Top Quark Mass Calibration for MC Event Generators

- An Update -

In collaboration with Bahman Dehnadi, Oliver Jin, Vicent Mateu and Simon Plätzer
work in progress

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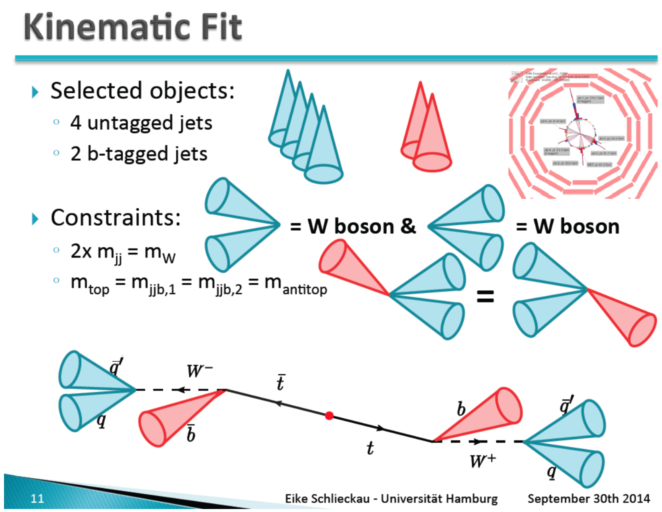
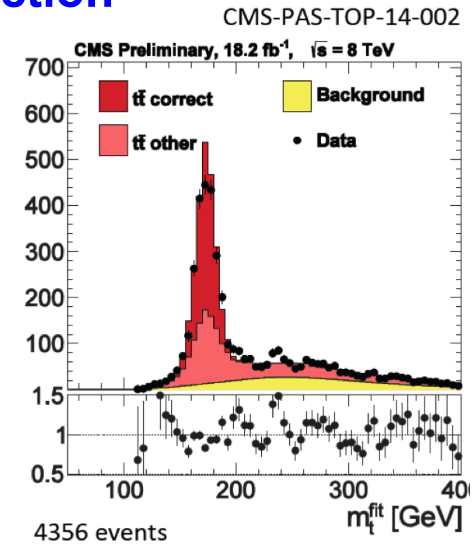
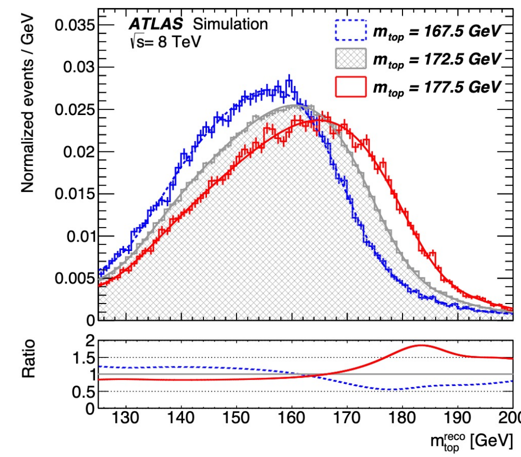
16th Internat. Symposium on Radiative Corrections, Crieff, Scotland, May 29 - June 2, 2023

Main Top Mass Measurements Methods

LHC+Tevatron: Direct Reconstruction





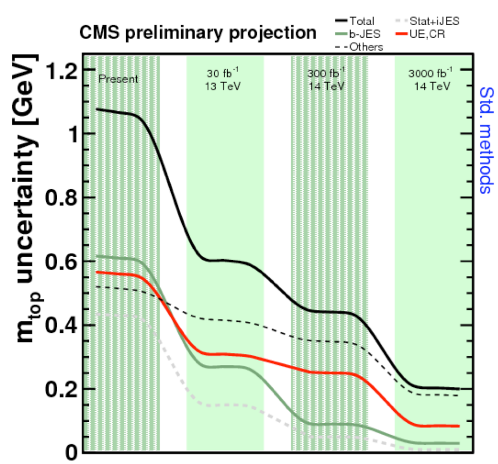


$$m_t^{MC} = 171.77 \pm 0.37 \text{ GeV}$$

CMS collaboration. arXiv: 2302.01967

kinematic mass determination

Determination of the best-fit value of the Monte-Carlo top quark mass parameter



⊕ High top mass sensitivity

⊖ Precision of MC ?

⊖ Meaning of m_t^{MC} ?

← Δm_t ~ 200 MeV (projection)

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 m_t^{MC} in principle determined by the precision of parton shower (PS)
  - For perfect NLL PS, we could control m_t^{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 many other sources of linear IR cutoff dependence
  - Q_0 dependence of m_t^{MC} is not related to any nonperturbative effect
- Hadronization model influences m_t^{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, no clear path how to address this without models
  - Consistency with systematic QCD methods (e.g. OPE) largely untested
- Coherent branching + massive eventshapes (e^+e^-): $$m_t^{\rm CB}(Q_0) = m_t^{\rm pole} - \frac{2}{3}\alpha_s(Q_0)\,Q_0 + \ldots$$
  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
  - $m_t^{\rm CB}(Q_0) = m_t^{\rm MSR}(Q_0) - 0.24\,\alpha_s(Q_0)\,Q_0$

Status of m_t^{MC} Interpretation

Numerical insights:

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

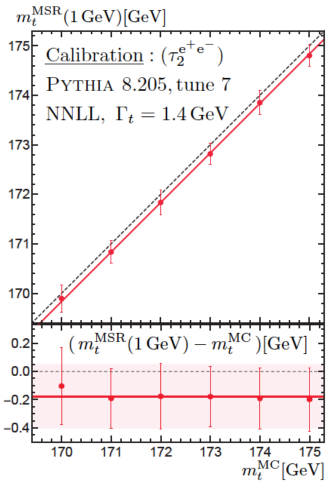
  Kieseler etal 1511.00841

- Top mass calibration: N^2LL+NLO e^+e^- 2-jettiness fitted to Pythia 8.205 pseudo data

  Butenschön etal 1608.01318

  1) Strongly mass-sensitive hadron level (as closely as possible related to direct measurement observables)
  1) Accurate hadron level 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	central	perturb.	incomp.
$m_{t,1\,\mathrm{GeV}}^{\rm MSR}$	$\mathrm{N^2LL}$	172.82	0.19	0.11
$m_{t,1\,\mathrm{GeV}}^{\rm MSR}$	NLL	172.80	0.26	0.14
$m_t^{\rm pole}$	$\mathrm{N^2LL}$	172.43	0.18	0.22
$m_t^{\rm pole}$	NLL	172.10	0.34	0.16
Ω_1	$\mathrm{N^2LL}$	0.42	0.07	0.03
Ω_1	NLL	0.41	0.07	0.02



NLL groomed jet mass:

→ ATL-PHYS-PUB-2021-034

Outline

- Introduction: direct top mass determinations and status of the interpretation of m_t^{MC}

- Top mass calibration

- Calibration of the Pythia Monte Carlo top mass parameter:
  $e^+e^- \rightarrow t\,t$ (2-jettiness)

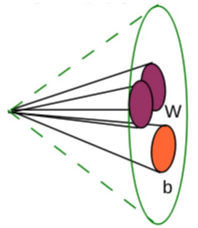
  Butenschön, Dehnadi, Mateu, Preisser, Stewart,AH 1608.01318

- Updates:
  - more observables,
  - more soft function renormalon subtractions
  - $(m_t/Q)^2$ power corrections

- Summary, future plans

All results shown are preliminary !

