Electroweak effects in Higgs boson production

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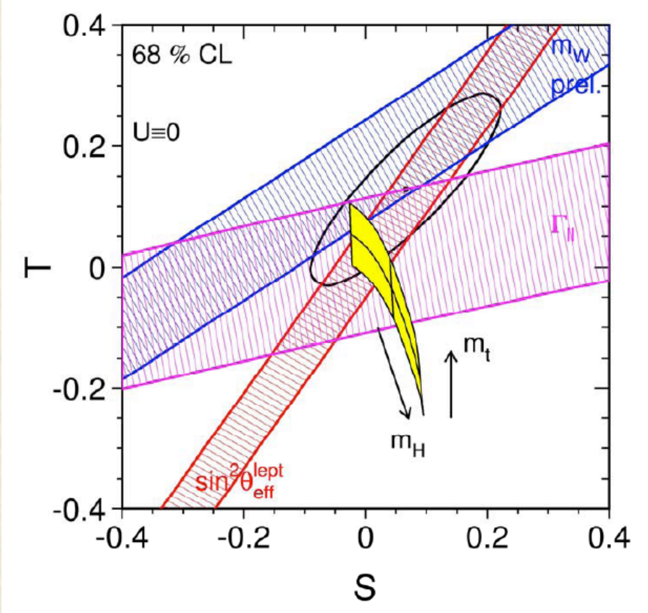
Outline

- Brief review of experiment, theory for SM Higgs
- Electroweak corrections and factorization
- Higgs EFT and check of factorization
- Updated numerics for the Tevatron and fun with PDFs
- The 1-jet bin

Why we expect a TeV scale Higgs

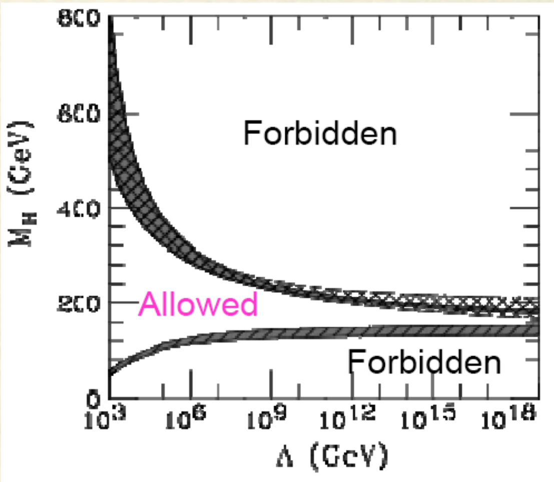
Last undiscovered particle of the SM

Many reasons to expect it (or something else) to be observed soon



$$a_0^0 \to -\frac{s}{32\pi v^2}$$

$$\Lambda_{NP} \leq 1.7\,\mathrm{TeV}$$

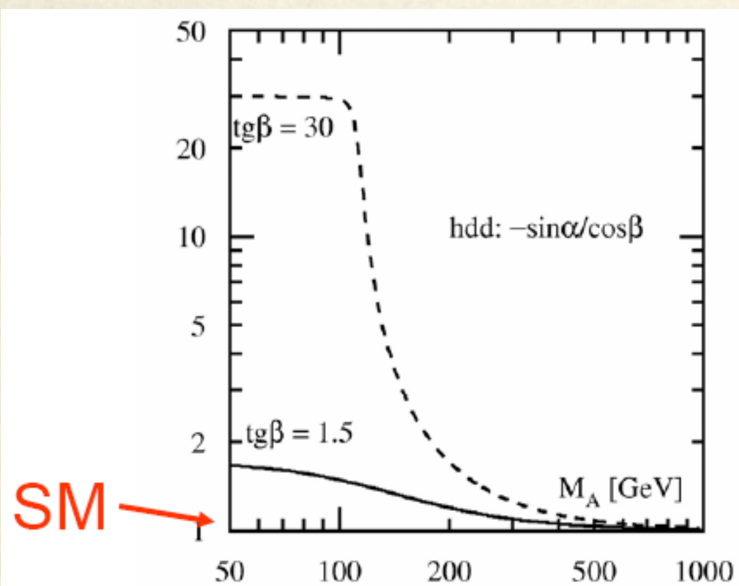


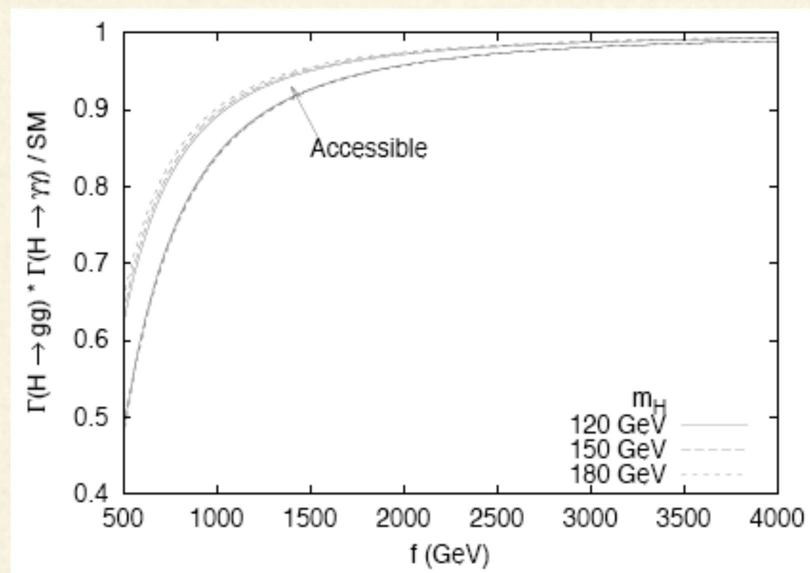
$$M_H^2 < \frac{32\pi^2 v^2}{9\log\left(\frac{Q^2}{v^2}\right)}$$

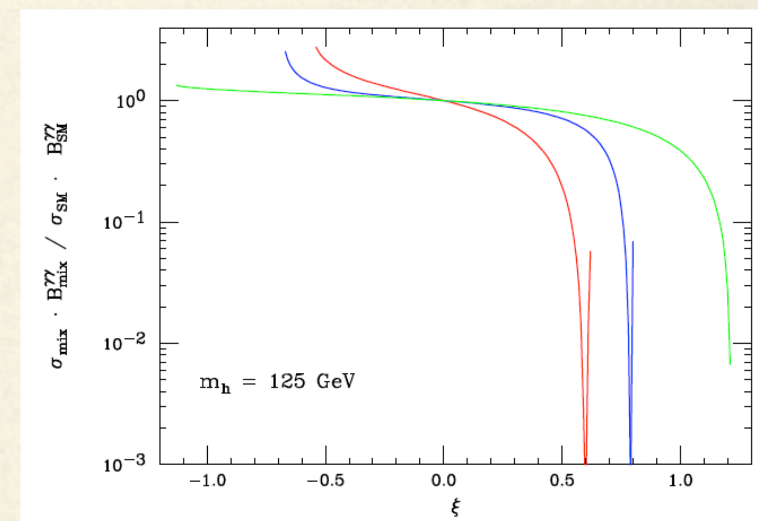
$$M_H^2 > \frac{3v^2}{2\pi^2}\log\left(\frac{\Lambda^2}{v^2}\right)$$

Higgs in SM extensions

The uncertainty in EWSB mechanism makes Higgs a portal into new physics at the TEV scale







S. Dawson

Han, Logan, McElrath '03

Hewett, Rizzo '02

Loop-induced gluon, photon modes can have O(1) deviations

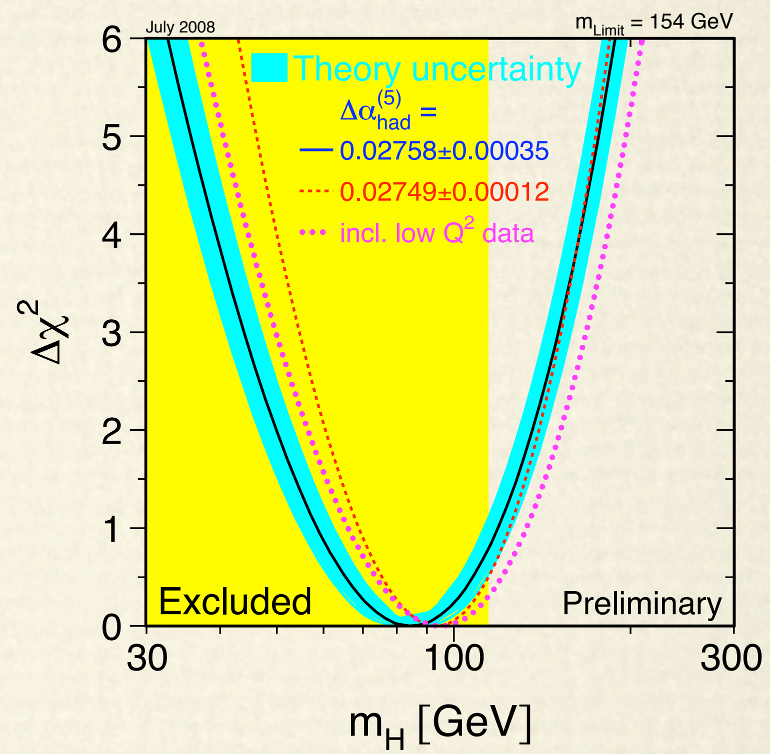
SM Higgs circa 2008

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

$$M_H = 84^{+34}_{-26}\,\mathrm{GeV}$$

Precision EW upper bound and direct search lower bound at 95% CL:

$$114 < M_H/\mathrm{GeV} < 154$$

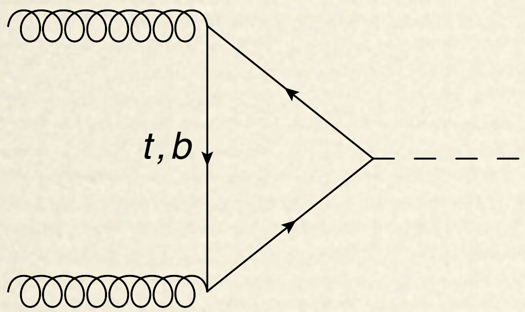


News from the Tevatron: Combined result from CDF, D0 exclude 170 GeV SM Higgs at 95% CL arXiv:0808.0534

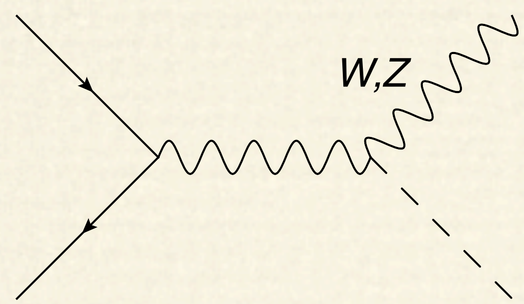
"Preliminary" exclusion at 160-170 GeV on Friday

