Top Quark Mass Calibration for MC Event Generators - An Update -

In collaboration with Bahman Dehnadi, Oliver Jin , Vicent Mateu and Simon Plätzer on the arXiv May/June

André H. Hoang

University of Vienna







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Outline

- Introduction: direct top mass determinations and status of the interpretation of mt^{MC}
- Top mass calibration
- Calibration of the Pythia Monte Carlo top mass parameter:
 e⁺e⁻ → t t (2-jettiness)
 Butenschön, Dehnadi, Mateu, Preisser, Stewart, AH 1608.01318
- Updates:

 more observables,
 - more soft function renormalon subtractions
 - (m_t/Q)² power corrections
- Summary, future plans

All results shown are preliminary !



Main Top Mass Measurements Methods





Status of m_t^{MC} Interpretation

Issue is not yet resolved, but a number of important insights have been gained.

First principles insights:

- "Scheme" of mt^{MC} in principle determined by the precision of parton shower (PS)
 - For perfect NLL PS, we could control mt^{MC} at NLO
 - Problem: PS have different precision depending on the observable (tested for inclusive observables)
 - Shower cut Q_0 represents IR resolution parameter: $m_t^{MC} = m_t^{MC}(Q_0)$, linear dependence
 - Realistic observables have have many other sources of linear IR cutoff dependence
- Hadronization model influences mt^{MC} indirectly as it corrects for PS imperfections
 - LHC Initial state effects (MPI, UE) not at all understood systematically from QCD: big problem for LHC direct top mass measurement interpretation, not clear path how to address this without models
 - Consistency with systematic QCD methods (e.g. OPE) largely untested
- Coherent branching + massive eventshapes (e⁺e⁻): $m_t^{CB}(Q_0) = m_t^{pole} \frac{2}{3} \alpha_s(Q_0) Q_0 + \dots$ AHH, Plätzer, Samitz 2018
- m_t^{pole} has $O(\Lambda_{QCD})$ renormalon \rightarrow more precision with MSR mass $m_t^{MSR}(R)$
 - m_t^{pole} ambiguity: 110 MeV 250 MeV, but unrelated to m_t^{MC} interpretation

Beneke etal 2016; AHH etal 2017

• $m_t^{\text{CB}}(Q_0) = m_t^{\text{MSR}}(Q_0) - 0.24 \, \alpha_s(Q_0) \, Q_0$



Status of m_t^{MC} Interpretation

Numerical insights:

• Combined LHC direct + total cross section analysis: $\left|m_t^{
m MC} - m_t^{
m pole} \right| < 2~{
m GeV}$

Kieseler etal 1511.00841

- Top mass calibration: N²LL+NLO e⁺e⁻ 2-jettiness fitted to Pythia 8.205 pseudo data
 - 1) Strongly mass-sensitive hadron level (as closely as possible related to direct measurement observables)
 - Accurate <u>hadron level</u> QCD predictions at ≥ NLL/NLO with full control over the quark mass scheme dependence.
 - 2) QCD masses as function of m_t^{MC} from fits of theory to MC samples.
 - 3) Cross check observable independence

	order	$\operatorname{central}$	perturb.	incomp.
$m_{t.1{ m GeV}}^{ m MSR}$	$N^{2}LL$	172.82	0.19	0.11
$m_{t,1{ m GeV}}^{ m MSR}$	NLL	172.80	0.26	0.14
$m_t^{ m pole}$	N^2LL	172.43	0.18	0.22
$m_t^{ m pole}$	NLL	172.10	0.34	0.16
Ω_1	$N^{2}LL$	0.42	0.07	0.03
Ω_1	NLL	0.41	0.07	0.02



Butenschön etal 1608.01318

NLL groomed jet mass: → ATL-PHYS-PUB-2021-034



Shape Observables

Shape observables: e+e- for $Q = 2p_T \gg m_t$ (boosted tops)

$$\tau_{2} = \frac{1}{Q} \min_{\vec{n_{t}}} \sum_{i} (E_{i} - |\vec{n_{t}} \cdot \vec{p_{i}}|) \qquad (2\text{-jettiness})$$

$$\tau_{s} = \rho_{a} + \rho_{b}, \quad \rho_{a,b} = \frac{1}{Q^{2}} (\sum_{i \in a,b} p_{i}) \quad (\text{sum of jet masses, sJM})^{\frac{1}{\sigma} \frac{d\sigma}{d\tau_{2}}} \left(\int_{\substack{a \in a,b \\ a \neq b}} p_{i} - \frac{1}{Q^{2}} \int_{\substack{a \in a,b \\ a \neq b}} p_{$$

Excellent mass sensitivity:

 $\begin{aligned} \tau_{2,\min} &= 1 - \sqrt{1 - 4\hat{m}^2} \qquad \text{(tree level)} \\ \tau_{s,\min} &= 2\hat{m}^2 \\ \tau_{m,\min} &= 2\hat{m}^2 + 2\hat{m}^4 \end{aligned} \qquad \hat{m}^2 \equiv \frac{m_t^2}{Q^2} \end{aligned}$

All observables agree at leading power! Differ by \hat{m}^2 power corrections

$$rac{\mathrm{d}\sigma}{\mathrm{d} au} = \mathcal{Q}^2 \sigma_0 \mathcal{H}_0(\mathcal{Q},\mu) \int d\ell \; J_0(\mathcal{Q}\ell,\mu) \, \mathcal{S}_0\left(\mathcal{Q} au-\ell,\mu
ight)$$

Scale hierarchy and sequence of EFTs:

 $Q \gg m_t \gg \Gamma_t \gg \Lambda_{\rm QCD}$ QCD \rightarrow SCET \rightarrow bHQET





