HIGGS PHYSICS AT THE LHC

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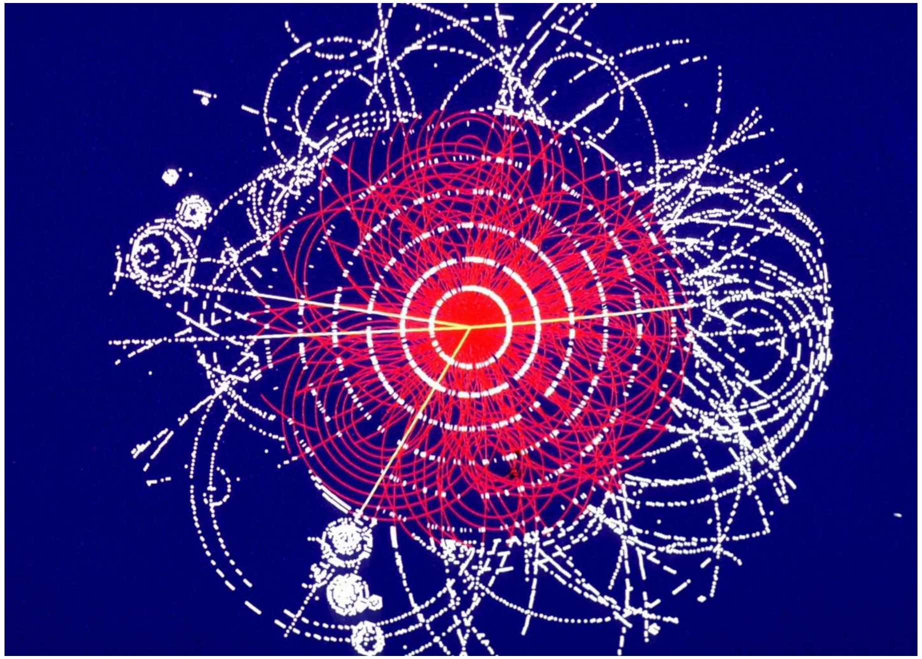
Discoveries of Higgs and Supersymmetry to Pioneer the particle physics in 21st Century
University of Tokyo, Nov. 24–25, 2005

- Goals of Higgs Physics
- SM Channels
- MSSM: H/A and $H^{\pm}$
- Coupling measurements
- QCD Corrections
- HVV vertex structure
- HHH coupling
- 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 $\Phi^\dagger \rightarrow (0, \frac{v+H}{\sqrt{2}})$

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

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

- 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

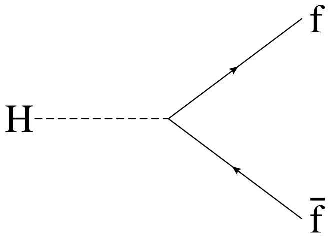
Kinetic energy term of Higgs doublet field:

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

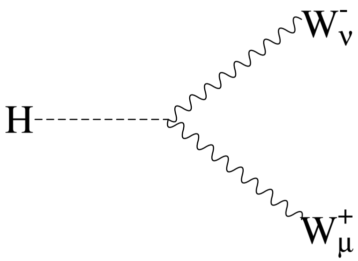
- W, Z mass generation: $m_W^2 = \left(\frac{gv}{2}\right)^2$, $m_Z^2 = \frac{(g^2+g'^2)v^2}{4}$
- WWH and ZZH couplings are generated
- Higgs couples propotional to mass: coupling strength $= 2\,m_V^2/v$ within SM

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

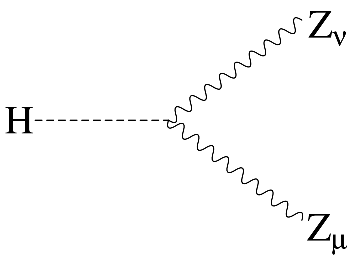
Feynman rules



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



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



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

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

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 Higgses

Fermions

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

$$\begin{aligned}\mathcal{L}_{\text{Yuk.}} &= -\Gamma_b \bar{b}_L \Phi_1^0 b_R - \Gamma_t \bar{t}_L \Phi_2^0 u_R + \text{h.c.} \\ &= -\Gamma_b \bar{b}_L \frac{v_1 + H\cos\alpha - h\sin\alpha + iA\,\sin\beta}{\sqrt{2}} b_R - \Gamma_t \bar{t}_L \frac{v_2 + H\sin\alpha + h\cos\alpha + iA\,\cos\beta}{\sqrt{2}} t_R + \ldots\end{aligned}$$

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

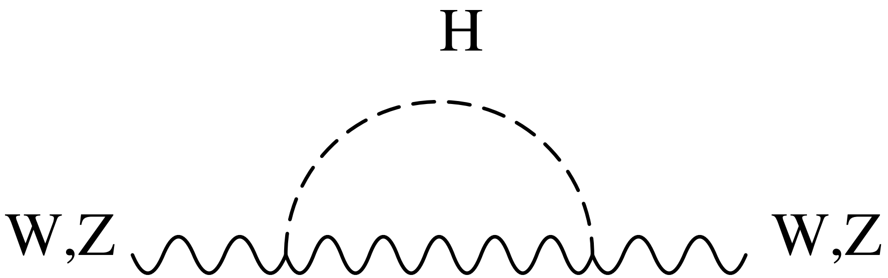
extra coupling factors for hVV and HVV couplings as compared to SM

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

Clues to the Higgs boson mass: SM case

Higgs mass is largely unconstrained by theory $\Longrightarrow$ need experimental input

Electroweak precision data from LEP, SLC, m_W, m_t, ...



SM predictions for observables depend logarithmically on Higgs mass

$$\sim \frac{\alpha}{\pi} \log \frac{m_H^2}{m_W^2}$$

Data require small such contribution

$$\Longrightarrow m_H \approx \text{ order } m_Z$$

SM Higgs mass fit to EW precision data

$$m_H = 91^{+45}_{-32} \text{ GeV}$$

Including theory uncertainty

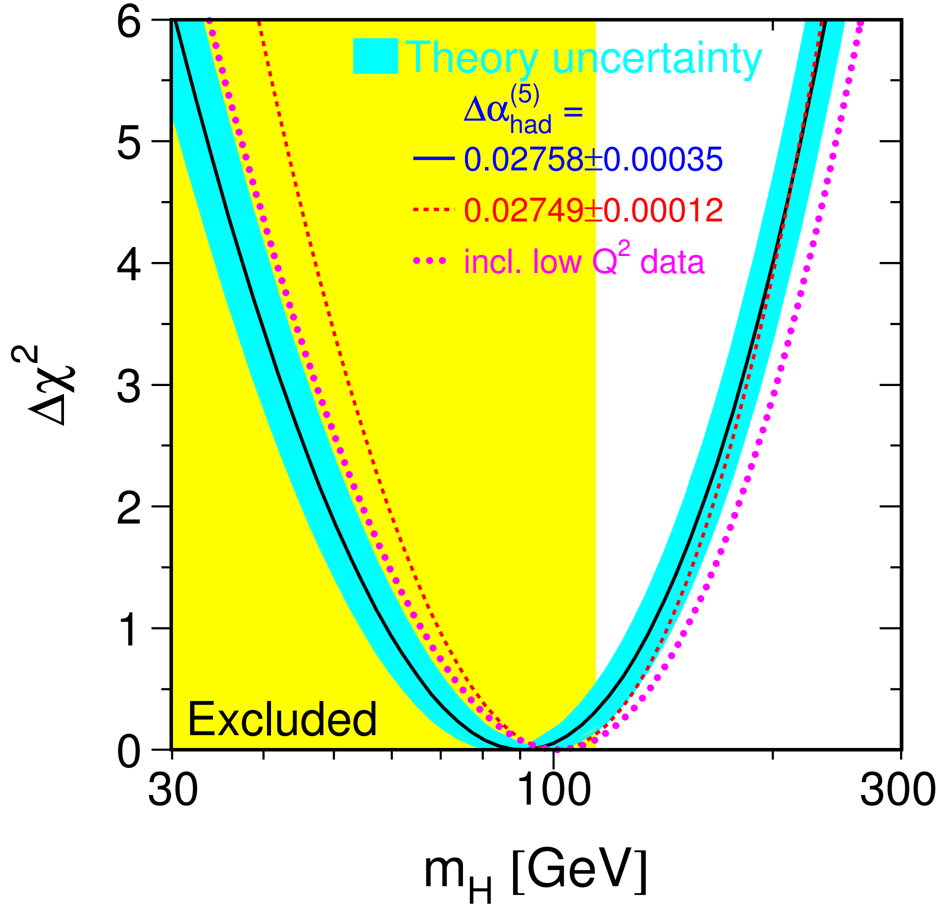
$$m_H < 186 \text{ GeV} \quad (95\% \text{ CL})$$

Does not include
Direct search limit from LEP

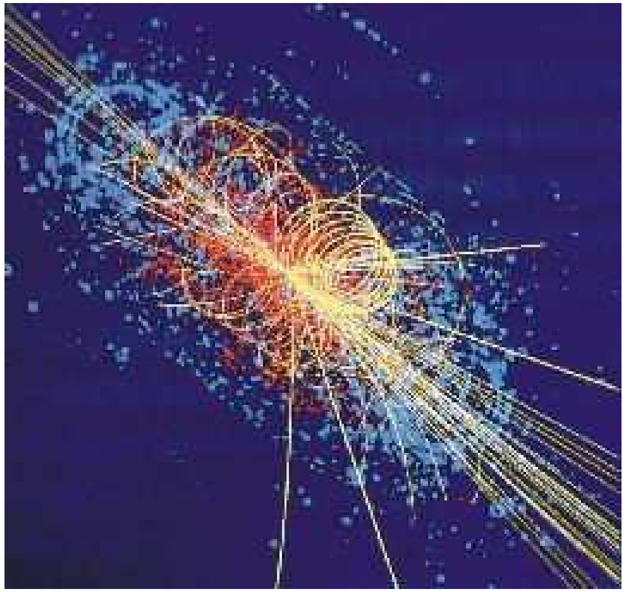
$$m_H > 114 \text{ GeV} \quad (95\% \text{ CL})$$

