Higgs Physics at the LHC

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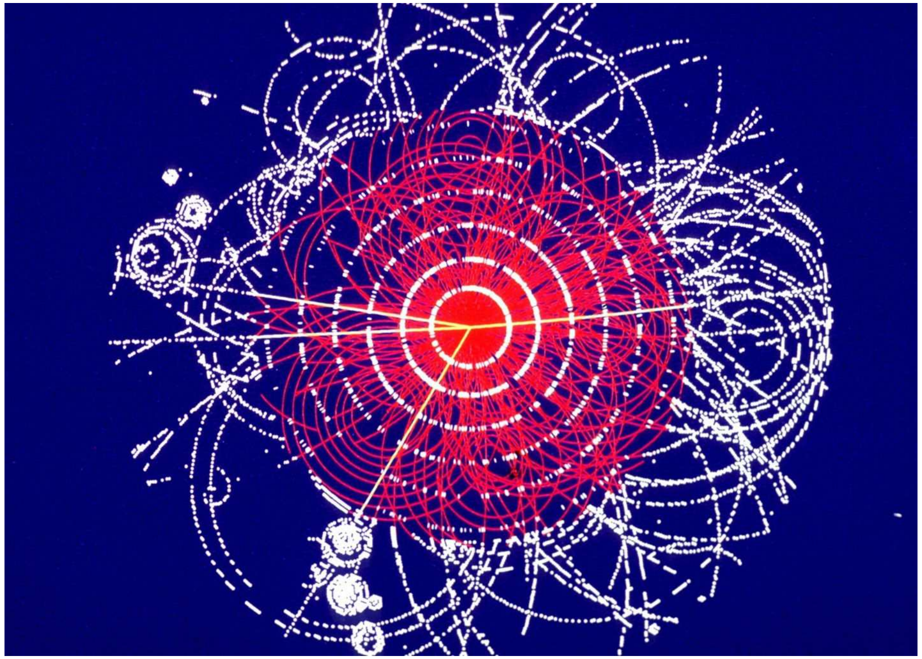
- Standard Search Channels
- Theoretical Precision
- Coupling Measurements
- CP properties
- Conclusions



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 $\Phi^\dagger \rightarrow (0, \frac{v+H}{\sqrt{2}})$

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

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

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

Higgs coupling to gauge bosons

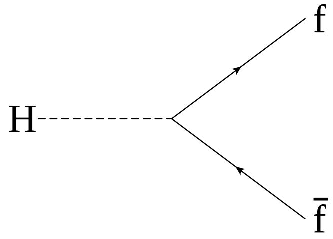
Kinetic energy term of Higgs doublet field:

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

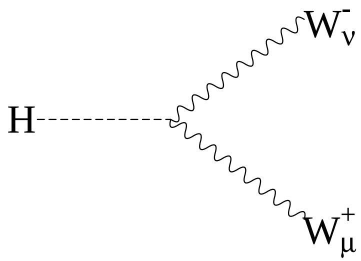
- W, Z mass generation: $m_W^2 = \left(\frac{gv}{2}\right)^2$, $m_Z^2 = \frac{(g^2+g'^2)v^2}{4}$
- WWH and ZZH couplings are generated
- Higgs couples propotional to mass: coupling strength $= 2\,m_V^2/v \sim g^2\,v$ within SM

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

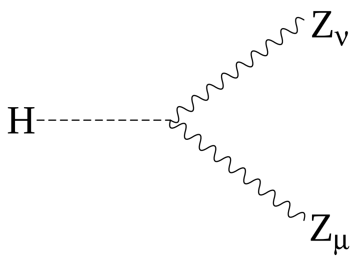
Feynman rules



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



$$i g\, m_W\, g_{\mu\nu}$$



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

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

The MSSM Higgs sector

The SM uses the conjugate field $\Phi_c = i\sigma_2\Phi^*$ to generate down quark and lepton masses. In supersymmetric models this must be an independent field

$$\begin{aligned}\mathcal{L}_{\text{Yukawa}} &= -\Gamma_d \bar{Q}_L \Phi_1 d_R - \Gamma_e \bar{L}_L \Phi_1 e_R + \text{h.c.} \\ &\quad -\Gamma_u \bar{Q}_L \Phi_2 u_R + \text{h.c.}\end{aligned}$$

Two complex Higgs doublet fields Φ_1 and Φ_2 receive mass and v.e.v.s v_1, v_2 from generalized Higgs potential. Mass eigenstates constructed out of these 8 real fields are

Neutral sector:

2 CP even Higgs bosons: h and H

1 CP odd Higgs boson: A

1 Goldstone boson: χ_0

Charged sector:

charged Higgs bosons: $H^\pm$

charged Goldstone boson: $\chi^\pm$

Goldstone bosons absorbed as longitudinal degrees of freedom of Z, $W^\pm$

Couplings of the MSSM neutral Higgses: h, H, A

Fermions

Two doublet fields Φ_1,Φ_2 mix, two v.e.v's $v_1 = v\cos\beta$, $v_2 = v\sin\beta$:

$$\mathcal{L}_{\text{Yuk.}} = -\Gamma_b \bar{b}_L \Phi_1^0 b_R - \Gamma_t \bar{t}_L \Phi_2^0 u_R + \text{h.c.}$$

$$= -\Gamma_b \bar{b}_L \frac{v_1 + H\cos\alpha - h\sin\alpha + iA\sin\beta}{\sqrt{2}} b_R - \Gamma_t \bar{t}_L \frac{v_2 + H\sin\alpha + h\cos\alpha + iA\cos\beta}{\sqrt{2}} t_R + \ldots$$

Expressed in terms of masses the Yukawa Lagrangian is

$$\mathcal{L}_{\text{Yuk.}} = -\frac{m_b}{v}\bar{b}\left(v + H\frac{\cos\alpha}{\cos\beta} - h\frac{\sin\alpha}{\cos\beta} - i\gamma_5 A\tan\beta\right) b - \frac{m_t}{v}\bar{t}\left(v + H\frac{\sin\alpha}{\sin\beta} + h\frac{\cos\alpha}{\sin\beta} - i\gamma_5 A\cot\beta\right) t$$

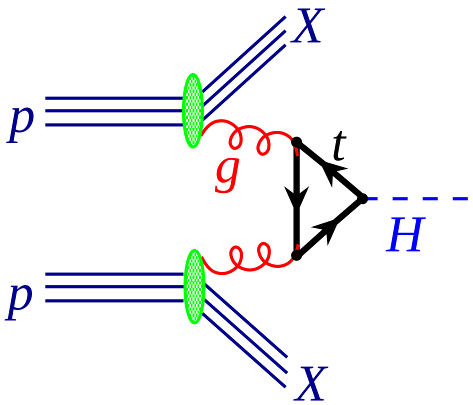
$\Longrightarrow$ coupling factors compared to SM hff coupling $-i\, m_f/v$

Gauge Bosons

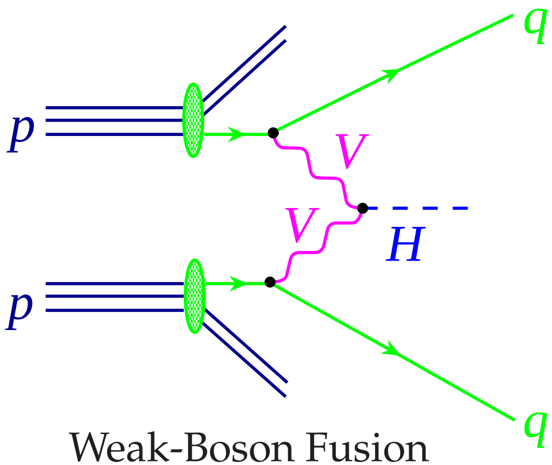
extra coupling factors for hVV and HVV couplings as compared to SM

