QCD AND ELECTROWEAK CORRECTIONS TO HIGGS PRODUCTION

Frank Petriello
University of Wisconsin, Madison

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Anastasiou, Boughezal, FP arXiv:0811:3458
Keung, FP arXiv:0905.2775

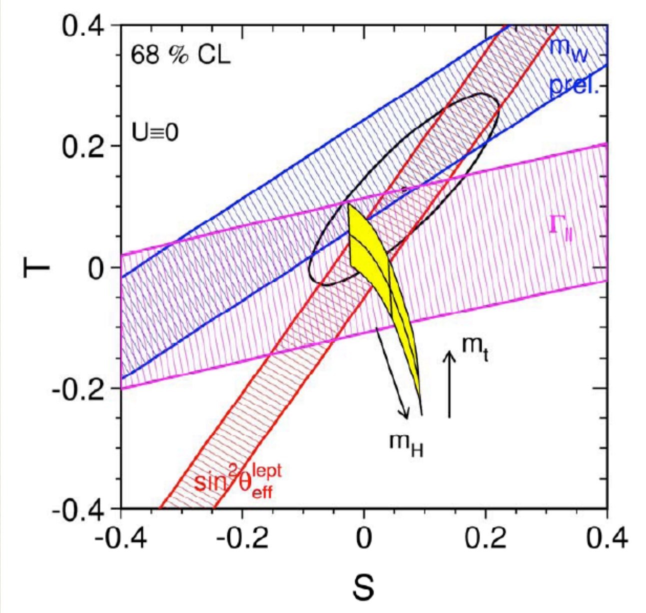
Outline

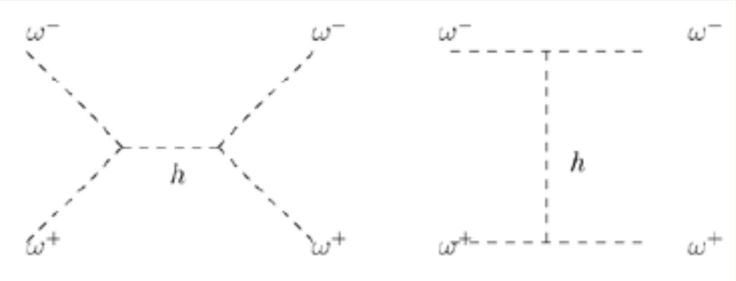
* Review of experiment, theory for SM Higgs
* Electroweak corrections to inclusive production
* Updated numerics and fun with PDFs
* Electroweak and quark-mass effects at high Higgs p_T

Why we expect a TeV scale Higgs

Last undiscovered particle of the SM

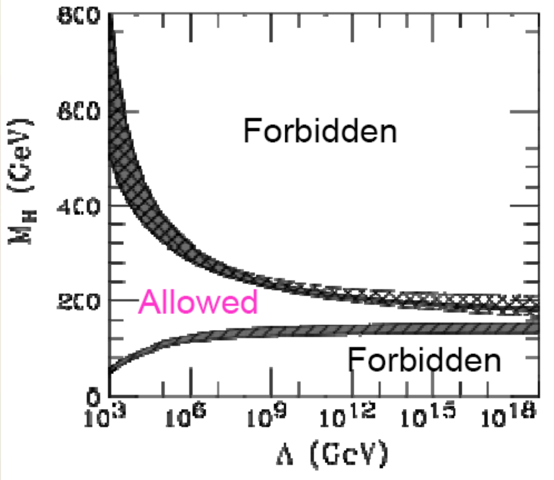
Many reasons to expect it (or something else) to be observed soon





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

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

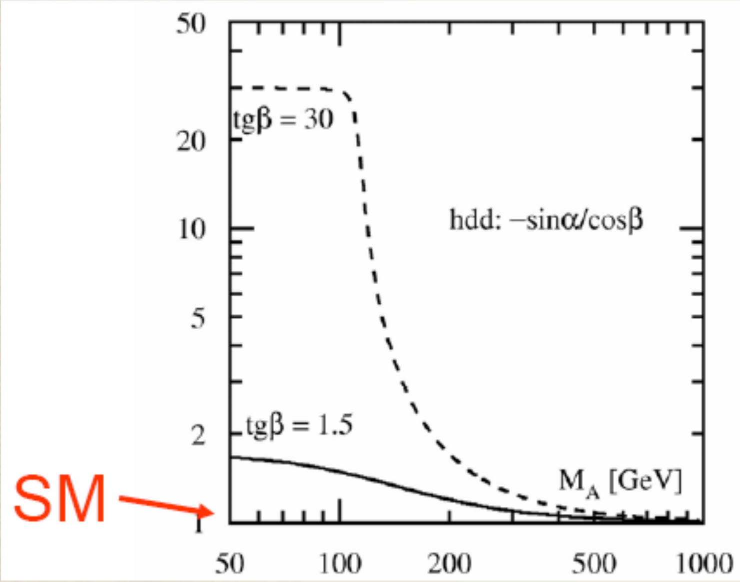


$$M_H^2 < \frac{32\pi^2 v^2}{9\log\left(\frac{Q^2}{v^2}\right)}$$

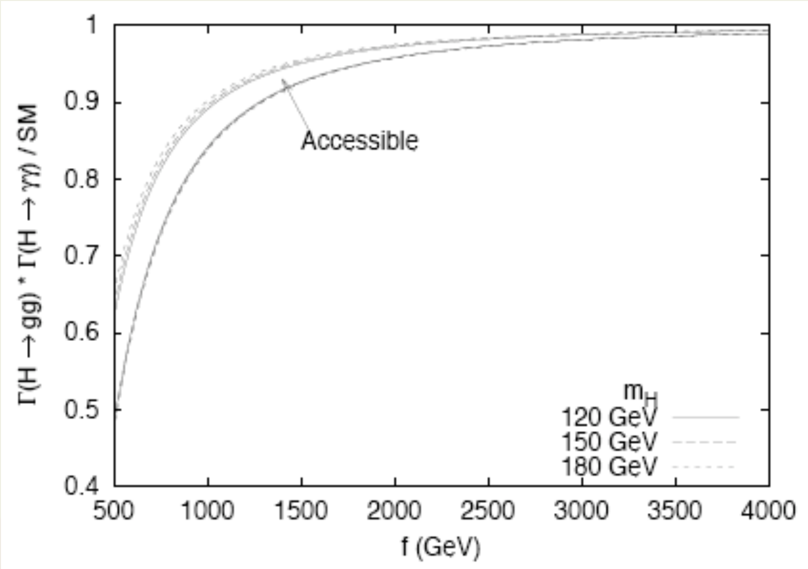
$$M_H^2 > \frac{3v^2}{2\pi^2}\log\left(\frac{\Lambda^2}{v^2}\right)$$

Higgs in SM extensions

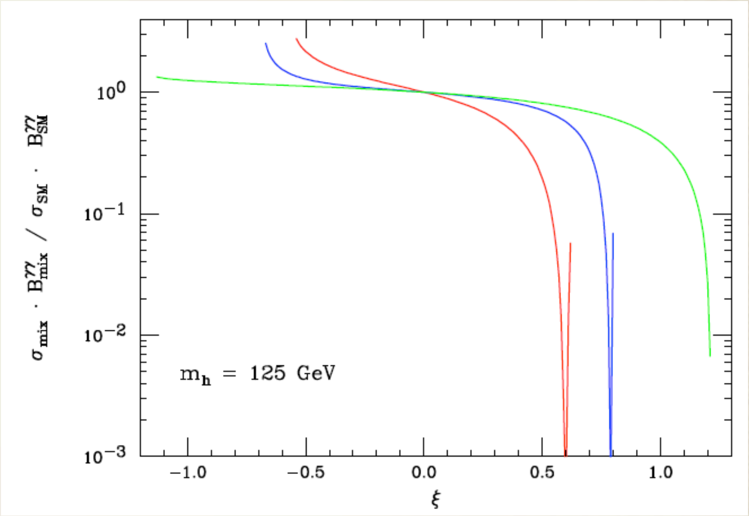
The uncertainty in EWSB mechanism makes Higgs a portal into new physics at the TEV scale



