

# A new observable to measure the top-quark mass at hadron colliders.



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**LBNL & UC Berkeley**

**Seattle, 2 July 2013**

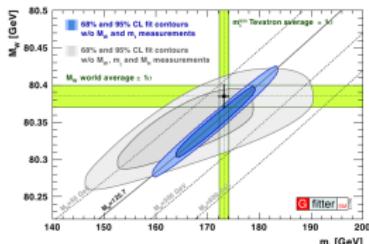
**EF Snowmass Meeting**

based on arXiv:1303.6415

SA, P. Fernandez, J. Fuster, A. Irles, S. Moch, P. Uwer, M. Vos

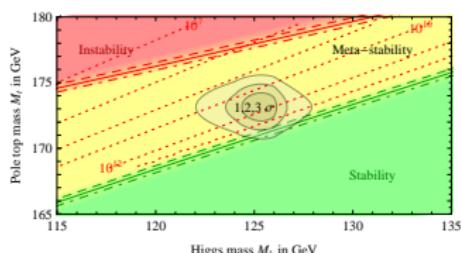
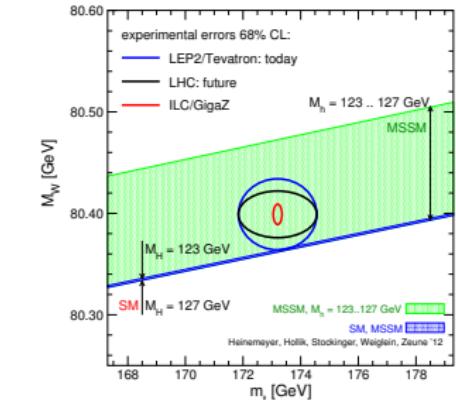
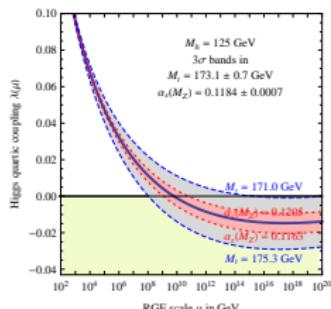
# Motivations for precise $m_t$ measurements

- ▶ Fundamental parameter of SM Lagrangian
- ▶ The top sector might play a role in EWSB
- ▶ Important parameter in SM (and MSSM) fits



- ▶ Crucial for vacuum (meta-)stability of SM at NNLO

DeGrassi et al. '12  
Alekhin, Djouadi, Moch '12



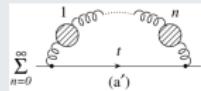
# Theoretical issues in determination of top-quark mass

- ▶ Confinement = free quarks not observable = no pole in the S-matrix
- ▶ Parameters of the theory measured through their influence on hadronic observables: fit  $\mathcal{O}^{\text{exp}}(\vec{x})$  with  $\mathcal{O}^{\text{th}}(m_t, \vec{x})$  and extract  $m_t$

Which mass are we measuring ? At least NLO required to fix the ren. scheme.

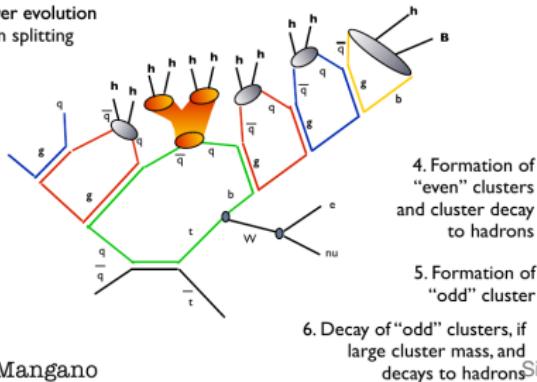
- ▶ Precise value depends on the  $m_t$  definition:  $m_t^{\text{pole}}$ ,  $m_t^{\overline{\text{MS}}}$ , etc.

Which scheme ? Some show better convergence (e.g.  $m_t^{\overline{\text{MS}}}$ ),  
some ill-defined beyond PT (IR renormalons  $\Delta_{m_t^{\text{pole}}} \propto \Lambda_{QCD}$ )



## ▶ Color reconnections

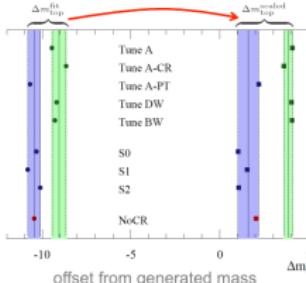
1. Hard Process
2. Shower evolution
3. Gluon splitting



## Non-perturbative effects at the LHC

[Skands,Wicke 08]

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



different offset for  
different tunes!

