

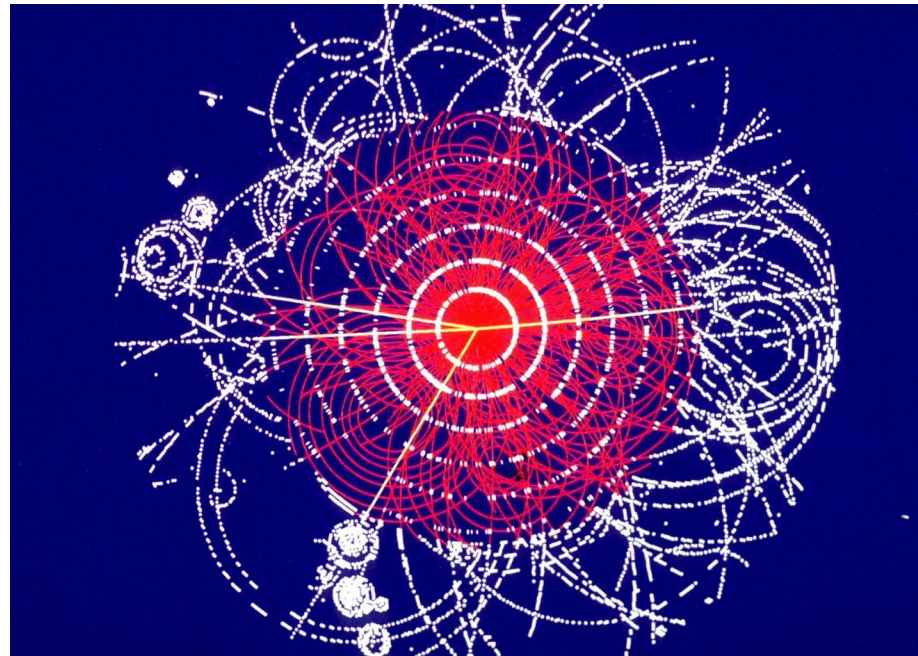
HIGGS PHYSICS AT THE LHC

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

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

- 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

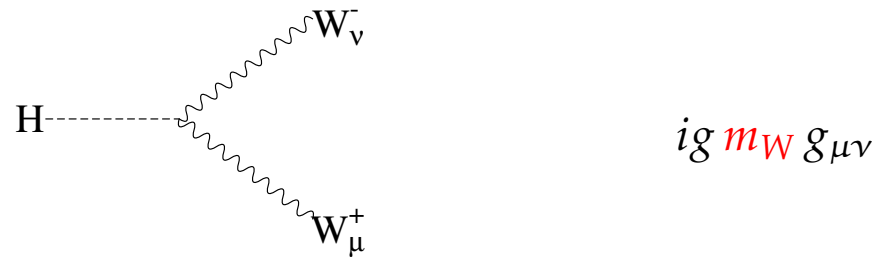
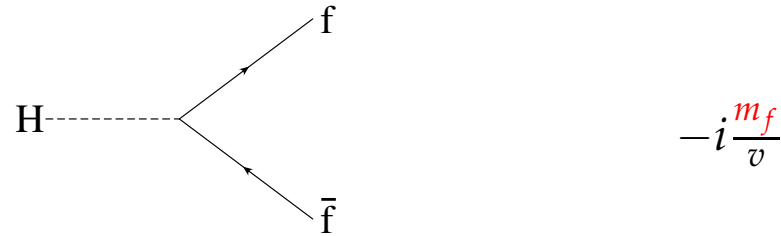
Kinetic energy term of Higgs doublet field:

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

- 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 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: χ^\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

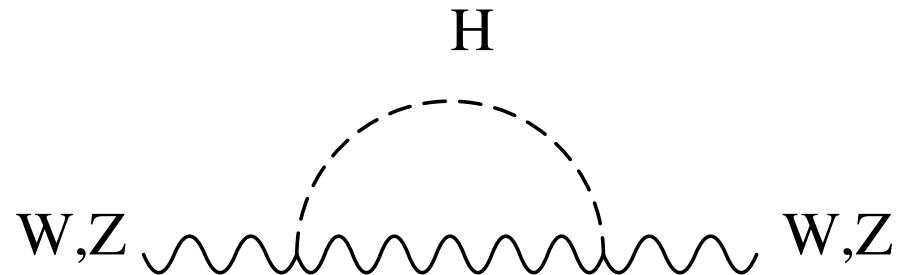
extra coupling factors for hVV and HVV couplings as compared to SM

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

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

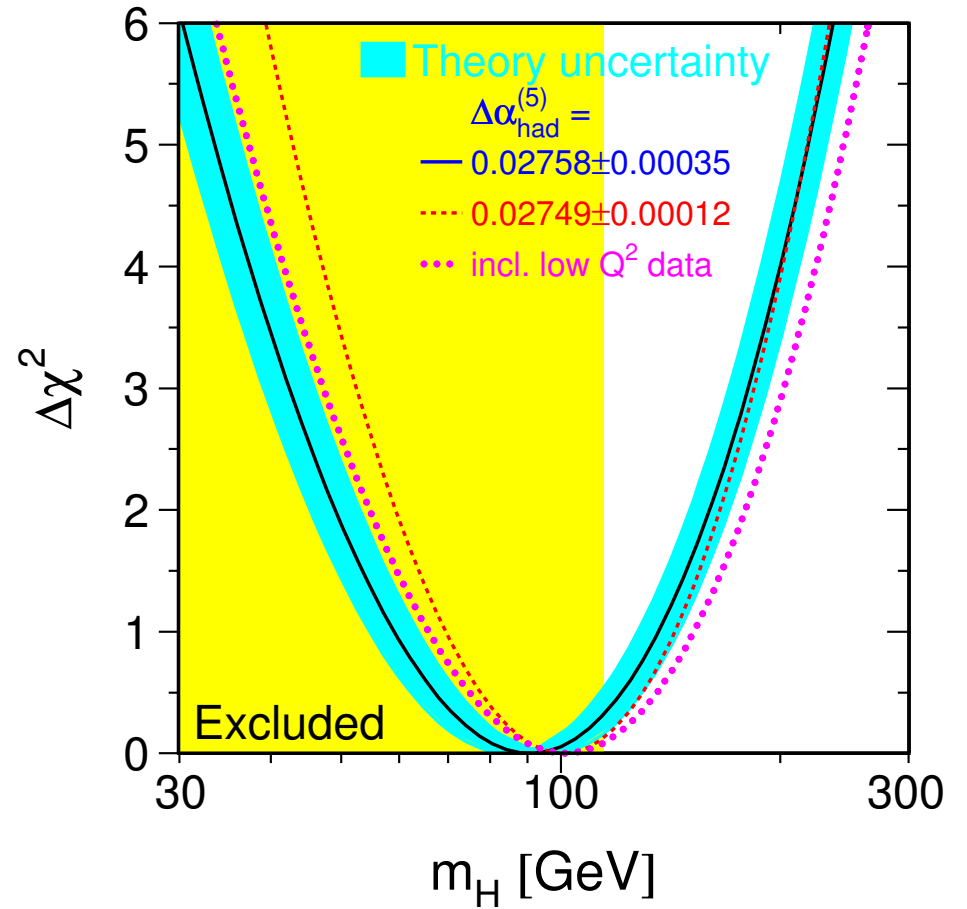
Direct search limit from LEP

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

Renormalize probability for

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

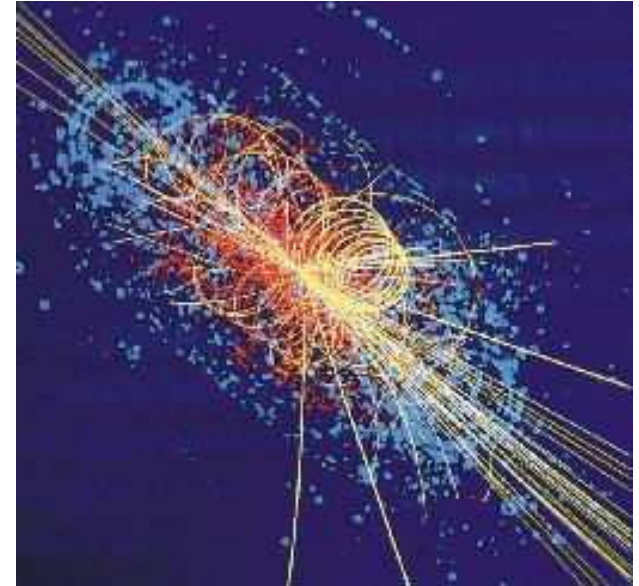
$$m_H < 219 \text{ GeV} \quad (95\% \text{ CL})$$



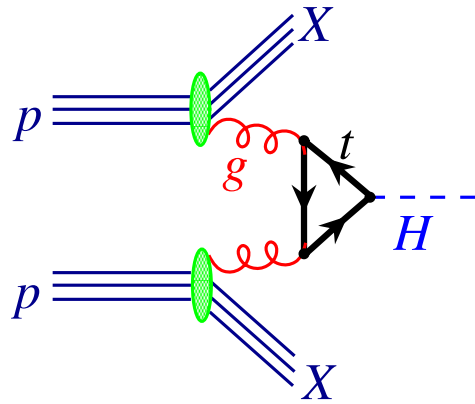
Higgs boson channels at LHC

Two steps

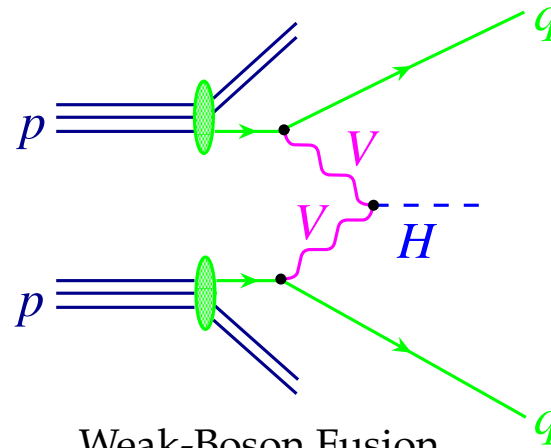
- **Production** of the Higgs boson
- **Detection** of the **decay products** of the Higgs boson and identification of the events