Shape Observables

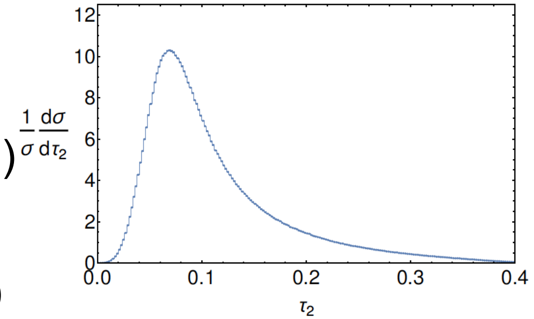


Shape observables: e+e- for $Q = 2p_T \gg m_t$ (boosted tops)

$$\tau_2 = \frac{1}{Q} \min_{\vec{n_t}} \sum_i (E_i - |\vec{n_t} \cdot \vec{p_i}|) \qquad \text{(2-jettiness)}$$

$$\tau_s = \rho_a + \rho_b, \quad \rho_{a,b} = \frac{1}{Q^2} (\sum_{i \in a,b} p_i) \qquad \text{(sum of jet masses, sJM)}$$

$$\tau_m = \tau_s + \frac{1}{2} \tau_s^2 \qquad \text{(modified jet masses, mJM)}$$



Excellent mass sensitivity:

$$\tau_{2,\min} = 1 - \sqrt{1 - 4\hat{m}^2} \qquad \text{(tree level)}$$

$$\tau_{s,\min} = 2\hat{m}^2 \qquad \hat{m}^2 \equiv \frac{m_t^2}{Q^2}$$

$$\tau_{m,\min} = 2\hat{m}^2 + 2\hat{m}^4$$

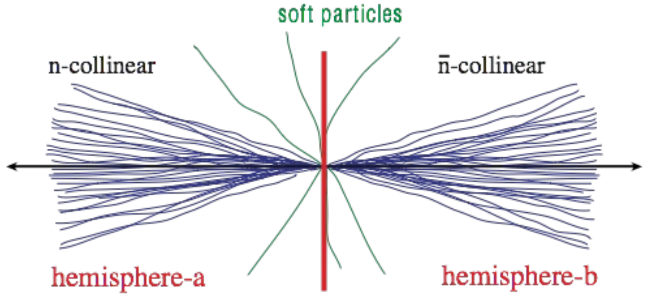
All observables agree at leading power!
Differ by $\hat{m}^2$ power corrections

$$\frac{d\sigma}{d\tau} = Q^2 \sigma_0 H_0(Q, \mu) \int d\ell \; J_0(Q\ell, \mu) \, S_0 \left(Q\tau - \ell, \mu\right)$$

Scale hierarchy and sequence of EFTs:

$$Q \gg m_t \gg \Gamma_t \gg \Lambda_{\rm QCD}$$

$$\text{QCD} \rightarrow \text{SCET} \rightarrow \text{bHQET}$$



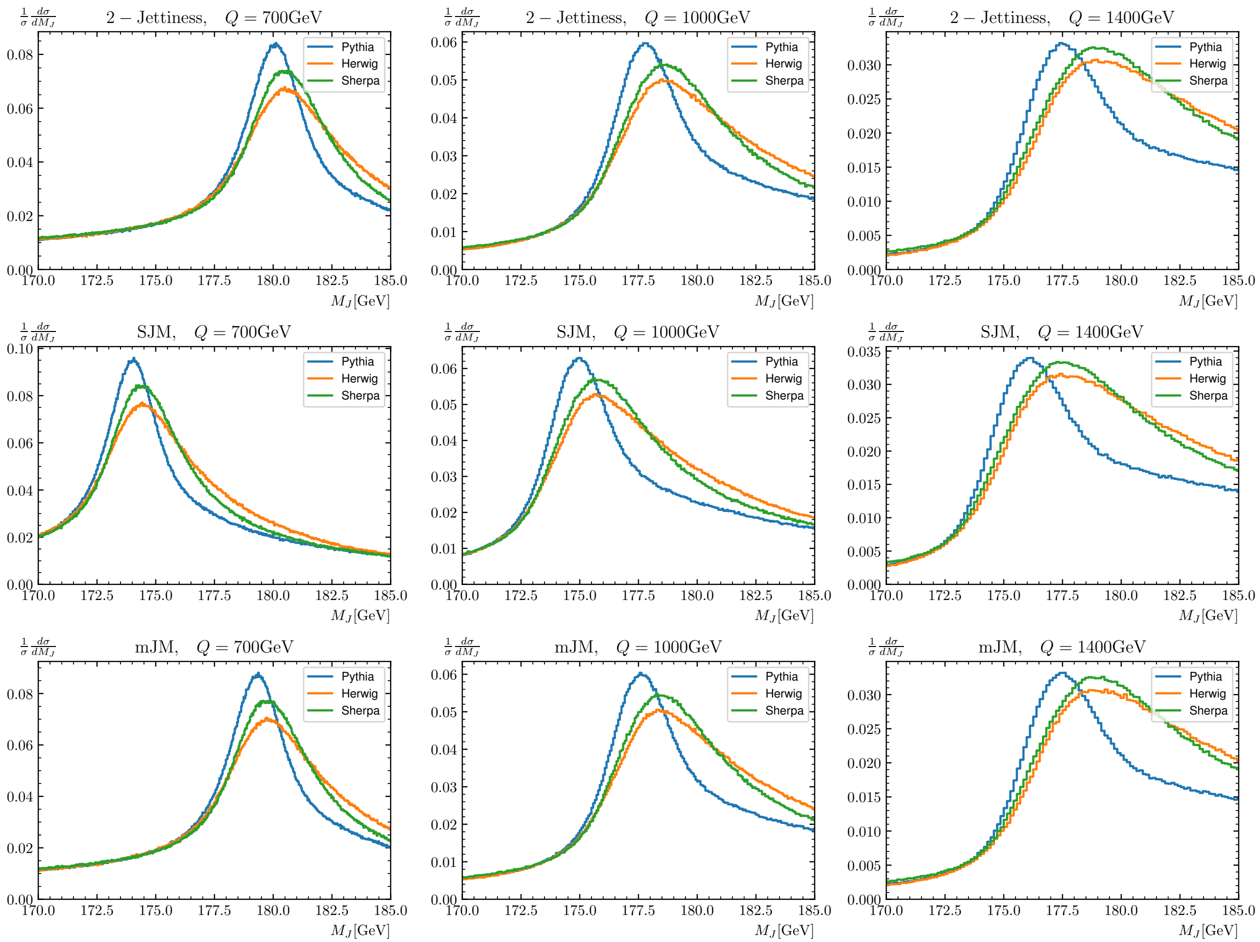
Shape Observables

m_t^{MC}=173 GeV

2-jettiness τ_2

sJM τ_s

mJM τ_m



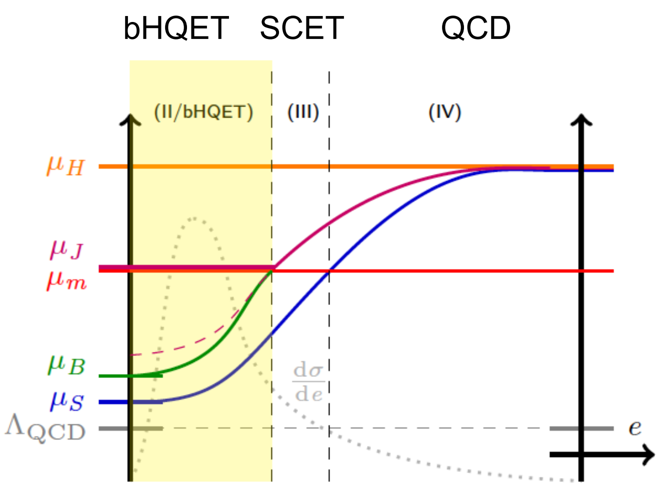
$$M_j \equiv \frac{Q^2}{2m_t}\,\tau$$

- Substantial differences between the shape observables
- Substantial differences between Monte Carlo event generators
- Substantial $\hat{m}^2 \sim \dfrac{1}{12}$ power corrections

N²LL + NLO matched distributions

$$\frac{\mathrm{d}\sigma_{\mathrm{full}}(\tau)}{\mathrm{d}\tau} = \frac{\mathrm{d}\sigma_{\mathrm{bHQET}}(\tau)}{\mathrm{d}\tau} + \frac{\mathrm{d}\sigma_{\mathrm{SCETns}}(\tau)}{\mathrm{d}\tau} + \frac{\mathrm{d}\sigma_{\mathrm{QCDns}}(\tau)}{\mathrm{d}\tau}$$

Fleming, AH, Mantry, Stewart 2007
Dehnadi PhD-Thesis (2018)



measurement function

$$\frac{1}{\sigma_0^C}\frac{\mathrm{d}\sigma_{\mathrm{bHQET}}^C}{\mathrm{d}\tau}\bigg|_{\mathrm{strict}} = m_t Q^2 H_Q^{(6)}(Q,\mu_H)U_{H_Q}^{(6)}(Q,\mu_H,\mu_m)H_m^{(6)}(m_t,\varrho,\mu_m)U_v^{(5)}(\varrho,\mu_m,\mu)$$
$$\times \int \mathrm{d}\ell\,\mathrm{d}\hat{s}\,\delta[\hat{s}_\tau - \hat{s} - \varrho\ell]$$
$$\times \int \mathrm{d}\hat{s}'\,U_B^{(5)}(\hat{s}-\hat{s}',\mu,\mu_B)J_{B,\tau}^{(5)}(\hat{s}',\Gamma_t,\delta m,\mu_B)$$
$$\times \int \mathrm{d}\ell'\,\mathrm{d}k\,U_S^{(5)}(\ell-\ell',\mu,\mu_S)\hat{S}_\tau^{(5)}(\ell'-k,\bar{\delta},\mu_S)F(k-2\overline{\Delta})$$

ultra-collinear bHQET jet function

large-angle soft function

non-perturbative soft function

QCD singular coefficients cannot be determined from EFT due to $\hat{m}^2$ power corrections

$$\frac{1}{\sigma_0^C}\frac{\mathrm{d}\sigma_{\mathrm{QCD}}^C}{\mathrm{d}\tau} = R_0^C(\hat{m})\left\{\delta(\tau-\tau_{\min}) + \frac{C_F\alpha_s}{4\pi}A_\tau^C(\hat{m})\delta(\tau-\tau_{\min}) + \frac{C_F\alpha_s}{4\pi}B_{\mathrm{plus}}(\hat{m})\left[\frac{1}{\tau-\tau_{\min}}\right]_+\right\} + \frac{C_F\alpha_s}{4\pi}F_\tau^{\mathrm{NS,C}}(\tau,\hat{m}) + \mathcal{O}(\alpha_s^2)$$

Plus distribution coefficient B_{plus} universal!

$$\hat{s}_\tau \equiv \frac{Q^2(\tau-\tau_{\min})}{m_t}$$

exact tree-level expression!

N^2LL + NLO matched distributions

MSR mass

Jain, Mateu, Preisser, AHH 2017

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

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

Lepenik, Mateu, AHH 2022

Shape function

Ligeti, Stewart, Tackmann 2008

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

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

$$g(z) = \frac{2}{3}[3 - e^{-4z}(3 + 12z + 24z^2 + 32z^3)] - 1$$

- 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 m_t-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

$$\Omega_1(\lambda,\Delta,3) = \Delta + \lambda(0.5c_0^2 + 0.47360764c_0c_1 + 0.10067713c_0c_2 + 0.094954074c_0c_3 + 0.54502418c_1^2 + 0.50700667c_1c_2 + 0.12507929c_1c_3 + 0.55015667c_2^2 + 0.50982331c_2c_3 + 0.55170015c_3^2)\,,$$

