

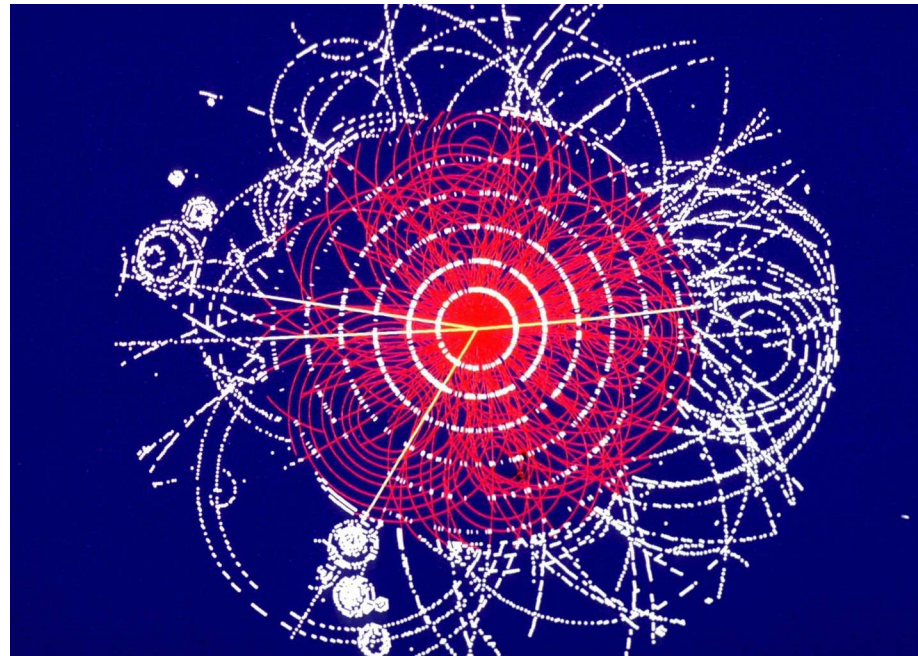
# HIGGS PHYSICS AT THE LHC

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

$$\begin{aligned} \mathcal{L}_{\text{Yukawa}} &= -\Gamma_d^{ij} \bar{Q}'_L{}^i \Phi d'_R{}^j - \Gamma_d^{ij*} \bar{d}'_R{}^i \Phi^\dagger Q'_L{}^j + \dots &= -\Gamma_d^{ij} \frac{v+H}{\sqrt{2}} \bar{d}'_L{}^i d'_R{}^j + \dots \\ &= -\sum_f m_f \bar{f} f \left(1 + \frac{H}{v}\right) \end{aligned}$$

- 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

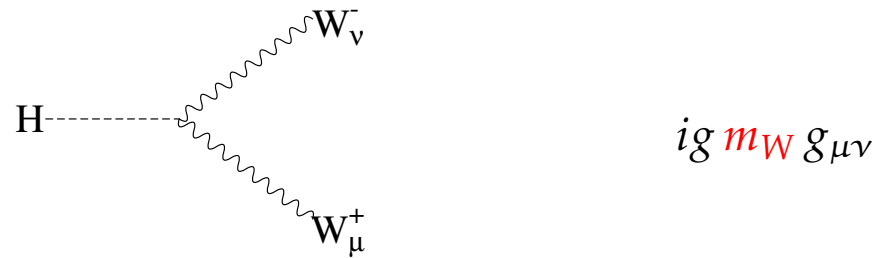
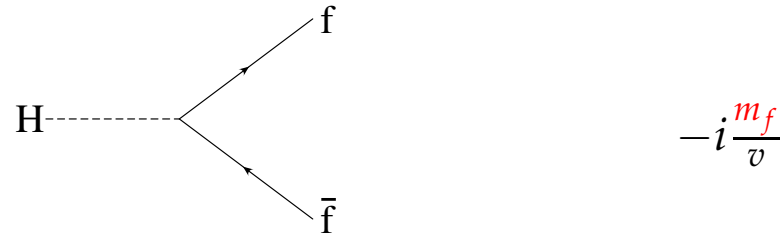
Kinetic energy term of Higgs doublet field:

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

- $W, Z$  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 =  $2 m_V^2 / v$  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



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

## 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

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

Two complex Higgs doublet fields  $\Phi_1$  and  $\Phi_2$  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:  $\chi_0$

### 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  $v_1 = v \cos \beta$ ,  $v_2 = v \sin \beta$ :

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

Expressed in terms of masses the Yukawa Lagrangian is

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

$\implies$  **coupling factors** compared to SM  $hff$  coupling  $-i m_f/v$

### Gauge Bosons

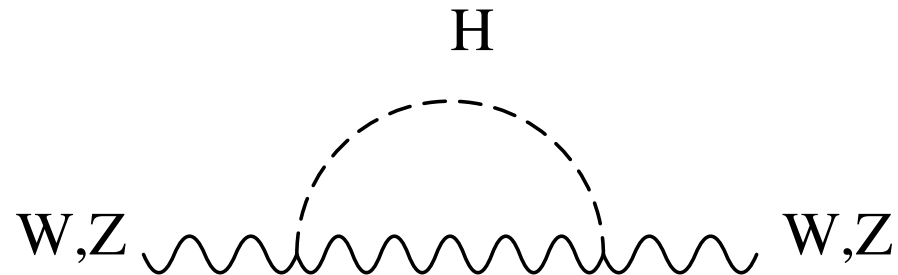
extra coupling factors for  $hVV$  and  $HVV$  couplings as compared to SM

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

## Clues to the Higgs boson mass: SM case

Higgs mass is largely unconstrained by theory  $\implies$  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

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

## 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

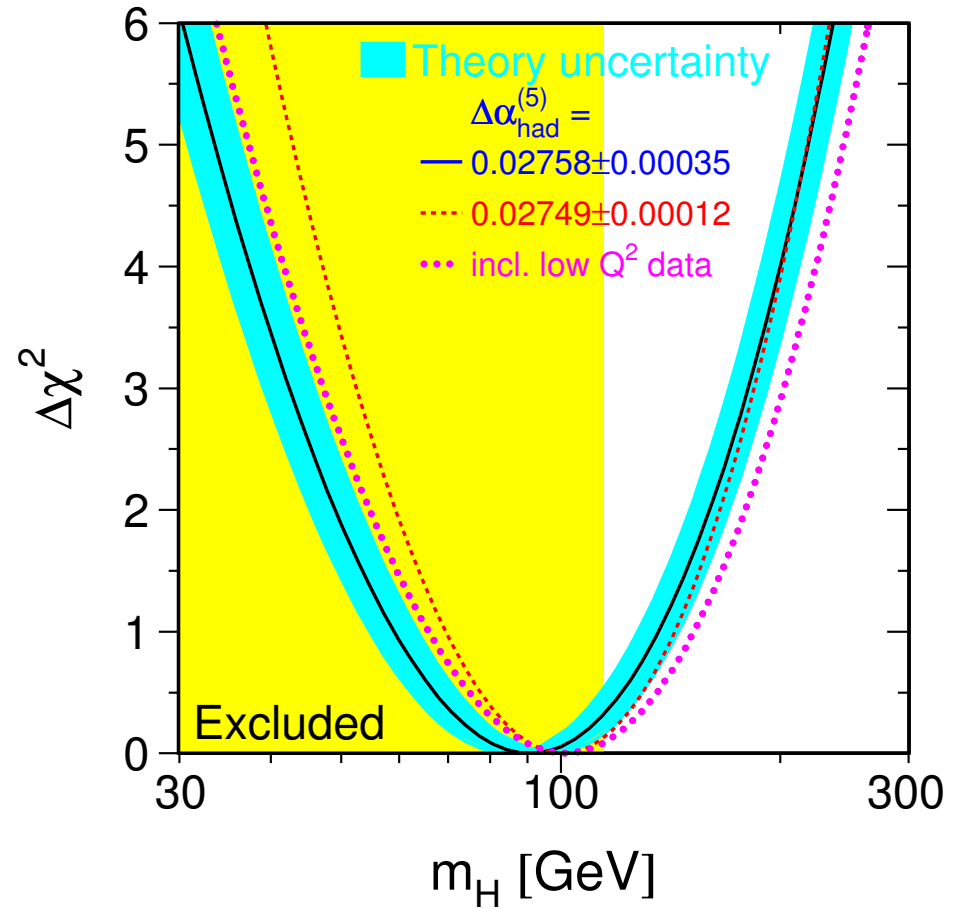
Direct search limit from LEP

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

Renormalize probability for

$m_H > 114 \text{ GeV}$  to 100%:

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

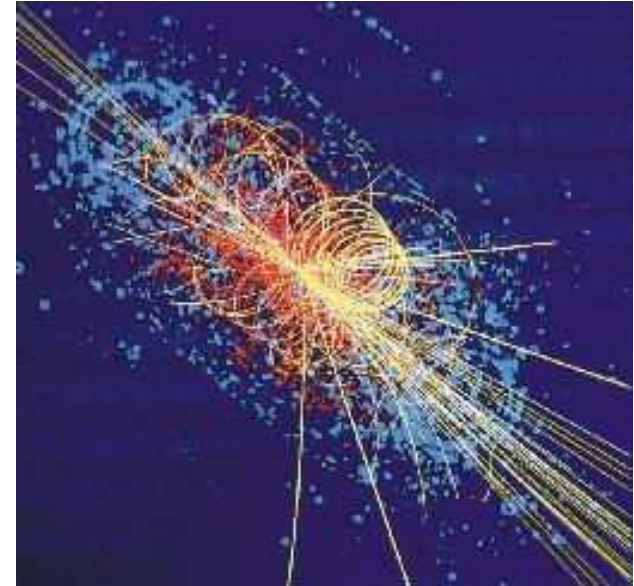




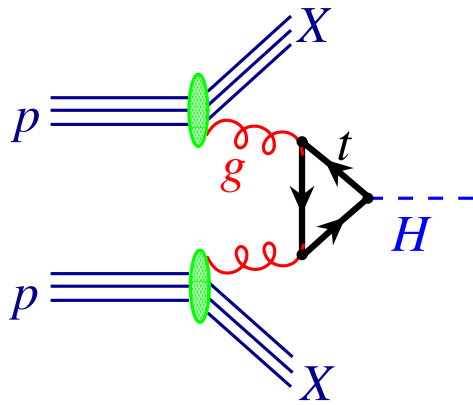
# Higgs boson channels at LHC

Two steps

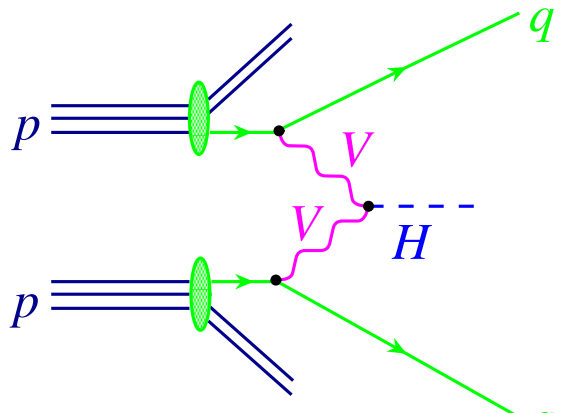
- **Production** of the Higgs boson
- **Detection** of the **decay products** of the Higgs boson and identification of the events



