RG-Improved Predictions for Top-Quark Pair Production at Hadron Colliders

Matthias Neubert
Johannes Gutenberg University Mainz
& Ruprecht Karls University Heidelberg

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Based on:

- IR singularities of scattering amplitudes in non-abelian gauge theories

  Thomas Becher, MN: 0901.0722 (PRL), 0903.1126 (JHEP), 0904.1021 (PRD)
  Andrea Ferroglia, Ben Pecjak, MN, Li Lin Yang: 0907.4791 (PRL), 0908.3676 (JHEP)

- Threshold resummation for Higgs production

  Valentin Ahrens, Thomas Becher, MN, Li Lin Yang: 0808.3008 (PRD), 0809.4283 (EPJC)

- Threshold resummation for top-quark pair production

  Andrea Ferroglia, Ben Pecjak, MN, Li Lin Yang: 0912.3375 (PLB) & 1003.5827 (→JHEP)

A tale of many scales

- Collider processes characterized by many scales: s, s_{ij}, M_i, Λ_{QCD}, ...
- Large Sudakov logarithms arise, which need to be resummed (e.g. parton showers, mass effects, aspects of underlying event)
- Effective field theories provide modern, elegant approach to this problem based on scale separation (factorization theorems) and RG evolution (resummation)

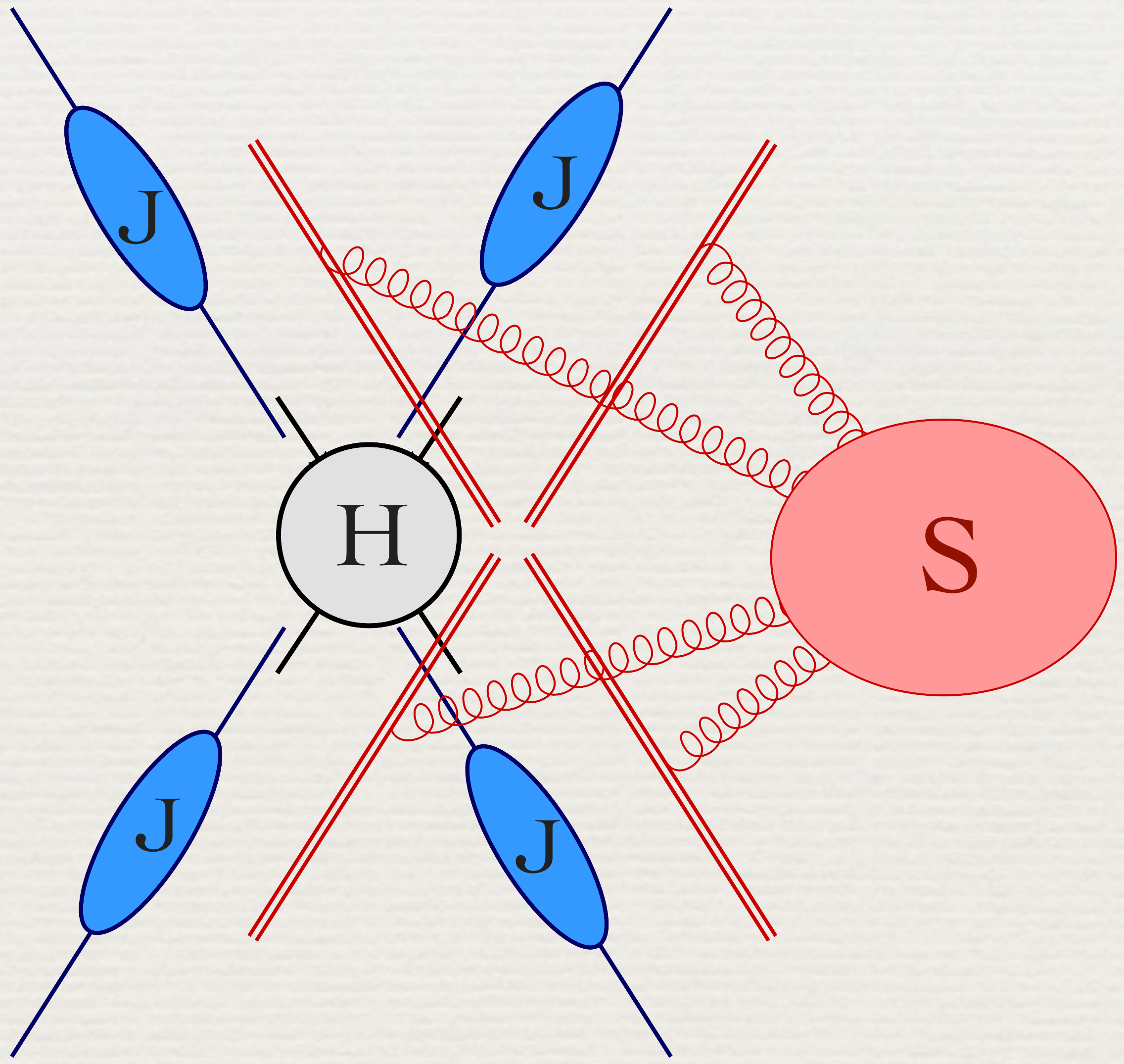
Soft-collinear factorization

Sen 1983; Kidonakis, Oderda, Sterman 1998

- Factorize cross section:

$$d\sigma \sim H(\{s_{ij}\},\mu) \prod_i J_i(M_i^2,\mu) \otimes S(\{\Lambda_{ij}^2\},\mu)$$

- Define components in terms of field theory objects in SCET
- Resum large Sudakov logarithms directly in momentum space using RG equations



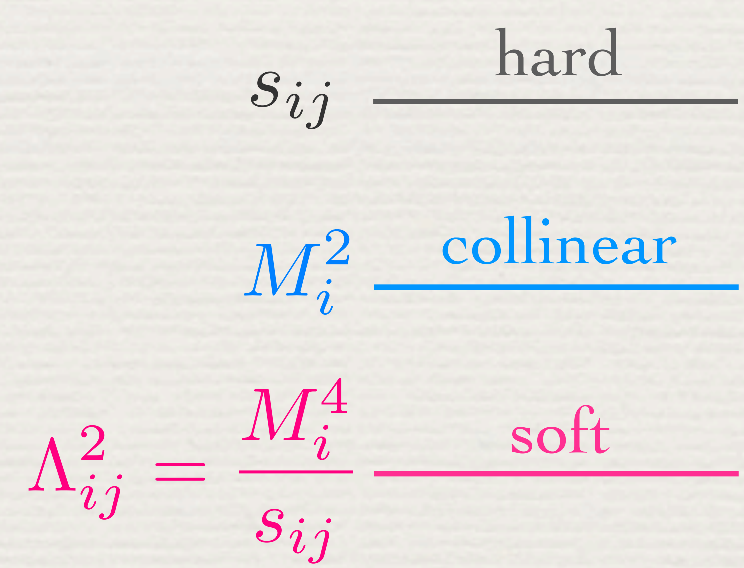
Soft-collinear effective theory (SCET)

Bauer, Pirjol, Stewart et al. 2001, 2002; Beneke et al. 2002; ...

- Two-step matching procedure:

- Integrate out hard modes, describe collinear and soft modes by fields in SCET

- Integrate out collinear modes (if perturbative) and match onto a theory of Wilson lines



SCET for n-jet processes

- n different types of collinear quark and gluon fields (jet functions J_i), interacting only via soft gluons (soft function S)
- Hard contributions ($Q \sim \sqrt{s}$) are integrated out and absorbed into Wilson coefficients:

$$\mathcal{H}_n = \sum_i \mathcal{C}_{n,i}(\mu)\, O_{n,i}^{\text{ren}}(\mu)$$

Bauer, Schwartz 2006

- Scale dependence controlled by RGE:

$$\frac{d}{d\ln\mu}\,|\mathcal{C}_n(\{\underline{p}\},\mu)\rangle = \mathbf{\Gamma}(\mu,\{\underline{p}\})\,|\mathcal{C}_n(\{\underline{p}\},\mu)\rangle$$

anomalous-dimension matrix of n-jet SCET operators

Goal: NLO+NNLL resummation

- Necessary ingredients:
  - **Hard functions:** from fixed-order results for on-shell amplitudes (but need amplitudes!)
  - **Jet functions:** from imaginary parts of two-point functions; needed at one-loop order (depend on cuts, jet definitions)
  - **Soft functions:** from matrix elements of Wilson-line operators
- Yields jet cross sections (not parton rates)
- Goes beyond parton showers, which are accurate only at LL order even after matching

Evolution of hard functions

- Technically most challenging aspect besides the computation of the hard functions is their evolution, governed by anomalous-dimension matrix of n-jet operators:

$$\frac{d}{d\ln\mu}\,|\mathcal{C}_n(\{p\},\mu)\rangle = \mathbf{\Gamma}\,|\mathcal{C}_n(\{p\},\mu)\rangle$$

- We have obtained completely general, multi-loop expressions for the anomalous-dimension matrices for generic n-jet processes with both massless and massive partons

Anomalous dimension to two loops

- General result:

extracted from:
Korchemsky, Radyushkin 1987

massless partons

massive partons

$$
\begin{aligned}
\mathbf{\Gamma}(\{\underline{p}\},\{\underline{m}\},\mu) &= \sum_{(i,j)} \frac{\boldsymbol{T}_i\cdot\boldsymbol{T}_j}{2}\,\gamma_{\rm cusp}(\alpha_s)\,\ln\frac{\mu^2}{-s_{ij}} + \sum_i \gamma^i(\alpha_s) \\
&\quad - \sum_{(I,J)} \frac{\boldsymbol{T}_I\cdot\boldsymbol{T}_J}{2}\,\gamma_{\rm cusp}(\beta_{IJ},\alpha_s) + \sum_I \gamma^I(\alpha_s) + \sum_{I,j} \boldsymbol{T}_I\cdot\boldsymbol{T}_j\,\gamma_{\rm cusp}(\alpha_s)\,\ln\frac{m_I\mu}{-s_{Ij}} \\
&\quad + \sum_{(I,J,K)} if^{abc}\,\boldsymbol{T}_I^a\,\boldsymbol{T}_J^b\,\boldsymbol{T}_K^c\,F_1(\beta_{IJ},\beta_{JK},\beta_{KI}) \\
&\quad + \sum_{(I,J)}\sum_k if^{abc}\,\boldsymbol{T}_I^a\,\boldsymbol{T}_J^b\,\boldsymbol{T}_k^c\,f_2\Big(\beta_{IJ},\ln\frac{-\sigma_{Jk}\,v_J\cdot p_k}{-\sigma_{Ik}\,v_I\cdot p_k}\Big) + \mathcal{O}(\alpha_s^3)\,.
\end{aligned}
$$

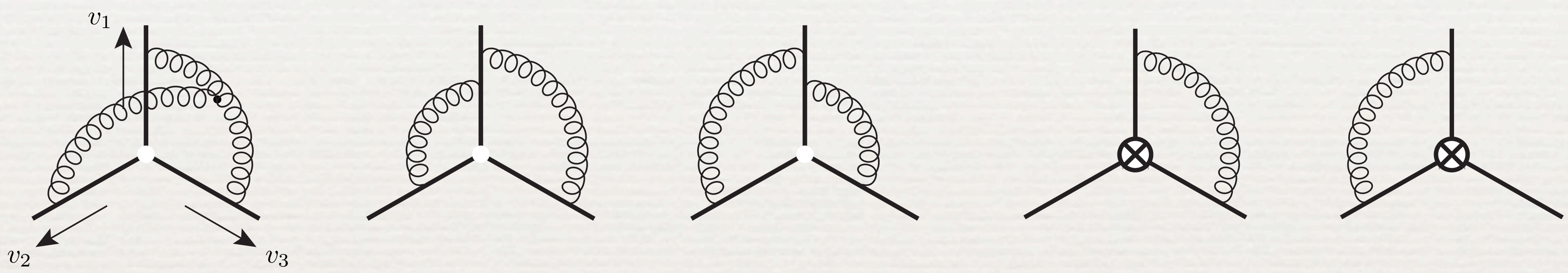
new!

