Higgs Physics near the Standard Model

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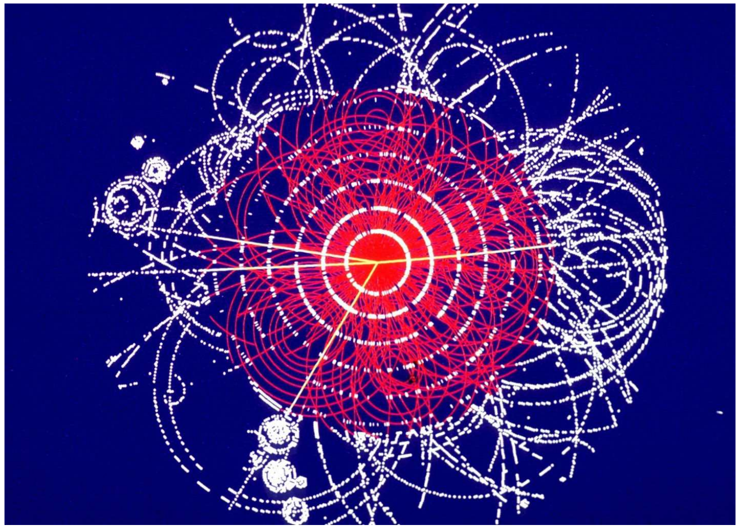
- Higgs Theory
- QCD and EW corrections
- Search channels at the LHC
- Measurement of Higgs couplings
- Tensor structure of HVV couplings
- Conclusions



Goals of Higgs Physics

Higgs Search = search for dynamics of $SU(2) \times U(1)$ breaking

- 2012: Discovery of a Higgs-like resonance at 126 GeV
- TASK: Measure its couplings and probe
  mass generation for gauge bosons and fermions

Fermion masses arise from Yukawa couplings via $\Phi^\dagger \rightarrow (0, \frac{v+H}{\sqrt{2}})$

$$\mathcal{L}_{\text{Yukawa}} = -\Gamma_d^{ij} \bar{Q}_L'^i \Phi d_R'^j - \Gamma_d^{ij*} \bar{d}_R'^i \Phi^\dagger Q_L'^j + \ldots \quad = -\Gamma_d^{ij} \frac{v+H}{\sqrt{2}} \bar{d}_L'^i d_R'^j + \ldots$$

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

- Test SM prediction: $\bar{f} f H$ Higgs coupling strength $= m_f/v$
- Observation of $H f \bar{f}$ Yukawa coupling is no proof that v.e.v exists

Higgs coupling to gauge bosons

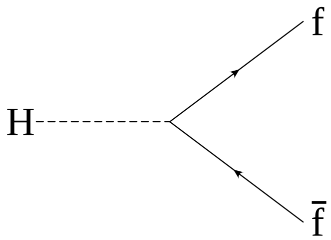
Kinetic energy term of Higgs doublet field:

$$(D^\mu\Phi)^\dagger(D_\mu\Phi) = \frac{1}{2}\partial^\mu H\partial_\mu H + \left[\left(\frac{gv}{2}\right)^2 W^{\mu+}W^-_\mu + \frac{1}{2}\frac{(g^2+g'^2)\,v^2}{4}Z^\mu Z_\mu\right]\left(1+\frac{H}{v}\right)^2$$

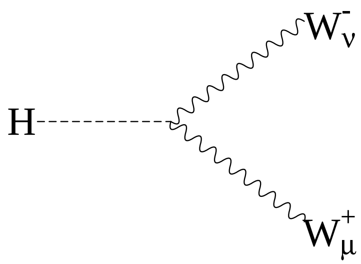
- W, Z mass generation: $m_W^2 = \left(\frac{gv}{2}\right)^2$, $m_Z^2 = \frac{(g^2+g'^2)v^2}{4}$
- WWH and ZZH couplings are generated
- Higgs couples proportional to mass: coupling strength $= 2\,m_V^2/v \sim g^2 v$ within SM

Measurement of WWH and ZZH couplings is essential for identification of H as agent of symmetry breaking: Without a v.e.v. such a trilinear coupling is impossible at tree level

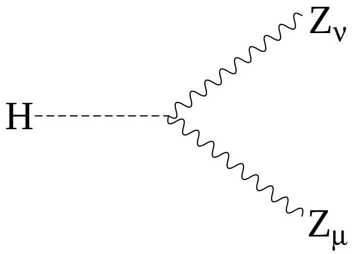
Feynman rules for SM Higgs couplings



$-i\frac{m_f}{v}\,1$



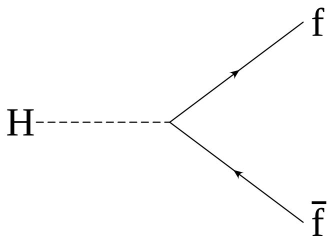
$ig\, m_W\, g_{\mu\nu}$



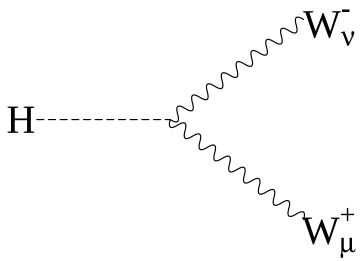
$i\, g\, \frac{1}{\cos\theta_W}\, m_Z\, g_{\mu\nu}$

Verify tensor structure of HVV couplings. Loop induced couplings lead to $HV_{\mu\nu}V^{\mu\nu}$ effective coupling and different tensor structure: $g_{\mu\nu} \quad \longrightarrow \quad q_1\cdot q_2\, g_{\mu\nu} - q_{1\nu}q_{2\mu}$

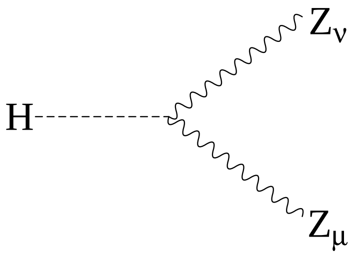
Deviations from SM Higgs coupling strengths



