Higgs Physics at the LHC

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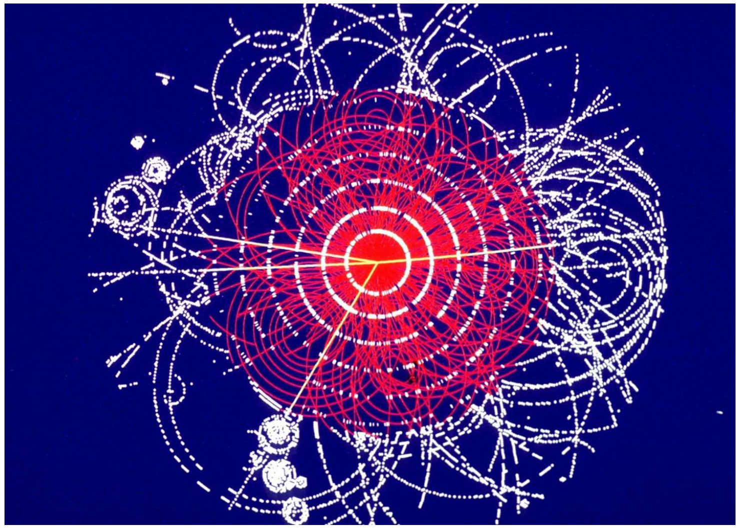
- Higgs Theory
- Search channels at the LHC
- Measurement of Higgs couplings
- New physics backgrounds?
- Tensor structure of HVV couplings
- Conclusions



Goals of Higgs Physics

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

- Discover the Higgs boson
- Measure its couplings and probe
  mass generation for gauge bosons and fermions

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

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

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

- 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

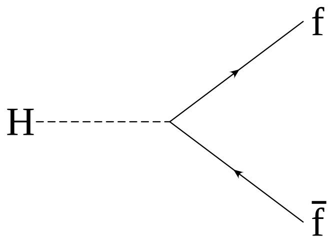
Kinetic energy term of Higgs doublet field:

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

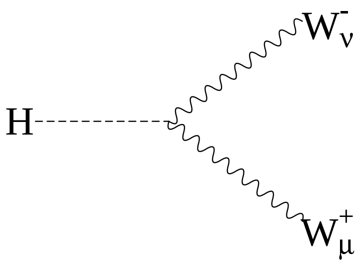
- W, Z mass generation: $m_W^2 = \left(\frac{gv}{2}\right)^2$, $m_Z^2 = \frac{(g^2+g'^2)v^2}{4}$
- WWH and ZZH couplings are generated
- Higgs couples proportional to mass: coupling strength $= 2\,m_V^2/v \sim g^2 v$ within SM

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

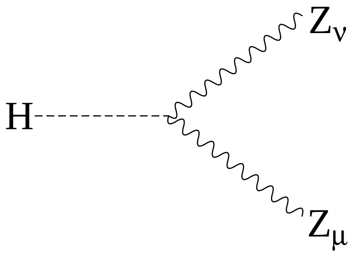
Feynman rules for SM Higgs couplings



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



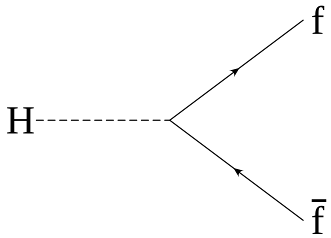
$$ig\,m_W\,g_{\mu\nu}$$



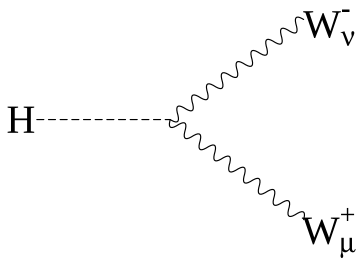
$$i\,g\,\frac{1}{\cos\theta_W}\,m_Z\,g_{\mu\nu}$$

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

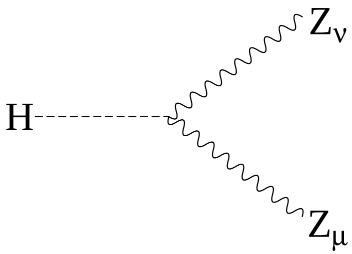
Deviations from SM Higgs coupling strengths



