Precise measurement of the top-quark mass

in the ℓ+jets channel at CMS – inclusive and differential studies

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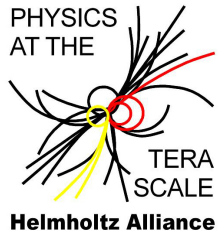
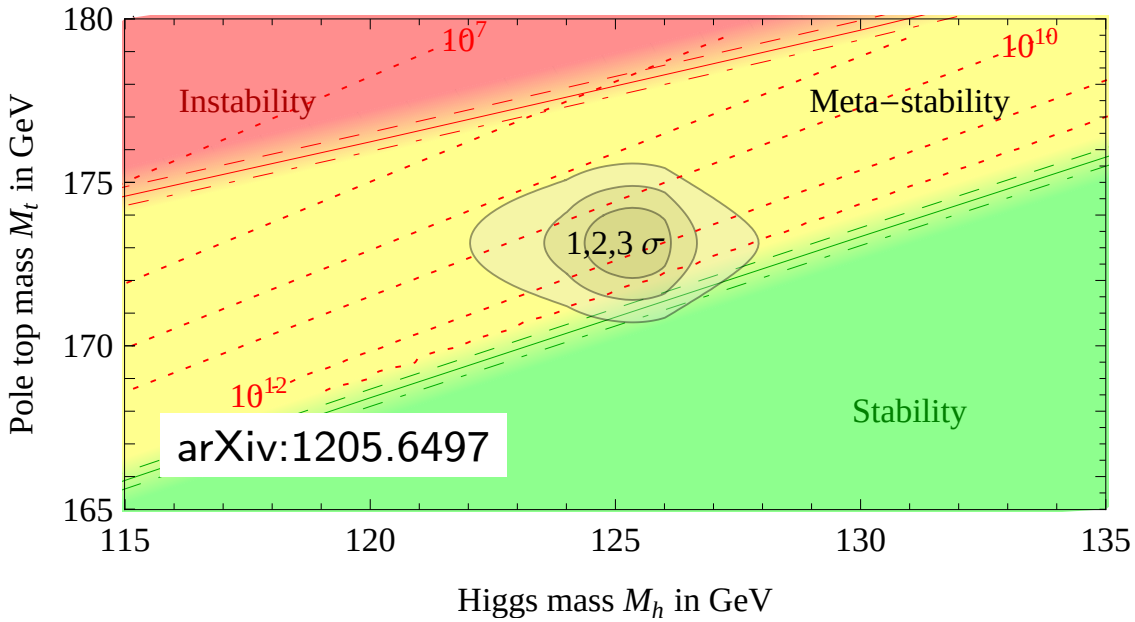


Measurement of the top-quark mass

Motivation

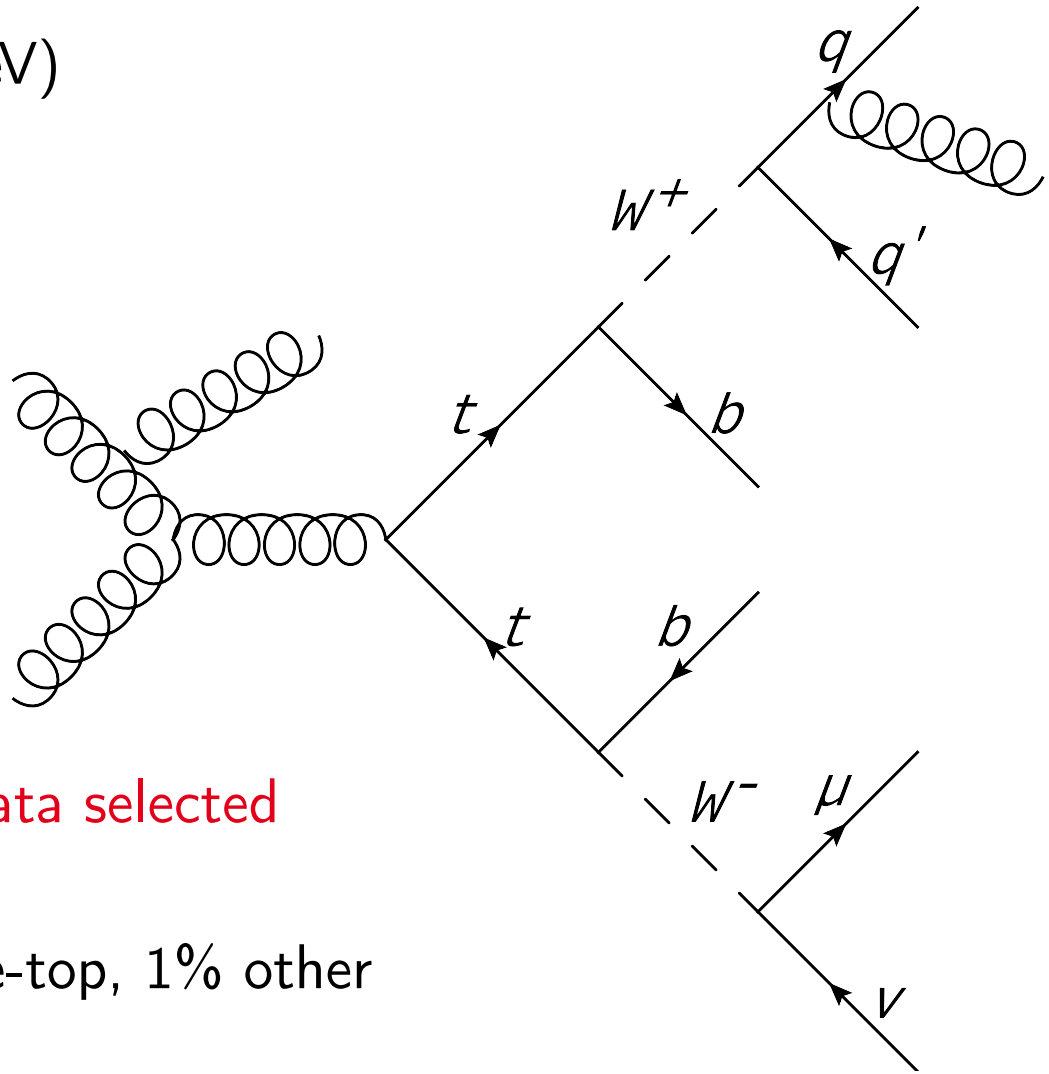
- m_t important parameter of Standard Model
- Benchmark for detector performance (Tevatron precision: 1 GeV)



