Strategies towards a precise measurements of the top-quark mass

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GK1504

Outline

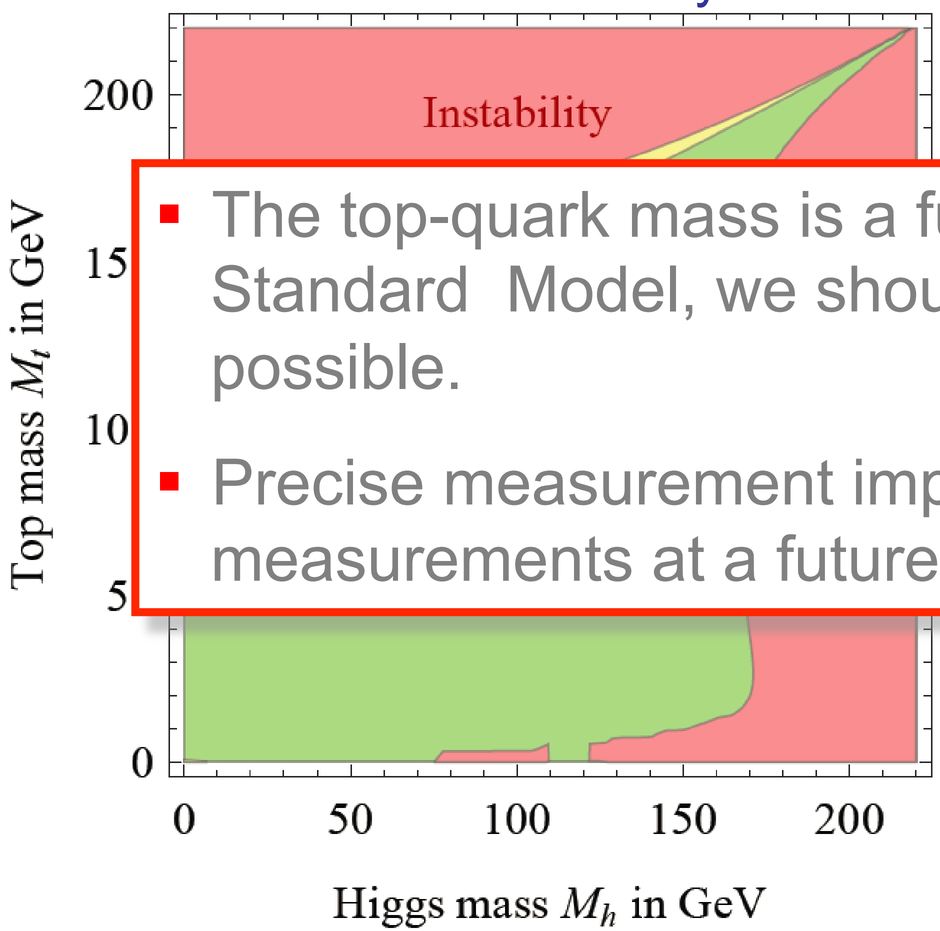
1. Motivation and introduction
2. Alternative methods
3. Summary

Why do we care about the top-quark mass ?

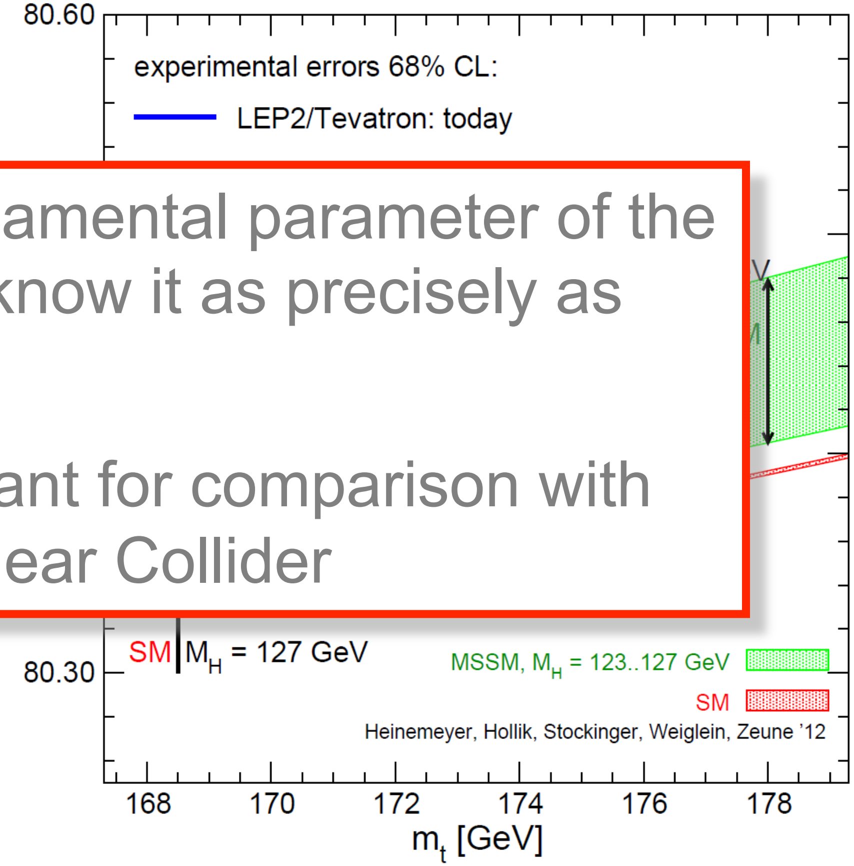
[Degrassi, Di Vita, Elias-Miro,Spinosa,Giudici ' 12, Alekhin, Djouadi, Moch ' 12]

[Heinemeyer, Hollik, Stockinger, Weiglein, Zeune '12]

Vacuum stability



Consistency of the SM



- The top-quark mass is a fundamental parameter of the Standard Model, we should know it as precisely as possible.
- Precise measurement important for comparison with measurements at a future Linear Collider

How do we measure a quark mass ?

…at least in theory

- We don't see free quarks, there is no pole in the *S*-matrix

→ top-quark mass is not an observable,
mass is just a parameter of the underlying theory

Precise value depends on the definition / renormalisation scheme (i.e. pole mass, $\overline{\text{MS}}$ mass)

- Determine / fit parameter from comparison of theoretical predictions and measurements

To fix the renormalisation scheme at least a NLO calculation is required

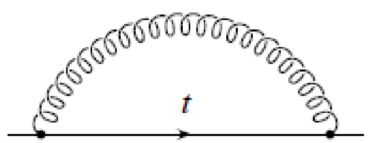
Pole mass vs running mass

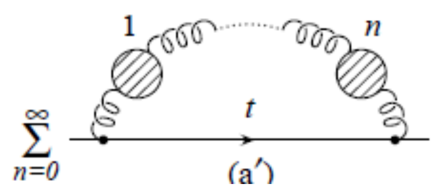
$$m_t = \overline{m}(\mu)\left(1 + \frac{\alpha_s(\mu)}{\pi}\left[\frac{4}{3} + \ln\left(\frac{\mu^2}{\overline{m}(\mu)^2}\right)\right] + O(\alpha_s^2)\right)$$

Which scheme should one use ?

- Perturbative expansion may converge better using specific scheme (resummation of large logs,…)
- Scheme might be ill defined beyond perturbation theory

Example: Renormalon ambiguity in pole mass

$\Sigma^{(1)} =$ 



$$\frac{16 m_R}{3\beta_0}\sum_{n=0}^{\infty} c_n a^{n+1}$$

$$c_n \overset{n\to\infty}{\longrightarrow} e^{-C/2} 2^n n!$$

[Bigi, Shifman, Uraltsev, Vainshtein 94 Beneke, Braun,94 Smith, Willenbrock 97]

There is no pole in full QCD !

Pole mass has intrinsic uncertainty of order Λ_{QCD}

Requirements for a precise quark mass determination

Checklist:

- ❑ Observable should show good sensitivity to m

$$\frac{\Delta O}{O} \leftrightarrow \frac{\Delta m_t}{m_t}$$

- ❑ Observable must be theoretically calculable

- ❑ Theory uncertainty must be small

  small non-perturbative corrections

- ❑ Observable must be "experimentally accessible"

- ❑ Well defined mass scheme

Top-quark mass: Experimental methods

- Template method (invariant mass of top decay products)
- Matrix element method
- …

Issues:

- Higher-order corrections ?
- Intrinsic limitations of pole mass ($\sim\Lambda_{\mathrm{QCD}}$)
- Precise relation