Carefully reconsider SM prediction in light of experimental sensitivity

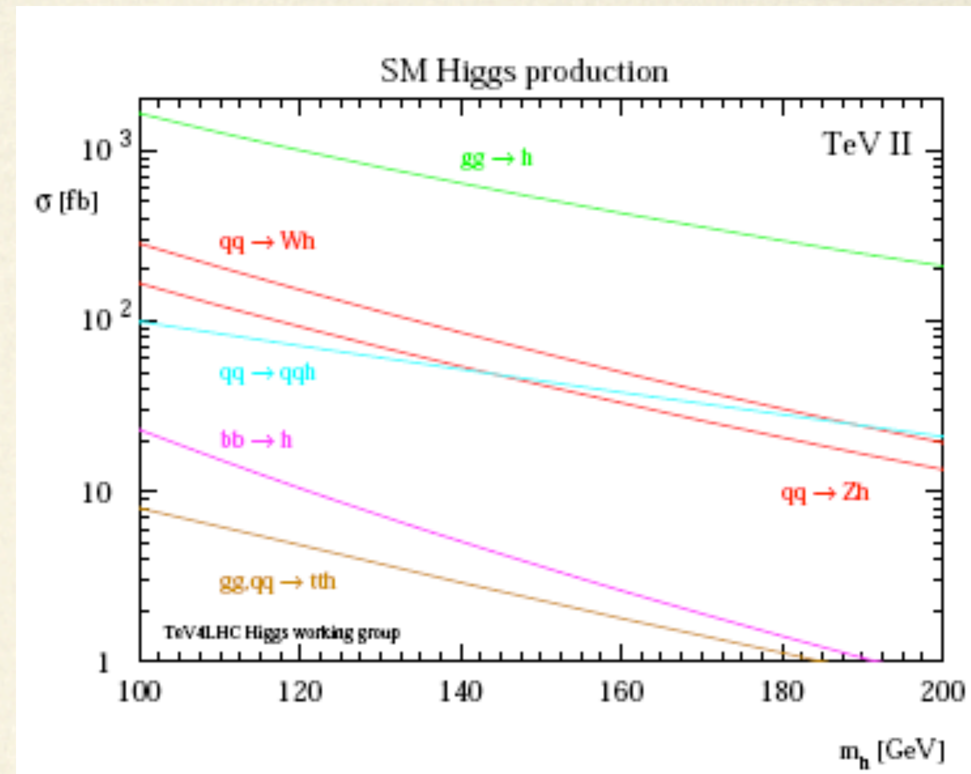
SM Higgs at the Tevatron

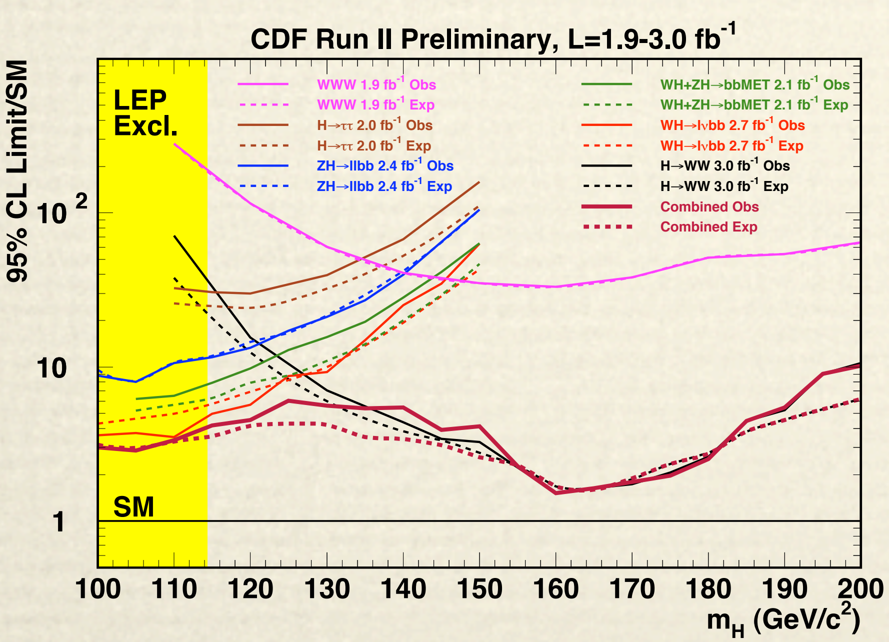


gg fusion dominant by factor of 10



Associated production essential for $M_H < 130\,\mathrm{GeV}$

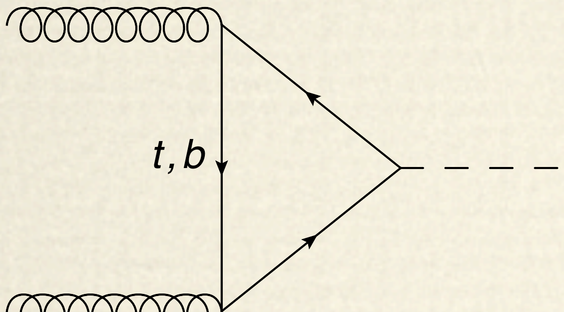




Exclusion limit entirely from gg→H→WW

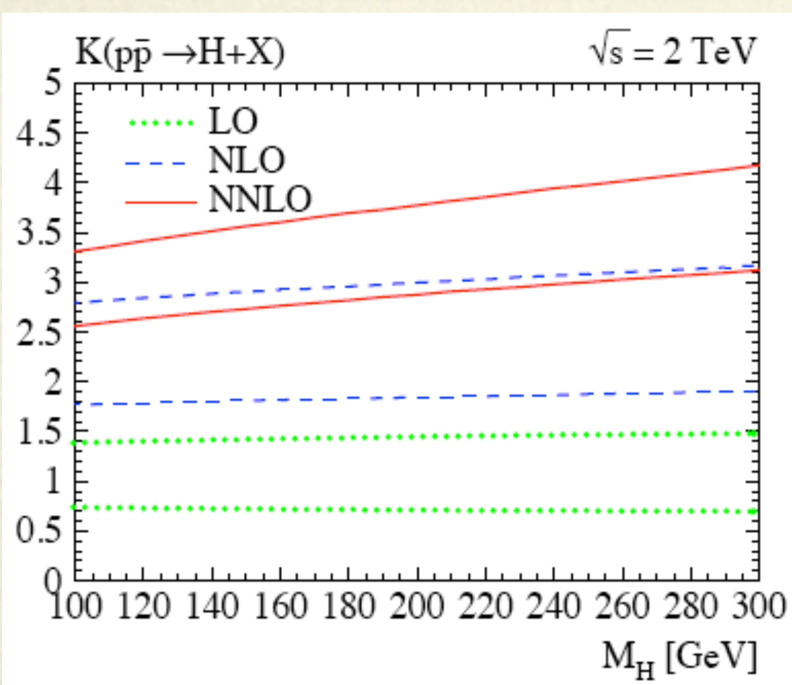
BR(H→WW) > 90% for 160-170 GeV Higgs

QCD corrections at NLO



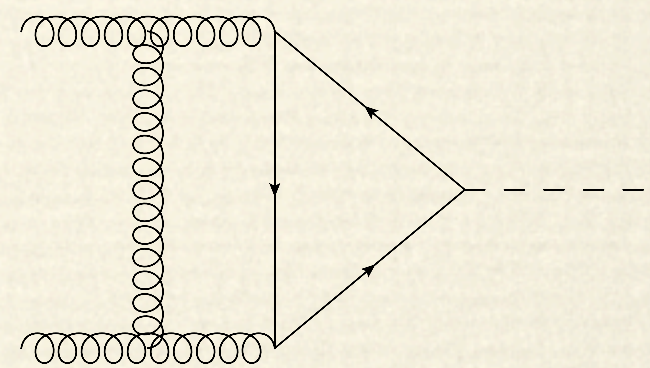
Top-loop dominant; bottom loop gives -10% correction from interference $\{m_b^2 \ln^2(M_H/m_b)\}$

What makes is sensitive to new physics (begins at 1-loop) also makes it tough to calculate



Harlander, Kilgore; Anastasiou, Melnikov 2002

E.g., need



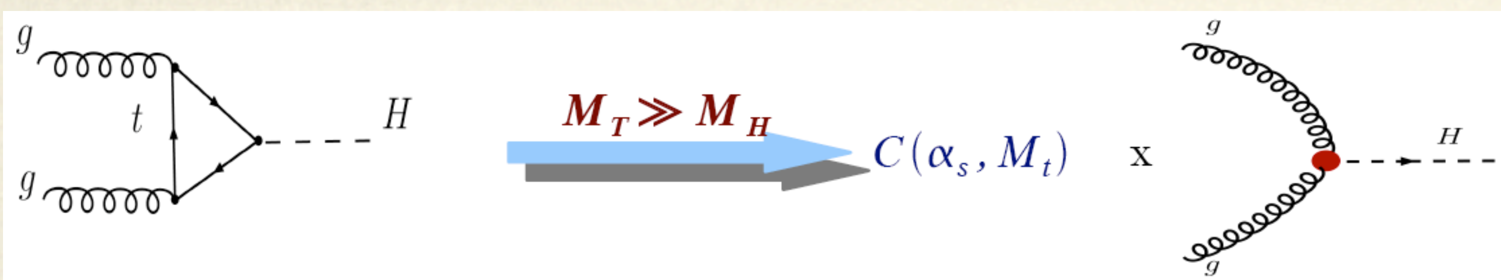
NLO corrections >100% at Tevatron

Effective theory for Higgs

Full NLO with mass dependence known (Djouadi, Graudenz, Spira, Zerwas 1995)

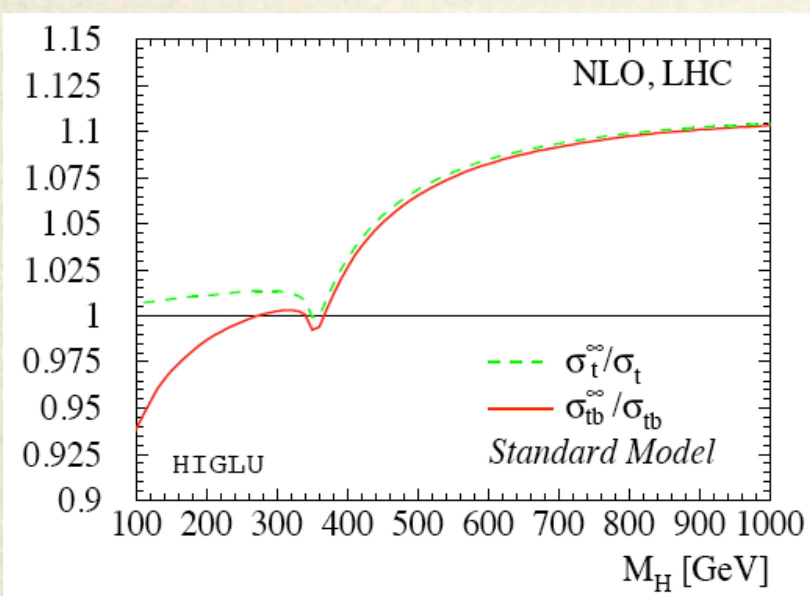
Difficult to go to NNLO and check convergence of expansion

Use EFT instead for top (Shifman et al. 1979; Ellis et al. 1988; S. Dawson; Djouadi, Spira, Zerwas 1991)



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

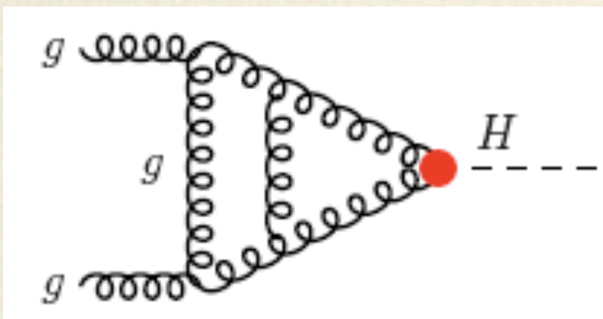
known through $O(\alpha_s^5)$: Schroder, Steinhauser; Chetyrkin, Kuhn, Sturm 2006



Harlander 2008

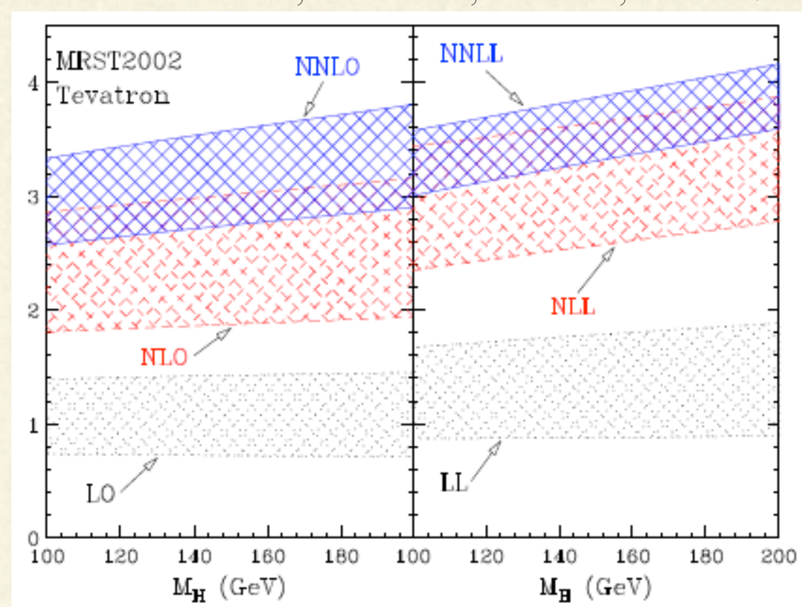
If normalized to full LO top mass dependence, good to <10% for 1 TeV Higgs; <1% below 200 GeV