1. Inclusive measurement (JHEP 12 (2012) 105)
   - Direct measurement of the top-quark mass
   - Ideogram method with kinematic fit
   - Simultaneous measurement of jet energy scale (JES)
2. Differential measurement (CMS PAS TOP-12-029)
   - Study dependency of the measured top-quark mass on event kinematics

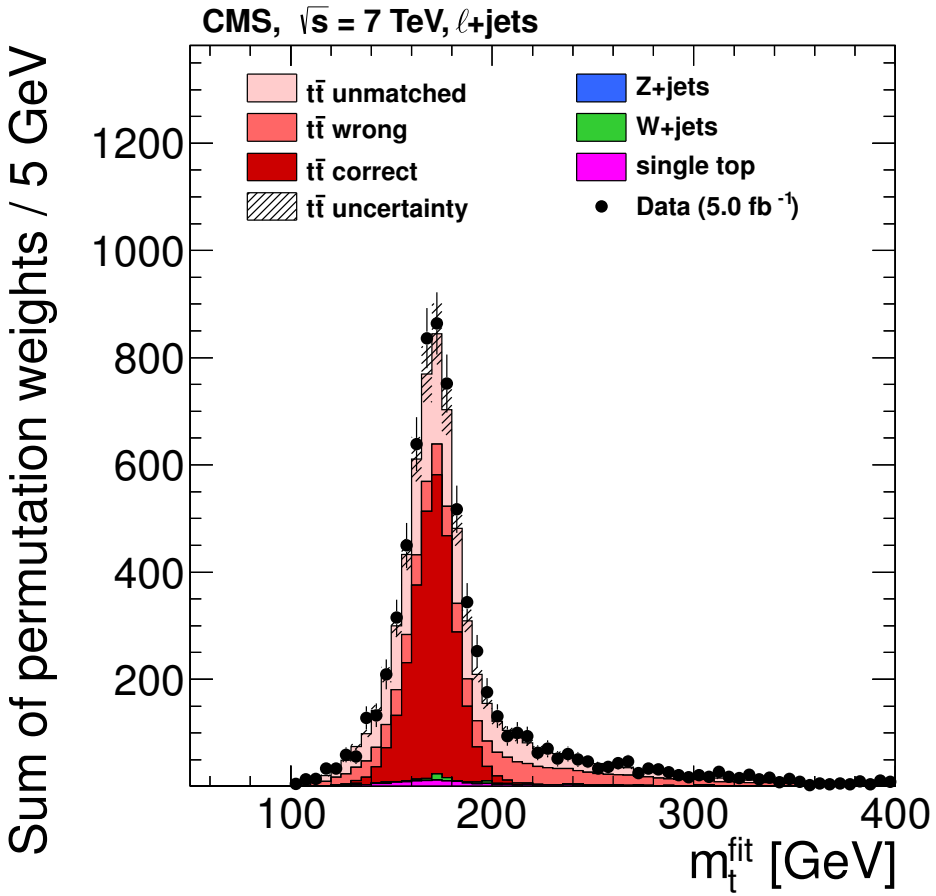
Event selection: lepton+jets final state

