Higgs boson production and decay

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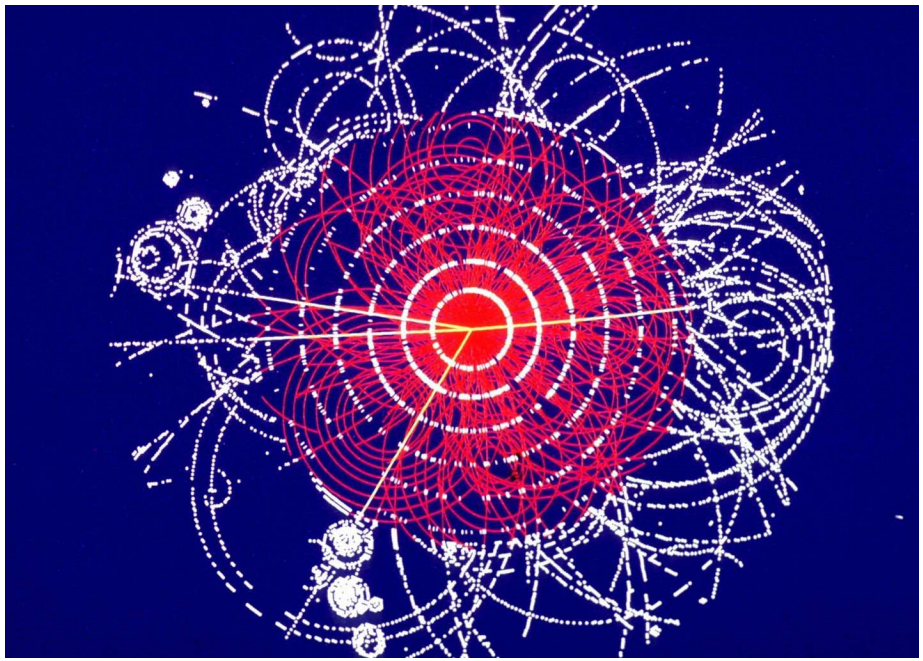
- Higgs interactions: SM and MSSM
- Decay modes
- Production at Hadron Colliders
- QCD corrections for production
- Central jet veto at NLO
- Summary



Funded by BMBF and DFG

Goals of Higgs Physics

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

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

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

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

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

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

Higgs coupling to gauge bosons

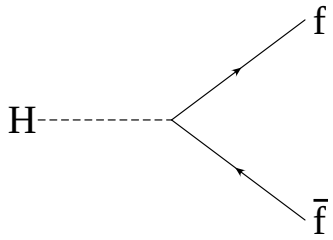
Kinetic energy term of Higgs doublet field:

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

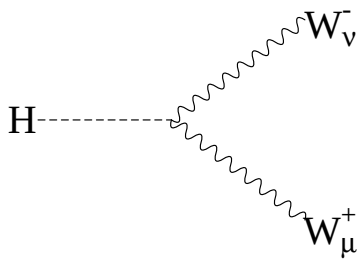
- W, Z mass generation: $m_W^2 = \left(\frac{gv}{2}\right)^2, m_Z^2 = \frac{(g^2+g'^2)v^2}{4}$
- WWH and ZZH couplings are generated
- Higgs couples propotional to mass: coupling strength $= 2\,m_V^2/v \sim g^2 v$ within SM

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

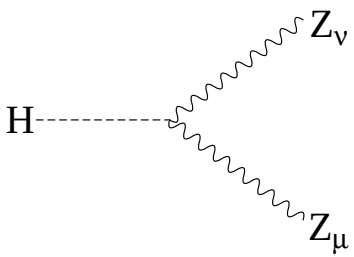
Feynman rules



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



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



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

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

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

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

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

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

SM Higgs mass fit to EW precision data

$$m_H = 87^{+36}_{-27}\ \text{GeV}$$

Including theory uncertainty

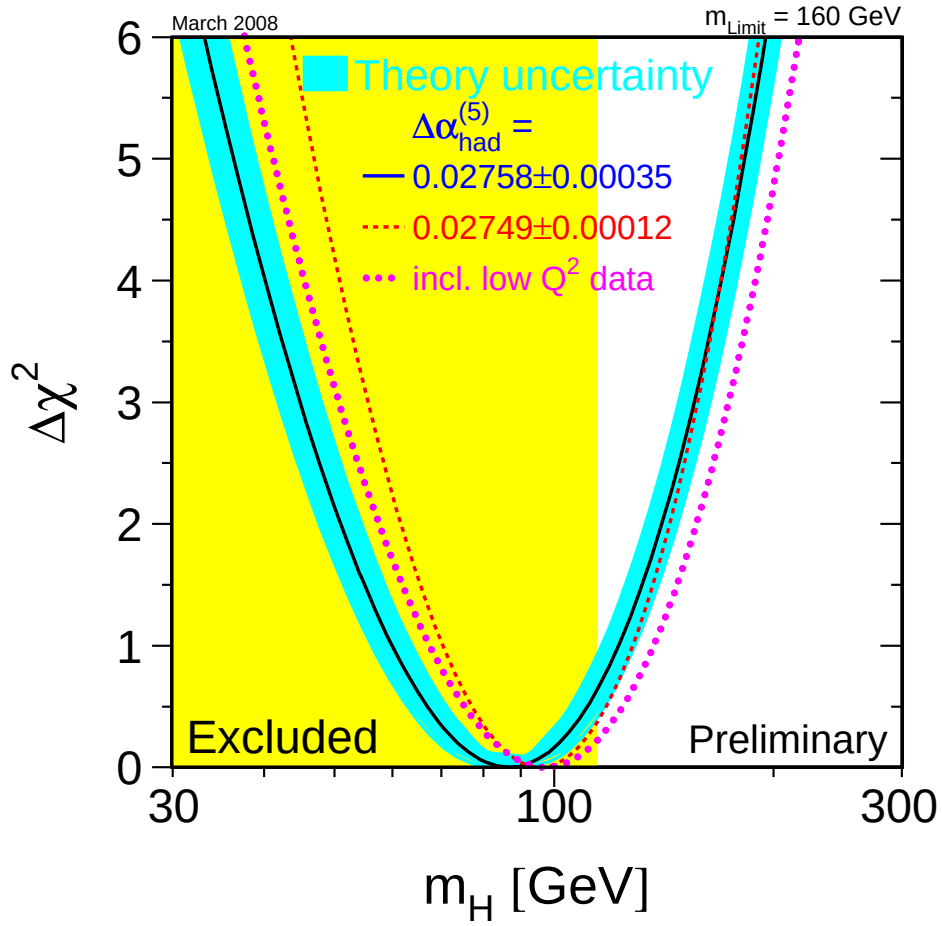
$$m_H < 160\ \text{GeV} \quad (95\%\ \text{CL})$$

Does not include
Direct search limit from LEP

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

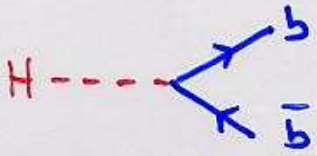
Renormalize probability for
$m_H > 114$ GeV to 100%:

$$m_H < 190\ \text{GeV} \quad (95\%\ \text{CL})$$



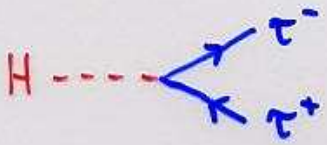
Main Higgs decay channels

$H \to b\bar{b}$



$m_H \lesssim 150$ GeV

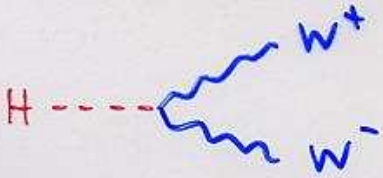
$H \to \tau^+\tau^-$



$m_H \lesssim 140$ GeV

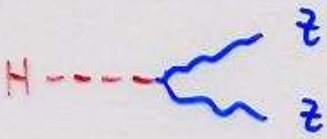
and into gauge bosons

$H \to W^+W^-$



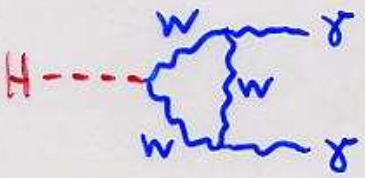
$m_H \gtrsim 120$ GeV

$H \to ZZ$



$m_H \gtrsim 120/180$ GeV

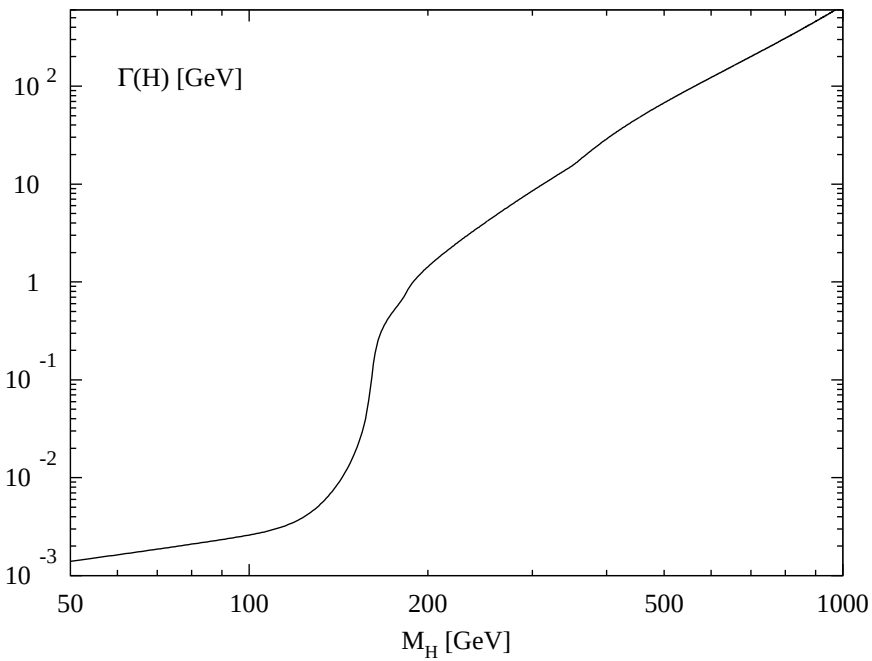
$H \to \gamma\gamma$

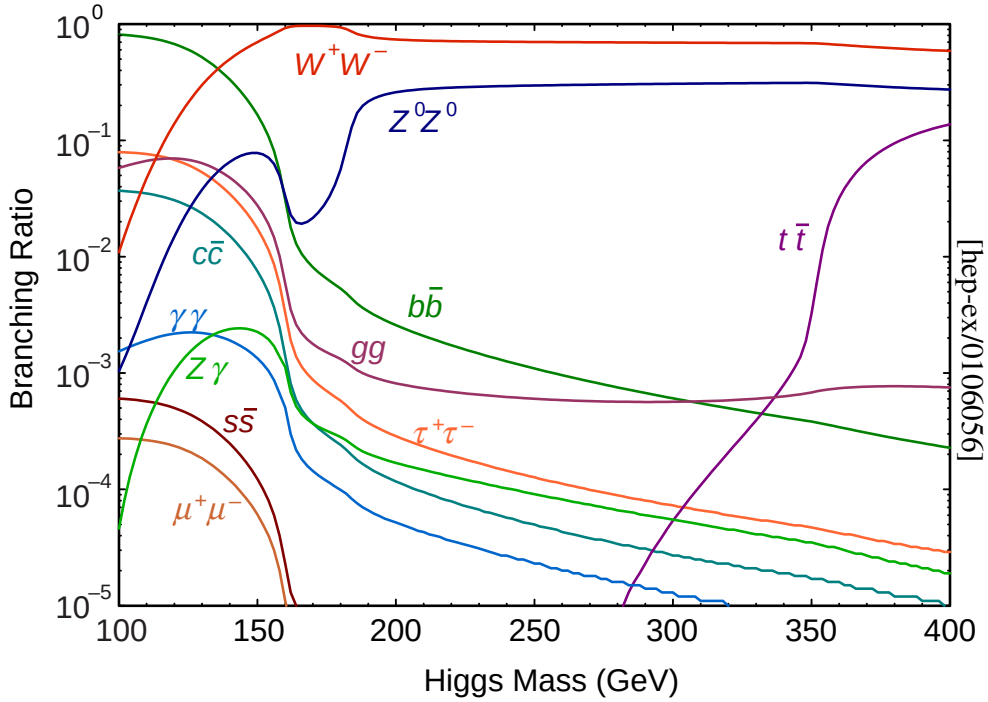


$m_H \lesssim 150$ GeV

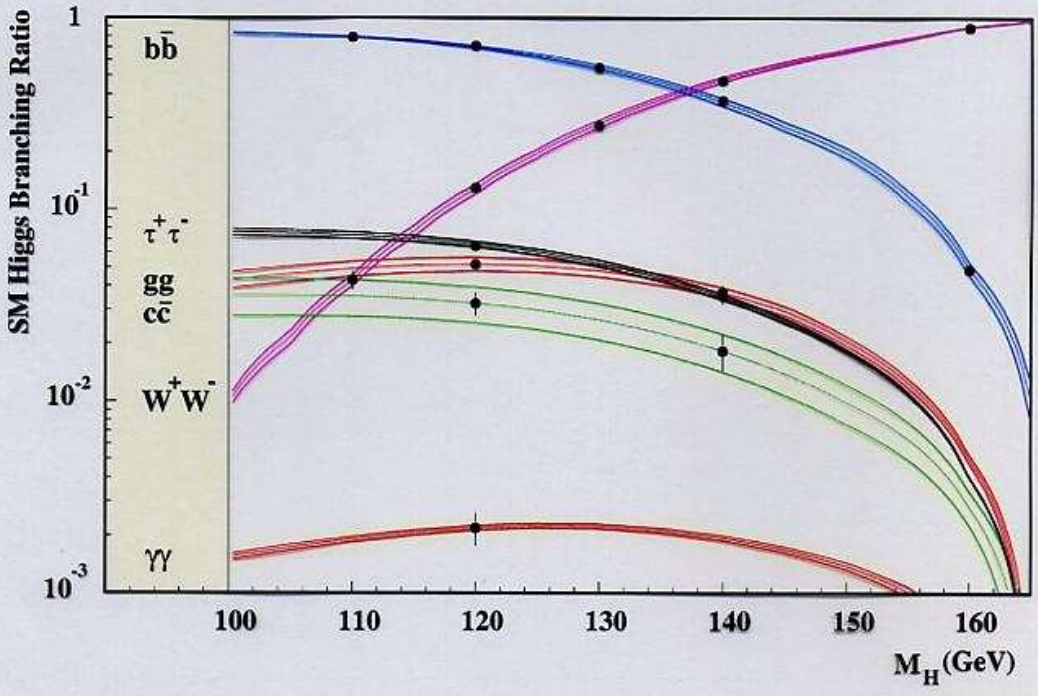
Decay of the SM Higgs

Higgs decay width and branching fractions within the SM





Present theoretical accuracy



Example: $M_H = 120$ GeV

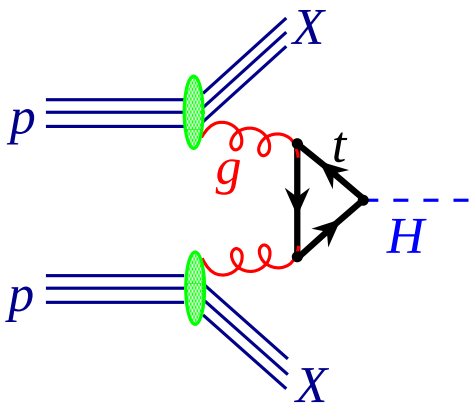
Decay mode:	$b\bar{b}$	WW^*	$\tau^+\tau^-$	$c\bar{c}$	gg	$\gamma\gamma$
Theory	1.4%	2.3%	2.3%	23%	5.7%	2.3%

Mainly due to: pole masses m_c and m_b, and $\alpha_s(\mu)$.

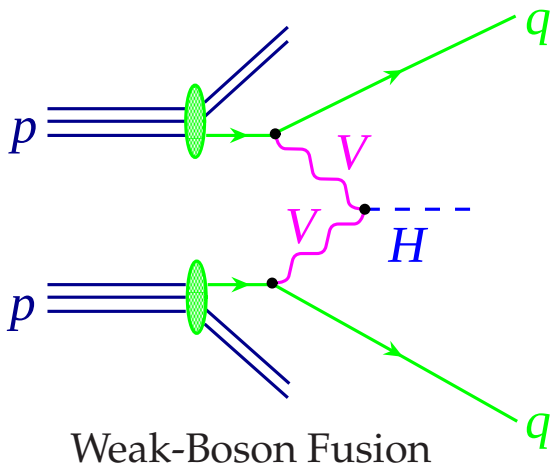
From HDECAY when (Carena et al., hep-ph/0106116)

$\alpha_s(M_Z) = 0.1185 \pm 0.0020$
$m_c(m_c) = 1.23 \pm 0.09$ GeV
$m_b(m_b) = 4.17 \pm 0.05$ GeV

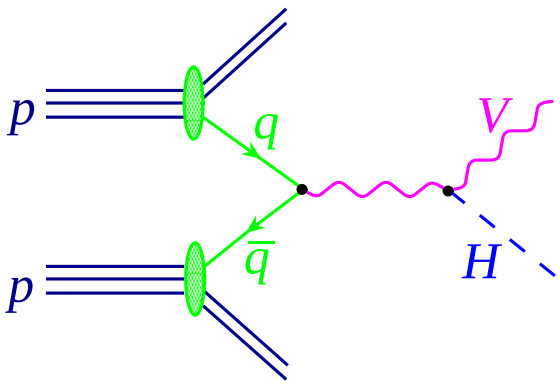
Higgs Production Modes at Hadron Colliders



