QCD-EW Effects in Higgs Production and a New Prediction for $gg \rightarrow H$ in SM

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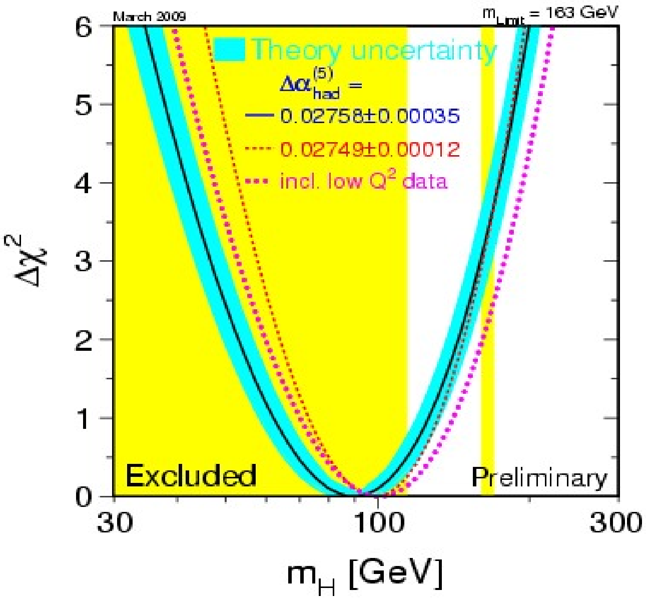
What we know about the SM Higgs Boson Mass today

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

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

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

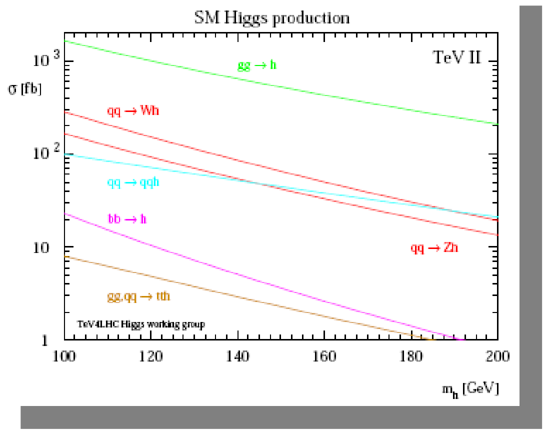
$$M_H < 163\,GeV$$
$$M_H > 114.4\,GeV$$

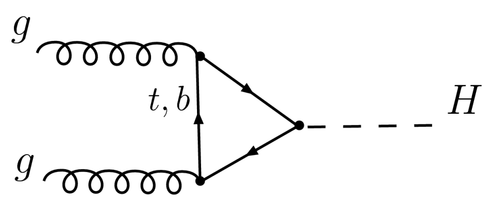


- News from the Tevatron: Combined results from CDF and D0 excluded a Higgs Boson mass of 170 GeV at 95% CL arXiv:0808.0534

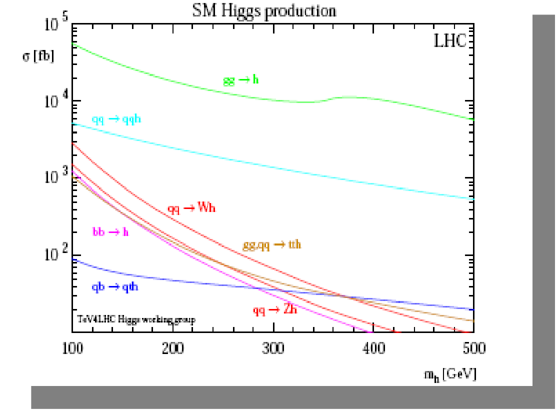
⇒ Extended recently to the range 160 < MH < 170 GeV arXiv:0903.4001

