Theoretical Status of Higgs Production at Hadron Colliders within the SM

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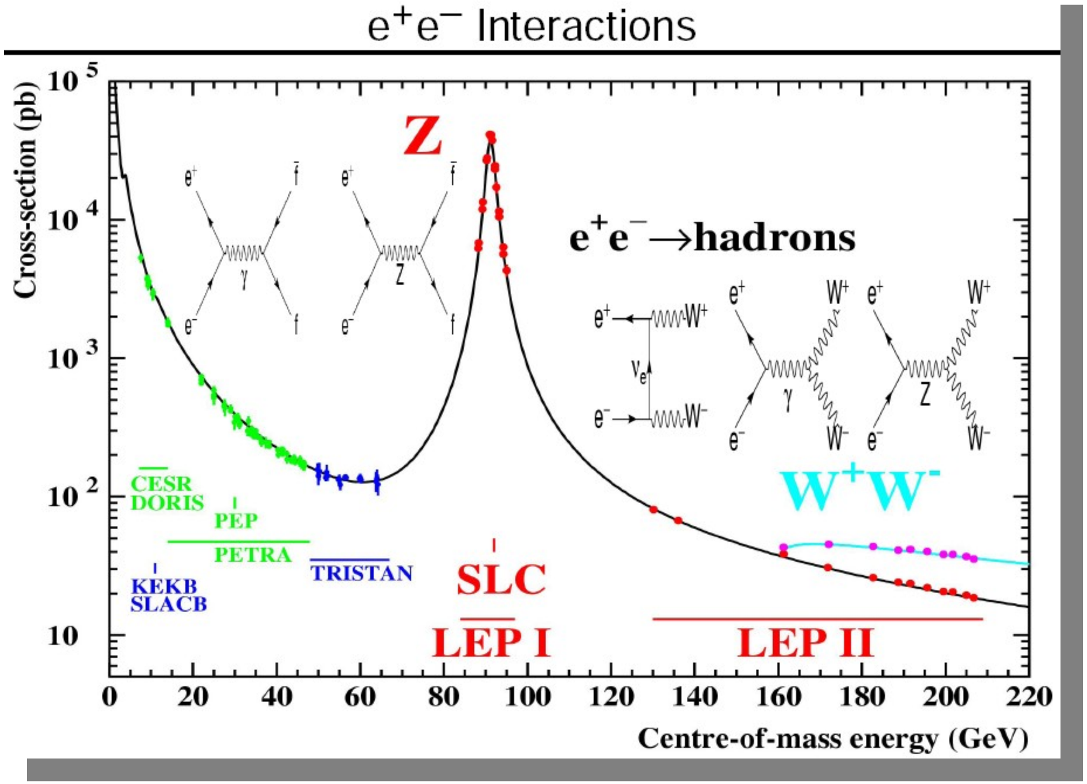
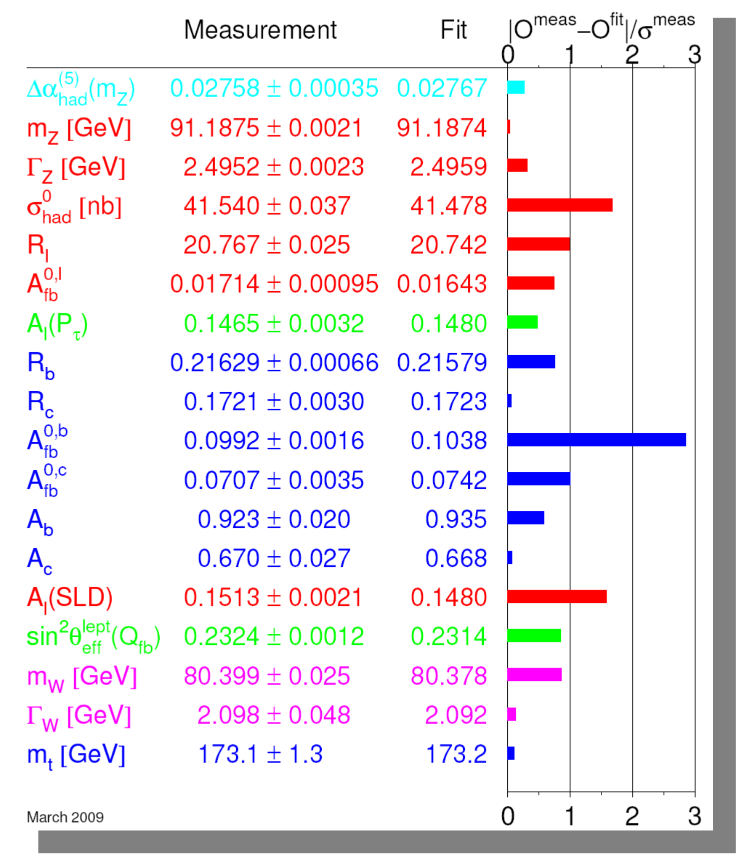
Success of the Standard Model





An amazing agreement between experimental measurements and theoretical predictions based on the Standard Model of electroweak and strong interactions

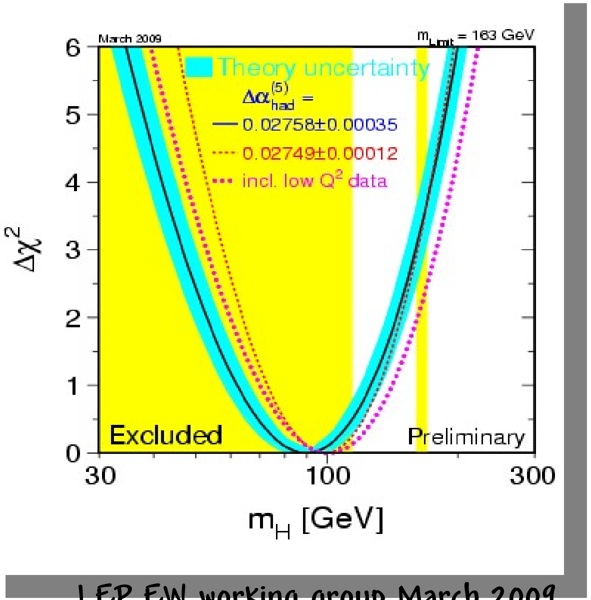
Yet the Higgs particle predicted by this model was not observed

Current Limits on the SM Higgs Mass

Combined efforts from direct searches and theoretical predictions were needed to set tighter limits on MH

- Current fit of electroweak parameters by LEP EW-working group predicts:

$$M_H = 90^{+36}_{-27}\,GeV$$



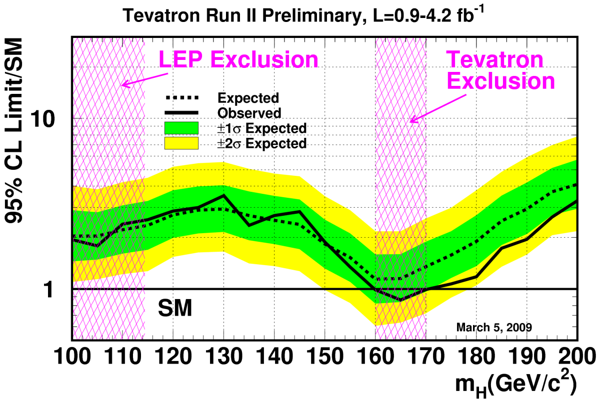
LEP EW working group March 2009

- Upper bound (from precision EW measurements) and lower bound (direct searches at LEP) at 95% CL:

$$M_H < 163\,GeV$$

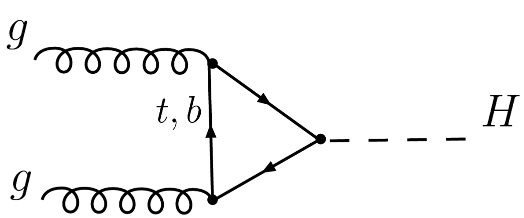
$$M_H > 114.4\,GeV$$

- Combined results from CDF and D0 excluded MH in the range 160-170 GeV at 95% CL arXiv:0903.4001

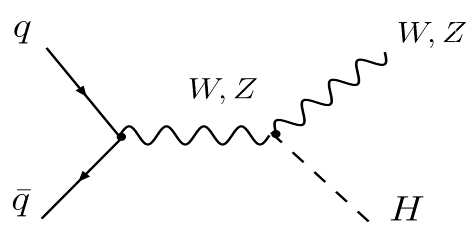


The SM Higgs Production at the Tevatron

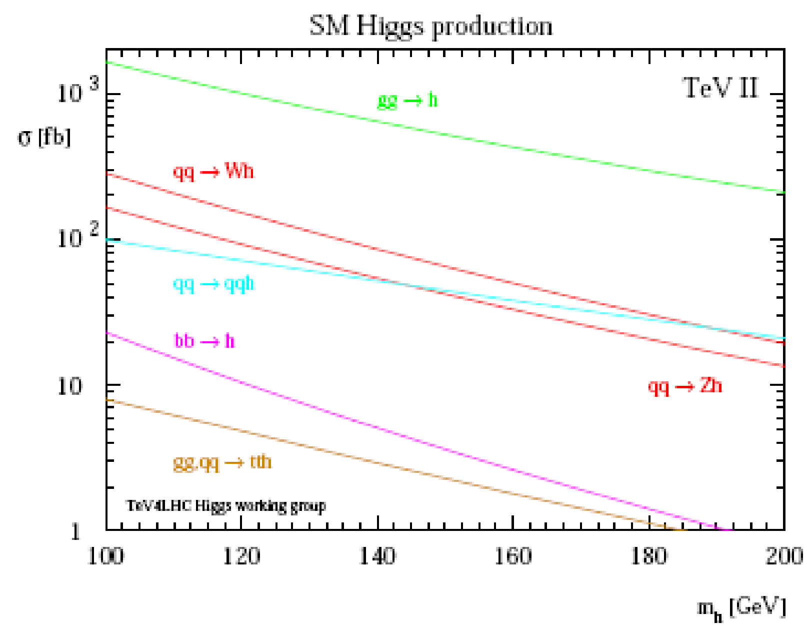
Gluon fusion dominates the two main production modes:

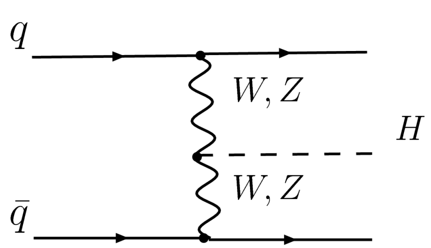


gg fusion



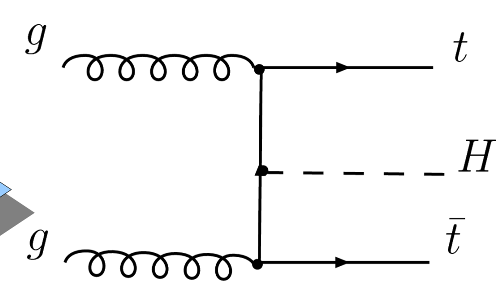
Associated production
With W, Z
essential for $M_H \leq 130\,GeV$





W, Z fusion:

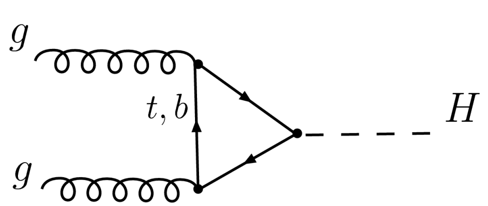
marginal processes due to their small cross sections



Associated production with tt

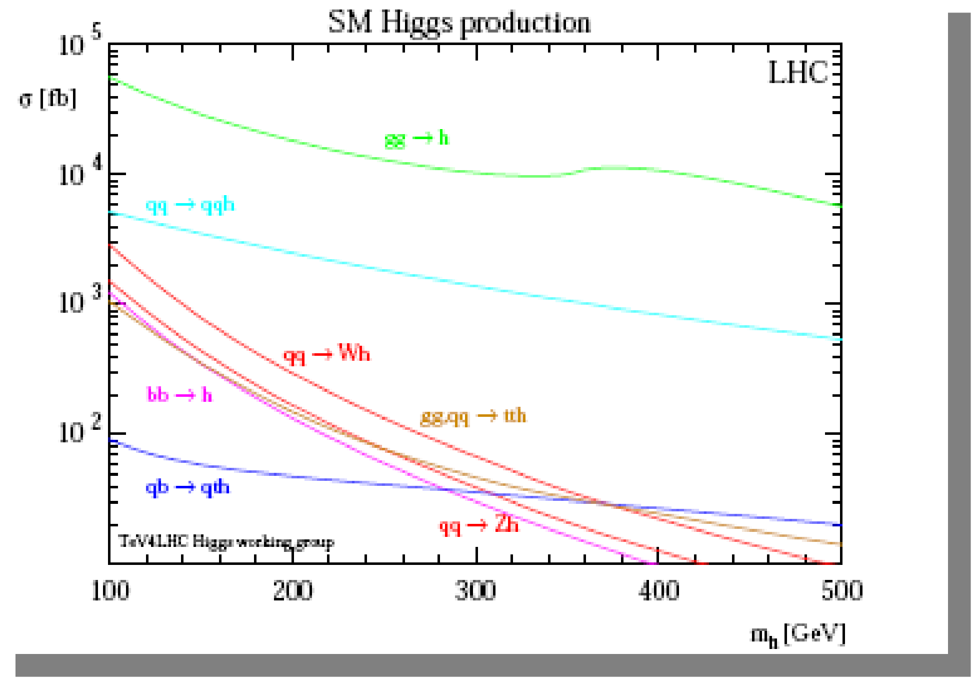
Production Mechanisms of SM Higgs at the LHC

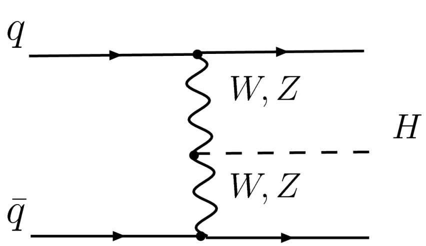
AT the LHC the SM Higgs Boson is produced mostly via four mechanisms:



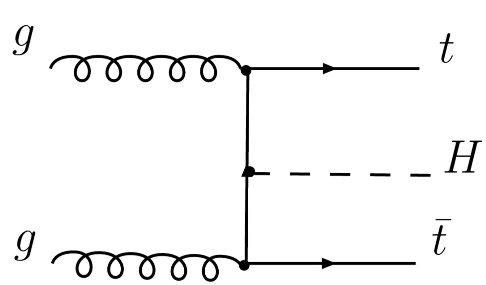
gg fusion

Dominant production mechanism over the whole range of M_H

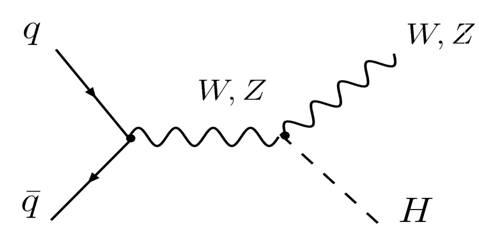




W, Z fusion:
increasingly important at high masses



Associated production with tt
clean measurement of top-yukawa coupling

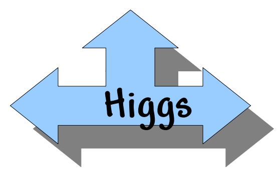


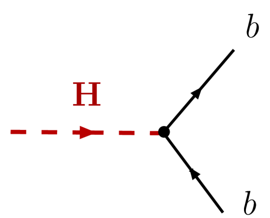
Associated production with W, Z

Decays of SM Higgs

In SM the Higgs coupling is strongest to the heaviest particles ⇒ 3 types of decays:

massive vector bosons

massive fermions  loop induced decays

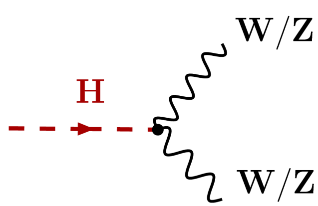


$H \rightarrow b\bar{b}$ dominant for $M_H \leq 130\,GeV$

$BR(H \rightarrow b\bar{b})$ = 90% for $M_H < 100\,GeV$

$BR(H \rightarrow \tau\tau)$ < 10%

$BR(H \rightarrow c\bar{c})$ < 5%

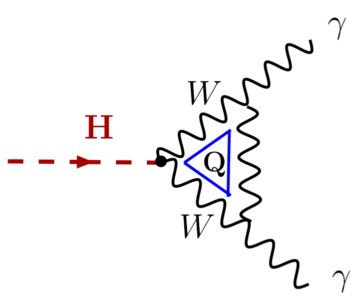


$H \rightarrow WW$ dominant for large masses

$BR(H \rightarrow WW)$ = 98% for $M_H \approx 160\,GeV$

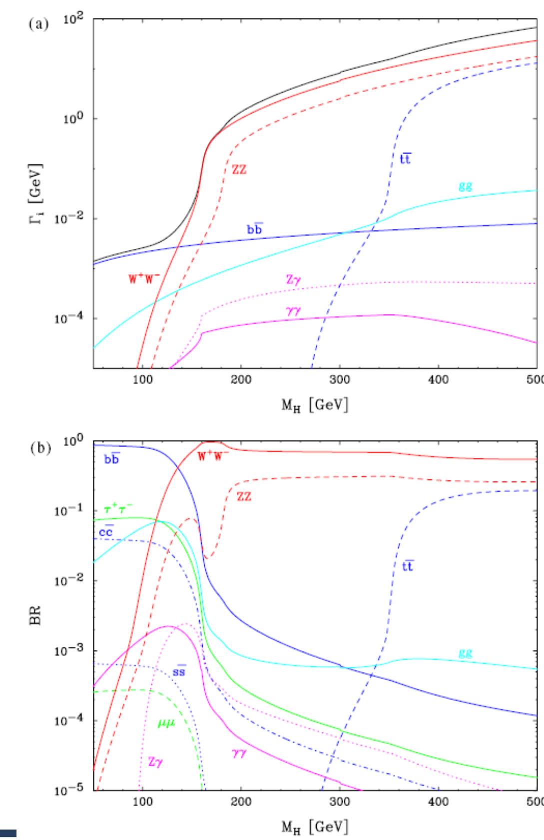
$BR(H \rightarrow ZZ)$ = ½ $BR(H \rightarrow WW)$ for $M_H \geq 200\,GeV$