$$hVV \sim \sin(\beta - \alpha) \qquad HVV \sim \cos(\beta - \alpha)$$

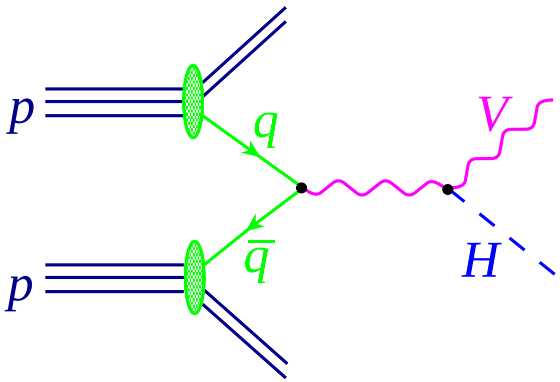
Higgs Production Modes at LHC



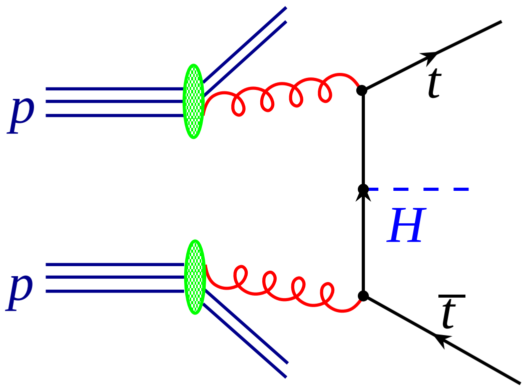
Gluon fusion



Weak-Boson Fusion

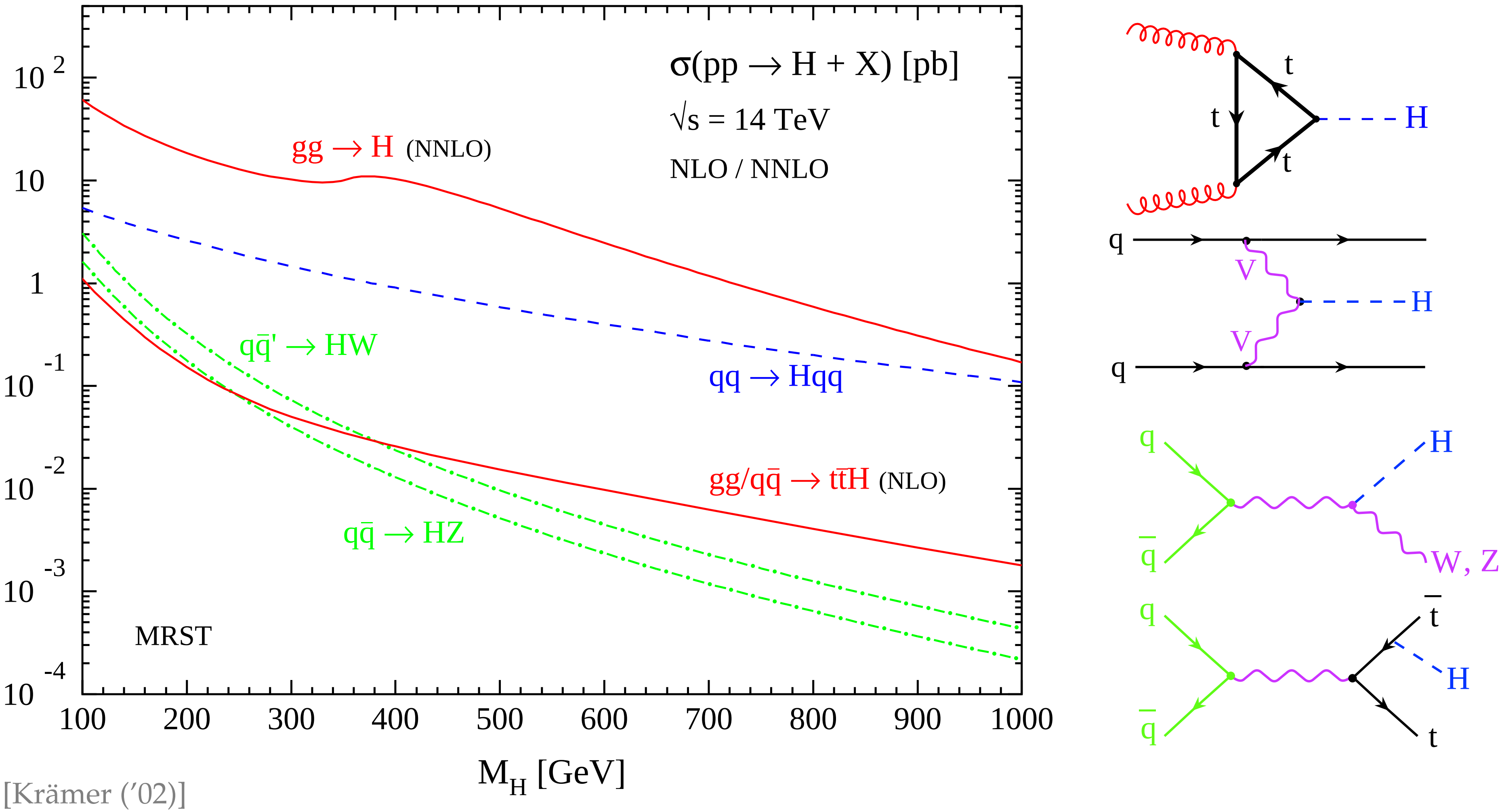


Higgs Strahlung



$t\bar{t}H$

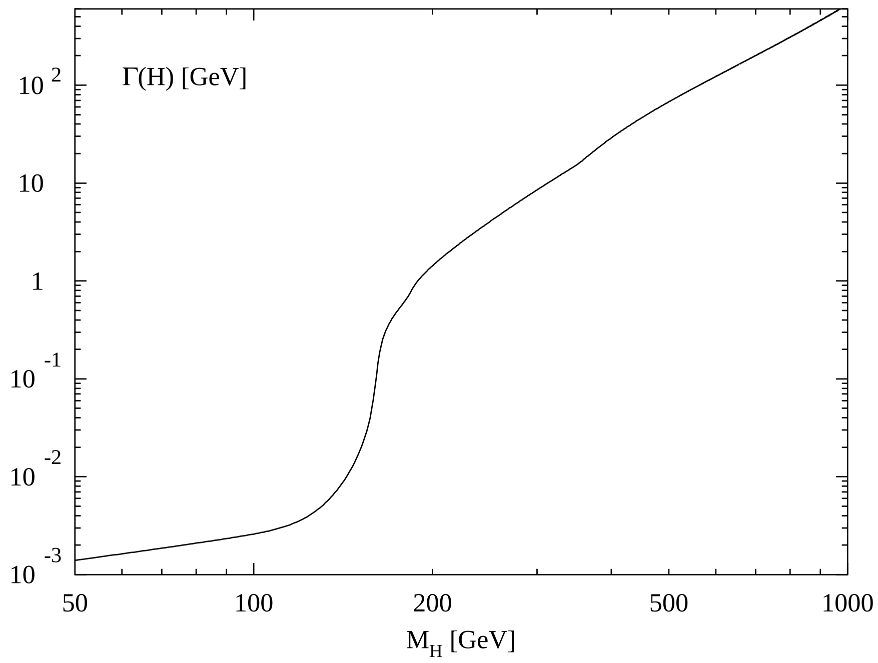
Total SM Higgs cross sections at the LHC

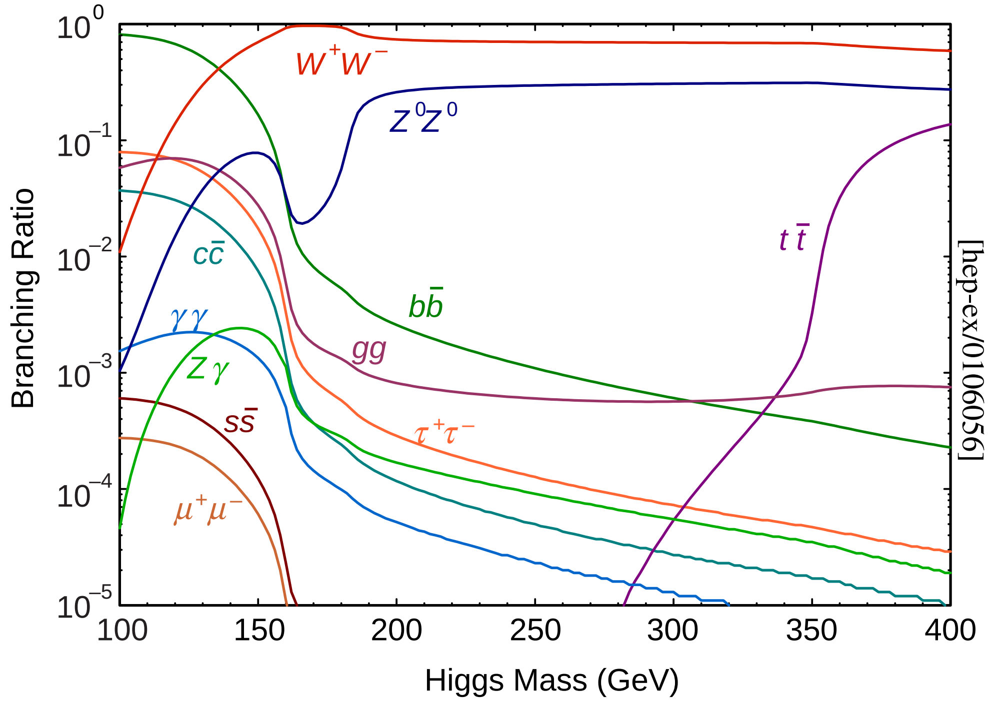


[Krämer ('02)]

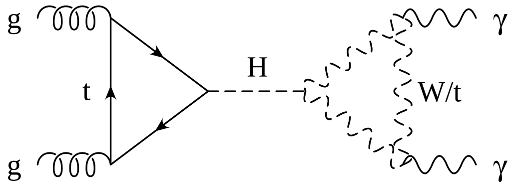
Decay of the SM Higgs

Higgs decay width and branching fractions within the SM





$H \to \gamma\gamma$



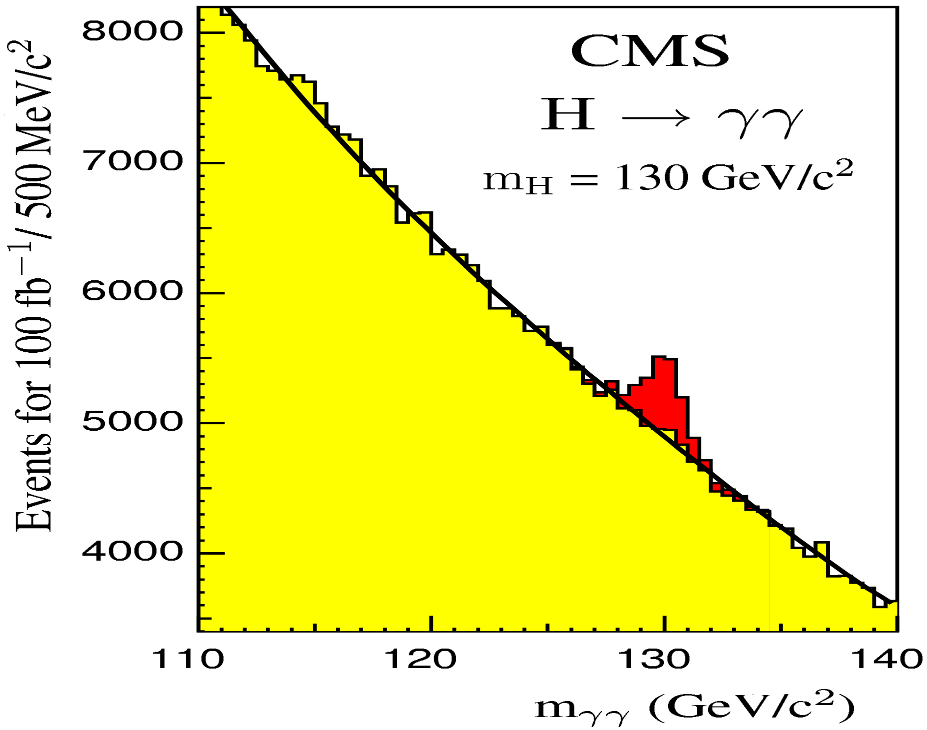
✗ $\mathrm{BR}(H \to \gamma\gamma) \approx 10^{-3}$

✗ large backgrounds from $q\bar{q} \to \gamma\gamma$ and $gg \to \gamma\gamma$

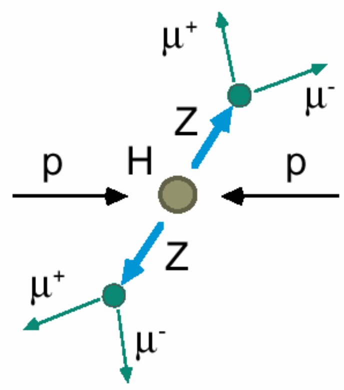
✓ but CMS and ATLAS will have excellent photon-energy resolution (order of 1%)

