Cross-sections for Higgs production

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LoopFest VIII

Radiative Corrections for the LHC and the ILC

Madison, May 7 2009

in collaboration with Massimiliano Grazzini

deF, Grazzini (2009)
Catani, deF, Grazzini, Nason (2003)

Outline

- Higgs production : gluon fusion
- Soft-virtual contributions
- Resummation
- Update on Higgs production
- Summary

- If there is a Higgs boson...

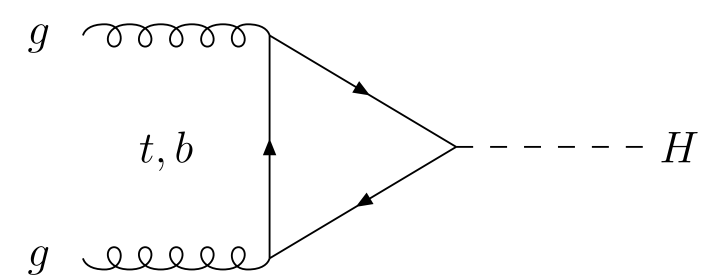
$M_H > 114.4\,\mathrm{GeV}$ LEP

$M_H < 163\,\mathrm{GeV}$ EW 95%CL

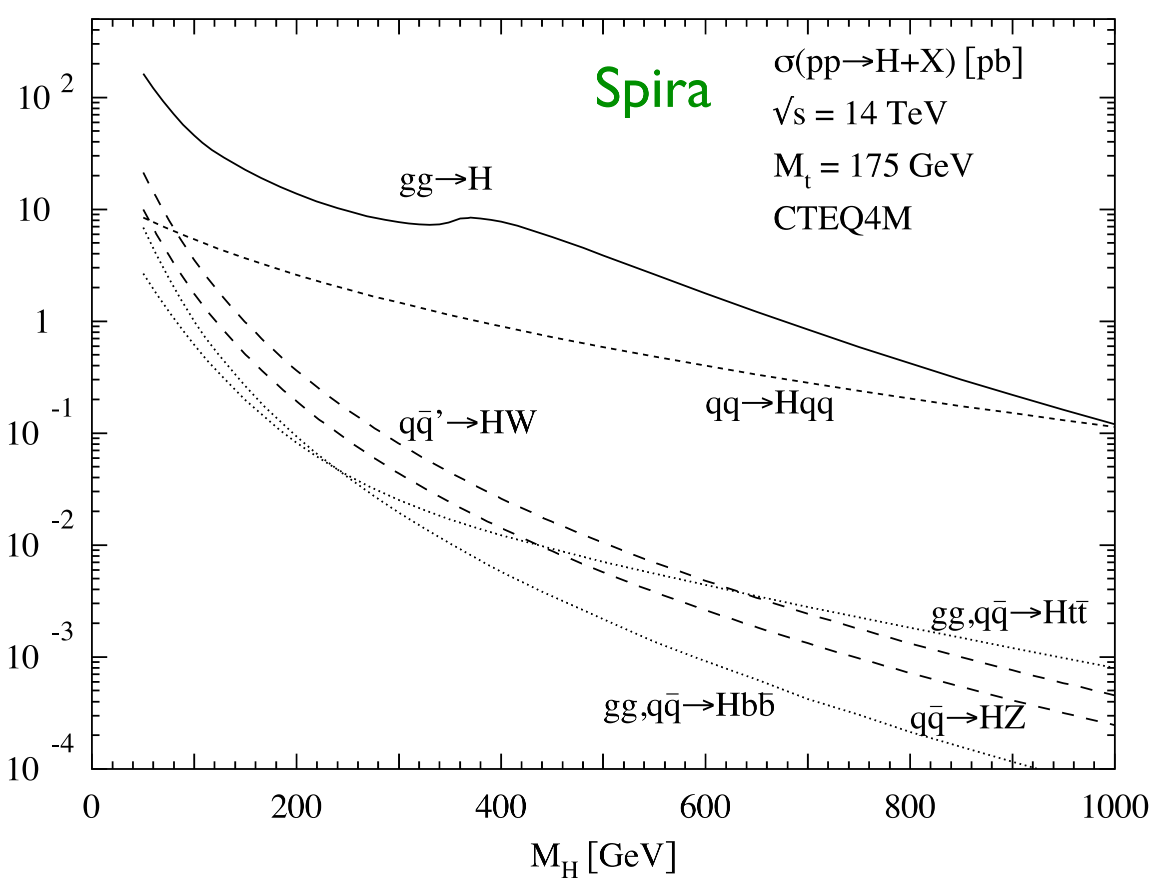
$M_H \neq 170\,\mathrm{GeV}$ Tevatron

Precise cross-sections needed for exclusion!

- gg fusion dominant production mechanism at hadronic colliders

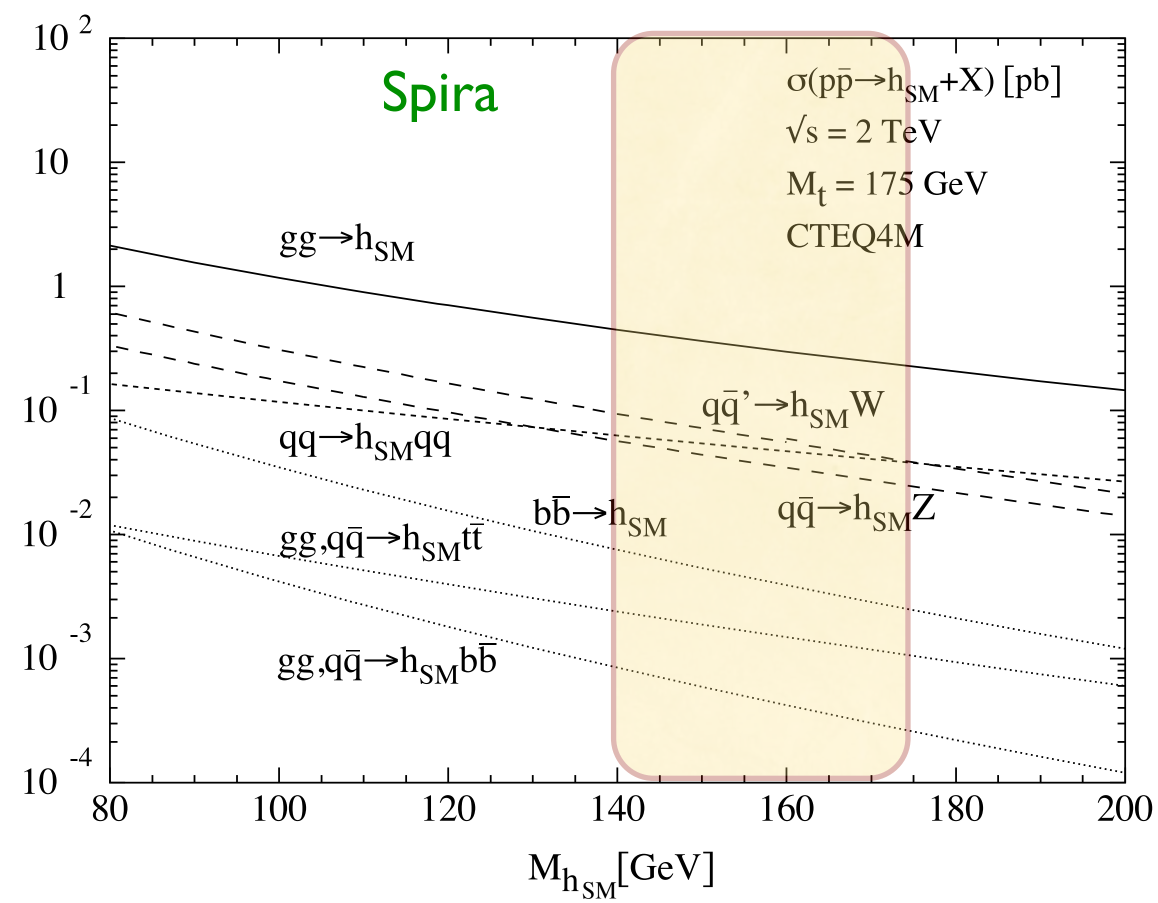


LHC



Tevatron

$gg \to H \to WW$



Total cross-section

Born — Luminosity — Coefficient

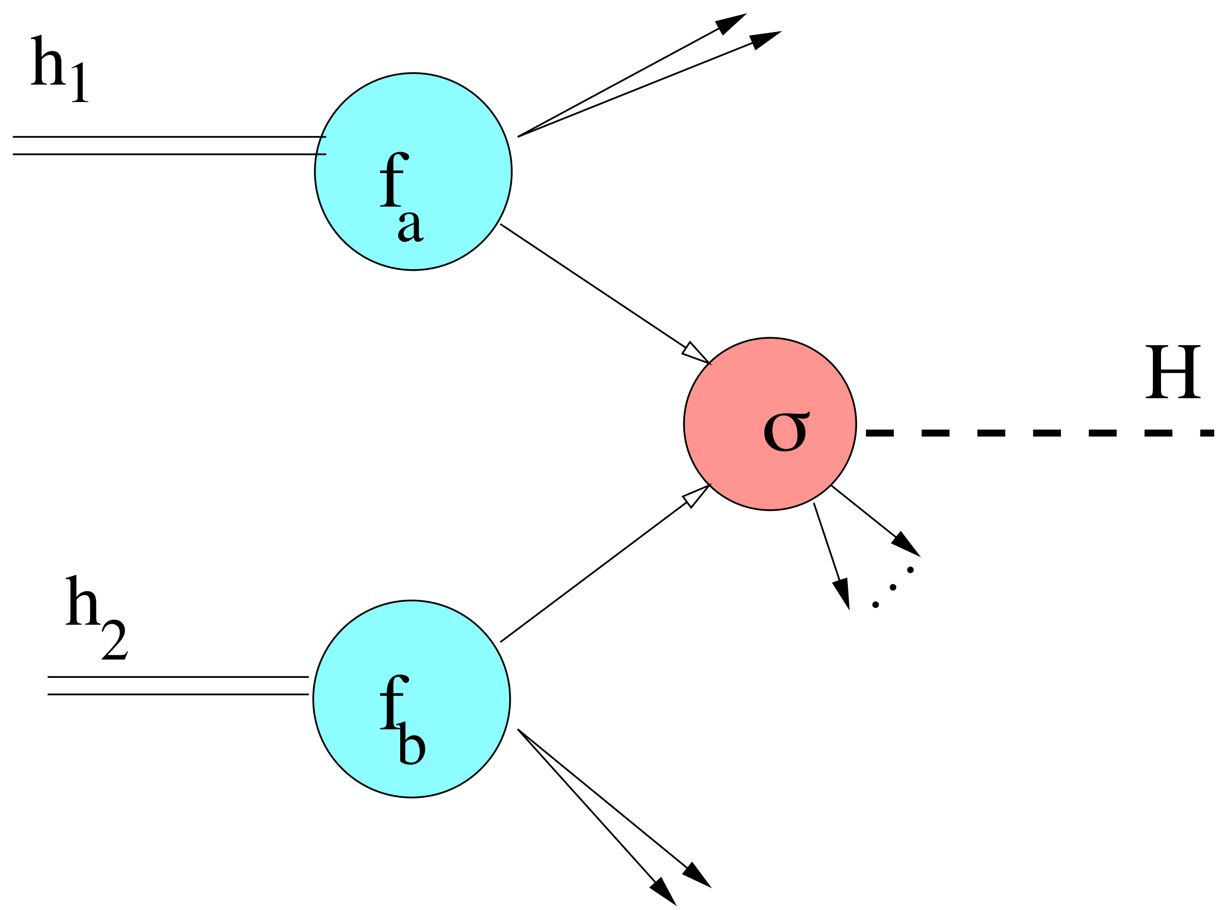
$$\sigma(S, M_H^2) = \sigma_0 \sum_{a,b} \int_0^1 dz \int_0^1 dx_1\, dx_2\, f_{a/H_1}(x_1, \mu_F^2)\, f_{b/H_2}(x_2, \mu_F^2)\, \delta\left(z - \frac{\tau}{x_1 x_2}\right) z\, G_{ab}(z; \alpha_s(\mu_R^2), M_H^2/\mu_R^2; M_H^2/\mu_F^2$$

$$\tau = M_H^2/S$$

$$\mathcal{L}\left(\frac{\tau}{z}, \mu_F^2\right)$$

$$z = M_H^2/\hat{s}$$

$$\hat{s} = x_1 x_2 S$$



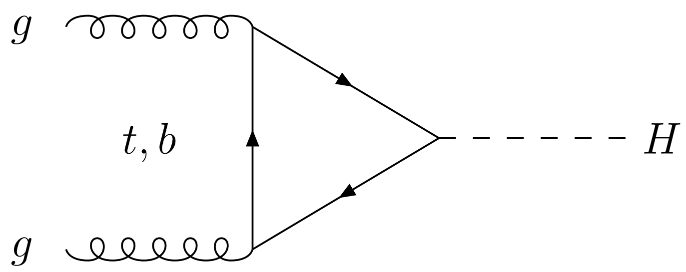
$z \longrightarrow 1$ **Partonic threshold**