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



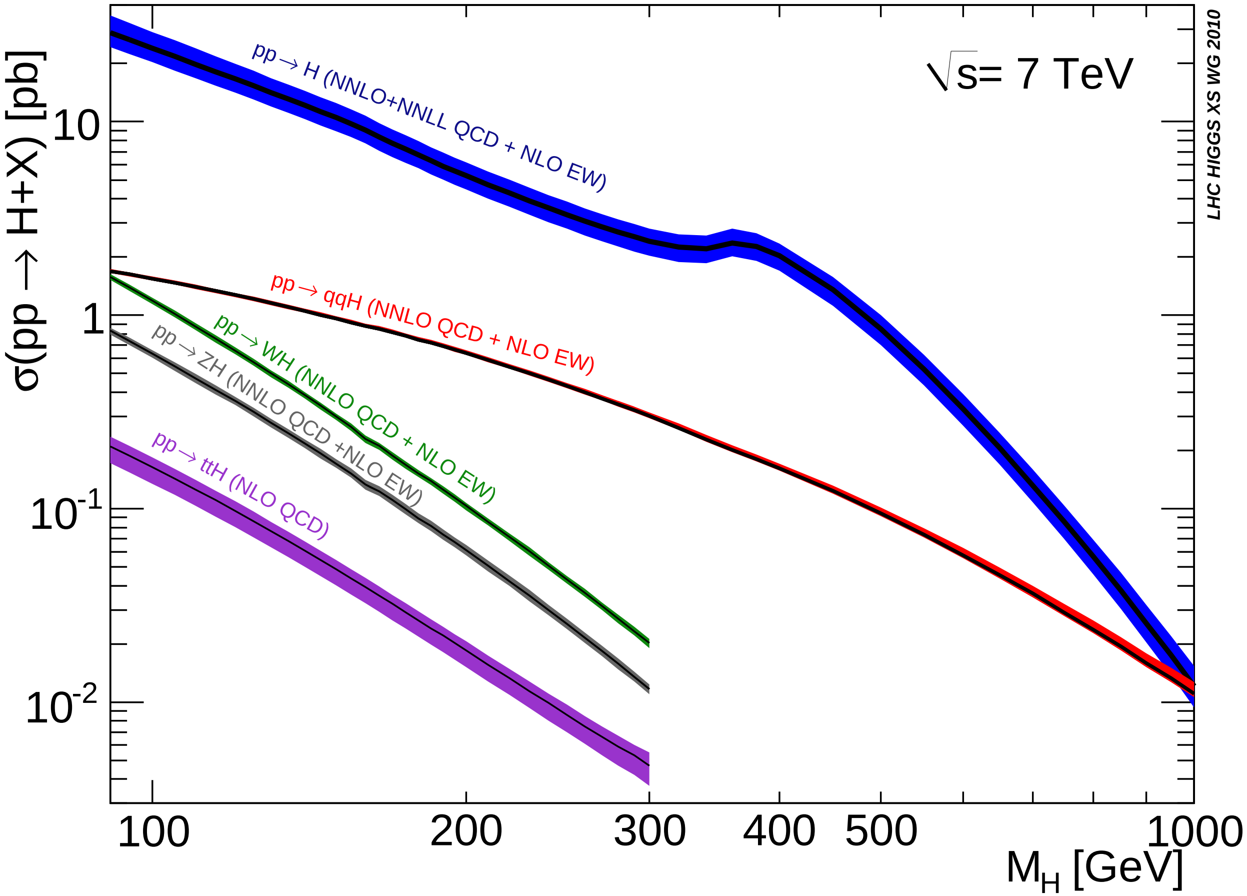
$$ig\,m_W\,(1+\Delta_W)g_{\mu\nu}$$

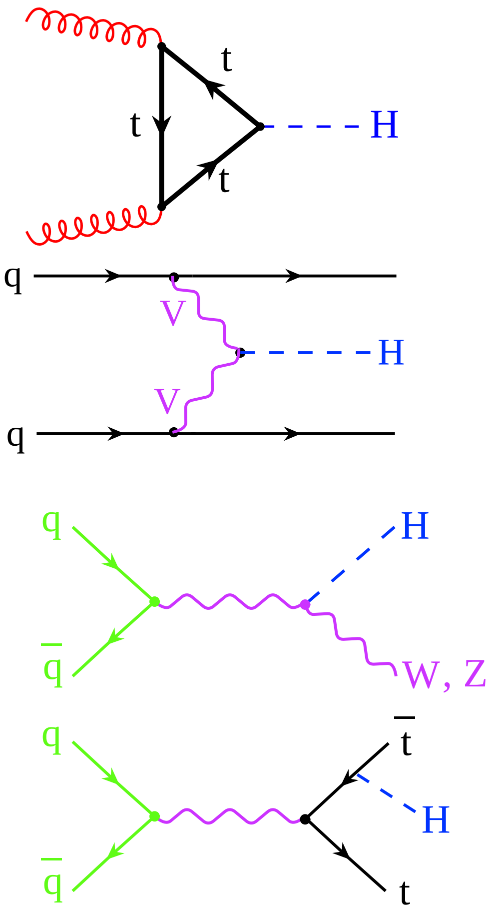


$$i\,g\,\frac{1}{\cos\theta_W}\,m_Z\,(1+\Delta_Z)g_{\mu\nu}$$

Goal: determine deviations Δ_X in HXX couplings from LHC and Tevatron data

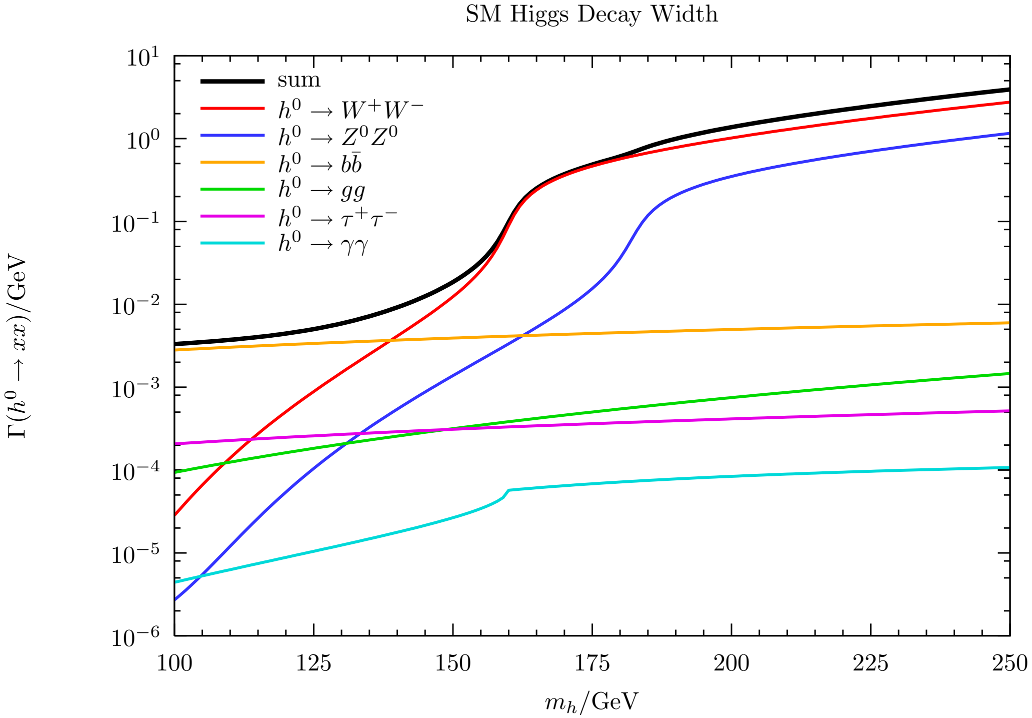
Total cross sections at the LHC

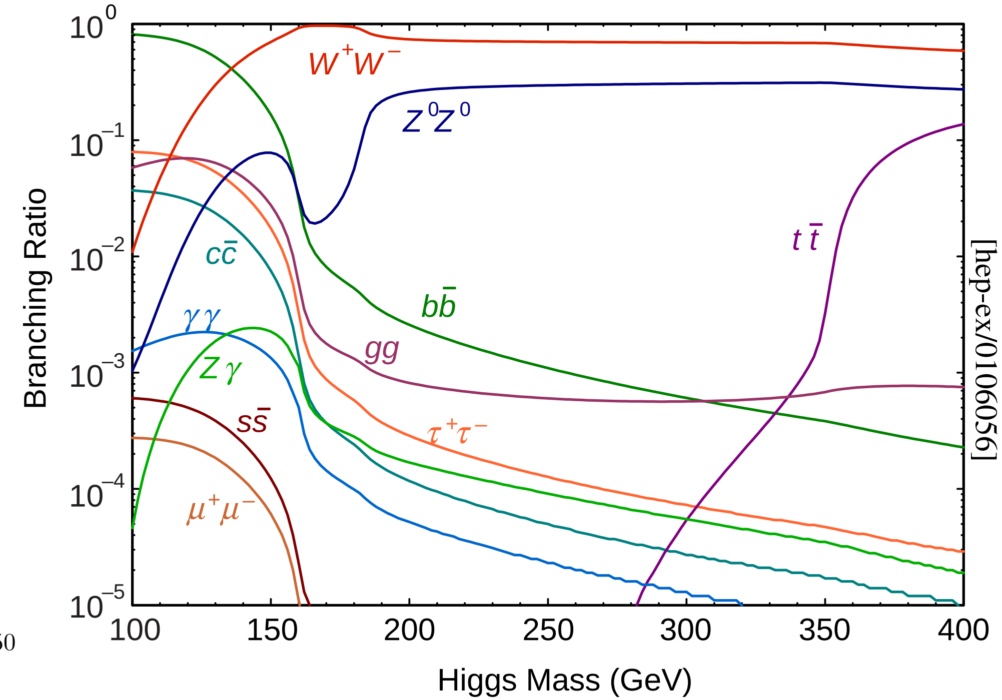




Decay of the SM Higgs

Higgs decay width and branching fractions within the SM





Main search channels

- inclusive searches for

$$H \to \gamma\gamma$$

  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 $120 \text{ GeV} \leq m_H$

- VBF searches for

$$H \to \gamma\gamma$$

$$H \to \tau\tau$$

  for $115 \text{ GeV} \leq m_H \leq 150$ GeV

- Search for boosted Higgs in VH associated production

$$H \to b\bar{b}$$

  for $115 \text{ GeV} \leq m_H \leq 140$ GeV

Main search channels (old version)

- inclusive searches for

$$H \to \gamma\gamma$$

invariant-mass peak, for $m_H < 150$ GeV

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

for $m_H \geq 130$ GeV and $m_H \neq 2m_W$.

$$H \to W^+W^- \to \ell^+\bar{\nu}\ell^-\nu$$

for 140 GeV $\leq m_H < 200$ GeV

- VBF searches for

$$H \to \gamma\gamma$$

$$H \to \tau\tau$$

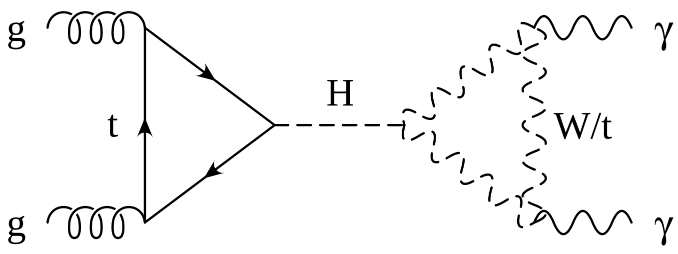
for 115 GeV $\leq m_H \leq 150$ GeV

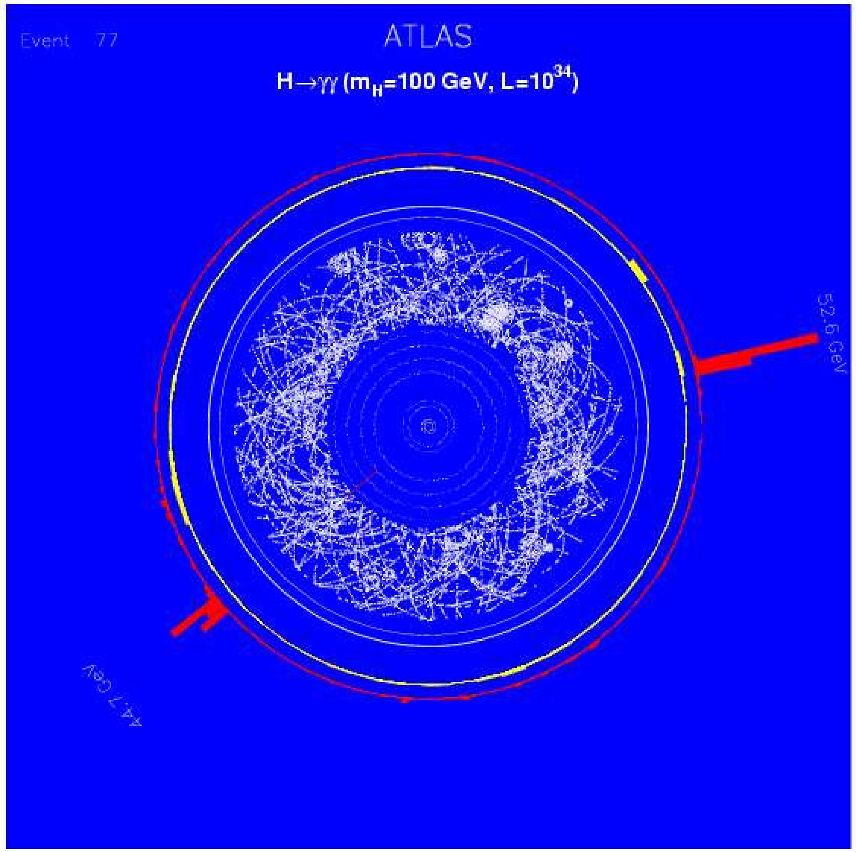
- Search for boosted Higgs in VH associated production