- Generalizes structure found for massless case
- Novel three-parton terms appear at two-loop order   Mitov, Sterman, Sung: 0903.3241; Becher, MN: 0904.1021

Calculation of three-parton terms

Ferroglia, MN, Pecjak, Yang: 0907.4791, 0908.3676

- Relevant two-loop diagrams:



- Surprisingly simple answer:

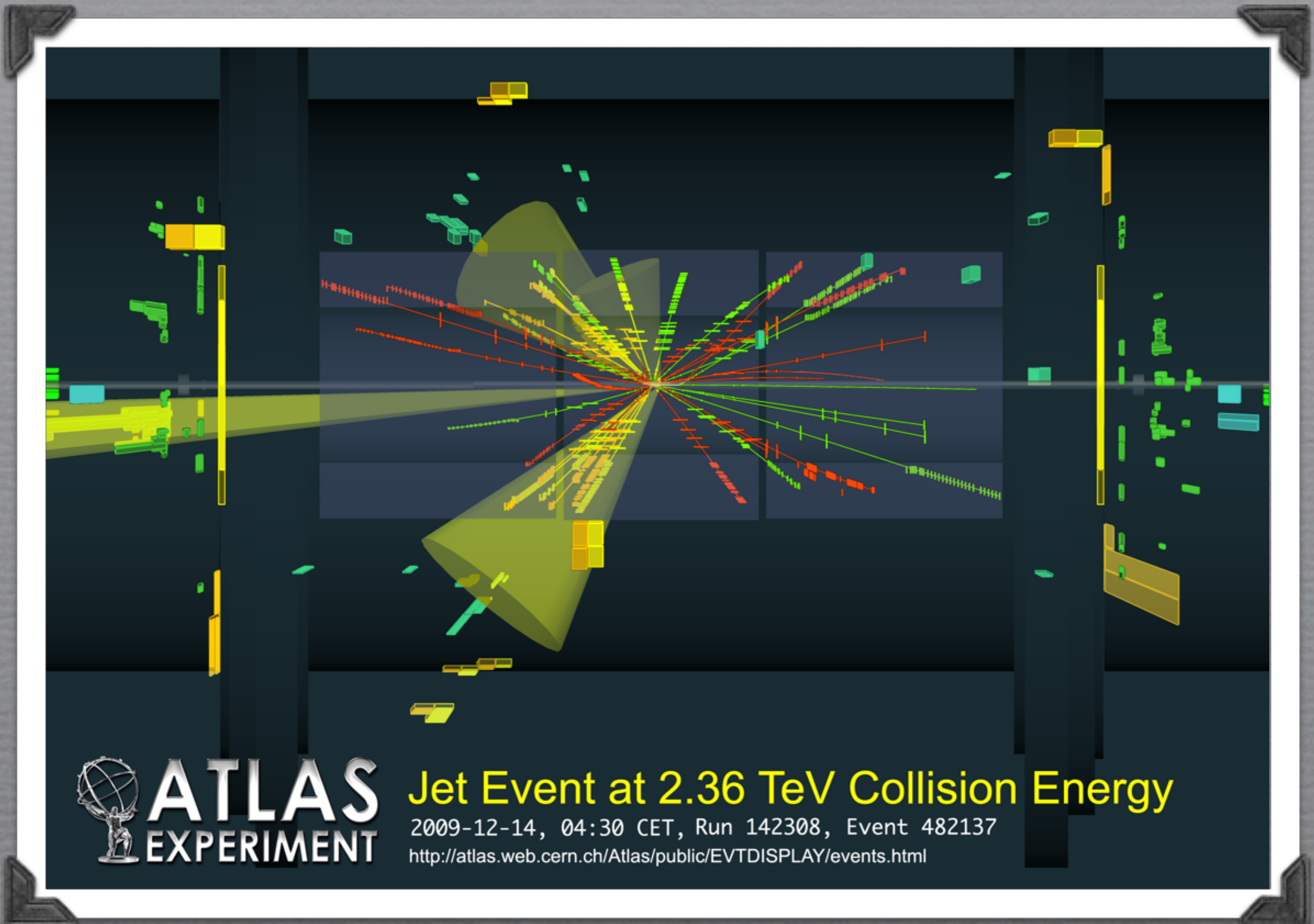
anti-symmetric in heavy-parton indices

$$F_1(\beta_{12},\beta_{23},\beta_{31}) = \frac{1}{3}\sum_{I,J,K}\epsilon_{IJK}\,\frac{\alpha_s}{4\pi}\,g(\beta_{IJ})\,\gamma_{\rm cusp}(\beta_{KI},\alpha_s)$$

$$f_2\Big(\beta_{12},\ln\frac{-\sigma_{23}\,v_2\cdot p_3}{-\sigma_{13}\,v_1\cdot p_3}\Big) = -\frac{\alpha_s}{4\pi}\,g(\beta_{12})\,\gamma_{\rm cusp}(\alpha_s)\,\ln\frac{-\sigma_{23}\,v_2\cdot p_3}{-\sigma_{13}\,v_1\cdot p_3}$$

with:

$$g(\beta) = \coth\beta\left[\beta^2 + 2\beta\,\ln(1-e^{-2\beta}) - \mathrm{Li}_2(e^{-2\beta}) + \frac{\pi^2}{6}\right] - \beta^2 - \frac{\pi^2}{6}$$



EFT-based predictions for top-quark pair production at hadron colliders

Ahrens, Ferroglia, MN, Pecjak, Yang: 0912.3375 & 1003.5827 (v2 to appear)

State of the art

- Fixed-order NLO calculations:
  - total cross section: Nason, Dawson, Ellis 1988; Beenakker et al. 1989
  - differential: Nason, Dawson, Ellis 1989; Mangano, Nason, Ridolfi 1992; Frixione, Mangano, Nason, Ridolfi 1995
  - A_{FB}^t: Kühn, Rodrigo 1998
- Fixed-order NNLO calculations:
  - none exist! (several pieces available)
  - "leading terms" (enhanced near threshold) for total cross section: Beneke, Falgari, Schwinn 2009; Czakon, Mitov, Sterman 2009
  - "leading terms" for distributions, A_{FB}^t **this work!**

State of the art

- Threshold resummation at NLL:
  - total cross section: Bonciani, Catani, Mangano, Nason 1998; Berger, Contopanagos 1995; Kidonakis, Laenen, Moch, Vogt 2001
  - distributions: Kidonakis, Vogt 2003; Banfi, Laenen 2005
  - A_{FB}^t: Almeida, Sterman, Vogelsang 2008
- Resummation at NNLL+NLO matching:
  - total cross section: Beneke, Falgari, Schwinn 2009; Czakon, Mitov, Sterman 2009 **& this work!**
  - distributions: **this work!**

Top-pair production at partial NNLO

Ferroglia, MN, Pecjak, Yang: 0908.3676

- Anomalous-dimension matrices in s-channel singlet-octet basis for $q\bar{q}, gg \to t\bar{t}$ channels:

$$\begin{aligned}
\mathbf{\Gamma}_{q\bar{q}} &= \left[C_F\, \gamma_{\rm cusp}(\alpha_s)\, \ln\frac{-s}{\mu^2} + C_F\, \gamma_{\rm cusp}(\beta_{34},\alpha_s) + 2\gamma^q(\alpha_s) + 2\gamma^Q(\alpha_s) \right] \mathbf{1} \\
&\quad + \frac{N}{2} \left[\gamma_{\rm cusp}(\alpha_s)\, \ln\frac{(-s_{13})(-s_{24})}{(-s)\, m_t^2} - \gamma_{\rm cusp}(\beta_{34},\alpha_s) \right] \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix} \\
&\quad + \gamma_{\rm cusp}(\alpha_s)\, \ln\frac{(-s_{13})(-s_{24})}{(-s_{14})(-s_{23})} \left[\begin{pmatrix} 0 & \frac{C_F}{2N} \\ 1 & -\frac{1}{N} \end{pmatrix} + \frac{\alpha_s}{4\pi}\, g(\beta_{34}) \begin{pmatrix} 0 & \frac{C_F}{2} \\ -N & 0 \end{pmatrix} \right] + \mathcal{O}(\alpha_s^3)
\end{aligned}$$

$$\begin{aligned}
\mathbf{\Gamma}_{gg} &= \left[N\, \gamma_{\rm cusp}(\alpha_s)\, \ln\frac{-s}{\mu^2} + C_F\, \gamma_{\rm cusp}(\beta_{34},\alpha_s) + 2\gamma^g(\alpha_s) + 2\gamma^Q(\alpha_s) \right] \mathbf{1} \\
&\quad + \frac{N}{2} \left[\gamma_{\rm cusp}(\alpha_s)\, \ln\frac{(-s_{13})(-s_{24})}{(-s)\, m_t^2} - \gamma_{\rm cusp}(\beta_{34},\alpha_s) \right] \begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \qquad (55) \\
&\quad + \gamma_{\rm cusp}(\alpha_s)\, \ln\frac{(-s_{13})(-s_{24})}{(-s_{14})(-s_{23})} \left[\begin{pmatrix} 0 & \frac{1}{2} & 0 \\ 1 & -\frac{N}{4} & \frac{N^2-4}{4N} \\ 0 & \frac{N}{4} & -\frac{N}{4} \end{pmatrix} + \frac{\alpha_s}{4\pi}\, g(\beta_{34}) \begin{pmatrix} 0 & \frac{N}{2} & 0 \\ -N & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \right] + \mathcal{O}(\alpha_s^3)\,.
\end{aligned}$$