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

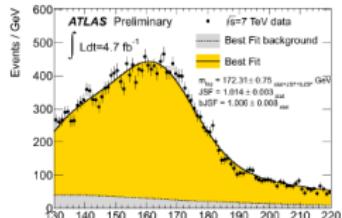
blue: pt-ordered PS  
green: virtuality ordered PS



# (Some) top-quark mass measurements at hadron colliders

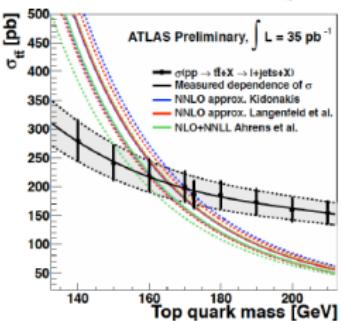
## ► Template method - Ideogram method

- ✗  $m_t^{MC} = m_t^{\text{pole}}(1 \pm \Delta)$ ,  $\Delta = ?$ , LO
- ✓ high-precision



## ► Matrix element method

- ✗ LO only, NLO under develop. ✓
- ✓ high-precision

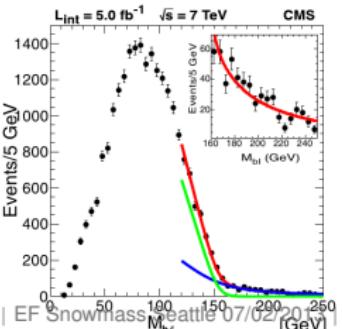


## ► Cross section

- ✓ theoretically clean, NLO, finite  $\Gamma_t$
- ✗ reduced sensitivity, threshold eff. included

## ► $J/\psi$ method

- ✓ NLO, small sensitivity to JES unc. and top reco.
- ✗ finite  $\Gamma_t$ , very-high statistics required



## ► Dilepton-specific

- ✓ NLO, JES unc., top reco., finite  $\Gamma_t$
- ✗ reduced sensitivity, high statistics required

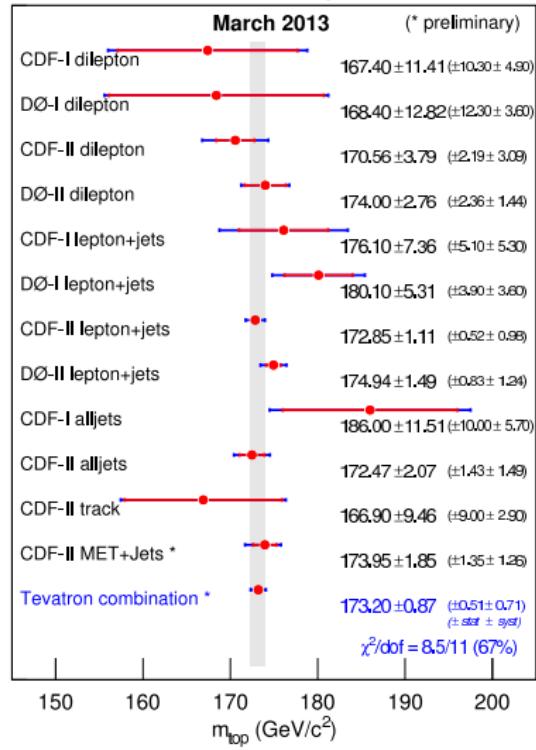
## ► Kinematic endpoint

- ✓ NLO?, small sensitivity to top reco.
- ✗ JES, finite  $\Gamma_t$ ?

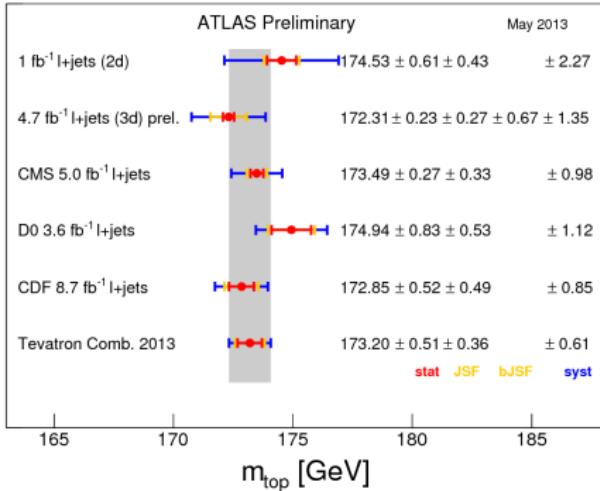
# Current results

## Tevatron

### Mass of the Top Quark



## LHC



- Dedicated studies of top-quark mass wrt event kinematics show small dependence  $\Rightarrow$  mismodelling is small at current precision.