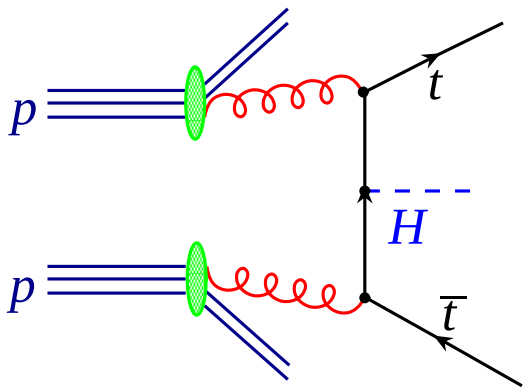
Gluon fusion



Weak-Boson Fusion

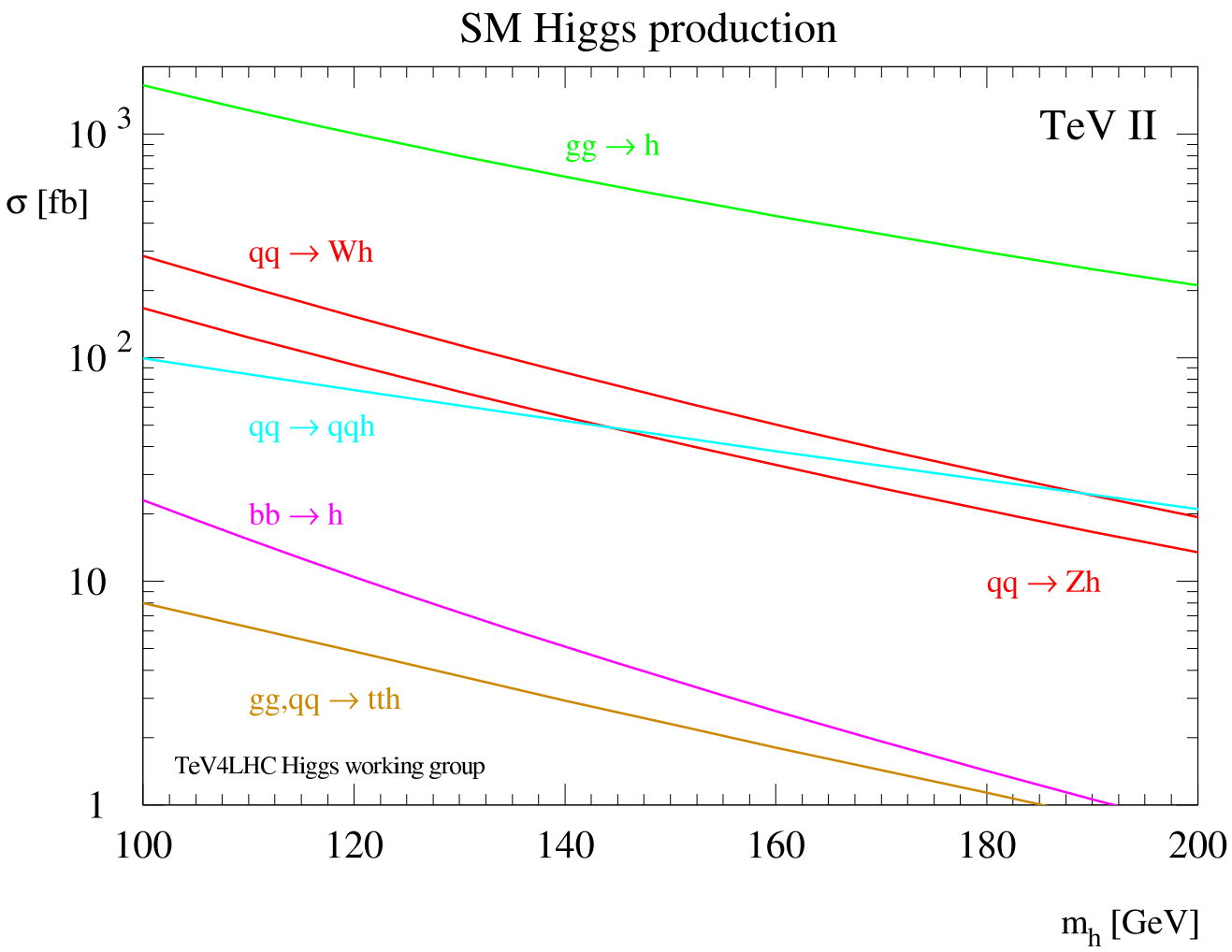


Higgs Strahlung

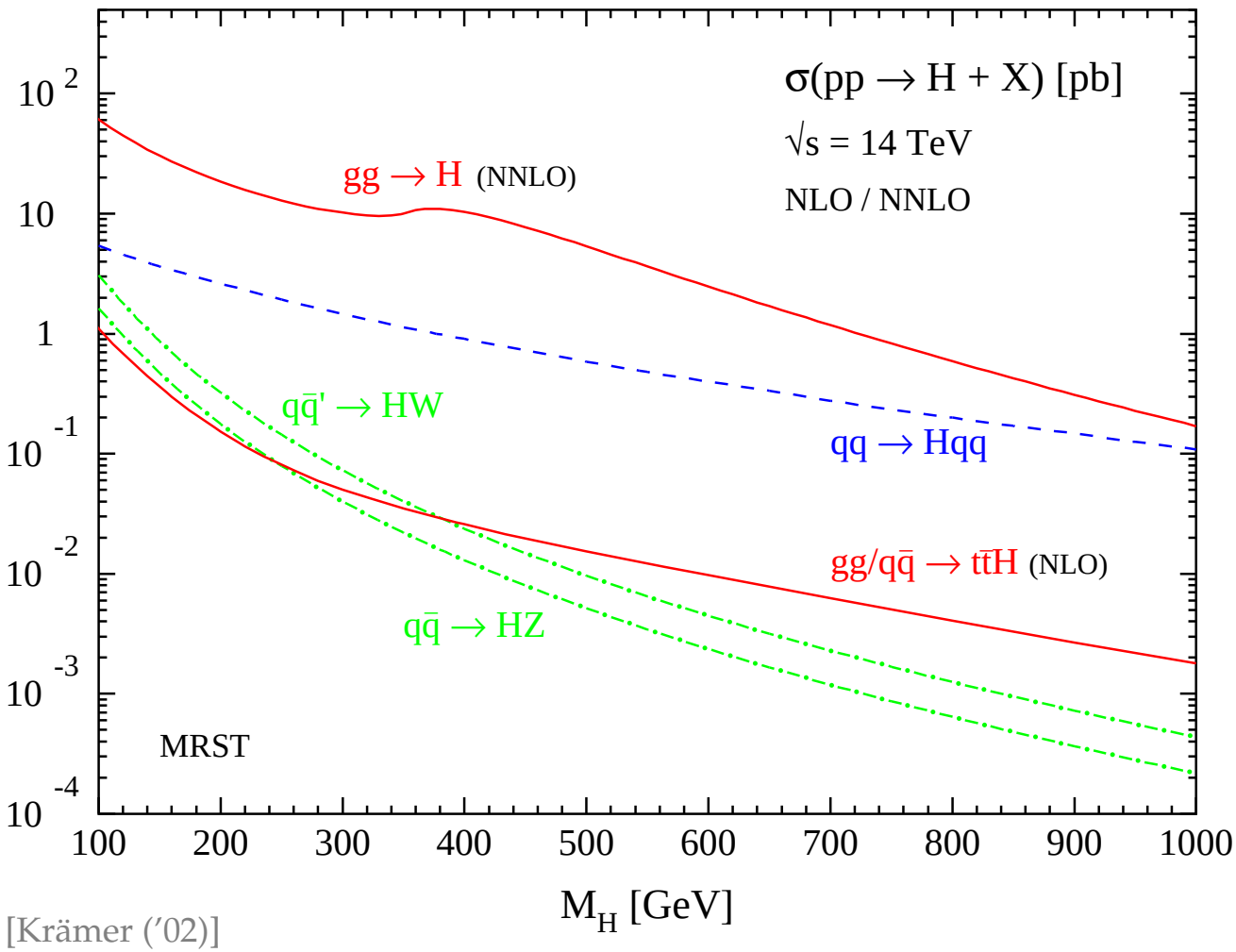


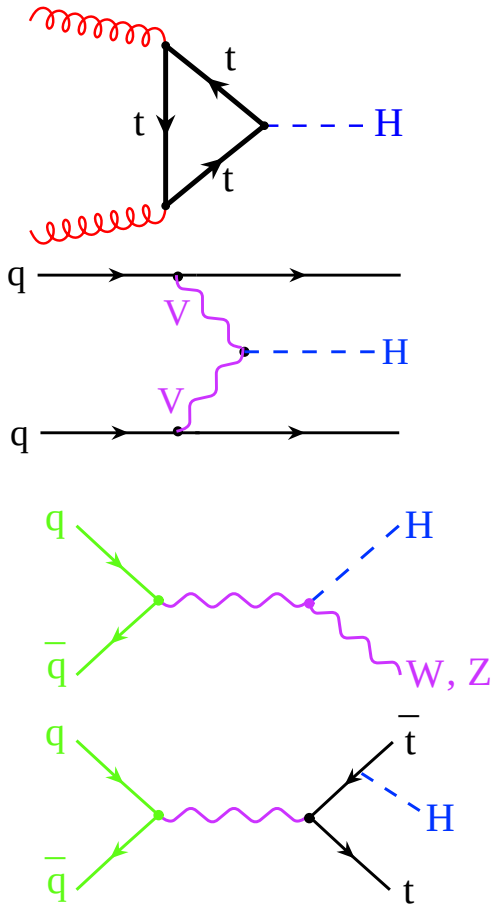
$t\bar{t}H$

Total cross sections at the Tevatron



Total cross sections at the LHC





[Krämer ('02)]

Inclusive search channels

- inclusive search for

$$H \to \gamma\gamma$$

  invariant-mass peak, for (at LHC) $m_H < 150$ GeV

- inclusive search for

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

  for $m_H \geq 130$ GeV and $m_H \neq 2m_W$ (at LHC).