$BR(H \rightarrow t\bar{t})$ at most 20% for $M_H \approx 350\,GeV$

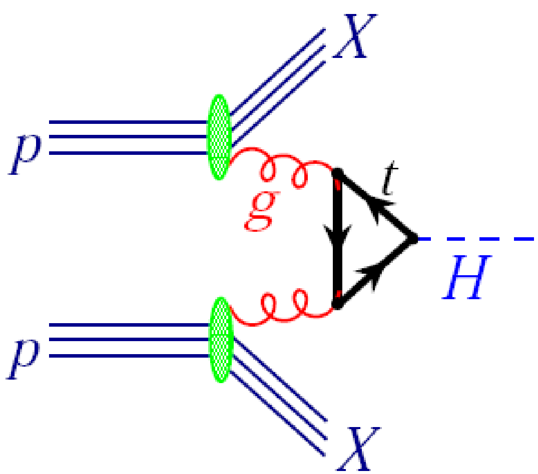


$H \rightarrow \gamma\gamma$ important for low MH masses

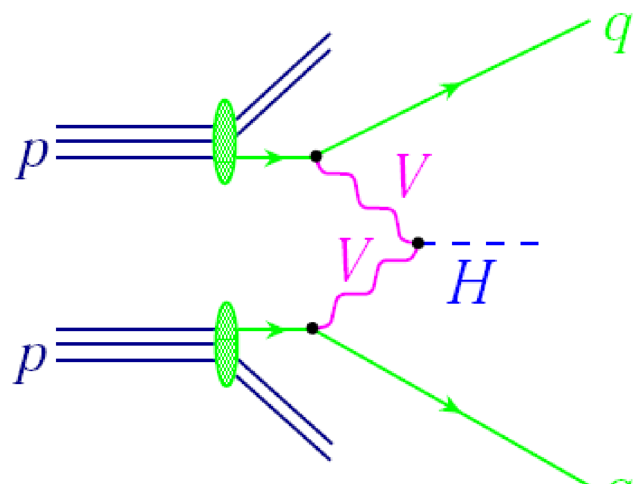
$BR(H \rightarrow \gamma\gamma) \approx 10^{-3}$



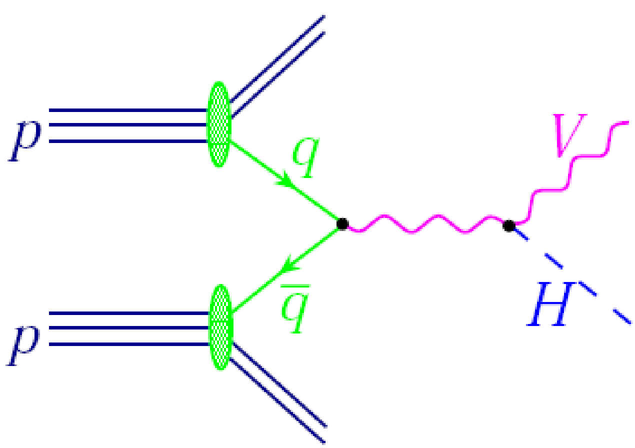
Focus on the dominant Higgs production cross sections at LHC



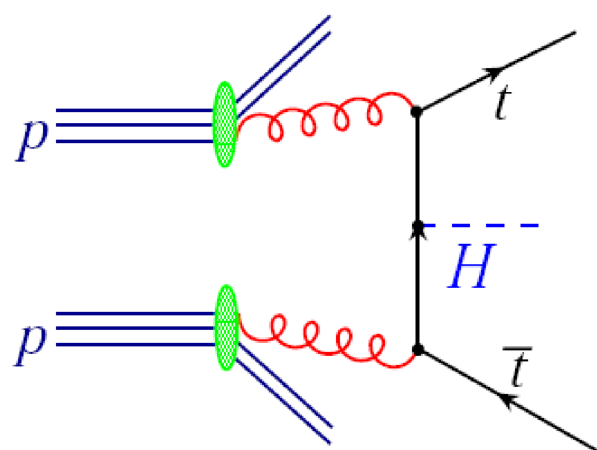
Gluon fusion



Weak-Boson Fusion



Higgs Strahlung



$t\bar{t}H$

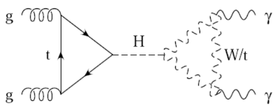
Gluon fusion: signal and background

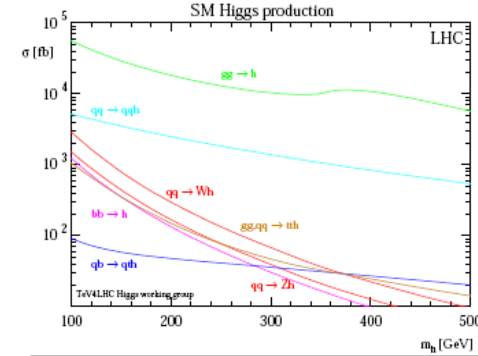
gg → H: largest cross section

Production signature: decay products

$M_H \leq 130\,\mathrm{GeV}$ dominant H → bb swamped by large QCD background

look for Higgs in $H \rightarrow \gamma\gamma$

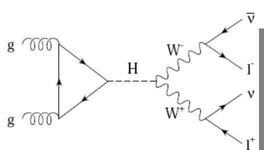


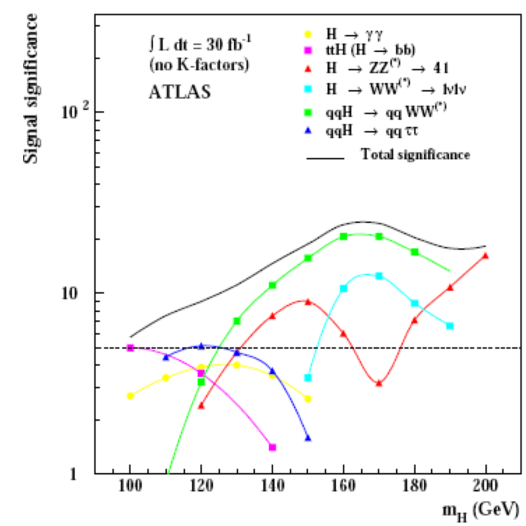


$140\,\mathrm{GeV} \leq M_H \leq 180\,\mathrm{GeV}$ $H \rightarrow WW \rightarrow l\,l\,\nu\,\bar{\nu}$

no mass peak BUT strong angular correlations between charged leptons

background from top quarks

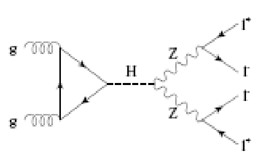




$M_H \geq 180\,\mathrm{GeV}$ $H \rightarrow Z\,Z \rightarrow 4\ leptons$

invariant mass of leptons can be reconstructed so background

can be measured from the data



gold-plated mode

$180 \leq M_H \leq 600\,GeV$

Precise theoretical predictions for signal and background cross sections are crucially needed for a Higgs discovery

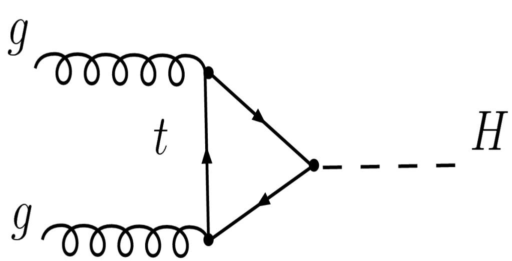
Gluon fusion: inclusive cross section

- $gg \to H$: LO is already 1-loop $\Rightarrow$ complicated higher order corrections

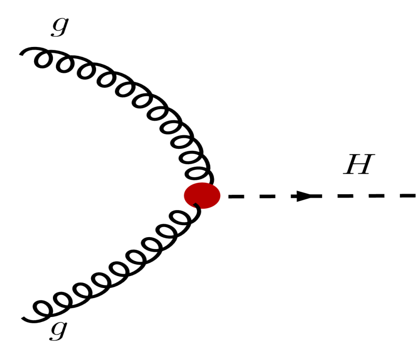
- In the limit where the top-quark is heavy and all other quarks are massless, integrate out the top and couple the gluons to the Higgs with the effective Lagrangian:

$$L_{ggh} = \frac{-H}{4v} C(\alpha_s) G^a_{\mu\nu} G^{\mu\nu}_a$$

$C(\alpha_s)$: known through α_s^5 Schroder, Steinhauser (2006); Chetyrkin , Kuhn, Sturm (2006)



$M_T \gg M_H$ $\Rightarrow$ $C(\alpha_s, M_t)$ x



Inclusive xsection of gg → H at NLO in QCD

QCD corrections at NLO: increase LO cross section by 80-100%

- Full theory: Graudenz, Spira, Zerwas (1993) ; Djouadi, Graudenz, Spira, Zerwas (1995); Harlander, Kant (2005); Anastasiou, Beerli, Bucherer, Daleo, Kunszt (2006); Aglietti, Bonciani, Degrassi, Vicini (2006)

