

Top Quark Mass Calibrations for PYTHIA with Thrust

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Collaborators:

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Particles and Interactions

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Outline

① Motivation

② Theoretical Setup

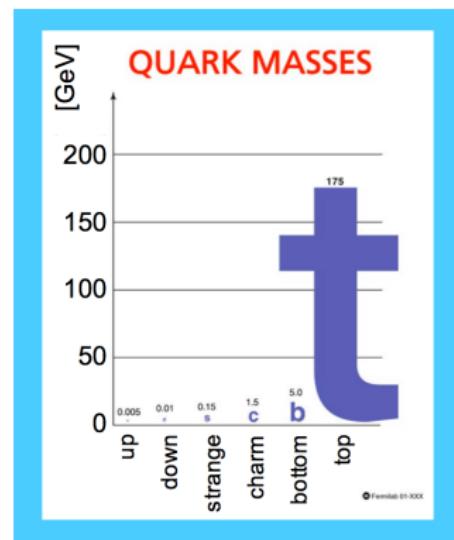
③ Calibrating PYTHIA's Top Mass Parameter

④ Results & Outlook

Motivation

- Precise knowledge of top quark mass very important:
 - Electroweak precision tests of the SM
 - Stability of the SM vacuum
 - Top production important as background for BSM searches
 - ...
- Experimental determinations are very precise
 - most precise values from “direct measurement”
 - many individual measurements with uncertainty below 1 GeV
 - relies on (General Purpose) Monte Carlo (MC) generators e.g. PYTHIA
 - average has a stated uncertainty of about 0.5%
[K.A.Olive et.al. (PDG) 2014]

$$m_t = 173.21 \pm 0.51(\text{stat}) \pm 0.71(\text{sys}) \text{ GeV}$$



Question: How should one interpret the “measured” top mass?

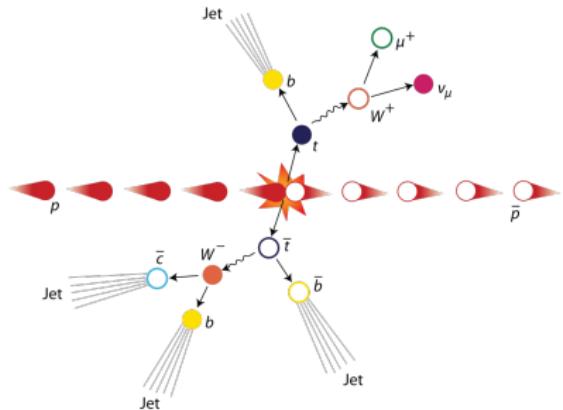
Top Mass Determinations at Hadron Colliders - MC Top Mass 1

- **Goal:** Reconstruct top from its decay products → invariant mass distribution
- Input:
 - ▶ Jet algorithm
 - ▶ Hadronization
 - ▶ Underlying event

MC used for estimating these effects

→ m_t^{MC} is determined

Question: What is m_t^{MC} ?

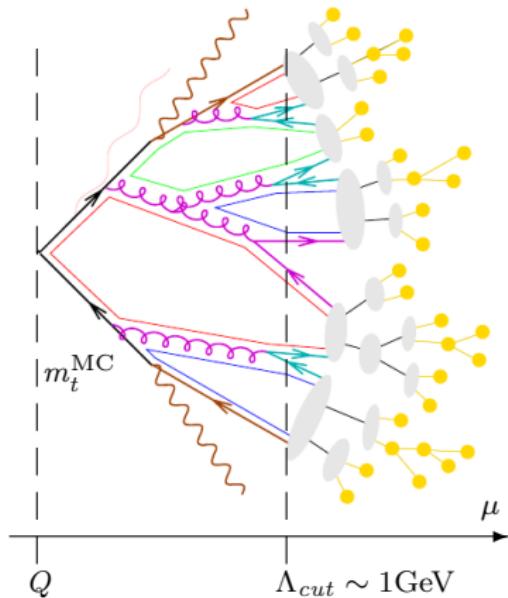


Top quark production at Tevatron [Wikipedia: Top Quark]

