Top quark mass calibration for Monte-Carlo event generators

Moritz Preisser
(University of Vienna)

Collaborators:
M. Butenschön (UHamburg), B. Dehnadi, A. Hoang (UVienna), V. Mateu (UAMadrid), I. Stewart (MIT)

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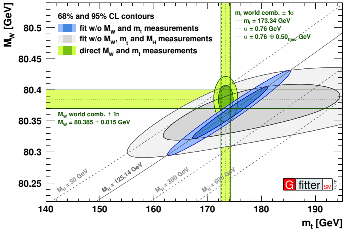
Outline

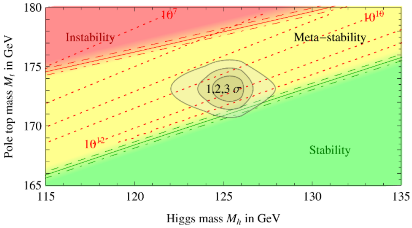
Motivation & Introduction

Motivation

- Top quark is the heaviest particle in the standard model
- 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
  - ...



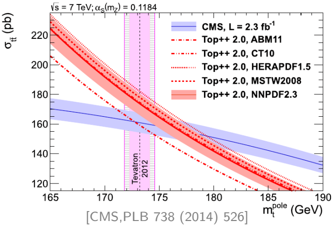
[GFitter,Phys. J. C (2014) 74]



[Degrassi et.al. 2012]

Top Mass Determinations

- Different methods available ($t\bar{t}$ production at hadron colliders)
  - total cross-section measurements $m_t^{\text{pole}} = 176.7^{+4.0}_{-3.4}$ GeV [K.A.Olive et.al. (PDG) 2014]
  - leptonic observables [Frixione, Mitov 2014; Kawabata 2016]
  - direct reconstruction measurements
  - ...

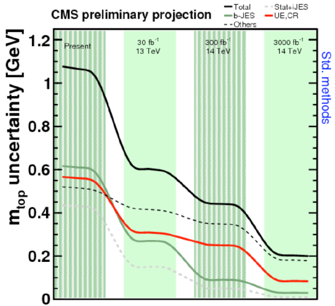


[CMS,PLB 738 (2014) 526]

- Direct reconstruction determinations are very precise
  - many individual measurements with uncertainty below 1 GeV → CMS combination reaches < 500 MeV
  - ➜ PDG quotes an uncertainty of ~ 900 MeV

$$m_{\text{t}} = 173.21 \pm 0.51(\text{stat}) \pm 0.71(\text{sys})\,\text{GeV}$$

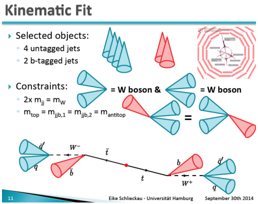
  - relies on (General Purpose) Monte Carlo (MC) generators e.g. `PYTHIA` to determine mass

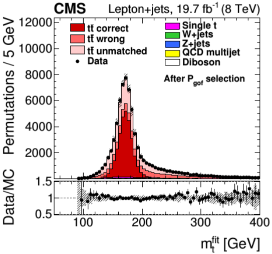


Question: How should one interpret the "measured" top mass?

Top Mass Determinations: Template Method

- **Goal:** Reconstruct top from its decay products
  $\rightarrow$ Observable $\sim$ invariant mass distribution
- Experimental side
  - Experimentally reconstructed decay products
  - Distribution for reconstructed top mass m_t^{reco}



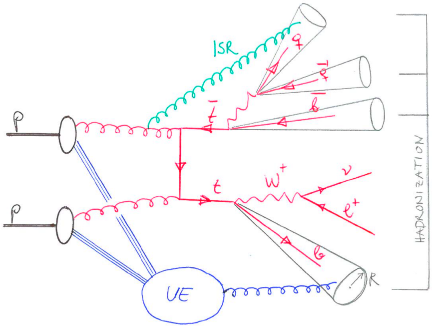


[CMS Phys. Rev. D 93, 072004]