NNLO in the EFT

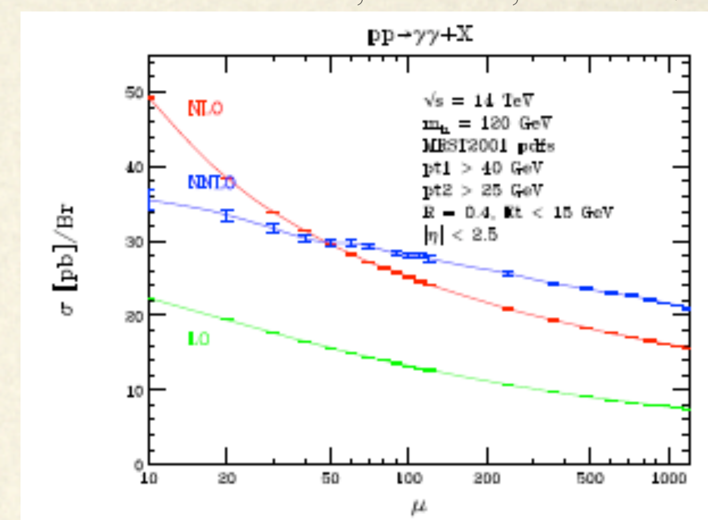


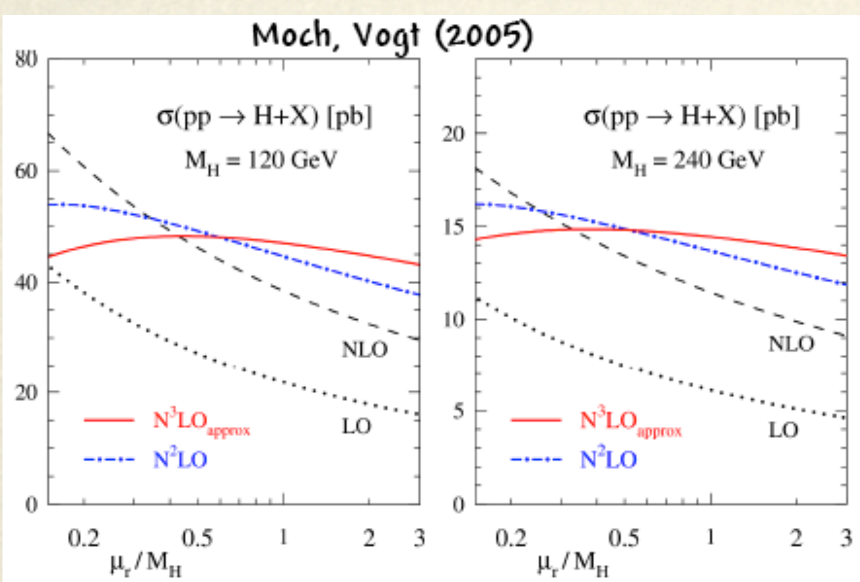
Harlander, Kilgore; Anastasiou, Melnikov; Ravindran, J. Smith, van Neerven 2002-3

Catani, de Florian, Grazzini, Nason 2003



Anastasiou, Melnikov, Petriello 2005





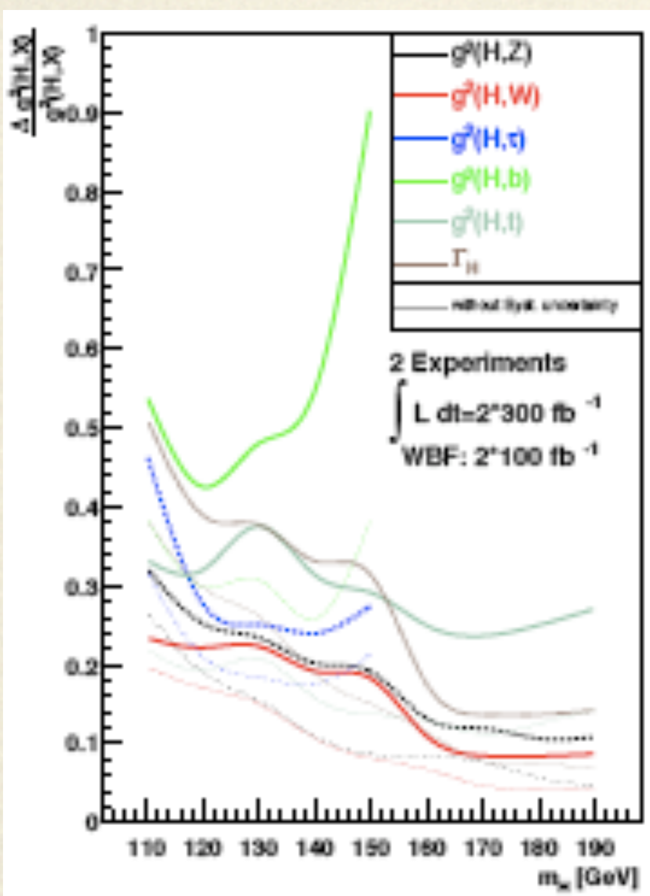
Full NNLO differential results known

Soft gluon resummation increase NNLO by 10%

N^3LO scale dependence indicates stability of expansion

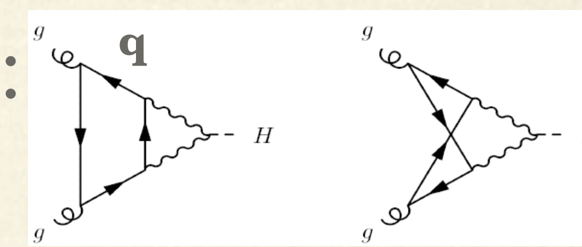
Electroweak corrections

Residual QCD uncertainty ~10% ⇨ EW corrections potentially important to match QCD and experimental precision

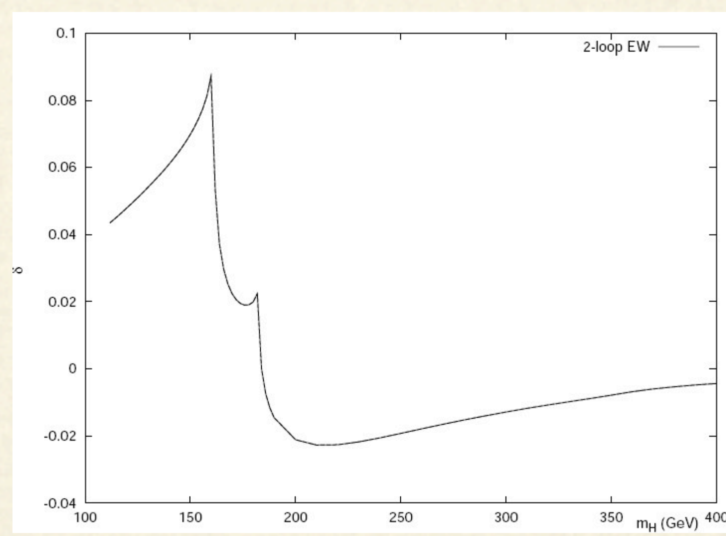


Duhrssen et al. 2004

Light-quark terms:



Aglietti, Bonciani, Degrassi, Vicini 2004

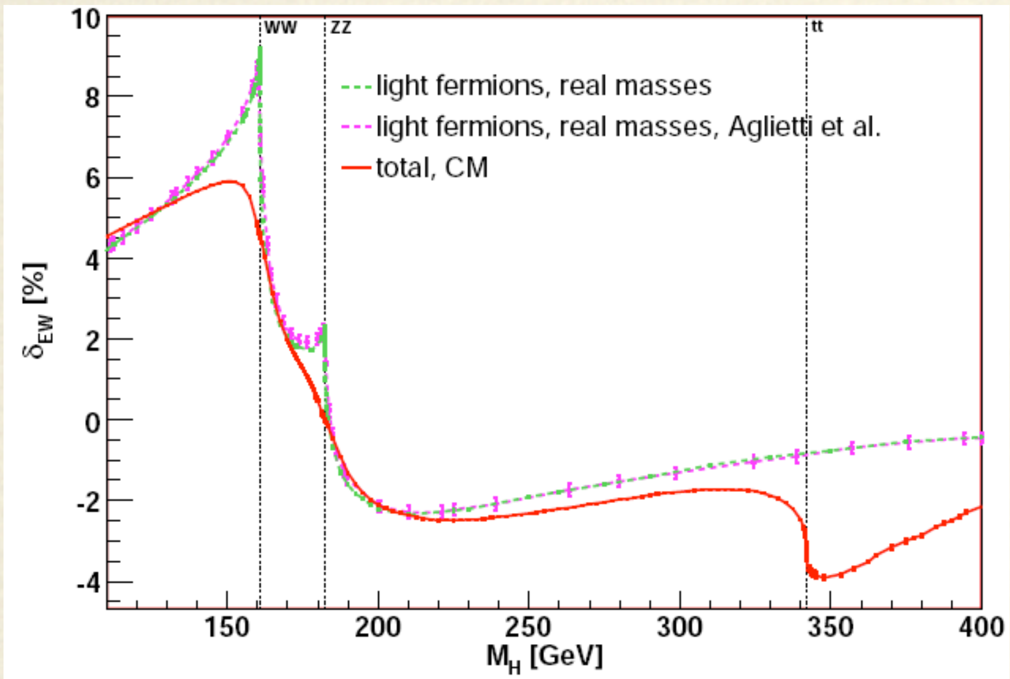


$$\sigma_{ew} = \sigma_0(1 + \delta_{ew})$$

⇨ Up to 9% at threshold relative to LO QCD

Thresholds and factorizationn

Actis, Passarino, Sturm, Uccirati 2008



Self-energy resummation needed near thresholds ➪ complex $M_{W,Z}$

Reduces corrections:

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

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

K-factor at Tevatron is ~3.5; how does QCD affect this?

Partial factorization: no QCD corrections, set K=1,1-2% of NNLO cross section

Complete factorization: same K for EW terms, remain 5-6% of NNLO ➪ 20% of LO QCD!