Gluon fusion





top-loop dominant
b-loop gives -10% from interference



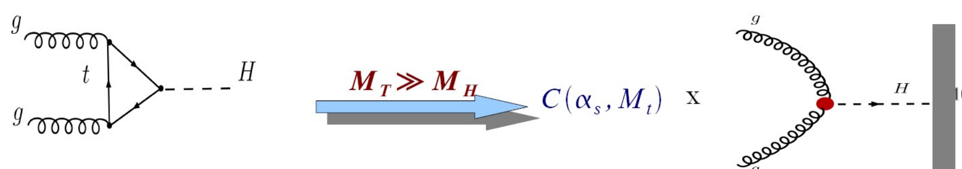
gg → H: largest cross section at Tevatron and LHC

LO is already 1-loop ⟹ complicated higher order corrections

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

available in full and effective theory: Graudenz @ al 93; Dawson @ al 91; Djouadi @ al 91

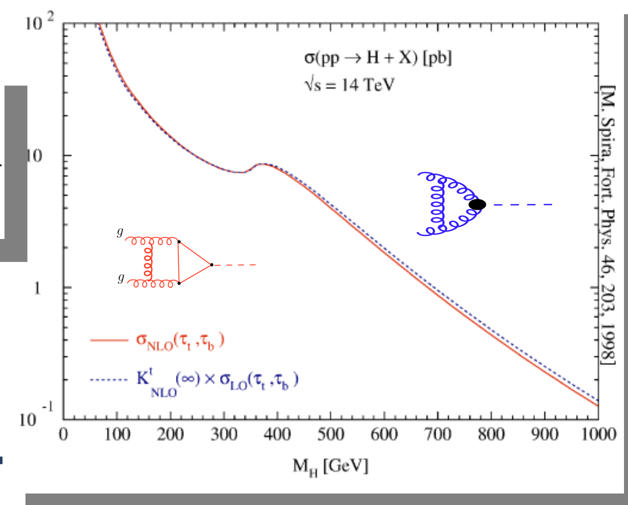
$$L_{ggh} = \frac{-H}{4v} C(\alpha_s) G^a_{\mu\nu} G^{\mu\nu}_a$$



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

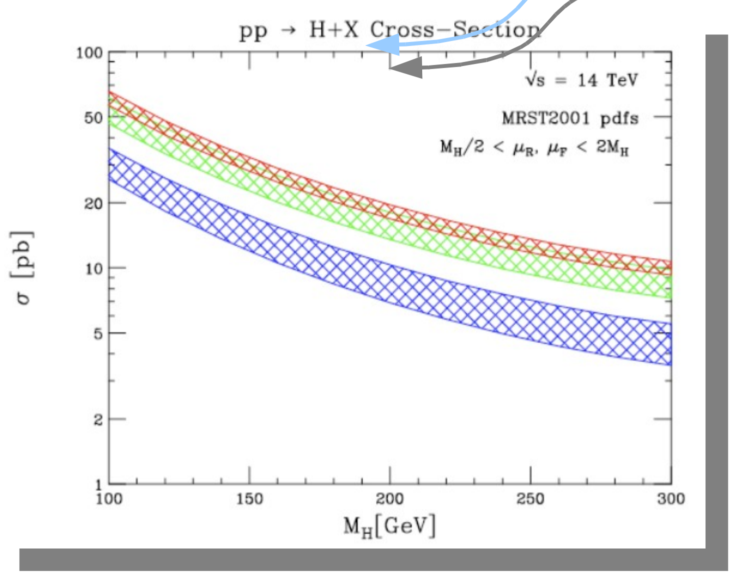
difference between $\sigma^{Exact,NLO}, \sigma^{\infty,NLO}$