QCD expansion

$$G_{ab}(z; \alpha_s(\mu_R^2), M_H^2/\mu_R^2; M_H^2/\mu_F^2) = \left(\frac{\alpha_s(\mu_R^2)}{\pi}\right)^2 G_{ab}^{(0)}(z) + \left(\frac{\alpha_s(\mu_R^2)}{\pi}\right)^3 G_{ab}^{(1)}(z; M_H^2/\mu_R^2; M_H^2/\mu_F^2) + \left(\frac{\alpha_s(\mu_R^2)}{\pi}\right)$$

$$+ \left(\frac{\alpha_s(\mu_R^2)}{\pi}\right)^4 G_{ab}^{(2)}(z; M_H^2/\mu_R^2; M_H^2/\mu_F^2) + \mathcal{O}(\alpha_s^5)$$

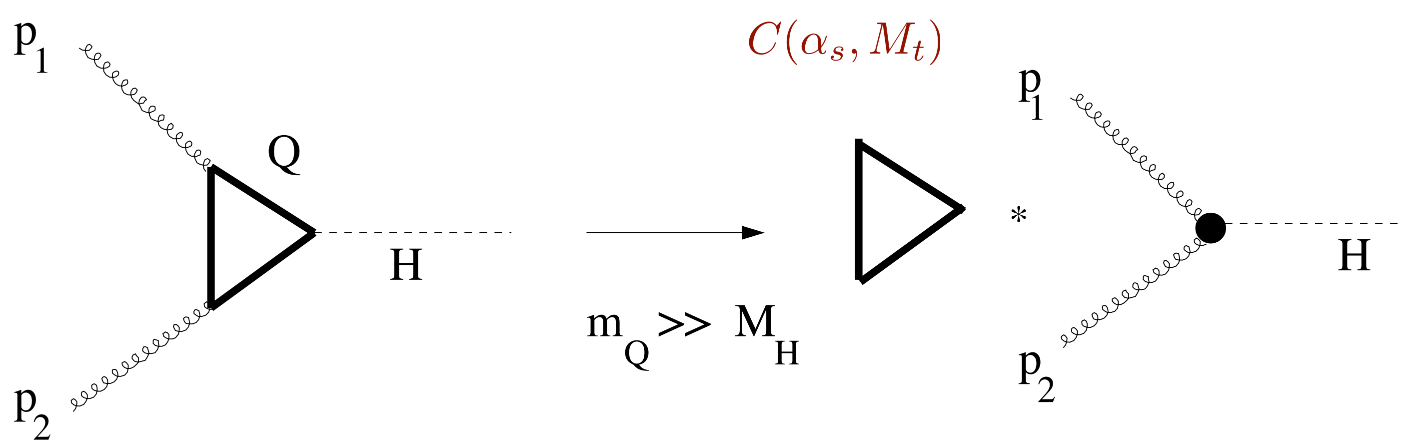
- Not an easy calculation



LO Ellis, Gaillard, Nanopoulos, Sachrajda (1977)

NLO Graudenz, Spira, Zerwas (1993)

- Effective Lagrangian $\mathcal{L}_{eff} = -\frac{1}{4}\left[1 - \frac{\alpha_S}{3\pi}\frac{H}{v}(1+\Delta)\right] \mathrm{Tr}\, G_{\mu\nu}G^{\mu\nu}$



$C(\alpha_s, M_t)$ known to $\mathcal{O}(\alpha_s^5)$ Schroder, Steinhauser (2006); Chetyrkin, Kuhn, Sturm (2006)

- Approximation works at the percent level for 'top' Schreck, Steinhauser (2007); Marzani et al (2008)

- If full Born result is retained → calculation of G coefficients

- Not a good approximation for 'bottom' ! dominated by b-t interference: small and negative

Within large M_t limit **NLO** Dawson (1991); Djouadi, Spira, Zerwas (1991)

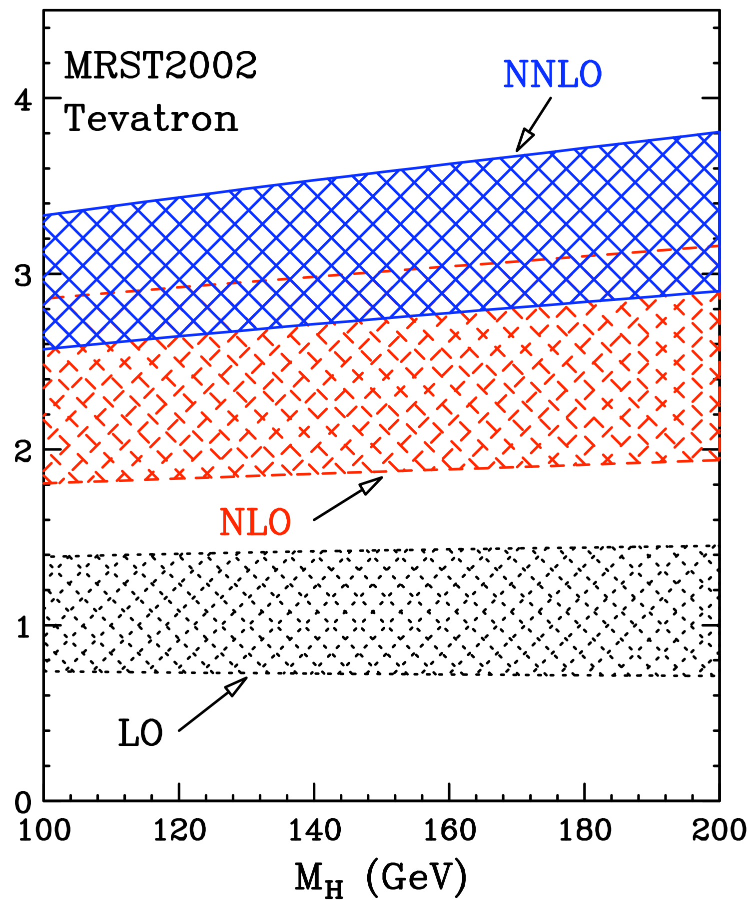
NNLO Harlander, Kilgore (2002); Anastasiou, Melnikov (2002); Ravindran, Smith, van Neerven (2003)

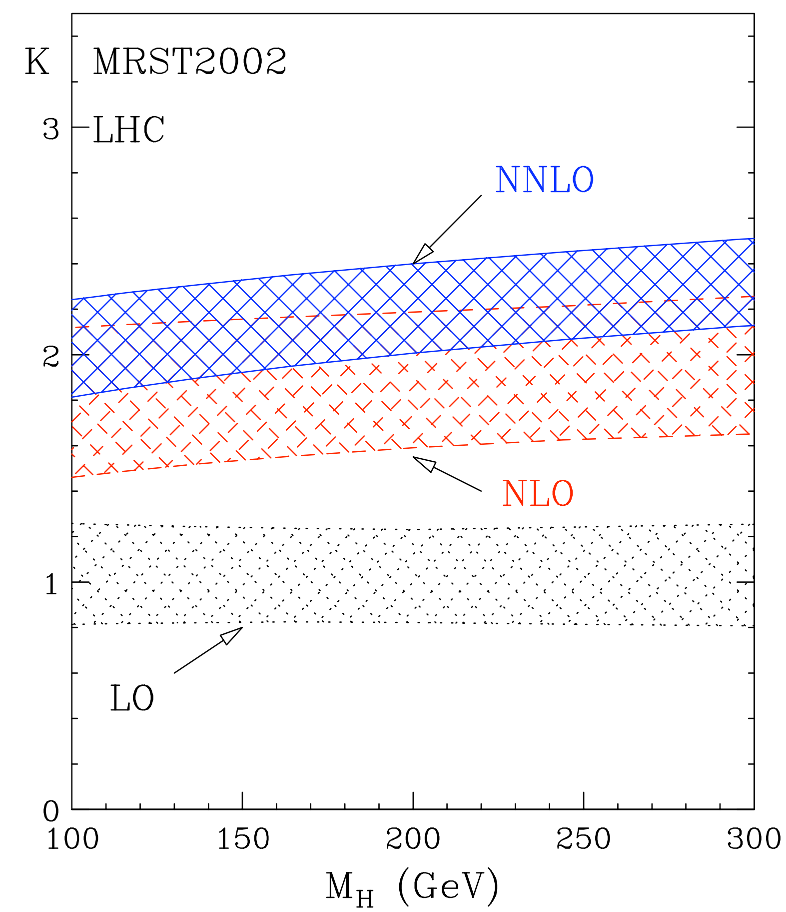
- QCD corrections are very large

$$K^{(N)NLO} = \frac{\sigma^{(N)NLO}(\mu_F, \mu_R)}{\sigma^{LO}(\mu_F = \mu_R = M_H)}$$

$$\mu_{F,R} = \chi_{F,R}\, M_H$$
$$0.5 \leq \chi_{F,R} \leq 2$$
$$0.5 \leq \frac{\chi_F}{\chi_R} \leq 2$$

NLO > 100%





NNLO ~ 40% $\alpha_s^2 \sim 1\%$ NNLO ~ 15-20%

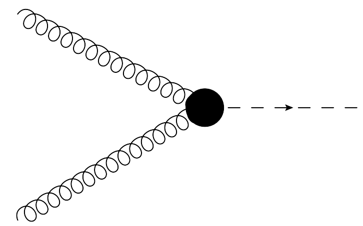
Large Coefficients

- Take a look at the coefficients

$z = M_H^2/\hat{s}$

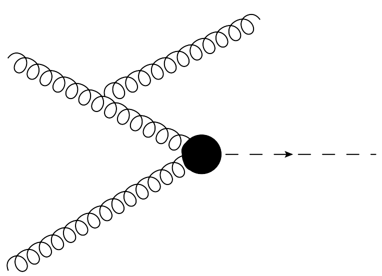
- LO

$$G_{ab}^{(0)}(z) = \delta_{ag}\delta_{bg}\ \delta(1-z)$$



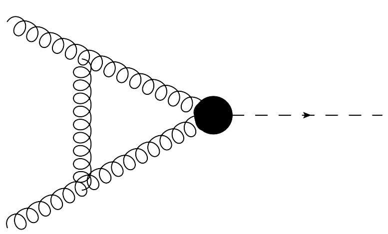
- NLO

$$G_{gg}^{(1)}(z; M_H^2/\mu_R^2; M_H^2/\mu_F^2) = \left(\frac{11}{2} + 6\zeta(2) + \frac{33-2N_f}{6}\ln\frac{\mu_R^2}{\mu_F^2}\right)\delta(1-z)$$



$$+6\ \ln\frac{M_H^2}{z\mu_F^2}\left(\frac{1}{1-z}\right)_+ + 12\left(\frac{\ln(1-z)}{1-z}\right)_+$$

singular $z \to 1$



$$+\left(P_{gg}^{real}(z) - \frac{2C_A}{1-z}\right)\ln\frac{M_H^2(1-z)^2}{z\mu_F^2}$$