$$H \to b\bar{b}$$

for 115 GeV $\leq m_H \leq 140$ GeV

$H \to \gamma\gamma$



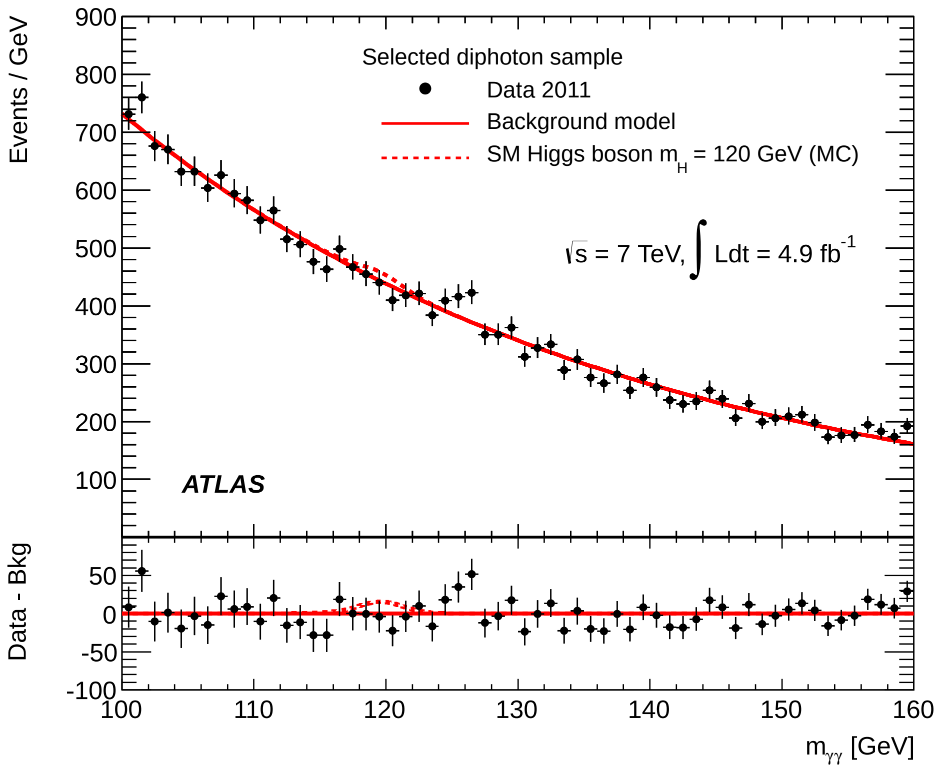


- BR$(H \to \gamma\gamma) \approx 10^{-3}$
- large backgrounds from $q\bar{q} \to \gamma\gamma$, $gg \to \gamma\gamma$ and jets misidentified as photons
- but CMS and ATLAS have excellent photon-energy resolution (order of 1%)

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

$H \longrightarrow \gamma\gamma$

- Look for a narrow $\gamma\gamma$ invariant mass peak
- Extrapolate background into the signal region from sidebands
- Indication for signal at $m_{\gamma\gamma} = 125$ GeV

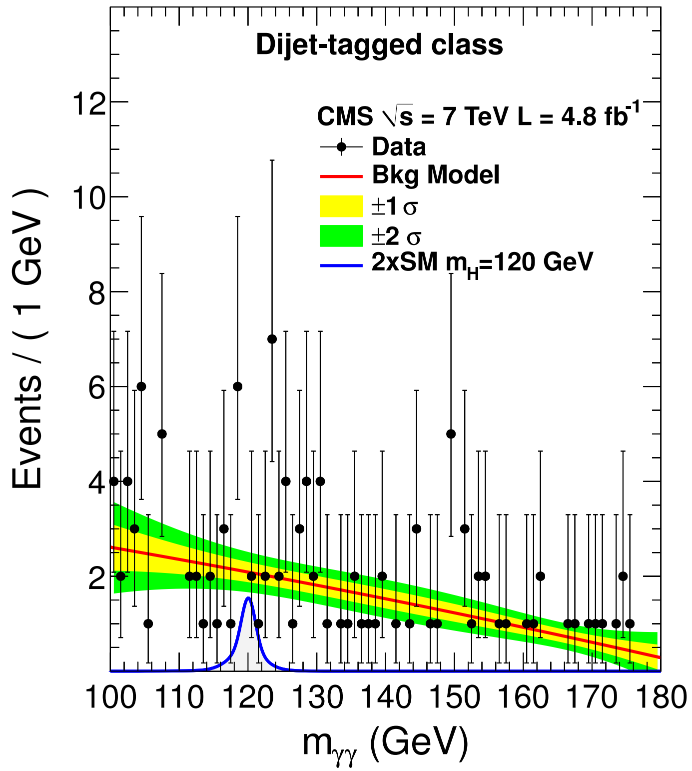


Landau-Yang theorem: $\gamma\gamma$ resonance cannot be spin1

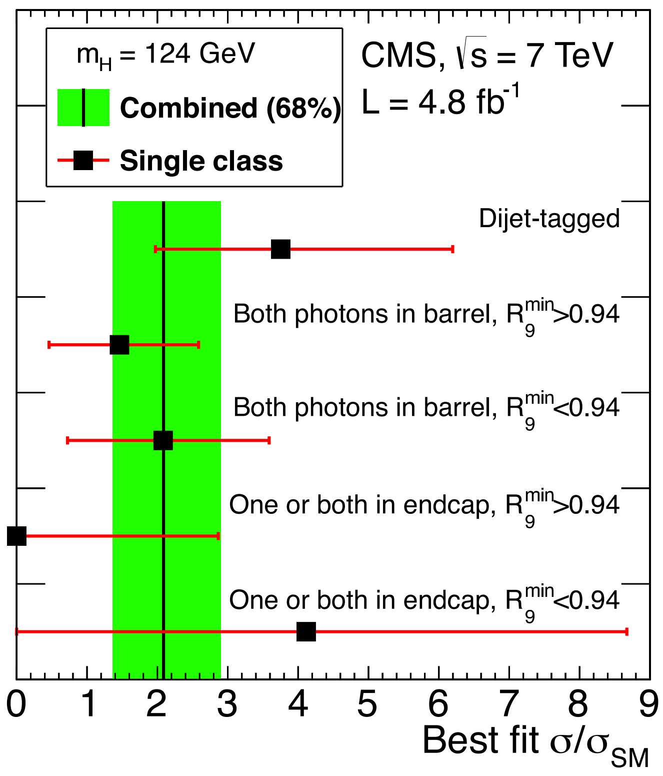
$\Longrightarrow$ New resonance at 125 GeV is most likely spin 0 (or perhaps spin 2)

$H \to \gamma\gamma$ in VBF

CMS data for VBF (2 jet) selection



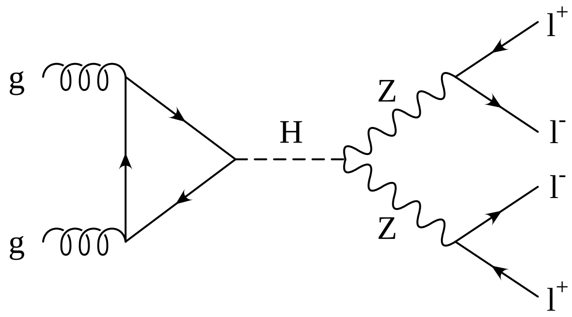
CMS $H \to \gamma\gamma$ signal strengths