Top Mass Determinations: Template Method

- **Goal:** Reconstruct top from its decay products
  → Observable ∼ invariant mass distribution
- Theoretical issues:
  - ISR & UE
  - Jet algorithms
  - Hadronization

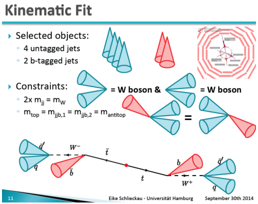
Consider $t\bar{t} \to \ell + jets$:

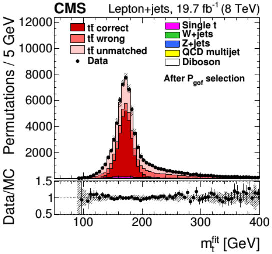


Top Mass Determinations: Template Method

- **Goal:** Reconstruct top from its decay products
  $\rightarrow$ Observable $\sim$ invariant mass distribution
- Experimental side
  - Experimentally reconstructed decay products
  - Distribution for reconstructed top mass m_t^{reco}
- Theoretical issues:
  - ISR & UE
  - Jet algorithms
  - Hadronization
- Use MC (simulated events) as a theory blackbox
  - carry out exp. procedure for different values of m_t^{MC}
  - ➜ m_t^{MC} is determined

Question: What is m_t^{MC}?





[CMS Phys. Rev. D 93, 072004]

Top Mass Determinations: MC Top Quark Mass

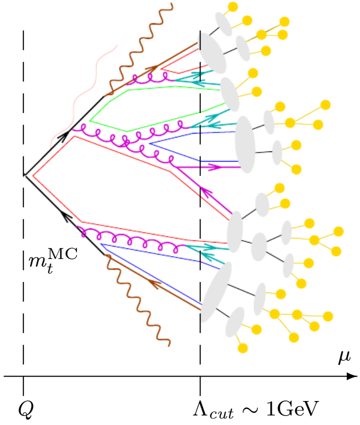
- Historically: all-order identification with m_t^{pole}
  - $\mathcal{O}(\Lambda_{\text{QCD}})$ renormalon ambiguity
  - convergence of mass extraction?

- Steps in the MC:
  - Hard ME - $t\bar{t}$ production
  - Parton shower - evolution down to the shower cutoff $\Lambda_{cut} \sim 1\text{GeV}$
  - Hadronization - model dependent

➜ related to short distance mass

$$m_t^{\text{MC}} : m_t^{\text{short-distance}}(1\text{GeV})$$

[Hoang, Stewart '08, Hoang '14]



[original picture D. Zeppenfeld]

MC Top Mass 2

- Short distance mass schemes:

  - $\overline{\text{MS}}$ mass: $\mu \geq \overline{m}(\overline{m})$:

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

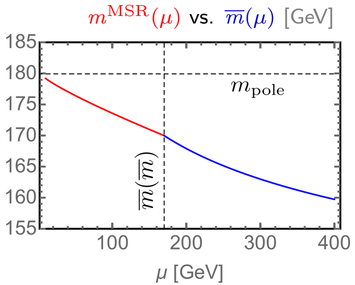
  - R-scale short distance mass: $R < \overline{m}(\overline{m})$
    e.g. **MSR** mass [Hoang, Jain, Scimemi, Stewart 2008]:

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

$$m^{\text{MSR}}(m^{\text{MSR}}) = \overline{m}(\overline{m})$$

absorbs fluctuations $> R$,

smoothly interpolates all R-scales



Strategy & Observable

Strategy

- **Strategy:** compare quark mass-sensitive hadron level QCD calculations with sample data from some MC
  - look into observables with strong kinematic mass sensitivity
  - get accurate hadron level QCD predictions ($\geq$NLO/NLL) with full control over quark mass scheme dependence
  - fit QCD masses to different values of $m_t^{\rm MC}$