Renormalize probability for
$m_H > 114$ GeV to 100%:

$$m_H < 219 \text{ GeV} \quad (95\% \text{ CL})$$



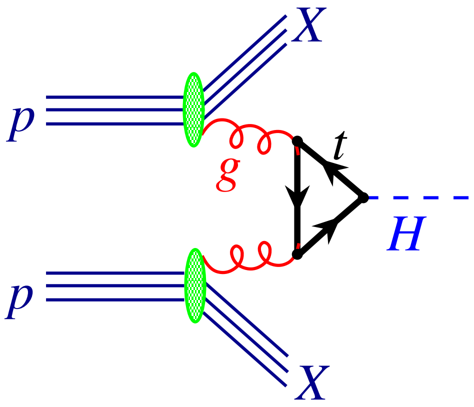
Higgs boson channels at LHC



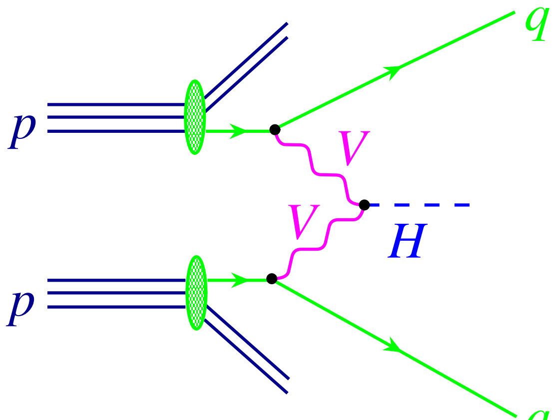
Two steps

- Production of the Higgs boson
- Detection of the decay products of the Higgs boson and identification of the events

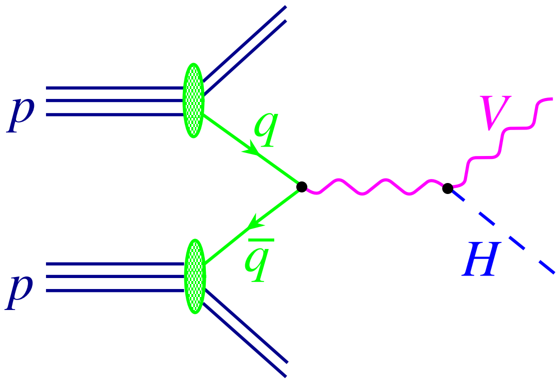
Production Modes



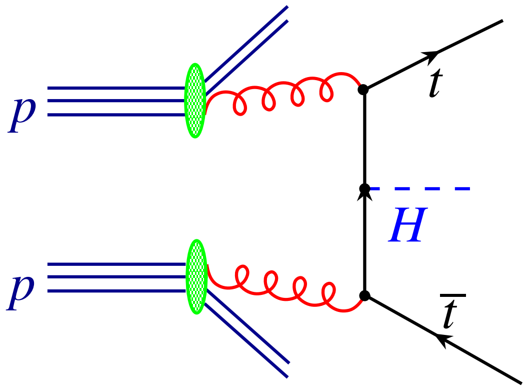
Gluon fusion



Weak-Boson Fusion

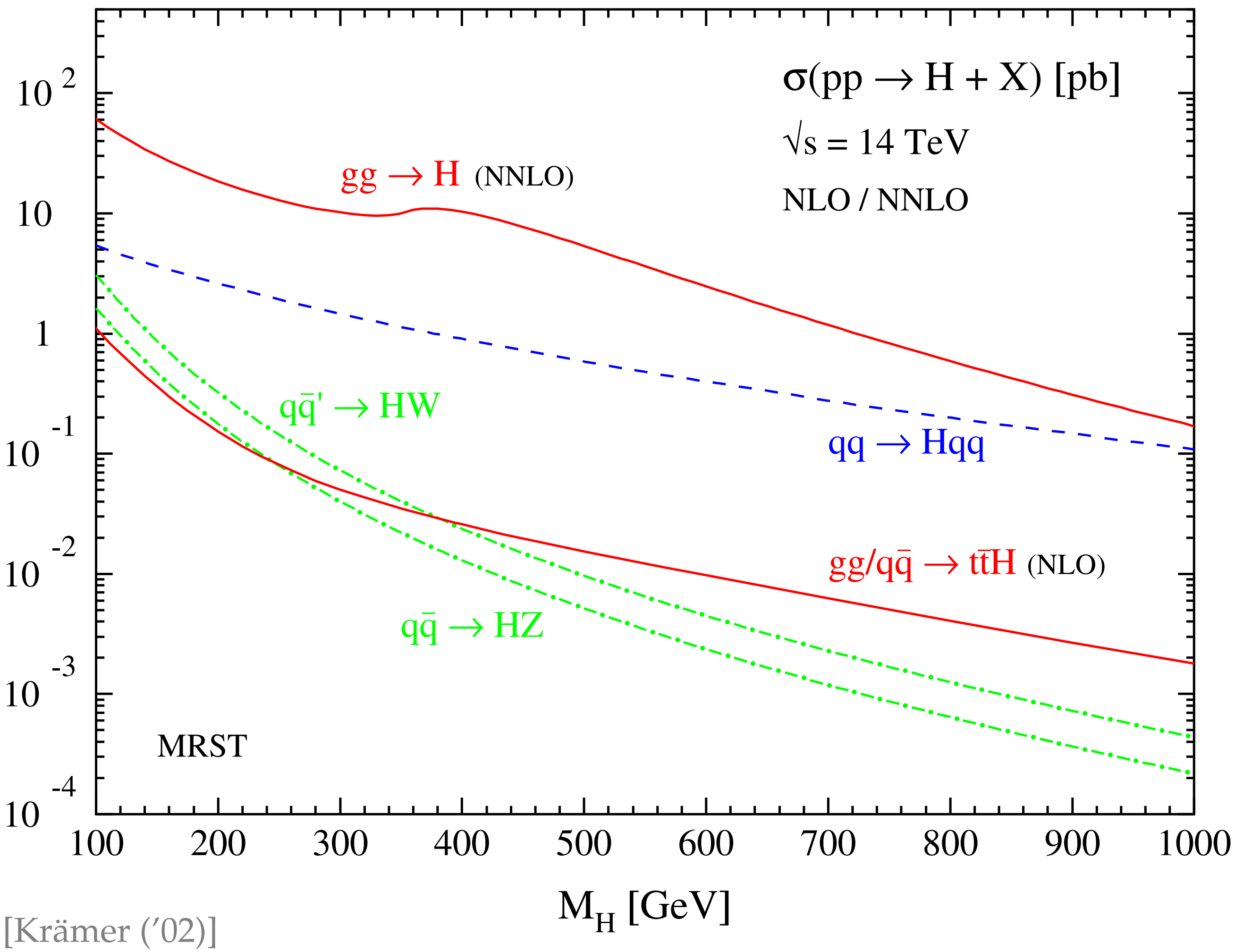


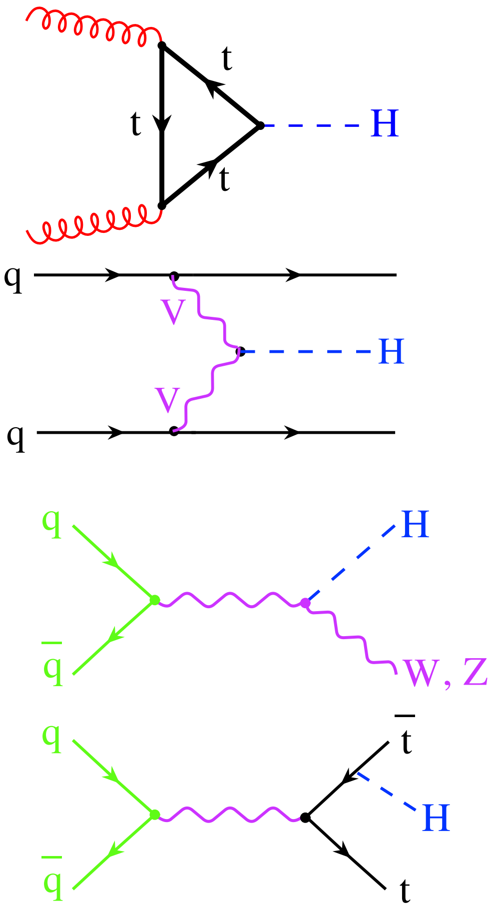
Higgs Strahlung



$t\bar{t}H$

Total cross sections at the LHC

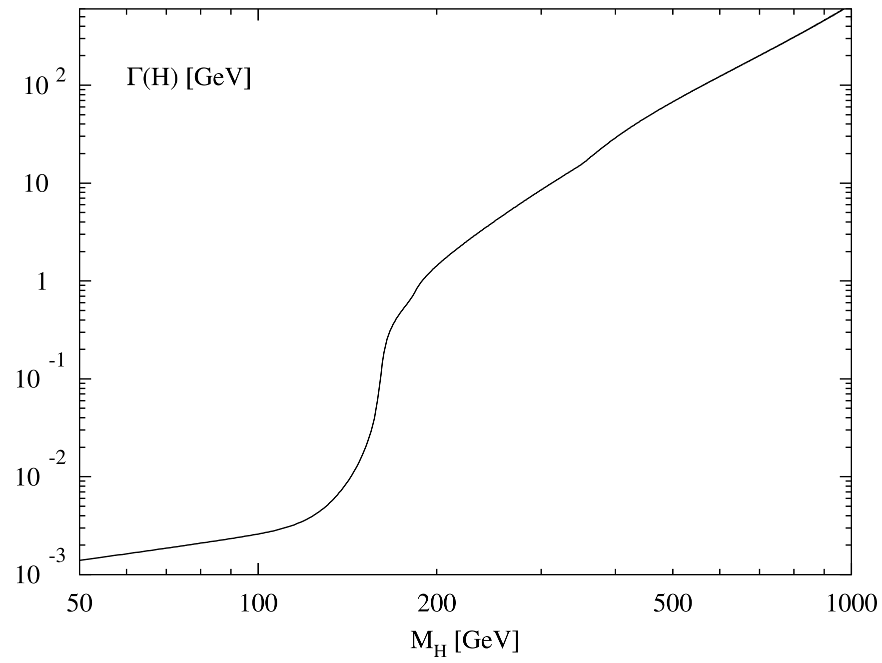


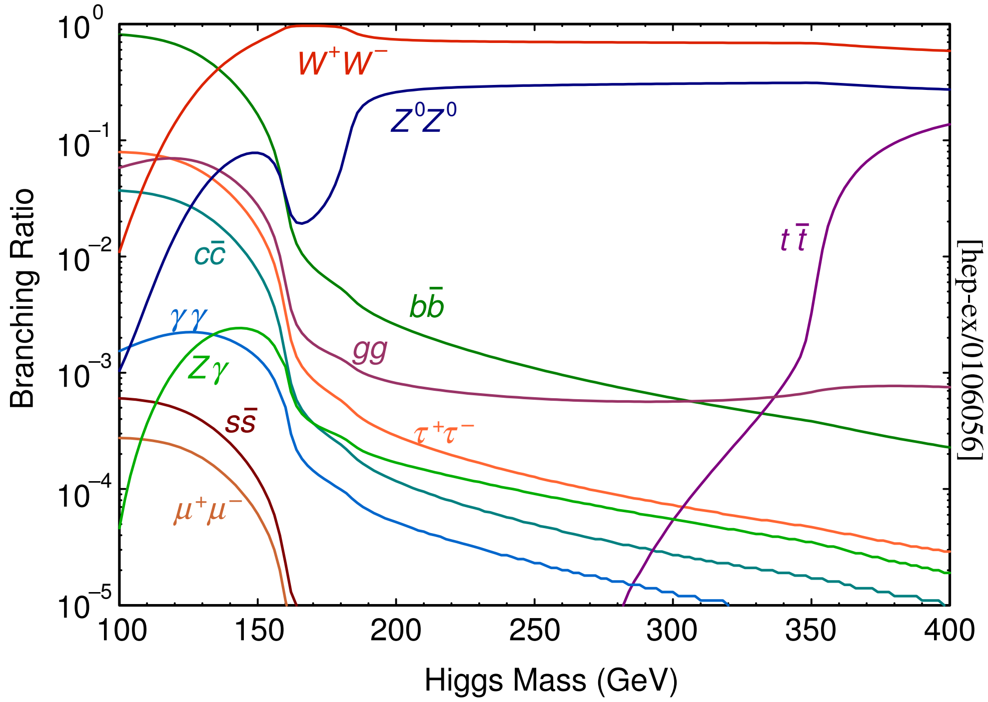


[Krämer ('02)]