(Pure) collinear $\ln\frac{q_{T\,max}^2}{\mu_F^2}$

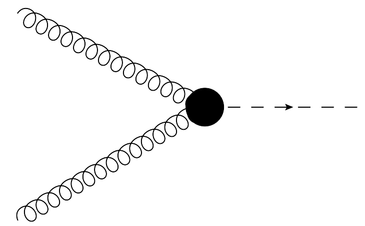
$$-\frac{11}{2}\frac{(1-z)^3}{z}$$

Hard

- Take a look at the coefficients $z = M_H^2/\hat{s}$

  - LO

$$G_{ab}^{(0)}(z) = \delta_{ag}\delta_{bg}\ \delta(1-z)$$



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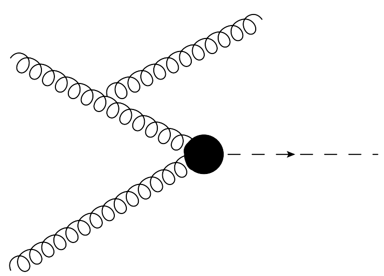

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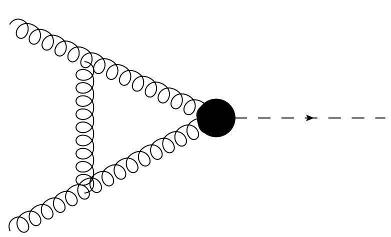

$$-\frac{11}{2}\frac{(1-z)^3}{z}$$

Hard

- Why $z \to 1$ if $S \gg M_H^2\ (\tau \ll 1)$

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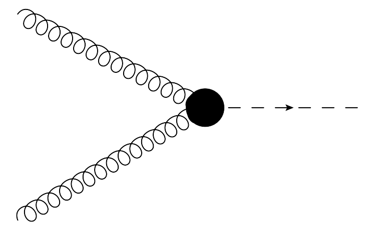

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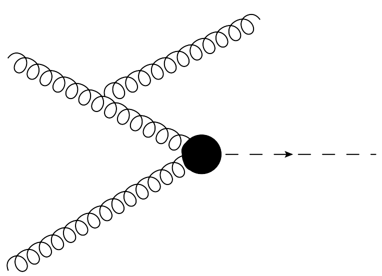

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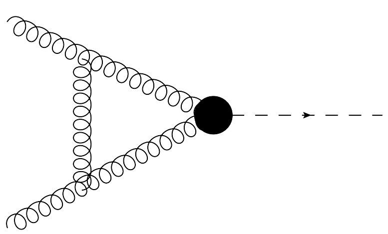

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(Pure) collinear $\ln\frac{q^2_{T\,max}}{\mu_F^2}$

$$-\frac{11}{2}\frac{(1-z)^3}{z}$$

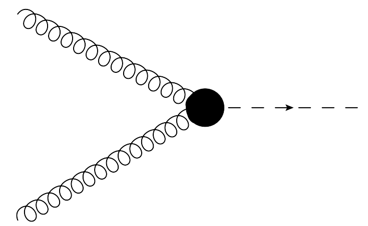
Hard

- Why $z \to 1$ if $S \gg M_H^2$ $(\tau \ll 1)$ Luminosity (gluon pdf) $\langle\hat{s}\rangle = \langle x_1 x_2\, s\rangle \ll S$
- Partonic Threshold : "Singular" contributions are dominant

- Take a look at the coefficients $z = M_H^2/\hat{s}$

  - LO

$$G_{ab}^{(0)}(z) = \delta_{ag}\delta_{bg}\ \delta(1-z)$$



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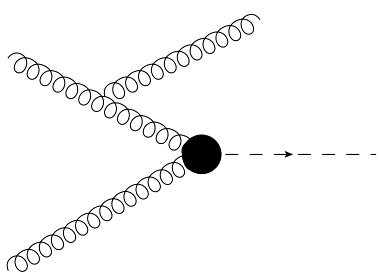

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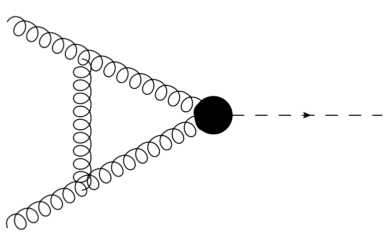

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- Partonic Threshold : "Singular" contributions are dominant

$G_{qg}^{(1)}$ and $G_{q\bar{q}}^{(1)}$: no singular contributions

- x-space not the best to look at "soft" approximations : distributions
- Natural space Mellin (also for resummation)

$$G_N = \int_0^1 dx\, x^{N-1} G(x) \qquad z \to 1 \;\Rightarrow\; N \to \infty$$

$$\left[\left(\frac{\ln(1-z)}{1-z}\right)_+\right]_N = \frac{1}{2}(\ln N + \gamma_E)^2 + \frac{\zeta(2)}{2} + \mathcal{O}(1/N)$$

$$[\delta(1-z)]_N = 1$$

$$[\ln(1-z)]_N = \frac{\ln N}{N} + \ldots$$

$$[z]_N = \mathcal{O}(1/N)$$

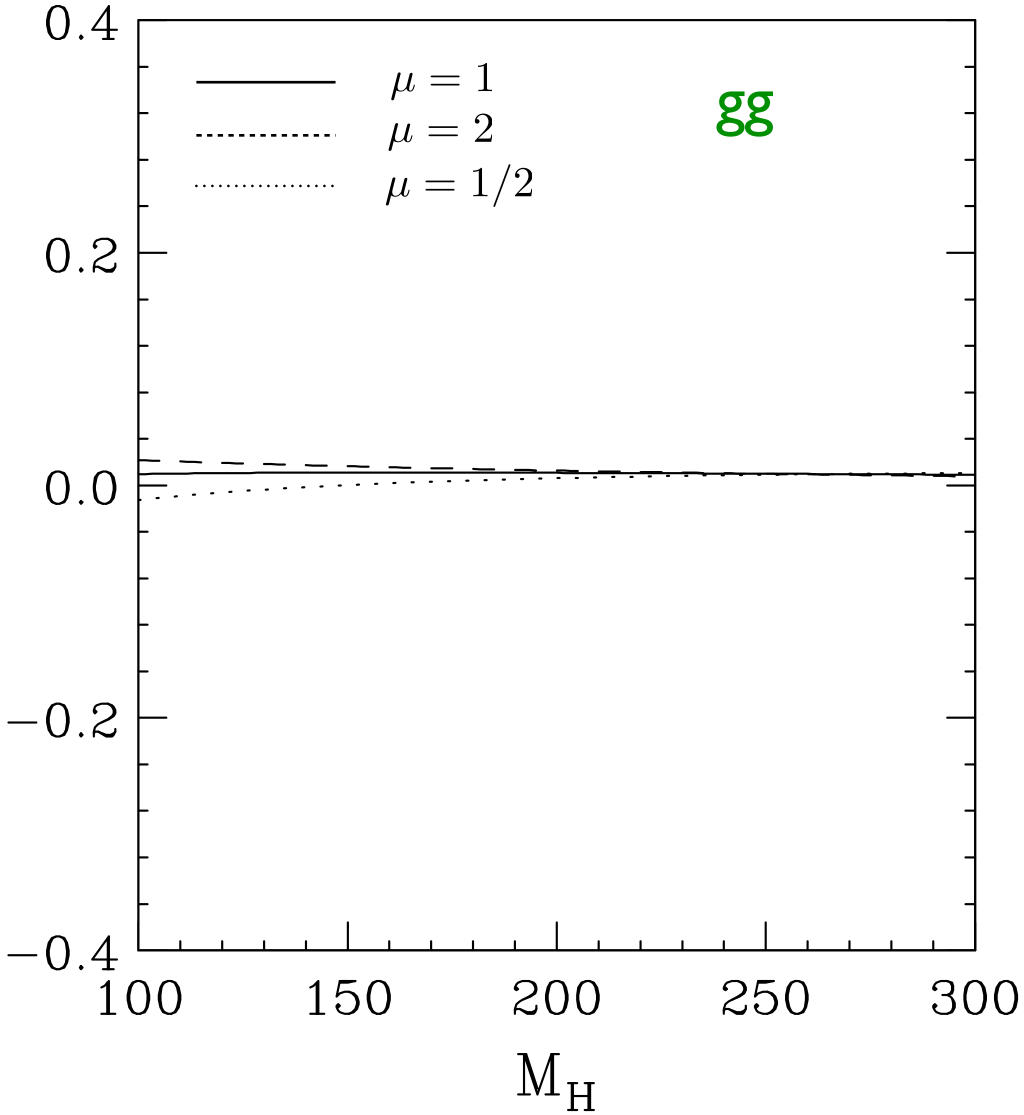
- Define 'Soft-Virtual' terms as those containing : $\ln^i N$ and constant not $\mathcal{O}(1/N)$
- 'Collinear' terms : $\frac{lnN}{N}$ *Leading collinear terms : Soft-Virtual-Collinear*
- 'Hard' terms : $\mathcal{O}(1/N)$ *small even for not very large N !*

- Check approximation gg

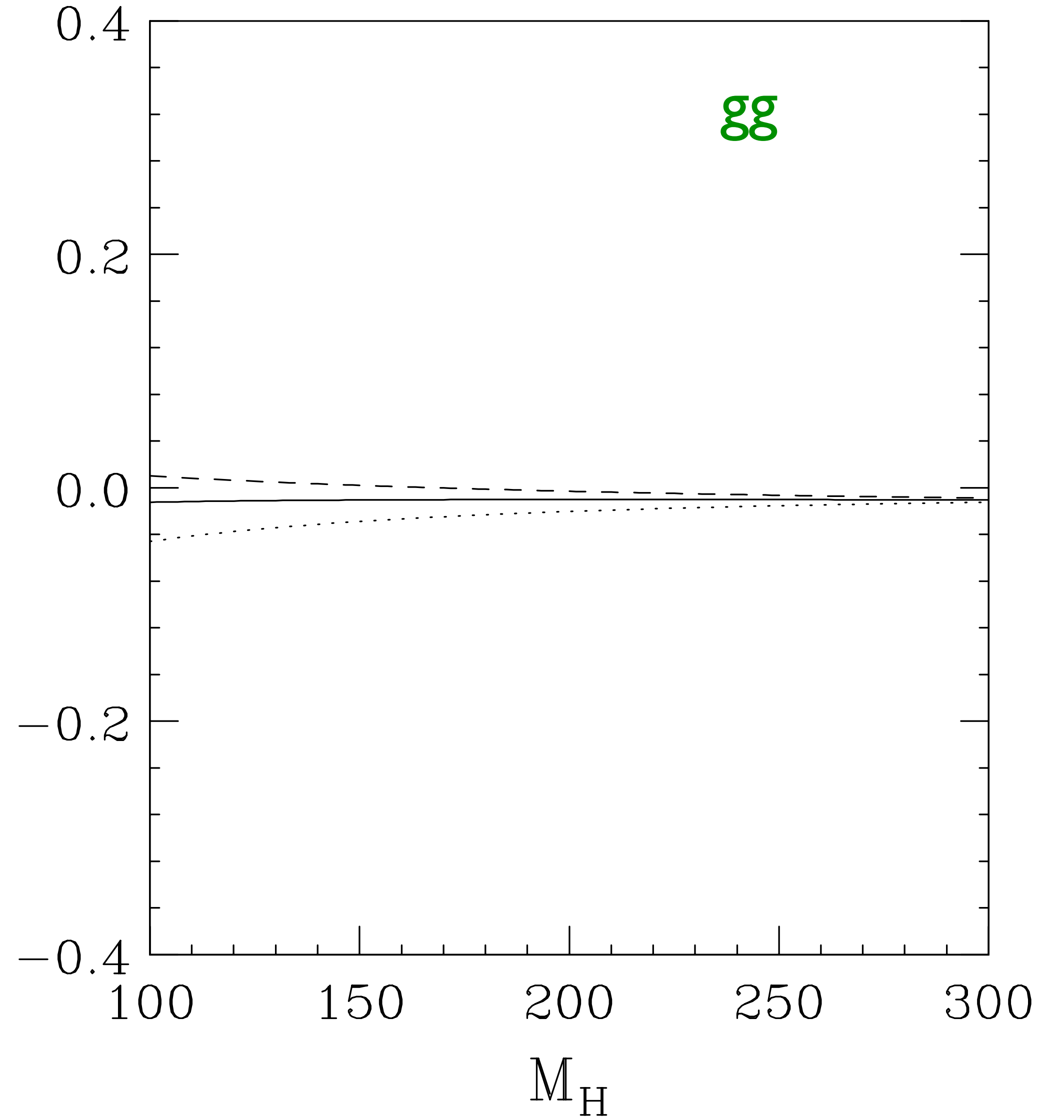
Tevatron MSTW2008

$$\Delta^{SV}(\mu) = \frac{\sigma^{SV}(\mu_F = \mu_R = \mu M_H) - \sigma(\mu_F = \mu_R = \mu M_H)}{\sigma(\mu_F = \mu_R = \mu M_H)}$$