Shape Observables



• Substantial $\hat{m}^2 \sim \frac{1}{12}$ power corrections



N²LL + NLO matched distributions





N²LL + NLO matched distributions

MSR mass

$$m_t^{\text{pole}} - m_t^{\text{MSR}}(R) = R \frac{C_F \alpha_s^{(5)}(R)}{\pi} + \dots$$

Jain, Mateu, Preisser, AHH 2017

- Renormalon subtraction through change of mass scheme
- We use $m_t^{MSR}(1 \text{ GeV})$ as the reference input mass
- R set equal to the μ_B (jet function renormalization scale)
- 2-loop RGE (R-Evolver library)
 Lepenik, Mateu, AHH 2022
- Can be related to any other short-distance mass with O(10 MeV) precision

Shape function

$$F(k;\lambda,\{c_i\},N) \equiv \frac{1}{\lambda} \left[\sum_{n=0}^N c_n f_n\left(\frac{k}{\lambda}\right) \right]^2 \,,$$

$$f_n(z) = 8\sqrt{\frac{2z^3(2n+1)}{3}}e^{-2z}P_n(g(z)),$$

$$g(z) = \frac{2}{3}[3 - e^{-4z}(3 + 12z + 24z^2 + 32z^3)] - \frac{2}{3}[3 - e^{-4z}(3 + 12z + 24z^2 + 32z^3)]$$

Ligeti, Stewart, Tackmann 2008

- We need N=3 to have sufficient flexibility to fit the shape function
- The first moment Ω_1 is the most relevant nonperturbative parameter
 - → Peak position modified by nonperturbative corrections $\delta M_J = \frac{Q}{m_t} \Omega_1 \sim 2 \text{ GeV for } \Omega_1 \sim 0.5 \text{ GeV}$
- Need data from several different Q values to lift mt-Q degeneracy

$$\Omega_1(\lambda, \Delta, N) = \frac{1}{2} \int_0^\infty k F(k - 2\Delta; \lambda, \{c_i\}, N) \, dk$$

Gap parameter

$$\begin{split} \Omega_1(\lambda,\Delta,3) &= \Delta + \lambda (0.5c_0^2 + 0.47360764c_0c_1 + 0.10067713c_0c_2 + 0.094954074c_0c_3 \\ &\quad + 0.54502418c_1^2 + 0.50700667c_1c_2 + 0.12507929c_1c_3 \\ &\quad + 0.55015667c_2^2 + 0.50982331c_2c_3 + 0.55170015c_3^2) \,, \end{split}$$
 Fit parameters: c₀ , c₁ , c₂

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N²LL + NLO matched distributions

Gap subtraction

$$S(\ell, \mu_S) = \int dk \, \hat{S}_{\tau}^{(5)}(\ell - k, \bar{\delta} = 0, \mu_S) F(k - 2\Delta)$$

=
$$\int dk \, \hat{S}_{\tau}^{(5)}(\ell - 2\bar{\delta}(R_s, \mu_S) - k, 0, \mu_S) F(k - 2\bar{\Delta}(R_s, \mu_S))$$

$$\bar{\delta}(R_s,\mu_S;\mathbf{A},n,\xi) \equiv \begin{cases} \frac{R_s}{2\xi} \frac{\mathrm{d}^n}{\mathrm{d}\ln(iy)^n} \log\left[\tilde{S}_\tau(y,\mu_S)\right]_{iy=\frac{\xi}{R_s}} \\ \frac{R_s}{2\xi} \frac{\mathrm{d}^n}{\mathrm{d}\ln(iy)^n} \log\left[\tilde{S}_\tau(y,R_s)\right]_{iy=\frac{\xi}{R_s}} \end{cases}$$
$$= R_s \sum_{i=1} d_i(R_s,\mu_S) \left[\frac{\alpha_s^{(5)}(\mu_S)}{4\pi}\right]^i$$

 Renormalon subtraction through redefinition of the gap parameter

$$\Delta = \overline{\Delta}(R_s, \mu_S) + \overline{\delta}(R_s, \mu_S)$$

Stewart, AHH 2007

Bachu, Mateu, Pathak, Stewart, AHH 2021

- Classes of pap subtraction schemes can be defined from the configuration space soft function
- if A=on \leftarrow with soft function anomalous dimension
- if $A{=}off$ \checkmark w/o soft function anomalous dimension
- 3 gap schemes with completely different character
- We use 2-loop RGEs and as reference input $ar{\Omega}_1(2~{\rm GeV},2~{\rm GeV})$

Gap scheme of original 2016 calibration analysis and for strong coupling event shape fits

$$\bar{\delta}^{(1)}(R_s,\mu_S) \equiv \bar{\delta}(R_s,\mu_S;\text{on},1,e^{-\gamma_E})$$
$$\bar{\delta}^{(2)}(R_s,\mu_S) \equiv \bar{\delta}(R_s,\mu_S;\text{off},0,e^{5\gamma_E})$$
$$\bar{\delta}^{(3)}(R_s,\mu_S) \equiv \bar{\delta}(R_s,\mu_S;\text{off},0,1)$$

$$d_1^{(1)}(R_s, \mu_S) = -19.0 \ln\left(\frac{\mu_S}{R_s}\right)$$
$$d_1^{(2)}(R_s, \mu_S) = -3.9$$
$$d_1^{(3)}(R_s, \mu_S) = -8.4$$

universität wien

Fit Procedure Details

• Code
$$\frac{\mathrm{d}\sigma}{\mathrm{d}\tau} = f(m_t^{\mathrm{MSR}}, \alpha_s(M_Z), \Gamma_t, c_0, c_1, c_2, \mu_H, \mu_m, \mu_B, \mu_S, R, R_s, \mathrm{gap})$$

