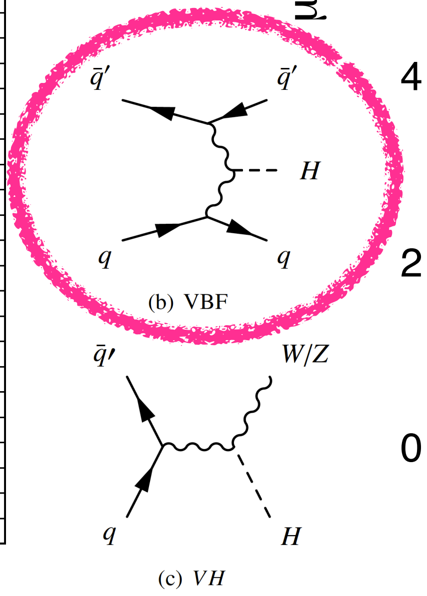
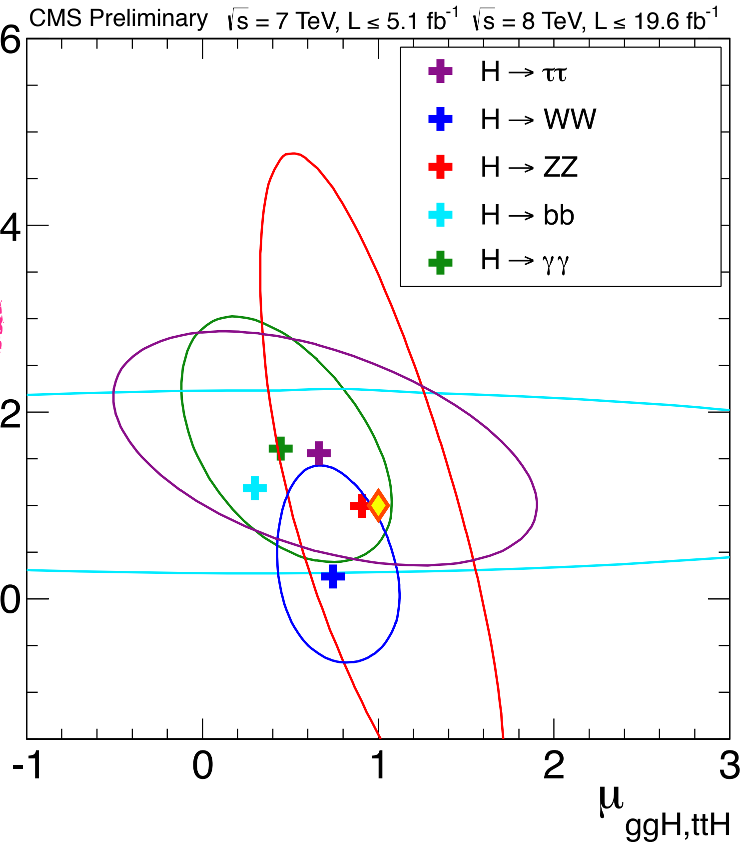
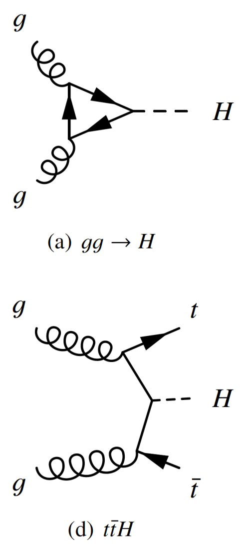
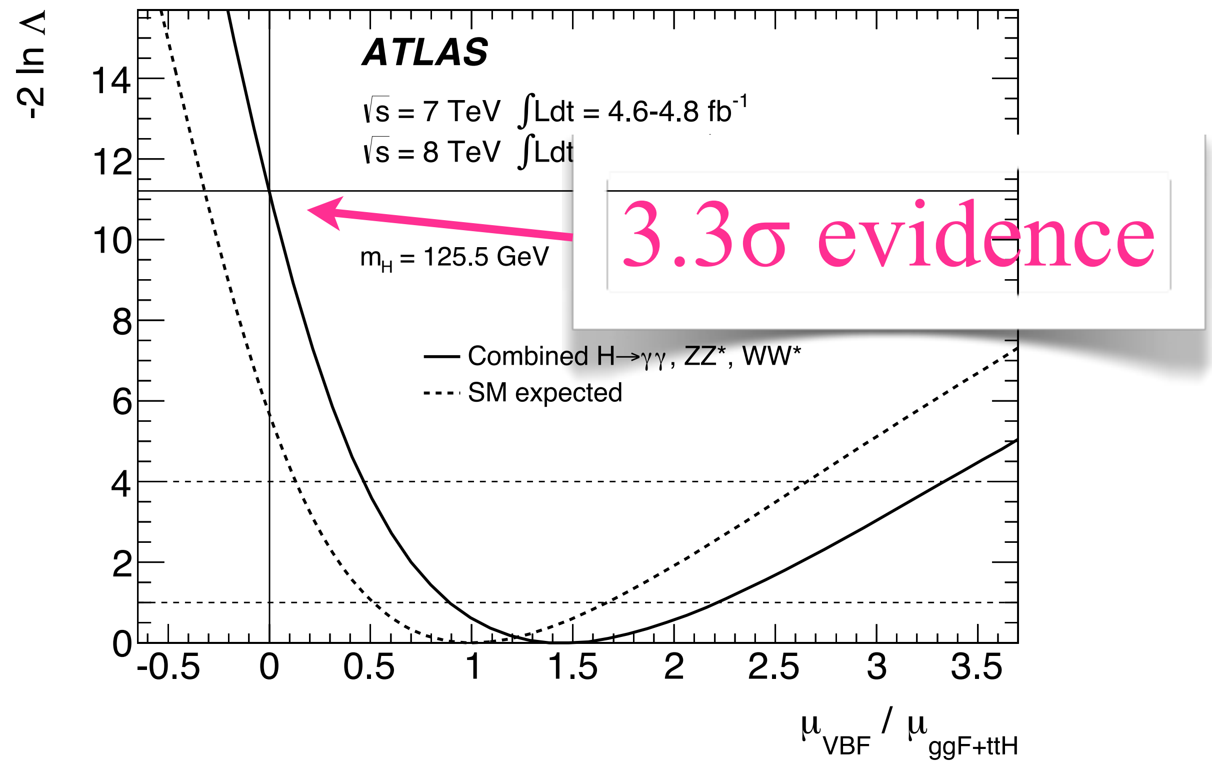




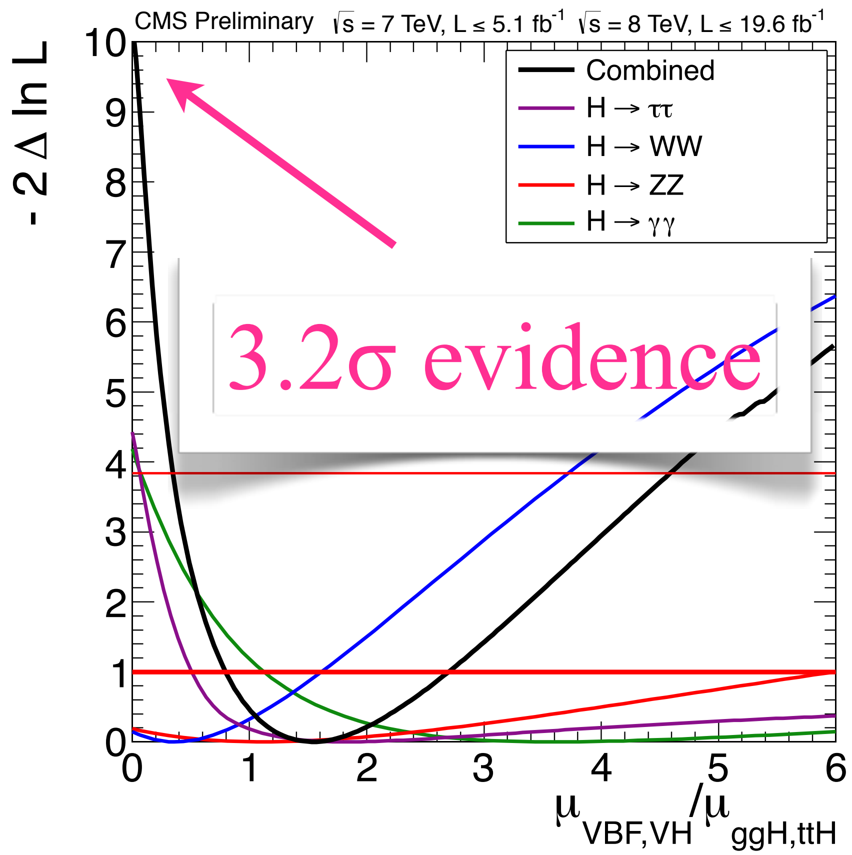
CMS PAS HIG-13-005







3.3σ evidence



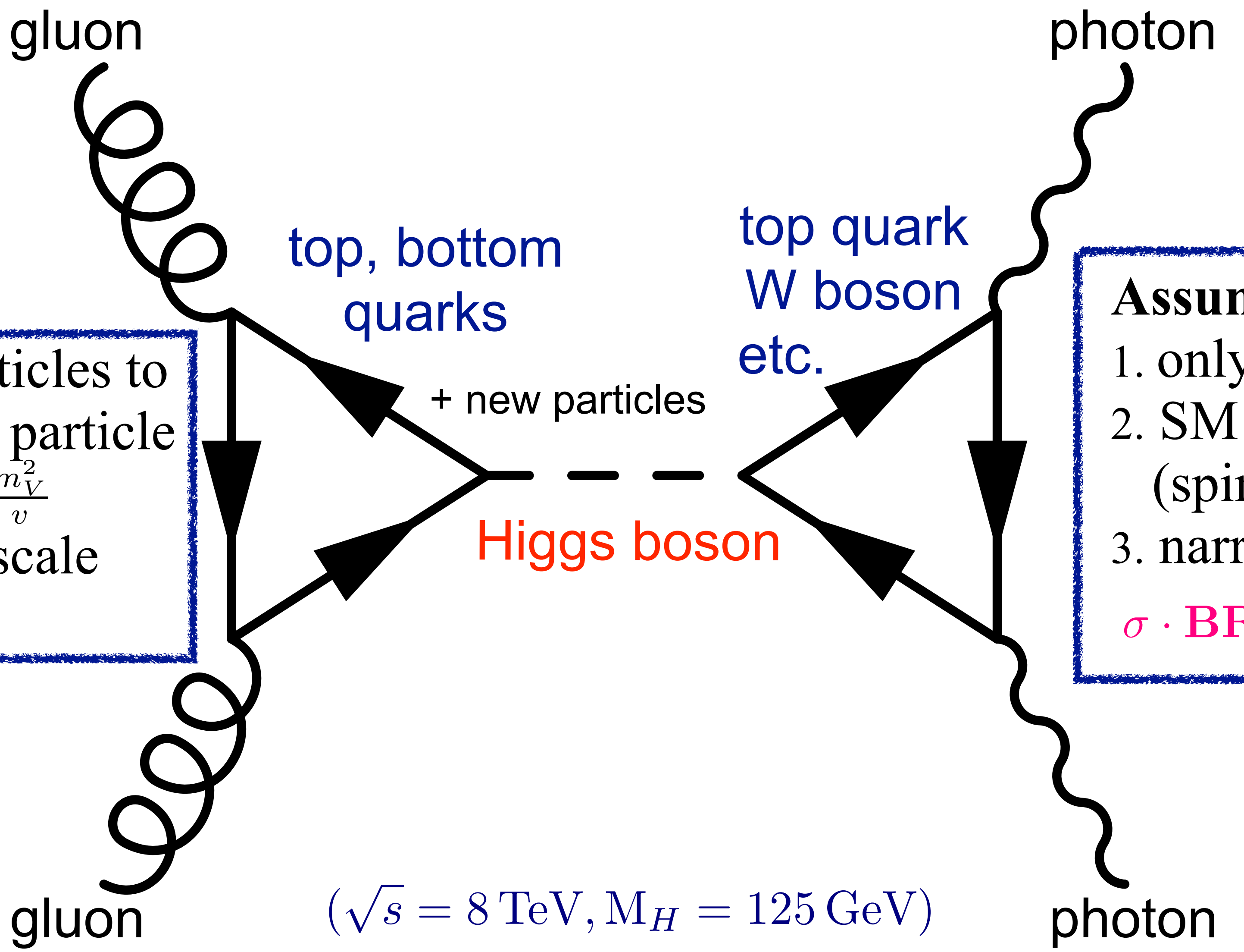
3.2σ evidence

LHC Higgs XS WG CERN Report 3 (arXiv:1307.1347)

3. Higgs coupling strength

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

- The coupling of SM particles to Higgs boson scales with particle mass: $g_F = \sqrt{2}\frac{m_f}{v}$, $g_V = 2\frac{m_V^2}{v}$
- Measure with coupling scale factors κ$_i$



$(\sqrt{s} = 8\,\mathrm{TeV}, \mathrm{M}_H = 125\,\mathrm{GeV})$

Assumptions

1. only 1 SM-like Higgs
2. SM tensor structure (spin 0, CP-even)
3. narrow width approx.

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

$$\kappa_g^2(\kappa_b, \kappa_t) \simeq 1.058\kappa_t^2 - 0.065\kappa_t\kappa_b + 0.007\kappa_b^2 \qquad \kappa_\gamma^2(\kappa_W, \kappa_t) \simeq |1.26\kappa_W - 0.27\kappa_t|^2$$

Destructive interference in both gg→H (top-bottom) and H→γγ (W-top) loops.

a) Higgs couplings to gauge bosons and fermions

- Assume all fermion couplings scale as κ_F while all vector boson couplings scale as κ_V.
- Assume no BSM contributions to Γ_H.

- Quad-fold ambiguity in sign of κ_F and κ_V.
  - One relative sign is physical.
  - Take $\kappa_V > 0$ as convention and look for $\pm\,\kappa_F$.
  - $\kappa_F < 0$ means sign of new physics.
  - Almost degenerate minima in the likelihood: one for $\kappa_F > 0$ and the other for $\kappa_F < 0$.
  - ATLAS H→γγ prefers $-\kappa_F$ but $\kappa_F > 0$ for global fit.
  - Electroweak precision data constrain $\kappa_F > 0$. ($\because$ with $\kappa_F < 0$, κ_V is further away from 1)

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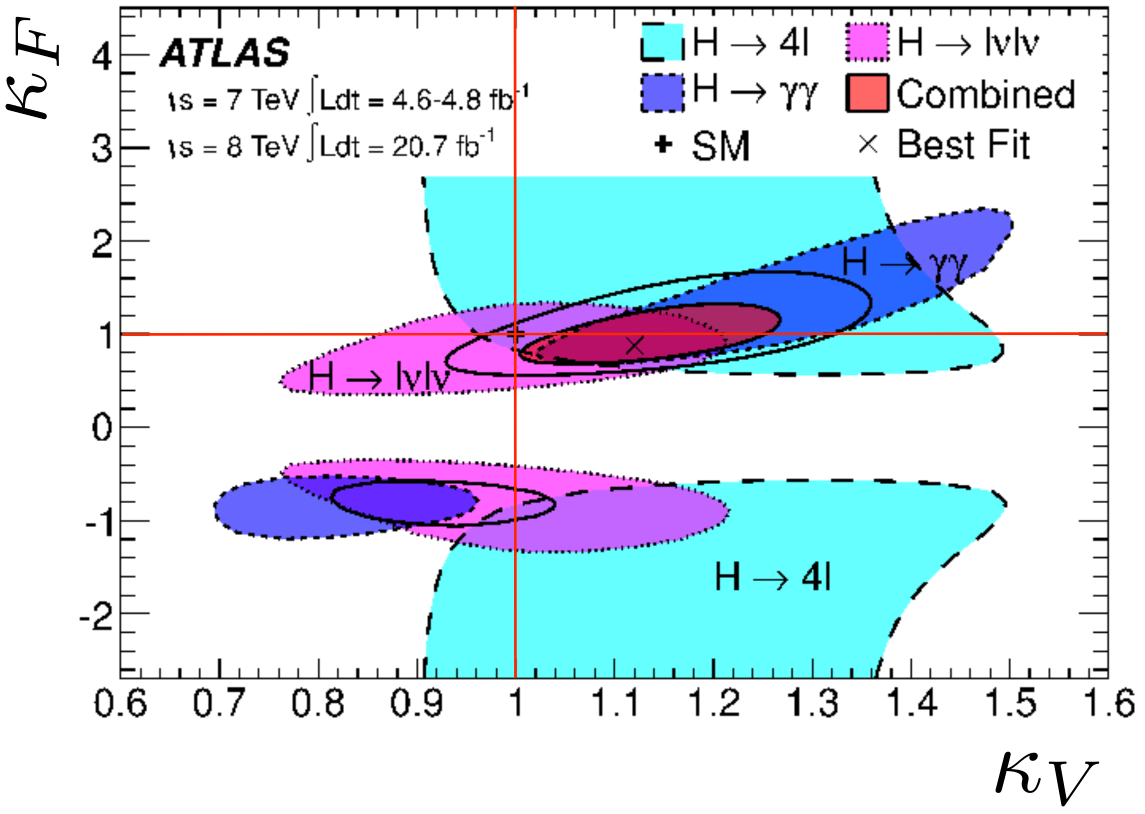
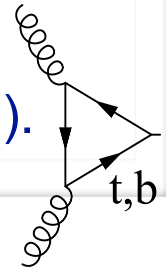


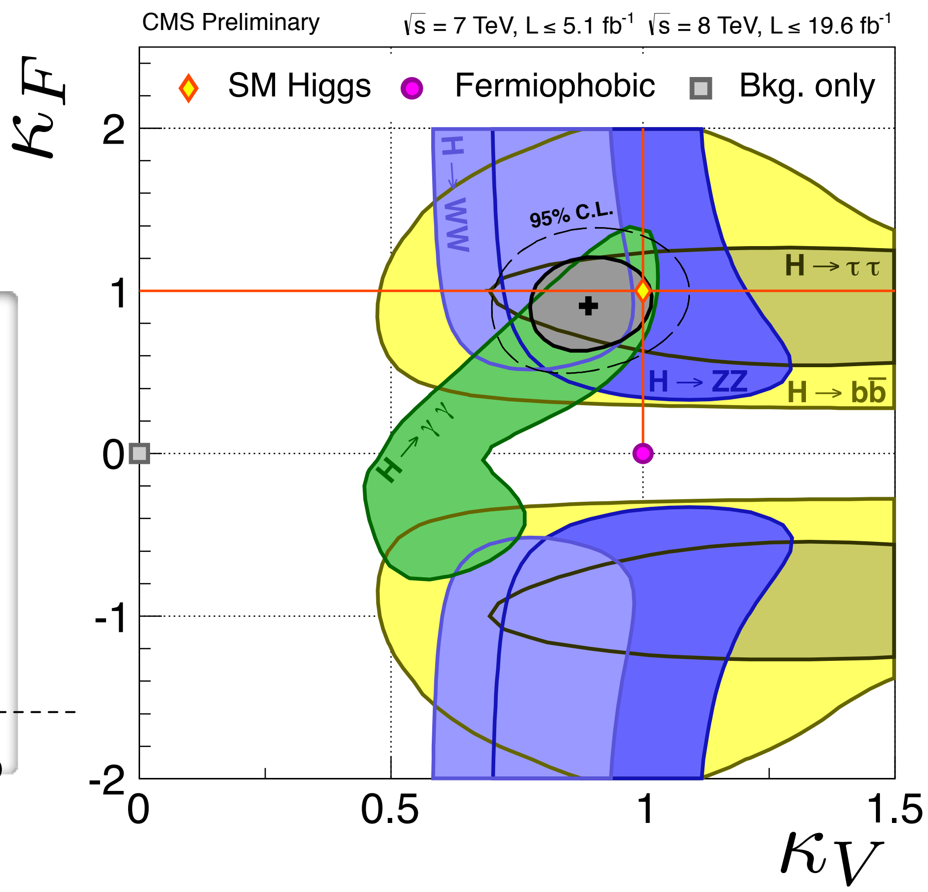
Data are compatible with SM predictions at 10-20% accuracy.