NLO

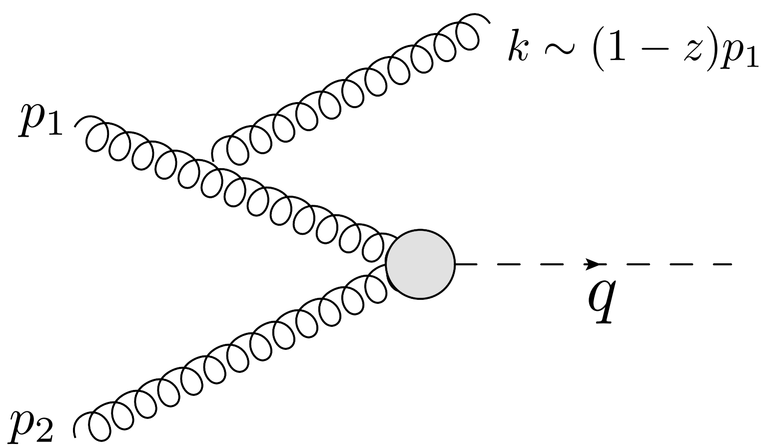


NNLO



- Reproduces gg channel at the % level : soft-virtual terms clearly dominate

- Not only identify dominant contributions : origin → prediction
- Logs originate from soft-gluon (collinear) emission : UNIVERSAL Factorization



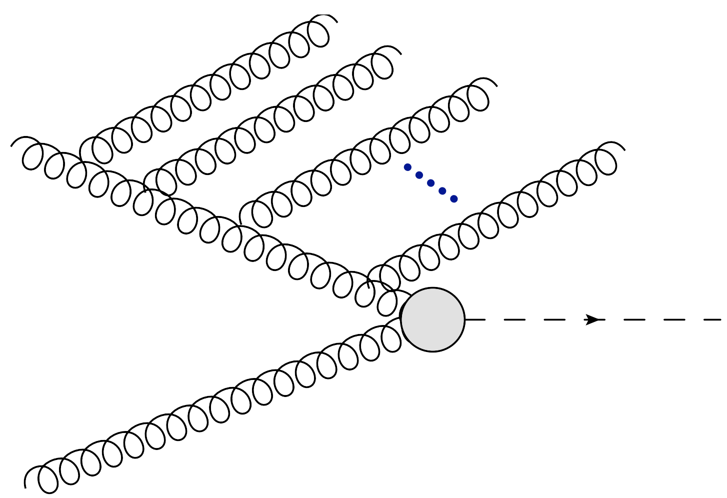
$$g^2 C_A \int \frac{d^3k}{(2\pi)^3 2E_k}\,\frac{2\,p_1\cdot p_2}{p_1\cdot q\; p_2\cdot q} \sim \alpha_s C_A \int \frac{dz}{1-z} \int^{(1-z)^2 M_H^2} \frac{dk_T^2}{k_T^2}$$

$z \longrightarrow 1$

soft

collinear

- Include multiple soft-gluon emission to all orders (to certain logarithmic accuracy)



Resummation

- Two logs appear at each order $\alpha_s^k \ln^{2k} N$ soft and collinear

- Resummation is achieved by showing that logarithmic contributions exponentiate

Sterman (1987); Catani, Trentadue (1989)

$$G^{(\mathrm{res})}_{gg,\,N} = \alpha_s^2 \;\; C_{gg}(\alpha_s) \;\; \Delta_N^H(\alpha_s, N)$$

Constant In N

Fully account for all Soft-virtual contributions

- Resumming is achieved by showing that logarithmic contributions exponentiate

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Constant In N

Fully account for all Soft-virtual contributions

- Sudakov radiative factor

$$\Delta_N^H(\alpha_s) = [\Delta_N^g(\alpha_s, N)]^2 \, \Delta_N^{(\mathrm{int})H}(\alpha_s, N)$$

soft-gluon collinear to parton $\Delta_N^g(\alpha_s, N) = \exp\left\{ \int_0^1 dz \, \frac{z^{N-1}-1}{1-z} \int_{\mu_F^2}^{(1-z)^2 M_H^2} \frac{dq^2}{q^2} \, A_g(\alpha_s(q^2)) \right\}$

soft-gluon at large angles $\Delta_N^{(\mathrm{int})H}(\alpha_s, N) = \exp\left\{ \int_0^1 dz \, \frac{z^{N-1}-1}{1-z} \; D_H(\alpha_s((1-z)^2 M_H^2)) \right\}$

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$$G^{(\mathrm{res})}_{gg,\,N} = \alpha_s^2 \; C_{gg}(\alpha_s) \; \Delta^H_N(\alpha_s, N)$$

Constant In N

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- Sudakov radiative factor

$$\Delta^H_N(\alpha_s) = [\Delta^g_N(\alpha_s, N)]^2 \, \Delta^{(\mathrm{int})H}_N(\alpha_s, N)$$

soft-gluon collinear to parton

$$\Delta^g_N(\alpha_s, N) = \exp\left\{ \int_0^1 dz \, \frac{z^{N-1}-1}{1-z} \int_{\mu_F^2}^{(1-z)^2 M_H^2} \frac{dq^2}{q^2} \, A_g(\alpha_s(q^2)) \right\}$$

soft-gluon at large angles

$$\Delta^{(\mathrm{int})H}_N(\alpha_s, N) = \exp\left\{ \int_0^1 dz \, \frac{z^{N-1}-1}{1-z} \; D_H(\alpha_s((1-z)^2 M_H^2)) \right\}$$

- Coefficients have a expansion free of logs

$$C_{gg} = 1 + \frac{\alpha_s}{\pi} C^{(1)}_{gg} + \left(\frac{\alpha_s}{\pi}\right)^2 C^{(2)}_{gg} + \ldots$$ Process dependent

soft term of AP kernel $A_g = \frac{\alpha_s}{\pi} A^{(1)}_g + \left(\frac{\alpha_s}{\pi}\right)^2 A^{(2)}_g + \left(\frac{\alpha_s}{\pi}\right)^3 A^{(3)}_g + \ldots$ Universal

$$D_H = \left(\frac{\alpha_s}{\pi}\right)^2 D^{(2)}_H + \ldots$$ Process dependent

Parisi (1980); Laenen, Sterman (1990); Eynck, Laenen, Magnea (2003); Ahrens, Becher, Neubert, Yang (2008)

- Some constant terms might exponentiate, but better keep the expansion well organized → constant in normalization C

$$\ln \Delta_N^H \sim \alpha_s^n \ln^{n+1} N + \alpha_s^n \ln^n N + \alpha_s^n \ln^{n-1} N + \ldots$$

systematic expansion towers of logs

LL	NLL	NNLL
1	$C^{(1)}$	$C^{(2)}$

← $\alpha_s^k \ln^{2k-4} N$ in σ

full accuracy at NNLO (k=2)

Parisi (1980); Laenen, Sterman (1990); Eynck, Laenen, Magnea (2003); Ahrens, Becher, Neubert, Yang (2008)

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LL	NLL	NNLL
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systematic expansion towers of logs

$\alpha_s^k \ln^{2k-4} N$ in σ

full accuracy at NNLO (k=2)

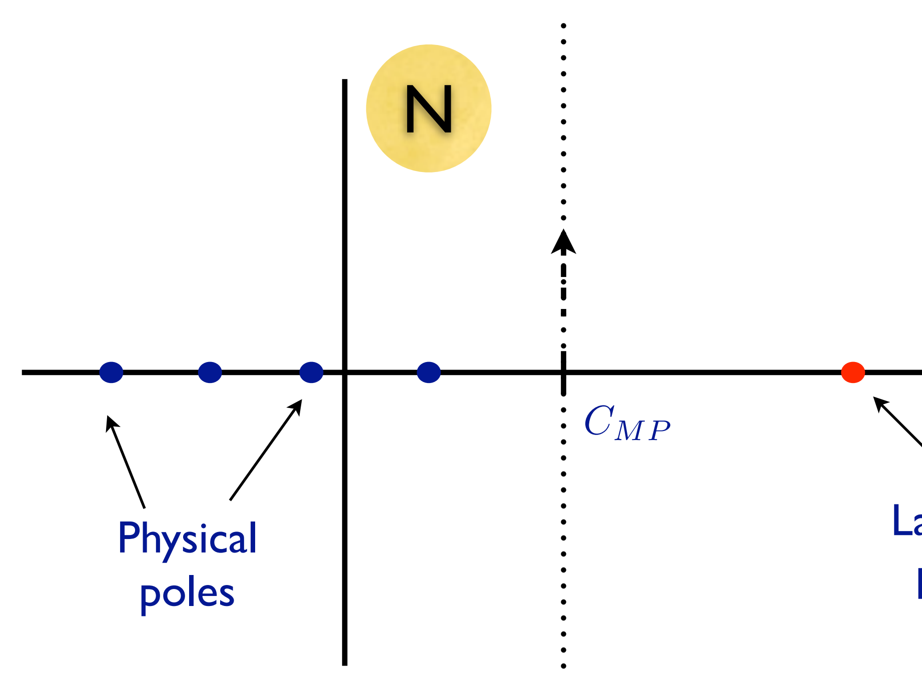
$$\ln \Delta_N^H = \ln N \, g^{(1)}(\lambda) + g^{(2)}(\lambda) + \alpha_s \, g^{(3)}(\lambda) + \ldots \qquad \lambda = \alpha_s \beta_0 \ln N$$

- Back from N space: Mellin Inverse

$$F(x) = \int_{C_{MP}-i\infty}^{C_{MP}+i\infty} \frac{dN}{2\pi i} \, x^{-N} \, F(N)$$

Landau pole $z \to 1$

$$\exp\left\{ \int_0^1 dz \, \frac{z^{N-1}-1}{1-z} \int_{\mu_F^2}^{(1-z)^2 M_H^2} \frac{dq^2}{q^2} \, A_g(\alpha_s(q^2)) \right\}$$



- Implement "Minimal Prescription" $\lambda \to 1/2$ pole at very large N

Catani, Mangano, Nason, Trentadue (1996)

- Profit from fixed order expansion to provide the best approach : matching

$$\sigma^{res} = \sigma^{N^k LL} + \underbrace{\sigma^{N^k LO} - \sigma^{N^k LL}}|_{N^k LO}$$

logs resummed

free of logs :`Hard terms'

- Best precision : NNLL+NNLO $g^{(1)}, g^{(2)}, g^{(3)}, C^{(1)}, C^{(2)}$
  - Leading collinear term $C^{(1)} \to C^{(1)} + 2A^{(1)} \frac{\ln N}{N}$ ➡ $\alpha_s^k \frac{\ln^{2k-1} N}{N}$

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logs resummed — free of logs :`Hard terms'

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- What about NNNLL ?