fit parameters

renormalization scales

- Grids in fit and renormalization scale profile function parameters (very fine bins)
- MC samples at Q= 600, 700, 800, ..., 1400 GeV
 - update: Pythia 8.205 \rightarrow Pythia 8.305 (Monash Tune 7), Herwig 7.2.2, Sherpa 2.2.11
 - masses: m_t^{MC} = 170, 171, 172, 173, 175, 175 GeV
 - width Γ_t = 1.4 GeV, Δ =0.05 GeV
 - Statistics: 10⁷ events for each parameter set
 - update: HepMC, Rivet, Yoda classes
- Fitting procedure
 - Take $\alpha_s(M_z)$ as input from world average. (Sensitivity to strong coupling very weak.)
 - χ^2 analysis standard [only relative values for χ^2_{min} matter]
 - 500 sets of profile functions (τ-dependent renormalization scales)
 - different Q sets: 6 sets of energies between 600 1400 GeV
 - different fit ranges: 3 choices of fit ranges in peak region

perturbative uncertainty 18 fit setups: compatibility uncertainty

We exactly reproduced the calibration results from 2016 for Pythia



Revisiting the 2016 Analysis

2016, Pythia 8.205, $m_{MC} = 173 \,\text{GeV}$

update, Pythia 8.305

	order	central	perturb.	incomp.	central	perturb.	incomp.
$m_{t.1{ m GeV}}^{ m MSR}$	$N^{2}LL$	172.82	0.19	0.11	172.82	0.17	0.10
$m_{t,1{ m GeV}}^{ m MSR}$	NLL	172.80	0.26	0.14	172.83	0.29	0.12
$m_t^{ m pole}$	N^2LL	172.43	0.18	0.22	172.40	0.18	0.20
$m_t^{ m pole}$	NLL	172.10	0.34	0.16	172.06	0.34	0.16
Ω_1	$N^{2}LL$	0.42	0.07	0.03	0.43	0.06	0.03
Ω_1	NLL	0.41	0.07	0.02	0.42	0.07	0.03

(in GeV)

Agreement within 30 MeV





Gap Scheme Independence



Gap term Δ in shape function needs to be fitted as well



Gap scheme independence if there is sufficient flexibility in shape function parametrization (gap scheme 2 for final results)



Observable Independence



 \rightarrow Observable independence not achieved with strict power counting approach and the exact expression for τ_{min} in the bHQET factorization formula

Soft $(m_t/Q)^2$ power corrections in the measurement function can lead to ~ 250 MeV effects in the top mass:

$$\delta[\hat{s}_{\tau} - \hat{s} - r_{\tau,s}(\hat{m})\varrho\ell] \qquad r_{\tau,s}(\hat{m}) = 1 + \mathcal{O}(\hat{m}^2)$$

$$\rightarrow \delta M_J \sim 2 \frac{m_t}{Q} \Omega_1 \sim 250 \text{ MeV}$$



Observable Independence

Consider soft momenta in the two hemispheres addition to tree-level top quark momenta



(soft momentum k_s contains soft top recoil)

2-jettiness:
$$au_2 = au_{\min} + \frac{k_s^+ + k_{\bar{s}}^-}{Q} \longrightarrow r_{\tau_2,s}(\hat{m}) = 1$$

sum of jet mass: $\tau_s = \frac{1}{Q^2} (p_n^+ p_n^- + p_{\bar{n}}^- p_{\bar{n}}^+)$

Energy conservation for the two hemispheres: $\Delta E \sim k_s$ cancels between hemispheres

$$\tau_s = \tau_{2,\min} + \frac{\sqrt{1 - 4\hat{m}^2}}{Q} \left(k_s^+ + k_{\bar{s}}^-\right) + \mathcal{O}(k_{s,\bar{s}})^2$$

$$\rightarrow r_{\tau_s,s}(\hat{m}) = \sqrt{1 - 4\hat{m}^2} = 1 - 2\hat{m}^2 + \mathcal{O}(\hat{m}^4)$$

<u>Modified jet mass:</u> $au_m = au_s + \frac{1}{2}\tau_s^2$

$$p_n^- + p_n^+ = Q + \Delta E$$
$$p_{\bar{n}}^- + p_{\bar{n}}^+ = Q - \Delta E$$

Cross check: soft power correction absent in modified jet mass!

$$r_{\tau_m,s}(\hat{m}) = 1 + \mathcal{O}(\hat{m}^4)$$



 \rightarrow Improved version of the bHQET factorization formula

$$\begin{aligned} \frac{1}{\sigma_0^C} \frac{\mathrm{d}\sigma_{\mathrm{BHQET}}^C}{\mathrm{d}\tau} \bigg|_{\mathrm{pow}\,1} &= R_0^C(\hat{m}) \, m_t Q^2 H_Q^{(6)}(Q,\mu_H) U_{H_Q}^{(6)}(Q,\mu_H,\mu_m) H_m^{(6)}(m,\varrho,\mu_m) U_v^{(5)}(\varrho,\mu_m,\mu) \\ & \times \int \mathrm{d}\ell \, \mathrm{d}\hat{s} \, \delta[\hat{s}_\tau - \hat{s} - r_{\tau,s}(\hat{m})\varrho\ell] \\ & \times \int \mathrm{d}\hat{s}' \, U_B^{(5)}(\hat{s} - \hat{s}',\mu,\mu_B) J_{B,\tau}^{(5)}(\hat{s}',\Gamma_t = 0,\delta m = 0,\mu_B) \\ & \times \int \mathrm{d}\ell' \, U_S^{(5)}(\ell - \ell',\mu,\mu_S) \hat{S}_\tau^{(5)}(\ell',\bar{\delta} = 0,\mu_S) \,, \end{aligned}$$

- soft power correction in measurement delta function
- global tree-level phase space factor
- absorb and <u>vary</u> the remaining distributional terms of the full QCD result