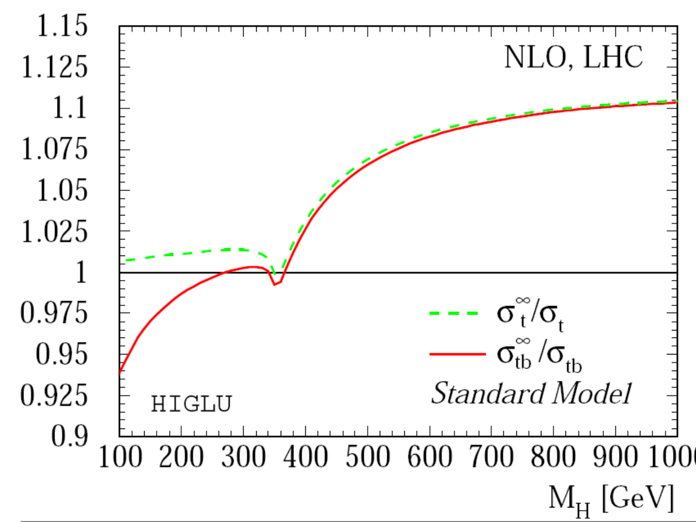
- Effective theory: Dawson (1991); Djouadi, Spira, Zerwas (1991)

Important: very good agreement between

$$\sigma^{Exact,NLO}, \sigma^{\infty,NLO}$$

with

$$\sigma^{\infty} \equiv \sigma^{LO}(m_t, m_b) \frac{\sigma(m_t \to \infty)}{\sigma^{LO}(m_t \to \infty)}$$



difference < 10% for up to 1 TeV and < 1% below 200 GeV

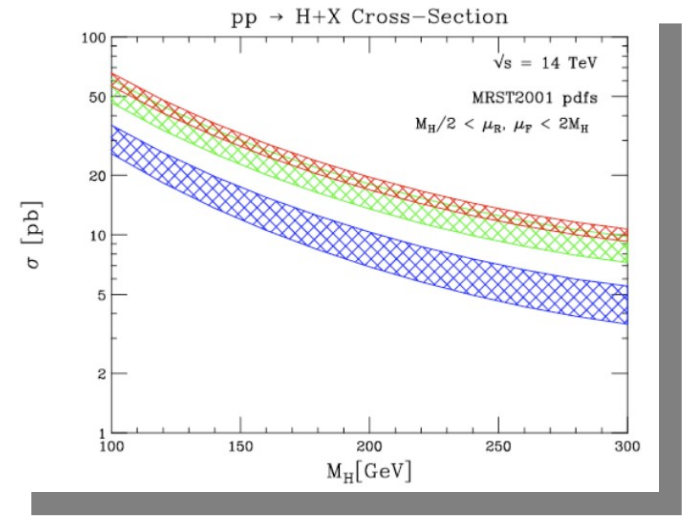
Inclusive xsection of $gg \rightarrow H$ at NNLO in QCD

- NNLO QCD contributions calculated in the large M_T limit:

increase xsection by 10-15%

Harlander, Kilgore (2002); Anastasiou, Melnikov (2002); Ravindran, Smith, van Neerven (2003)

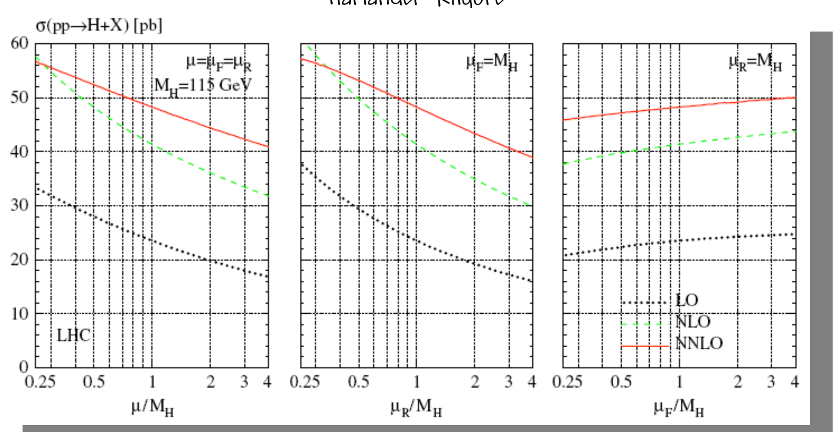
.Anastasiou-Melnikov



NNLO Corrections are significantly smaller than NLO contributions

$\Rightarrow$ converging perturbative series

Harlander-Kilgore

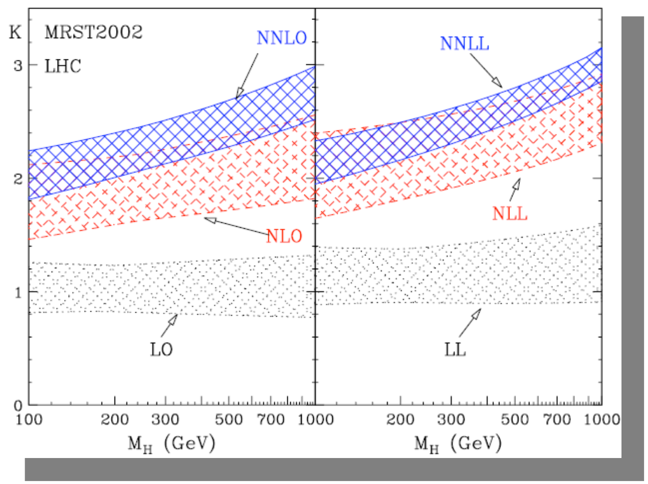


Reduction of renormalization and factorization scale dependence

Inclusive QCD xsection of $gg \to H$

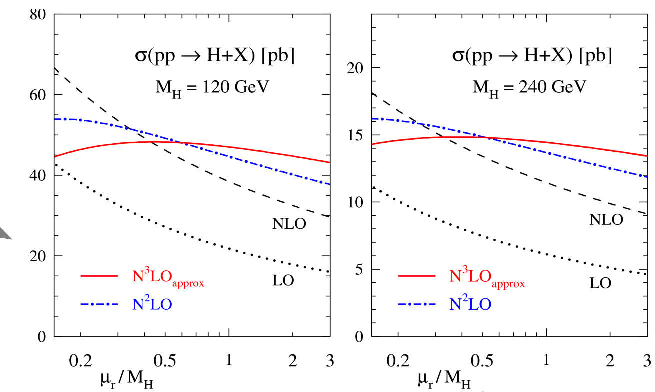
Inclusion of resummed soft-gluon effects shows
a good stability of the perturbative result

Catani, de Florian, Grazzini, Nason (2003)



$K_{LHC}^{NNLO} \sim 2$

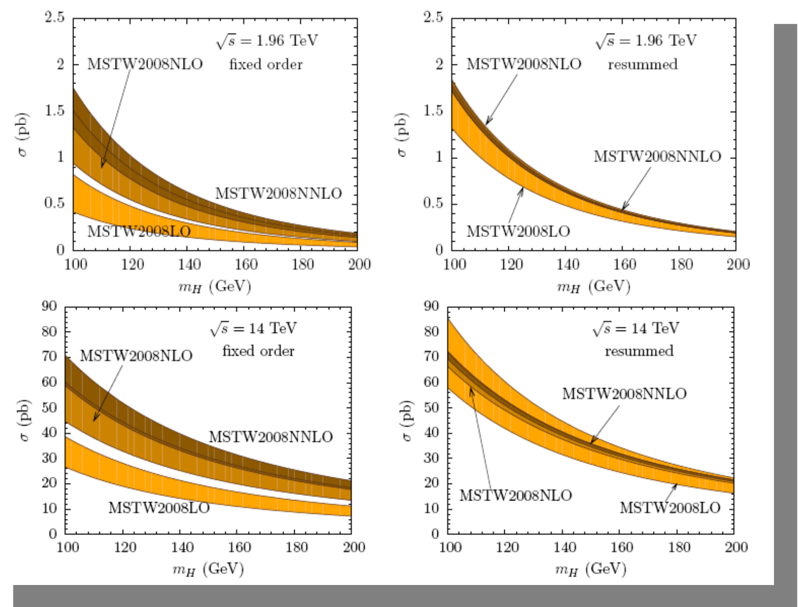
Moch, Vogt (2005)



Soft terms through $N^3 LO$
stabilize μ_R-dependence

NNLL: an additional 6%
to total xsection

Ahrens, Becher, Neubert, Yang (2008)



Large K factor for $gg \to H$ is due to $(C_A \pi \alpha_s)^L$ coming from the analytic continuation of the gluon form factor to time-like momentum transfer

$$\sigma_{LO}^{resummed} > \sigma_{LO}^{non-resummed}$$

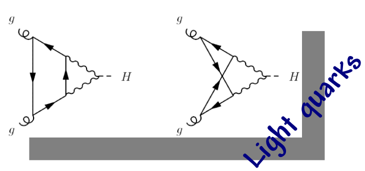
therefore smaller K-factor → for small MH: $K_{LHC}^{NNLO, resummed} \sim 1$