CMS-TOP-12-029

ATLAS-PHYS-PUB-2013-005



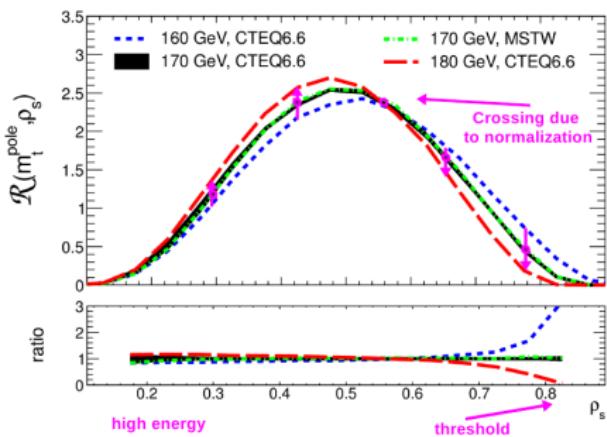
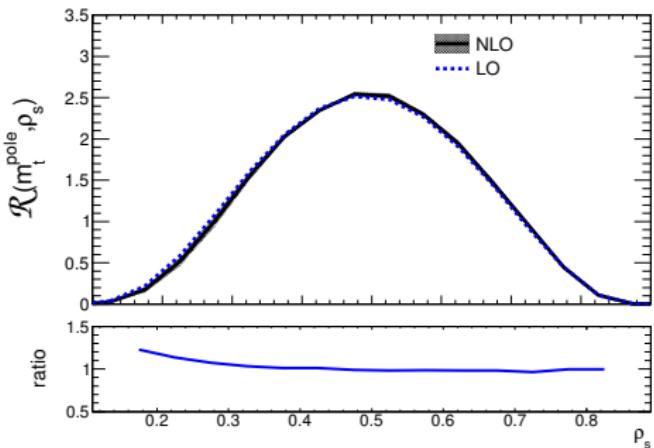
# New\* proposal : top-quark mass from jet rates

\* cfr.  $m_b$  from 3-jets rate  
@ LEP [Bilenky et al. '95]

- ▶ Study  $t\bar{t} + 1\text{-jet}$  events : large rate at the LHC ( $\gtrapprox 30\%$ ), NLO and NLO+PS available
- ▶ Experimentally accessible, errors reduced through normalization factor