S. Dawson



Han, Logan, McElrath '03



Hewett, Rizzo '02

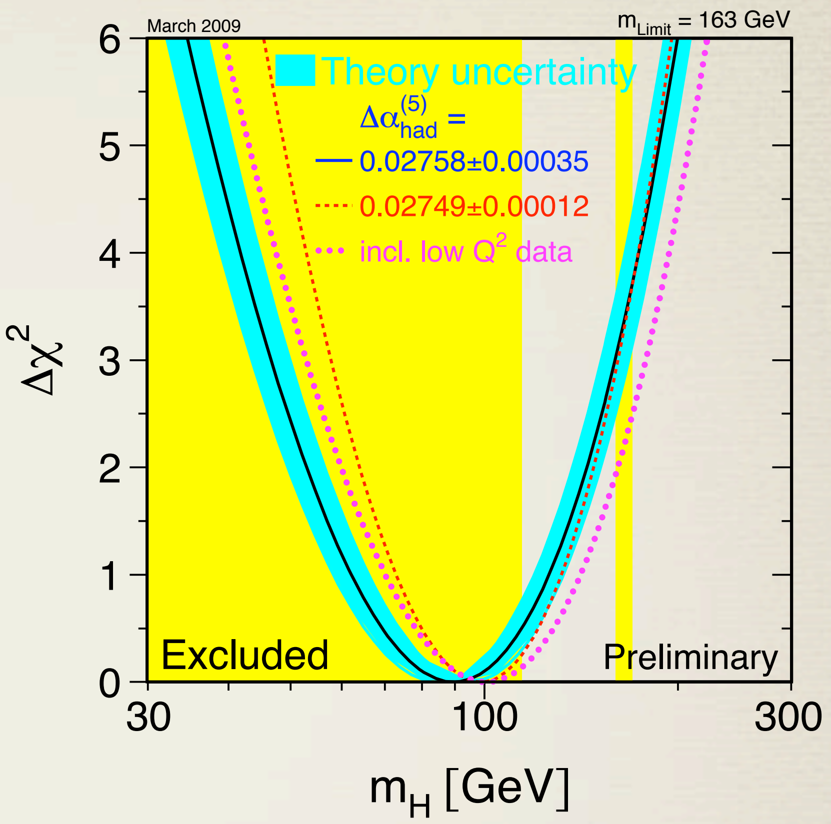
Loop-induced gluon, photon modes can have O(1) deviations

SM Higgs circa 2008

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

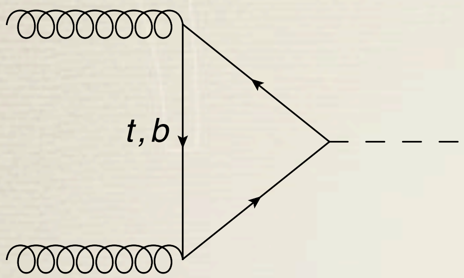
$$114 < M_H/\mathrm{GeV} < 163$$

News from the Tevatron: First exclusion in 2008; new combined results exclude 160-170 GeV SM Higgs at 95% CL arXiv:0903.4001

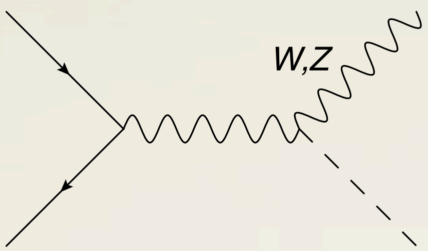


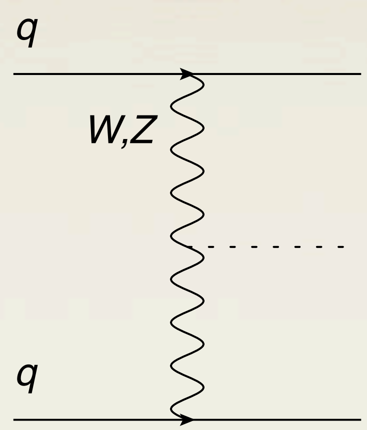
Carefully reconsider SM prediction in light of experimental sensitivity

