

Status of $t\bar{t}$ cross section predictions

Sven-Olaf Moch

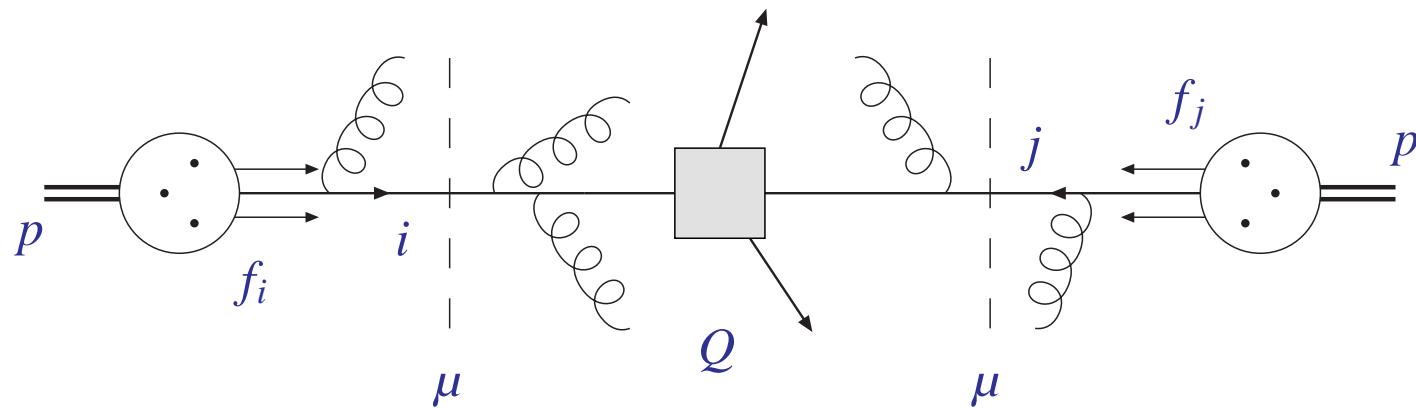
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CERN Theory Institute, *Perturbative higher-order effects at work at the LHC - HO10*, Geneva, July 06, 2010

Perturbative QCD at colliders

- Hard hadron-hadron scattering
 - constituent partons from each incoming hadron interact at short distance (large momentum transfer Q^2)



- QCD factorization at scale μ
 - separate sensitivity to dynamics from different scales

$$\sigma_{pp \rightarrow t\bar{t}X} = \sum_{ij} f_i(\mu^2) \otimes f_j(\mu^2) \otimes \hat{\sigma}_{ij \rightarrow t\bar{t}X} (\alpha_s(\mu^2), Q^2, \mu^2)$$

- subprocess cross section $\hat{\sigma}_{ij \rightarrow t\bar{t}X}$ for parton types i, j

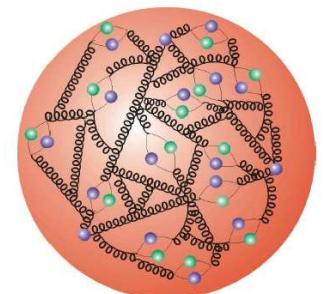
Hard scattering cross section

- Standard approach to uncertainties in theoretical predictions

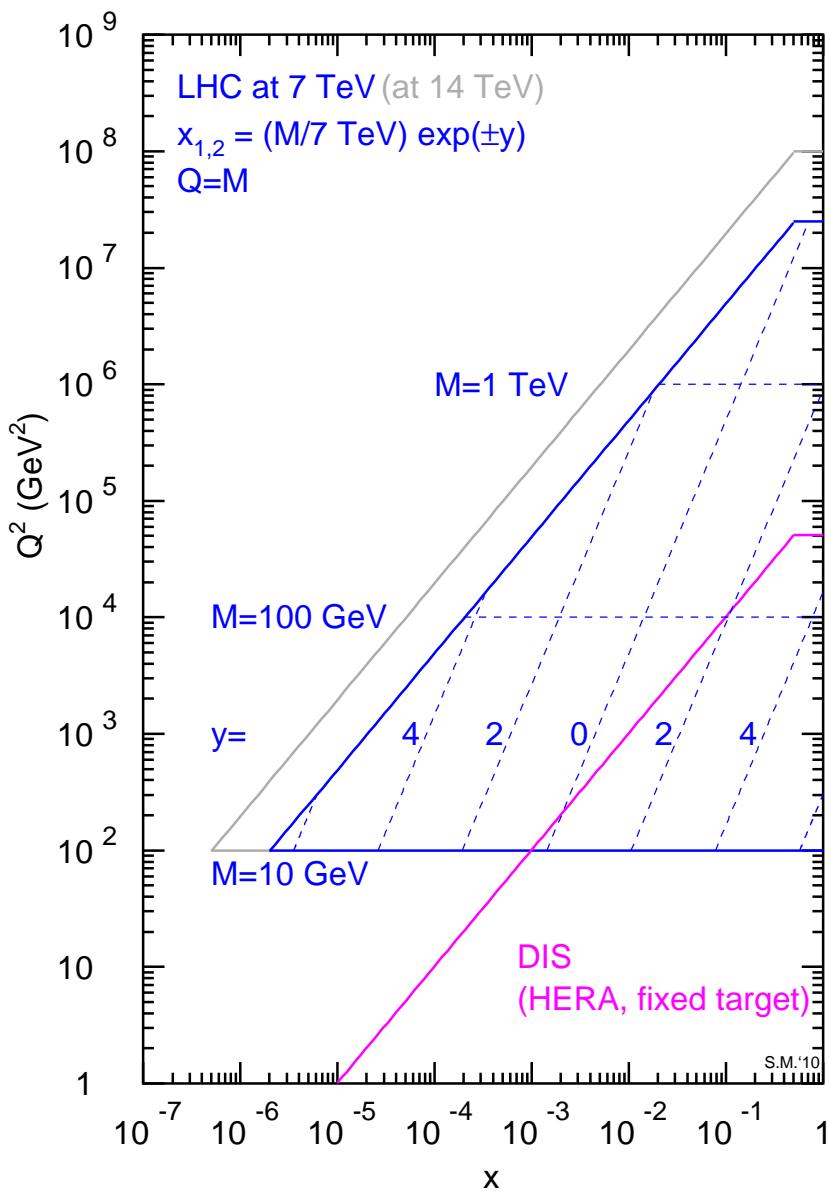
- variation of factorization scale μ : $\frac{d}{d \ln \mu^2} \sigma_{pp \rightarrow X} = \mathcal{O}(\alpha_s^{l+1})$

$$\sigma_{pp \rightarrow t\bar{t}X} = \sum_{ijk} f_i(\mu^2) \otimes f_j(\mu^2) \otimes \hat{\sigma}_{ij \rightarrow t\bar{t}}(\alpha_s(\mu^2), Q^2, \mu^2)$$

- Parton cross section $\hat{\sigma}_{ij \rightarrow t\bar{t}}$ calculable perturbatively in powers of α_s
 - constituent partons from incoming protons interact at short distances of order $\mathcal{O}(1/Q)$
- Parton luminosity $f_i \otimes f_j$
 - proton: very complicated multi-particle bound state
 - colliders: wide-band beams of quarks and gluons



Parton luminosity at LHC

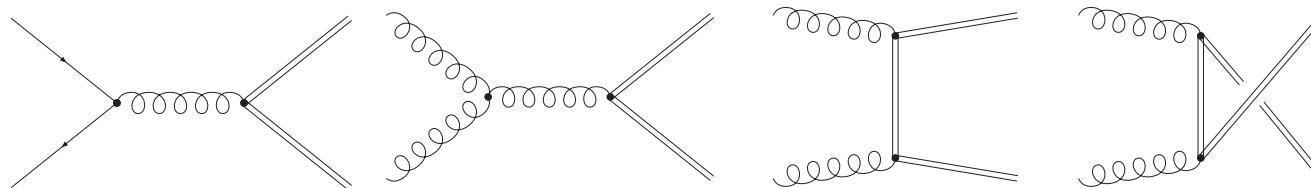


- LHC will run at 7 TeV until end of 2011 years, up to 1 fb^{-1}
- $t\bar{t}$ cross section is $\simeq 1/4$ rate with respect to run at 14 TeV
 - larger PDF uncertainties
- Parton kinematics restricted to larger effective $\langle x \rangle = M/\sqrt{S}$
 - 100 GeV physics: small- x , sea partons
 - TeV scales: large- x
- Limited discovery reach
 - less phase space available for heavy mass states
 - use 7 TeV for accurate SM benchmarking

Top quark production

- Leading order Feynman diagrams

$$\begin{array}{ccc} q + \bar{q} & \longrightarrow & Q + \bar{Q} \\ g + g & \longrightarrow & Q + \bar{Q} \end{array}$$

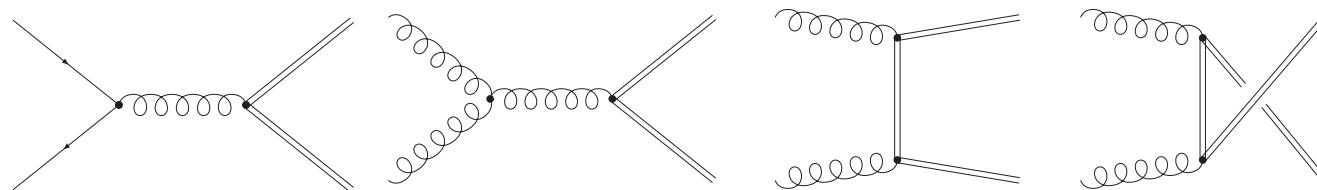


- NLO in QCD Nason, Dawson, Ellis '88; Beenakker, Smith, van Neerven '89; Mangano, Nason, Ridolfi '92; Bernreuther, Brandenburg, Si, Uwer '04; Mitov, Czakon '08; ...
 - accurate to $\mathcal{O}(15\%)$ at LHC

Top quark production

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$$\begin{array}{ccc} q + \bar{q} & \longrightarrow & Q + \bar{Q} \\ g + g & \longrightarrow & Q + \bar{Q} \end{array}$$



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Challenge

- Improve theory predictions and reduce theoretical uncertainty
 - hard scattering cross section $\hat{\sigma}_{ij \rightarrow t\bar{t}}$
 - parton luminosity $f_i \otimes f_j$