$$-i\frac{m_f}{v}\left(1+\Delta_f\right)$$



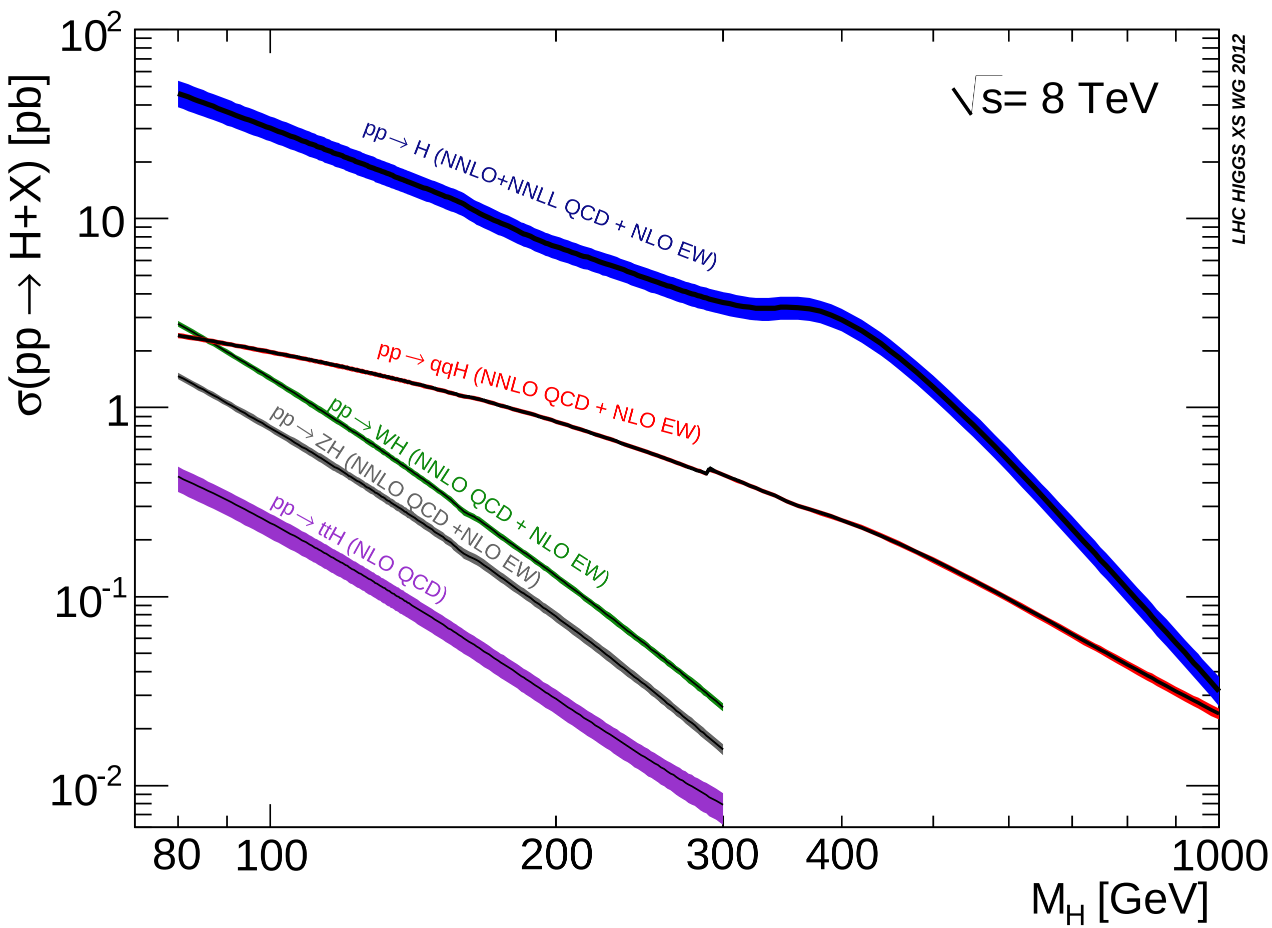
$$ig\, m_W\, (1+\Delta_W) g_{\mu\nu}$$

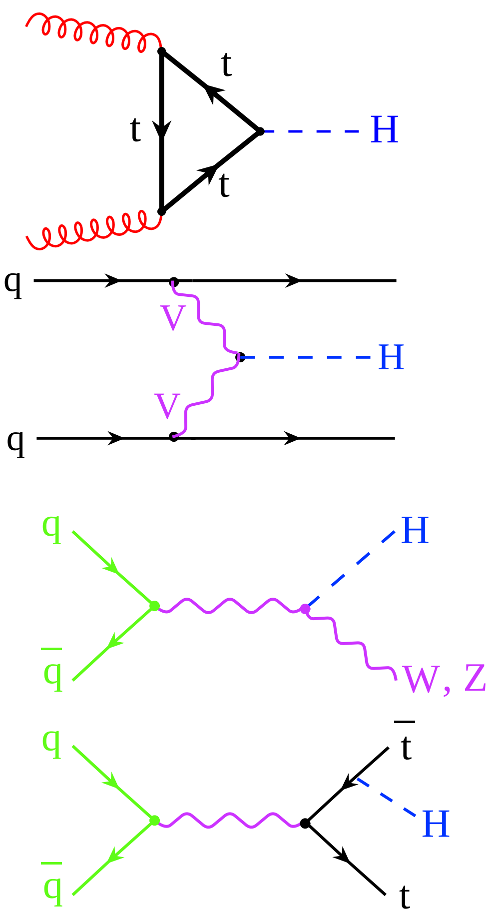


$$i\, g\, \frac{1}{\cos\theta_W}\, m_Z\, (1+\Delta_Z) g_{\mu\nu}$$

Goal: determine deviations Δ_X in HXX couplings from LHC data

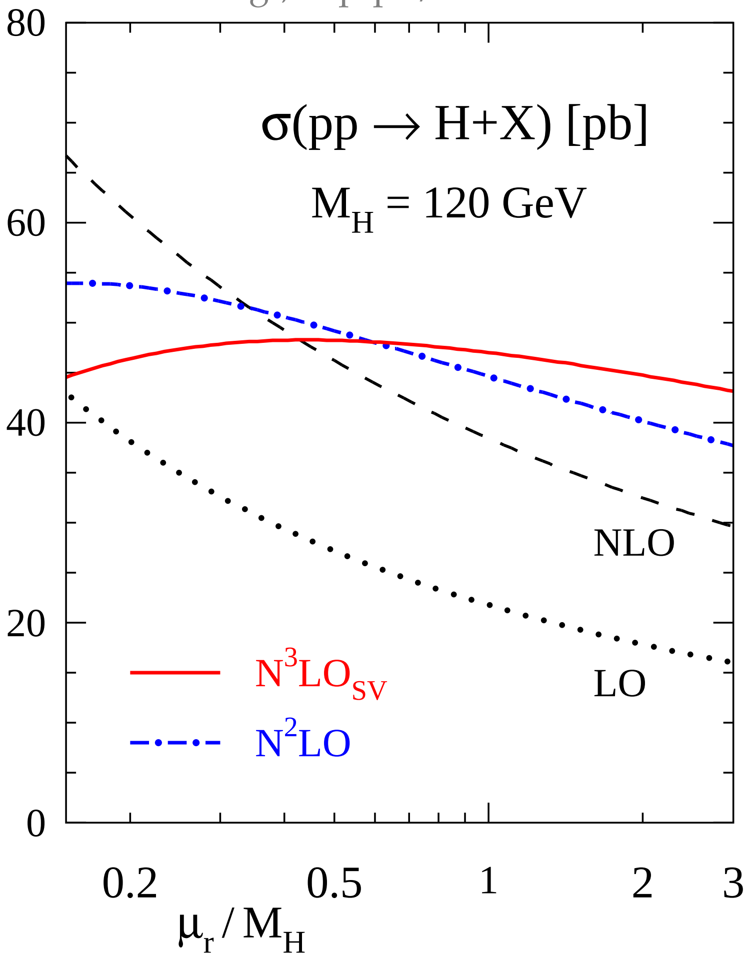
Total cross sections at the LHC





QCD corrections to $gg \to H$

Moch & Vogt, hep-ph/0508265



- Large QCD corrections: K-factor of about 2
- Stabilization of scale dependence needs N^3LO or at least NNLO corrections
- Cross section estimate for $m_H = 126$ GeV at 8 TeV from LHC XS WG, determined at NNLL QCD and NLO EW

$$\sigma(gg \to H) = 19.22\,\text{pb} \pm 14.7\%$$

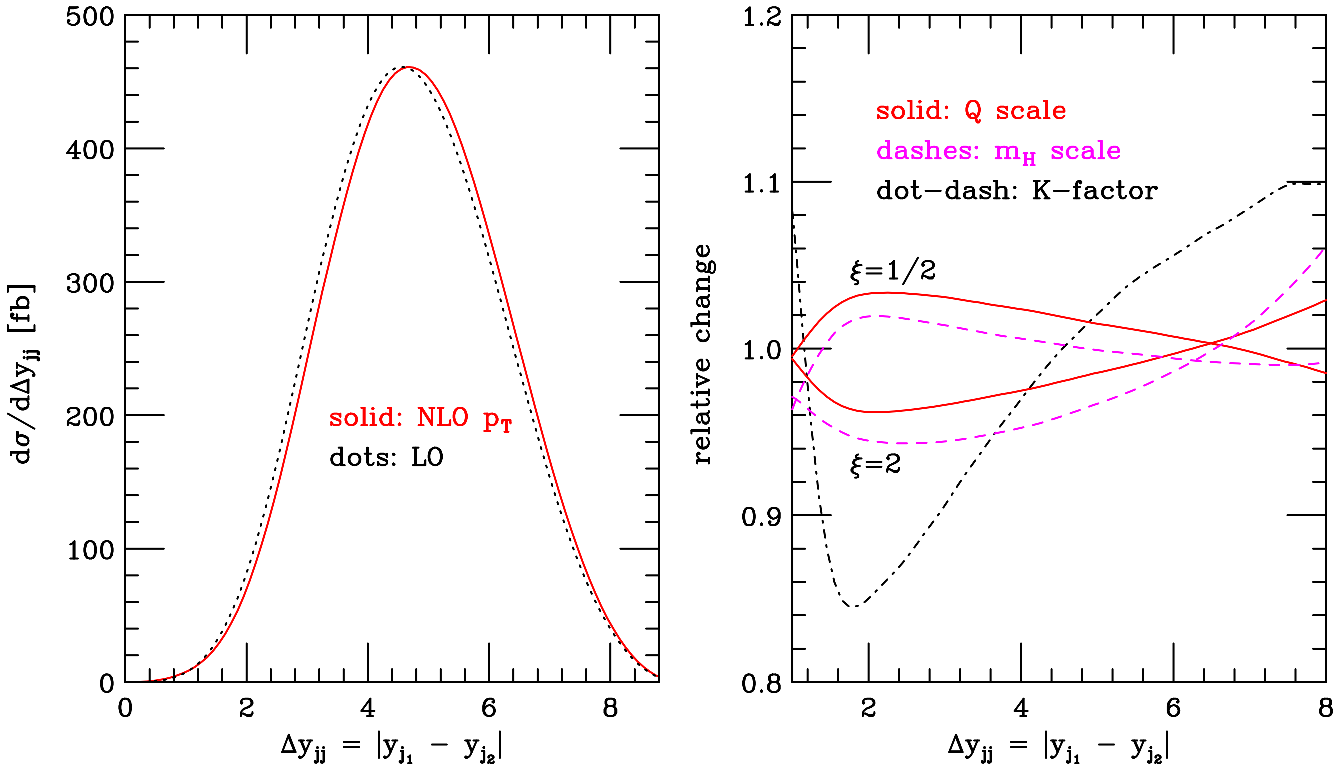
- Error is linear combination of $\approx 7.5\%$ scale uncertainty and $\approx 7.2\%$ from gluon pdf and α_s error
- Additional uncertainty from use of effective hgg vertex (heavy top approximation) is estimated to be below 2%

NLO corrections to VBF

- Small QCD corrections of order 10%
- Tiny scale dependence of NLO result
  - $\pm 5\%$ for distributions
  - $< 1\%$ for σ_{total}
- pdf error is below 3% since pdf's are dominated by valence quarks
- $\approx -5\%$ EW corrections included

  Ciccolini, Denner, Dittmaier, 0710.4749

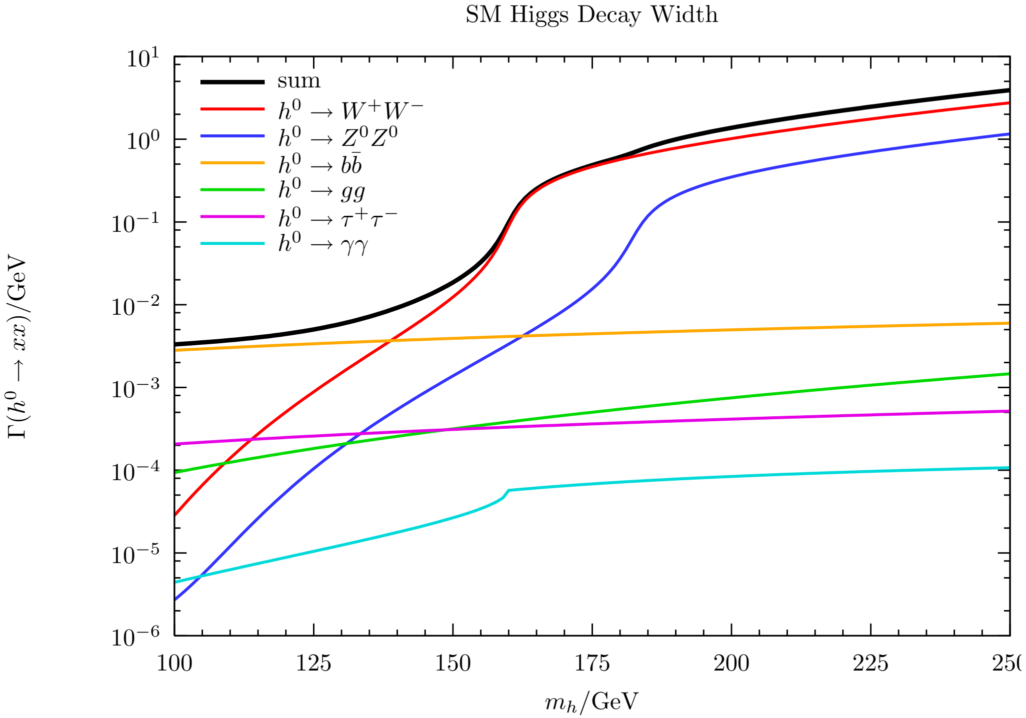
  Figy, Palmer, Weiglein arXiv:1012.4789
- Very small cross section error of about 3% for $m_H = 126$ GeV