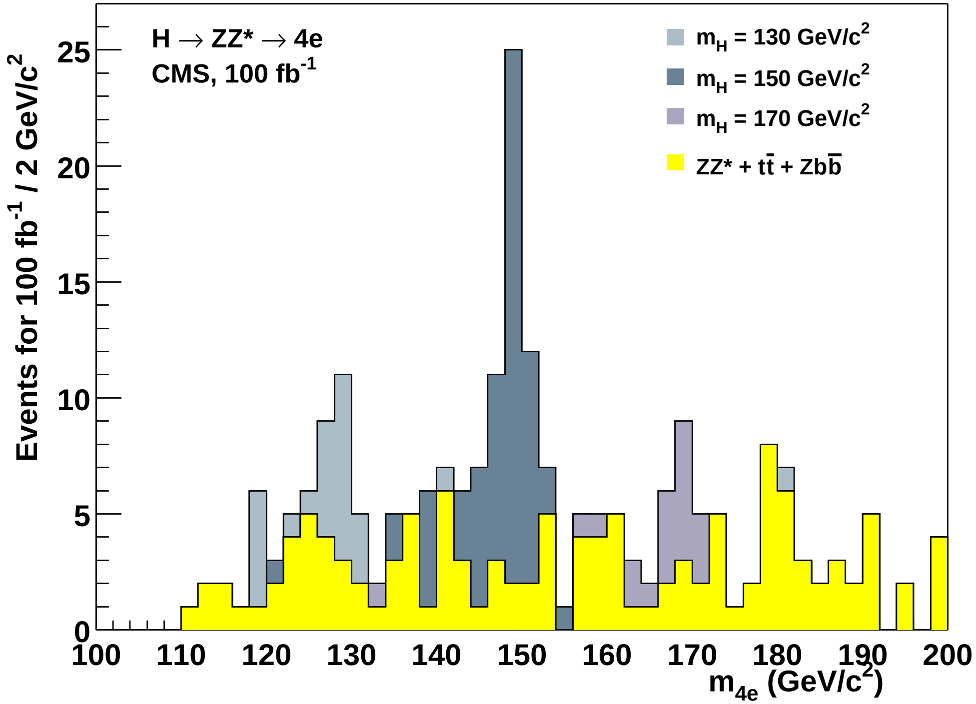
✓ Look for a narrow $\gamma\gamma$ invariant mass peak

✓ extrapolate background into the signal region from sidebands.



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





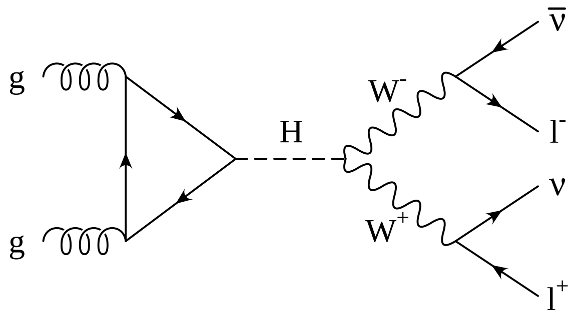
✓ invariant mass of the charged leptons fully reconstructed

For $m_H \approx 0.6$–1 TeV, use the “silver-plated” mode $H \to ZZ \to \nu\bar{\nu}\ell^+\ell^-$

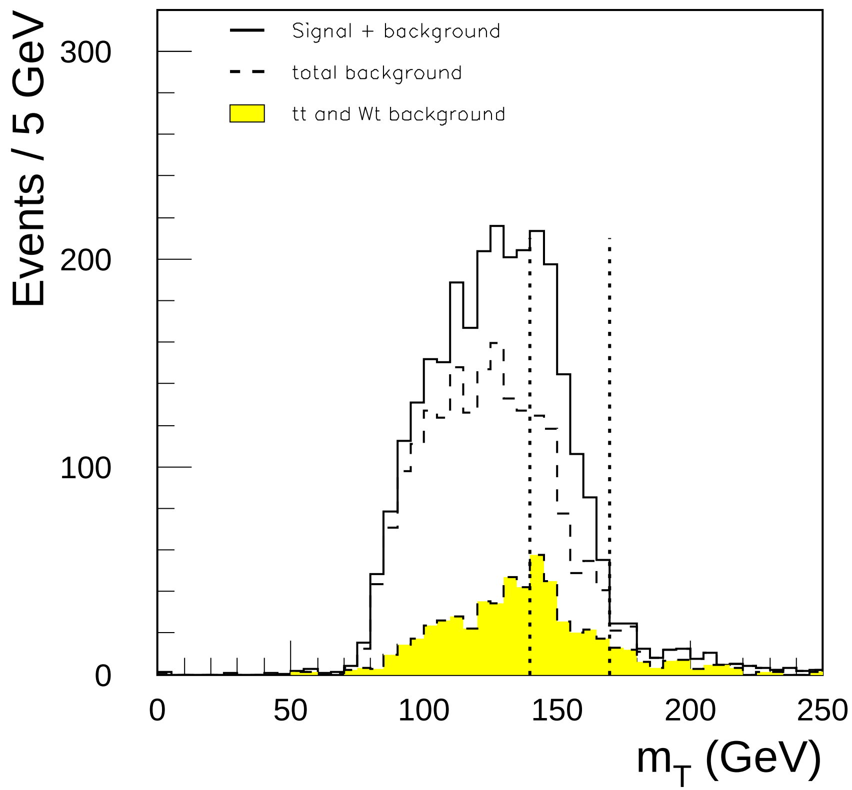
✓ $\mathrm{BR}(H \to \nu\bar{\nu}\ell^+\ell^-) = 6\ \mathrm{BR}(H \to \ell^+\ell^-\ell^+\ell^-)$

✓ the large missing E_T allows a measurement of the transverse mass

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



ATLAS TDR



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

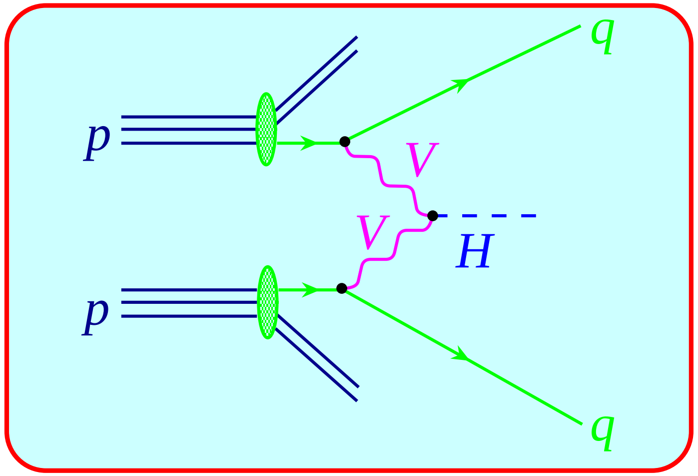
$$m_T = \sqrt{2\, p_T^{\ell\ell}\, \not{E}_T \,(1 - \cos(\Delta\Phi))}$$

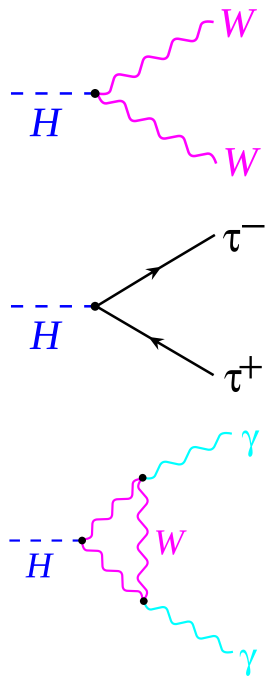
- ✗ background and signal have similar shape $\Longrightarrow$ must know the background normalization precisely

$m_H = 170\,\mathrm{GeV}$

integrated luminosity = 20 fb^{-1}

Weak Boson Fusion





$m_H > 120$ GeV

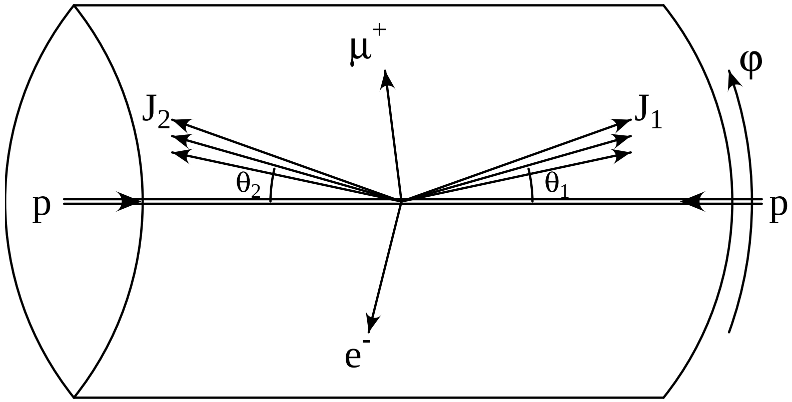
$m_H < 140$ GeV

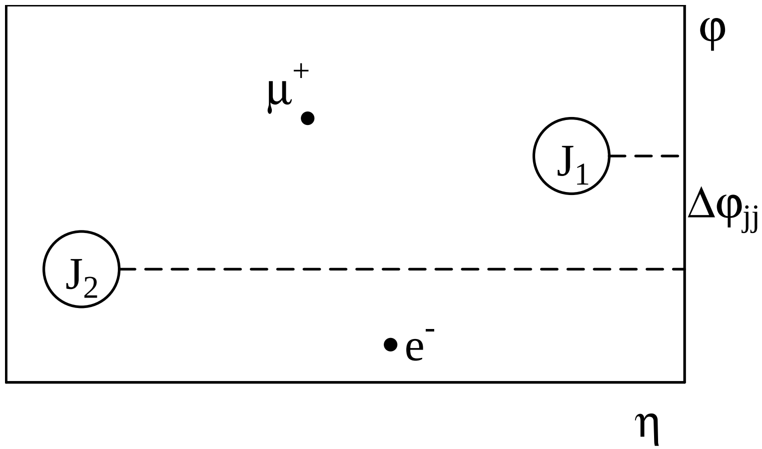
$m_H < 150$ GeV

[Eboli, Hagiwara, Kauer, Plehn, Rainwater, D.Z. ...]

