Top-quark pair production: New results and recent developments

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PHYSICS AT THE TERA SCALE
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SFB TR9

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Outline

1. Motivation
2. Hadronic top-quark pair production
3. The top-quark mass
4. Conclusion

Motivation

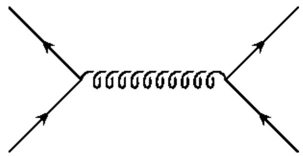
- Top-quark = heaviest elementary fermion discovered so far
  - Short lifetime → decays as a quasi free quark
  - Behaves as predicted in the SM ? Still point like ?
  - Top mass important parameter in the SM
  - Very sensitive to EWSB

→ Top plays important role in many SM extensions

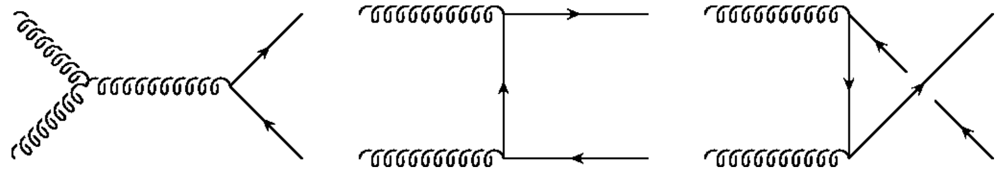
Top-quark physics important for consistency checks of the SM and new physics searches

Main production mechanism LHC: top-quark pair production

Hadronic top-quark pair production



~90% @ Tevatron, 10% @ LHC



~10% @ Tevatron, 90% @ LHC

- State of the art until recently:

NLO +NLL QCD

[Dawson, Ellis, Nason '89, Beenakker et al '89,'91,Bernreuther, Brandenburg, Si, PU '04, Czakon,Mitov 08]

[Bonciani, Catani, Mangano,Nason '98, Kidonakis, Laenen, Moch, Vogt 01]

$$\frac{\Delta\sigma_{th}}{\sigma_{th}} \approx \begin{cases} {}^{+5\%}_{-10\%}\ \text{(scale)}\ {}^{+6\%}_{-4\%}\ \text{(pdf) Tevatron} \\ \pm 11.5\%\ \text{(scale)}\ \pm(2-3)\%\ \text{(pdf) LHC} \end{cases}$$

[Moch, PU 08, Cacciari, Frixone, Mangano, Nason Ridolfi 08, Kidonakis Vogt 08]

$$\sigma_{t\bar{t}} = 161.9 \pm 2.5(\text{stat.})^{+5.1}_{-5.0}(\text{syst.}) \pm 3.6(\text{lumi})\ \text{pb},\ \delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}} \sim 4.2\%$$

[CMS dilepton channel, see Christian Schwanenberger's talk]

Theory status: Total cross section

[Ahrens, Baernreuther, Beneke, Bonciani, Cacciari, Catani, Czakon, Ferroglia, Kidonakis, Laenen, Mangano, Mitov, Moch, Nason, Neubert, Pecjak, Ridolfi, Schwinn, Sterman, PU, Vogt, Yang…]

- Beyond NLO QCD:

$(\beta = \sqrt{1 - 4m^2/s})$

NNLO approx

- Soft gluon resummation $(\ln(\beta), \ln^2(\beta) \ldots)$
- Threshold corrections $(1/\beta, 1/\beta^2 \ldots)$
- Full scale NNLO (in)dependence (RGE: $\ln(\mu), \ln^2(\mu)$)
- Combined soft and Coulomb resummation [→ C. Schwinns talk]

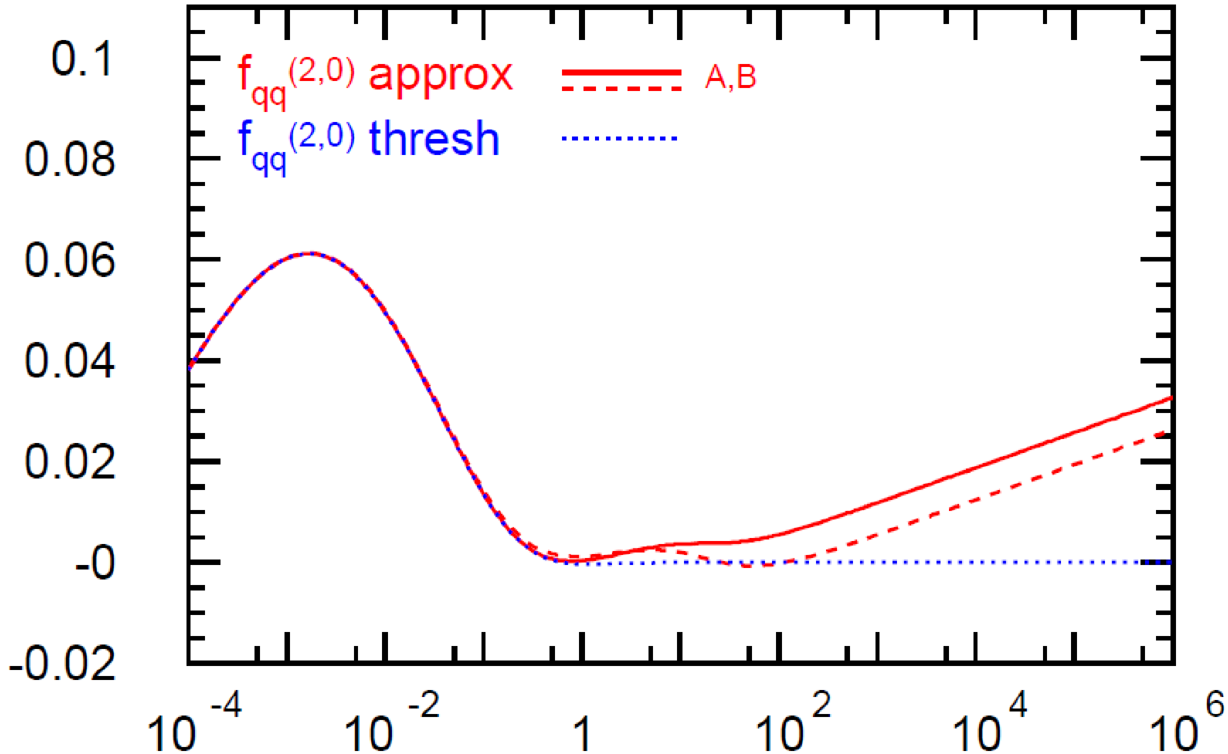
NEW '12:

- High energy behavior [Ball, Ellis '01, Moch, PU, Vogt '12]
- NNLO QCD for qq→tt [Baernreuther, Czakon, Mitov '12]

High energy behavior through BFKL dynamics

[Moch, PU, Vogt '12]

$$\sigma_{ij} = \frac{\alpha_s^2}{m_t^2}\left(f_{ij}^{(0)} + 4\pi\alpha_s f_{ij}^{(1,0)} + (4\pi\alpha_s)^2 f_{ij}^{(2,0)} + \ldots\right) \quad (\mu_r = \mu_f = m_t)$$