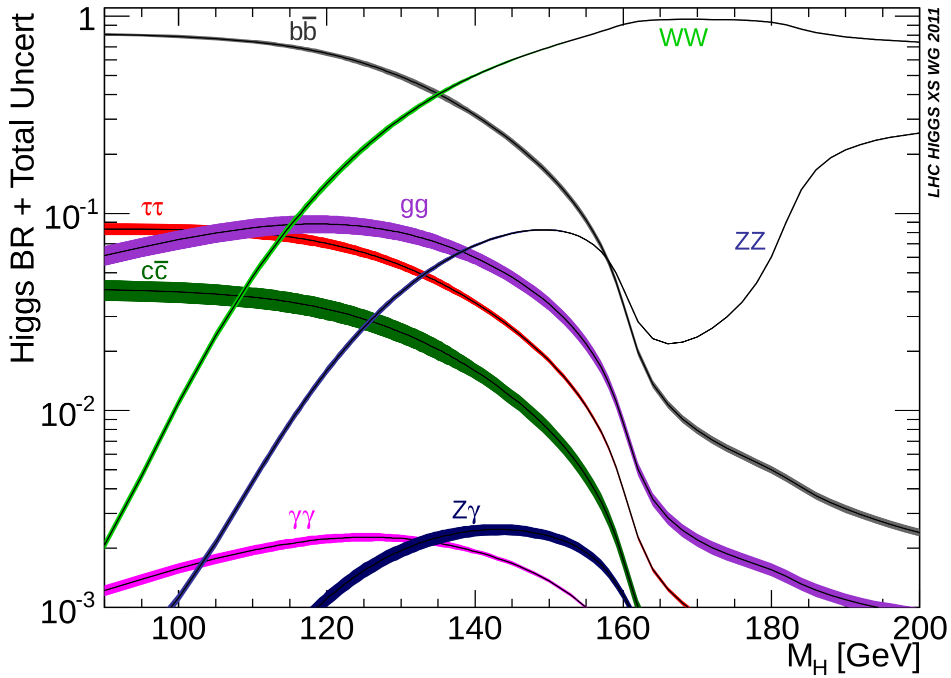


$m_H = 120$ GeV, typical VBF cuts

Decay of the SM Higgs

Higgs decay width and branching fractions within the SM





SM predictions for relevant $m_H = 126$ GeV branching ratios have typical uncertainties of $\approx 5\%$

Highly correlated since driven by error on $H \to \bar{b}b$ partial width and hence Γ_{tot}

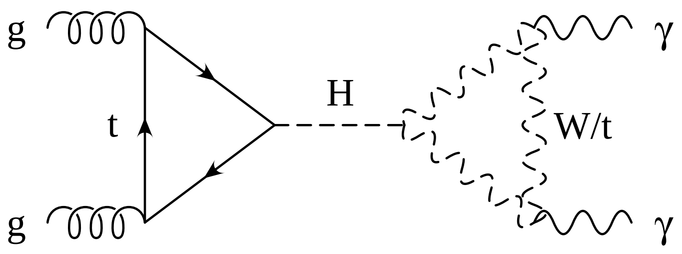
Main channels for Higgs observation

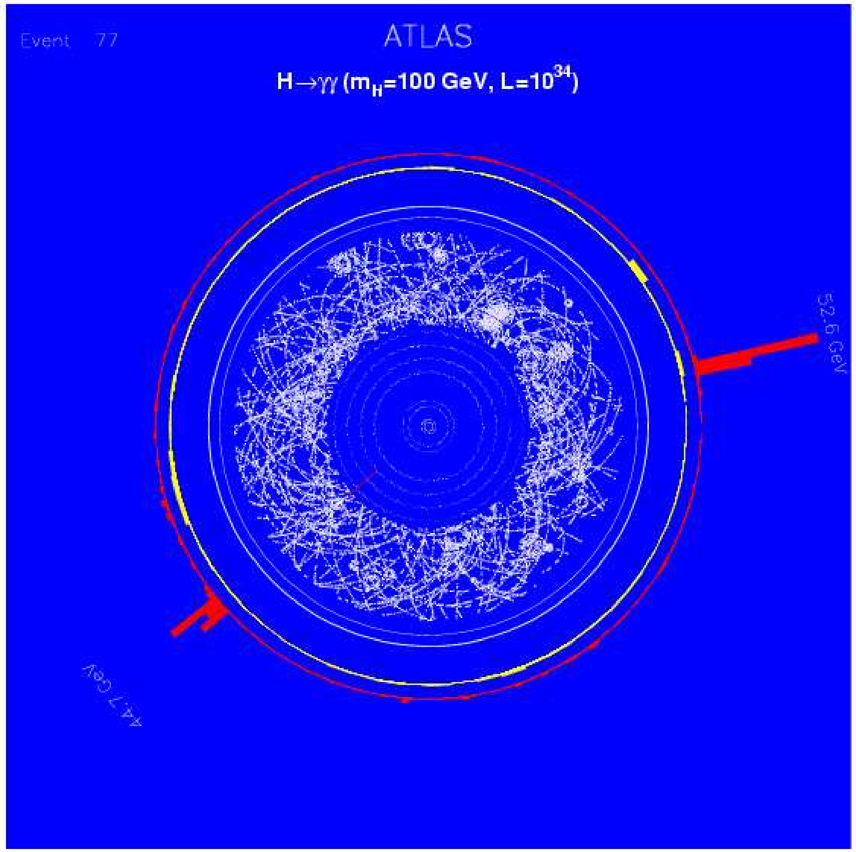
- inclusive production, 90% of which is gluon fusion, with subsequent decay
  - $H \to \gamma\gamma$ invariant-mass peak, for $m_H < 150$ GeV
  - $H \to ZZ^* \to \ell^+\ell^-\ell^+\ell^-$ for $m_H \geq 120$ GeV and $m_H \neq 2m_W$.
  - $H \to W^+W^- \to \ell^+\bar{\nu}\ell^-\nu$ for $120 \text{ GeV} \leq m_H \leq 190$ GeV
  - $H \to \tau\tau$ for $115 \text{ GeV} \leq m_H \leq 150$ GeV

- VBF searches for
  - $H \to \gamma\gamma$ for $115 \text{ GeV} \leq m_H \leq 150$ GeV
  - $H \to \tau\tau$ for $115 \text{ GeV} \leq m_H \leq 150$ GeV
  - $H \to W^+W^- \to \ell^+\bar{\nu}\ell^-\nu$ for $115 \text{ GeV} \leq m_H \leq 190$ GeV

- Search for boosted Higgs in VH associated production
  - $H \to b\bar{b}$ for $115 \text{ GeV} \leq m_H \leq 140$ GeV

$H \to \gamma\gamma$



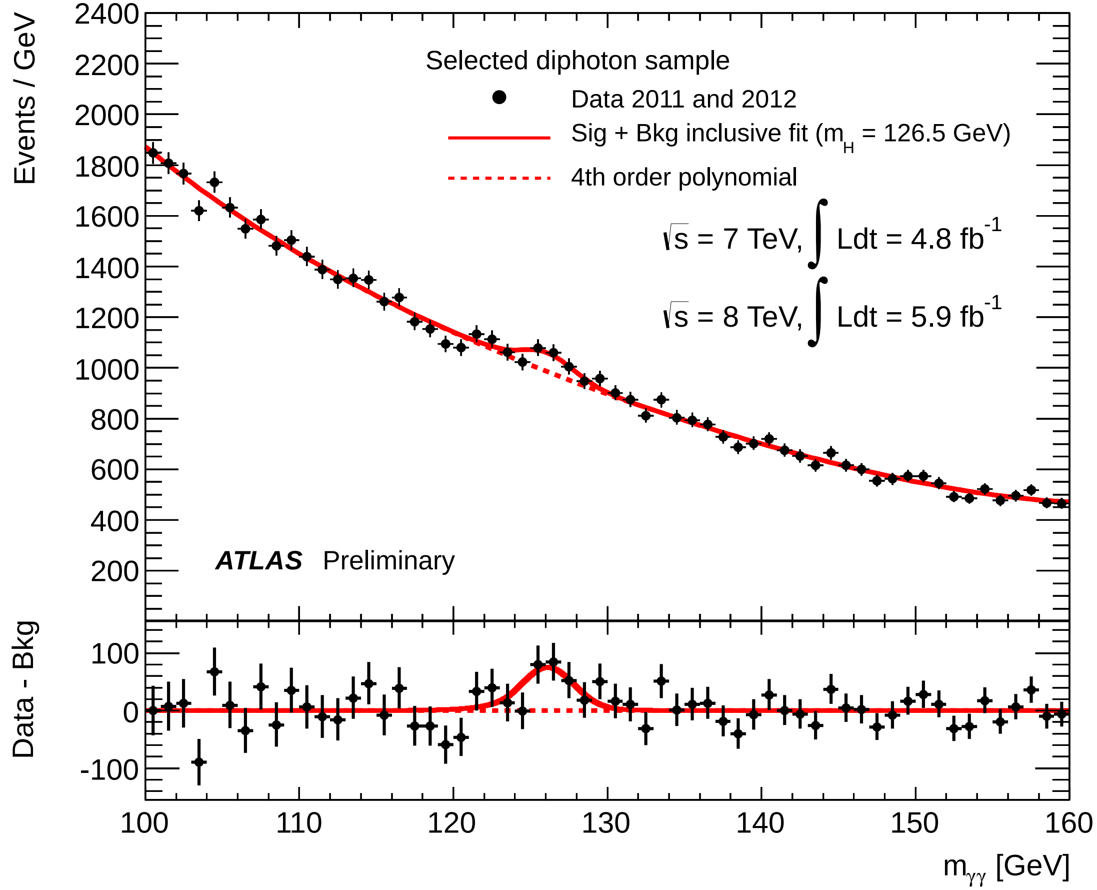


- BR($H \to \gamma\gamma$) $\approx 10^{-3}$
- large backgrounds from $q\bar{q} \to \gamma\gamma$, $gg \to \gamma\gamma$ and jets misidentified as photons
- but CMS and ATLAS have excellent photon-energy resolution (order of 1%)

Rate is proportional to $|a g_{Htt} + b g_{Hbb}|^2$ times $|c g_{HWW} - d g_{Htt}|^2$

$H \longrightarrow \gamma\gamma$

- Look for a narrow $\gamma\gamma$ invariant mass peak
- Extrapolate background into the signal region from sidebands
- Observation of signal at $m_{\gamma\gamma} = 126$ GeV