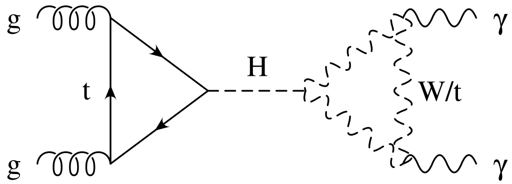
Decay of the SM Higgs

Higgs decay width and branching fractions within the SM

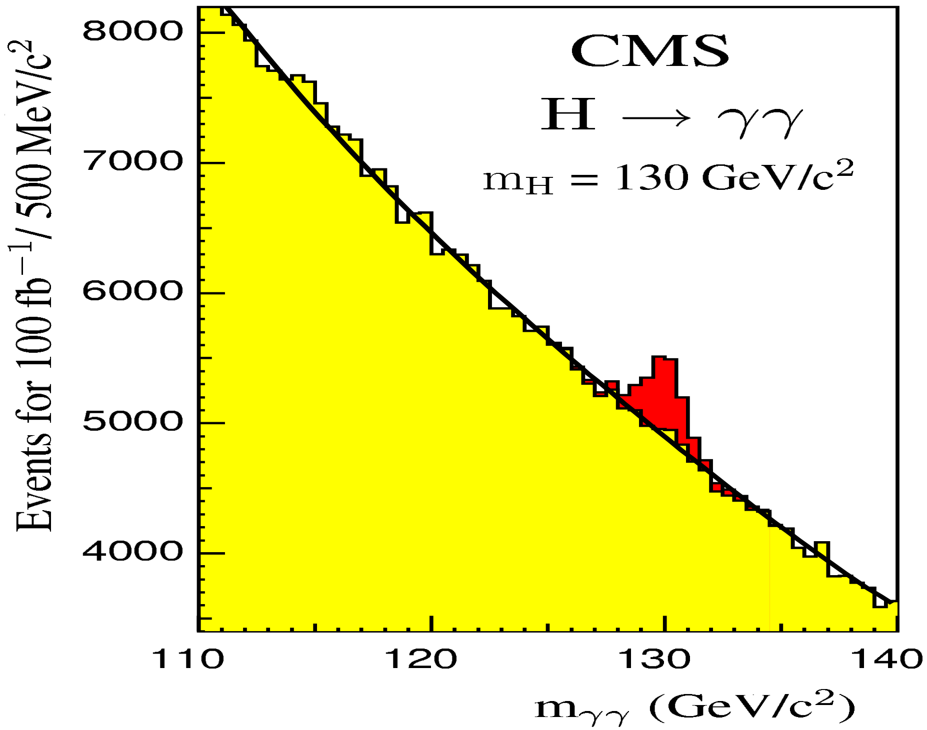




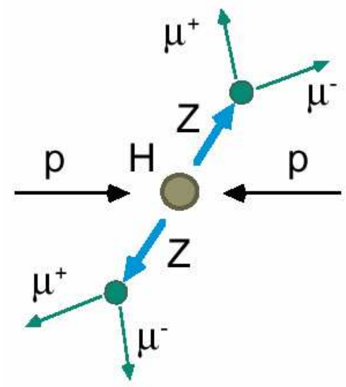
$H \longrightarrow \gamma\gamma$

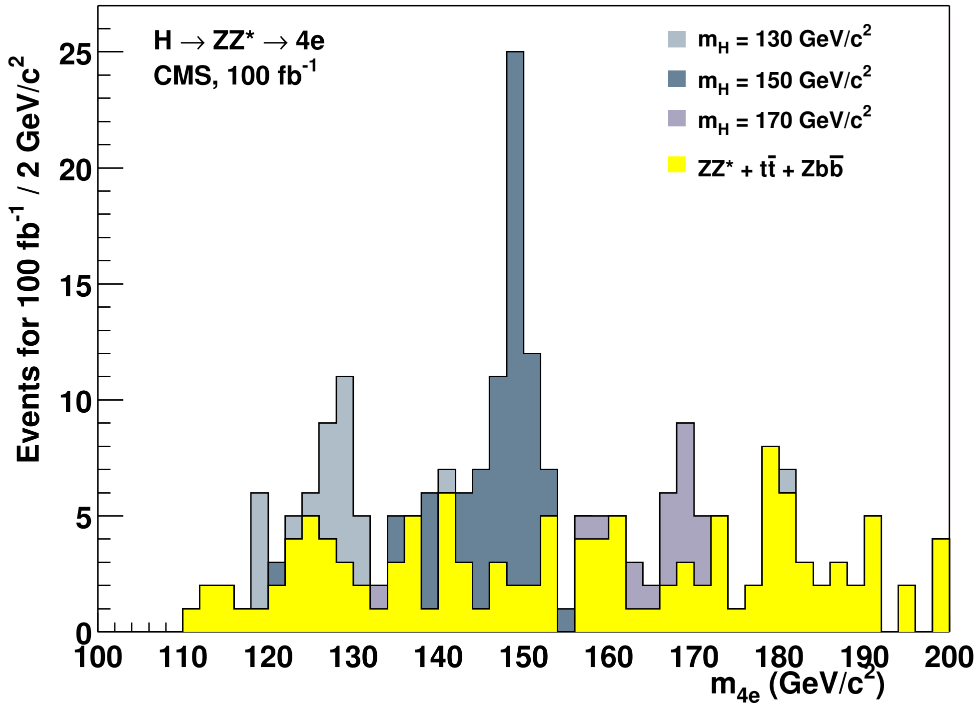


- ✗ BR$(H \to \gamma\gamma) \approx 10^{-3}$
- ✗ large backgrounds from $q\bar{q} \to \gamma\gamma$ and $gg \to \gamma\gamma$
- ✓ but CMS and ATLAS will have excellent photon-energy resolution (order of 1%)
- ✓ Look for a narrow $\gamma\gamma$ invariant mass peak
- ✓ extrapolate background into the signal region from sidebands.



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





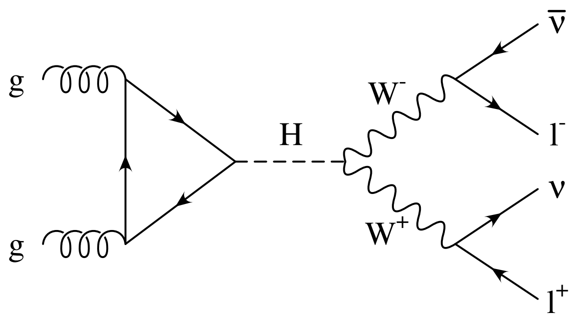
✓ invariant mass of the charged leptons fully reconstructed

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

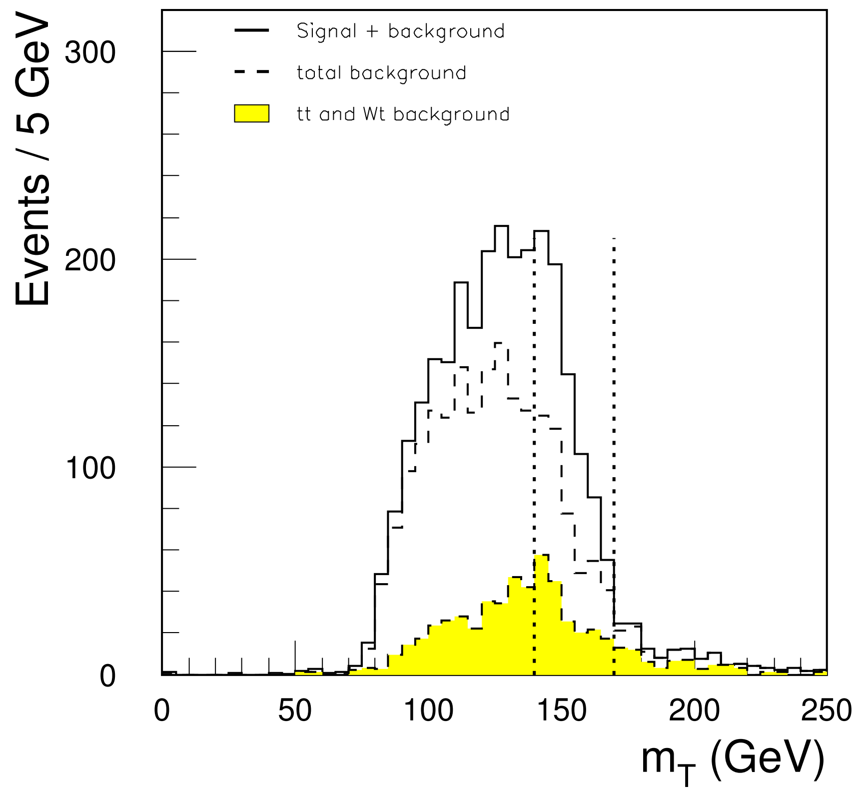
✓ $\mathrm{BR}(H \to \nu\bar{\nu}\ell^+\ell^-) = 6\ \mathrm{BR}(H \to \ell^+\ell^-\ell^+\ell^-)$