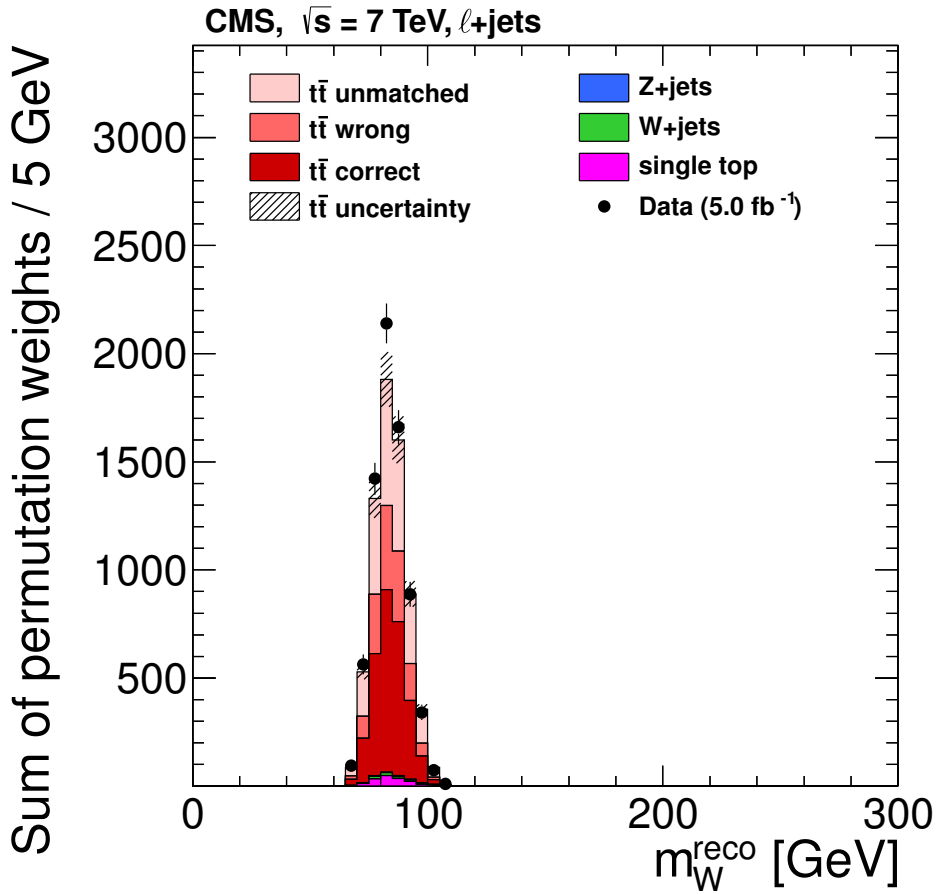
- Trigger for isolated muon or electron + jets ($p_T > 24$ GeV)
- Exactly 1 isolated lepton with $p_T > 30$ GeV, $|\eta| < 2.1$ (veto additional isolated e, μ)
- ≥ 4 "particle flow" jets (anti-k_t, $R = 0.5$) with $p_T > 30$ GeV, $|\eta| < 2.4$
- ≥ 2 jets b-tagged among the 4 leading jets
- 17985 events in 5 fb^{-1} 2011 data selected
- Composition: 92% $t\bar{t}$, 3% W+jets, 4% single-top, 1% other



Event reconstruction

- Assign 4 leading jets to partons from $t\bar{t}$ decay (obey b-tag)
  - Kinematic fit with constraints: $m_W = 80.4$ GeV, $m_t = m_{\bar{t}}$
  - Weight each permutation by $P_{gof} = \exp\left(-\frac{1}{2}\chi^2\right)$, select $P_{gof} > 0.2$
- 5192 events in 5 fb^{-1} 2011 data (96% $t\bar{t}$, 44% *correct*)

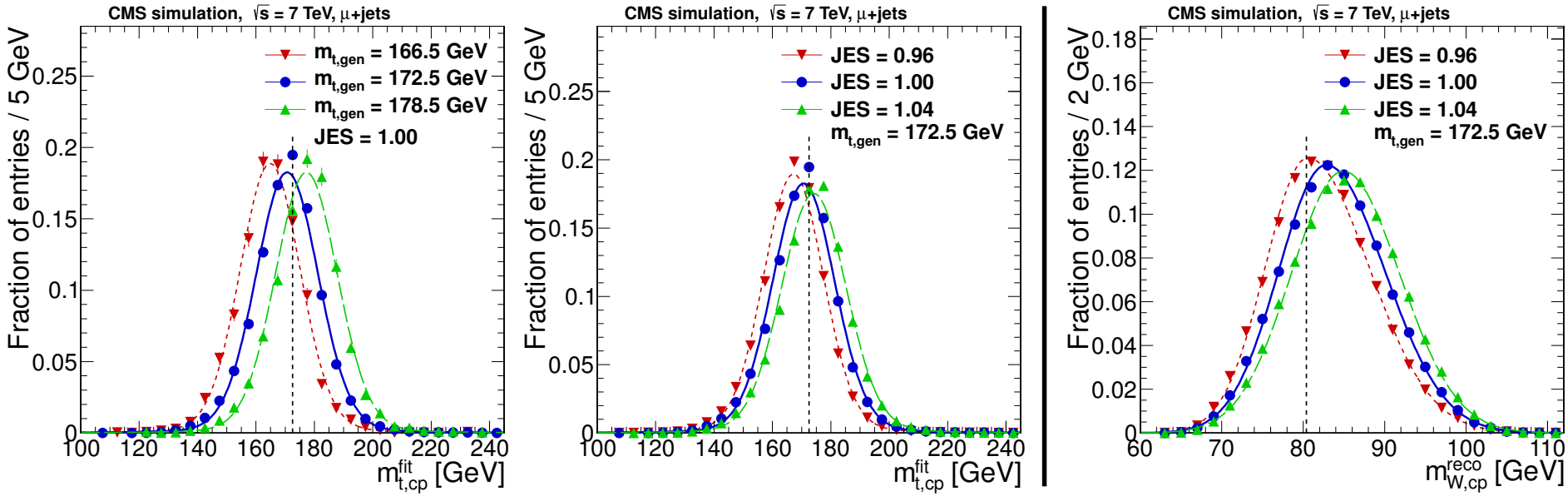




Ideogram method: probability densities

- Simulated samples with
  - 9 different top masses: 161.5–184.5 GeV
  - 3 different JES: 0.96, 1.00, 1.04
- Fit m_t^{fit}, m_W^{reco} distributions with analytical expressions
- Parametrize linearly in m_t, JES, $m_t \times$ JES