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



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

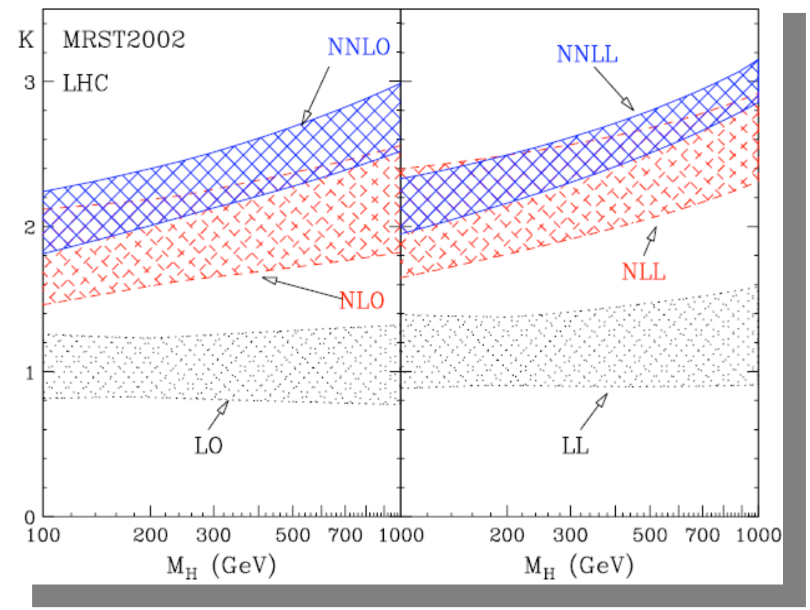
NNLO QCD contributions calculated in the large M_T limit: increase xsection by 10-15%



NNLO Corrections are significantly smaller than NLO contributions ⇒ converging perturbative series

Harlander @ al (2002); Anastasiou @ al(2002); Ravindran @ al (2003)

Resummation of soft gluon effects at NNLL: an additional 6% to total xsection



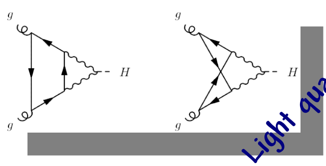
Catani, de Florian, Grazzini, Nason (2003)

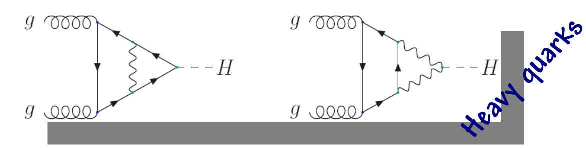
NLO Electroweak Corrections to gg → H

Residual uncertainty from QCD: 9-11%

→ EW Corrections could be important for matching precision of QCD predictions

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



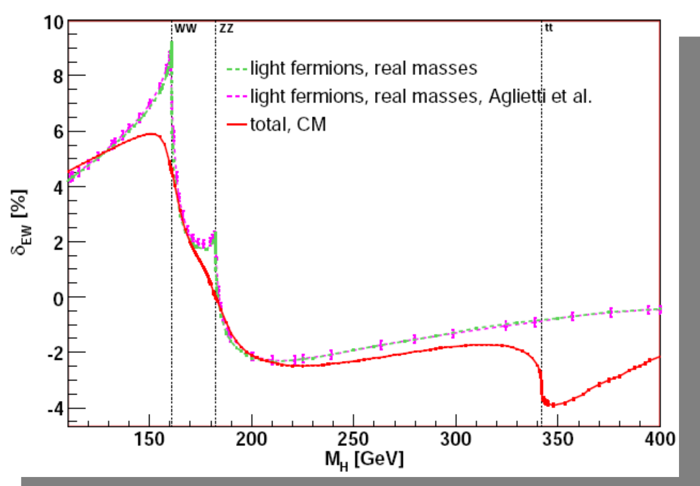


Aglietti, Bonciani, Degrassi, Vicini (2004); Degrassi, Maltoni (2004)

- Light quarks (analytically): real Mw, Mz → δ_{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 $M_H > 2\,M_W$



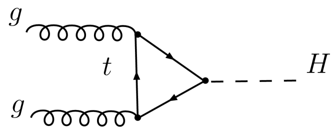
Light quarks + top:

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

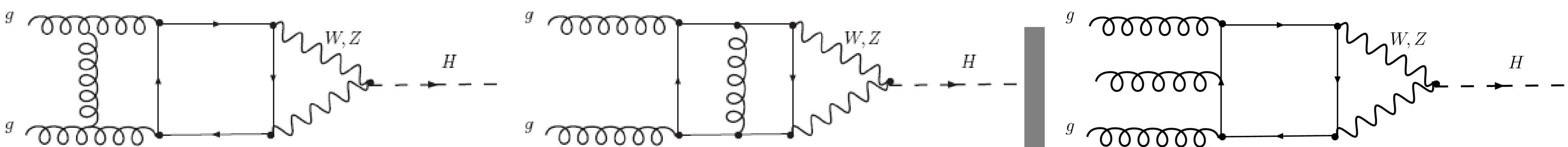
What about mixed EW-QCD effects ?