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

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



ATLAS TDR



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

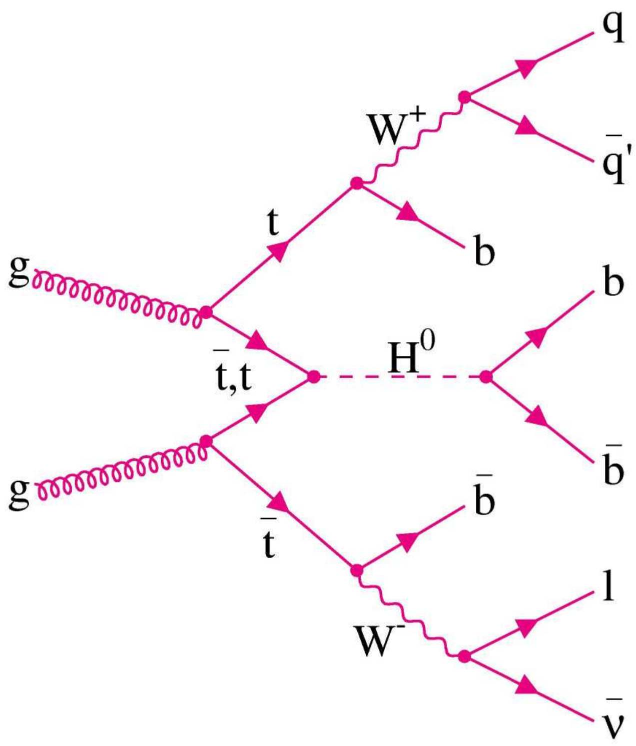
integrated luminosity = 20 fb^{-1}

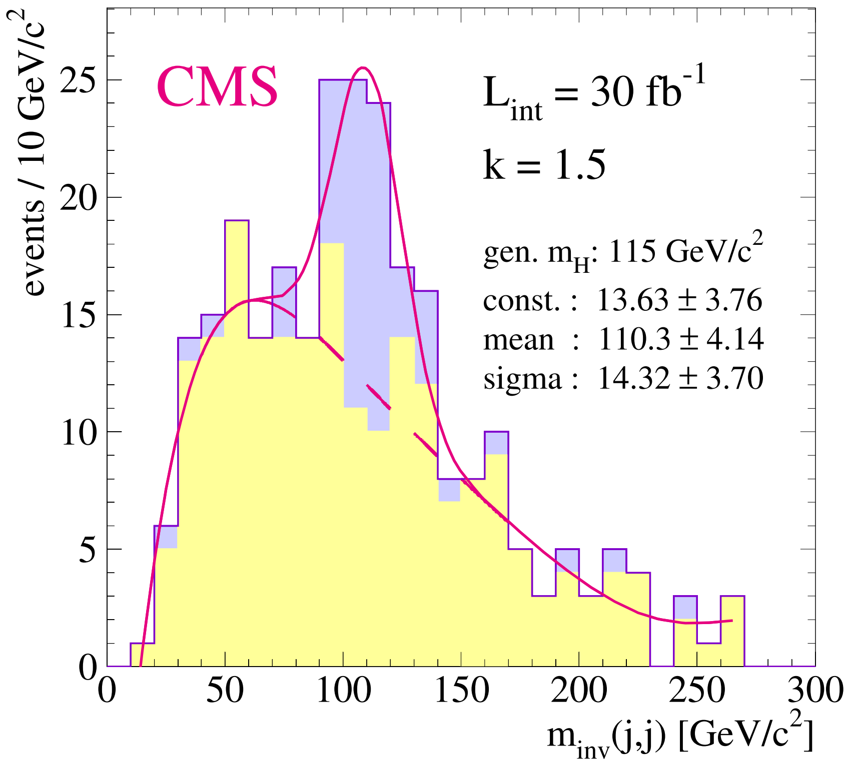
- ✓ Exploit $\ell^+\ell^-$ angular correlations
- ✓ measure the transverse mass with a Jacobian peak at m_H

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

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

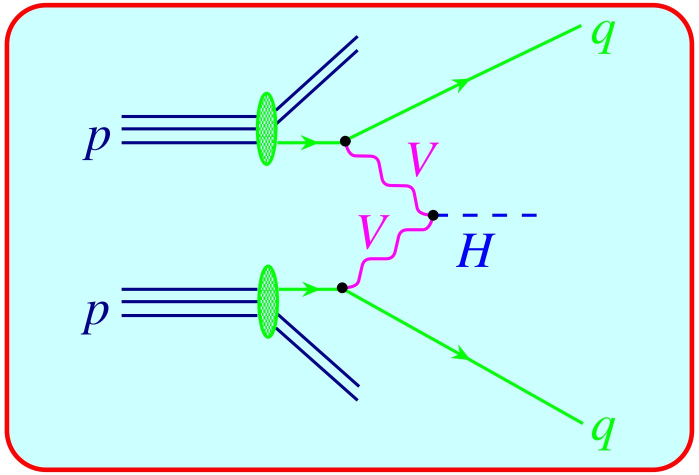
$t\bar{t}H \longrightarrow t\bar{t}b\bar{b}$

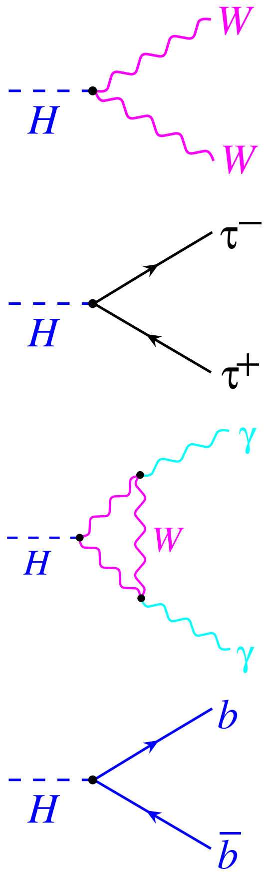




- ✓ $h_t = t\bar{t}H$ Yukawa coupling $\Longrightarrow$ measure h_t^2 BR$(H \to b\bar{b})$
- ✗ must know the background normalization precisely

Weak Boson Fusion





$m_H > 120$ GeV

$m_H < 140$ GeV

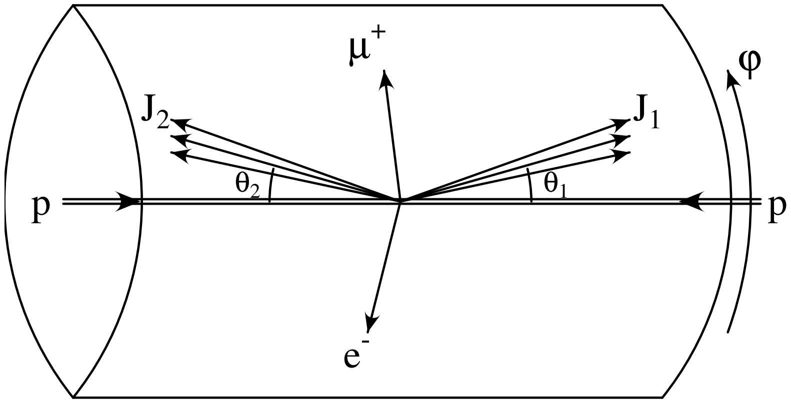
$m_H < 150$ GeV

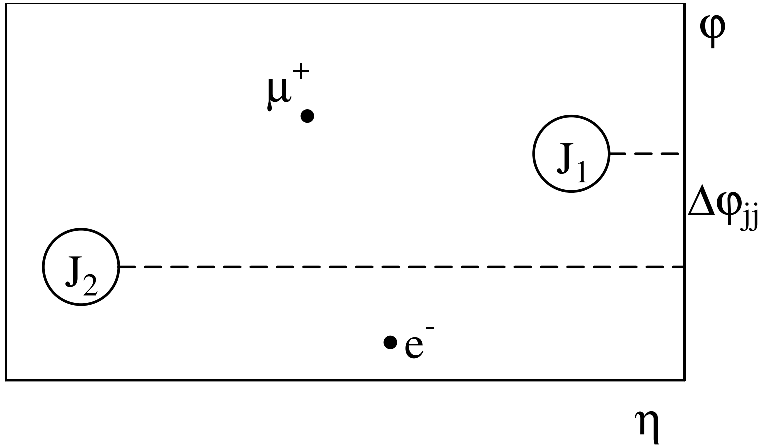
$m_H < 140$ GeV

[Eboli, Hagiwara, Kauer, Plehn, Rainwater, D.Z. . . .] [Mangano, Moretti, Piccinini, Pittau, Polosa ('03)]

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 $H \to WW$

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:

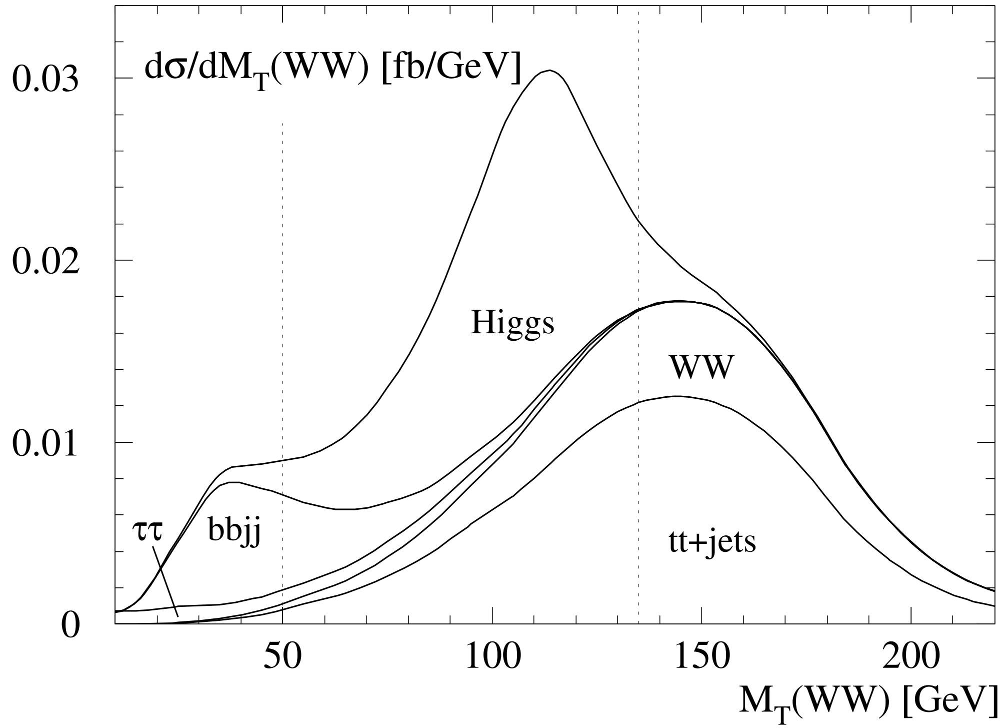
$$E_{T,ll} = \sqrt{\mathbf{p}_{T,ll}^2 + m_{ll}^2}$$