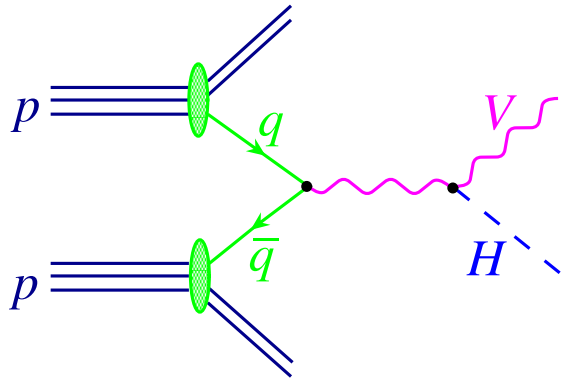
# Production Modes



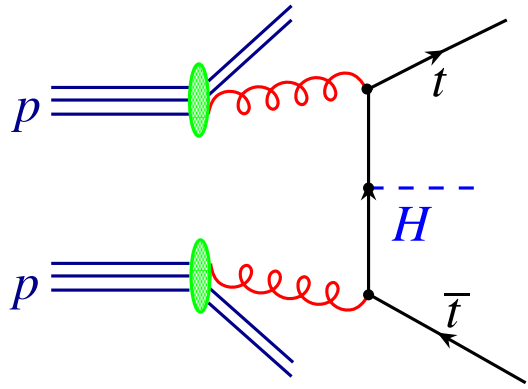
Gluon fusion



Weak-Boson Fusion

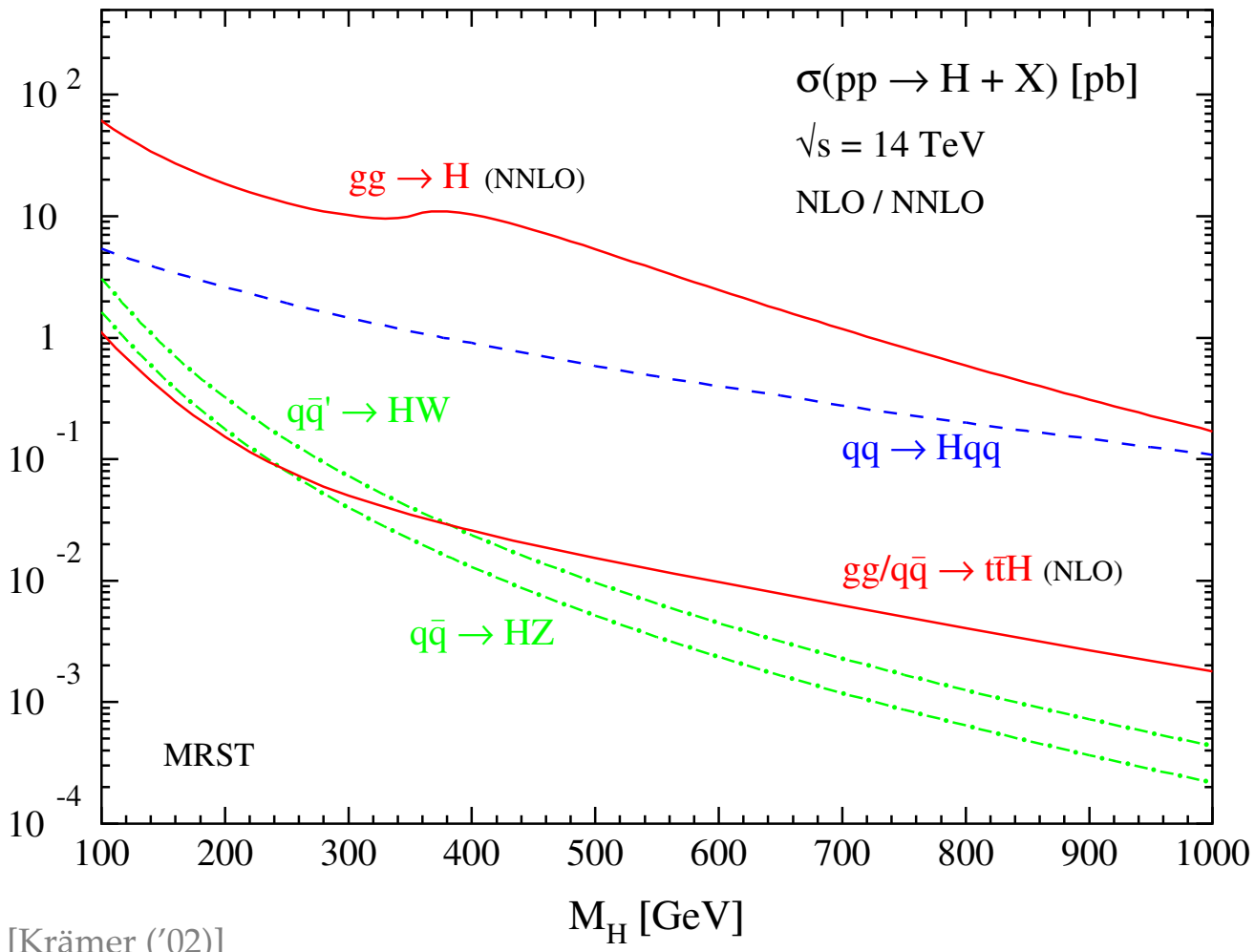


Higgs Strahlung

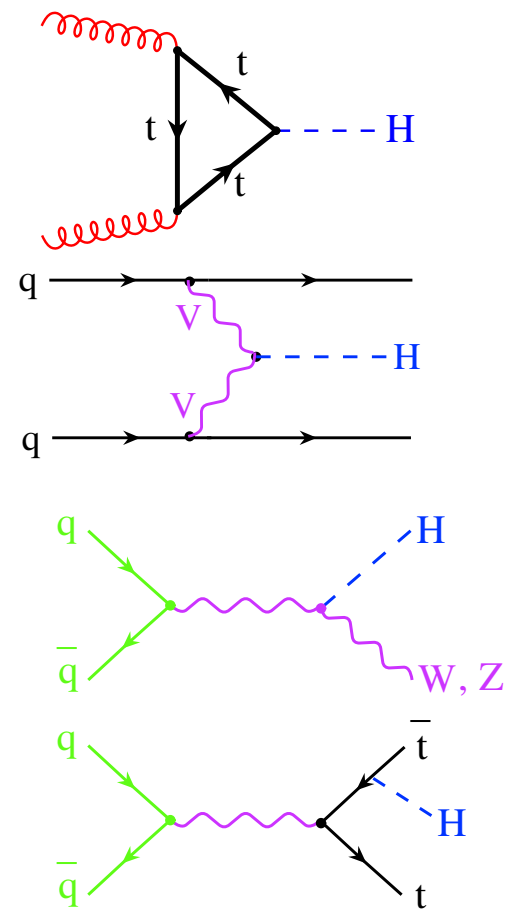


$t\bar{t}H$

# Total cross sections at the LHC

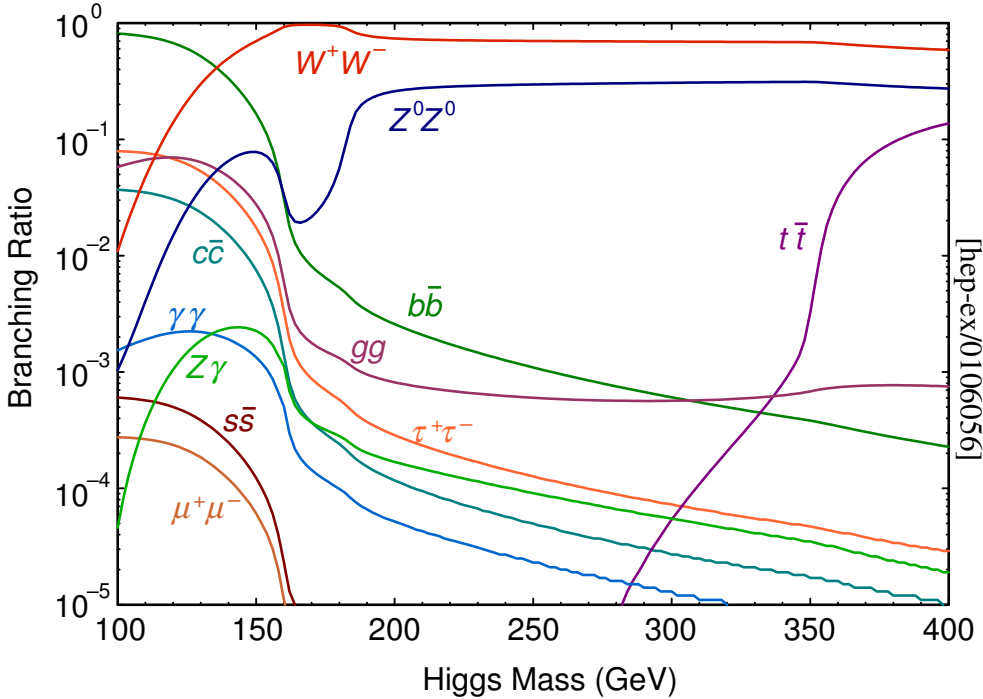
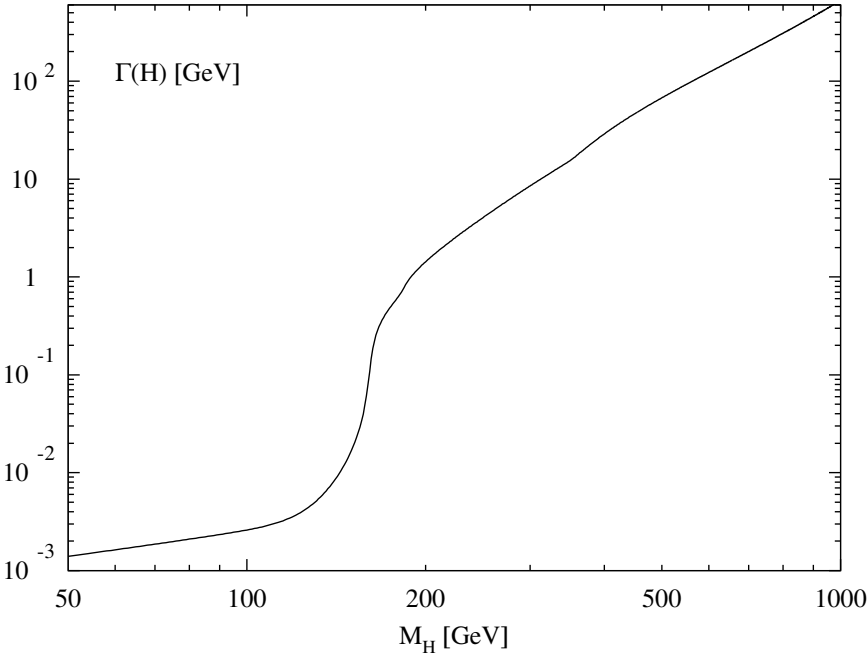