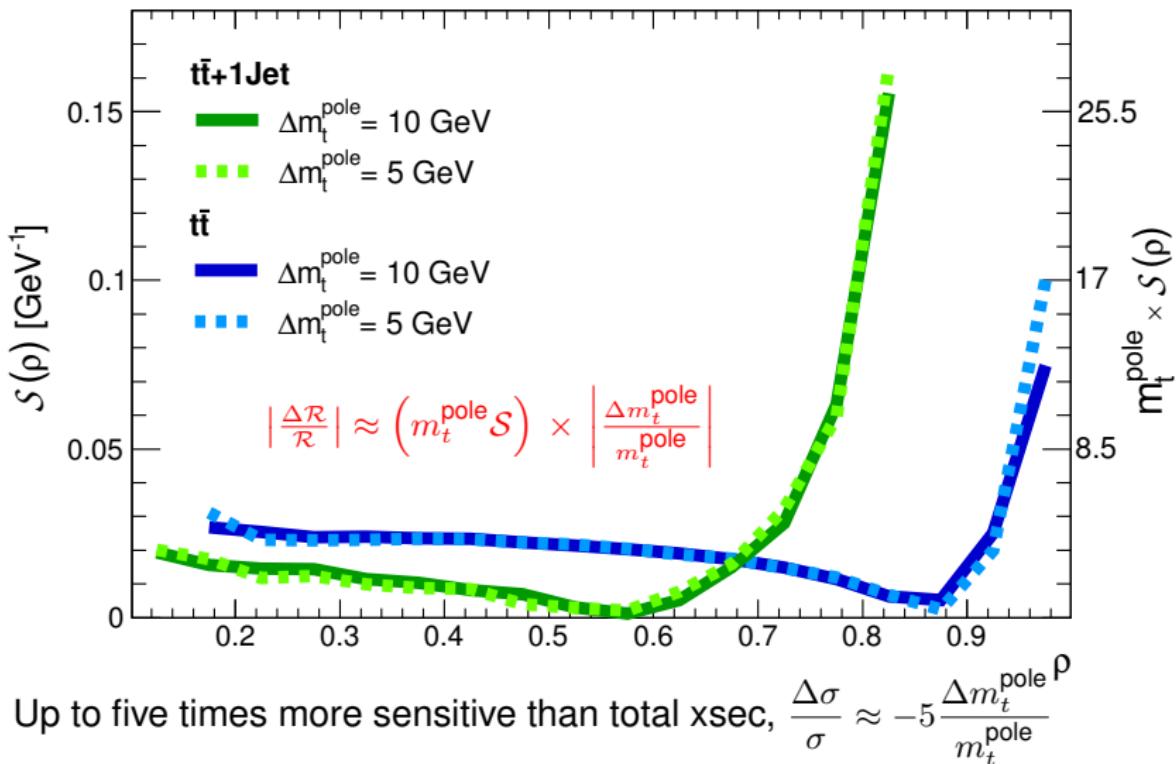
$$\mathcal{R}(m_t^{\text{pole}}, \rho_s) = \frac{1}{\sigma_{t\bar{t}+1\text{-jet}}} \frac{d\sigma_{t\bar{t}+1\text{-jet}}}{d\rho_s}(m_t^{\text{pole}}, \rho_s), \quad \rho_s = \frac{2m_0}{\sqrt{s_{t\bar{t}j}}}, \quad m_0 = 170 \text{ GeV}$$

- ▶ Theoretically well defined, calculable at NLO, small uncertainties and small NP corrections,  $\mathcal{R}(m_t^{\overline{\text{MS}}}, \rho_s)$  also possible. Low  $\rho_s$  control region  $s_{t\bar{t}j}$  reco.



# Sensitivity on $m_t$

- Linear approximation  $\mathcal{S}(\rho_s) = \sum_{\eta=\pm 1} \frac{|\mathcal{R}(m_t^{\text{pole}}, \rho_s) - \mathcal{R}(m_t^{\text{pole}} + \eta \Delta m_t^{\text{pole}}, \rho_s)|}{2|\Delta| \mathcal{R}(m_t^{\text{pole}}, \rho_s)}$



- Up to five times more sensitive than total xsec,  $\frac{\Delta \sigma}{\sigma} \approx -5 \frac{\Delta m_t^{\text{pole}}}{m_t^{\text{pole}}}$

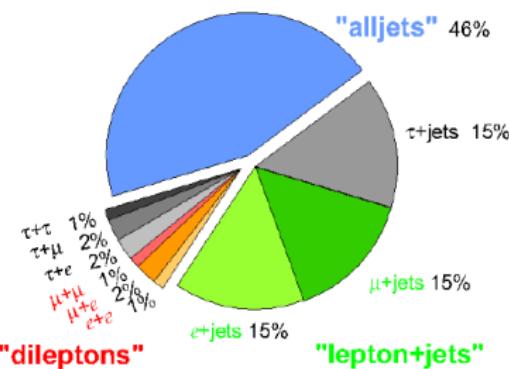


# Experimental viability study

- ▶ Event selection (**lepton+jets**):

1. one lepton ( $\ell = e, \mu$ ) with  $p_T > 25$  GeV and  $|\eta| < 2.5$ ;
2. missing  $E_T > 30$  GeV
3.  $M_T^W > 35$  GeV
4.  $\geq 3$  jets within  $|\eta| < 2.5$ , hardest with  $p_T > 50$  GeV, other two  $p_T > 25$  GeV;
5. two additional identified  $b$ -jets
6. two light jets inv. mass compatible with  $m_W$  within 20%
7. two reconstructed top-jet system masses within 20%

