Top quark production at Tevatron and LHC
– *precision issues* –

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In a nutshell

What this talk will not tell you:

- We have the complete NNLO QCD result for top quark hadro-production.

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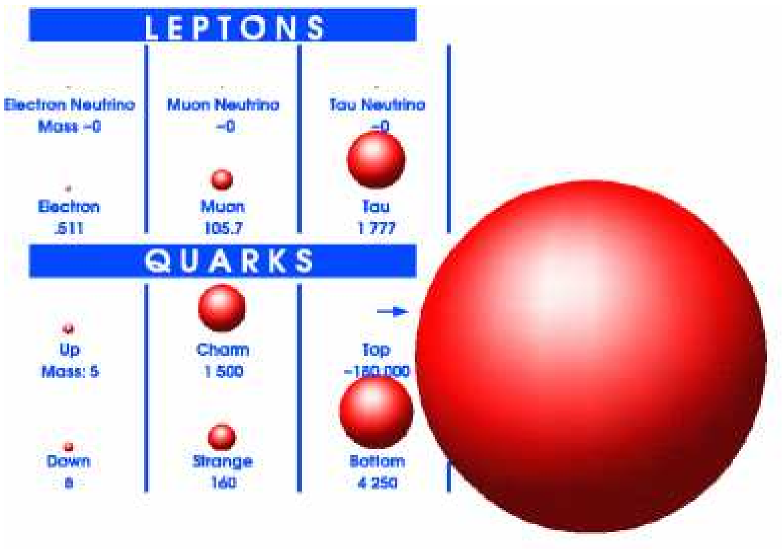
What this talk will tell you:

- Important parts of the NNLO QCD result are known – and they contribute in the entire phase-space.
- We have presently the best phenomenological prediction.

Plan

- Some new results on the heaviest elementary particle



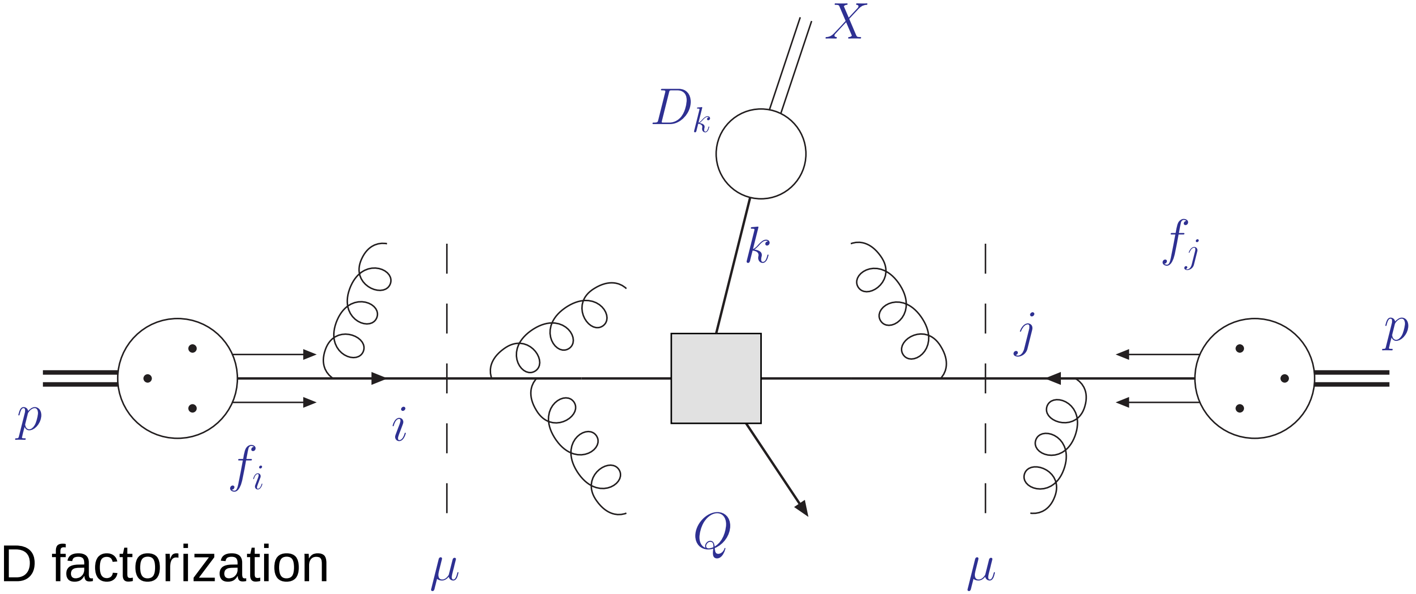
- Report based on recent work done in collaboration with
  - P. Uwer on arXiv:0804.1476 and on arXiv:0807.2794
  - Y. Kiyo, J.H. Kühn, M. Steinhauser and P. Uwer on arXiv:0812.0919
  - U. Langenfeld on arXiv:0901.0802
  - U. Langenfeld and P. Uwer to appear

Proton colliders

- Tevatron: energy frontier at $\sqrt{S} = 1.96$TeV
  top quark discovery
- LHC: in comissioning phase
  Higgs boson search at highest energies: $\sqrt{S} = 14$TeV

Perturbative QCD at colliders

- Hard hadron-hadron scattering
  - constituent partons from each incoming hadron interact at short



- QCD factorization
  - separate sensitivity to dynamics from different scales

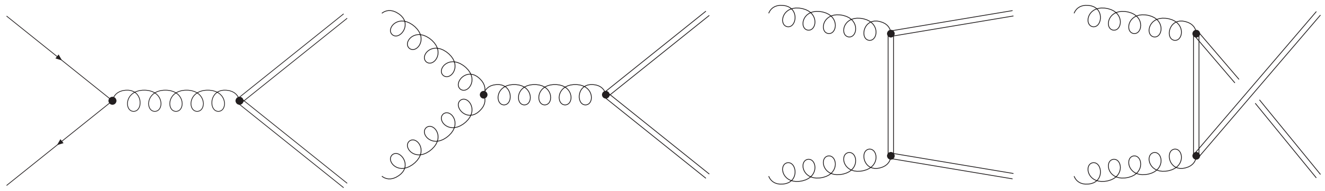
$$\sigma_{pp\to X} = \sum_{ijk} f_i(\mu^2) \otimes f_j(\mu^2) \otimes \hat{\sigma}_{ij\to k}\left(\alpha_s(\mu^2), Q^2, \mu^2\right) \otimes D_{k\to X}(\mu^2)$$

  - factorization scale μ, subprocess cross section $\hat{\sigma}_{ij\to k}$ for parton types i, j and hadronic final state X

Top quark production

- Leading order Feynman diagrams

$$q + \bar{q} \longrightarrow Q + \bar{Q}$$
$$g + g \longrightarrow Q + \bar{Q}$$



- NLO in QCD Nason, Dawson, Ellis ‘88; Beenakker, Smith, van Neerven ‘89; Mangano, Nason, Ridolfi ‘92; Bernreuther, Brandenburg, Si, Uwer ‘04; Mitov, Czakon ‘08; . . .
  - accurate to $\mathcal{O}(15\%)$ at LHC
- Much activity towards higher orders in QCD
  - one-loop squared terms (NLO $\times$ NLO) Anastasiou, Mert Aybat ‘08; Kniehl, Merebashvili, Körner, Rogal ‘08
  - analytic two-loop fermionic corrections for $q\bar{q} \to t\bar{t}$ Bonciani, Ferroglia, Gehrmann, Maitre, Studerus ‘08
  - numerical result for two-loop virtual $q\bar{q} \to t\bar{t}$ Czakon ‘08

Strategy

- First steps towards higher orders in QCD: explore limits

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Small mass limit

- Study of massive QCD amplitudes in limit $m \to 0$
  - look at soft and collinear limits
  - exploit relation of massive to massless amplitudes
- Two-loop virtual corrections to $\mathrm{q\bar{q}} \to \mathrm{t\bar{t}}$ and $\mathrm{gg} \to \mathrm{t\bar{t}}$ in small-mass limit $m^2 \ll s, t, u$ S.M., Czakon, Mitov '07

Threshold resummation

- Partonic threshold $s \simeq 4m^2$
  - Sudakov-type logarithms $\ln \beta$ with velocity of heavy quark $\beta = \sqrt{1 - 4m^2/s}$
  - long history of resummation Kidonakis, Sterman '97; Bonciani, Catani, Mangano, Nason '98; Kidonakis, Laenen, S.M., Vogt '01; ...

Threshold resummation

- Threshold at $s \simeq 4m_t^2$
  - parton cross section exhibit Sudakov-type logarithms $\ln(\beta)$ with velocity of heavy quark $\beta = \sqrt{1 - 4m_t^2/s}$ at n$^{\rm th}$-order
- All order resummation of large logarithms $\alpha_s^n \ln^{2n}(\beta) \longleftrightarrow \alpha_s^n \ln^{2n}(N)$
  - resummation in Mellin space (renormalization group equation)
- Resummed cross section in Mellin space

$$\frac{\hat{\sigma}^N_{ij,\,I}(m^2)}{\hat{\sigma}^{(0),N}_{ij,\,I}(m^2)} = g^0_{ij,\,I}(m^2) \cdot \exp\left(G^{N+1}_{ij,\,I}(m^2)\right) + \mathcal{O}(N^{-1} \ln^n N)$$

  - exponent in singlet-octet color basis decomposition $I = 1, 8$

$$G^N_{q\bar{q}/gg,\,I} \quad = \quad G^N_{\rm DY/Higgs} + \delta_{I,8} G^N_{Q\bar{Q}}$$

- Renormalization group equations for functions $G^N_{\rm DY/Higgs}$ and $G^N_{Q\bar{Q}}$
  - well-known exponentiation from factorization in soft/collinear limit

The radiative factors

- Production of color singlet final state from parton-parton scattering described by $G^N_{\mathrm{DY/Higgs}}$

$G^N_{\mathrm{DY/Higgs}} =$

$$\int_0^1 dz\, \frac{z^{N-1} - 1}{1 - z} \int_{\mu_f^2}^{4m^2(1-z)^2} \frac{dq^2}{q^2}\, 2\, A_i(\alpha_s(q^2)) + D_i(\alpha_s(4m^2[1 - z]^2))$$

  - well known anomalous dimensions A_i (collinear gluon emission) and D_i (process dependent gluon emission at large angles)
    Vogt ‘00; Catani, Grazzini, de Florian, Nason ‘03; S.M., Vermaseren, Vogt ‘05

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Vogt ‘00; Catani, Grazzini, de Florian, Nason ‘03; S.M., Vermaseren, Vogt ‘05