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

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

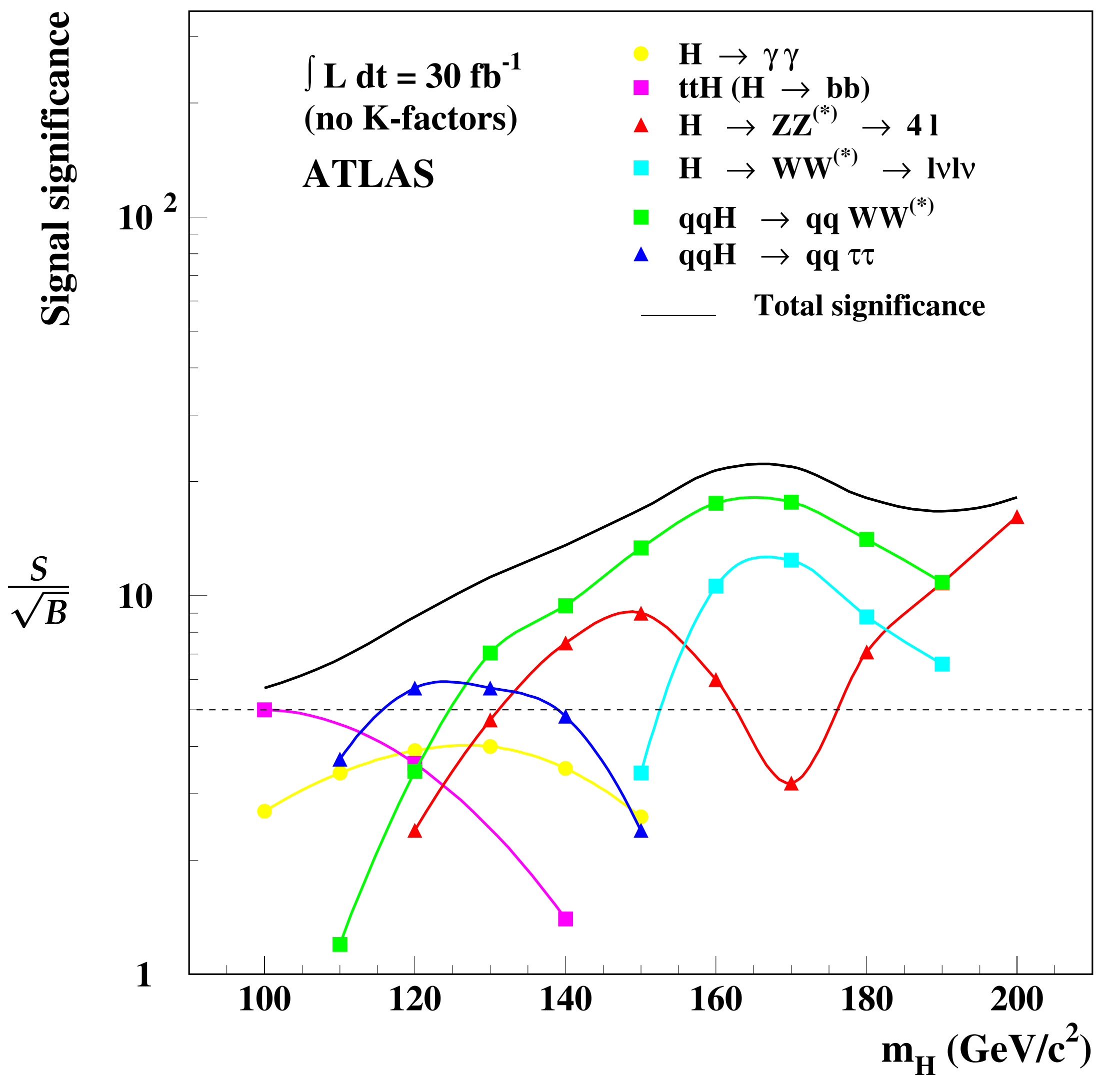
Observe Jacobian peak below $M_T = m_H$

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



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

Higgs discovery potential



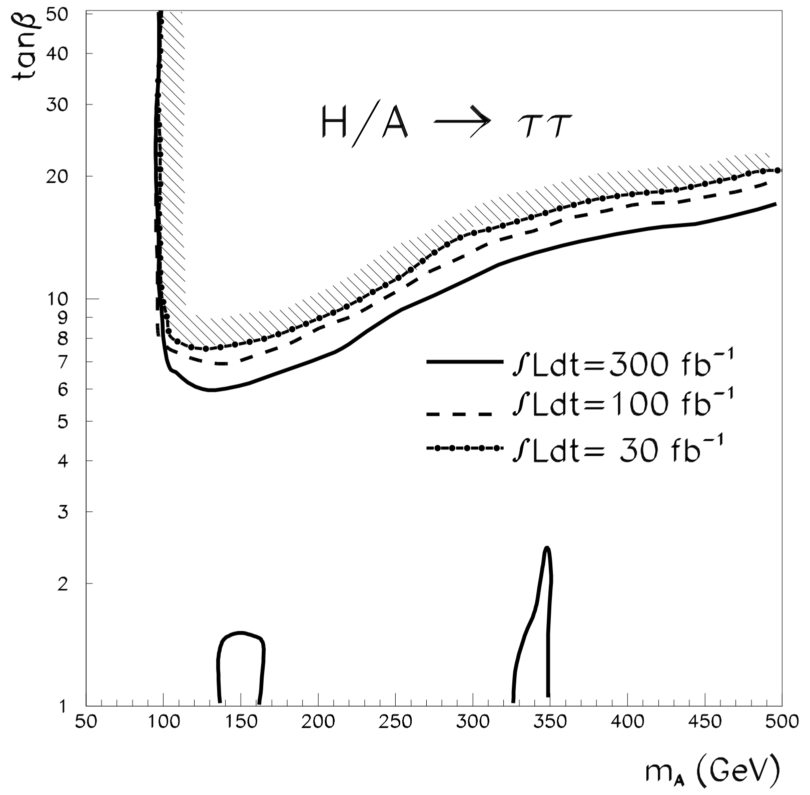
Reach for H/A discovery within MSSM

Enhancement of
Hbb and *Abb* coupling
by factor $\tan\beta$
compared to SM Higgs

$\Longrightarrow$ large production cross section for $pp \to \bar{b}bH/A$

$\Longrightarrow$ decay dominated by $H/A \to \bar{b}b,\ \tau^+\tau^-$

ATLAS TDR



5σ discovery contours

Reach for $H^{\pm}$ discovery within MSSM

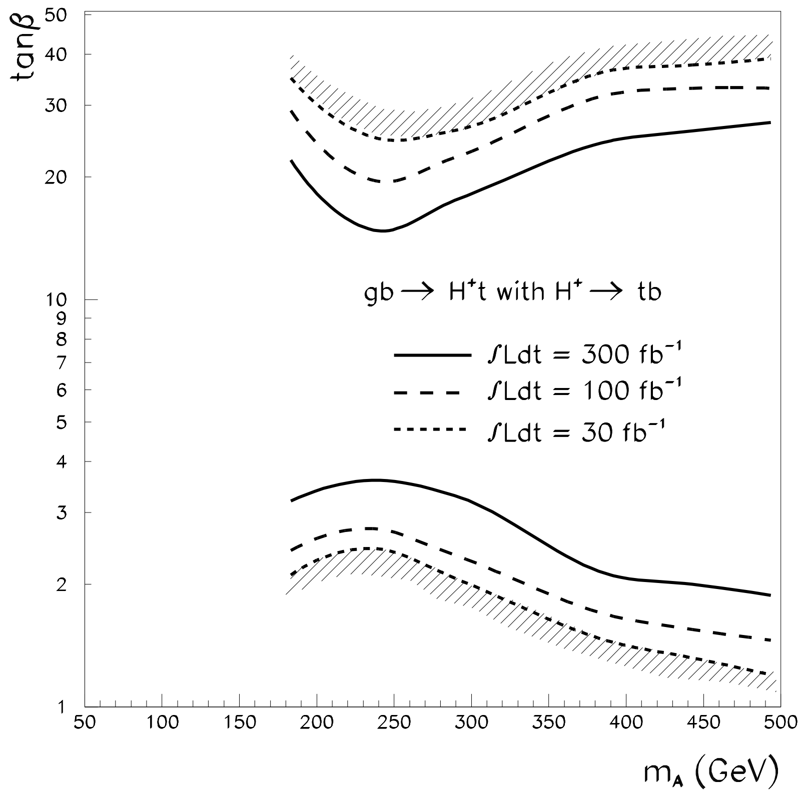
ATLAS TDR

- For $m_{H^{\pm}} > m_t + m_b$ expect $H^{\pm} \to tb$ decay
- Dominant production process

$$gg \to H^{\pm} tb$$

b-quark has low p_T: $gb \to H^{\pm} t$ is dominant subprocess

- Main background from $\bar{t}t(+\text{jets})$ production



5σ discovery contours

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

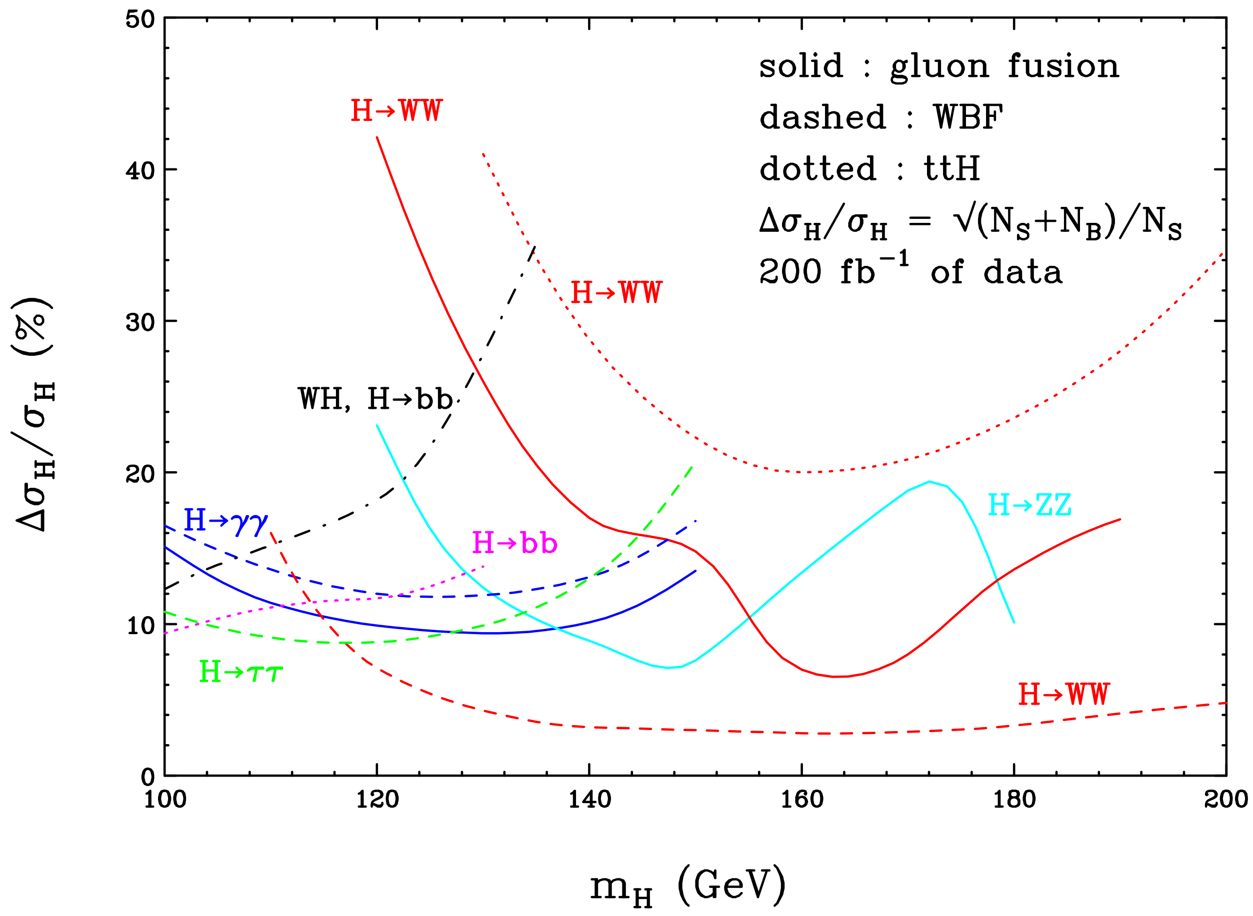
Loose bounds on scaling factor:

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

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

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

Statistical and systematic errors at LHC

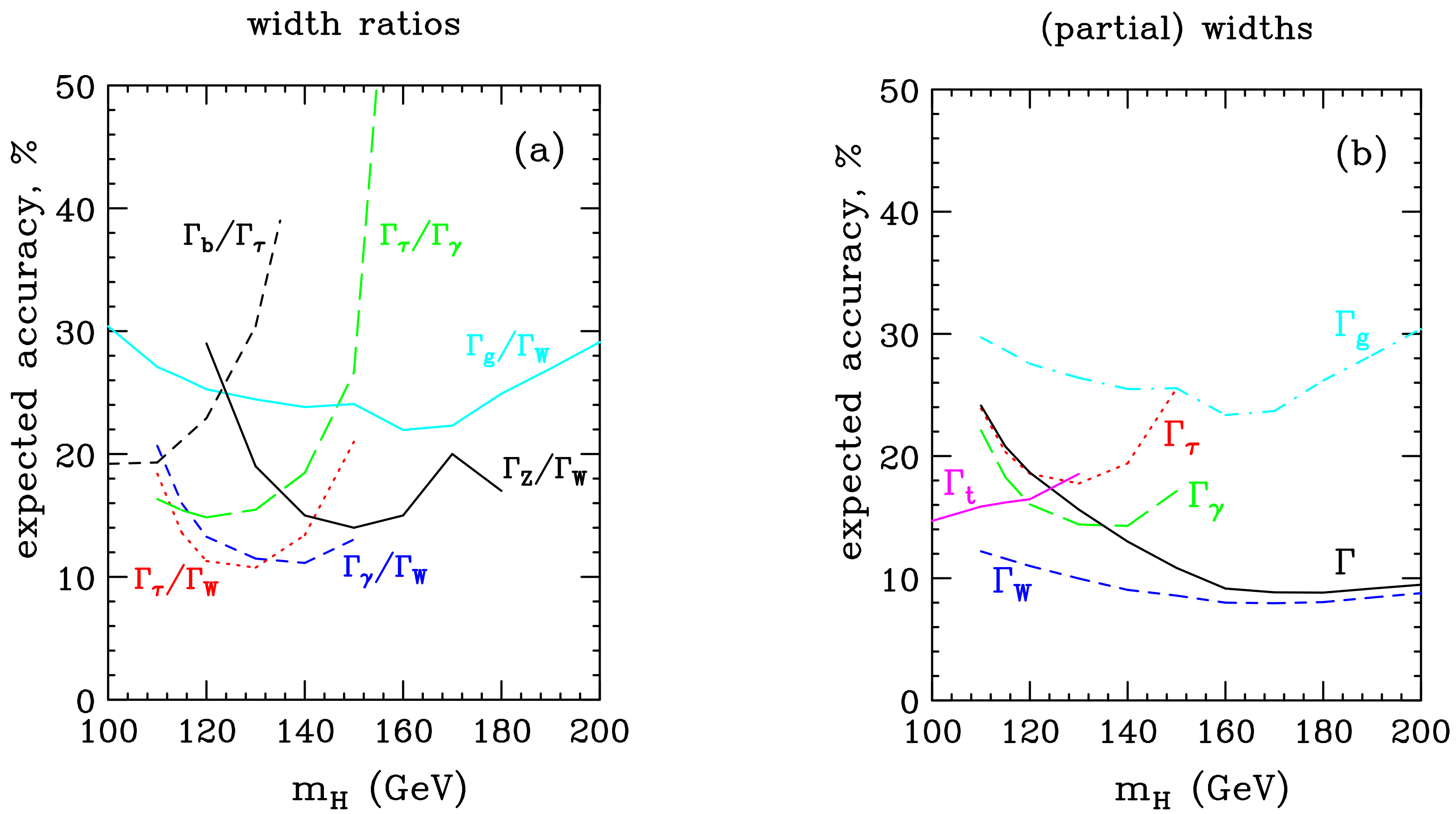


Assumed errors in fits to couplings:

- QCD/PDF uncertainties
  - ±5% for WBF
  - ±20% for gluon fusion
- luminosity/acceptance uncertainties
  - ±5%

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

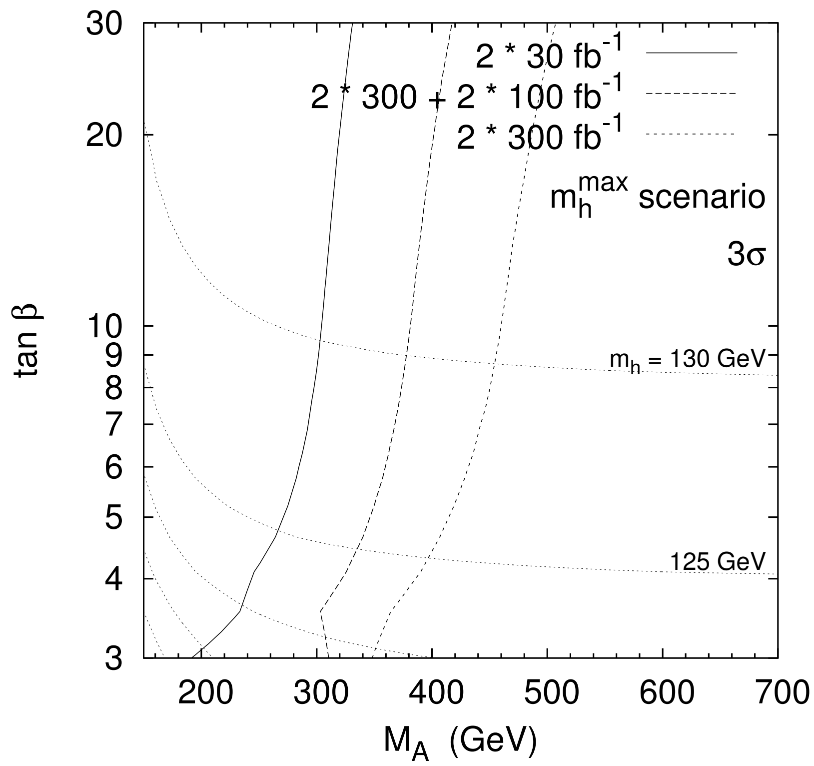
Consider modest m_A:

- 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 $h \to \tau\tau$ in WBF
- suppressed $h \to \gamma\gamma$ and $h \to WW$ rates in WBF

3σ-effects or more at small m_A



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

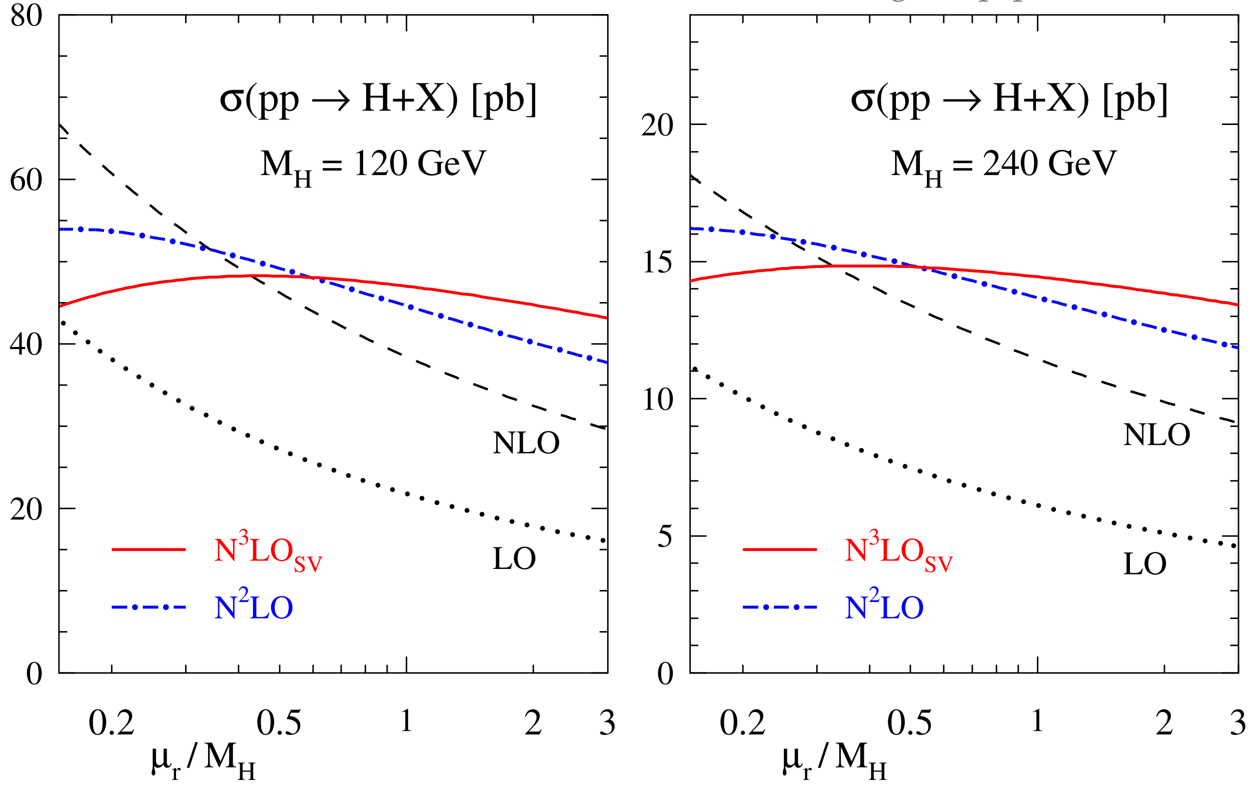
$\Longrightarrow$ need QCD corrections to production cross sections