  ✓ Exponent already known $g^{(4)} \to \alpha_s^2 (\alpha_s \ln N)^n$ Moch, Vermaseren, Vogt (2005)

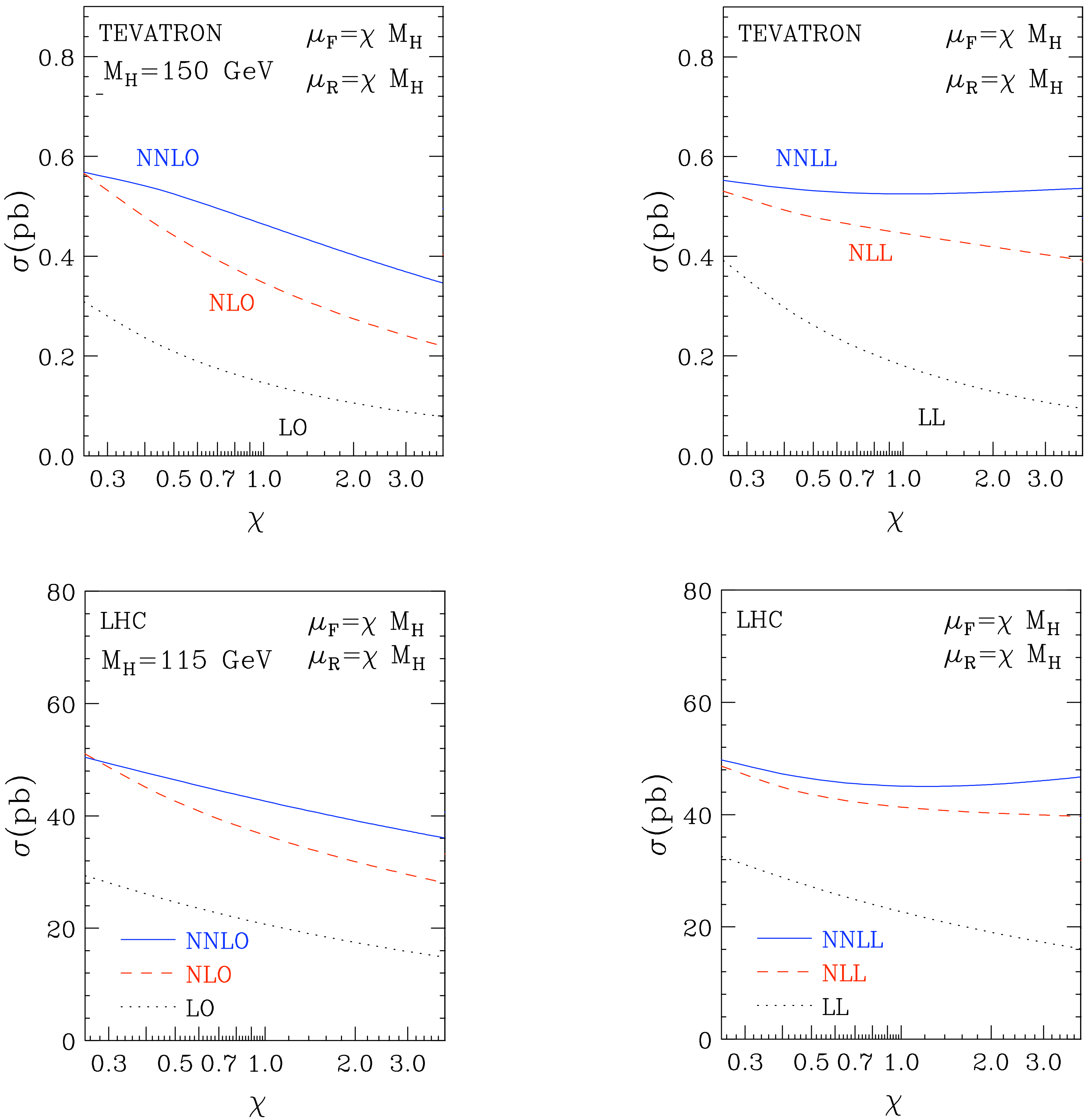
  $C^{(3)}$ unknown yet (requires 3-loop form factor)

  $$\alpha_s^3 C^{(3)} \exp g^{(1)} \to \alpha_s^2 (\alpha_s \ln N)(\alpha_s \ln N)^n$$

  NNNLO missing for matching

- Control of factorization and renormalization scale dependence to same logarithmic accuracy

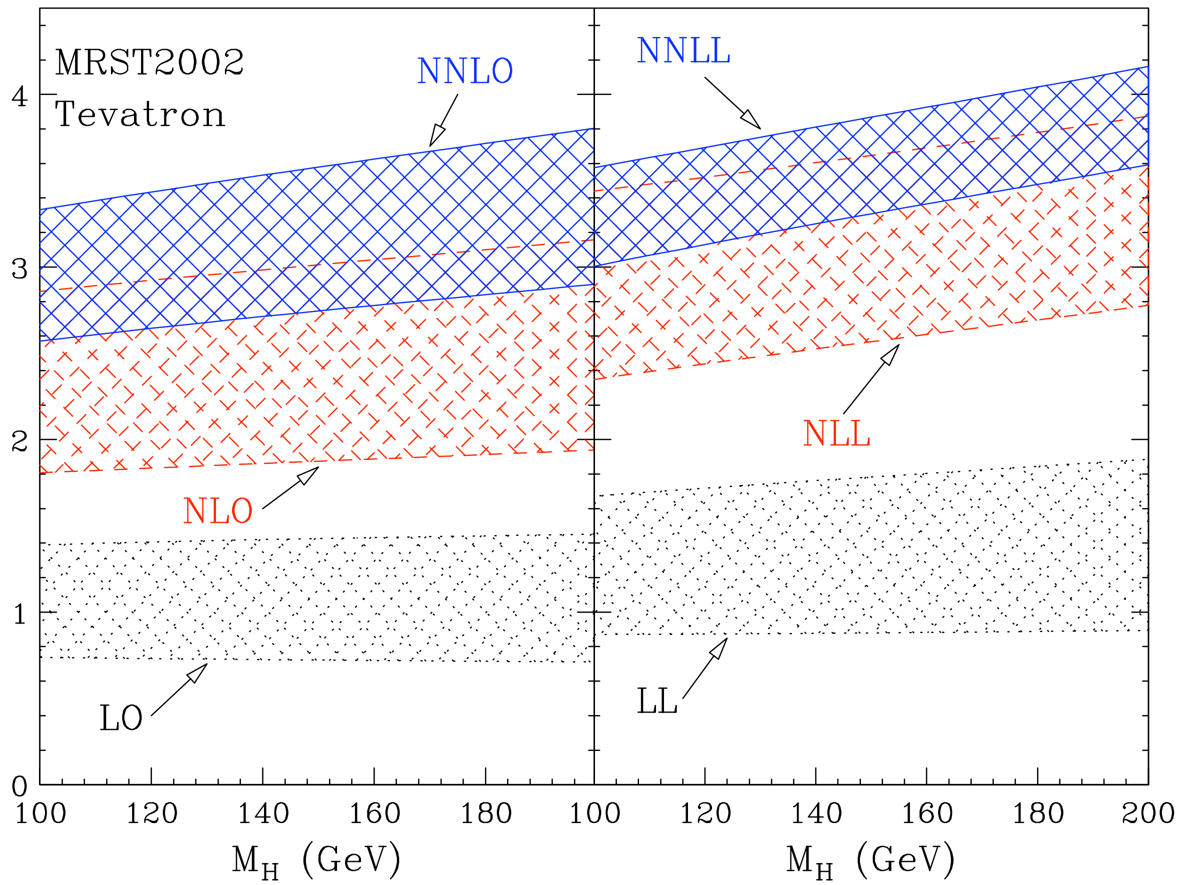
Catani, deF, Grazzini, Nason (2003)



- Resummation : reduction in scale dependence

Resummation : K-factors

Catani, deF, Grazzini, Nason (2003)