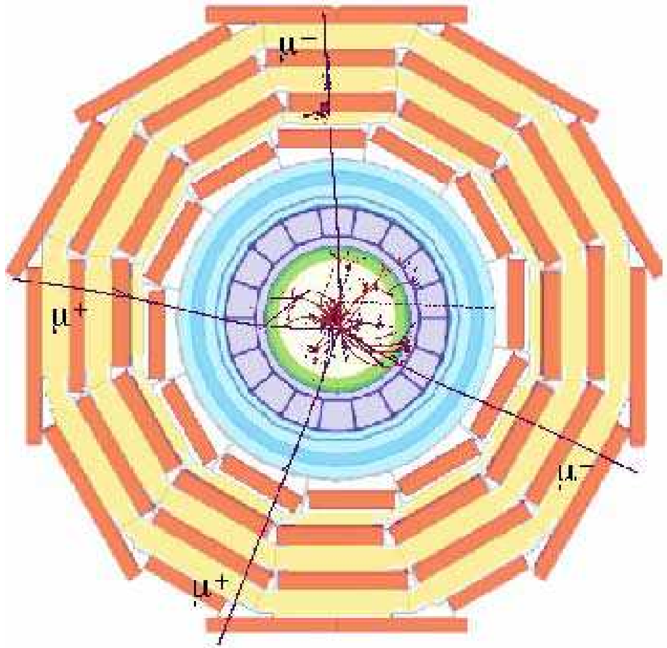


VBF rate is proportional to g^2_{HVV} times $|c g_{HWW} - d g_{Htt}|^2$

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

The gold-plated mode

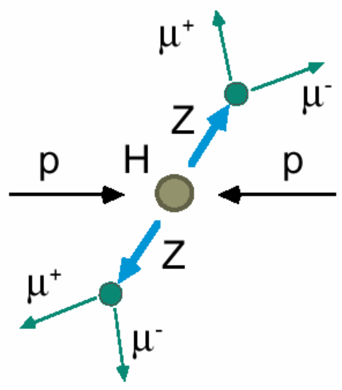


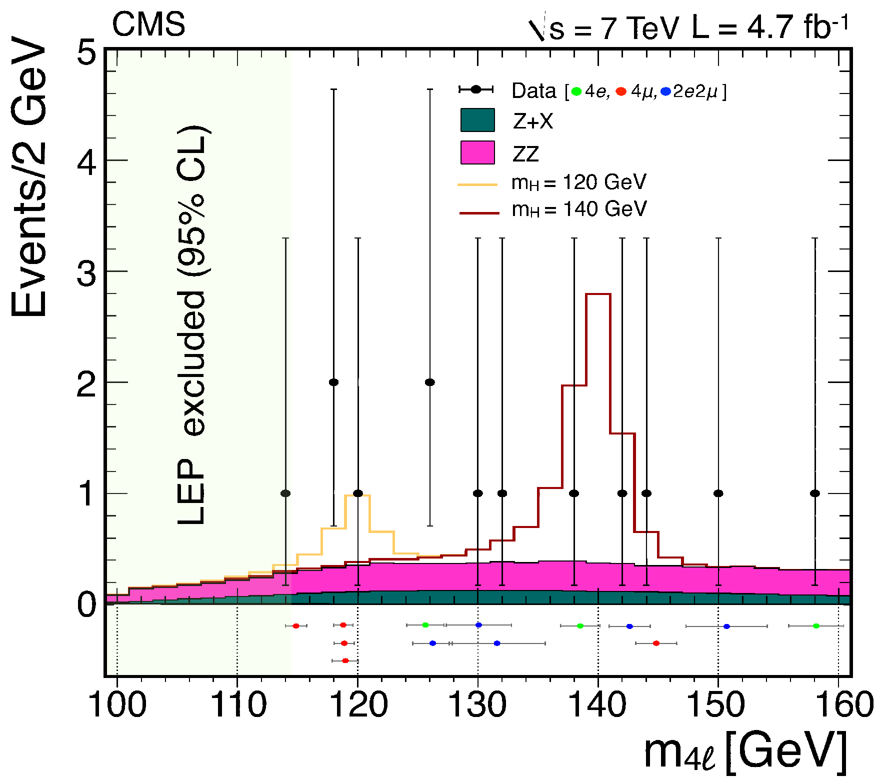


- Most important and clean search mode for $m_H < 600$ GeV (with hole around $2m_W$)
- Continuum, limited, irreducible background from $q\bar{q} \to ZZ$
- small BR$(H \to \ell^+\ell^-\ell^+\ell^-) \approx 0.15\%$ (even smaller when $m_H < 2m_Z$)

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

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

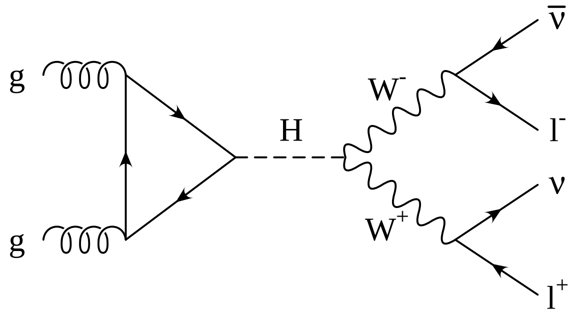


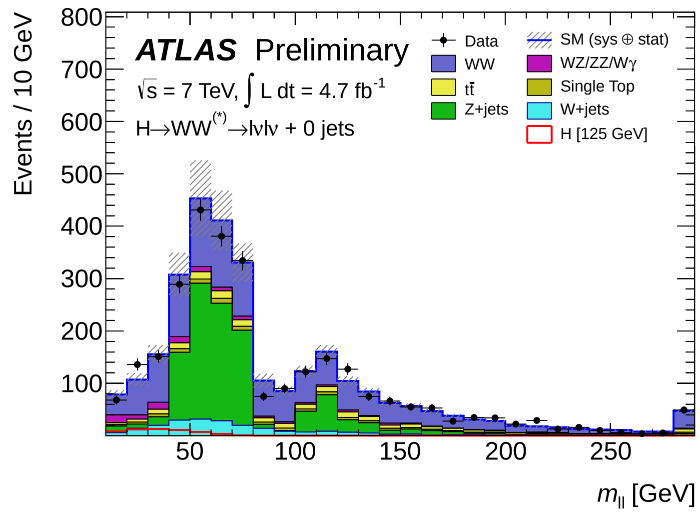


- invariant mass of the charged leptons fully reconstructed

CMS and ATLAS see indication for excess events around $m_{ZZ} = 125$ GeV

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

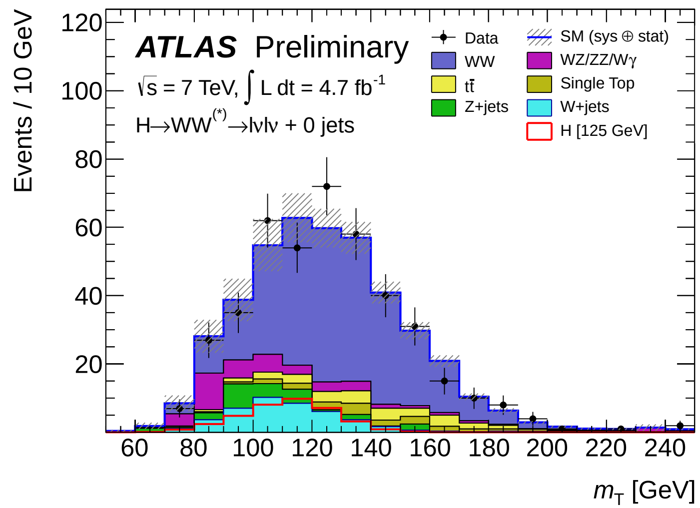




- Exploit $\ell^+\ell^-$ angular correlations
- measure the transverse mass with a Jacobian peak at m_H

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

- signal produces broad peak $\Longrightarrow$ must know the background normalization precisely



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

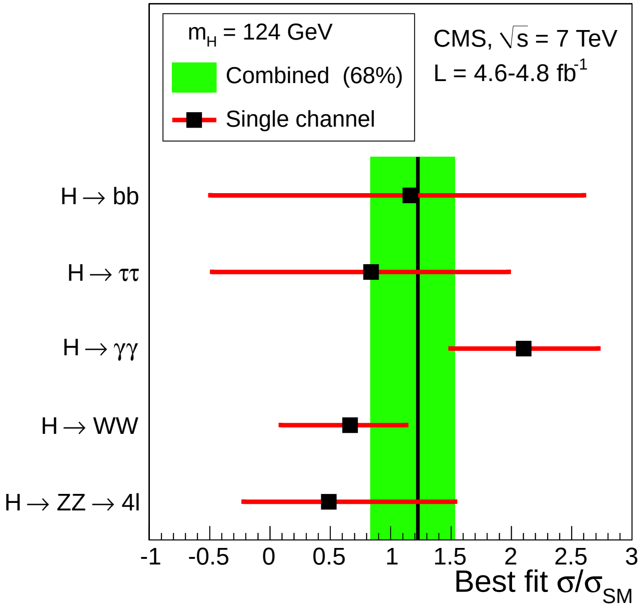
Observation of inclusive $H \rightarrow WW$ signal at 125 GeV is challenging, as demonstrated by 2011 ATLAS results

125 GeV	Signal	WW	$WZ/ZZ/W\gamma$	$t\bar{t}$	W + jets	Total Bkg.	Observed
0-jet	25 ± 7	110 ± 12	12 ± 3	7 ± 2	27 ± 16	173 ± 22	174
1-jet	6 ± 2	18 ± 3	6 ± 3	7 ± 2	5 ± 3	45 ± 7	56
2-jet	0.4 ± 0.2	0.3 ± 0.2		0.2 ± 0.1		0.5 ± 0.2	0

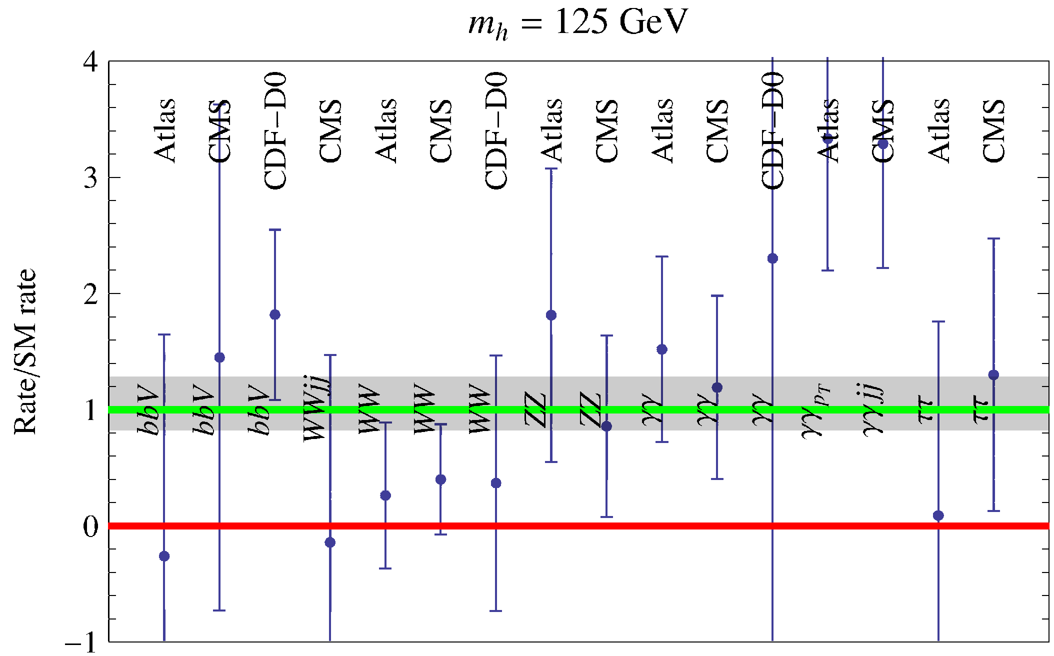
- no signal in 0-jet sample, some enhancement in 1-jet sample
- Observation is limited by systematic errors:
  QCD extrapolation from control region for $q\bar{q} \rightarrow WW$ background
  determination of jets faking leptons ($W+$ jets background)
- $m_H = 125$ GeV was originally considered below sensitivity region of inclusive search
- VBF search for $H \rightarrow WW$ has better signal to background ratio but needs much more statistics