Example: *correct permutations*



$P_{cp}\left(m_t^{\mathrm{fit}} | m_t, \mathrm{JES}\right)$ $\qquad$ $P_{cp}\left(m_W^{\mathrm{reco}} | \mathrm{JES}\right)$

Ideogram method

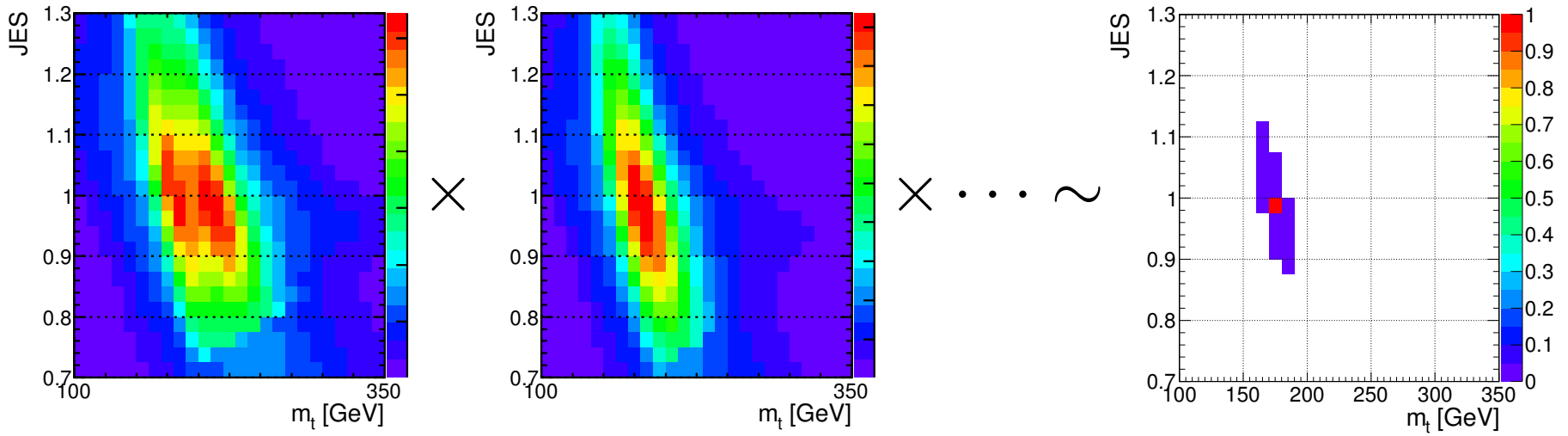
- Calculate likelihood for event with n permutations,
  j denotes *correct*, *wrong* and *unmatched* permutations

$$\mathcal{L}\left(\text{event}|m_t, \text{JES}\right) = \sum_{i=0}^{n} P_{gof}\left(i\right) P\left(m_{t,i}^{fit}, m_{W,i}^{reco}|m_t, \text{JES}\right),$$

$$P\left(m_{t,i}^{fit}, m_{W,i}^{reco}|m_t, \text{JES}\right) = \sum_{j} f_j P_j\left(m_{t,i}^{fit}|m_t, \text{JES}\right) \cdot P_j\left(m_{W,i}^{reco}|m_t, \text{JES}\right)$$

- Most likely m_t and JES by maximizing

$$\mathcal{L}\left(m_t, \text{JES}|\text{sample}\right) \sim \prod_{\text{events}} \mathcal{L}\left(\text{event}|m_t, \text{JES}\right)^{w_{\text{event}}}$$