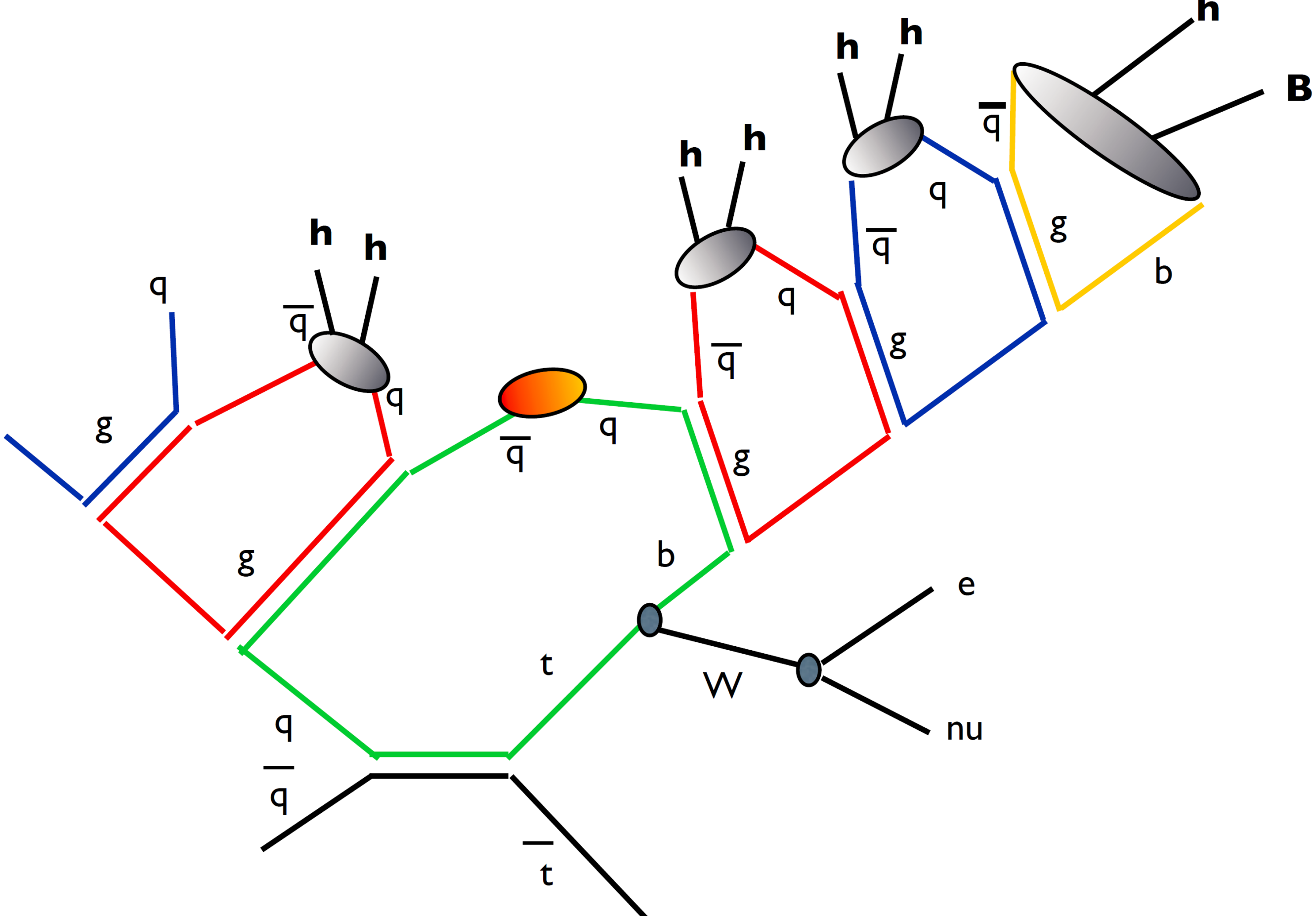
$$m_{\mathrm{MC}} = m_{\mathrm{Pole}}(1 \pm \Delta)$$

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

Not necessarily independent

Color reconnection

[Mangano, Top workshop, July 2012, CERN]



$$p_t \neq p_W + \sum_i p^i_{\text{had}}$$

Impact on current measurements

Color reconnection:

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

[Skands,Wicke '08]

Relation: measured mass ←→ pole mass:

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

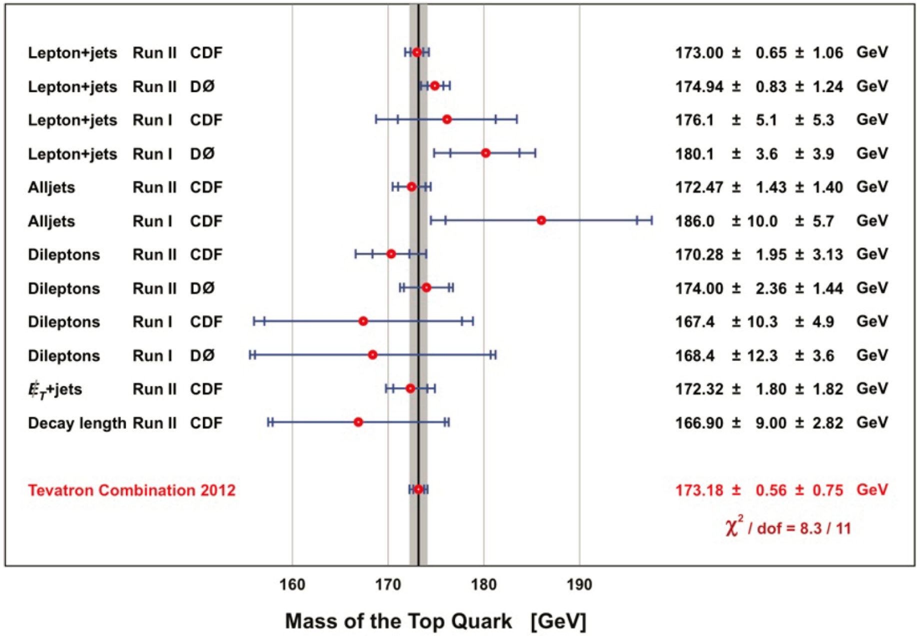
$$\Delta = \begin{cases} \frac{\Lambda}{m} \approx 0.13\% \\ \frac{\Gamma}{m} \approx 0.8\% \\ \frac{\alpha_s}{\pi} \approx 3.7\% \end{cases}$$

?

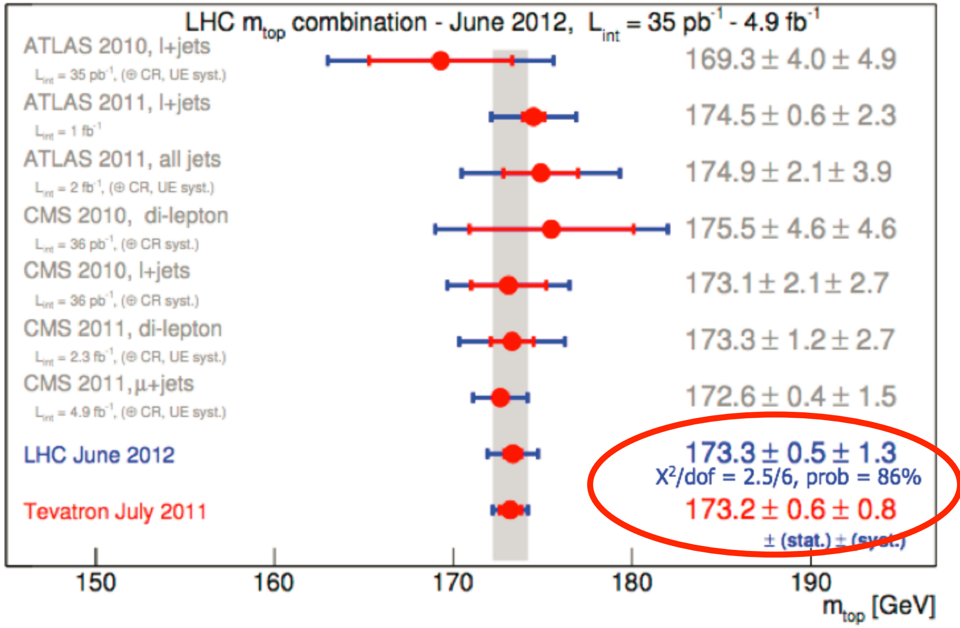
[Pich, Benasque Conf. ' 12]