Summary of measured channels

CMS data



ATLAS, CMS, Tevatron Giardino et al.arXiv:1203.4254



$\tau\tau$ rate in VBF is proportional to g^2_{HVV} times $g^2_{H\tau\tau}$

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

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)

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

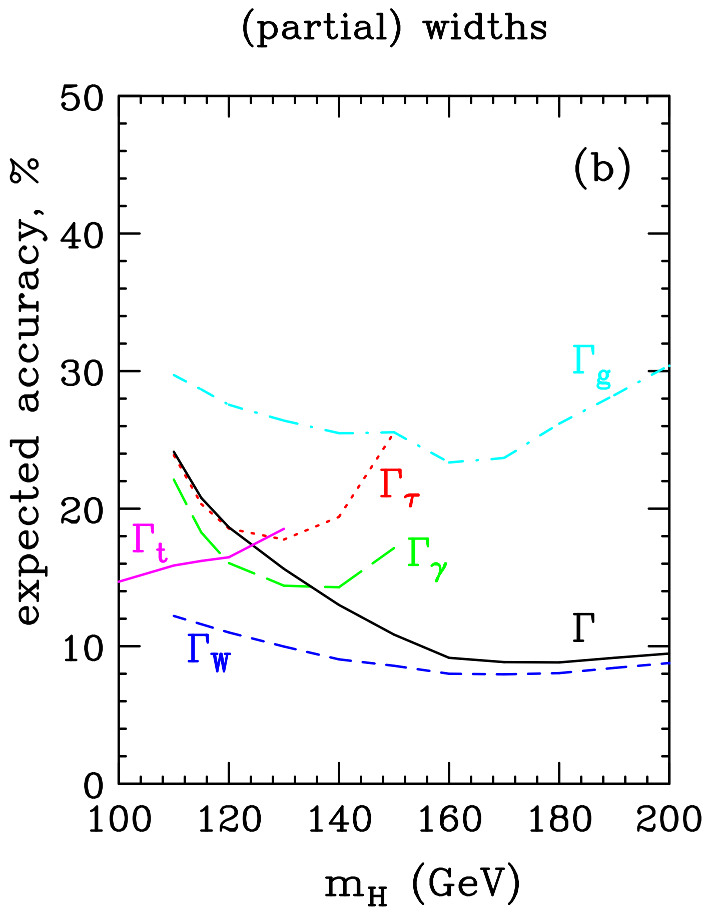
Fit LHC data within constrained models

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 new analyses of 2011 LHC data:
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

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

SFitter analysis of Higgs couplings at LHC

- Parametrize deviations from SM couplings

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

- 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

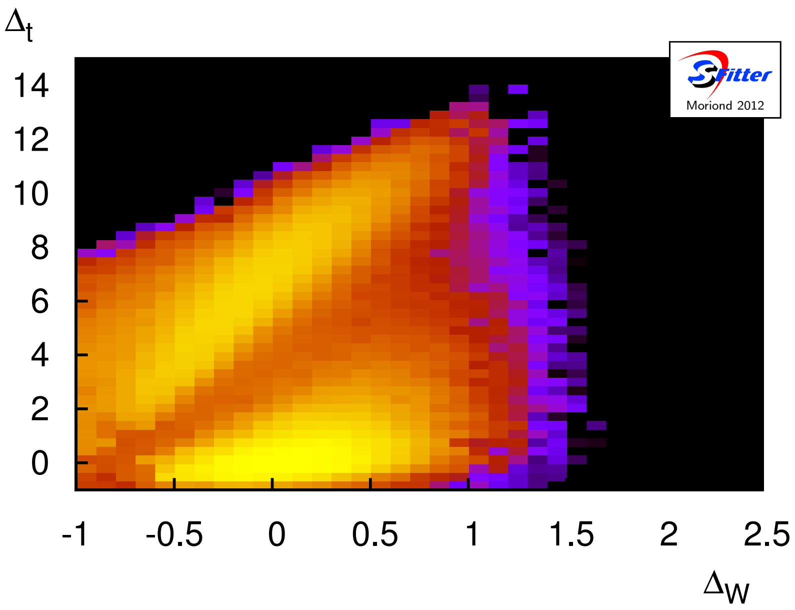
- Background expectations, exp. errors, etc. from published analyses
- cross-checked with exclusion and signal-strength plots

List of input channels

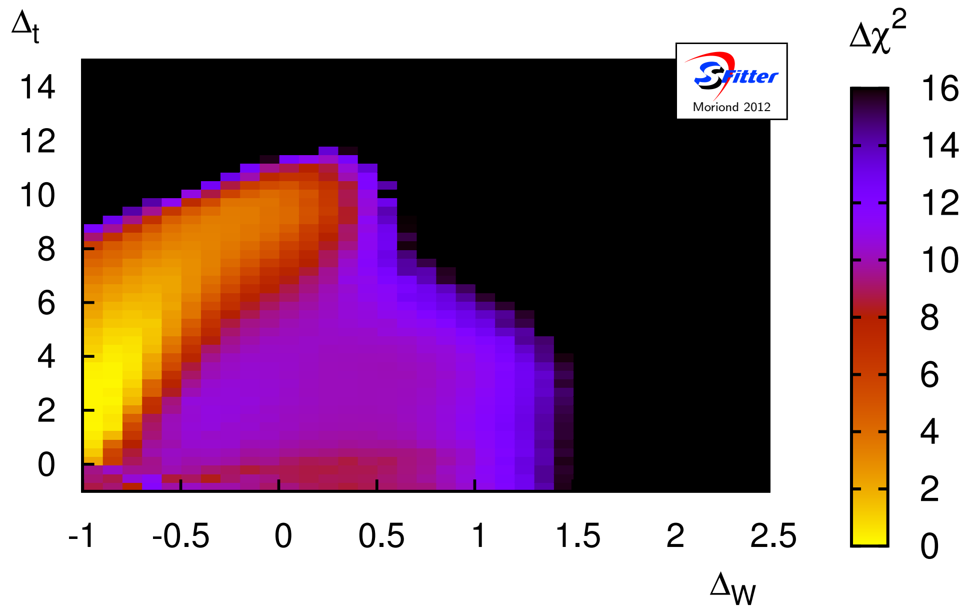
ATLAS		CMS	
$\gamma\gamma$		$\gamma\gamma$	
$ZZ \to 4\ell$		$\gamma\gamma$	di-jet
WW	0-jet	$ZZ \to 4\ell$	
WW	1-jet	WW	0-jet
WW	2-jet	WW	1-jet
$\tau\tau$	0-jet	WW	2-jet
$\tau\tau$	1-jet	$\tau\tau$	0/1-jet
$\tau\tau$	VBF	$\tau\tau$	Boosted
$\tau\tau$	VH	$\tau\tau$	VBF
$b\bar{b}$	WH	$b\bar{b}$	WH
$b\bar{b}$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