- $G^N_{Q\bar{Q}}$ accounts for gluon emission from octet final state

$$G^N_{Q\bar{Q}} \quad = \quad \int\limits_0^1 dz\, \frac{z^{N-1}-1}{1-z}\, D_{Q\bar{Q}}(\alpha_s([1-z]^2 4m^2))$$

  - anomalous dimension $D_{Q\bar{Q}}$ (cf. pole of form factor for massive quarks)

$$D^{(1)}_{Q\bar{Q}} = -A^{(1)}_g\,, \qquad\qquad D^{(2)}_{Q\bar{Q}} = -A^{(2)}_g = -A^{(1)}_g K$$

$D^{(2)}_{Q\bar{Q}}$ consistent with Mitov, Sterman, Sung ‘09; Becher, Neubert ‘09

Accuracy under control

- Control over logarithms $\ln(N)$ with $\lambda = \beta_0 \alpha_s \ln(N)$ to N^{k}LL accuracy

$$G^N_{ij\,I} = \ln N \cdot g^1_{ij}(\lambda) + g^2_{ij,\,I}(\lambda) + \alpha_s\, g^3_{ij,\,I}(\lambda) + \dots$$

  - $g^1(\lambda)$: LL
    Laenen, Smith, v.Neerven '92; Berger, Contopanagos '95; Catani, Mangano, Nason, Trenatedue '96
  - $g^2(\lambda)$: NLL
    Bonciani, Catani, Mangano, Nason '98; Kidonakis, Laenen, S.M., Vogt '01
  - $g^3(\lambda)$: NNLL
    S.M., Uwer '08
- Resummed G^N predicts fixed orders in perturbation theory
  - generating functional for towers of large logarithms

New results

- NNLO cross section for heavy-quark hadro-production near threshold (all powers of $\ln\beta$ and Coulomb corrections) S.M., Uwer '08; Langenfeld, S.M., Uwer to appear
  - e.g. gg-fusion for $n_f = 5$ light flavors at $\mu = m_t$

$$\hat{\sigma}^{(1)}_{gg\to t\bar{t}} = \hat{\sigma}^{(0)}_{gg\to t\bar{t}}\left\{96\ln^2\beta - 9.5165\ln\beta + 35.322 + 5.1698\frac{1}{\beta}\right\}$$

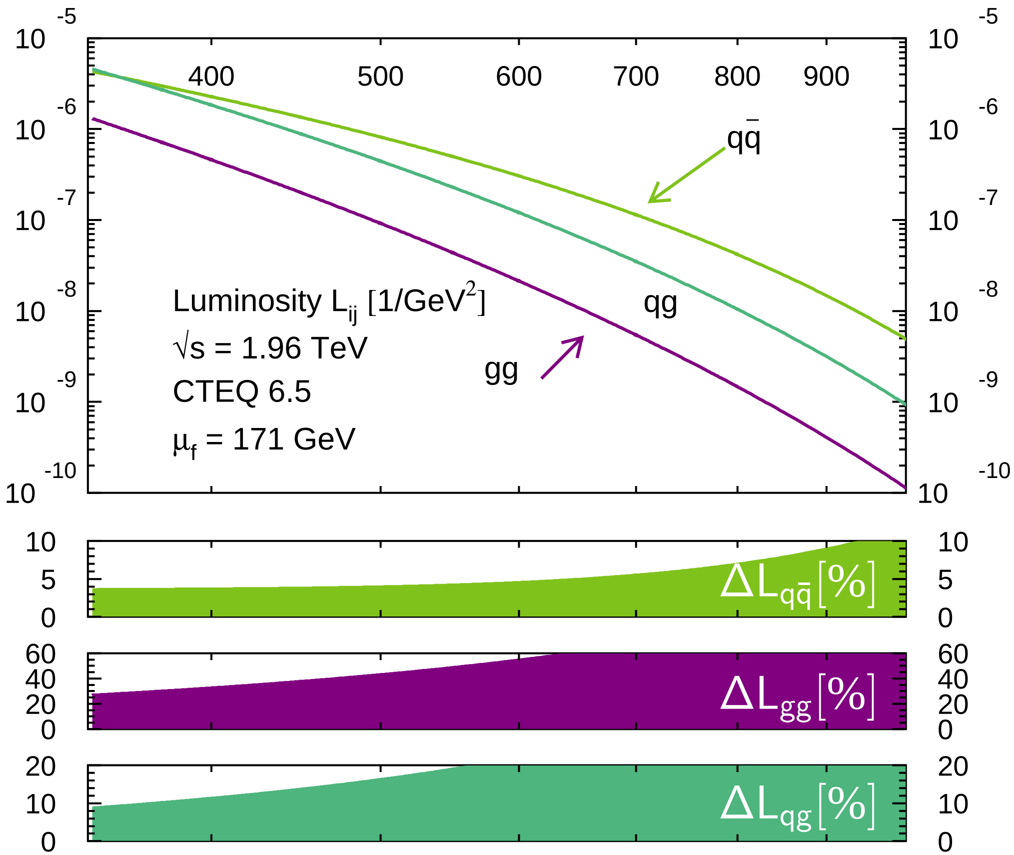
$$\hat{\sigma}^{(2)}_{gg\to t\bar{t}} = \hat{\sigma}^{(0)}_{gg\to t\bar{t}}\left\{4608\ln^4\beta - 1894.9\ln^3\beta + \left(-912.35 + 496.30\frac{1}{\beta}\right)\ln^2\beta \right.$$
$$\left. + \left(3031.1 + 321.14\frac{1}{\beta}\right)\ln\beta + 68.547\frac{1}{\beta^2} - 196.93\frac{1}{\beta} + C^{(2)}_{gg}\right\}$$

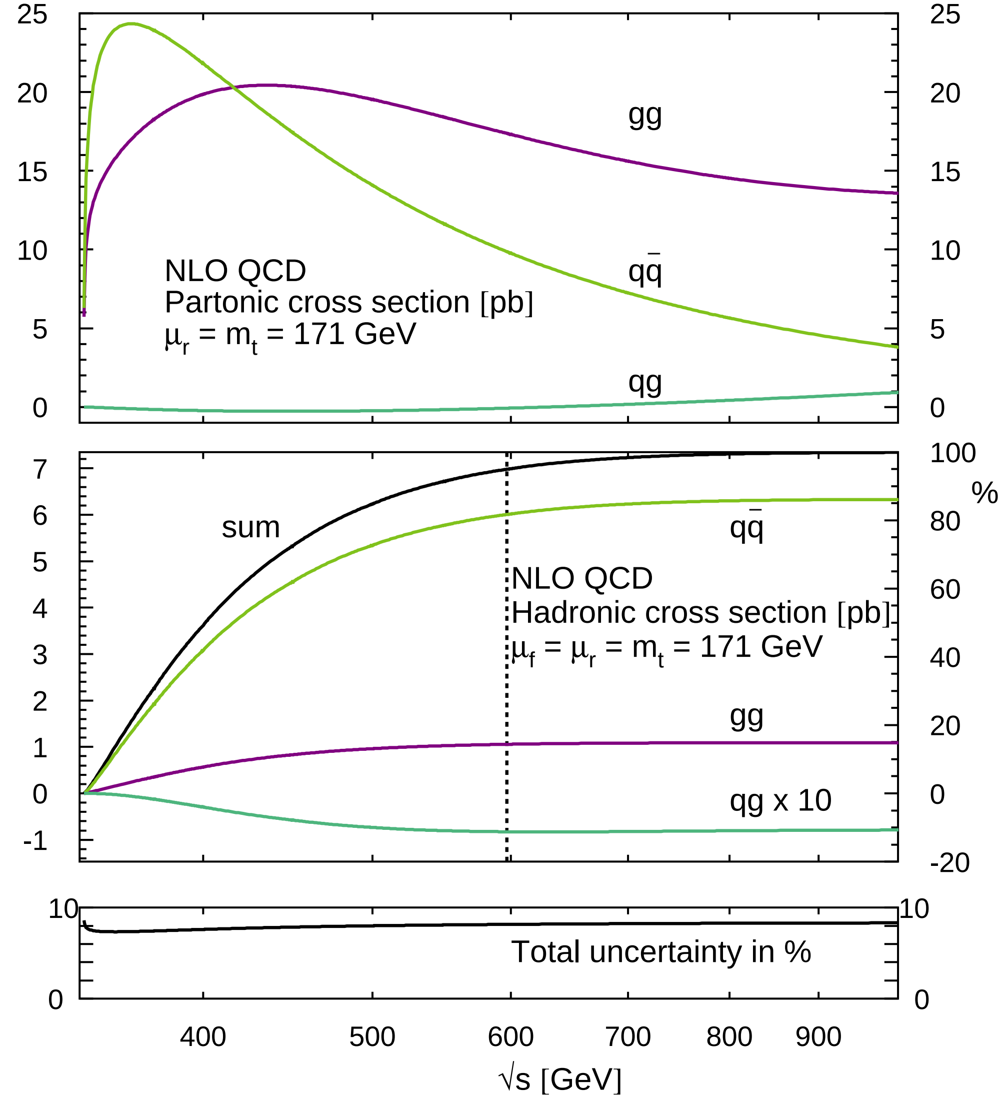
Upshot

- Best approximation to complete NNLO
- Similar results for new massive colored particles (4th generation quarks, squarks, gluinos, . . .) S.M., Uwer '08; S.M., Langenfeld '08