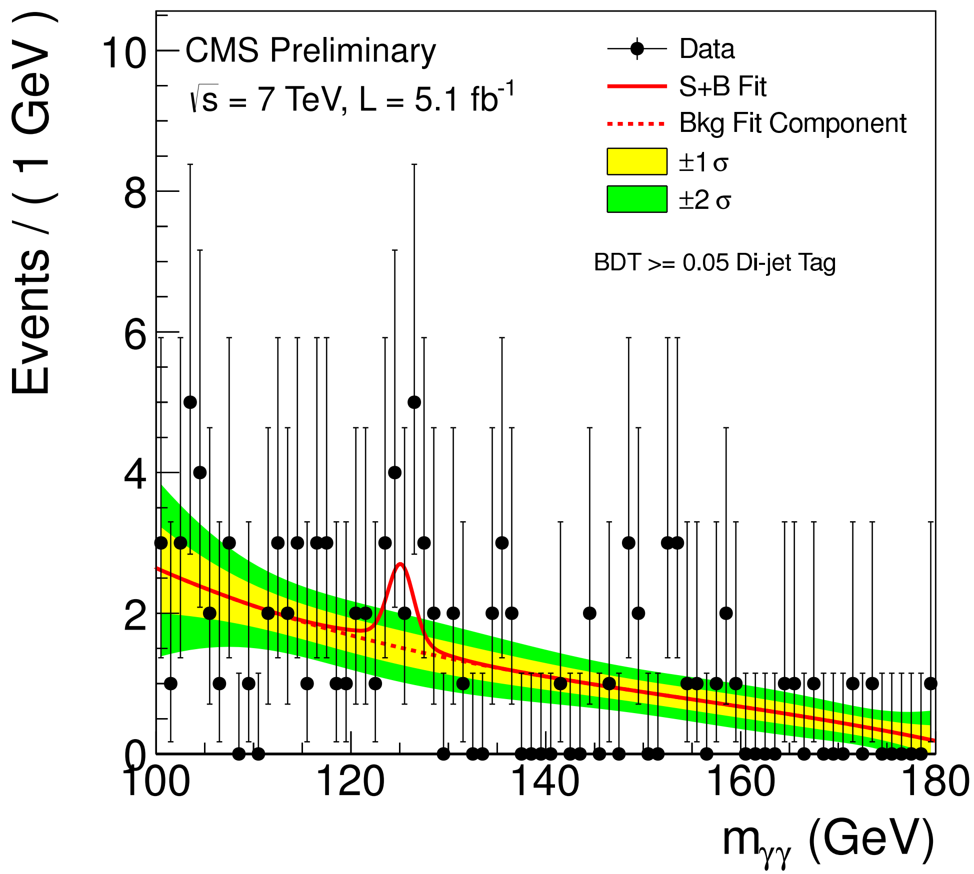


Landau-Yang theorem: $\gamma\gamma$ resonance cannot be spin1

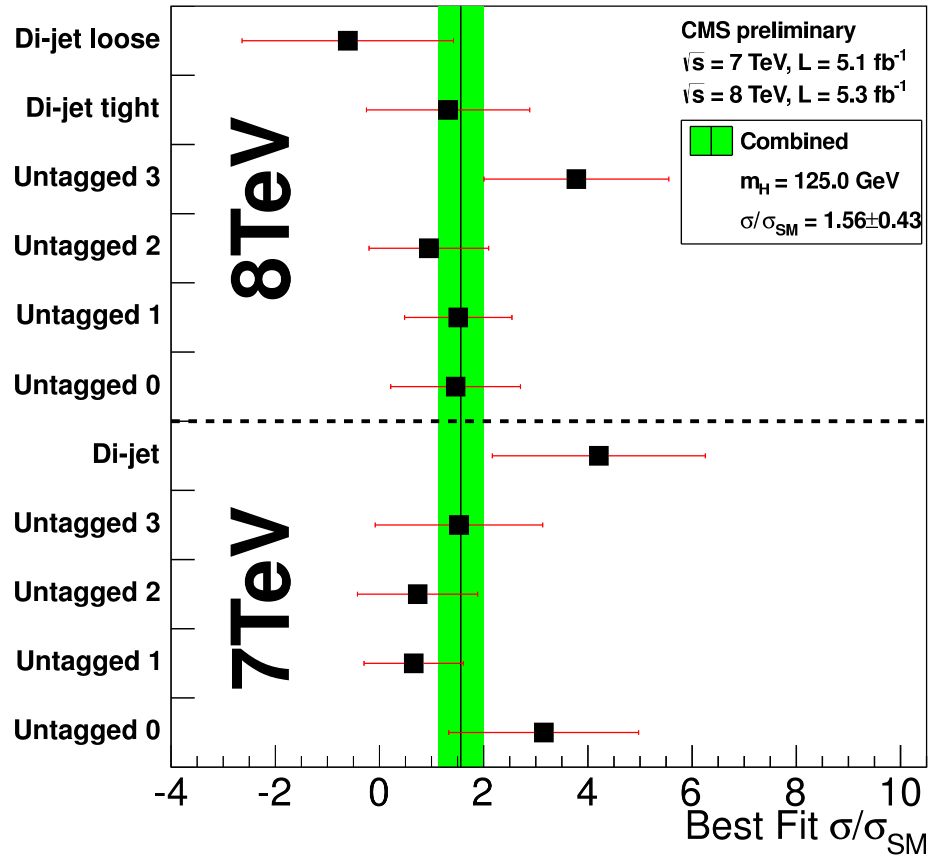
$\Longrightarrow$ New resonance at 126 GeV is most likely spin 0 (or perhaps spin 2)

$H \to \gamma\gamma$ in VBF

CMS data for VBF dijet selection



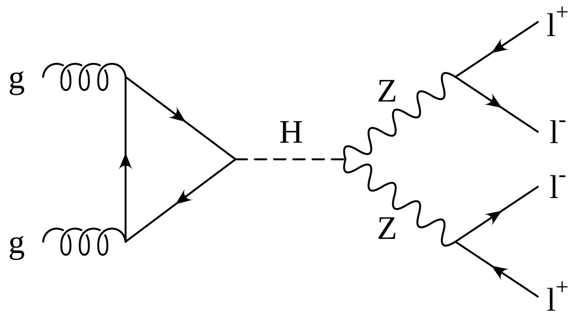
CMS $H \to \gamma\gamma$ signal strengths

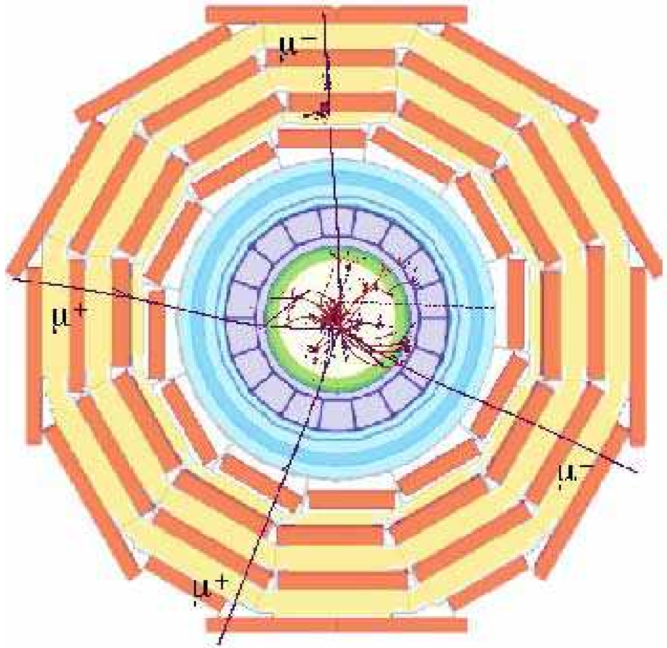


VBF rate is proportional to $Ag^2_{HWW} + Bg^2_{HZZ}$ times $|cg_{HWW} - dg_{Htt}|^2$

$H \to ZZ \to \ell^+\ell^-\ell^+\ell^-$

The gold-plated mode

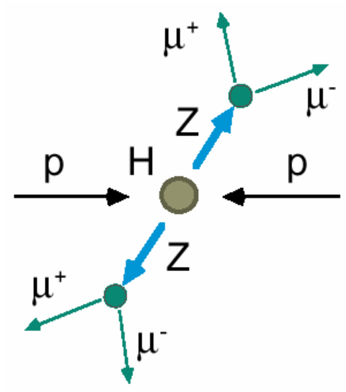




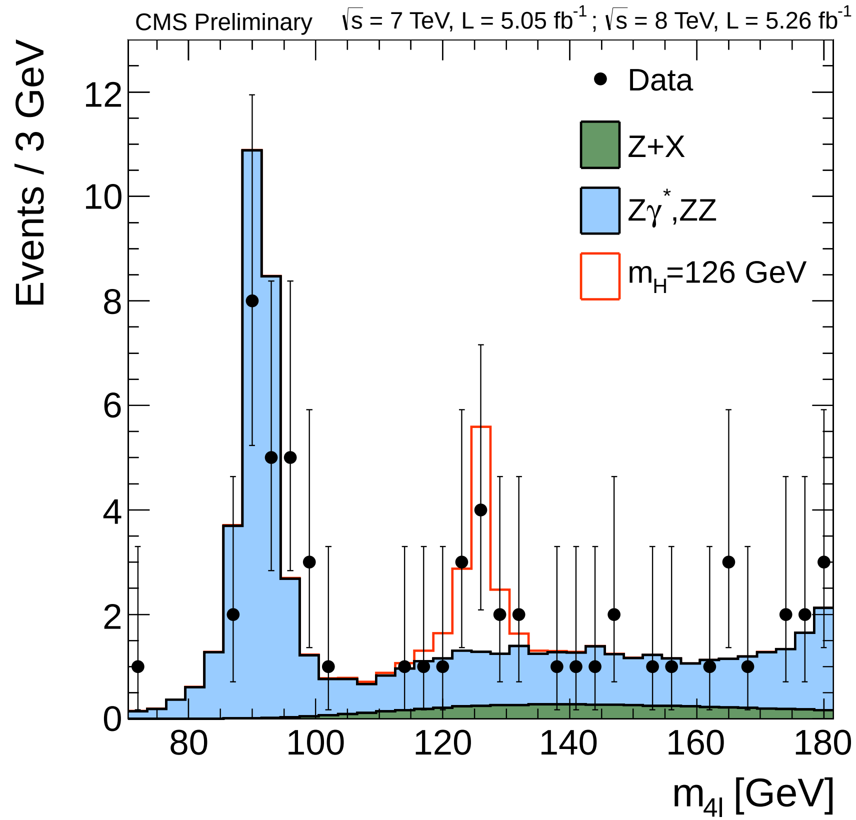
- Most important and clean search mode for $m_H < 600$ GeV (with hole around $2m_W$)
- Continuum, limited, irreducible background from $q\bar{q} \to ZZ$
- small BR$(H \to \ell^+\ell^-\ell^+\ell^-) \approx 0.15\%$ (even smaller when $m_H < 2m_Z$)