Most measurements can be performed at the LHC with statistical accuracies on the measured cross sections times decay branching ratios, $\sigma\times$ BR, of order 10% (sometimes even better).

WBF signature





$$\eta = \frac{1}{2} \log \frac{1 + \cos\theta}{1 - \cos\theta}$$

Characteristics:

- energetic jets in the forward and backward directions ($p_T > 20$ GeV)
- Higgs decay products between tagging jets
- Little gluon radiation in the central-rapidity region, due to colorless W/Z exchange (central jet veto: no extra jets with $p_T > 20$ GeV and $|\eta| < 2.5$)

Example: Parton level analysis of $H \to WW$

Kauer, Plehn, Rainwater, D.Z. hep-ph/0012351

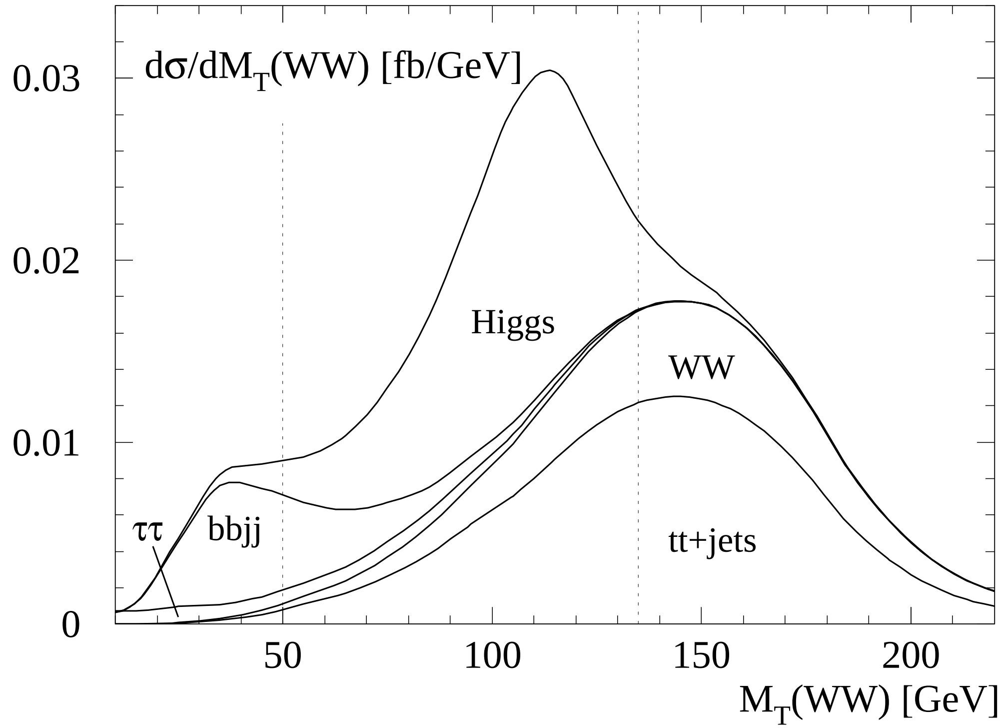
Near threshold: W and W^* almost at rest in Higgs rest frame $\Longrightarrow$ use $m_{ll} \approx m_{\nu\nu}$ for improved transverse mass calculation:

$$E_{T,ll} = \sqrt{\mathbf{p}_{T,ll}^2 + m_{ll}^2}$$

$$\not{E}_T = \sqrt{\not{\mathbf{p}}_T^2 + m_{\nu\nu}^2} \approx \sqrt{\not{\mathbf{p}}_T^2 + m_{ll}^2}$$

$$M_T = \sqrt{(\not{E}_T + E_{T,ll})^2 - (\mathbf{p}_{T,ll} + \not{\mathbf{p}}_T)^2}$$

Observe Jacobian peak below $M_T = m_H$

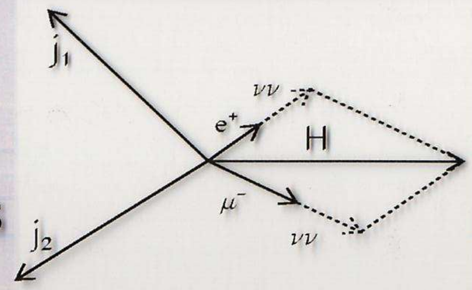


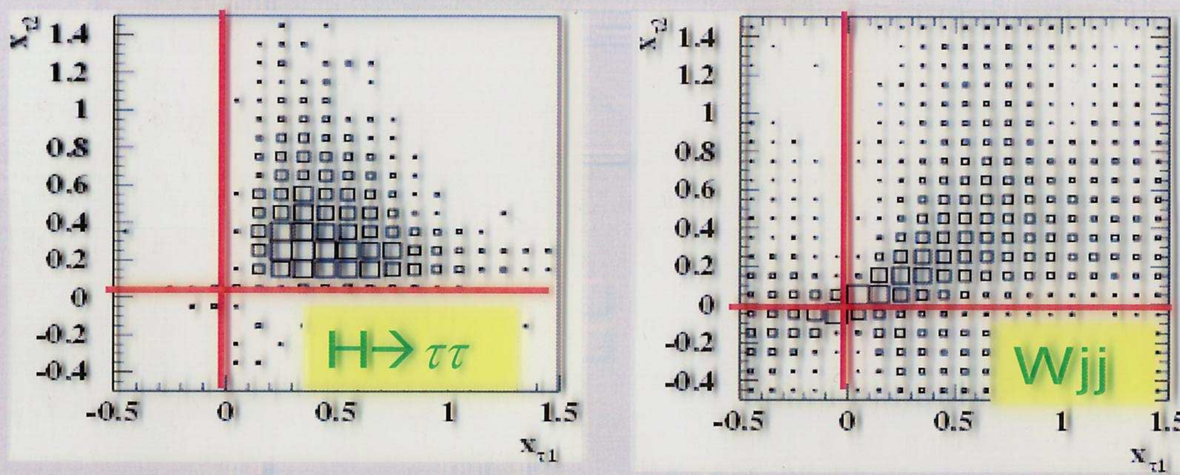
Transverse mass distribution for $m_H = 115$ GeV and $H \to WW^* \to e^{\pm}\mu^{\mp}\not{p}_T$

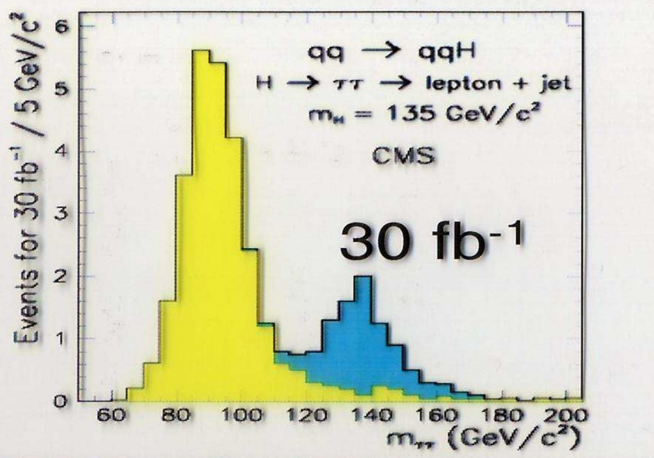
Weak Boson Fusion: $H \to \tau\tau$

Mass can be reconstructed in collinear approximation

x_τ = momentum fraction carried by tau decay products







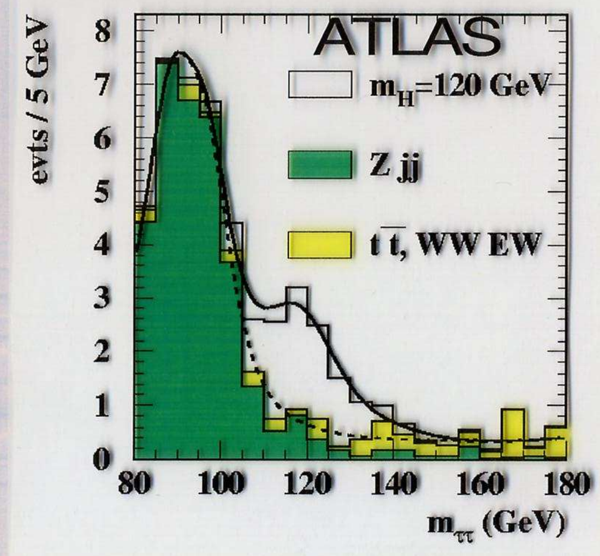
σ_M = 11 to 12 GeV

★significance > 5 for 30 fb^{-1} and M_H=110 to 140 GeV ($\tau\tau \to e\mu$, $\tau\tau \to ll$, $\tau\tau \to l$ had)