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

$$m_t^{\rm MC} = m_t^{\rm pole} + \Delta_{t,{\rm MC}}^{\rm pole} \qquad \Delta_{t,{\rm MC}} \simeq \mathcal{O}(1{\rm GeV})$$

Uncertainties we address in our e^+e^- study

- perturbative uncertainty
- scale uncertainties
- electroweak effects
- strong coupling α_s
- non-perturbative parameters

Additional pp systematics

- PS + UE
- color reconnection
- intrinsic uncertainty

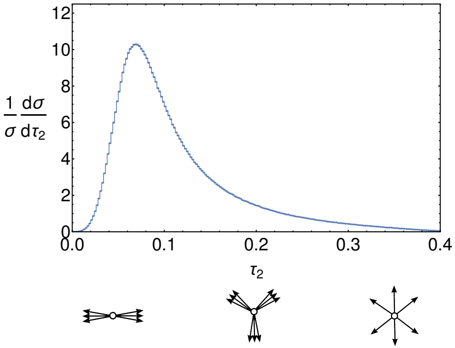
Massive Event Shapes

- We use 2-jettiness τ_2 for **boosted tops** (c.o.m. energy $Q \gg m_t \sim$ high p_T) in $e^+e^- \to t\bar{t} \to$ hadrons

  mass sensitive version of thrust

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

peak position is highly mass sensitive



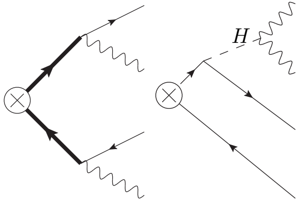
- for $\tau_2 \ll 1$ (peak):

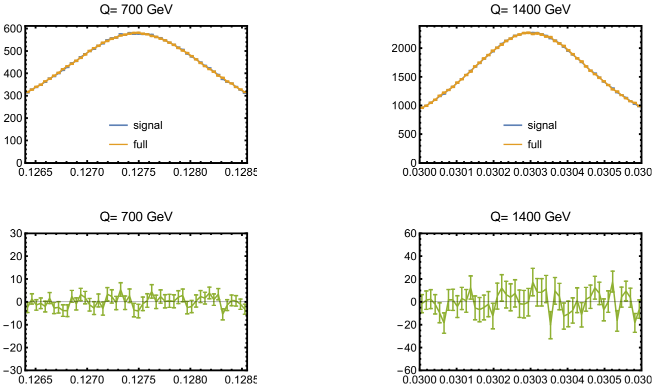
$$\tau_2 \approx \frac{M_1^2 + M_2^2}{Q^2}$$

  hemisphere masses M_i

MG5 study: $e^+e^- \to W^+W^-b\bar{b}$ - signal $t\bar{t}$ vs full

- Non-resonant contributions are irrelevant for τ_2 distribution
  - `PYTHIA` (or similar MCs) will give a good description of the production process at LO
  - hemisphere invariant mass $\sim$ top invariant mass (no pollution from background)



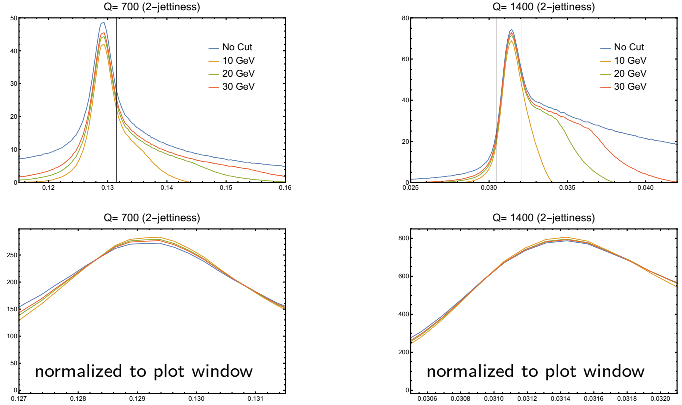


PYTHIA8 study: hemisphere mass cuts

- In our theory description we treat the top decay as inclusive w.r.t. hemisphere
  - violated by decay products which cross to the other hemisphere
  - no differential impact in resonance region (irrelevant when normalized to signal region)