Impact on current measurements

Tevatron



LHC



Different channels and different experiments give consistent results

⬇

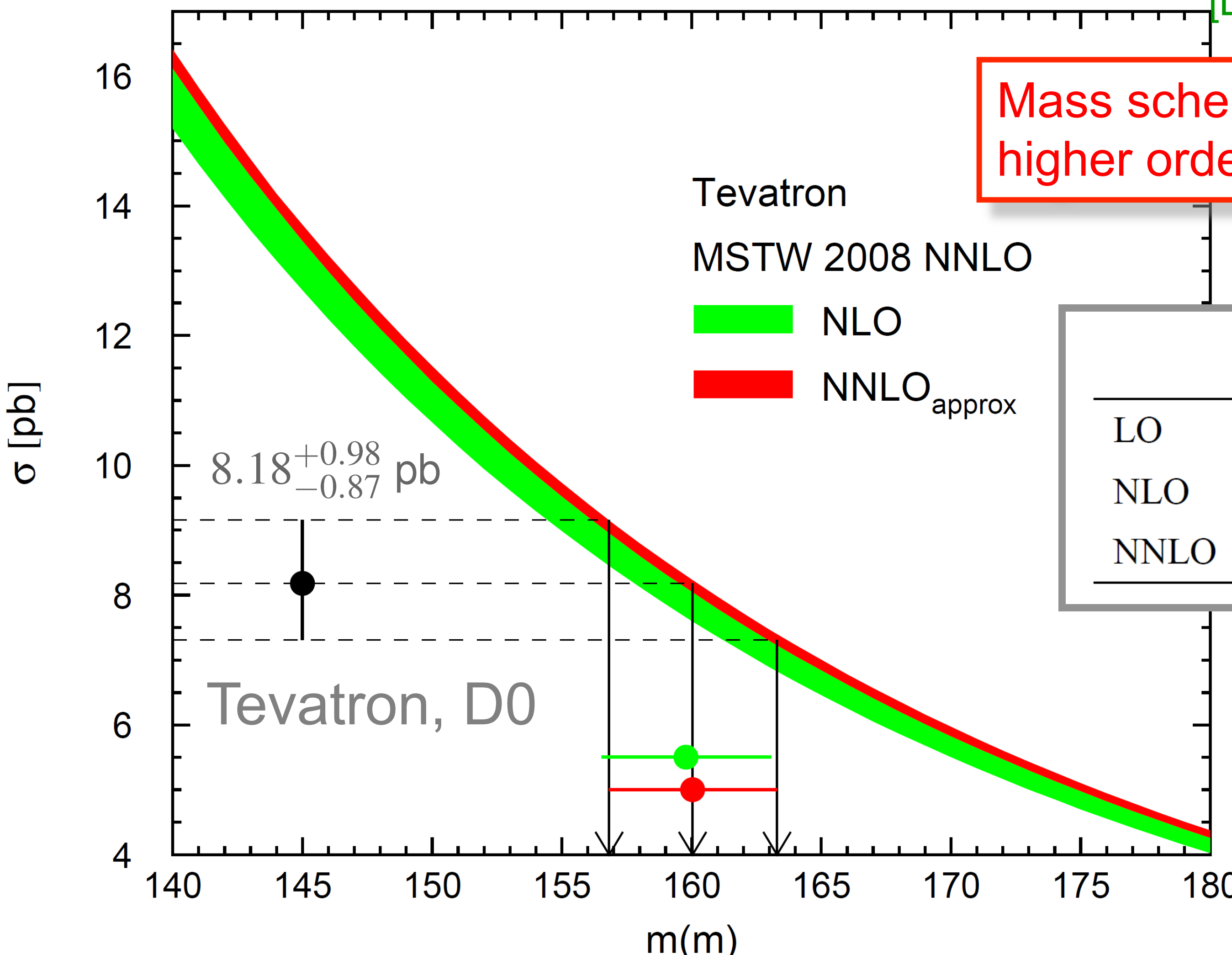
Large effects unlikely

Alternative Methods

1. Top-quark mass determination from cross section
2. Invariant mass of J/Ψ + lepton in top decay / M_{Bl}
3. Top-quark mass from jet rates
4. Threshold scan in e+e- annihilation

$\overline{\text{MS}}$ mass from cross section

[Langenfeld, Moch, PU 09]



Mass scheme well defined, higher orders can be included

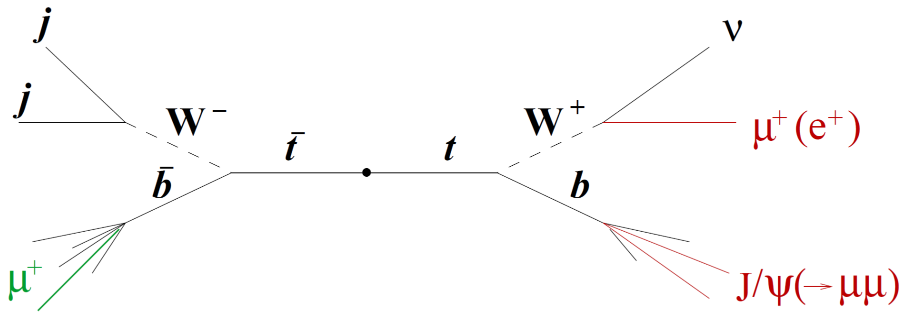
	$\overline{m}$ [GeV]	m_t [GeV]
LO	$159.2^{+3.5}_{-3.4}$	$159.2^{+3.5}_{-3.4}$
NLO	$159.8^{+3.3}_{-3.3}$	$165.8^{+3.5}_{-3.5}$
NNLO	$160.0^{+3.3}_{-3.2}$	$168.2^{+3.6}_{-3.5}$

$$m_t = 168.9^{+3.5}_{-3.4}$$

only exp. uncertainties

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

Top mass in leptonic final states with J/Ψ



[A. Kharchilava, CMS-Note 1999-065, Phys. Lett. B476 (2000) 73, Corcella, Mangano, Seymour '00, Chierici, Dierlamm, CMS-Note 2006-058]

Average $M_{J/\Psi\ell}$ is correlated with m_t

Advantages:

- Experimentally very clean
- Independent from production
- Good sensitivity

} $\Delta m_t \approx 1\text{GeV}$

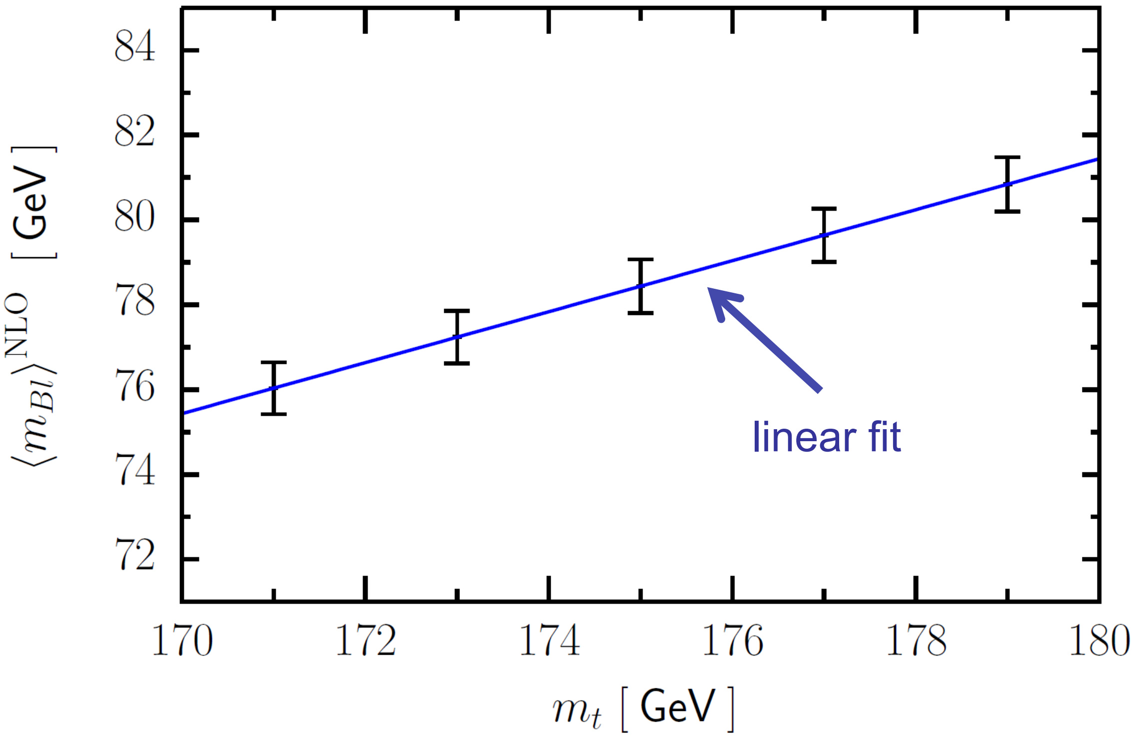
Disadvantages:

- Small branching fraction → $O(100/fb)$
- Relies on Monte Carlo modeling
- Which mass do we measure ?

Top mass in leptonic final states with J/Ψ

Recent progress:

[Biswas, Melnikov, Schulze '10]



- Slope difference of 0.01 compared to MC results → 3 GeV shift

NLO corrections are important

- Further studies required

$\langle M_{B\ell} \rangle$ at NLO accuracy in QCD

Top-quark mass from jet-rates (ttj)

[S. Alioli, P.Fernandez, J.Fuster, A. Irles, S. Moch, PU, M. Vos, to appear]

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

[S. Alioli, P.Fernandez, J.Fuster, A. Irles, S. Moch, PU, M. Vos, to appear]

To enhance mass sensitivity study:

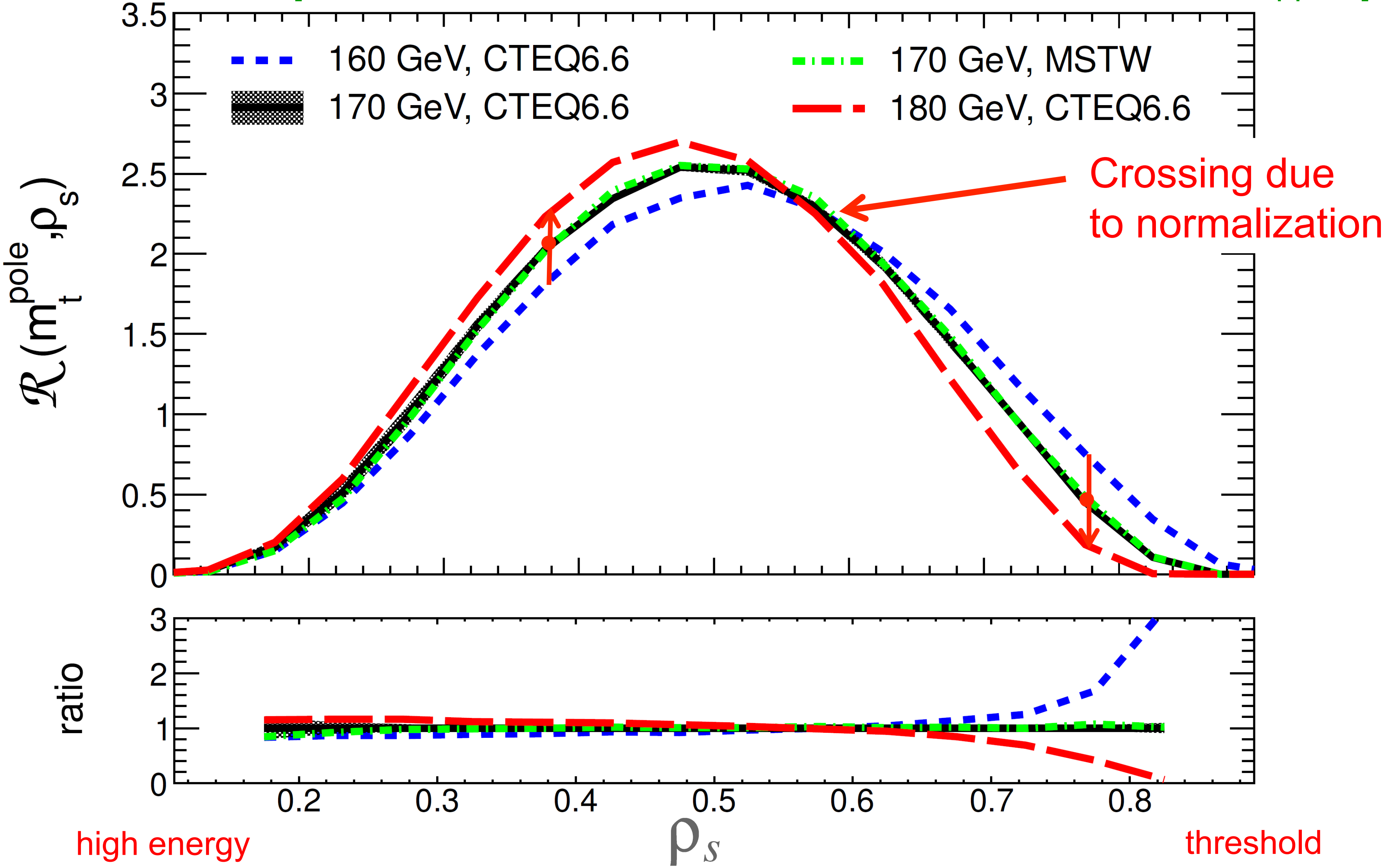
$$\mathcal{R}(m_{\text{Pole}}, \rho_s) = \frac{1}{\sigma_{t\bar{t}+1\text{Jet}}} \frac{d\sigma_{t\bar{t}+1\text{Jet}}}{d\rho_s}(m_{\text{Pole}})$$