★background estimate: ~10%

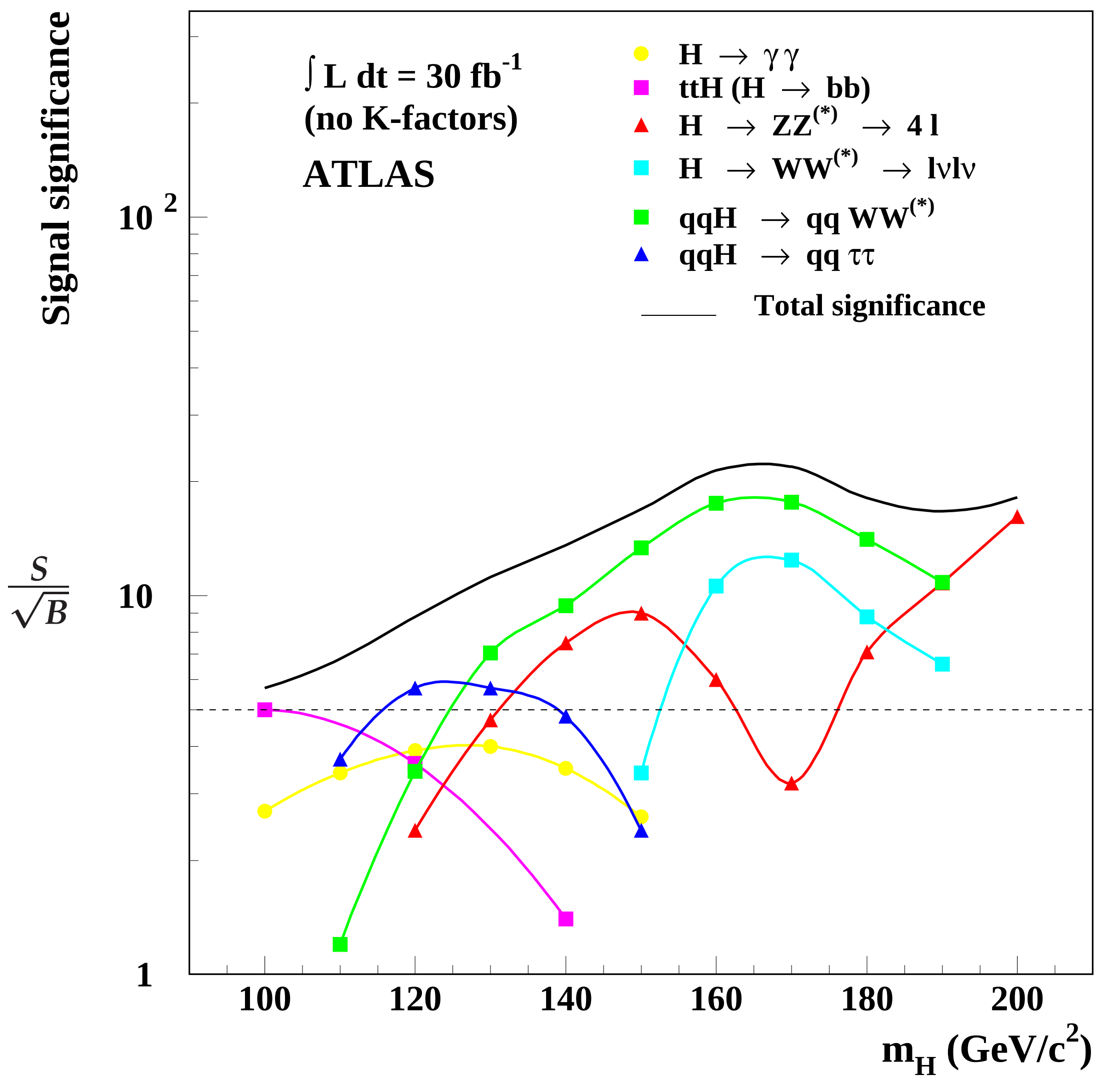
for M_H>125 GeV from side bands

for M_H>125 GeV from normalisation of $Z \to \tau\tau$ peak



$H \to \tau\tau \to e\mu$ 30 fb^{-1}

Higgs discovery potential



Early measurements for Higgs physics

Discovery of Higgs boson may take 5–10 fb^{-1}, perhaps more . . .
It certainly requires a well understood and calibrated detector

- optimistic case: $m_H \approx 160$ GeV, $H \to WW$
- challenging case: $m_H \approx 120$ GeV, $H\tau\tau$ and Hbb couplings substantially enhanced by large $\tan\beta$ effects

$\Longrightarrow$ no visible $H \to \gamma\gamma$, $H \to ZZ$ or $H \to WW$ signals

$\Longrightarrow$ must search in VBF channel $qq \to qqH$, $H \to \tau\tau$ or in $t\bar{t}H$, $H \to b\bar{b}$

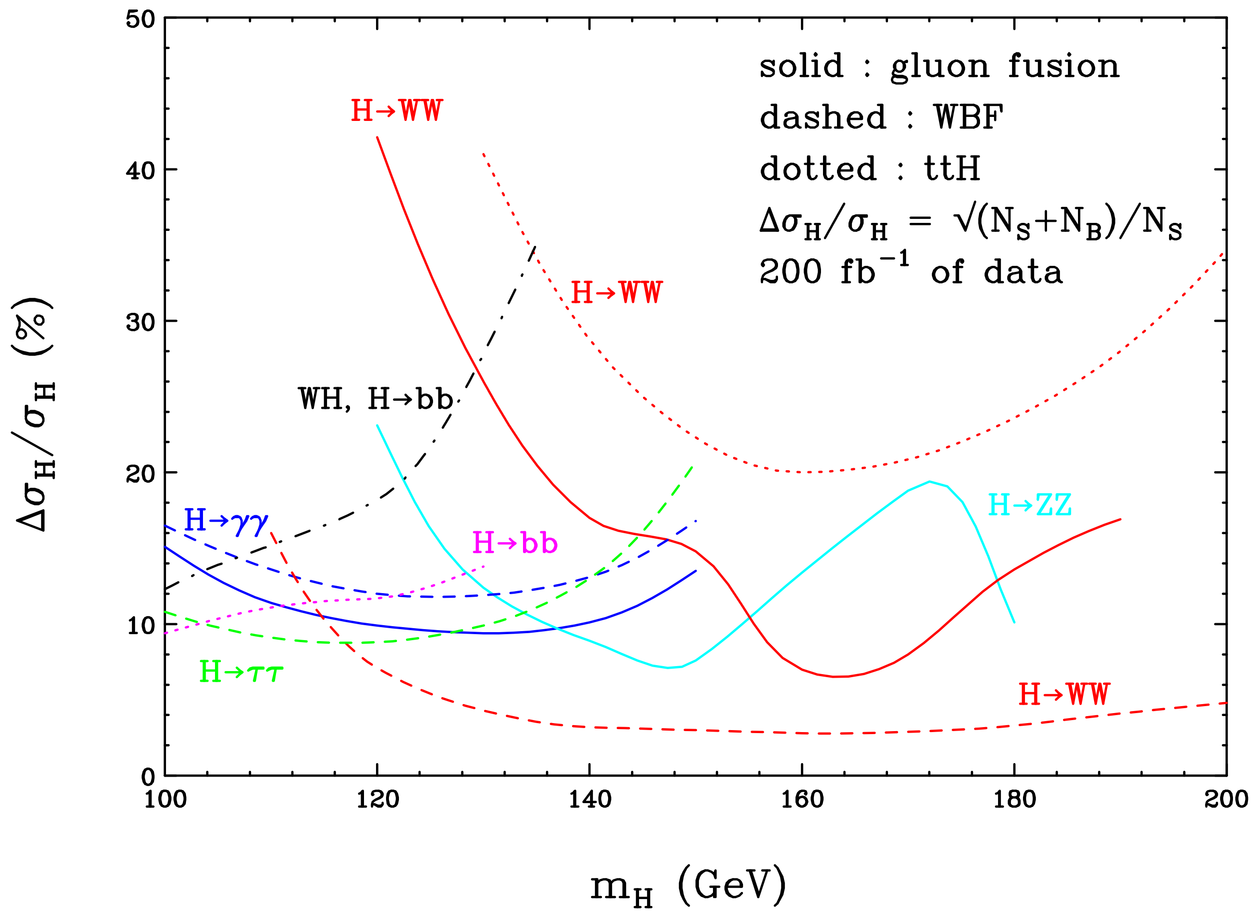
Early data will settle many open questions

- underlying event structure and pile-up at high luminosity

$\Longrightarrow$ does forward jet tagging work at high luminosity?

- measure dominant backgrounds: $t\bar{t}$, jets, DY+jets, . . .
- study actual event characteristics

Statistical and systematic errors at LHC



Assumed errors in fits to couplings:

- QCD/PDF uncertainties
  - $\pm5\%$ for WBF
  - $\pm15\%$ for gluon fusion
- luminosity/acceptance uncertainties
  - $\pm5\%$

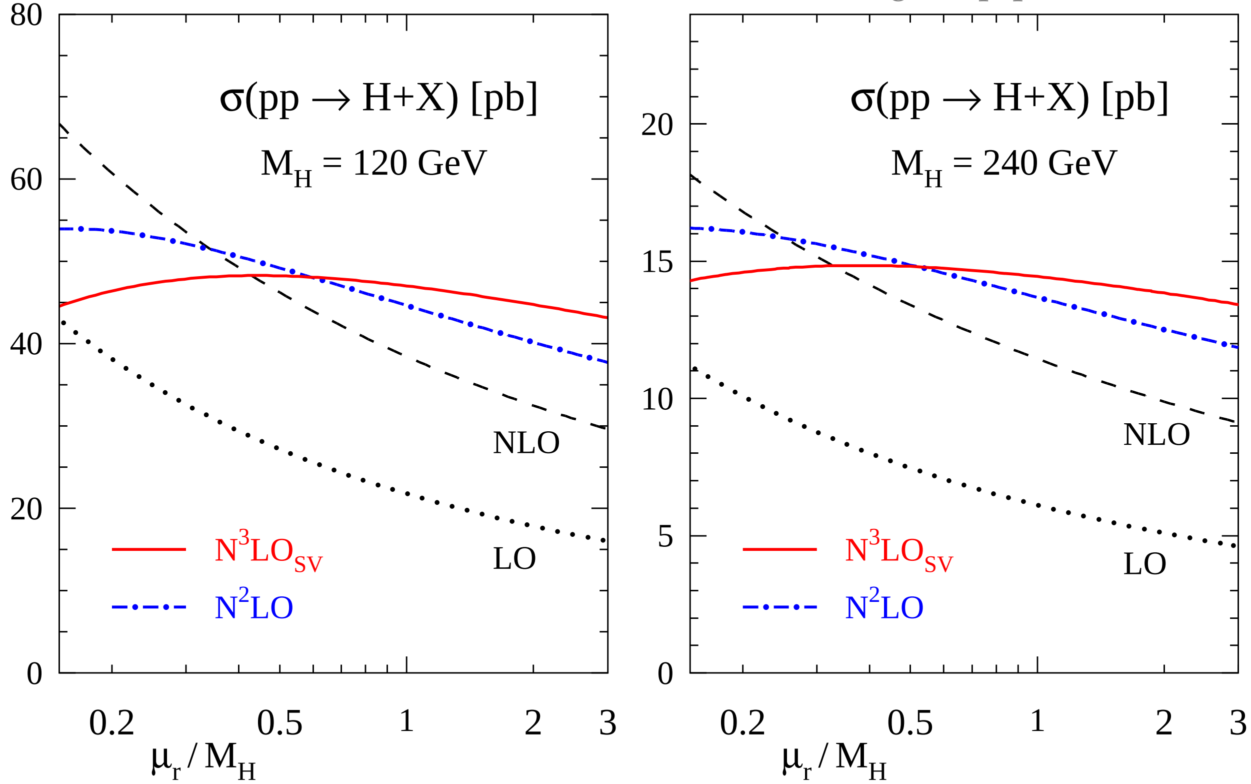
QCD corrections for Higgs production

Measurement of partial widths at 10–20% level or couplings at 5–10% level requires predictions of SM production cross sections at 10% level or better
$\Longrightarrow$ need QCD corrections to production cross sections. Much work in recent years