ATLAS: $\kappa_V \in [1.05,1.22]$ at 68% C.L. $\kappa_F \in [0.76,1.18]$ at 68% C.L.
CMS: $\kappa_V \in [0.74,1.06]$ at 95% C.L. $\kappa_F \in [0.61,1.33]$ at 95% C.L.

Fermiophobic model (κ_F=0) is ruled out at >5σ (via ggF loop).



CMS PAS HIG-13-005



b) Custodial, weak-isospin and quark-lepton symmetries

- Custodial symmetry $\kappa_W = \kappa_Z$?
  - Measure the coupling ratio λ_{WZ} via
    1. Ratio of BR (BR_{WW}/BR_{ZZ})
    2. Ratio of coupling with/without H→γγ
- Weak isospin symmetry $\kappa_u = \kappa_d$?
  - 2HDM (MSSM) predicts different couplings for up and down type fermions.
- Quark and lepton symmetry $\kappa_l = \kappa_q$?

$$\lambda_{WZ} = \frac{\kappa_W}{\kappa_Z}, \quad \lambda_{du} = \frac{\kappa_d}{\kappa_u}, \quad \lambda_{\ell q} = \frac{\kappa_\ell}{\kappa_q}$$

ATLAS: $\lambda_{WZ} \in [0.61, 1.04]$ at 68% C.L.

CMS: $\lambda_{WZ} \in [0.60 \pm 1.40]$ at 95% C.L.

$\lambda_{du} \in [0.74 \pm 1.95]$ at 95% C.L.

$\lambda_{lq} \in [0.57 \pm 2.05]$ at 95% C.L.

No sign of violation in custodial, weak-isospin and lepton symmetries.

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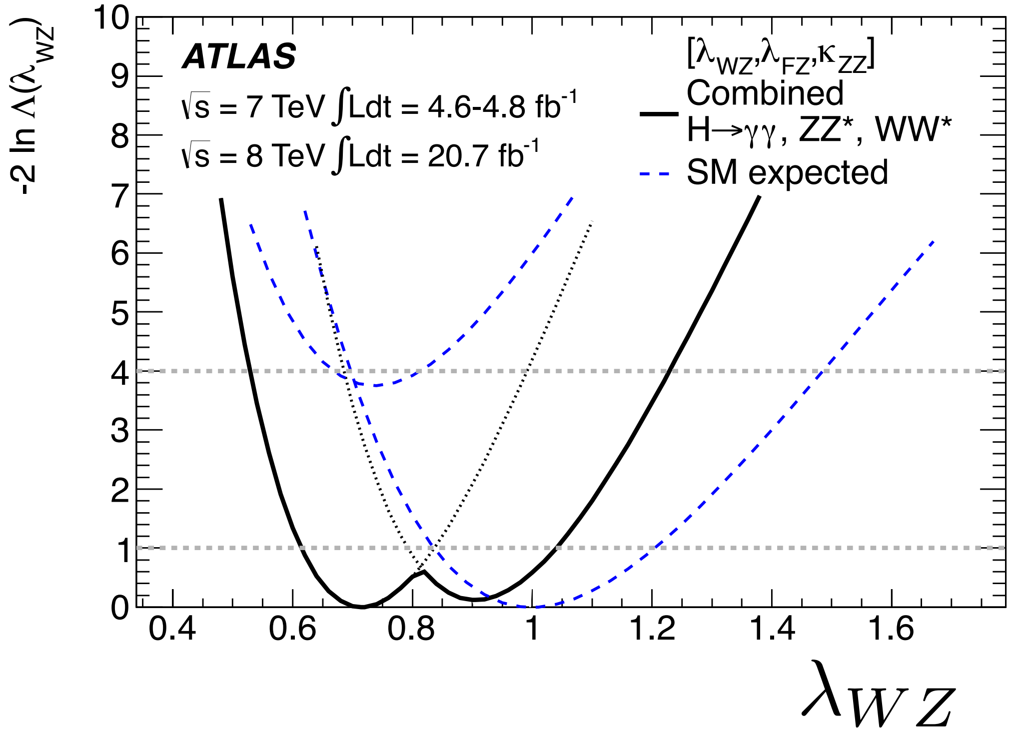
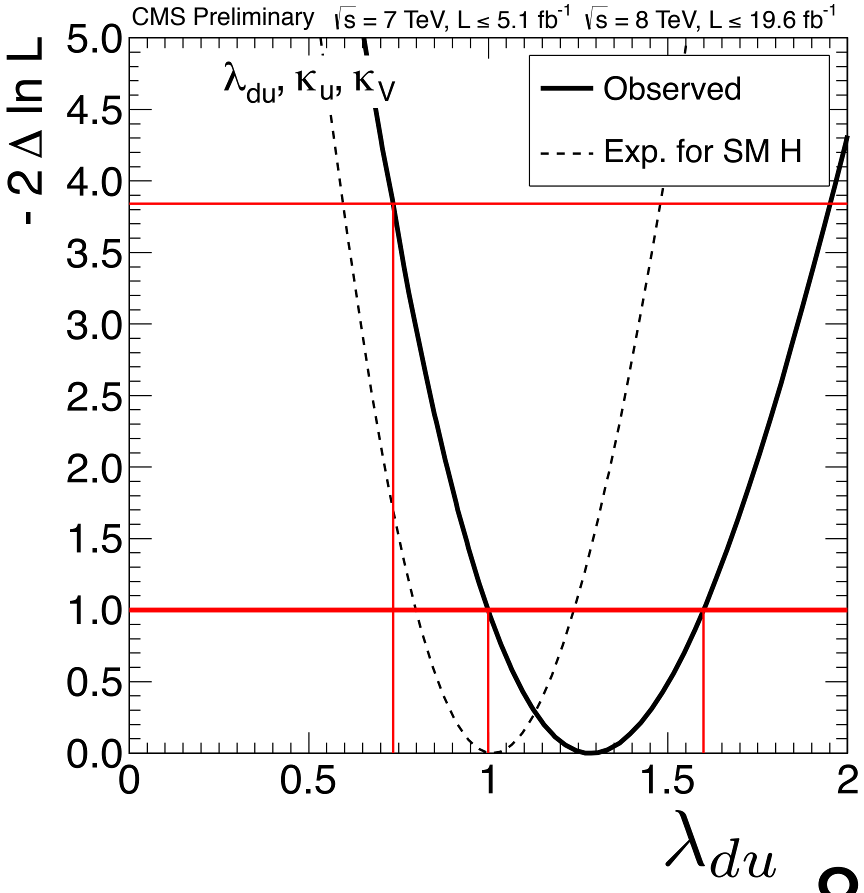
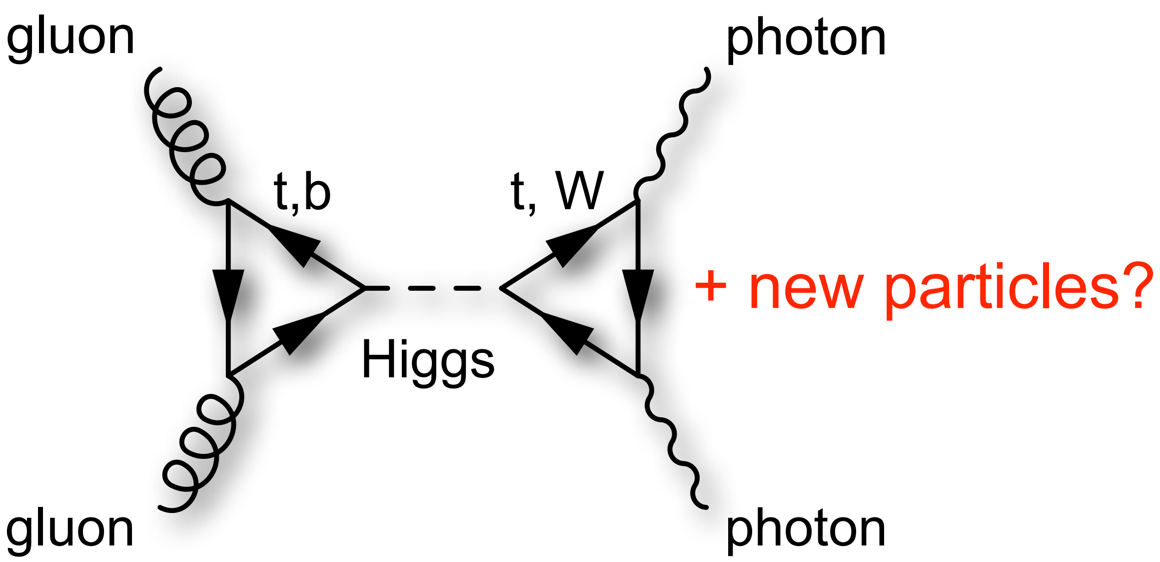
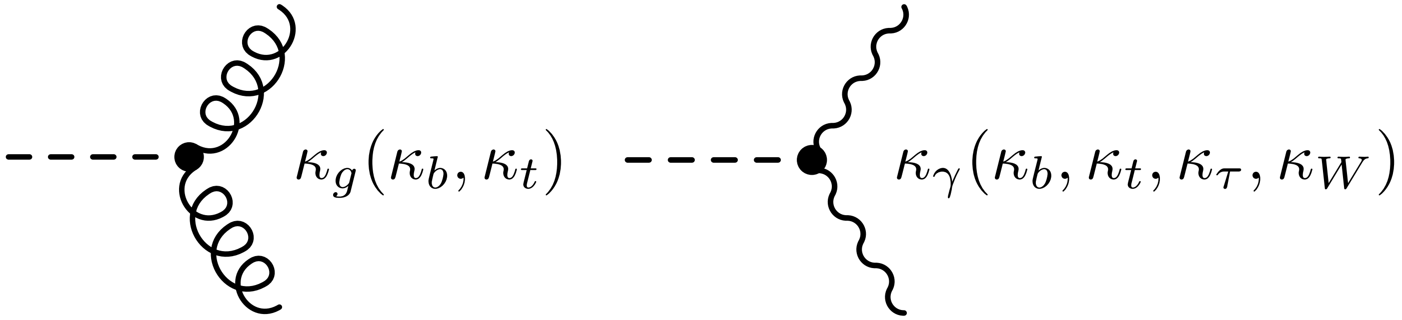


CMS PAS HIG-13-005



c) Loop induced Higgs couplings: κ_{gluon} vs κ_γ





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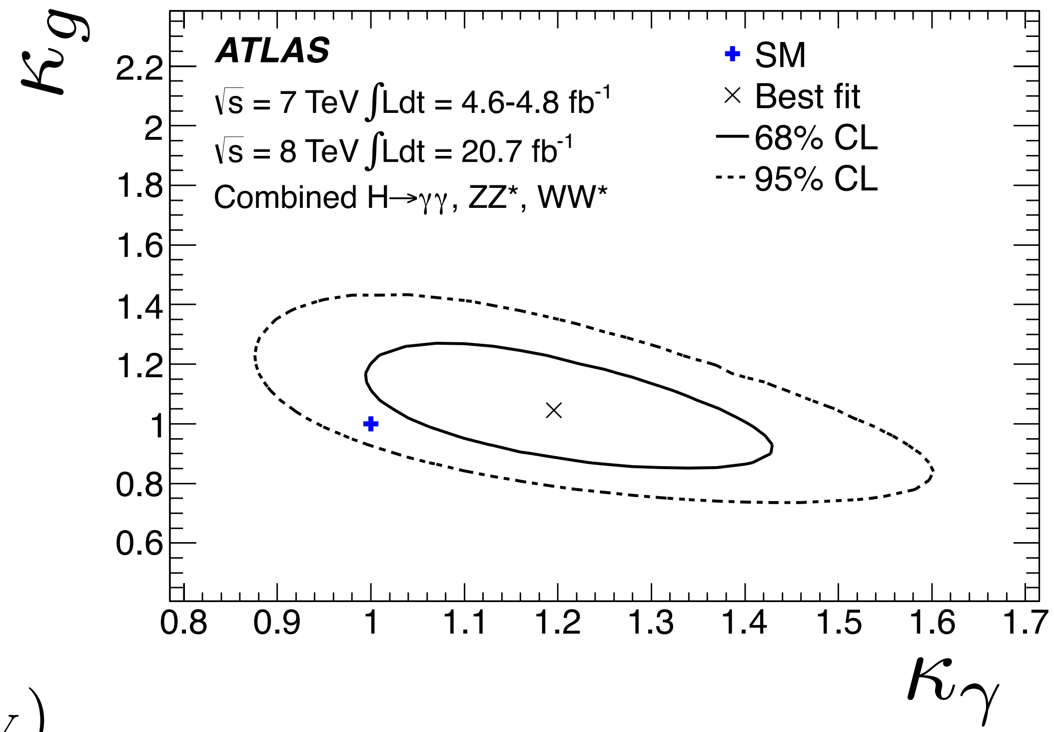


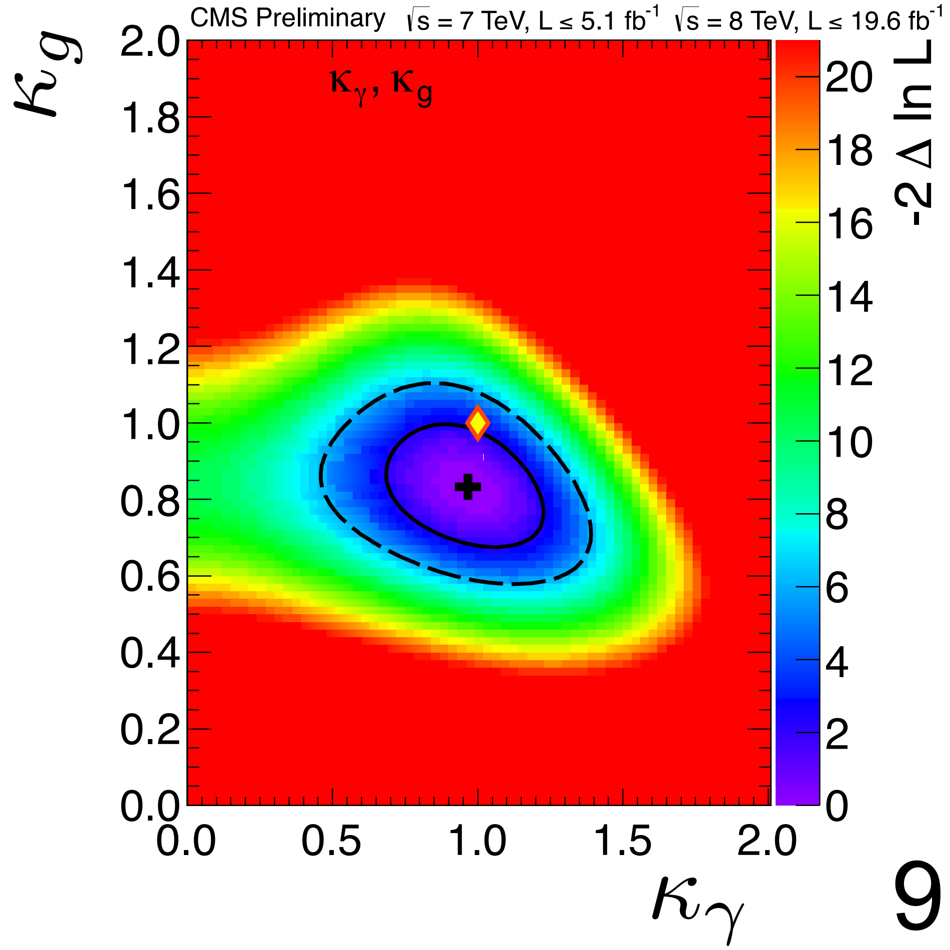
- Assume tree level couplings to SM particles as in the SM (i.e. $\kappa_W=\kappa_Z=\kappa_b=\kappa_\tau=\kappa_t,...=1$) and new particles do not contribute to the Higgs boson width.

Data are compatible with SM predictions at 10-15% accuracy.

ATLAS: $\kappa_g = 1.04\pm0.14$ at 68% C.L. $\kappa_\gamma = 1.20\pm0.15$ at 68% C.L.
CMS: $\kappa_g \in [0.63,1.05]$ at 95% C.L. $\kappa_\gamma \in [0.59,1.30]$ at 95% C.L.