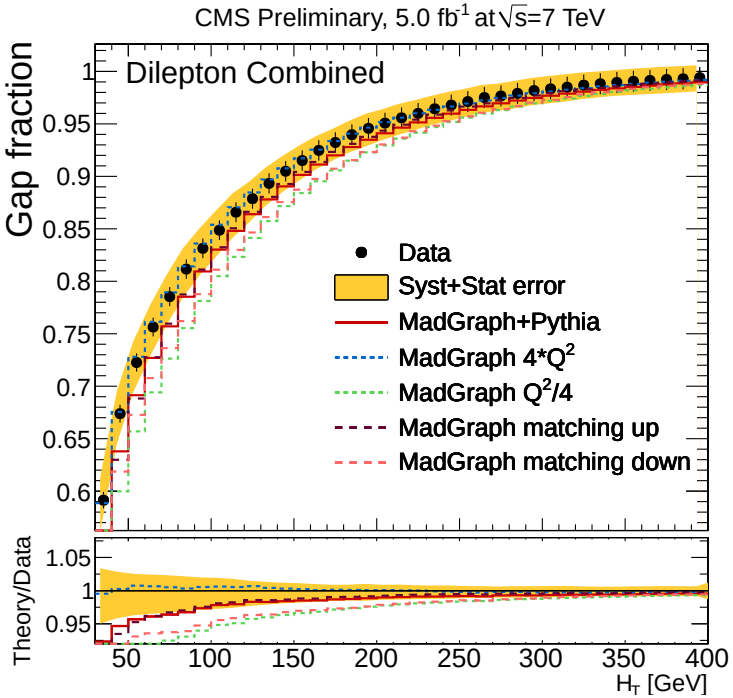
$t\bar{t}$ modelling uncertainties

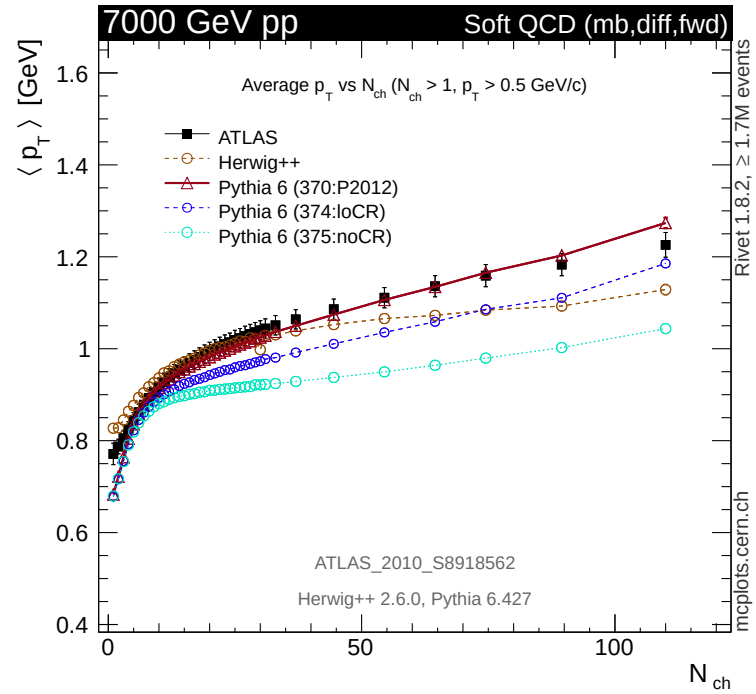
Perturbative QCD

- Factorization and renormalization scales
  Vary by factors of $1/2$ and 2 $\rightarrow$ 0.24 GeV
- ME-PS matching threshold
  Vary by factors of $1/2$ and 2 $\rightarrow$ 0.18 GeV
- MC generator (as cross-check)
  MadGraph vs. Powheg $\rightarrow$ 0.04 GeV

Non-perturbative QCD

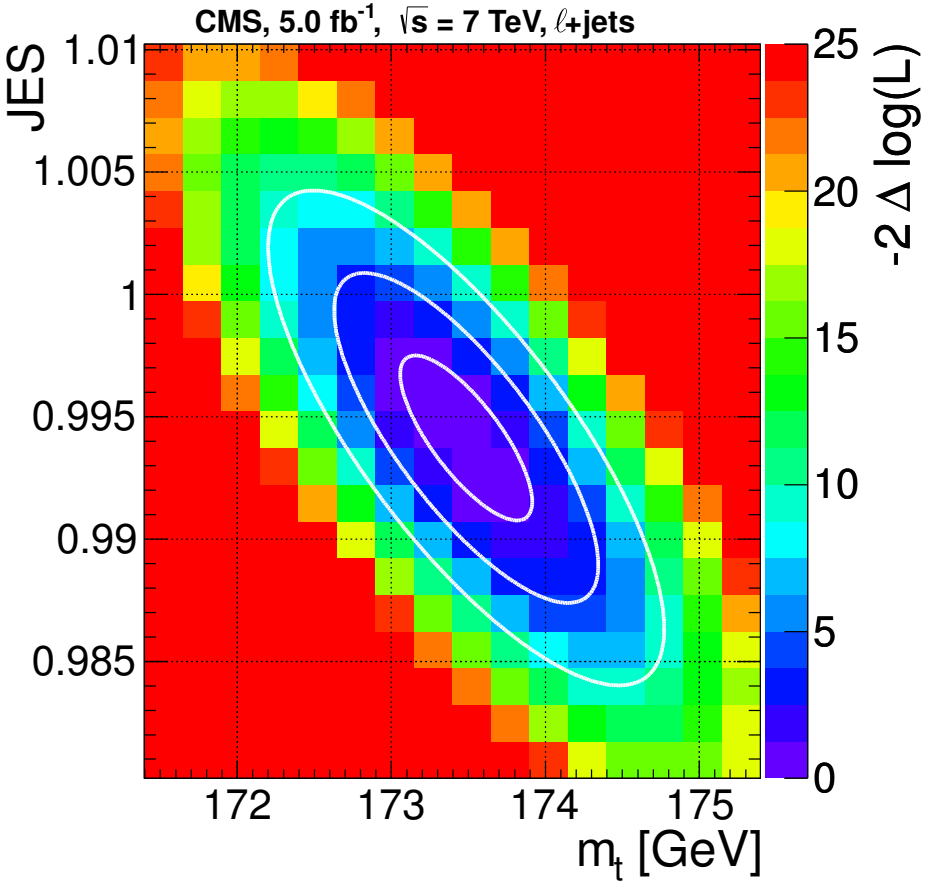
- Hadronization (included as b-JES)
  Pythia vs. Herwig $\rightarrow$ 0.61 GeV
- Underlying event
  Tunes with more/less MPI $\rightarrow$ 0.15 GeV
- Colour reconnection
  Tunes with CR on/off $\rightarrow$ 0.54 GeV





Result of inclusive measurement

- Validate method using MC pseudo-experiments (bootstrapping)
- Then run machinery on collision data...