SM Higgs production

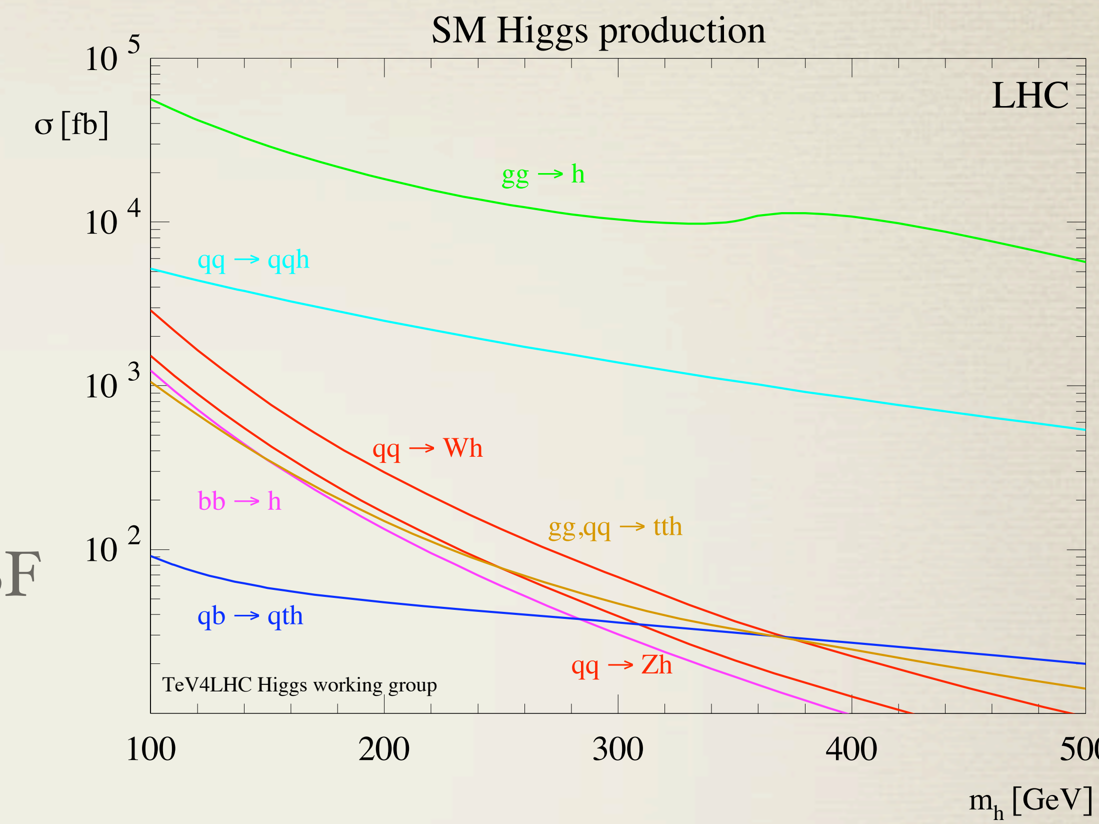


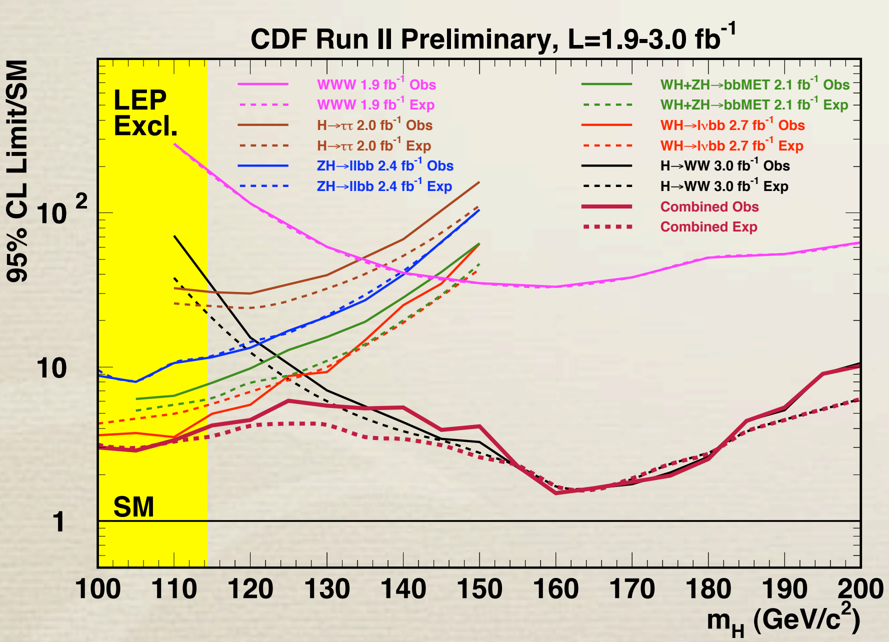
gg fusion dominant by factor of 10





Associated production, WBF essential for light Higgs

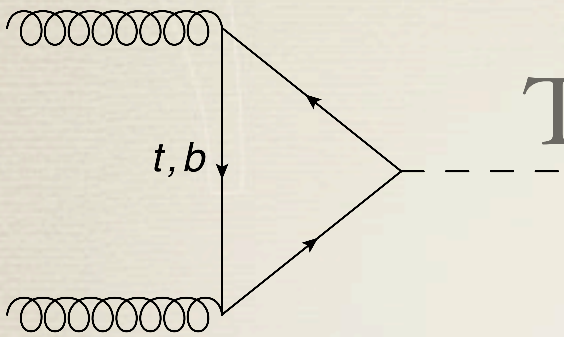




Tevatron exclusion limit entirely from gg→H→WW

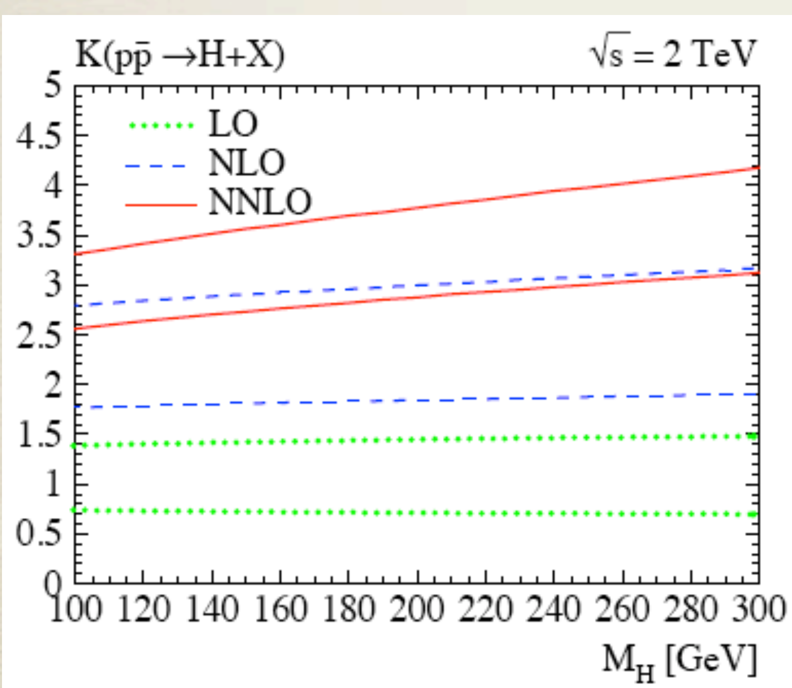
BR(H→WW) > 90% for 160-170 GeV Higgs

QCD corrections at NLO



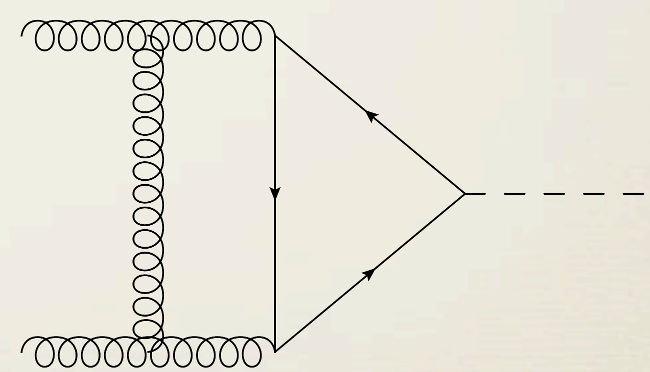
Top-loop dominant; bottom loop gives
-10% correction from interference $\{m_b^2 \ln^2(M_H/m_b)\}$

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



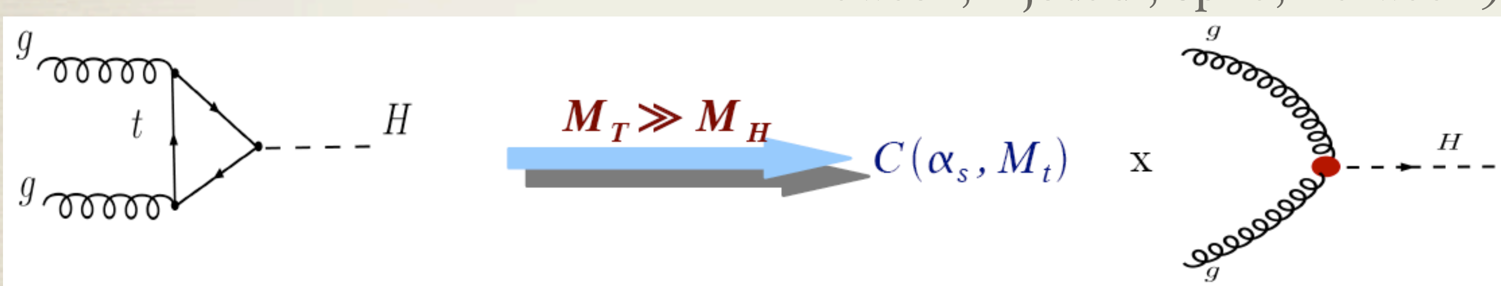
NLO corrections >100% at Tevatron, LHC

Effective theory for Higgs

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

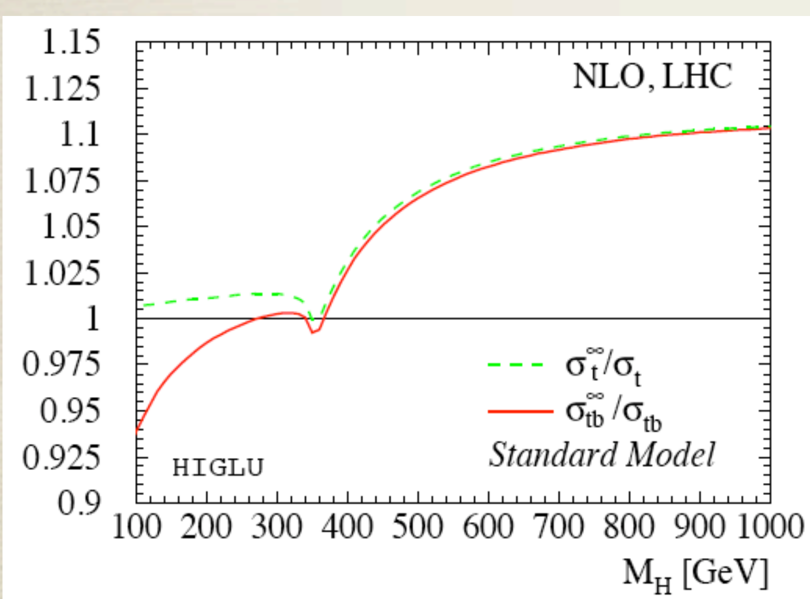
Difficult to go to NNLO and check convergence of expansion

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



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

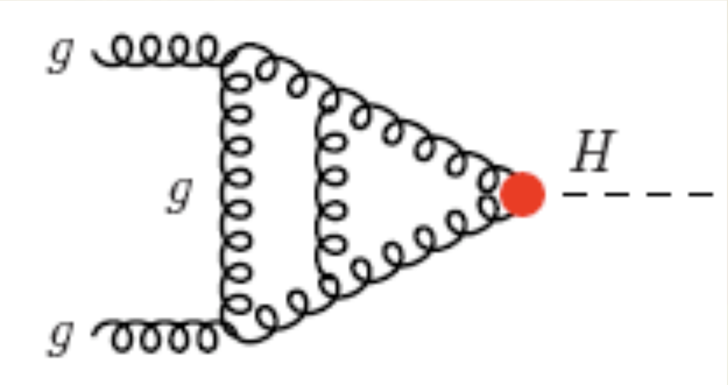
known through $O(\alpha_s^5)$: Schroder, Steinhauser; Chetyrkin, Kuhn, Sturm 2006