Cuts on hemisphere invariant mass above and below:

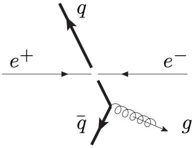
$$M_i^{\mathrm{cut}} = m_t^{\mathrm{MC}} \pm \Delta^{\mathrm{cut}}$$



Theory Input

Large Logarithms

- Look at massless 2-jettiness distribution (very similar in the massive case)
- Typical integrated NLO τ_2 cross-section: $\Sigma(\tau_2) = \int_0^{\tau_2} \mathrm{d}\tau_2{}' \frac{1}{\sigma_0} \frac{\mathrm{d}\sigma}{\mathrm{d}\tau_2{}'}$

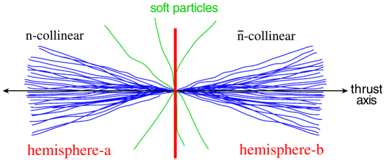


$$\Sigma(\tau_2) = 1 + \frac{\alpha_s C_F}{4\pi}\left[a_{12}\log^2(\tau_2) + a_{11}\log(\tau_2) + c_1\right] + \mathcal{O}(\alpha_s^2)$$

problem with large logarithms at small τ_2 $\rightarrow$ bad convergence

- Large hierarchies between involved scales
  - Hard scale: $\sim Q$
  - Jet scale: $\sim Q\sqrt{\tau_2}$
  - Soft scale: $\sim Q\tau_2$

  scales are event-shape dependent
  $\rightarrow$ see later (profile functions)



- Reorganize cross-section by considering $\alpha_s \log(\tau_2) \sim \mathcal{O}(1)$

$$\begin{aligned} \ln(\Sigma) \sim\ & \alpha_s\,[\ln^2 + \ln + 1] && \text{LL} \\ & + \alpha_s^2\,[\ln^3 + \ln^2 + \ln + 1] && \text{NLL} \\ & + \alpha_s^3\,[\ln^4 + \ln^3 + \ln^2 + \ln + 1] + \ldots && \text{N}^2\text{LL} \end{aligned}$$

Resummation and Massless Factorization Theorem in SCET

- Soft-Collinear Effective Theory (SCET) is the proper EFT for this situation
- For the peak region (dijet) we can derive a factorization formula in SCET which separates the involved scales

$$\frac{1}{\sigma_0}\frac{\mathrm{d}\sigma^{\mathrm{SCET}}}{\mathrm{d}\tau} = Q\,H(Q,\mu)\int \mathrm{d}s\; J_\tau(s,\mu)\,S_\tau(Q\,\tau - \frac{s}{Q},\mu)$$

- Use RGE for each cross-section part to resumm logs of all occuring scales into *evolution kernels* $\rightarrow$ we choose $\mu = \mu_J$

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

- Also include subleading full theory (nonsingular) contributions. The cross-section is given by:
  $\mu_H = \mu_S = \mu_J \equiv \mu$

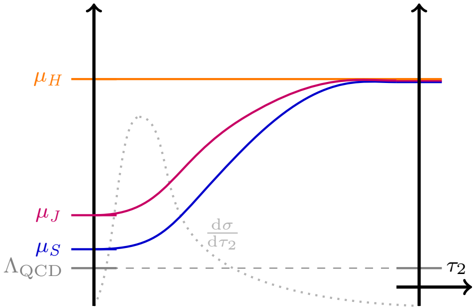
$$\frac{\mathrm{d}\sigma^{\mathrm{QCD}}}{\mathrm{d}\tau} = \frac{\mathrm{d}\sigma^{\mathrm{SCET}}}{\mathrm{d}\tau} + \frac{\mathrm{d}\sigma^{\mathrm{ns}}}{\mathrm{d}\tau}$$

- How do we choose the scales $\mu_H/\mu_J/\mu_S$ and how does the mass enter?