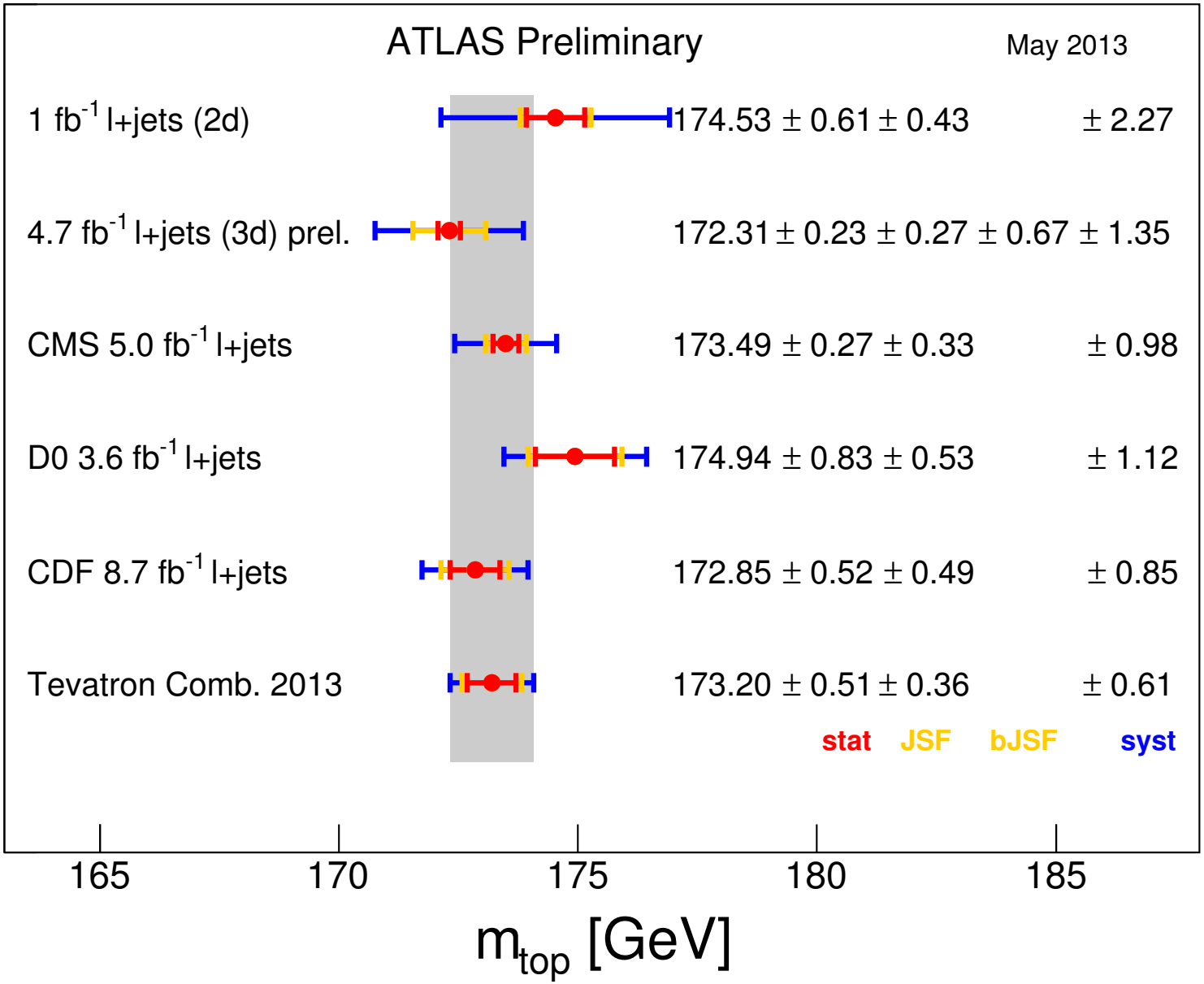


$$m_t = 173.49 \pm \underbrace{0.43}_{\text{stat+JES}} \pm \underbrace{0.98}_{\text{syst}} \text{ GeV}$$

$$\text{JES} = 0.994 \pm \underbrace{0.003}_{\text{stat+JES}} \pm \underbrace{0.008}_{\text{syst}}$$

- Documentation:
  CMS TOP-11-015, JHEP 12 (2012) 105, arXiv:1209.2319

Measurements from Tevatron and LHC



How to interpret m_t^{exp}?

- Measurements designed for sensitivity in peak region $\rightsquigarrow$ pole mass?

$$\overbrace{\text{collision data} \longleftrightarrow \underbrace{(\text{N})\text{LO+LL simulation}}_{\text{experimental domain}}}^{\text{theory domain}} \longleftrightarrow \text{NNLO+NNLL calculation}$$