No sign of BSM signal in the gg→H and H→γγ loops.

CMS PAS HIG-13-005



d) Constraints on BSM branching ratios

- Invisible Higgs decay
- Accessible via H+1-jet (mono-jet), VBF and VH processes.
- Limit with ZH(H→inv) at 95% C.L.
  - ATLAS $BR_{inv} < 0.65$ (expected 0.84)
  - CMS $BR_{inv} < 0.75$ (expected 0.91)

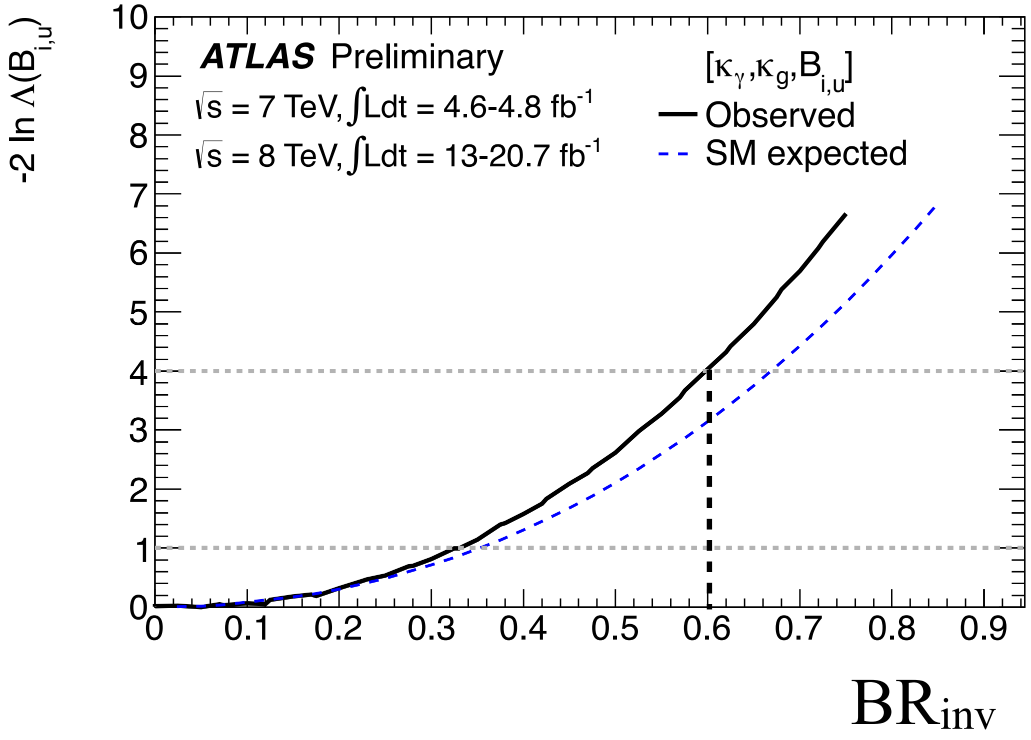
Via coupling measurement, parameterize:

$$\Gamma_H = \Gamma_{SM} + \Gamma_{BSM}$$

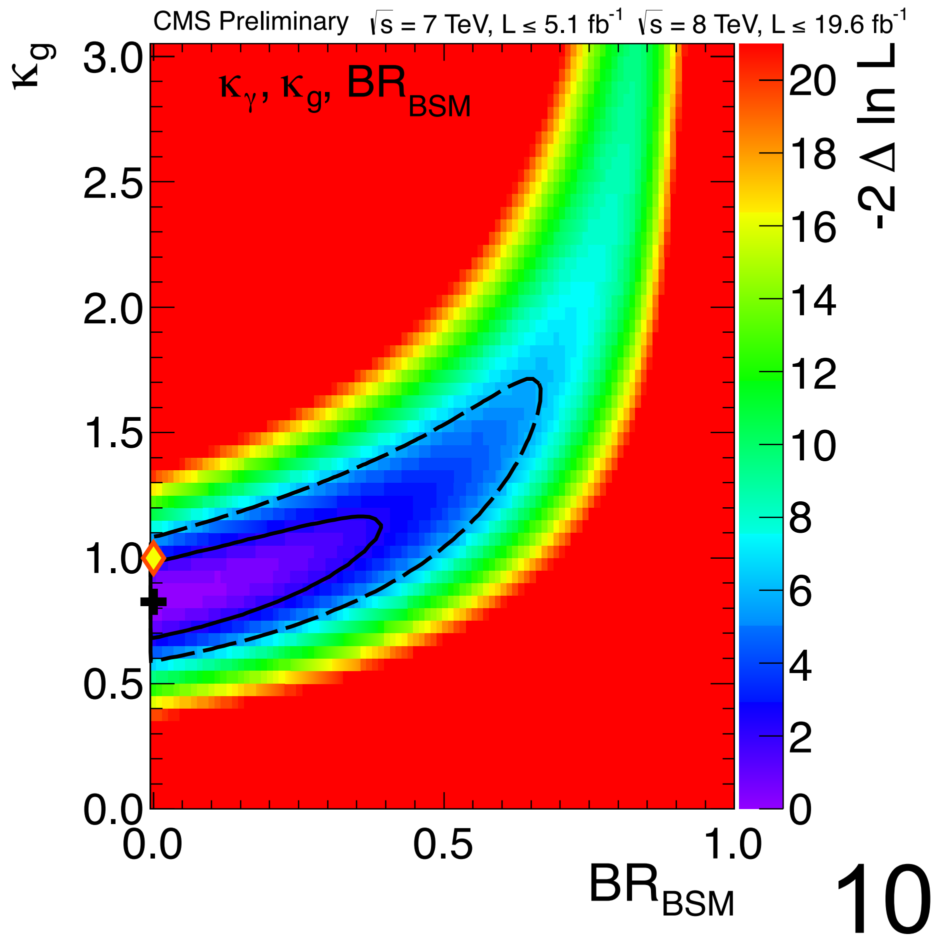
$$BR_{BSM} = \frac{\Gamma_{BSM}}{\Gamma_{SM}}$$

Assume: $\kappa_W = \kappa_b \ldots = 1$ and 3 parameter fit (κ_γ, κ_g, BR_{BSM})

ATLAS-CONF-2013-34



CMS PAS HIG-13-005

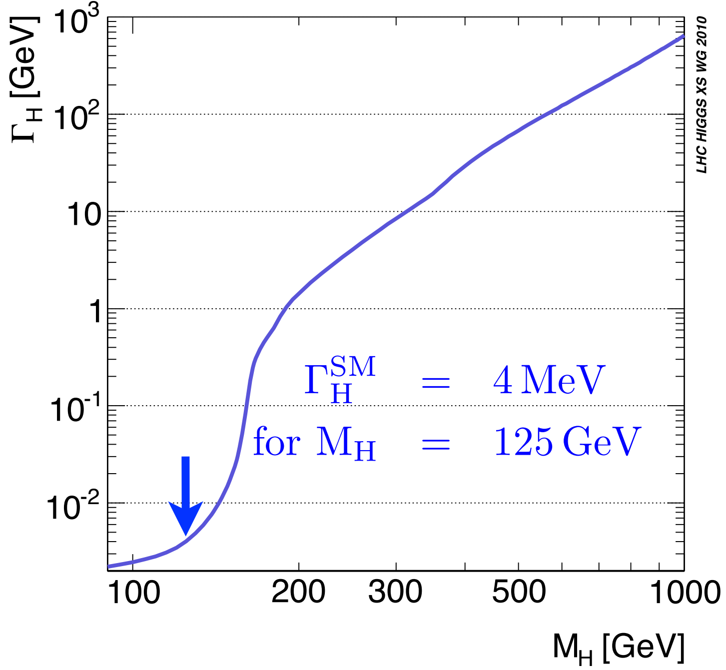


ATLAS: $BR_{BSM} < 0.60$ at 95% C.L. (0.67 expected)
CMS: $BR_{BSM} < 0.52$ at 95% C.L. (0.56 expected)

No sign of Higgs decay to BSM ⇨ **stringent limit on Dark Matter**

e) Higgs decay width measurements

LHC Higgs XS WG



1. Via direct measurements

   CMS PAS HIG-13-016

   CMS H→γγ mass spectrum $\Gamma_H < 6.9$GeV at 95% C.L.

2. Via Higgs coupling or invisible Higgs search

   BR(inv)<50% limit corresponds to $\Gamma_H < 2\Gamma_H^{SM}$ (= 8MeV) assuming couplings to SM particles are as in the SM.

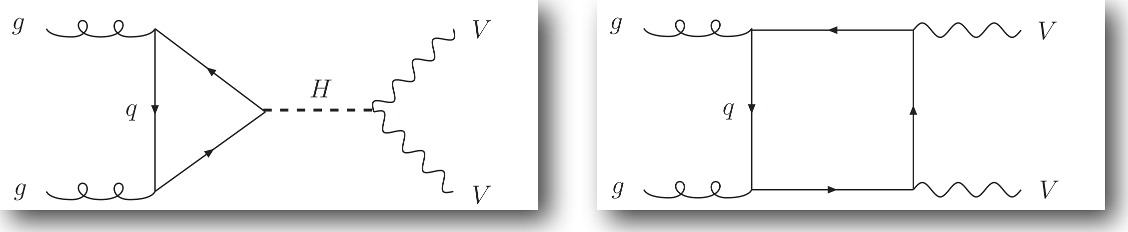
3. Via Higgs interferometry

   Destructive interference between Higgs signal and gg→VV continuum background.

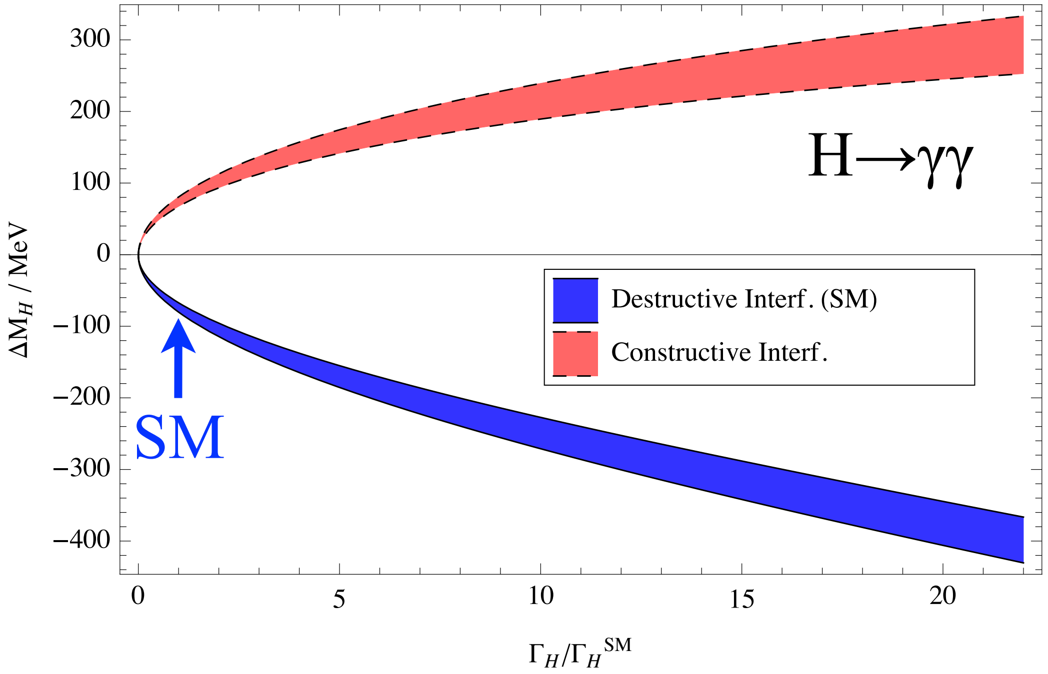
   H→γγ (S. Martin, L. Dixon) - mass shift (depends on Higgs p_T) $\Delta M_{\gamma\gamma} = -70$MeV for SM at NLO.

   H→WW^*/ZZ^* (N. Kauer, G. Passarino) - mass spectrum in high-mass end above $M_{4l} > 2M_{top}$.

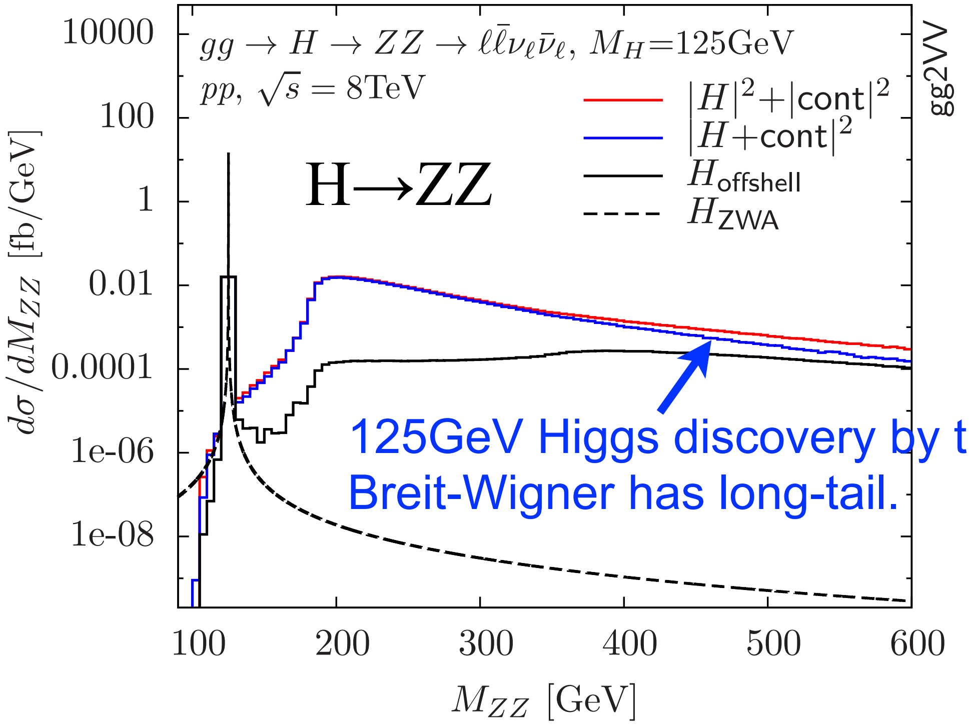
   Sensitivity on $\Delta\Gamma_H \lesssim O(100\text{MeV})$ is feasible?



Dixon, Li 2013



Kauer, Passarino 2012



125GeV Higgs discovery by theorist!
Breit-Wigner has long-tail.