Recent theory activities

- General structure of massive QCD amplitudes
 - relate massive to massless amplitudes in limit $m \rightarrow 0$ Mitov, S.M. '06
 - two-loop virtual corrections to $q\bar{q} \rightarrow t\bar{t}$ and $gg \rightarrow t\bar{t}$
 - small-mass limit $m^2 \ll s, t, u$ Czakon, Mitov, S.M. '07
 - complete IR singularities Ferroglio, Neubert, Pecjak, Yang '09
- Exact virtual amplitudes
 - one-loop squared terms ($\text{NLO} \times \text{NLO}$)
Anastasiou, Mert Aybat '08; Kniehl, Merebashvili, Körner, Rogal '08
 - two-loop virtual corrections for $q\bar{q} \rightarrow t\bar{t}$
(analytic, n_f -terms) Bonciani, Ferroglio, Gehrmann, Maitre, Studerus '08;
(analytic, two-loop planar) Bonciani, Ferroglio, Gehrmann, Studerus '09;
(numerical result) Czakon '08
- Complete NLO corrections to $t\bar{t}$ in association with jets
 - $t\bar{t} + 1$ jet at NLO Dittmaier, Uwer, Weinzierl '07-'08; Melnikov, Schulze '10
 - $t\bar{t} + 2$ jets at NLO Bevilacqua, Czakon, Papadopoulos, Worek '10

Recent theory activities (cont'd)

- Threshold resummation
 - updates of cross section predictions based on resummation
S.M., Uwer '08; Cacciari, Frixione, Mangano, Nason, Ridolfi '08; Kidonakis, Vogt '08;
Beneke, Czakon, Falgari, Mitov, Schwinn '09;
Ahrens, Ferroglia, Neubert, Pecjak, Yang '10
 - coulomb corrections
Hagiwara, Sumino, Yokoya '08; Kiyo, Kühn, S.M., Steinhauser, Uwer '08
- Definition of mass parameter Hoang, Jain, Scimemi, Stewart '08
- Parton luminosity
 - precision PDFs for LHC (NNLO global analyses)
Martin, Stirling, Thorne, Watt '08; Alekhin, Blümlein, Klein, S.M. '09;
Jimenez-Delgado, Reya '09
 - correlation of cross section at NLO with gluon PDFs
Nadolsky, Lai, Cao, Huston, Pumplin, Stump, Tung, Yuan '08
 - benchmarking of PDFs under way

NLO

- Cross section for heavy-quark hadro-production (scaling functions f_{ij})

$$\hat{\sigma}_{ij \rightarrow t\bar{t}} = \frac{\alpha_s^2}{m_t^2} \left\{ f_{ij}^{(0)}(\rho) + (4\pi\alpha_s) f_{ij}^{(1)}(\rho, \mu_f/m_t, \mu_r/\mu_f) \right\}$$

- Perturbative expansion at NLO

NLO

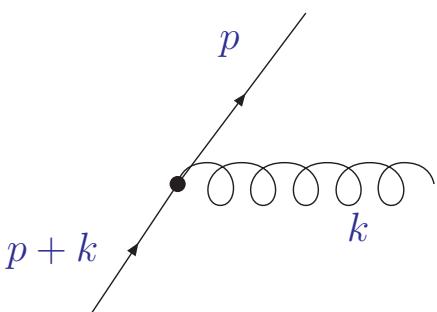
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- Perturbative expansion at NLO

Strategy beyond NLO

- Use universal features of soft/collinear regions of phase space
 - double logarithms from singular regions in Feynman diagrams
 - propagator vanishes for: $E_g = 0$, soft $\theta_{qg} = 0$ collinear

$$\begin{aligned} \frac{1}{(p+k)^2} &= \frac{1}{2p \cdot k} = \frac{1}{2E_q E_g (1 - \cos \theta_{qg})} \\ \alpha_s \int d^4 k \frac{1}{(p+k)^2} &\longrightarrow \alpha_s \int dE_g d\sin \theta_{qg} \frac{1}{2E_q E_g (1 - \cos \theta_{qg})} \\ &\longrightarrow \alpha_s \ln^2(\dots) \end{aligned}$$


Beyond NLO: all-order resummation

- Cross section for heavy-quark hadro-production (scaling functions f_{ij})

$$\hat{\sigma}_{ij \rightarrow t\bar{t}} = \frac{\alpha_s^2}{m_t^2} \left\{ f_{ij}^{(0)}(\rho) + (4\pi\alpha_s) f_{ij}^{(1)}(\rho, \mu_f/m_t, \mu_r/\mu_f) \right. \\ \left. + f_{ij}^{\text{resummed}}(\alpha_s, N, \mu_f/m_t, \mu_r/\mu_f) + \mathcal{O}(N^{-1} \ln^n N) \right\}$$

- 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)
 - long history Kidonakis, Sterman '97; Bonciani, Catani, Mangano, Nason '98; Kidonakis, Laenen, S.M., Vogt '01; ...
- Upshot:
 - $f_{ij}^{\text{resummed}} \simeq \exp \left(\alpha_s \ln^2 N \right) + \mathcal{O}(N^{-1} \ln^n N)$

Beyond NLO: NNLO_{approx}

- Cross section for heavy-quark hadro-production (scaling functions f_{ij})

$$\hat{\sigma}_{ij \rightarrow t\bar{t}} = \frac{\alpha_s^2}{m_t^2} \left\{ f_{ij}^{(0)}(\rho) + (4\pi\alpha_s) f_{ij}^{(1)}(\rho, \mu_f/m_t, \mu_r/\mu_f) + (4\pi\alpha_s)^2 f_{ij}^{(2)}(\rho, \mu_f/m_t, \mu_r/\mu_f) + \mathcal{O}(\alpha_s^3) \right\}$$

- General structure at NNLO
 - dependence on factorization and renormalization scale
 $L_M = \ln(\mu_f^2/m_t^2)$ and $L_R = \ln(\mu_r^2/\mu_f^2)$

$$\begin{aligned} f_{ij}^{(1)}(\rho, \mu_f/m_t, \mu_r/m_t) &= f_{ij}^{(10)} + L_M f_{ij}^{(11)} + 2\beta_0 L_R f_{ij}^{(0)}, \\ f_{ij}^{(2)}(\rho, \mu_f/m_t, \mu_r/m_t) &= f_{ij}^{(20)} + L_M f_{ij}^{(21)} + L_M^2 f_{ij}^{(22)} + 3\beta_0 L_R f_{ij}^{(10)} \\ &\quad + 3\beta_0 L_R L_M f_{ij}^{(11)} + 2\beta_1 L_R f_{ij}^{(0)} + 3\beta_0^2 L_R^2 f_{ij}^{(0)} \end{aligned}$$

- only unknown: $f_{ij}^{(20)}$ (but knowledge of threshold logarithms)
- all other function known through renormalization group equations

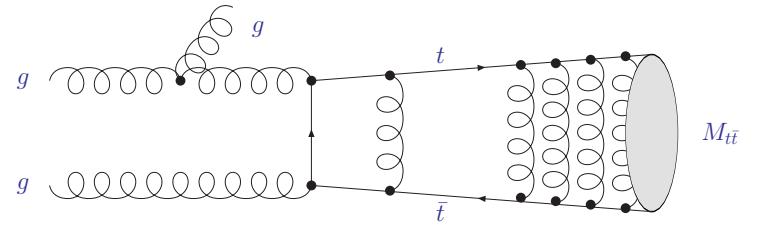
Two-loop results

- NNLO cross section for heavy-quark hadro-production near threshold
S.M, Uwer '08; Beneke, Czakon, Falgari, Mitov, Schwinn '09
 - e.g. gg -fusion for $n_f = 5$ light flavors at $\mu = m_t$

$$f_{gg}^{(10)} = \frac{f_{gg}^{(0)}}{(16\pi^2)} \left\{ 96 \ln^2 \beta - 9.5165 \ln \beta + 35.322 + 5.1698 \frac{1}{\beta} \right\}$$
$$f_{gg}^{(20)} = \frac{f_{gg}^{(0)}}{(16\pi^2)^2} \left\{ 4608 \ln^4 \beta - 1894.9 \ln^3 \beta + \left(-912.35 + 496.30 \frac{1}{\beta} \right) \ln^2 \beta \right.$$
$$\left. + \left(2456.7 + 321.14 \frac{1}{\beta} \right) \ln \beta + 68.547 \frac{1}{\beta^2} - 8.6226 \frac{1}{\beta} + C_{gg}^{(2)} \right\}$$