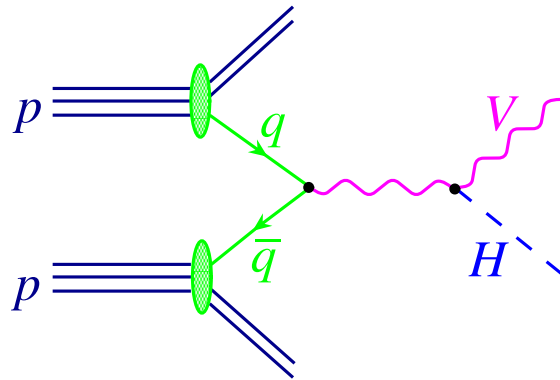
Production Modes



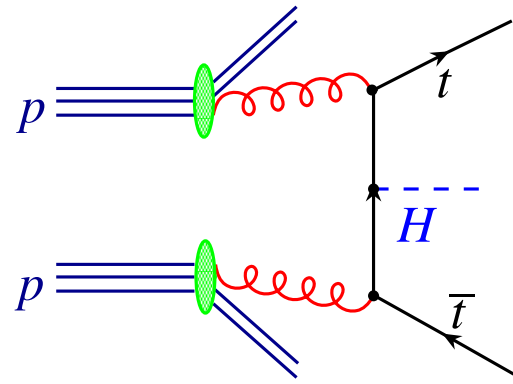
Gluon fusion



Weak-Boson Fusion

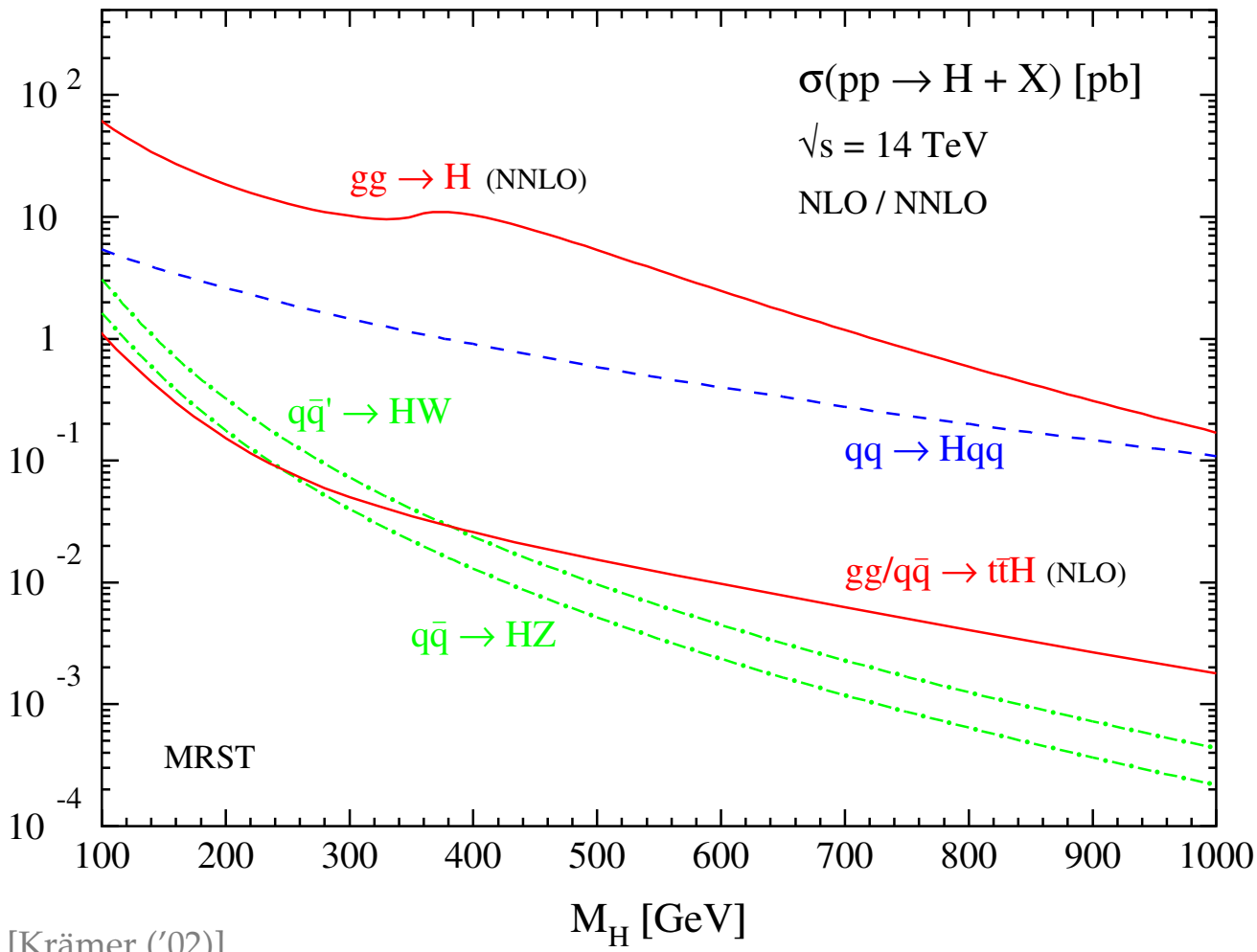


Higgs Strahlung

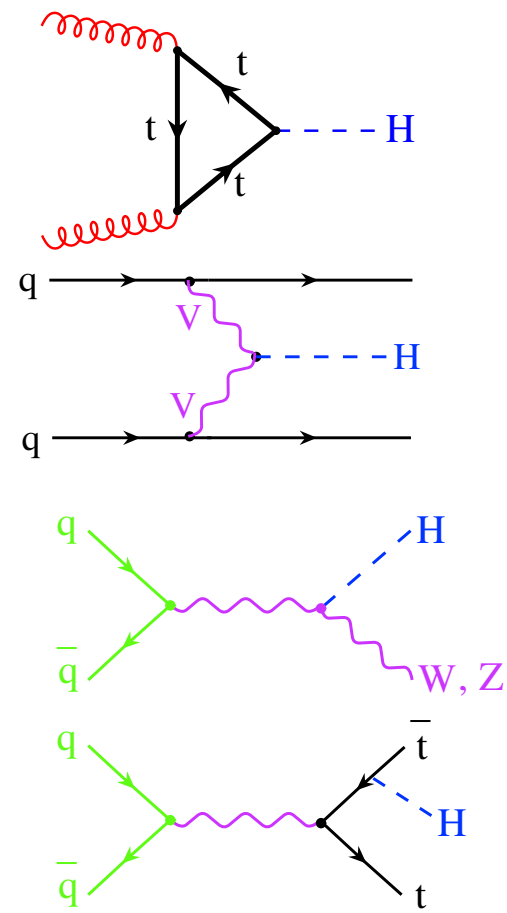


$t\bar{t}H$

Total cross sections at the LHC

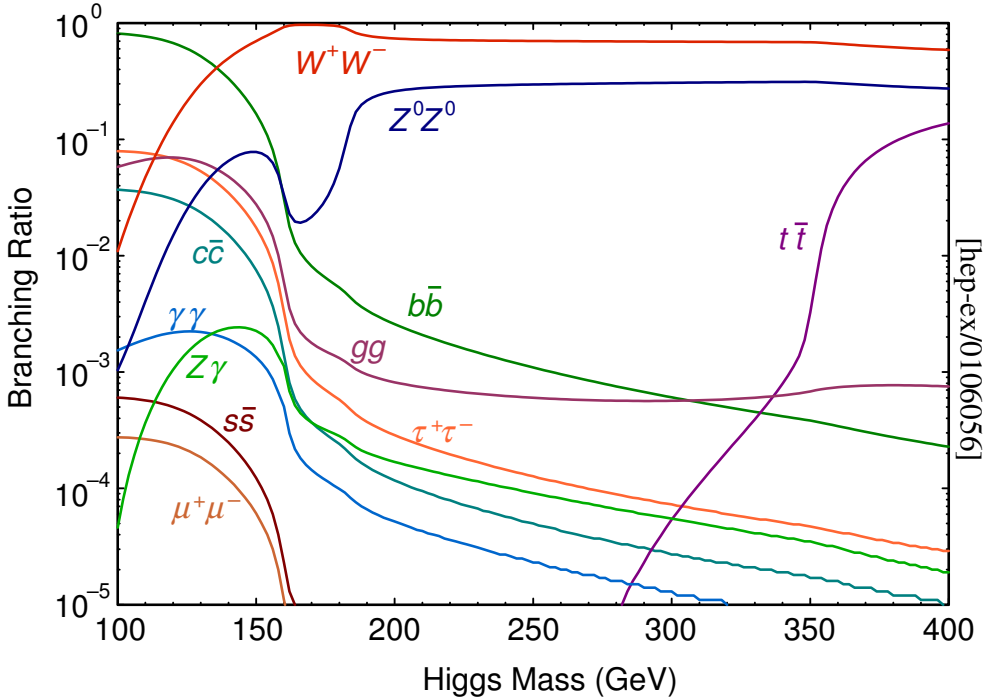
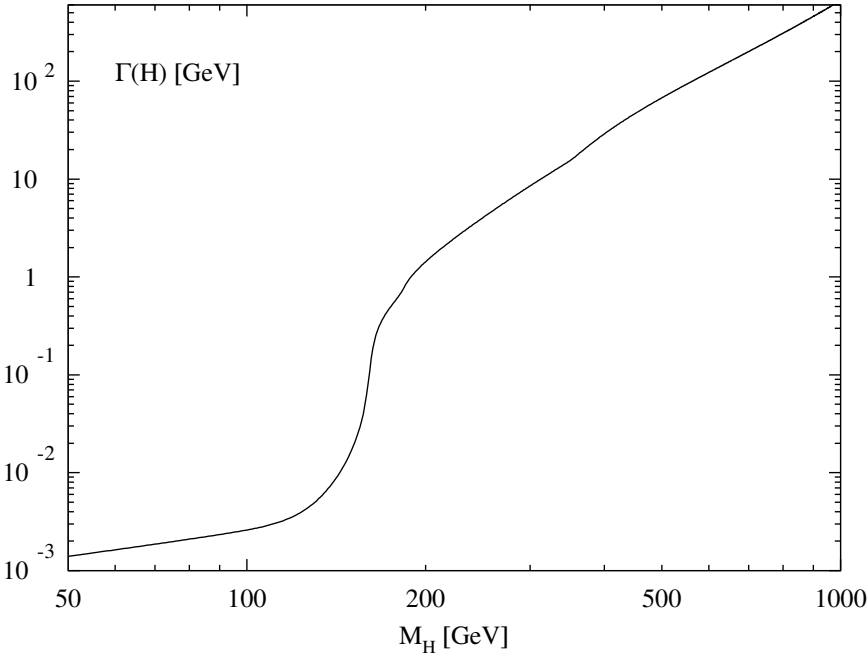