Fit parameters: c_0 , c_1 , c_2

N^{2}LL + NLO matched distributions

Gap subtraction

Stewart, AHH 2007

- Renormalon subtraction through redefinition of the gap parameter

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

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

Bachu, Mateu, Pathak, Stewart, AHH 2021

- Classes of pap subtraction schemes can be defined from the configuration space soft function

$$\bar{\delta}(R_s,\mu_S;\mathrm{A},n,\xi) \equiv \begin{cases} \frac{R_s}{2\xi}\frac{\mathrm{d}^n}{\mathrm{d}\ln(iy)^n}\log\left[\tilde{S}_\tau(y,\mu_S)\right]_{iy=\frac{\xi}{R_s}} & \text{if A=on} \\ \frac{R_s}{2\xi}\frac{\mathrm{d}^n}{\mathrm{d}\ln(iy)^n}\log\left[\tilde{S}_\tau(y,R_s)\right]_{iy=\frac{\xi}{R_s}} & \text{if A=off} \end{cases}$$

$$= R_s \sum_{i=1} d_i(R_s,\mu_S)\left[\frac{\alpha_s^{(5)}(\mu_S)}{4\pi}\right]^i$$

if A=on ← with soft function anomalous dimension

if A=off ← w/o soft function anomalous dimension

- 3 gap schemes with completely different character
- We use 2-loop RGEs and $\bar{\Omega}_1(2\ \mathrm{GeV}, 2\ \mathrm{GeV})$ as reference input

$$\bar{\delta}^{(1)}(R_s,\mu_S) \equiv \bar{\delta}(R_s,\mu_S;\mathrm{on},1,e^{-\gamma_E}) \qquad d_1^{(1)}(R_s,\mu_S) = -19.0\ \ln\left(\frac{\mu_S}{R_s}\right)$$
$$\bar{\delta}^{(2)}(R_s,\mu_S) \equiv \bar{\delta}(R_s,\mu_S;\mathrm{off},0,e^{5\gamma_E}) \qquad d_1^{(2)}(R_s,\mu_S) = -3.9$$
$$\bar{\delta}^{(3)}(R_s,\mu_S) \equiv \bar{\delta}(R_s,\mu_S;\mathrm{off},0,1) \qquad d_1^{(3)}(R_s,\mu_S) = -8.4$$

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

Fit Procedure Details

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

  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 → 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: 10^7 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) — perturbative uncertainty
  - different Q sets: 6 sets of energies between 600 – 1400 GeV
  - different fit ranges: 3 choices of fit ranges in peak region

  } 18 fit setups: compatibility uncertainty

We exactly reproduced the calibration results from 2016 for Pythia

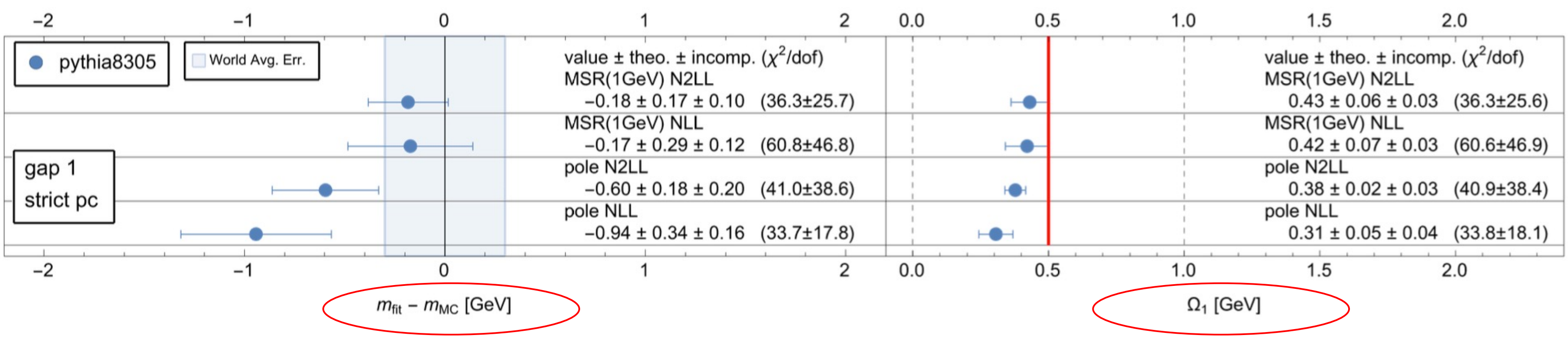
Revisiting the 2016 Analysis

2016, Pythia 8.205, $m_{MC} = 173\,\mathrm{GeV}$ | update, Pythia 8.305

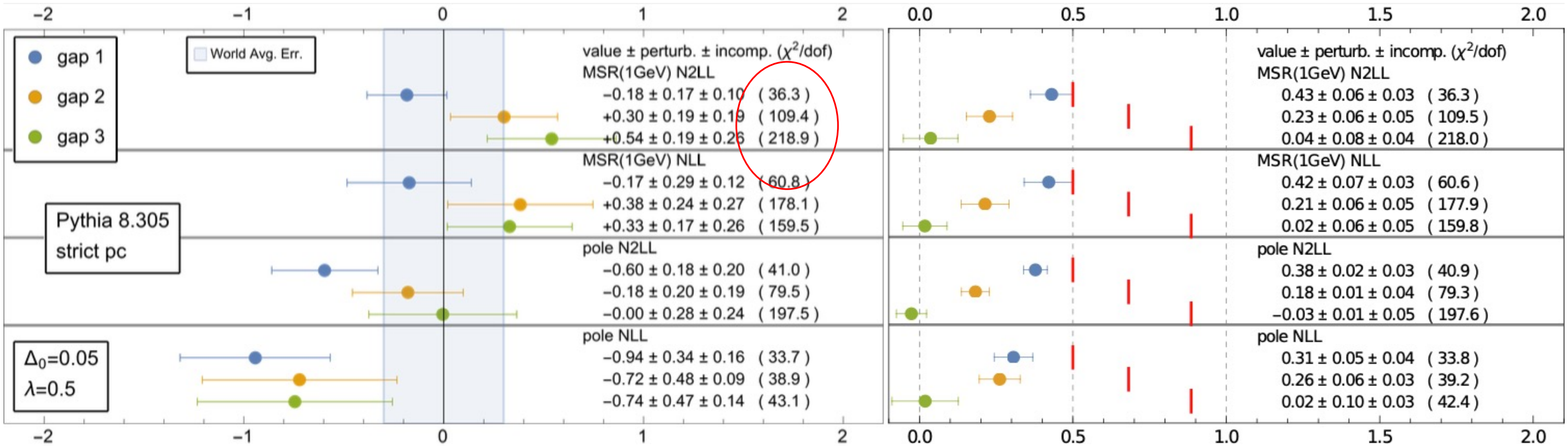
	order	central	perturb.	incomp.	central	perturb.	incomp.
$m_{t,1\,\mathrm{GeV}}^{\mathrm{MSR}}$	$\mathrm{N^2LL}$	172.82	0.19	0.11	172.82	0.17	0.10
$m_{t,1\,\mathrm{GeV}}^{\mathrm{MSR}}$	NLL	172.80	0.26	0.14	172.83	0.29	0.12
m_t^{pole}	$\mathrm{N^2LL}$	172.43	0.18	0.22	172.40	0.18	0.20
m_t^{pole}	NLL	172.10	0.34	0.16	172.06	0.34	0.16
Ω_1	$\mathrm{N^2LL}$	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)