Top-pair production at partial NNLO

- Can use these results to predict leading singular terms near partonic threshold $z = M^2/\hat{s} \to 1$
- Obtain NNLO coefficients of distributions

$$P_n'(z) = \left[\frac{1}{1-z}\ln^n\left(\frac{M^2(1-z)^2}{\mu^2 z}\right)\right]_+$$

  and (partially) of δ(1-z)
- Yields presently best estimate of NNLO terms
- Note: includes some subleading terms ~ ln(z) beyond distributions $P_n(z) = \left[\frac{\ln^n(1-z)}{1-z}\right]_+$

Top-pair production at NNLL+NLO

Ahrens, Ferroglia, MN, Pecjak, Yang: 1003.5827

- Solving RG equations, leading singular terms can be resummed to all orders in perturbation theory with NNLL accuracy
- Resummed hard-scattering coefficients in momentum space: Becher, MN 2006

$$C(z, M, m_t, \cos\theta, \mu_f) = \exp\left[4a_{\gamma^\phi}(\mu_s, \mu_f)\right] \times \mathrm{Tr}\Big[\boldsymbol{U}(M, m_t, \cos\theta, \mu_h, \mu_s)\, \boldsymbol{H}(M, m_t, \cos\theta, \mu_h)\, \boldsymbol{U}^\dagger(M, m_t, \cos\theta, \mu_h, \mu_s) \times \tilde{\boldsymbol{s}}\left(\ln\frac{M^2}{\mu_s^2} + \partial_\eta, M, m_t, \cos\theta, \mu_s\right)\Big] \frac{e^{-2\gamma_E\eta}}{\Gamma(2\eta)} \frac{z^{-\eta}}{(1-z)^{1-2\eta}}$$

- Then match onto NLO fixed-order results

Top-pair production at NNLL+NLO

Ahrens, Ferroglia, MN, Pecjak, Yang: 1003.5827

- Solving RG equations, leading singular terms can be resummed to all orders in perturbation theory with NNLL accuracy
- Resummed hard-scattering coefficients in momentum space:

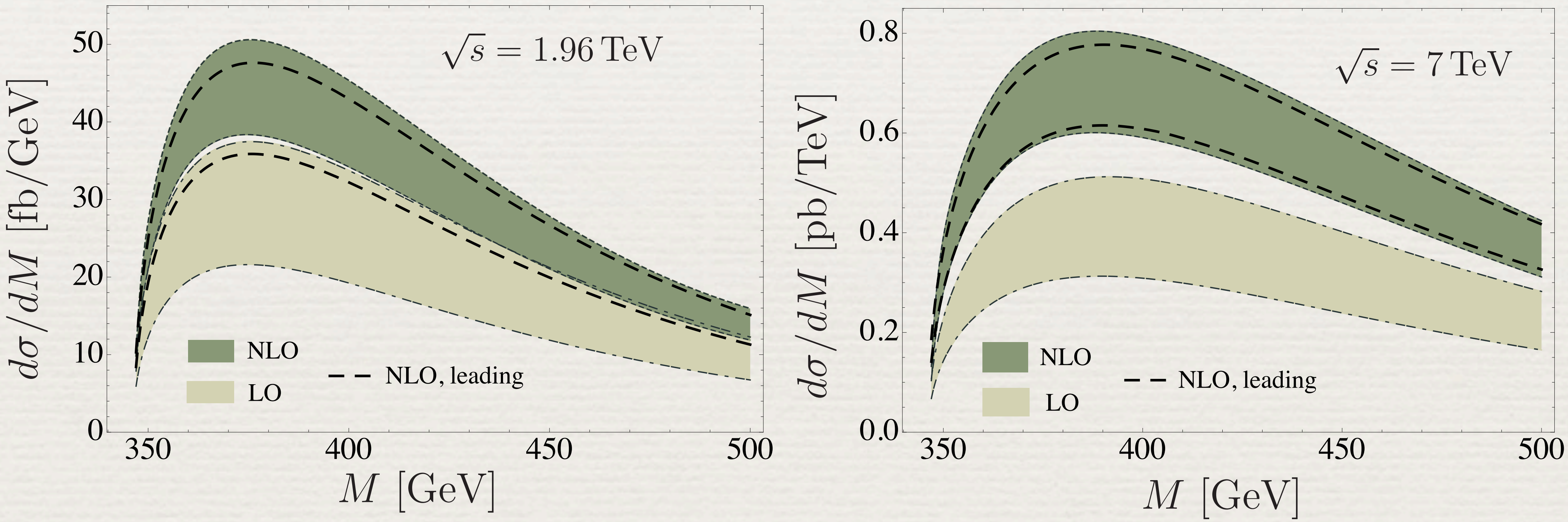
RG-impr. PT	log accuracy	$\Gamma_{\rm cusp}$	γ^h, γ^ϕ	$\boldsymbol{H}$, $\tilde{\boldsymbol{s}}$
LO	NLL	2-loop	1-loop	tree-level
NLO	NNLL	3-loop	2-loop	1-loop

$$C(z,M,m_t,\cos\theta,\mu_f) = \exp\left[4a_{\gamma^\phi}(\mu_s,\mu_f)\right] \times \text{Tr}\Big[\boldsymbol{U}(M,m_t,\cos\theta,\mu_h,\mu_s)\,\boldsymbol{H}(M,m_t,\cos\theta,\mu_h)\,\boldsymbol{U}^\dagger(M,m_t,\cos\theta,\mu_h,\mu_s) \times \tilde{\boldsymbol{s}}\left(\ln\frac{M^2}{\mu_s^2}+\partial_\eta,M,m_t,\cos\theta,\mu_s\right)\Big]\frac{e^{-2\gamma_E\eta}}{\Gamma(2\eta)}\frac{z^{-\eta}}{(1-z)^{1-2\eta}}$$

- Then match onto NLO fixed-order results

Dominance of threshold terms

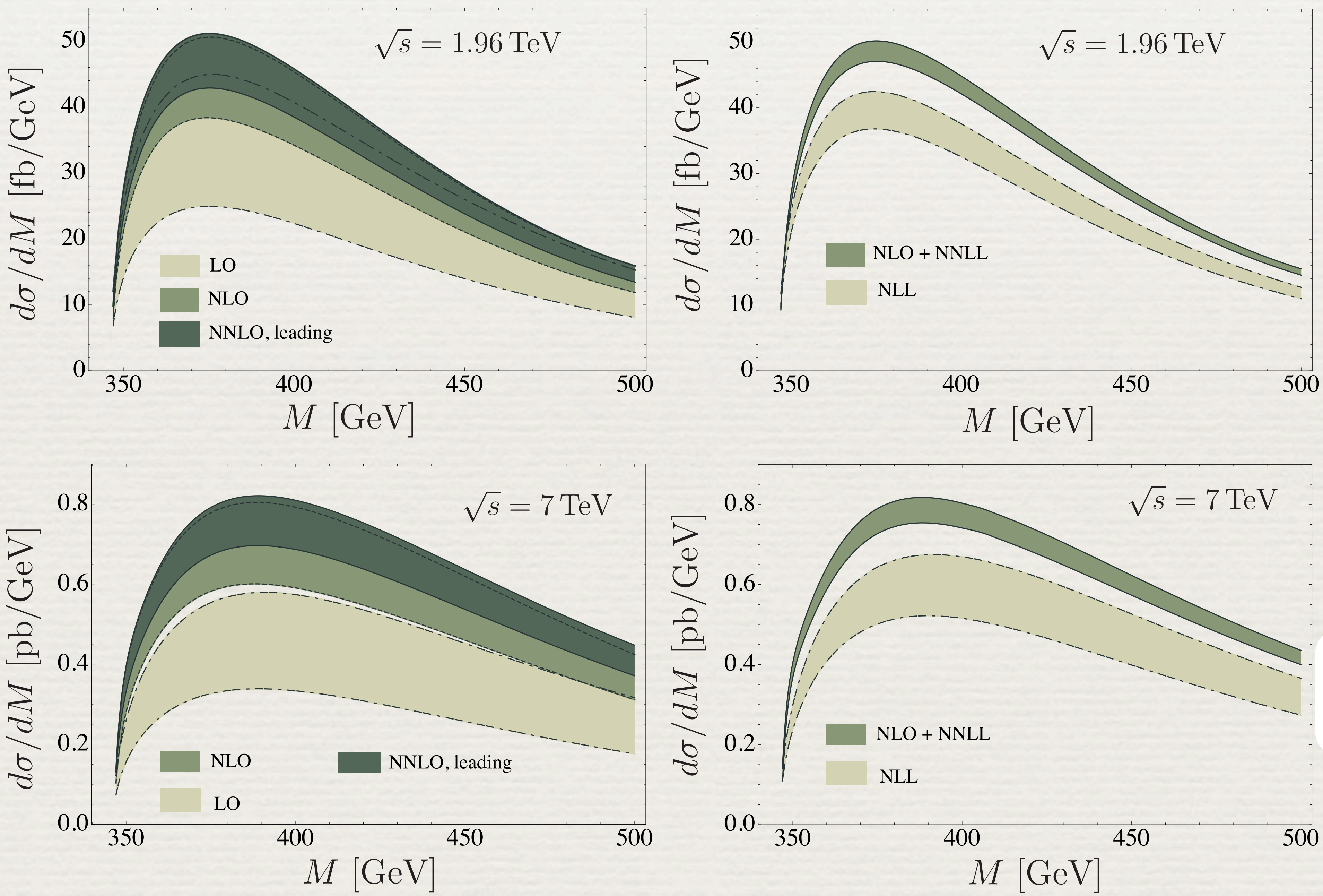
- Fixed-order results for invariant mass distribution at Tevatron and LHC:



- Leading singular terms near partonic threshold $z = M^2/\hat{s} \to 1$ give dominant contributions even at low and moderate M values

Invariant mass distributions

- Fixed-order vs. resummed PT (matched to NLO):