Profile log-likelihood Map

SM expectation



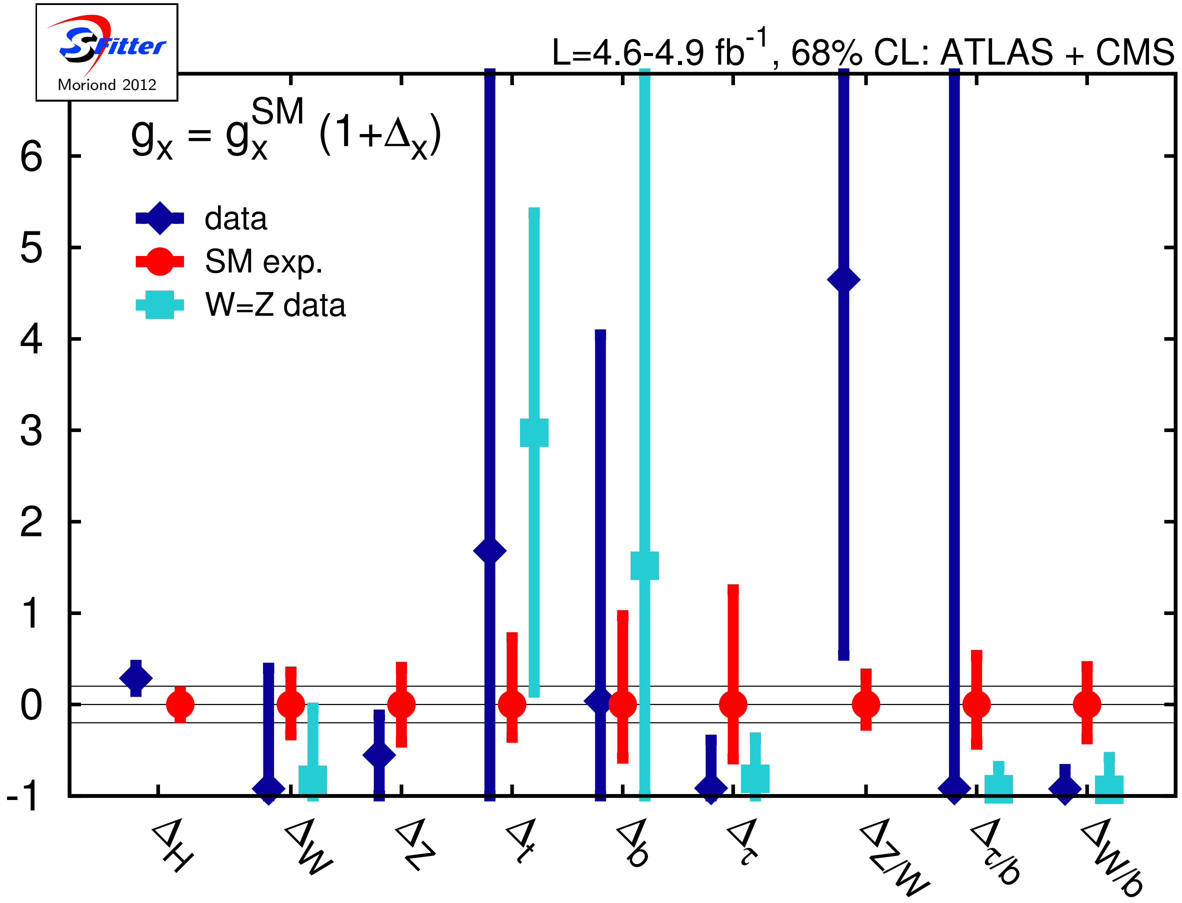
Data



- Secondary solution in SM case: ($\Delta\chi^2 = 0.86$)
- Large top Yukawa-coupling $\rightarrow$ sign of Higgs-photon coupling flipped

- no excess in $H \rightarrow WW$ channels $\rightarrow \Delta_W \rightarrow$ -1 preferred
- Higgs-photon coupling induced by top $\rightarrow \Delta_t$ larger
- $\rightarrow$ looks similar to secondary solution

Central values and errors on couplings

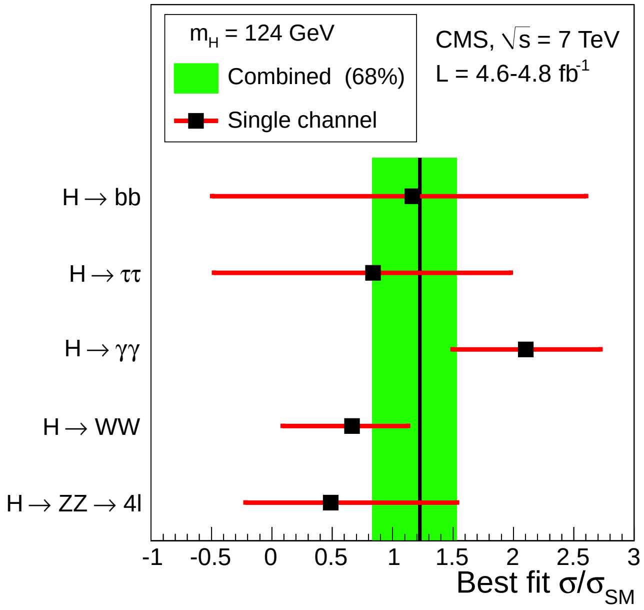


- single-parameter modifier Δ_H already constrained to 14 %
- significant deviations from expectations (size of errors)
- values consistent with secondary solution in SM
- SM matches well nevertheless: $\chi^2 = 13.2 \ / \ 22$ d.o.f. cf. best-fit point: $\chi^2 = 9.3 \ / \ 22$ d.o.f.

For more details see talk by Tilman Plehn

Summary of measured channels

CMS data



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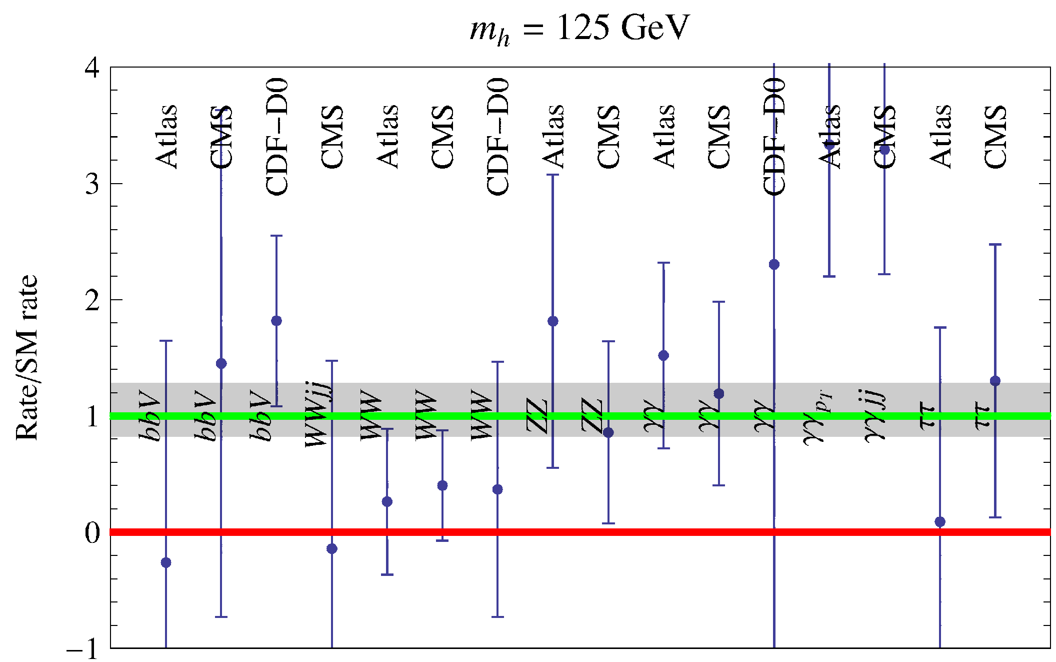


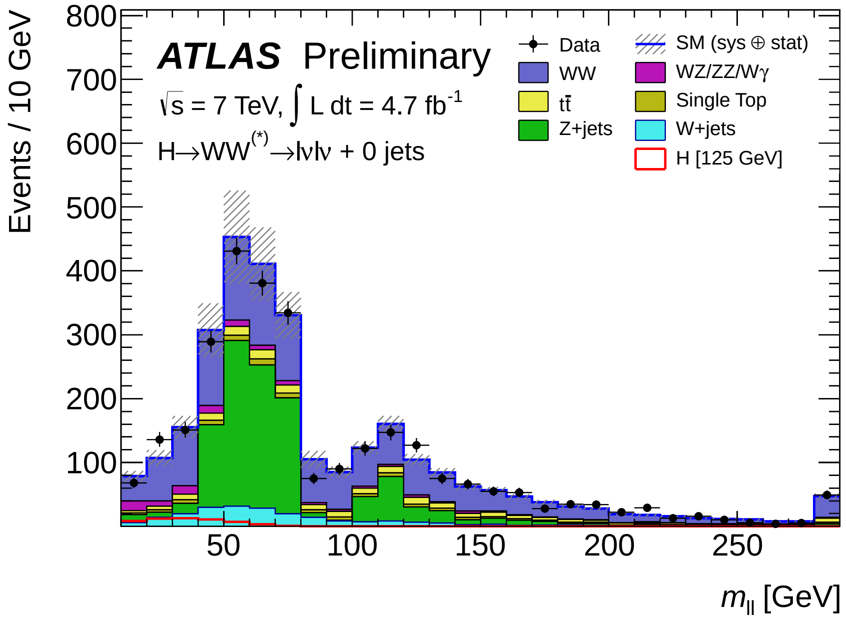
Surprising observation: *WW* rate is low for all measurements

Even inclusive *WW* deficit is not really significant at this point, however.

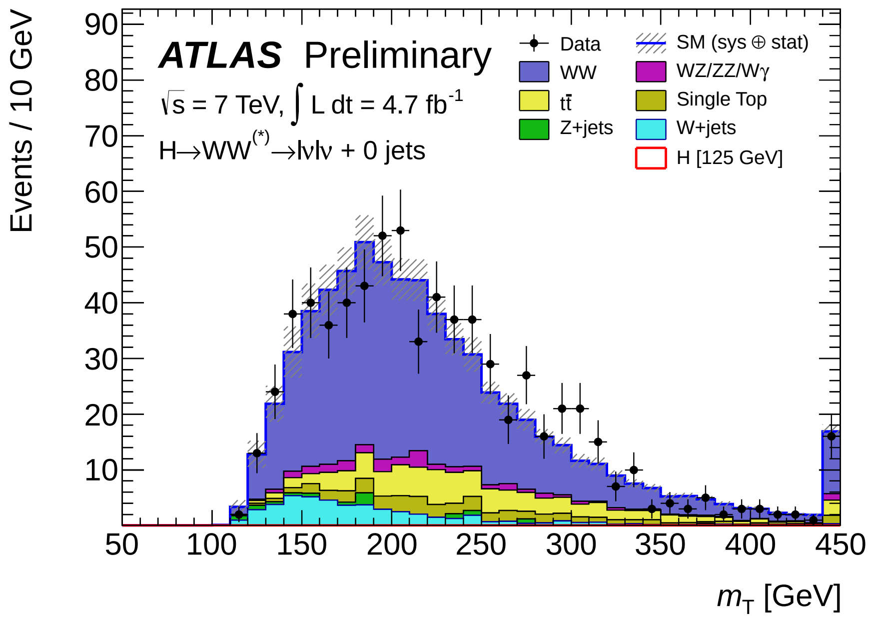
Sign of new physics????