Rate is proportional to $|a g_{Htt} + b g_{Hbb}|^2$ times g^2_{HZZ}

$H \to ZZ \to \ell^+\ell^-\ell^+\ell^-$

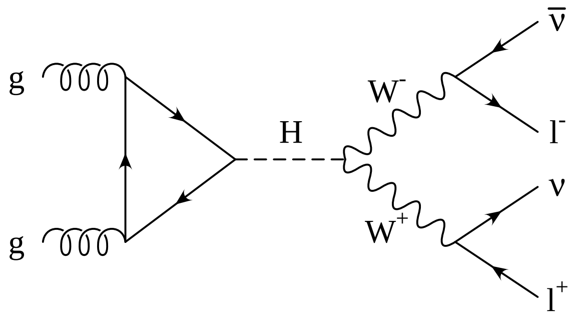


- invariant mass of the charged leptons fully reconstructed

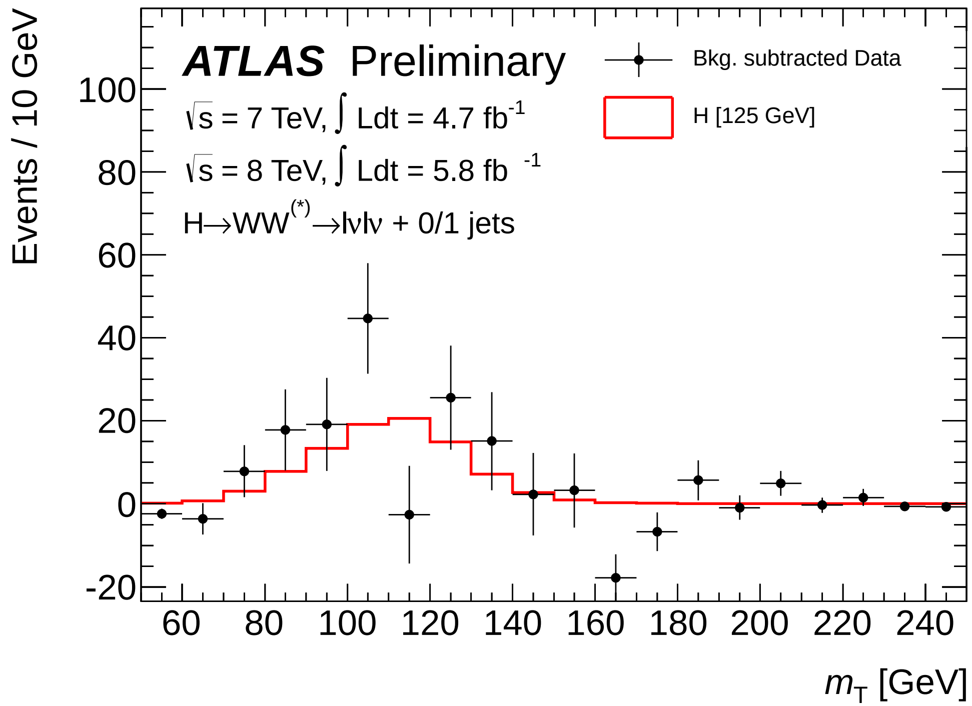


CMS and ATLAS observe resonance around $m_{ZZ} = 126$ GeV

$H \longrightarrow WW \longrightarrow \ell^+ \bar{\nu} \ell^- \nu$



Exploit $\ell^+\ell^-$ angular correlations



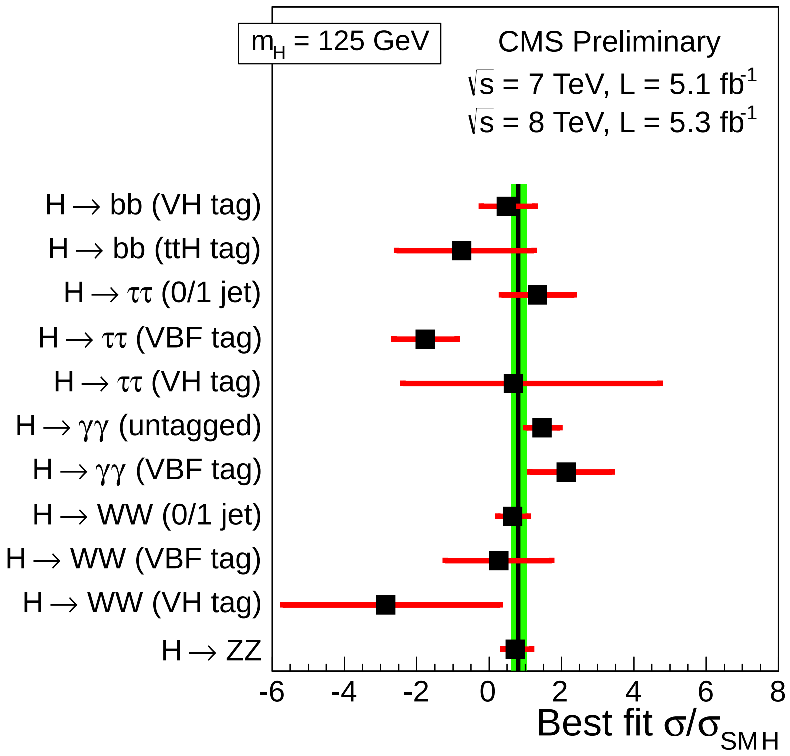
measure the transverse mass with a Jacobian peak at m_H

$$m_T = \sqrt{(E_T^{\ell\ell} + E_T^{miss})^2 - (\mathbf{p}_T^{\ell\ell} + \mathbf{p}_T^{miss})^2}$$

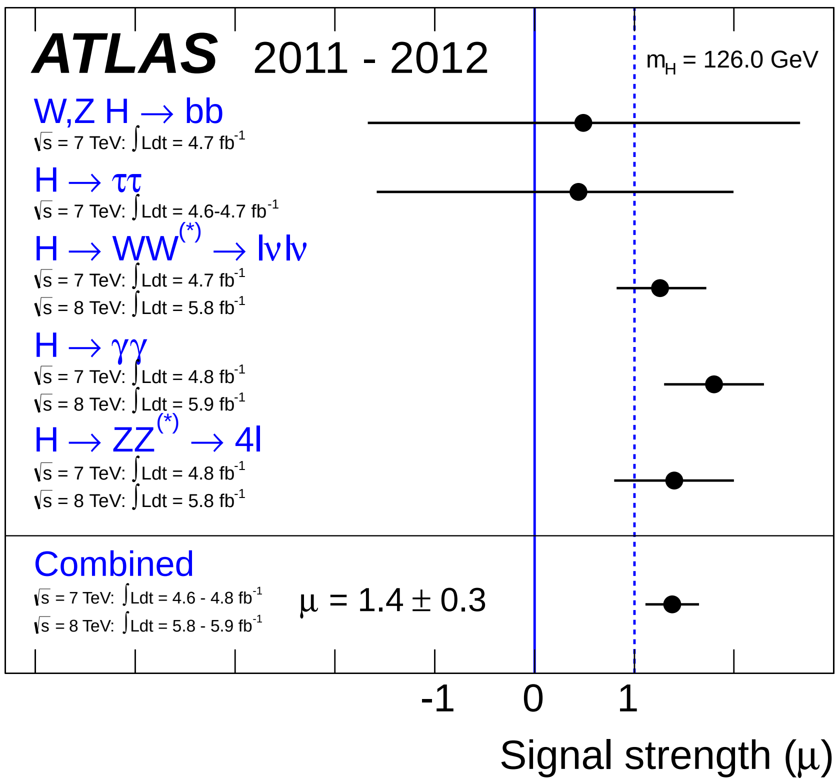
Rate is proportional to $|ag_{Htt} + bg_{Hbb}|^2$ times g_{HWW}^2