[Krämer ('02)]

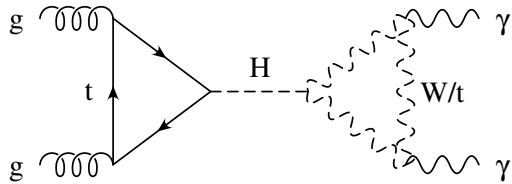


Decay of the SM Higgs

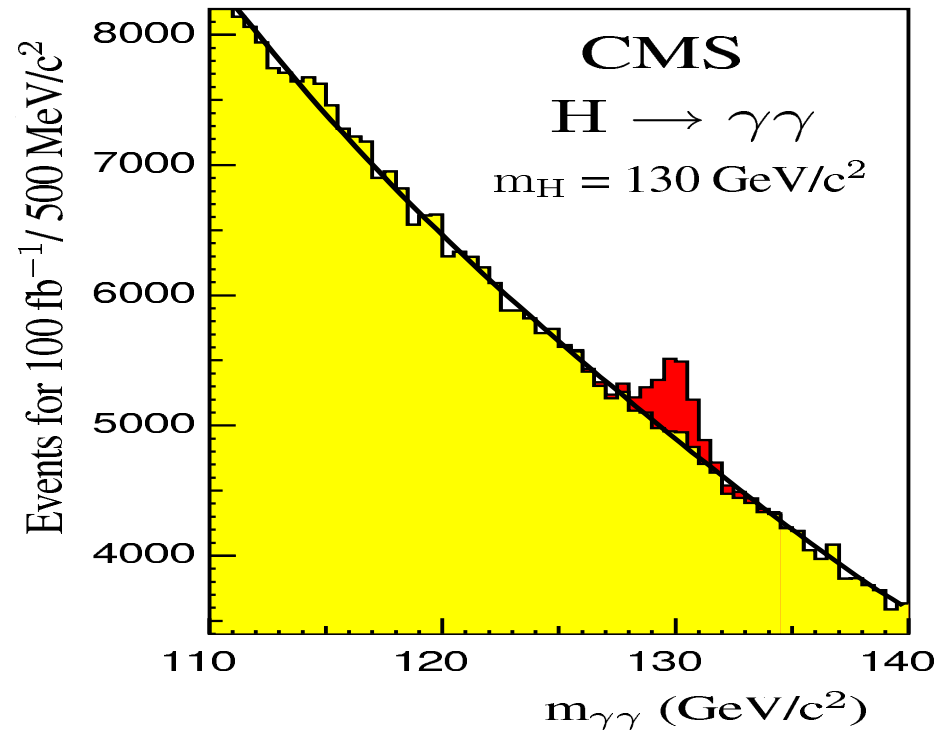
Higgs decay width and branching fractions within the SM



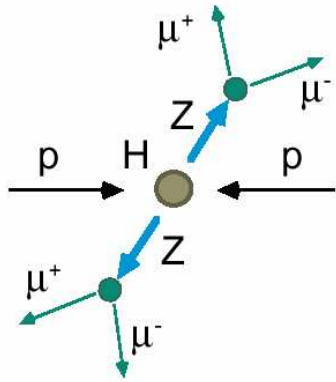
$H \rightarrow \gamma\gamma$



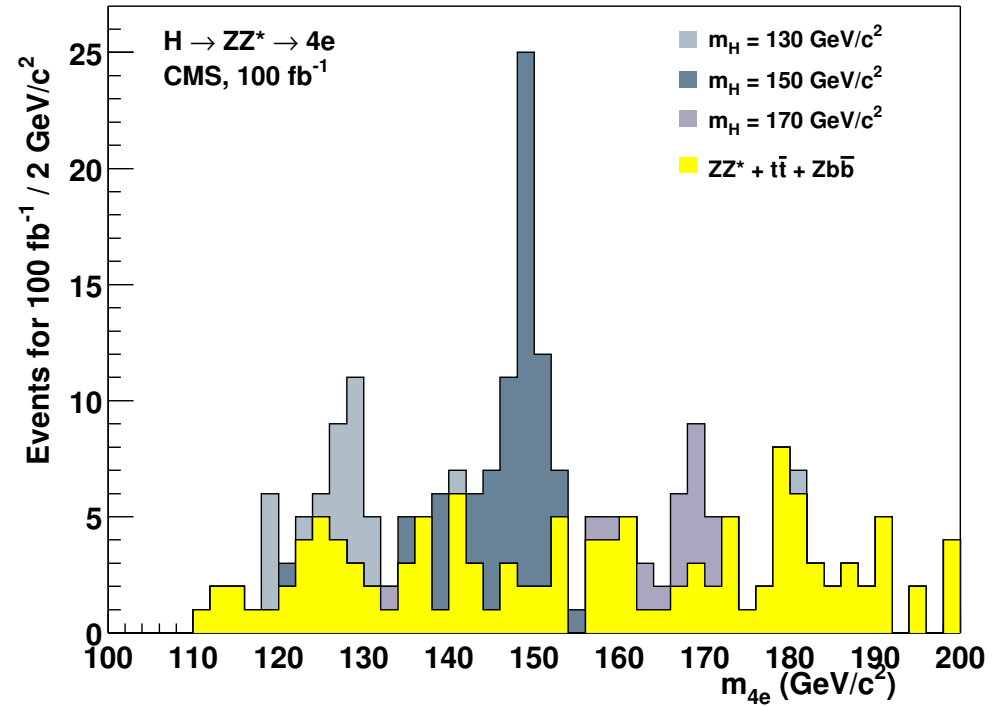
- ✗ $\text{BR}(H \rightarrow \gamma\gamma) \approx 10^{-3}$
- ✗ large backgrounds from $q\bar{q} \rightarrow \gamma\gamma$ and $gg \rightarrow \gamma\gamma$
- ✓ but CMS and ATLAS will have excellent photon-energy resolution (order of 1%)
- ✓ Look for a narrow $\gamma\gamma$ invariant mass peak
- ✓ extrapolate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



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



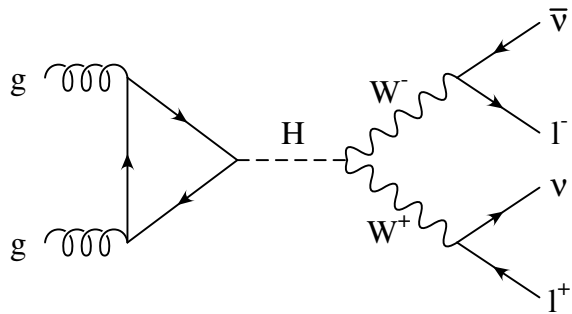
✓ invariant mass of the charged leptons fully reconstructed



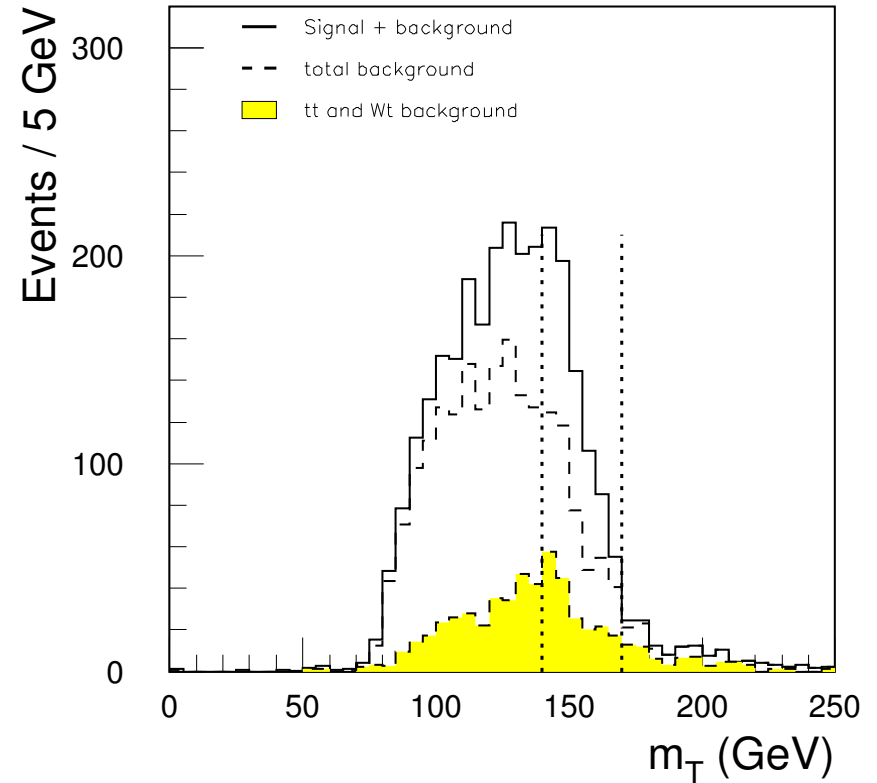
For $m_H \approx 0.6\text{--}1\text{ TeV}$, use the “silver-plated” mode $H \rightarrow ZZ \rightarrow \nu\bar{\nu}\ell^+\ell^-$