Total cross section at Tevatron

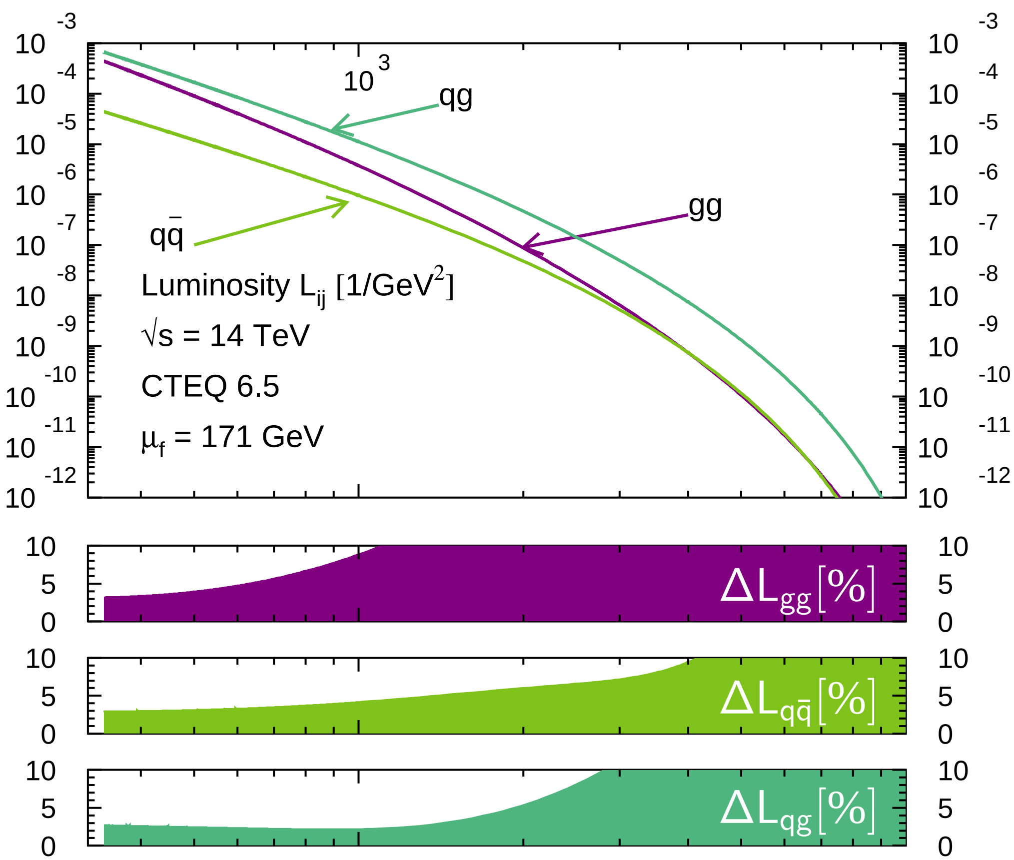
$$\sigma_{pp\to t\bar{t}} = \sum_{ij} f_i \otimes f_j \otimes \hat{\sigma}_{ij\to t\bar{t}}$$

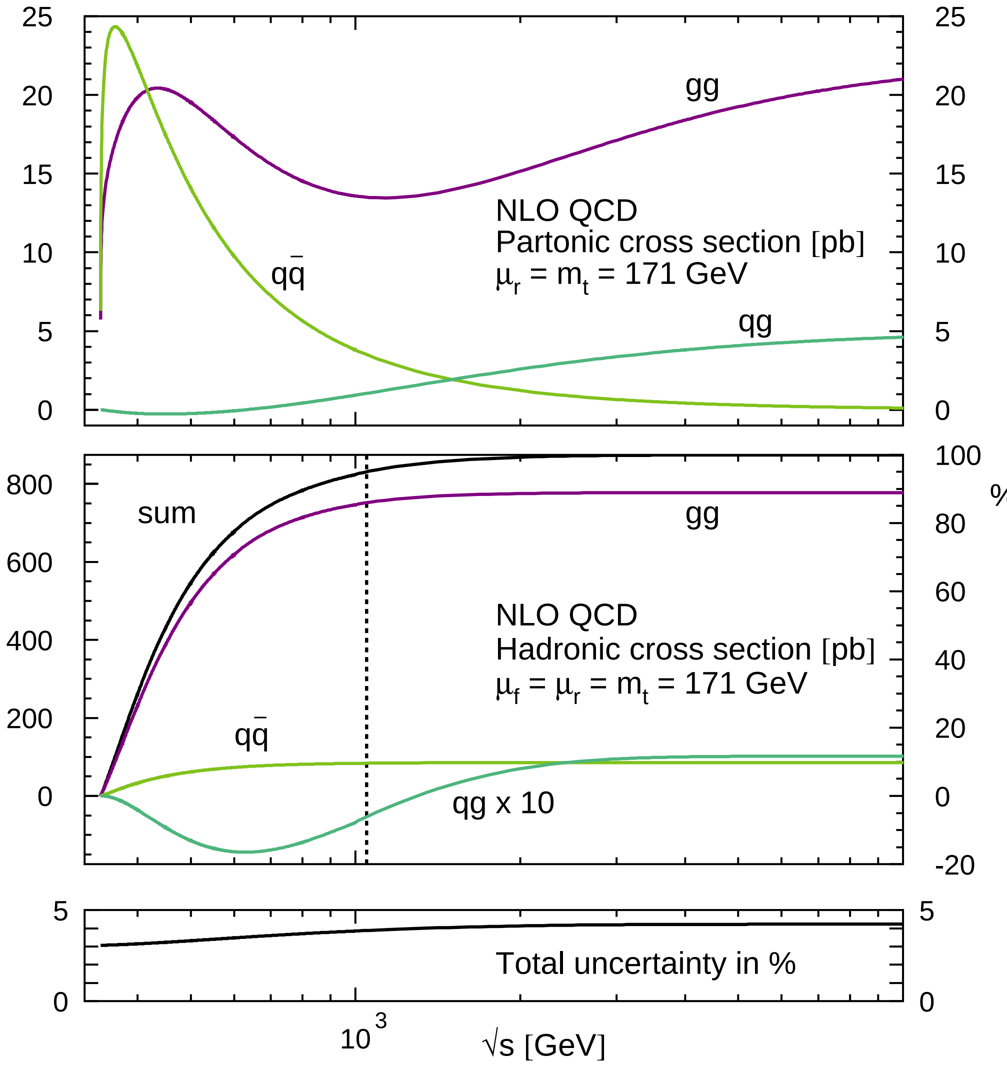




Total cross section at LHC

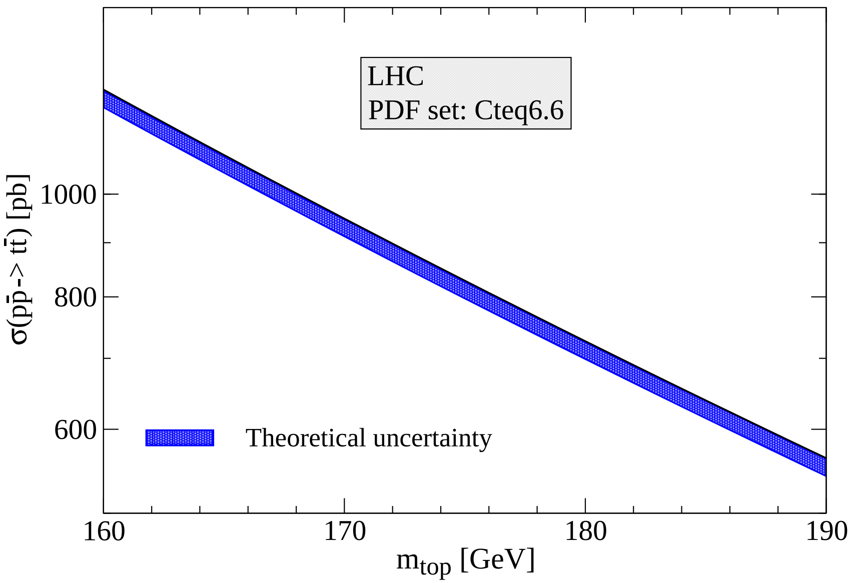
$$\sigma_{pp\to t\bar{t}} = \sum_{ij} f_i \otimes f_j \otimes \hat{\sigma}_{ij\to t\bar{t}}$$



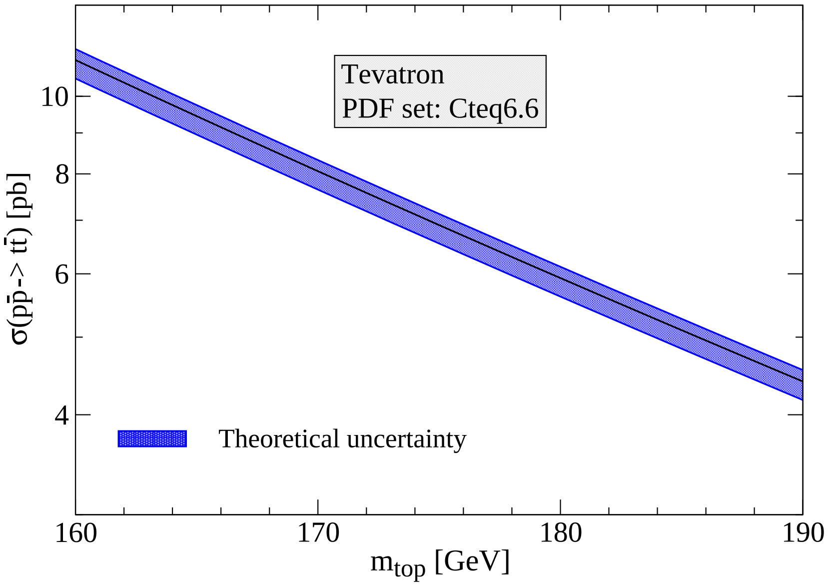


Mass dependence

- Parametrize mass dependence with a fit around $x = (m_t/\text{GeV} - 173)$
  $\sigma(\mu) = a + bx + cx^2 + dx^3 + ex^4 + fx^5 + gx^6$
  - fit precise to per mille accuracy in range $150\ \text{GeV} \leq m_t \leq 220\ \text{GeV}$
  - various scale and PDF choices: $\mu = m_t/2, m_t, 2m_t$, CTEQ6.6, MSTW2008, . . .