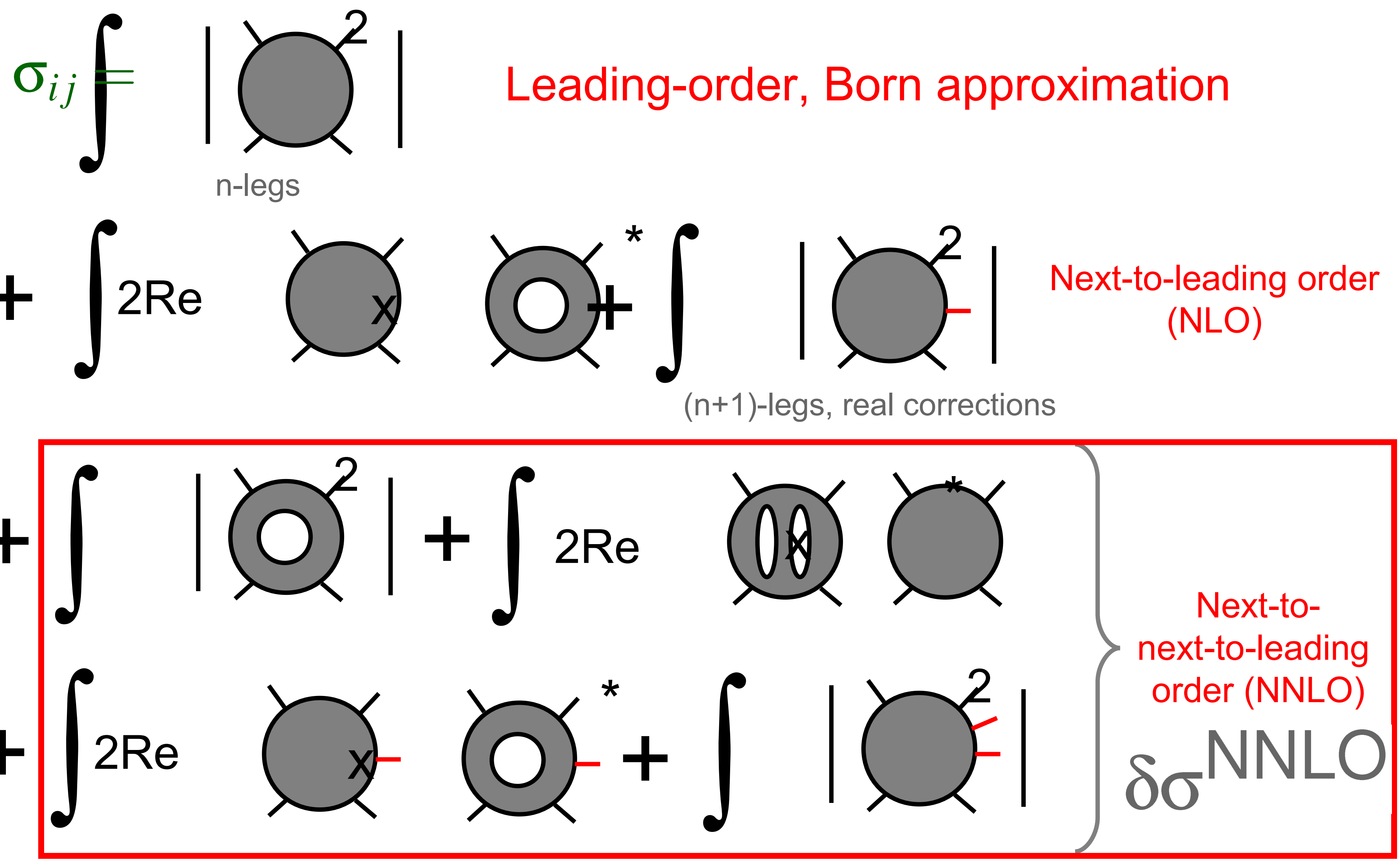
threshold

$$\eta = \frac{s}{4m^2} - 1$$

high energy

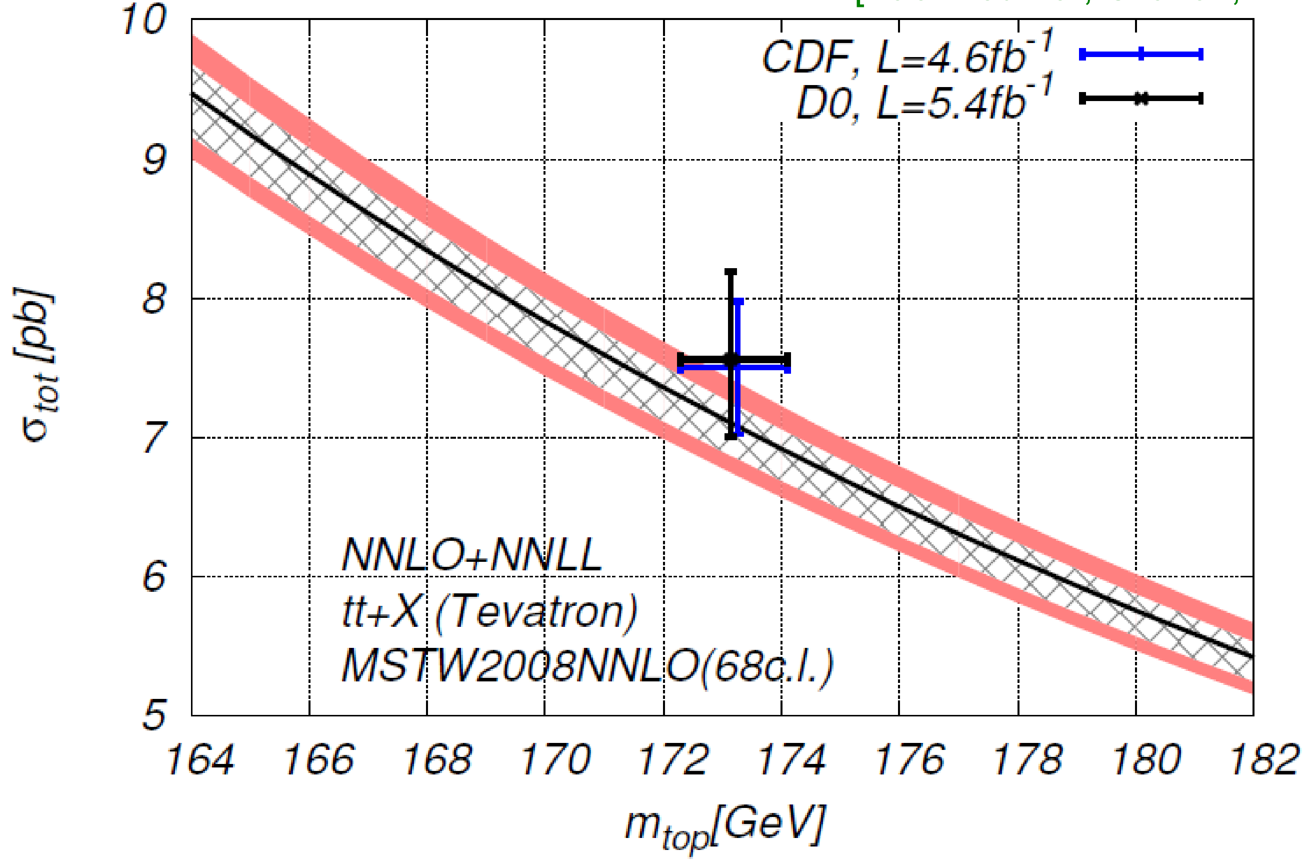
→ Recently confirmed by direct calculation [Czakon, Mitov '12]

Top-Quark Pair Production @ NNLO



Recent progress: qq→tt @ NNLO/NNLL

[Baernreuther, Czakon, Mitov arXiv:1204.5201]



Tevatron: $\sigma_{\text{tot}}^{\text{res}} = 7.067 \begin{array}{l} +0.143\,(2.0\%) \\ -0.232\,(3.3\%) \end{array} [\text{scales}] \begin{array}{l} +0.186\,(2.6\%) \\ -0.122\,(1.7\%) \end{array} [\text{pdf}]$

~3%

gg→tt @ NNLO is underway

Comparison with $\text{NNLO}_{\text{approx}}$

Fixed order NNLO: [Baernreuther, Czakon, Mitov arXiv:1204.5201]

$$\sigma_{\text{tot}}^{\text{NNLO}} = 7.005\ {}^{+0.202\,(2.9\%)}_{-0.310\,(4.4\%)}\ [\text{scales}]\ {}^{+0.170\,(2.4\%)}_{-0.122\,(1.7\%)}\ [\text{pdf}]$$

$\text{NNLO}_{\text{approx}}$ [HATHOR, Aliev, Lacker, Langenfeld, Moch, PU, Wiedermann '10]

$$\sigma_{\text{tot}}^{\text{NNLO}} = 7.058^{+0.196(2.8\%)}_{-0.315(4.4\%)}(\text{scales})^{+0.17(2.4\%)}_{-0.12(1.7\%)}(\text{pdf})$$

Based on threshold logs + RGE + Coulomb singularity

No qg contribution included in NNLO!

➡ Agreement better than 1 % !

HATHOR = HAdronic Top and Heavy quark crOss section calculatoR

Available tools

Hathor [Aliev, Lacker, Langenfeld, Moch, PU, Wiedermann '10,'12]

NNLO for qq, $\text{NNLO}_{\text{approx}}$ for qg, gg,
full scale dependence, Coulomb sing. high energy behavior, MS mass

"Mainz group" [Ahrens, Ferroglia, Neubert, Pecjak, Yang '10]

$\text{NNLO}_{\text{approx}}$ for gg, qq, NNLL resummation, MS mass

Top++ [Czakon, Mitov '11]

NNLO for qq, $\text{NNLO}_{\text{approx}}$ for gg, NNLL resummation

Topix [Beneke, Falgari, Klein, Piclum, Schwinn, Ubiali, Yan '12]

NNLO for qq, NNLL resummation, combined soft/coulomb resummation

Iphone version ???