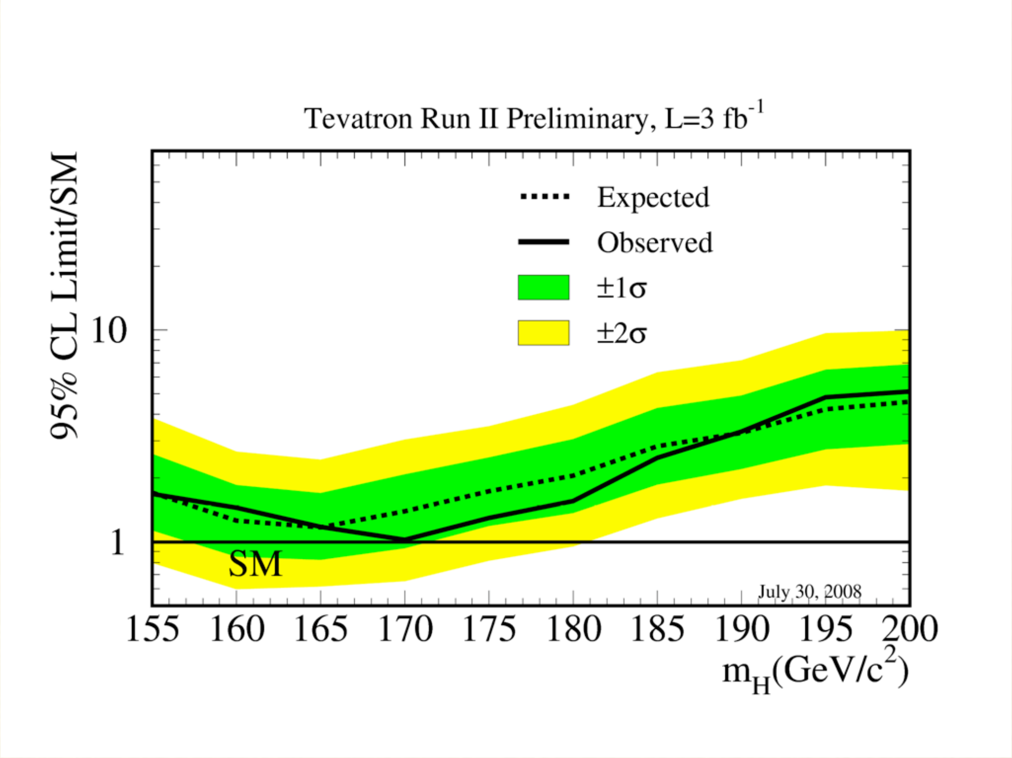
Tevatron exclusion

M_H=170 GeV excluded

What went into the SM prediction:

- Complete factorization assumed
- Same QCD corrections for t,b
- Old PDFs (MRST 2002)

Combined CDF, D0 results (2008)



Goals:
- Test complete factorization hypothesis
- Provide updated SM prediction

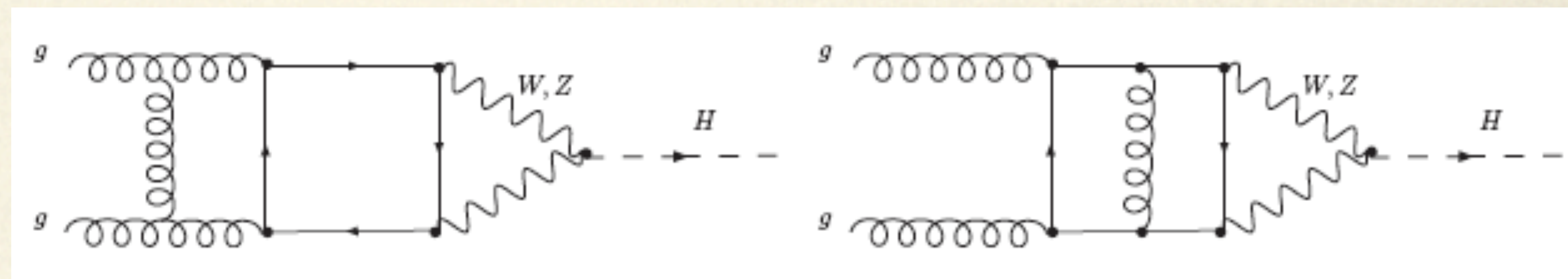
Testing factorization

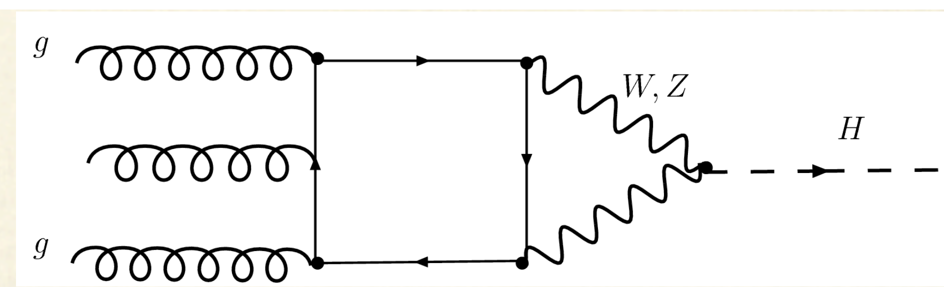
Full test of CF would require $O(\alpha\alpha_s)$ corrections

3-loop virtual

+

2-loop real emission



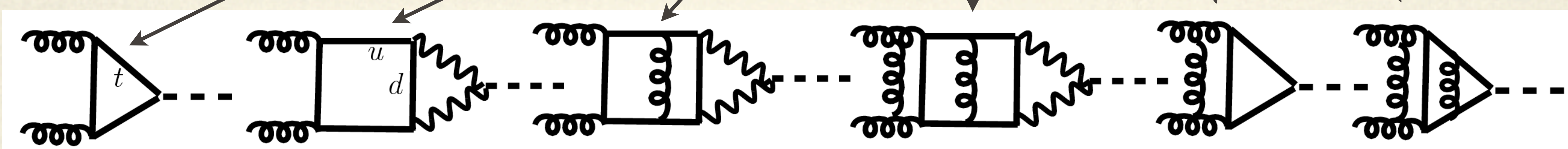


Can we instead test using an EFT approach?

EFT formulation

$$\mathcal{L} = -\alpha_s \frac{C_1}{4v} H G^a_{\mu\nu} G^{a\mu\nu}$$

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



Radius of convergence: $M_H \leq M_W$

However, top-quark EFT valid to 1 TeV>$2m_t$; reason to expect similar here

⇨ *exact* for dominant radiation pieces in resummation limit $\tau = M_H^2/\hat{S} \to 1$ for all M_H

Marzani et al. ‘08

Factorization in EFT

$$\mathcal{L} = -\alpha_s \frac{C_1}{4v} H G^a_{\mu\nu} G^{a\mu\nu}$$

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

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

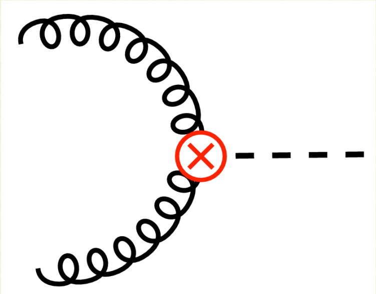
Factorization holds if $C_{1w}=C_{1q}$, $C_{2w}=C_{2q}$

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

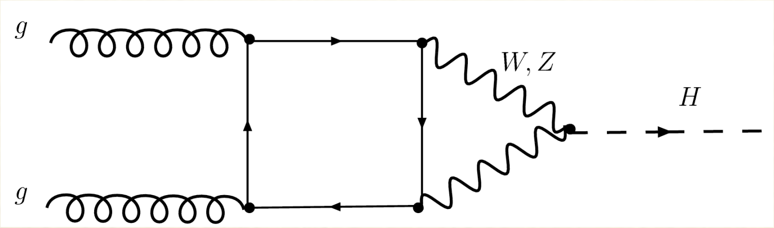
$$\lambda_{EW} = \frac{3\alpha}{16\pi s_W^2}\left\{\frac{2}{c_W^2}\left[\frac{5}{4} - \frac{7}{3}s_W^2 + \frac{22}{9}s_W^4\right] + 4\right\}$$

Matching to the EFT I

Matching at O(α):



$$= -\frac{1}{3\pi}\frac{\alpha_s}{v}\lambda_{EW}\mathcal{M}_0$$

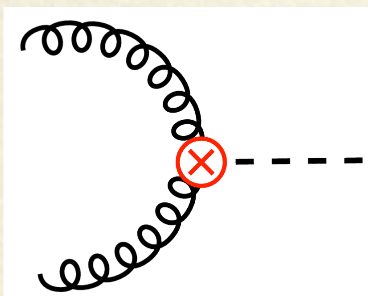


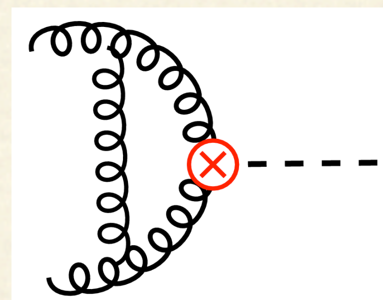
$$= \mathcal{A}^{(2)}(M_H^2 = 0)\mathcal{M}_0 + \mathcal{O}\left(\frac{M_H^2}{M_{W,Z}^2}\right)$$