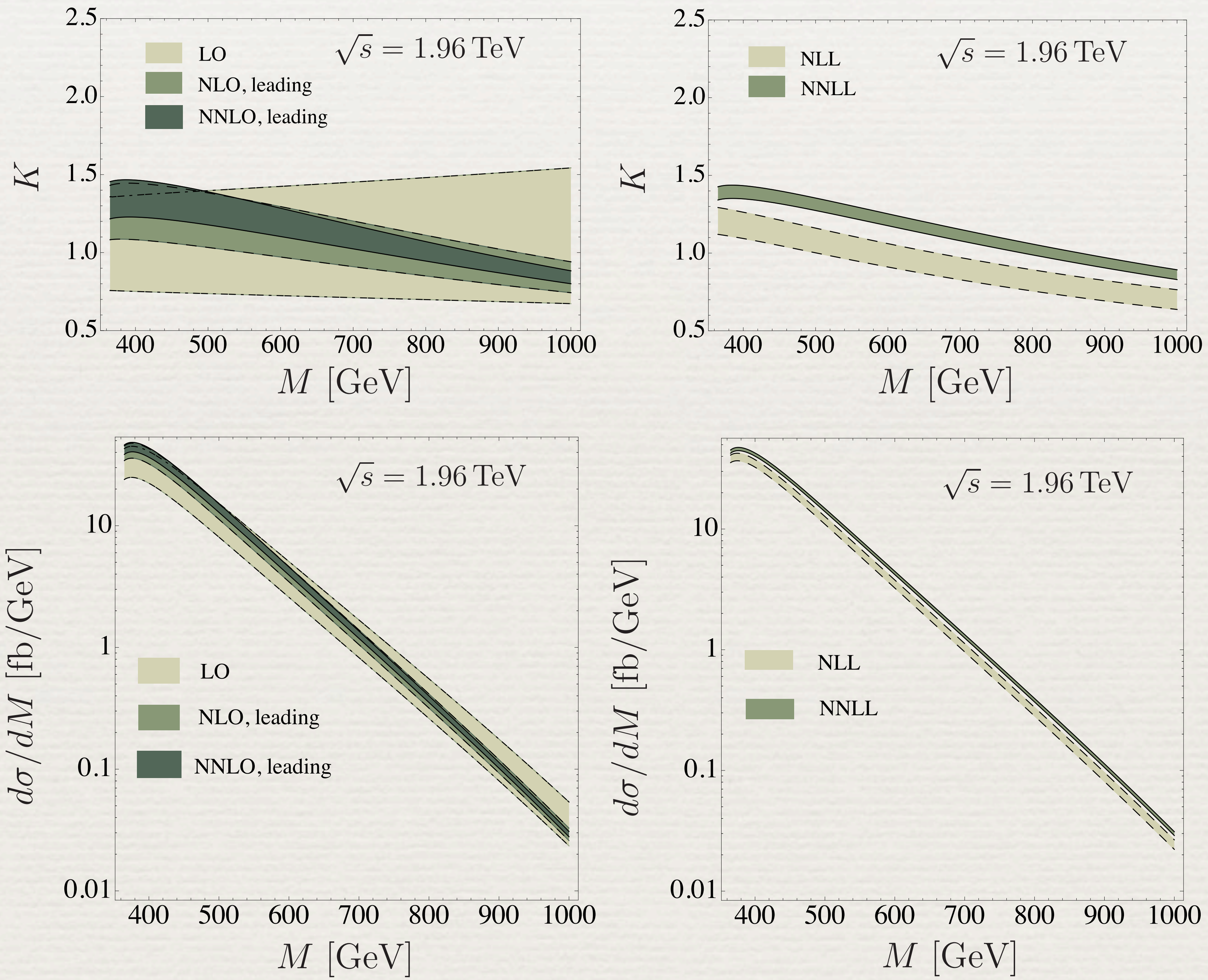


NNLO
(partial)
NLO
LO

NNLL+NLO
NLL+LO

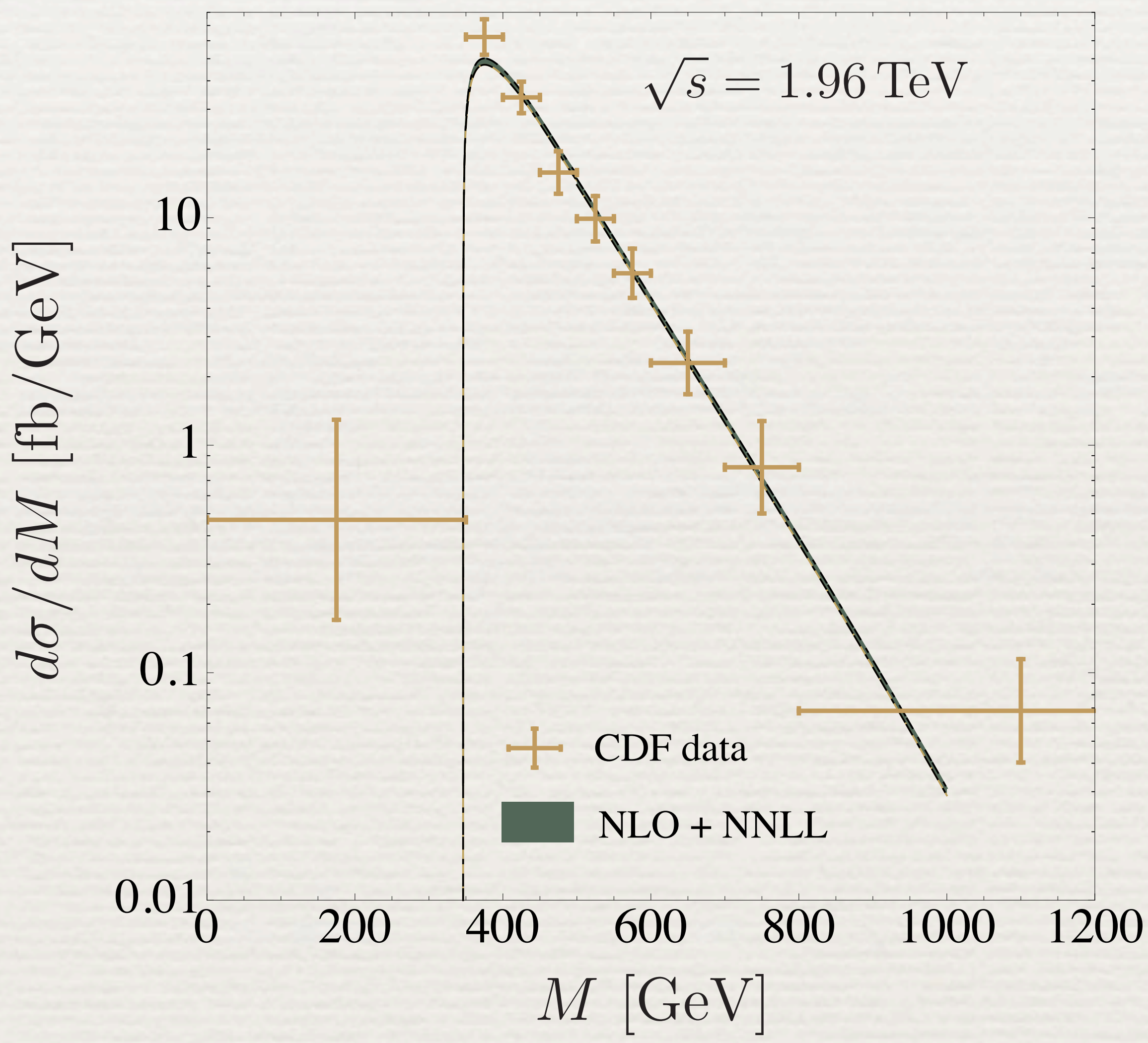
Invariant mass distributions

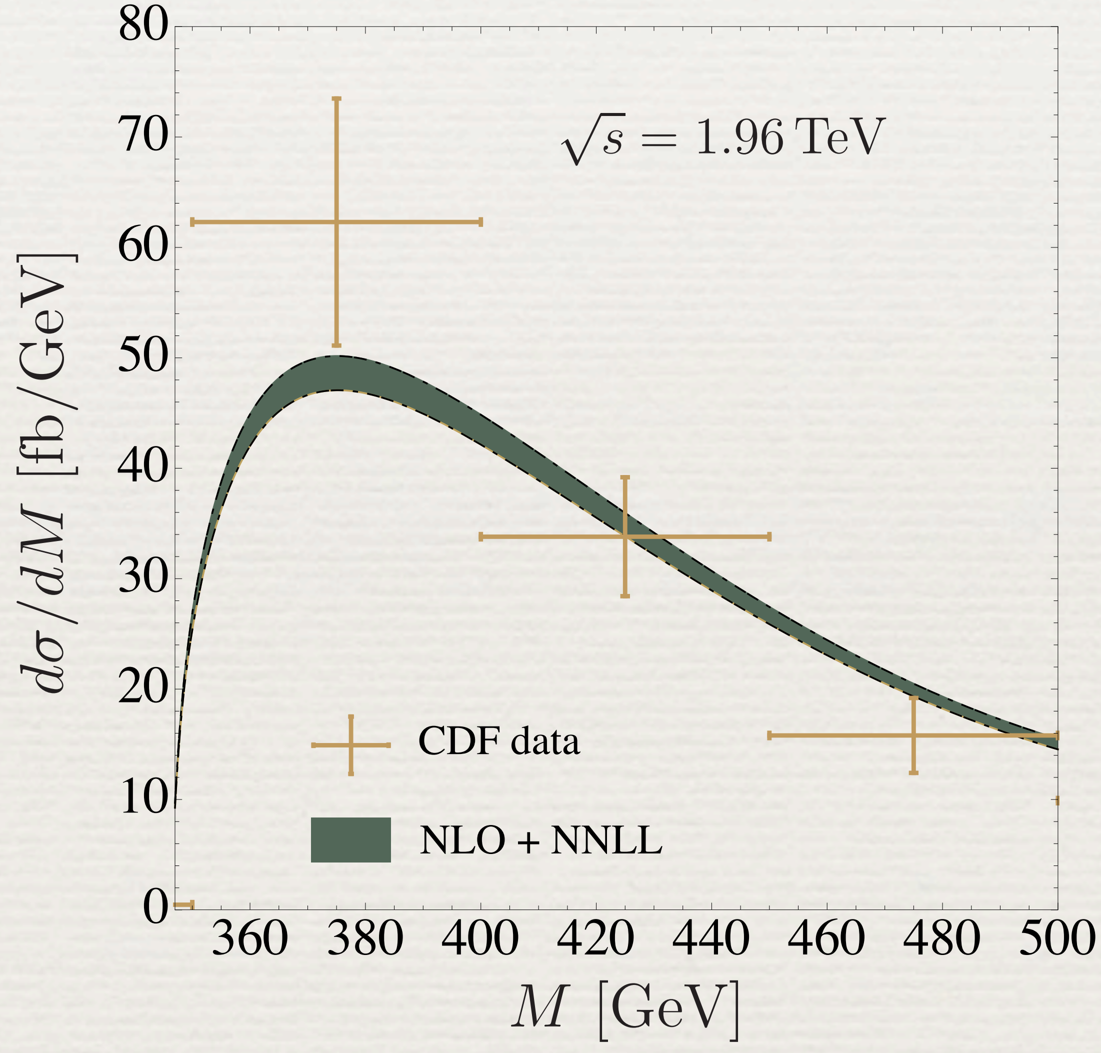
- High-mass region (Tevatron):