Top Mass Determinations at Hadron Colliders - MC Top Mass 1

- **Goal:** Reconstruct top from its decay products → invariant mass distribution
- Input:
 - ▶ Jet algorithm
 - ▶ Hadronization
 - ▶ Underlying event
- MC used for estimating these effects
 - m_t^{MC} is determined
- Steps in the MC:
 - ▶ Hard ME - $t\bar{t}$ production
 - ▶ Parton shower - evolution down to the shower cutoff $\Lambda_{\text{cut}} \sim 1\text{GeV}$
 - + additional cutoff for top Γ_t
 - (▶ Hadronization - model dependent)
- in principle a short distance mass

$$m_t^{\text{MC}} = m_t^{\text{short-distance}} + \mathcal{O}(1\text{GeV})$$



[original picture D. Zeppenfeld]

[Hoang, Stewart '08, Hoang '14]

MC Top Mass 2

- Short distance mass schemes:

- ▶ $\overline{\text{MS}}$ mass: $\mu \geq \overline{m}(\overline{m})$ ($n_l + 1$ flavors): $\overline{m}(\overline{m}) - m^{\text{pole}} = -\overline{m}(\overline{m}) \sum_{n=1} a_{n0} \left(\frac{\alpha_s(\overline{m})}{4\pi} \right)^n$

- ▶ R-scale short distance mass: $R < \overline{m}(\overline{m})$ (n_l flavors) e.g. **MSR mass** [Hoang, Jain, Scimemi, Stewart 2008]: absorbs fluctuations $> R$, smoothly interpolates all R-scales

$$m^{\text{MSR}}(R) - m^{\text{pole}} = -R \sum_{n=1} a_{n0} \left(\frac{\alpha_s(R)}{4\pi} \right)^n, \quad m^{\text{MSR}}(m^{\text{MSR}}) = \overline{m}(\overline{m})$$

- **Aim:** Would like to arrive at relation: [Hoang, Stewart '08; Hoang '14]

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- **Strategy:** compare MC-independent quark mass-sensitive hadron level predictions with sample data from some MC

- ▶ relation should not depend on studied process \rightarrow look at $e^+ e^- \rightarrow t\bar{t} + X \rightarrow \text{hadrons}$
- ▶ should only depend on which MC program is used \rightarrow for now we focus on PYTHIA

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$$m_t^{\text{MC}} = m_t^{\text{MSR}}(R \simeq 1\text{GeV}) + \Delta_{t,\text{MC}}(R \simeq 1\text{GeV})$$

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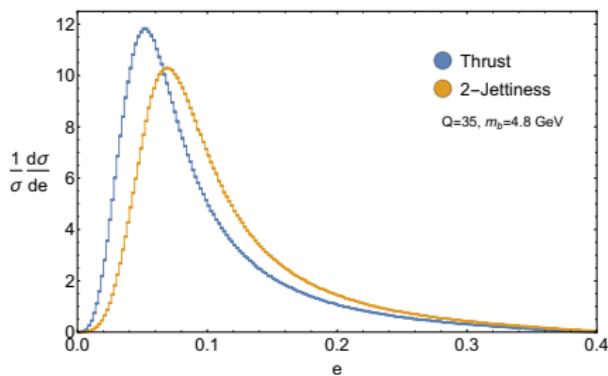
- Use SCET setup for fully quark mass dependent thrust (2-jettiness) distribution

Talk by A.Hoang SCET2014, B.Dehnadi SCET2015

Massive Event Shapes

- Very popular observables for $e^+ e^- \rightarrow \text{hadrons}$ are (global) event-shapes
- Look at 2-jettiness τ_2 (thrust)