Profile Functions & scenarios

- The logs occuring in Hard, Jet- and Soft-function are the following:
  - hard: $\log(\frac{Q^2}{\mu_H^2})$
  - jet: $\log(\frac{Q^2\tau_2}{\mu_J^2})$
  - soft: $\log(\frac{Q\tau_2}{\mu_S})$

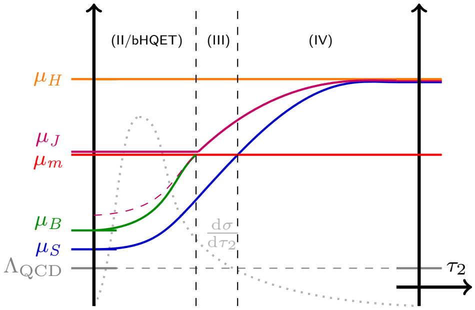
  $\rightarrow$ the characteristic scales will depend on the event-shape.



Profile Functions & scenarios

- The logs occuring in Hard, Jet- and Soft-function are the following:
  - hard: $\log(\frac{Q^2}{\mu_H^2})$
  - jet: $\log(\frac{Q^2(\tau_2 - \tau_2{}^{\min})}{\mu_J^2})$, $\log(\frac{Q^2(\tau_2 - \tau_2{}^{\min} + \hat{m}^2)}{\mu_J^2})$ $\rightarrow$ for $\mu_J^2 \lesssim \hat{m}^2$ need bHQET
  - soft: $\log(\frac{Q(\tau_2 - \tau_2{}^{\min})}{\mu_S})$

  $\rightarrow$ the characteristic scales will depend on the event-shape. $\mu_m \sim m$



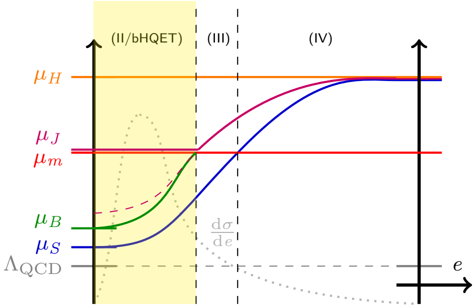
- Massive case introduces different scale hierarchies $\rightarrow$ changes RG evolution

Theory Description - EFT treatment

- Boosted top jets

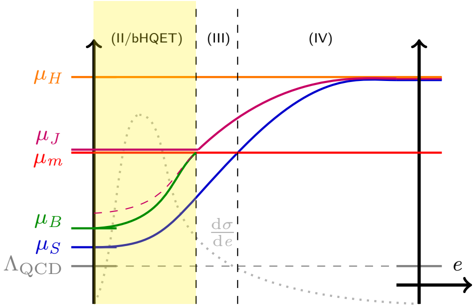
  [Fleming, Hoang, Mantry, Stewart 2007]

$$\frac{d\sigma^{\mathrm{bHQET}}}{d\tau} = Q\, H(Q, m, \mu_H)\, U_H^{(n_f)}(Q, \mu_H, \mu_m)\, H_m^{(n_f)}(Q, \mu_m)\, U_m^{(n_l)}(Q, m, \mu_m, \mu_B)$$
$$\times \int ds\, d\ell\; B_e^{(n_l)}(s, m, \mu_B)\, U_S^{(n_l)}(\ell, \mu_B, \mu_S)\, S_e^{(n_l)}\Big(Q(\tau - \tau_{\min}) - \frac{s}{Q} - \ell, \mu_S\Big)$$



Theory Description - EFT treatment

- Developments:
  - VFNS for final state jets (with massive quarks)
    [Gritschacher, Hoang, Jemos, Mateu, Pietrulewicz '13 '14]
    [Butenschön, Dehnadi, Hoang, Mateu '16 (to appear)]