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

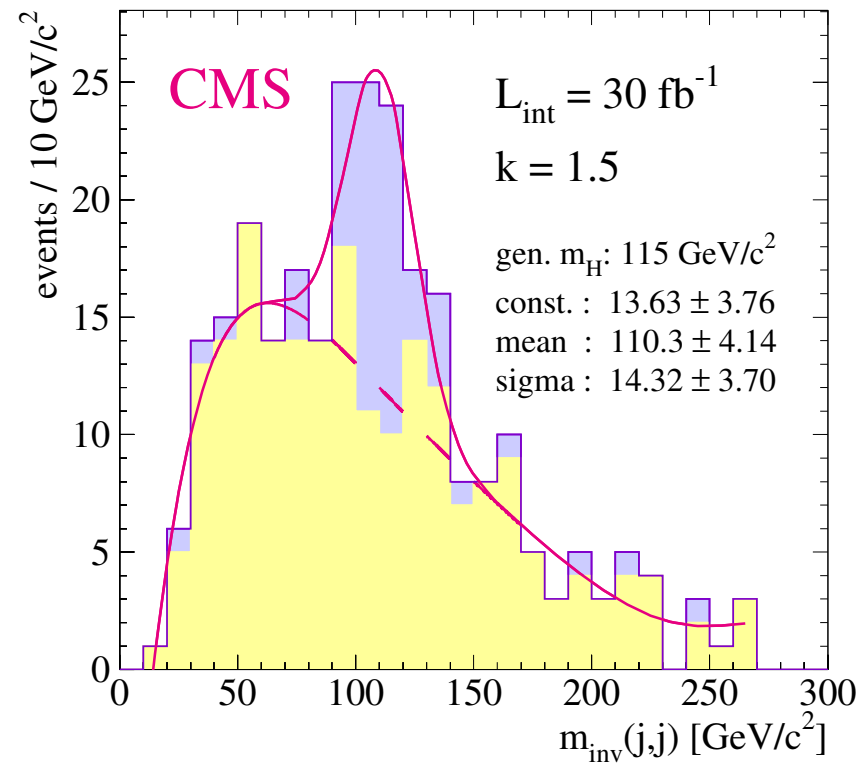
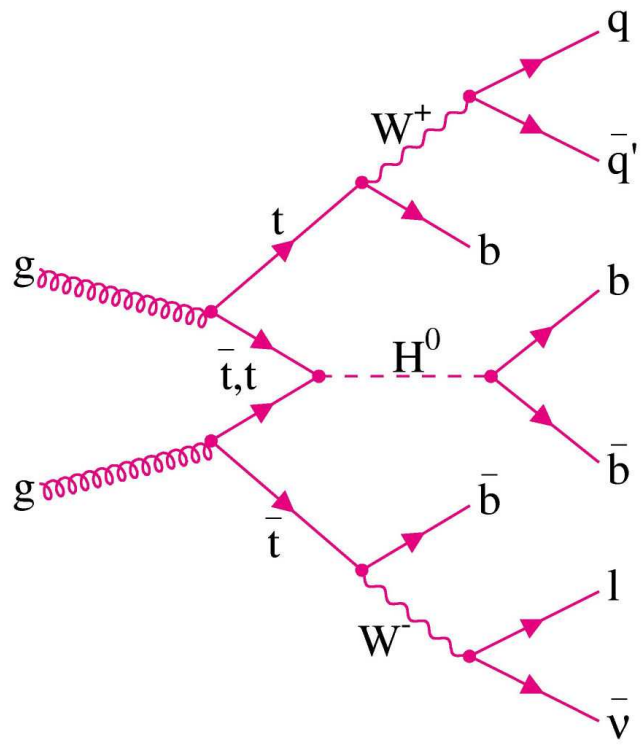
$$m_T = \sqrt{2 p_T^{\ell\ell} \cancel{E}_T (1 - \cos(\Delta\Phi))}$$

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

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

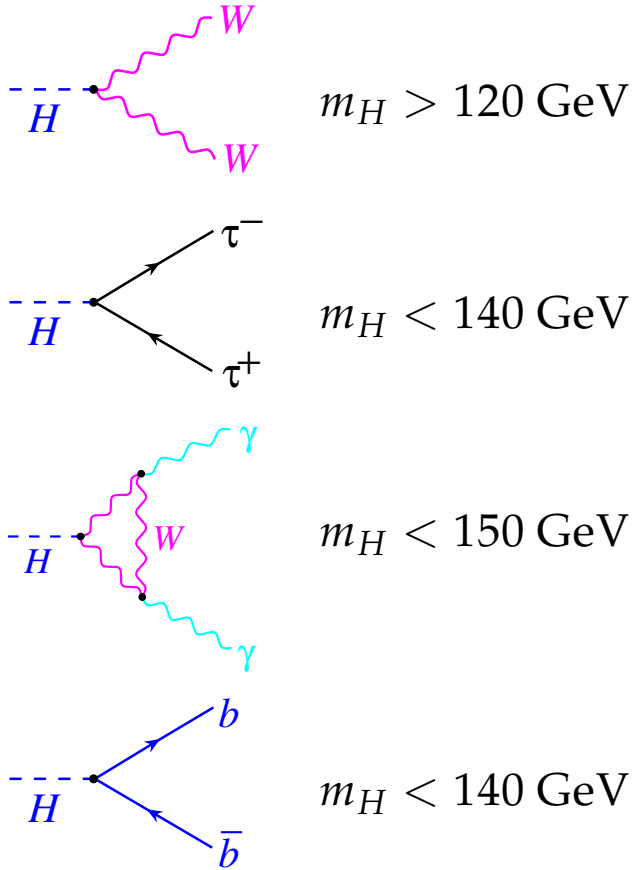
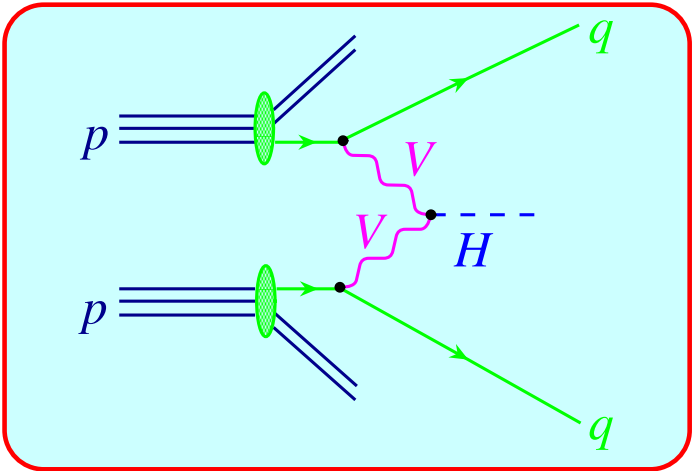
$$\text{integrated luminosity} = 20 \text{ fb}^{-1}$$

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



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

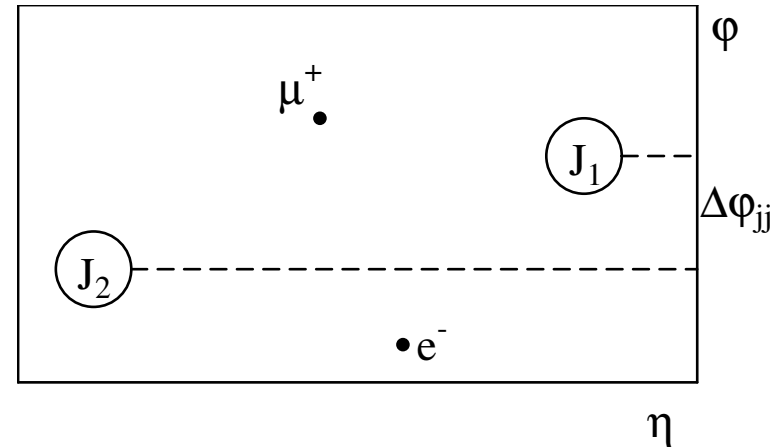
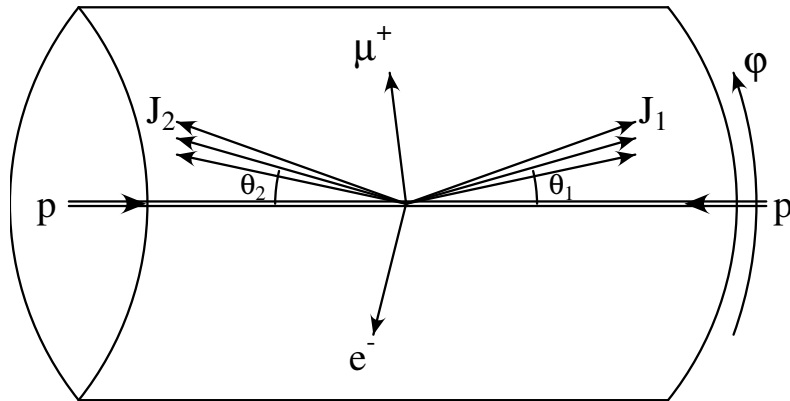
Weak Boson Fusion



[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:

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

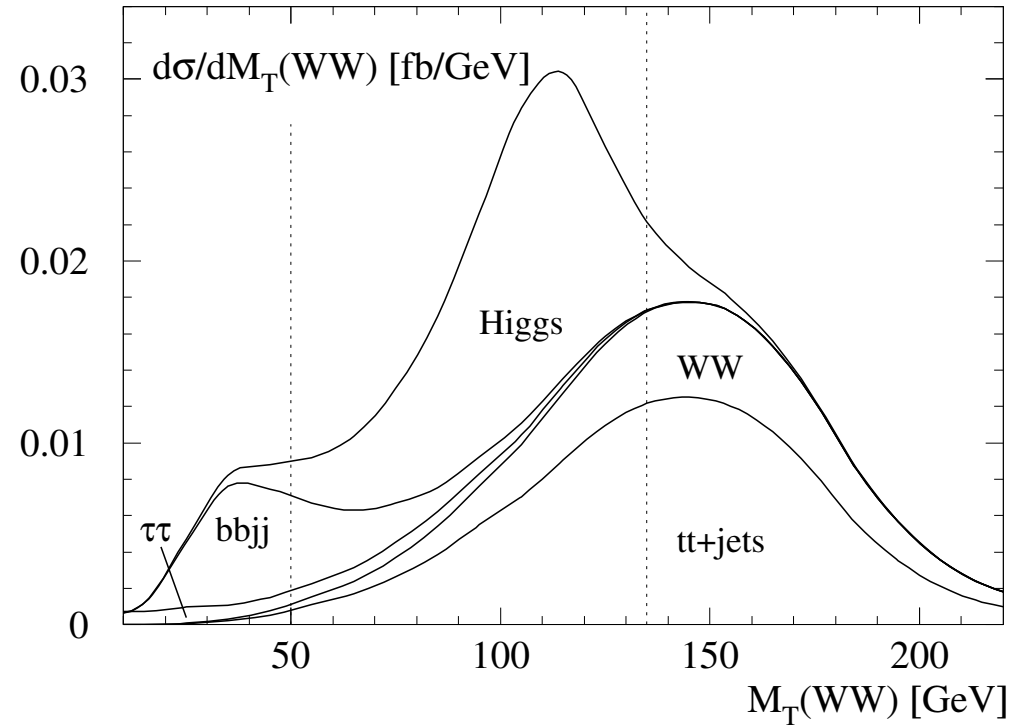
$$\cancel{E}_T = \sqrt{\mathbf{p}'_T{}^2 + m_{\nu\nu}^2} \approx \sqrt{\mathbf{p}'_T{}^2 + m_{ll}^2}$$