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



- In dijet region: $\tau_2 \approx \frac{M_1 + M_2}{Q^2}$
- Well suited for case of massive quarks
- Additional shift of $\sim \frac{2m^2}{Q^2}$
→ high mass sensitivity



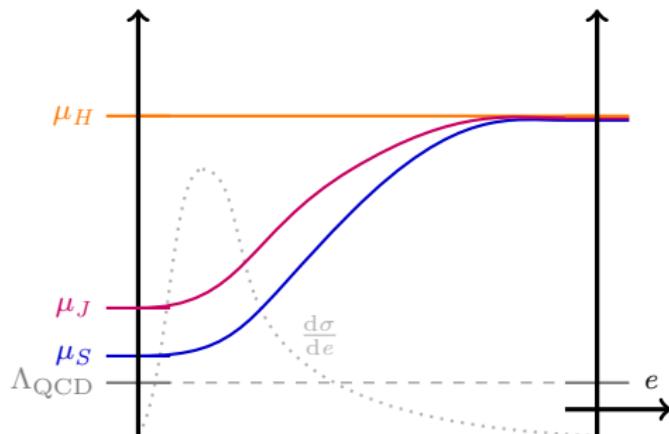
EFT Treatment - Recap

see talk of A.Hoang at SCET2014 and B.Dehnadi at SCET2015

- Massless case

[Bauer, Lee, Fleming, Sterman 2008; Berger, Kucs, Sterman 2003]

$$\frac{1}{\sigma_0} \frac{d\sigma^{\text{SCET}}}{d\tau} = Q H(Q, \mu_H) U_H(Q, \mu_H, \mu = \mu_J) \int ds d\ell J_e(s, \mu_J) \\ \times U_S(\ell, \mu_J, \mu_S) S_\tau(Q \tau - \frac{s}{Q} - \ell, \mu_S)$$



EFT Treatment - Recap

see talk of A.Hoang at SCET2014 and B.Dehnadi at SCET2015

- Introducing massive quarks

- ▶ VFNS for final state jets (with massive quarks)

[Gritschacher, Hoang, Jemos, Mateu, Pietrulewicz '13 '14]

[Butenschön, Dehnadi, Hoang, Mateu '16 (to appear)]

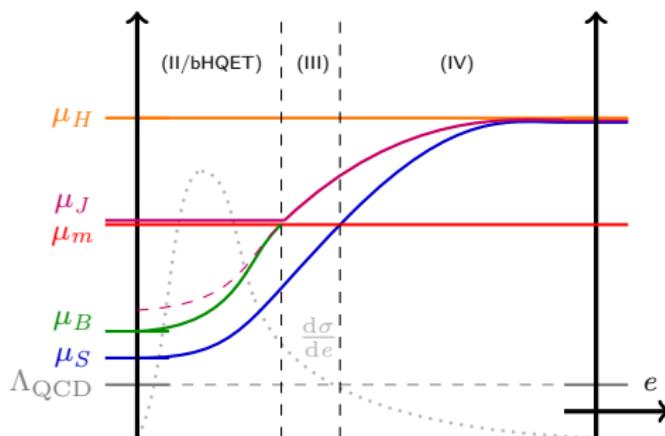
- #### ► Boosted top jets

[Fleming, Hoang, Mantry, Stewart 2007]

- ▶ Non-perturbative power-corrections are included via a shape function F_{mod}

[Korchemsky, Sterman 1999]