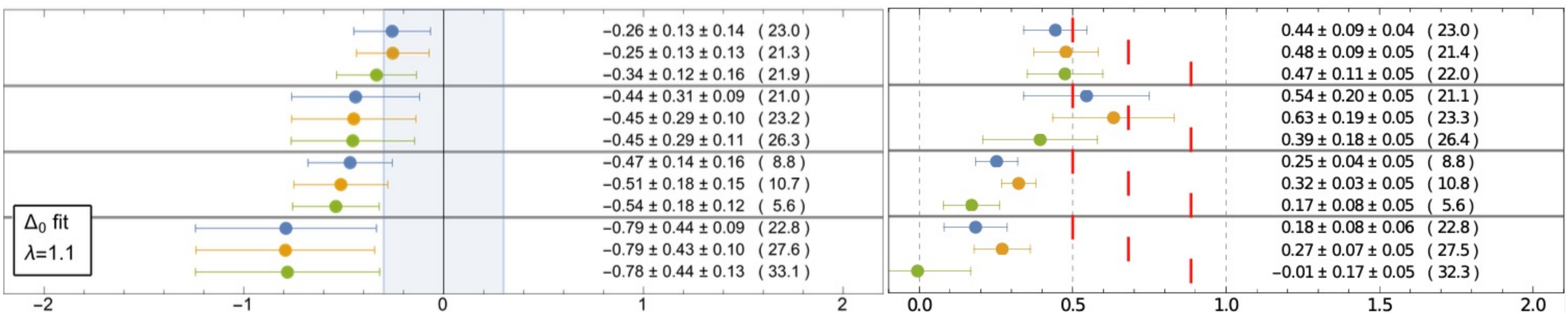
- Agreement within 30 MeV



Gap Scheme Independence

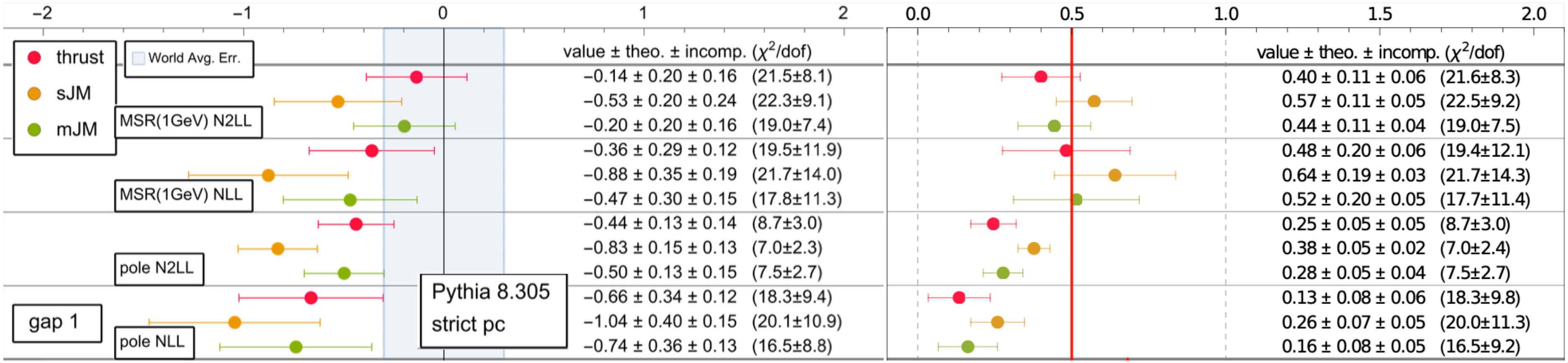


➡ Gap term Δ in shape function needs to be fitted as well



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

Observable Independence



→ Observable independence not achieved with strict power counting approach and the exact expression for $\tau_{\min}$ 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:

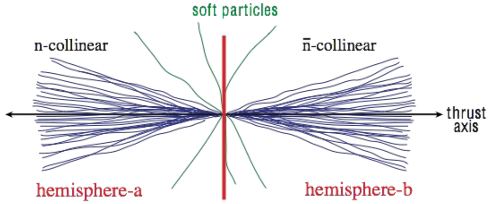
$$\delta[\hat{s}_\tau - \hat{s} - r_{\tau,s}(\hat{m})\varrho\ell] \qquad r_{\tau,s}(\hat{m}) = 1 + \mathcal{O}(\hat{m}^2)$$

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

Observable Independence

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

$$p_n = m_t v_+ + k_s$$
$$p_{\bar{n}} = m_t v_- + k_{\bar{s}}$$



(soft momentum k_s contains soft top recoil)

<u>2-jettiness:</u> $\tau_2 = \tau_{\min} + \dfrac{k_s^+ + k_{\bar{s}}^-}{Q}$ $\rightarrow$ $r_{\tau_2,s}(\hat{m}) = 1$

<u>sum of jet mass:</u> $\tau_s = \dfrac{1}{Q^2}(p_n^+ p_n^- + p_{\bar{n}}^- p_{\bar{n}}^+)$