At LHC QCD corrections to 

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

$O(\alpha)$ 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 (complete factorisation) ?

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

Partial & Complete Factorization of EW and QCD Corrections

Two assumptions were made:

- No QCD enhancement to light quarks → Partial factorization (Actis et al (2008))

$$\hat{\sigma}_{ij} = \sigma^{(0)}_{\rm EW}\, G^{(0)}_{ij}(z) + \sigma^{(0)} \sum_{n=1}^{\infty} \left(\frac{\alpha_s}{\pi}\right)^n G^{(n)}_{ij}(z)$$

1-2% increase in total xsection

- QCD enhancement to light quarks = QCD enhancement to top quark — Aglietti et al (2006), Actis et al (2008)

→ Complete Factorization

$$\hat{\sigma}^{CF}_{ij} = \sigma^{(0)}_{\rm EW} G_{ij}(z;\alpha_s)$$

5-6% increase in total xsection

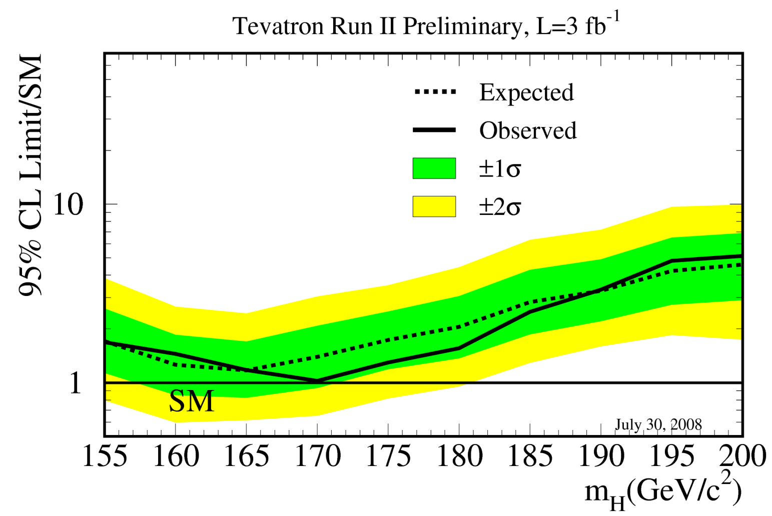
Complete Factorization assumption used in the Tevatron exclusion limits !

Looking under the hood

Combined CDF-D0 results (2008)

The Tevatron observed 95% CL upper limit on the xsection vs the predicted SM xsection

$M_H = 170\, GeV$ is excluded !



What went into the predicted xsection:

- the complete factorization assumption was used
- b-quark contributions with the same QCD enhancement as top Catani et al (2003)
- old PDFs (MRST2002)