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

Observe Jacobian peak below

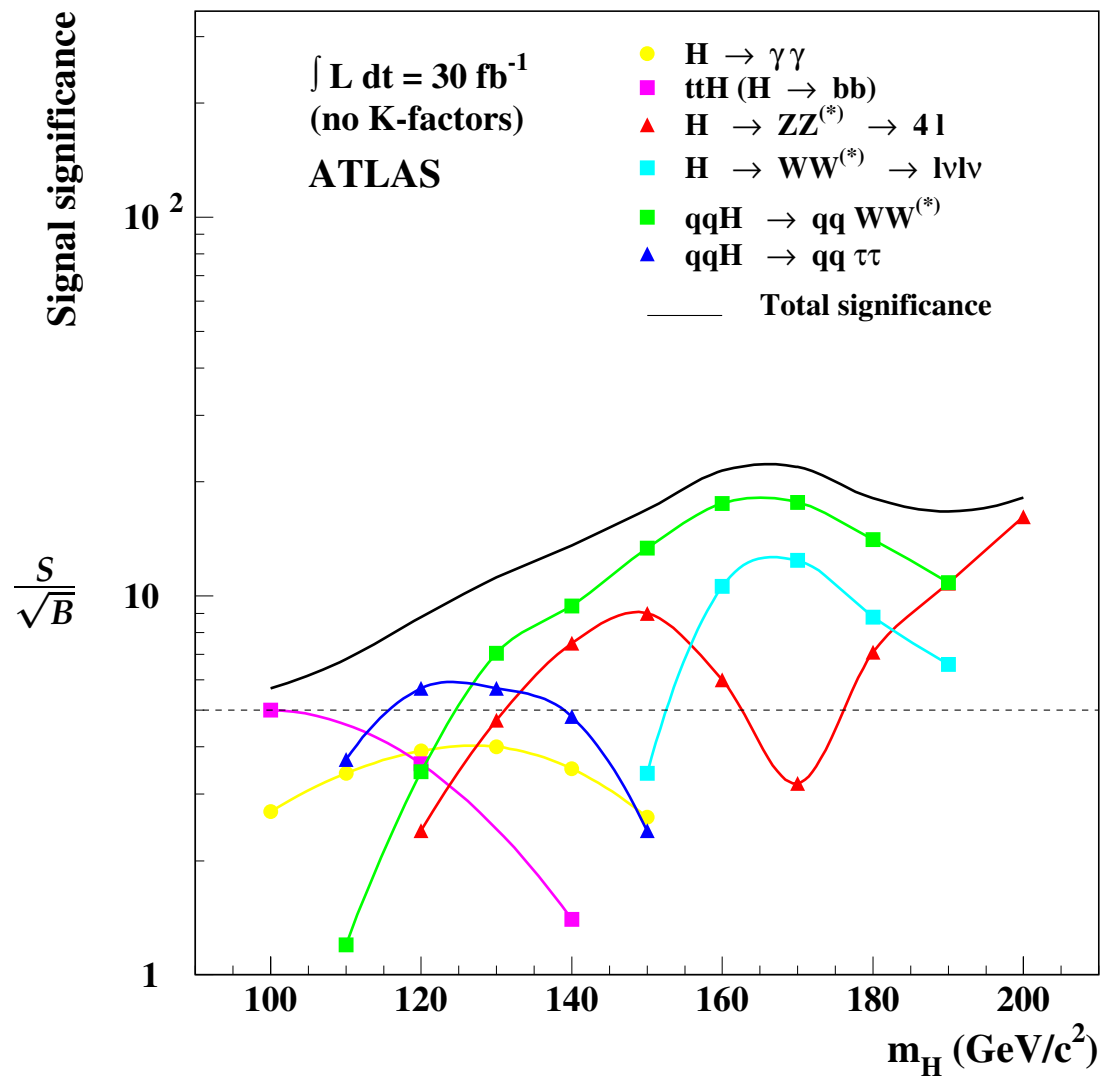
$$M_T = m_H$$

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

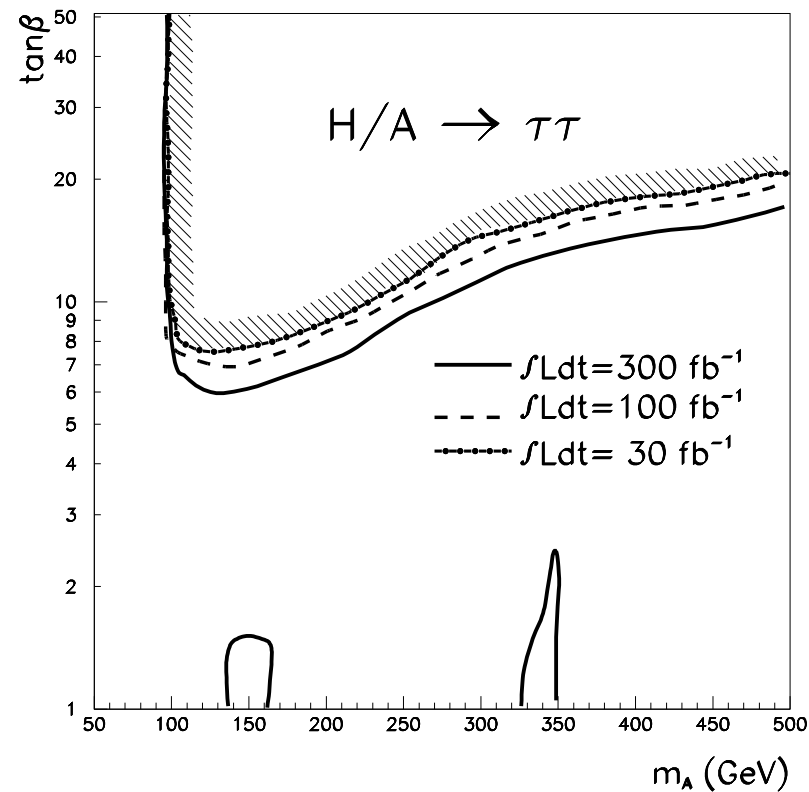


Reach for H/A discovery within MSSM

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 $H/A \rightarrow \bar{b}b, \tau^+\tau^-$