Beyond inclusive cross section

[Ahrens, Ferroglia, Neubert, Pecjak, Yang '10]

[Kidonakis '10]

Results available also for forward-backward charge asymmetry

[Almeida, Sterman, Vogelsang 08][Ahrens, Ferroglia, Neubert, Pecjak, Yang 10,11][Kidonakis 11]

→ No significant change of one-loop predictions

Theory well prepared for precision physics with tops

Top-quark mass: Experimental methods

[for details see Christian Schwanenbergers talk]

- Template method
- Matrix element method

Issues:

- Intrinsic limitations of pole mass ($\sim\Lambda_{\text{QCD}}$)
- Precise relation

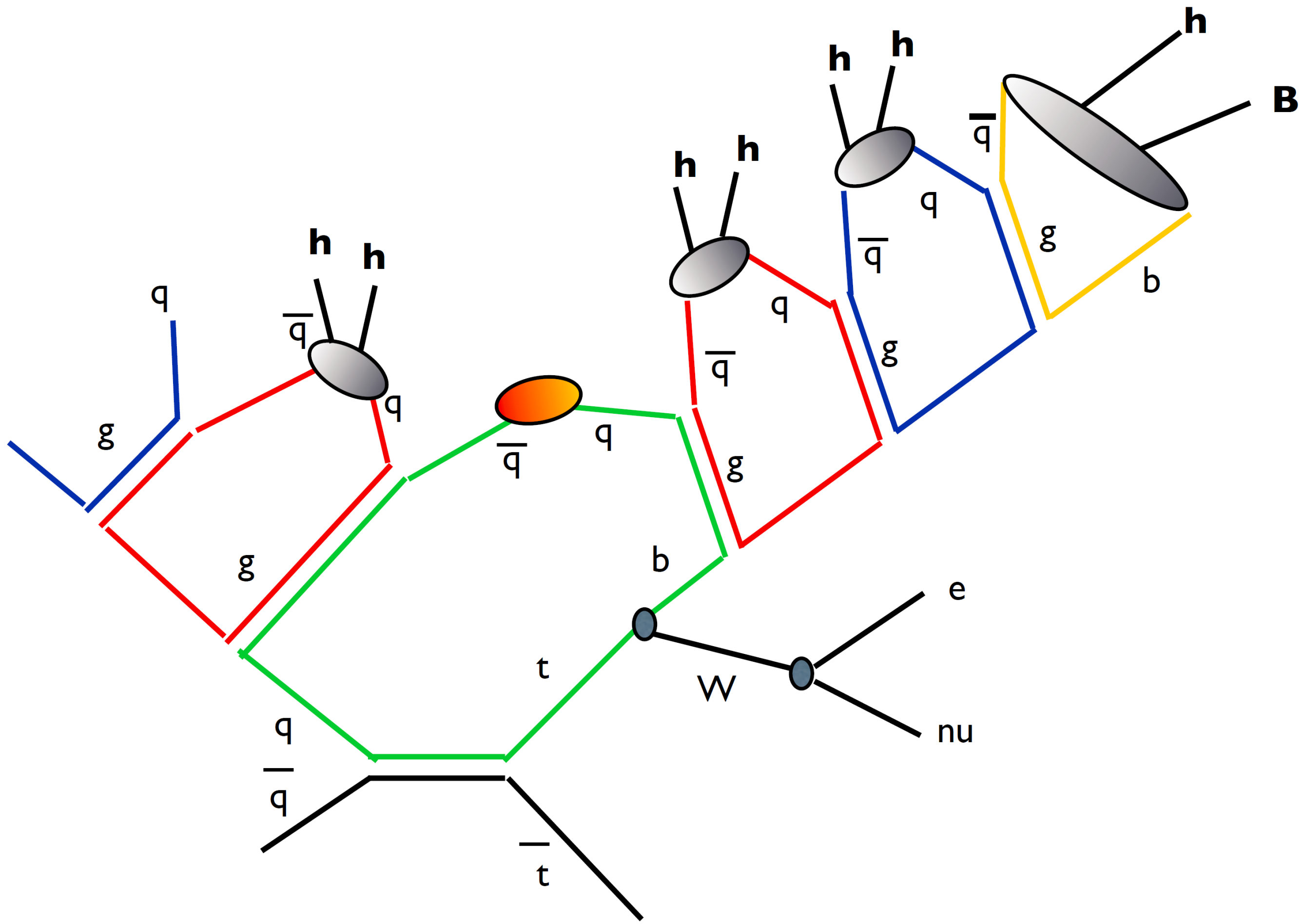
$$m_{\text{MC}} = m_{\text{Pole}}\,(1 \pm \Delta)$$

- Reconstruction of top momentum from color neutral hadrons / color reconnection

} Not independent

Color reconnection

[Mangano, Top workshop, July 2012, CERN]



Distinguish between "odd" and "even" clusters in MC

Impact on current measurements

Color reconnection:

$$\Delta m \stackrel{?}{=} 500\text{MeV}$$

[Skands,Wicke '08]

Relation: measured mass ←→ pole mass:

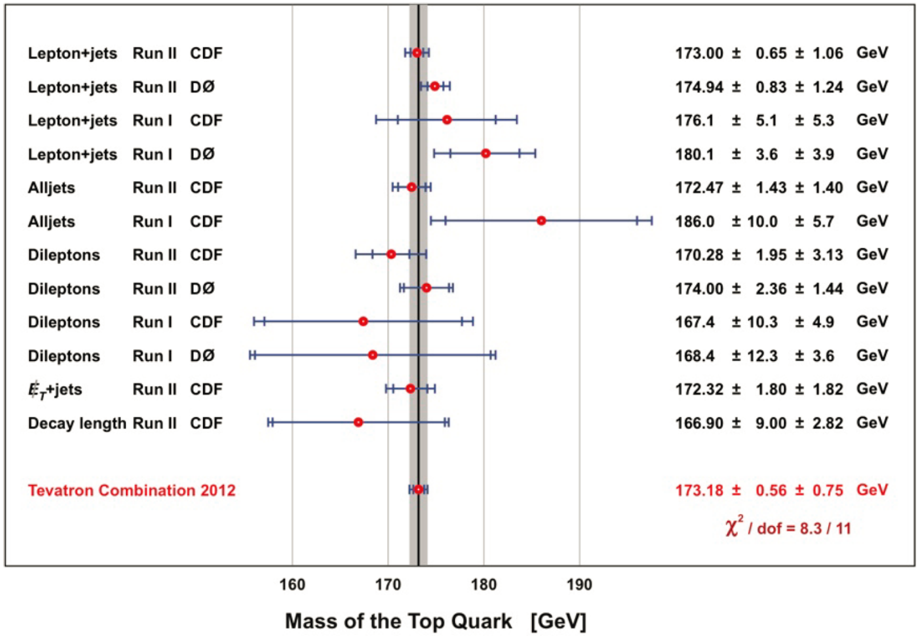
$$m_{\text{MC}} = m_{\text{Pole}} (1 \pm \Delta)$$

$$\Delta = \begin{cases} \frac{\Lambda}{m} \approx 0.13\% \\ \frac{\Gamma}{m} \approx 0.8\% \\ \frac{\alpha_s}{\pi} \approx 3.7\% \end{cases}$$

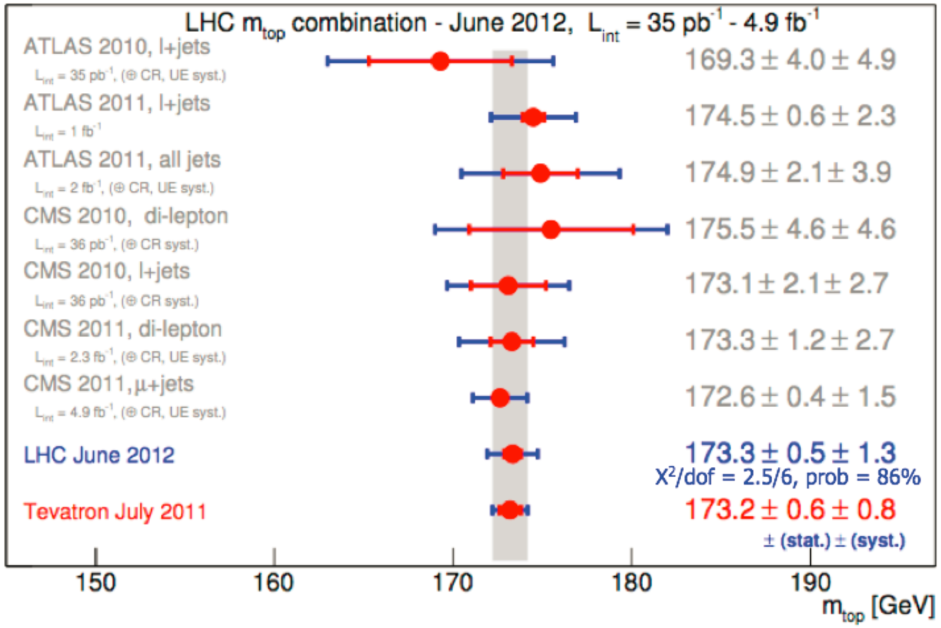
?