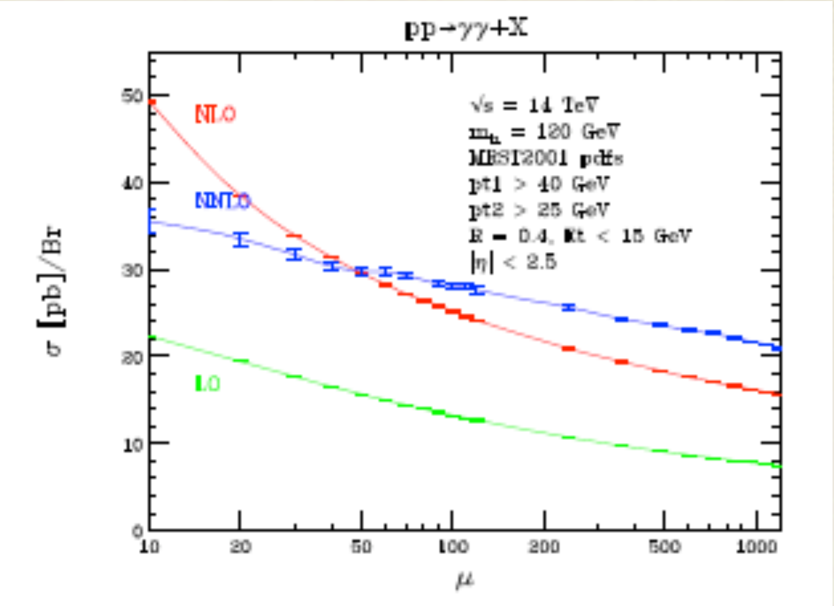
Harlander 2008

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

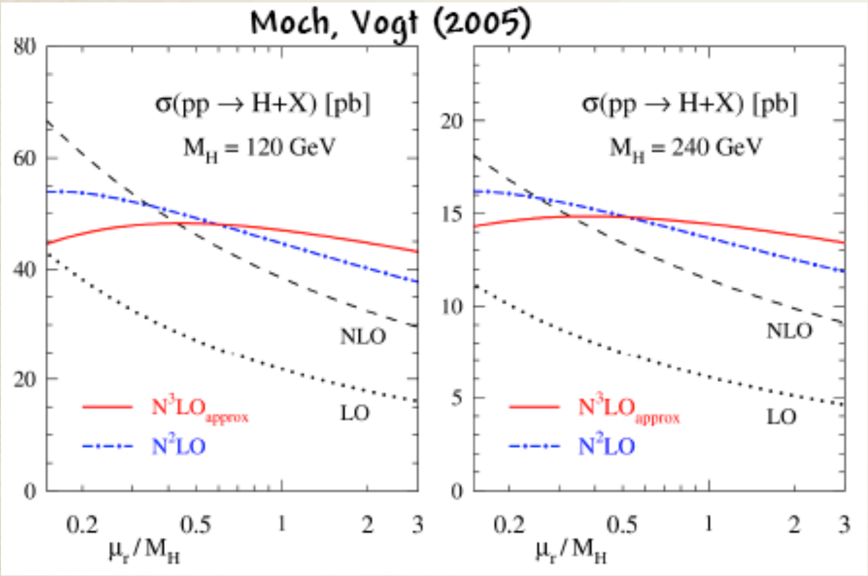
NNLO in the EFT



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



Anastasiou, Melnikov, FP 2005



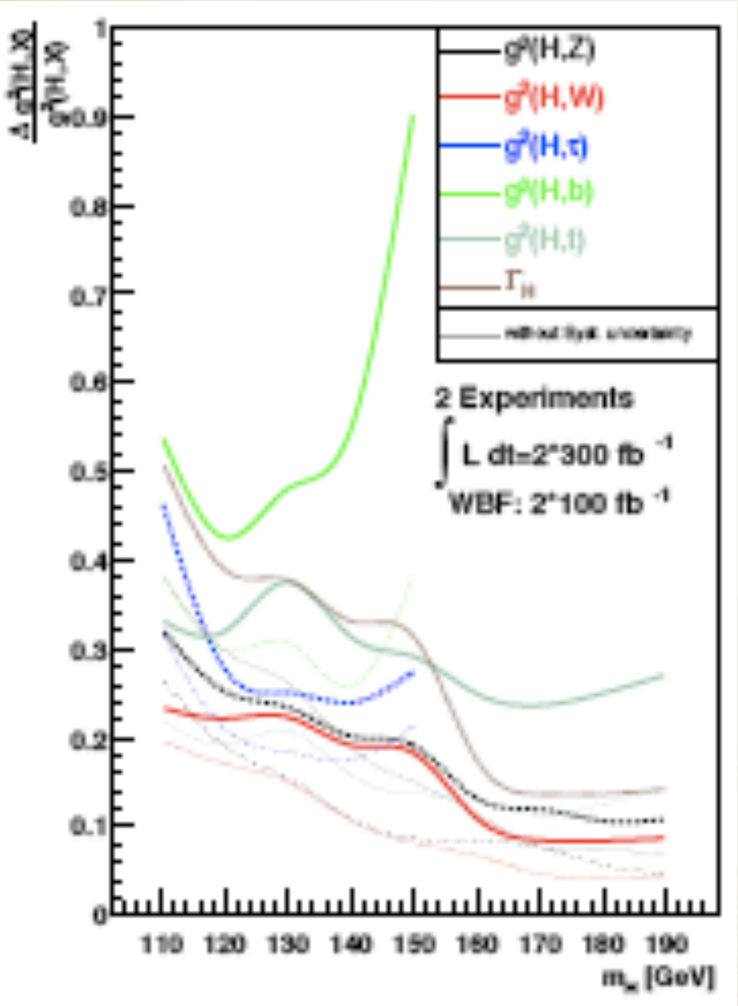
Full NNLO differential results known

K-factor: ~3.5 at Tevatron, ~2 at LHC

N3LO scale dependence indicates stability of expansion

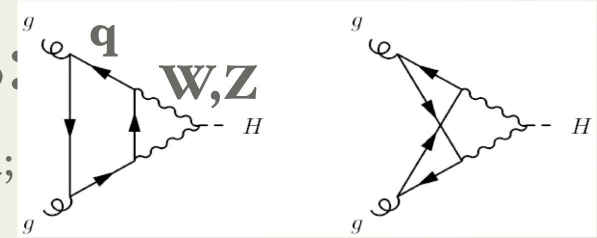
Electroweak corrections

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



Duhrssen, Heinemeyer, Logan, Rainwater, Weiglein, Zeppenfeld 2004

Light-quark terms:



Aglietti, Bonciani, Degrassi, Vicini 2004; Actis, Passarino, Sturm, Uccirato 2008

➪ Up to 9% at threshold relative to LO QCD

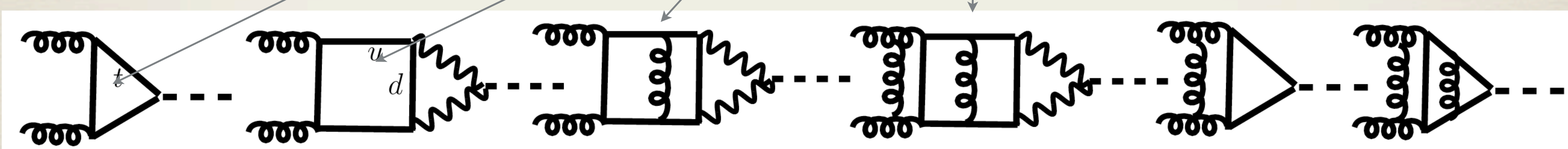
Do they receive the same large K-factor as the top-quark terms?

➪ test in EFT formulation

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 (gluon pdf shape)

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

Anastasiou, Boughezal, FP 2008

Factorization in EFT

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

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

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

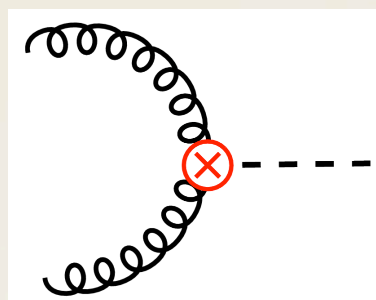
Factorization holds if $C_{1w}=C_{1q}$, $C_{2w}=C_{2q}$

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

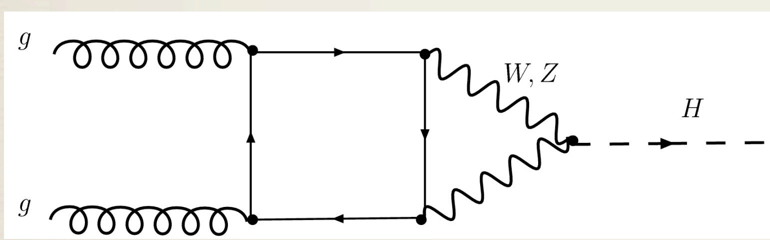
$$\lambda_{EW} = \frac{3\alpha}{16\pi s_W^2}\left\{\frac{2}{c_W^2}\left[\frac{5}{4} - \frac{7}{3}s_W^2 + \frac{22}{9}s_W^4\right] + 4\right\}$$