Higgs coupling measurements summary

↪ R. Godbole : plenary talk

R. Patel, A. Falkowski : parallel talks

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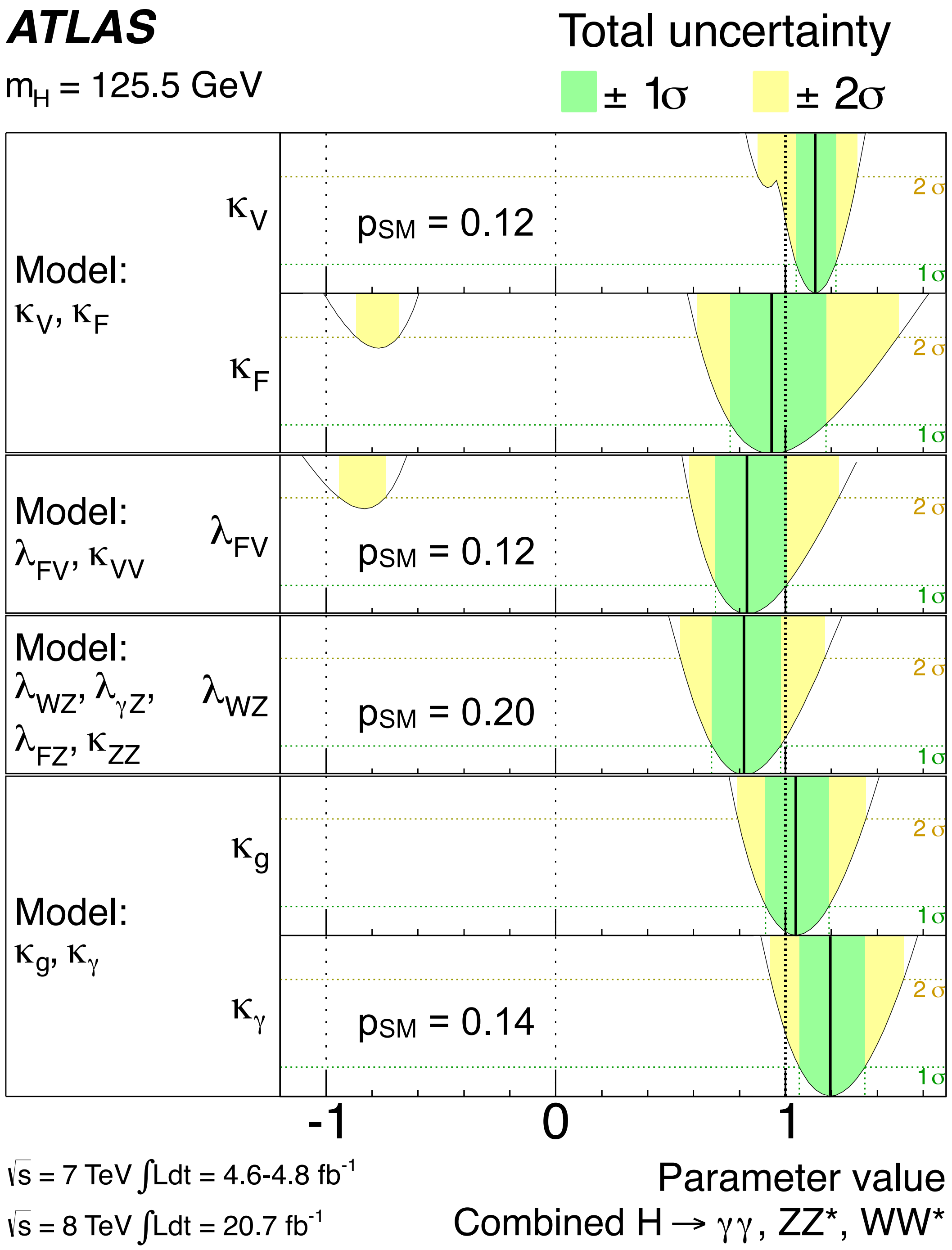
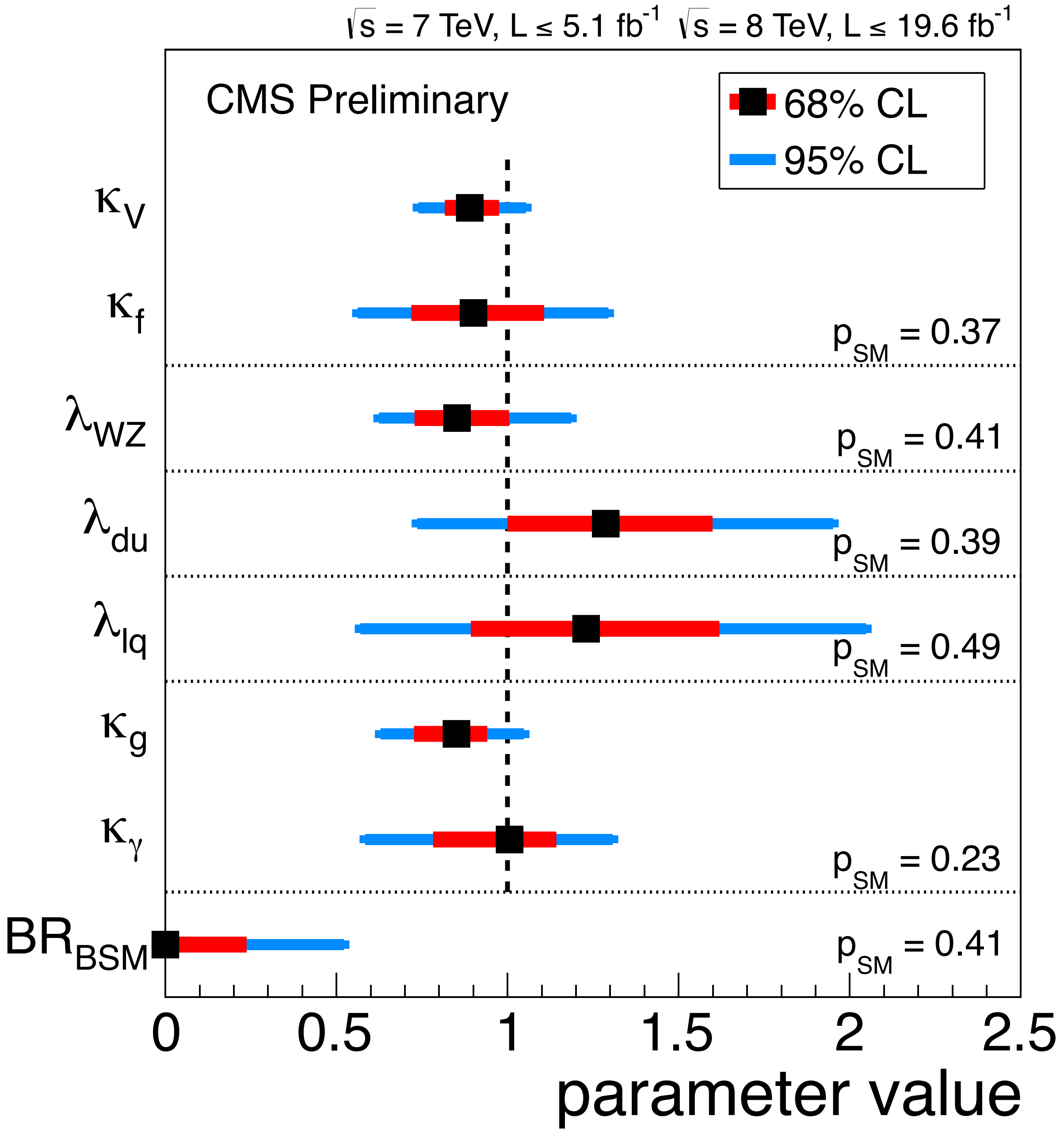


CMS PAS HIG-13-005

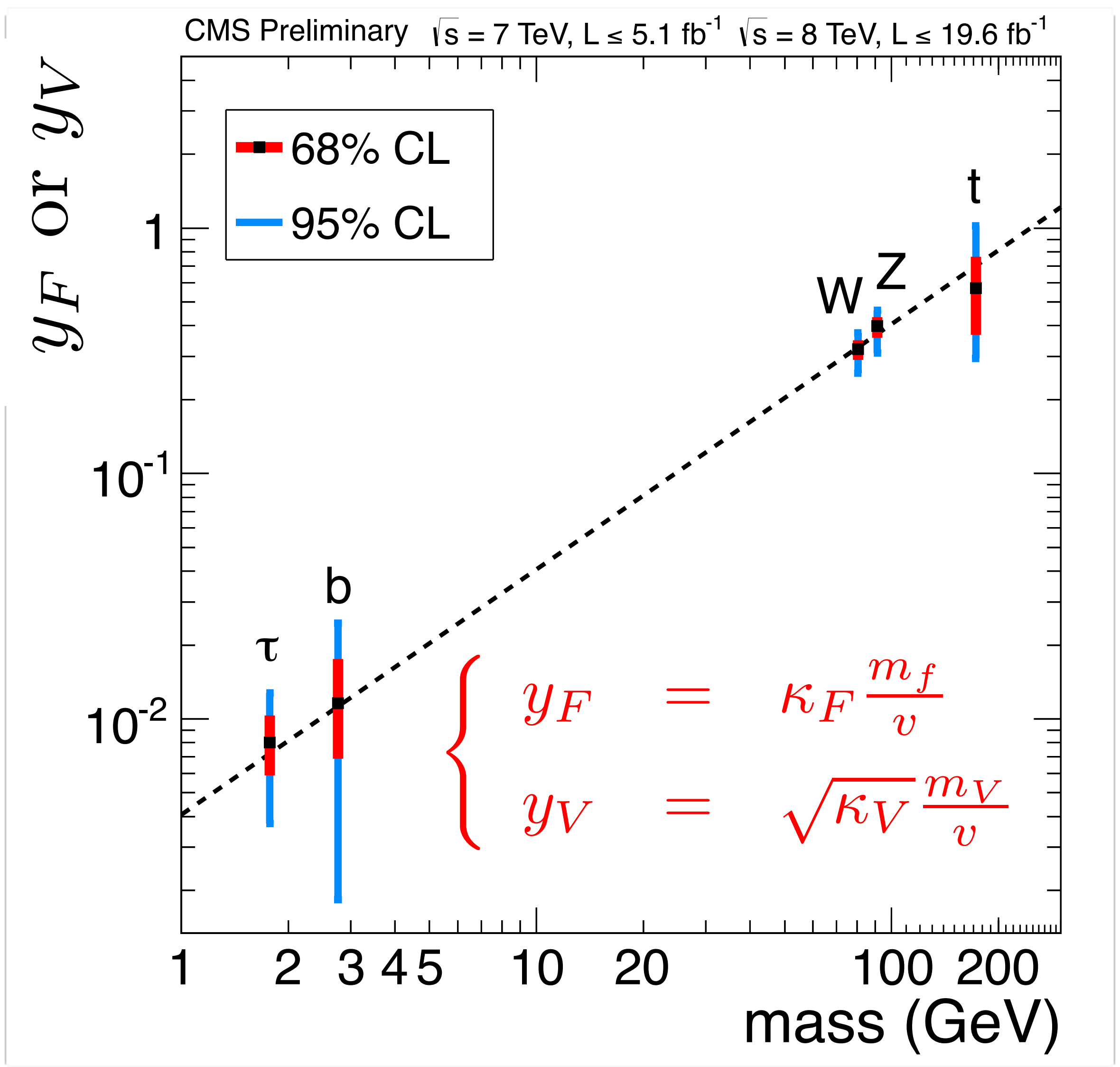


- Different couplings of Higgs-gauge boson and Higgs-Yukawa couplings, coupling ratios (VV, FV, du, lq), loop induced couplings, BSM BR have been tested.
- All are consistent with the Standard Model !

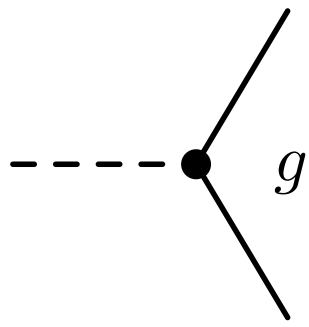
Couplings versus Mass - Higgs-gauge boson and Yukawa -

- Electroweak symmetry breaking needs to explain:
  - Non-zero mass of W/Z gage bosons and fermions.
  - Unitarity conservation below 1 TeV.
- Non-linear relation would indicate the Higgs sector is not single doublet.

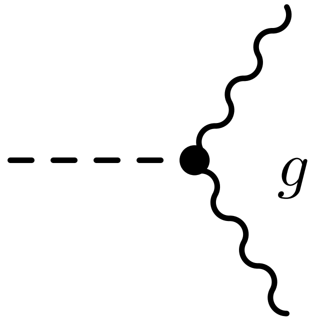
CMS PAS HIG-13-005



$m_b(m_b) = 4.16\,\mathrm{GeV}, m_b(M_H) = 2.76\,\mathrm{GeV}$



$$g_F = \sqrt{2}\frac{m_f}{v}$$



$$g_V = 2\frac{m_V^2}{v}$$

LHC wants to add
- Higgs self-couplig λ
- Rare decay H→μμ

etc.

LHC Higgs XS WG CERN Report 3 (arXiv:1307.1347)

4. Higgs Boson Quantum Numbers

- What are the quantum numbers of observed state X ?
  - J^{PC}: J=spin, P=parity, C=charge conjugation

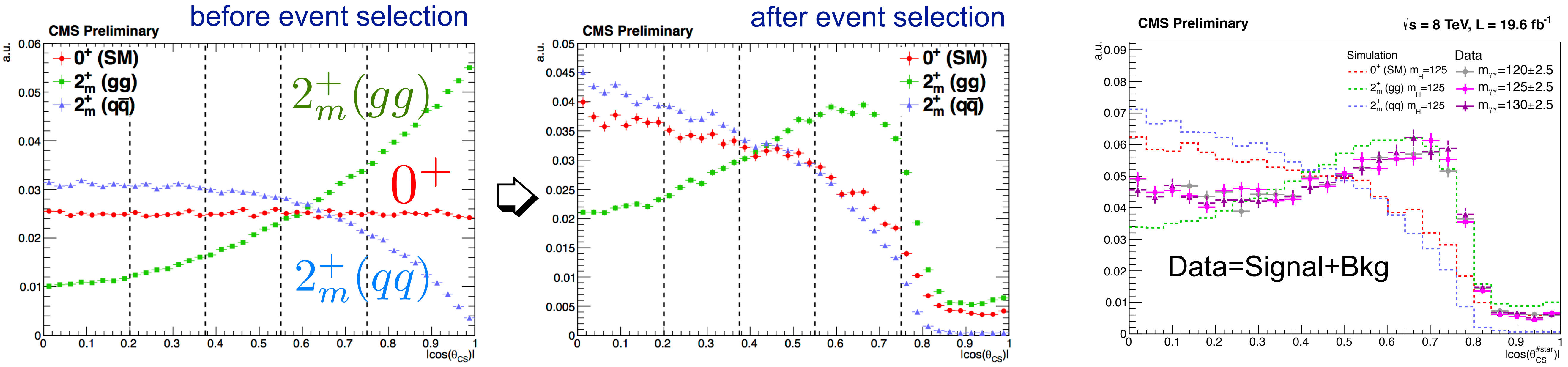
- Spin0: Standard Model Higgs boson
  - The Standard Model Higgs boson is scalar particle (0^+).
  - CP-mixing/violation in spin-0 can exist but small in many BSM models.
- Spin1: Landau-Yang theorem
  - Landau-Yang theorem forbids the direct decay of an on-shell spin-1 particle into a pair of massless particles.
  - Observation of H→γγ rules out the possibility that the new resonance has spin 1, and fixes C=1 (barring C violating effects in the Higgs sector).
  - This theorem strictly applies to an on-shell resonance (*i.e.* small width hypothesis).
- Spin2: graviton
  - Theoretically difficult. Velo-Zwanziger problem with U(1) gauge field.
  - Who will be responsible for electroweak symmetry breaking?
  - Why haven't we observed analogous KK excitations of SM gauge bosons?

But experimentalists are not biased with theory. Let's try with H→γγ, ZZ^* and WW^*.

a) Spin/CP study in H→γγ

Decay angle cosθ* in di-photon (Collins-Soper) rest frame: $|\cos\theta^*| = \frac{|\sinh(\Delta\eta^{\gamma\gamma})|}{\sqrt{1+(p_T^{\gamma\gamma}/m_{\gamma\gamma})^2}}\frac{2p_T^{\gamma 1}p_T^{\gamma 2}}{m_{\gamma\gamma}^2}$

CMS PAS HIG-13-016



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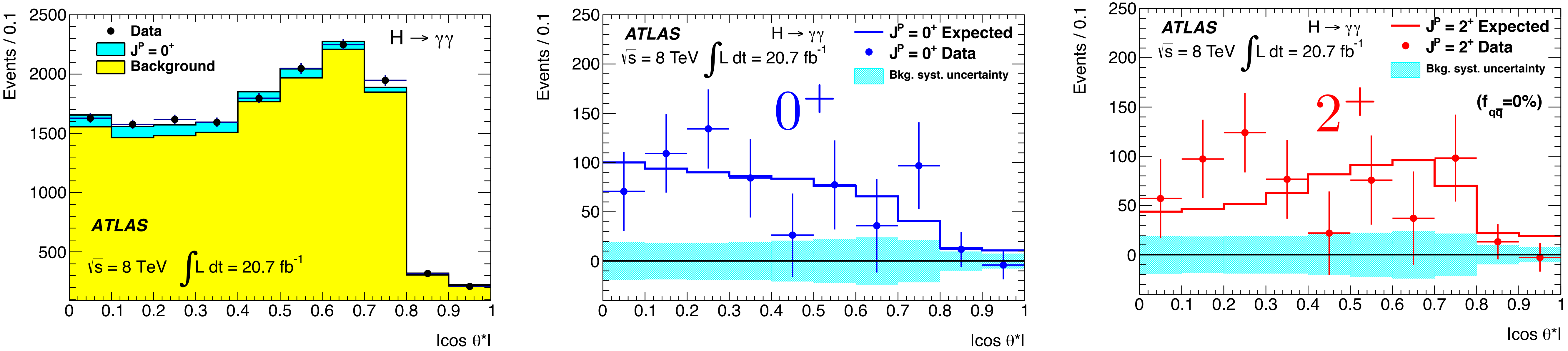
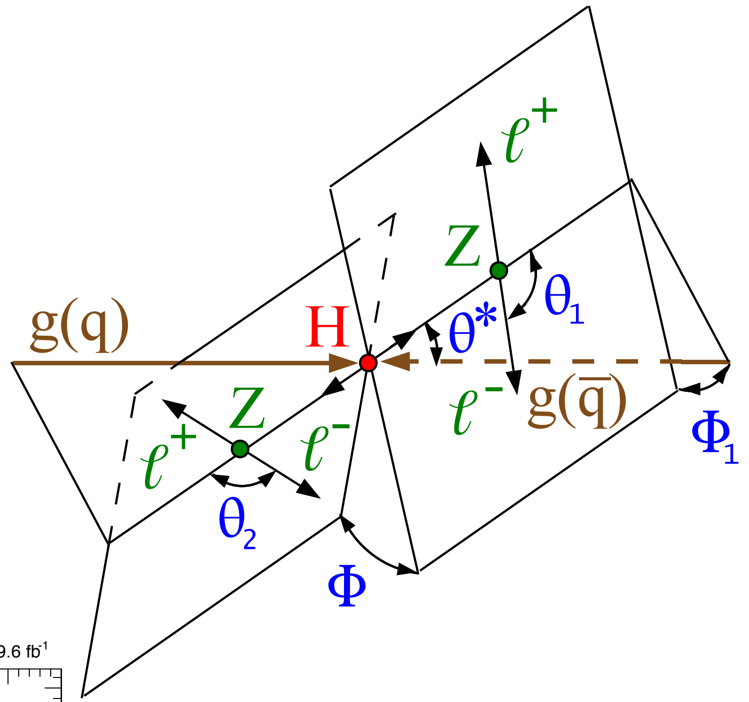


No event yield information (cross section) is used but shape only in these analyses.

b) Spin/CP study in $H \to ZZ^* \to 4$ leptons



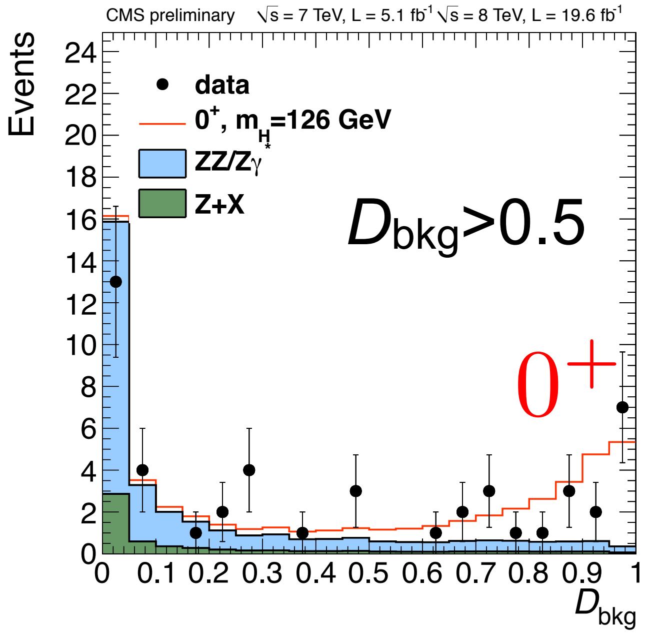
- Full final state reconstruction with 7 variables
  1. invariant masses: m_{Z1}, m_{Z2}

$$\left.\begin{array}{ll}\text{2. production angles:} & \Phi_1,\ \theta^* \\ \text{3. decay angles:} & \Phi,\ \theta_1,\ \theta_2\end{array}\right\}\vec{\Omega}$$