5σ 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

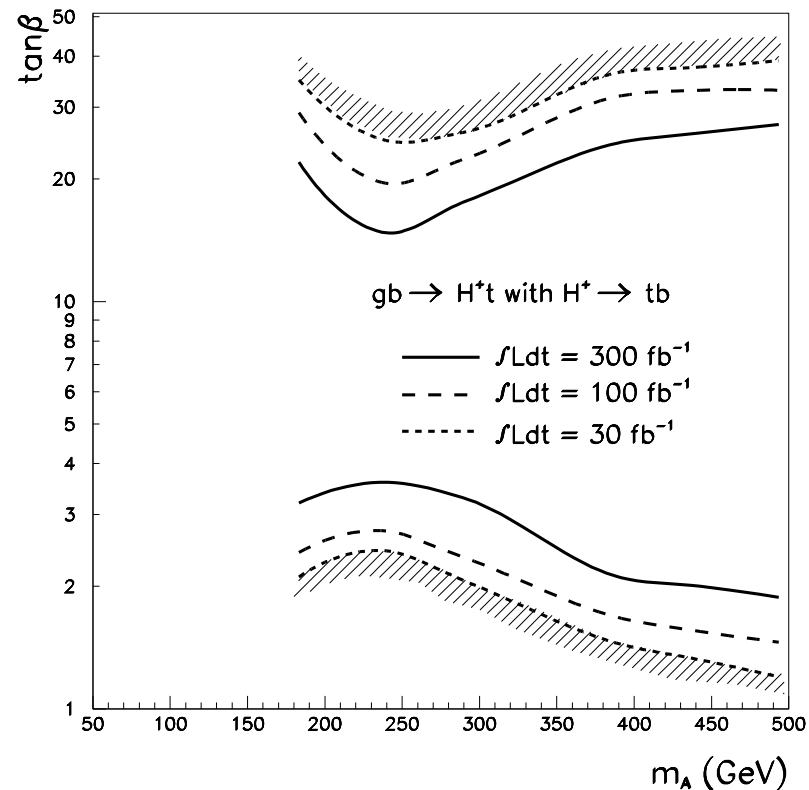
$$gg \rightarrow H^\pm tb$$

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



5σ 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

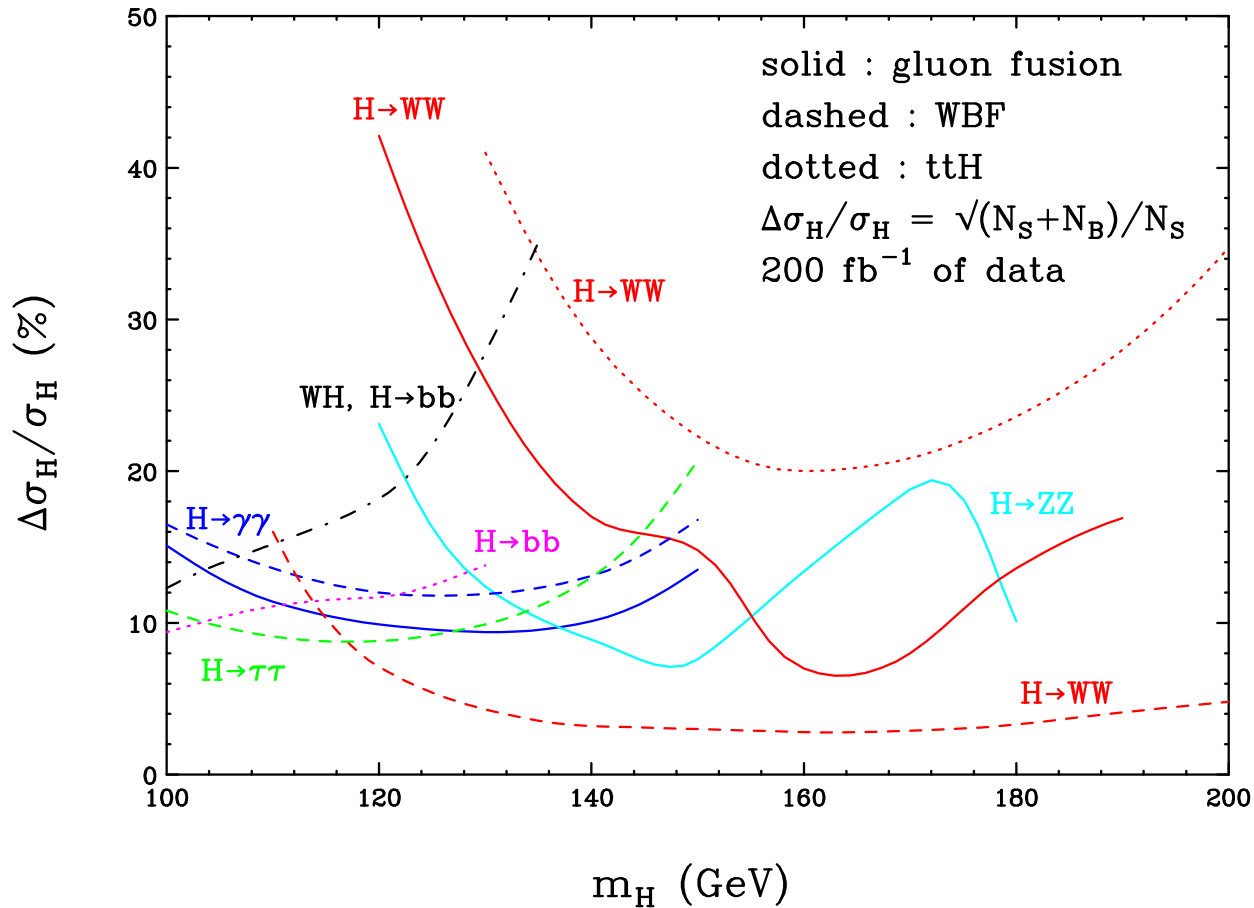
Loose bounds on scaling factor:

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

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%

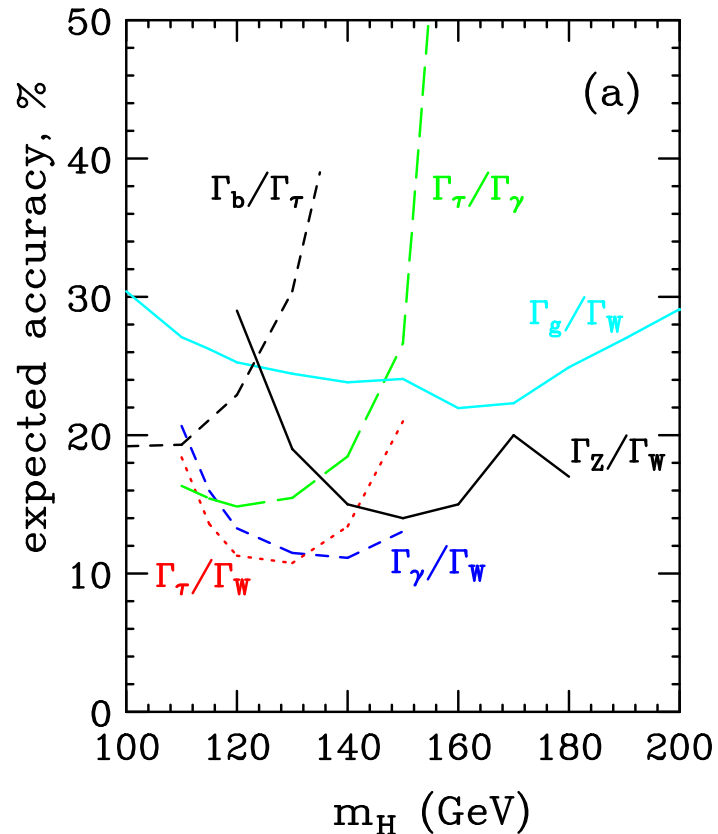
Fit LHC data within constrained models

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

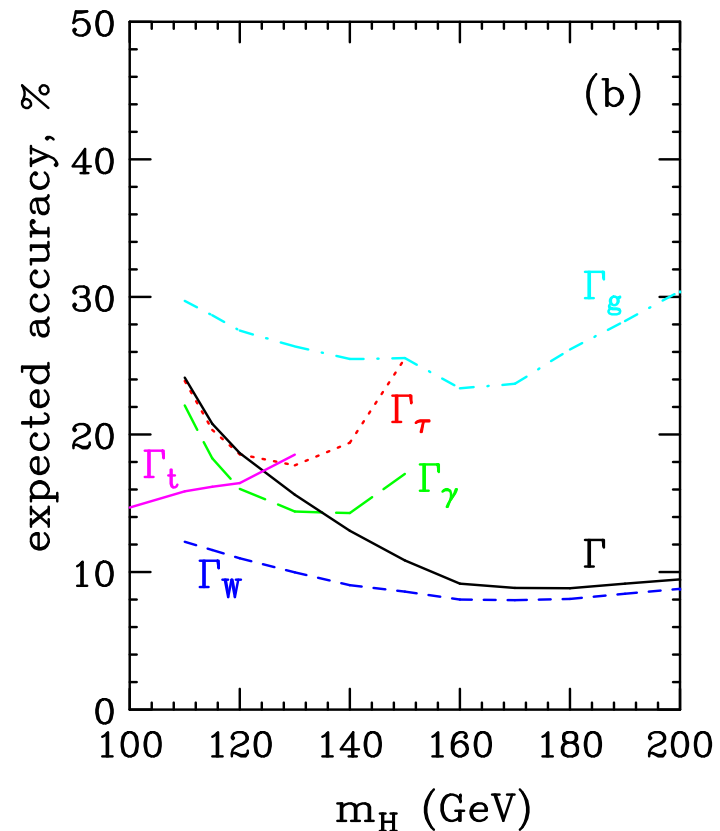
• $\frac{g_{HWW}}{g_{HZZ}} = \text{SM value}$

• no exotic channels

width ratios



(partial) widths



With 200 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

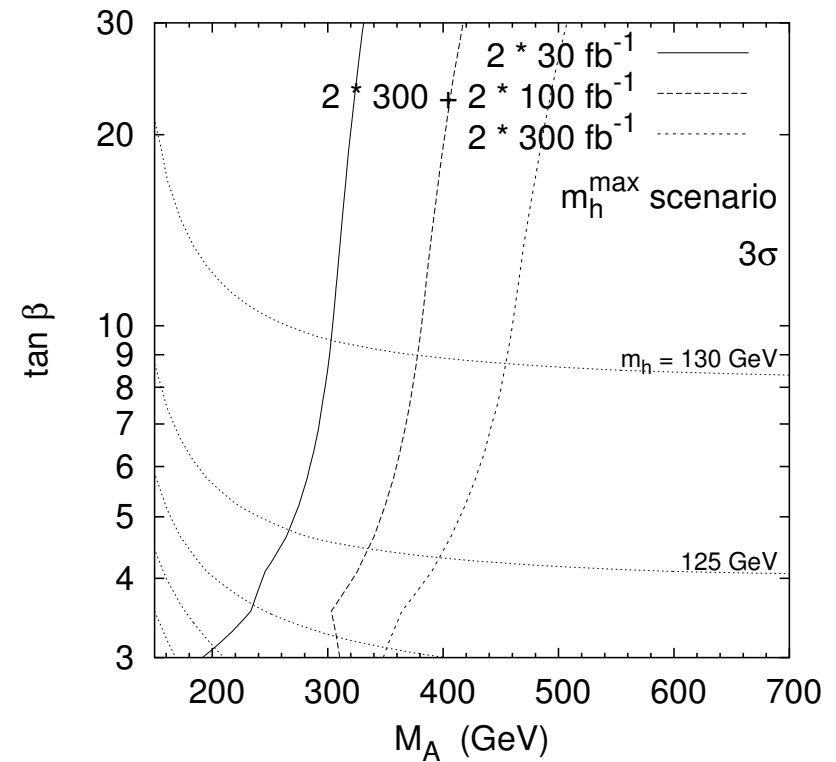
Consider modest m_A :

- 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

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**

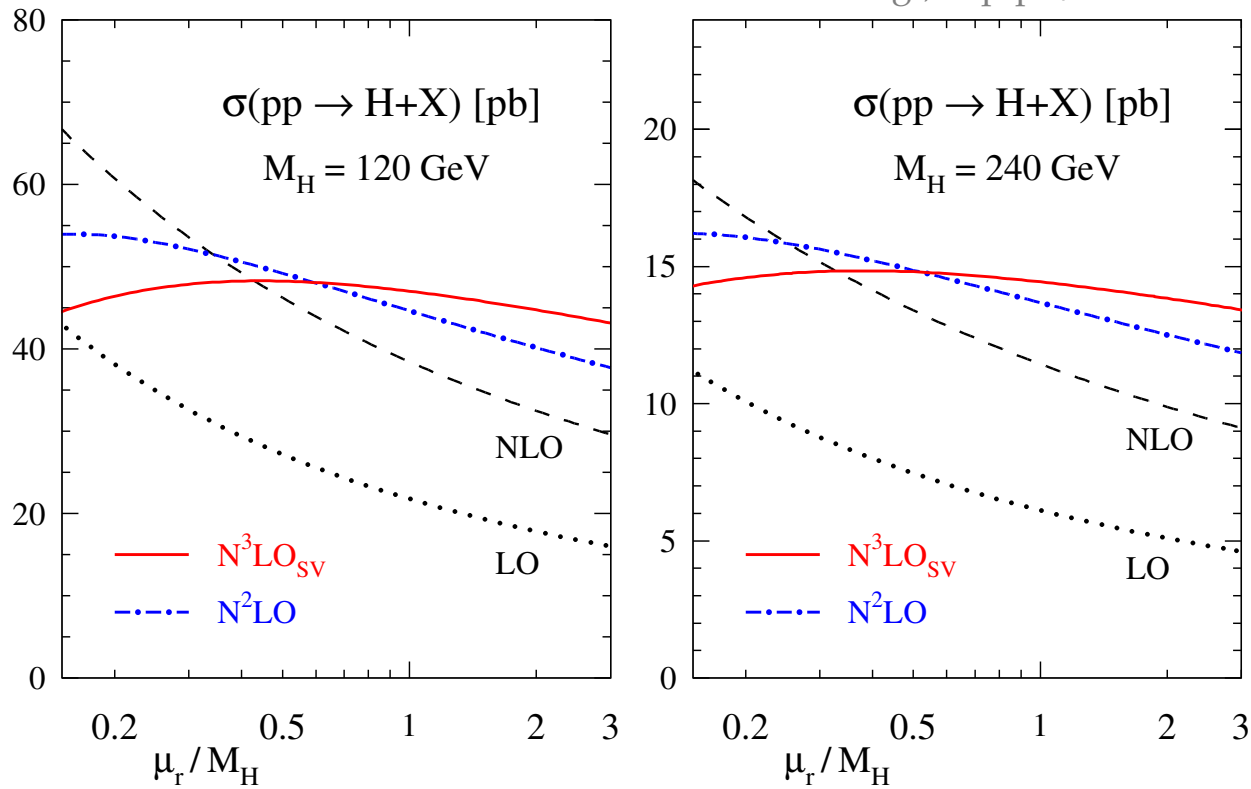
⇒ need QCD corrections to production cross sections