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

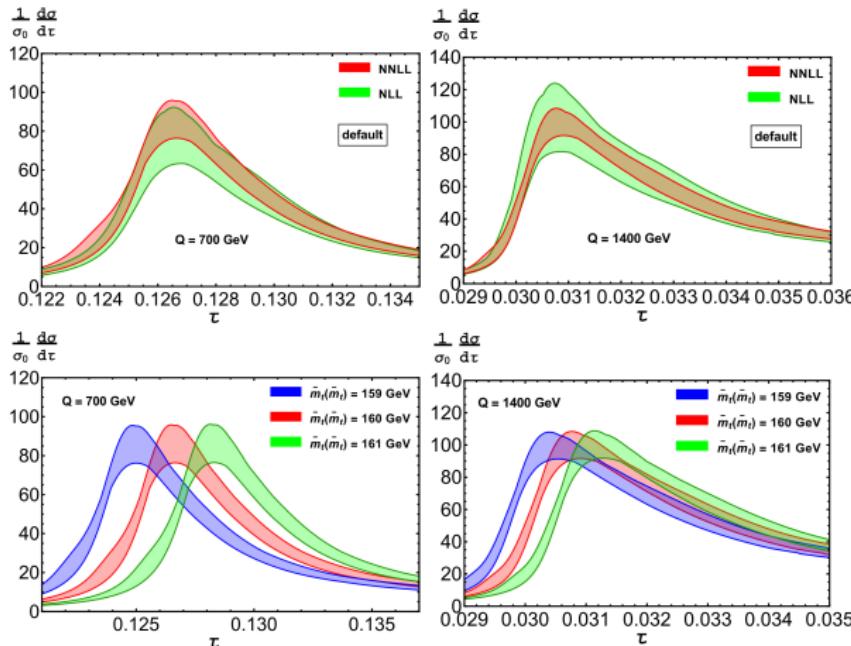


NNLL + NLO
 + non-singular + hadronization
 + renormalon-subtraction

Convergence, Mass Sensitivity

- $\frac{d\sigma}{d\tau} = f(m_t^{\text{MSR}}, \alpha_s(m_Z), \Omega_1, \Omega_2, \dots, \mu_H, \mu_J, \mu_S, \mu_M, R, \Gamma_t)$

any scheme non-perturbative renorm. scales finite lifetime



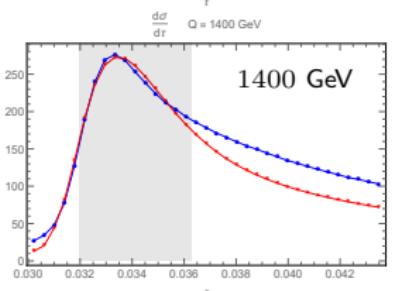
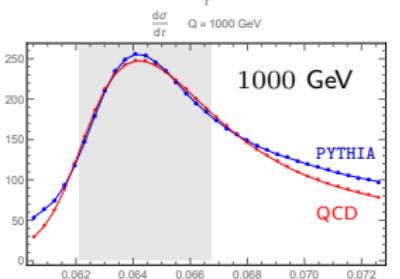
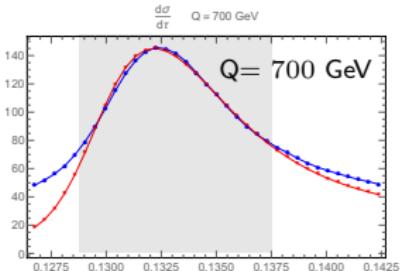
- Good convergence
- Reduction of scale uncertainty (NLL to NNLL)
- Control over whole distribution
- Higher mass sensitivity for lower Q
- Finite lifetime effects included
- Dependence on non-perturbative parameters

Fitting Procedure

- $\frac{d\sigma}{d\tau} = f(m_t^{\text{MSR}}, \alpha_s(m_Z), \Omega_1, \Omega_2, \dots, \mu_H, \mu_J, \mu_S, \mu_M, R, \Gamma_t)$
any scheme non-perturbative renorm. scales finite lifetime
- Generating Pythia Samples: at 10 different energies: $Q = 700, 800, 900, \dots, 1400, 2000 \text{ GeV}$
 - ▶ 6 masses: $m_t^{\text{PYTHIA}} = 170, 171, 172, 173, 174, 175 \text{ GeV}$
 - ▶ 5 width: $\Gamma_t = 0.1, 0.7, 1.4, 2.0 \text{ GeV} + \text{pythia default}$ (m_t^{PYTHIA} dependent)
 - ▶ 3 tunes: 7 (default), 3, 1 to estimate systematic uncertainties of PYTHIA
 - ▶ 8 external smearing (detector effects): $\Omega_{\text{smear}} = 0, 0.5, 1.0, 1.5, 2.0, 2.0, 3.0, 3.5 \text{ GeV}$
 - ▶ Statistics: 10^6 events for each set of parameters