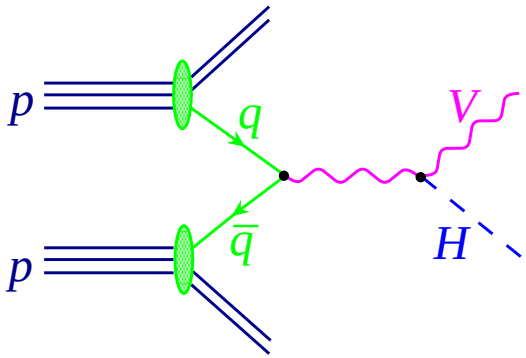
- inclusive search for

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

  for $140 \text{ GeV} \leq m_H \leq 200$ GeV

Inclusive production is dominated by gluon fusion
$\Longrightarrow$ probe Higgs Yukawa coupling to top quark

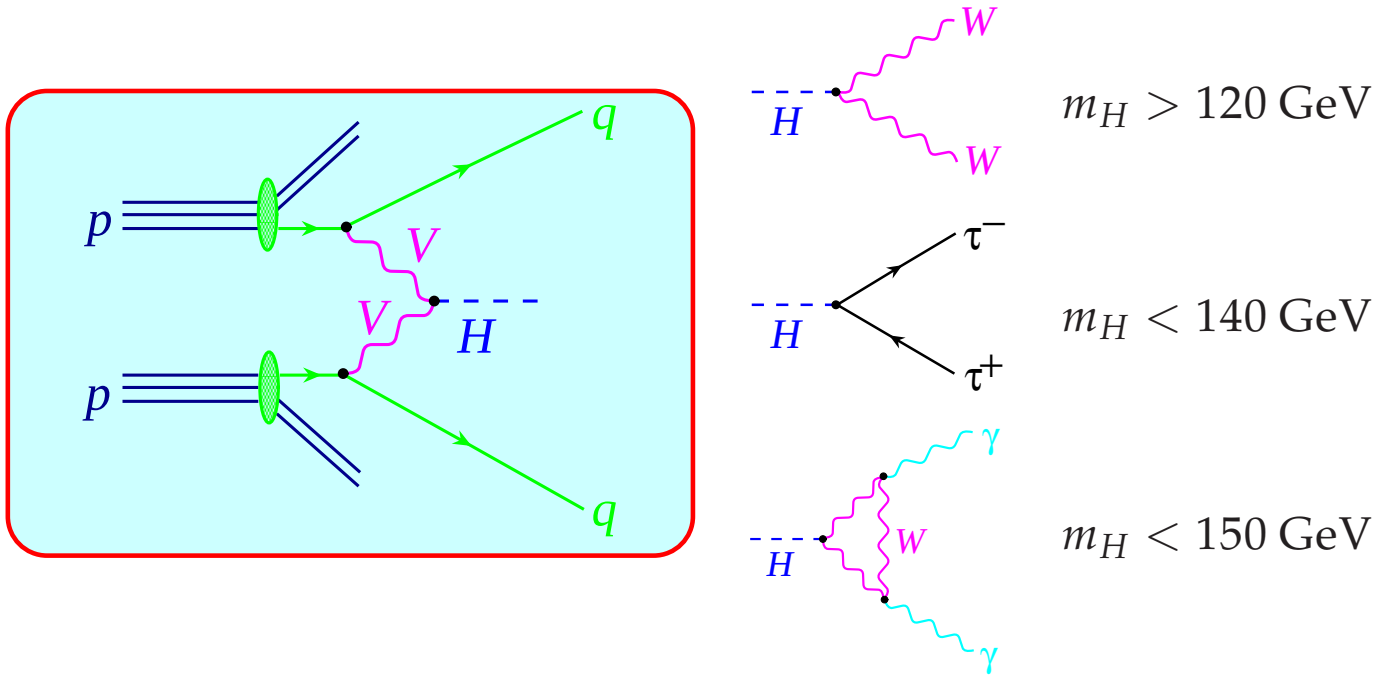
Higgsstrahlung



- Search for subsequent decay $H \to b\bar{b}$
- Provides information on Hbb coupling once HVV coupling has been measured in VBF

- Higgsstrahlung ist leading signal channel at the Tevatron for m_H below 140 GeV
- LHC backgrounds to Higgsstrahlung worse than at Tevatron
- Promising new strategy for LHC: look for $p_T(H) > 200$ GeV events and $b\bar{b}$ substructure in fat *Higgs jets* [Butterworth, Davison, Rubin, Salam arXiv:0802.2470]

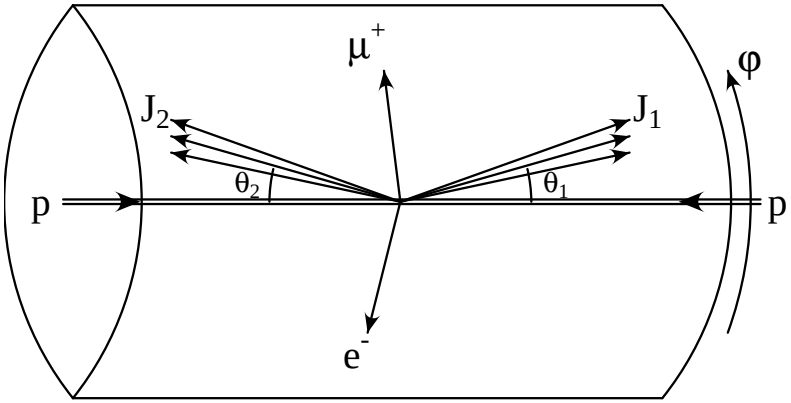
Vector Boson Fusion at the LHC

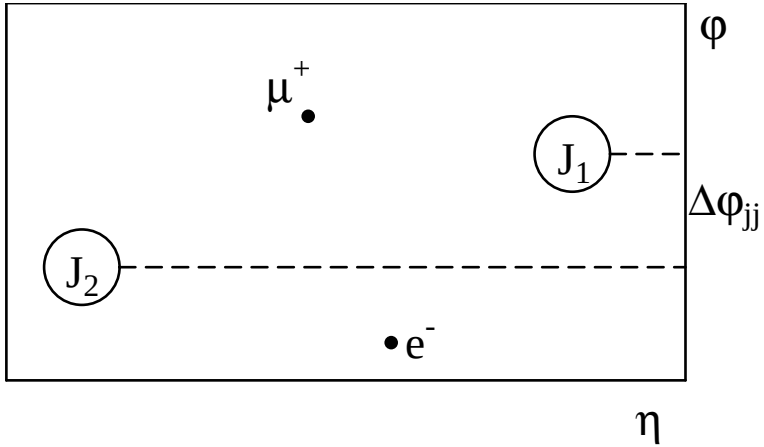


[Eboli, Hagiwara, Kauer, Plehn, Rainwater, D.Z. . . .]

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).

VBF 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 between tagging jets)

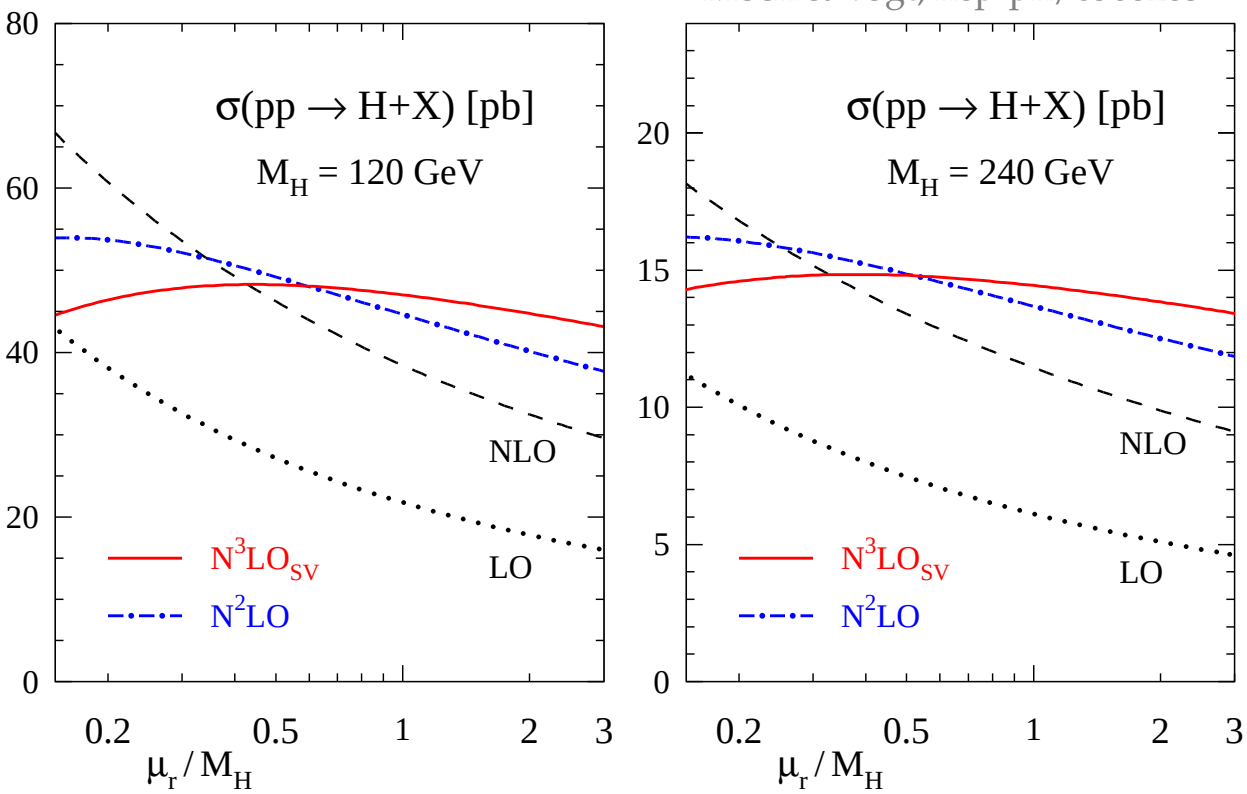
Corrections for Higgs production cross sections