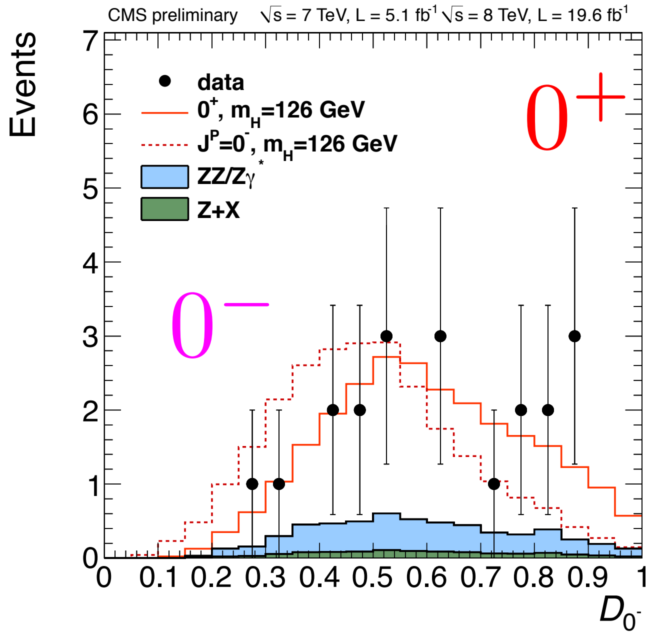
analogy to $\pi^0 \to e^+e^-e^+e^-$

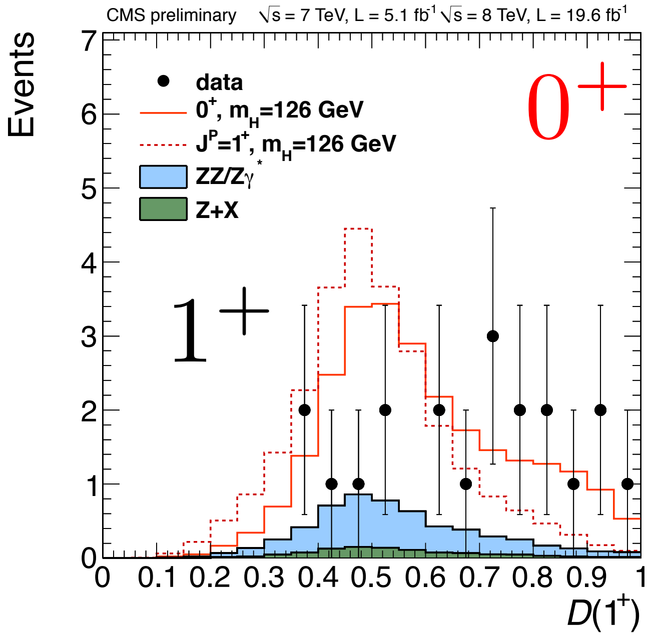
Matrix element based discriminant D_{JP}

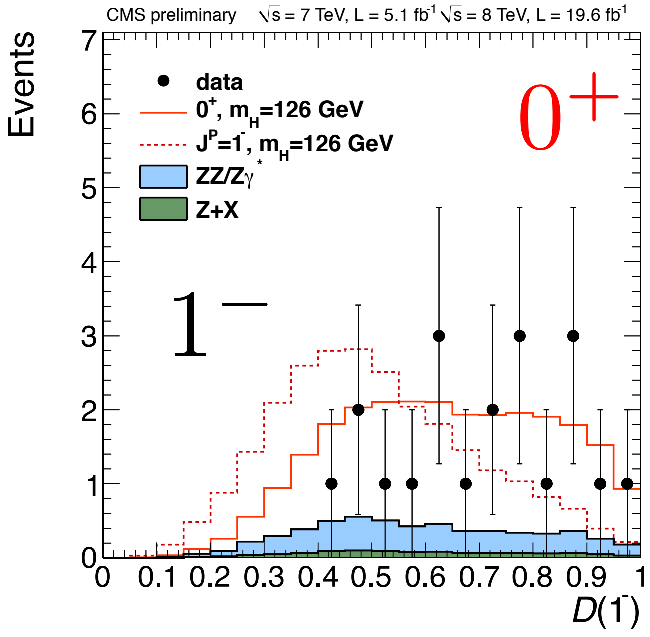
$$\mathcal{D}_{JP} = \frac{\mathcal{P}_{\mathrm{SM}}}{\mathcal{P}_{\mathrm{SM}} + \mathcal{P}_{JP}} = \left[1 + \frac{\mathcal{P}_{JP}\left(m_{Z_1}, m_{Z_2}, \vec{\Omega} | m_{4l}\right)}{\mathcal{P}_{\mathrm{SM}}\left(m_{Z_1}, m_{Z_2}, \vec{\Omega} | m_{4l}\right)}\right]^{-1}$$

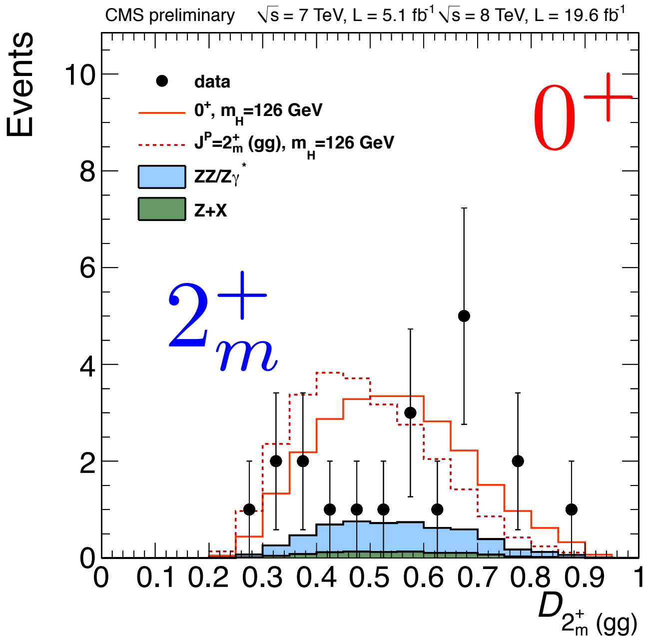


CMS PAS HIG-13-002





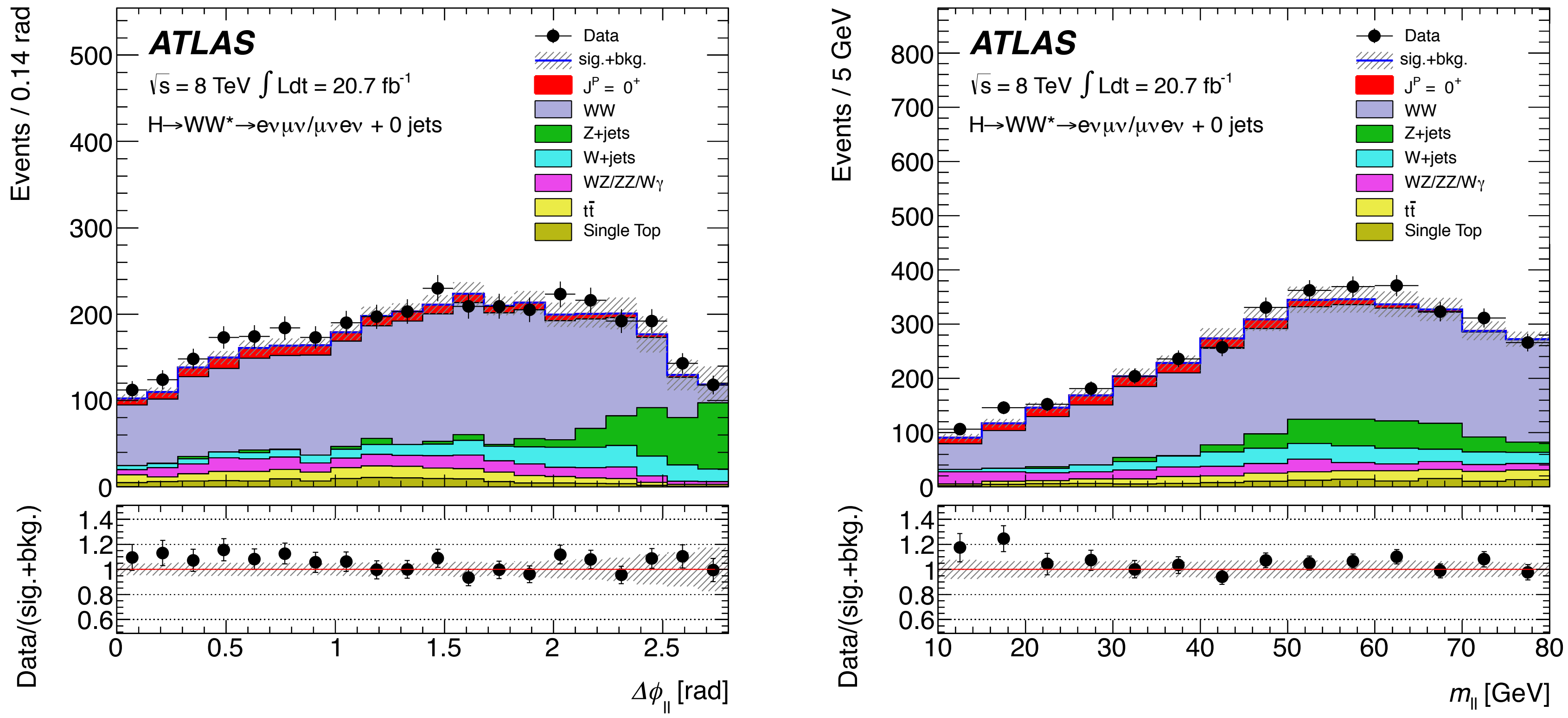




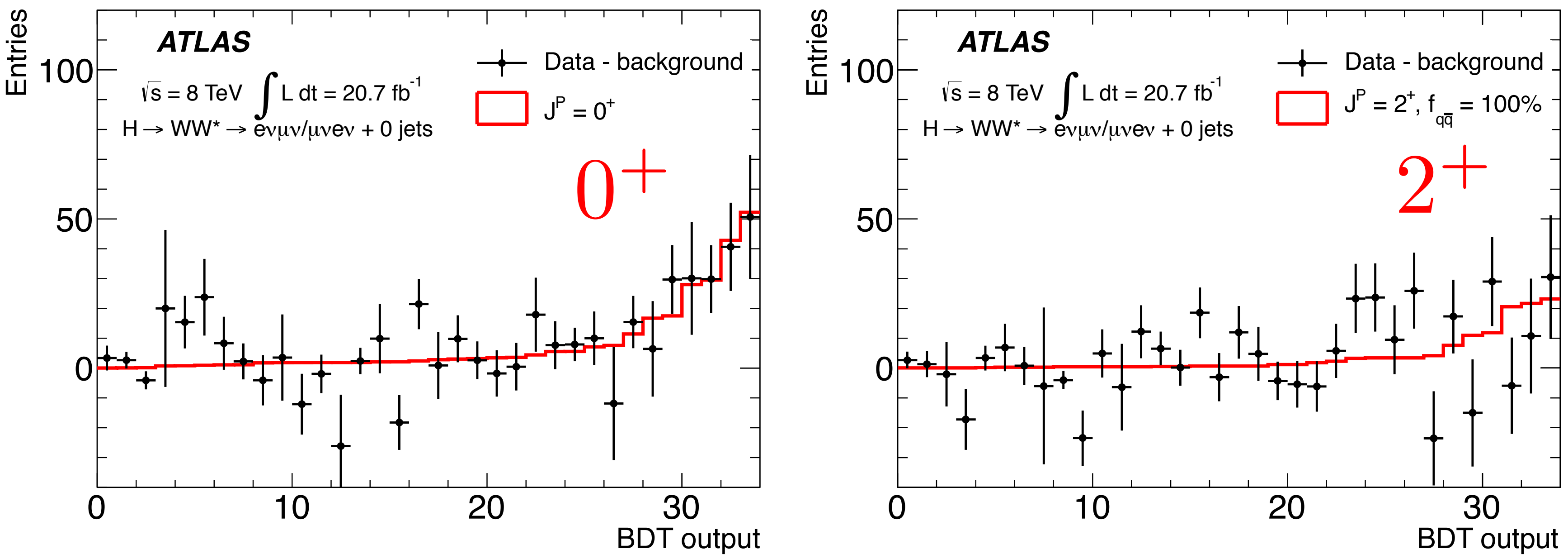
c) Spin/CP study in $H\to WW^*\to l\nu l\nu$

- Kinematical variables sensitive to J^P: $\Delta\phi_{ll},\ M_{ll},\ m_{\mathrm{T}}$ ...

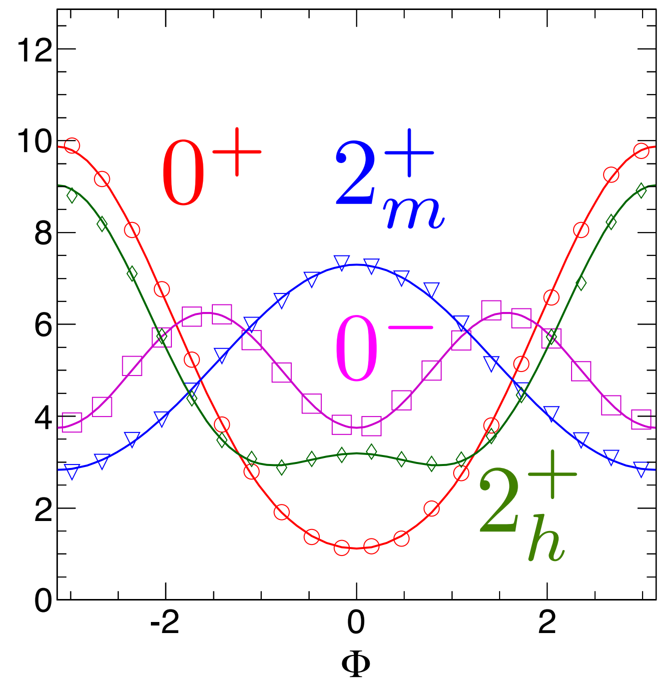
CERN-PH-EP-2013-102



Make use of spin correlation in $H\to WW^*\to l\nu l\nu$ decay.



Bolognesi et al., 2012



Test statistic:

$$q = -\log \frac{\mathcal{L}(J^P_{\mathrm{alt}}, \hat{\hat{\mu}}_{J^P_{\mathrm{alt}}}, \hat{\hat{\theta}}_{J^P_{\mathrm{alt}}})}{\mathcal{L}(J^P = 0^+, \hat{\hat{\mu}}_{0^+}, \hat{\hat{\theta}}_{0^+})}$$

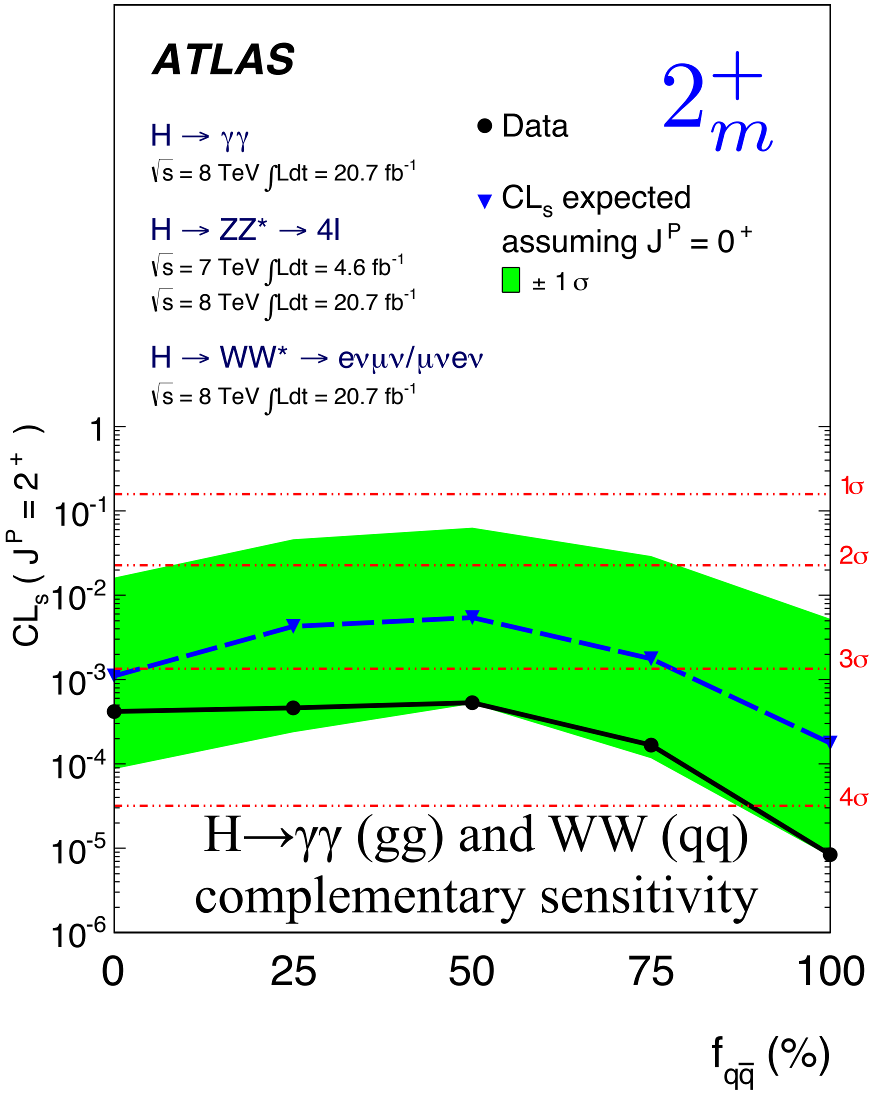
CLs:

$$\int_{q_0}^{+\infty} p\,dq$$

$$\mathrm{CL_s}(J^P_{\mathrm{alt}}) = \frac{p_0(J^P_{\mathrm{alt}})}{1 - p_0(0^+)}$$