- $gg \to H$ (all but NLO in $m_t \to \infty$ limit)
  - NLO for finite m_t: Graudenz, Spira, Zerwas (1993)
  - NNLO: Harlander, Kilgore (2001); Anastasiou, Melnikov (2002); Ravindran, Smith, van Neerven (2003)
  - NNLL: Catani, de Florian, Grazzini, Nason (2003)
  - N^3LO in soft approximation: Moch, Vogt (2005)
- Hjj by gluon fusion at NLO: Campbell, Ellis, Zanderighi (2005)
- weak boson fusion
  - total cross section at NLO: Han, Willenbrock (1991)
  - distributions at NLO: Figy, Oleari, D.Z (2003); Campbell, Ellis, Berger (2004)
- $\bar{t}tH$ production at NLO: Beenakker et al.; Dawson, Orr, Reina, Wackeroth (2002)
- $\bar{b}bH$ production at NLO: Dittmaier, Krämer, Spira; Dawson et al. (2003)

QCD corrections to $gg \to H$

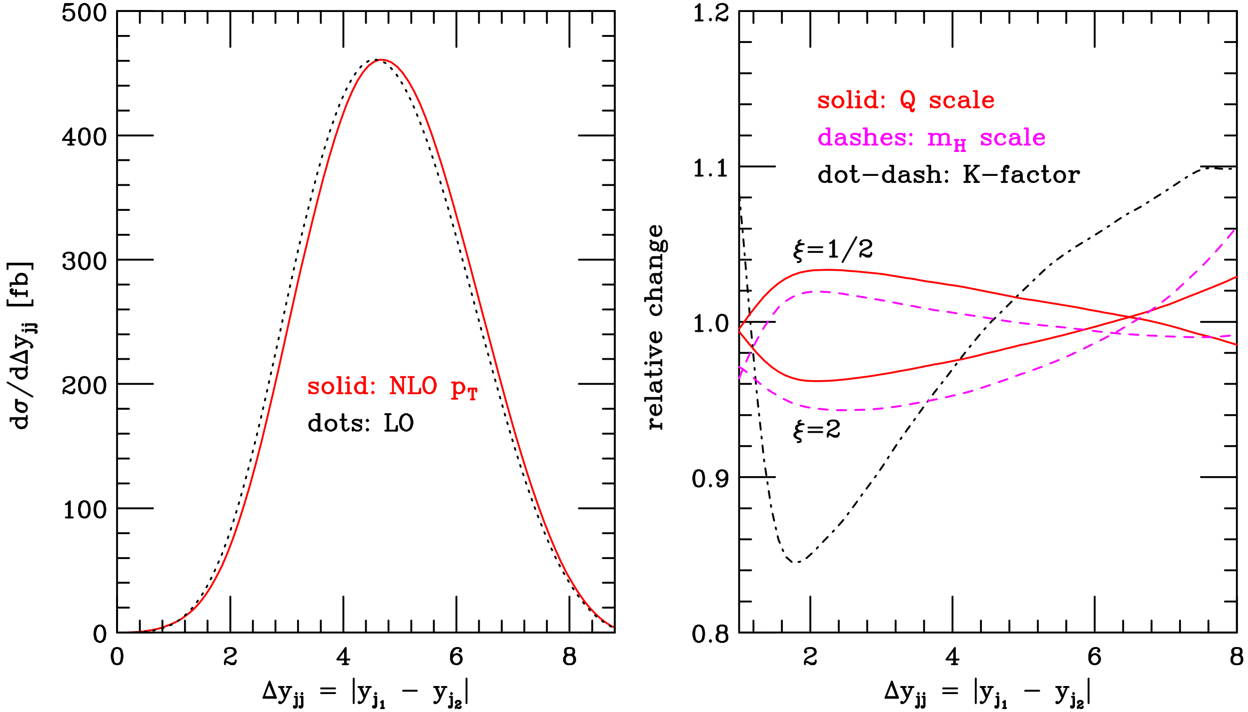
Moch & Vogt, hep-ph/0508265



- ✓ Huge improvement in recent years
- ✓ Remaining scale uncertainty below 10%
- ✓ Uncertainty from gluon pdf $\approx 4 - 7\%$
- ✗ What is K-factor for cross section with cuts? Most problematic: central jet veto against $\bar{t}t$ background for $H \to WW$ search

NLO QCD corrections to VBF

- ✓ Small QCD corrections of order 10%
- ✓ Tiny scale dependence of NLO result
  - $\pm 5\%$ for distributions
  - $< 2\%$ for σ_{total}
- ✓ K-factor is phase space dependent
- ✓ QCD corrections under excellent control
- ✗ Need electroweak corrections for 5% uncertainty



$m_H = 120$ GeV, typical VBF cuts

NLO QCD correction for VBF now available in VBFNLO: Figy, Hankele, Jäger, Klämke, Oleari, DZ, ...
parton level Monte Carlo for Hjj, Wjj, Zjj, W^+W^-jj, $ZZjj$ production at NLO QCD

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:

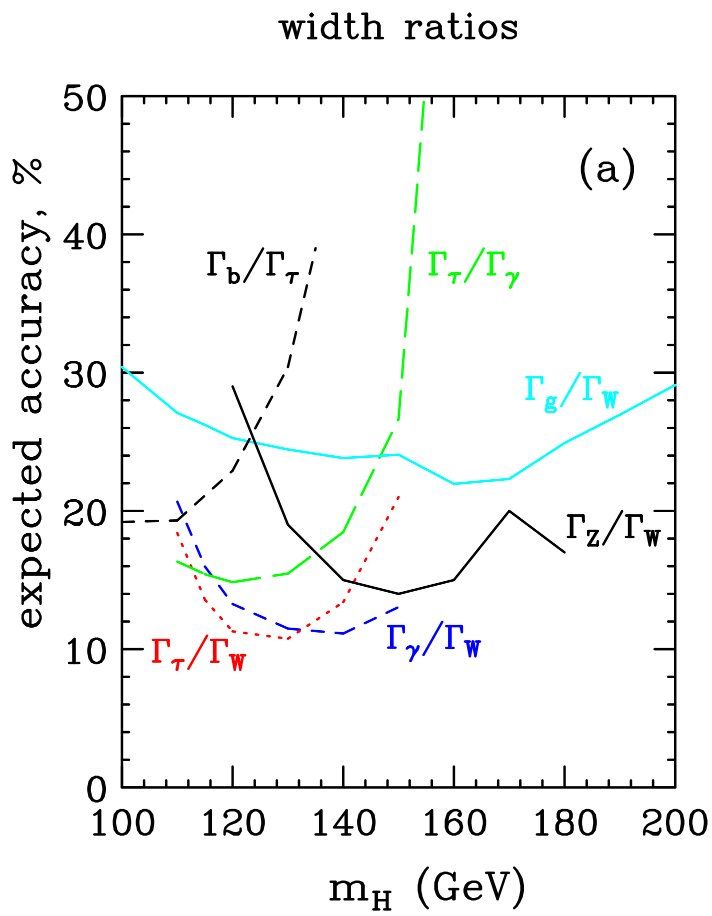
$$f^2 \Gamma > \sum_{obs.} f \Gamma_x \qquad \Longrightarrow \qquad f > \sum_{obs.} \frac{\Gamma_x}{\Gamma} = \sum_{obs.} BR(H \to xx) (= \mathcal{O}(1))$$

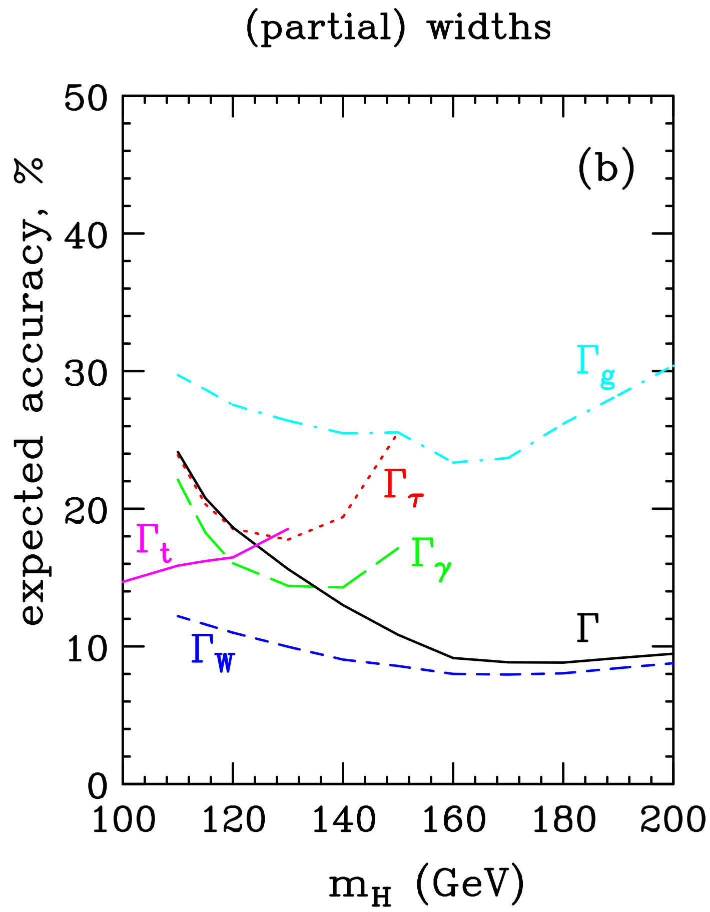
Total width below experimental resolution of Higgs mass peak ($\Delta m = 1 \ldots 20$ GeV)

$$f^2 \Gamma < \Delta m \qquad \Longrightarrow \qquad f < \sqrt{\frac{\Delta m}{\Gamma}} < \mathcal{O}(10 - 40)$$

Fit LHC data within constrained models

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





With 200 fb^{-1} measure partial width with 10–30% errors, couplings with 5–15% errors