Observable Independence

-2	-1	0	1	2	0.0	0.5	1.0	1.5	2.0
hrust	World Avg. Err		value ± theo. ± incom	b. (χ^2/dof)				value ± theo. ± ind	comp. (χ^2 /dof)
		 1	-0.17 ± 0.14 ± 0.14	(20.8±7.4)				0.45 ± 0.10 ± 0).04 (21.0±7.5)
😑 sJM	L		-0.65 ± 0.13 ± 0.18	(22.5±7.8)		⊢_ ● ↓ →	1	0.63 ± 0.11 ± 0).04 (22.7±7.9)
n IM	MSR(1GeV) N2LL	⊢− −−	-0.26 ± 0.15 ± 0.15	(18.4±6.6)		⊢ ,	i I	0.49 ± 0.10 ± 0).03 (18.5±6.8)
			$-0.40 \pm 0.28 \pm 0.14$	(23.5±13.1)	1			0.61 ± 0.19 ± 0).04 (23.4±13.3)
		4	-0.91 ± 0.36 ± 0.18	(27.1±15.4)			⊢	0.75 ± 0.20 ± 0).03 (27.1±15.7)
	MSR(1GeV) NLL		-0.51 ± 0.30 ± 0.16	(21.7±12.4)				0.65 ± 0.19 ± 0).03 (21.6±12.6)
			-0.52 ± 0.19 ± 0.17	(9.8±4.6)		HeH	1	0.31 ± 0.04 ± 0	0.03 (9.8±4.6)
			-0.87 ± 0.20 ± 0.15	(8.3±3.1)		⊢ ●-	1	0.45 ± 0.04 ± 0	0.03 (8.2±3.1)
	pole N2LL		-0.57 ± 0.19 ± 0.17	(8.4±3.9)		H H	1	0.33 ± 0.04 ± 0).03 (8.4±3.9)
	 		-0.76 ± 0.40 ± 0.14	(27.2±13.6)		•	1	0.27 ± 0.07 ± 0).04 (27.0±13.8)
strict pc			-1.11 ± 0.45 ± 0.15	(31.1±16.1)	1		1	0.37 ± 0.08 ± 0	0.04 (31.0±16.4)
	pole NLL		-0.83 ± 0.41 ± 0.14	(25.0±12.9)	⊢	→ →	1	0.30 ± 0.08 ± 0	0.04 (24.9±13.1)
		⊢	+0.00 ± 0.11 ± 0.14	(15.5±6.5)				0.40 ± 0.10 ± 0	0.03 (15.5±6.3)
			-0.44 ± 0.09 ± 0.15	(14.6±5.6)				0.51 ± 0.12 ± 0	0.03 (14.8±5.8)
Pythia	8.305	H	-0.08 ± 0.11 ± 0.15	(13.2±5.5)		⊢ ● ¦ 	-	0.43 ± 0.10 ± 0).03 (13.2±5.4)
gap 2		H	-0.06 ± 0.16 ± 0.14	(15.6±10.0)	1		-	0.66 ± 0.16 ± 0	0.02 (15.9±10.1)
3			-0.56 ± 0.15 ± 0.20	(16.0±10.8)			•i	0.79 ± 0.18 ± 0	0.02 (16.4±11.1)
			-0.16 ± 0.15 ± 0.15	(13.9±9.1)		· · · · •		0.69 ± 0.17 ± 0	0.02 (14.2±9.2)
			-0.36 ± 0.18 ± 0.19	(22.7±8.8)		●	1	0.27 ± 0.03 ± 0	0.05 (22.8±8.7)
	⊢ ●		-0.64 ± 0.22 ± 0.17	(23.8±9.3)		HOH I	1	0.37 ± 0.03 ± 0	0.03 (23.9±9.1)
		• · · · · · · · · · · · · · · · · · · ·	-0.42 ± 0.19 ± 0.19	(19.6±7.8)		⊷ .	1	0.30 ± 0.03 ± 0	0.04 (19.8±7.7)
			-0.51 ± 0.22 ± 0.14	(17.5±10.7)	⊢		I I	0.29 ± 0.07 ± 0	0.03 (17.6±11.0)
absorb (rs	=1)		-0.81 ± 0.24 ± 0.14	(17.8±11.8)		→ → → {	1	0.38 ± 0.07 ± 0	0.03 (18.0±12.1)
L			-0.57 ± 0.23 ± 0.14	(15.5±9.8)	F F		1	0.31 ± 0.07 ± 0	0.03 (15.6±10.0)
		⊢	-0.04 ± 0.15 ± 0.15	(17.2±7.0)	H +		i i	0.35 ± 0.15 ± 0	0.04 (17.1±6.9)
		⊢	-0.14 ± 0.17 ± 0.13	(16.8±6.9)			1	0.38 ± 0.14 ± 0).03 (16.9±6.8)
			-0.07 ± 0.18 ± 0.14	(15.1±6.5)	⊢ ⊢		1	0.35 ± 0.16 ± 0	0.03 (15.0±6.4)
		⊢ −−−1	-0.05 ± 0.17 ± 0.14	(15.1±9.5)			1	0.58 ± 0.16 ± 0	0.03 (15.4±9.7)
		⊢	-0.15 ± 0.14 ± 0.12	(14.8±10.6)			- i	0.62 ± 0.18 ± 0	0.03 (15.1±10.7)
			$-0.08 \pm 0.16 \pm 0.12$	(13.2±8.7)			1	0.59 ± 0.16 ± 0).03 (13.4±8.9)
	H		$-0.36 \pm 0.22 \pm 0.20$	(19.7±12.9)	⊢ ●		1	0.21 ± 0.11 ± 0).06 (19.8±12.9)
		• · · · · · · · · · · · · · · · · · · ·	-0.41 ± 0.26 ± 0.17	(19.5±14.7)	⊢●		1	0.24 ± 0.09 ± 0).04 (20.1±14.8)
			-0.31 ± 0.23 ± 0.20	(16.7±11.2)			1	0.20 ± 0.13 ± 0	0.06 (16.7±11.1)
	—		-0.51 ± 0.22 ± 0.14	(16.9±10.4)	⊢●		1	0.21 ± 0.07 ± 0	0.03 (17.1±10.6)
absorb	⊢ −−•		-0.52 ± 0.25 ± 0.12	(16.5±10.7)			1	0.23 ± 0.09 ± 0	0.03 (16.5±10.8)
			-0.51 ± 0.22 ± 0.12	(14.9±9.4)				0.21 ± 0.07 ± 0	0.04 (15.0±9.6)
-2		0	1	2		0.5	10	15	20
L	'		1	2	0.0	0.5	1.0	1.5	2.0
		m _{fit} – m _{MC} [GeV]					Ω_1 [Ge	V]	