LHC



Tevatron

Recent theory activities

- Updates of cross section predictions based on resummation
  Cacciari, Frixione, Mangano, Nason, Ridolfi ‘08; Kidonakis, Vogt ‘08
- Correlation of cross section at NLO with gluon PDFs
  Nadolsky, Lai, Cao, Huston, Pumplin, Stump, Tung, Yuan ‘08;

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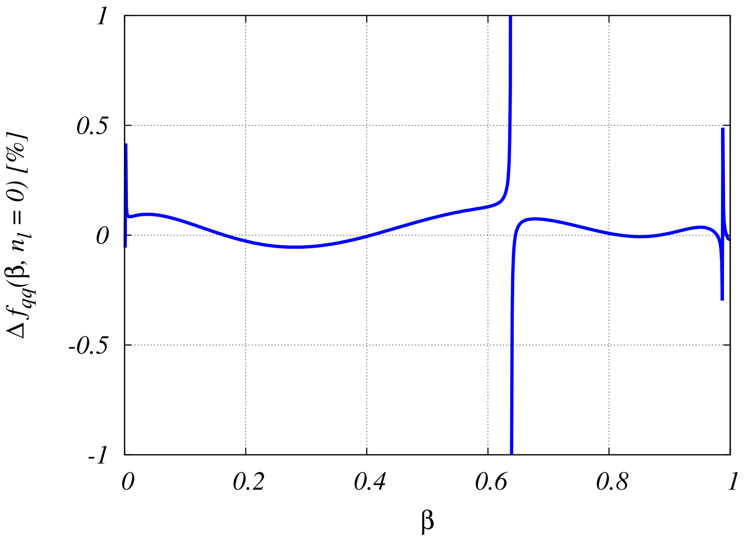
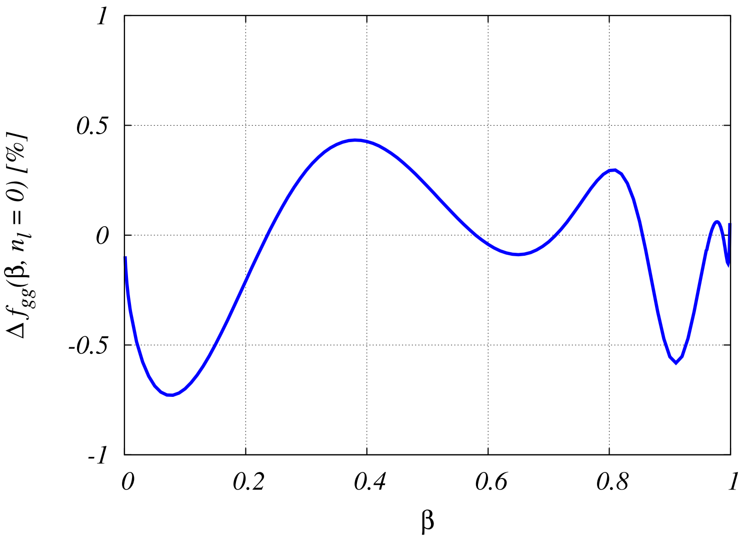
Progress at NLO

- Complete analytic calculation at NLO Mitov, Czakon ‘08
  - check quality of fit of NDE Nason, Dawson, Ellis ‘88 (fit OK to $\mathcal{O}(1\%)$)





Theory improvements

- Improved matching at NLO
  - consistent color-singlet and color-octet contributions at NLO
    Petrelli, Cacciari, Greco, Maltoni, Mangano ‘97; Hagiwara, Sumino, Yokoya ‘08
- Subleading logarithms $\beta^2 \ln(\beta) \longleftrightarrow \ln(N)/N$
  - effect modeled in N-space (scheme $A = 2$)
    Bonciani, Catani, Mangano, Nason ‘98
    $\hat{\sigma}^{\rm res}_{\rm NLL} \times (1 - A/(N + A - 1))$
  - recent progress in all-order exponentiation of power-suppressed terms (test cases F_L and Drell-Yan)
    Laenen, Magnea, Stavenga ’08; Moch, Vogt ’09; Grunberg, Ravindran ’09
- First step: contribution of qg-channel
  - leading term near threshold $\sim \beta^3 \ln^3 \beta$ (power suppressed by β^2)
  - include gq-channel at two loops because of large gq-parton luminosity at LHC

Scale dependence (I)

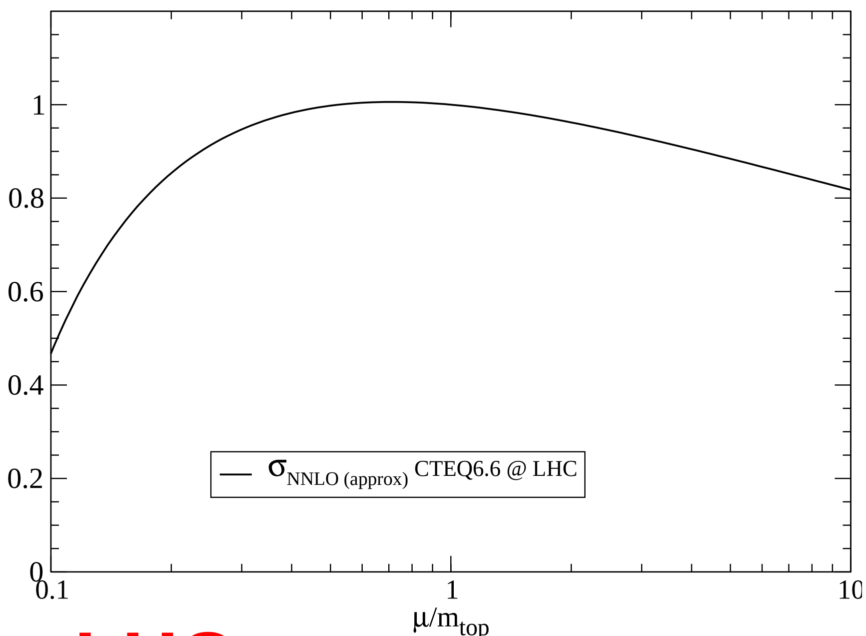
- Variation of renormalization and factorization scale $\mu_R \neq \mu_F$
- Renormalization group methods predict all terms $L = \ln(\mu^2/m_t^2)$

$$
\begin{aligned}
\sigma_{t\bar{t}} \quad &= \quad \sigma^{(0)} + \alpha_s(\mu) \left\{ \sigma^{(1)} + L\, \sigma_L^{(1)}(\sigma^{(0)}, \beta_0, P_0) \right\} \\
&+ \quad \alpha_s^2(\mu) \left\{ \sigma^{(2)} + L\, \sigma_L^{(2)}(\sigma^{(0)}, \sigma^{(1)}, \beta_0, \beta_1, P_0, P_1) + L^2\, \sigma_{L^2}^{(2)}(\sigma^{(0)}, \beta_0, P_0) \right\}
\end{aligned}
$$

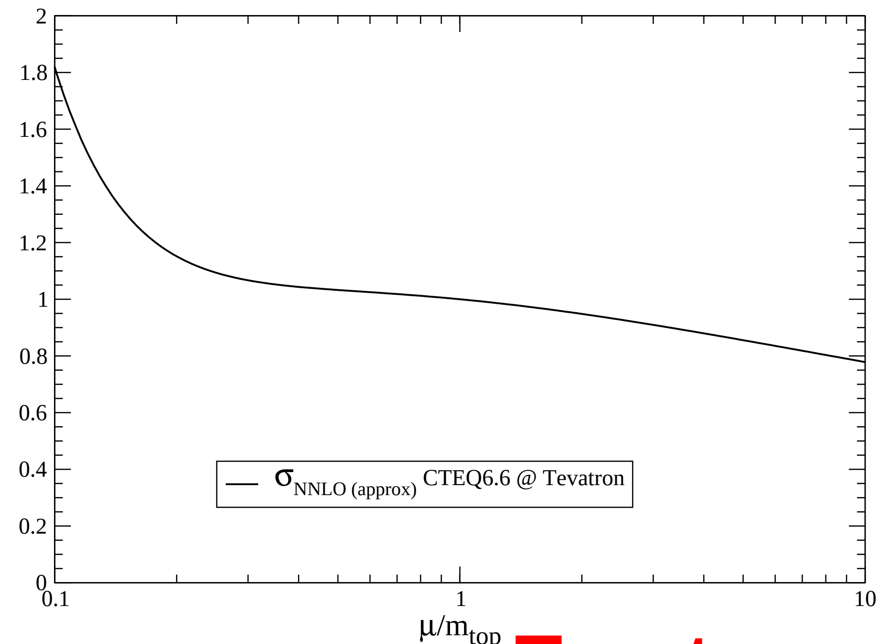
  - relax $\mu = \mu_R = \mu_F$ in study of theoretical uncertainty
  - allow for independent variation $\mu_R \neq \mu_F$

Scale dependence (II)

- Theoretical uncertainty from variation of scales $\mu = \mu_R = \mu_F$
  - plot with PDF set CTEQ6.6 (but largely independent on PDFs)
  - mass $m_t = 173$ GeV (from $m_t = 173.1 \pm 1.3$ GeV Tevatron winter '09)
  - very stable predictions in range $\mu \in [m_t/2, 2m_t]$
    - $-3\% \leq \Delta\sigma \leq +0.5\%$ at LHC
    - $-4\% \leq \Delta\sigma \leq +3\%$ at Tevatron