Impact on current measurements

Tevatron



LHC



Different channels and different experiments give consistent results

⬇

Large effects unlikely

Alternative method: Top-quark mass from jet-rates (ttj)

[Work in progress S. Alioli, J.Fuster, A. Irles, S. Moch, PU, M. Vos]

Use tt+1-jet events

→ Large event rates (~30 % of inclusive tt events)

→ NLO corrections available [Dittmaier, PU, Weinzierl ´07,´08, Melnikov, Schulze ’10, Melnikov, Scharf, Schulze ´12]

→ NLO+shower available [Alioli, Moch, PU ´11, Kardos, Papadopoulos, Trocsanyi ‘11]

Similar to b-quark mass measurement at LEP using 3-jet rates [Bilenky, Fuster, Rodrigo, Santarmaria ‘95]

- Less sensitive to color reconnection
- Mass parameter fixed through NLO calculation
- MS mass in principle possible

Top-quark mass from jet rates

[Work in progress S. Alioli, J.Fuster, A. Irles, S. Moch, PU, M. Vos]

To enhance mass sensitivity study:

$$\frac{dn_3}{d\rho_s}(m_{\text{Pole}}) = \frac{1}{\sigma_{t\bar{t}+1\text{Jet}}} \frac{d\sigma_{t\bar{t}+1\text{Jet}}}{d\rho_s}(m_{\text{Pole}})$$

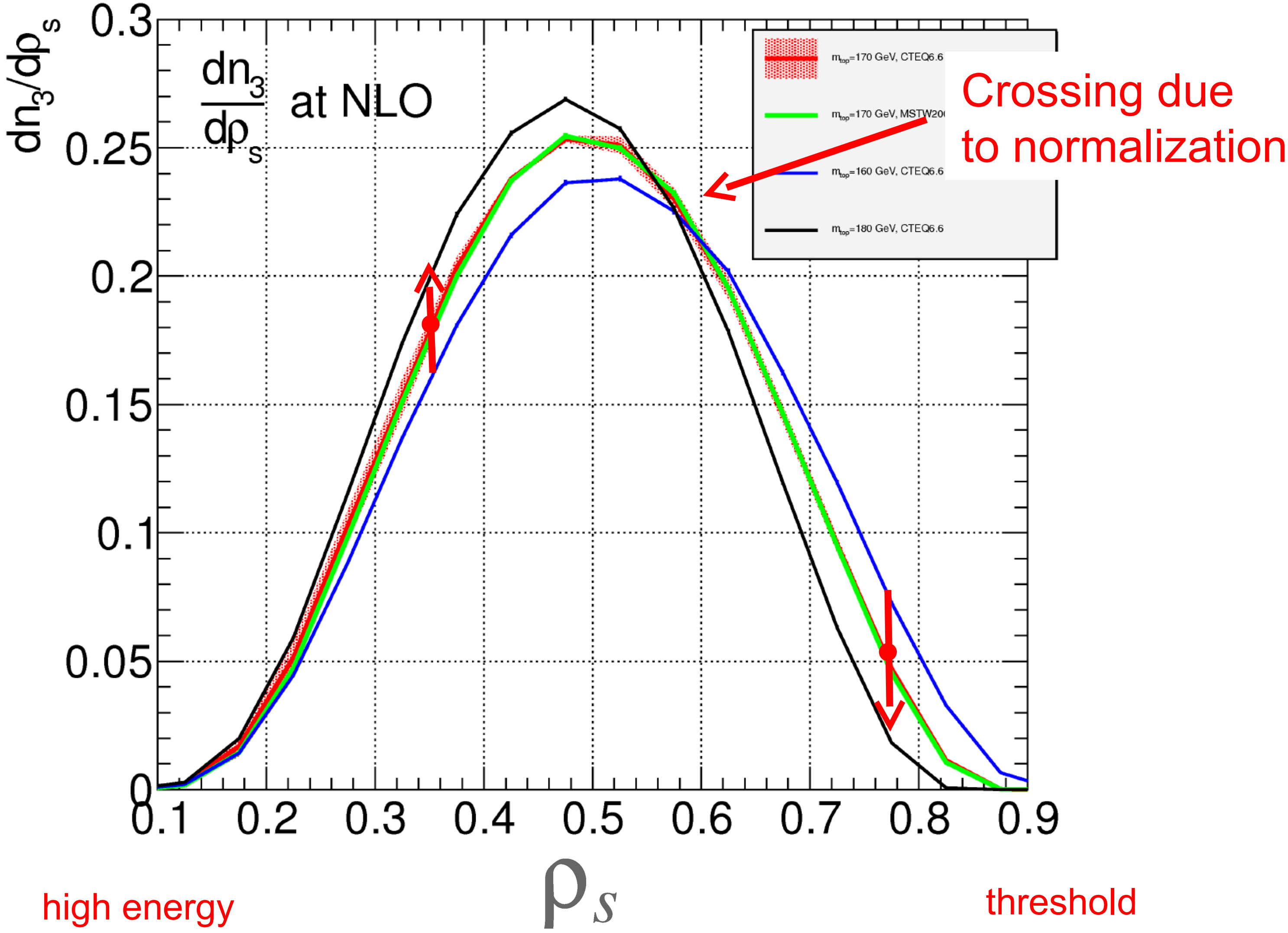
with $\rho_s = \frac{2m_0}{\sqrt{s_{t\bar{t}+1\text{Jet}}}}, \quad m_0 = O(m)$

$\rho = 4m_t^2/\hat{s}$

i.e. m_0 = 170 GeV

Mass dependence

[Work in progress S. Alioli, J.Fuster, A. Irles, S. Moch, PU, M. Vos]