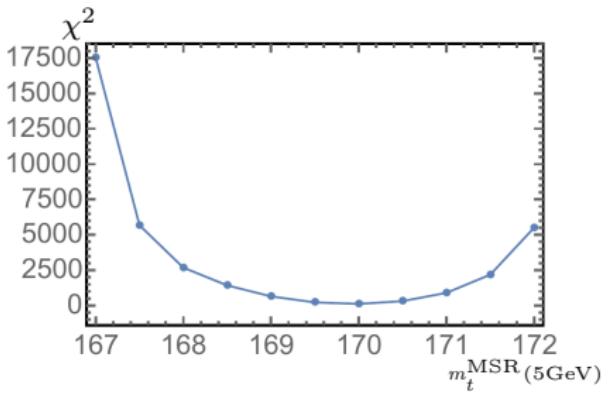
Now: everything is set for the fit

- ▶ Fit parameters (measured from PYTHIA): $m_t^{\text{MSR}}, \alpha_s(m_Z), \Omega_1, \Omega_2, \dots$
- ▶ First step: preliminary analysis using default parameters
- ▶ Second step: analysis with 500 sets of profiles (for renorm. scales)

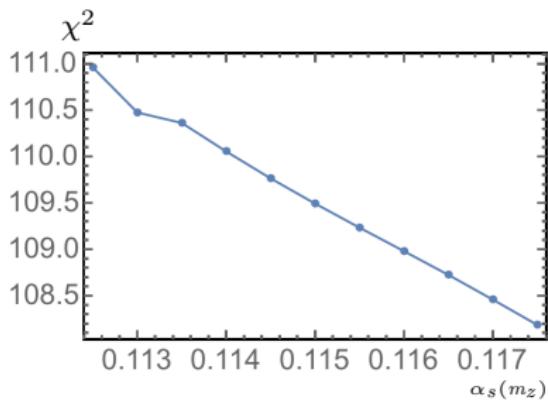


default ren. scales; $\Gamma_t = 1.4$ GeV; tune 7;
 $\Omega_{\text{smear}} = 2.5$ GeV; $Q = 700, 1000, 1400$ GeV;
peak(60/80)%

- Good agreement of PYTHIA 8.215 with N²LL + NLO QCD description
- Discrepancies away from Peak
 - ▶ Top decay correct at NLO in peak
 - ▶ Subleading finite lifetime effects
 - ▶ PYTHIA less reliable in tail



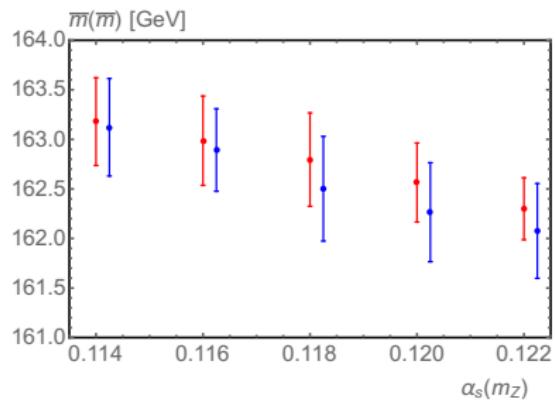
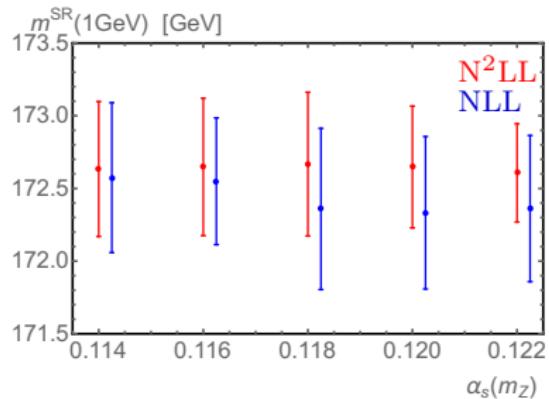
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→ Observe: $\chi^2_{\min} \sim \mathcal{O}(100)$