$$\int_{-\infty}^{q_0} p\,dq$$

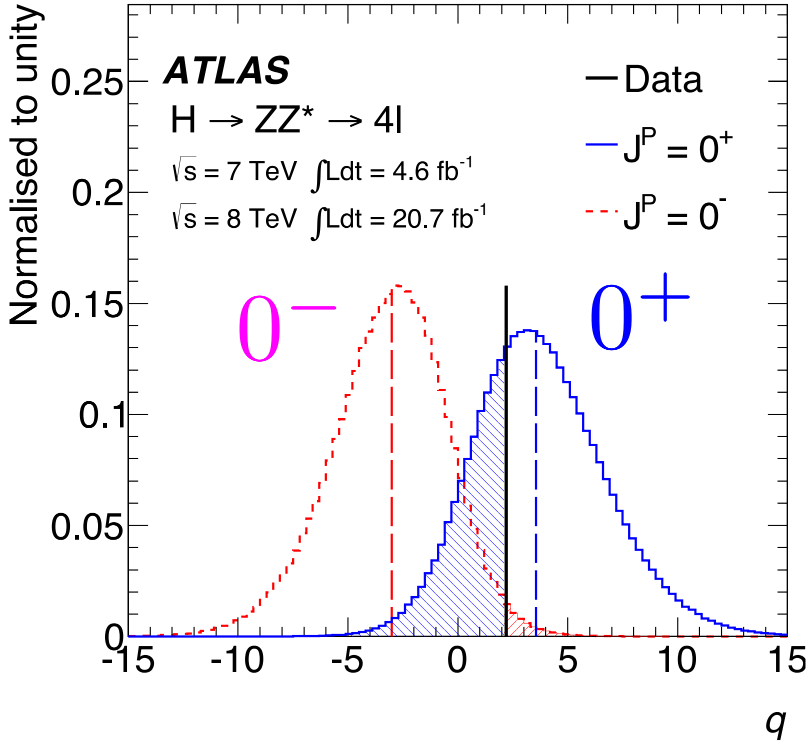
CERN-PH-EP-2013-102



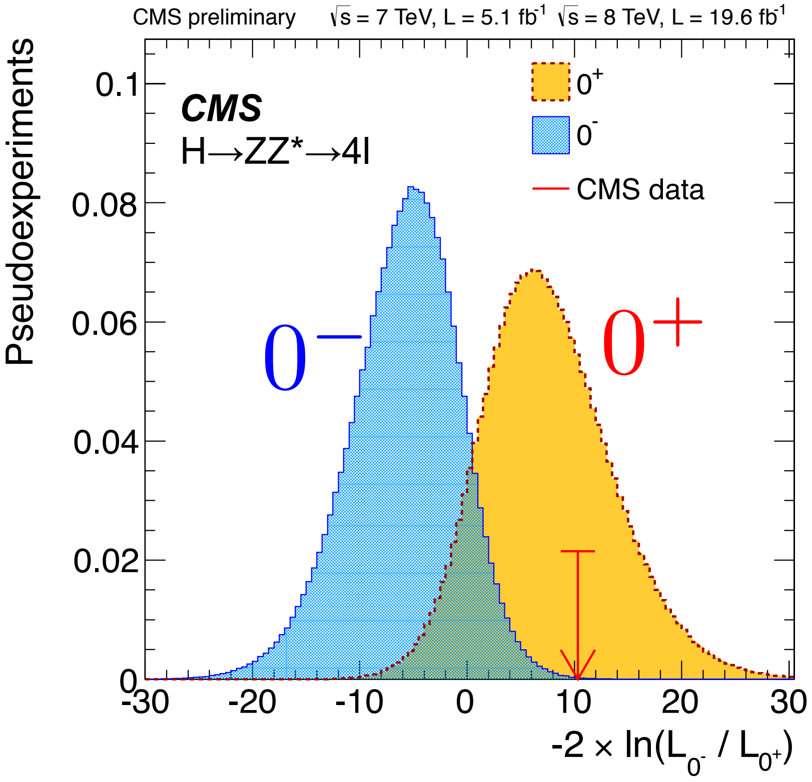
H→γγ (gg) and WW (qq) complementary sensitivity

Spin/CP 0^+ vs 0^-

CERN-PH-EP-2013-102

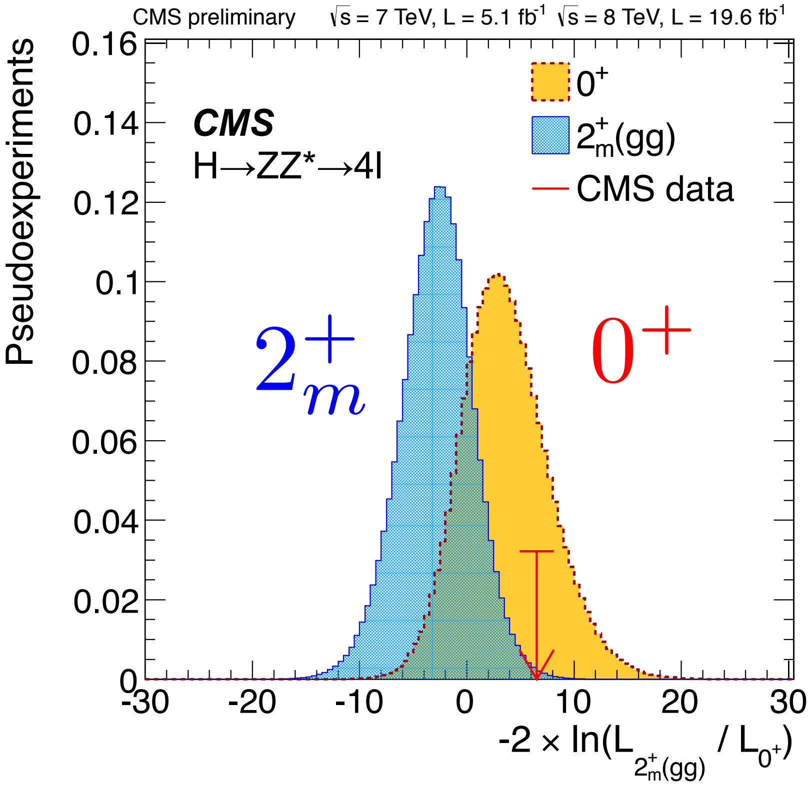


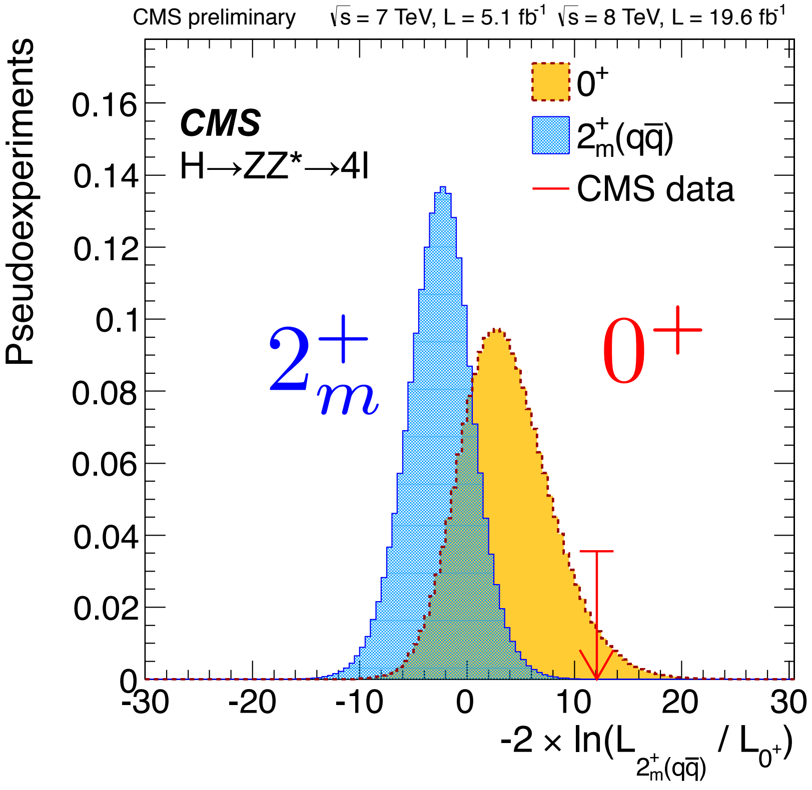
CMS PAS HIG-13-002



Spin/CP 0^+ vs 2^+

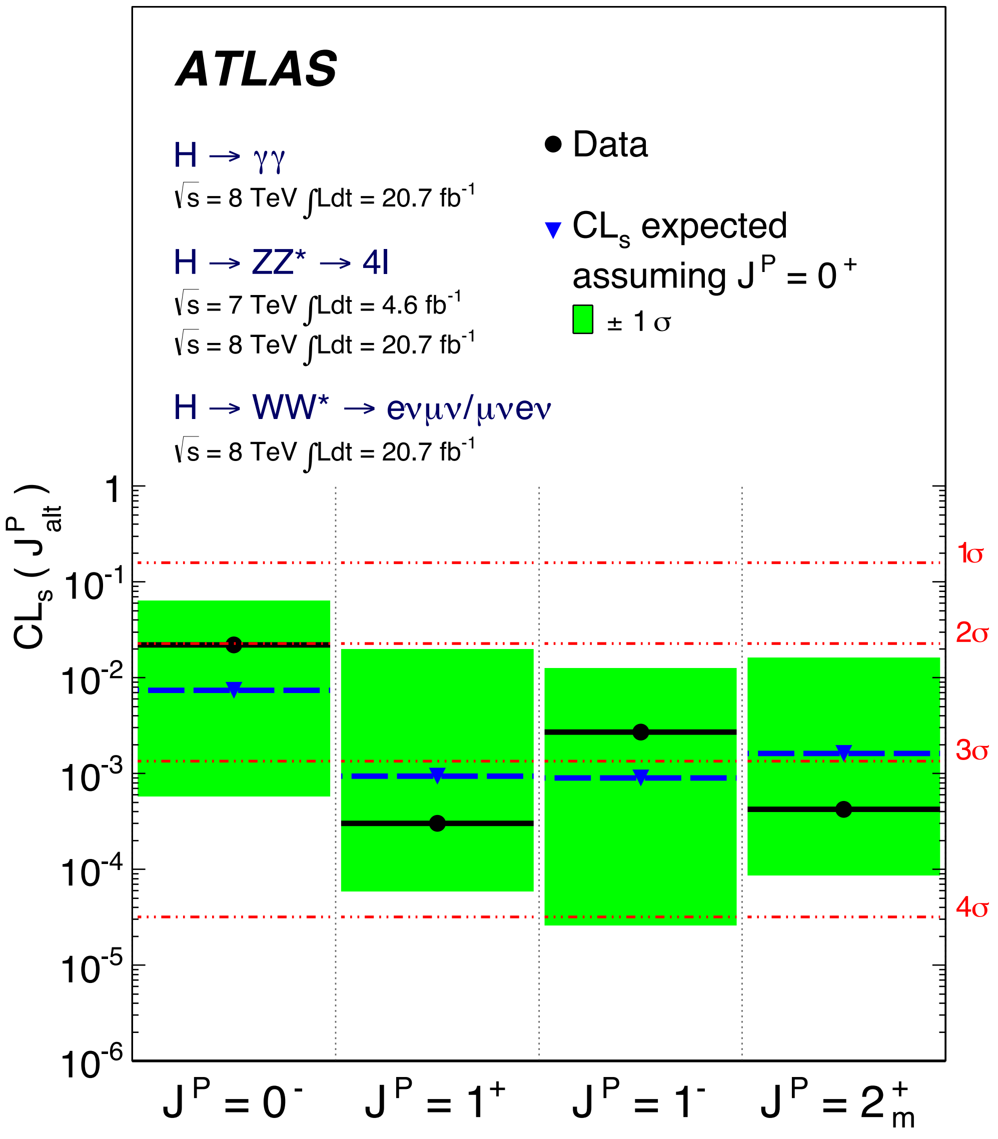
CMS PAS HIG-13-002





Higgs spin/CP: combined results

J^P	production	particle	ATLAS CLs	CMS CLs
0^-	gg→X	pseudoscalar	2.2% (H→ZZ*)	0.16% (H→ZZ*)
1^+	qq→X	exotic pseudovector	0.030% (H→ZZ*,WW*)	<0.1% (H→ZZ*)
1^-	qq→X	exotic vector	0.27% (H→ZZ*,WW*)	<0.1% (H→ZZ*)
2^+	gg/qq→X	graviton minimal couplings	0.042% (gg) (H→γγ,ZZ*,WW*)	0.6% (gg) (H→ZZ*,WW*) 60.9% (H→γγ)



CERN-PH-EP-2013-102

- Exclude pure $J^P=0^-$, $1^\pm$, 2^+ (minimal coupling) at more than 97.8% C.L..
(but note that LHC has not tested all models!)
- Other production modes in study: VBF (phi difference in tagged jets), WH/ZH (invariant mass distributions are discriminant for $J^P=0^\pm$, 2^+).

Probing the tensor structure in spin $0^{\pm}$

$$A_{VV} = \frac{1}{v}\epsilon_1^{*\mu}\epsilon_2^{*\nu}\left(a_1 g_{\mu\nu}m_H^2 + a_2 q_\mu q_\nu + a_3\epsilon_{\mu\nu\alpha\beta}q_1^\alpha q_2^\beta\right) = A_1 + A_2 + A_3$$

- CMS study in H→ZZ*→4l final state
- In the SM at LO, $a_1=1$ and $a_2=a_3=0$
- Test CP-odd amplitude A_3
  - In many BSM model, CP-odd $A_3 \sim O(10^{-10})$, ex. MSSM
- When a_1 dominates f_{a3} is CP-violating fraction

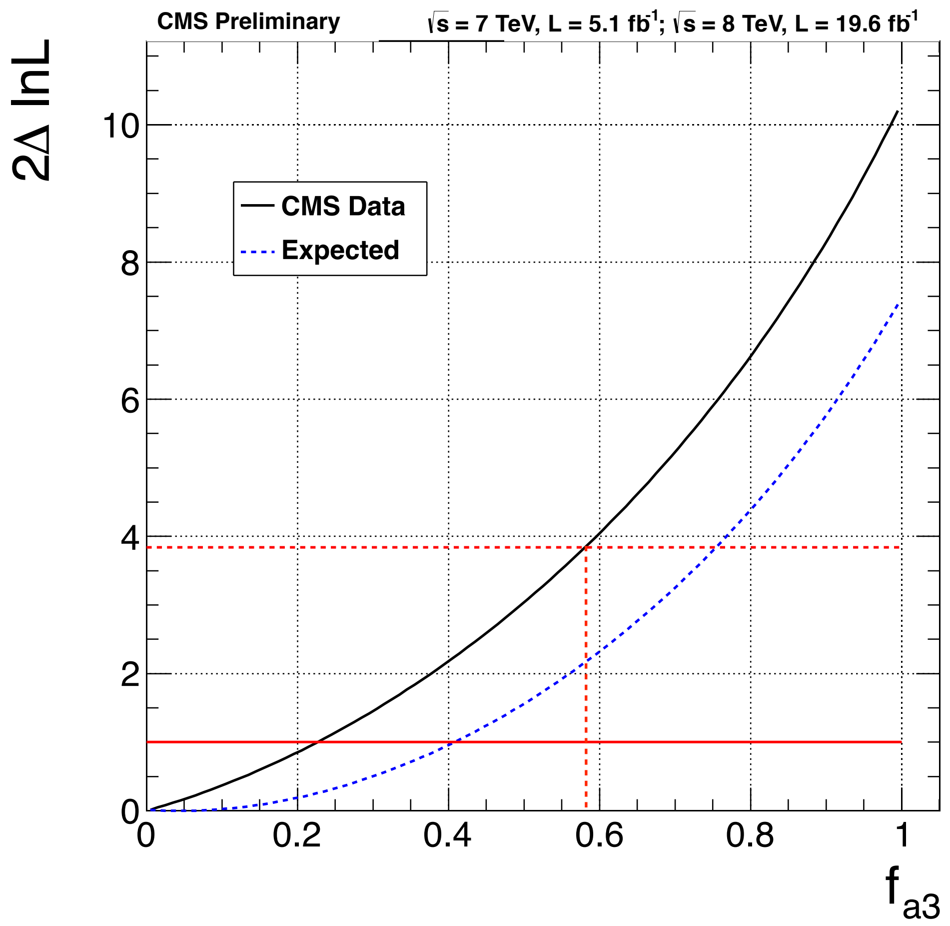
$$\mathcal{M}(H \to ZZ^* \to 4l) = A_1 + A_3$$