Tevatron

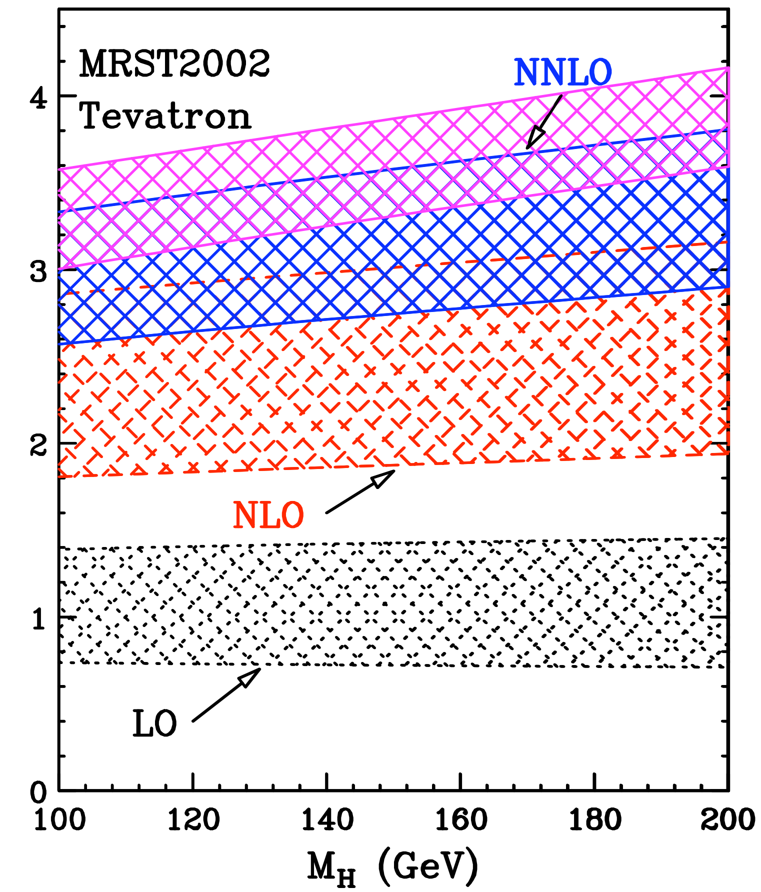
NNLL effect

+ 12/15 %

$$\mu_{F,R} = \chi_{F,R} M_H$$

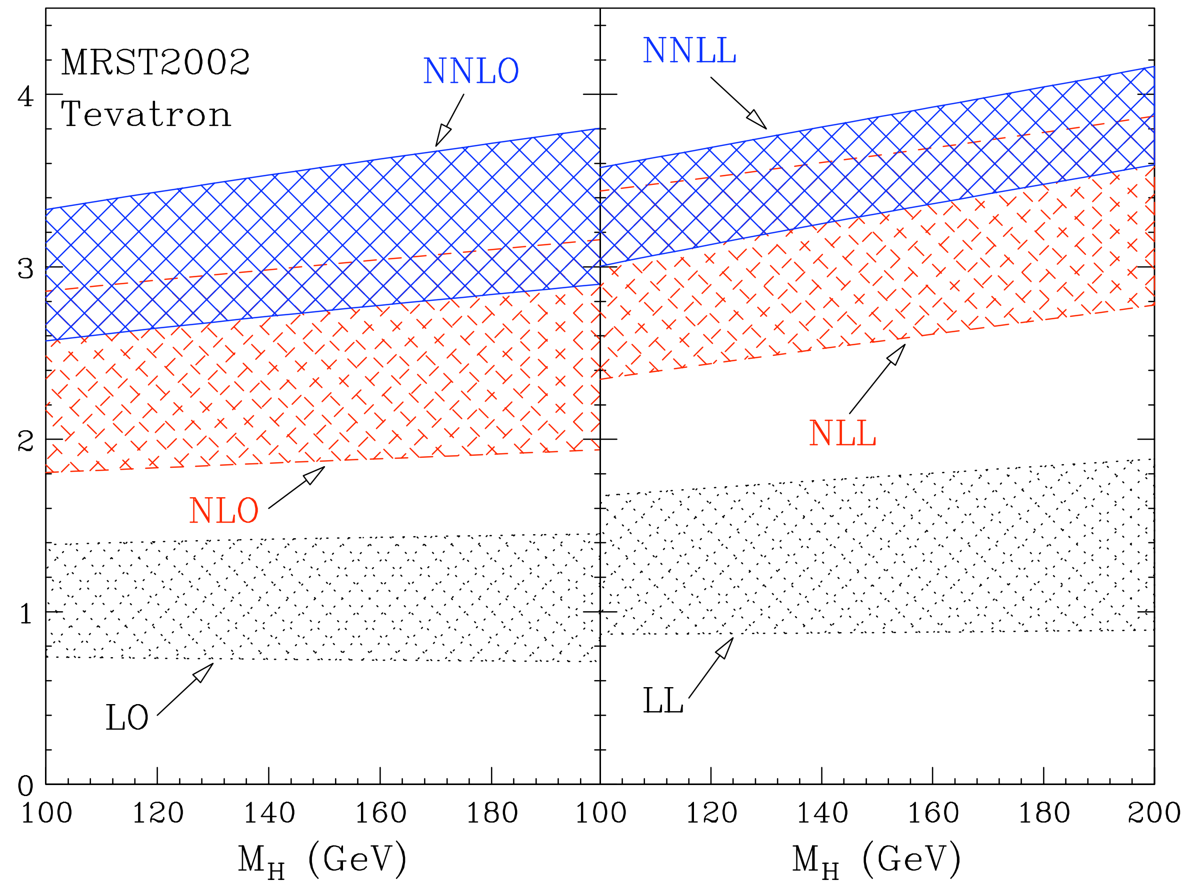
$$0.5 \le \chi_{F,R} \le 2$$

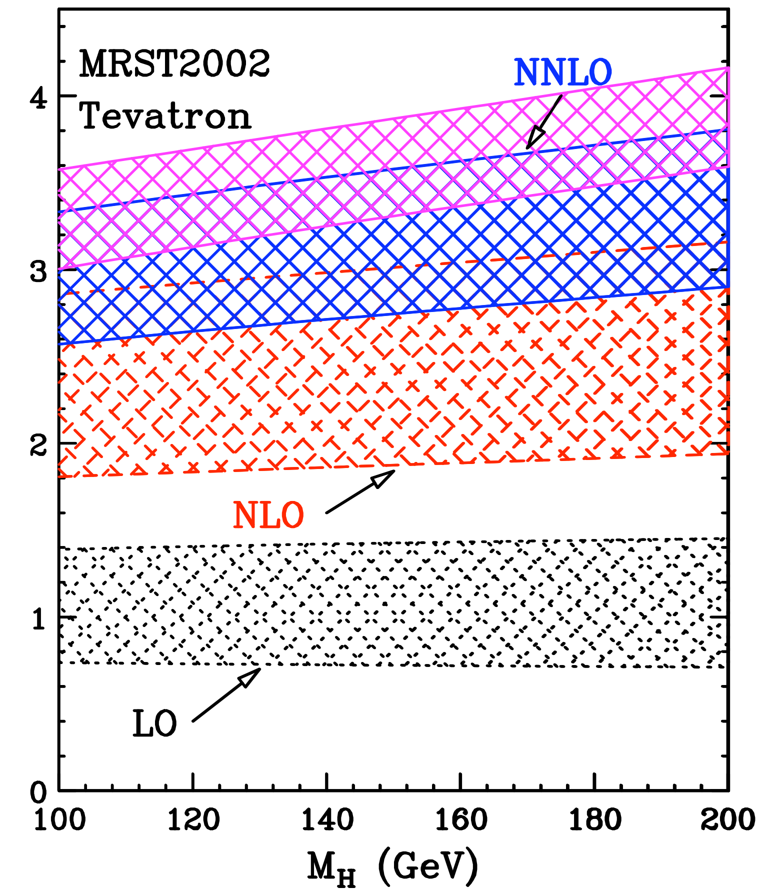
$$0.5 \le \frac{\chi_F}{\chi_R} \le 2$$



Resummation : K-factors

Catani, deF, Grazzini, Nason (2003)





Tevatron

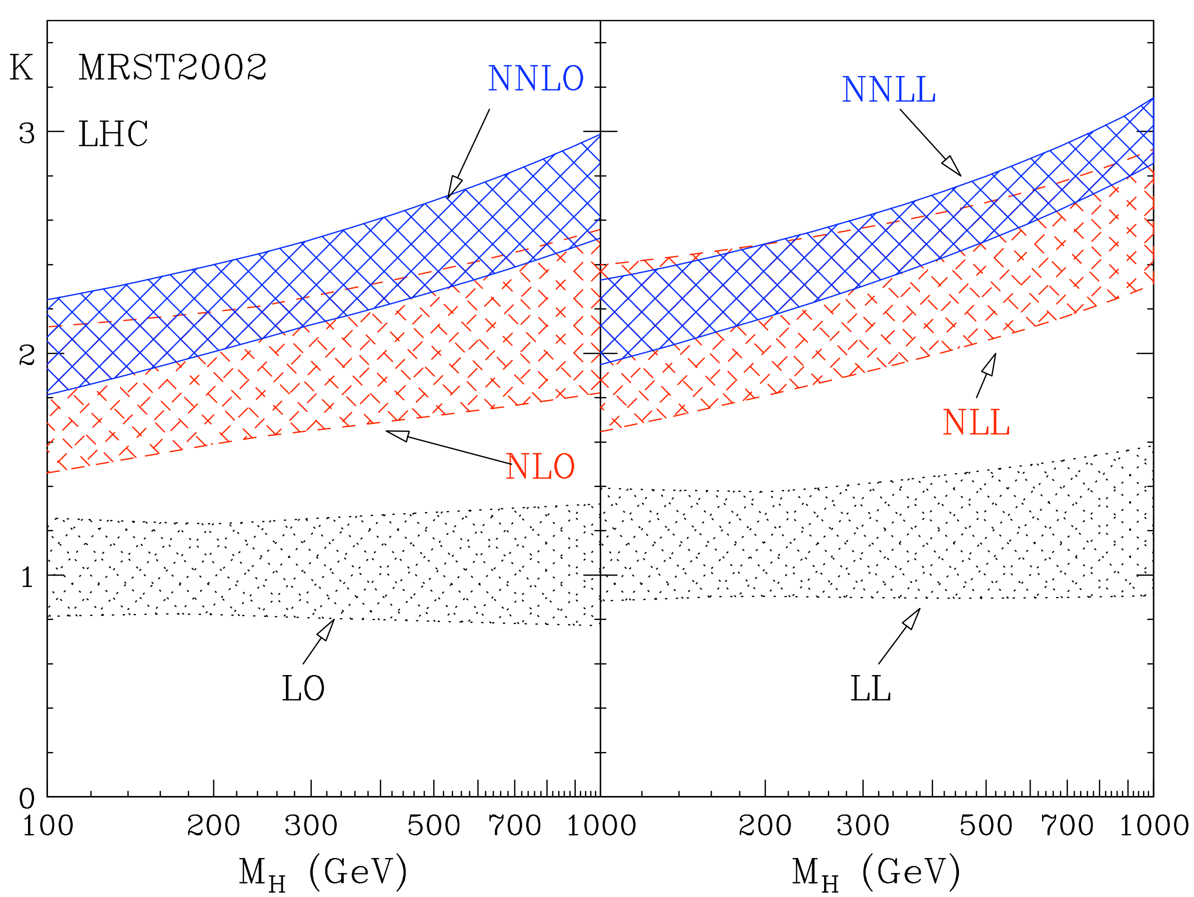
NNLL effect

+ 12/15 %

$$\mu_{F,R} = \chi_{F,R}\, M_H$$

$$0.5 \leq \chi_{F,R} \leq 2$$

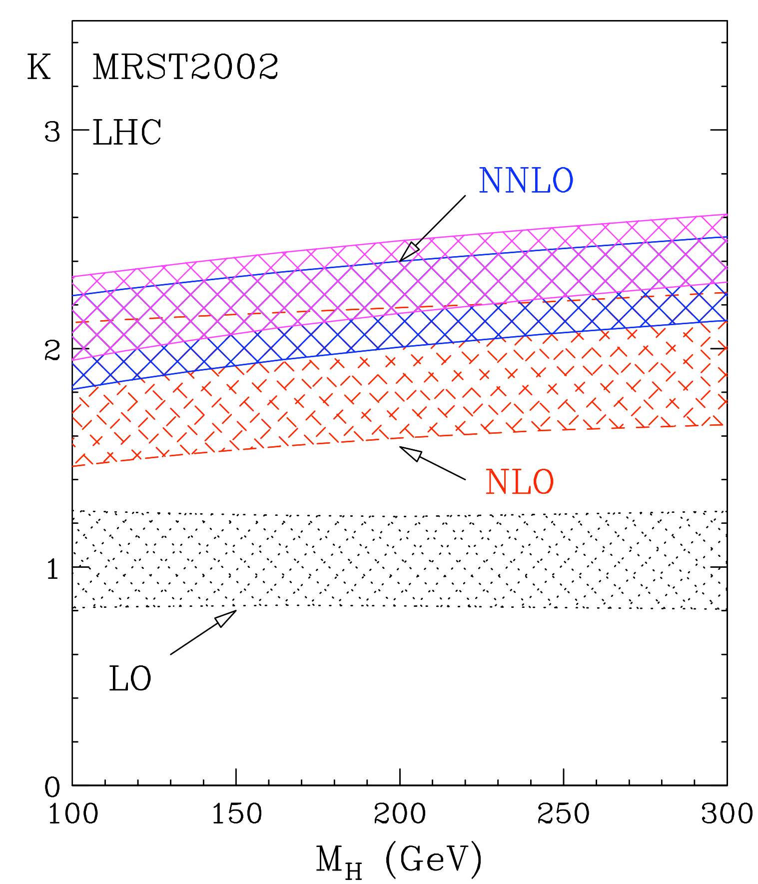
$$0.5 \leq \frac{\chi_F}{\chi_R} \leq 2$$