[Krämer ('02)]

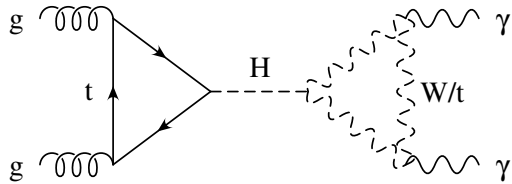


# Decay of the SM Higgs

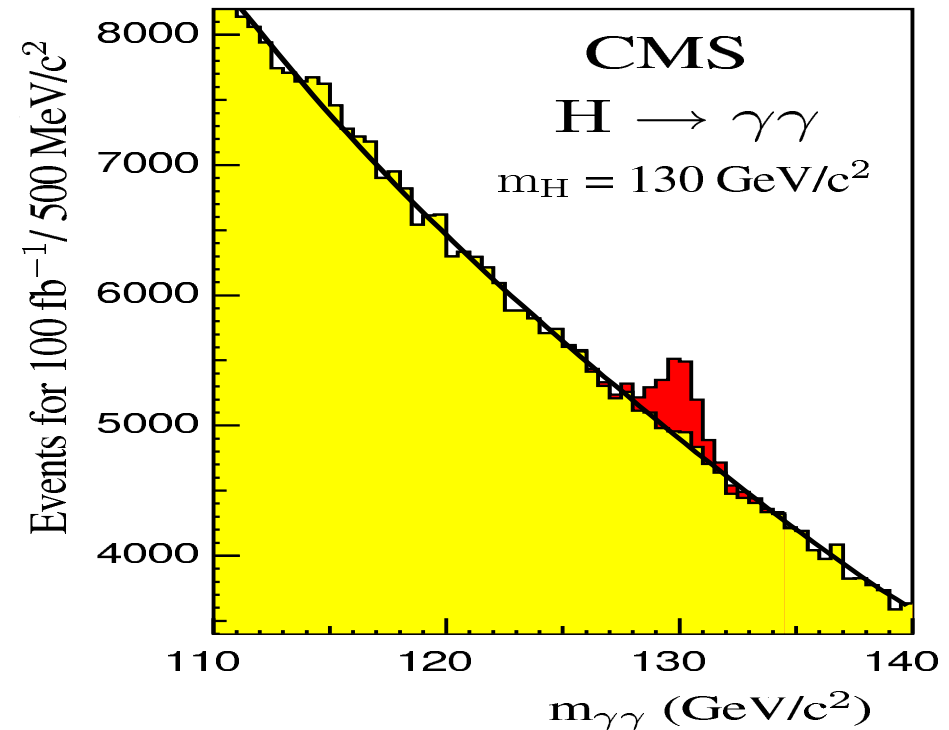
Higgs decay width and branching fractions within the SM



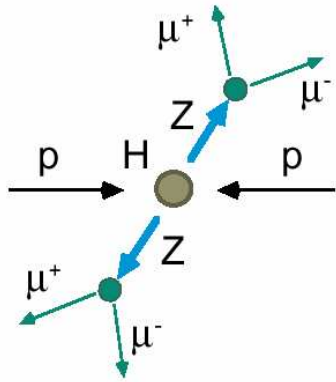
# $H \rightarrow \gamma\gamma$



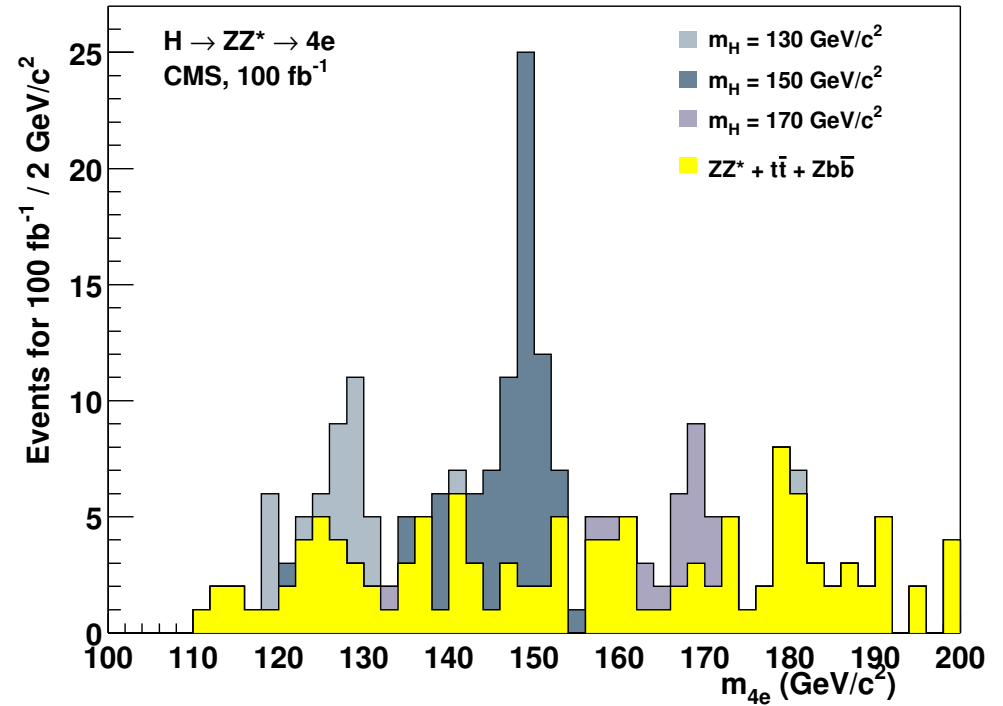
- ✗  $\text{BR}(H \rightarrow \gamma\gamma) \approx 10^{-3}$
- ✗ large backgrounds from  $q\bar{q} \rightarrow \gamma\gamma$  and  $gg \rightarrow \gamma\gamma$
- ✓ but CMS and ATLAS will have excellent photon-energy resolution (order of 1%)
- ✓ Look for a narrow  $\gamma\gamma$  invariant mass peak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



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



✓ invariant mass of the charged leptons fully reconstructed

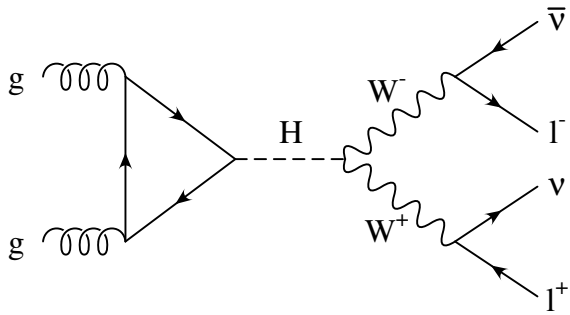


For  $m_H \approx 0.6-1 \text{ TeV}$ , use the “silver-plated” mode  $H \rightarrow ZZ \rightarrow \nu\bar{\nu}\ell^+\ell^-$

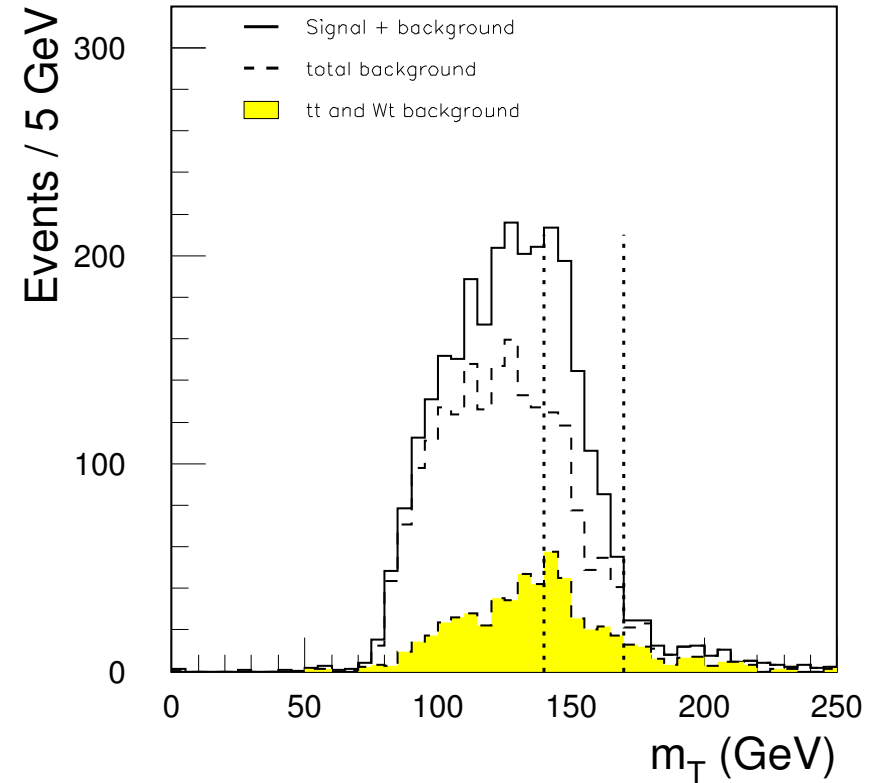
✓  $\text{BR}(H \rightarrow \nu\bar{\nu}\ell^+\ell^-) = 6 \text{ BR}(H \rightarrow \ell^+\ell^-\ell^+\ell^-)$