$$f_{a3} = \frac{|A_3|^2}{|A_1|^2 + |A_3|^2}$$

$$f_{a3} = 0.00^{+0.23}_{-0.00}$$

$$f_{a3} < 0.58 \text{ at } 95\% \text{ C.L. (exp. } 0.76)$$

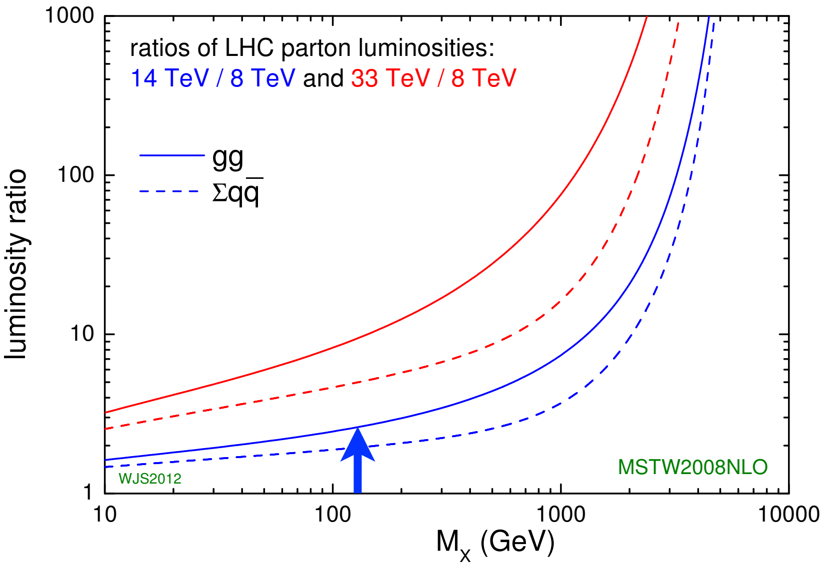
CMS PAS HIG-13-002



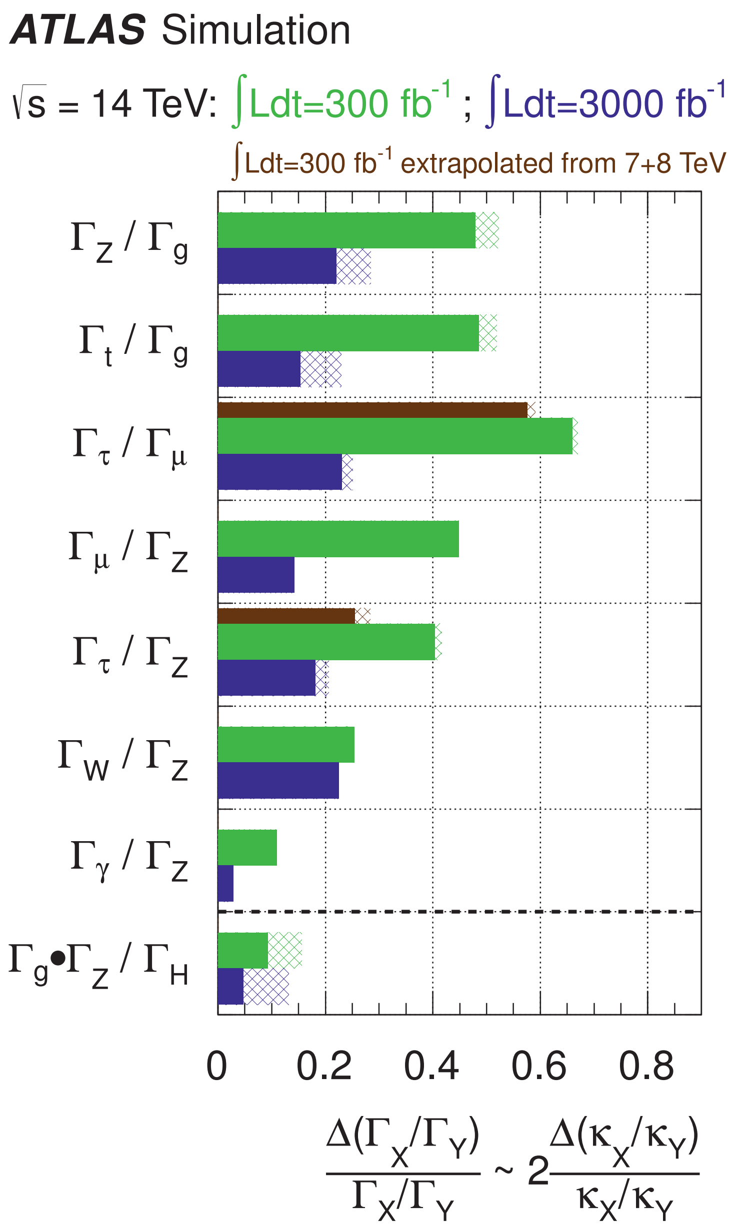
- **Anomalous coupling approach** (current LHC analysis method)
  - Amplitude compatible with Lorentz and gauge invariance. Momentum dependent form-factors. Consistent only at LO.
- **Effective Lagrangian approach** (future plan)
  - General effective Lagrangian compatible with Lorentz and gauge invariance. Consistent beyond LO.
- Coupling of a pseudoscalar (0^-) particle A to VV is loop induced that can be suppressed. Thus study in X→ff (Yukawa sector) will become important.

5. High Luminosity LHC (HL-LHC)

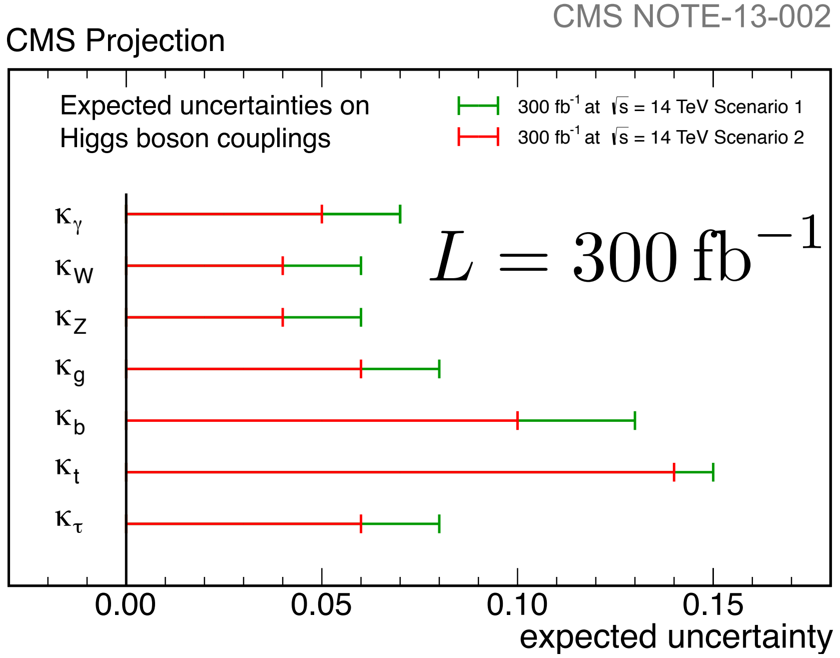
- ECFA HL-LHC with L=300 fb^{-1} (3 ab^{-1}) physics study.
- Higgs mass precision ΔM_H ~100 (50) MeV.
- Access to top-Yukawa coupling via ttH, and rare decay H→μμ.
- Coupling precision of 10 to 5% reachable (even few% in κ_γ/κ_Z).
- Detector performances (trigger, lepton-id, fake, τ/b-id) are crucial.
- Theory uncertainty dominates - challenge for theorists!

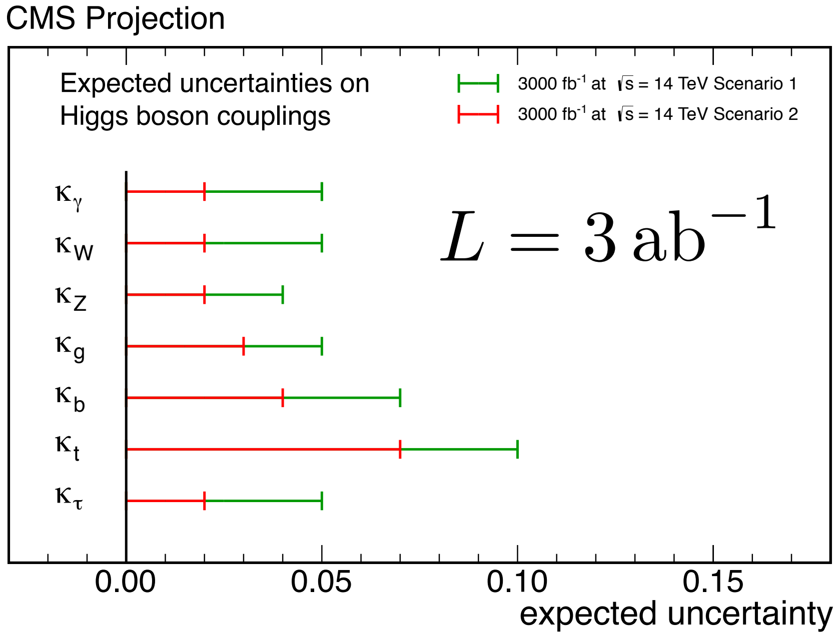


ATLAS-PHYS-PUB-2013-007



CMS NOTE-13-002



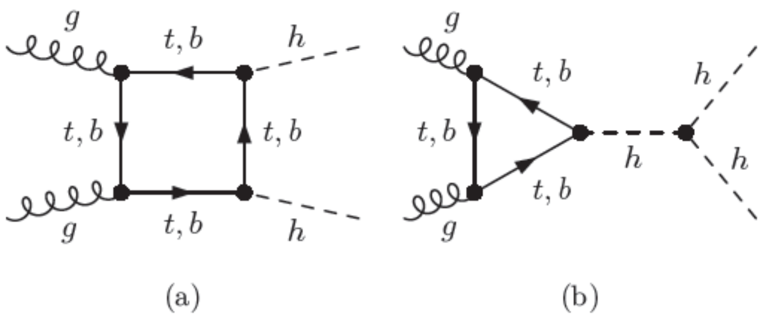


	σ(14TeV)/σ(8TeV)
gg→H	**2.6** ($M_X=M_H$)
qq→qqH	**2.6** (probes high M_X)
qq→VH	**2.1** ($M_X=M_V+M_H$)
gg→ttH	**4.7** (phase space+M_X)

Scenario 1
current systematic uncert.
Scenario 2
theory uncert. ↘ 1/2
other systematics ↘ 1/√L

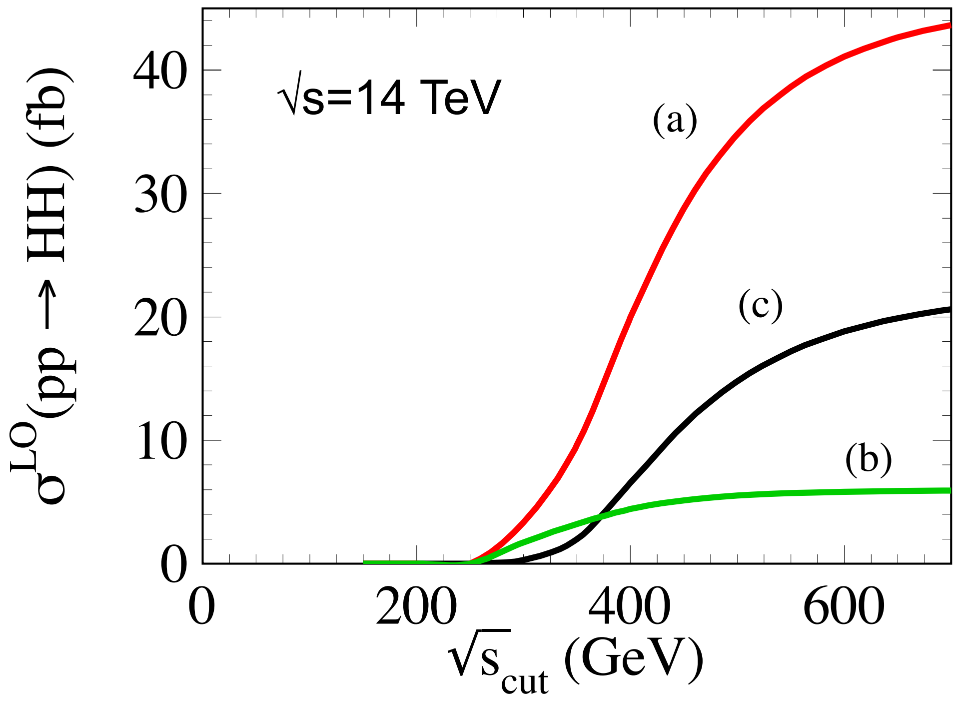
Higgs potential - Higgs self-coupling

- One of the core physics programmes at HL-LHC, but very challenging in both experiment and theory.
- Is it feasible to measure Higgs self-coupling at 20-30% level at HL-LHC ?

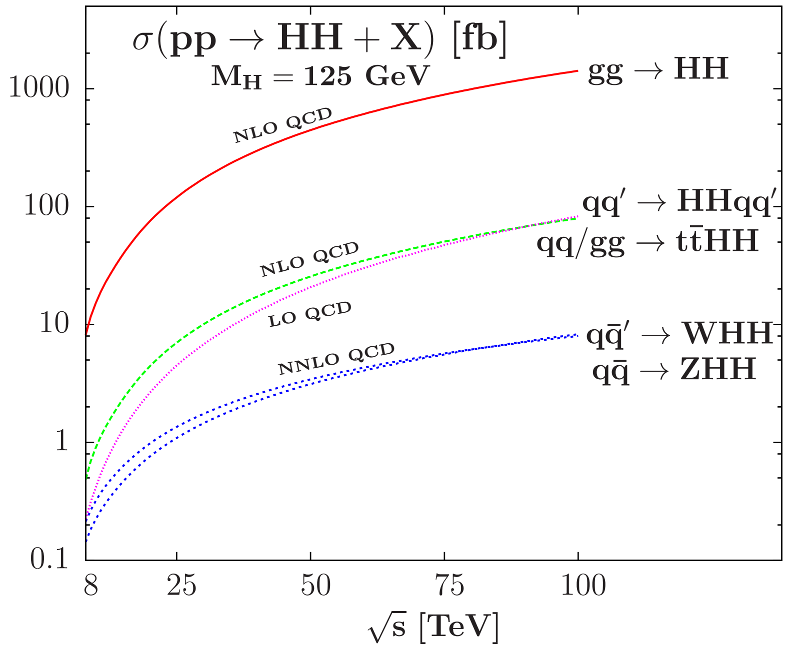


Destructive interference between box (a) and triangle (b) diagrams.

J. Grigao et al., 2013



J. Baglio et al., 2013



Now being discussed at ECFA HL-LHC study + LHC Higgs XS WG.

1. which channels to explore as benchmark, ex. HH→bbγγ, bbττ etc.,
2. new ideas on analysis methods, ex. interference effect in kinematical variables, boosted Higgs regime, HH+jets, etc.,
3. strategy for common (NLO) MC tool developments in various channels in gg→HH/ttHH, qq→qqHH/WHH/ZHH, MSSM h/H/A/$H^\pm$ pair production.

Summary

Higgs Property Measurements at LHC

- Higgs boson mass (M_H) & decay width (Γ_H)
  $\hookrightarrow$ M_H measured at 3 per mille precision. No sign of BSM in Γ_H, BR_{inv}.
- Higgs couplings to gauge bosons (g_V) and fermions (g_F)
  $\hookrightarrow$ Consistent with the SM prediction, $g_V \propto m_V^2$, $g_F \propto m_f$. Next, study in $d\sigma/dX$.
- Higgs boson quantum numbers J^{PC} and tensor structure
  $\hookrightarrow$ Evidence for scalar nature of 0^+. No evidence for CP-mixture.
- Higgs potential - Higgs self-coupling λ
  $\hookrightarrow$ Remains as an important territory to conquer in HL-LHC.
- Beyond the Standard Model Higgs (MSSM, 2HDM, etc.)
  $\hookrightarrow$ No evidence, but keep looking for BSM Higgs(es) and exotic Higgs decays.

- We have observed the fist elementary particle of scalar - Higgs boson.
  - Brout-Englert-Higgs mechanism: what an incredible purely theoretical idea !!!
  - Experimentalists will make every endeavor for BSM physics discovery !!

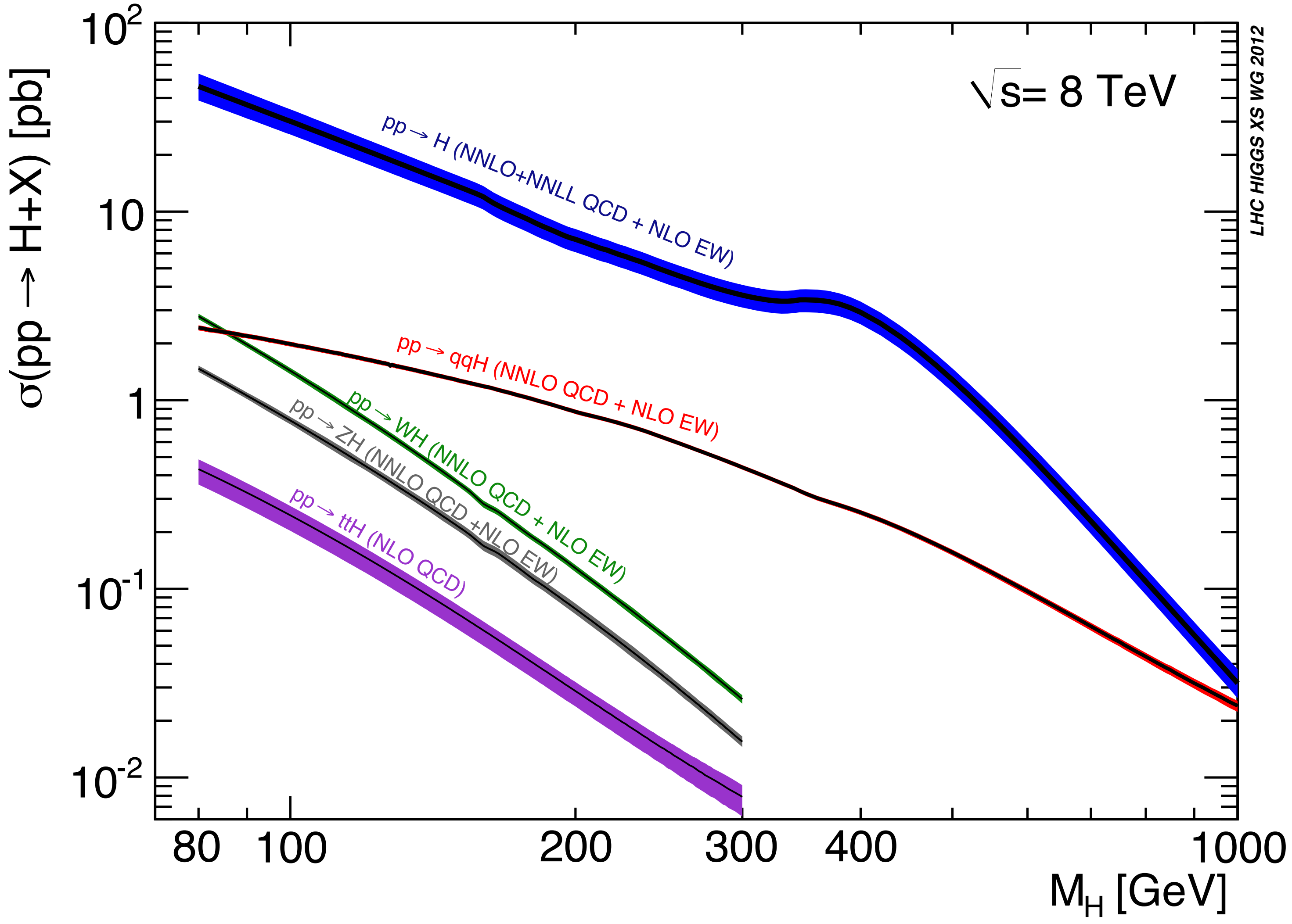
- LHC - hadron collider now enters in precision measurement era !