Comparison with CDF data

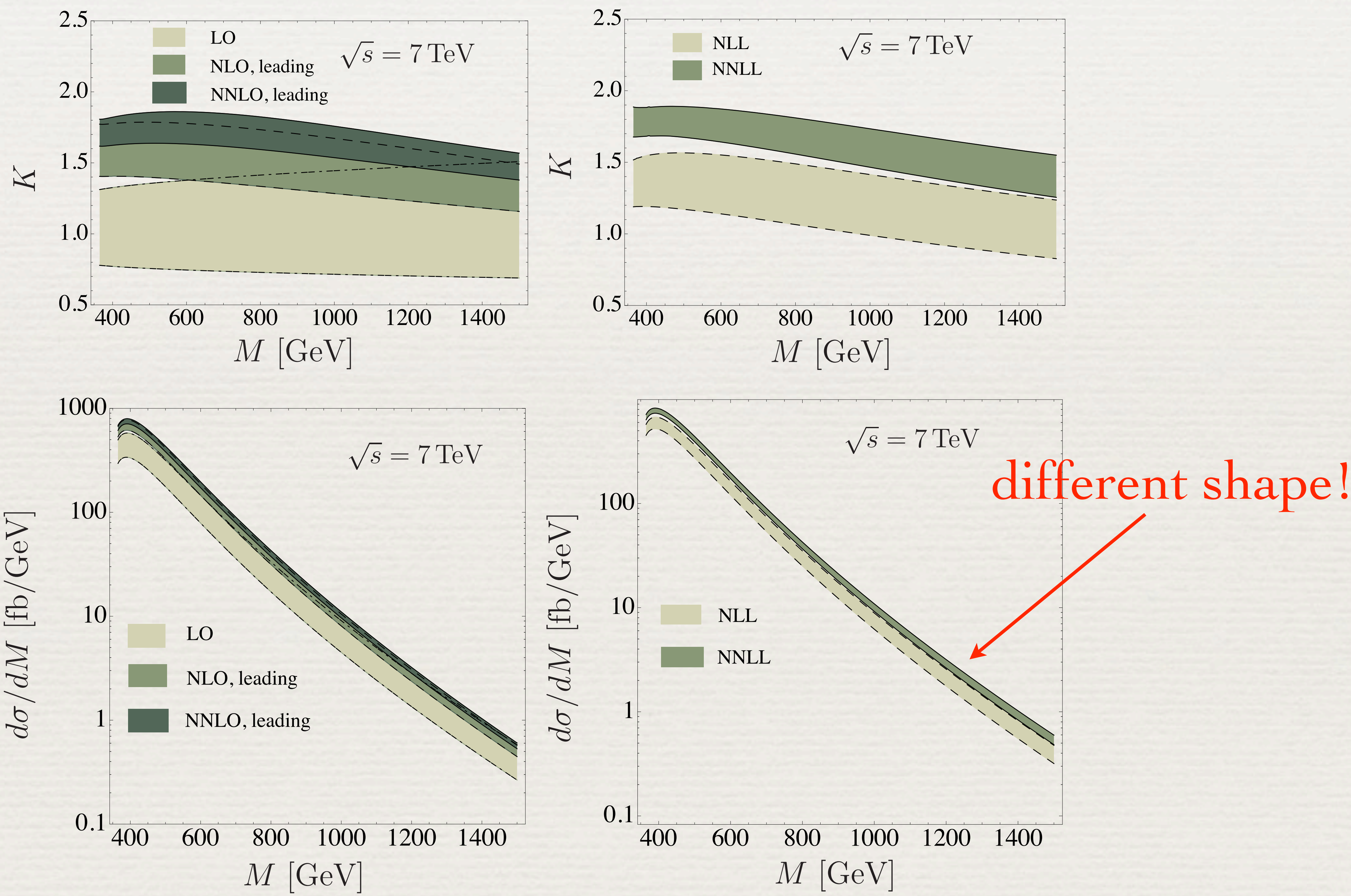
- Overlay (not a fit!) for m_t=173.1 GeV:





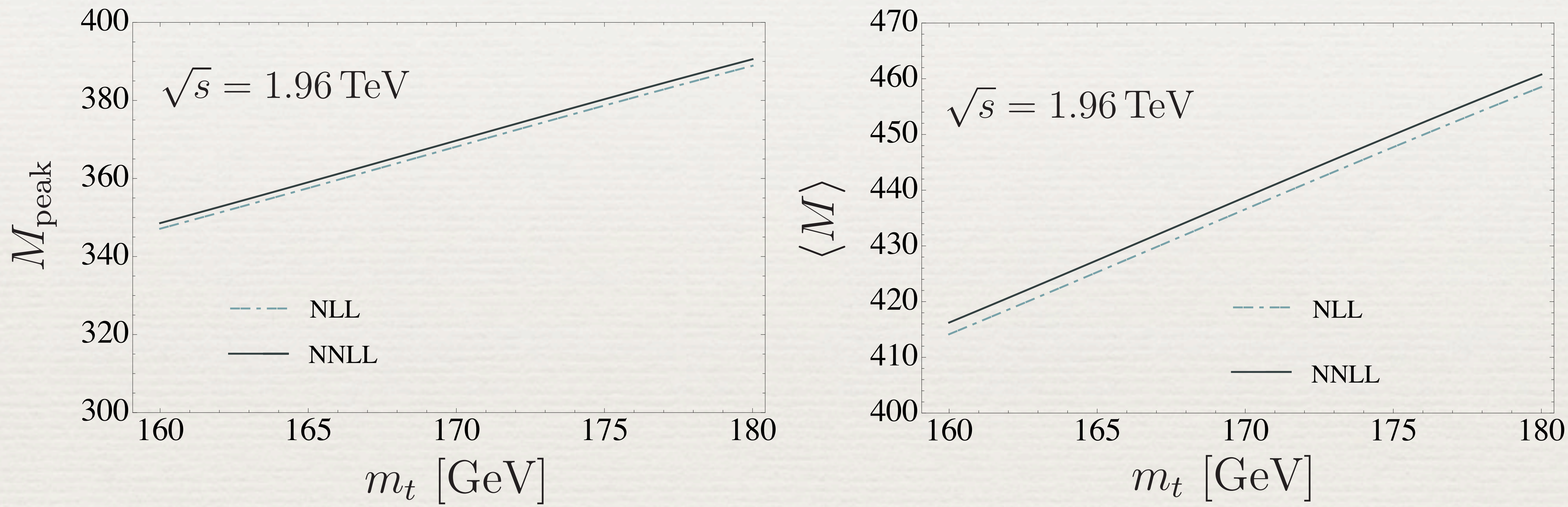
Invariant mass distributions

- High-mass region (LHC):



Features of inv. mass distribution

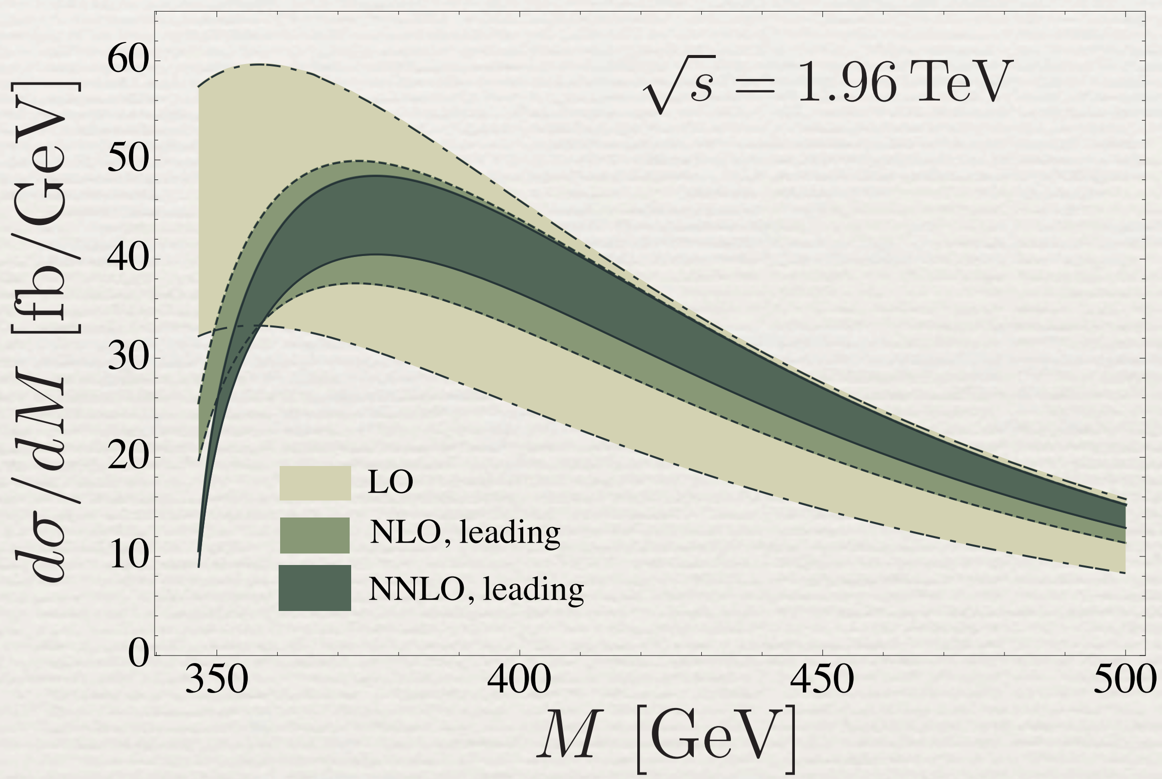
- Mass dependence (pole scheme):