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

i.e. m_0 = 170 GeV

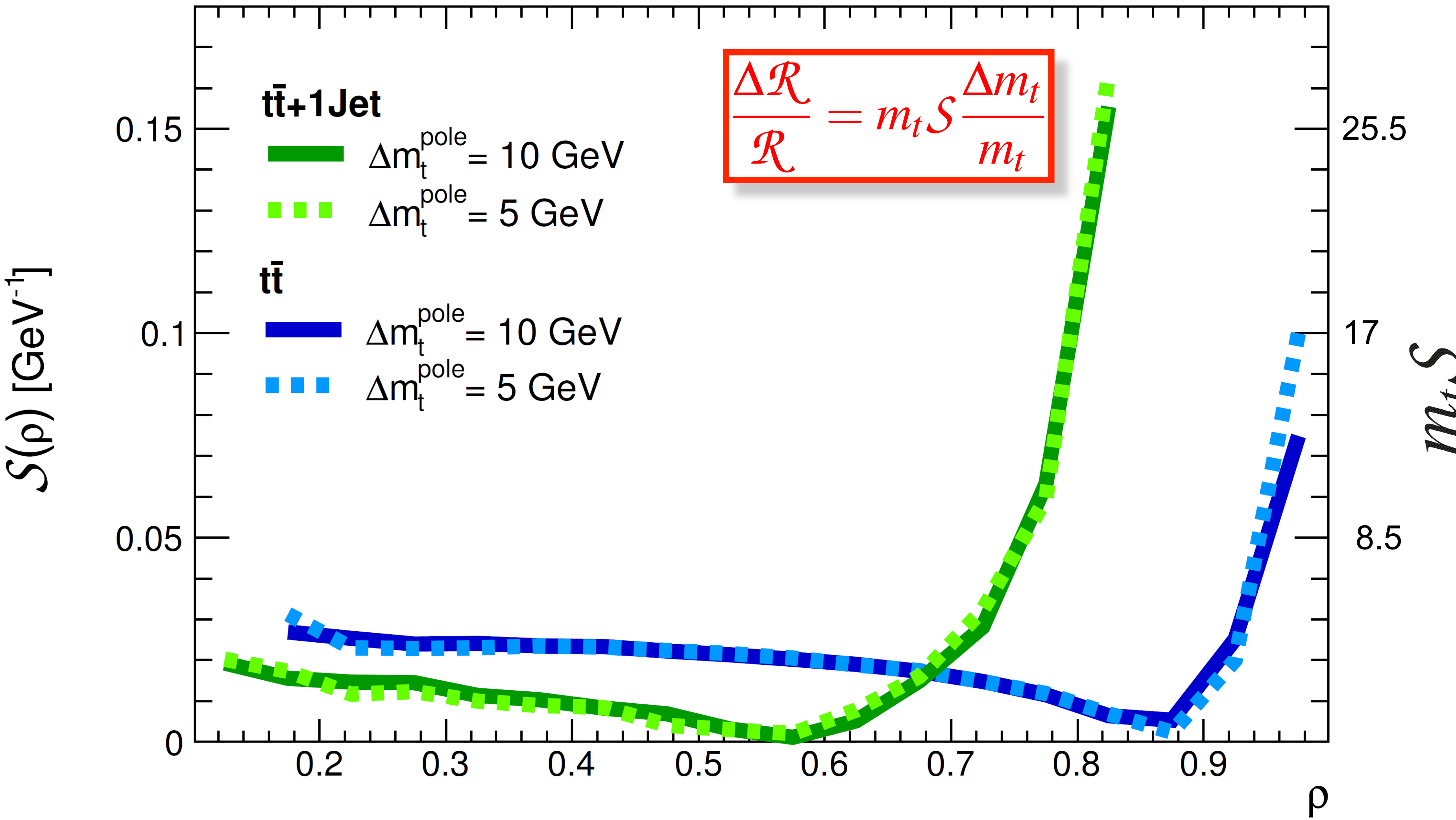
Mass dependence

[S. Alioli, P.Fernandez, J.Fuster, A. Irles, S. Moch, PU, M. Vos, to appear]



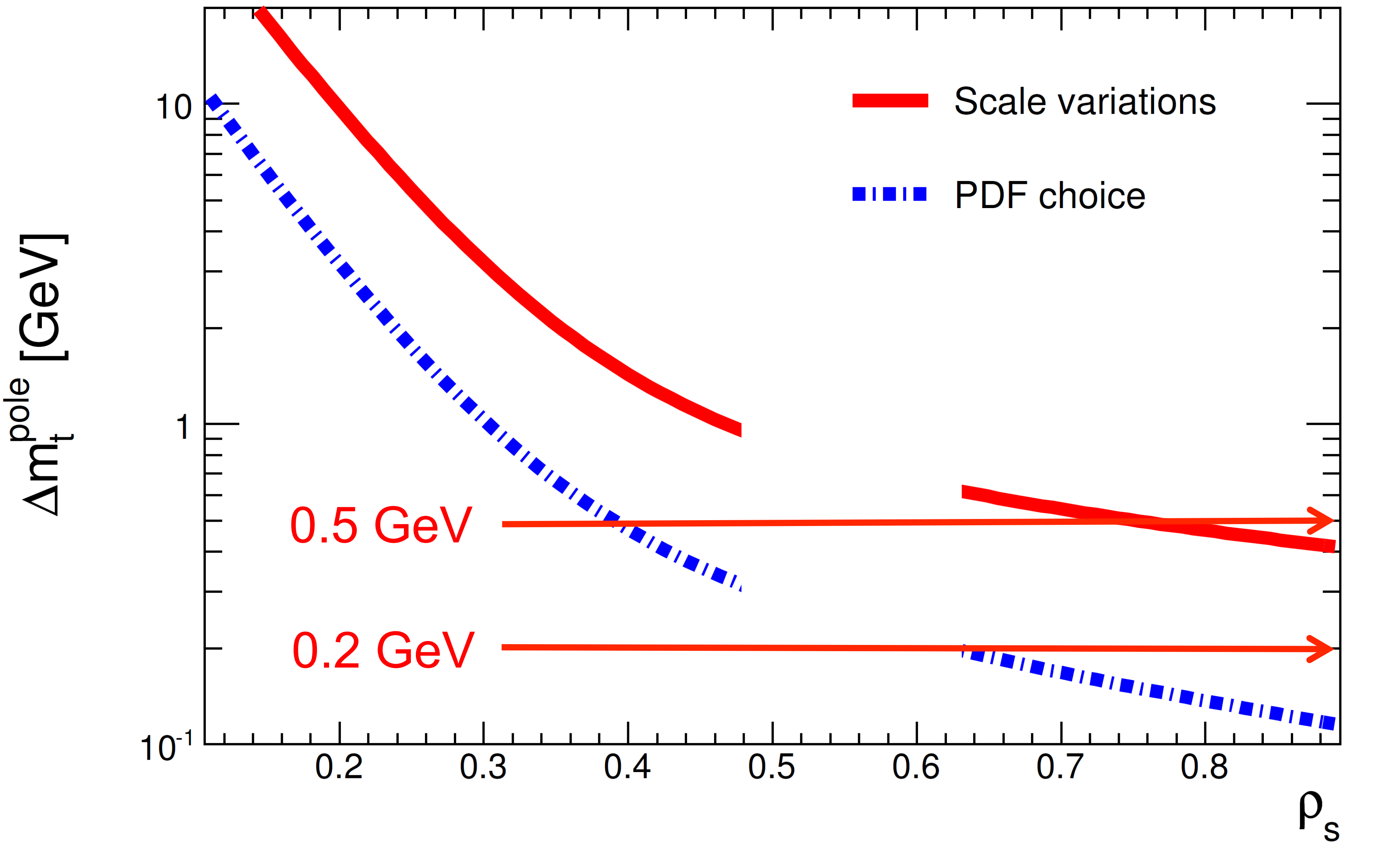
Sensitivity

[S. Alioli, P.Fernandez, J.Fuster, A. Irles, S. Moch, PU, M. Vos, to appear]