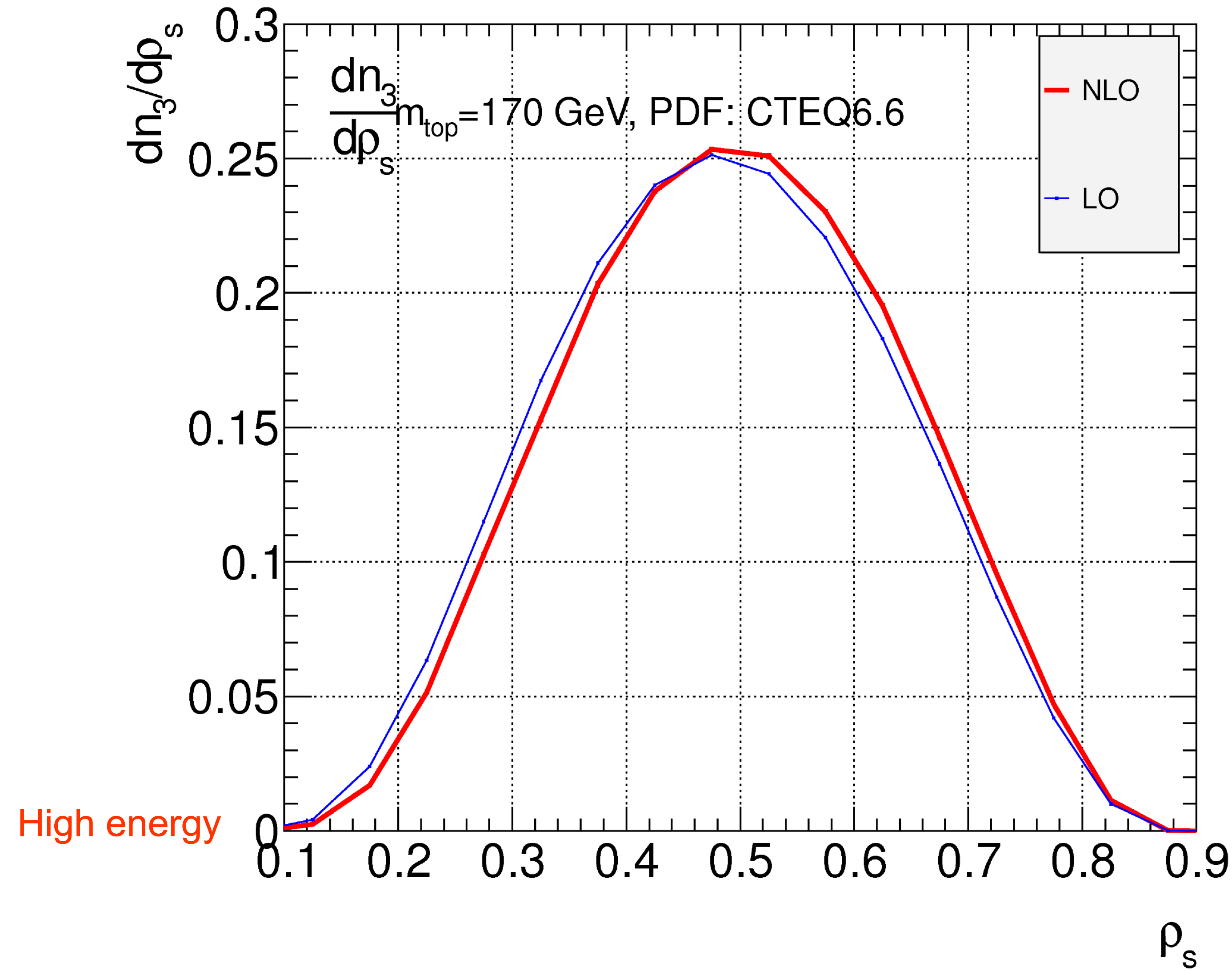


high energy

threshold

Impact of higher order corrections

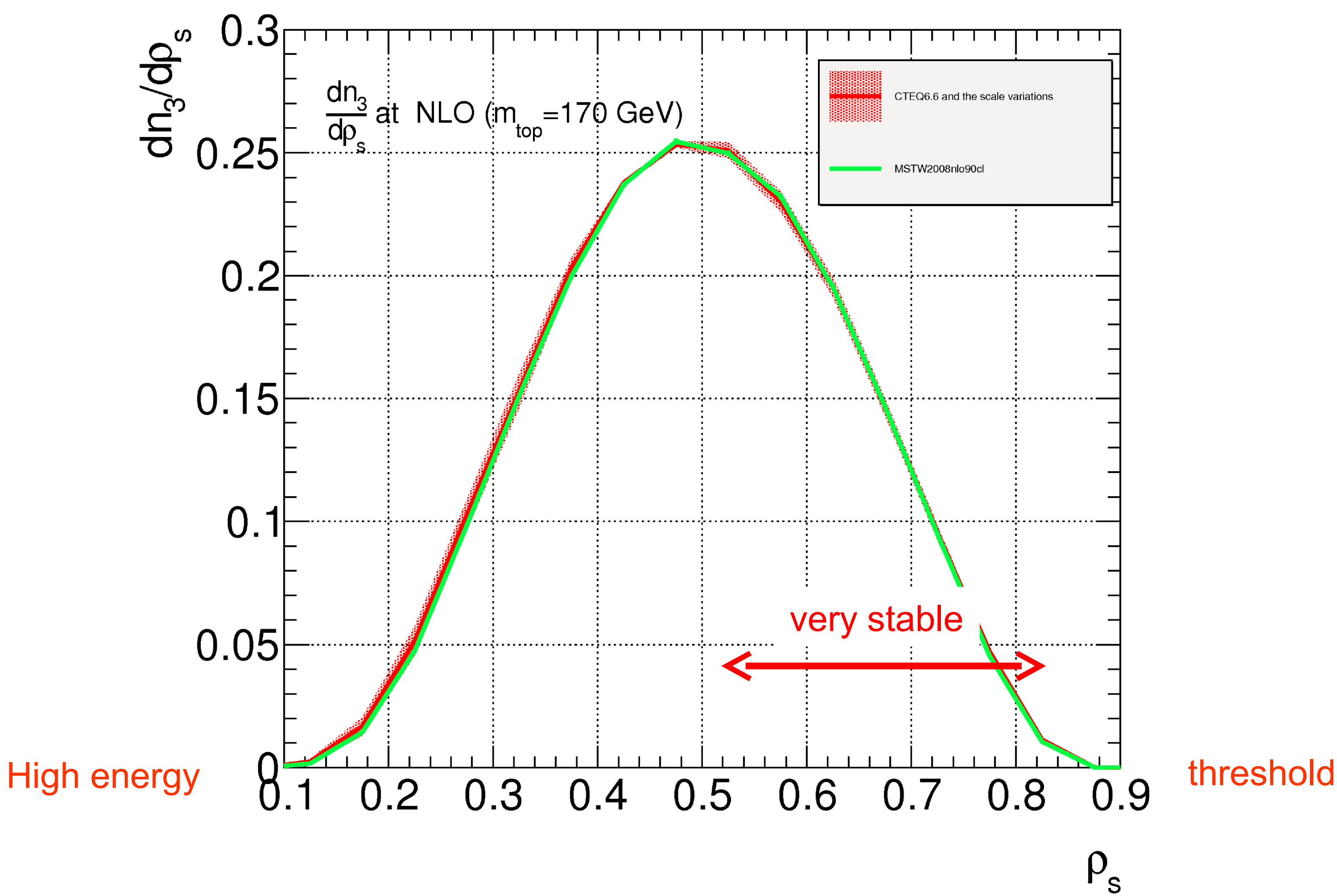
[Work in progress S. Alioli, J.Fuster, A. Irles, S. Moch, PU, M. Vos]



- Consistent with scale variation
- ttj: Corrections in general moderate
- Hard corrections → small ρ