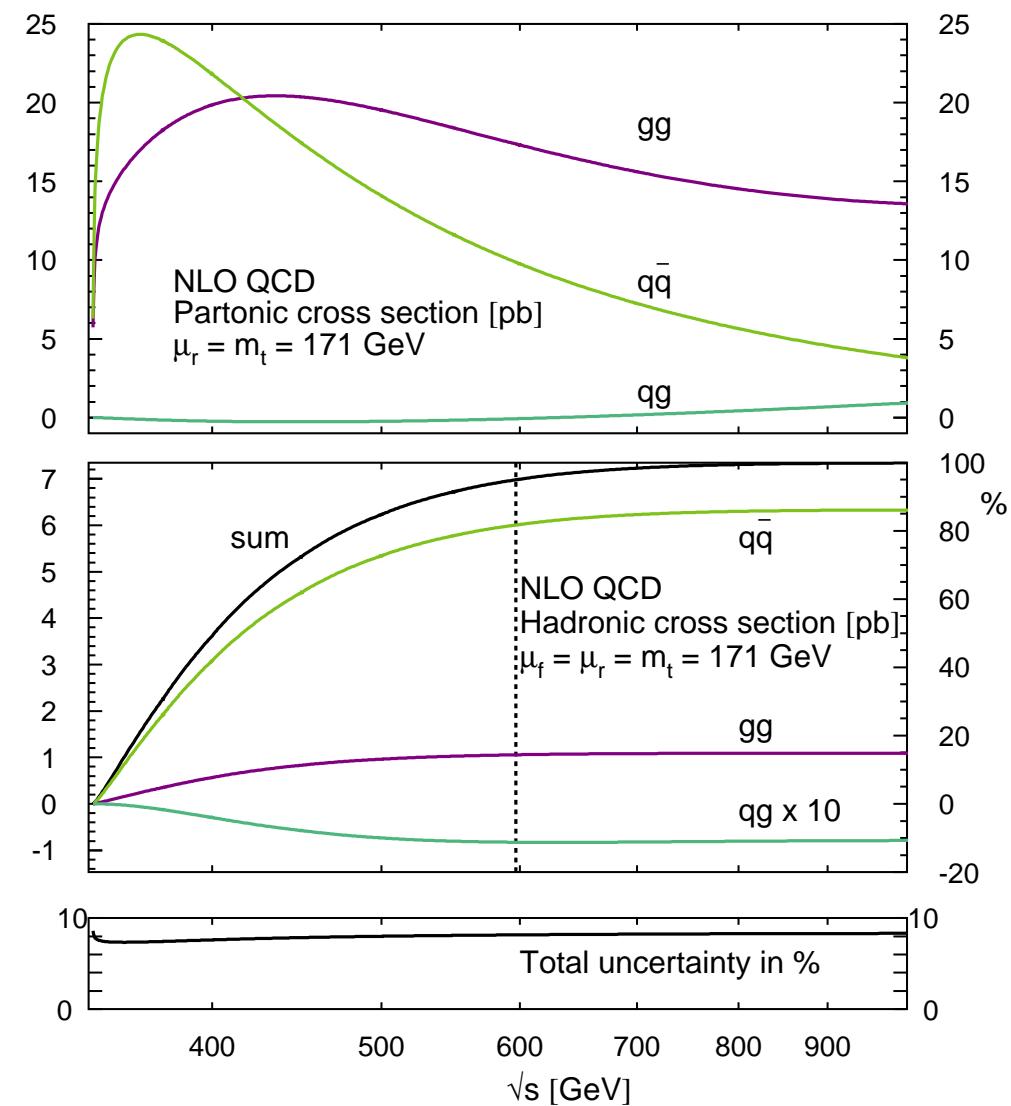
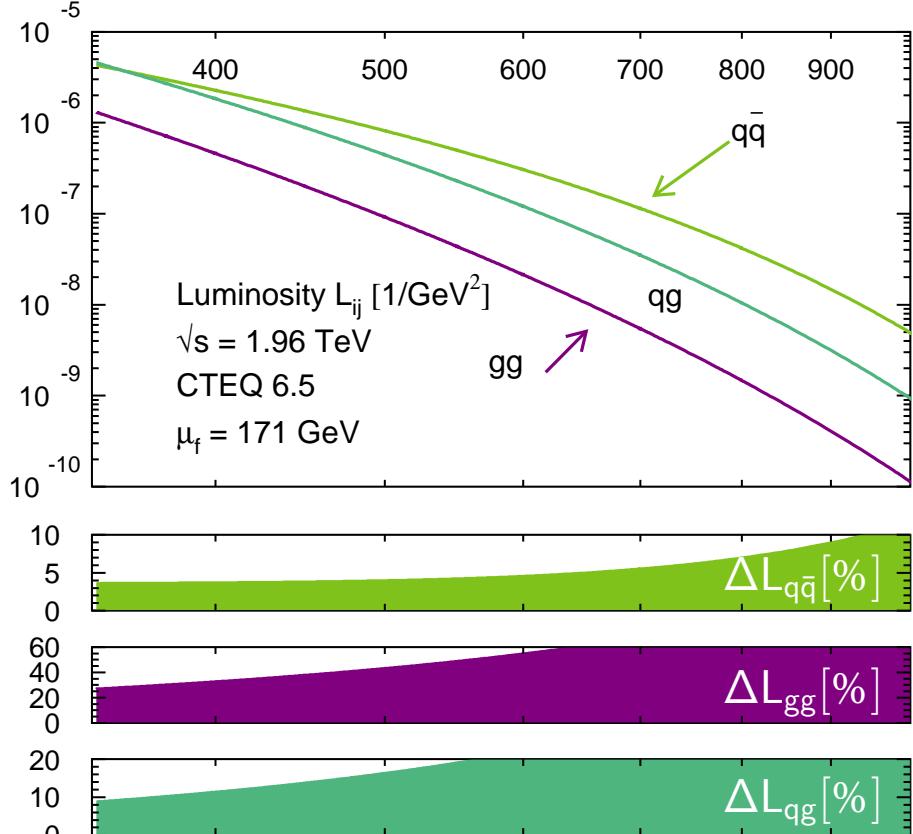
Who's who

- Sudakov logarithms in $\ln \beta$ (generated from resummed cross sections)
- $1/\beta$ -terms from Coulomb corrections
resummation to all orders
in non-relativistic QCD
- unknown constant $C_{gg}^{(2)}$



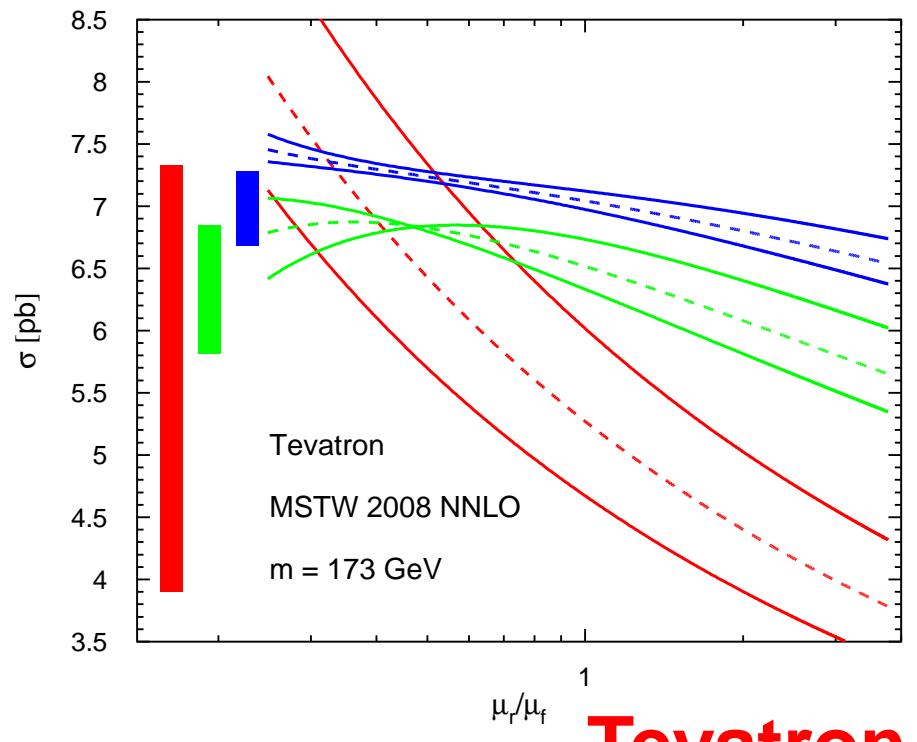
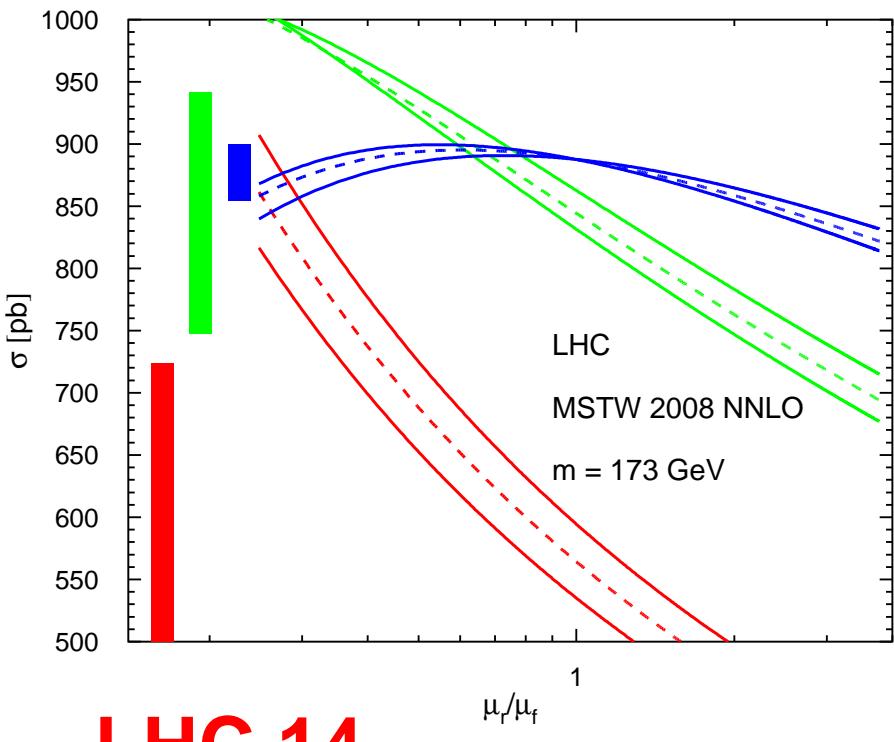
Total cross section at Tevatron

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



Scale dependence

- Theoretical uncertainty from variation of scales μ_R, μ_F
 - plot with PDF set MSTW 2008 (but largely independent on PDFs)
 - mass $m_t = 173 \text{ GeV}$ (from $m_t = 173.1 \pm 1.3 \text{ GeV}$ Tevatron winter '09)
 - stable predictions in range $\mu_R, \mu_F \in [m_t/2, 2m_t]$
 - $-3\% \leq \Delta\sigma \leq +1\%$ at LHC
 - $-5\% \leq \Delta\sigma \leq +3\%$ at Tevatron



The total cross section

- Theory prediction at NNLO_{approx} accuracy
 - pole mass $m_t = 173 \text{ GeV}$
 - theoretical uncertainty from variation of $\mu_R, \mu_F \in [m_t/2, 2m_t]$
 - NNLO PDF set and α_s , e.g. MSTW 2008

$$\sigma_{\text{LHC}} = 157.0 \text{ pb} \quad {}^{+2.1}_{-6.5} \text{ pb (scale)} \quad {}^{+4.4}_{-4.4} \text{ pb (MSTW2008)}$$

$$\sigma_{\text{TeV}} = 6.93 \text{ pb} \quad {}^{+0.15}_{-0.32} \text{ pb (scale)} \quad {}^{+0.14}_{-0.14} \text{ pb (MSTW2008)}$$