Matching to the EFT I

Matching at O(α):



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

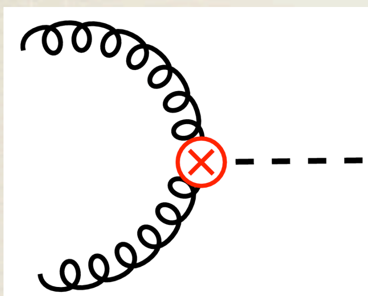


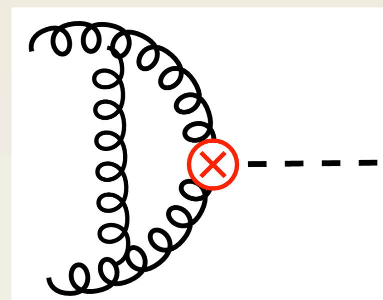
$$= \mathcal{A}^{(2)}(M_H^2 = 0)\mathcal{M}_0 + \mathcal{O}\left(\frac{M_H^2}{M_{W,Z}^2}\right)$$

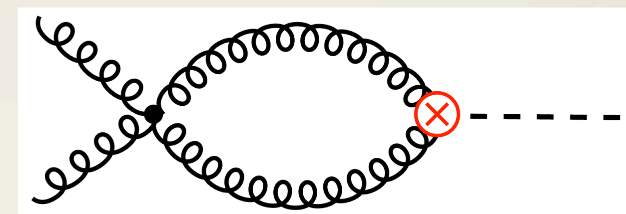
➪ Equate to get λ_{EW}

Matching to the EFT II

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







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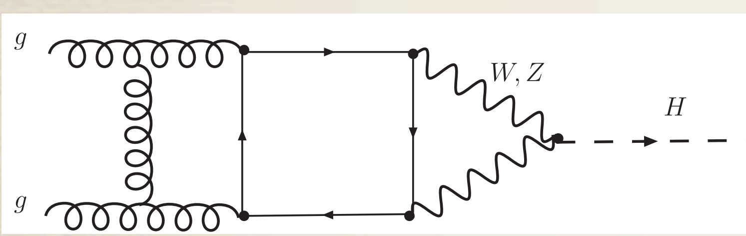
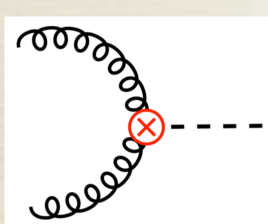
$$-\frac{1}{3\pi}\frac{\alpha_s}{v}\lambda_{EW}\left(\alpha_s C_{1w}\right)\mathcal{M}_0$$



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



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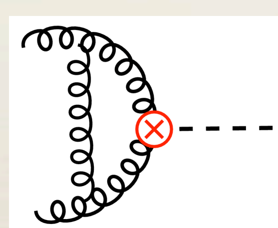

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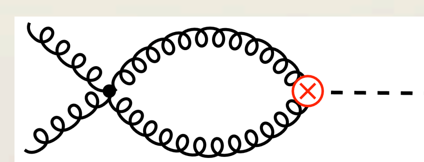

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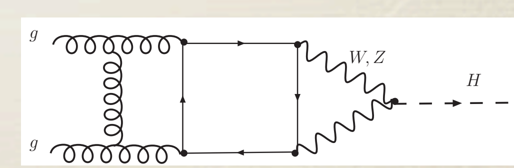


➪ gives C_{IW}

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 K-factor

EFT supports that EW corrections get same K-factor as top contributions

actual result →

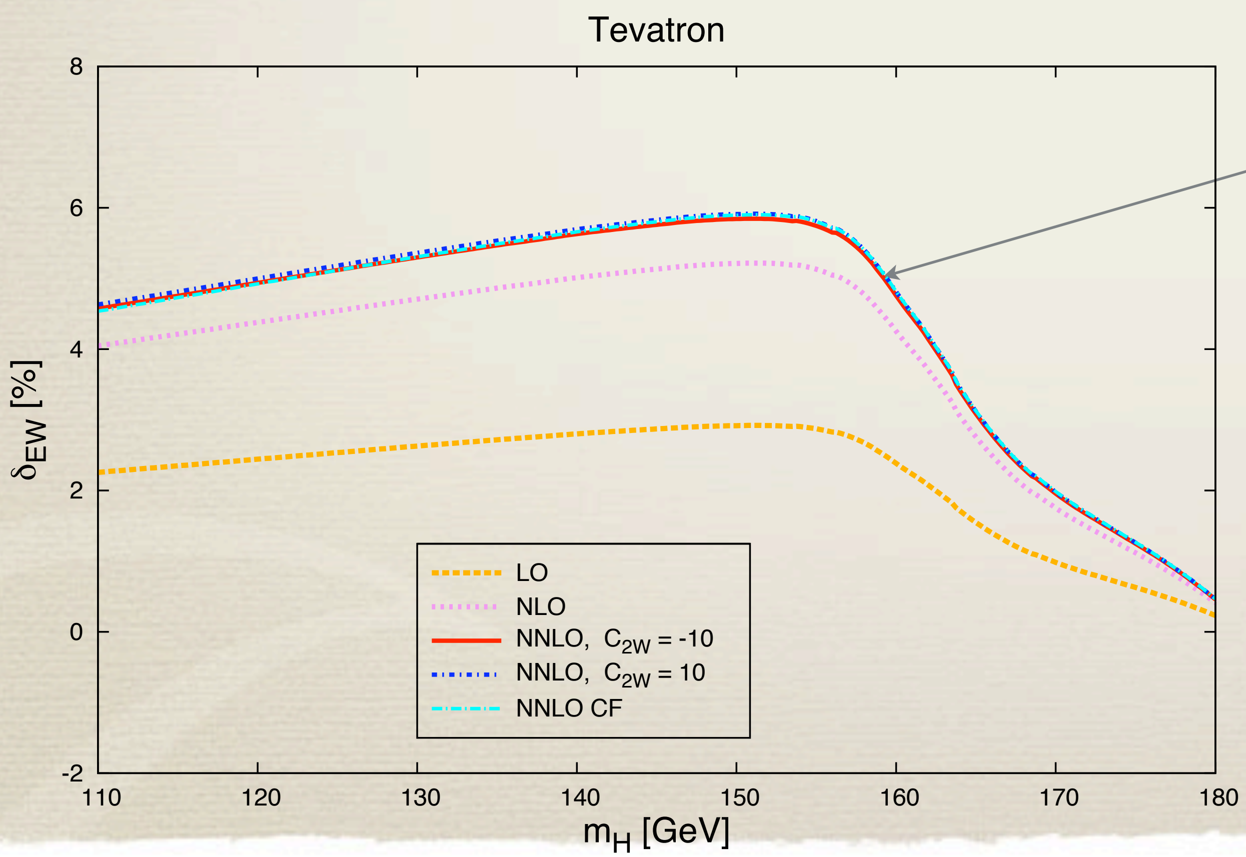
$$\sigma_{EW}^{LO} = \sigma_{t,lf}^{(0)} G_{ij}^{(0)}(z) \quad ,$$

