Top Quark Mass Calibration for Monte-Carlo event generators

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Top Mass Measurements

Direct Measurements

- most precise
- compare differential distributions of top decay products at hadron colliders with simulations by Monte-Carlo event generators (MC)
- MCs use partly first principles QCD and partly modeling (e.g. parton shower, hadronization)
- measured mass is the mass parameter m_t^{MC} of the MC
- CMS and ATLAS combinations have reached uncertainties < 500 MeV

$m_t^{\mathrm{MC}} = 172.44 \pm 0.48\,\mathrm{GeV}$ (CMS combination 2015)

$m_t^{\mathrm{MC}} = 172.69 \pm 0.48\,\mathrm{GeV}$ (ATLAS combination 2018)

$m_t^{\mathrm{MC}} = 172.76 \pm 0.30\,\mathrm{GeV}$ (PDG average 2020)

How is m_t^{MC} related to renormalized QCD masses?

Frequently identified with m_t^{pole} , but

Pole scheme:

- absorbs all self-energy corrections into mass definition
- $\mathcal{O}(\Lambda_{\mathrm{QCD}})$ renormalon ambiguity: 110 MeV [Beneke, Marquard, Nason, Steinhauser 2017]
  250 MeV [Hoang, Lepenik, Preisser 2017]

Parton shower: evolution down to shower cutoff at $Q_0 \simeq$ 1GeV

$\rightarrow m_t^{\mathrm{MC}} \simeq m_t^{\mathrm{MSR}}$ $(R \simeq Q_0 \simeq$ 1GeV) [Hoang, Stewart '08, Hoang '14]

MSR scheme:

- short distance mass
- R is an infrared cutoff
- no renormalon problem

Calibrating the MC Top Mass

Aim: obtain numerical relation between m_t^{MC} and any renormalized QCD mass

Method: comparison between QCD computations and MC samples

- strongly mass-sensitive observable
- accurate hadron level QCD predictions at $\geq$ NLO/NNLL with full control over quark mass scheme dependence
- QCD masses as function of m_t^{MC} from fits of observable

Observable: 2-Jettiness in $e^+e^- \to t\bar{t}$ for c.o.m. energies $Q \gg m_t$

$$\tau_2 = 1 - \max_{\vec{n}} \frac{\sum_i |\vec{n} \cdot \vec{p}_i|}{Q}$$

Excellent mass sensitivity of peak position

$$\tau_2^{\text{peak}} = 1 - \sqrt{1 - 4\, m_t^2/Q^2} \quad \text{(tree level)}$$

$$\simeq 2\, m_t^2/Q^2 \quad (m_t^2 \ll Q^2)$$

Theory Description

Boosted top jets: bHQET + SCET [Fleming, Hoang, Mantry, Stewart 2007]

$$\frac{\mathrm{d}\sigma^{\mathrm{part}}}{\mathrm{d}\tau} = Q\, H(Q, m, \mu_H)\, U_H^{(n_l+1)}(Q, \mu_H, \mu_m)\, H_m^{(n_l+1)}(Q, \mu_m)\, U_m^{(n_l)}(Q, m, \mu_m, \mu_B)$$

$$\times \int \mathrm{d}s\, \mathrm{d}l\, B_e^{(n_l)}(s, m, \mu_B)\, U_S^{(n_l)}(l, \mu_B, \mu_S)\, S_e^{(n_l)}\Big(Q(\tau - \tau_{\min}) - \frac{s}{Q} - l, \mu_S\Big)$$

- Large logarithms of ratios of scales are resummed
- Implemented LO + NLL and NLO + N2LL

Non-perturbative corrections factorize into a shape function

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\tau} = \frac{\mathrm{d}\sigma^{\mathrm{part}}}{\mathrm{d}\tau} \otimes F_{\mathrm{mod}}(\Omega_1, \Omega_2, \ldots)$$

Calibration Details

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\tau} = f\,(m_t^{\mathrm{MSR}}, \alpha_S(m_Z), \Omega_1, \Omega_2, \Omega_3, \mu_H, \mu_J, \mu_S, \mu_M, R, \Gamma_t)$$

any scheme non-perturbative renorm. scales finite lifetime

Generating MC samples

MCs: PYTHIA 8.305, $\overbrace{\text{Herwig 7.2.2, Sherpa 2.2.11}}^{\text{new}}$

Q values: 600, 700, 800, … , 1400 GeV

masses: m_t^{MC} = 170, 171, 172, 173, 174, 175 GeV

top width: Γ_t = 1.4 GeV

Statistics: 10^7 events for each set of parameters

Fitting Procedure

Fit parameters: $m_t^{\mathrm{MSR/pole}}, \Omega_i$ (very weak sensitivity to $\alpha_S(m_Z)$ → use world avg.)