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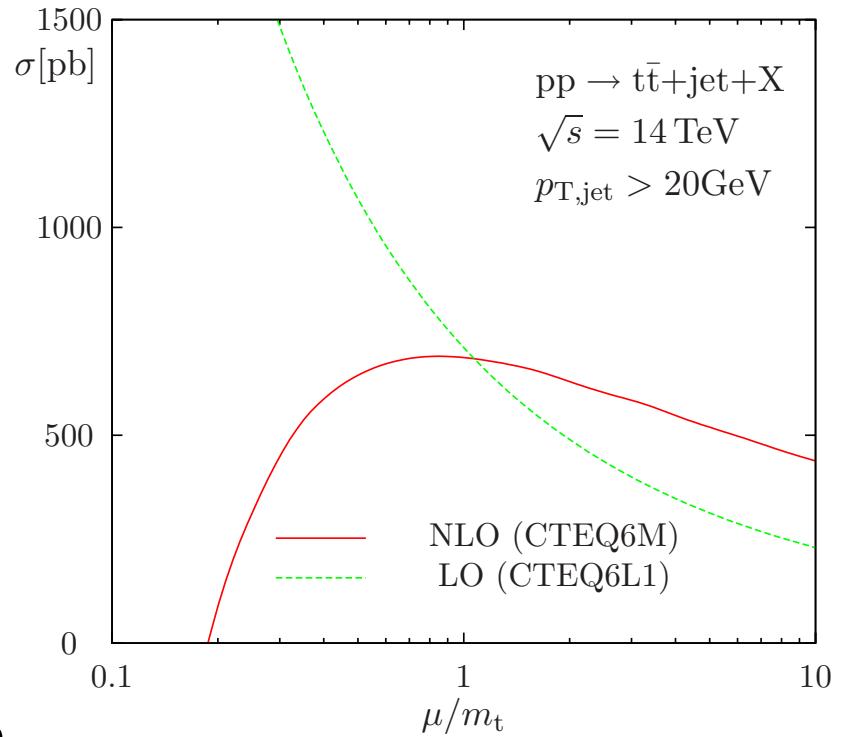
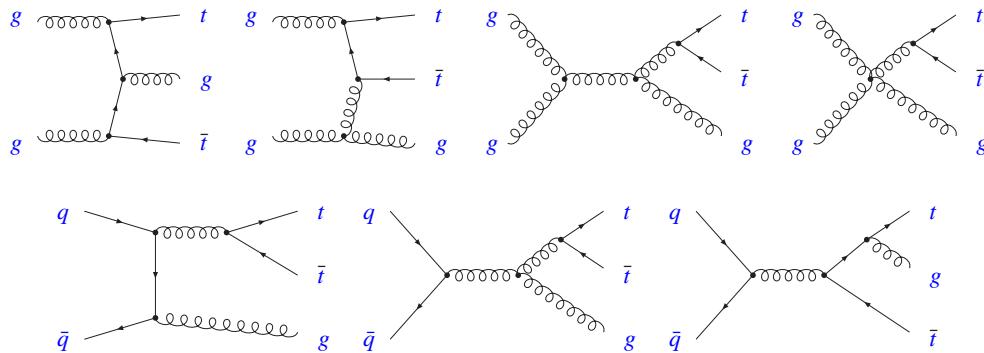
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Quality control

- Check of systematics: variation of $C_{gg}^{(2)}$
 - recall $f_{gg}^{(20)} \simeq f_{gg}^{(0)} \{ 4608 \ln^4 \beta + \dots + C_{gg}^{(2)} \}$
- Estimate systematic uncertainty of total cross section $\Delta\sigma \sim \mathcal{O}(2\%)$
 - $\Delta\sigma \sim \mathcal{O}(3 - 4) \text{ pb}$ at LHC 7 TeV ($\mathcal{O}(10 - 15) \text{ pb}$ at 14 TeV)
 - $\Delta\sigma \sim \mathcal{O}(0.15 - 0.2) \text{ pb}$ at Tevatron

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

- LHC: large rates for production of $t\bar{t}$ -pairs with additional jets
- NLO corrections to $t\bar{t}$ +jet production are part of NNLO corrections for inclusive $t\bar{t}$ production



- Check of systematics: hard radiation
 - at scale $\mu_R = \mu_F = m_t$ corrections are almost zero
 - threshold resummation captures dominant contributions

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

$p_{T,\text{jet,cut}}$ [GeV]	$\sigma_{t\bar{t}\text{jet}} [\text{pb}]$	
	LO	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

$p_{T,\text{jet,cut}}$ [GeV]	$\sigma_{t\bar{t}\text{jet}} [\text{pb}]$	
	LO	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 14

- Cross section $\sigma_{t\bar{t}\text{jet}}$ for different values of $p_{T,\text{jet,cut}}$ for $\mu = \mu_R = \mu_F = \{m_t/2, m_t, 2m_t\}$ with PDF sets CTEQ6L1, CTEQ6M Dittmaier, Uwer, Weinzierl '07-'08

Concordance approach

Cacciari, Czakon, Mangano, Mitov, S.M., Nason, Uwer [to appear]

- Philosophy
 - genuine NLO approach improved with threshold logarithms only
 - technically: truncation of $f_{ij}^{(2)} = f_{ij}^{(20)} + L_M f_{ij}^{(21)} + L_M^2 f_{ij}^{(22)} + \dots$ to logarithmic accuracy in $\ln \beta$
- Conservative estimate of theoretical uncertainty
 - scale variation of $\mu_R, \mu_F \in [m_t/2, 2m_t]$ with $1/2 \leq \mu_R/\mu_F \leq 2$
 - e.g. pole mass $m_t = 173 \text{ GeV}$ and NNLO PDF set MSTW08

$$\sigma_{\text{LHC}} = 155.4 \text{ pb} \quad {}^{+1.3}_{-6.3} \text{ pb (scale)} \quad {}^{+4.4}_{-4.4} \text{ pb (MSTW2008)}$$

$$\sigma_{\text{TeV}} = 6.92 \text{ pb} \quad {}^{+0.01}_{-0.41} \text{ pb (scale)} \quad {}^{+0.14}_{-0.14} \text{ pb (MSTW2008)}$$

preliminary

HATHOR

C++ package

Aliev, Lacker, Langenfeld, S.M. Uwer [to appear]

- Cross section evaluation done entirely in Hathor class

```
unsigned int scheme = Hathor::LO | Hathor::NLO | Hathor::NNLO;  
double mt = 171., muf=171., mur=171.;  
double val,err,chi2a,up,down;  
Lhapdf pdf( "MSTW2008nnlo68cl" );    ← PDF choice  
Hathor XS(pdf)
```



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Lhapdf pdf( "MSTW2008nnlo68cl" );    ← PDF choice  
Hathor XS(pdf)  
  
XS.setPrecision(Hathor::MEDIUM);  
XS.getXsection(mt,mur,muf);    →  $\sigma = 164.3^{+4.6}_{-9.2}$  pb (scale unc.)  
XS.getResult(0,val,err,chi2a);
```



HATHOR

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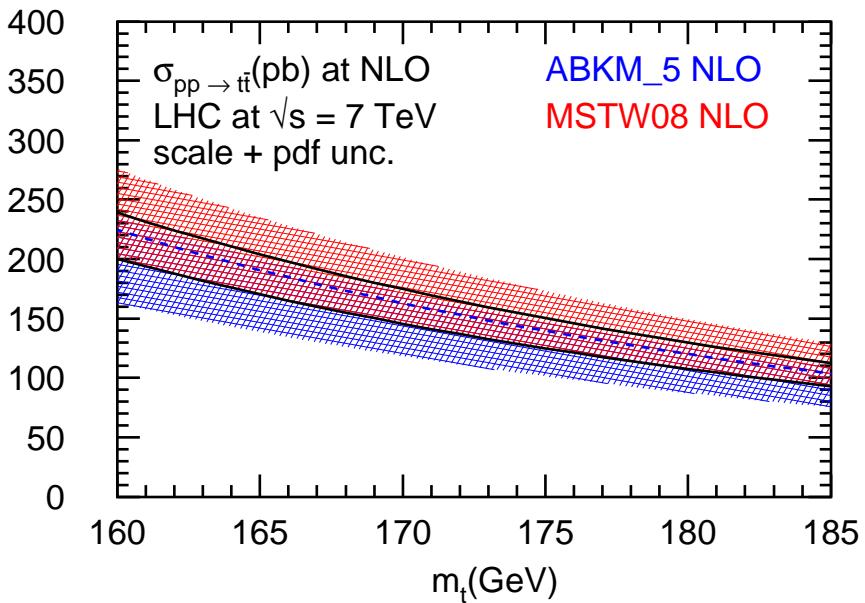
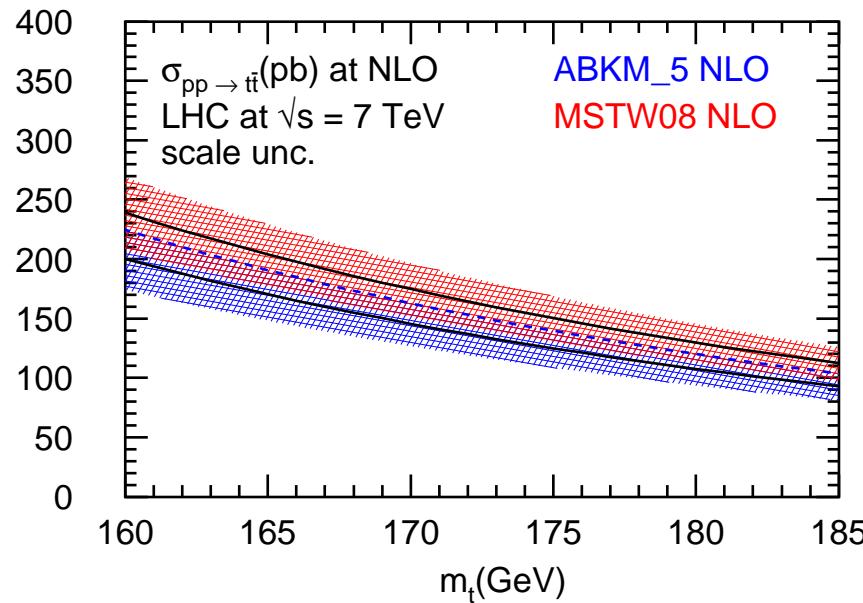
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XS.getResult(0,val,err,chi2a);  
  
XS.setScheme(scheme | Hathor::PDF_SCAN); ← with PDF error scan  
XS.setPrecision(Hathor::LOW);  
XS.getXsection(mt,mur,muf); } →  $\sigma = 164.3^{+4.6}_{-9.2}$  pb (sc.)  $^{+4.4}_{-4.4}$  pb (PDF unc.)  
XS.getPdfErr(up,down);
```