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

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



ATLAS TDR



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

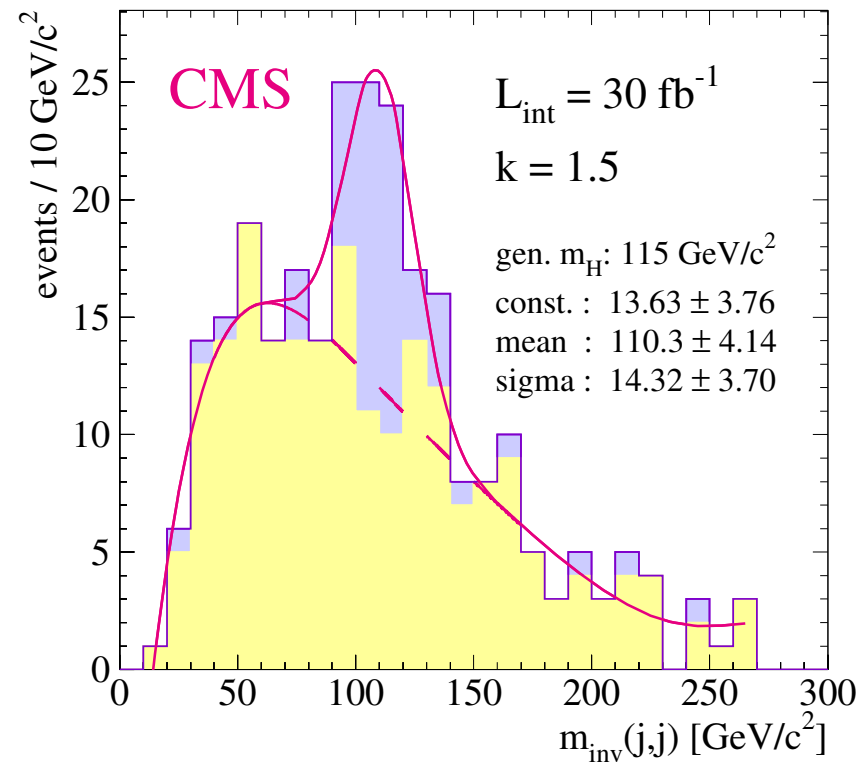
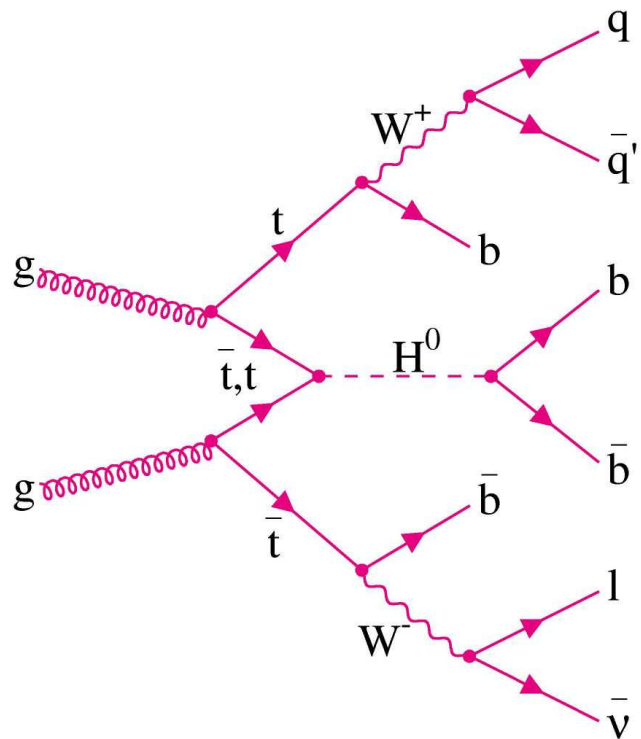
$$m_T = \sqrt{2 p_T^{\ell\ell} \cancel{E}_T (1 - \cos(\Delta\Phi))}$$

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

$$m_H = 170 \text{ GeV}$$

$$\text{integrated luminosity} = 20 \text{ fb}^{-1}$$

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

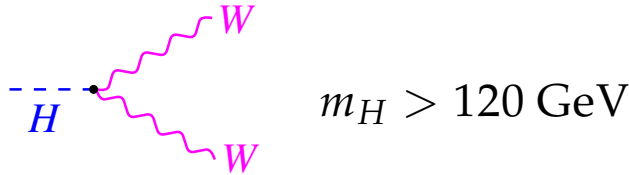
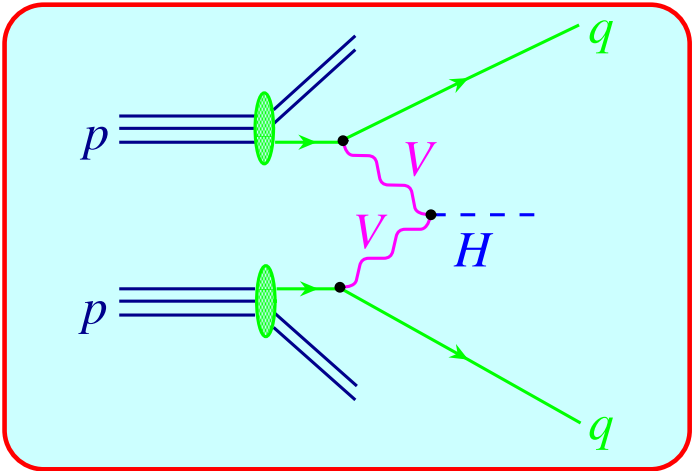


✓  $h_t = t\bar{t}H$  Yukawa coupling  $\implies$  measure  $h_t^2 \text{BR}(H \rightarrow b\bar{b})$

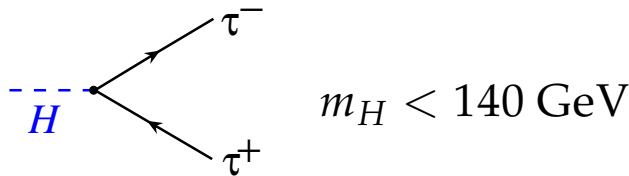
✗ must know the background normalization precisely



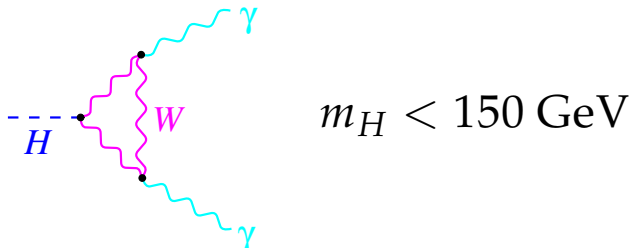
# Weak Boson Fusion



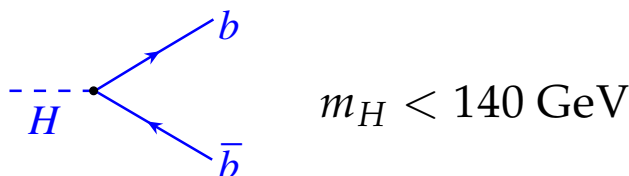
$m_H > 120 \text{ GeV}$



$m_H < 140 \text{ GeV}$



$m_H < 150 \text{ GeV}$

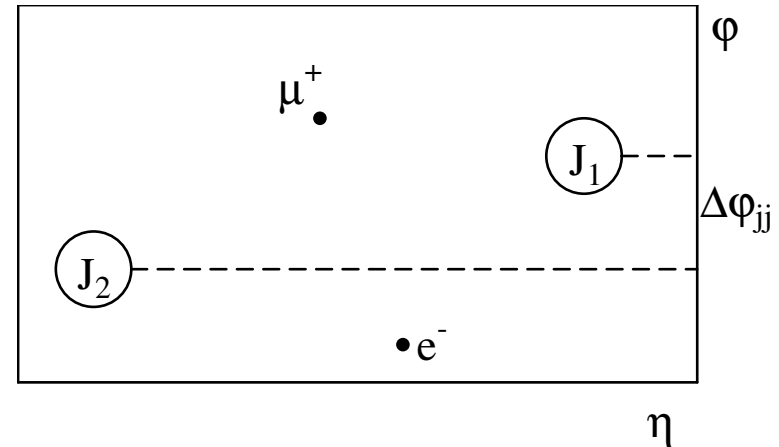
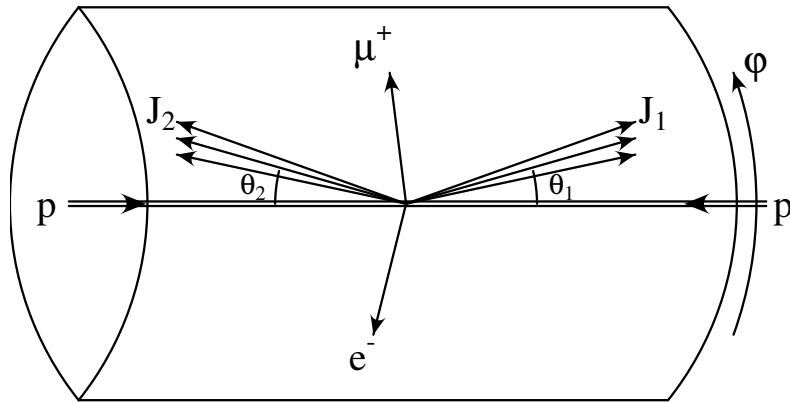


$m_H < 140 \text{ GeV}$

[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,  $\sigma \times \text{BR}$ , 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 $H \rightarrow WW$

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

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

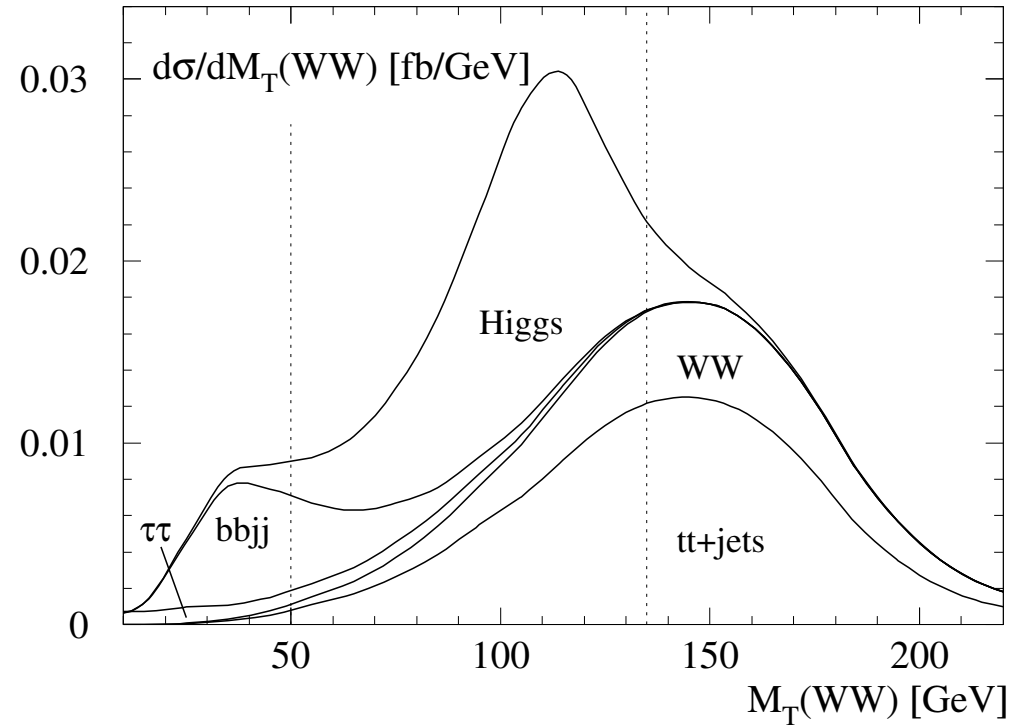
$$\cancel{E}_T = \sqrt{\mathbf{p}'_T{}^2 + m_{\nu\nu}^2} \approx \sqrt{\mathbf{p}'_T{}^2 + m_{ll}^2}$$