Summary of measured channels

CMS data



ATLAS data

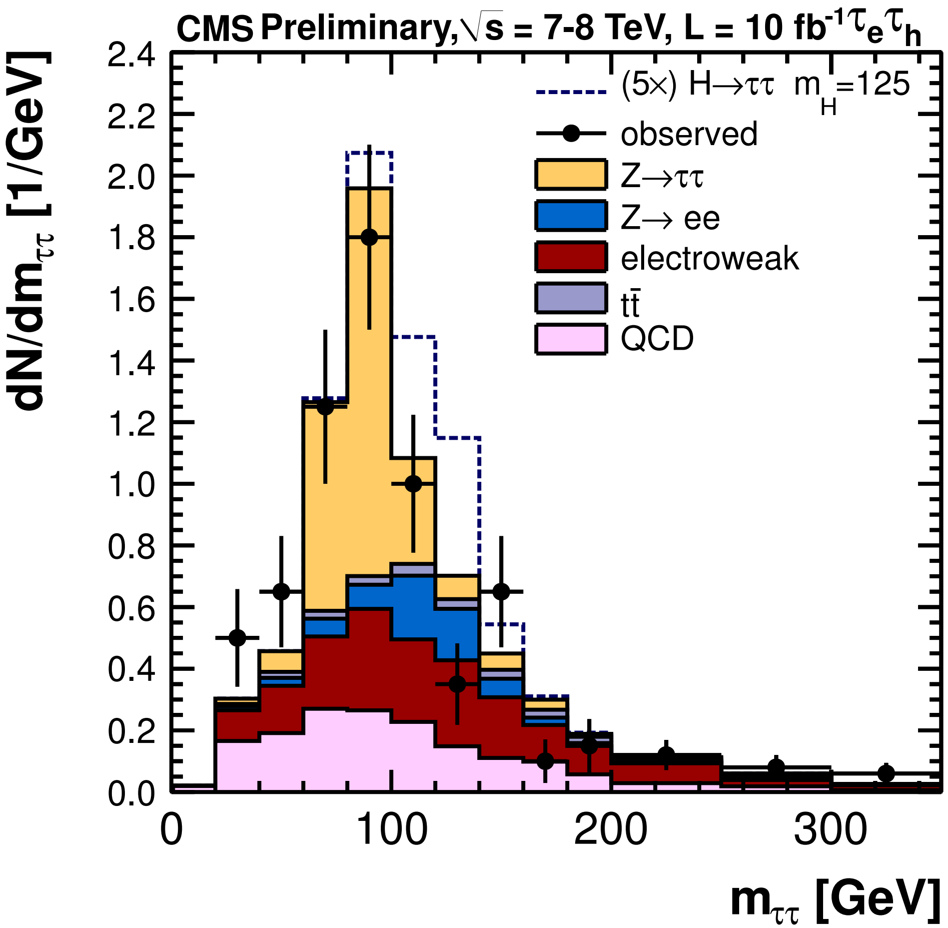


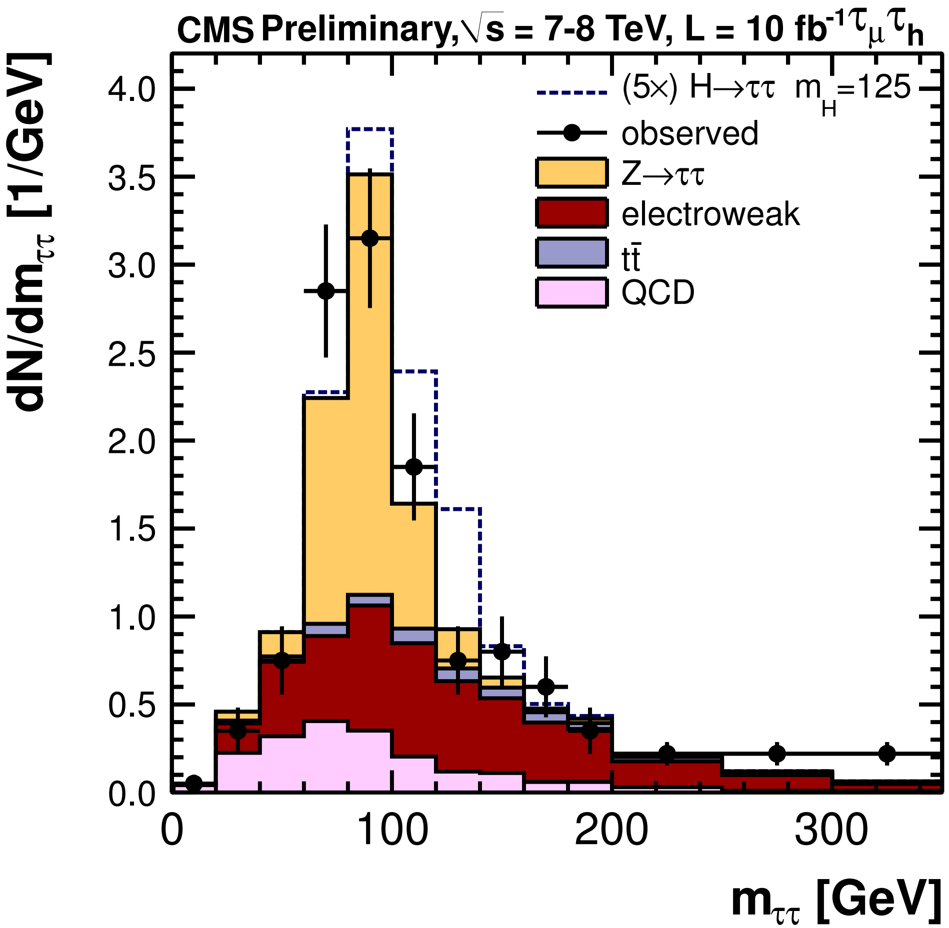
$\tau\tau$ rate in VBF is proportional to $Ag^2_{HWW} + Bg^2_{HZZ}$ times $g^2_{H\tau\tau}$

$b\bar{b}$ rate in VH associated production is proportional to g^2_{HVV} times g^2_{Hbb}

Higgs decay to tau pairs

Most sensitive search channel is VBF:





Dips near $m_{\tau\tau} = 130$ GeV look like fluctuations

Measuring Higgs couplings at LHC

LHC rates for partonic process $pp \to H \to xx$ given by $\sigma(pp \to H) \cdot BR(H \to xx)$

$$\sigma(H) \times \mathrm{BR}(H \to xx) = \frac{\sigma(H)^{\mathrm{SM}}}{\Gamma_p^{\mathrm{SM}}} \cdot \frac{\Gamma_p \Gamma_x}{\Gamma} ,$$

Measure products $\Gamma_p \Gamma_x / \Gamma$ for combination of processes ($\Gamma_p = \Gamma(H \to pp)$)

Problem: rescaling fit results by common factor f

$$\Gamma_i \to f \cdot \Gamma_i , \qquad \Gamma \to f^2 \Gamma = \sum_{obs} f \Gamma_i + \Gamma_{rest}$$

leaves observable rate invariant $\Longrightarrow$ no model independent results at LHC

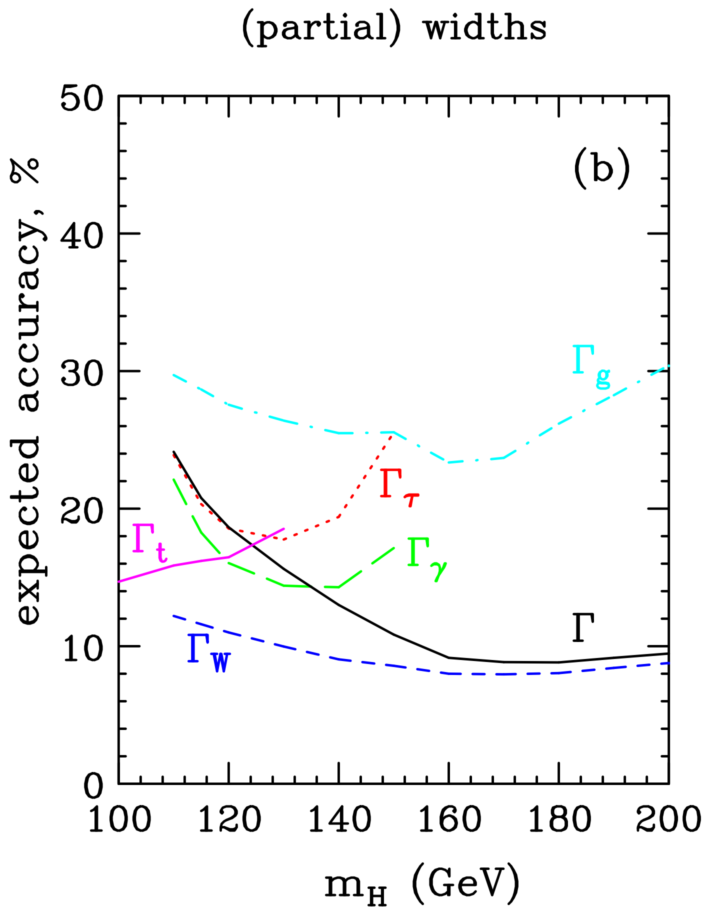
Loose bounds on scaling factor:

$$f^2 \Gamma > \sum_{obs.} f \Gamma_x \qquad \Longrightarrow \qquad f > \sum_{obs.} \frac{\Gamma_x}{\Gamma} = \sum_{obs.} BR(H \to xx) (= \mathcal{O}(1))$$

Total width below experimental resolution of Higgs mass peak ($\Delta m = 1 \ldots 2$ GeV)

$$f^2 \Gamma < \Delta m \qquad \Longrightarrow \qquad f < \sqrt{\frac{\Delta m}{\Gamma}} < \mathcal{O}(20)$$

Fit LHC data within constrained models



Make assumptions on relations between Higgs couplings, on deviations from SM rates

Assumptions in 2000 analysis Kinnunen, Nikitenko, Richter-Was, DZ hep-ph/0002036

- $\frac{g_{H\tau\tau}}{g_{Hbb}}$ = SM value
- $\frac{g_{HWW}}{g_{HZZ}}$ = SM value
- no exotic channels

Expected errors at LHC14 with 200 fb^{-1} of data

Many analyses of 2011 and 2012 LHC data, including arXiv:1202.3144, arXiv:1202.3415, arXiv:1202.3697, arXiv:1203.3456, arXiv:1203.4254, arXiv:1203.5083, arXiv:1203.6826, arXiv:1204.0464, arXiv:1204.4817, arXiv:1205.2699, arXiv:1205.6790, arXiv:1207.6108, arXiv:1207.1347, arXiv:1207.1693, arXiv:1207.1717

Below: SFitter analysis of Lafaye, Plehn, Rauch, Zerwas

SFitter analysis of Higgs couplings at LHC

- Parameterize deviations from SM couplings

$$g_i = g_i^{\text{SM}} \ (1 + \Delta_i)$$

- Five free parameters $i = W, Z, t, b, \tau$ plus generation universality
- Loop-induced couplings change from modifying contributing tree-level couplings
- Δ_H: common parameter modifying all (tree-level) couplings
- Assume no add. contribution to total width

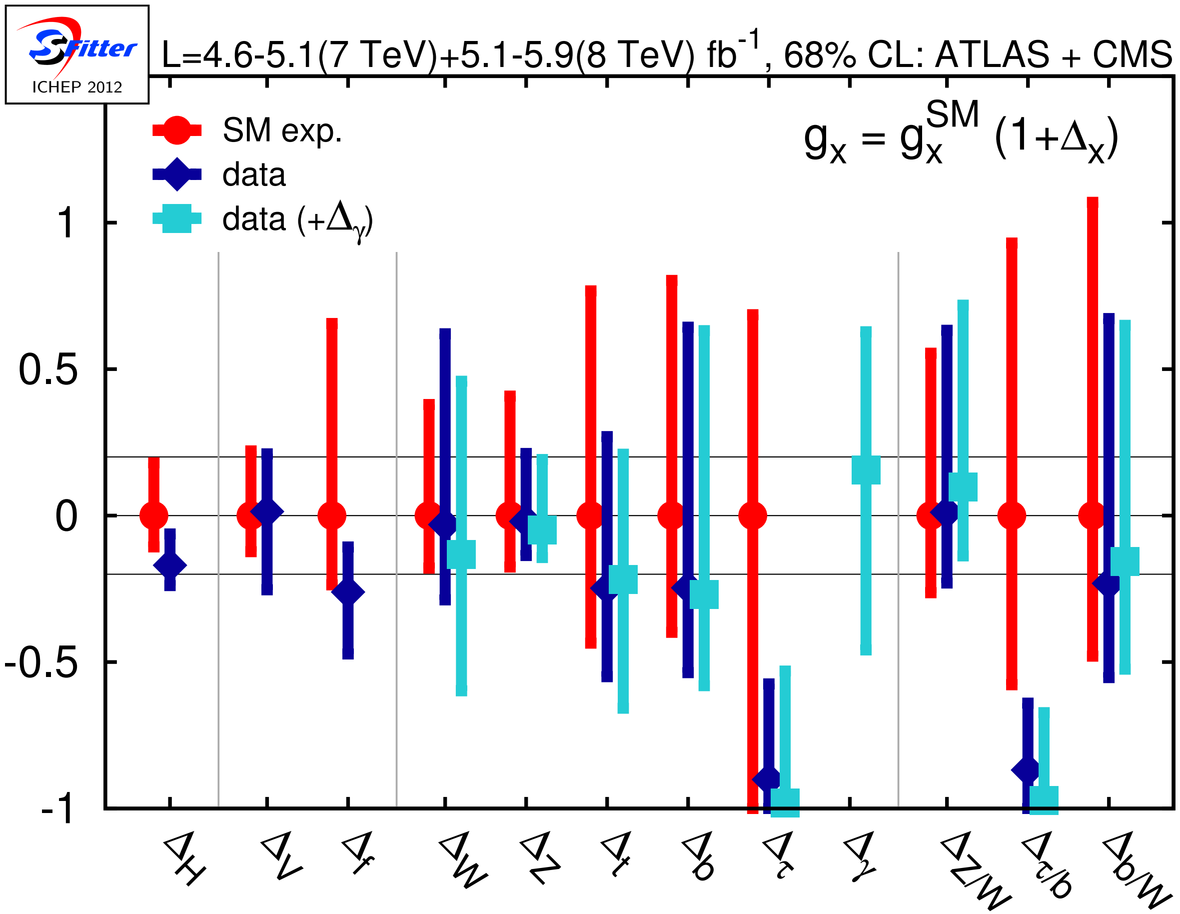
- Background expectations, exp. errors, etc. from published analyses
- cross-checked with exclusion and signal-strength plots