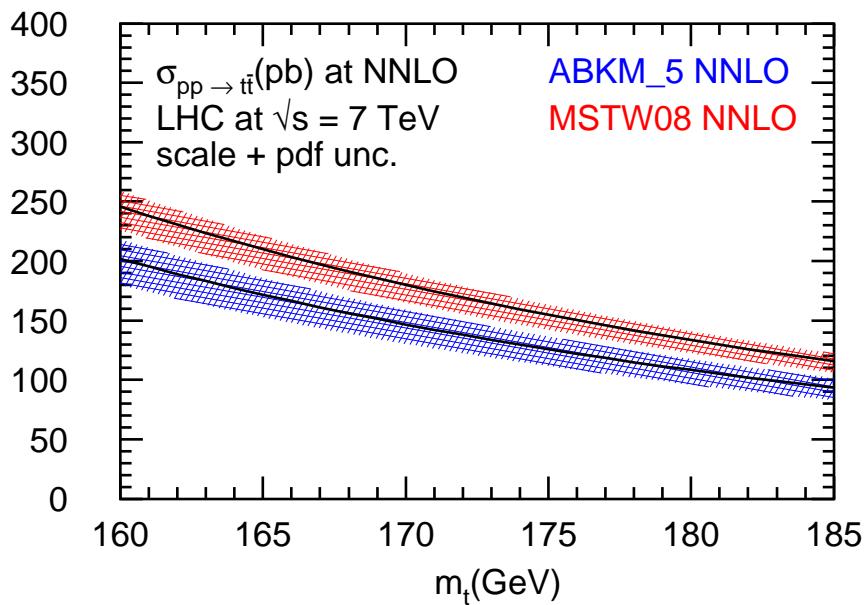
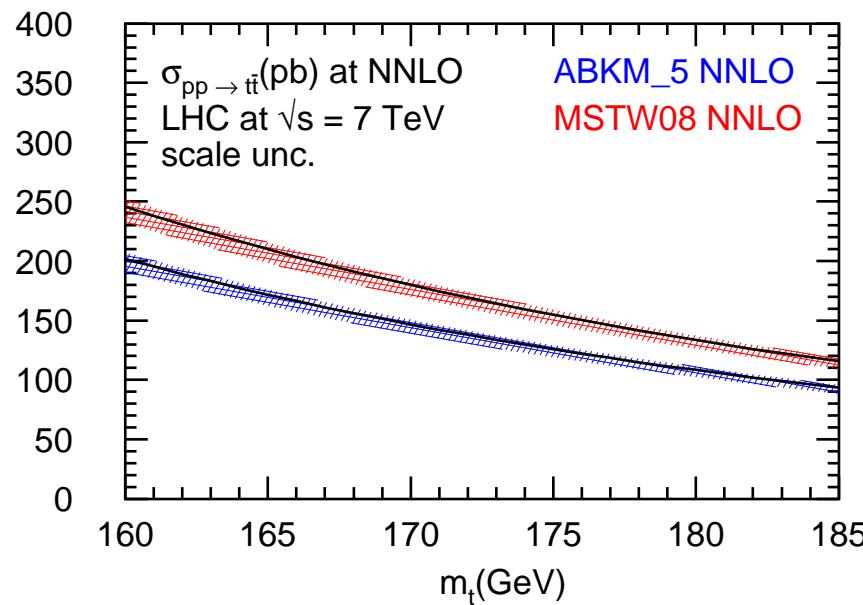
Dependence on parton distributions

- Comparision of NLO and NNLO_{approx}
- Theoretical uncertainty from scale variation: $\mu_R, \mu_F \in [m_t/2, 2m_t]$
 - uncertainties: scale (left) and scale + PDF (right)
- Sizeable difference between the ABKM/MSTW sets at NNLO well outside the PDF uncertainty
 - due to value of α_s and shape of gluon PDFs at $\langle x \rangle = 2m_t/\sqrt{s}$
 - can only be settled with first LHC data



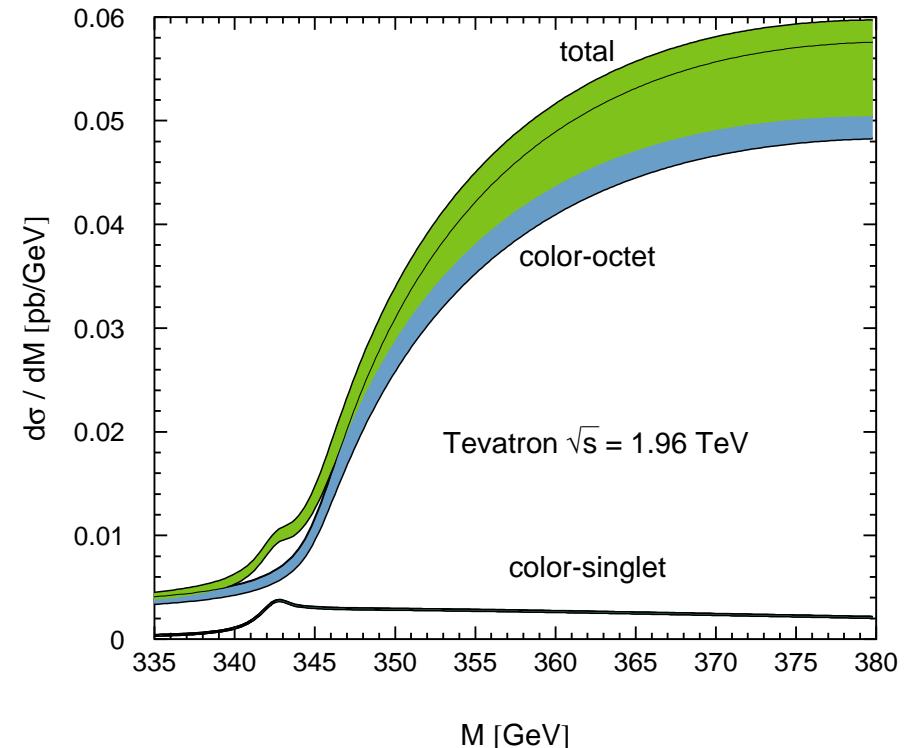
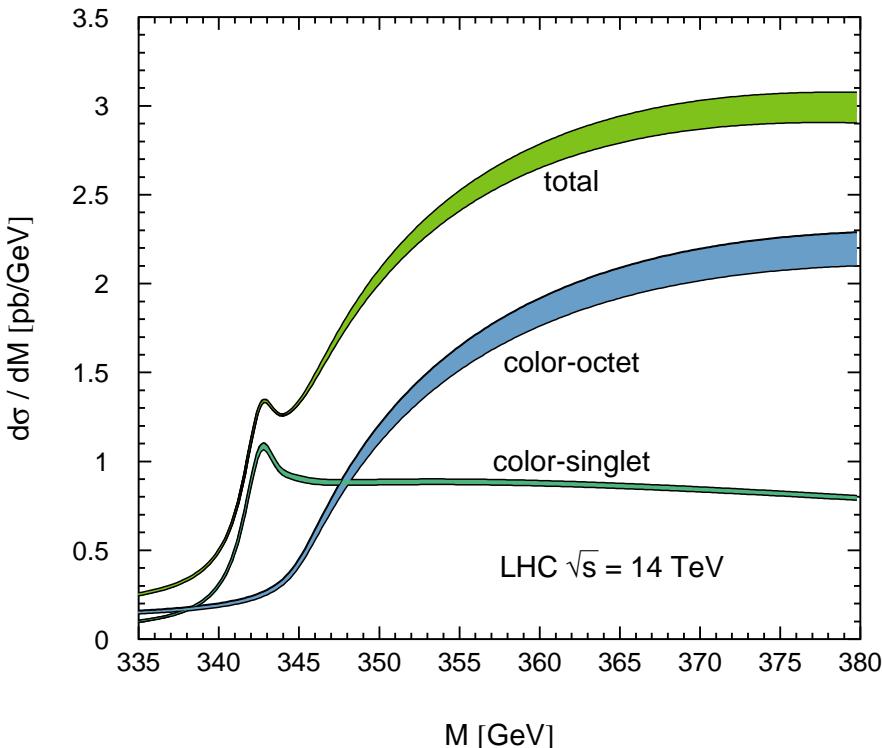
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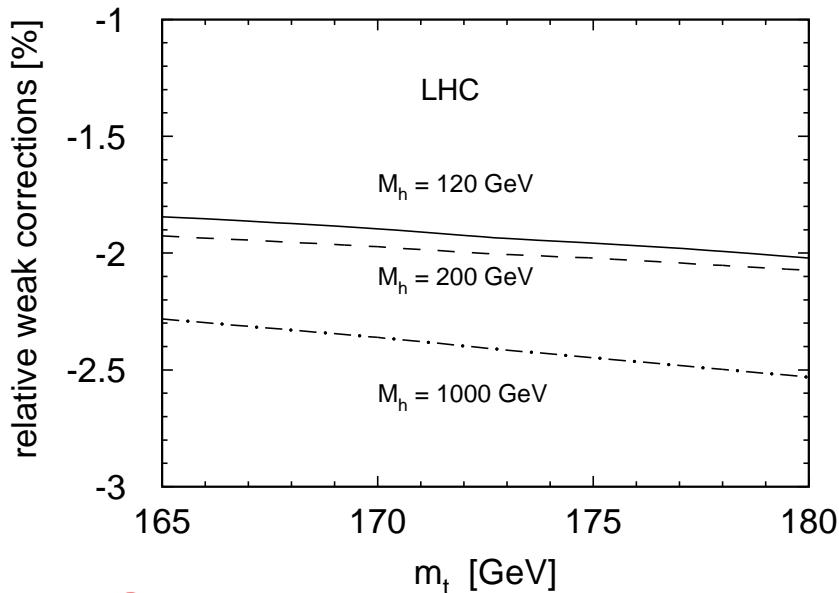
Resummation of Coulomb corrections