- Very strong sensitivity to top mass
 - Very low sensitivity to strong coupling
- Take α_s as input

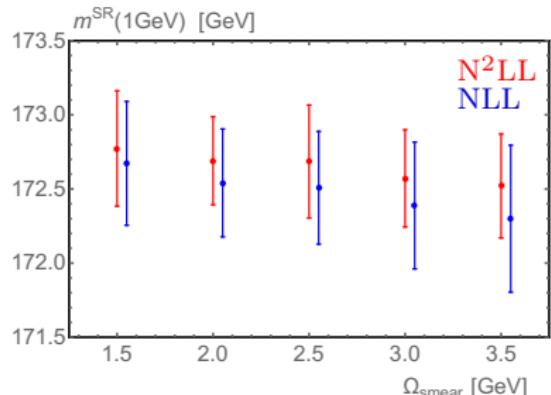
- χ^2_{\min} and δm_t^{stat} do not have any physical meaning
- We use rescaled χ^2/dof (PDG prescription) to define “intrinsic MC compatibility uncertainty”



500 profiles; $\Gamma_t = 1.4 \text{ GeV}$; tune 1, 3, 7;
 $\Omega_{\text{smear}} = 1.5, 2.0, 2.5, 3.0, 3.5 \text{ GeV}$;
 $Q = 700, 1000, 1400 \text{ GeV}$; peak(60/80)%

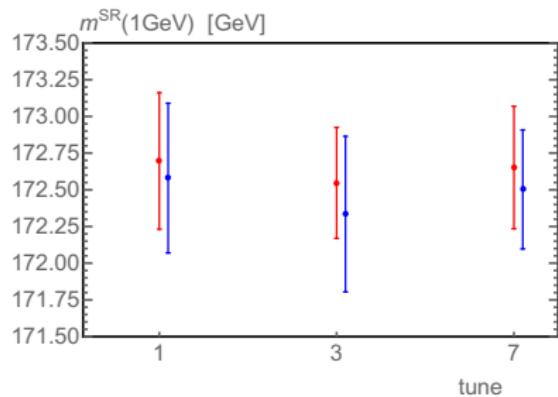
$$m_t^{\text{PYTHIA}} = 173 \text{ GeV}$$

- Very low sensitivity of m_t^{MSR} on $\alpha_s(m_z)$
- Larger sensitivity of \overline{MS} mass on $\alpha_s(m_z)$
- MC top mass is indeed closely related to $m_t^{\text{MSR}}(R \sim 1\text{GeV})$



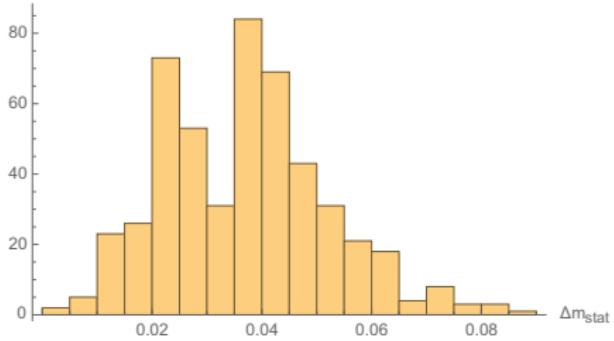
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- “Detector effects” \ll perturbative uncertainty
 - MC tune dependence \ll perturbative uncertainty
- MC top mass is indeed closely related to $m_t^{\text{MSR}}(R \sim 1\text{GeV})$