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

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

top-quark assumption →

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



Almost complete numerical agreement

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

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

Anastasiou, Boughezal, FP 2008

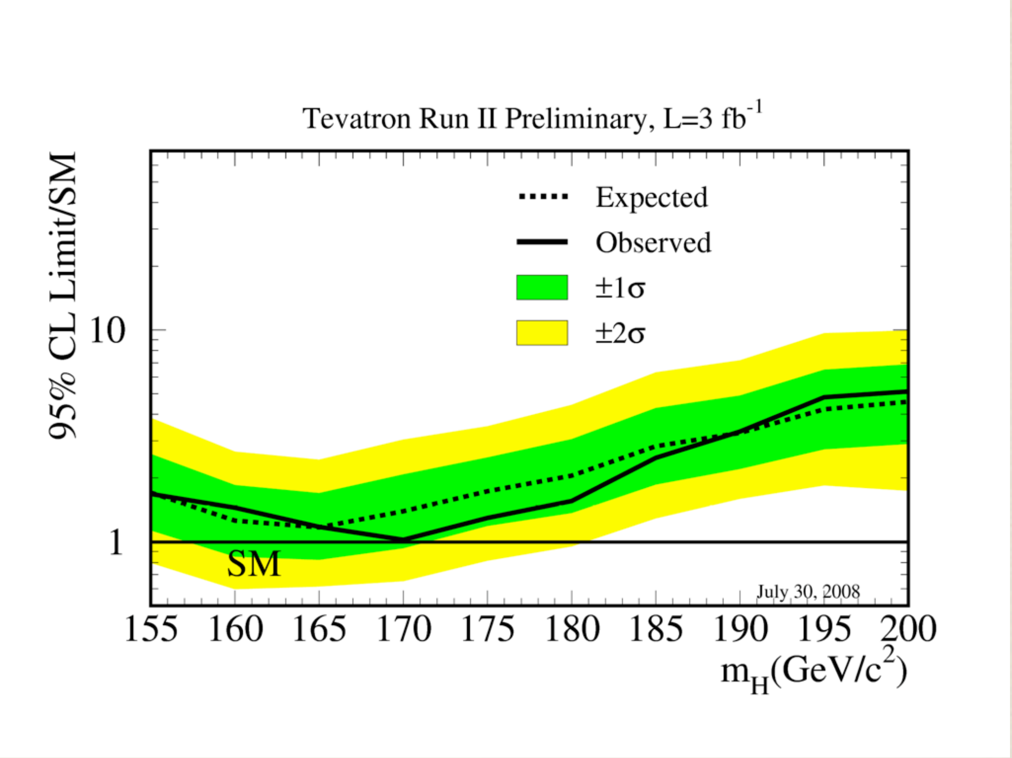
Tevatron exclusion

First limits: M_H=170 GeV excluded

What went into the SM prediction:

- Same K-factors assumed ✓
- Same QCD corrections for t,b
- Old PDFs (MRST 2002)

Combined CDF, D0 results (2008)



arXiv:0808.0534

Provide updated SM prediction that updates these assumptions

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

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 ≤ M_H ≤ 180 GeV

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

Circa January 2009

MSTW 2008 PDF release arXiv:0901.0002

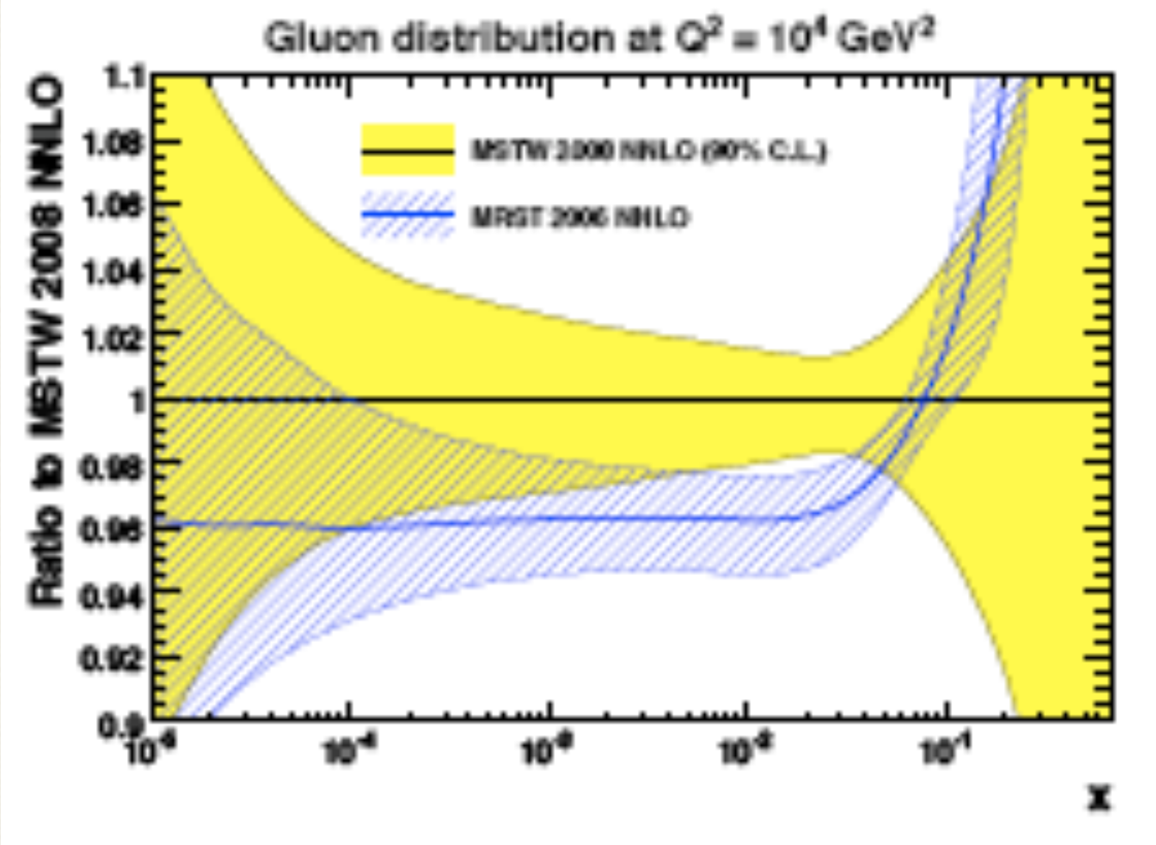
- Run II inclusive jet data
- Decrease of $\alpha_s(M_Z)$ from 0.119→0.117
- Gluon density decreased at x~0.1
- gg luminosity error increased from 5%→10%

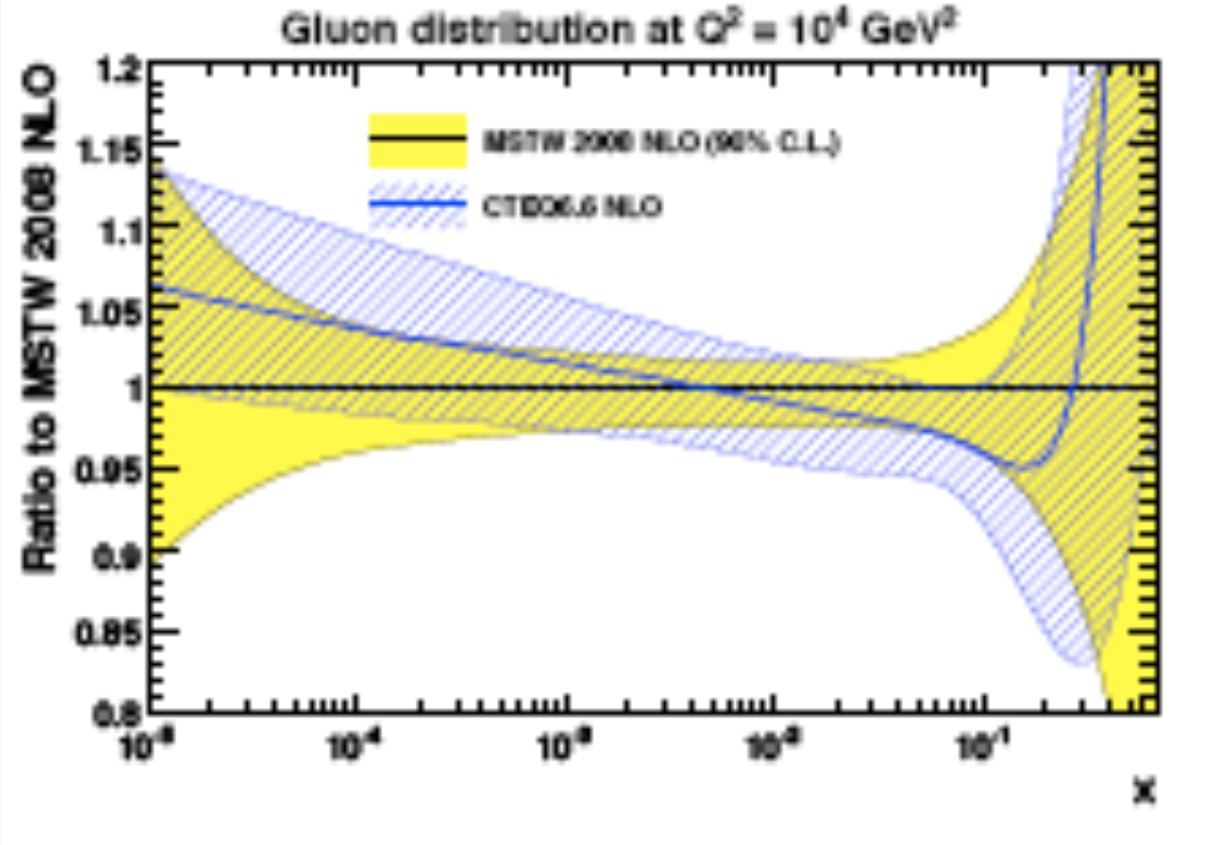
M_H=170 GeV:

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

~10-15% decrease in predicted cross section !