 \rightarrow Observable independent results obtained for top mass and Ω_1



Final Results (Pythia)

-2	-1	0	1	2	0.0	0.5	1.0	1.5	2.0
• thrust	World Avg. Err.		value ± theo. ± incomp	(χ^2/dof)				value ± theo. ± incomp	. (χ²/dof)
		⊢	-0.02 ± 0.18 ± 0.16	(16.4±7.0)		⊢		0.32 ± 0.16 ± 0.04	(16.4±7.0)
sJM 🗧	<u> </u>		-0.13 ± 0.17 ± 0.14	(15.3±7.0)		⊢ ↓ ●		$-0.70 \pm 0.18 \pm 0.37$	(15.4±6.9)
mJM	MSR(1GeV) N2LL		-0.06 ± 0.20 ± 0.16	(14.2±6.4)		⊢	1	0.33 ± 0.16 ± 0.04	(14.2±6.3)
]	⊢	-0.04 ± 0.19 ± 0.14	(13.9±8.7)	1	·●	1	$0.56 \pm 0.16 \pm 0.04$	(14.1±8.9)
		⊢	-0.16 ± 0.14 ± 0.13	(12.9±9.7)		⊢↓ ●		$0.61 \pm 0.18 \pm 0.02$	(13.2±10.2)
	MSR(1GeV) NLL	⊢	-0.06 ± 0.18 ± 0.13	(12.0±7.9)		· - 	1	0.57 ± 0.16 ± 0.03	(12.2±8.1)
			-0.30 ± 0.20 ± 0.22	(20.9±11.5)		●	1	$0.19 \pm 0.12 \pm 0.06$	(21.2±11.5)
			$-0.40 \pm 0.26 \pm 0.17$	(20.7±13.9)		_	1	0.23 ± 0.08 ± 0.05	(20.9±13.8)
	pole N2LL		-0.27 ± 0.21 ± 0.21	(17.7±10.0)		• i	1	$0.18 \pm 0.14 \pm 0.07$	(17.9±10.0)
		● (-0.45 ± 0.20 ± 0.12	(12.8±7.6)		●	1	$0.16 \pm 0.06 \pm 0.04$	(12.9±7.9)
gap 1			-0.51 ± 0.24 ± 0.11	(12.0±8.2)	1	⊢ ●	1	0.23 ± 0.07 ± 0.03	(12.1±8.5)
	pole NLL		-0.46 ± 0.21 ± 0.11	(11.0±6.8)		●	1	$0.17 \pm 0.06 \pm 0.04$	(11.1±7.1)
		⊢	-0.04 ± 0.15 ± 0.15	(17.2±7.0)				0.35 ± 0.15 ± 0.04	(17.1±6.9)
			-0.14 ± 0.17 ± 0.13	(16.8±6.9)		⊢	1	0.38 ± 0.14 ± 0.03	(16.9±6.8)
Pythia	8.305		-0.07 ± 0.18 ± 0.14	(15.1±6.5)		⊢	I I	0.35 ± 0.16 ± 0.03	(15.0±6.4)
absorb		⊢	-0.05 ± 0.17 ± 0.14	(15.1±9.5)	1		1	0.58 ± 0.16 ± 0.03	(15.4±9.7)
		⊢ − − − − − − − − − −	-0.15 ± 0.14 ± 0.12	(14.8±10.6)				0.62 ± 0.18 ± 0.03	(15.1±10.7)
		⊢	-0.08 ± 0.16 ± 0.12	(13.2±8.7)			l i	0.59 ± 0.16 ± 0.03	(13.4±8.9)
			-0.36 ± 0.22 ± 0.20	(19.7±12.9)			1	$0.21 \pm 0.11 \pm 0.06$	(19.8±12.9)
	H	(-0.41 ± 0.26 ± 0.17	(19.5±14.7)	1		1	0.24 ± 0.09 ± 0.04	(20.1±14.8)
			-0.31 ± 0.23 ± 0.20	(16.7±11.2)		••••		$0.20 \pm 0.13 \pm 0.06$	(16.7±11.1)
	⊢ (-0.51 ± 0.22 ± 0.14	(16.9±10.4)	-		1	0.21 ± 0.07 ± 0.03	(17.1±10.6)
gap 2	⊢ ●		-0.52 ± 0.25 ± 0.12	(16.5±10.7)		→ →	1	0.23 ± 0.09 ± 0.03	(16.5±10.8)
	⊢−−− ●		-0.51 ± 0.22 ± 0.12	(14.9±9.4)			1	0.21 ± 0.07 ± 0.04	(15.0±9.6)
			-0.12 ± 0.17 ± 0.18	(22.0±11.7)				0.33 ± 0.15 ± 0.07	(22.2±11.7)
		⊢	$-0.22 \pm 0.20 \pm 0.15$	(21.8±12.2)		⊢		0.37 ± 0.13 ± 0.06	(22.0±12.2)
			-0.11 ± 0.18 ± 0.17	(19.5±10.5)	1	⊢ −− +		0.34 ± 0.16 ± 0.07	(19.5±10.4)
			-0.08 ± 0.17 ± 0.14	(15.7±9.4)				$0.23 \pm 0.18 \pm 0.04$	(15.9±9.4)
			-0.14 ± 0.18 ± 0.12	(15.4±9.7)				$0.26 \pm 0.21 \pm 0.02$	(15.5±9.7)
			$-0.08 \pm 0.18 \pm 0.13$	(13.7±8.5)	_			0.24 ± 0.19 ± 0.03	(13.9±8.5)
	⊢ ●		-0.52 ± 0.26 ± 0.10	(5.5±3.7)	-		1	$0.00 \pm 0.20 \pm 0.11$	(5.6±3.8)
	H		-0.25 ± 0.28 ± 0.04	(4.2±3.3)				-0.06 ± 0.28 ± 0.05	(4.3±3.4)
	—		$-0.45 \pm 0.25 \pm 0.08$	(4.3±3.0)				-0.03 ± 0.23 ± 0.09	(4.4±3.0)
			-0.64 ± 0.33 ± 0.20	(26.0±24.7)				-0.08 ± 0.19 ± 0.02	(26.6±26.1)
gap 3	⊢ ●		-0.52 ± 0.31 ± 0.12	(23.4±19.7)				-0.12 ± 0.21 ± 0.05	(23.3±19.5)
	⊢		-0.57 ± 0.31 ± 0.22	(23.1±21.5)				$-0.13 \pm 0.20 \pm 0.06$	(23.2±22.2)
2	1		1	2	0.0	05	10	15	20
-2	-1	U	I	2	0.0	0.5	1.0	1.5	2.0
		$m_{\rm fit}$ – $m_{\rm MC}$ [GeV]					Ω ₁ [Ge [\]	/]	