Top Pair Branching Fractions

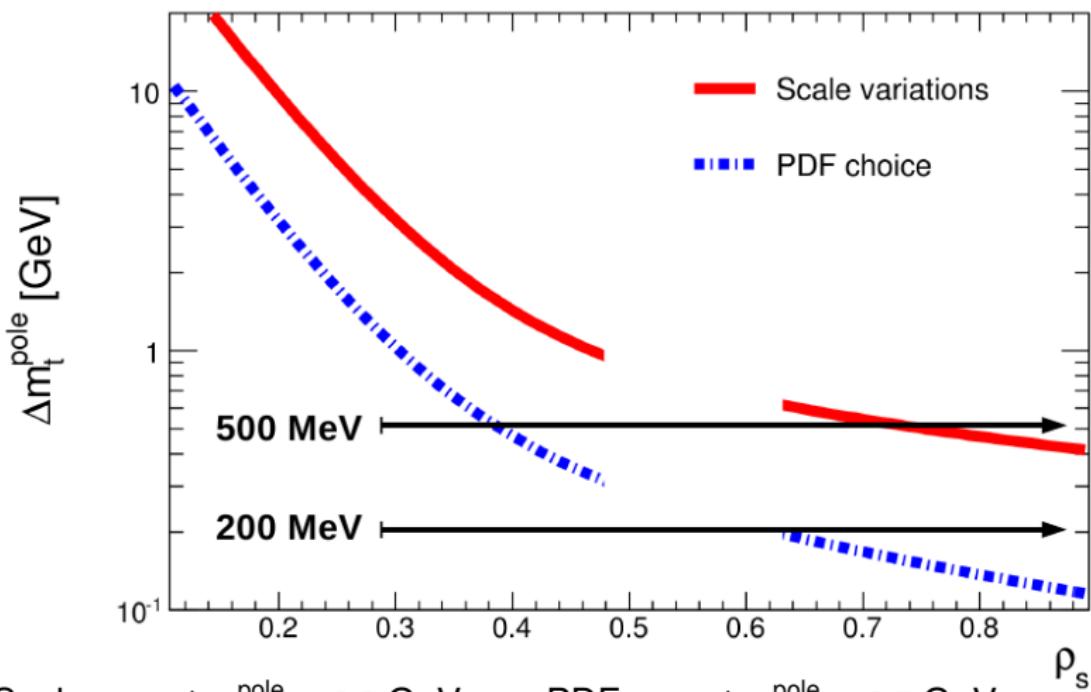


- ▶ Background contamination kept at the 5-10% level : : QCD (1,2) , single top and  $W+jets$  (3,4,5)
- ▶ Preliminary study with no detector-specific tools.  
Room for improvement when done by experimental collaborations.
- ▶ Dilepton channel also possible, but reduced statistics.



# Theoretical uncertainties

- Scale and PDF uncertainties:  $\frac{\Delta \mathcal{R}_\mu / \mathcal{R}(m_t^{\text{pole}}, \rho_s)}{\mathcal{S}(\rho_s)}, \frac{\Delta \mathcal{R}_{\text{PDF}} / \mathcal{R}(m_t^{\text{pole}}, \rho_s)}{\mathcal{S}(\rho_s)}$



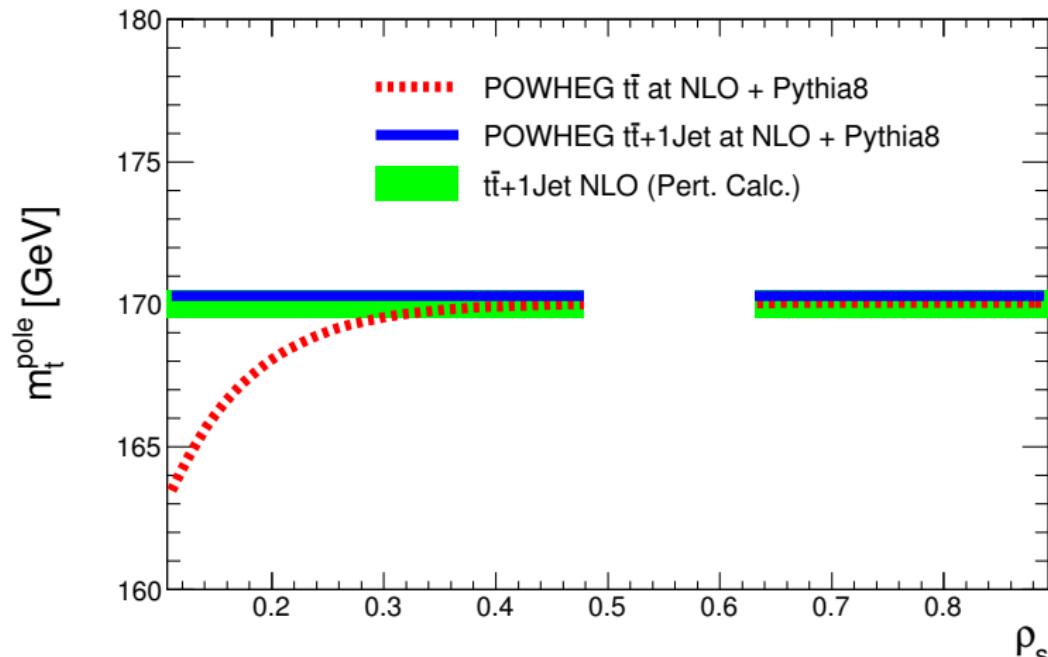
► Scale unc.  $\Delta m_t^{\text{pole}} \approx 0.2 \text{ GeV}$