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

Observe Jacobian peak below

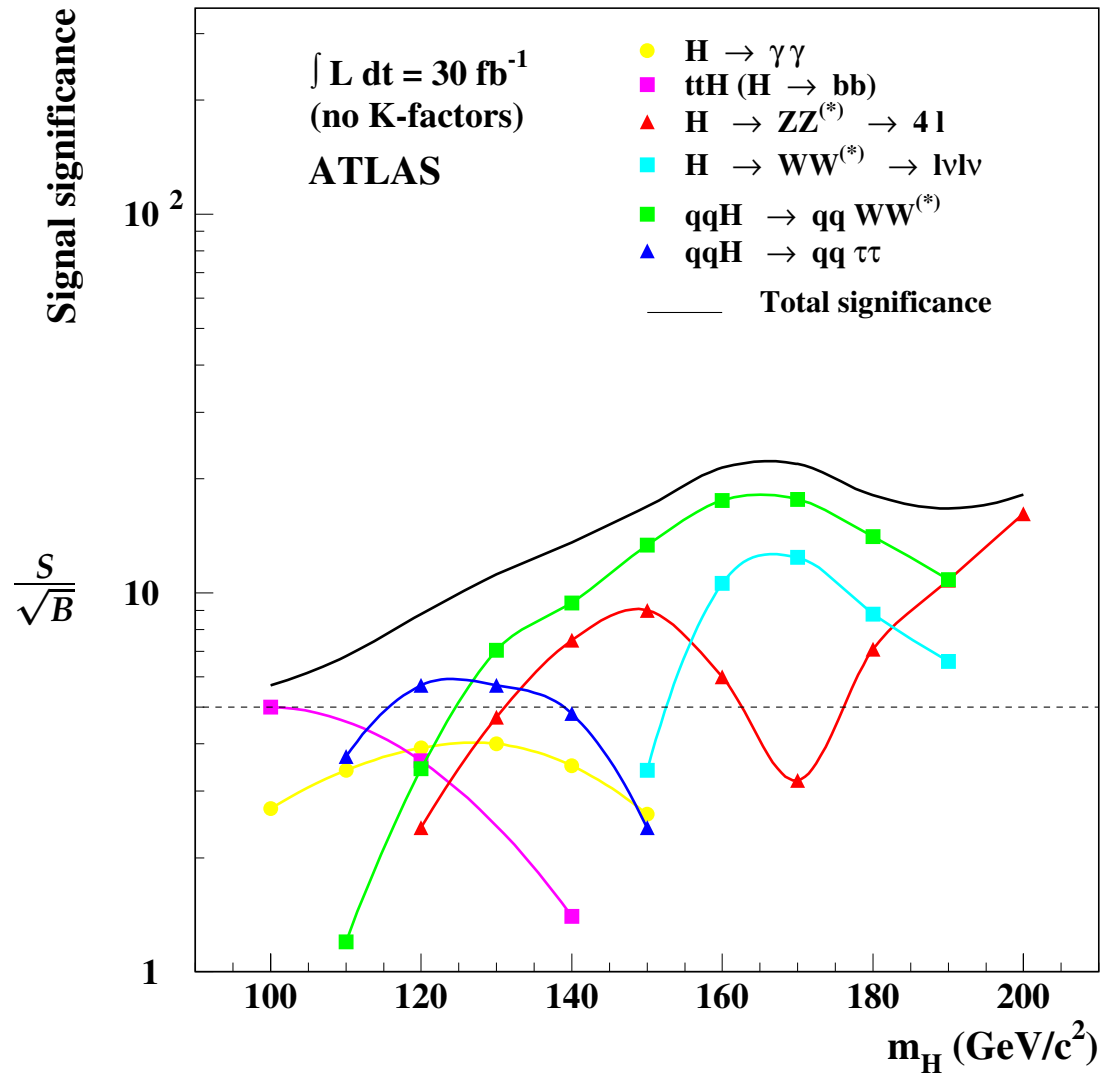
$$M_T = m_H$$

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



Transverse mass distribution for  $m_H = 115$  GeV and  $H \rightarrow WW^* \rightarrow e^\pm \mu^\mp \cancel{p}_T$

# Higgs discovery potential

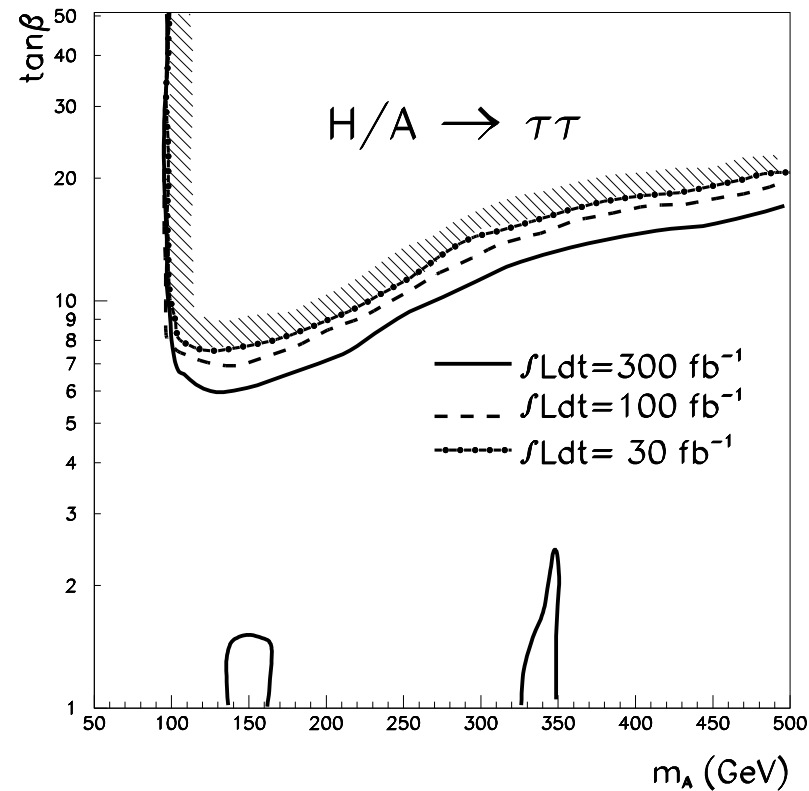


# Reach for H/A discovery within MSSM

ATLAS TDR

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

- ⇒ large production cross section for  $pp \rightarrow \bar{b}bH/A$
- ⇒ decay dominated by  $H/A \rightarrow \bar{b}b, \tau^+\tau^-$



$5\sigma$  discovery contours

# Reach for $H^\pm$ discovery within MSSM

- For  $m_{H^\pm} > m_t + m_b$  expect  $H^\pm \rightarrow tb$  decay

- Dominant production process

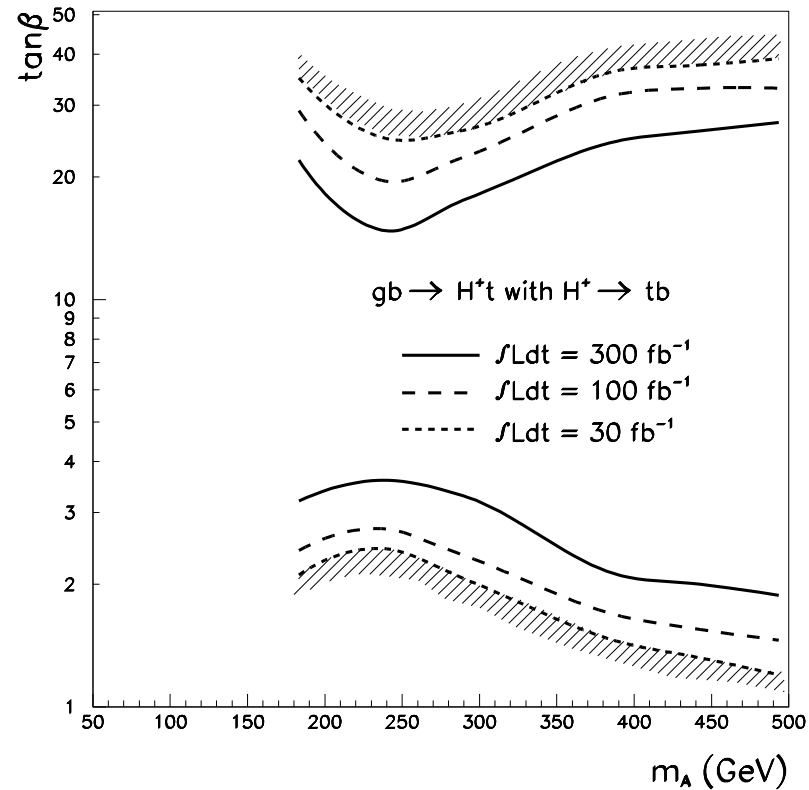
$$gg \rightarrow H^\pm tb$$

b-quark has low  $p_T$ :