Measurement of Higgs couplings from measured signal rates
$\Longrightarrow$ need QCD corrections to production cross sections. Much progress 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)
  - N^3LO in soft approximation: Moch, Vogt (2005)
- Hjj by gluon fusion at NLO: Campbell, Ellis, Zanderighi (2006)
- Higgsstrahlung: implemented in MC@NLO Frixione, Webber
- weak boson fusion
  - distributions at NLO: Figy, Oleari, D.Z (2003); Campbell, Ellis, Berger (2004)
  - 1-loop EW corrections: Ciccolini, Denner, Dittmaier (2007)
  - approx. NLO QCD to $Hjjj$: Figy, Hankele, D.Z (2007)
- $\bar{t}tH$ 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)

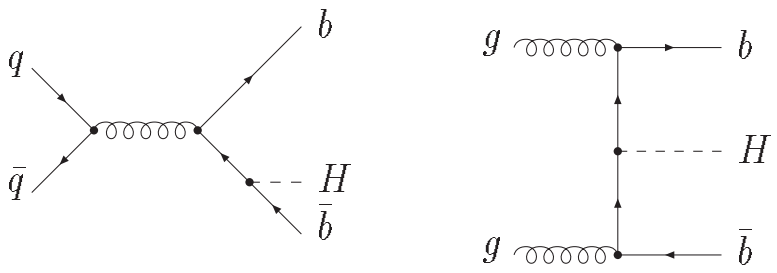
QCD corrections to $gg \to H$

Moch & Vogt, hep-ph/0508265



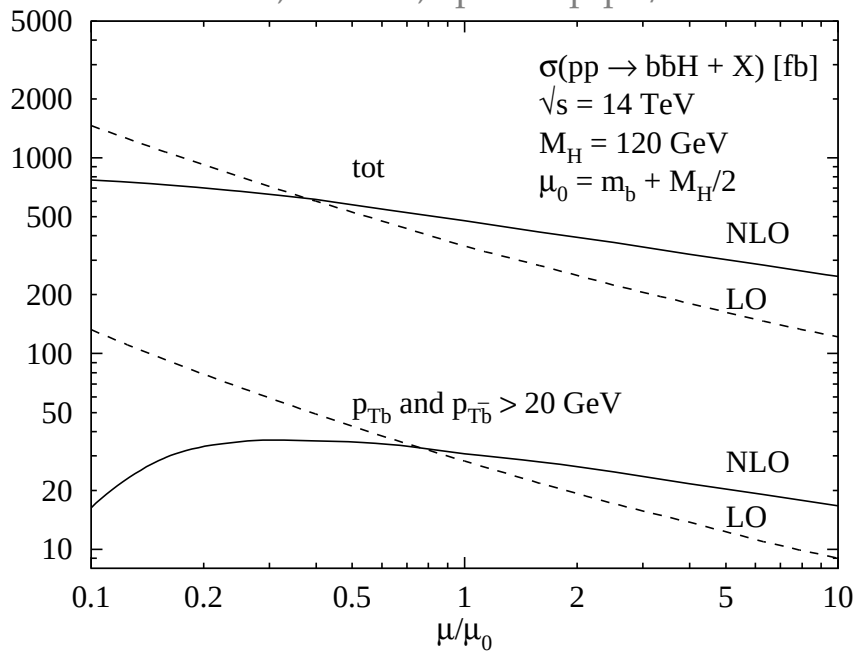
- ✓ Huge improvement in recent years
- ✓ Remaining scale uncertainty below 10%
- ✓ Uncertainty from gluon pdf $\approx 4 - 7\%$
- ✓ K-factor for cross section with cuts (central jet veto against $\bar{t}t$ background for $H \to WW$ search) has similar uncertainties [Anastasiou, Dissertori, Stöckli, Webber arXiv:0801.2682]

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



- 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 section known at NNLO Harlander, Kilgore (2003)

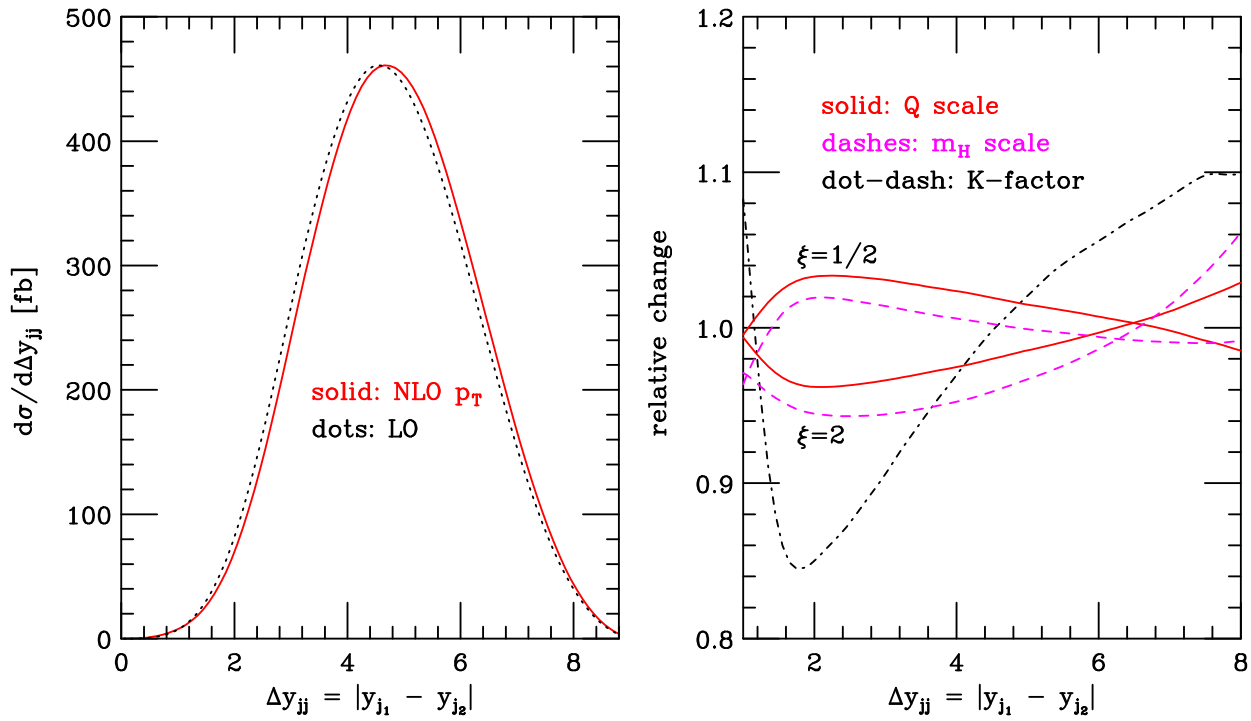
Dittmaier, Krämer, Spira hep-ph/0309204



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

NLO QCD corrections to VBF

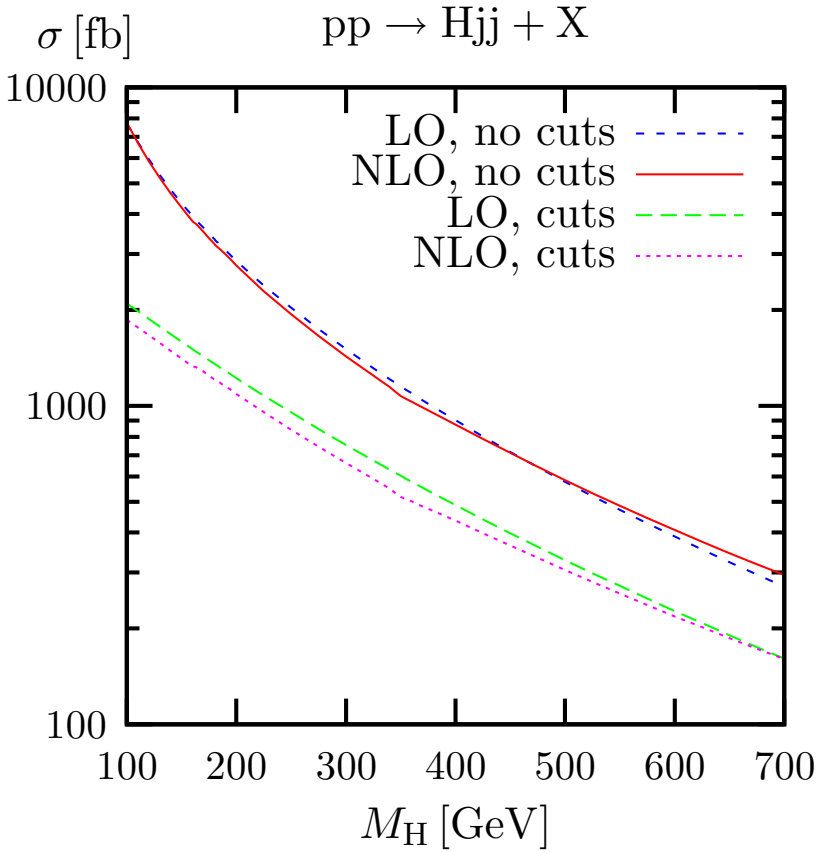
- ✓ Small QCD corrections of order 10%
- ✓ Tiny scale dependence of NLO result
  - $\pm 5\%$ for distributions
  - $< 2\%$ for σ_{total}
- ✓ K-factor is phase space dependent
- ✓ QCD corrections under excellent control
- ✗ Need electroweak corrections for 5% uncertainty