PDF unc.  $\Delta m_t^{\text{pole}} \approx 0.5 \text{ GeV}$



# Theoretical uncertainties

- ▶ Impact of higher-orders and parton showers: calculate  $\mathcal{R}_{NLO}$  and extract top-quark mass that would fit the distribution from generated events

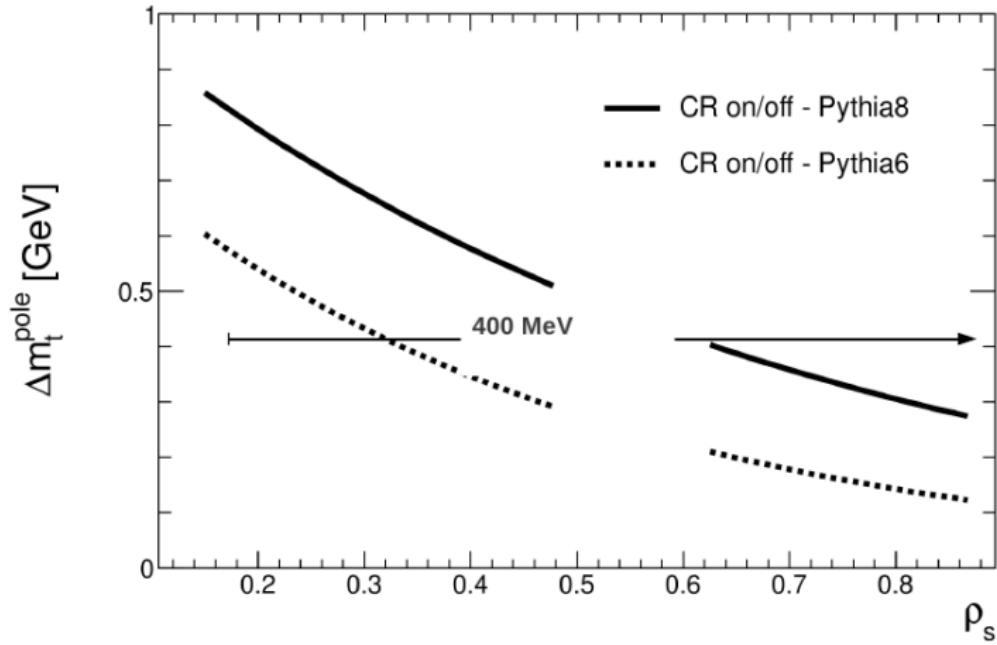


- ▶ POWHEG+Pythia vs. MC@NLO+Herwig gives  $\Delta m_t^{\text{pole}} \approx 0.2 \text{ GeV}$