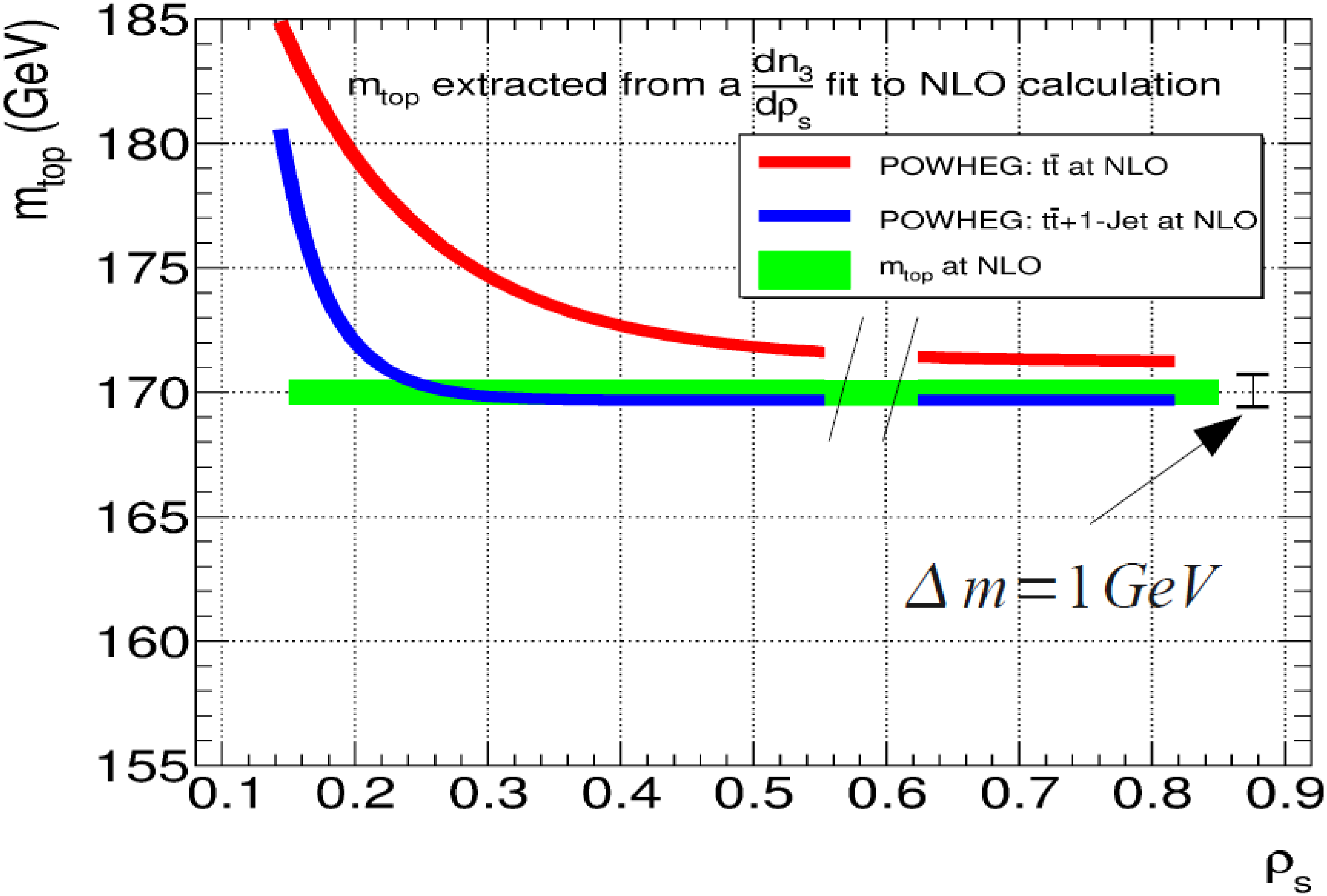
Scale and PDF uncertainties

[Work in progress S. Alioli, J.Fuster, A. Irles, S. Moch, PU, M. Vos]



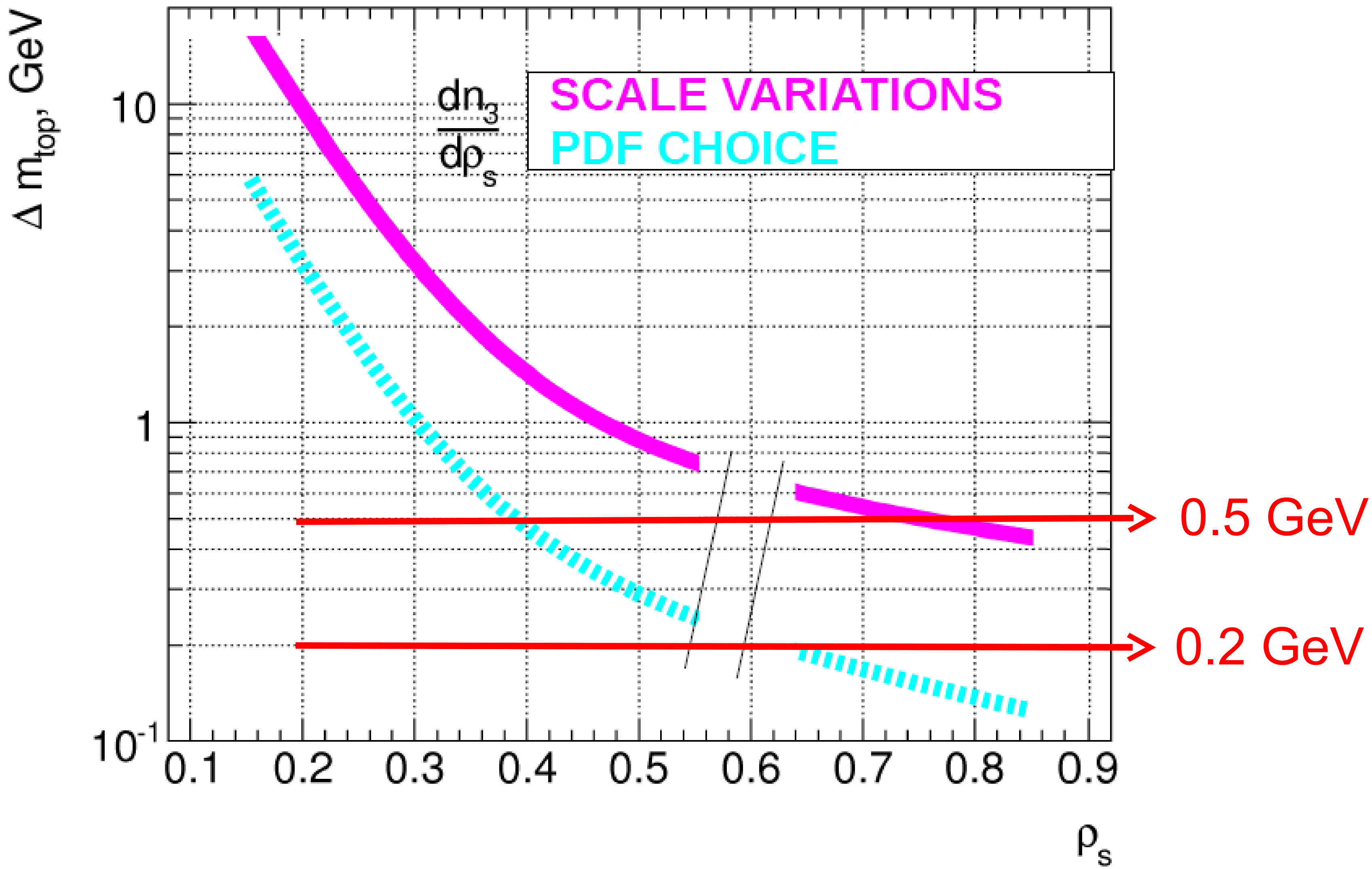
Toy experiment

[Work in progress S. Alioli, J.Fuster, A. Irles, S. Moch, PU, M. Vos]



Impact of scale and PDF uncertainties

[Work in progress S. Alioli, J.Fuster, A. Irles, S. Moch, PU, M. Vos]



Estimate of uncertainties

[Work in progress S. Alioli, J.Fuster, A. Irles, S. Moch, PU, M. Vos]

	Source of uncertainty	Impact on the top quark mass
Theoretical uncertainties	μ variations	~ 0.5 GeV
	PDF choice	~ 0.2 GeV
Experimental uncertainties	MC comparison	~ 0.4 ± 0.3 GeV
	JES	~ 0.8 GeV
	Statistics (5 fb-1)	~ 1.2 GeV

1 GeV

$$\Delta JES = \pm 3\%$$

→ Promising alternative

Summary

- Top-quarks physics is precision physics
- Complete NNLO for qq channel now available
- Many new results beyond inclusive tt production
- How well do we understand current mass measurements ?
- Important to study alternative methods for top-quark mass determination
- Top-quark mass from jet rates looks promising

High energy behavior through BFKL dynamics

[Ball, Ellis '01, Moch, PU, Vogt '12]

$$\hat{\sigma}(\omega) = \int_0^1 d\rho \rho^{\omega-1} \sigma(\rho) \qquad (\rho = 4m_t^2/\hat{s})$$

ρ→1, large ω
"Threshold region"
Soft-collinear factorization

ρ→0, small ω
High energy behavior
BFKL

$$\hat{\sigma} = \sigma_{LO}\left(1 + \sum_{j=1}^{\infty}\sum_{k=1}^{2j} b_{jk}\alpha_s^j \ln^k \omega\right)$$

$$\hat{\sigma} \sim \frac{\alpha_s^2}{m_t^2}\sum_{j=0}^{\infty}\alpha_s^j \sum_{k=0}^{\infty} c_{jk}\left(\frac{\alpha_s}{\omega}\right)^k$$

$$\frac{1}{\omega} \leftrightarrow \text{const}_\rho \qquad \frac{1}{\omega^2} \leftrightarrow \ln(\rho)$$

High energy behavior through BFKL dynamics

- Possible to predict leading high-energy behavior
- Available BFKL input not sufficient to calculate sub-leading behavior in NNLO
- Often large numerical cancellations between leading and sub-leading behavior