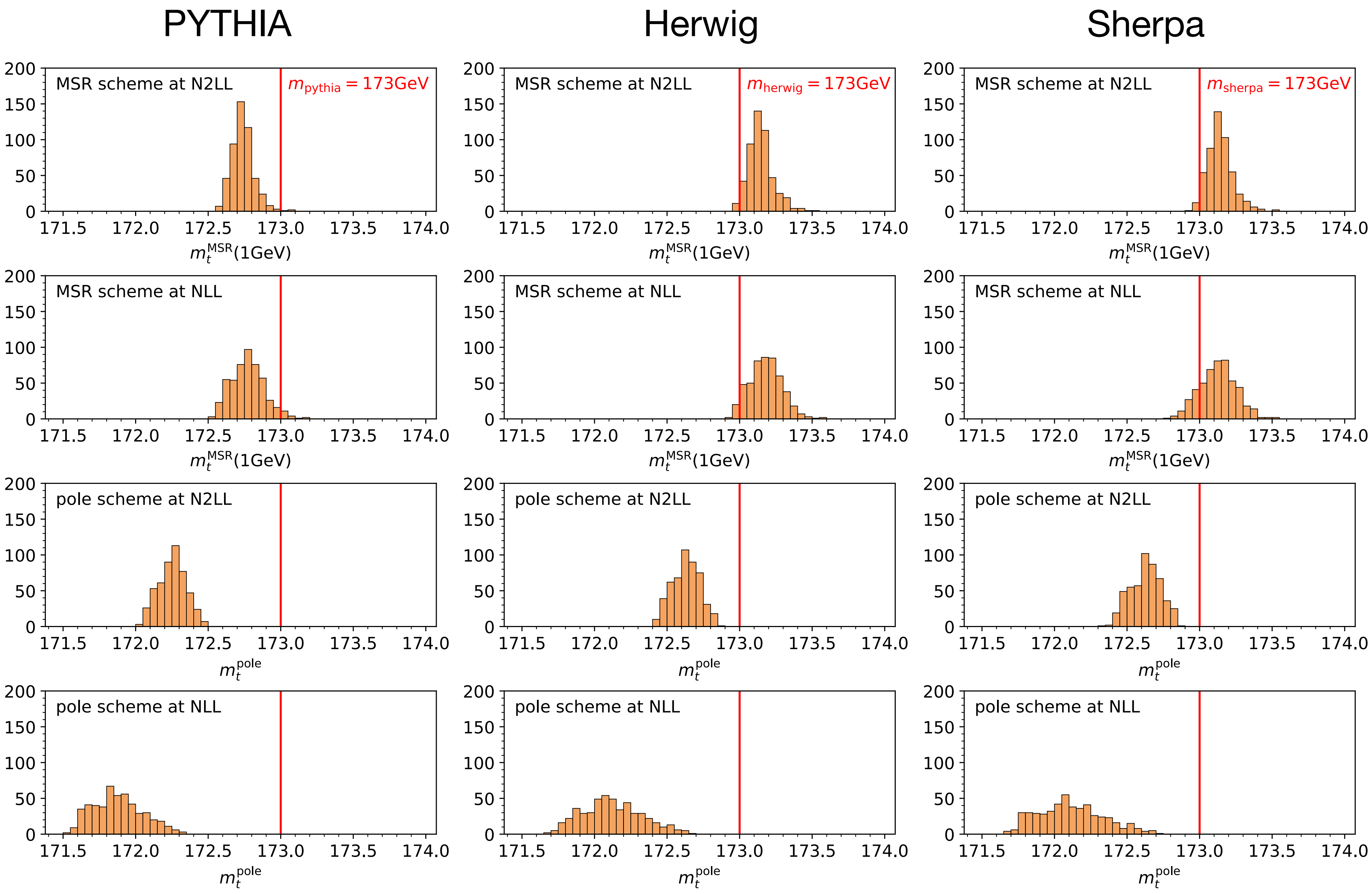
Standard fit based on χ^2 minimisation

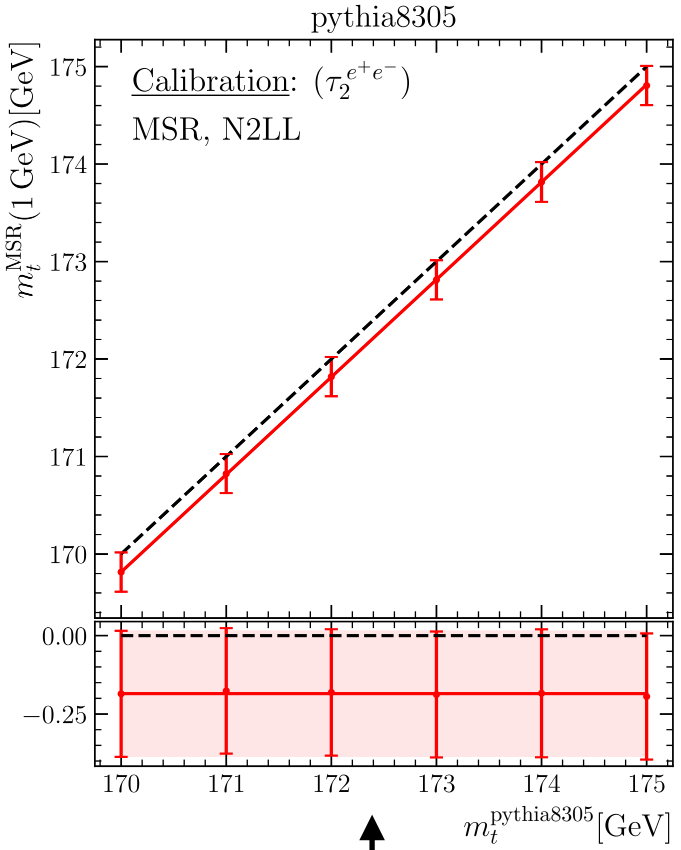
500 sets of **profiles** (τ_2 dependent renorm. scales)

$$\left.\begin{array}{l}\text{7 \textbf{Q-sets} from energies between 600 and 1400 GeV}\\ \text{3 \textbf{fit-ranges} - (xx/yy)\% of maximum peak height}\end{array}\right\}\ \text{21 datasets}$$

Preliminary !

Fit Results: Stability & Convergence





combination of best fit values (profiles & datasets)

dependence on $m_t^{\rm MC}$ ~ constant shift

similar for other MCs and scheme/order

Input: $m_t^{\rm MC}$ = 173 GeV

500 profiles

Q=600, 700, … , 1400GeV
peak (60/80)%

Good convergence and stability for $m_t^{\rm MSR}$ (1 GeV)