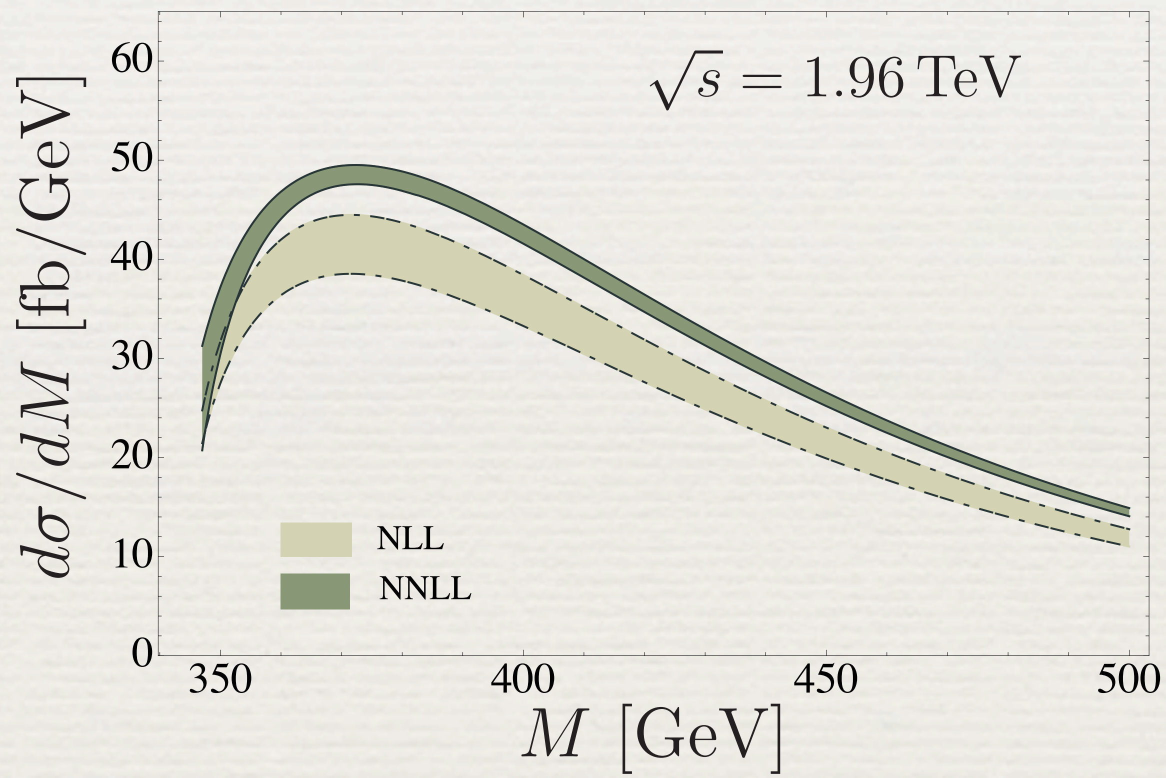


- In future, this may provide high-precision determination of top-quark mass

Features of inv. mass distribution

- Spectrum predictions in $\overline{\text{MS}}$ scheme, obtained with $\overline{m}_t(\overline{m}_t) = 164.0\,\text{GeV}$:



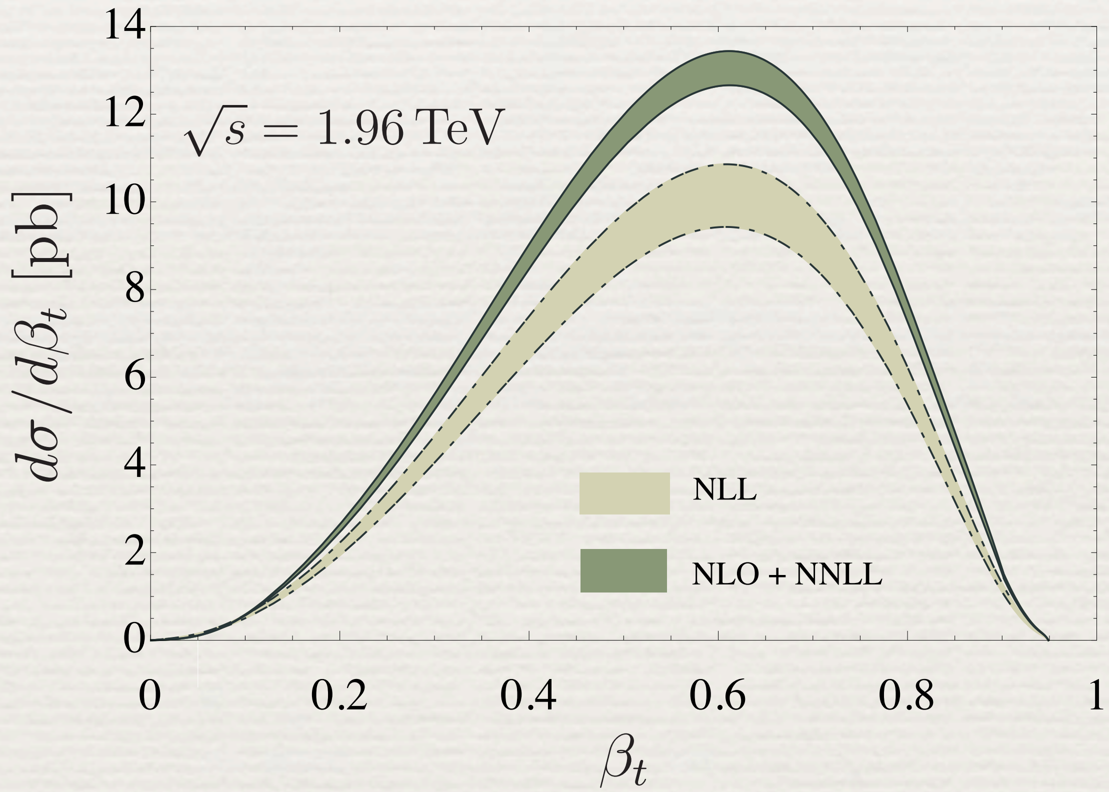


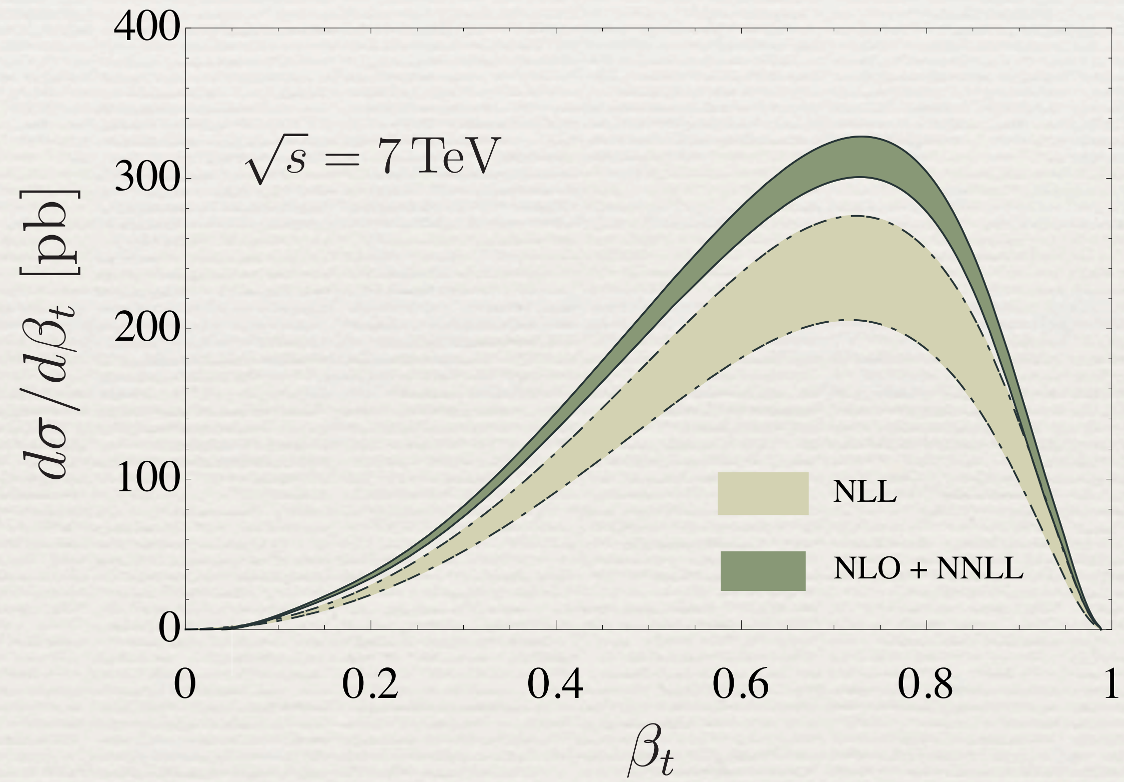
- Improved convergence

see also: Langenfeld, Moch, Uwer 2009

Velocity distribution

- Transform to relative 3-velocity of top quarks in $t\bar{t}$ rest frame: $\beta_t = \sqrt{1 - \frac{4m_t^2}{M^2}}$