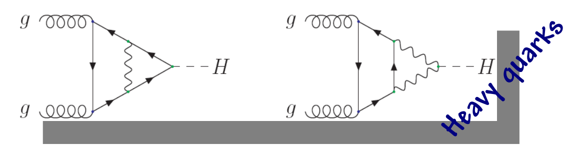
NLO Electroweak Corrections to $gg \to H$

Residual uncertainty from QCD: 9-11%

EW Corrections could be important for matching precision of QCD predictions

$$\sigma_{ew} = \sigma_0 (1 + \delta_{ew})$$



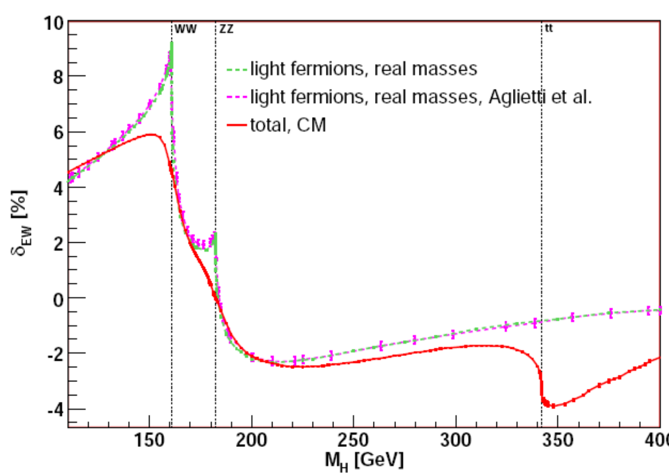


Aglietti, Bonciani, Degrassi, Vicini (2004); Degrassi, Maltoni (2004)

- Light quarks (analytically): real Mw, Mz $\rightarrow \delta_{EW}$ up to 9%
- Top quark: Taylor expansion for $M_H < 2 M_W$

Actis, Passarino, Sturm, Uccirati (2008)

- Light quarks: complex Mw, Mz everywhere
- Top quark: extend calculation to $M_H > 2 M_W$



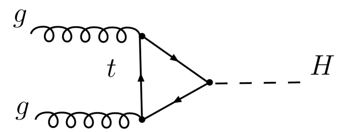
Light quarks + top:

δ_{EW} :(+4)-(+6)% $\quad 115\,GeV \le M_H \le 160\,GeV$

δ_{EW} :(-4) - (+4)% $\quad 160\,GeV \le M_H \le 400\,GeV$

Light quarks do not dominate above 180GeV

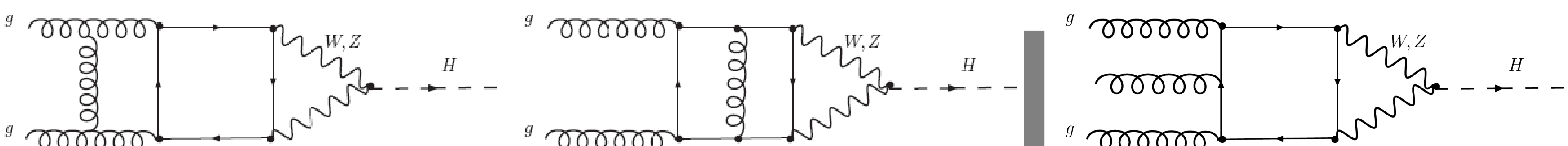
What about mixed EW-QCD effects ?

At LHC QCD corrections to 

$\sigma(gg \to H) \approx \sigma_{\rm LO}(1 + 0.7 + 0.3 + \cdots) \approx 2\sigma_{\rm LO}$

$O(\alpha)$ up to 6% of LO → $O(\alpha\alpha_s)$?

What we need:



+...

several loops & several scales $M_W / M_Z, M_H$

Quite hard with the current computational capabilities !

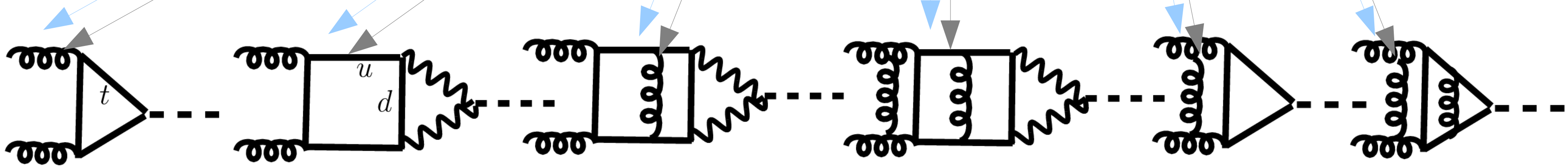
Can we just assume the mixed EW-QCD is the same as EW x QCD (factorization) ?

We need to check that... possible if we use an effective field theory approach again

EFT formulation (Anastasiou, R.B, Petriello 2008)

$$L_{eff} = -\alpha_s \frac{C_1}{4v} H\, G^a_{\mu\nu} G^{a\mu\nu}$$

$$C_1 = -\frac{1}{3\pi}\left\{1 + \lambda_{EW}\left[1 + a_s C_{1w} + a_s^2 C_{2w}\right] + a_s C_{1q} + a_s^2 C_{2q}\right\}$$



Radius of convergence $M_H \leq M_W$;however top-quark EFT valid up to 1 TeV > 2Mt, expect similarity here. Soft gluons dominate the cross section for $\tau = \frac{M_H^2}{s} \to 1$

$$C_{1q} = \frac{11}{4}, \quad C_{2q} = \frac{2777}{288} + \frac{19}{16}L_t + N_F\left(-\frac{67}{96} + \frac{1}{3}L_t\right)$$

$$\lambda_{EW} = \frac{3\alpha}{16\pi s_W^2}\left\{\frac{2}{c_W^2}\left[\frac{5}{4} - \frac{7}{3}s_W^2 + \frac{22}{9}s_W^4\right] + 4\right\}$$

Complete Factorization holds if $C_{1w} = C_{1q}$ & $C_{2w} = C_{2q}$

$$C_1^{fac} = -\frac{1}{3\pi}\left(1 + \lambda_{EW}\right)\left\{1 + a_s C_{1q} + a_s^2 C_{2q}\right\}$$

EW-QCD effects & a new inclusive xsection prediction (Anastasiou, RB, Petriello)

$C_{1w}=\frac{7}{6}$ to be compared with $C^{fac}_{1w} = C_{1q} = 11/4$

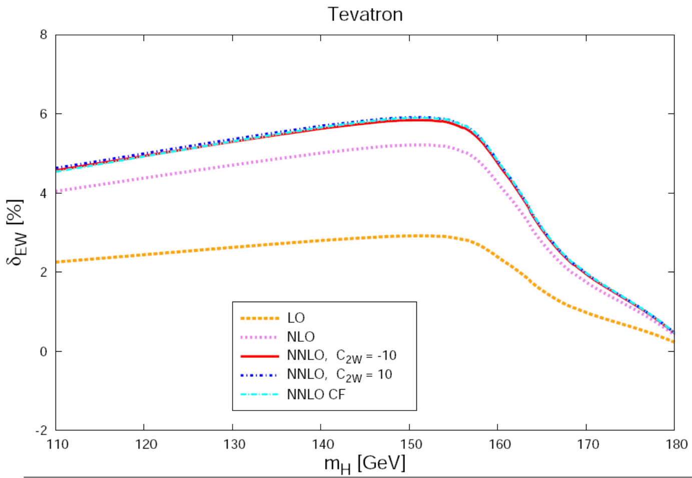
Violation of complete factorization assumption

Numerical effect on hadronic cross section?

QCD corrections in EFT

$$G_{ij}(z;\alpha_s) = \sum_{n=0}^{\infty} \left(\frac{\alpha_s}{\pi}\right)^n G^{(n)}_{ij}(z)$$

$$G^{(0)}_{ij}(z) = \delta_{ig}\delta_{jg}\delta(1-z)$$



Difference between complete factorization and $a_s(C_{1w}-C_{1q})$ small as compared to $a_s G^{(1)}(z)$

$$\sigma^{NNLO}_{QCD} = \sigma^{(0)} G_{ij}(z;\alpha_s) + \sigma^{(0)}_b G^{(0)}_{ij}(z) K_{bb} + \sigma^{(0)}_{t,b} G^{(0)}_{ij}(z) K_{tb} \ ,$$

$$\sigma^{LO}_{EW} = \sigma^{(0)}_{t,lf} G^{(0)}_{ij}(z) \ ,$$

$$\sigma^{NLO}_{EW} = \sigma^{(0)}_{t,lf} \left\{ G^{(0)}_{ij}(z)\left[1 + a_s(C_{1w} - C_{1q})\right] + a_s G^{(1)}_{ij}(z) \right\} \ ,$$

Used the calculated mixed EW-QCD result →

$$\sigma^{NNLO}_{EW} = \sigma^{(0)}_{t,lf} \left\{ G^{(0)}_{ij}(z)\left[1 + a_s(C_{1w} - C_{1q}) + a_s^2\left(C_{2w} - C_{2q} + C_{1q}(C_{1q} - C_{1w}\right)\right] + a_s G^{(1)}_{ij}(z)\left[1 + a_s(C_{1w} - C_{1q})\right] + a_s^2 G^{(2)}_{ij} \right\} \ ,$$