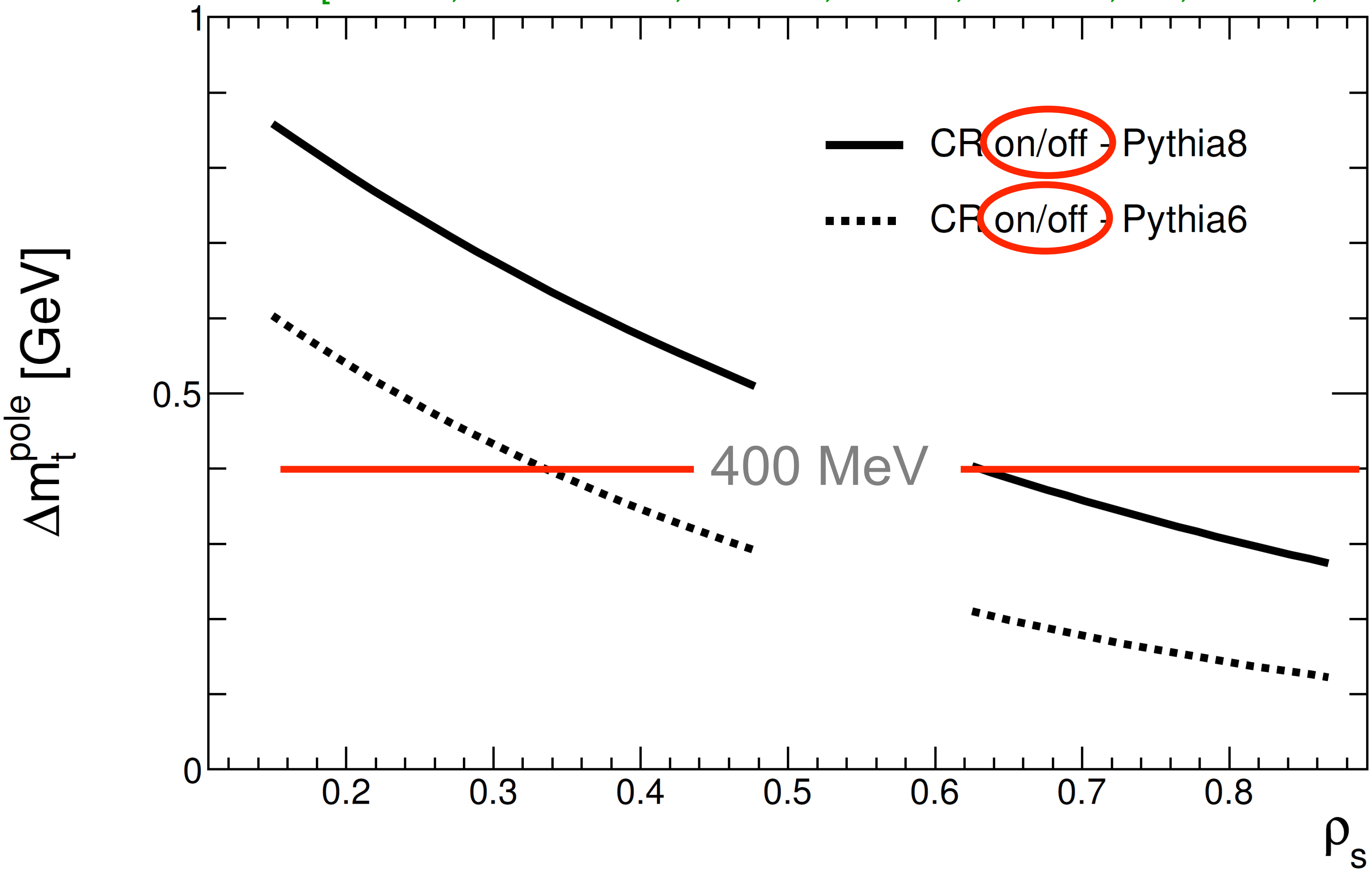
Scale and PDF uncertainties

[S. Alioli, P.Fernandez, J.Fuster, A. Irles, S. Moch, PU, M. Vos, to appear]



Color reconnection

[S. Alioli, P.Fernandez, J.Fuster, A. Irles, S. Moch, PU, M. Vos, to appear]



Very conservative estimate, in practice expect smaller effect

Estimate of uncertainties

[S. Alioli, P.Fernandez, J.Fuster, A. Irles, S. Moch, PU, M. Vos, to appear]

- PDF uncertainty: ~0.2 GeV
- Scale uncertainty: ~0.5 GeV
- Color reconnect.: ~0.4 GeV
- JES (+/- 3%): ~0.8 GeV

} 1 GeV

Mass independent unfolding possible

→ Promising alternative

Summary

- Top-quark mass uncertainty about 1 GeV achieved
- So far different measurements look consistent
- How well do we understand current mass measurements ?
- Precise theoretical predictions required
- Important to study alternative methods for top-quark mass determination
- Top-quark mass from jet rates looks promising

Thank you for your attention

Conversion between schemes

Example: Pole mass ← → $\overline{\text{MS}}$ mass:

$$m_t = \overline{m}(\mu)\left(1+\frac{\alpha_s(\mu)}{\pi}\left[\frac{4}{3}+\ln\left(\frac{\mu^2}{\overline{m}(\mu)^2}\right)\right]+O(\alpha_s^2)\right)$$

Pole mass

$\overline{\text{MS}}$ mass "Running mass"

Important:

- Difference is formally of higher order in coupling constant
- Difference can be numerically significant

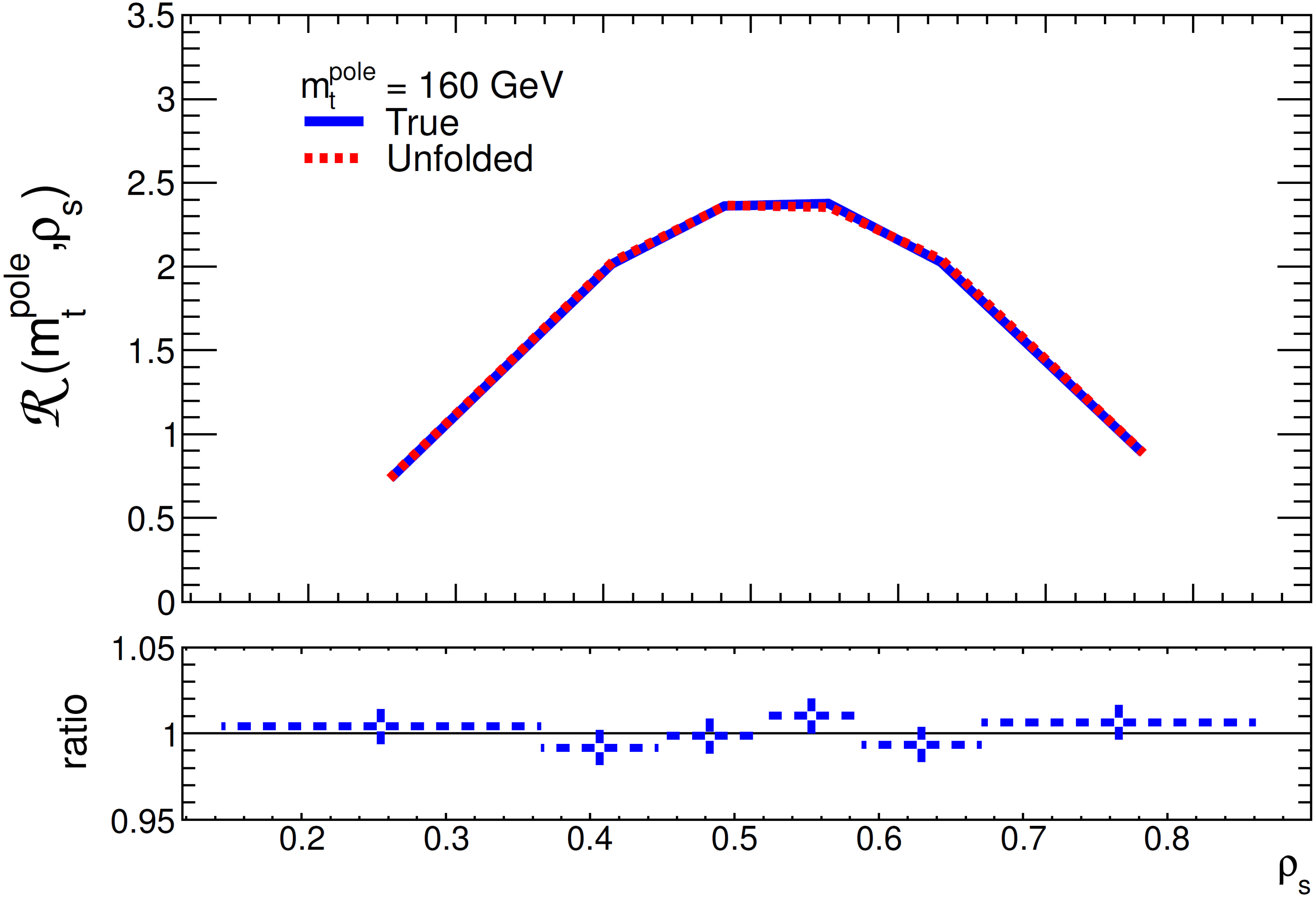
$$m_t \approx \overline{m}(\mu)(1+4\%+\ldots)$$

$$m_t = (165.0+7.6+1.6+0.51)\ \text{GeV}$$

[Chetyrkin,Steinhauser 99]