List of input channels for 2011 data

ATLAS		CMS	
$\gamma\gamma$		$\gamma\gamma$	
$ZZ \to 4\ell$		$\gamma\gamma$	di-jet
WW	0-jet	$ZZ \to 4\ell$	
WW	1-jet	WW	0-jet
WW	2-jet	WW	1-jet
$\tau\tau$	0-jet	WW	2-jet
$\tau\tau$	1-jet	$\tau\tau$	0/1-jet
$\tau\tau$	VBF	$\tau\tau$	Boosted
$\tau\tau$	VH	$\tau\tau$	VBF
$b\bar{b}$	WH	$b\bar{b}$	WH
$b\bar{b}$	$Z(\to \ell\bar{\ell})H$	$b\bar{b}$	$Z(\to \ell\bar{\ell})H$
$b\bar{b}$	$Z(\to \nu\bar{\nu})H$	$b\bar{b}$	$Z(\to \nu\bar{\nu})H$

plus inclusion of 2012 data (ICHEP)

Central values and errors on couplings

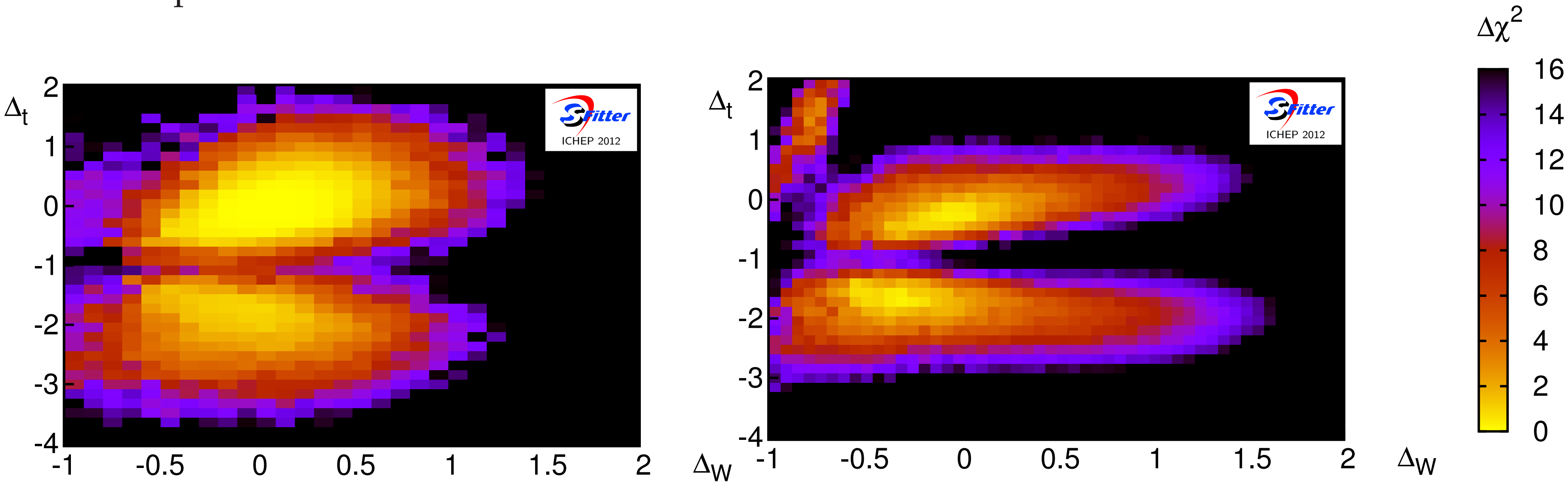


- SM provides good overall description
- Two parameter fit with $\Delta_V \equiv \Delta_W = \Delta_Z$ and $\Delta_f \equiv \Delta_b = \Delta_\tau = \Delta_t$ gives improvement to $\chi^2/\text{d.o.f.} = 29.0/52$
- Five parameter fit does not give further improvement: $\chi^2/\text{d.o.f.} = 27.7/49$

Profile log-likelihood Map: Δ_t – Δ_W correlation

SM expectation

2011 + 2012 Data



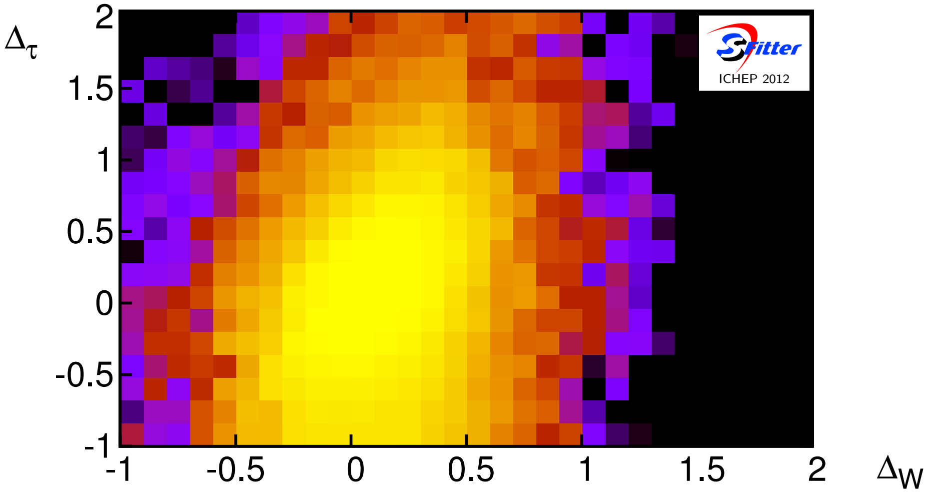
Three local χ^2 minima of five parameter fit

Δ_W	Δ_Z	Δ_t	Δ_b	Δ_τ	χ^2/d.o.f.
-0.03	-0.02	-0.25	-0.25	-0.90	27.7/49
-0.05	-0.04	-0.34	-1.73	-0.70	27.6/49
-0.29	-0.09	-1.65	-0.32	-0.70	27.7/49

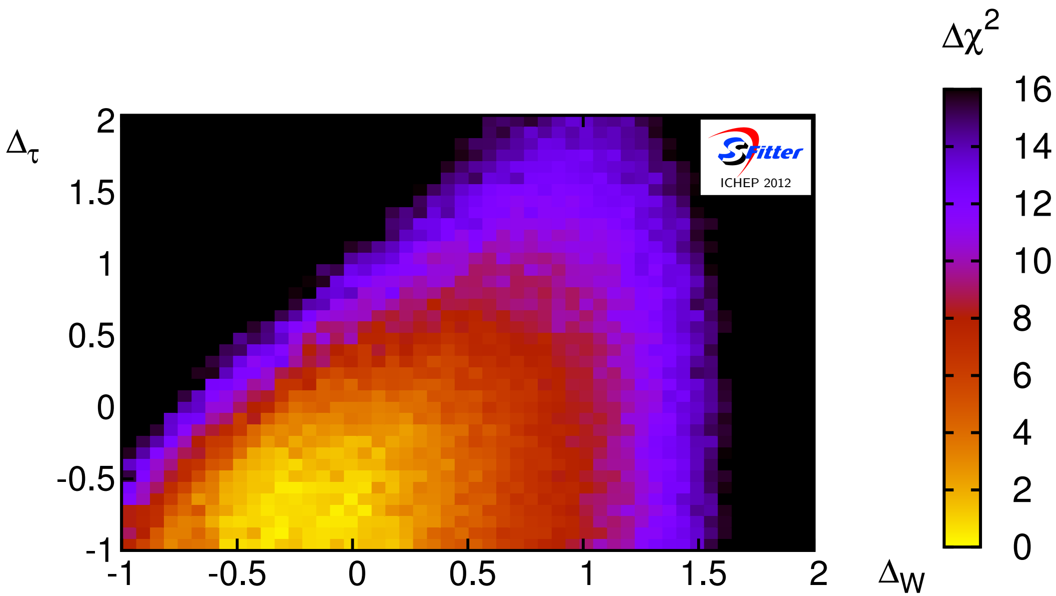
- SM at $\Delta_t = \Delta_W = 0$ looks fine
- Minimum at flipped g_b ($\Delta_b = -1.73$) gives very similar rates to first line
- Minimum at negative g_t ($\Delta_t = -1.65$) enhances $H \to \gamma\gamma$ partial width (constructive interference with W loop)

Profile log-likelihood Map: Δ_τ – Δ_W correlation

SM expectation



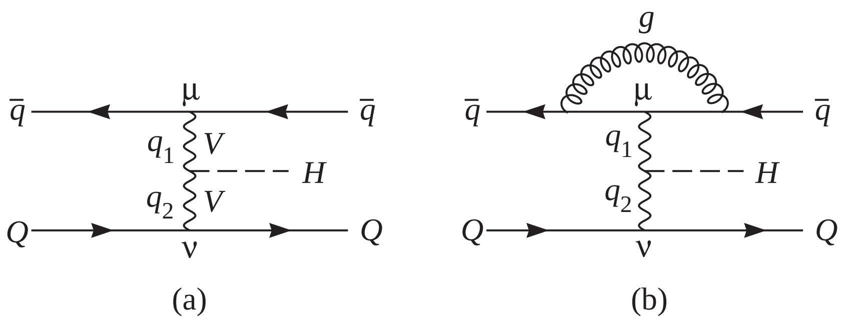
2011 + 2012 Data



- More $H \to \tau\tau$ data needed for significant statement on $H\tau\tau$ coupling