Used complete factorization →

$$\sigma^{NNLO\ CF}_{EW} = \sigma^{(0)}_{t,lf} G_{ij}(z;\alpha_s) \ ,$$

New Prediction (Anastasiou, R.B, Petriello 2008; Grazzini, de Florian 2009)

Tevatron

used MRST 2008 PDFs

m_H[GeV]	σ^{best}[pb]	m_H[GeV]	σ^{best}[pb]
110	1.417 (±7% pdf)	160	0.4344 (±9% pdf)
115	1.243 (±7% pdf)	165	0.3854 (±9% pdf)
120	1.094 (±7% pdf)	170	0.3444 (±10% pdf)
125	0.9669 (±7% pdf)	175	0.3097 (±10% pdf)
130	0.8570 (±8% pdf)	180	0.2788 (±10% pdf)
135	0.7620 (±8% pdf)	185	0.2510 (±10% pdf)
140	0.6794 (±8% pdf)	190	0.2266 (±11% pdf)
145	0.6073 (±8% pdf)	195	0.2057 (±11% pdf)
150	0.5439 (±9% pdf)	200	0.1874 (±11% pdf)
155	0.4876 (±9% pdf)	–	–

- Values for xsection are up to 6% lower than previous predictions
- Theoretical uncertainty from scale dependence obtained by varying

$$\mu \in [\frac{M_H}{4}, M_H] \rightarrow [-11\%, +7\%]$$

- PDF errors estimated using error eigenvectors provided with MRST2008 fit
they are a factor of 2 larger than previous predictions

$$\sigma^{best} = \sigma^{NNLO}_{EW} + \sigma^{NNLO}_{QCD}$$

$$\sigma^{NNLO}_{QCD} = \sigma^{(0)} G_{ij}(z;\alpha_s) + \sigma^{(0)}_b G^{(0)}_{ij}(z) K_{bb} + \sigma^{(0)}_{t,b} G^{(0)}_{ij}(z) K_{tb}$$

NNLO large-m_t K-factor, exact LO result

Exact NLO b^2, t-b interferences K-factors

$1.4 \le K_{bb,tb} \le 1.7$ for $120 \le M_H \le 180$ GeV;
3.5 used for both in old Catani et al. study

New prediction accounted for in the Tevatron exclusion limit of SM Higgs mass In 160-170GeV

NNLO Differential xsection for gg $\to$ H

Impact of higher order corrections on the rate and shape of the corresponding distributions may be strongly dependent on the choice of experimental cuts

- First NNLO calculation that fully takes into account experimental cuts:

  FEHiP gg $\to$ **H** $\to \gamma\gamma$ Anastasiou, Melnikov, Petriello (2005)

  - Extended to include $H \to W\,W \to l\,l\,\nu\,\bar{\nu}$ Anastasiou, Dissertori, Stockli (2007)

M_H, GeV	$\sigma^{\rm cut}_{\rm NNLO}/\sigma^{\rm inc}_{\rm NNLO}$	$K^{(2)}_{\rm cut}/K^{(2)}_{\rm inc}$
110	0.590	0.981
115	0.597	0.968
120	0.603	0.953
125	0.627	0.970
130	0.656	1.00
135	0.652	0.98

σ (fb)	LO	NLO	NNLO
$\mu = \frac{M_H}{2}$	21.002 ± 0.021	22.47 ± 0.11	18.45 ± 0.54
$\mu = M_H$	17.413 ± 0.017	21.07 ± 0.11	18.75 ± 0.37
$\mu = 2M_H$	14.529 ± 0.014	19.50 ± 0.10	19.01 ± 0.27

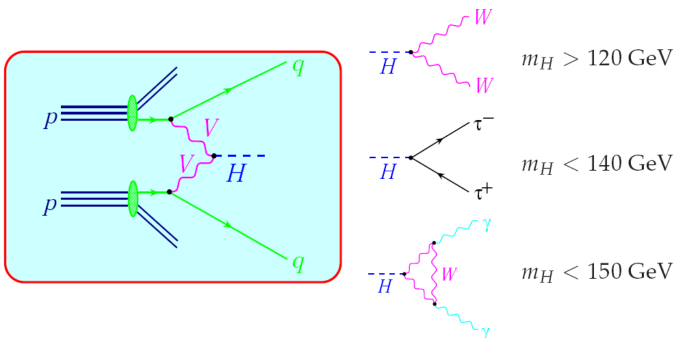
- An independent implementation/method with all decay modes:

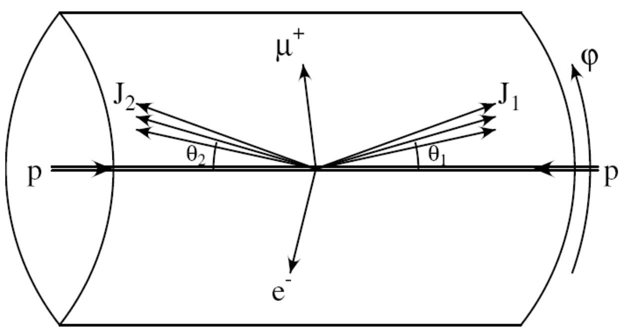
  HNNLO H $\to \gamma\gamma$, $H \to WW \to l\,l\,\nu\,\bar{\nu}$, H $\to$ Z Z $\to$ 4 leptons

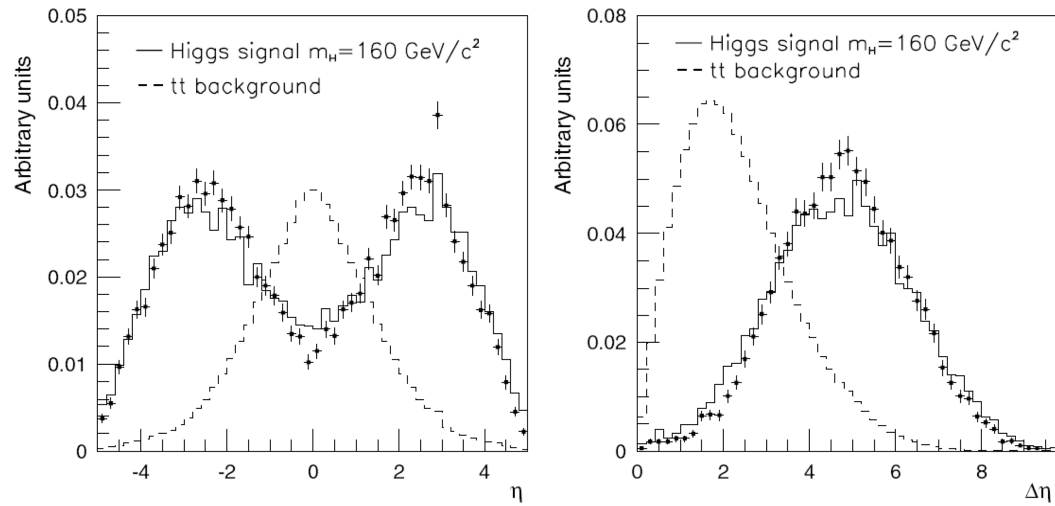
  Catani, Grazzini (2007); Grazzini (2008)

Vector Boson Fusion (VBF)

Attractive channel for discovery (distinctive signature, $\sigma_{VBF} \approx 0.1\sigma_{gg}$) and measurement of Higgs coupling





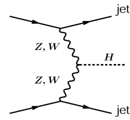


signature

- Energetic jets in the forward and backward directions (PT > 20GeV)
- Large rapidity separation and large invariant mass of the two tagging jets
- Higgs decay products typically between tagging jets
- Little jet activity in central-rapidity region due to the colorless exchanged W/Z
- Applied cuts to achieve a clear separation from background are:

$$P_{T\ j} > 20\text{GeV}\ ,\ |\eta_j| \le 4-5,\ \Delta\eta \equiv |\eta_1-\eta_2| \ge 4,\ \eta_1 \cdot \eta_2 < 0$$

VBF theoretical status

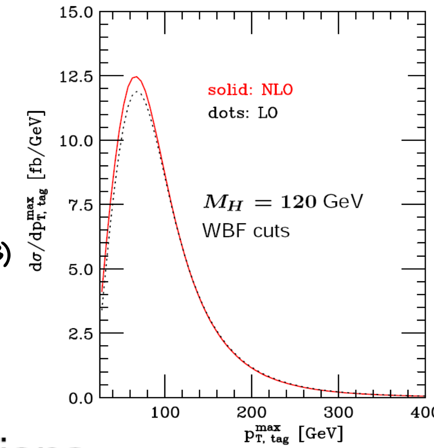


- NLO QCD Corrections to total xsection (5-10%): Han, Valencia, Willenbrock (1992)

  Distributions at NLO:

  Figy, Oleari, Zeppenfeld (2003); Figy, Zeppenfeld (2004); Berger, Campbell (2004);