<u>Modified jet mass:</u> $\tau_m = \tau_s + \dfrac{1}{2}\tau_s^2$

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

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

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

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

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

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

Observable Independence

→ Improved version of the bHQET factorization formula

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

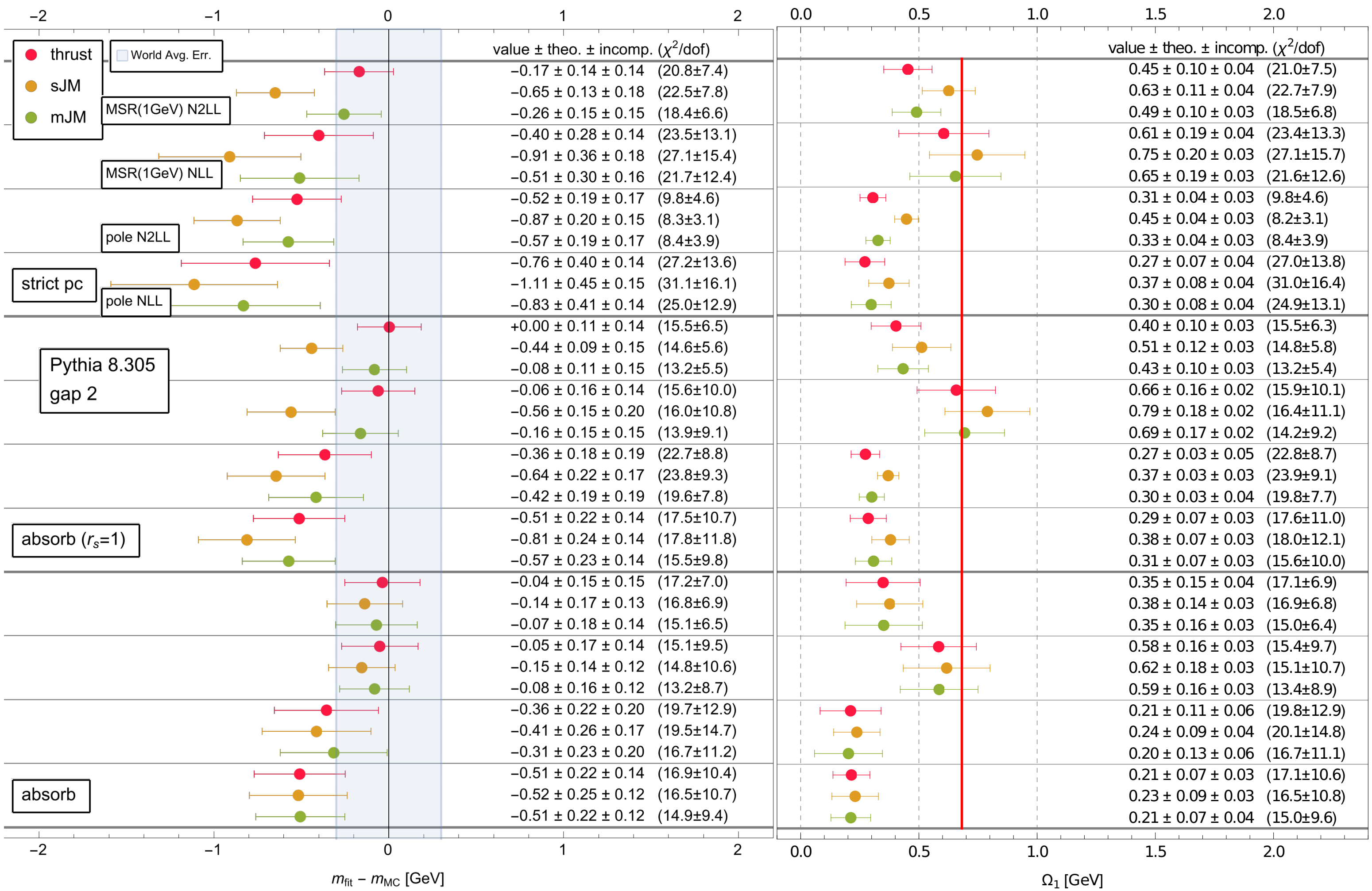
$$\frac{\mathrm{d}\tilde{\sigma}^C_{\mathrm{bHQET}}}{\mathrm{d}\tau} = \frac{\mathrm{d}\sigma^C_{\mathrm{bHQET}}}{\mathrm{d}\tau}\bigg|_{\mathrm{pow}\,1,\{H_Q\to\tilde{H}_Q, H_m\to\tilde{H}_m, J^{(5)}_{B,\tau}\to\tilde{J}^{(5)}_{B,\tau}\}}$$

Estimates the uncertainty in the treatment of soft power corrections

$$\tilde{H}_Q(\mu_H) = H_Q(\mu_H) + \frac{C_F\alpha_s(\mu_H)}{4\pi}(1-\xi_J-\xi_B)\xi_{A1}\, h_\tau^C(\hat{m})$$
$$\tilde{H}_m(\mu_m) = H_m(\mu_m) + \frac{C_F\alpha_s(\mu_m)}{4\pi}\xi_J\xi_{A1} h_\tau^C(\hat{m})$$
$$m_t^2\tilde{J}^{(5)}_{B,\tau}(\hat{s},\mu_B) = m_t^2 J^{(5)}_{B,\tau}(\hat{s},\mu_B) + \frac{C_F\alpha_s(\mu_B)}{4\pi}\left\{\xi_B\xi_{A1}h_\tau^C(\hat{m})\,\delta(\hat{s}) + \xi_{B1}\, b(\hat{m})\frac{1}{m}\left[\frac{1}{\hat{s}/m}\right]_+\right\}$$

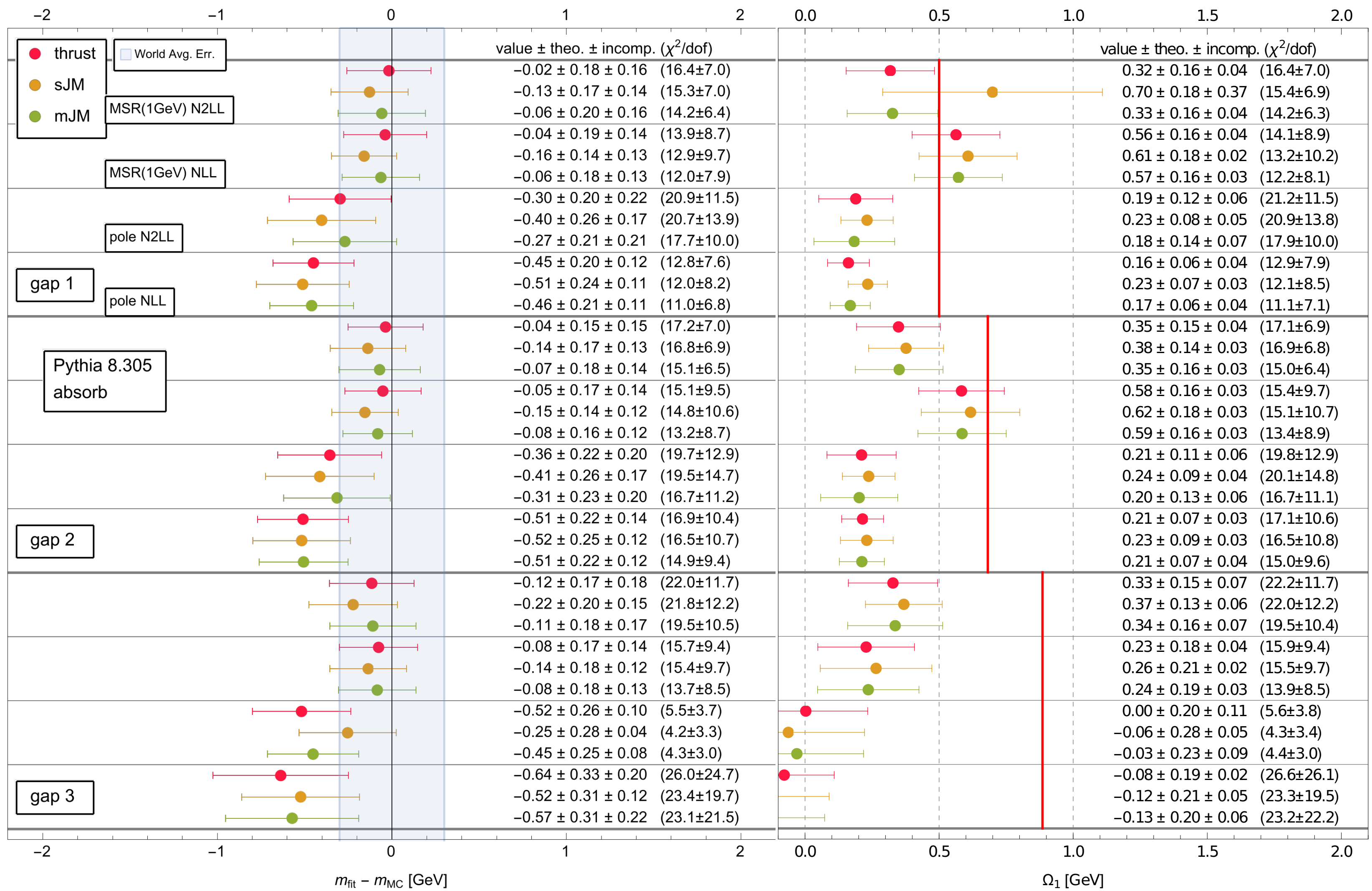
- soft power correction in measurement delta function
- global tree-level phase space factor
- absorb and <u>vary</u> the remaining distributional terms of the full QCD result