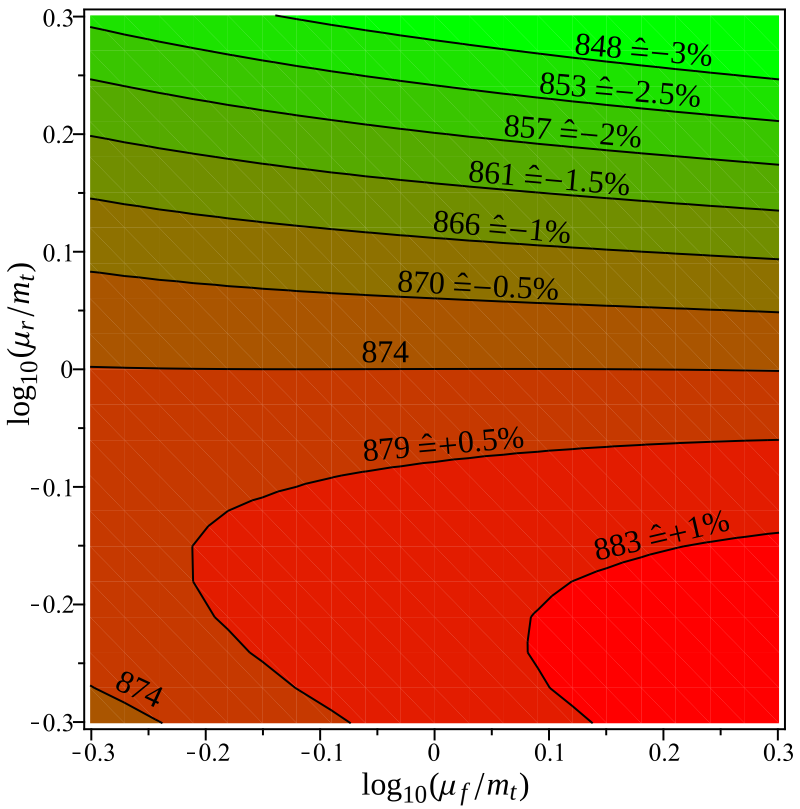
LHC

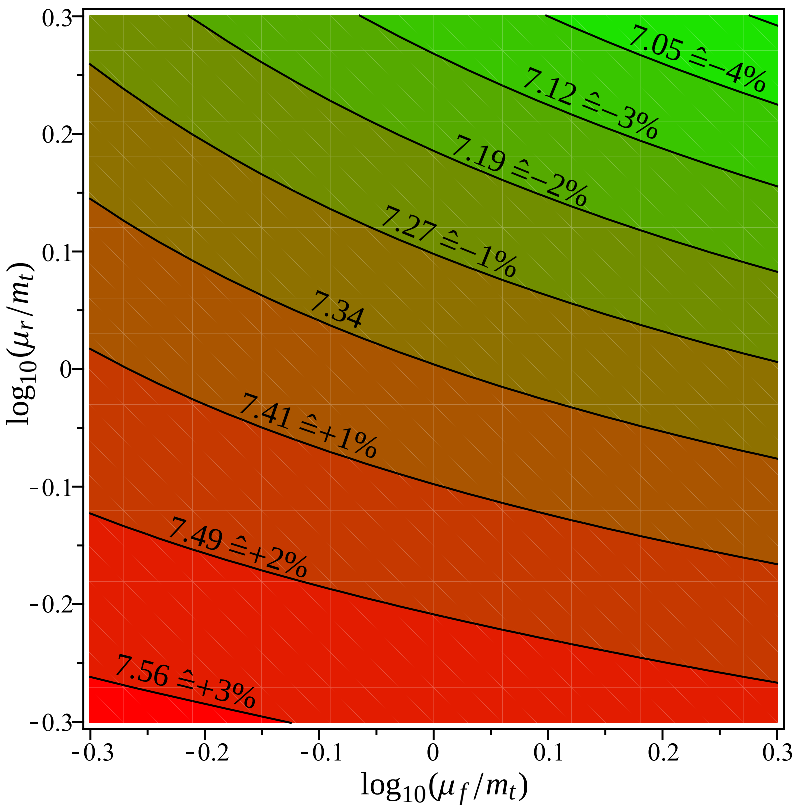


Tevatron

Scale dependence (III)

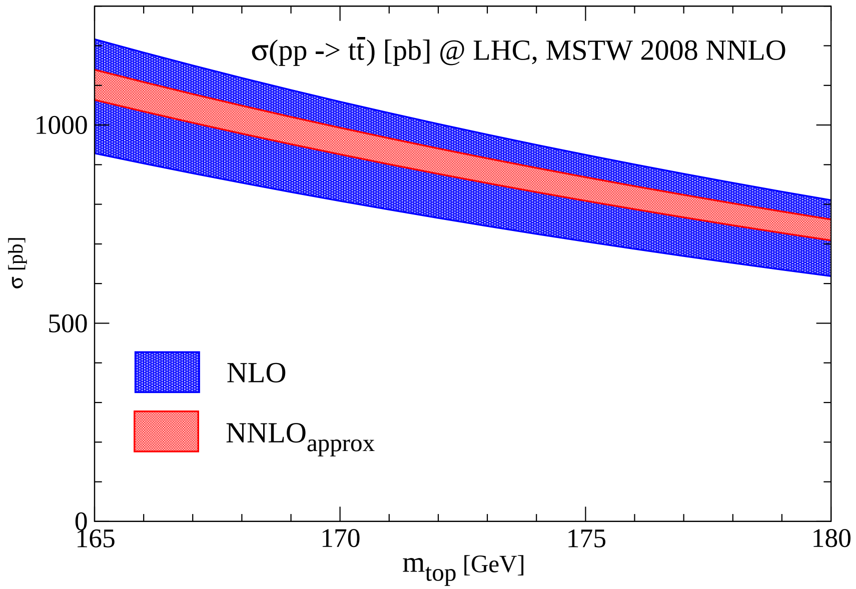
- Contour lines of total cross section for $\mu_R \neq \mu_F$
  - independent variation of renormalization and factorization scale
  - range corresponds to $\mu_R, \mu_F \in [m_t/2, 2m_t]$
  - plot with PDF set CTEQ6.6 (but largely independent on PDFs)

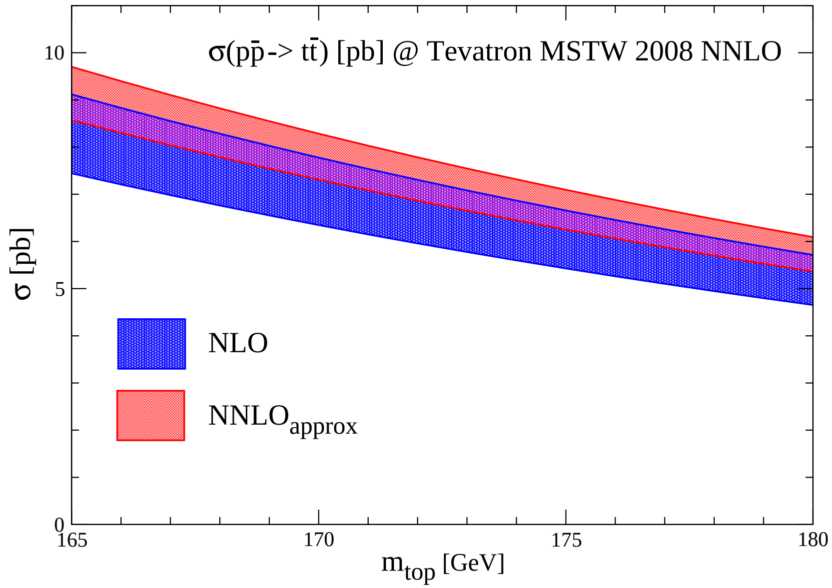




Total theory uncertainty

- NLO (with MSTW2008 PDF set)
  - scale uncertainty $\mathcal{O}(10\%) \oplus$ PDF uncertainty $\mathcal{O}(5\%)$
- $\text{NNLO}_{\text{approx}}$ (with MSTW2008 PDF set)
  - scale uncertainty $\mathcal{O}(3\%) \oplus$ PDF uncertainty $\mathcal{O}(2\%)$
- Theory at NNLO matches anticipated experimental precision $\mathcal{O}(10\%)$

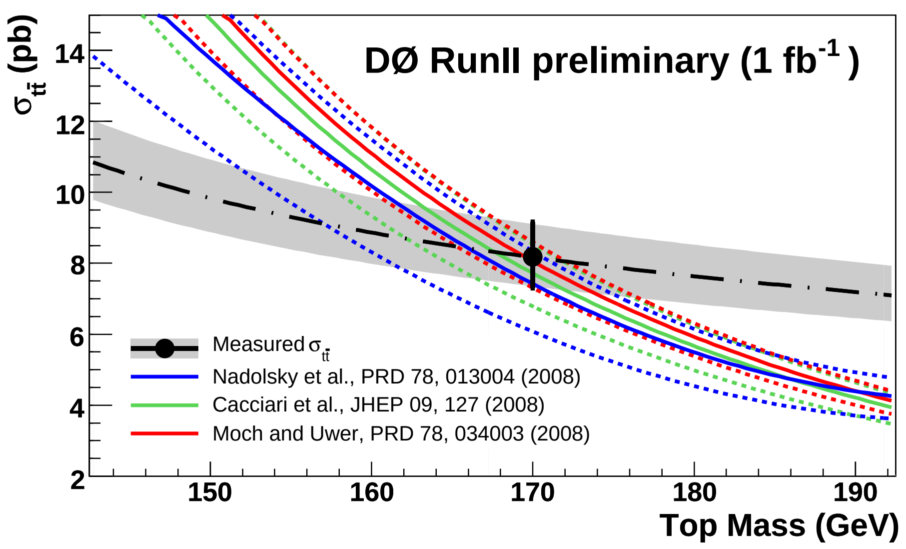


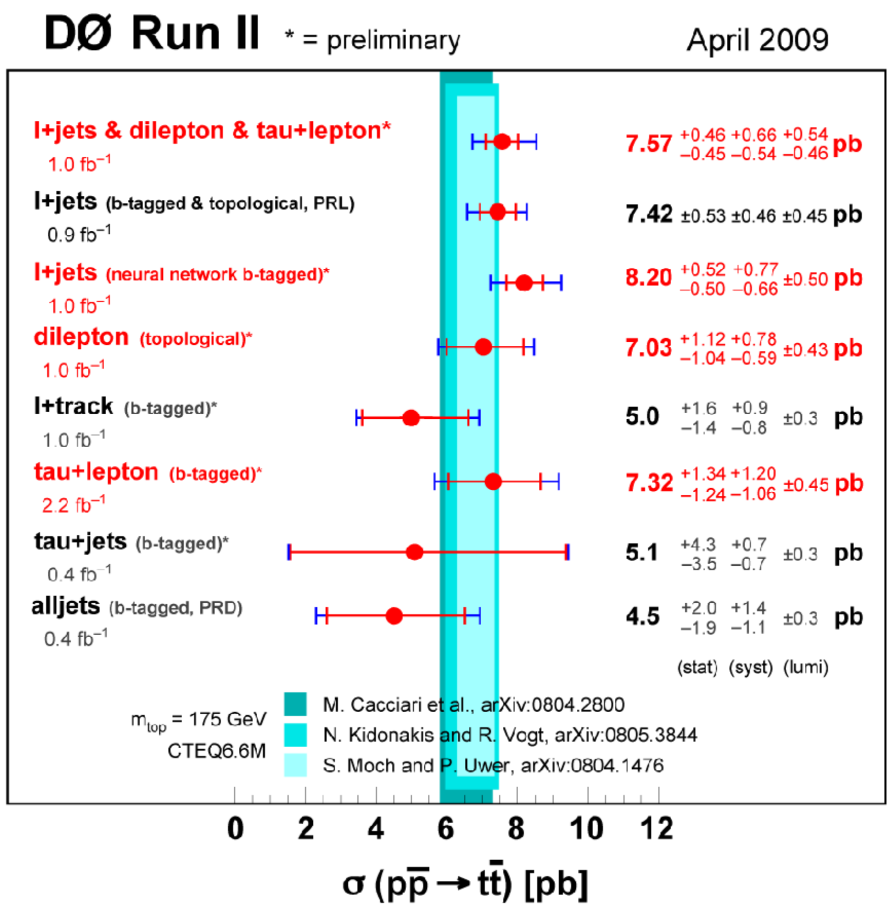


LHC **Tevatron**

Tevatron analyses

- Total cross section and different channels of Tevatron analyses (theory uncertainty band from scale variation)
- NNLO allows for precision determinations of m_t from total cross section (slope $d\sigma/dm_t$)





Quality control

- Total cross section with $m_t = 173$ GeV at scale $\mu = \mu_R = \mu_F$
  - numbers from `arXiv:0804.1476`, `arXiv:0807.2794`

	CTEQ6.6	MSTW08
$\sigma_{\mathrm{LO}}[\mathrm{pb}]$	553	
$\sigma_{\mathrm{NLO}}[\mathrm{pb}]$	831	
$\sigma_{\mathrm{NNLO}}[\mathrm{pb}]$	872	