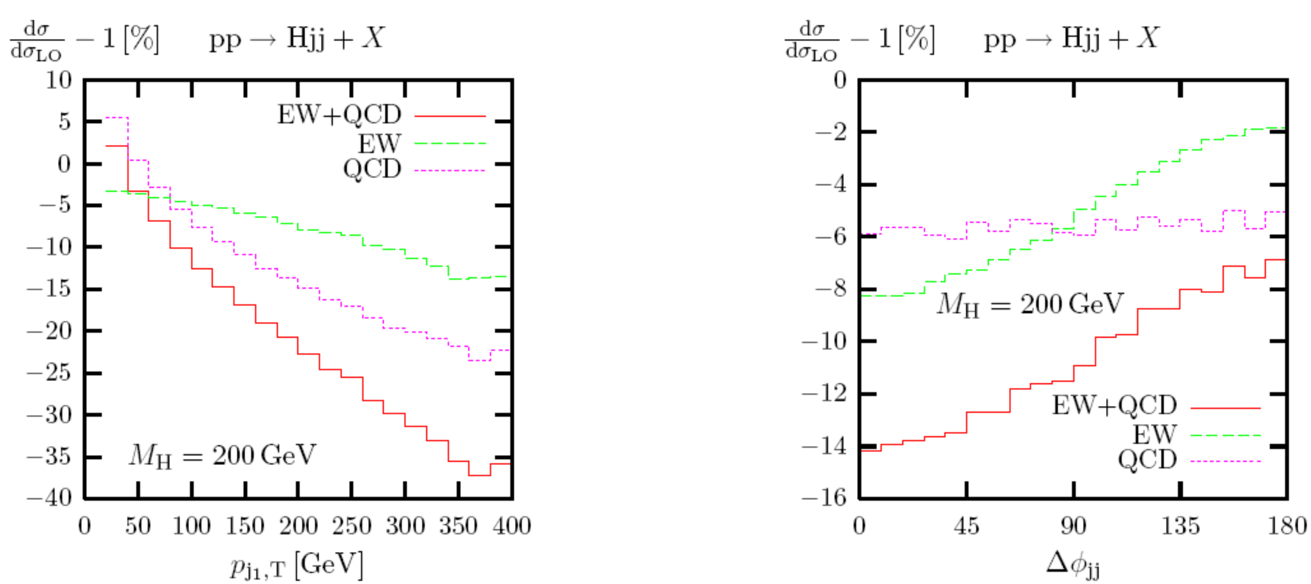
  VBFNLO: A Parton level Monte Carlo for processes with electroweak bosons, Arnold et al (2008)



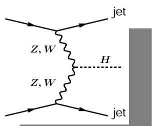
- EW+QCD: Ciccolini, Denner, Dittmaier (2007)

NLO EW corrections to inclusive cross sections and distributions

☞ NLO EW corrections non-negligible, modify cross sections and distort distributions by up to 10%



VBF theoretical status



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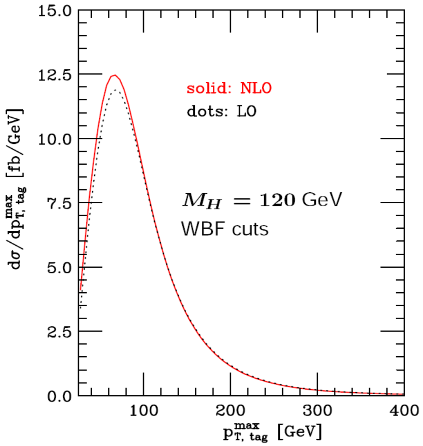
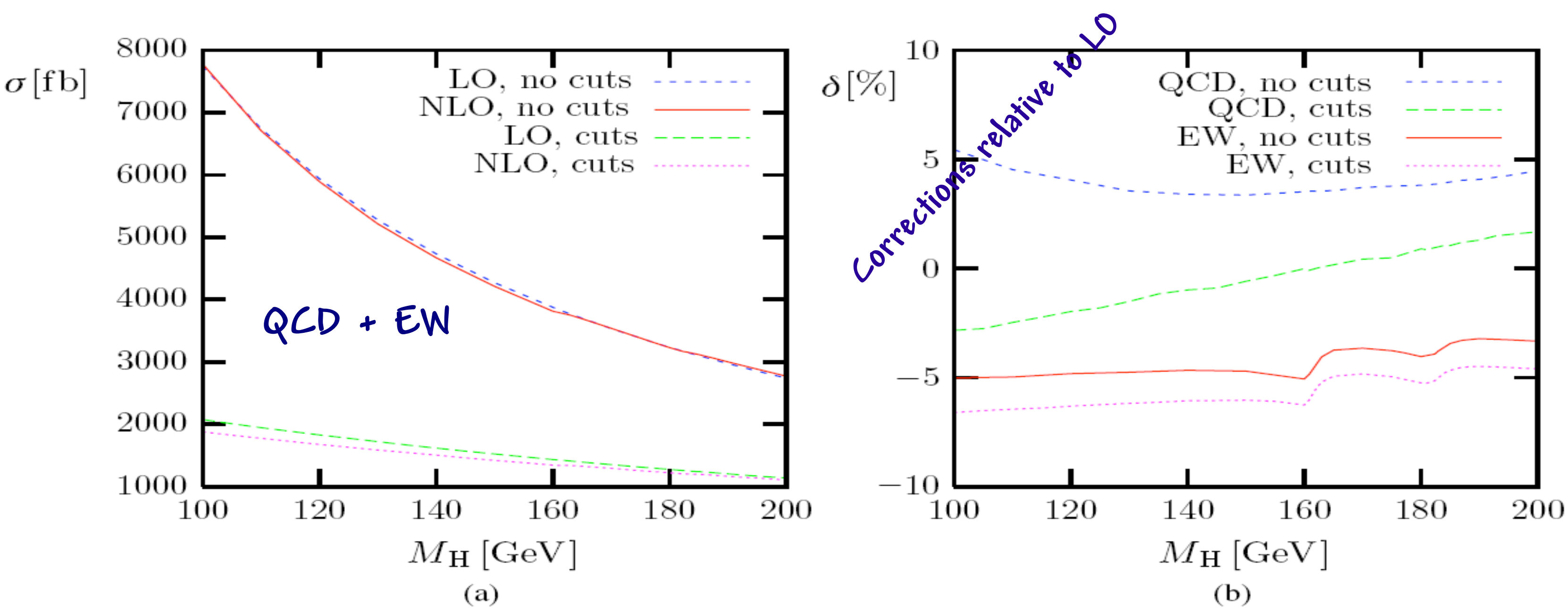
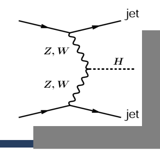
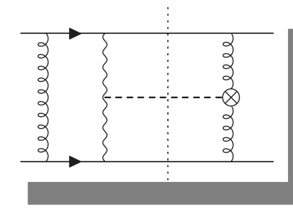




VBF theoretical status

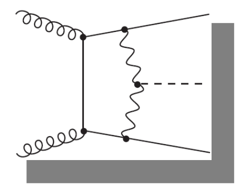


- Mixed QCD/EW Bredenstein, Hagiwara, Jaeger (2008)
- Gluon fusion/VBF interference Anderesen, Binoth, Heinrich, Smillie (2007)



+...

- Gluon induced VBF Harlander, Vollinga, Webber (2008)



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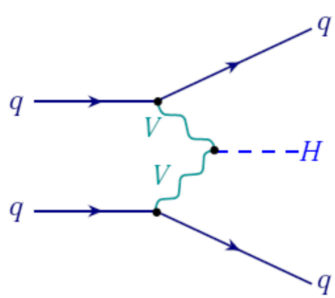
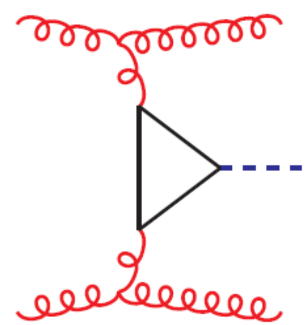


vs.



$gg \to H$+2 jets: [Del Duca, Kilgore, Oleari, Schmidt, Zeppenfeld '01] → LO full Mtop dependence

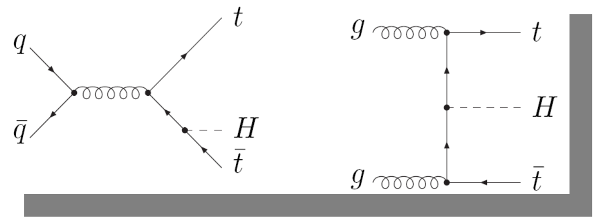
NLO for $m_t \to \infty$: [Campbell, Ellis, Zanderighi '06] → virtual + real + prediction

$gg \to H + n$ jets: [Andersen, Del Duca, White '08]

Decaying W/Z + jj @ NLO Oleari, Zeppenfeld (2004) ; decaying WW/ZZ + jj @ NLO Jaeger, Oleari, Zeppenfeld (2006)

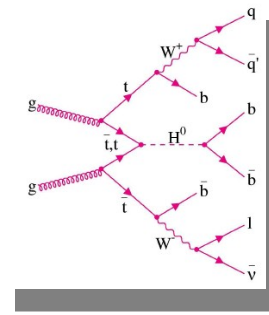
Associated production with tt pair

$pp \to t\bar{t}H$ offers the possibility of a clean measurement of the top Yukawa coupling