$gb \rightarrow H^\pm t$  is dominant subprocess

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

ATLAS TDR



$5\sigma$  discovery contours

## Measuring Higgs couplings at LHC

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

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

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

**Problem:** rescaling fit results by common factor  $f$

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

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

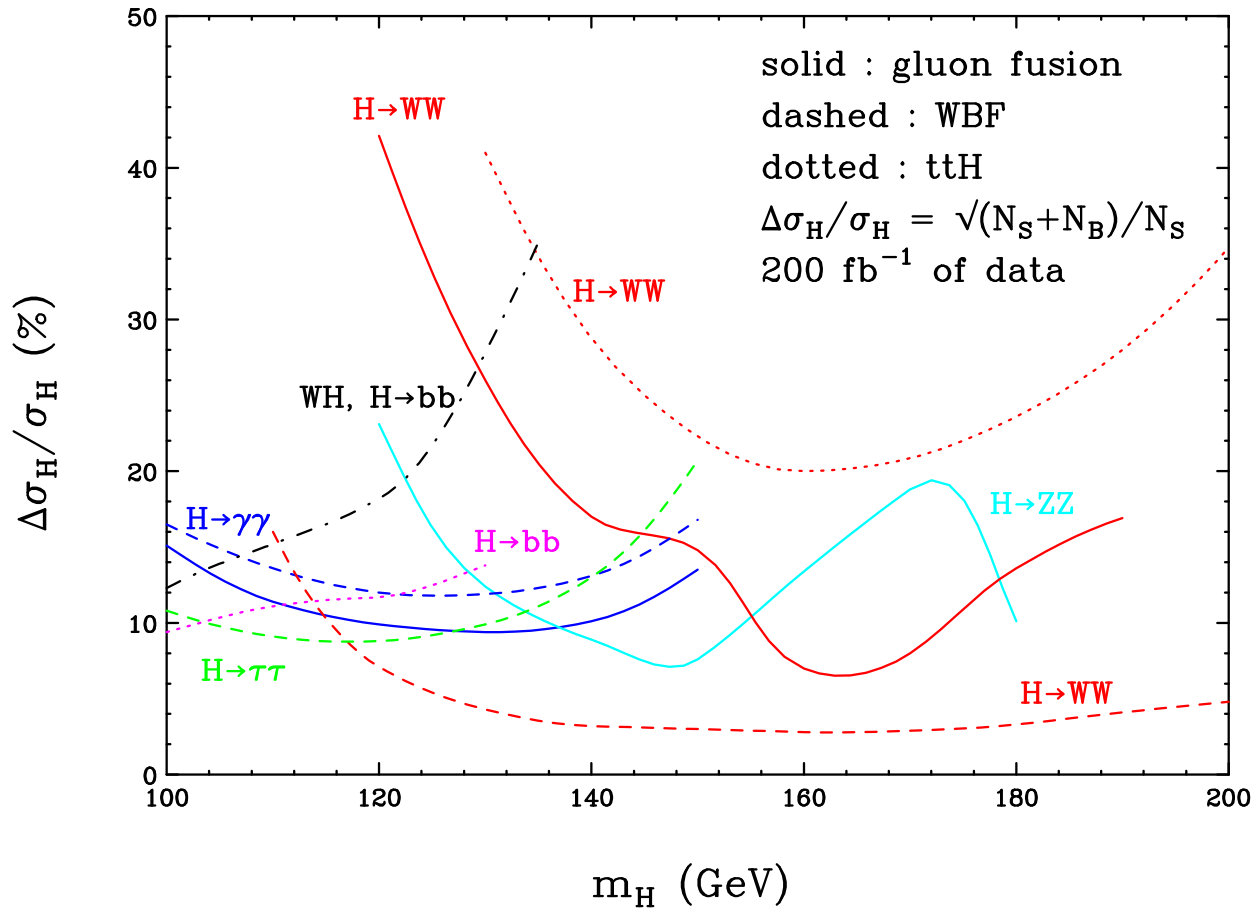
Loose bounds on scaling factor:

$$f^2 \Gamma > \sum_{obs} f \Gamma_x \quad \implies \quad f > \sum_{obs} \frac{\Gamma_x}{\Gamma} = \sum_{obs} BR(H \rightarrow xx) (= \mathcal{O}(1))$$

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

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

## 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%



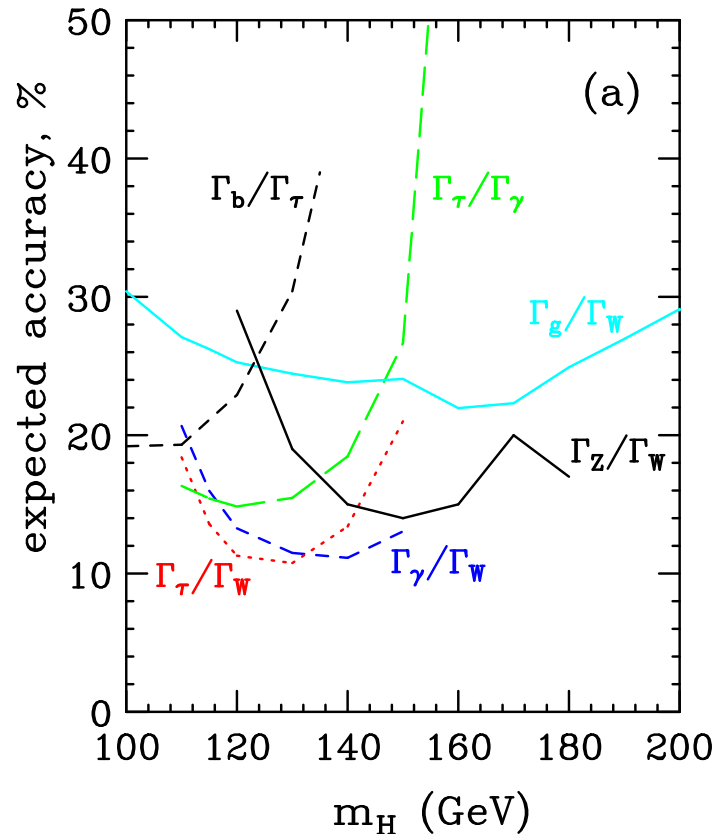
# Fit LHC data within constrained models

•  $\frac{g_{H\tau\tau}}{g_{Hbb}} = \text{SM value}$

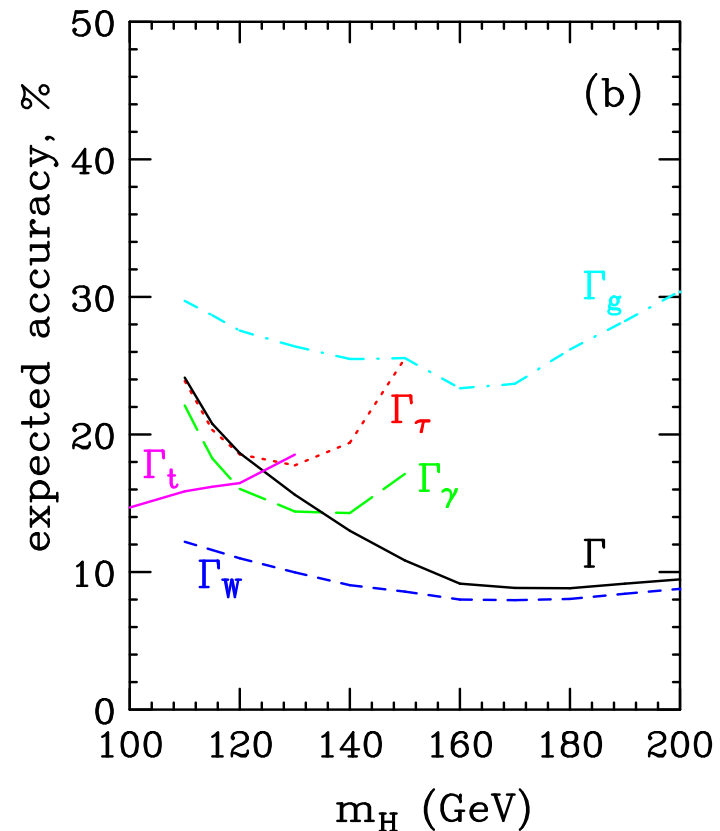
•  $\frac{g_{HWW}}{g_{HZZ}} = \text{SM value}$

• no exotic channels

width ratios



(partial) widths



With  $200 \text{ fb}^{-1}$  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

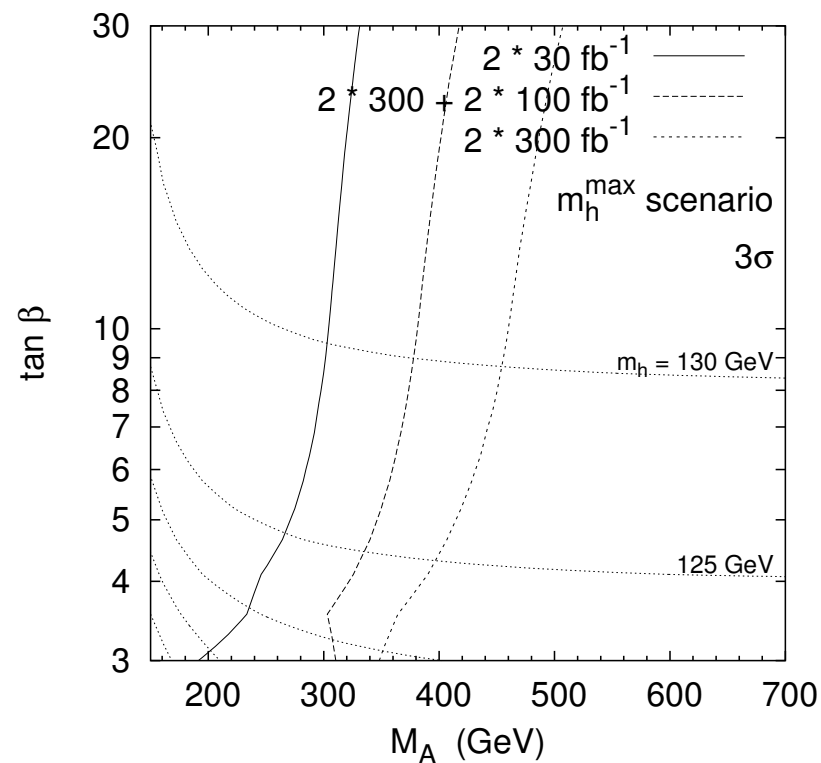
Consider modest  $m_A$ :

- 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  $h$



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

$3\sigma$ -effects or more at small  $m_A$



## QCD corrections for Higgs production

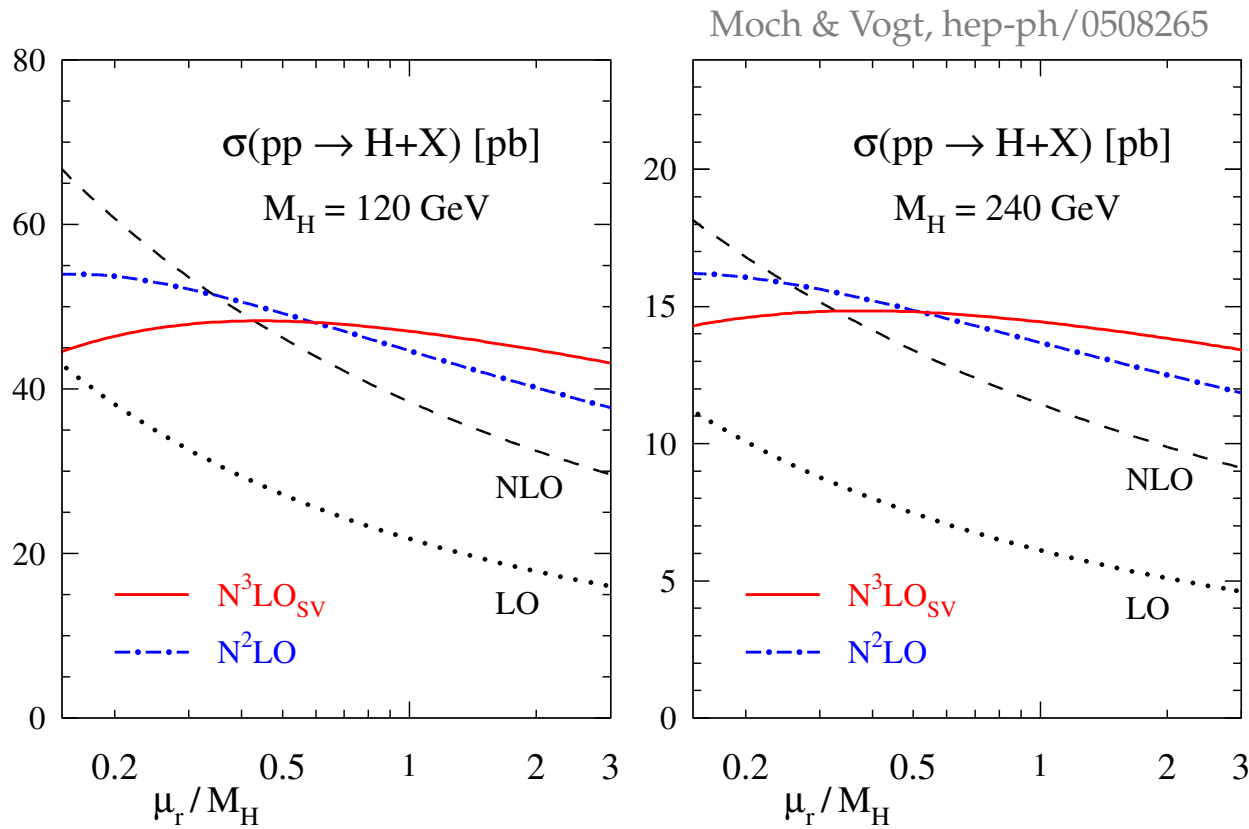
Measurement of **partial widths** at **10–20% level** or **couplings** at **5–10% level** requires **predictions** of SM production cross sections at **10% level or better**