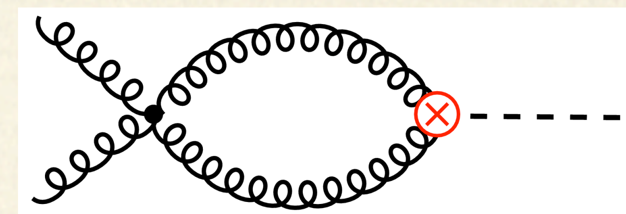
➪ Equate to get λ_{EW}

Matching to the EFT II

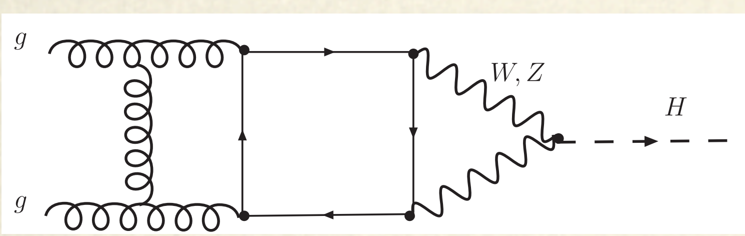
Matching at O($\alpha\alpha_s$):



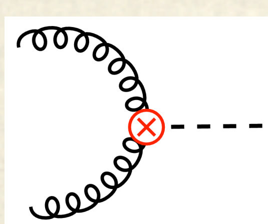
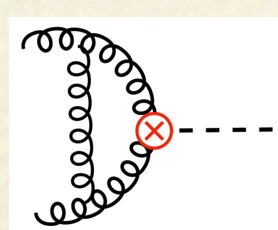
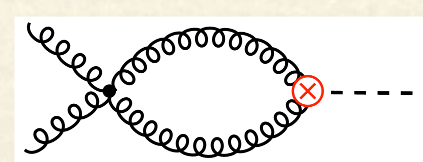
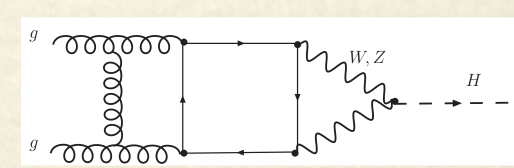




$$= -\frac{1}{3\pi}\frac{\alpha_s}{v}\lambda_{EW}\,(\alpha_s C_{1w})\,\mathcal{M}_0$$



$$= \mathcal{A}^{(3)}(M_H^2 = 0)\mathcal{M}_0 + \mathcal{O}\left(\frac{M_H^2}{M_{W,Z}^2}\right)$$

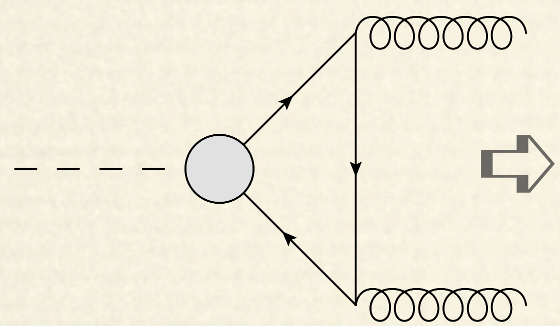
 –  –  = 

⇨ gives C_{1w}

EFT justification

Did we get all the needed operators?

Only other same-order operator: $\frac{H}{v}\bar{q}\not{D}q$



➪ vanishes when inserted into EFT graphs

Large-mass Feynman integral expansion: V. Smirnov

$$\mathcal{F}_\Gamma \sim \sum_\gamma \mathcal{F}_{\Gamma/\gamma} \circ \mathcal{T}_{k,p_i}\mathcal{F}_\gamma$$

Reduced graphs: only light lines, quantum corrections to operators

Subgraphs: contain all massive props, Taylor expand (EFT operators)

Check that all 0,1,2,3-loop subgaphs contained in EFT or higher power ✔

Calculational procedure

Generate 3-loop diagrams for $g(p_1)+g(p_2)\rightarrow H(p_H)$

Taylor expand each diagram in M_H by applying:

$$\mathcal{D}\mathcal{F} = \sum_{n=0}^{\infty} (p_1 \cdot p_2)^n \left[D_n \mathcal{F}\right]_{p_1=p_2=0}$$

$$D_0 = 1, \quad D_1 = \frac{1}{d}\Box_{12}, \quad D_2 = -\frac{1}{2(d-1)d(d+2)}\left\{\Box_{11}\Box_{22} - d\,\Box_{12}^2\right\}$$

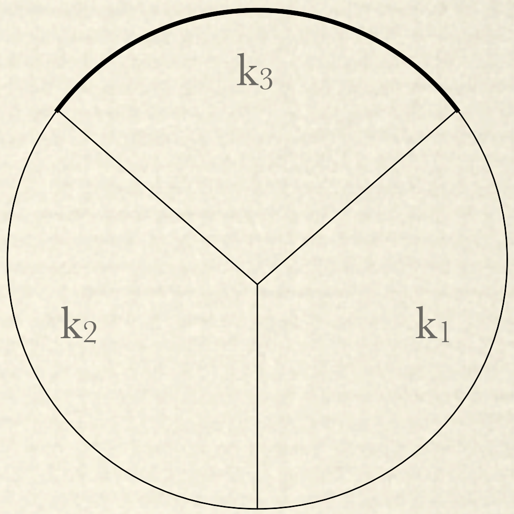
$$\sum \mathcal{F} = \mathcal{A}\left\{g_{\mu\nu} - \frac{p_{2\mu}p_{1\nu}}{p_1 \cdot p_2}\right\}\delta^{ab}\,\epsilon_a^\mu(p_1)\epsilon_b^\nu(p_2) \equiv \mathcal{M}_{\mu\nu}^{ab}\epsilon_a^\mu(p_1)\epsilon_b^\nu(p_2)$$

$$\mathcal{A} = \frac{1}{8\,(d-2)}\left\{g^{\mu\nu} - \frac{p_1^\mu p_2^\nu + p_2^\mu p_1^\nu}{p_1 \cdot p_2}\right\}\delta_{ab}\,\mathcal{M}_{\mu\nu}^{ab}$$

Leading term in A gives C_{1w} upon comparison with L_{EFT}; need through n=2

Structure of result

Coefficents in expansion are 3-loop vacuum bubbles:



$$\mathcal{I}(\vec{\nu}_i) = \int \prod_{j=1}^{3} d^d k_j \frac{1}{k_1^{2\nu_1} k_2^{2\nu_2} (k_3^2 - M_{W,Z}^2)^{\nu_3} (k_1 - k_2)^{2\nu_4} (k_2 - k_3)^{2\nu_5} (k_3 - k_1)^{2\nu_6}}$$

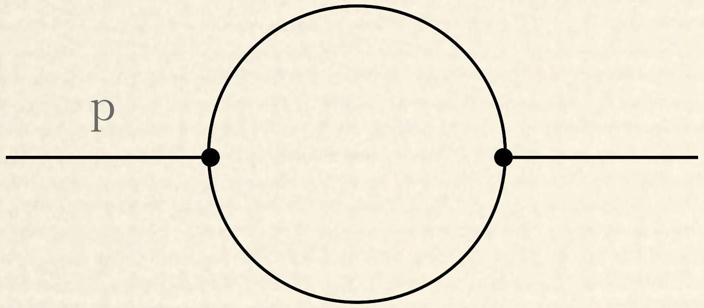
$$= \int \prod_{j=1}^{3} d^d k_j \mathcal{D}$$

Use integration-by-parts identities Chetyrkin, Tkachov '81;

Lorentz invariance gives 9 eqs: $\int \prod_{j=1}^{3} d^d k_j \partial_i \left[k_k \mathcal{D} \right] = 0$

Integration-by-parts

In a simple case: 1-loop bubble diagrams



$$\mathcal{I}(\nu_1, \nu_2) = \int d^d k \, \frac{1}{k^{2\nu_1}(k+p)^{2\nu_2}}$$

Set $\displaystyle \int d^d k \, \frac{\partial}{\partial k^\mu} \left[\frac{k^\mu}{k^{2\nu_1}(k+p)^{2\nu_2}} \right] = 0$

Derive $(d - 2\nu_1 - \nu_2)\mathcal{I}(\nu_1, \nu_2) - \nu_2 \mathcal{I}(\nu_1 - 1, \nu_2 + 1) + \nu_2 p^2 \mathcal{I}(\nu_1, \nu_2 + 1) = 0$

Apply to $\displaystyle \mathcal{I}(1,1) \Rightarrow \mathcal{I}(1,2) = -\frac{d-3}{p^2}\mathcal{I}(1,1)$

Apply functional relation to progressively more complicated integrals; all in terms of I(1,1)

Integration-by-parts

Example of IBP equation for 3-loop calculation:

$$\{-\nu_4 \mathbf{1}^- \mathbf{4}^+ - \nu_6 \mathbf{1}^- \mathbf{6}^+ + \nu_4 \mathbf{2}^- \mathbf{4}^+ + \nu_6 \mathbf{3}^- \mathbf{6}^+ + \nu_6 \mathbf{6}^+ + (d - 2\nu_1 - \nu_4 - \nu_6)\}\, I(\nu_1, \nu_2, \nu_3, \nu_4, \nu_5, \nu_6) = 0$$

Operators acting on the arguments of *I*

Apply IBP eqs to list of *seed* integrals: **I**(1,0,1,1,1,0), **I**(1,0,1,2,-1,1), ...