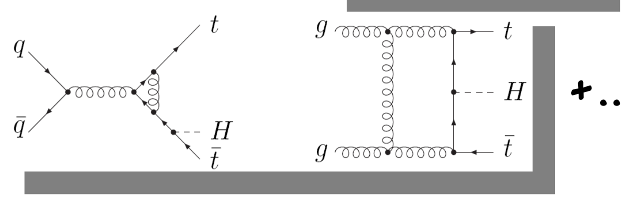
signature

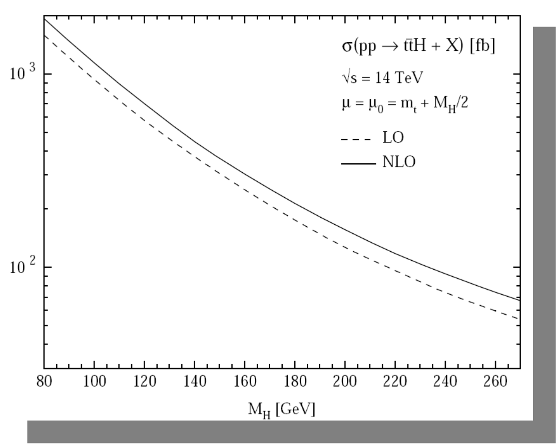
four b-quarks in association with two W bosons



QCD NLO to $t\bar{t}H$ increase signal xsection by almost 20%

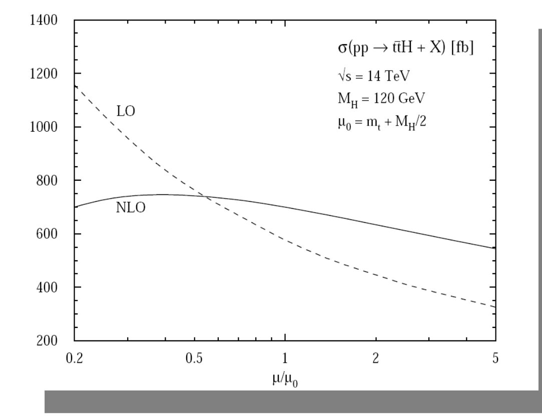
Beenakker et al (2001, 2003); Dawson et al (2002, 2003)





$\mu_F = \mu_R = \mu_0$

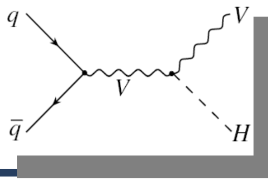
significant reduction of renormalization and factorization scales in xsection



Full NLO QCD corrections to $pp \to t\bar{t}H \to t\bar{t}b\bar{b}$ Bredenstein, Denner, Dittmaier, Pozzorini (2009)

- Discouraging recent re-analysis: difficult to see Higgs in pp→ttH due to large ttbb background (CMS 2006)

Higgs Strahlung

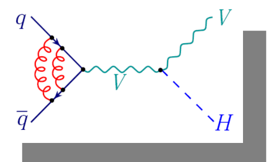


pp→ VH + X (V=W/Z): less important at LHC due to small cross section

NLO QCD corrections: increase xsection by 30% Han, Willenbrock (1991)

NNLO QCD corrections: increase xsection by 5-10% Brein, Djouadi, Harlander (2004)

→ reduction of scale uncertainty from 10% (LO) to 5%(NLO) to 2% (NNLO)



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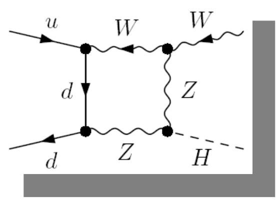
$O(\alpha)$ EW corrections: -5% to -10% Ciccolini, Dittmaier, Kramer (2003)



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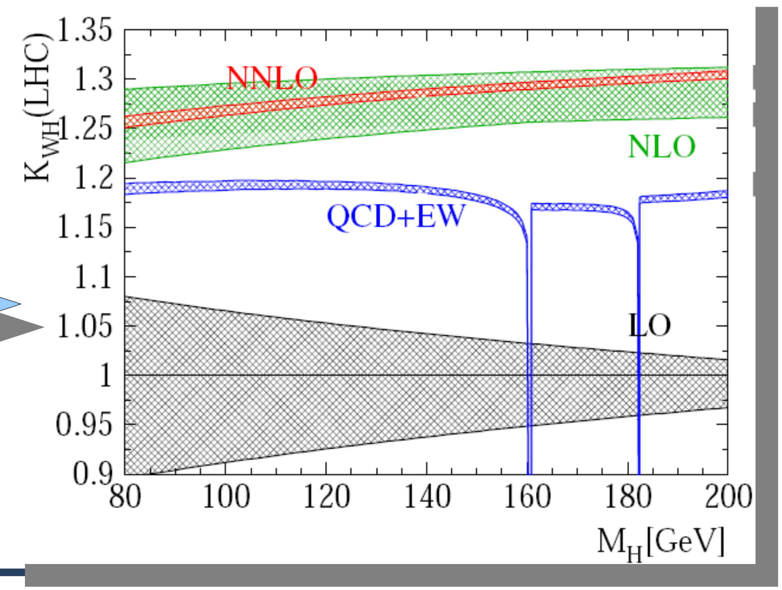
Bands reflect the variation of the xsection upon variation of muF and muR within a factor of 3 around MH+MW →



Summary

- Theoretical research in Higgs physics is a very rich and active field
  - Important Higgs production channels at LHC are known at NLO QCD and sometimes also EW. For $gg \rightarrow H$, NNLO QCD & mixed QCD/EW results are available.
  - New results for inclusive cross sections (gluon fusion channel with NNLO accuracy).
  - Large efforts to provide Monte Carlo Programs for differential distributions to allow a close comparison of predictions with experimental data.

Just waiting for the LHC to turn on and uncover the nature of Higgs if it exists....

Backup Slides

Resummation of π^2-enhanced terms with SCET (Ahrens, Becher, Neubert, Yang (2008))

Large K factor for gg $\rightarrow$H is due to $(C_A \pi \alpha_s)^L$ coming from the analytic continuation of the gluon form factor to time-like momentum transfer $\ln(-q_H^2) = \ln(|q_H^2|) - i\pi$

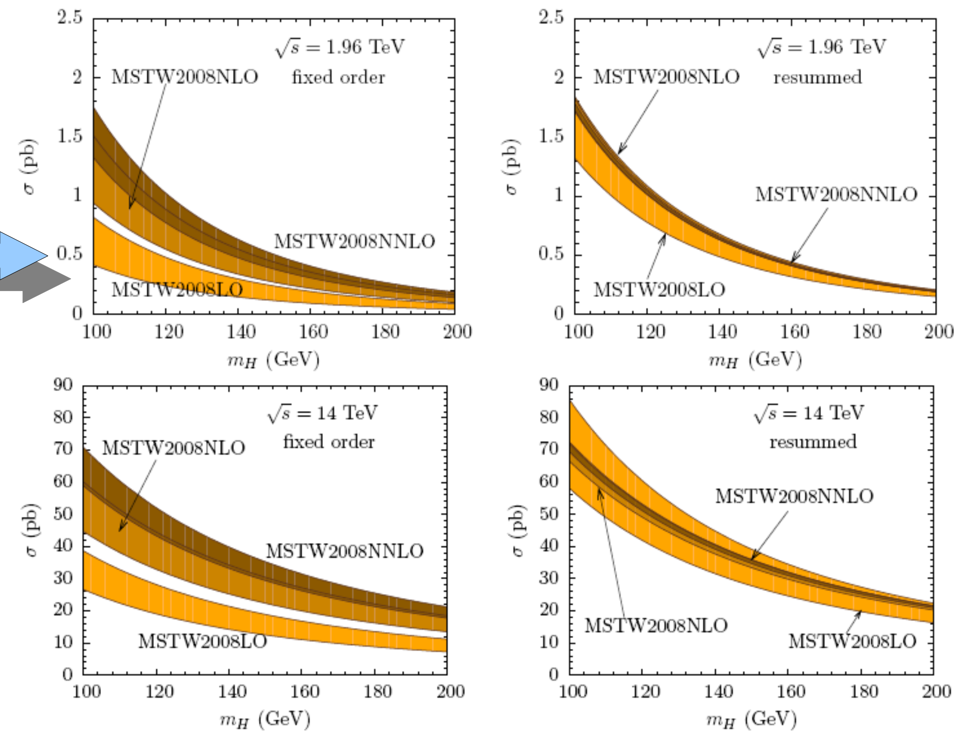
Idea :

each 1-loop vertex contributes $\frac{1}{\epsilon^2}$ IR singularity $\rightarrow$ $(\ln(-q^2))^2$

$$(\ln(-q^2))^2 = \ln(|q^2|)^2 - 2\, i\, \pi\, \ln(|q^2|) - \pi^2$$

Origin of the resummed π^2 enhanced terms

Cross section after adding perturbative LO, NLO and NNLO results to resummed π^2-enhanced terms (dominate)



- Larger predictions for xsection than old results
- Smaller scale uncertainties

$$\sigma_{LO}^{resummed} > \sigma_{LO}^{non-resummed}$$

Therefore smaller K-factor.

for small mH: $K_{LHC}^{NNLO,resummed} \sim 1$