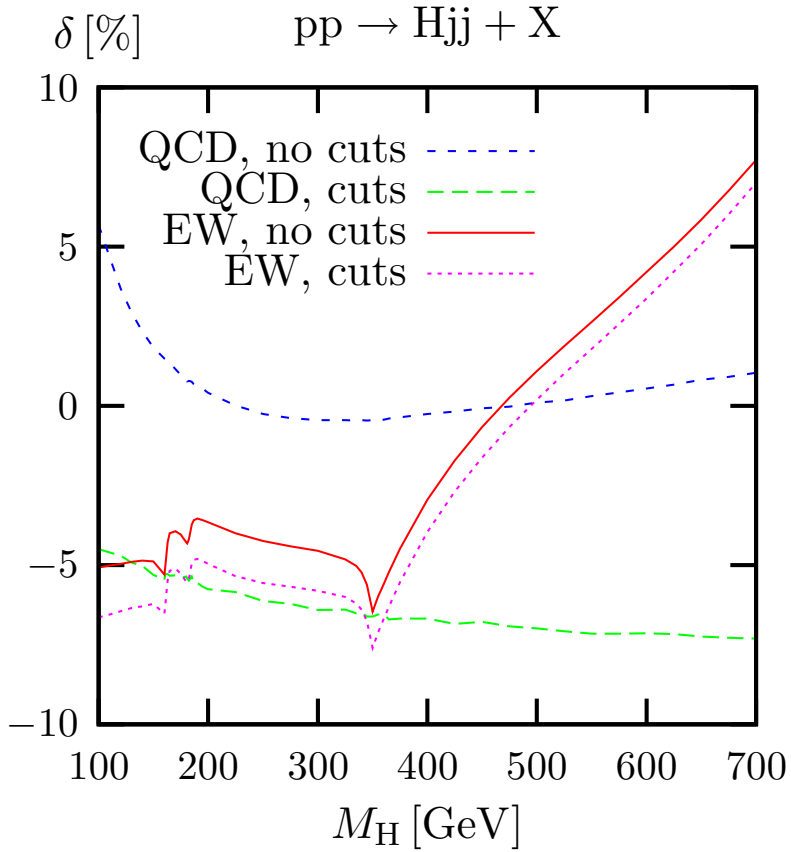


$m_H = 120$ GeV, typical VBF cuts

QCD + EW corrections to Hjj production

Cross sections without and with VBF cuts: $p_T(j) > 20$ GeV $\quad |y_{j_1} - y_{j_2}| > 4, \;\; y_{j_1} \cdot y_{j_2} < 0$



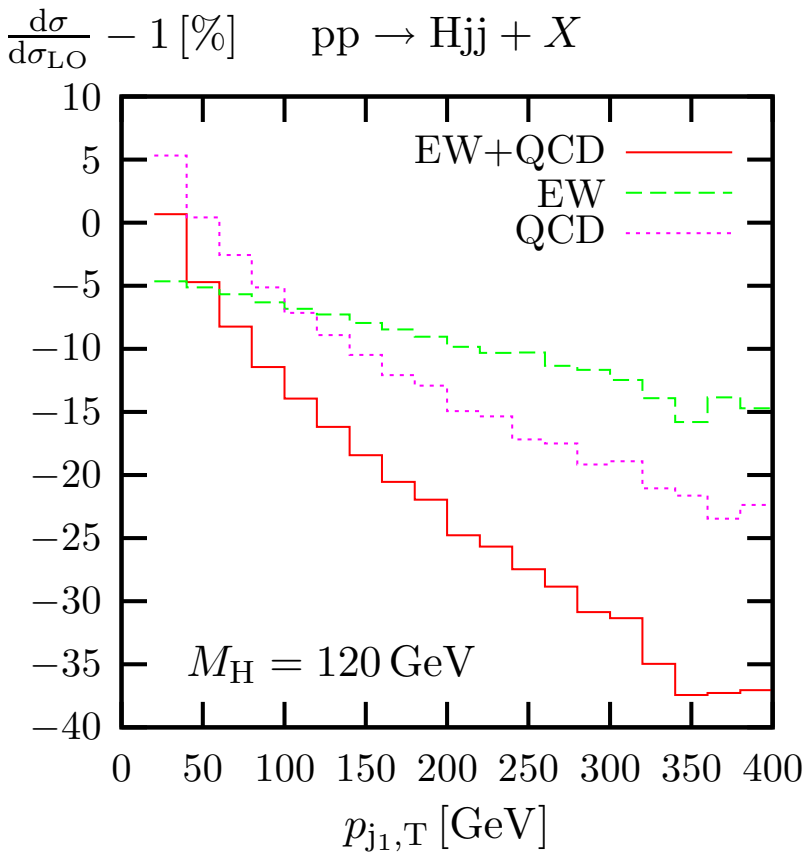


Ciccolini, Denner, Dittmaier, arXiv:0710.4749

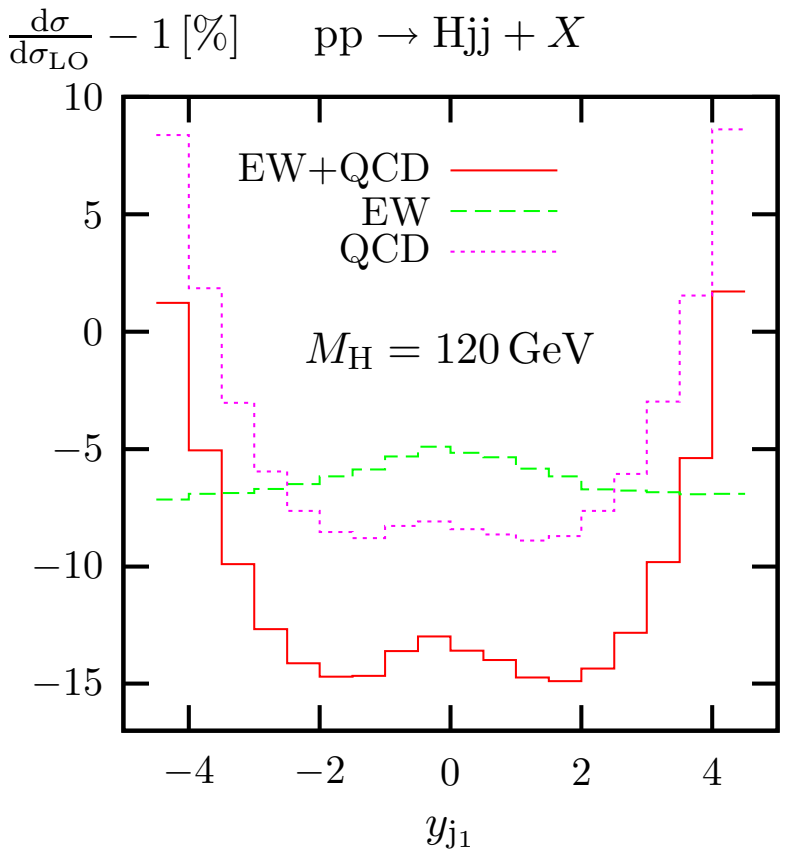
Relative size of 1-loop corrections

Consider distributions of hardest jet in the event:

p_T distribution



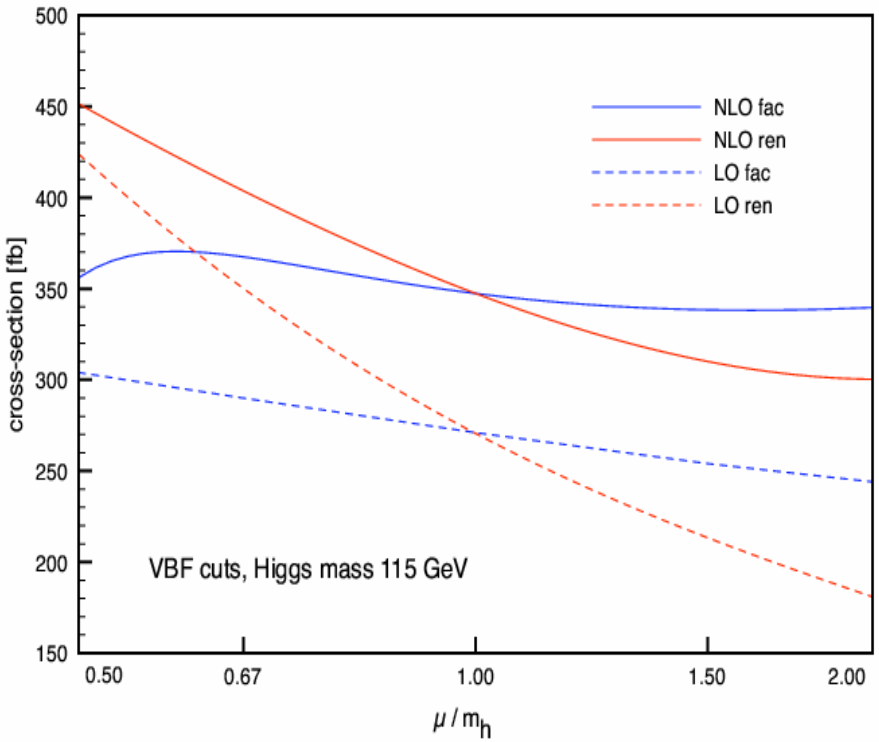
rapidity distribution

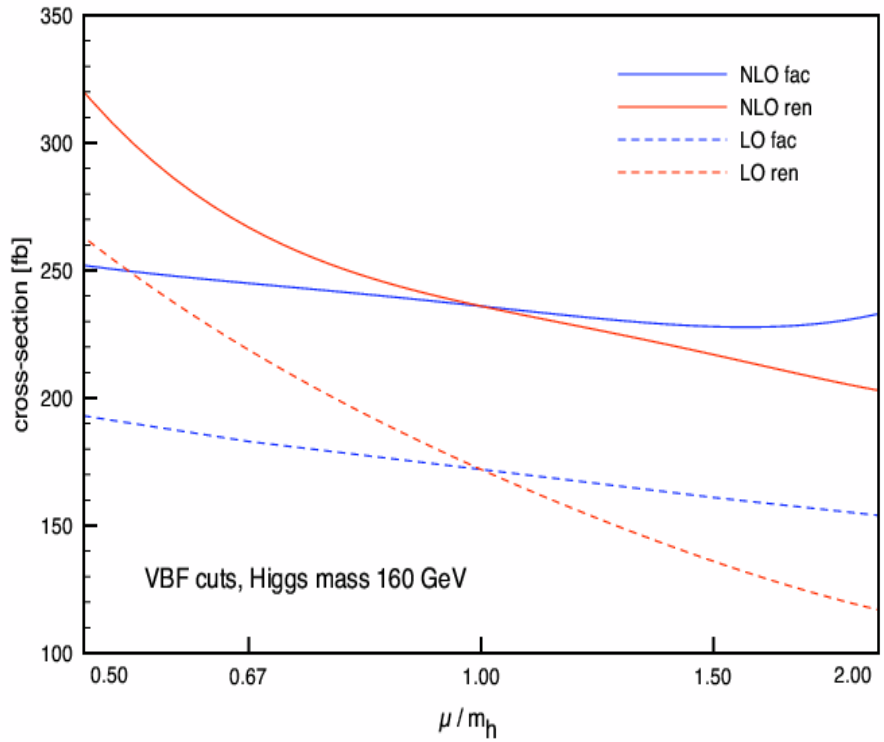


strong shape changes by QCD corrections, EW corrections affect mostly normalization

Hjj cross section for gluon fusion

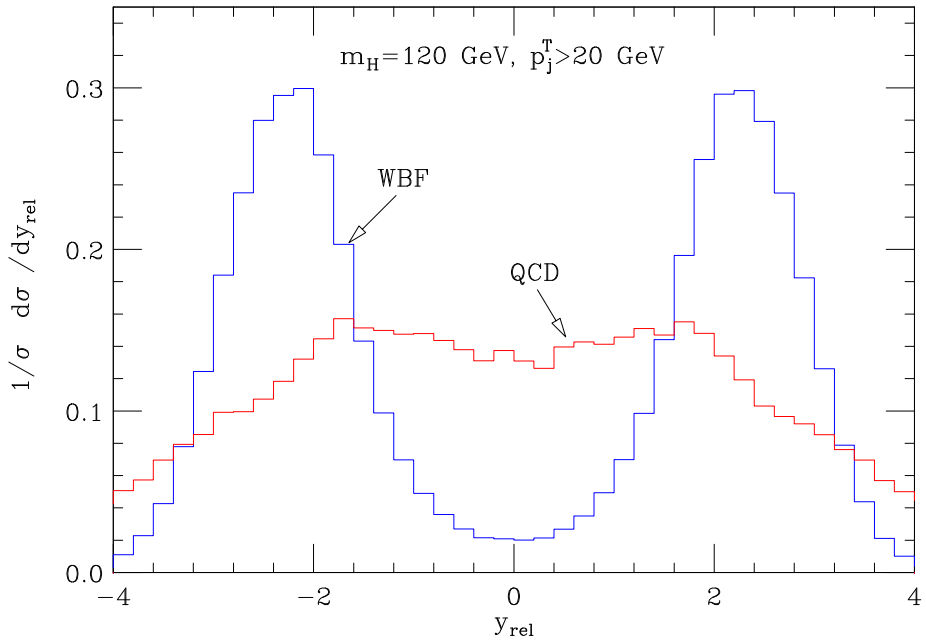
Calculation of Hjj cross section at NLO in $m_t \to \infty$ limit by Campbell, Ellis, Zanderighi, hep-ph/0608194

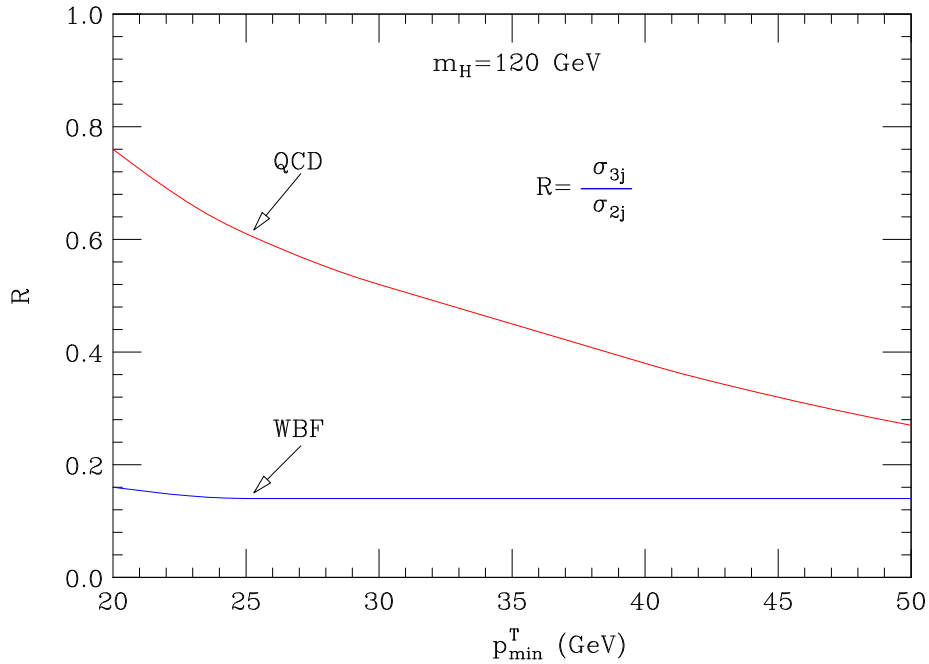




- Modest increase of cross section at 1-loop: K-factor of order 1.2 - 1.4
- Reduced scale dependence at NLO: remaining scale uncertainty $\approx \pm 20\%$

Central Jet Veto: $Hjjj$ from VBF vs. gluon fusion

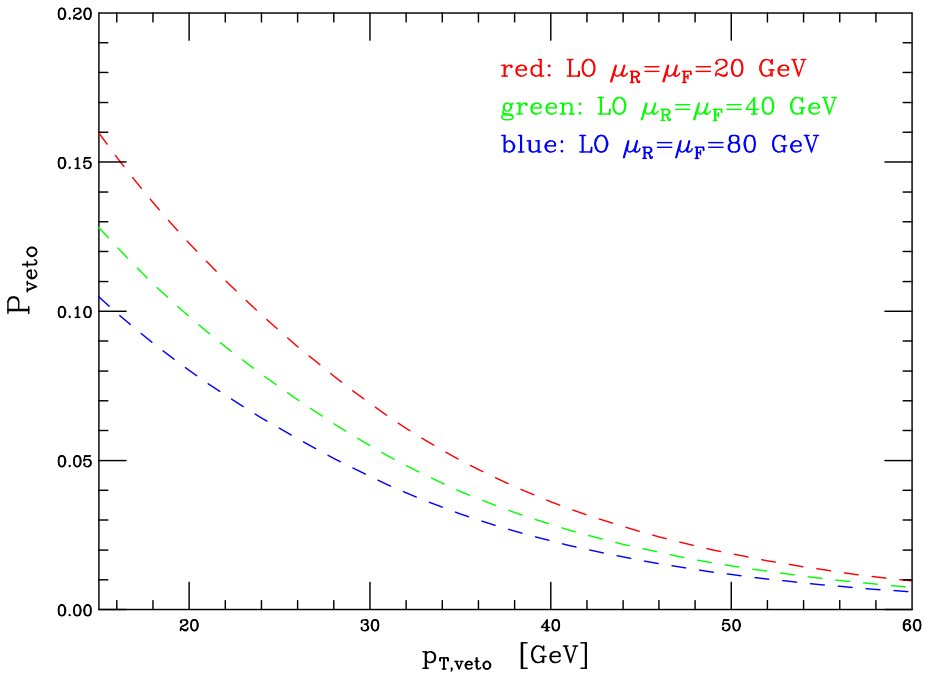




[Del Duca, Frizzo, Maltoni, JHEP 05 (2004) 064]

- A distinguishing feature of VBF is that at LO no color is exchanged in the t-channel.
- The central-jet veto is based on the different radiation pattern expected for VBF versus its major backgrounds [hep-ph/9412276, hep-ph/0012351]
- Central jet veto can be used to distinguish Higgs production via GF from VBF

VBF Higgs signal and CJV



$$p_{Tj}^{veto} > p_{T,veto}, \quad \eta_j^{veto} \in (\eta_j^{\text{tag 1}}, \eta_j^{\text{tag 2}})$$

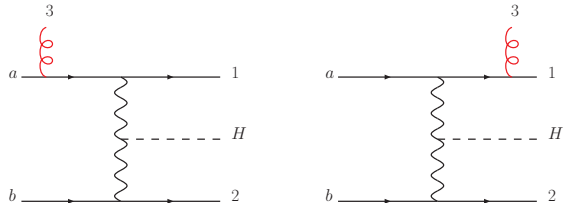
$$P_{\text{veto}} = \frac{1}{\sigma_2^{NLO}} \int_{p_{T,veto}}^{\infty} dp_{Tj}^{veto} \frac{d\sigma_3^{LO}}{dp_{Tj}^{veto}}$$