  - Non-perturbative power-corrections are included via a shape function
    [Korchemsky, Sterman 1999]
    [Hoang, Stewart 2007]
    [Ligeti, Stewart, Tackmann 2008]

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

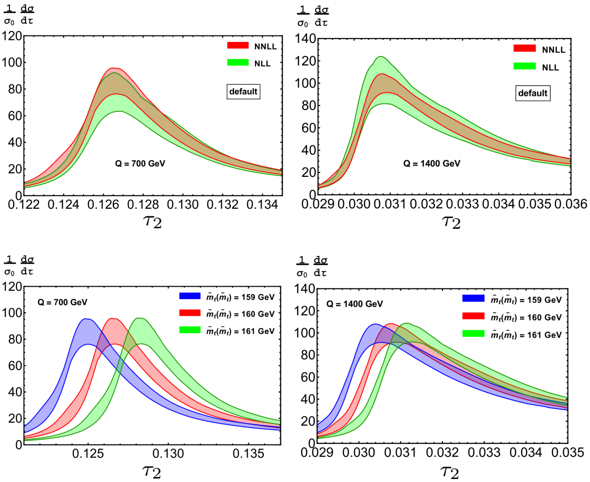
  - Gap-scheme
  - MSR mass & R-evolution
    [Hoang, Jain, Scimemi, Stewart 2010]

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

Convergence, Mass Sensitivity

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

  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

Calibrating PYTHIAs Top Mass Parameter

1608.01318

so far, e^+e^- calibration

Preparing the Fits

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

  any scheme non-perturbative renorm. scales finite lifetime

- Generating PYTHIA Samples:

  at different energies: $Q = 600, 700, 800, ..., 1400$ GeV

  - masses: $m_t^{\mathrm{MC}} = 170, 171, 172, 173, 174, 175$ GeV
  - width: $\Gamma_t = 1.4$ GeV
  - Statistics: 10^7 events for each set of parameters

- Feed MC data into **Fitting Procedure:** all ingredients are there

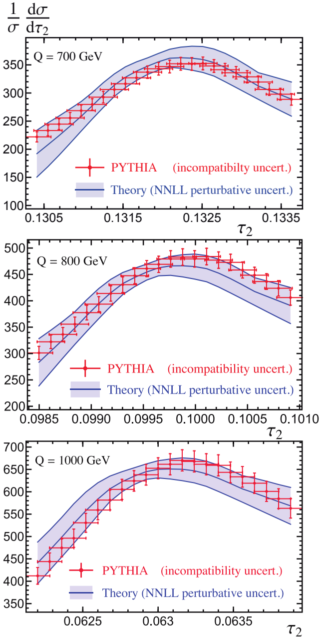
  Fit parameters: m_t^{MSR}, $\alpha_s(m_Z)$, $\Omega_1, \Omega_2, \ldots$

  - standard fit based on χ^2 minimization
  - analysis with 500 sets of profiles (τ_2 dependent renorm. scales) for the each MC sample
  - different Q-sets: 7 sets with energies between 600 - 1400 GeV

    different n-sets: 3 choices for fitranges - (xx/yy)% of maximum peak height

- High sensitivity to top quark mass but almost no sensitivity to α_s $\rightarrow$ α_s as input

Fit Results: Pythia vs. Theory



- Good agreement of PYTHIA 8.205 with $N^2LL + NLO$ QCD description in peak region
- Perturbative uncertainties on theory side estimated via scale variations (profiles)
- MC incompatibility uncertainty estimate intrinsic difference between MC & theory via difference between different Q- & n-sets