Gluon distributions





MSTW 2008 closer to CTEQ 6.6 gluon

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

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

Central value shift but not PDF systematic shift accounted for in newest analysis; becomes one of the largest systematic errors

Anastasiou, Boughezal, FP 2008

Numerical results for LHC

Old

M_H	$\sigma^{NNLO}_{\rm min}$	$\sigma^{NNLO}_{\rm ref}$	$\sigma^{NNLO}_{\rm max}$	$\sigma^{NNLL}_{\rm min}$	$\sigma^{NNLL}_{\rm ref}$	$\sigma^{NNLL}_{\rm max}$
100	47.71	53.30	59.02	51.22	56.36	61.28
110	41.08	45.77	50.55	44.12	48.41	52.47
120	35.81	39.80	43.85	38.46	42.10	45.52
130	31.52	34.96	38.45	33.87	37.00	39.92
140	27.99	30.99	34.02	30.09	32.80	35.32
150	25.05	27.69	30.34	26.94	29.31	31.51
160	22.56	24.90	27.25	24.28	26.37	28.31
170	20.45	22.54	24.64	22.02	23.88	25.59
180	18.65	20.52	22.40	20.08	21.74	23.27
190	17.09	18.79	20.48	18.39	19.90	21.27
200	15.74	17.28	18.83	16.96	18.32	19.55
210	14.57	15.98	17.39	15.70	16.94	18.07
220	13.55	14.85	16.14	14.60	15.74	16.78
230	12.65	13.86	15.05	13.65	14.70	15.65
240	11.87	12.99	14.10	12.81	13.78	14.67
250	11.19	12.24	13.28	12.08	12.99	13.81
260	10.60	11.58	12.55	11.45	12.30	13.06
270	10.09	11.01	11.93	10.90	11.70	12.42
280	9.648	10.53	11.39	10.42	11.18	11.86
290	9.270	10.11	10.94	10.02	10.74	11.39
300	8.960	9.773	10.57	9.696	10.38	11.00

New

m_H	$\sigma^{\rm best}$	Scale	PDF
100	74.58	$^{+7.18}_{-7.54}$	$^{+1.86}_{-2.45}$
110	63.29	$^{+5.87}_{-6.20}$	$^{+1.54}_{-2.02}$
120	54.48	$^{+4.88}_{-5.18}$	$^{+1.30}_{-1.70}$
130	47.44	$^{+4.12}_{-4.38}$	$^{+1.12}_{-1.45}$
140	41.70	$^{+3.47}_{-3.75}$	$^{+0.97}_{-1.25}$
150	36.95	$^{+3.02}_{-3.24}$	$^{+0.85}_{-1.10}$
160	32.59	$^{+2.60}_{-2.79}$	$^{+0.73}_{-0.97}$
170	28.46	$^{+2.22}_{-2.39}$	$^{+0.65}_{-0.84}$
180	25.32	$^{+1.92}_{-2.08}$	$^{+0.58}_{-0.74}$
190	22.63	$^{+1.68}_{-1.83}$	$^{+0.52}_{-0.66}$
200	20.52	$^{+1.49}_{-1.63}$	$^{+0.48}_{-0.60}$
210	18.82	$^{+1.34}_{-1.47}$	$^{+0.45}_{-0.55}$
220	17.38	$^{+1.22}_{-1.33}$	$^{+0.42}_{-0.51}$
230	16.15	$^{+1.11}_{-1.22}$	$^{+0.39}_{-0.48}$
240	15.10	$^{+1.03}_{-1.12}$	$^{+0.37}_{-0.45}$
250	14.19	$^{+0.95}_{-1.04}$	$^{+0.36}_{-0.43}$
260	13.41	$^{+0.88}_{-0.97}$	$^{+0.35}_{-0.41}$
270	12.74	$^{+0.83}_{-0.91}$	$^{+0.33}_{-0.39}$
280	12.17	$^{+0.78}_{-0.86}$	$^{+0.33}_{-0.38}$
290	11.71	$^{+0.74}_{-0.82}$	$^{+0.32}_{-0.37}$
300	11.34	$^{+0.71}_{-0.78}$	$^{+0.32}_{-0.36}$

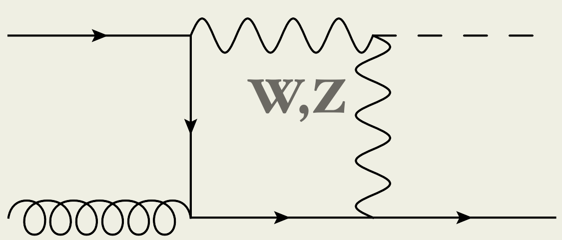
Increase of 25% at low M_H; 10% at higher masses

de Florian, Grazzini 2009

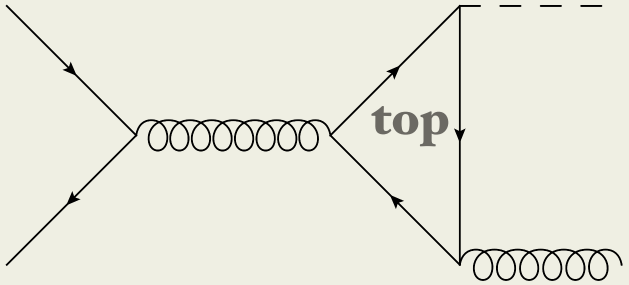
EW effects at high p_T

Other EW effects not yet included? *Yes*

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



Current 1-jet bin:



⇨ same order

Matches to $\dfrac{\partial_\nu H}{v} \dfrac{G^{\mu\nu} \bar{q}\gamma_\mu q}{M^2_{W,Z}}$

Vanishes for $p_g \propto p_{1,2}$

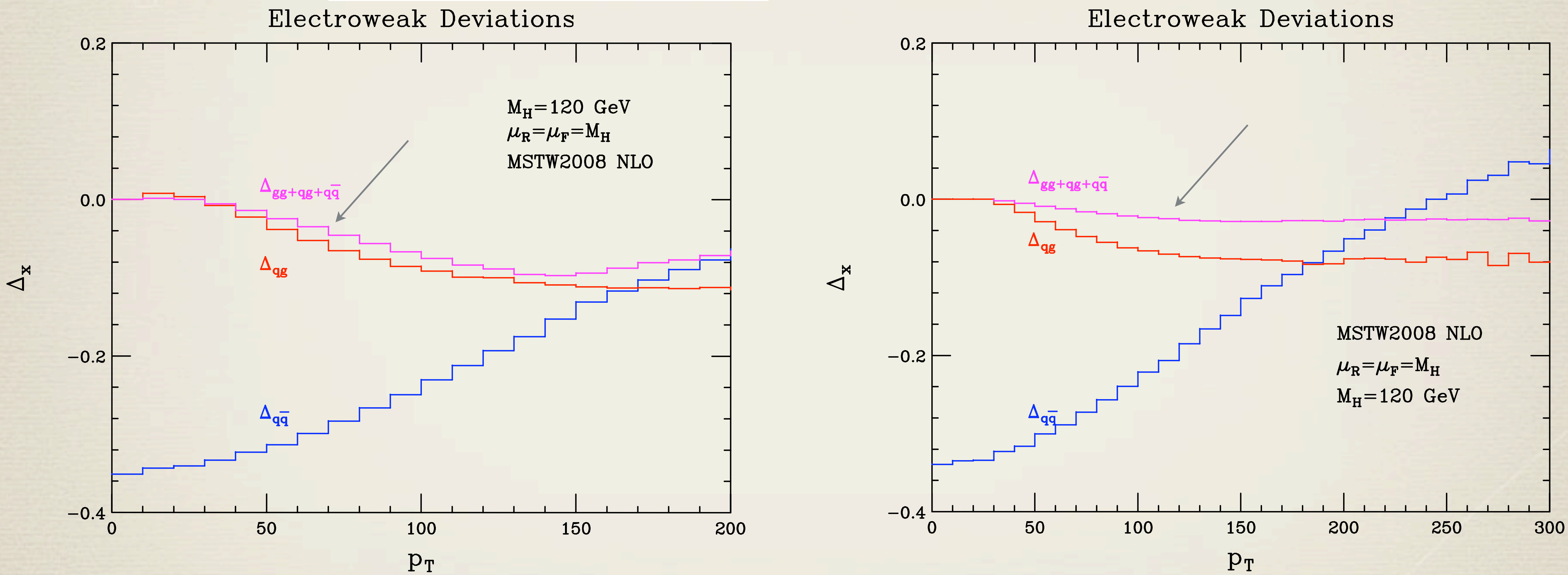
⇨ hard p_T spectrum

~45% of exclusion from 1,2-jet bins M. Herndon, private communicaton

W.Y. Keung, FP 2009

Numerical results

$$\sigma^{approx} = \left(\frac{\sigma^{exact}_{gg\to H}}{\sigma^{EFT}_{gg\to H}}\right)\sigma^{EFT} \qquad \Delta_x = \frac{\sigma_x - \sigma^{approx}}{\sigma^{approx}}$$