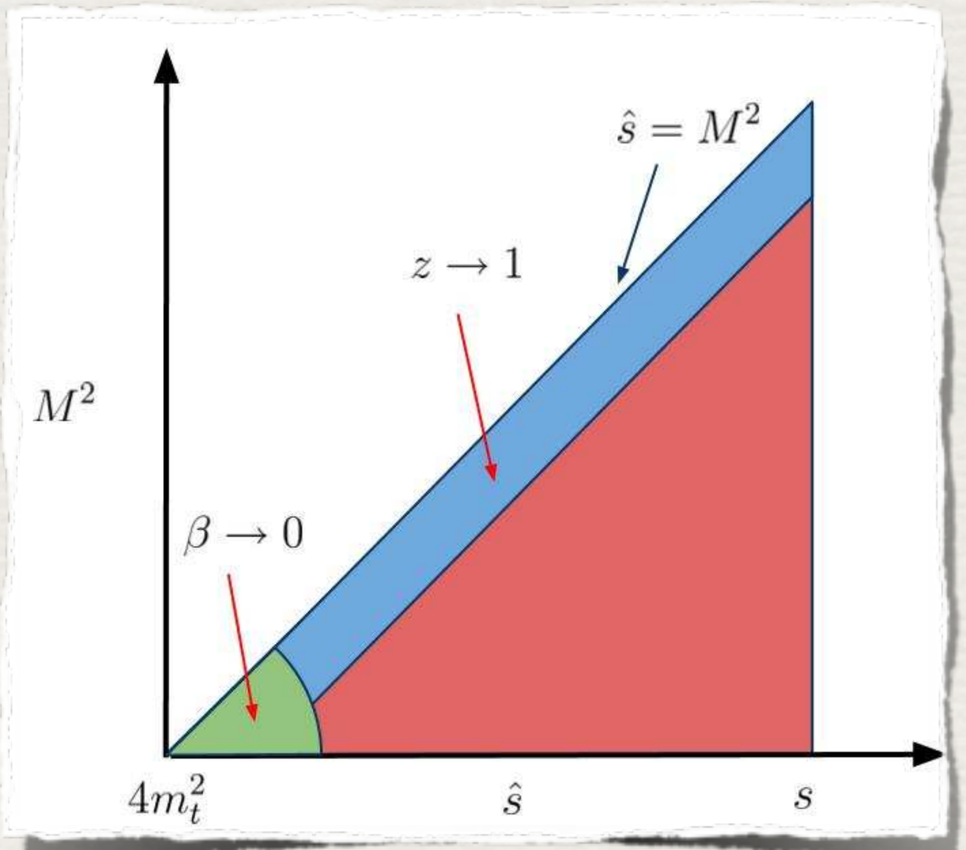


- Top quarks are predominantly relativistic, $\beta_t \sim 0.4$-0.9 not small

Total cross section

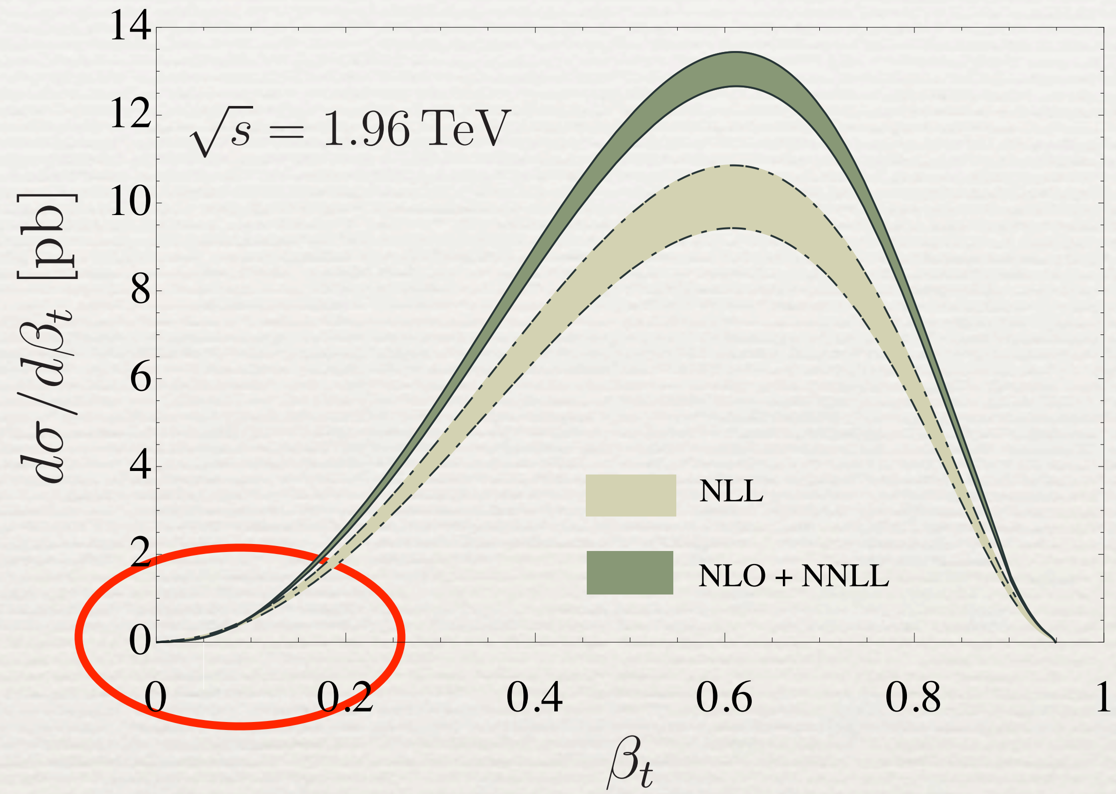
- Computed at NLO already in 1988
- Usually, resummation is done around absolute threshold at $\hat{s}=4m_t^2$
- Mixed Coulomb and soft gluon singularities arise for $\beta = \sqrt{1 - 4m_t^2/\hat{s}} \to 0$
- Obtain partial NNLO results based on small-β expansion

  Moch, Uwer 2008; Beneke et al. 2009
- But this covers only a tiny of phase space!



Total cross section

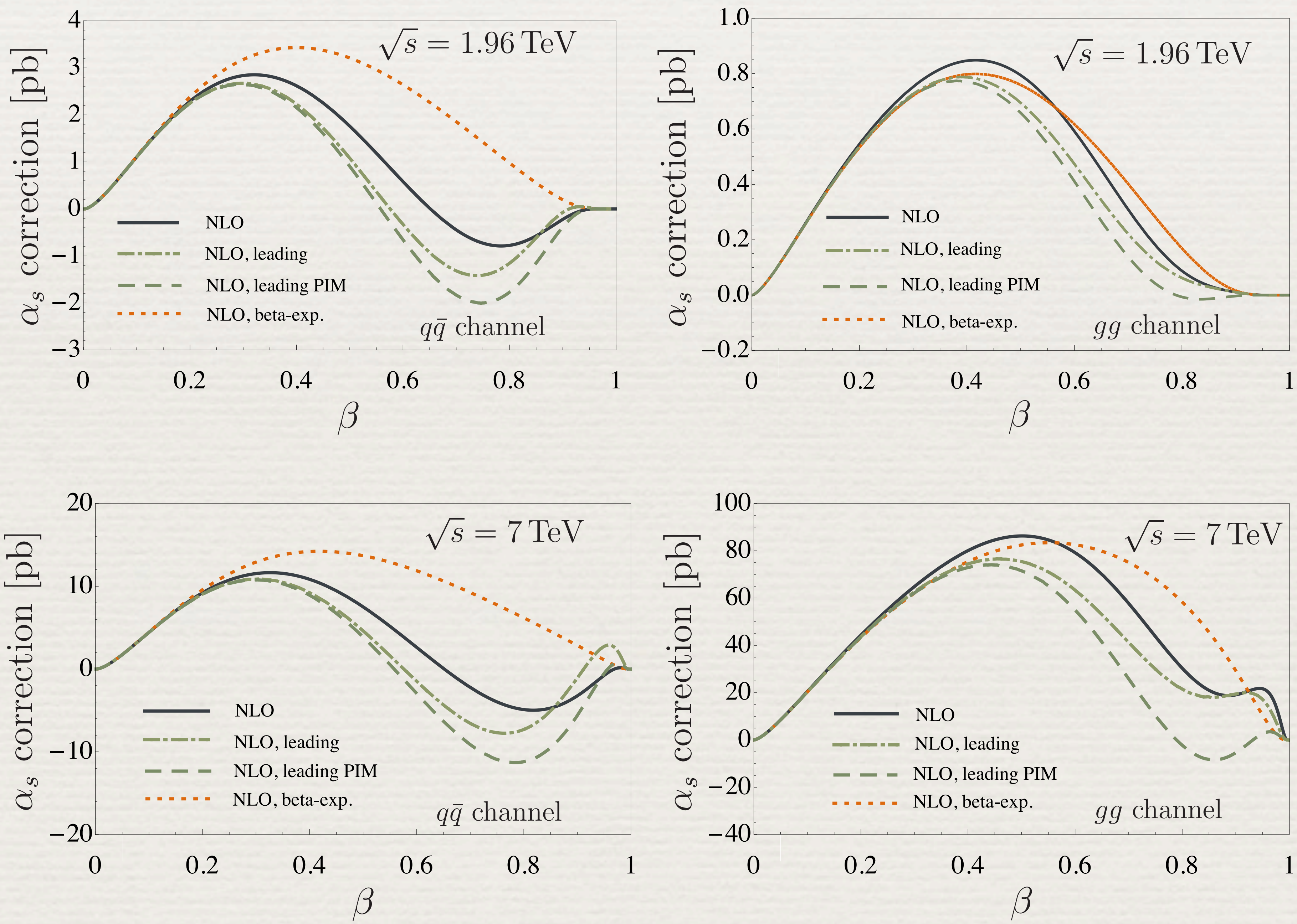
- Fact that $\beta \geq \beta_t$ and shape of β_t distribution imply that **small-β region is unimportant** for the total cross section



- In our approach, soft gluon effects are resummed also far above absolute threshold
- Different systematics & more accurate results!

Total cross section

- Comparison of approximations to NLO corrections (including parton luminosities):



$$\beta = \sqrt{1 - \frac{4m_t^2}{\hat{s}}}$$

Total cross section

- Detailed predictions for total cross sections:

Cross section (pb)	Tevatron	LHC (7 TeV)	LHC (10 TeV)	LHC (14 TeV)
σ_{LO}	$4.49^{+1.71+0.24}_{-1.15-0.19}$	84^{+29+4}_{-20-5}	217^{+70+10}_{-49-11}	$495^{+148+19}_{-107-24}$
σ_{NLL}	$5.07^{+0.37+0.28}_{-0.36-0.18}$	112^{+18+5}_{-14-5}	276^{+47+10}_{-37-11}	$598^{+108+19}_{-94\ -19}$
$\sigma_{\mathrm{NLO,\ leading}}$	$5.49^{+0.78+0.31}_{-0.78-0.20}$	134^{+16+7}_{-17-7}	341^{+34+14}_{-38-14}	761^{+64+25}_{-75-26}
σ_{NLO}	$5.79^{+0.79+0.33}_{-0.80-0.22}$	133^{+21+7}_{-19-7}	341^{+50+14}_{-46-15}	$761^{+105+26}_{-101-27}$
$\sigma_{\mathrm{NLO+NNLL}}$	$6.30^{+0.19+0.31}_{-0.19-0.23}$	149^{+7+8}_{-7-8}	373^{+17+16}_{-15-16}	821^{+40+24}_{-42-31}
$\sigma_{\mathrm{NNLO,\ approx}}$ (scheme A)	$6.14^{+0.49+0.31}_{-0.53-0.23}$	146^{+13+8}_{-12-8}	369^{+34+16}_{-30-16}	821^{+71+27}_{-65-29}
$\sigma_{\mathrm{NNLO,\ approx}}$ (scheme B)	$6.05^{+0.43+0.31}_{-0.50-0.23}$	139^{+9+7}_{-9-7}	349^{+23+15}_{-23-15}	773^{+47+25}_{-50-27}

scale uncertainty ↗ ↖ PDF uncertainty

- Singular terms dominate NLO corrections
- Resummation stabilizes scale dependence

Total cross section

- Small-β expansion misses important NLO effects:

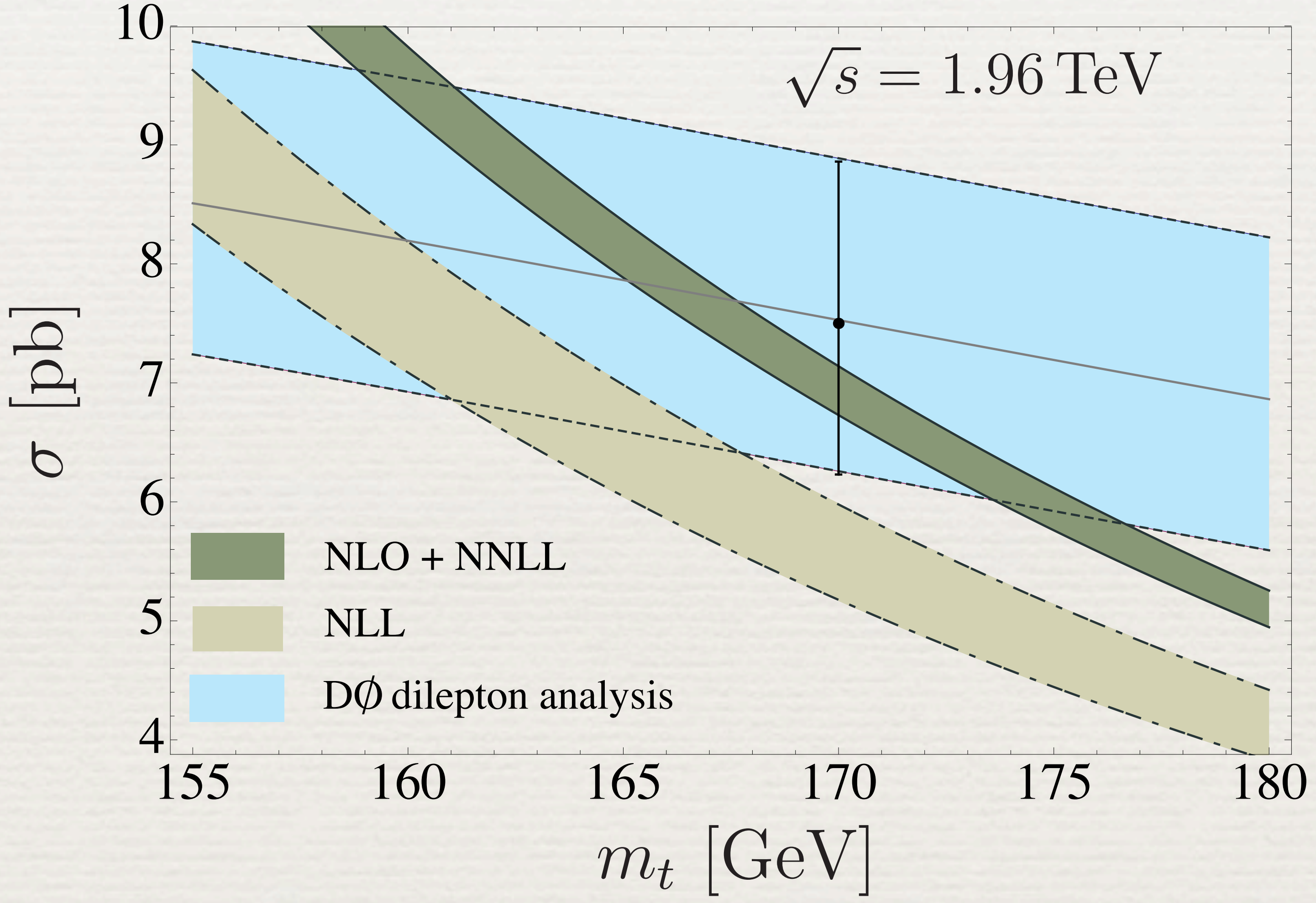
Cross section (pb)	Tevatron	LHC (7 TeV)	LHC (10 TeV)	LHC (14 TeV)
σ_{NLO}	$5.79^{+0.79+0.33}_{-0.80-0.22}$	133^{+21+7}_{-19-7}	341^{+50+14}_{-46-15}	$761^{+105+26}_{-101-27}$
$\sigma_{\text{NLO, leading}}$	$5.49^{+0.78+0.31}_{-0.78-0.20}$	134^{+16+7}_{-17-7}	341^{+34+14}_{-38-14}	761^{+64+25}_{-75-26}
$\sigma_{\text{NLO, }\beta\text{-exp. v1}}$	$6.59^{+0.96+0.38}_{-0.95-0.25}$	151^{+15+8}_{-18-8}	386^{+30+15}_{-39-16}	863^{+49+29}_{-73-30}
$\sigma_{\text{NLO, }\beta\text{-exp. v2}}$	$8.22^{+0.54+0.49}_{-0.88-0.33}$	157^{+12+8}_{-16-8}	395^{+24+14}_{-36-15}	877^{+49+29}_{-73-30}
$\sigma_{\text{NLO+NNLL}}$	$6.30^{+0.19+0.31}_{-0.19-0.23}$	149^{+7+8}_{-7-8}	373^{+17+16}_{-15-16}	821^{+40+24}_{-42-31}
$\sigma_{\text{NNLO, }\beta\text{-exp. v1}}$	$6.98^{+0.17+0.37}_{-0.40-0.27}$	156^{+2+8}_{-6-8}	$394^{+2\ +16}_{-10-17}$	$871^{+0\ +29}_{-14-31}$
$\sigma_{\text{NNLO, }\beta\text{-exp.+potential v1}}$	$6.95^{+0.16+0.36}_{-0.39-0.26}$	159^{+3+8}_{-7-8}	$401^{+6\ +17}_{-12-17}$	$888^{+7\ +30}_{-19-32}$
$\sigma_{\text{NLO, }\beta\text{-exp. v2}}$	$8.22^{+0.54+0.49}_{-0.88-0.33}$	157^{+12+8}_{-16-8}	395^{+24+14}_{-36-15}	877^{+49+29}_{-73-30}
$\sigma_{\text{NNLO, }\beta\text{-exp.+potential v2}}$	$7.30^{+0.00+0.39}_{-0.18-0.28}$	158^{+3+8}_{-6-8}	$398^{+7\ +16}_{-13-17}$	880^{+12+29}_{-22-31}

scale uncertainty → first superscript/subscript; PDF uncertainty → second superscript/subscript

- Likely that this remains true at NNLO

Total cross section

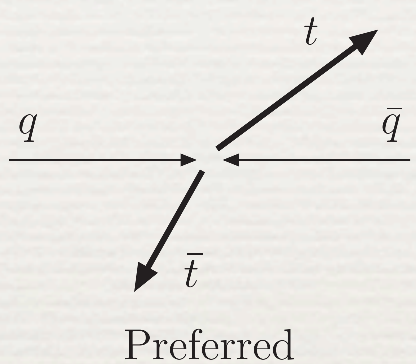
- Mass dependence (pole scheme):

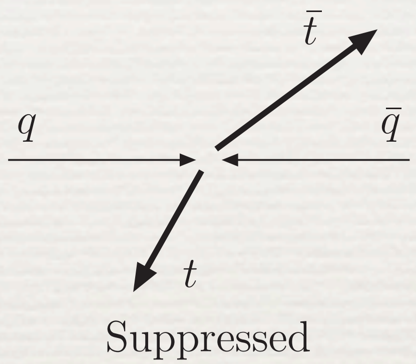


- Extract $m_t = (166.4^{+10.3}_{-7.6})\,\text{GeV}$, in agreement with world average m_t=(173.1±1.3) GeV

Forward-backward asymmetry

- At Tevatron, top-quark are emitted preferably in direction of incoming quark





- Define inclusive asymmetry:

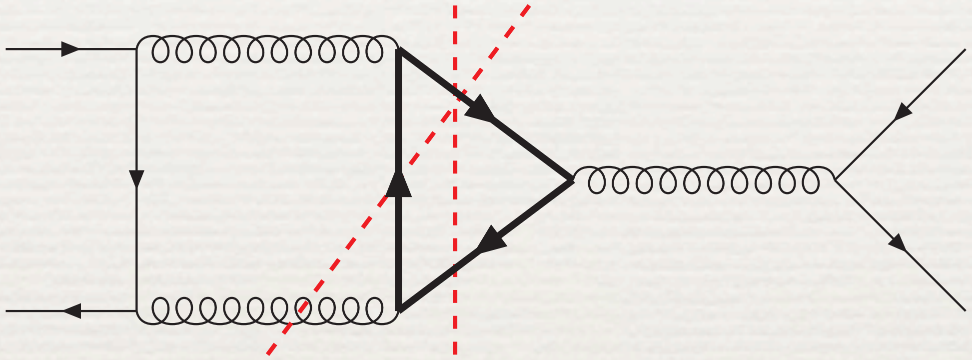
$$A^t_{\rm FB} \equiv \frac{\int_{4m_t^2}^{s} dM \left(\int_0^1 d\cos\theta \frac{d^2\sigma^{N_1N_2\to t\bar{t}X}}{dM\,d\cos\theta} - \int_{-1}^0 d\cos\theta \frac{d^2\sigma^{N_1N_2\to t\bar{t}X}}{dM\,d\cos\theta}\right)}{\int_{4m_t^2}^{s} dM \left(\int_0^1 d\cos\theta \frac{d^2\sigma^{N_1N_2\to t\bar{t}X}}{dM\,d\cos\theta} + \int_{-1}^0 d\cos\theta \frac{d^2\sigma^{N_1N_2\to t\bar{t}X}}{dM\,d\cos\theta}\right)}$$

- Surprising result by CDF:

$$A_{FB}^t|_{exp} = (19.3 \pm 6.9)\%$$

Forward-backward asymmetry

- Non-zero contributions arise first at one-loop order, from interference terms such as:



- Predictions:

	$0.2 < \mu_f/\text{TeV} < 0.8$		$m_t/2 < \mu_f < 2m_t$	
	$\Delta\sigma_{\text{FB}}$ [pb]	A^t_{FB} [%]	$\Delta\sigma_{\text{FB}}$ [pb]	A^t_{FB} [%]
NLL	$0.29^{+0.16}_{-0.16}$	$5.8^{+3.3}_{-3.2}$	$0.31^{+0.16}_{-0.17}$	$5.9^{+3.4}_{-3.3}$
NLO, leading	$0.19^{+0.09}_{-0.06}$	$5.2^{+0.4}_{-0.4}$	$0.31^{+0.16}_{-0.10}$	$5.7^{+0.5}_{-0.4}$
NLO	$0.25^{+0.12}_{-0.07}$	$6.7^{+0.6}_{-0.4}$	$0.40^{+0.21}_{-0.13}$	$7.4^{+0.7}_{-0.6}$
NLO+NNLL	$0.40^{+0.06}_{-0.06}$	$6.6^{+0.6}_{-0.5}$	$0.45^{+0.08}_{-0.07}$	$7.3^{+1.1}_{-0.7}$
NNLO, approx (scheme A)	$0.37^{+0.10}_{-0.08}$	$6.4^{+0.9}_{-0.7}$	$0.48^{+0.11}_{-0.10}$	$7.5^{+1.3}_{-0.9}$
NNLO, approx (scheme B)	$0.34^{+0.08}_{-0.07}$	$5.8^{+0.8}_{-0.6}$	$0.45^{+0.09}_{-0.09}$	$6.8^{+1.1}_{-0.8}$

Conclusions

- Effective field theory provides efficient tools for addressing difficult collider-physics problems
- Systematic "derivation" of factorization theorems (known ones and ones to be discovered) and simple, transparent resummation techniques
- Detailled applications exist for Drell-Yan, Higgs, and top-quark pair production
- Longer-term goal is to understand resummation at NNLL+NLO order for jet processes, such as $pp \to n$ jets+V/H at LHC (with $n \leq 3$, $V = \gamma, Z, W$)