Distinguishing the MSSM Higgs sector from the SM

Alternative: compare data to predictions of specific models

Example: m_H^{max} scenario of LEP analyses

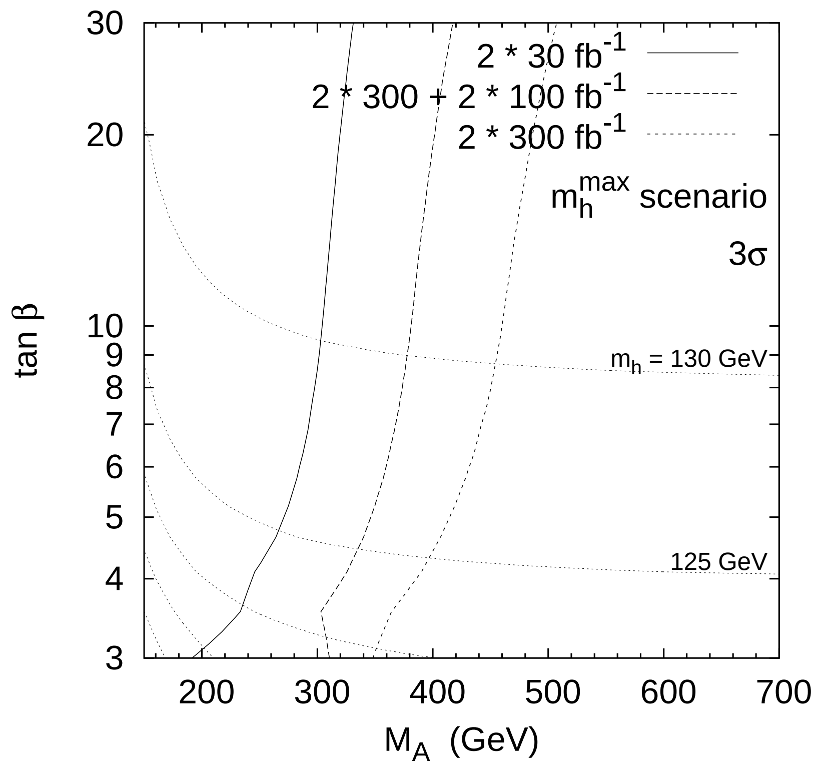
Consider modest m_A:

- decoupling almost complete for hWW and $h\gamma\gamma$ (effective) vertices
- enhanced hbb and $h\tau\tau$ couplings compared to SM increases total width of h

$\Longrightarrow$

- $\approx$ SM rates for $h\rightarrow\tau\tau$ in WBF
- suppressed $h\rightarrow\gamma\gamma$ and $h\rightarrow WW$ rates in WBF

3σ-effects or more at small m_A



Absolute branching ratio measurement from $pp \to ppH$?

- Observe inclusive Higgs mass peak in recoil invariant mass spectrum
- For these events measure fraction with two b jets in central detector or other high branching ratio Higgs signal

Alternative if trigger on central event is required:

- Observe Higgs mass peak in recoil invariant mass spectrum for e.g. bb and WW signatures in central detector
- Ratio of rates gives ratio of partial widths, e.g. Γ_b/Γ_W

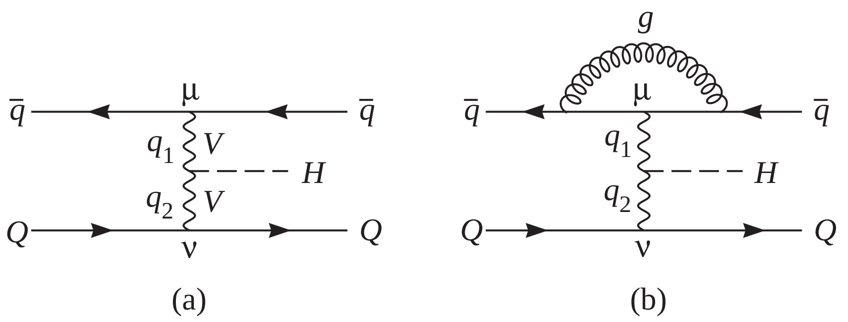
Obtain information on $\Gamma_b = \Gamma(H \to bb)$
$\Longrightarrow$ improved bound on

$$f > \sum_{obs.} \frac{\Gamma_x}{\Gamma} = \sum_{obs.} BR(H \to xx)$$

Note: need ≥ 100 events for competitive statistical errors

Tensor structure of the HVV coupling

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



$$T^{\mu\nu} = a_1 \, g^{\mu\nu} + a_2 \, (q_1 \cdot q_2 \, g^{\mu\nu} - q_1^\nu q_2^\mu) + a_3 \, \varepsilon^{\mu\nu\rho\sigma} \, q_{1\rho} q_{2\sigma}$$

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

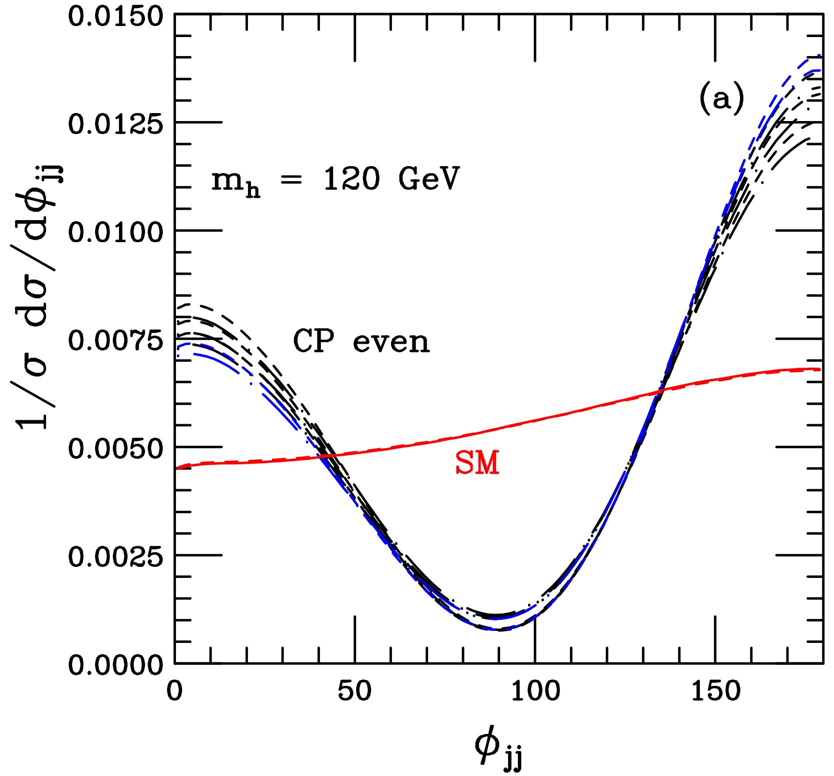
CP even $\quad \mathcal{L}_{eff} \sim H V_{\mu\nu} V^{\mu\nu} \longrightarrow a_2$

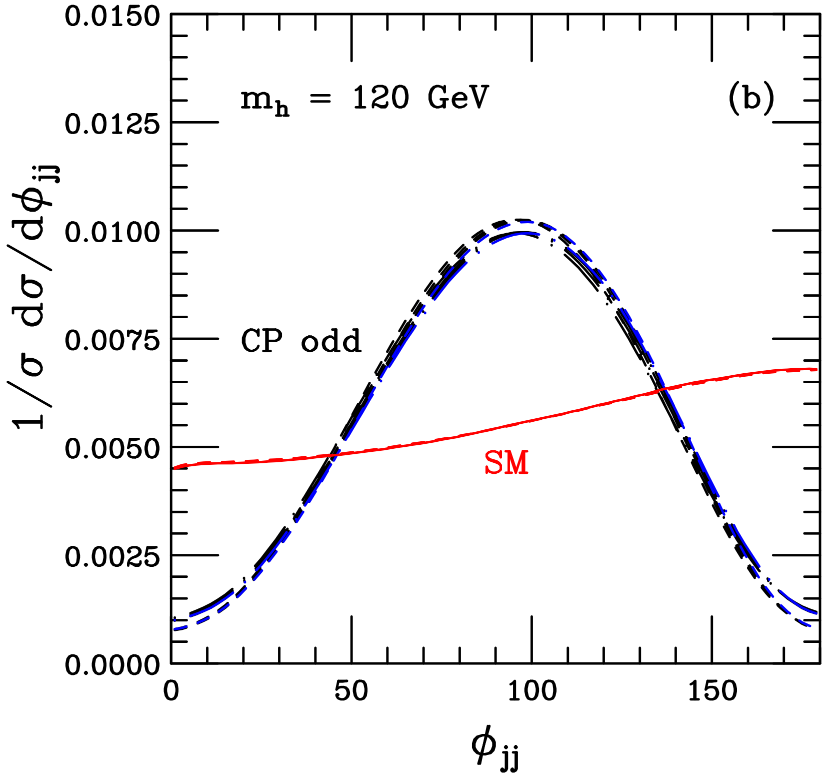
CP odd $\quad \mathcal{L}_{eff} \sim H V_{\mu\nu} \tilde{V}^{\mu\nu} \longrightarrow a_3$

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

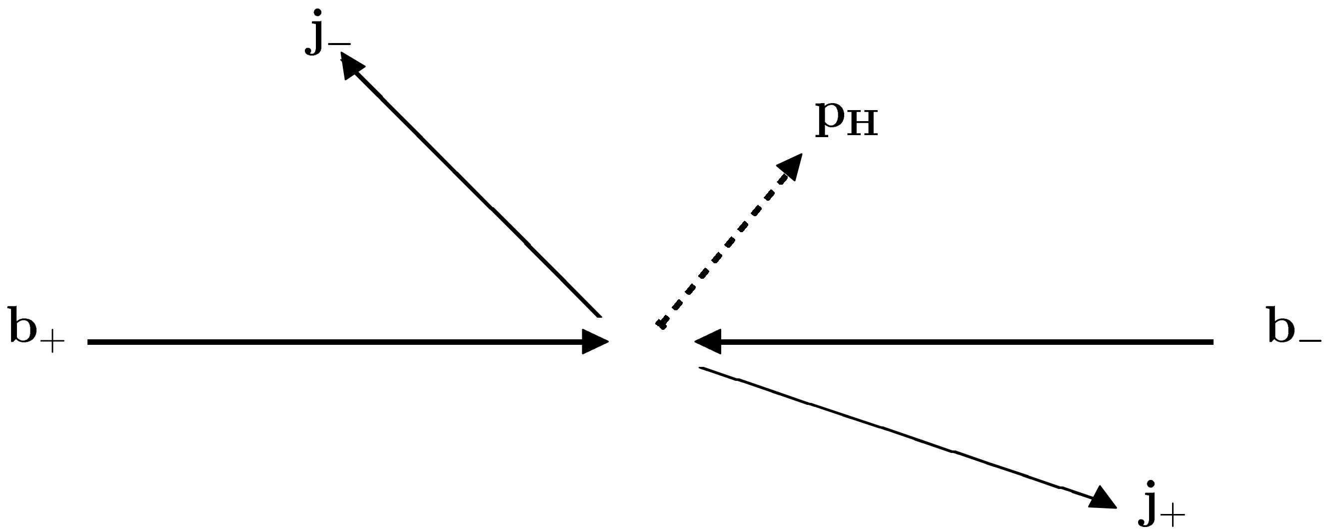




Dip structure at 90° (CP even) or 0/180° (CP odd) only depends on tensor structure of *HVV* vertex. Very little dependence on form factor, LO vs. NLO, Higgs mass etc.