Data driven $q\bar{q} \to WW$ background determination

ATLAS control region (+ $\Delta\phi_{ll} < 1.8$):
$m_{ll} > 80/106$ GeV



full control region (no $\Delta\phi_{ll} < 1.8$ cut)

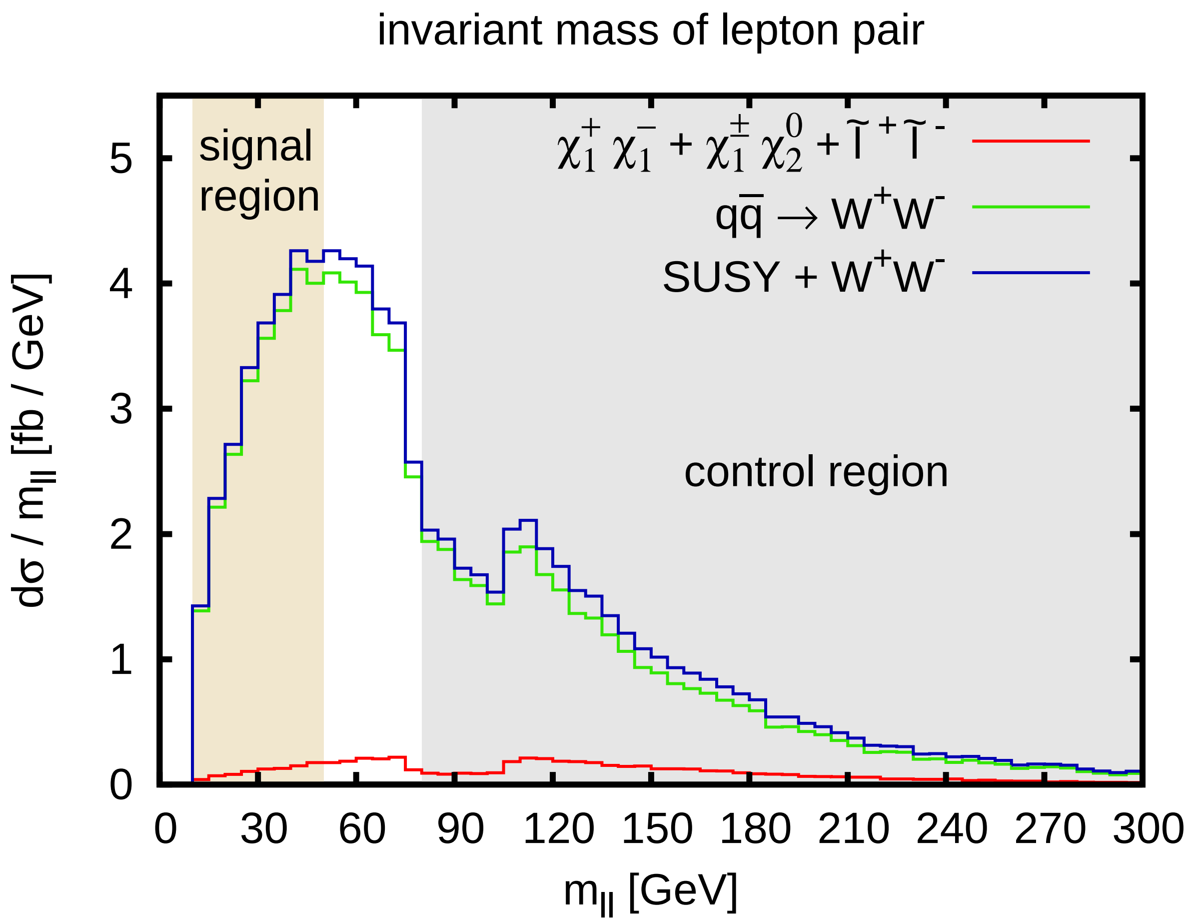


Measure WW background in high m_{ll} region
Extrapolate to signal region ($m_{ll} < 50$ GeV) with predicted MC shape
Shape uncertainty of extrapolation $\approx 10\%$ (from QCD scale uncertainty alone)

New physics backgrounds?

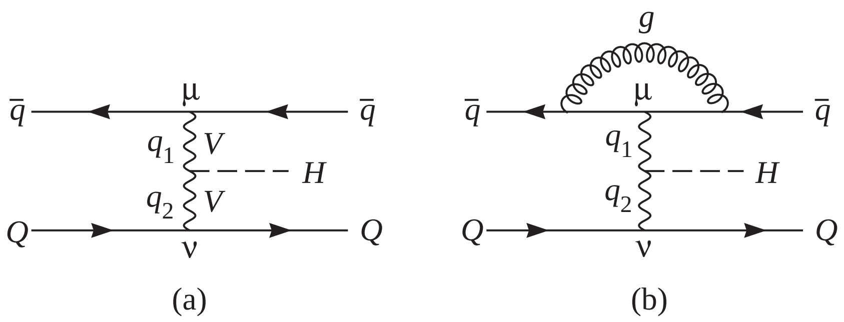
Extra contributions in control region can lead to overestimate of background in signal region

Example:
Intermediate mass charginos
and sleptons,
heavy squarks and gluinos
Feigl, Rzehak, DZ in prep.



Tensor structure of the HVV coupling

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



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

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

Physical interpretation of terms:

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

loop induced couplings for neutral scalar

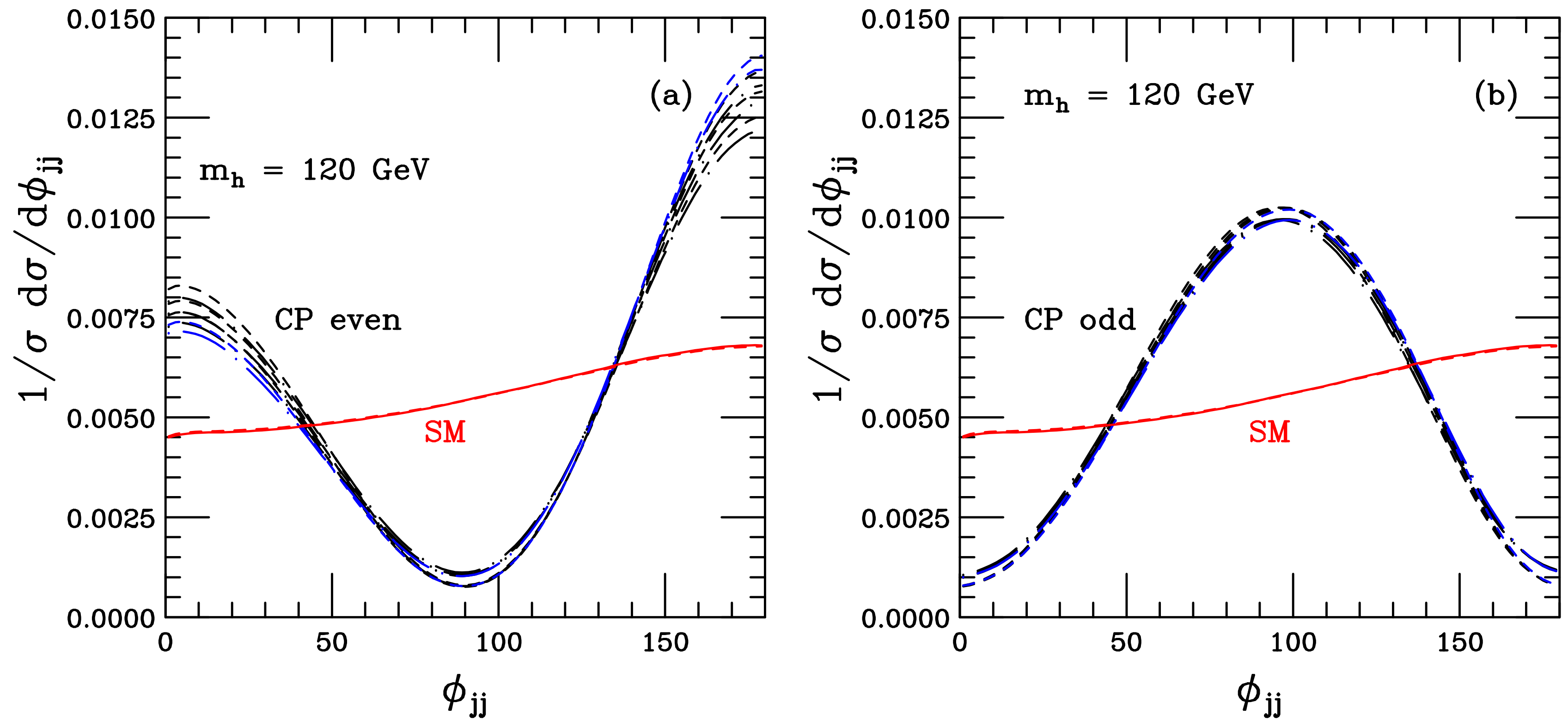
CP even $\quad \mathcal{L}_{eff} \sim H V_{\mu\nu} V^{\mu\nu} \longrightarrow a_2$