Solve resulting system of equations Laporta '01

>100000 seeds; express in terms of 2 *master integrals*: **I**(1,0,1,1,1,0) and **I**(1,1,1,0,1,1)

Some examples

$$\begin{aligned}
\mathcal{I}(1,1,1,1,1,1) &= \frac{2(3d-8)(3d-10)}{(d-4)^2}\,\mathcal{I}(1,0,1,1,1,0) - \frac{2(d-3)}{d-4}\,\mathcal{I}(1,1,1,0,1,1) \\
\mathcal{I}(1,-1,1,1,1,1) &= \frac{d-2}{d-4}\,\mathcal{I}(1,0,1,1,1,0) \\
\mathcal{I}(1,1,1,1,2,1) &= -\frac{3(3d-8)(3d-10)(d-5)}{(d-6)(d-4)}\,\mathcal{I}(1,0,1,1,1,0) + (2d-6)\,\mathcal{I}(1,1,1,0,1,1) \\
\mathcal{I}(1,-2,1,1,1,3) &= \frac{d(d-2)(3d-8)}{(d-8)(d-6)(d-4)}\,\mathcal{I}(1,0,1,1,1,0) \\
\mathcal{I}(1,1,3,1,2,3) &= \frac{9}{16}\,\frac{(3d-14)(3d-20)(3d-10)(3d-16)(3d-8)(d-7)}{(d-8)(d-10)}\,\mathcal{I}(1,0,1,1,1,0) \\
&\quad + \frac{3}{8}(3d-20)(d-3)(d-4)(d-5)(d-6)\,\mathcal{I}(1,1,1,0,1,1)
\end{aligned}$$

Can evaluate master integrals via simple Gamma functions

Analytical result

No renormalization needed (finite renormalization needed for top quark case)

C_{1w}=7/6, compared to factorization hypothesis $C_{1w}=C_{1q}=11/4$

$(C_{1q}-C_{1w})/C_{1q} \approx 0.6 \Rightarrow O(1)$ violation of assumption

Numerical effect on hadronic cross section?

Numerical test of CF

QCD corrections in EFT

$$\hat{\sigma}_{ij} = \sigma^{(0)} G_{ij}(z;\alpha_s) \qquad G_{ij}(z;\alpha_s) = \sum_{n=0}^{\infty} \left(\frac{\alpha_s}{\pi}\right)^n G_{ij}^{(n)}(z) \qquad G_{ij}^{(0)}(z) = \delta_{ig}\delta_{jg}\delta(1-z)$$

partial factorization →

$$\sigma_{EW}^{LO} = \sigma_{t,lf}^{(0)} G_{ij}^{(0)}(z) \ ,$$

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

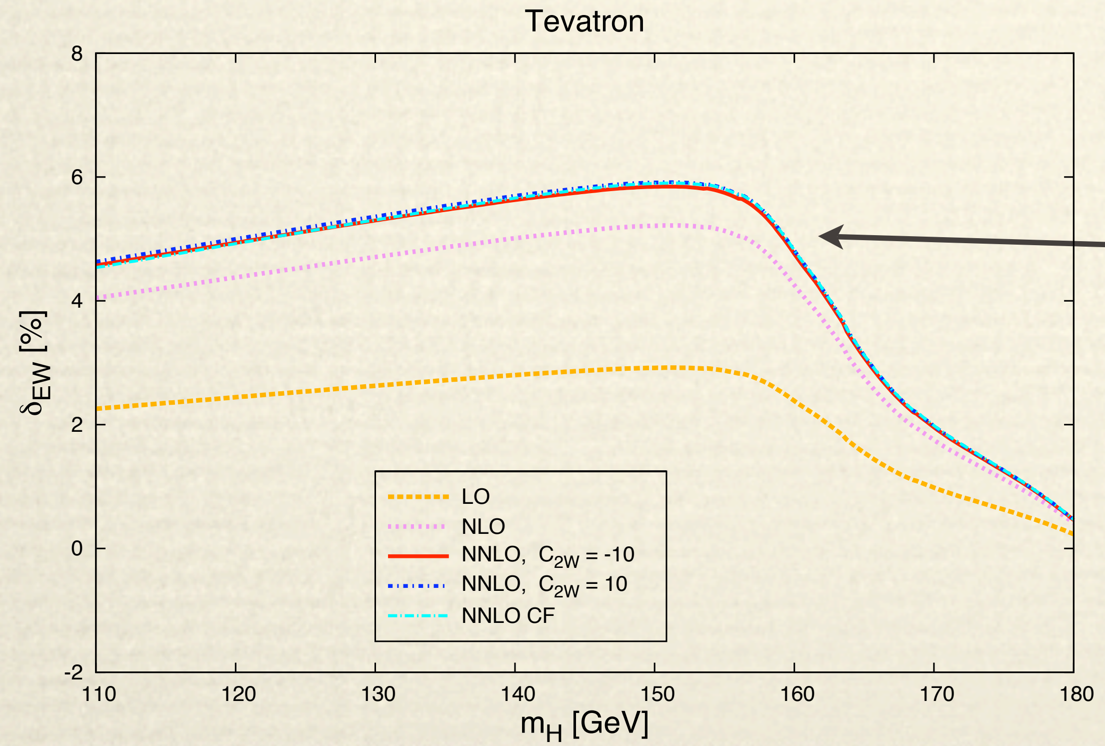
actual result →

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

complete factorization →

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

Full mass-dependent 2-loop EW corrections



Difference between CF and actual: $a_s(C_{1w} - C_{1q})$

Small compared to $a_s G^{(1)}(z)$

Updated cross section

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

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

NNLO large-m_t K-factor, exact LO result

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

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

Choose $\mu = M_H/2$ to reproduce central value of resummation to better then 1% Catani, de Florian, Grazzini, Nason '03

Comparison of pole, MSbar b-quark mass (<1% change)

Use of newer MRST PDFs ...

Circa December 2008

A short lesson on PDFs and their errors...

MRST 2002 →2006: increase of α_s and gluon density

For M_H=170 GeV:

original	MRST 2006 PDFs	K_{tb}, K_{bb}	EW effects
0.3542	0.3650	0.3868	0.3943

Act constructively to increase by 7-10%

True for $120 \leq M_H \leq 180$ GeV

(Note: PDF systematic error ±5%, 90% CL)

Circa January 2009

MSTW 2008 PDF release arXiv:0901.0002

- Run II inclusive jet data
- Decrease of $\alpha_s(M_Z)$ from 0.119→0.117
- Gluon density decreased at x~0.1
- gg luminosity error increased from 5%→10%

M_H=170 GeV:

MRST 2001	MRST 2004	MRST 2006	MSTW 2008
0.3833	0.3988	0.3943	0.3444

~10-15% decrease in predicted cross section !

Numerical results for 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)	–	–

[+7%,-11%] scale error

Now 4-6% *lower* than used in 2008 Tevatron exclusion for M_H=150-170 GeV

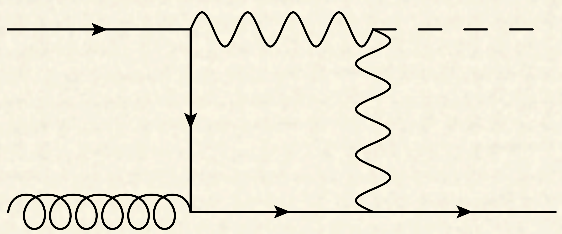
PDF systematic error factor of 2 *larger*: ±10%

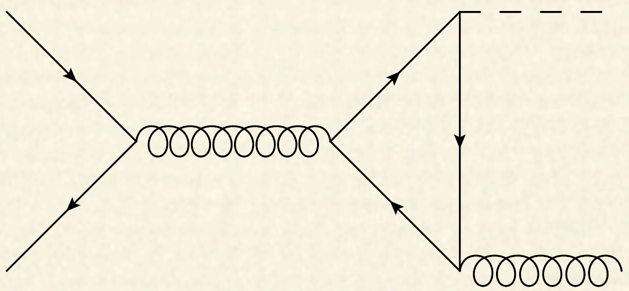
Accounted for in new analysis and supposedly negated by analysis improvements and statistics, but Friday's CDF-9713, D0-5889 apparently still use 5% PDF errors...