# Theoretical uncertainties

- Colour reconnection effects: different CR models in Pythia6 vs. Pythia8

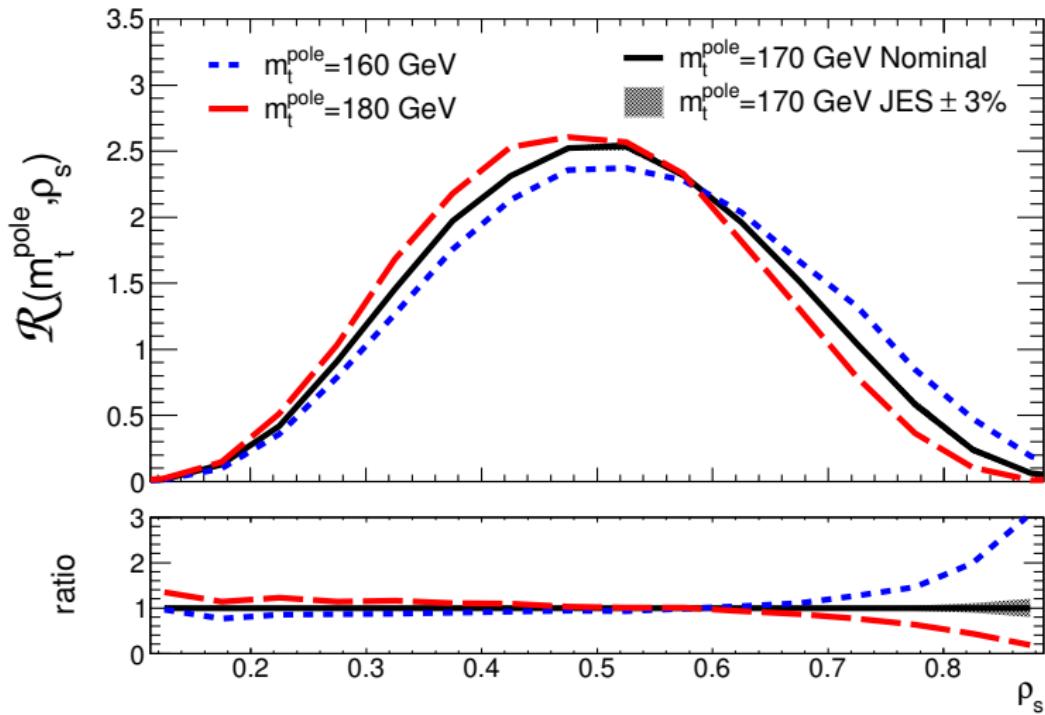


- Switching CR on/off very conservative estimate:  $\Delta m_t^{\text{pole}} \leq 0.4 \text{ GeV}$



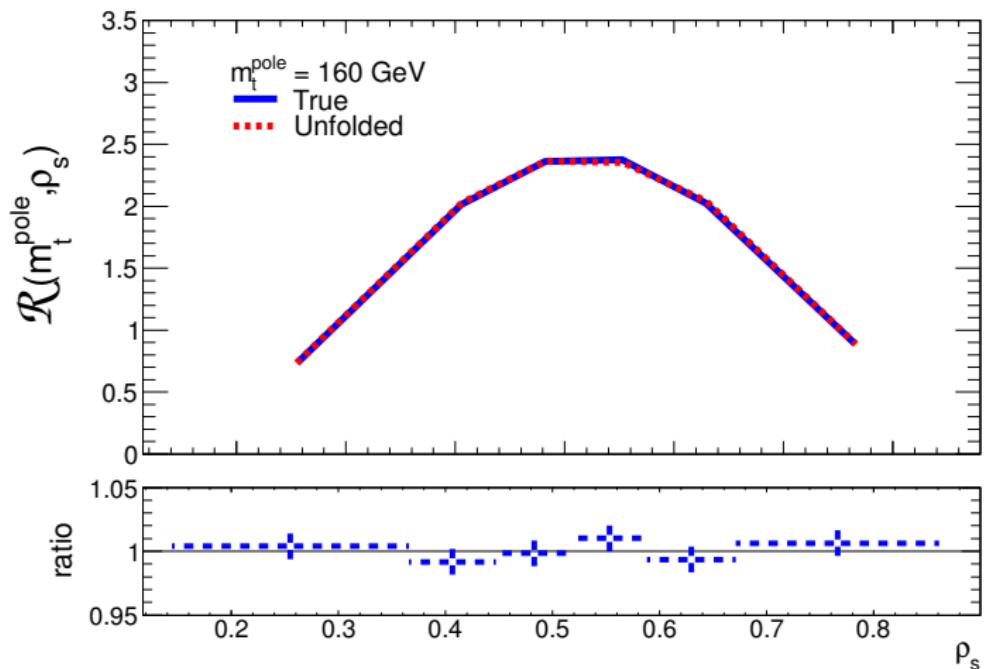
# Experimental uncertainties

- ▶ Jet Energy Scale uncertainty  $\pm 3\%$  results in  $\Delta m_t^{\text{pole}} \approx 0.8 - 1.0 \text{ GeV}$



# Experimental uncertainties

- Mass independent unfolding: associated unc.  $\Delta m_t^{\text{pole}} \approx 0.3 \text{ GeV}$  (stat.)