Final Results (Herwig)

-2	-1	0	1	2	0.0	0.5	1.0	1.5	2.0
• thrust	World Avg. Err.		value ± theo. ± incomp	. (χ²/dof)				value ± theo. ± incomp	b. (χ^2 /dof)
			-0.16 ± 0.16 ± 0.25	(17.7±17.6)		· - - ●		0.63 ± 0.22 ± 0.08	(17.8±18.1)
sJM 🥚 sJM	⊢		-0.25 ± 0.22 ± 0.21	(11.7±10.4)				0.63 ± 0.19 ± 0.09	(11.8±10.5)
mJM	MSR(1GeV) N2LL		-0.17 ± 0.18 ± 0.22	(16.9±16.0)		·		0.62 ± 0.24 ± 0.09	(17.0±16.2)
			-0.23 ± 0.17 ± 0.24	(16.5±16.7)	-			0.82 ± 0.20 ± 0.07	(16.7±16.7)
	⊢	(-0.32 ± 0.12 ± 0.19	(10.4±10.4)				0.84 ± 0.20 ± 0.06	(10.6±10.6)
	MSR(1GeV) NLL		-0.20 ± 0.16 ± 0.22	(15.6±15.1)			- -	0.82 ± 0.20 ± 0.07	(15.7±15.2)
		• 1	-0.38 ± 0.18 ± 0.22	(7.8±4.9)	1		1	0.42 ± 0.17 ± 0.09	(7.7±4.8)
			-0.45 ± 0.23 ± 0.18	(6.4±4.1)			1	0.43 ± 0.13 ± 0.07	(6.4±4.0)
	pole N2LL		-0.33 ± 0.22 ± 0.21	(7.6±4.2)			1	$0.41 \pm 0.17 \pm 0.08$	(7.6±4.2)
	·	_	-0.54 ± 0.11 ± 0.19	(10.5±8.6)			1	$0.42 \pm 0.21 \pm 0.11$	(10.4±8.4)
gap 1	— ——		-0.59 ± 0.13 ± 0.17	(7.9±6.4)		⊢	i.	$0.44 \pm 0.18 \pm 0.10$	(7.8±6.2)
	pole NLL		-0.51 ± 0.11 ± 0.21	(10.4±8.1)			1	$0.41 \pm 0.20 \pm 0.12$	(10.3±7.9)
		⊢ → →	-0.12 ± 0.15 ± 0.20	(11.2±9.2)			4	0.58 ± 0.16 ± 0.11	(11.2±9.2)
		⊢	-0.19 ± 0.19 ± 0.17	(8.3±5.7)				0.59 ± 0.12 ± 0.10	(8.2±5.6)
Herwig	g 7.2.3	⊢	-0.13 ± 0.18 ± 0.20	(11.1±8.5)	1	⊢ <u>†</u> ● – –		0.57 ± 0.18 ± 0.12	(11.1±8.5)
absort	b	⊢	-0.16 ± 0.14 ± 0.21	(10.3±8.6)	1			$0.76 \pm 0.13 \pm 0.11$	(10.4±8.8)
		⊢	-0.26 ± 0.10 ± 0.15	(7.2±5.9)			•	0.79 ± 0.15 ± 0.08	(7.2±6.0)
			-0.13 ± 0.12 ± 0.22	(10.0±8.1)				0.77 ± 0.14 ± 0.10	(10.1±8.2)
	⊢ ●		-0.61 ± 0.38 ± 0.26	(6.1±4.0)	1	⊢ − − − − − − − − − −	1	0.44 ± 0.18 ± 0.07	(6.1±4.0)
	⊢ ●		-0.49 ± 0.25 ± 0.17	(5.3±3.3)			1	$0.43 \pm 0.14 \pm 0.08$	(5.3±3.3)
	⊢ ●		-0.51 ± 0.36 ± 0.20	(6.2±3.7)				0.42 ± 0.18 ± 0.07	(6.2±3.7)
	⊢	f	-0.75 ± 0.24 ± 0.18	(4.0±2.7)			i i	0.36 ± 0.19 ± 0.09	(4.0±2.7)
gap 2	⊢ ●		-0.57 ± 0.18 ± 0.16	(4.1±2.9)			I.	$0.31 \pm 0.20 \pm 0.08$	(4.2±2.9)
	⊢		-0.64 ± 0.21 ± 0.17	(4.2±2.8)			1	0.35 ± 0.19 ± 0.09	(4.2±2.7)
			-0.18 ± 0.18 ± 0.20	(9.3±6.5)		· · · · · · · · · · · · · · · · · · ·		$0.51 \pm 0.16 \pm 0.11$	(9.4±6.7)
	H		-0.23 ± 0.21 ± 0.16	(6.8±4.4)		⊢	i.	0.54 ± 0.13 ± 0.09	(6.8±4.4)
			-0.15 ± 0.20 ± 0.21	(9.2±5.9)	1	· · · · · · · · · · · · · · · · · · ·		0.51 ± 0.17 ± 0.11	(9.2±6.0)
		⊢ − − − − 1	-0.03 ± 0.28 ± 0.18	(7.1±4.5)				0.33 ± 0.14 ± 0.13	(7.1±4.6)
		F (-0.05 ± 0.24 ± 0.14	(5.5±3.3)				$0.36 \pm 0.16 \pm 0.10$	(5.5±3.3)
		• • • • • • • • • • • • • • • • • • •	+0.02 ± 0.27 ± 0.21	(7.2±4.2)	⊢		1	$0.32 \pm 0.14 \pm 0.14$	(7.2±4.3)
H	•		-1.08 ± 0.68 ± 0.38	(9.4±9.9)			1	0.37 ± 0.25 ± 0.12	(9.4±9.8)
	⊢−−−−		-0.46 ± 0.31 ± 0.21	(10.0±10.5)		• • • • • • • • • • • • • • • • • • • •		0.23 ± 0.30 ± 0.07	(9.7±10.1)
	••		-0.81 ± 0.53 ± 0.25	(9.6±9.8)	⊢			0.39 ± 0.19 ± 0.07	(9.7±9.8)
			-0.71 ± 0.69 ± 0.18	(7.7±12.5)			1	$0.11 \pm 0.28 \pm 0.05$	(7.8±12.9)
gap 3	— ——	1	-0.82 ± 0.51 ± 0.15	(8.0±9.8)	• • • • • • • • • • • • • • • • • • •			$0.02 \pm 0.36 \pm 0.04$	(8.1±9.8)
	• • • • • • • • • • • • • • • • • • •		$-0.69 \pm 0.57 \pm 0.28$	(7.1±10.6)				0.03 ± 0.27 ± 0.04	(7.2±10.5)
2		0	1		0.0	0.5	1.0	15	20
-2	-1	U	I	2	0.0	0.5	1.0	1.5	2.0
		m _{fit} – m _{MC} [GeV]					Ω ₁ [GeV]		