⇒ need QCD corrections to production cross sections

Much work in recent years

- $gg \rightarrow H$  (all but NLO in  $m_t \rightarrow \infty$  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<sup>3</sup>LO 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)**

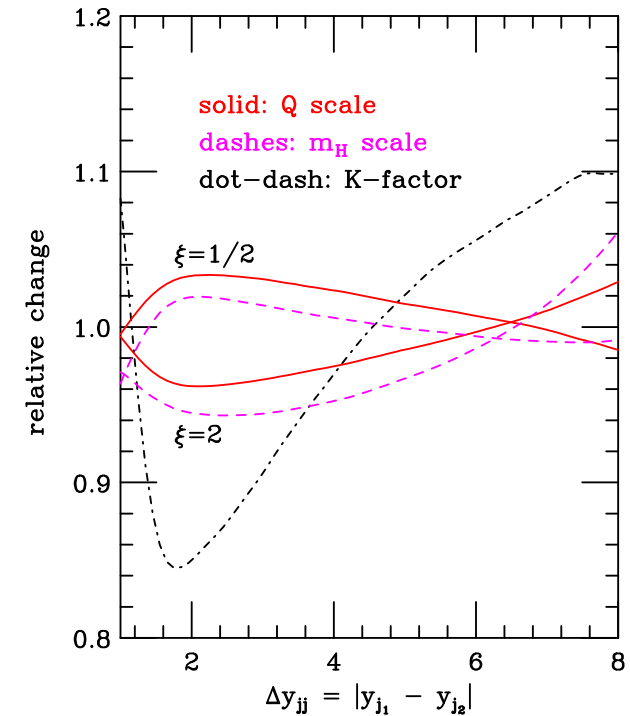
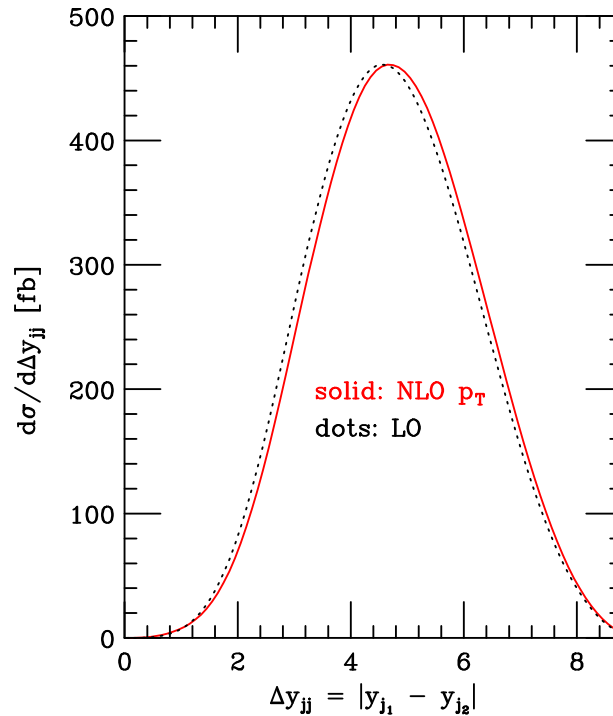
# QCD corrections to $gg \rightarrow H$



- ✓ 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  $H \rightarrow WW$  search

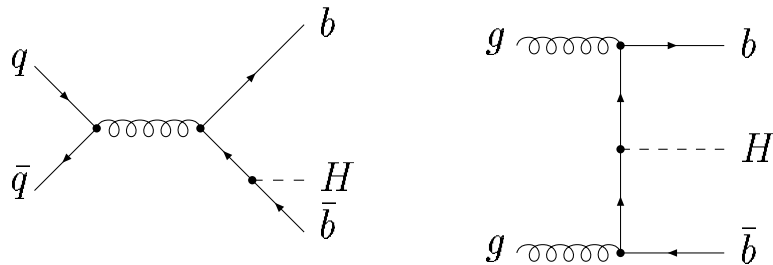
# NLO QCD corrections to WBF

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

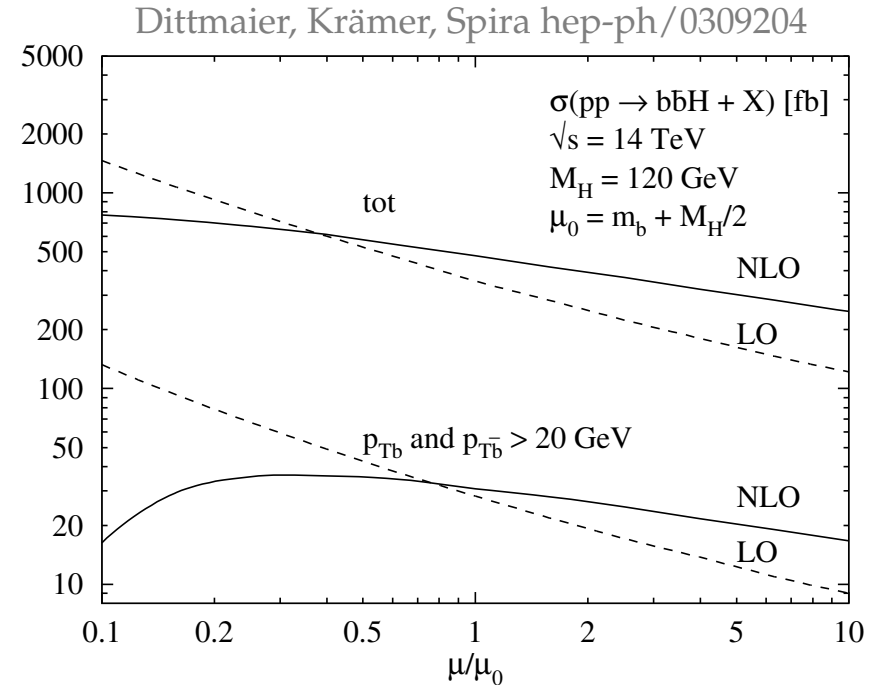


$m_H = 120$  GeV, typical WBF cuts

# NLO QCD corrections to $b\bar{b}H$ production



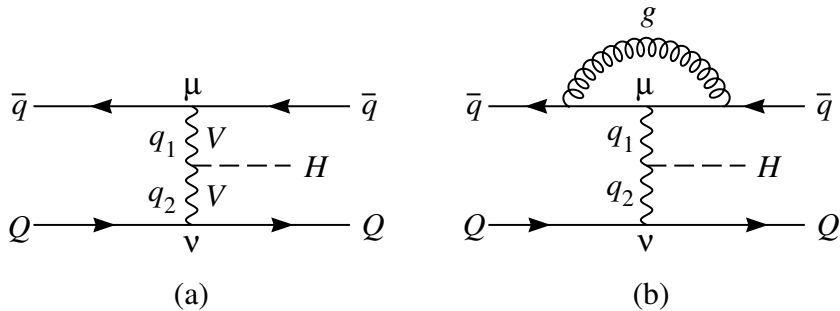
- Discovery channel for H/A in the MSSM at sizeable  $\tan \beta$
- NLO corrections known for  $b\bar{b}H$  final state
- b-quarks at low  $p_T$ : effective process is  $b\bar{b} \rightarrow H$ : cross section known at NNLO  
Harlander, Kilgore (2003)



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

# Tensor structure of the $HVV$ coupling

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



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

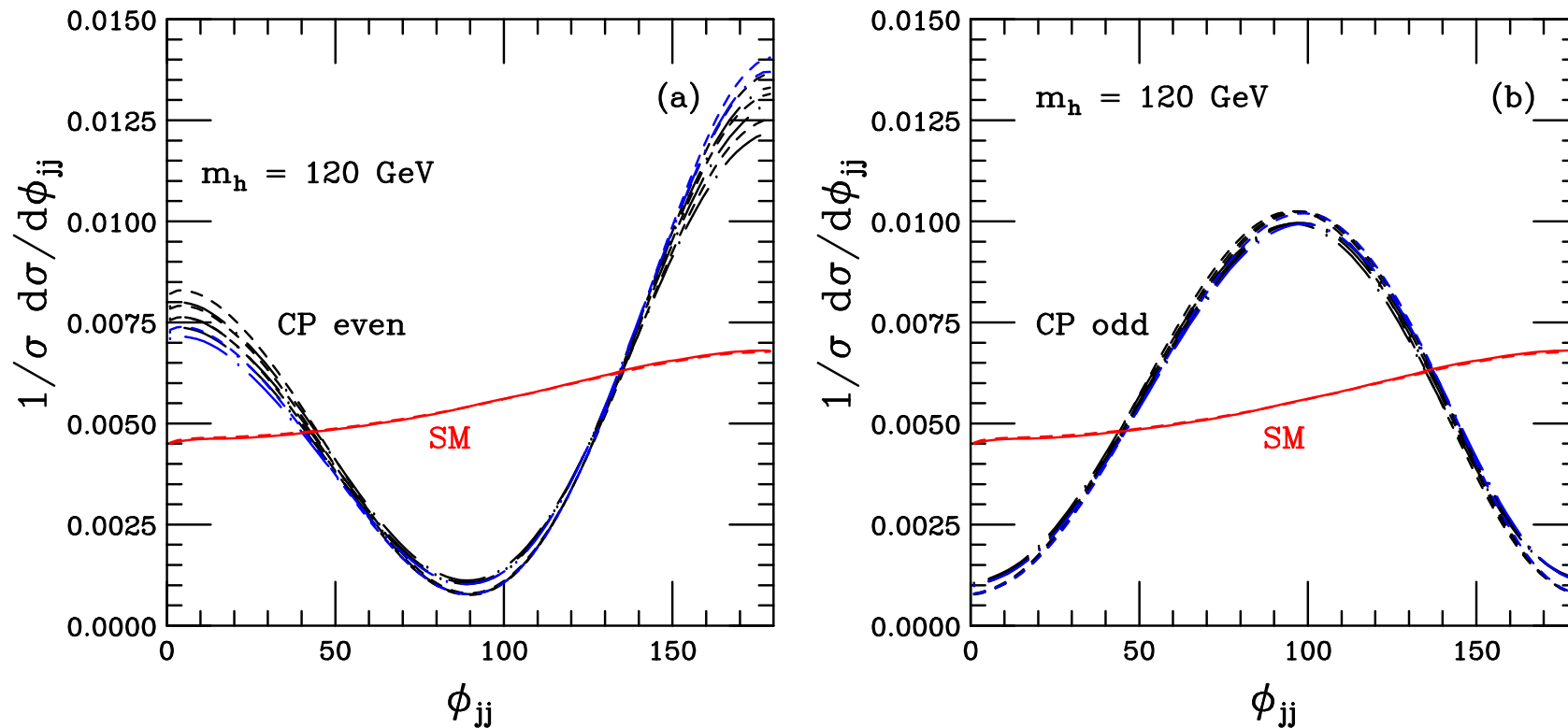
Must distinguish  $a_1, a_2, a_3$  experimentally