- Assuming final efficiency  $\approx 1\%$  and  $5 \text{ fb}^{-1}$  collected luminosity, expected error is  $\approx 1.4 \text{ GeV}$  stat. in the  $\rho_s > 0.65$  bin.
- Extrapolated to  $20 \text{ fb}^{-1}$   $\Delta m_t^{\text{pole}} \approx 0.7 \text{ GeV}$



# Conclusions

- ▶ Top-quark physics is precision physics at the LHC
- ▶ Current precision  $\mathcal{O}(1 \text{ GeV})$  already impressive.
- ▶ **Theoretical interpretation not so well under control.**
- ▶ At least NLO needed to fix renormalization scheme.
- ▶ Several methods available for NLO top mass, important to take advantage of all of them.
- ▶ Observable proposed here complements existing approaches. NLO top-quark mass definition, theoretical and experimental uncertainties evaluated at  $\mathcal{O}(1 \text{ GeV})$  or below

## Outlook:

- ▶ Analysis presented here being performed by ATLAS group in Valencia.
- ▶ LHC upgrade top-factory:  $300 \text{ fb}^{-1}$  at  $13 \text{ TeV}$  will produce  $\approx 50\text{M}$  ttbar events in the lepton+jet channel,  $10\text{M}$  events in the dilepton channel,  $15\text{M}$  single tops
- ▶ Extreme precision in  $e^+e^-$ : threshold scans at LC will reach  $\mathcal{O}(0.1\text{GeV})$  with dedicated run, theoretically very clean ( $N^3\text{LO}$  and NNLL).

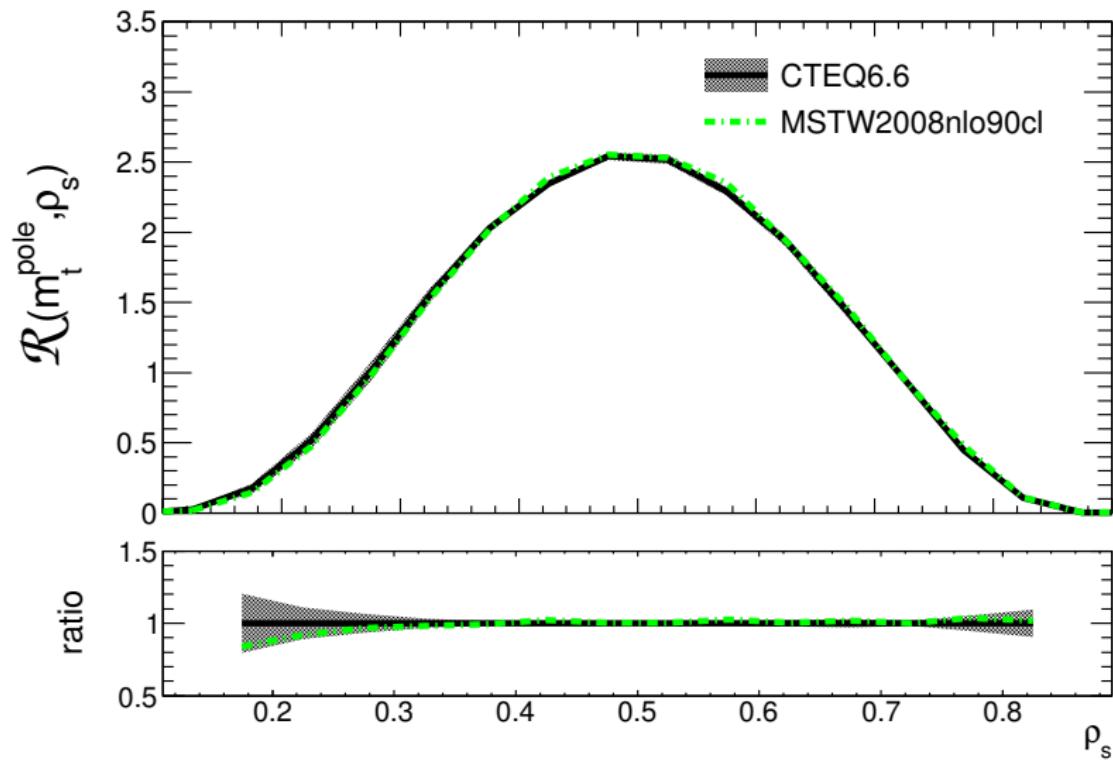
***Thank you for your attention!***



# BACKUP



# Scale and PDF variations



# Impact of NLO fixed-order corrections