LHC

	CTEQ6.6	MSTW08
$\sigma_{\mathrm{LO}}[\mathrm{pb}]$	5.47	
$\sigma_{\mathrm{NLO}}[\mathrm{pb}]$	6.79	
$\sigma_{\mathrm{NNLO}}[\mathrm{pb}]$	7.34	

Tevatron

Quality control

- Total cross section with $m_t = 173$ GeV at scale $\mu = \mu_R = \mu_F$
  - numbers from this study

	CTEQ6.6	MSTW08
$\sigma_{\rm LO}$[pb]	553	
$\sigma_{\rm NLO}$[pb]	831	
$\sigma_{\rm NNLO}$[pb]	872 + 2	

LHC

CTEQ6.6	MSTW08
5.47	
6.79	
7.34+0.0	

Tevatron

Quality control

- Total cross section with $m_t = 173$ GeV at scale $\mu = \mu_R = \mu_F$
  - numbers from this study

	CTEQ6.6	MSTW08
$\sigma_{\mathrm{LO}}[\mathrm{pb}]$	553	564
$\sigma_{\mathrm{NLO}}[\mathrm{pb}]$	831	844
$\sigma_{\mathrm{NNLO}}[\mathrm{pb}]$	874	887

LHC

CTEQ6.6	MSTW08
5.47	5.27
6.79	6.52
7.34	7.04

Tevatron

Quality control

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$\sigma_{\rm NNLO}[\rm pb]$	874	887	7.34	7.04
	LHC		**Tevatron**	

- Compare exact results against

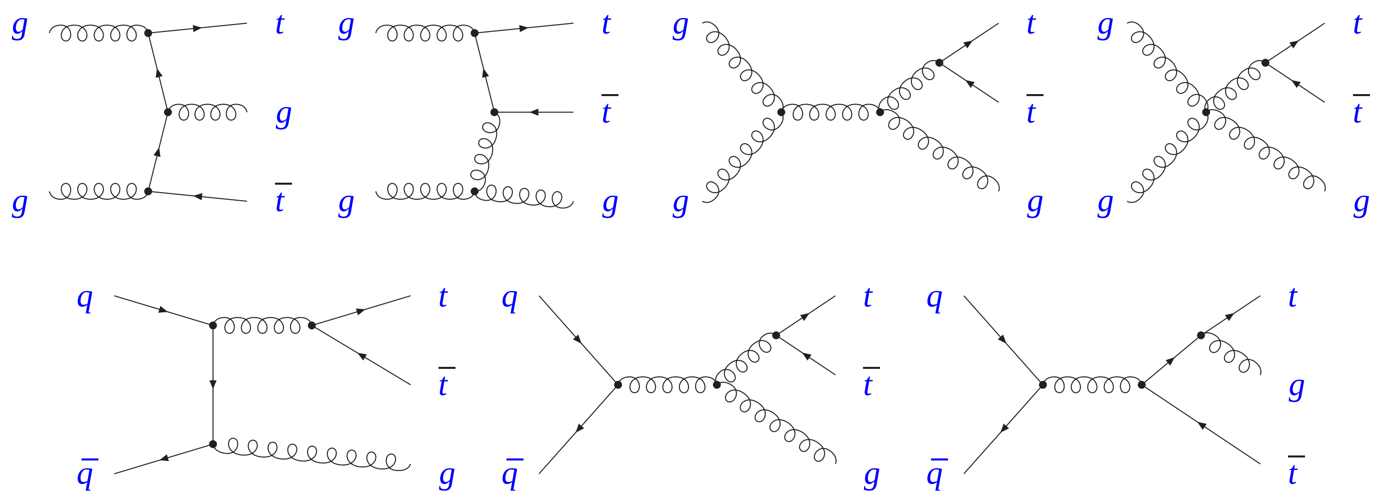
$$\hat{\sigma}^{(n)}_{\rm N...LL} = \hat{\sigma}^{(0)} \left\{ \# \ln^{2n} \beta + \dots + \# \ln \beta + \dots + \frac{\#}{\beta} \right\}$$

  - can be checked at NLO (and at NNLO for scale dependent terms)
  - systematics typically better than $\hat{\sigma}^{(n)}_{\rm N...LL} / \hat{\sigma}^{(n)}_{\rm exact} \lesssim \mathcal{O}(30\%)$

- Estimate systematic uncertainty of total cross section $\Delta\sigma \sim \mathcal{O}(2\%)$
  - $\Delta\sigma \sim \mathcal{O}(10 - 15)\,\rm pb$ at LHC
  - $\Delta\sigma \sim \mathcal{O}(0.15 - 0.2)\,\rm pb$ at Tevatron

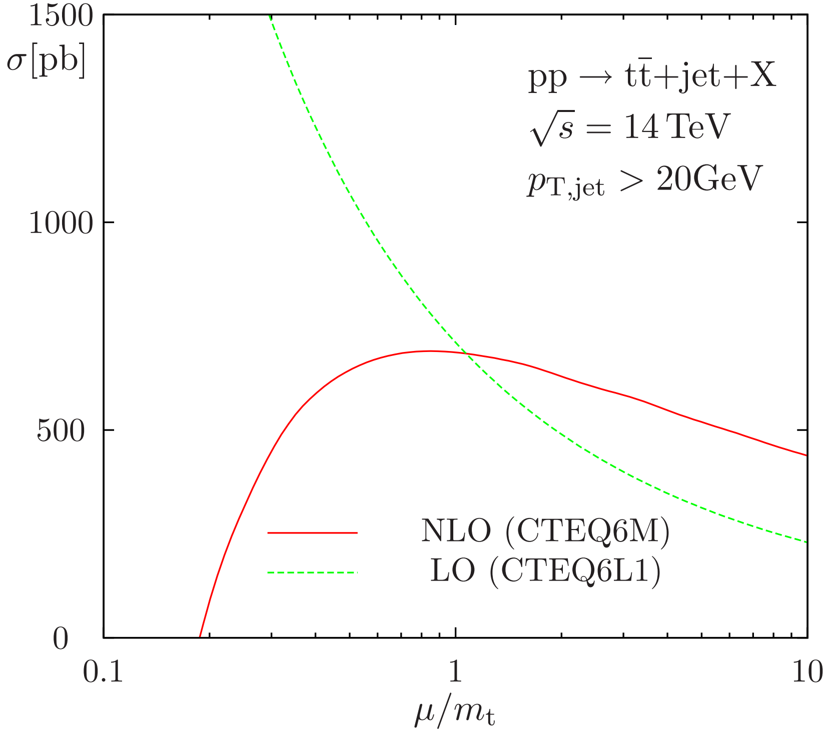
$t\bar{t}+$ jet production (I)

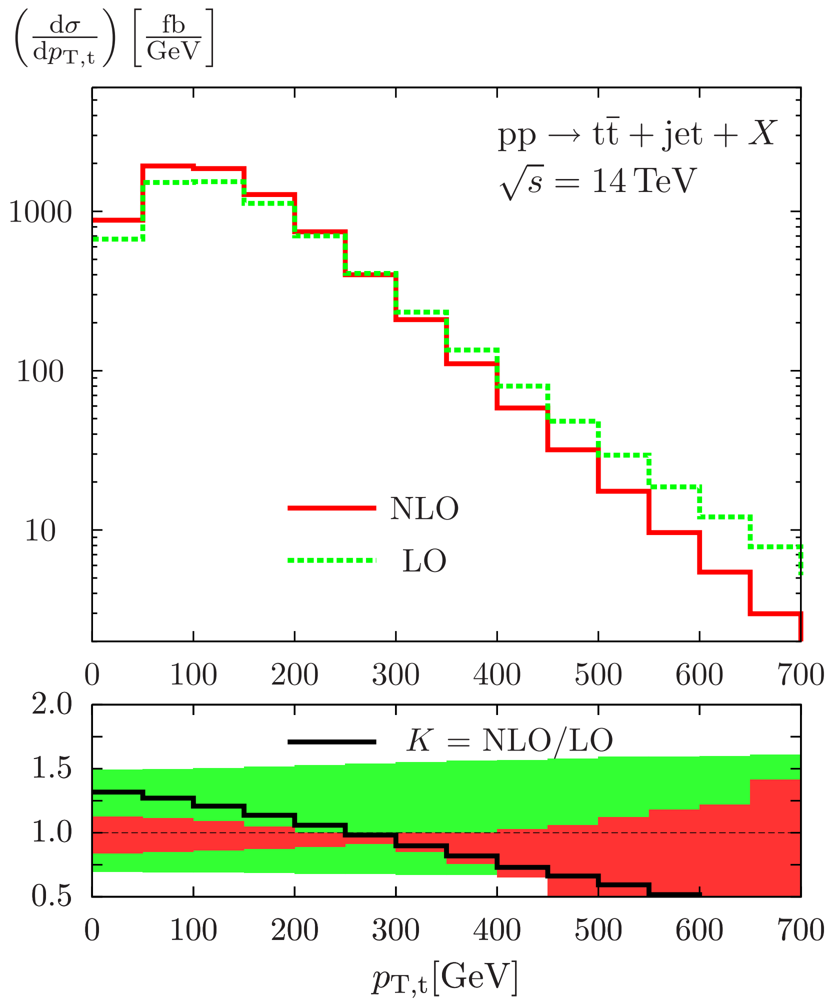
- LHC: large rates for production of $t\bar{t}$-pairs with additional jets
  - sample Feynman diagrams for $t\bar{t}+$ jet production at LO



- NLO corrections to $t\bar{t}+$jet production are part of NNLO corrections for inclusive $t\bar{t}$ production
  - at scale $\mu_R = \mu_F = m_t$ corrections are almost zero
  - threshold resummation captures dominant contributions

$t\bar{t}+$ jet production (II)





- Impressive state-of-the-art NLO QCD result Dittmaier, Uwer, Weinzierl '07-'08
  - much improved scale dependence of total rate
  - transverse-momentum distributions of top-quark $p_{T,t}$ along with K-factor and scale variation $m_t/2 \le \mu \le 2m_t$

$t\bar{t}+$ jet production (III)

$p_{\mathrm{T,jet,cut}}$ [GeV]	$\sigma_{\mathrm{t\bar{t}jet}}\,[\mathrm{pb}]$ LO	$\sigma_{\mathrm{t\bar{t}jet}}\,[\mathrm{pb}]$ NLO
20	$1.583(2)^{+0.96}_{-0.55}$	$1.791(1)^{+0.16}_{-0.31}$
30	$0.984(1)^{+0.60}_{-0.34}$	$1.1194(8)^{+0.11}_{-0.20}$
40	$0.6632(8)^{+0.41}_{-0.23}$	$0.7504(5)^{+0.072}_{-0.14}$
50	$0.4670(6)^{+0.29}_{-0.17}$	$0.5244(4)^{+0.049}_{-0.096}$