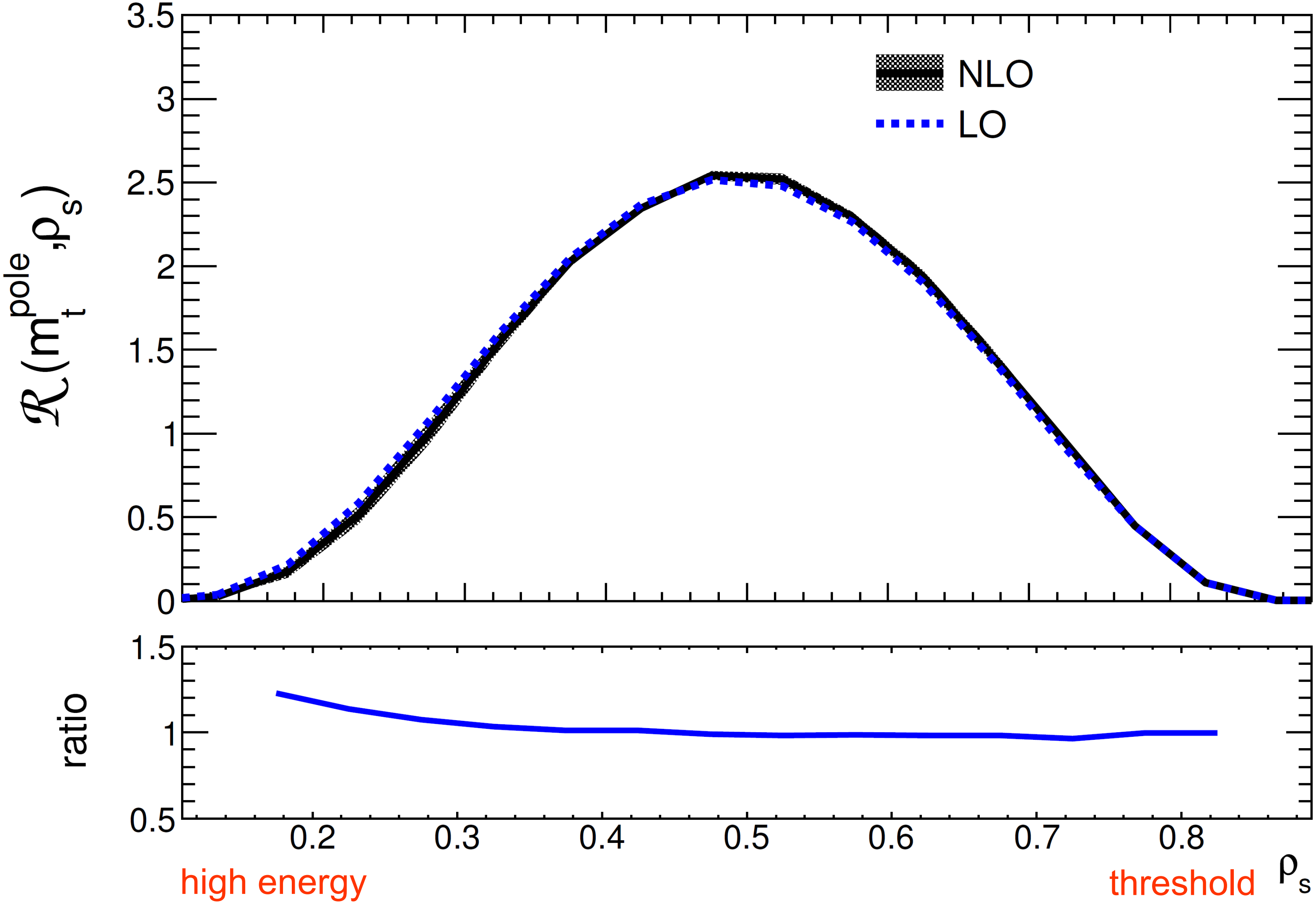
Unfolding

[S. Alioli, P.Fernandez, J.Fuster, A. Irles, S. Moch, PU, M. Vos, to appear]

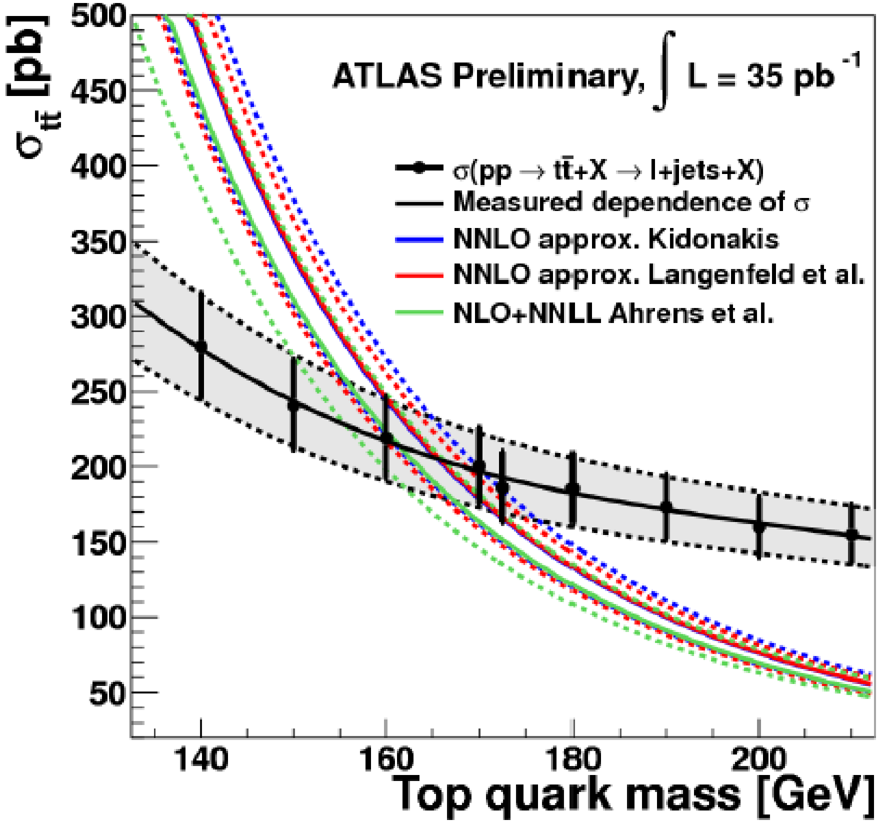


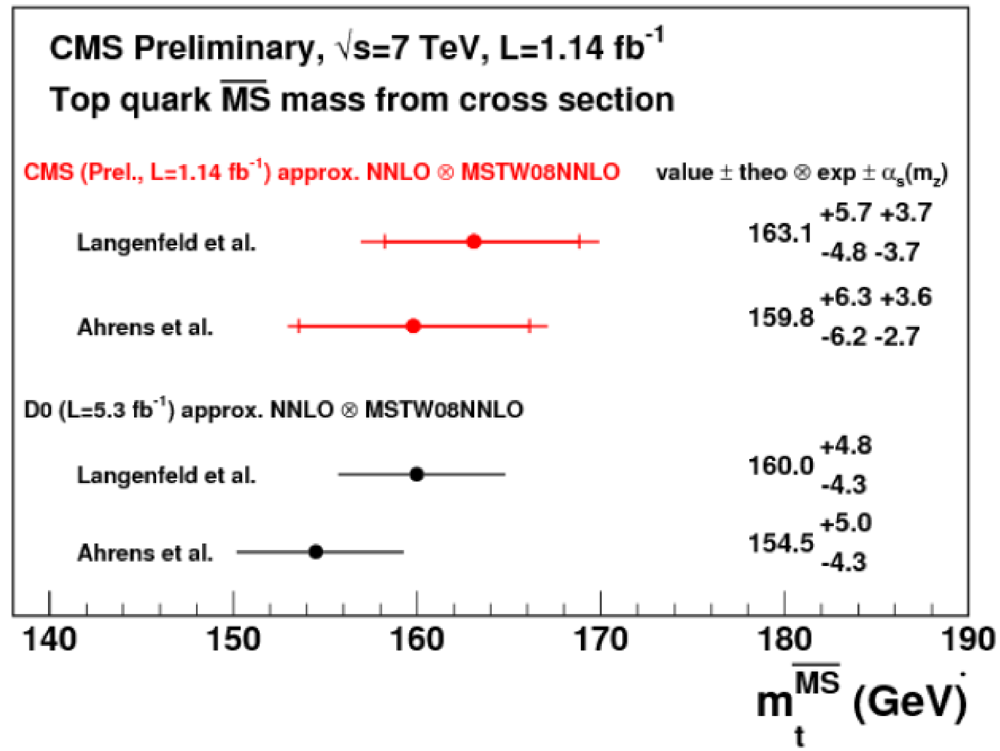
Impact of higher order corrections

[S. Alioli, P.Fernandez, J.Fuster, A. Irles, S. Moch, PU, M. Vos, to appear]