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

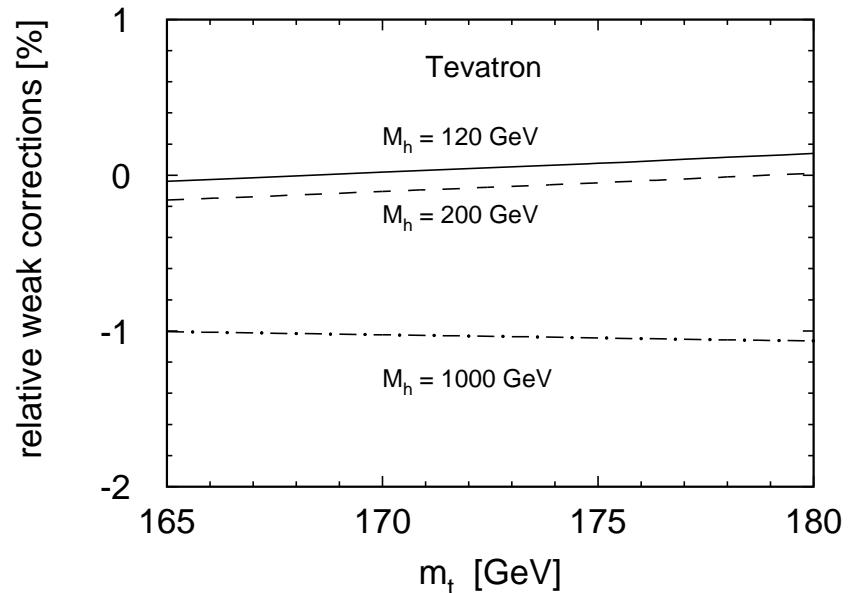


Electroweak corrections

- Electroweak corrections (ratio of $\sigma_{\text{EW}}/\sigma_{\text{LO}}$) Beenakker, Denner, Hollik, Mertig, Sack, Wackerlo '94; Bernreuther, Fücker '05; Kühn, Uwer, Scharf '06
- Effect depends on Higgs mass
(choices $m_H = 120\text{GeV}$, $m_H = 200\text{GeV}$, $m_H = 1000\text{GeV}$)



LHC 14



Tevatron

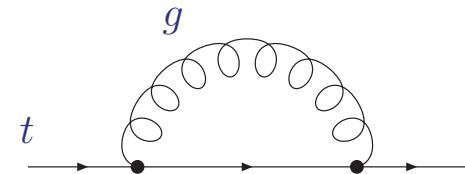
- Tevatron: vanishing contribution for light Higgs
- LHC: $\mathcal{O}(2\%)$ with respect to σ_{LO}
negative contribution to total cross section $\Delta\sigma_{\text{EW}} \simeq \mathcal{O}(10 - 15) \text{ pb}$

Mass dependence of cross section

Pole mass scheme

- Based on (unphysical) concept of top-quark being a free parton

$$\not{p} - m_t - \Sigma(p, m_t) \Big|_{p^2 = m_t^2}$$



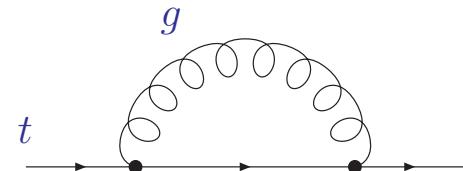
- heavy-quark self-energy $\Sigma(p, m_t)$ receives contributions from regions of all loop momenta – also from momenta of $\mathcal{O}(\Lambda_{\text{QCD}})$

Mass dependence of cross section

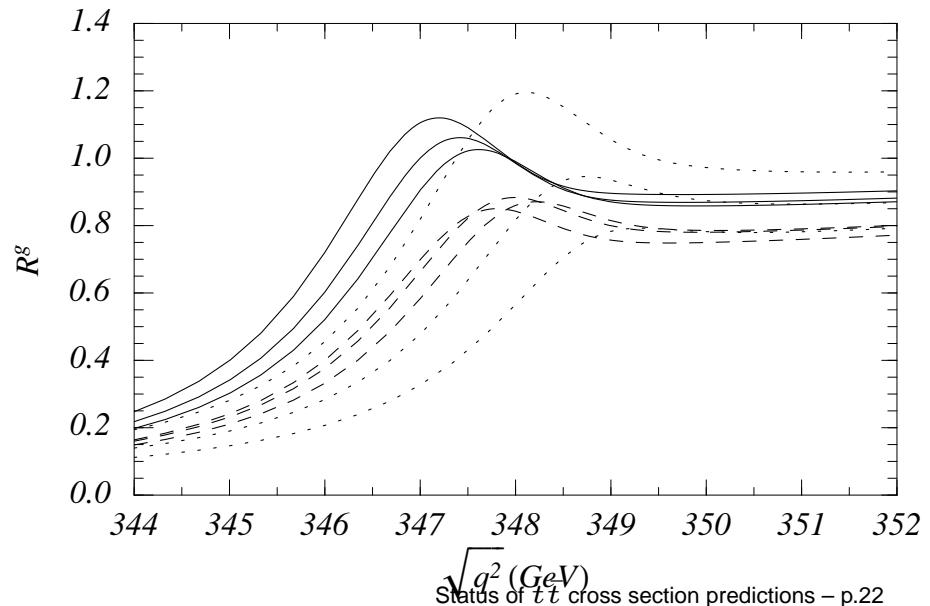
Pole mass scheme

- Based on (unphysical) concept of top-quark being a free parton

$$\not{p} - m_t - \Sigma(p, m_t) \Big|_{p^2 = m_t^2}$$

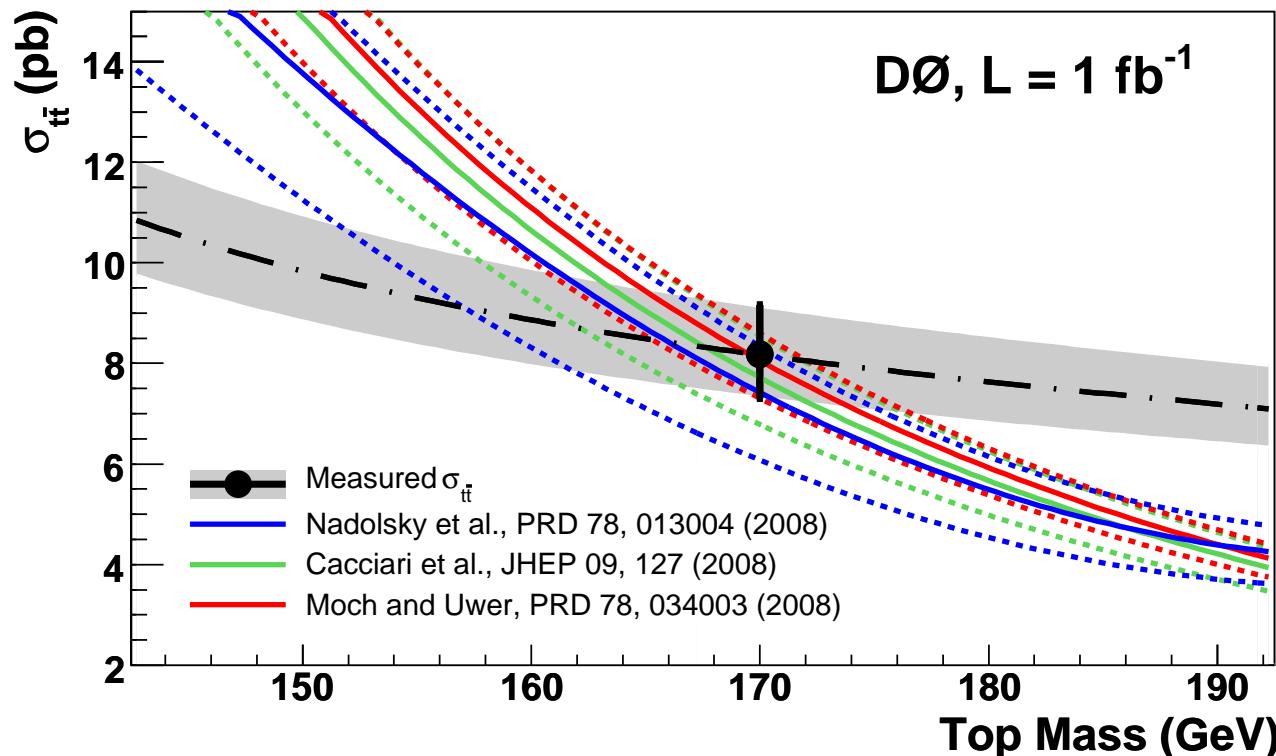


- heavy-quark self-energy $\Sigma(p, m_t)$ receives contributions from regions of all loop momenta – also from momenta of $\mathcal{O}(\Lambda_{\text{QCD}})$
- Pole mass measurements are strongly order-dependent
 - e.g. threshold scan of cross section in e^+e^- collision
Beneke, Signer, Smirnov '99;
Hoang, Teubner '99;
Melnikov, Yelkhovsky '98;
Penin, Pivovarov '99;
Yakovlev '99
 - LO (dotted), NLO (dashed), NNLO (solid)