2009: the exclusion extended to the range 160-170GeV

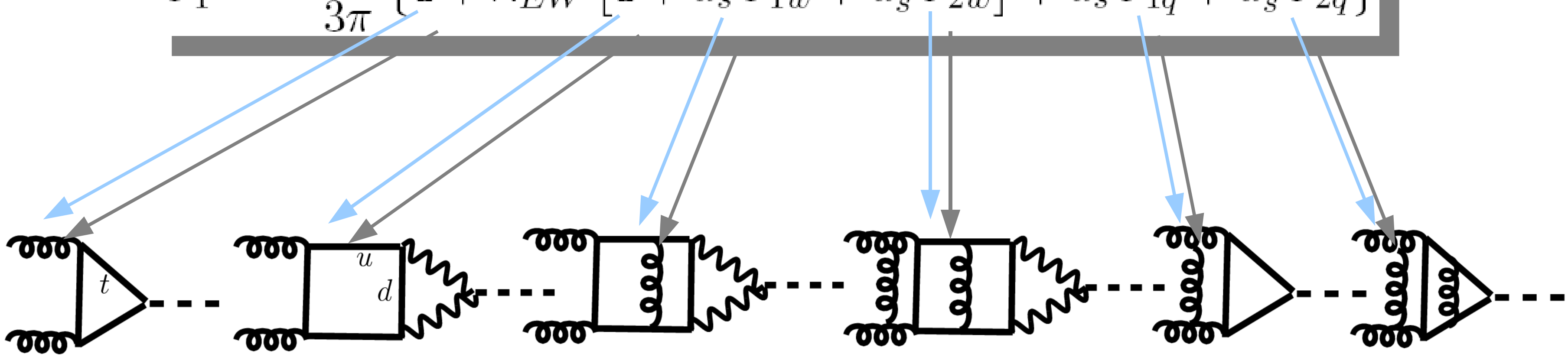
Our Goals (Anastasiou, RB, Petriello (2008)):

- Check the validity of complete factorization assumption
- Provide most up-to-date QCD prediction of $\sigma(gg \to H)$ with best current estimates of K-factors and newest PDFs

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, reason to expect similarity here

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

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

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

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

Results I

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

agrees with Aglietti et al (2004)

$$C_{1w} = \frac{7}{6}$$

to be compared with

$$C_{1w}^{fac} = C_{1q} = 11/4$$

Violation of Factorization assumption !

Numercial effect on cross section ?

Results 2

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

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

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

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

$$a_s = \frac{\alpha_s}{\pi}$$

$$\sigma_b^{(0)} = \frac{G_F \alpha_s^2}{512\sqrt{2}\pi} |\mathcal{G}_b|^2,$$

$$\sigma_{t,b}^{(0)} = \frac{G_F \alpha_s^2}{512\sqrt{2}\pi} \left[2\,\mathrm{Re}\left(\mathcal{G}_t \mathcal{G}_b^*\right)\right],$$

$$\sigma_{t,lf}^{(0)} = \frac{G_F \alpha_s^2}{512\sqrt{2}\pi} \left[2\,\mathrm{Re}\left(\mathcal{G}_t \mathcal{G}_{lf}^*\right)\right]$$