Tevatron

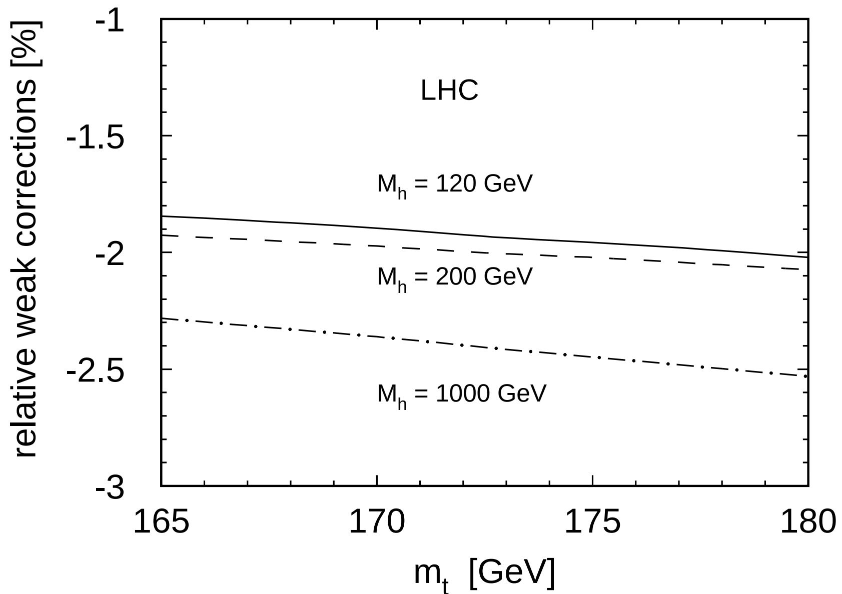
$p_{\mathrm{T,jet,cut}}$ [GeV]	$\sigma_{\mathrm{t\bar{t}jet}}\,[\mathrm{pb}]$ LO	$\sigma_{\mathrm{t\bar{t}jet}}\,[\mathrm{pb}]$ NLO
20	$710.8(8)^{+358}_{-221}$	$692(3)3^{-40}_{-62}$
50	$326.6(4)^{+168}_{-103}$	$376.2(6)^{+17}_{-48}$
100	$146.7(2)^{+77}_{-47}$	$175.0(2)^{+10}_{-24}$
200	$46.67(6)^{+26}_{-15}$	$52.81(8)^{+0.8}_{-6.7}$

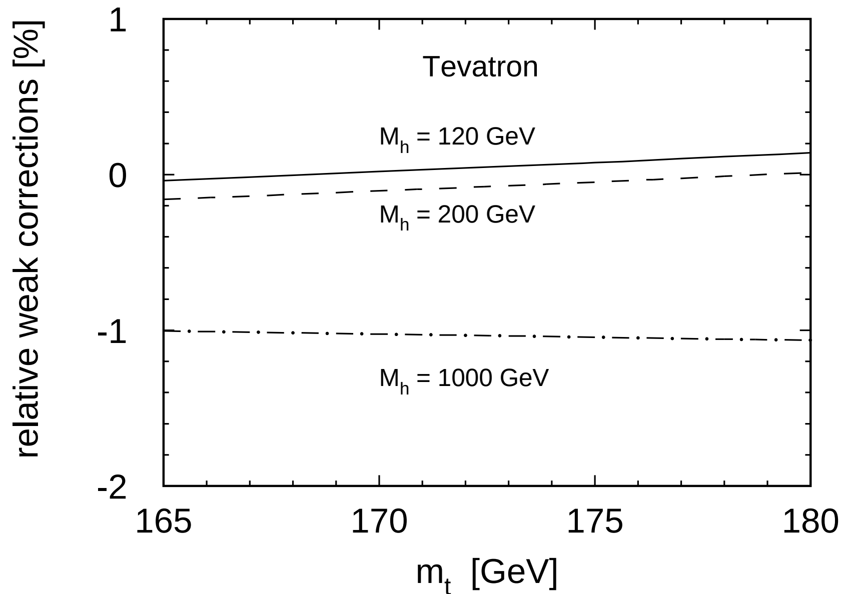
LHC

- Cross section $\sigma_{\mathrm{t\bar{t}jet}}$ for different values of $p_{\mathrm{T,jet,cut}}$ for $\mu = \mu_R = \mu_F = \{m_{\mathrm{t}}/2, m_{\mathrm{t}}, 2m_{\mathrm{t}}\}$ with PDF sets CTEQ6L1, CTEQ6M
  Dittmaier, Uwer, Weinzierl ‘07-‘08

Electroweak corrections

- Electroweak corrections (ratio of $\sigma_{\mathrm{EW}}/\sigma_{\mathrm{LO}}$)
  Bernreuther, Fücker '05; Kühn, Uwer,Scharf '06
- Effect depends on Higgs mass
  (choices $m_H = 120$GeV, $m_H = 200$GeV, $m_H = 1000$GeV)



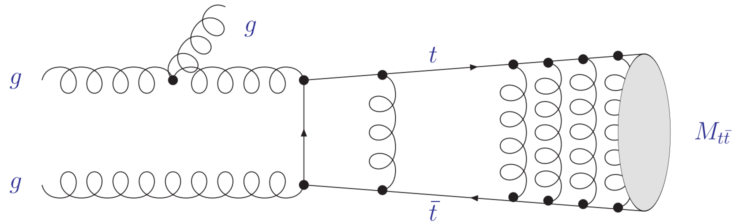


LHC **Tevatron**

- Tevatron: vanishing contribution for light Higgs
- LHC: $\mathcal{O}(2\%)$ with respect to σ_{LO}
  negative contribution to total cross section $\Delta\sigma_{\mathrm{EW}} \simeq \mathcal{O}(10-15)$ pb

Coulomb corrections

- Heavy quark production very close to threshold
  - resummation of Coulomb corrections $\sim 1/\beta$ to all orders (non-relativistic QCD)
  - NRQCD factorization Bodwin, Braaten, Lepage '95
- Much work (theory and phenomenology) for ILC
  - fixed center-of-mass energy S allows threshold scan at $\sqrt{S} \sim 2m_t$
  - dominant color-singlet production $\rightarrow t\bar{t}\left({}^3S_1^{[1]}\right)$
- Effects on top-mass measurement at LHC Hagiwara, Sumino, Yokoya '08
- Detailed study in NRQCD assembling existing knowledge at NLO/NLL Kiyo, Kühn, S.M., Steinhauser, Uwer '08
  - complete NLO NRQCD result Petrelli, Cacciari, Greco, Maltoni, Mangano '97 (corrections by Hagiwara, Sumino, Yokoya '08)
  - NLL resummation Cacciari '99