Azimuthal angle distribution and Higgs CP properties

Kinematics of Hjj event:



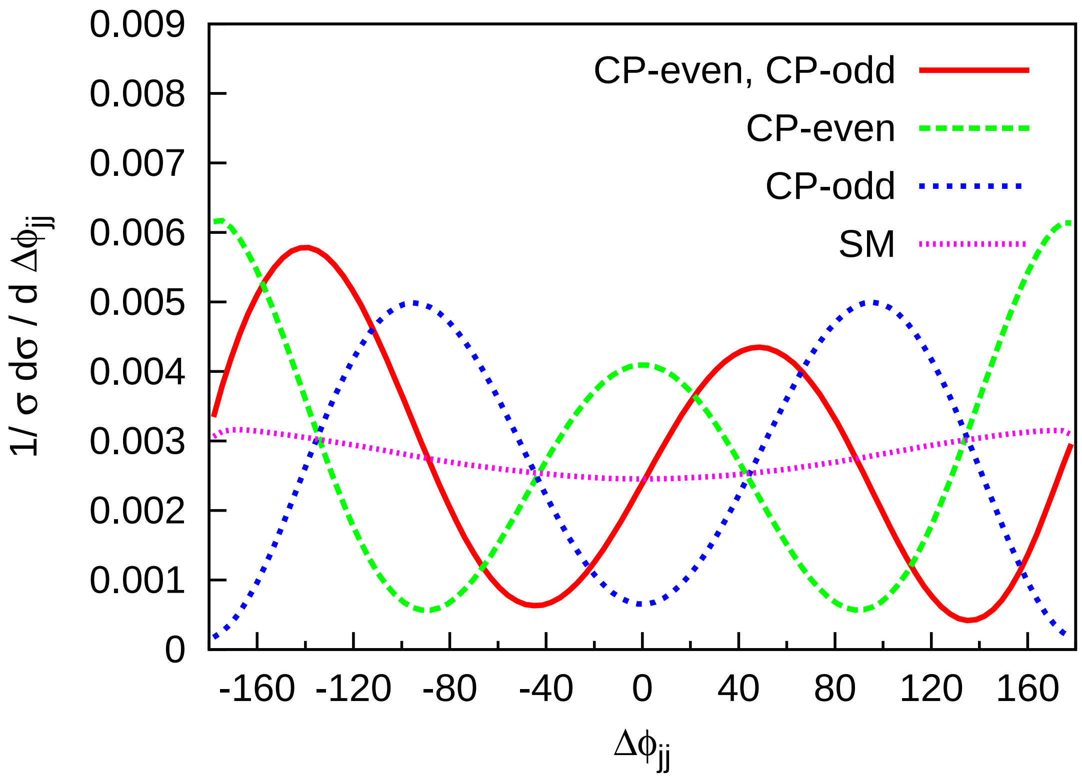
Define azimuthal angle between jet momenta j_+ and j_- via

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

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

Work with Vera Hankele, Gunnar Klämke and Terrance Figy: hep-ph/0609075

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

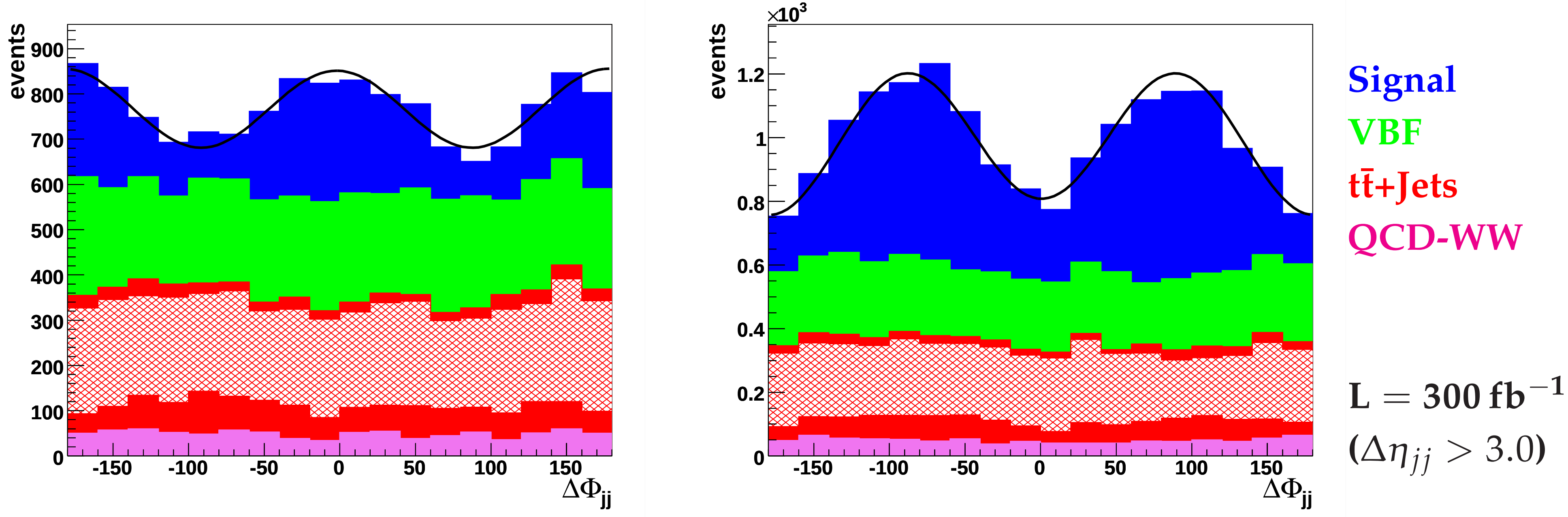
Position of minimum of $\Delta\phi_{jj}$ distribution measures relative size of CP-even and CP-odd couplings. For

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

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

$\Delta\Phi_{jj}$-Distribution in gluon fusion

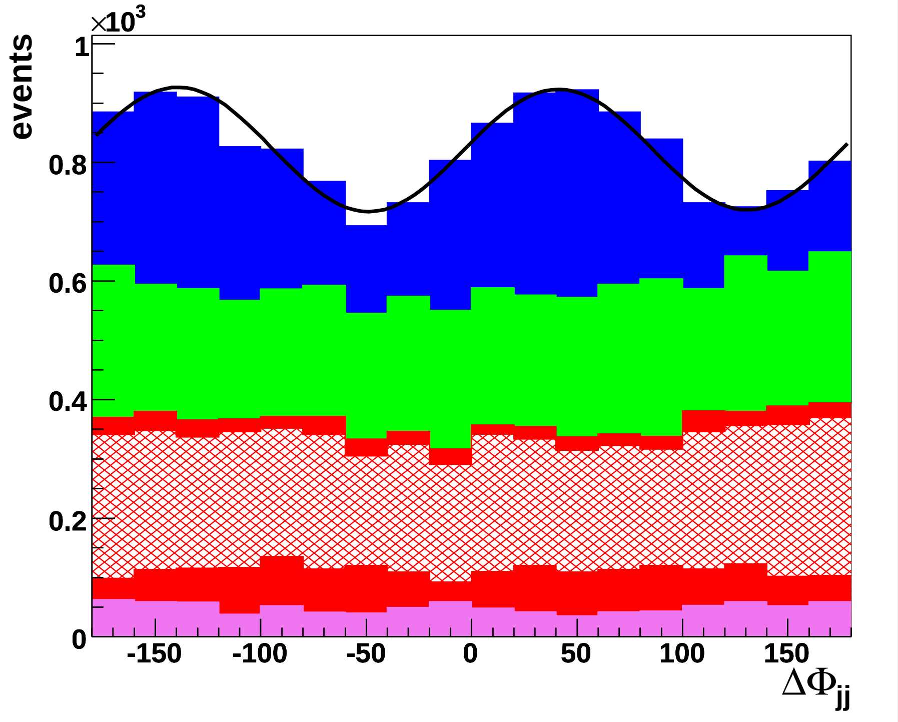
Fit to Φ_{jj}-distribution with function $f(\Delta\Phi) = N(1 + A\cos[2(\Delta\Phi - \Delta\Phi_{max})] - B\cos(\Delta\Phi))$



CP-even	CP-odd
$A = 0.100 \pm 0.039$	$A = 0.199 \pm 0.034$
$\Delta\Phi_{max} = 5.8 \pm 15.3$	$\Delta\Phi_{max} = 93.7 \pm 5.1$

fit of the background only : $A = 0.069 \pm 0.044$ and $\Delta\Phi_{max} = 64 \pm 25$
(mean values of 10 independent fits of data for $L = 30\ fb^{-1}$ each)

$\Delta\Phi_{jj}$-Distribution: CP violating case



CP-mixture: equal CP-even and CP-odd contributions

$$A = 0.153 \pm 0.037$$

$$\Delta\Phi_{max} = 45.6 \pm 7.3$$

Conclusions

- LHC will observe a SM-like Higgs boson in multiple channels, with $5 \ldots 20\%$ statistical errors
  $\Longrightarrow$ great source of information on Higgs couplings
- Higgs boson CP properties and structure of the HVV and Hgg vertices can be obtained from jet-angular correlations in WBF and gluon fusion
- Obtaining direct information on $H \rightarrow bb$ is very difficult. Can $pp \rightarrow ppH$ help?