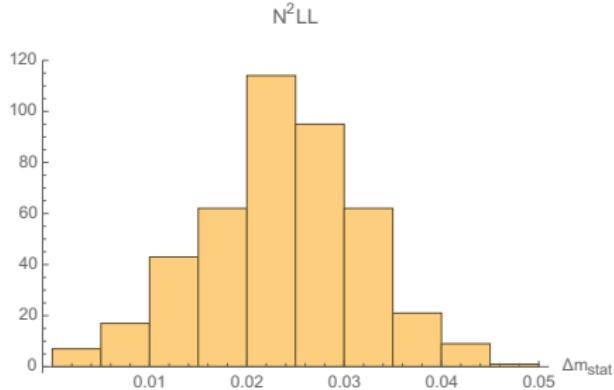
NLL

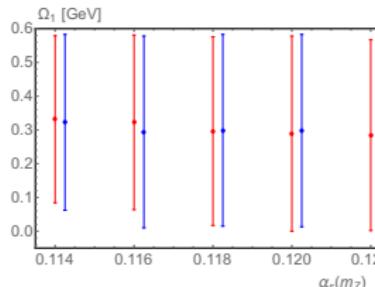


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- “MC compatibility error” \sim tuning error \sim “detector effect” error
- Effects < 100 MeV
(maybe estimate for ultimate precision)

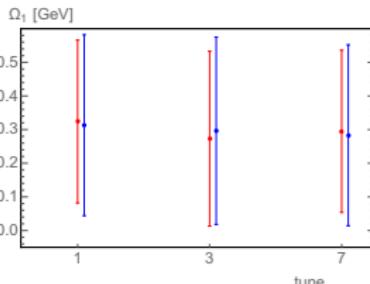
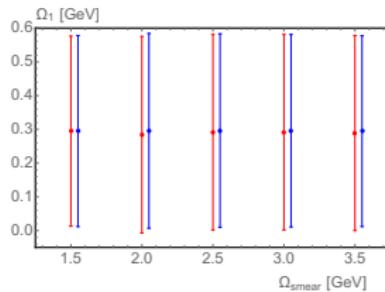
 $N^2\text{LL}$ 



N²LL
NLL

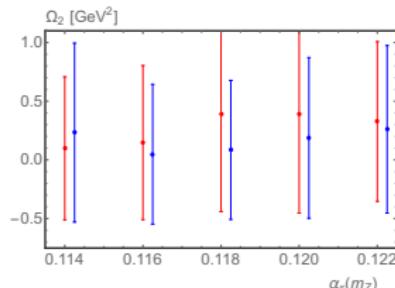
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$$m_t^{\text{PYTHIA}} = 173 \text{ GeV}$$



- Reliable determination of non-perturbative matrix element Ω_1
- Expected $\delta m_t \sim \delta \Omega_1$
- Compatible with α_s tail fits \rightarrow larger errors
 $\Omega_1 = 0.276 \pm 0.155$ GeV (N²LL)

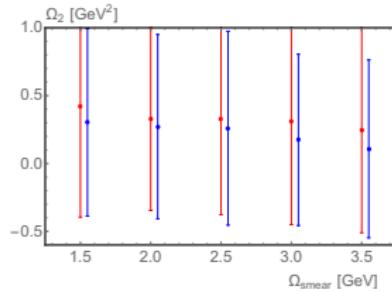
[Abbate, Fickinger, Hoang, Mateu, Stewart 2011]