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

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

QCD corrections to top for large M_t

Note: tb-interference is negative

Results 2

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

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

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

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

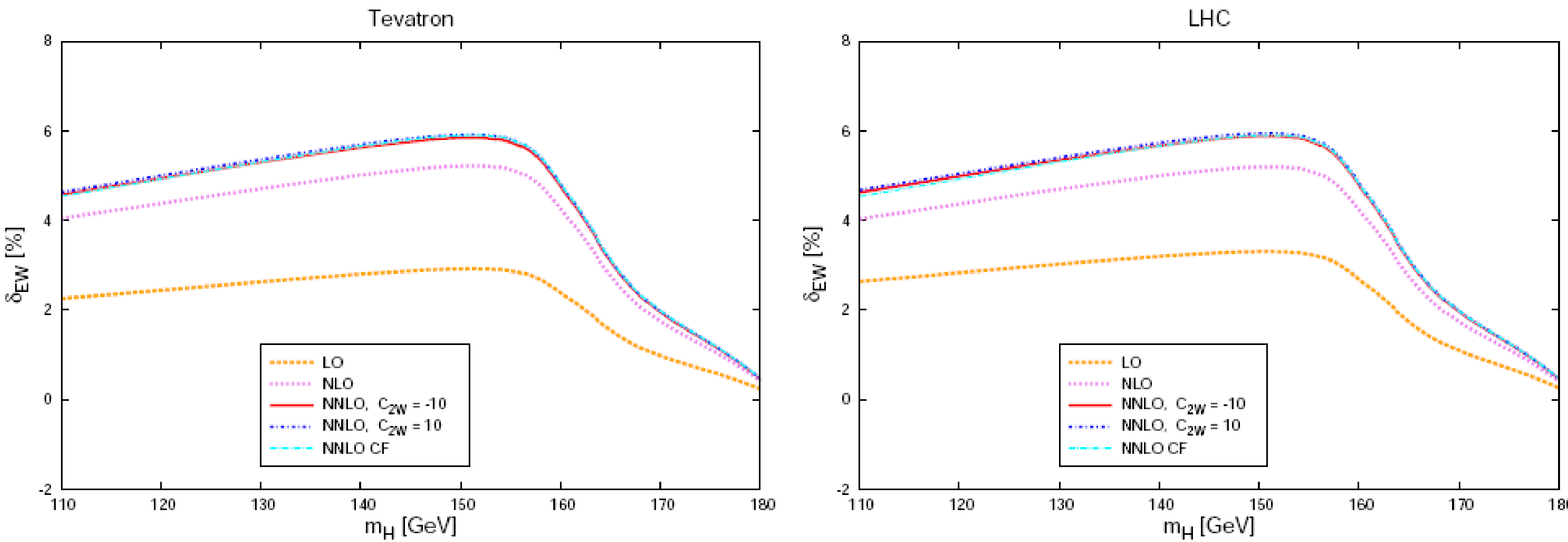
used MRST 2008 PDFs

Included are:

- NNLO K-factor computed in large M_t and normalized to exact LO top-result
- $O(\alpha)$ (exact results by Actis et al (2008)) & new $O(\alpha\alpha_s)$ light-quark results
- b-quark results with excat NLO K_{tb}, K_{bb}

Note for $120\text{GeV} \le M_H \le 180\text{GeV} : 1.2 \le K_{tb}^{NLO}, K_{bb}^{NLO} \le 1.5$ to be compared with $K_t^{NNLO} \sim 3.5$ used by Catani et al (2003) & Tevatron

Results 2



We use:

G_F, M_W, M_Z as input parameters

pole $M_t = 170.9\, GeV$

$\overline{MS}\, m_b$ with $\overline{m_b}(10\text{GeV}) = 3.609\text{GeV}$
Kuhn et al (2007)

Plotted is $\delta^x_{EW} = 100 \frac{\sigma^x_{EW}}{\sigma^{NNLO}_{QCD}}$

pure QCD-contributions dominate:

$a_s(C_{1W} - C_{1q}), a_s^2(C_{2W} - C_{2q})$ Smaller than $a_s G^{(1)}_{ij}, a_s^2 G^{(2)}_{ij}$

$\sigma(g\, g \to H)$ receives almost the entire 5-6% shift indicated by Complete Factorization

Results 2

New predicted xsection based on the following changes wrt old one (Catani et al 2003) :

- Exact NLO K_{tb}, K_{bb} instead of NNLO K_t for b-contributions
- Msbar mb instead of pole mass (results only 1.5% larger than with pole mass)
- The new δ_{EW} (4-6% instead of the old 5-8%)
- MSTW 2008 PDFs instead of MRST2002

Resummation effects accounted for approximately by choosing $\mu_F = \mu_R = M_H/2$
reproduces central value to better than 1% Catani et al 2003

An example : MH=170GeV (σ in pb)

original	MSTW 2008 PDFs	K_{tb}, K_{bb}	EW effects
0.3542	0.3212	0.3377	0.3444

Intrecate interplay of multiple effects

To be compared with old prediction (Catani et al 2003) enhanced by the shift of Aglietti et al: 0.3652

A decrease of 6% in xsection !

Results 2: New Prediction

Tevatron

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 4-6% lower than used in 2008 exclusion by Tevatron for MH = 150-170 GeV
- 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

New results accounted for in new Tevatron analysis: extended exclusion range to 160-170GeV

Summary

1) While QCD and EW corrections dont factorise, numerical effect on cross section is small

2) Provided an updated theoretical prediction for inclusive $\sigma(g\, g \rightarrow H)$

with best current estimates of K-factors and newest PDFs (MRST2008)

Updated prediction is 4-6% lower than what was previously used by Tevatron in 2008 exclusion

Our new results accounted for in new Tevatron analysis in addition to their new data: extended exclusion range to 160-170GeV arXiv:0903.4001 [hep-exp]