Theorists

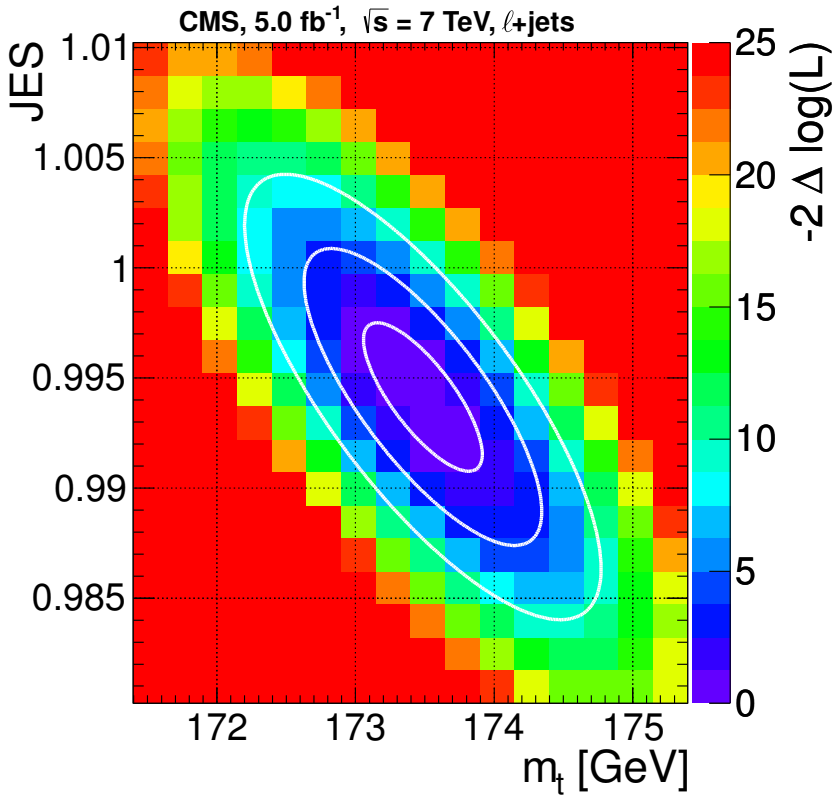
- Complementary approaches of MC and calc, no analytical relation
- Scheme uncertainty $m_t^{mc} \rightarrow m_t^{pole}$ approx. 1 GeV (shower cut-off)

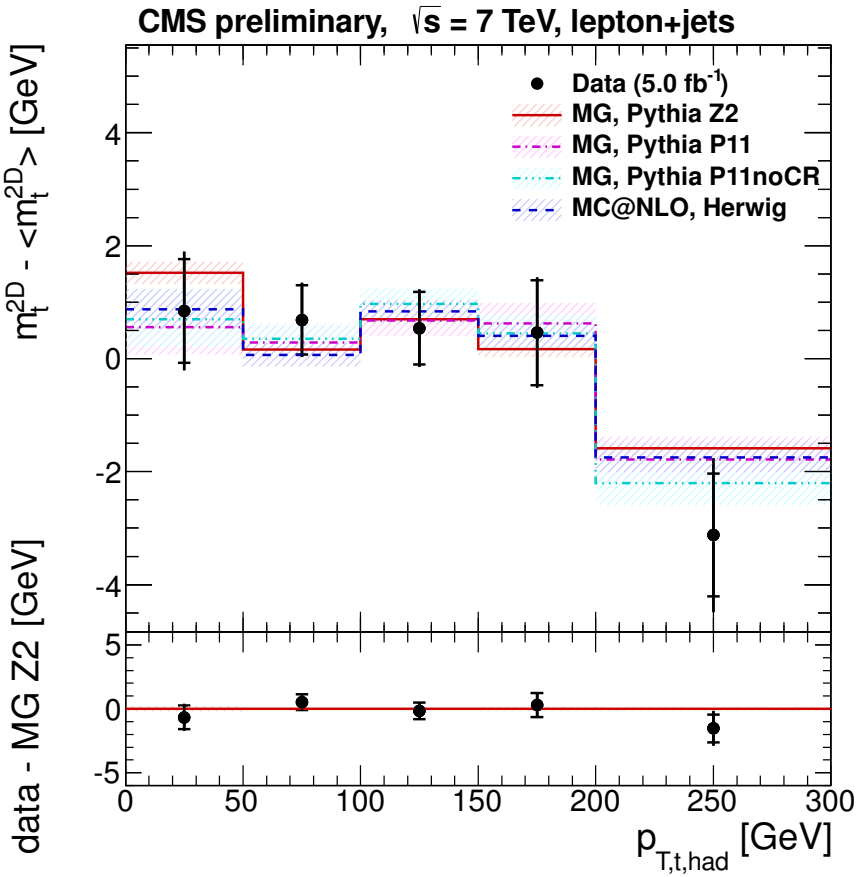
Experimentalists

- Run analyses on LO+LL and NLO+LL MC $\rightarrow$ agreement
- m_t measured at Tevatron (2 TeV) and LHC (7 TeV) $\rightarrow$ agreement
- Mismodelling could show up in differential mass measurements
  $\rightarrow$ Study dependence of measured m_t on event kinematics!