Convergence & Stability: MSR vs Pole Mass

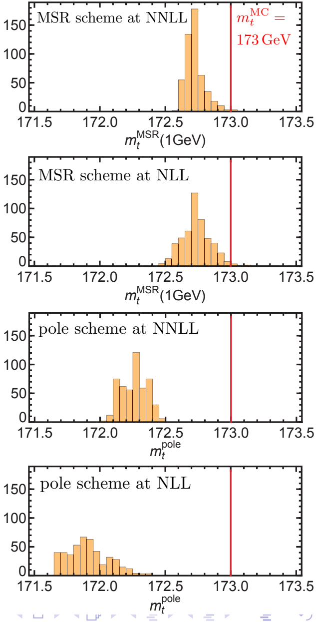
500 profiles; $\alpha_s = .118$; $\Gamma_t = 1.4$ GeV; tune 7;
$Q = 700, 1000, 1400$ GeV; peak$(60/80)\%$

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

fit to find $m_t^{\mathrm{MSR}}(1\mathrm{GeV})$ or m_t^{pole}

- Good convergence and stability for $m_t^{\mathrm{MSR}}(1\mathrm{GeV})$
- Pole mass numerically not at all close to m_t^{MC}

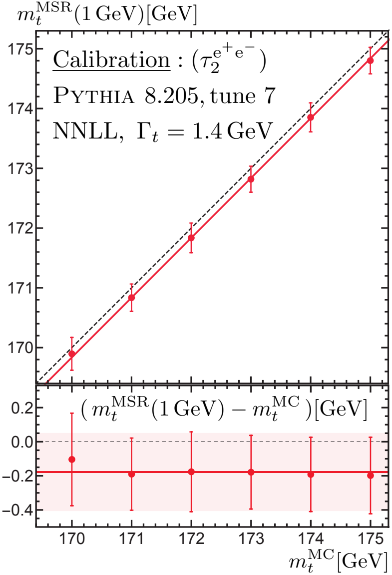
  900/600 MeV difference at NLL/NNLL!



Final Results

- All investigated MC top mass values show consistent picture
- MC top quark mass is indeed closely related to MSR mass

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



$m_t^{\mathrm{MC}} = 173\,\mathrm{GeV}$ $(\tau_2^{e^+e^-})$

mass	order	central	perturb.	incompatibility	total
$m_{t,1\,\mathrm{GeV}}^{\mathrm{MSR}}$	NLL	172.80	0.26	0.14	0.29
$m_{t,1\,\mathrm{GeV}}^{\mathrm{MSR}}$	$\mathrm{N^2LL}$	172.82	0.19	0.11	0.22
m_t^{pole}	NLL	172.10	0.34	0.16	0.38
m_t^{pole}	$\mathrm{N^2LL}$	172.43	0.18	0.22	0.28

Conclusion & Outlook

- First precise MC top quark mass calibration based on e^+e^- 2-jettiness
  1608.01318

  QCD calculations at $\mathrm{NNLL} + \mathrm{NLO}$ based on an extension of the SCET approach to include massive quark effects

- Top mass calibration for PYTHIA 8.205 in terms of Pole and MSR mass.
  For $m_t^{\mathrm{MC}} = 173$ GeV at NNLL:
  - $m_t^{\mathrm{pole}} = 172.43 \pm 0.28\ \mathrm{GeV}$
  - $m_t^{\mathrm{MSR}}(1\mathrm{GeV}) = 172.82 \pm 0.22\ \mathrm{GeV} \quad \rightarrow \quad \mathrm{m_t^{MC}} \simeq \mathrm{m_t^{MSR}}(1\mathrm{GeV})$

Outlook:

- Other observables & $(\mathrm{N^3LL} + \mathrm{N^2LO})$
- pp 2-jettiness analysis, and mass calibration with pp MC data

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  - $m_t^{\mathrm{MSR}}(1\mathrm{GeV}) = 172.82 \pm 0.22\ \mathrm{GeV} \quad \rightarrow \quad \mathrm{m_t^{MC}} \simeq \mathrm{m_t^{MSR}}(1\mathrm{GeV})$

Outlook:

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Thank you for your attention!