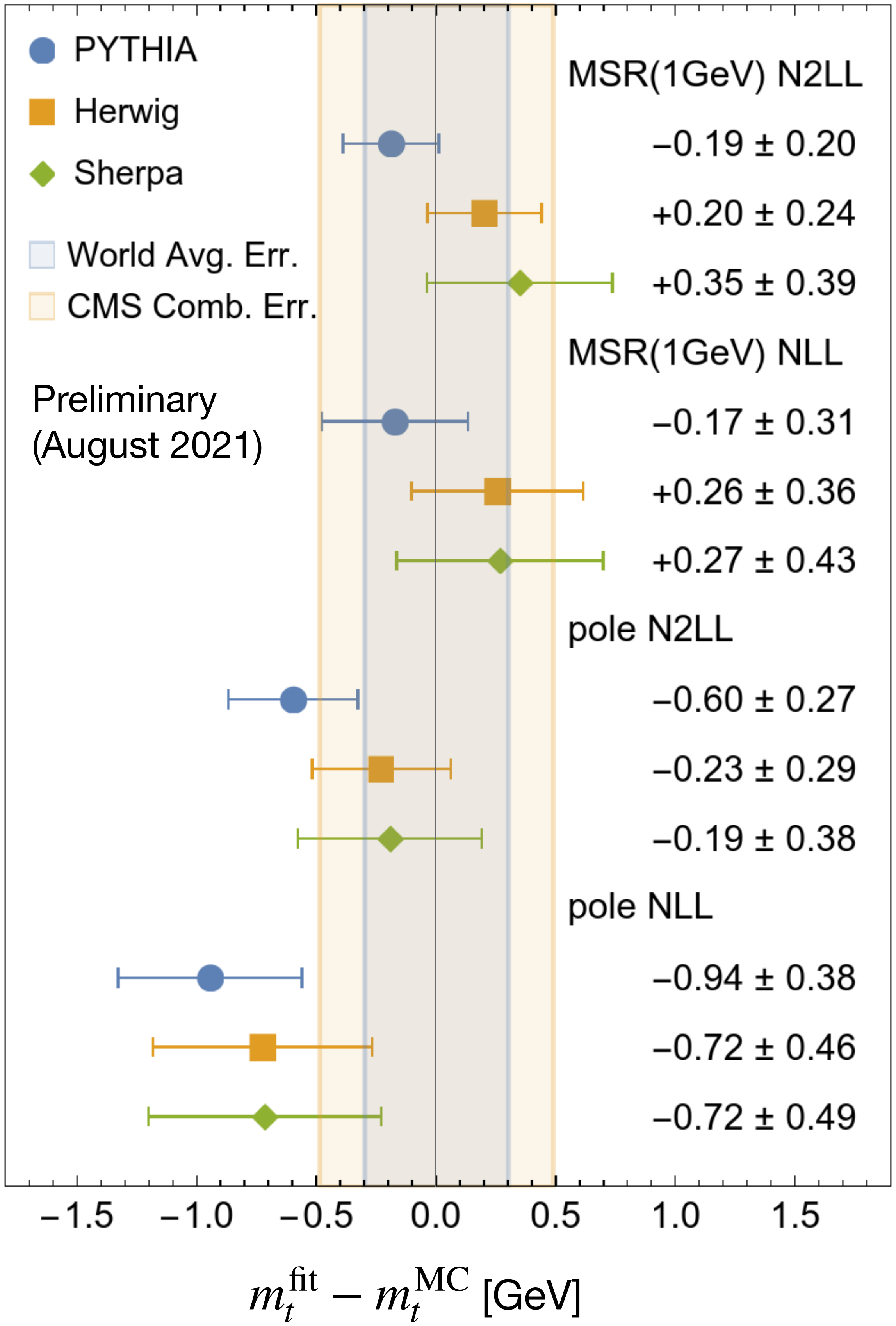
Instability between orders for $m_t^{\rm pole}$

Relations between MC top masses and Lagrangian masses differ by 400 —600 MeV for the different MCs

Similar results for other datasets

Preliminary !

Fit Results: Summary



within uncertainties:
$m_t^{\mathrm{MC}} \simeq m_t^{\mathrm{MSR}}$(1GeV)

stable theory prediction: dominant QCD corrections properly absorbed into mass definition

MC top quark mass parameter is indeed closely related to the MSR mass

difference between MCs ≃ 150 — 600 MeV

pole mass shows bad convergence

theoretically it receives large always positive scale dependent corrections at each order related to $\mathcal{O}(\Lambda_{\mathrm{QCD}})$ renormalon

fitted values don't capture full uncertainty

pole mass numerically and conceptually less compatible

Preliminary !

Conclusions

- Update to original mass calibration for PYTHIA 8.205
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- PYTHIA 8.305 results are practically identical to old version

- New fits for Herwig 7.2 and Sherpa 2.2.11 further support $m_t^{\mathrm{MC}} \simeq m_t^{\mathrm{MSR}}$ (R ≃ 1GeV)

- Top mass parameters of different MCs are different!
  Difference of calibration results between MCs ≃ 150 — 600 MeV

$$\boxed{\begin{aligned} m_t^{\mathrm{MSR}}(1\mathrm{GeV}) - m_t^{\mathrm{PYTHIA}} &= -0.19 \pm 0.20\,\mathrm{GeV} \\ m_t^{\mathrm{MSR}}(1\mathrm{GeV}) - m_t^{\mathrm{Herwig}} &= +0.20 \pm 0.24\,\mathrm{GeV} \\ m_t^{\mathrm{MSR}}(1\mathrm{GeV}) - m_t^{\mathrm{Sherpa}} &= +0.35 \pm 0.39\,\mathrm{GeV} \end{aligned}}$$

- Soon implemented in QCD calculation:
  2nd observable to check universality of our 2-Jettiness results