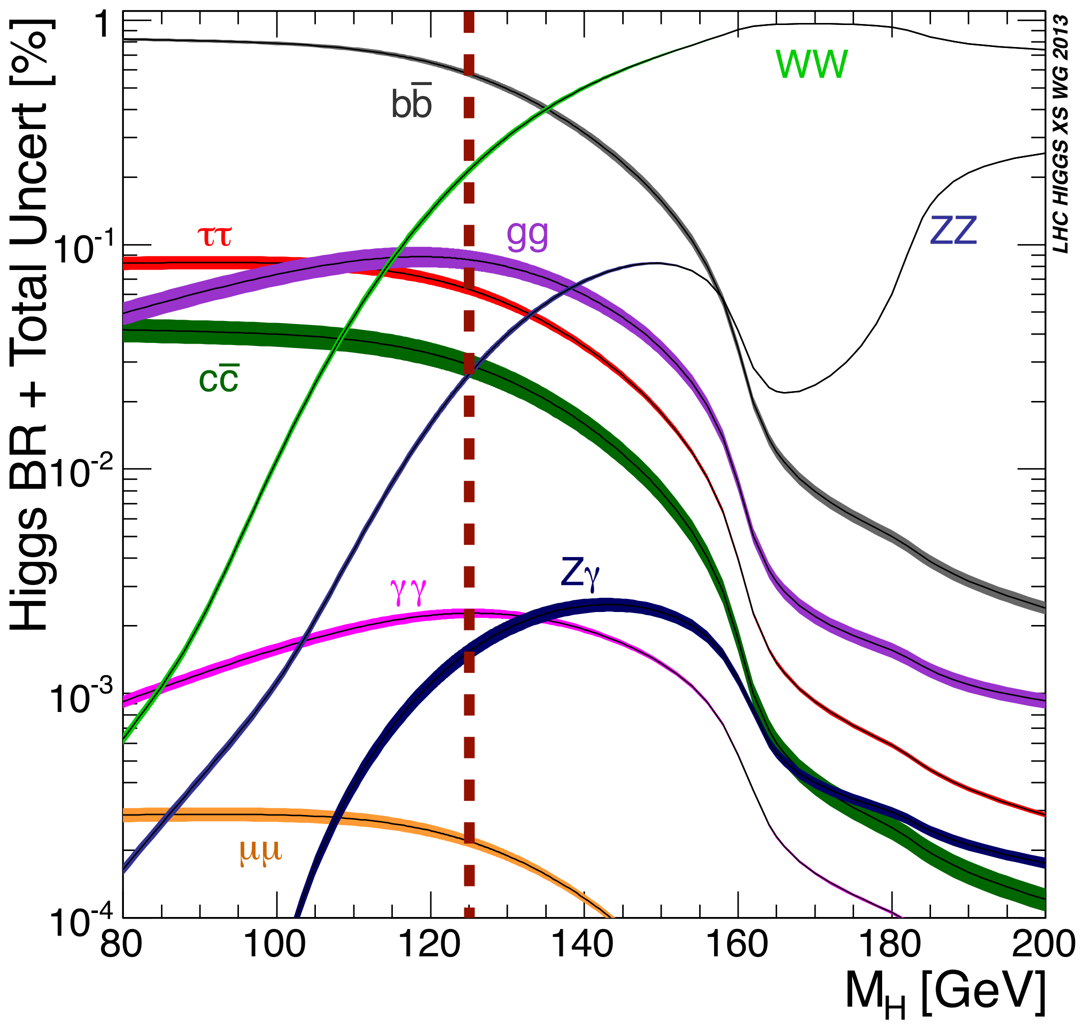
R. Tanaka, “Comprehensible Higgs”,
Science, Vol.79, No.5, p.488,
Iwanami publishing Co., Japan, May 2009

Backup

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

LHC Higgs Cross Section Working Group

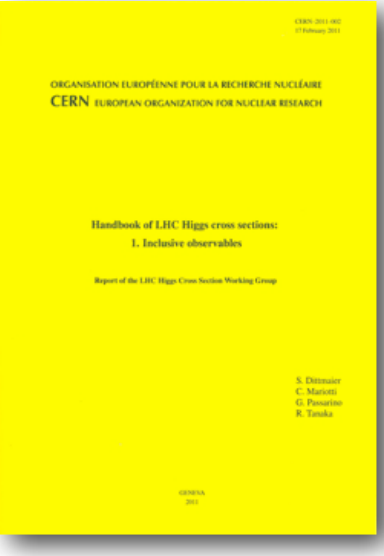




LHC Higgs XS WG CERN Report Trilogy

Handbook of LHC Higgs Cross Sections:

1. Inclusive Observables (CERN 2011-002, 151 pp)
2. Differential Distributions (CERN 2012-002, 275 pp)
3. Higgs Properties (CERN 2013-004, 392 pp)



ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Handbook of LHC Higgs cross sections:
1. Inclusive observables

Report of the LHC Higgs Cross Section Working Group

S. Dittmaier
C. Mariotti
G. Passarino
R. Tanaka

GENEVA
2011

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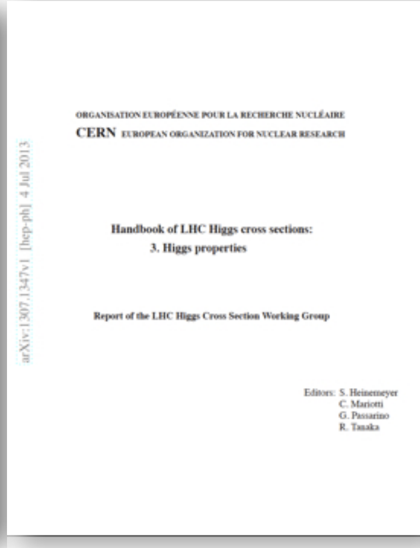
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Handbook of LHC Higgs cross sections:
2. Differential Distributions

Report of the LHC Higgs Cross Section Working Group

Editors: S. Dittmaier
C. Mariotti
G. Passarino
R. Tanaka

GENEVA
2012



arXiv:1307.1347v1 [hep-ph] 4 Jul 2013

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Handbook of LHC Higgs cross sections:
3. Higgs properties

Report of the LHC Higgs Cross Section Working Group

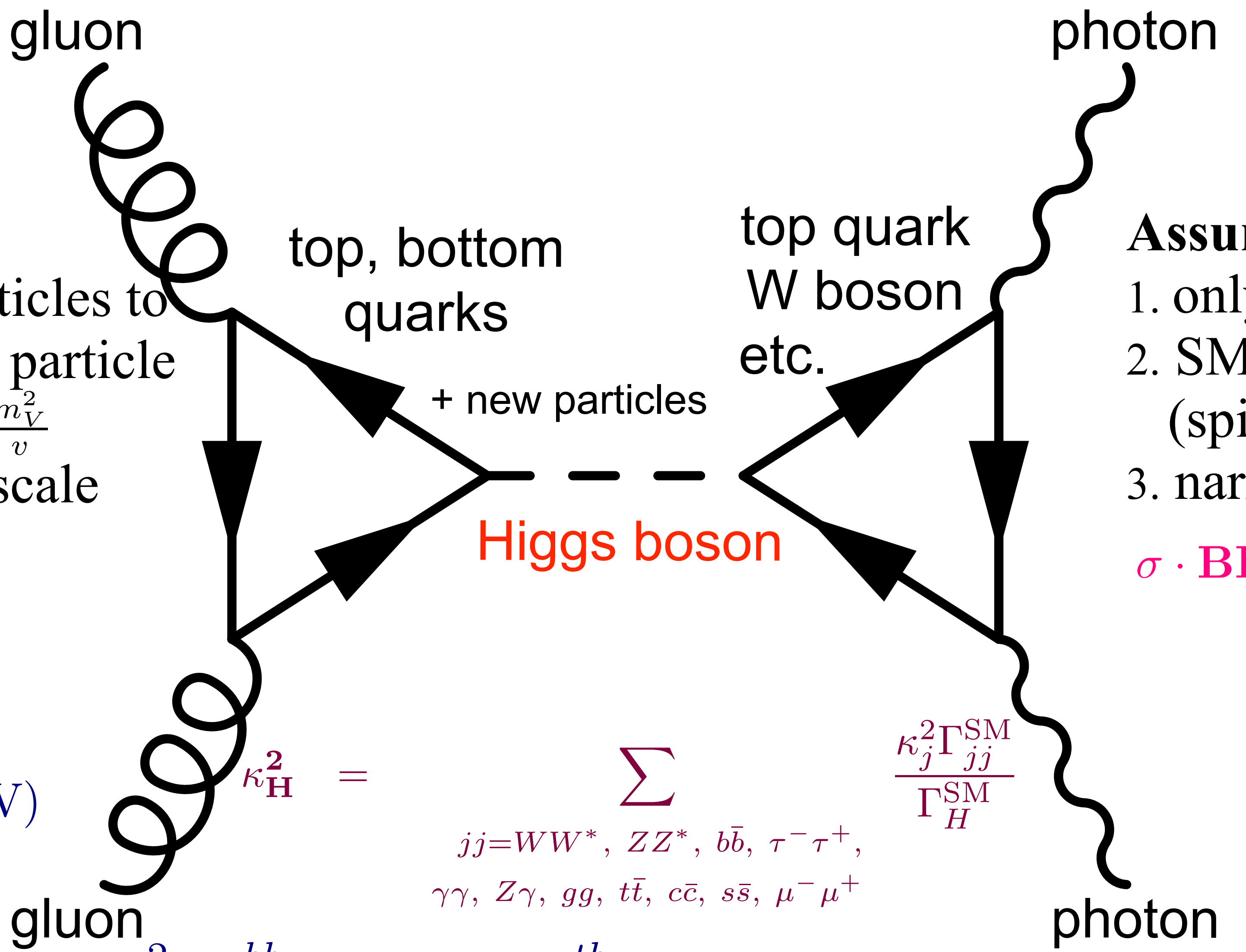
Editors: S. Heinemeyer
C. Mariotti
G. Passarino
R. Tanaka

LHC Higgs XS WG CERN Report 3 (arXiv:1307.1347)

Higgs coupling strength

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

- The coupling of SM particles to Higgs boson scales with particle mass: $g_F = \sqrt{2}\frac{m_f}{v},\ g_V = 2\frac{m_V^2}{v}$
- Measure with coupling scale factors κᵢ



Assumptions

1. only 1 SM-like Higgs
2. SM tensor structure (spin 0, CP-even)
3. narrow width approx.

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

$$\kappa_{\mathbf{H}}^{\mathbf{2}} \;=\; \sum_{\substack{jj=WW^*,\ ZZ^*,\ b\bar{b},\ \tau^-\tau^+,\\ \gamma\gamma,\ Z\gamma,\ gg,\ t\bar{t},\ c\bar{c},\ s\bar{s},\ \mu^-\mu^+}} \frac{\kappa_j^2\Gamma_{jj}^{\mathrm{SM}}}{\Gamma_H^{\mathrm{SM}}}$$

$(\sqrt{s} = 8\,\mathrm{TeV}, \mathrm{M}_H = 125\,\mathrm{GeV})$

$$\kappa_{\mathbf{g}}^{\mathbf{2}}(\kappa_{\mathbf{b}},\kappa_{\mathbf{t}}) \;=\; \frac{\kappa_t^2\cdot\sigma_{ggH}^{tt} + \kappa_b^2\cdot\sigma_{ggH}^{bb} + \kappa_t\kappa_b\cdot\sigma_{ggH}^{tb}}{\sigma_{ggH}^{tt} + \sigma_{ggH}^{bb} + \sigma_{ggH}^{tb}}$$
$$\simeq\; 1.058\kappa_t^2 + 0.007\kappa_b^2 - 0.065\kappa_t\kappa_b$$

$$\kappa_{\gamma}^{\mathbf{2}}(\kappa_{\mathbf{b}},\kappa_{\mathbf{t}},\kappa_{\tau},\kappa_{\mathbf{W}}) \;=\; \frac{\sum_{i,j}\kappa_i\kappa_j\cdot\Gamma_{\gamma\gamma}^{ij}}{\sum_{i,j}\Gamma_{\gamma\gamma}^{ij}}$$
$$\simeq\; |1.26\kappa_{\mathrm{W}} - 0.27\kappa_t|^2$$

Destructive interference in both gg→H (top-bottom) and H→γγ (top-W) loops.

Note on Coupling versus Mass relation

- Recent discussions on quark mass (M. Spira)

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

1. One can define quark mass for Yukawa coupling,

$$\bar{g}_Q(M_H), \bar{g}_Q(M_Q), g_Q^{\text{pole}}$$

2. Though above are theoretically equivalent, running mass evaluated at Higgs mass scale is better to avoid the offset due to non-universal corrections in quarks and leptons,

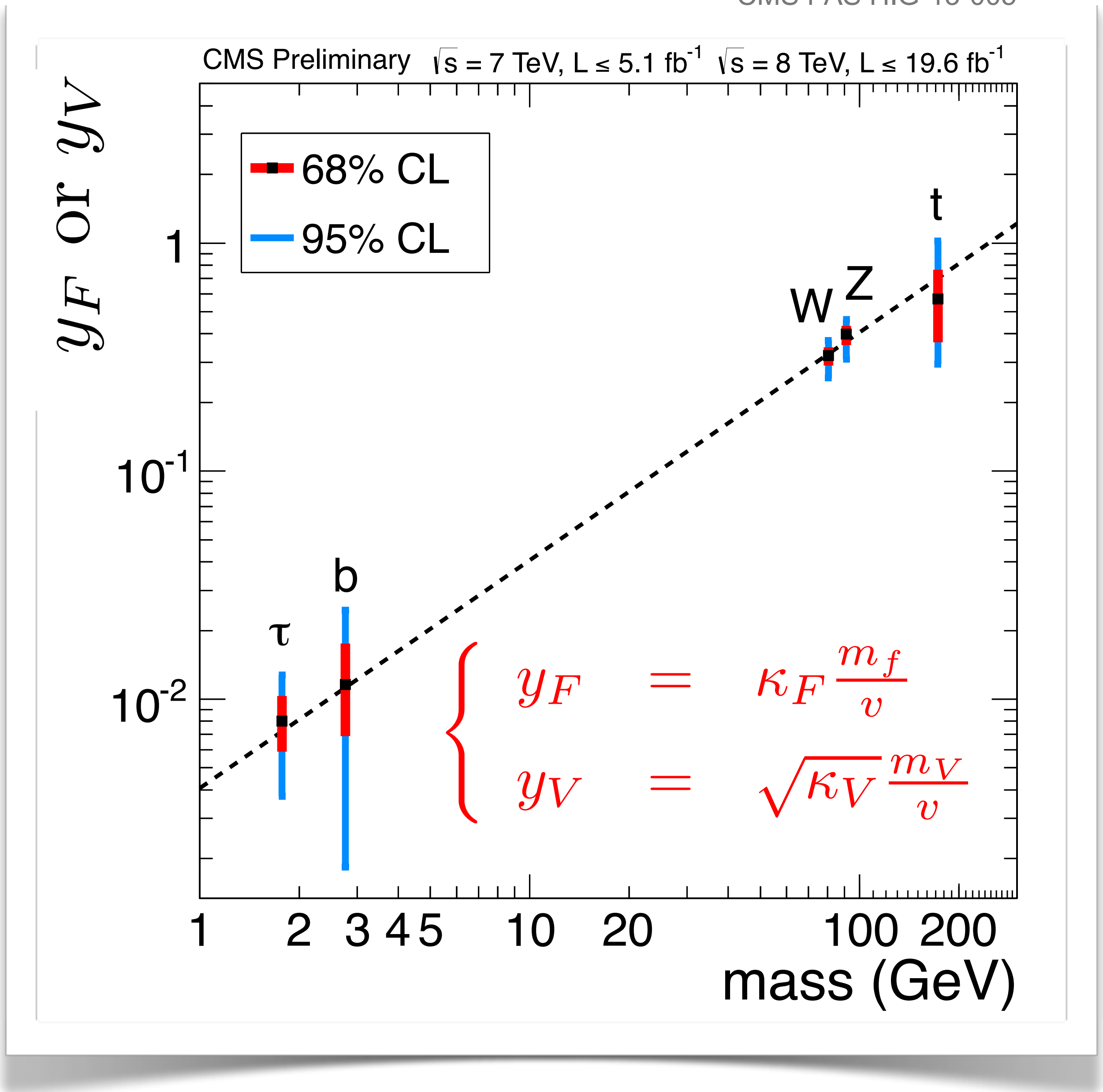
$$\Gamma(H \to Q\bar{Q}) = \bar{g}_Q^2(M_H)\frac{3M_H}{16\pi}\left\{1 + \frac{17}{3}\frac{\alpha_s}{\pi} + \mathcal{O}(\alpha_s^2)\right\}$$

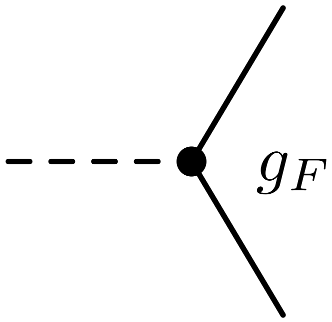
$$m_b(m_b) = 4.16\,\text{GeV}, m_b(M_H) = 2.76\,\text{GeV}$$

3. Use pole mass for top quark (172.5GeV).

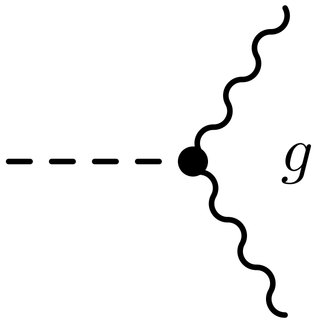
4. Use PDG values for leptons and W/Z boson masses. The universal QED corrections for leptons are small.

CMS PAS HIG-13-005





$$g_F = \sqrt{2}\frac{m_f}{v}$$



$$g_V = 2\frac{m_V^2}{v}$$