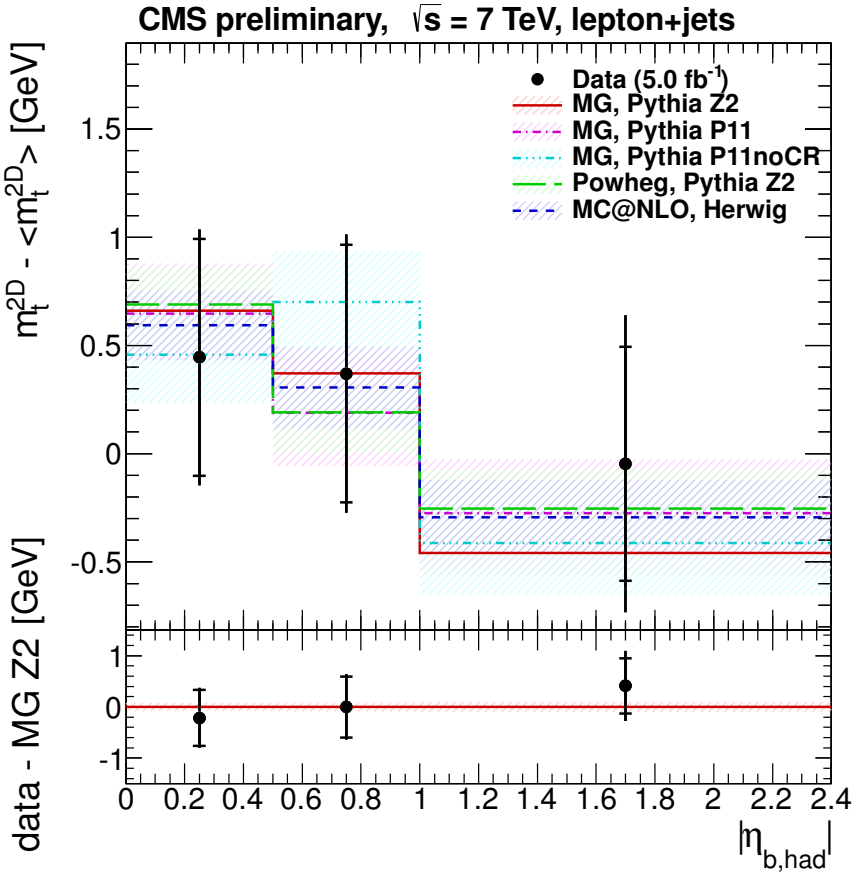
Differential mass measurement

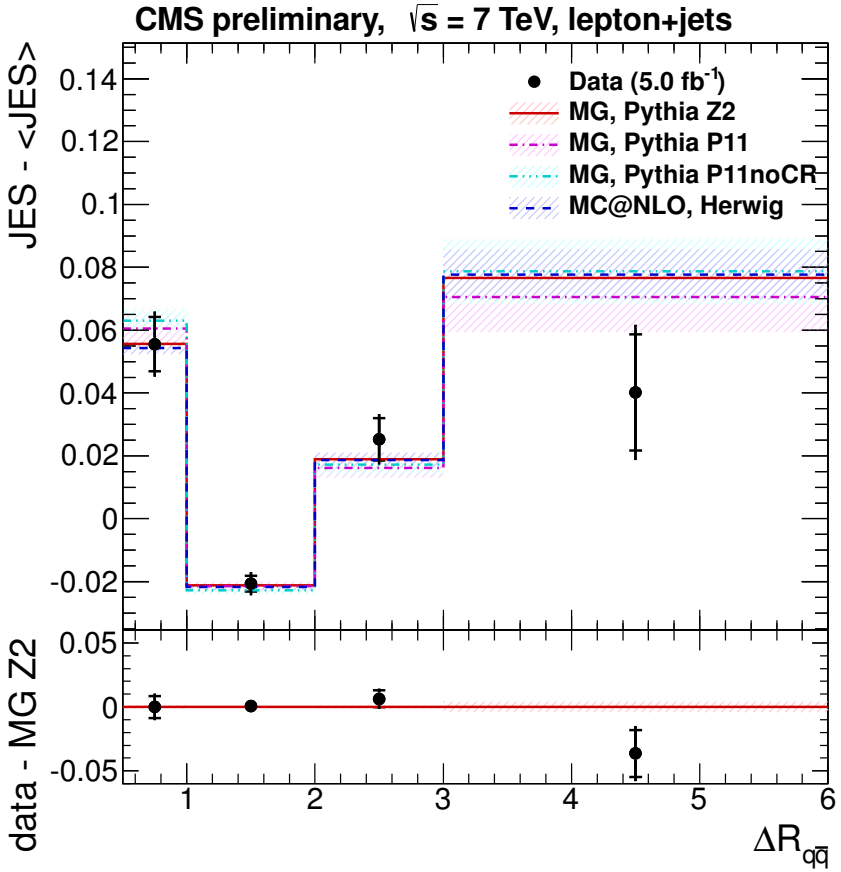
- Start with mass measurement in lepton+jets channel
- Apply to subsets depending on value of kinematic observable $X \in \{p_{T,t}, \eta_b, \dots\}$ (Mangano, TOPLHCWG, July 2012)
- Get m_t^{1D} (JES $= 1$), JES, m_t^{2D} in dependency of X
- Subtract value of inclusive measurement, compare to models





Differential mass measurement





- Good description of data, also with overlapping jets
- No significant differences between models
- Tested 12 observables, global $\chi^2/\text{ndf} = 68.58/78$
  $\rightarrow P\left(\chi^2, \text{ndf}\right) = 0.77$ (data vs. MadGraph Z2)

Summary & outlook

1. Simultaneous measurement of m_t und JES (JHEP 12 (2012) 105)
   - Most precise single measurement! $m_t = 173.49 \pm 1.07$ GeV
   - Interpretation of m_t^{exp} is ongoing work in theory and experiment
   - Overall consistency is found using different simulations, different colliders/energies (2/7/8 TeV)
2. Differential measurement in 12 observables (CMS PAS-TOP-12-029)
   - All tested models compatible with data

Prospects

- Constrain modelling uncertainties with data
- Repeat analyses with 8 TeV data (>20k high-purity $t\bar{t}$ events)
- Long-term
  - Simulation with improved mass definition
  - Complementary methods (HL-LHC)