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

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

## Azimuthal angle correlations

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



Dip structure at  $90^\circ$  (CP even) or  $0/180^\circ$  (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

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

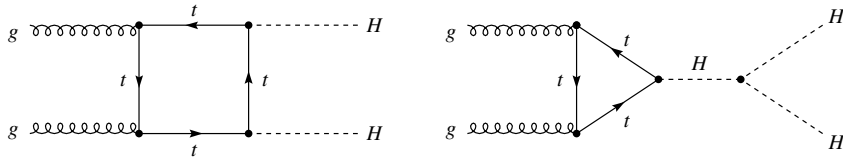
$$\sigma(gg \rightarrow HH) \approx 20 - 30 \text{ fb at 14 TeV}$$

Gianotti et al., hep-ph/0204087

⇒ Higgs mass:  $m_H^2 = 2\lambda v^2$

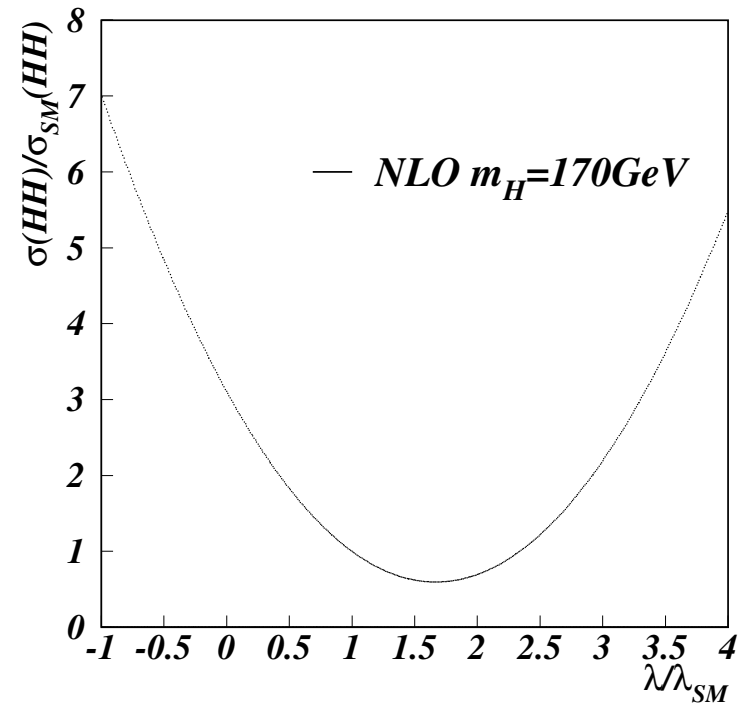
HHH coupling:  $6\lambda v = 3m_H^2/v$

Probe this relation in  $gg \rightarrow HH$



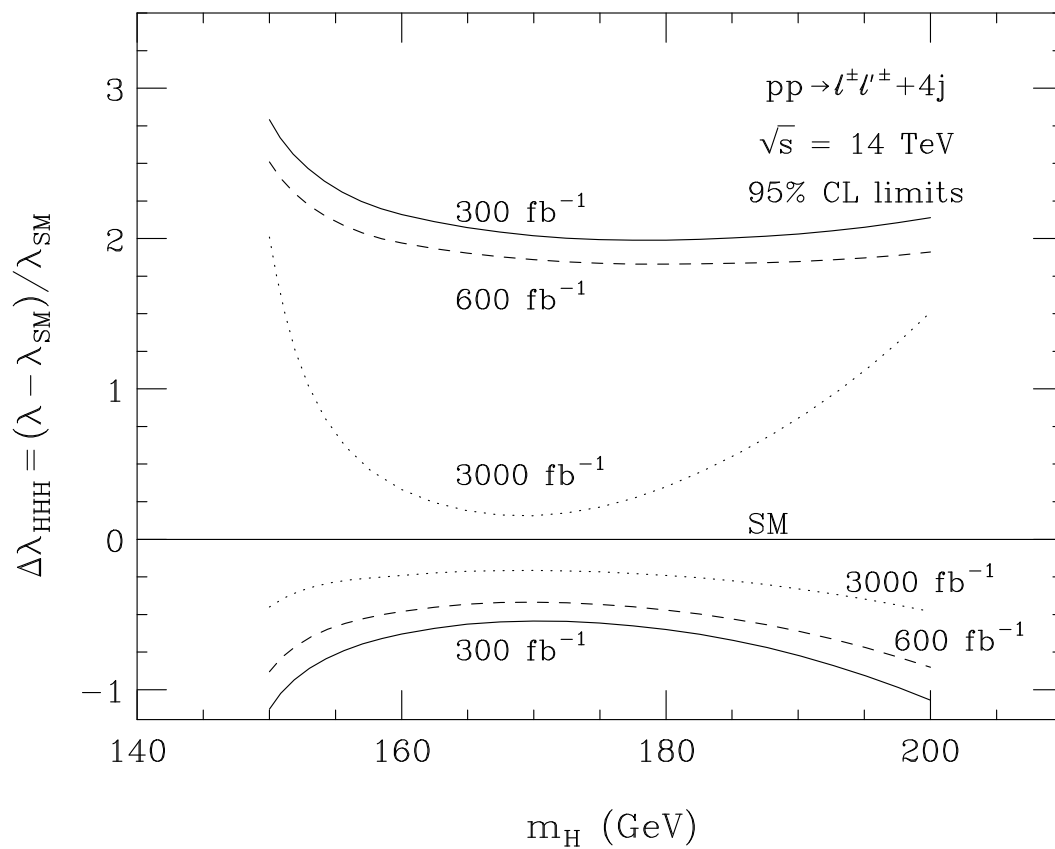
Most sensitive decay channel:

$$\begin{aligned} HH &\rightarrow W^+W^-W^+W^- \\ &\rightarrow l^\pm l'^\pm + 4j + \cancel{p}_T \end{aligned}$$



# LHC sensitivity to $HHH$ coupling

Baur, Plehn, Rainwater: hep-ph/0211224



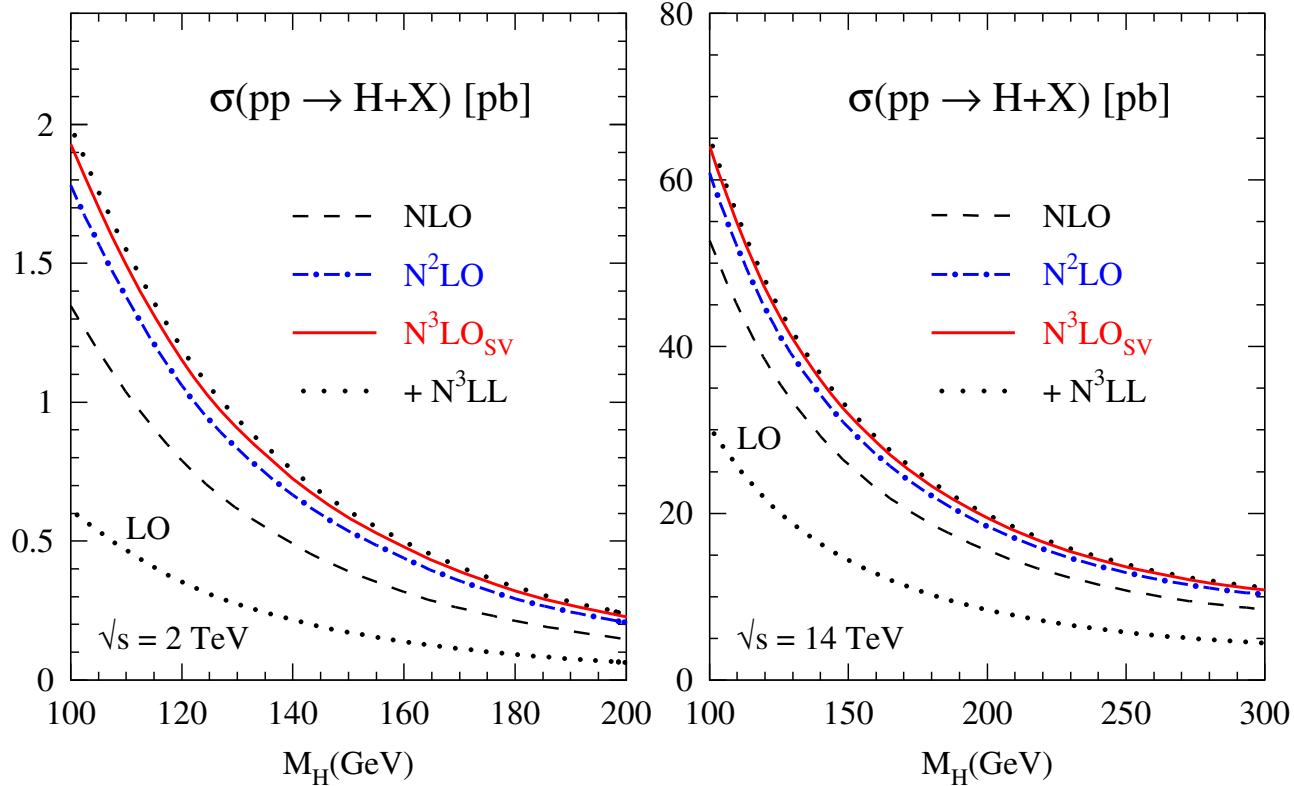
- Need very high luminosity for serious measurement of self coupling
- SLHC sensitivity: up to  $\pm 20\%$

## Conclusions

- LHC will observe a SM-like Higgs boson in multiple channels, with 5...20% statistical errors  
⇒ 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  
⇒ 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 $gg \rightarrow H$

Moch & Vogt, hep-ph/0508265



Cross section as function of  $m_H$  for Tevatron and LHC