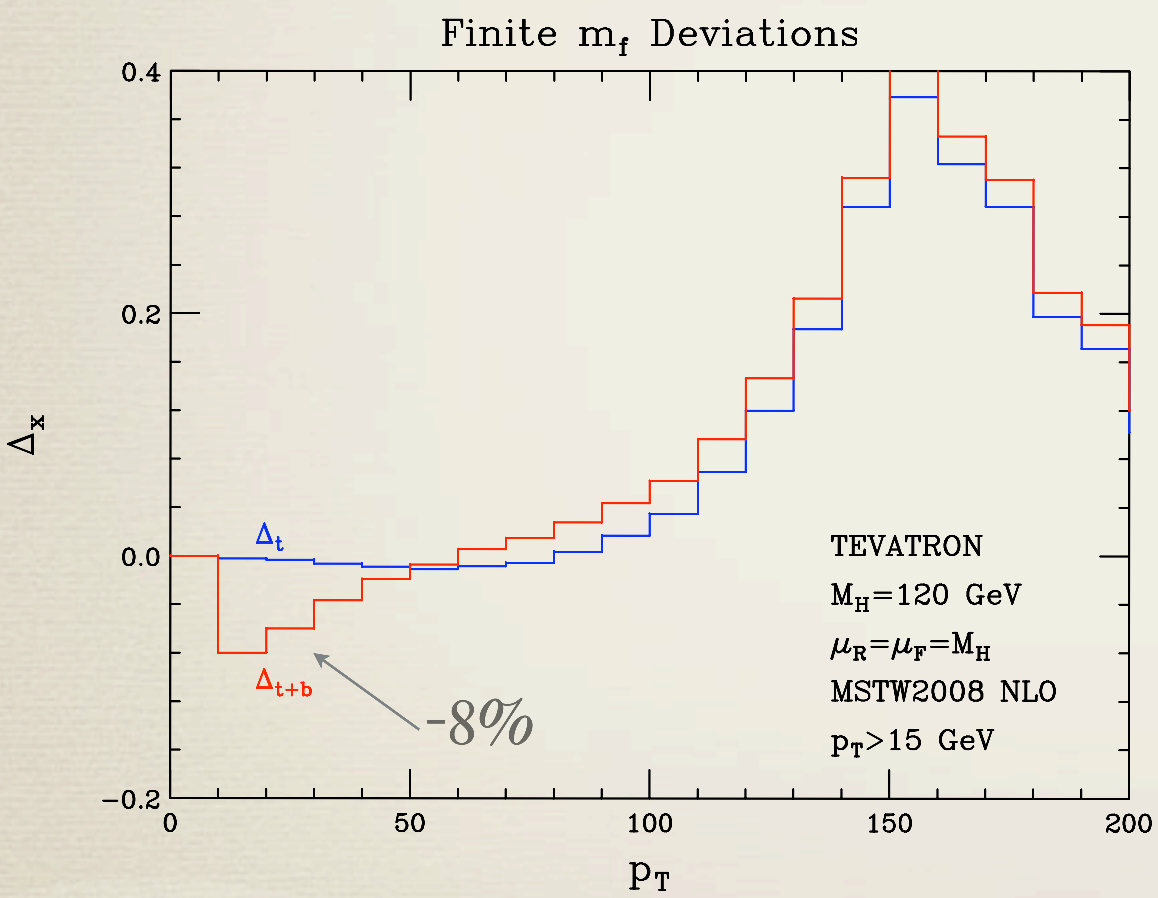


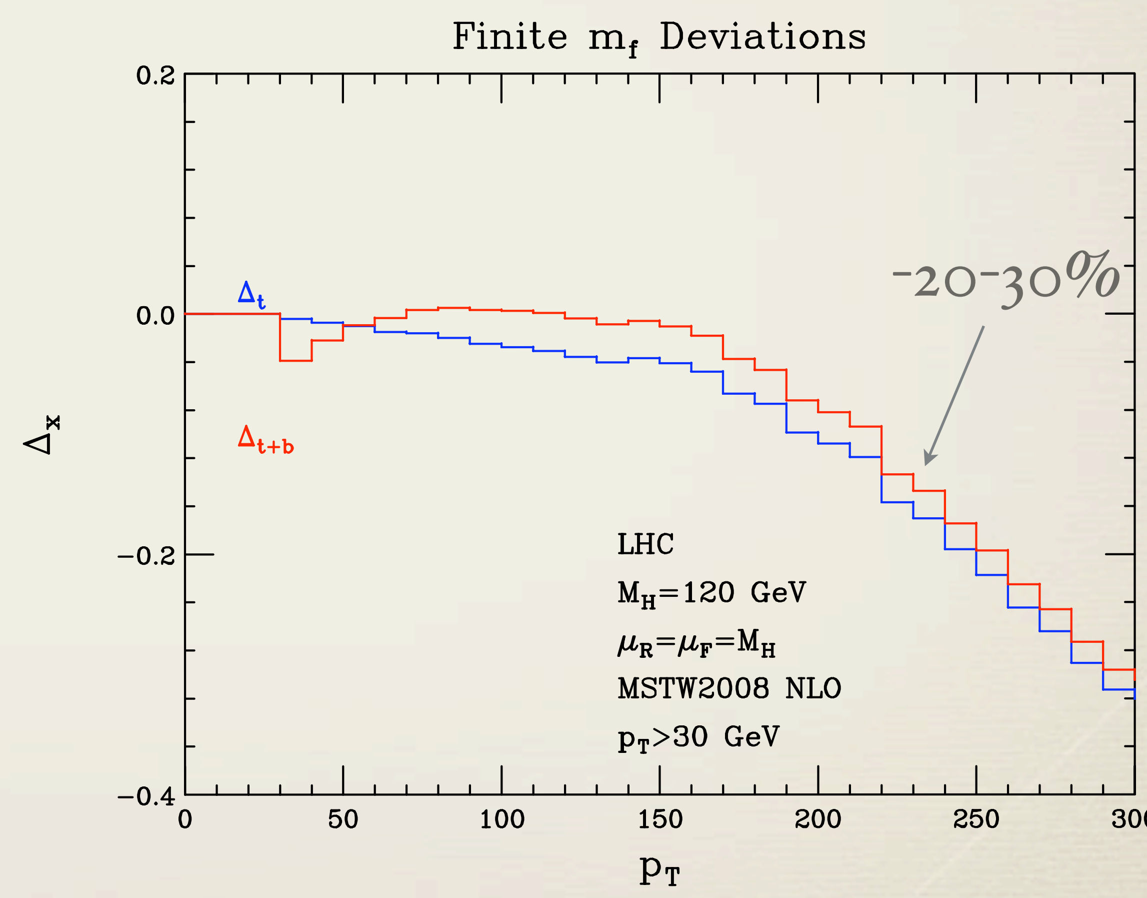
Destructive interference with top contribution; reaches -8% at Tevatron, -3% at LHC

W.Y. Keung, FP 2009

Quark-mass effects on pT

Study p_T dependence of other deviations from common $m_t \rightarrow \infty$ approximation: finite top mass and b quarks





Relevant for $H \rightarrow \gamma\gamma$, WW analyses that select high p_T Abdullin et al.; Mellado et al.

W.Y. Keung, FP 2009

Conclusions

* Precision prediction for Higgs production at hadron colliders with EW+QCD corrections complete
* Updated cross section 5-6% *lower* then Tevatron used in 2008 exclusion
* PDF systematic error factor of 2 *larger*; effect on Tevatron exclusion limits?
* EW effects at high Higgs p_T can reach -8% destructive interference; deviations from infinite top mass approximation can reach -30%