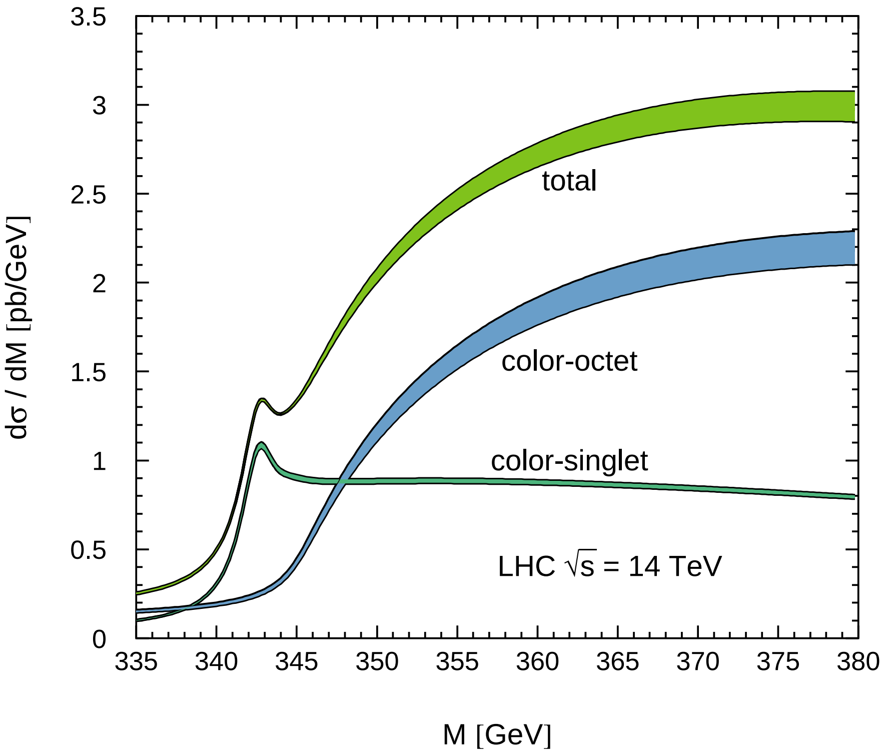


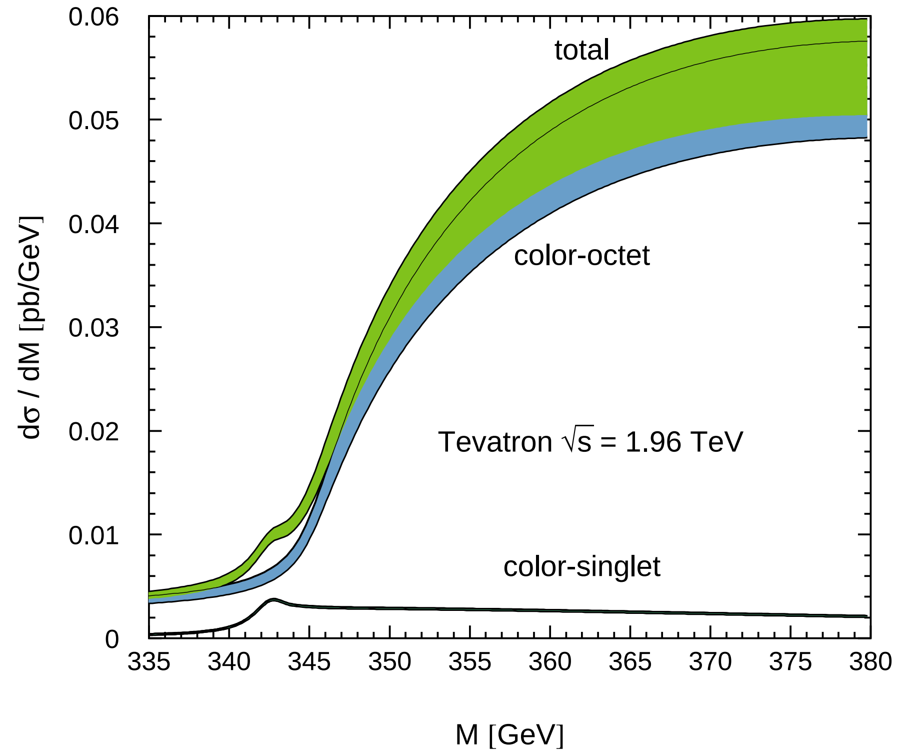
Coulomb corrections

- Recall master equation $\sigma_{pp\to t\bar{t}} = \sum_{ij} f_i \otimes f_j \otimes \hat{\sigma}_{ij\to t\bar{t}}$
- Convolution with PDFs $f_i \otimes f_j$
  - top-quark pairs produced as color-singlets and color-octets $\to t\bar{t}\left({}^{2s+1}S_J^{[1,8]}\right)$
  - threshold at $M_{t\bar{t}} \sim 2m_t$ with $M_{t\bar{t}} = (p_t + p_{\bar{t}})^2$
- NRQCD factorization of partonic cross section into $\hat{\sigma}_{ij\to t\bar{t}} = F_{ij\to T} \otimes G(M_{t\bar{t}})$
  - free $t\bar{t}$ production rate F
  - evolution factor into “boundstate” (Green’s function) G
- Differential kinematics $\dfrac{d\hat{\sigma}_{ij\to t\bar{t}}}{dM_{t\bar{t}}^2} = F_{ij\to T} \times \Im G^{[1,8]}(M_{t\bar{t}})$
  - factorization of soft-collinear dynamics (real emission radiation)
  - matching at NLO and NLL resummation

Invariant mass distristribution

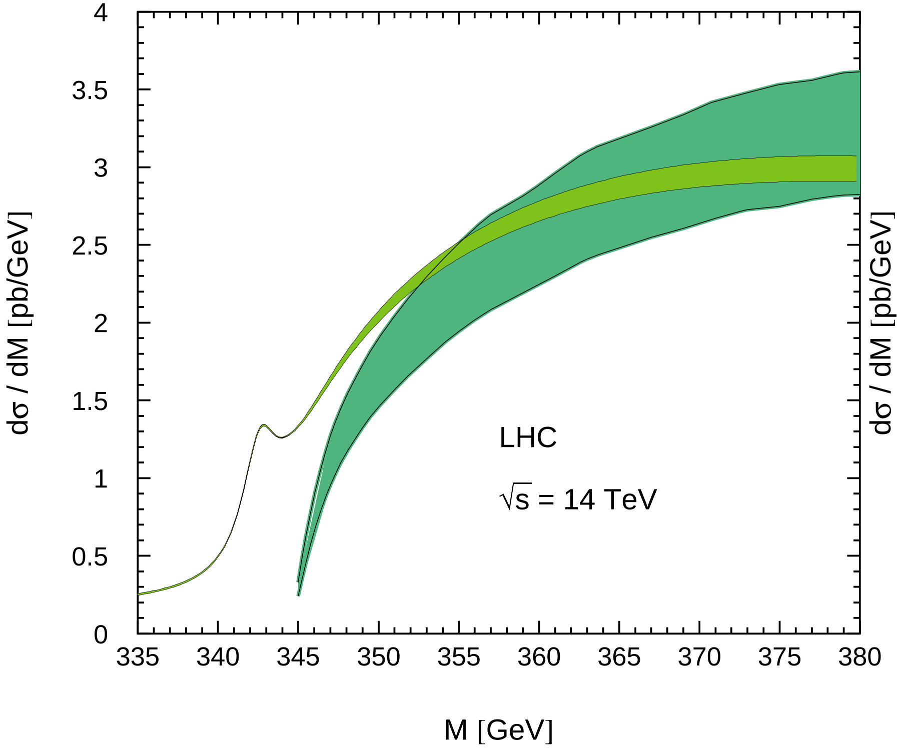
- $d\sigma/dM_{t\bar{t}}$ at LHC driven by large gluon luminosity
  - $gg \to t\bar{t}\left({}^1S_0^{[1]}\right)$ dominates
- $d\sigma/dM_{t\bar{t}}$ at Tevatron with small bound state effects
  - $q\bar{q}$-channel large with only color-octet configurations only

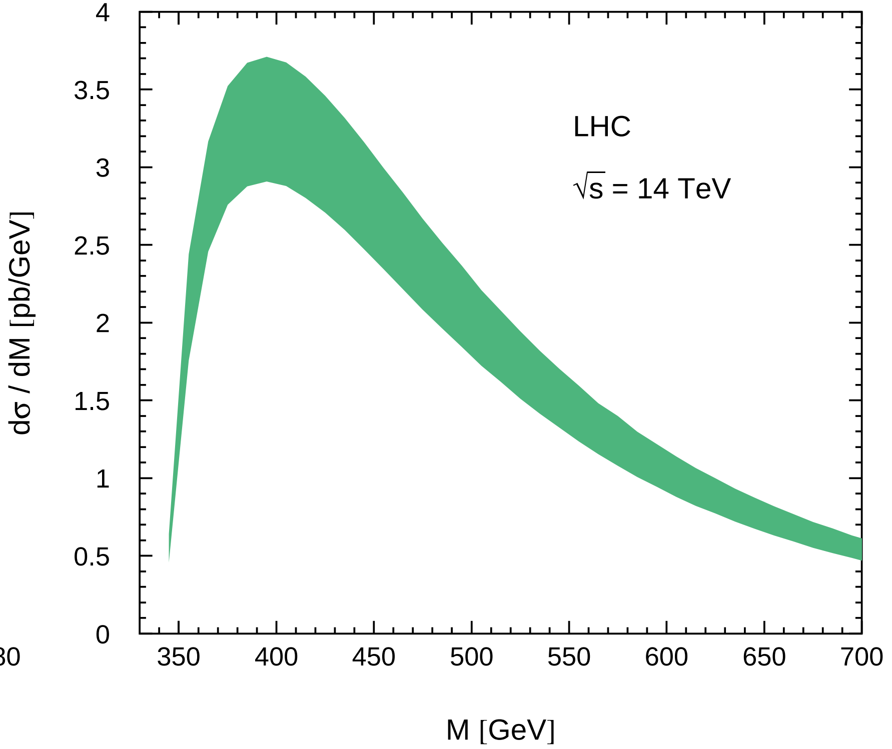




Matching to fixed order

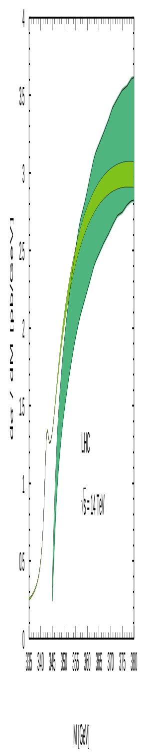
- $d\sigma/dM_{t\bar{t}}$ with at LHC
  - compare NLL resummed result in NRQCD with (plain vanilla) NLO (use HVQMNR Mangano, Nason, Ridolfi '92)
  - consistency check OK

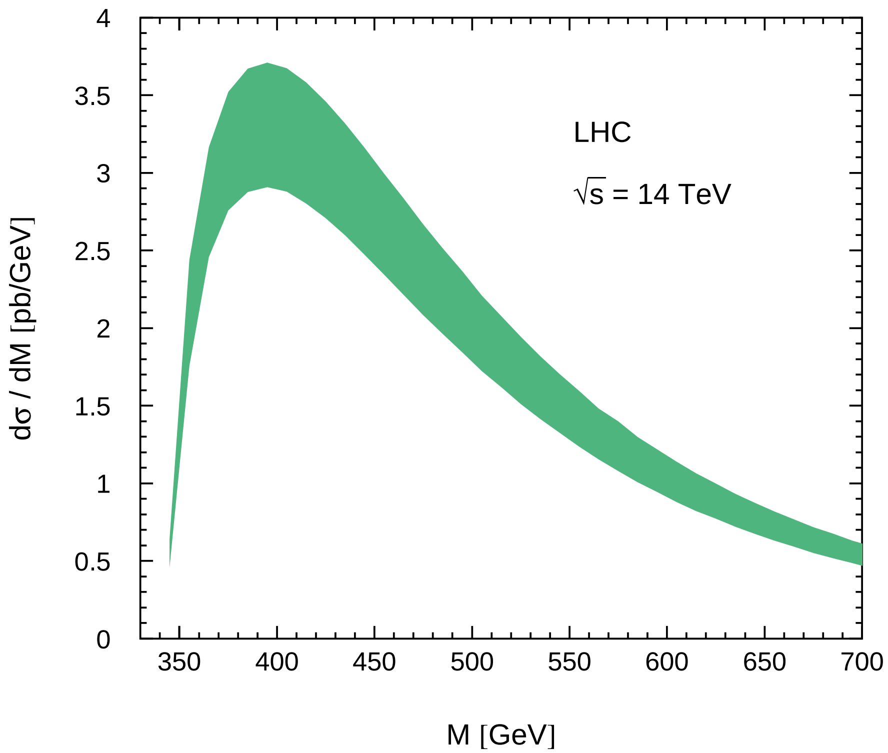




Invariant mass distristribution

- Resolution of bound state effects in $d\sigma/dM_{t\bar{t}}$ at LHC difficult (requires rather fine binning)
  - uncertainty of total cross section $\Delta\sigma \simeq \mathcal{O}(10)$ pb
  - extrapolation of $M_{t\bar{t}}$-distribution affected by $gg \to t\bar{t}\left({}^1S_0^{[1]}\right)$





Summary

- Top quark theory
  - improved understanding of theory and application of new concepts
  - resummation important for Tevatron and LHC phenomenology
- Total cross section
  - NNLO$_{\mathrm{approx}}$ prediction with exact scale dependence $\mu_R \neq \mu_F$ ($\ln(\mu_R/m)$, $\ln(\mu_F/m)$-terms)
  - cross check on systematics with NLO correction to $t\bar{t}+$ jet
  - investigation of theoretical uncertainty (scale)

    $\Delta\sigma \sim \mathcal{O}(\pm 3)\%$ at LHC

    $\Delta\sigma \sim \mathcal{O}(\pm 4)\%$ at Tevatron
- Other corrections
  - electroweak corrections
  - bound state effects for $t\bar{t}$-system
  - ...