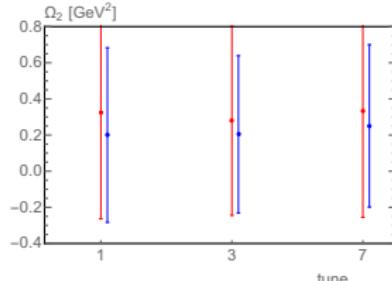
N²LL
NLL

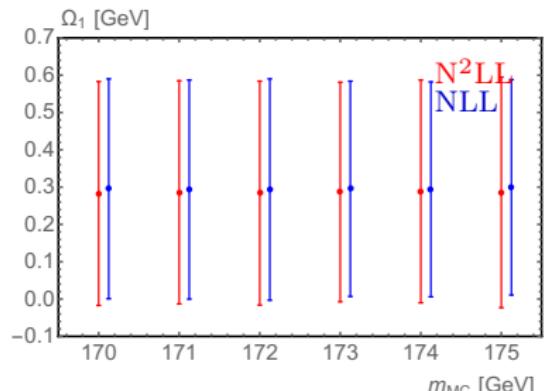
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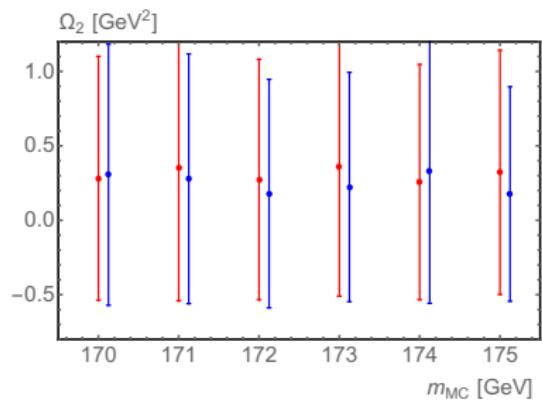
- Ω_1 encodes dominant power correction
- Expected large error due to little sensitivity
- Reliable determination of non-perturbative matrix element Ω_2





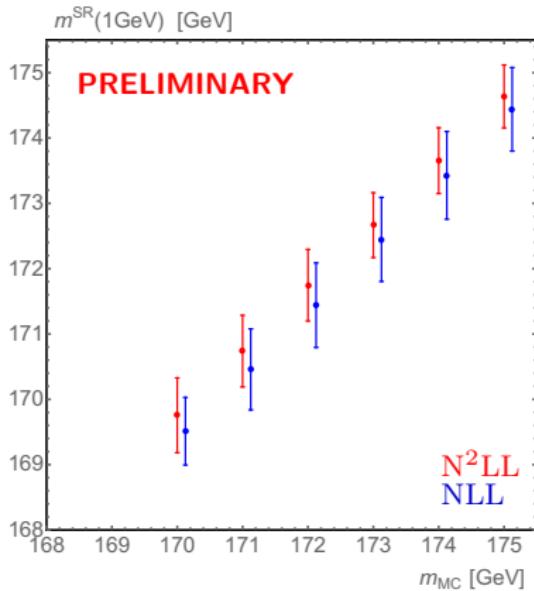
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- Non-perturbative matrix elements $\Omega_{1,2}$ independent of top mass

Final Result



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$$m_t^{\text{PYTHIA}} = 173 \text{ GeV}$$

- Many checks still need to be done
- Calibration error: 0.5 GeV seems feasible at N²LL

Conclusion & Outlook

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- First precise MC top quark mass calibration based on e^+e^- 2-jettiness: preliminary results
- $N^2LL + NLO$ QCD calculations based on an extension of the SCET approach concerning massive quark effects
- MC mass calibration in terms of MSR mass with perturbative error $\mathcal{O}(500\text{MeV})$ appears feasible at $N^2LL + NLO$
- Intrinsic MC error seems $\mathcal{O}(100\text{MeV})$

Outlook:

- Fully verified error analysis $N^2LL + NLO$ on the way
- Heavy jet mass, C-parameter (N^2LL) → work in progress
- Calibration for other MC generators

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