EW effects in the 1-jet bin

Other EW effects not yet included? *Yes* (w/W. Y. Keung)

$$q\bar{q} \to Hg, \;\; qg \to Hq$$ through W, Z



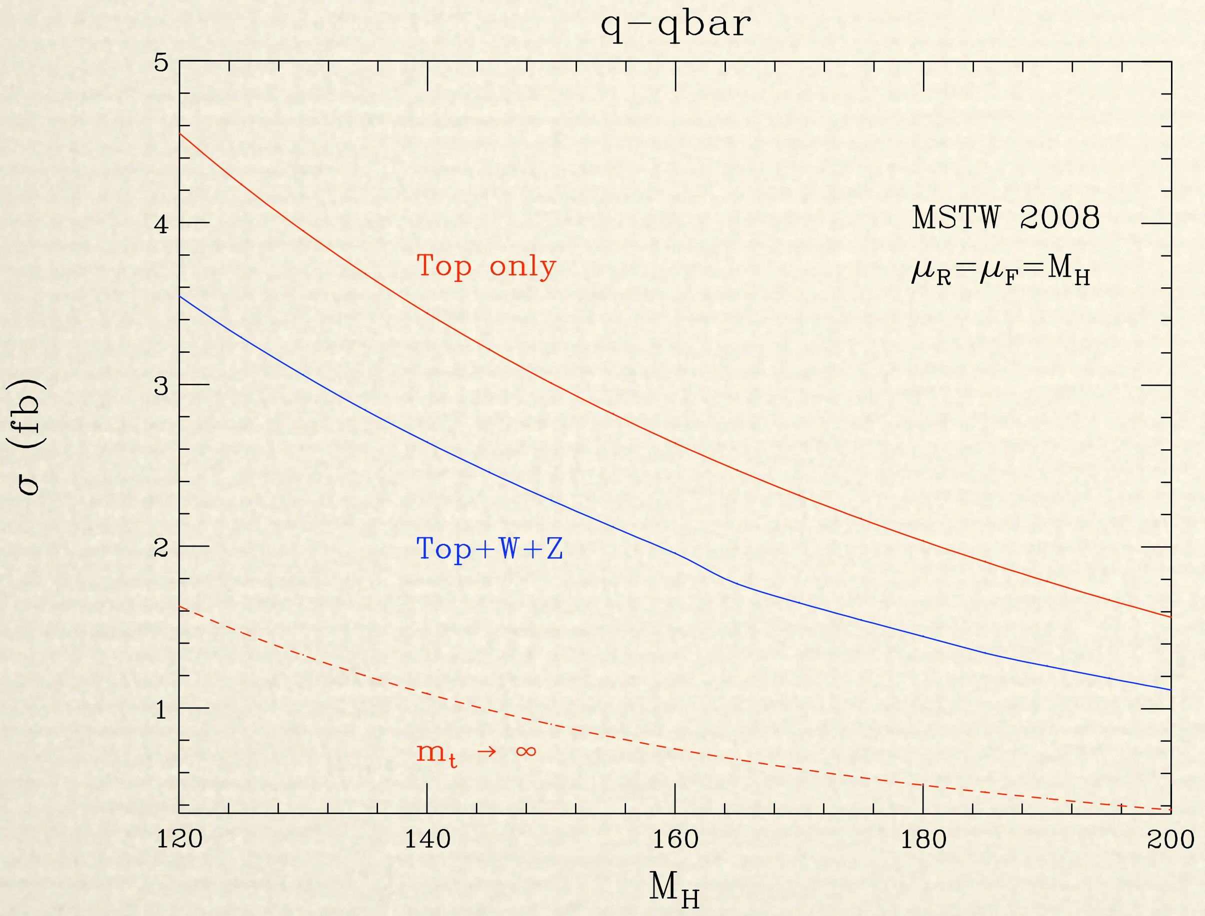
Current 1-jet bin:  ⇨ same order

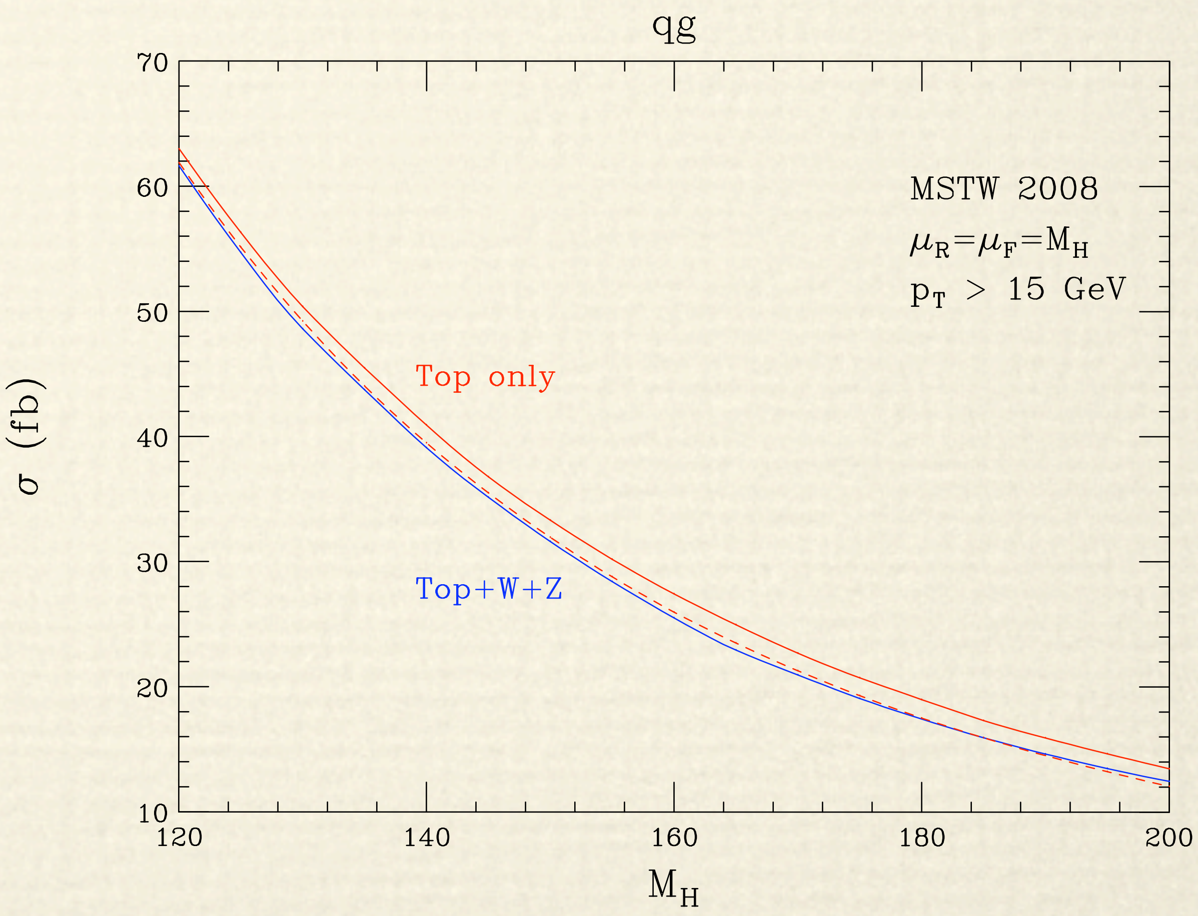
Matches to $$\frac{\partial_\nu H}{v}\,\frac{G^{\mu\nu}\,\bar{q}\gamma_\mu q}{M_{W,Z}^2}$$ Not included in current treatment

~30% of exclusion from 1-jet bin M. Herndon, private communicaton

Preliminary 1-jet bin

Preliminary numerics: small destructive interference at the percent level, small effect on current treatment





Conclusions

- While QCD, EW corrections don't factorize, numerical difference is small
- Updated cross section 5% *lower* then Tevatron used in 2008 exclusion
- PDF systematic error factor of 2 *larger*
- Effect on Tevatron exclusion limits?
- Missing effects in the 1-jet bin under study