Final Results (Sherpa)

-2	-1	0	1	2	0.0	0.5	1.0	1.5	2.0
http://	World Avg. Err		value ± theo. ± incomp. (χ	(² /dof)			v	alue ± theo. ± incomp	. (χ²/dof)
	- World / Ug. Em.		$-0.18 \pm 0.13 \pm 0.16$ (8)	3.4±8.7)			+	$0.62 \pm 0.18 \pm 0.06$	(8.3±8.3)
SJM			$-0.27 \pm 0.19 \pm 0.14$ (4	1.9±4.0)		⊢ –	-	0.64 ± 0.17 ± 0.04	(4.9±4.1)
mJM	MSR(1GeV) N2LL	⊢	$-0.22 \pm 0.17 \pm 0.13$ (7	7.6±7.5)				0.62 ± 0.20 ± 0.05	(7.5±7.1)
			$-0.22 \pm 0.15 \pm 0.16$ (7	7.8±7.7)	1		•	0.81 ± 0.17 ± 0.05	(7.9±7.9)
	+	($-0.33 \pm 0.08 \pm 0.12$ (4	1.3±4.1)				$0.84 \pm 0.18 \pm 0.04$	(4.4±4.4)
	MSR(1GeV) NLL	⊢	$-0.23 \pm 0.12 \pm 0.14$ (7	7.0±6.6)		⊢	•	0.82 ± 0.17 ± 0.05	(7.1±6.9)
	, 	• ($-0.40 \pm 0.18 \pm 0.17$ (5)	5.3±2.6)	-		1	0.45 ± 0.17 ± 0.03	(5.3±2.6)
			$-0.49 \pm 0.22 \pm 0.12$ (4)	l.3±1.8)	I I		I I	$0.46 \pm 0.12 \pm 0.04$	(4.3±1.8)
	pole N2LL	• • • • • • • • • • • • • • • • • • • •	$-0.38 \pm 0.24 \pm 0.16$ (5	5.0±2.2)		⊢		0.45 ± 0.17 ± 0.04	(5.0±2.3)
	, 	-	$-0.59 \pm 0.09 \pm 0.13$ (5)	5.0±4.2)	+		1	$0.42 \pm 0.20 \pm 0.07$	(4.9±4.0)
gap 1			$-0.62 \pm 0.11 \pm 0.11$ (3)	3.3±2.7)	I.		l.	$0.44 \pm 0.20 \pm 0.06$	(3.2±2.5)
	pole NLL	-	$-0.58 \pm 0.09 \pm 0.12$ (4	l.6±3.8)		_	I.	$0.42 \pm 0.20 \pm 0.07$	(4.5±3.6)
		I	-0.18 ± 0.15 ± 0.15 (5	5.9±4.1)				$0.61 \pm 0.15 \pm 0.04$	(5.9±4.1)
		⊢	$-0.23 \pm 0.18 \pm 0.12$ (4	l.1±2.2)		i →		$0.61 \pm 0.12 \pm 0.04$	(4.1±2.1)
Sherpa	2.2.11	⊢	$-0.22 \pm 0.18 \pm 0.12$ (5)	5.4±3.6)	i.	· · · · · · · · · · · · · · · · · · ·	l I	$0.61 \pm 0.17 \pm 0.04$	(5.4±3.6)
absorb		⊢ ● − − −	$-0.21 \pm 0.13 \pm 0.14$ (5)	5.3±3.8)				$0.78 \pm 0.12 \pm 0.06$	(5.3±3.9)
			$-0.27 \pm 0.08 \pm 0.10$ (3)	3.5±2.3)				$0.80 \pm 0.12 \pm 0.04$	(3.6±2.4)
		⊢ _	$-0.21 \pm 0.11 \pm 0.12$ (4	l.9±3.4)		· · · · · •		0.78 ± 0.12 ± 0.06	(4.9±3.4)
	⊢		$-0.63 \pm 0.37 \pm 0.13$ (4	.4±2.3)	I.		I.	$0.46 \pm 0.16 \pm 0.03$	(4.4±2.4)
	⊢		$-0.53 \pm 0.24 \pm 0.10$ (3)	3.9±1.8)		⊢	1	$0.47 \pm 0.12 \pm 0.04$	(3.9±1.8)
	⊢ ●		$-0.53 \pm 0.36 \pm 0.10$ (4	l.1±2.1)				$0.46 \pm 0.16 \pm 0.03$	(4.1±2.3)
	⊢		$-0.70 \pm 0.17 \pm 0.12$ (3)	3.6±1.8)	i i		1	$0.44 \pm 0.13 \pm 0.03$	(3.5±1.8)