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)
- weak boson fusion
  - total cross section at NLO: Han, Willenbrock (1991)
  - distributions at NLO: Figy, Oleari, D.Z (2003); Campbell, Ellis, Berger (2004)
- $\bar{t}tH$ associated production at NLO: Beenakker et al.; Dawson, Orr, Reina, Wackeroth (2002)
- $\bar{b}bH$ associated production at NLO: Dittmaier, Krämer, Spira; Dawson et al. (2003)

QCD corrections to $gg \to H$

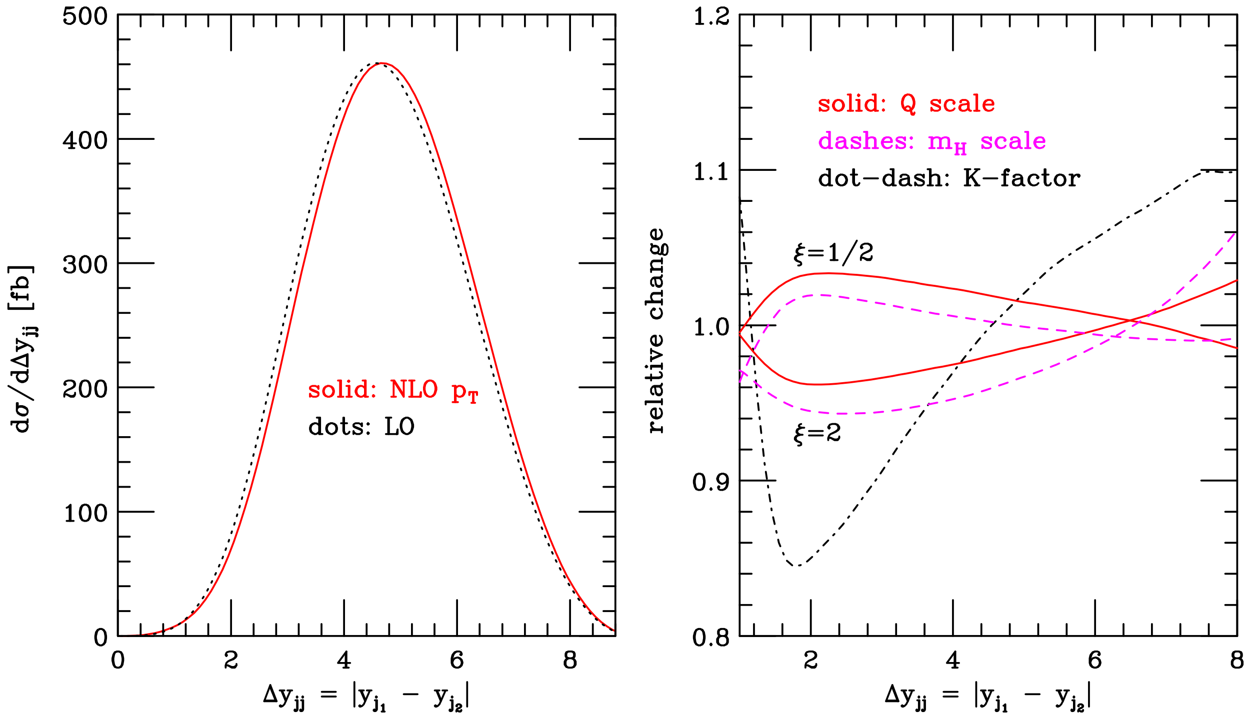
Moch & Vogt, hep-ph/0508265



- ✓ 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

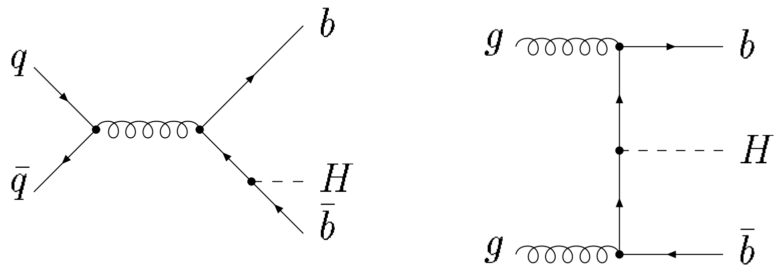
NLO QCD corrections to WBF

- ✓ 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

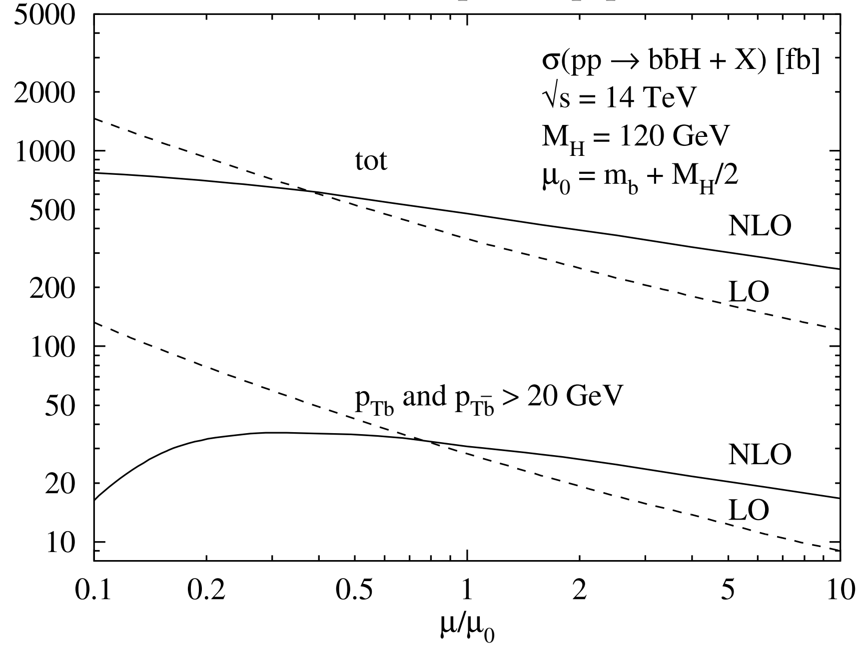


$m_H = 120$ GeV, typical WBF cuts

NLO QCD corrrections to $b\bar{b}H$ production



Dittmaier, Krämer, Spira hep-ph/0309204

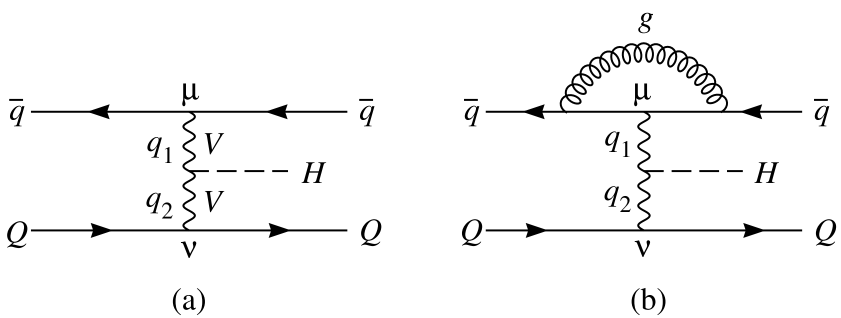


scale dependence of inclusive vs.
double b-tagged cross section

- Discovery channel for H/A in the MSSM at sizeable tan β
- NLO corrections known for $\bar{b}bH$ final state
- b-quarks at low p_T: effective process is $\bar{b}b \to H$: cross ssection known at NNLO Harlander, Kilgore (2003)

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 $\mathcal{L}_I \sim HV_\mu V^\mu \longrightarrow a_1$

loop induced couplings for neutral scalar

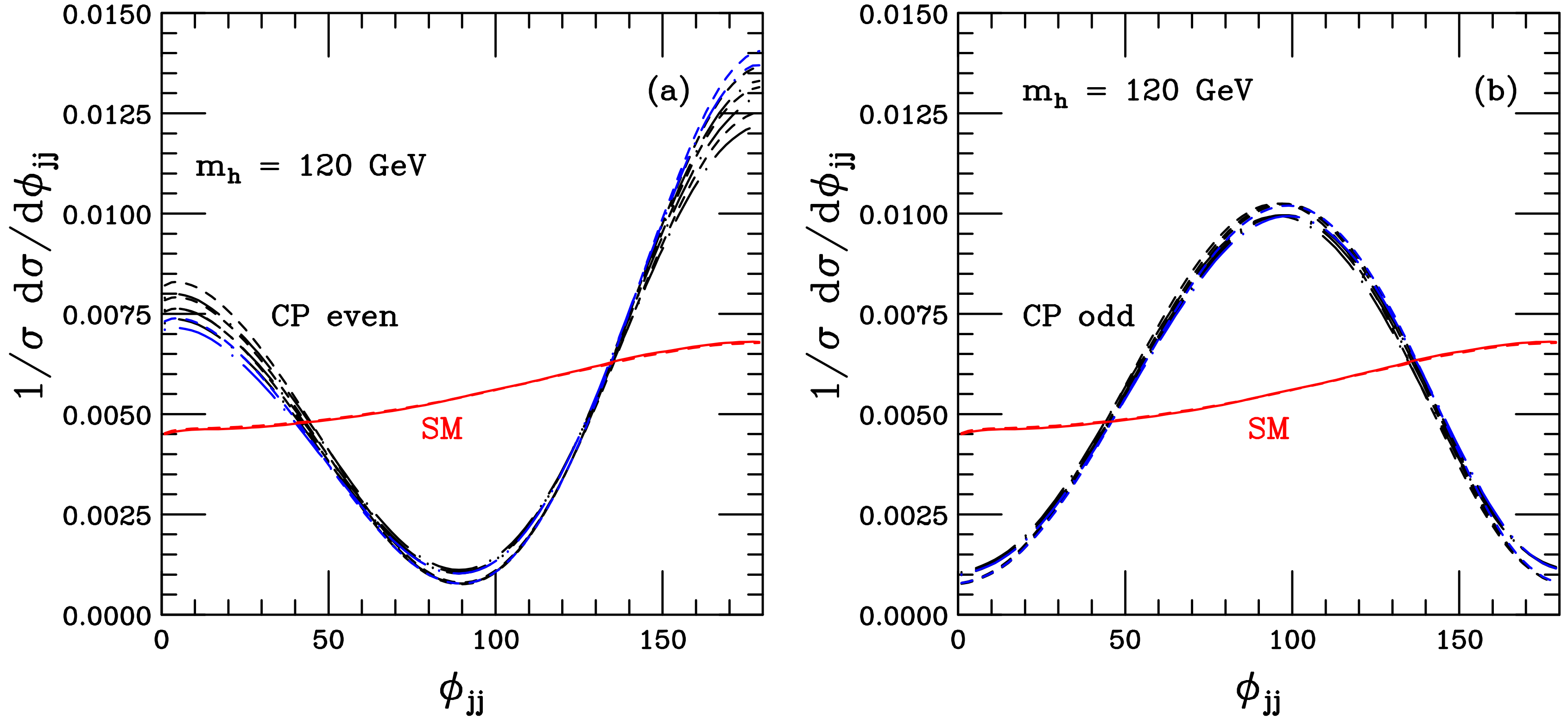
CP even $\mathcal{L}_{eff} \sim HV_{\mu\nu}V^{\mu\nu} \longrightarrow a_2$

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

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.