➡ Ansatz for sub-leading behavior

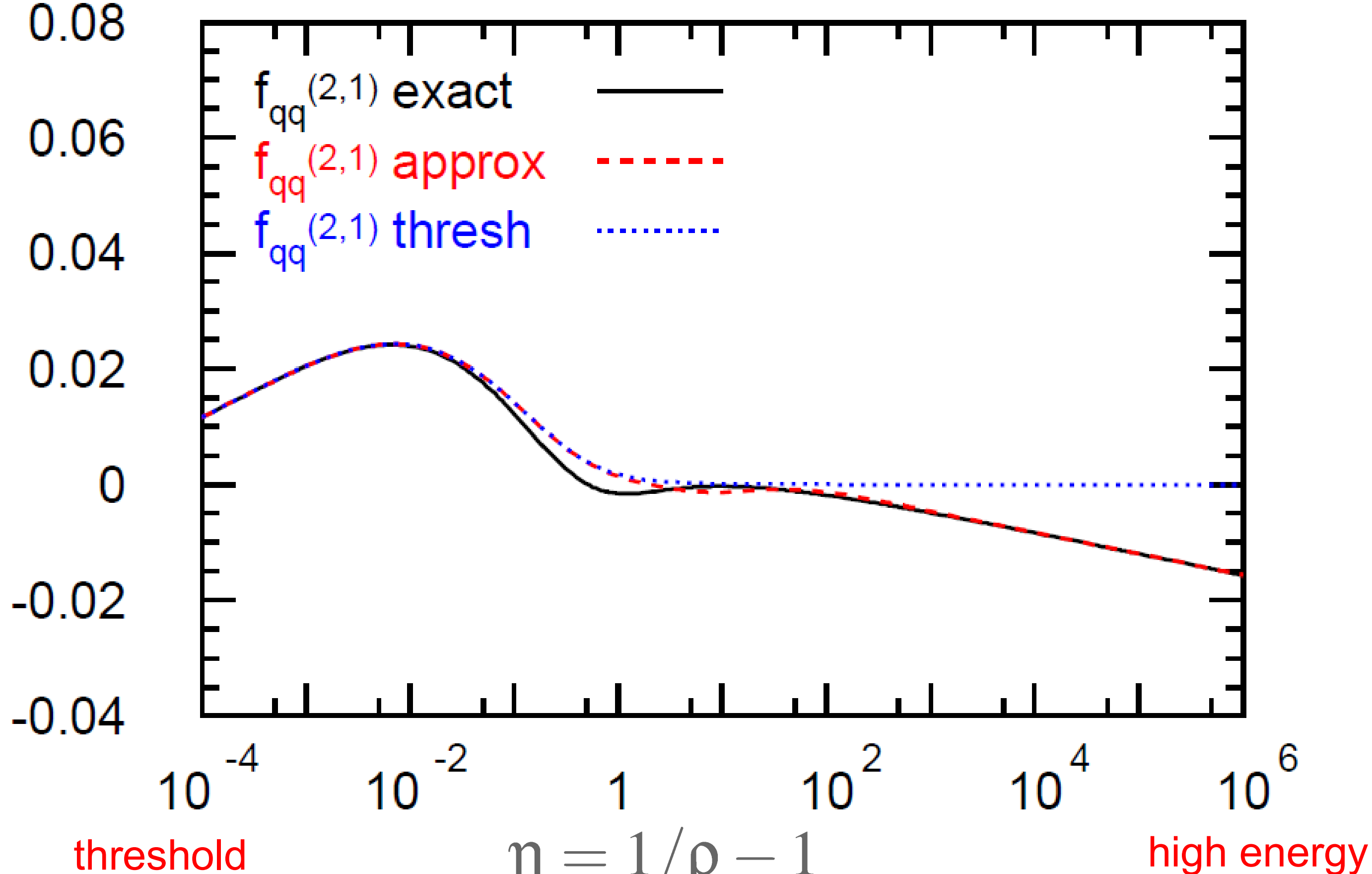
➡ Match high-energy behavior with threshold information

Useful to further constrain NNLO cross section

Consistency check

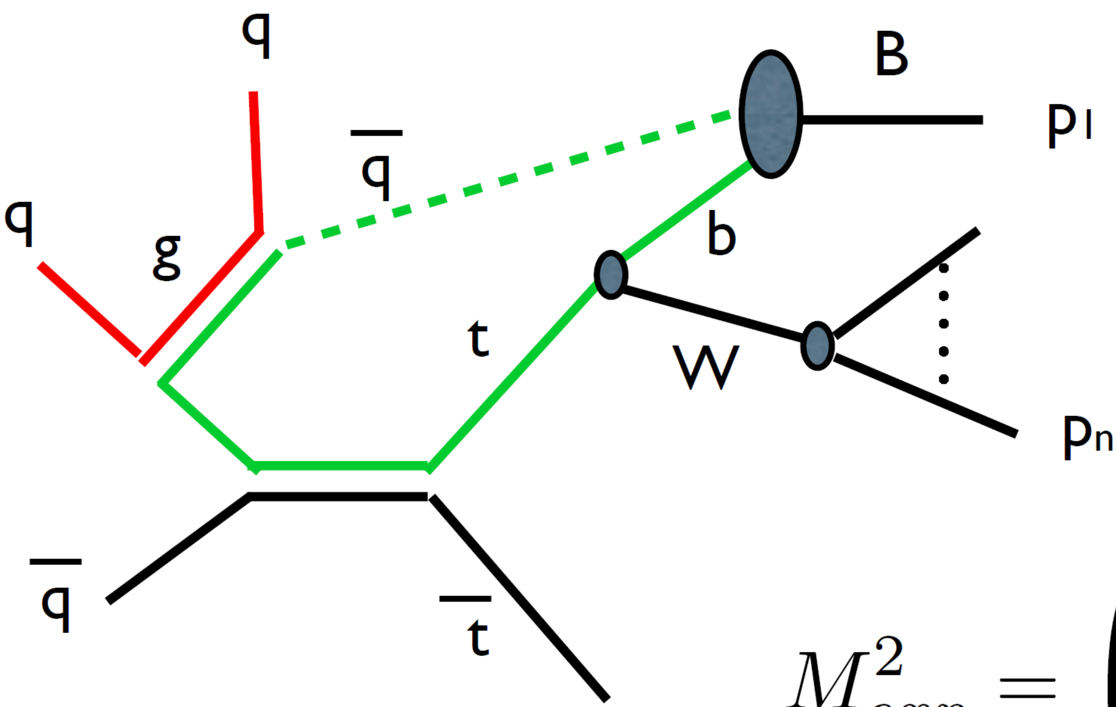
$$\sigma_{ij}^{(2)} = \frac{\alpha_s^2}{m_t^2}(4\pi\alpha_s)^2 \left(f_{ij}^{(2,0)} + \ln\left(\frac{\mu^2}{m_t^2}\right) f_{ij}^{(2,1)} + \ln^2\left(\frac{\mu^2}{m_t^2}\right) f_{ij}^{(2,2)} \right)$$

RGE



Color reconnection

[Mangano, Top workshop, July 2012, CERN]



$$M^2_{exp} = \left(\sum_{i=1,\ldots,n} p_i \right)^2$$

Application: Top mass from cross section

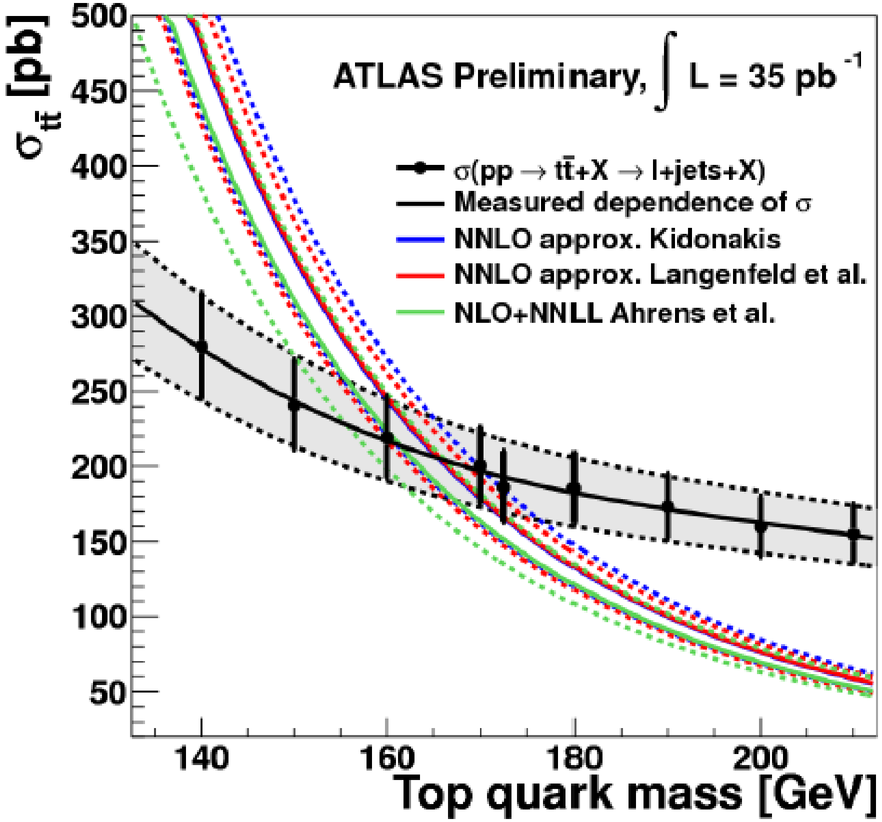
[Sven Moch, prepared for Top2012 Winchester]