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 \(2003\)](#)
 - N³LO 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 $gg \rightarrow H$

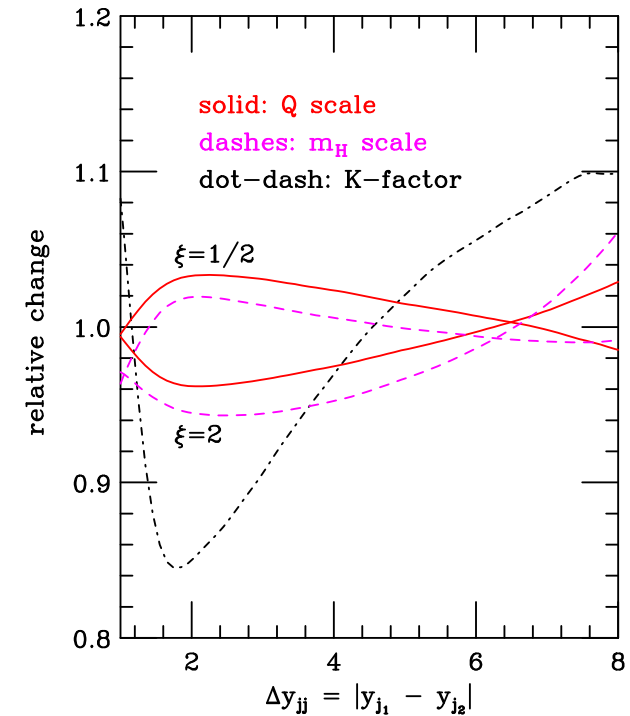
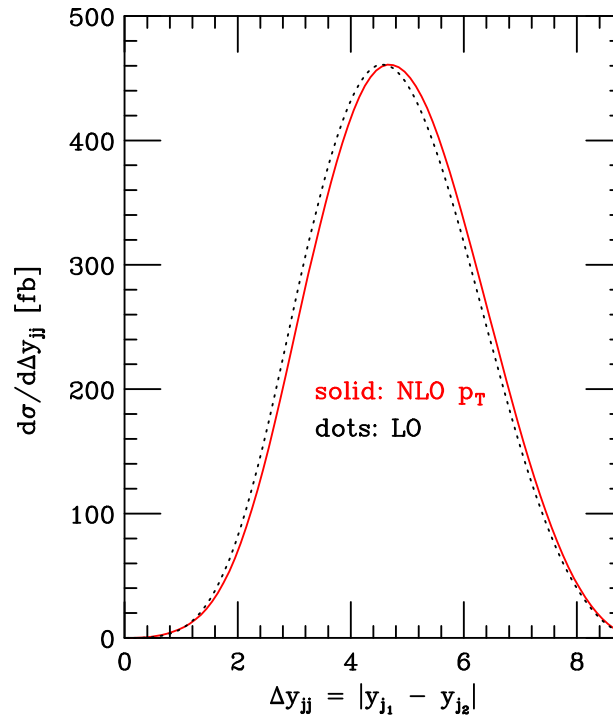
Moch & Vogt, hep-ph/0508265



- ✓ 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 $t\bar{t}$ background for $H \rightarrow WW$ search

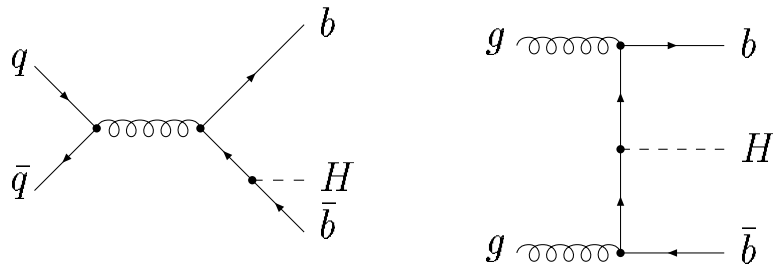
NLO QCD corrections to WBF

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

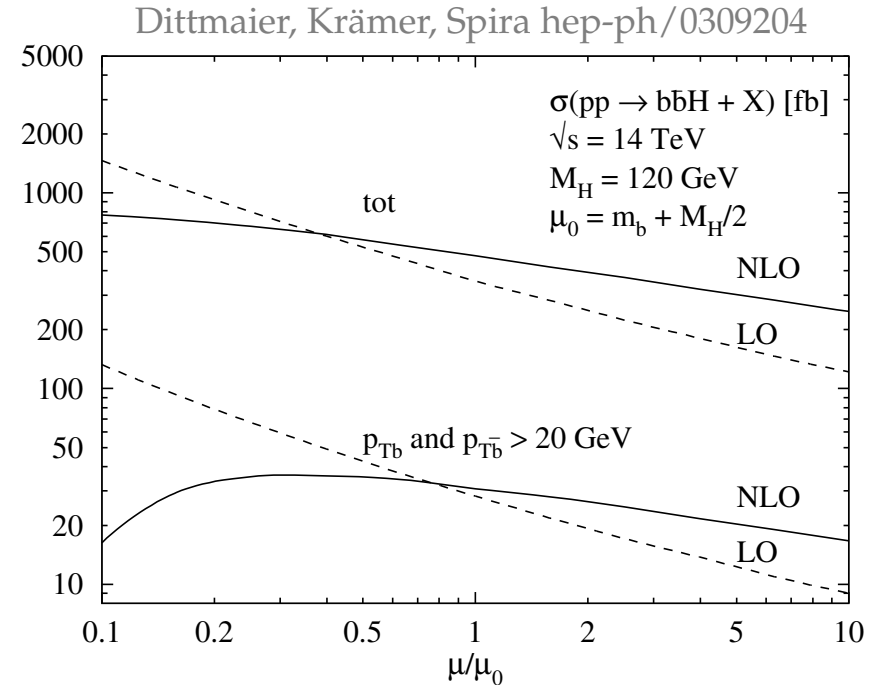


$m_H = 120$ GeV, typical WBF cuts

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



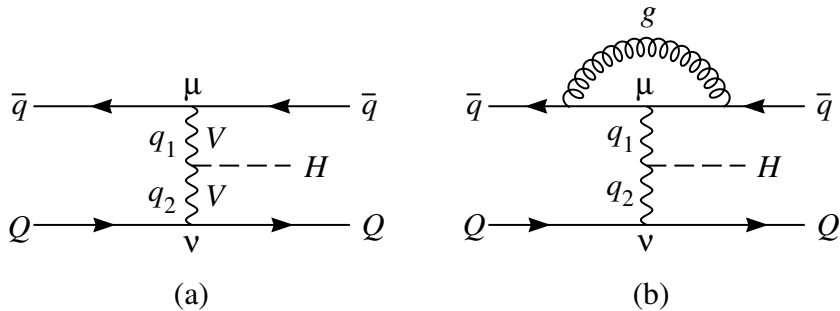
- Discovery channel for H/A in the MSSM at sizeable $\tan \beta$
- NLO corrections known for $\bar{b}bH$ final state
- b-quarks at low p_T : effective process is $\bar{b}b \rightarrow H$: cross section known at NNLO
Harlander, Kilgore (2003)



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

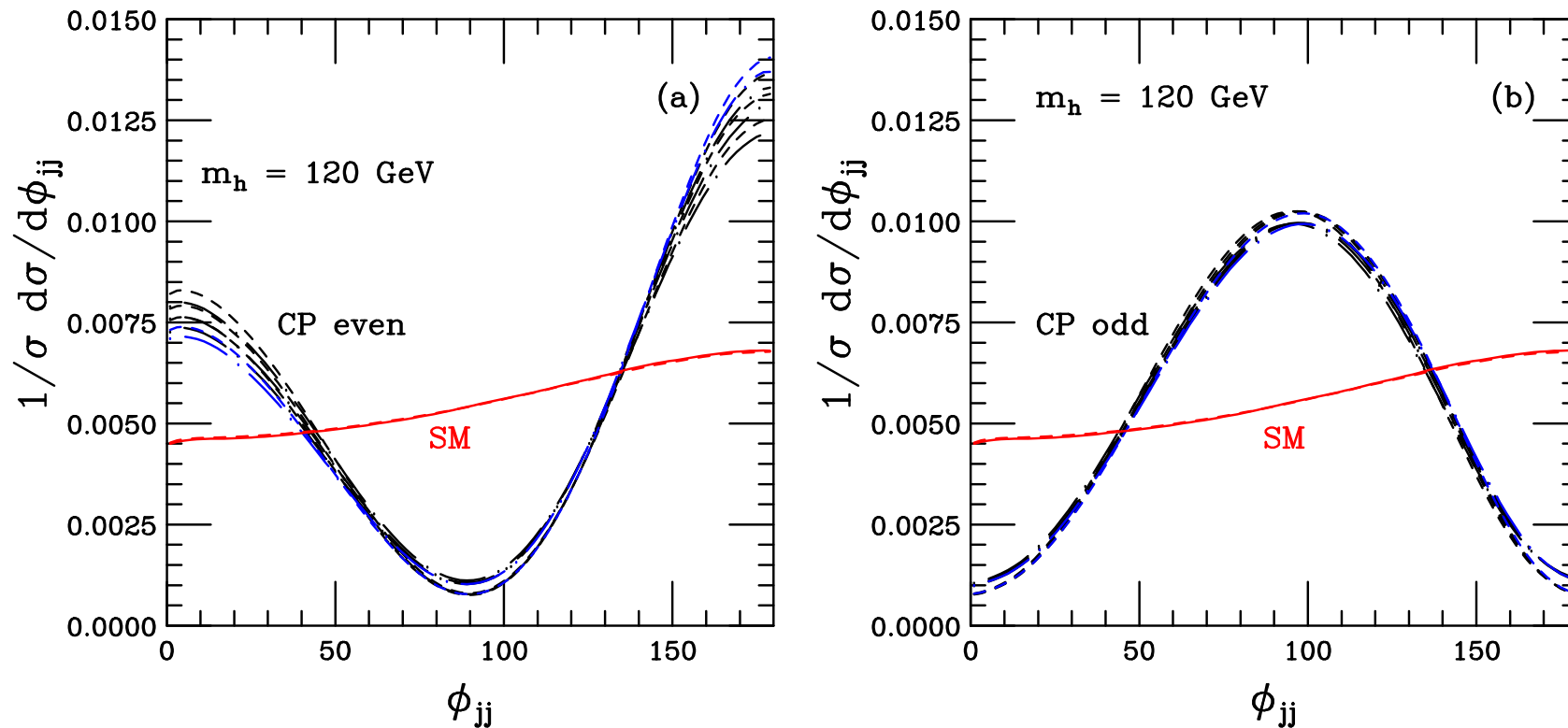
Must distinguish a_1, a_2, a_3 experimentally