Top quark mass from cross section





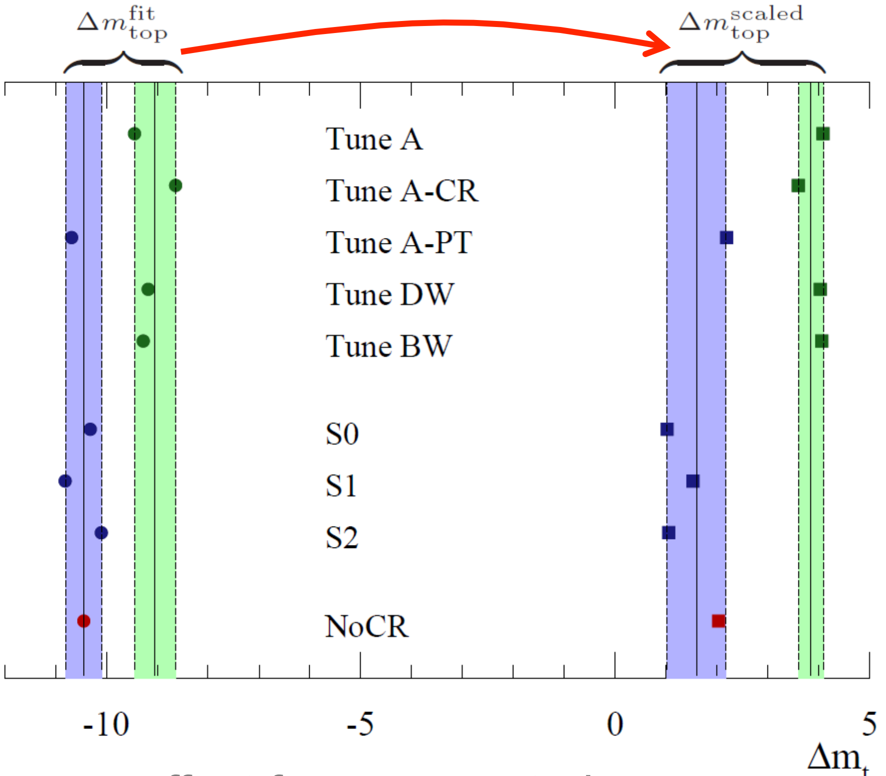
Mass scheme well defined, higher orders can be included

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

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

Recent progress: Jetmass in e+e-

Study high energetic tops in different hemispheres [Hoang 07,08]

factorisation in hard scattering and soft functions

Double differential invariant mass distribution:

$$Q = 5 \times 172 \text{ GeV}$$

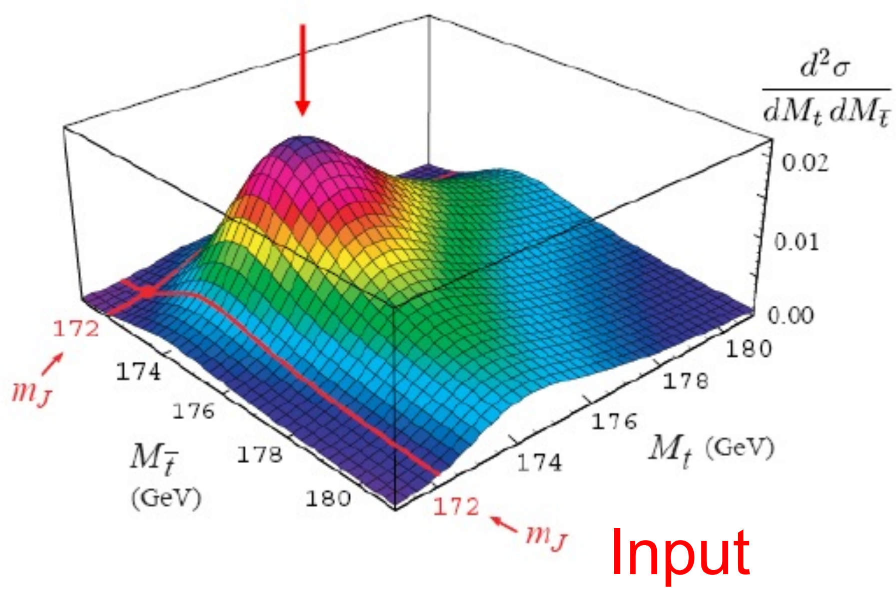
$$\Gamma = 1.43 \text{ GeV}$$

$$m_J(2\,\text{GeV}) = 172 \text{ GeV}$$

$$\mu_\Gamma = 5 \text{ GeV}$$

$$\mu_\Lambda = 1 \text{ GeV}$$

$$a = 2.5\,, \quad b = -0.4$$
$$\Lambda = 0.55 \text{ GeV}$$

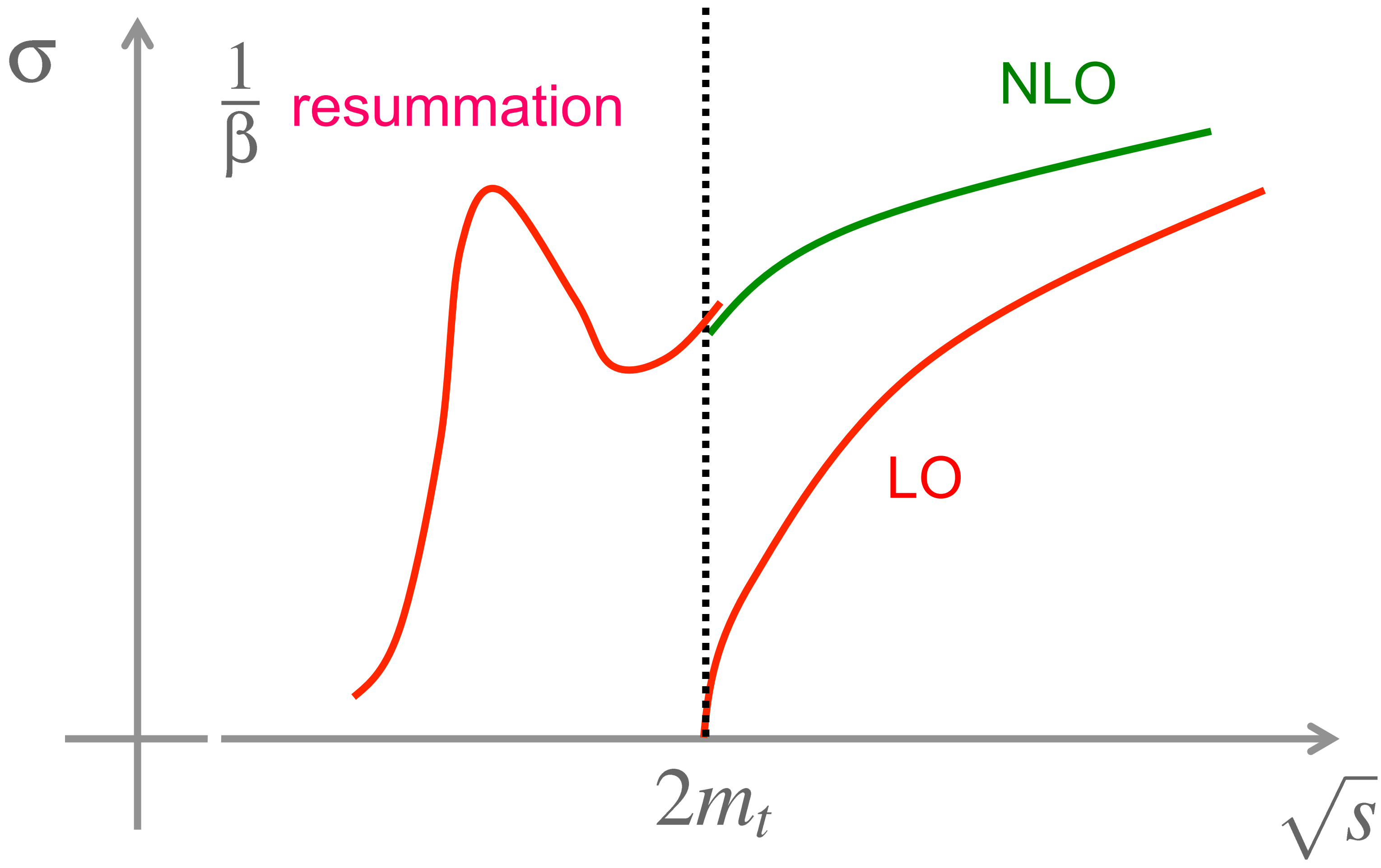


Non-perturbative corrections shift peak by ~2.4 GeV
and broaden the distribution

Top mass from threshold scan at LC

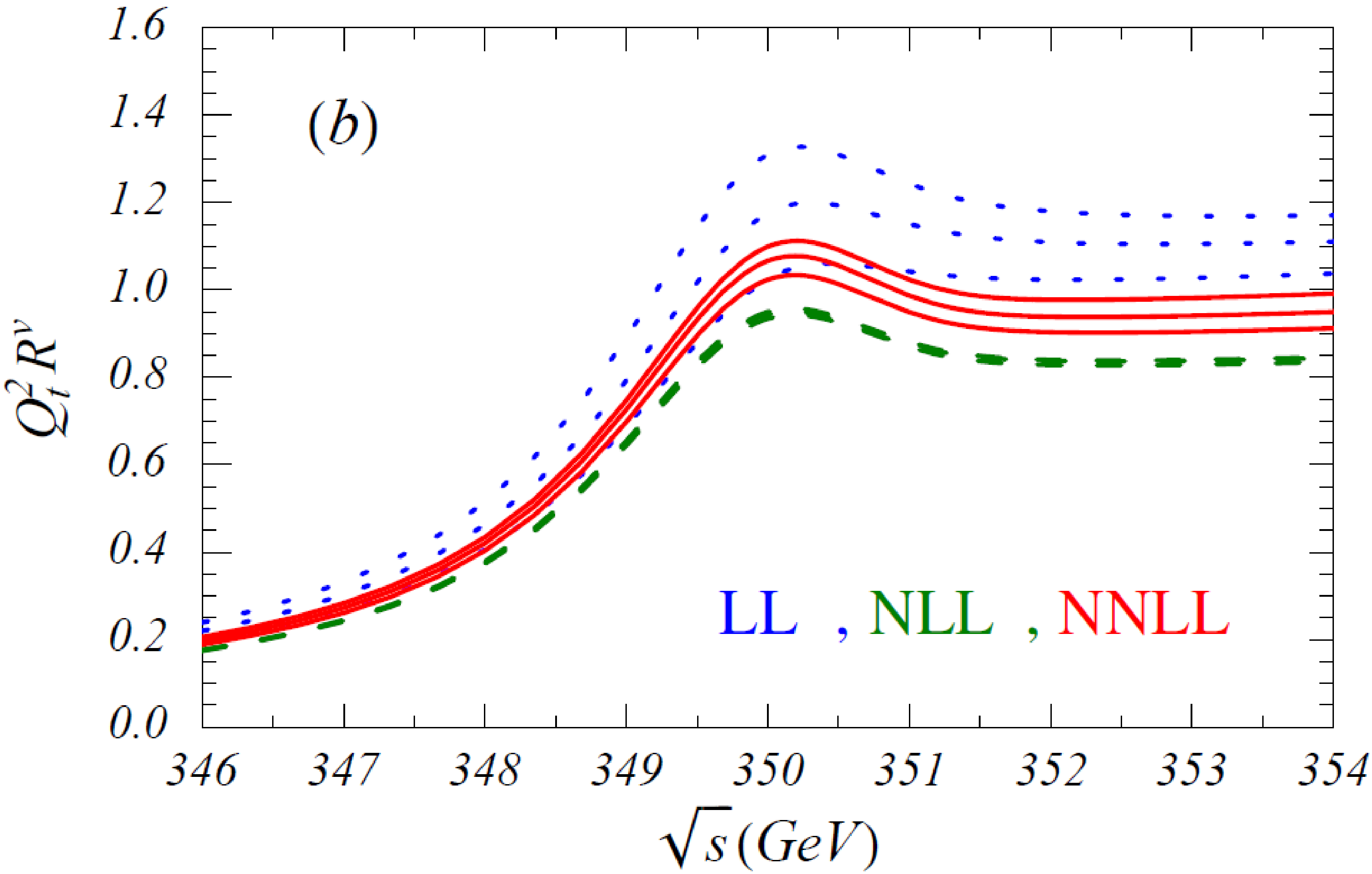
[Kühn '81, Bigi, Dokshitzer, Khoze, Kühn, Zerwas '86, Fadin,Khoze '87

Mass determination via remnant of 1S resonance



Higher order corrections towards full NNNLO

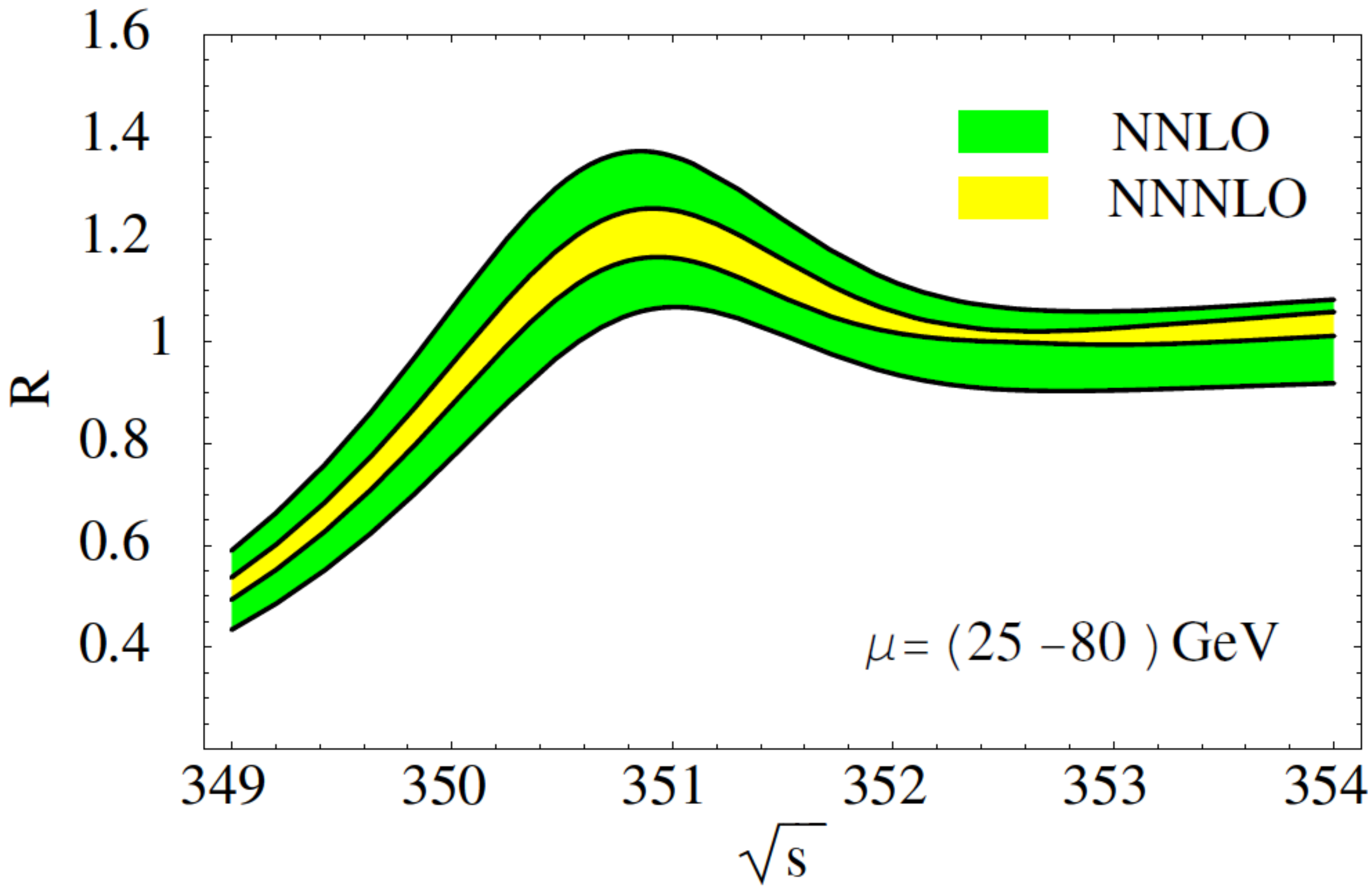
[Hoang '03]



Peak position stable, normalisation improved $\pm(3-6)\%$

Higher order corrections towards full NNNLO

[Beneke, Kiyo, Schuller 08]



Important shift due to non-logarithmic NNNLO terms, still missing: consistent treatment of finite width effects

Important

- Peak position remains stable

  → 100 MeV estimate from TDR still valid

- Taking higher order corrections into account:

  shape and normalisation is stabilized

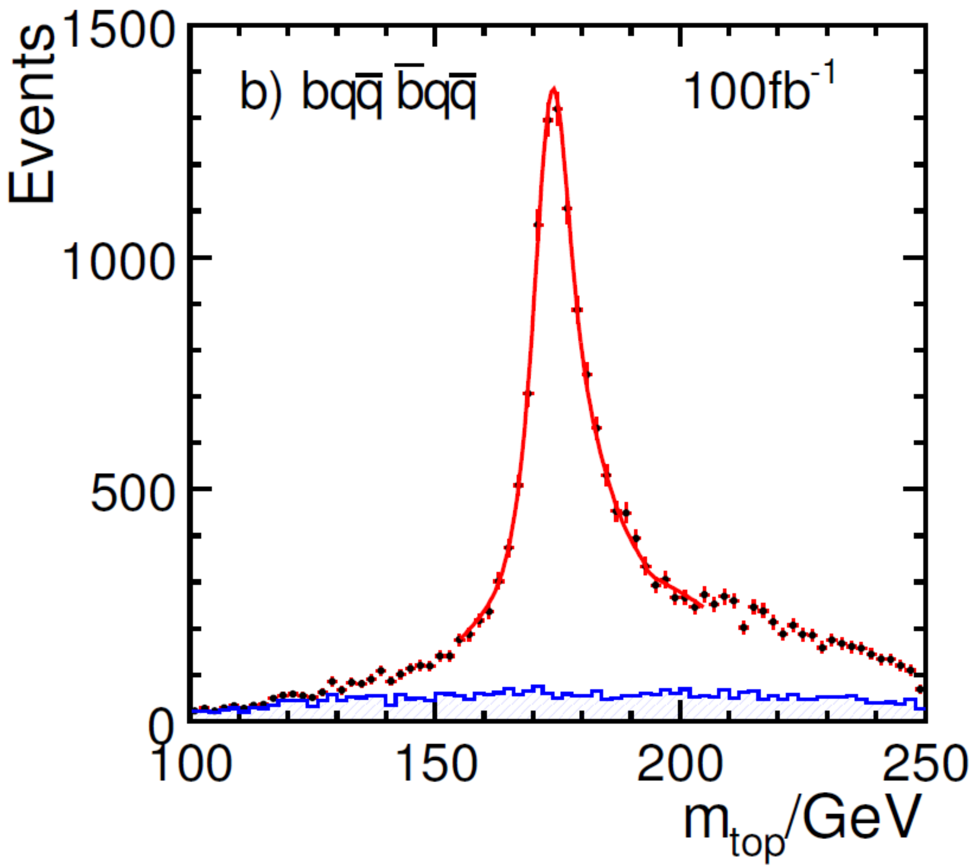
  → important for top-width and Yukawa coupling

➡ after tremendous theory effort,
observable rather well under control

Drawback: Dedicated threshold run required

Alternative Methods

[ILD, arXiv 1006.3396]



90 MeV precision (stat) for 500 GeV and 100/fb

However:

- precise relation to specific mass scheme ?
- theory prediction ?
- theoretical uncertainties ?