LHC

NNLL effect

+ 6 %



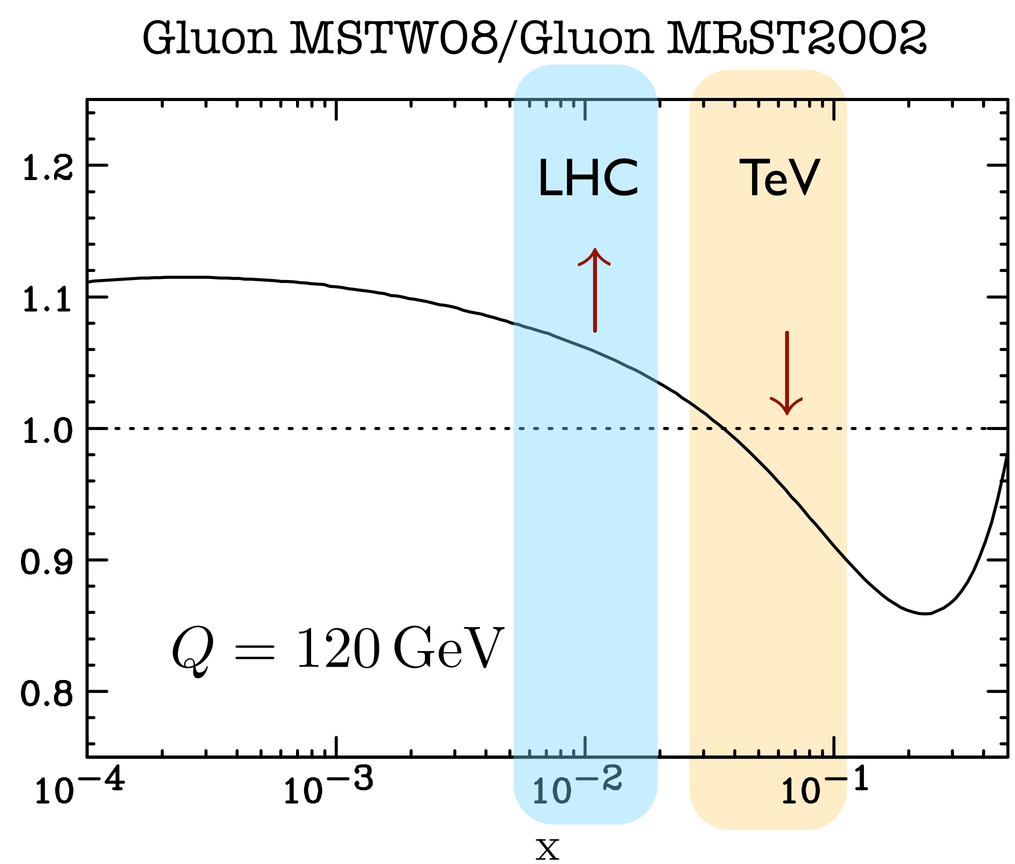
Update on Higgs Cross-section

- New NNLO pdfs : MRST2002 → MSTW2008

  - Large modifications in the gluon pdf $\uparrow\downarrow$
  - Change in coupling constant

$$\alpha_s(M_Z) \quad 0.1154 \to 0.1171$$

$$\sigma \sim \mathcal{O}(\alpha_s^3) \quad \uparrow \sim 5\%$$



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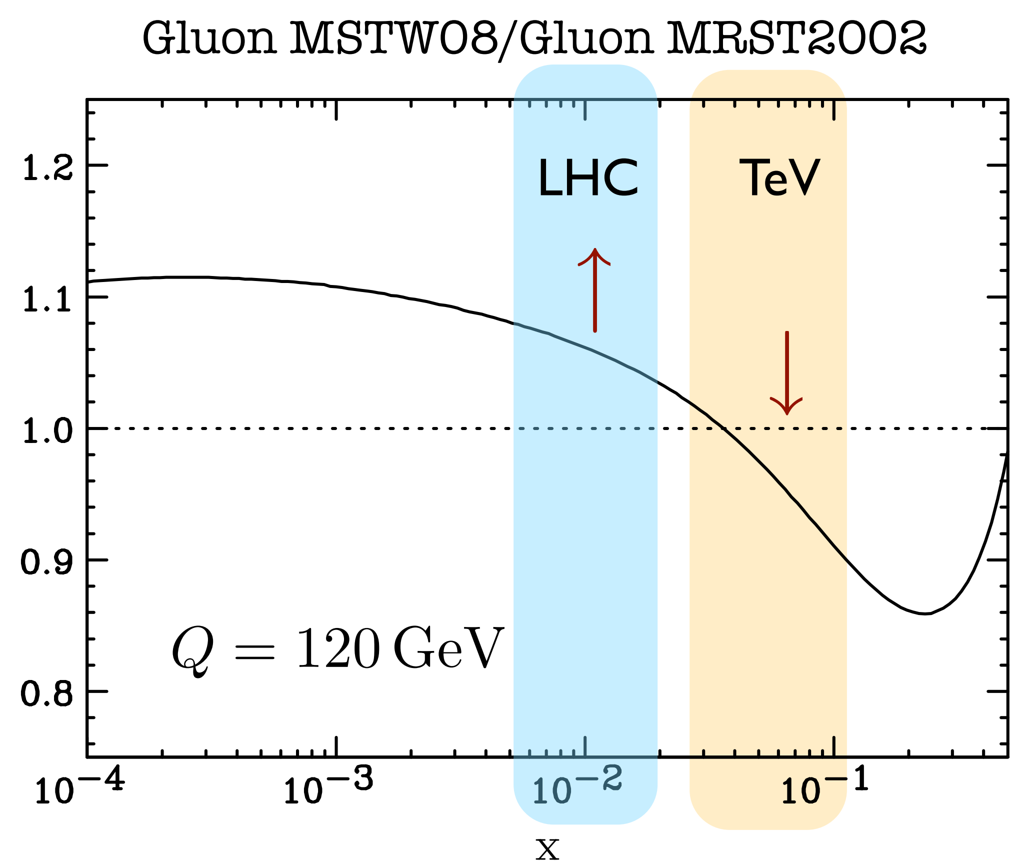
- New NNLO pdfs : MRST2002 → MSTW2008

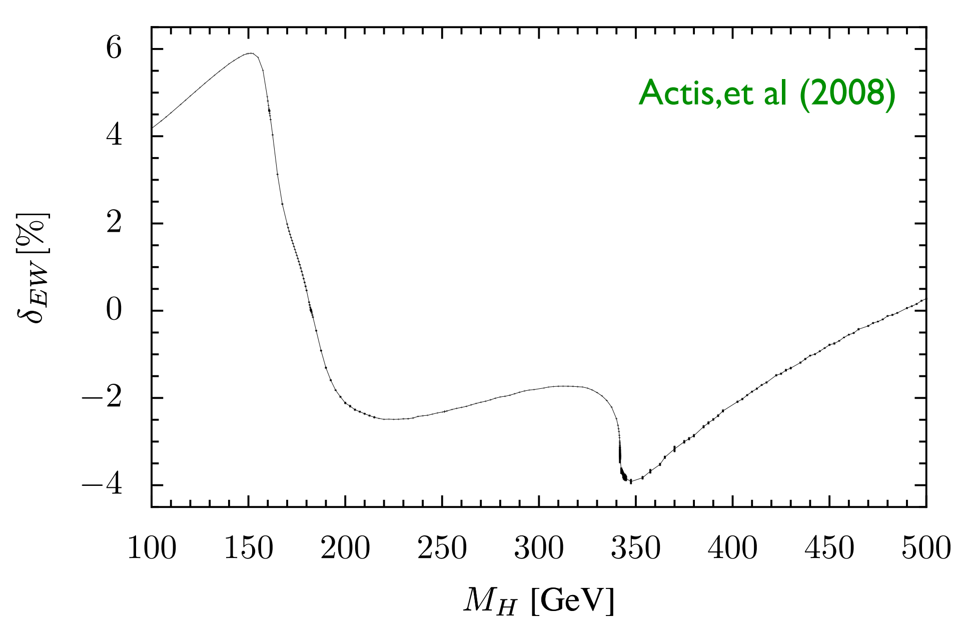


  - Large modifications in the gluon pdf ↑↓
  - Change in coupling constant

$$\alpha_s(M_Z) \quad 0.1154 \to 0.1171$$

$$\sigma \sim \mathcal{O}(\alpha_s^3) \quad \uparrow \sim 5\%$$

- Two-loop ElectroWeak corrections computed



Aglietti, Bonciani, Degrassi, Vicini (2004)
Degrassi, Maltoni (2004)
Actis, Passarino, Sturm, Uccirati (2008)
Anastasiou, Boughezal, Petriello (2008)

Update on Higgs Cross-section

- Update to MSTW 2008 NNLO distributions (pdf uncertainties)

- Use effective Lagrangian for top quark contribution and normalize to Born result

- Core of the cross-section: top quark contribution computed to NNLL+NNLO accuracy

- Bottom contribution and top-bottom interference exact at NLO↑ $\sigma^{QCD} = \sigma_{top}^{NNLL+NNLO} + \sigma_{bottom}^{NLO}$ Anastasiou, Boughezal, Petriello (2008)

- Include EW effects assuming complete factorization

$$\sigma^{best} = (1 + \delta_{EW})\, \sigma^{QCD}$$

Actis, Passarino, Sturm, Uccirati (2008)

- Update masses $m_t = 170.9\,\mathrm{GeV}$ $m_b = 4.8\,\mathrm{GeV}$

Tevatron

$2003 \rightarrow 2009$

$m_H = 115\,\text{GeV} \quad +9\%$

$m_H = 200\,\text{GeV} \quad -9\%$

$m_H = 170\,\text{GeV} \quad -2\%$

m_H	σ^{best}	Scale	PDF
100	1.861	$^{+0.192}_{-0.174}$	$^{+0.094}_{-0.101}$
105	1.618	$^{+0.165}_{-0.149}$	$^{+0.085}_{-0.091}$
110	1.413	$^{+0.142}_{-0.127}$	$^{+0.077}_{-0.083}$
115	1.240	$^{+0.123}_{-0.110}$	$^{+0.070}_{-0.075}$
120	1.093	$^{+0.107}_{-0.095}$	$^{+0.065}_{-0.069}$
125	0.967	$^{+0.094}_{-0.083}$	$^{+0.059}_{-0.063}$
130	0.858	$^{+0.082}_{-0.072}$	$^{+0.054}_{-0.058}$
135	0.764	$^{+0.073}_{-0.063}$	$^{+0.050}_{-0.053}$
140	0.682	$^{+0.065}_{-0.056}$	$^{+0.046}_{-0.049}$
145	0.611	$^{+0.057}_{-0.049}$	$^{+0.042}_{-0.045}$
150	0.548	$^{+0.051}_{-0.044}$	$^{+0.039}_{-0.042}$

m_H	σ^{best}	Scale	PDF
155	0.492	$^{+0.045}_{-0.039}$	$^{+0.036}_{-0.038}$
160	0.439	$^{+0.040}_{-0.034}$	$^{+0.033}_{-0.035}$
165	0.389	$^{+0.036}_{-0.030}$	$^{+0.030}_{-0.032}$
170	0.349	$^{+0.032}_{-0.027}$	$^{+0.028}_{-0.029}$
175	0.314	$^{+0.029}_{-0.024}$	$^{+0.026}_{-0.027}$
180	0.283	$^{+0.026}_{-0.021}$	$^{+0.024}_{-0.025}$
185	0.255	$^{+0.023}_{-0.019}$	$^{+0.022}_{-0.023}$
190	0.231	$^{+0.021}_{-0.017}$	$^{+0.020}_{-0.021}$
195	0.210	$^{+0.019}_{-0.015}$	$^{+0.019}_{-0.020}$
200	0.192	$^{+0.017}_{-0.014}$	$^{+0.018}_{-0.019}$

TH uncertainties (pert/non-pert.)