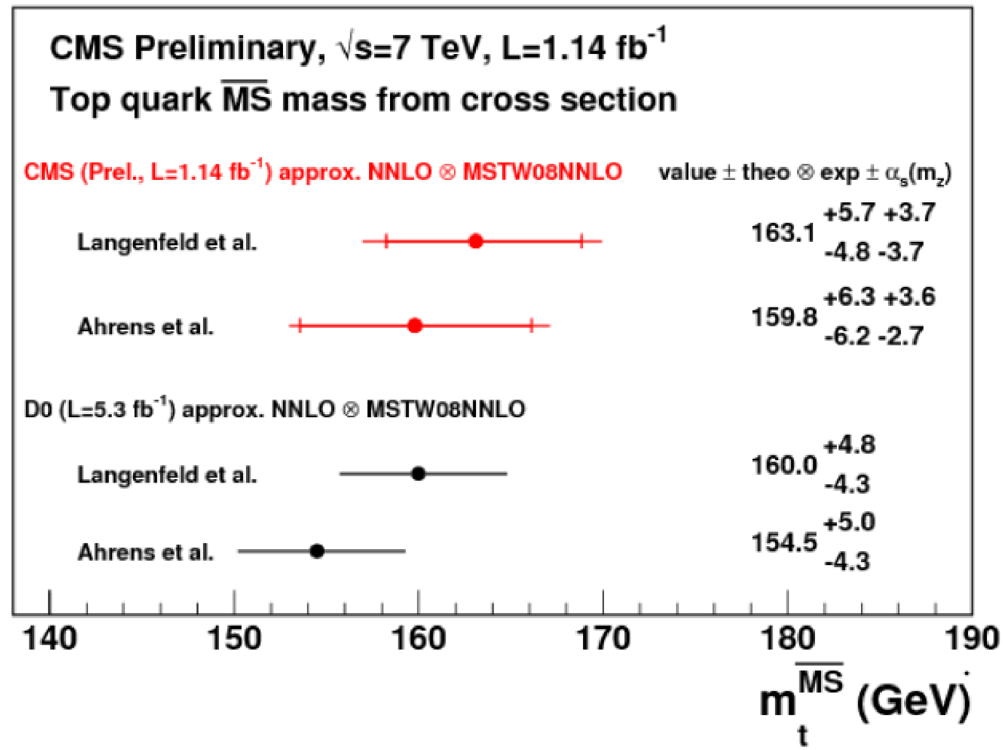
- Determine top quark mass from Tevatron cross section data
  - $\sigma_{t\bar{t}} = 7.56^{+0.63}_{-0.56}$ pb D0 coll. arXiv:1105.5384
  - $\sigma_{t\bar{t}} = 7.50^{+0.48}_{-0.48}$ pb CDF coll. CDF-note-9913
- Fit of m_t for individual PDFs
  - parton luminosity at Tevatron driven by $q\bar{q}$
  - $\overline{\mathrm{MS}}$-scheme for $m_t^{\overline{\mathrm{MS}}}(m_t)$, then scheme transformation to pole mass m_t^{pole} at NNLO

	ABM11	JR09	MSTW08	NN21
$m_t^{\overline{\mathrm{MS}}}(m_t)$	$162.0\,^{+2.3}_{-2.3}\,^{+0.7}_{-0.6}$	$163.5\,^{+2.2}_{-2.2}\,^{+0.6}_{-0.2}$	$163.2\,^{+2.2}_{-2.2}\,^{+0.7}_{-0.8}$	$164.4\,^{+2.2}_{-2.2}\,^{+0.8}_{-0.2}$
m_t^{pole}	$171.7\,^{+2.4}_{-2.4}\,^{+0.7}_{-0.6}$	$173.3\,^{+2.3}_{-2.3}\,^{+0.7}_{-0.2}$	$173.4\,^{+2.3}_{-2.3}\,^{+0.8}_{-0.8}$	$174.9\,^{+2.3}_{-2.3}\,^{+0.8}_{-0.3}$
(m_t^{pole})	$(169.9\,^{+2.4}_{-2.4}\,^{+1.2}_{-1.6})$	$(171.4\,^{+2.3}_{-2.3}\,^{+1.2}_{-1.1})$	$(171.3\,^{+2.3}_{-2.3}\,^{+1.4}_{-1.8})$	$(172.7\,^{+2.3}_{-2.3}\,^{+1.4}_{-1.2})$

→ Consistent with direct measurements

Top quark mass from cross section





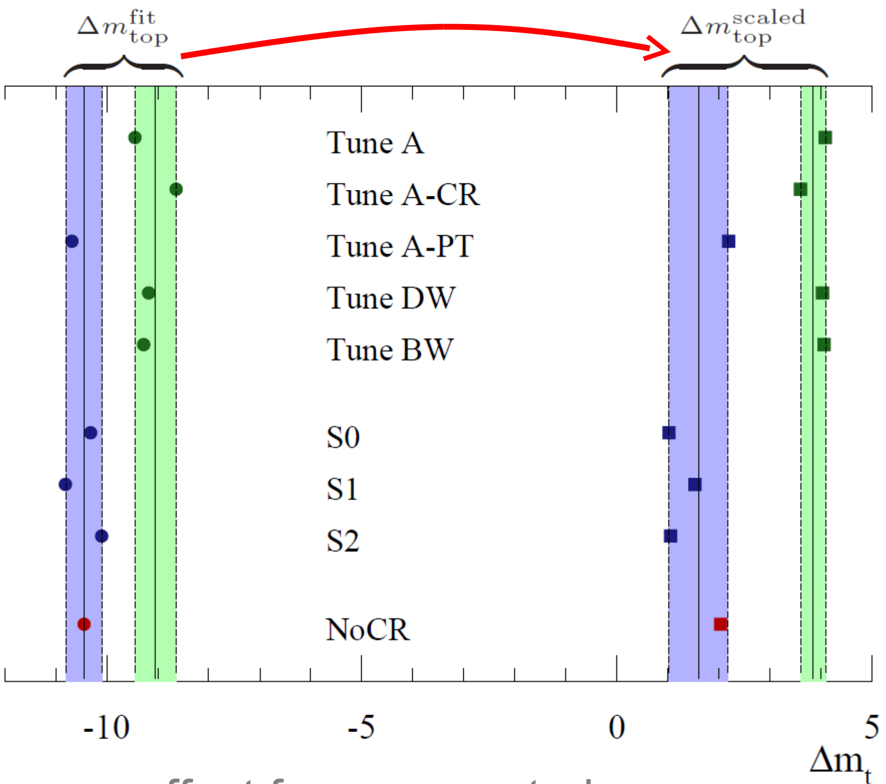
Mass scheme well defined, higher orders can be included

Drawback: Limited sensitivity to m_t $\quad \frac{\Delta\sigma_{t\bar{t}}}{\sigma_{t\bar{t}}} \approx 5 \frac{\Delta m_t}{m_t}$

Non-perturbative effects at the LHC

[Skands,Wicke '08]

Simulate top mass measurement using different models/tunes for non-perturbative physics / colour reconnection



offset from generated mass

different offset for different tunes!

Non-perturbative effects result in uncertainty of the order of 500 MeV

blue: pt-ordered PS
green: virtuality ordered PS