Backup

Pole mass - MSR mass relation

$$\alpha_s(M_Z) = 0.118$$
$$n_f = 5$$

$$\begin{aligned} m_t^{\rm pole} - m_t^{\rm MSR}(1\,{\rm GeV}) = & \overset{\mathcal{O}(\alpha_s)}{0.173} + \overset{\mathcal{O}(\alpha_s^2)}{0.138} + \overset{\mathcal{O}(\alpha_s^3)}{0.159} + \overset{\mathcal{O}(\alpha_s^4)}{0.23}\ {\rm GeV} \\ & + 0.53 + 1.43 + 4.54 + 16.6\ {\rm GeV} \\ & + 68.6 + 317.7 + 1629 + 9158\ {\rm GeV} \end{aligned}$$

← calculated

← extrapolated

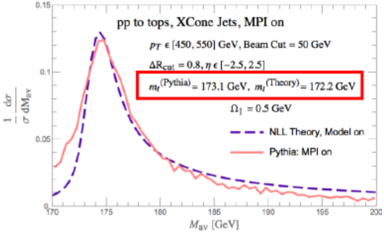
- No precise/stable determination of $m_t^{\rm pole}$

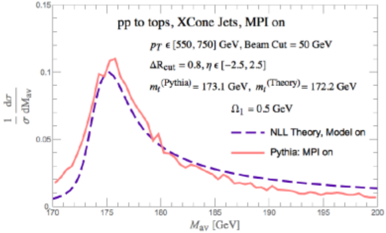
pp-2-jettiness

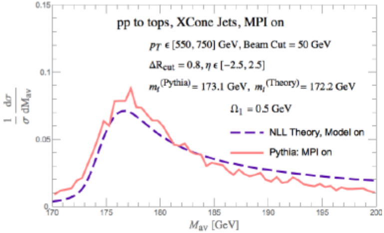
- Aditya Pathak (MIT) at Boost2016: pp-2-jettiness at NLL

Pythia with hardonization and MPI turned on

- One choice for Ω_1 which works for all p_T ranges.
- Here a soft model with $\Omega_1 = 0.5$ GeV reproduces the MPI and hadronization effects for the peak location.





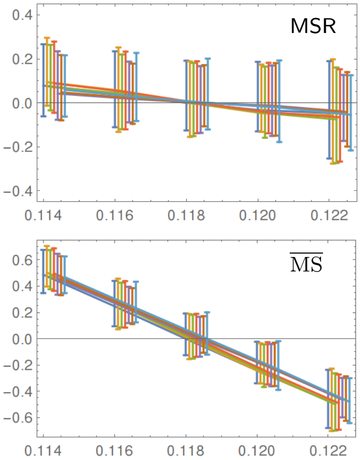


Results: MSR/$\overline{\text{MS}}$ parametric dependence on α_s

500 profiles; $\Gamma_t = 1.4$,-1 GeV;tune 7;
diff. Q-sets; peak$(60/80)\%$

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

- α_s dependence:
  $m^{\text{scheme}}[\alpha_s] - m^{\text{scheme}}[.118]$
- small dependenence of MSR mass on α_s
  ~ 50 MeV error $(\delta\alpha_s = .002)$
- large sensitivity of $\overline{\text{MS}}$ mass on α_s
- not an error:
  calculated from MSR with high accuracy



Results: tune dependence

500 profiles; $\Gamma_t = 1.4$,-1 GeV;tune $1, 3, 7$;
diff. Q-sets; peak$(60/80)\%$

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

- tune dependence:
  $m^{\mathrm{MSR}}[\mathrm{tune}] - \mathrm{m}^{\mathrm{MSR}}[7]$

- clear sensitivity to tune
- m^{MC} will depend on tune
- tune dependence is not a calibration uncertainty:

  (different tune $\Rightarrow$ different MC $\Rightarrow$ m_t^{MC})