- Scale dependence ± 9 to $\pm 10\%$

$\mu_{F,R} = \chi_{F,R}\, M_H$

$0.5 \leq \chi_{F,R} \leq 2$

$0.5 \leq \dfrac{\chi_F}{\chi_R} \leq 2$

(NNLO $\sim 14\%$)

- 'PDF uncertainty' ± 6 to $\pm 10\%$
- 'EW uncertainty' : partial vs complete factorization -3 to $+2\%$

LHC

$2003 \rightarrow 2009$

$m_H = 115\,\text{GeV}$ $+30\%$

$m_H = 300\,\text{GeV}$ $+9\%$

mostly pdf and coupling

m_H	σ^{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	$^{+2.60}_{-2.79}$	$^{+0.73}_{-0.97}$

m_H	σ^{best}	Scale	PDF
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	$^{+1.11}_{-1.22}$	$^{+0.39}_{-0.48}$

m_H	σ^{best}	Scale	PDF
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	$^{+0.71}_{-0.78}$	$^{+0.32}_{-0.36}$

TH uncertainties

- Scale dependence ± 10 to $\pm 7\%$

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$$0.5 \leq \chi_{F,R} \leq 2$$
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- 'PDF uncertainty' $\pm 3\%$

- 'EW uncertainty' : partial vs complete factorization -3 to $+1\%$

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- ‘PDF uncertainty’ $\pm 3\%$

- ‘EW uncertainty’ : partial vs complete factorization -3 to $+1\%$

- Caution about ‘PDF uncertainty’

    Real PDF uncertainty might exceed ‘error’ bands

    ✓ from 2002 to 2008 many changes (NNLO kernels)

    - but check from 2006 to 2008

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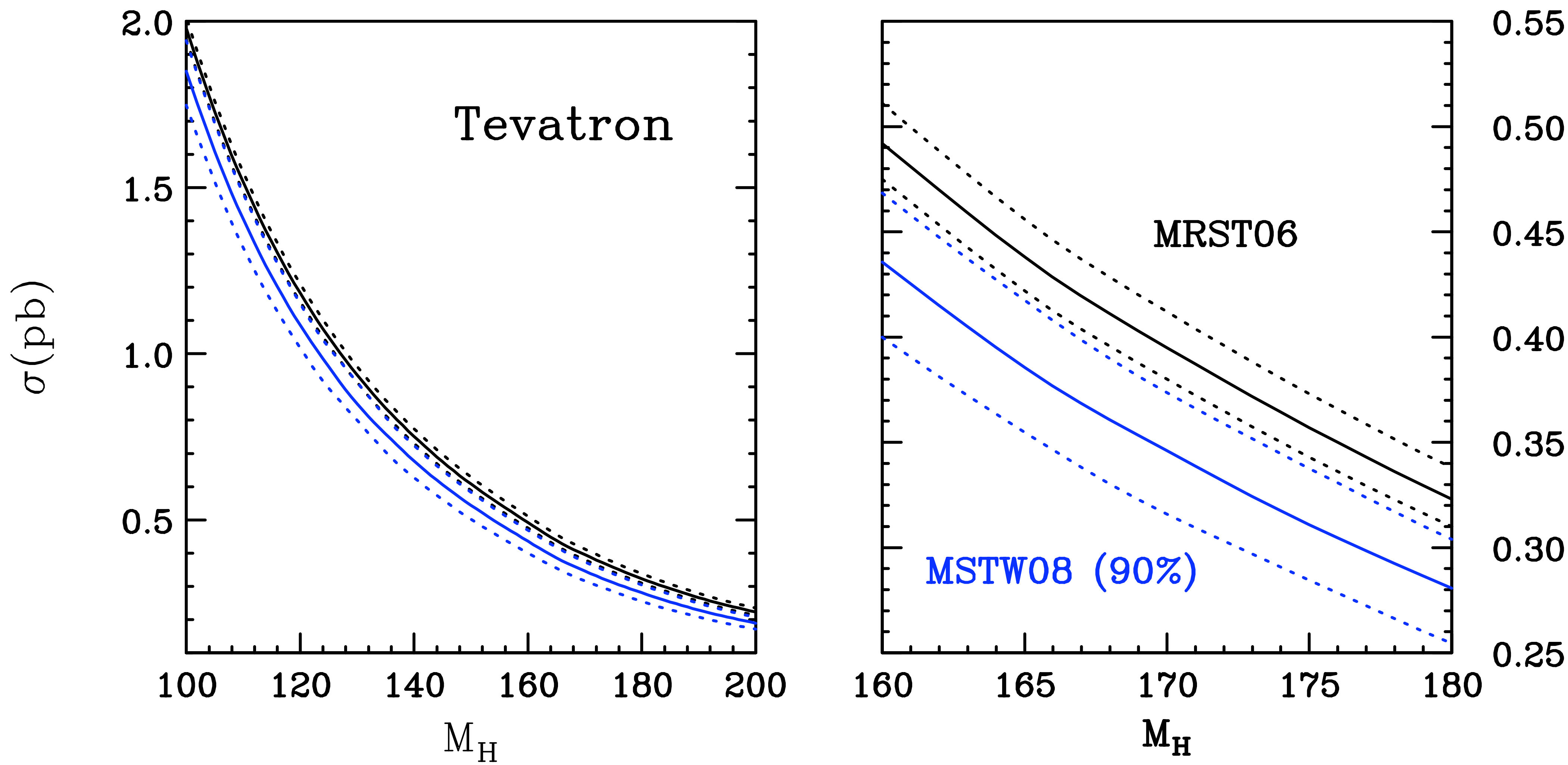

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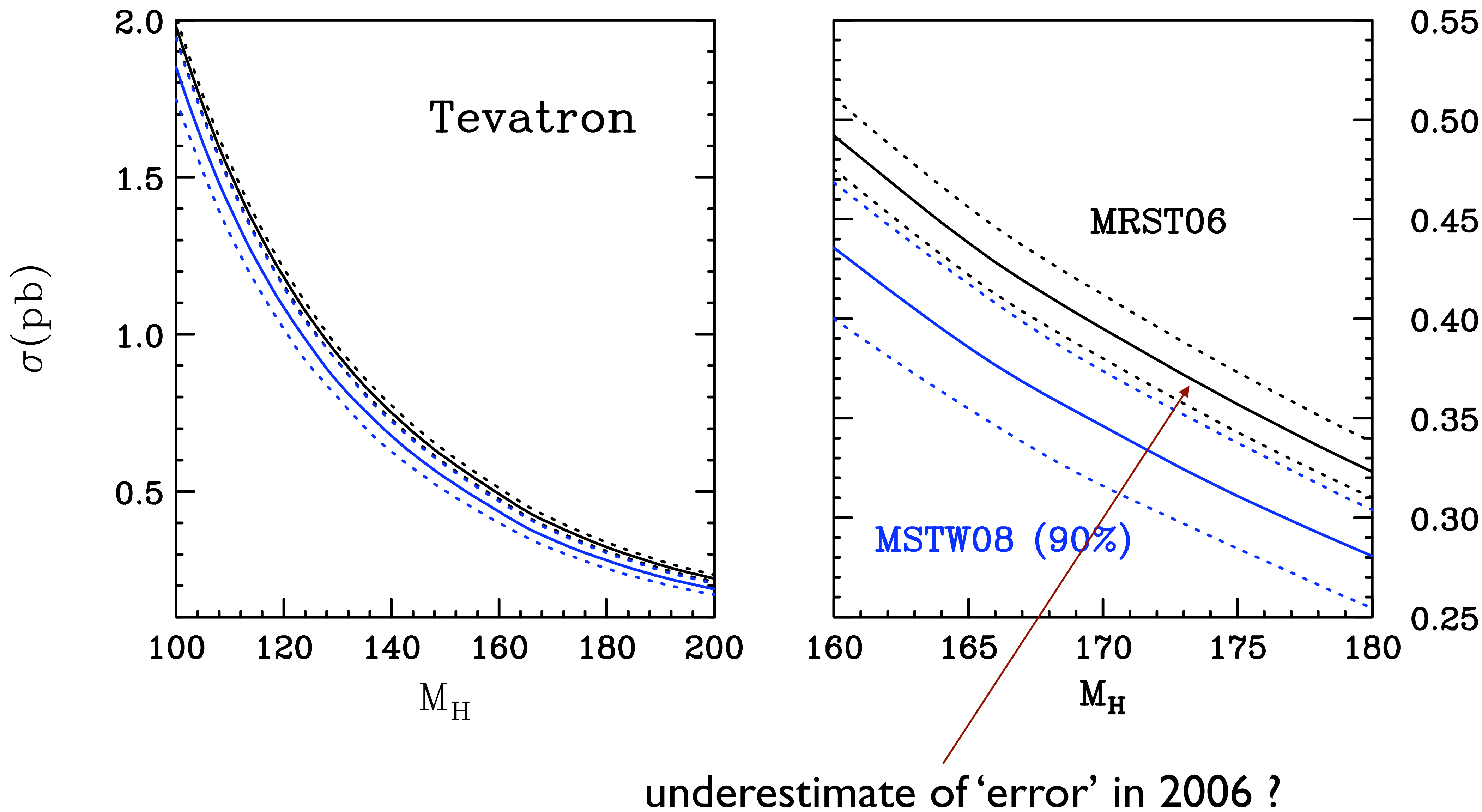

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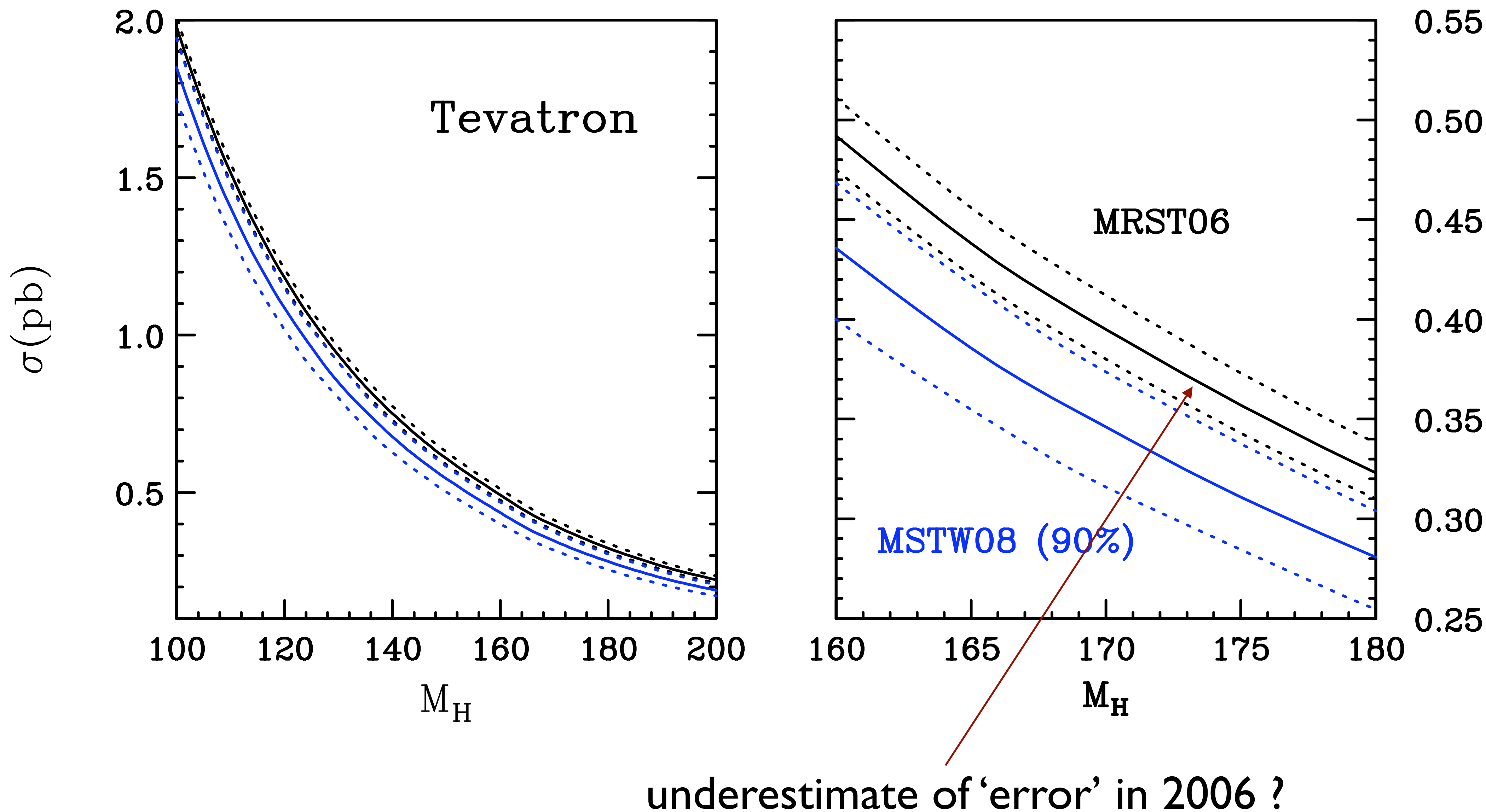

- Results very similar to those by Anastasiou, Boughezal, Petriello (2008)
  - Tevatron $\Delta \lesssim 2.5\%$

Summary

- Resummation provides a way to improve the calculation for Higgs cross-section
- NNLL+NNLO precision for gluon fusion
- Update: EW corrections, new pdfs, bottom@NLO
- Update: significant modifications at the LHC
- Update: non-negligible change at Tevatron
- Uncertainties : take into account for Higgs mass limits

~ 10% from scale dependence

pdf uncertainty not trivial ! α_s?