gap 2	⊢	н —	$-0.62 \pm 0.17 \pm 0.08$ (3)	3.5±1.9)	I.		I.	0.41 ± 0.15 ± 0.05	(3.5±1.9)
	⊢		$-0.65 \pm 0.14 \pm 0.09$ (3)	3.4±1.7)				$0.42 \pm 0.13 \pm 0.04$	(3.4±1.7)
	I		$-0.25 \pm 0.16 \pm 0.14$ (5)	5.5±3.0)	-			0.56 ± 0.15 ± 0.05	(5.5±3.1)
	⊢	—	$-0.30 \pm 0.19 \pm 0.11$ (4	l.0±1.7)	l.	⊢		0.57 ± 0.12 ± 0.03	(4.0±1.7)
	F	—	$-0.26 \pm 0.20 \pm 0.11$ (5)	5.0±2.6)		⊢		$0.56 \pm 0.16 \pm 0.05$	(5.0±2.7)
		⊢ − − − − − − − − − −	$-0.13 \pm 0.23 \pm 0.10$ (4	l.4±2.1)		⊢		$0.39 \pm 0.13 \pm 0.05$	(4.4±2.1)
		⊢	$-0.10 \pm 0.22 \pm 0.11$ (3)	3.4±1.4)	E F			0.36 ± 0.15 ± 0.05	(3.5±1.4)
			$-0.11 \pm 0.22 \pm 0.09$ (4)	l.1±1.9)	I.		1	$0.39 \pm 0.13 \pm 0.05$	(4.1±1.9)
	⊢	-	$-0.88 \pm 0.42 \pm 0.17$ (6)	6.6±7.3)	⊢ ⊢			$0.39 \pm 0.19 \pm 0.10$	(6.7±7.2)
	H		$-0.44 \pm 0.32 \pm 0.09$ (6)	6.7±7.6)				$0.23 \pm 0.34 \pm 0.07$	(6.4±7.2)
	⊢		$-0.73 \pm 0.36 \pm 0.10$ (6)	6.3±6.8)	⊢			$0.36 \pm 0.16 \pm 0.09$	(6.3±6.7)
	⊢		$-0.72 \pm 0.50 \pm 0.18$ (8)	3.4±10.6)				$0.09 \pm 0.22 \pm 0.07$	(9.0±12.5)
gap 3	H		$-0.78 \pm 0.38 \pm 0.12$ (8)	3.4±9.5)	 			$0.00 \pm 0.24 \pm 0.08$	(8.4±9.5)
			$-0.66 \pm 0.44 \pm 0.12$ (7	7.4±9.1)		<u> </u>		0.05 ± 0.24 ± 0.09	(7.9±10.8)
2		0				05	10	15	20
-2	-1	U	I I	2	0.0	0.5	1.0	L.J	2.0
		m _{fit} – m _{MC} [GeV]					Ω1 [GeV]		



Final Results (all)



- Final results: 2-jettiness, gap 2
- mt^{MC} for all MCs consistent
- calibration to pole mass has larger uncertainties
- soft nonperturbative effects: $\Omega_1^{\text{Pythia}} < \Omega_1^{\text{Herwig}}, \Omega_1^{\text{Sherpa}}$

Outlook on upcoming results

Dynamical hadronization model in Herwig

- Shower cutoff Q_0 as an IR factorization scale (invariance under Q_0 variations)
- Control over mt^{MC} through tuning
- Calibration as diagnostic tool for consistency

- Analytic shower cut dependence of top decay differential distributions for boosted top production
 - Generalization of calibration for inclusive shape observables to top decay differential observables
- LHC: MPI and UE still need to be better understood from the QCD perspective



Backup Slides



Final Results (all)





2-Jettiness for Top Production (QCD)





Masses Loop-Theorists Like to use