- Scale variation at LO for σ_{3j}: $+33\%$ to -17% for $p_{T,veto} = 15$ GeV
- The uncertainty in P_{veto} feeds into the uncertainty of coupling measurements at the LHC
- In order to constrain couplings more precisely, the NLO QCD corrections to $Hjjj$ are needed: T. Figy, V. Hankele, and DZ, arXiv:0710.5621

Ingredients of the NLO Calculation

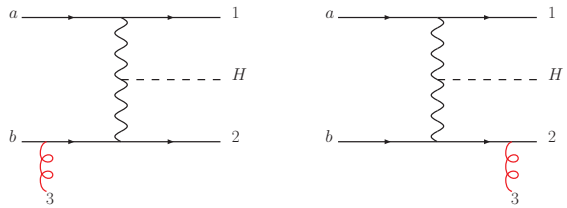
- Born: 3 final state partons + Higgs via VBF

$$\mathcal{M}_B = \delta_{i_2 i_b} t^{a_3}_{i_1 i_a} \left[\mathcal{M}_{B,1a} : \right.$$



$$\left. \right]$$

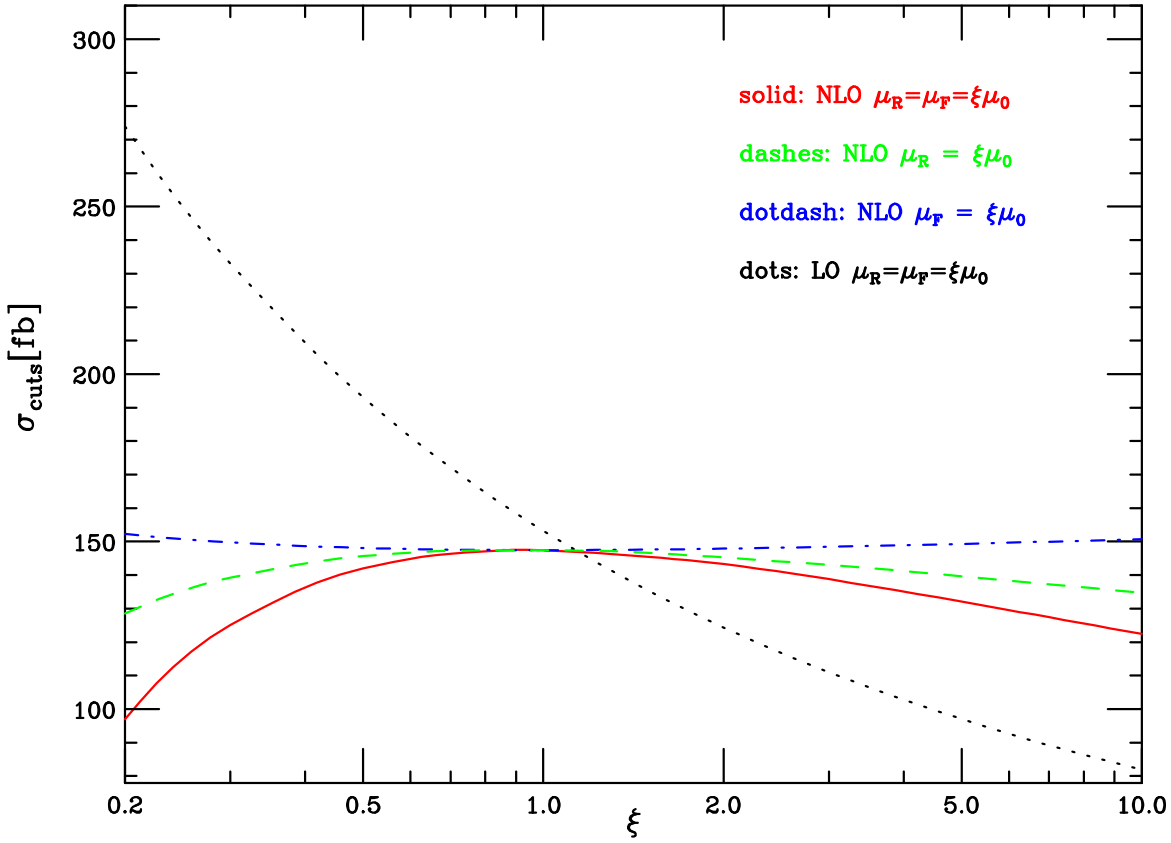
$$+ \quad \delta_{i_1 i_a} t^{a_3}_{i_2 i_b} \left[\mathcal{M}_{B,2b} : \right.$$



$$\left. \right]$$

- Catani, Seymour subtraction method
- Real emission corrections: 4 final state partons + Higgs via VBF
- Virtual corrections: Two classes of gauge invariant subsets
  - Box + Vertex + Propagator
  - Pentagon + Hexagon are small and can be neglected

Total $Hjjj$ Cross Section at the LHC: NLO vs LO

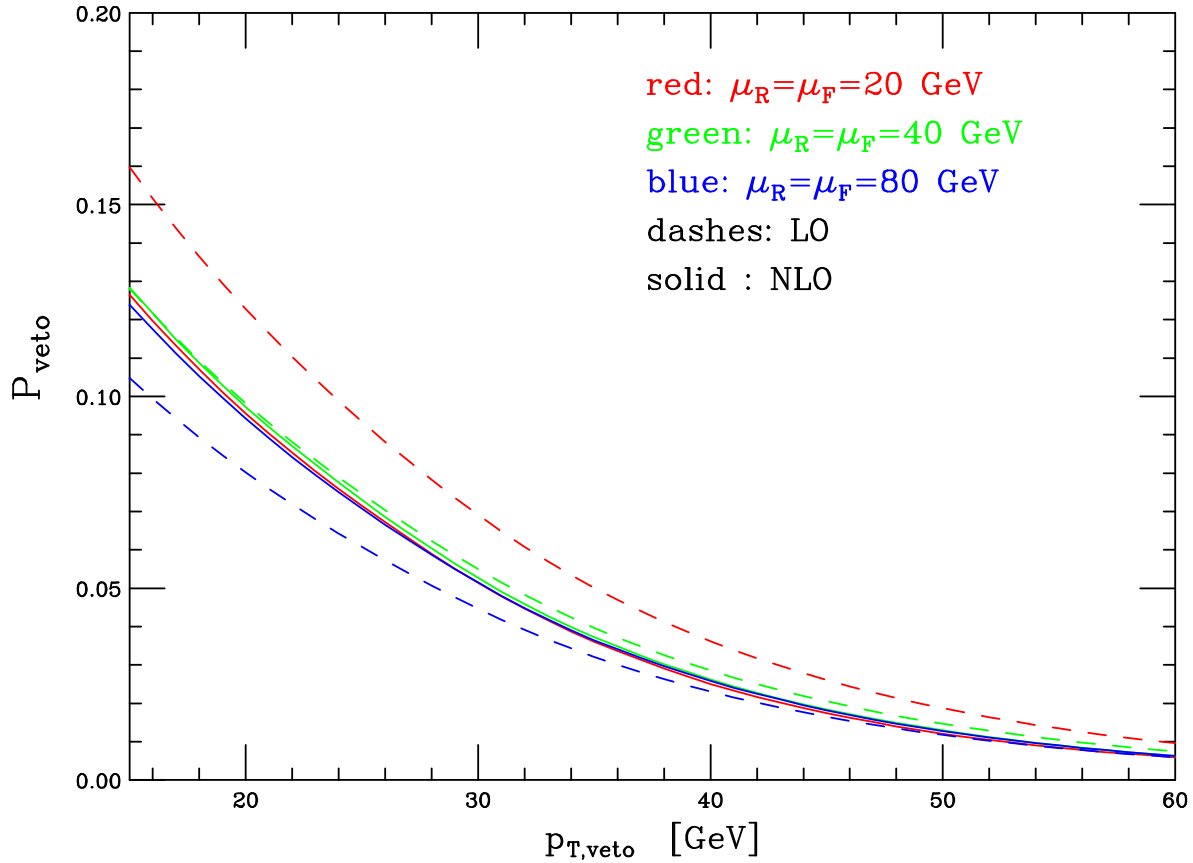


$\mu_0 = 40$ GeV

$\xi = 2^{\mp 1}$ scale variations:

- LO: $+26\%$ to -19%
- NLO: less than 5%

Veto Probability for the VBF Signal



$$P_{\rm veto} = \frac{1}{\sigma_2^{NLO}} \int_{p_{T,veto}}^{\infty} dp_{Tj}^{veto} \frac{d\sigma_3}{dp_{Tj}^{veto}}$$

Scale variations, $p_{T,veto} = 15$ GeV:

- LO: $+33\%$ to -17%
- NLO: -1.4% to -3.4%

Reliable prediction for perturbative part of veto probability at NLO

Summary

- Higgs search at Tevatron and LHC should reveal last particle predicted by the SM... or discover a richer symmetry breaking sector
- 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
- Gauge boson fusion processes provide important facets of this information, both on absolute values of couplings but also on their tensor structure.
- Loop corrections to signal processes provide predictions with $\sim 10\%$ accuracy or better for all relevant SM processes.

NLO QCD correction for VBF available in VBFNLO: parton level Monte Carlo for Hjj, Wjj, Zjj, W^+W^-jj, $ZZjj$ production by Bozzi, Figy, Hankele, Jäger, Klämke, Oleari, Worek, DZ, ...
Available at http://www-itp.physik.uni-karlsruhe.de/vbfnlo/