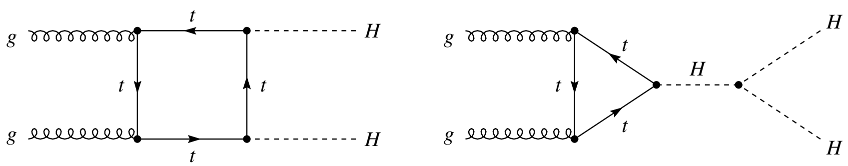
Probing the Higgs potential

$$V(\Phi) = \lambda \left(\Phi^\dagger \Phi - \frac{v^2}{2} \right)^2$$

$\Longrightarrow$ Higgs mass: $m_H^2 = 2\lambda v^2$

HHH coupling: $6\lambda v = 3m_H^2/v$

Probe this relation in $gg \to HH$

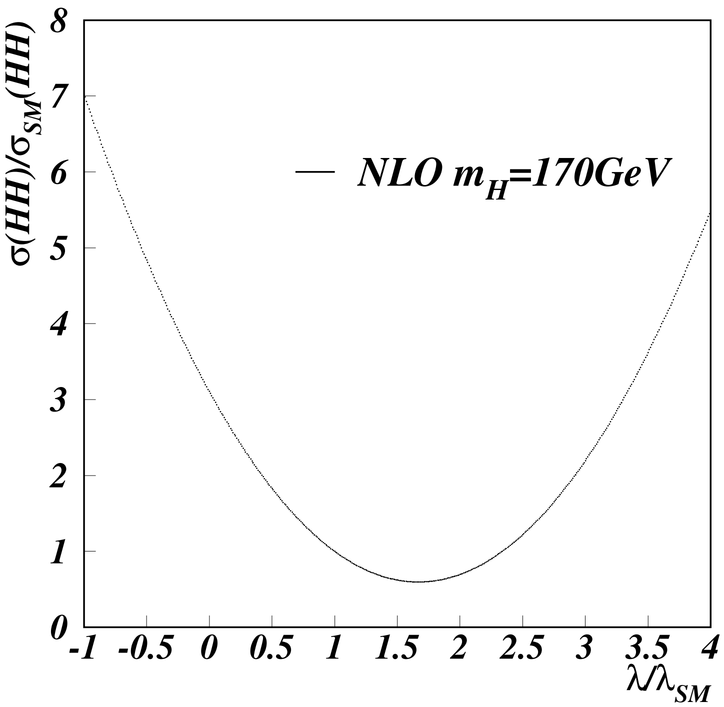


Most sensitive decay channel:

$$HH \to W^+W^-W^+W^-$$
$$\to l^\pm l'^\pm + 4j + \not{p}_T$$

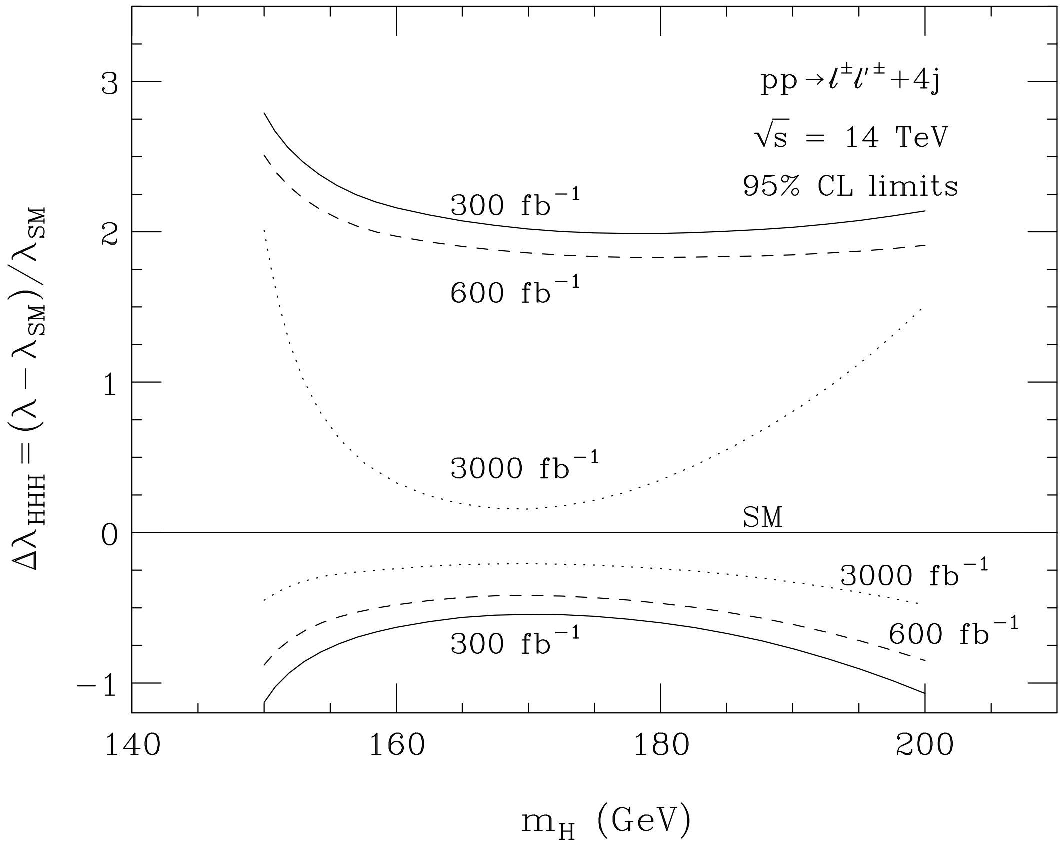
$\sigma(gg \to HH) \approx 20 - 30$ fb at 14 TeV

Gianotti et al., hep-ph/0204087



LHC sensitivity to HHH coupling

Baur, Plehn, Rainwater: hep-ph/0211224



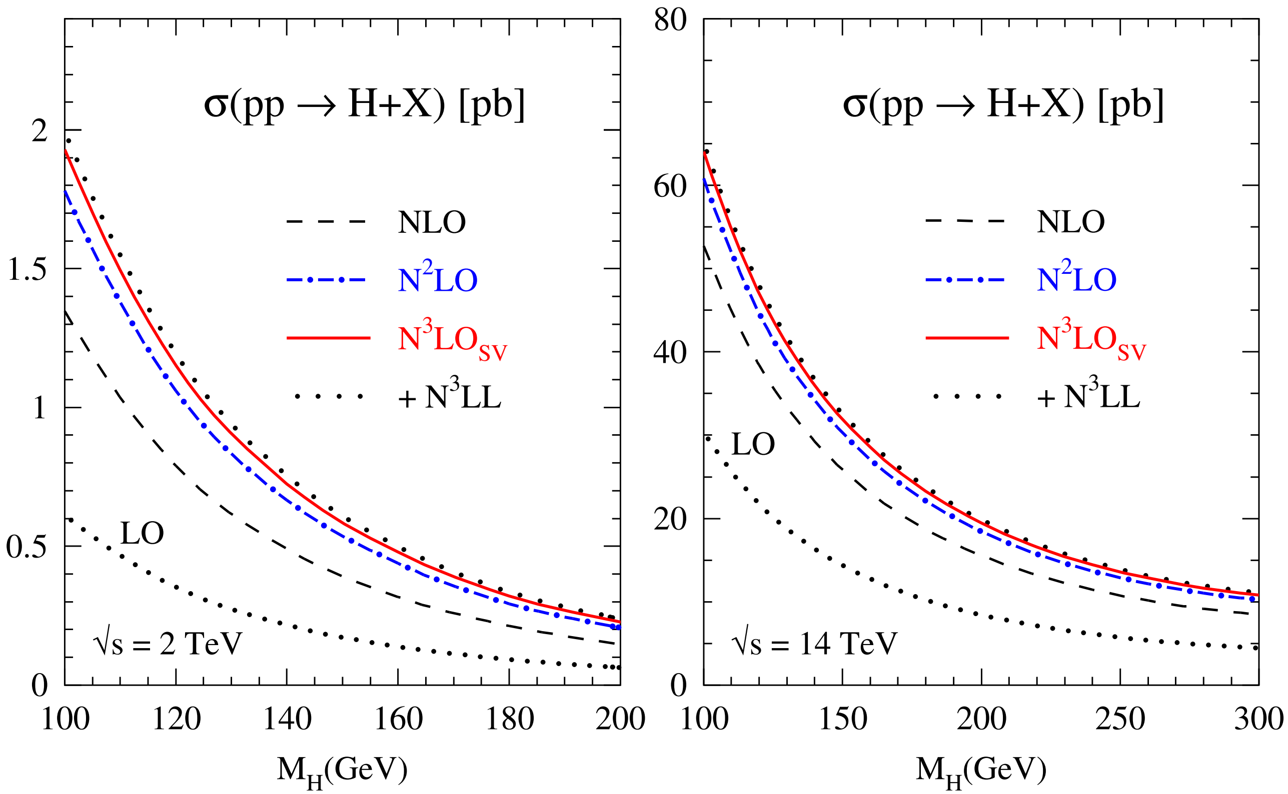
- Need very high luminosity for serious measurement of self coupling
- SLHC sensitivity: up to ±20%

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
- Extraction of couplings at the LHC requires knowledge of NLO QCD corrections for signal and important backgrounds
- Absence of HVV and AVV couplings for the heavy H/A of supersymmetry make their observation more challenging
  $\Longrightarrow$ Need large $\tan\beta$ rate enhancement for discovery
- Higgs boson CP properties from jet-angular correlations in WBF and gluon fusion
- Higgs boson self couplings are big challenge: SLHC may give information for favorable Higgs mass range ($m_H > 160$ GeV) in which $HH \rightarrow WWWW$ observation is possible

QCD corrections to $gg \to H$

Moch & Vogt, hep-ph/0508265



Cross section as function of m_H for Tevatron and LHC