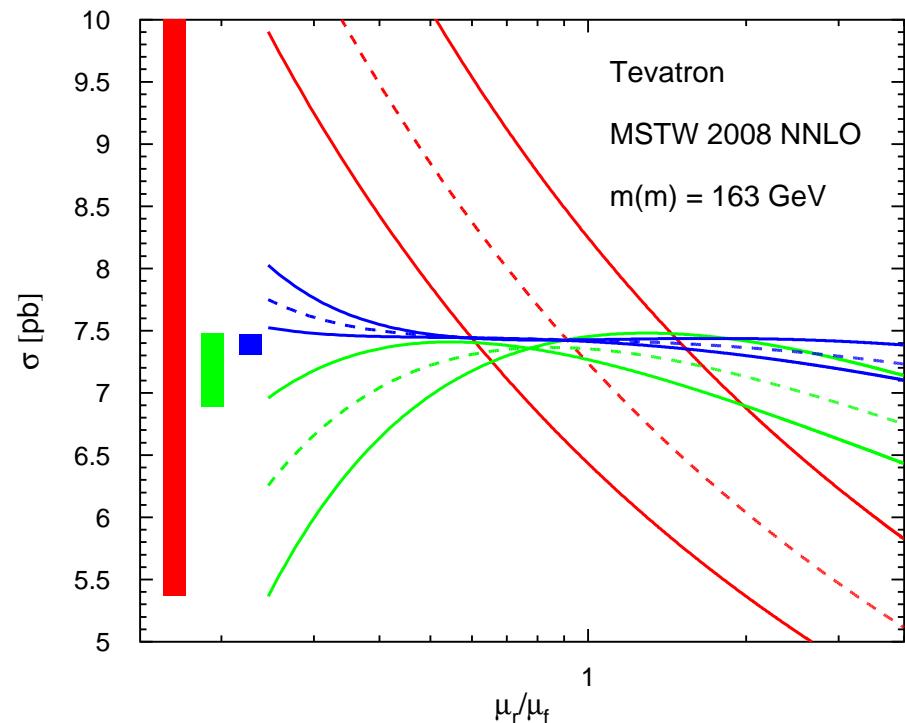
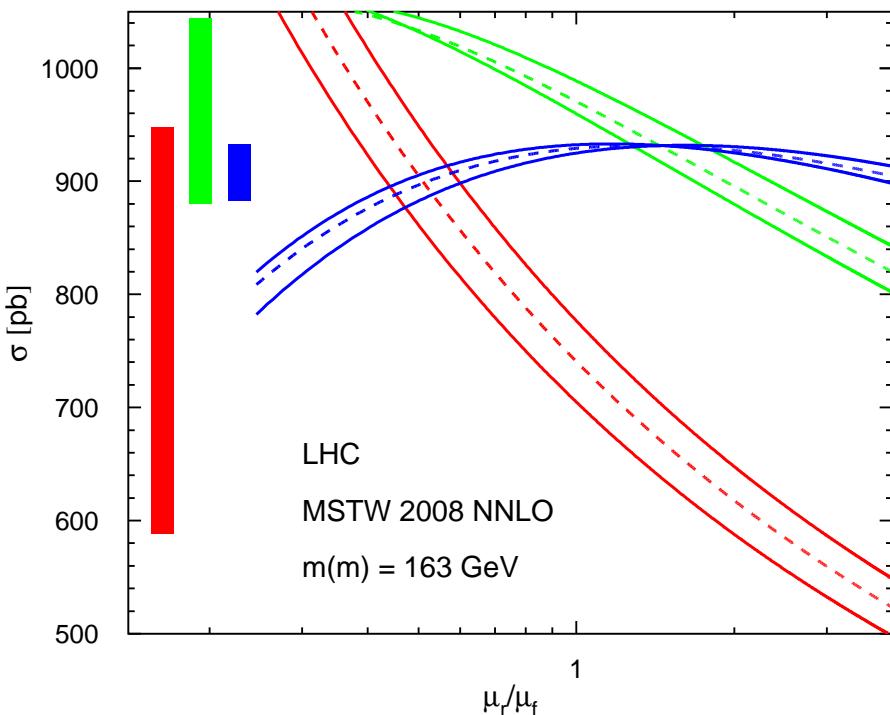
Tevatron analyses

- Total cross section and different channels of Tevatron analyses (theory uncertainty band from scale variation)
- Determination of m_t from total cross section (slope $d\sigma/dm_t$)
 - e.g. DZero '09: NLO $m_t = 165.5^{+6.1}_{-5.9}$; NNLO $m_t = 169.1^{+5.9}_{-5.2}$, ...



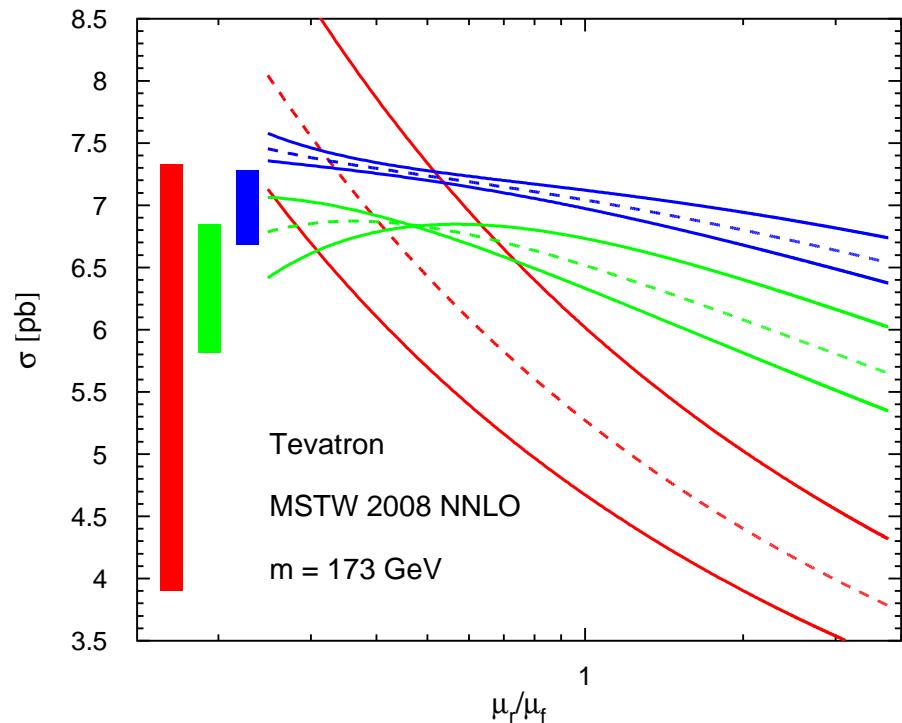
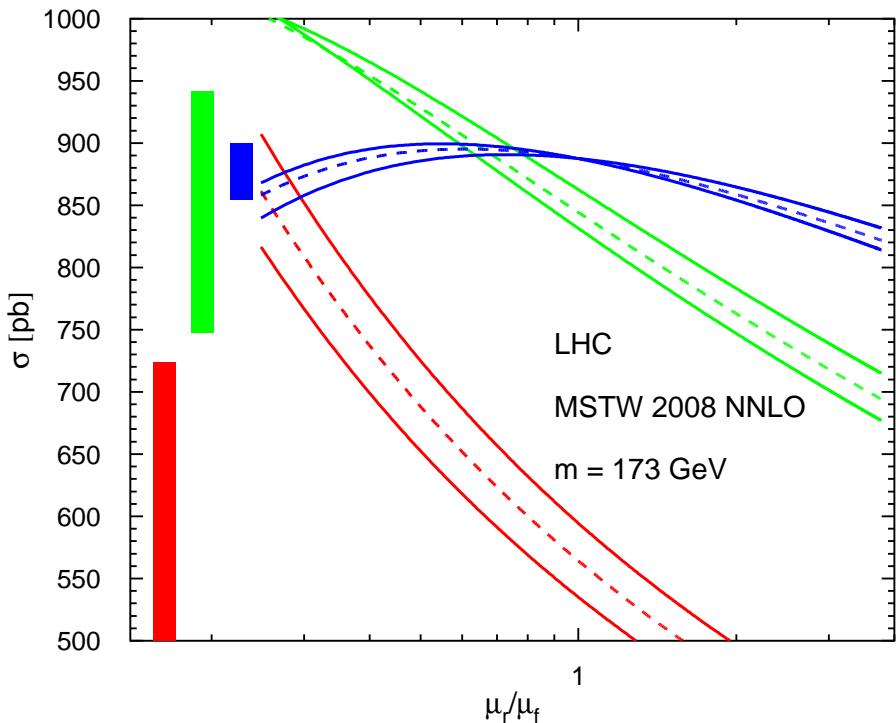
The running top-quark mass

- \overline{MS} mass definition $m(\mu_R)$ realizes running mass (scale dependence)
 - short distance mass probes at scale of hard scattering
 - conversion between pole mass and \overline{MS} mass definition in perturbation theory: $m_t = m(\mu_R) \left(1 + a_s(\mu_R)d^{(1)} + a_s(\mu_R)^2 d^{(2)}\right)$
- Scale dependence greatly reduced



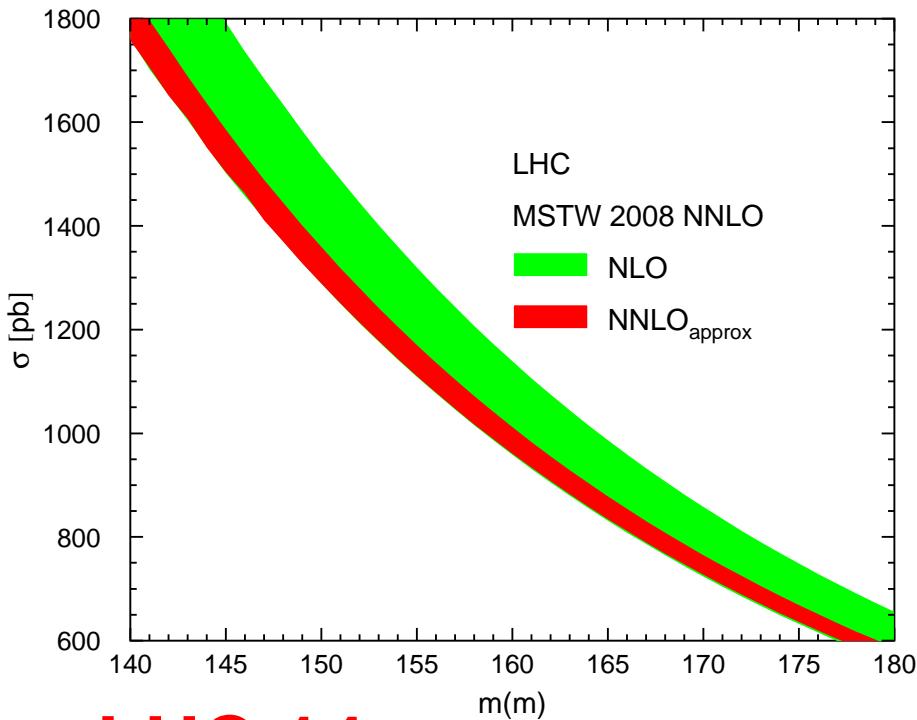
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- Pole mass scheme for comparison