Tensor structure of the HVV coupling

Most general HVV vertex $T^{\mu\nu}(q_1, q_2)$



$$
\begin{aligned}
T^{\mu\nu} \quad &= \quad a_1\, g^{\mu\nu} \; + \\
&\quad\; a_2\, \left(q_1 \cdot q_2\, g^{\mu\nu} - q_1^{\nu} q_2^{\mu}\right) + \\
&\quad\; a_3\, \varepsilon^{\mu\nu\rho\sigma}\; q_{1\rho} q_{2\sigma}
\end{aligned}
$$

The $a_i = a_i(q_1, q_2)$ are scalar form factors

Physical interpretation of terms:

SM Higgs $\qquad \mathcal{L}_I \sim H V_\mu V^\mu \longrightarrow \; a_1$

loop induced couplings for neutral scalar

CP even $\qquad \mathcal{L}_{eff} \sim H V_{\mu\nu} V^{\mu\nu} \longrightarrow \; a_2$

CP odd $\qquad \mathcal{L}_{eff} \sim H V_{\mu\nu} \tilde{V}^{\mu\nu} \longrightarrow \; a_3$

Must distinguish a_1, a_2, a_3 experimentally

Size estimates for a_2 terms

a_2 for the four HVV combinations can be derived from effective Lagrangian

$$\mathcal{L} = \frac{g_{5e}^{HZZ}}{2\Lambda_5} H Z_{\mu\nu} Z^{\mu\nu} + \frac{g_{5e}^{HWW}}{\Lambda_5} H W^+_{\mu\nu} W_-^{\mu\nu} + \frac{g_{5e}^{HZ\gamma}}{\Lambda_5} H Z_{\mu\nu} A^{\mu\nu} + \frac{g_{5e}^{H\gamma\gamma}}{2\Lambda_5} H A_{\mu\nu} A^{\mu\nu}$$

- SU(2) multiplets in triangle graphs producing these effective couplings tend to produce all four of same order of magnitude
- However
  - $H \to ZZ \to 4\ell$ and $H \to WW \to \ell^+\ell^-\nu\bar{\nu}$ partial widths are strongly suppressed by being off-shell and by small leptonic branching ratios
  - No such suppressions for $H \to \gamma\gamma$

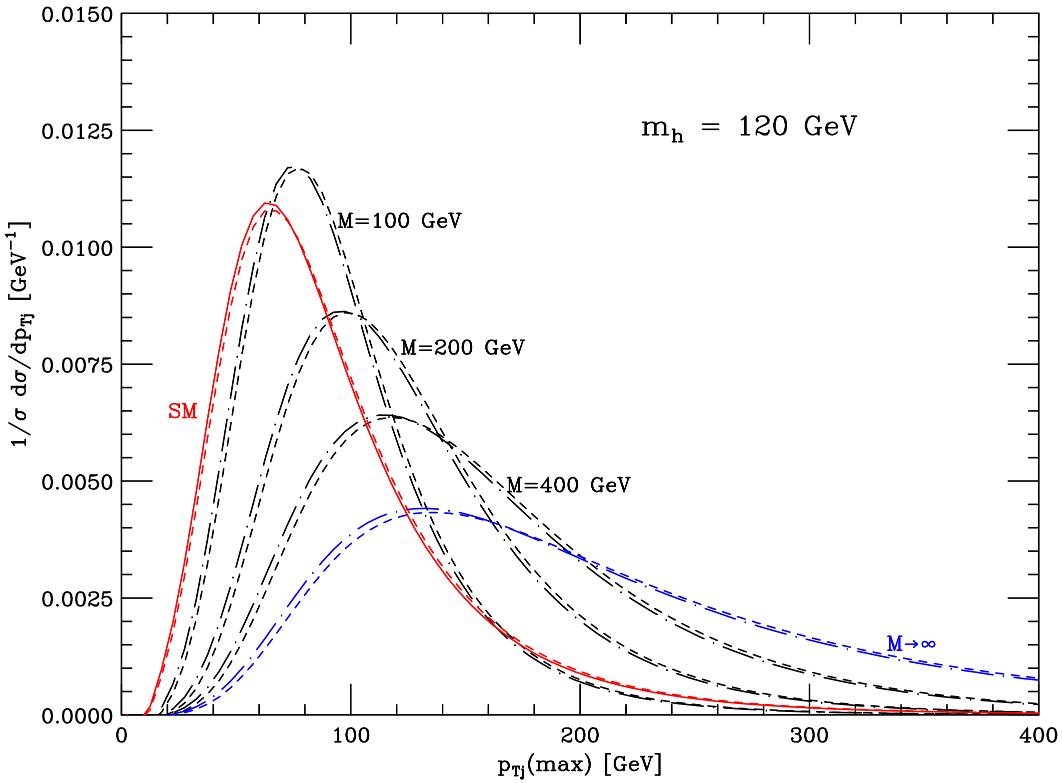
  $\Longrightarrow$ Need $g_{5e}^{HZZ} \approx g_{5e}^{HWW} \approx 1000\, g_{5e}^{H\gamma\gamma}$ in absence of SM a_1 term
- $HZ\gamma$ coupling must also be suppressed (would see on-shell $H \to Z\gamma \to \ell^+\ell^-\gamma$ otherwise)

$\Longrightarrow$ Substantial fine tuning needed

$\Longrightarrow$ Loop induced HWW and HZZ couplings, i.e. a_2 or a_3 couplings as origin of observed $H \to WW$ and $H \to ZZ$ decays are highly unlikely

Effect of non-standard HVV couplings on p_T of jets in VBF

Higher dimensional operators enhance production at large momentum transfer
$\Longrightarrow$ harder p_T spectra of jets for anomalous HVV couplings



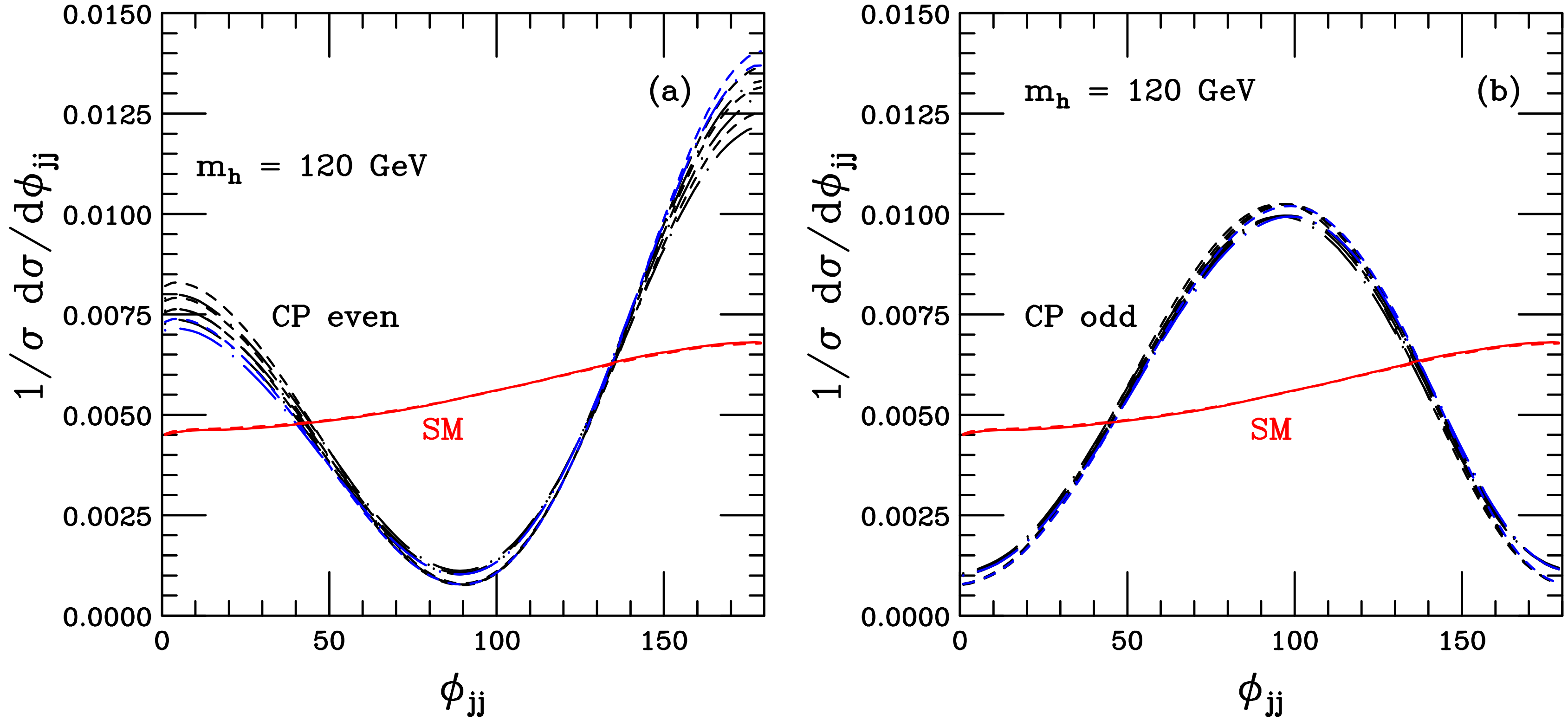
Form factors $a_i(q_1, q_2)$ chosen as

$$a_i(0,0)\ \frac{M^2}{q_1^2 - M^2}\ \frac{M^2}{q_2^2 - M^2}$$

... unless form-factors are chosen to reproduce SM distributions

Azimuthal angle correlations in VBF

Tell-tale signal for non-SM coupling is azimuthal angle between tagging jets



Dip structure at 90° (CP even) or 0/180° (CP odd) only depends on tensor structure of HVV vertex. Very little dependence on form factor, LO vs. NLO, Higgs mass etc.

Conclusions

- LHC has observed a boson, H, at 126 GeV whose couplings are compatible with the SM Higgs boson
- Given a resonance in $\gamma\gamma$ channel, new particle is most likely spin 0. Spin 2 must still be excluded.
- Improved measurement of Higgs coupling strengths will be continuing task for the coming years
- A purely loop induced HWW or HZZ coupling is very unlikely since data require them to be much larger than the loop induced $H\gamma\gamma$ and $HZ\gamma$ couplings
- VBF production and $H \to ZZ \to llll$ will be important to measure the tensor structure of the HVV vertex and give final confirmation that HWW and HZZ couplings have SM tensor structure, i.e. that H is indeed the Higgs boson