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

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° (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

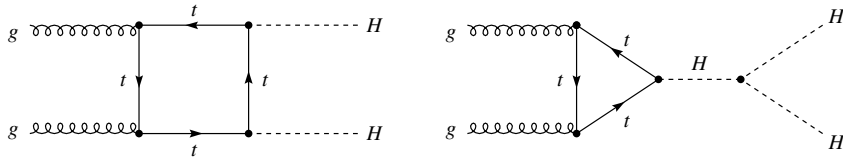
$$V(\Phi) = \lambda \left(\Phi^\dagger \Phi - \frac{v^2}{2} \right)^2$$

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

Gianotti et al., hep-ph/0204087

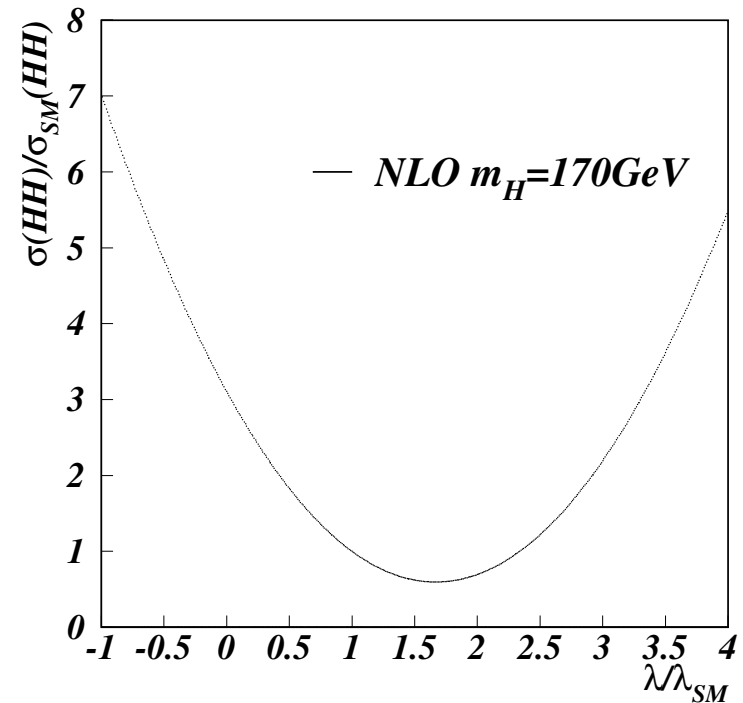
\Rightarrow Higgs mass: $m_H^2 = 2\lambda v^2$
 HHH coupling: $6\lambda v = 3m_H^2/v$

Probe this relation in $gg \rightarrow HH$



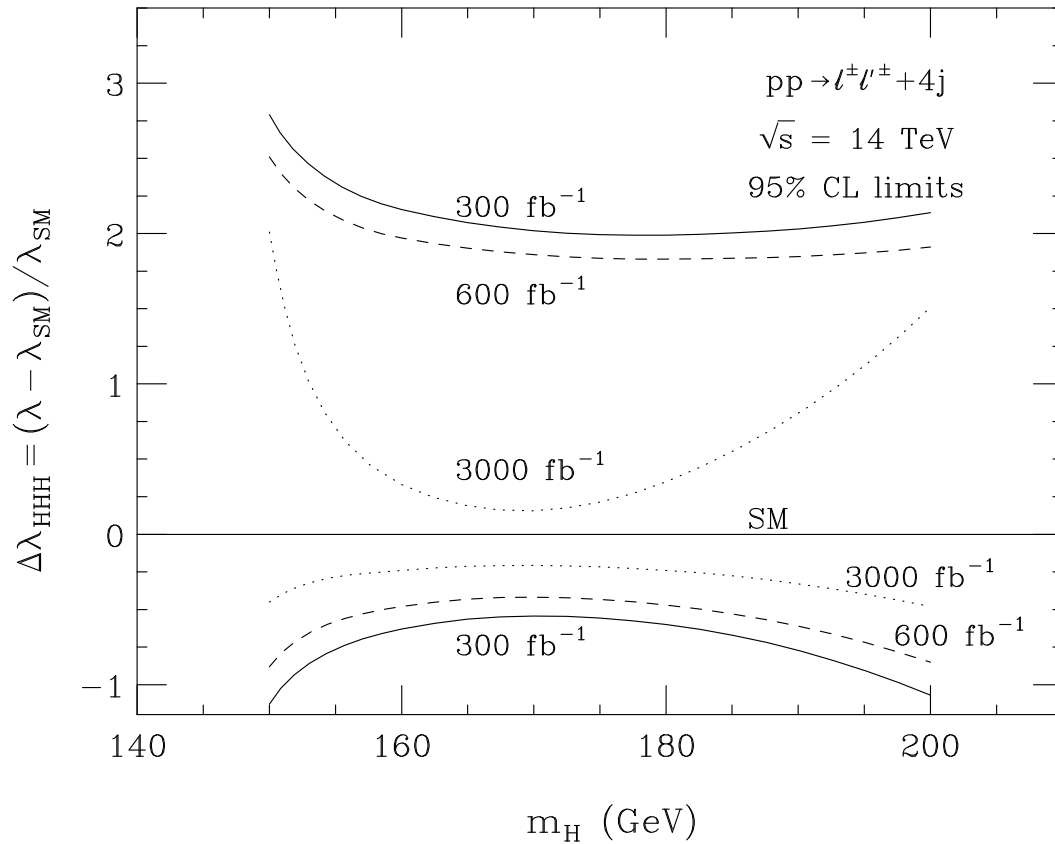
Most sensitive decay channel:

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



LHC sensitivity to HHH coupling

Baur, Plehn, Rainwater: hep-ph/0211224



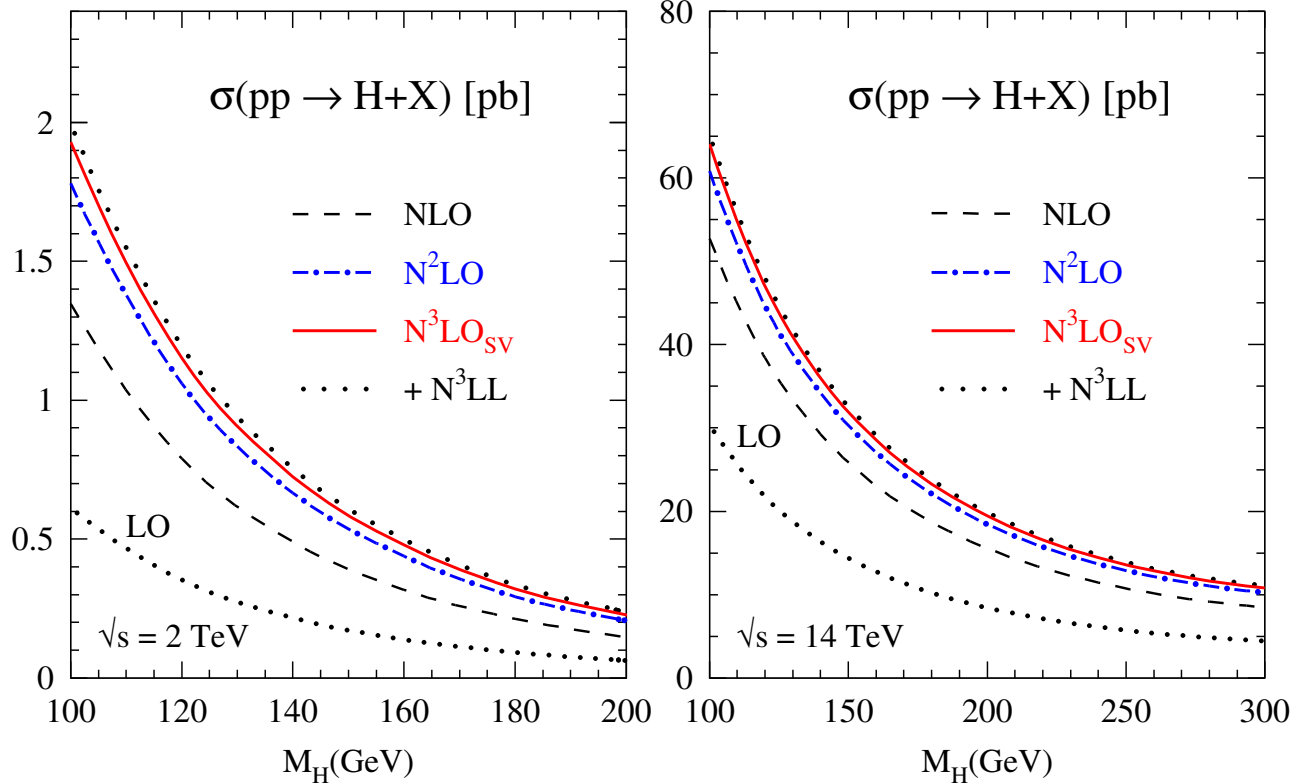
- Need very high luminosity for serious measurement of self coupling
- SLHC sensitivity: up to $\pm 20\%$

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