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

Must distinguish a_1, a_2, a_3 experimentally

Azimuthal angle correlations

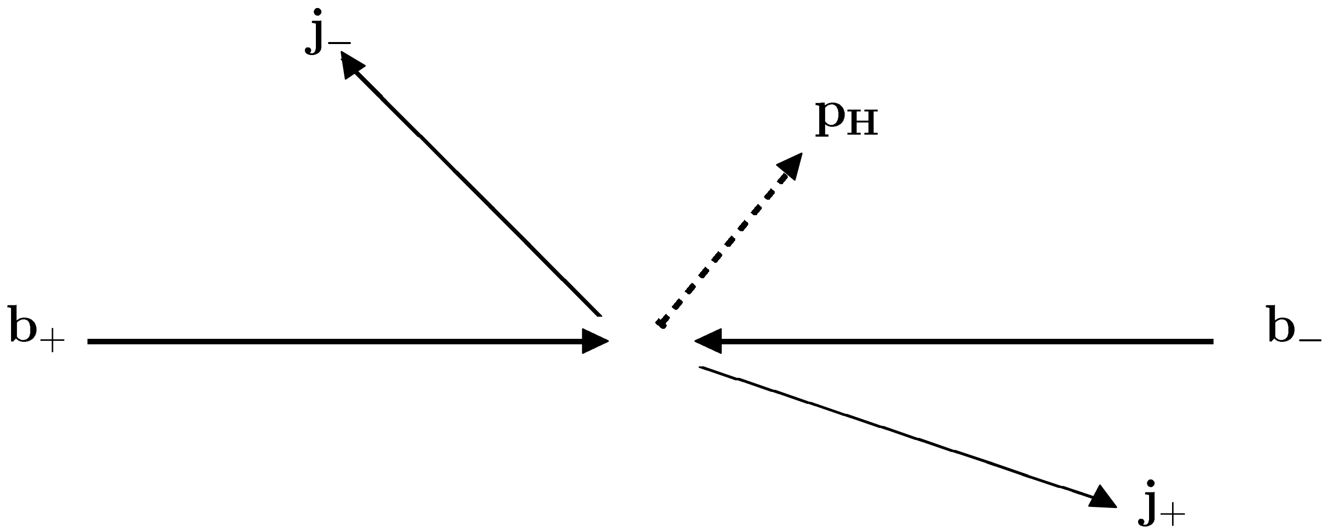
Tell-tale signal for non-SM coupling is azimuthal angle between tagging jets



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.

Azimuthal angle distribution and Higgs CP properties

Kinematics of Hjj event:

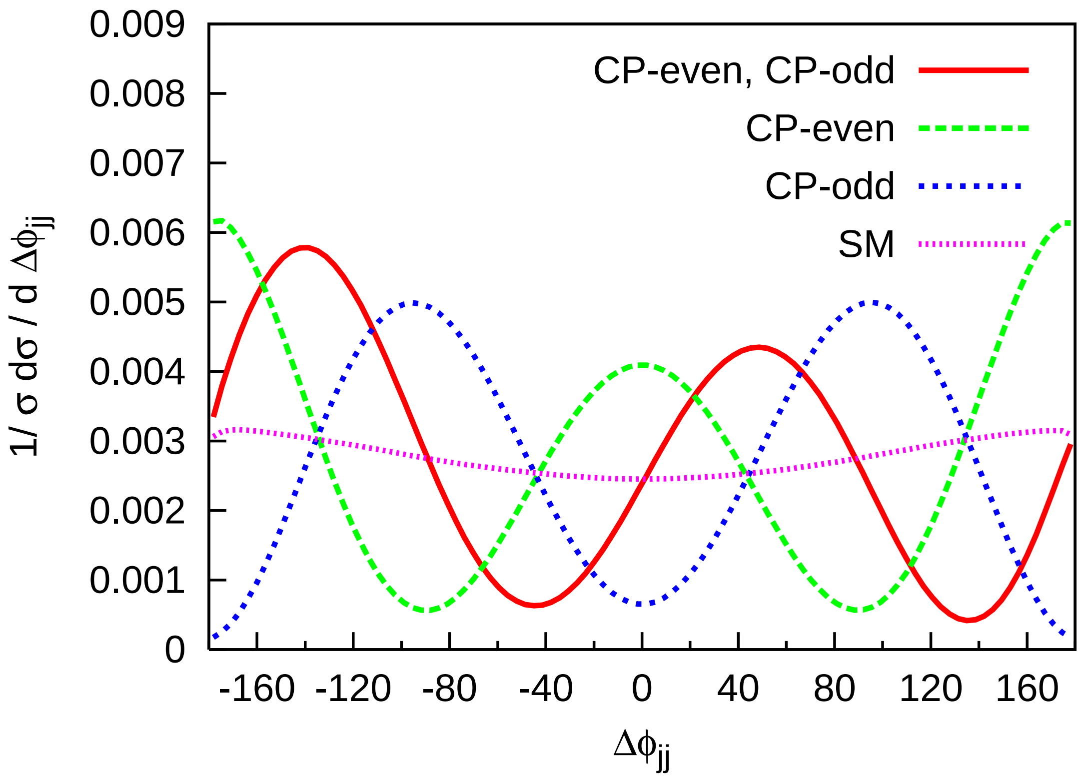


Define azimuthal angle between jet momenta j_+ and j_- via

$$\varepsilon_{\mu\nu\rho\sigma} b_+^\mu j_+^\nu b_-^\rho j_-^\sigma = 2 p_{T,+} p_{T,-} \sin(\phi_+ - \phi_-) = 2\, p_{T,+} p_{T,-} \sin \Delta\phi_{jj}$$

- $\Delta\phi_{jj}$ is a parity odd observable
- $\Delta\phi_{jj}$ is invariant under interchange of beam directions $(b_+, j_+) \leftrightarrow (b_-, j_-)$

Signals for CP violation in the Higgs Sector



mixed CP case:
$a_2 = a_3, a_1 = 0$

pure CP-even case:
a_2 only

pure CP odd case:
a_3 only

Position of minimum of $\Delta\phi_{jj}$ distribution measures relative size of CP-even and CP-odd couplings. For

$$a_1 = 0, \qquad a_2 = d \, \sin\alpha, \qquad a_3 = d \, \cos\alpha,$$

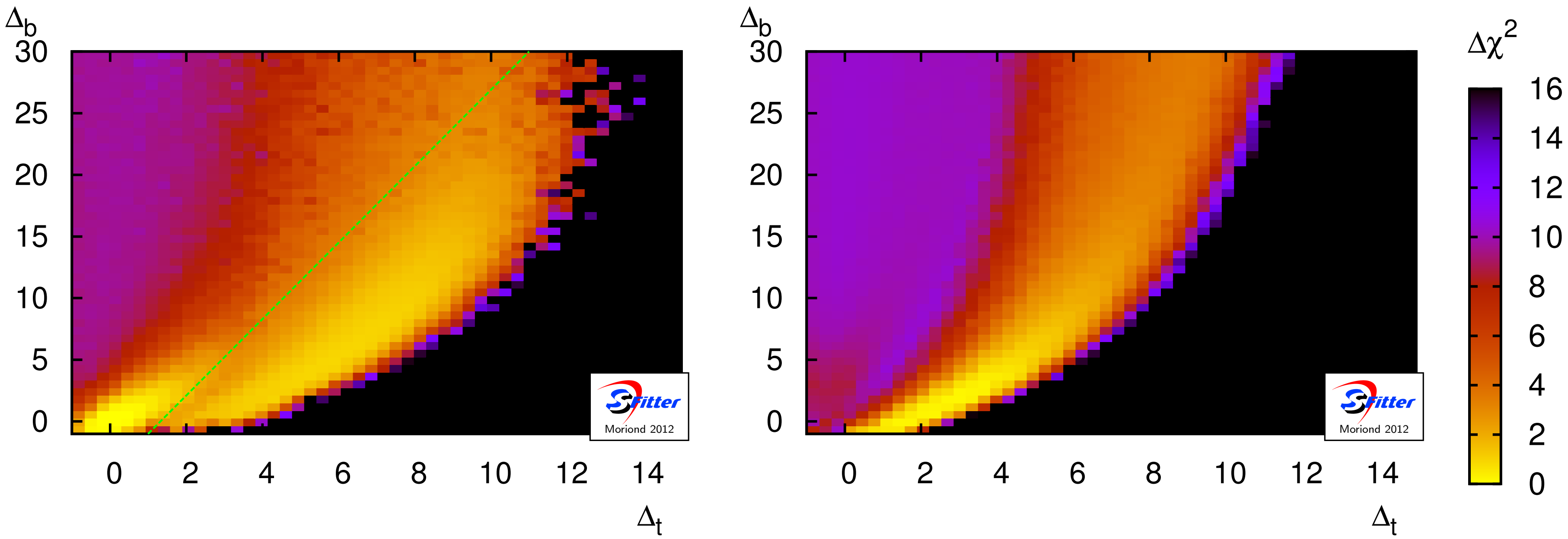
$\Longrightarrow$ Minimum at $-\alpha$ and $\pi - \alpha$

Conclusions

- LHC has first hints for a Higgs boson at a mass around 125 GeV
- Given a resonance in $\gamma\gamma$ channel, new particle is most likely spin 0
- Measurement of Higgs couplings will be most important task after discovery can be claimed
- Present statistics is too low for significant statements on Higgs couplings. Huge improvements expected in the future
- VBF production and $H \to ZZ \to llll$ will be important to measure the tensor structure of the HVV vertex

Secondary Solution – Backup

SM expectation Data



green line: split of primary and secondary SM solution

- large top-Yukawa coupling requires large bottom-Yukawa coupling
  $\longrightarrow$ Enhancement in gluon-fusion counter-balanced by reduced branching ratio
- $\Delta_b \sim 30 \longrightarrow \Gamma_H \sim 2$ GeV $\longrightarrow$ still fine