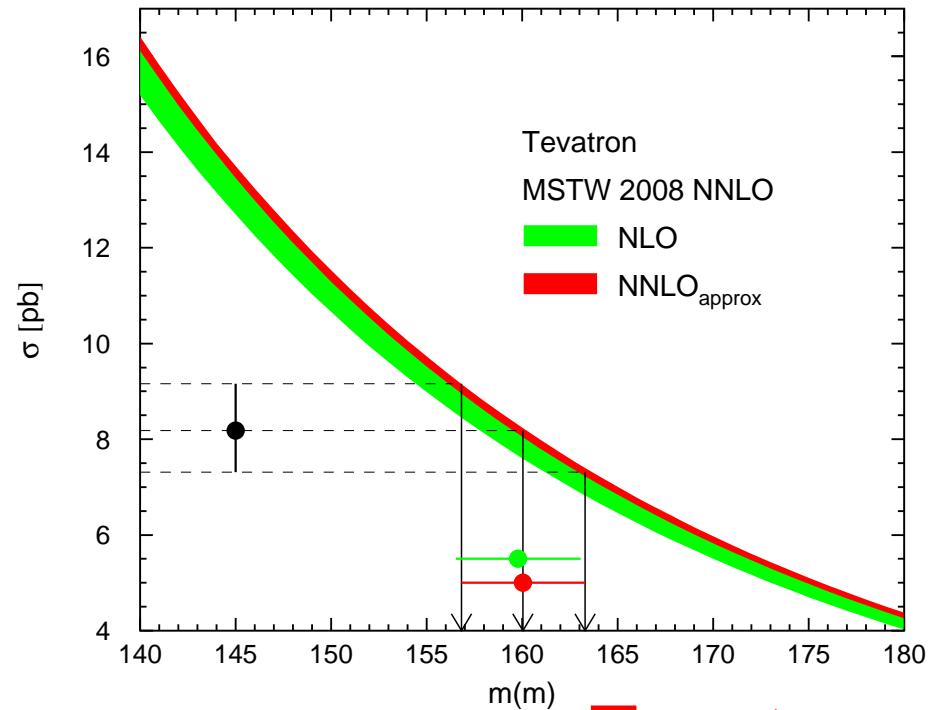


Mass dependence in \overline{MS} mass scheme

- Total top-quark cross section as function of \overline{m}
 - theoretical uncertainty (band) due to variation of $\mu_R \in [\overline{m}/2, 2\overline{m}]$ for fixed set $\mu_F \in \overline{m}/2, \overline{m}, 2\overline{m}$



LHC 14

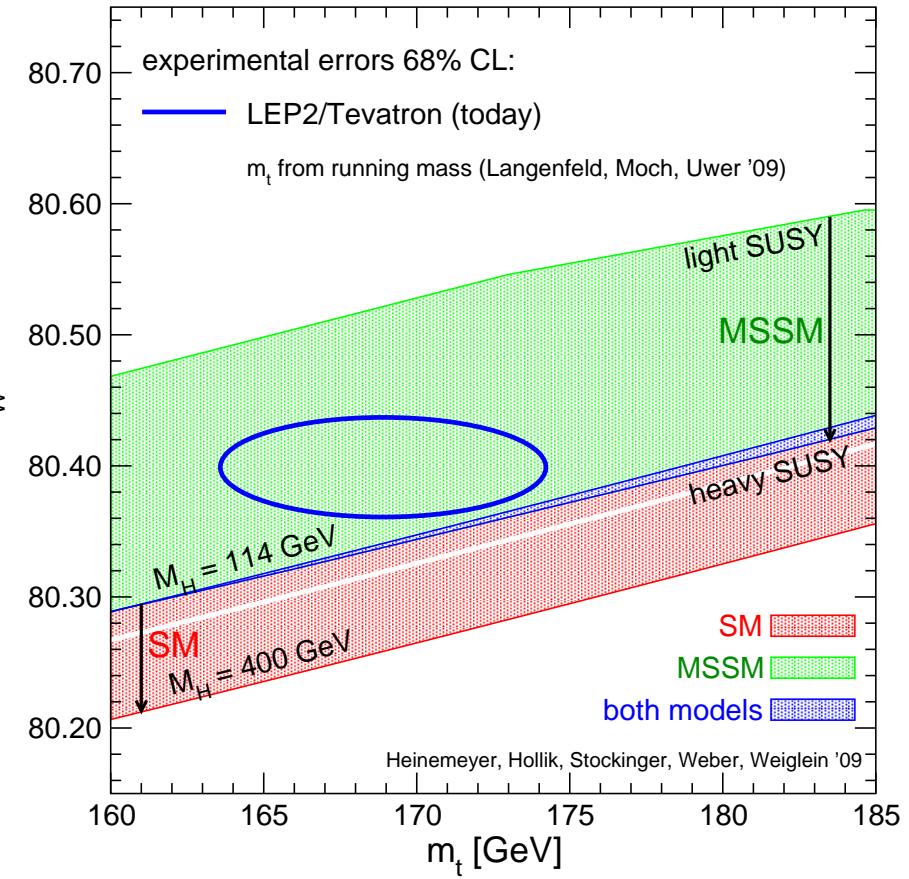
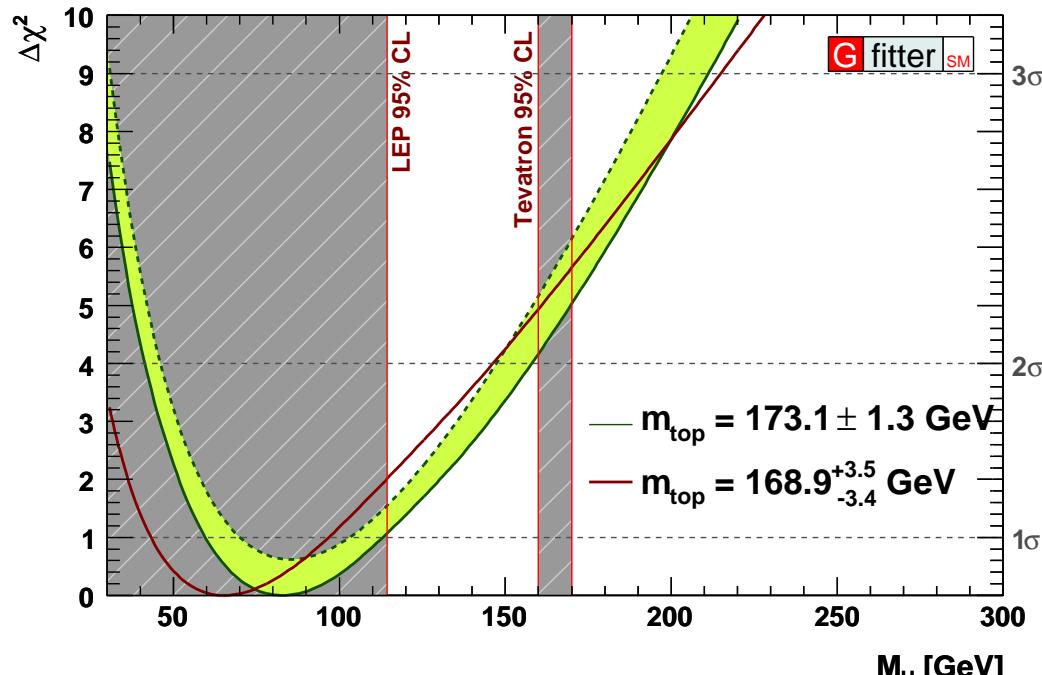


Tevatron

- First direct determination of $m(m)$ Langenfeld, S.M., Uwer '09
 - \overline{MS} mass $m(m) = 160.0^{+3.3}_{-3.2} \text{ GeV}$
 - conversion to pole mass $m_t = 168.9^{+3.5}_{-3.4} \text{ GeV}$

Implications for indirect Higgs searches

- Electroweak precision data constrains M_H



- pole mass $m_t = 168.9^{+3.5}_{-3.4}$ GeV
(lighter top-quark masses disfavor SM Higgs sector)

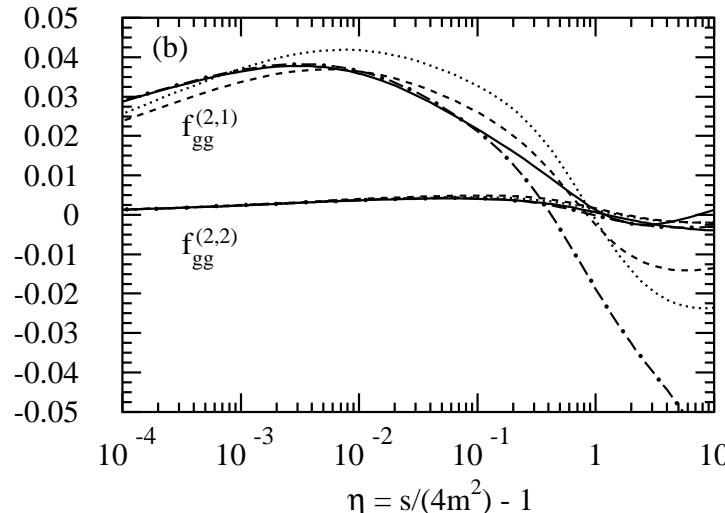
Summary

- Top quark theory
 - much recent progress for Tevatron and LHC phenomenology
 - improved understanding of theory and application of new concepts
- Total cross section
 - NNLO_{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
 - electroweak corrections
 - bound state effects for $t\bar{t}$ -system
- \overline{MS} mass definition
 - running top-quark mass of $m(\mu = m) = 160.0^{+3.3}_{-3.2}$ GeV
 - greatly reduced scale dependence
 - much improved convergence of perturbation theory

Extra slides

Other recent developments

- Total cross section from invariant mass distribution $d\sigma/dM_{t\bar{t}}$
Ahrens, Ferroglia, Neubert, Pecjak, Yang '10
 - resummation of threshold logarithms in $\ln(1 - M_{t\bar{t}}^2/s)/(1 - M_{t\bar{t}}^2/s)$
- Cross section numbers significantly lower
 - $\sigma_{\text{LHC}} = 146 \text{ pb} \quad {}^{+7}_{-7} \text{ pb (scale)} \quad {}^{+8}_{-8} \text{ pb (MSTW2008)}$
 - $\sigma_{\text{TeV}} = 6.48 \text{ pb} \quad {}^{+0.17}_{-0.21} \text{ pb (scale)} \quad {}^{+0.32}_{-0.25} \text{ pb (MSTW2008)}$
- Open issues:
 - impact of scale choices μ_s, μ_h, μ_f
 - compatibility at high energy (BFKL asymptotics at small- x)



Kidonakis, Laenen, S.M., Vogt '01