Observable Independence

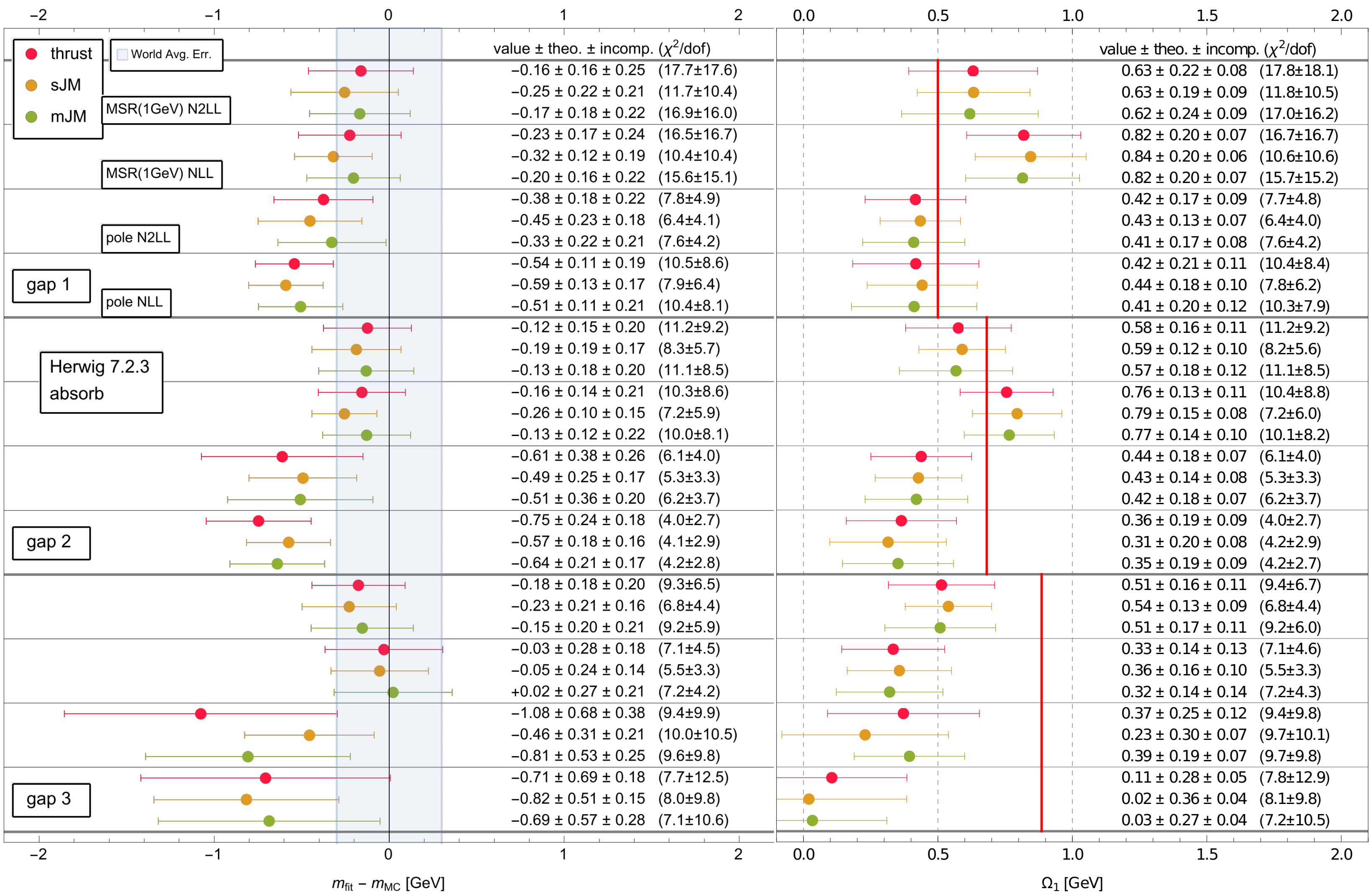


→ Observable independent results obtained for top mass and Ω_1

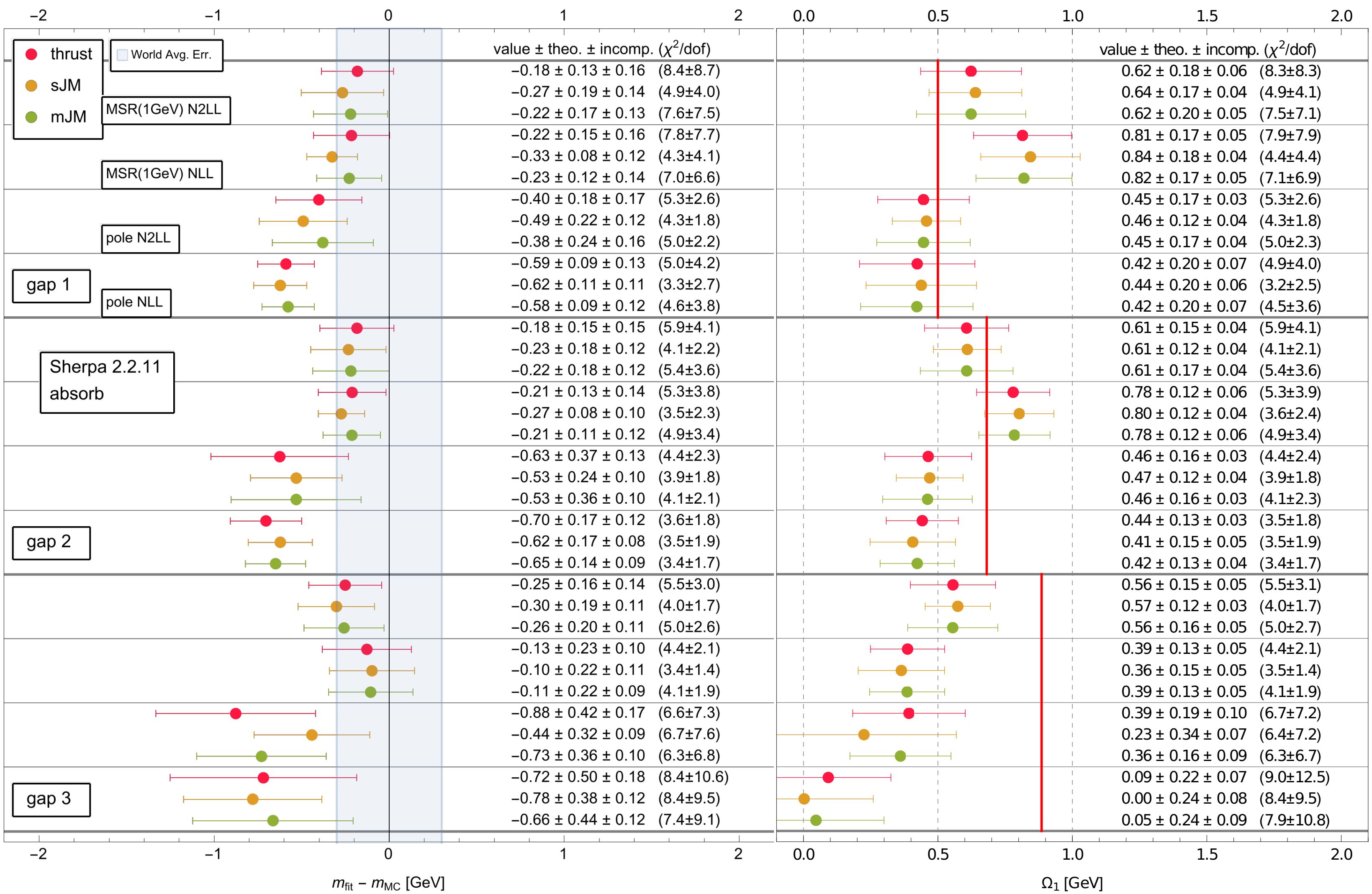
Final Results (Pythia)



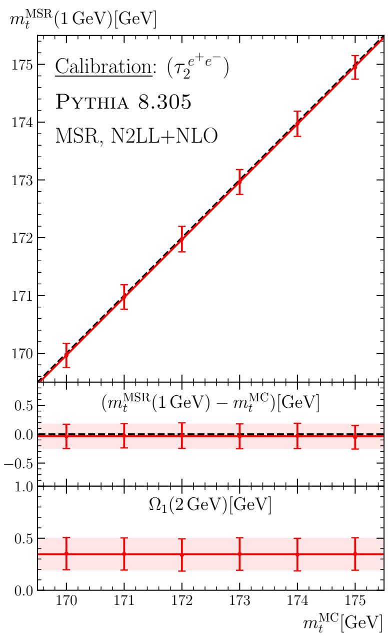
Final Results (Herwig)

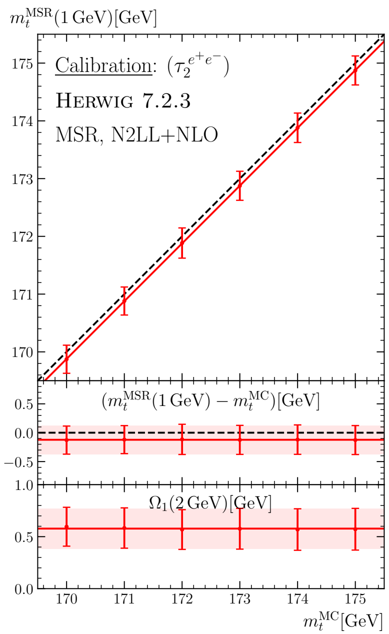


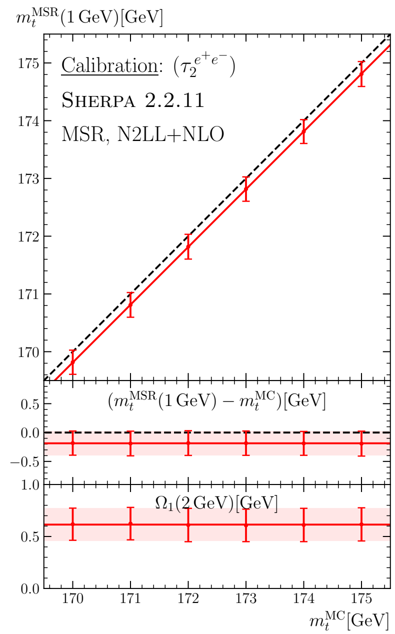
Final Results (Sherpa)

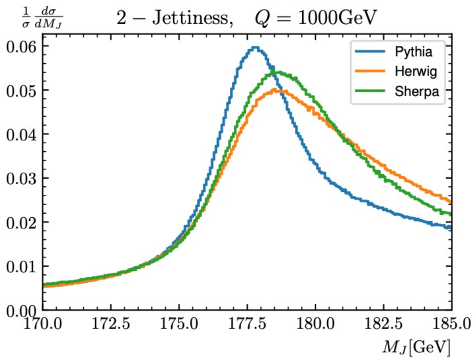


Final Results (all)









$$m_t^{\rm P{\scriptsize YTHIA}} = m_t^{\rm MSR}(1\,{\rm GeV}) + (0.03 \pm 0.21)\,{\rm GeV}$$
$$m_t^{\rm H{\scriptsize ERWIG}} = m_t^{\rm MSR}(1\,{\rm GeV}) + (0.12 \pm 0.25)\,{\rm GeV}$$
$$m_t^{\rm S{\scriptsize HERPA}} = m_t^{\rm MSR}(1\,{\rm GeV}) + (0.19 \pm 0.21)\,{\rm GeV}$$

$$m_t^{\rm P{\scriptsize YTHIA}} = m_t^{\rm pole} + (0.35 \pm 0.30)\,{\rm GeV}$$
$$m_t^{\rm H{\scriptsize ERWIG}} = m_t^{\rm pole} + (0.61 \pm 0.46)\,{\rm GeV}$$
$$m_t^{\rm S{\scriptsize HERPA}} = m_t^{\rm pole} + (0.63 \pm 0.39)\,{\rm GeV}$$

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

Outlook on upcoming results

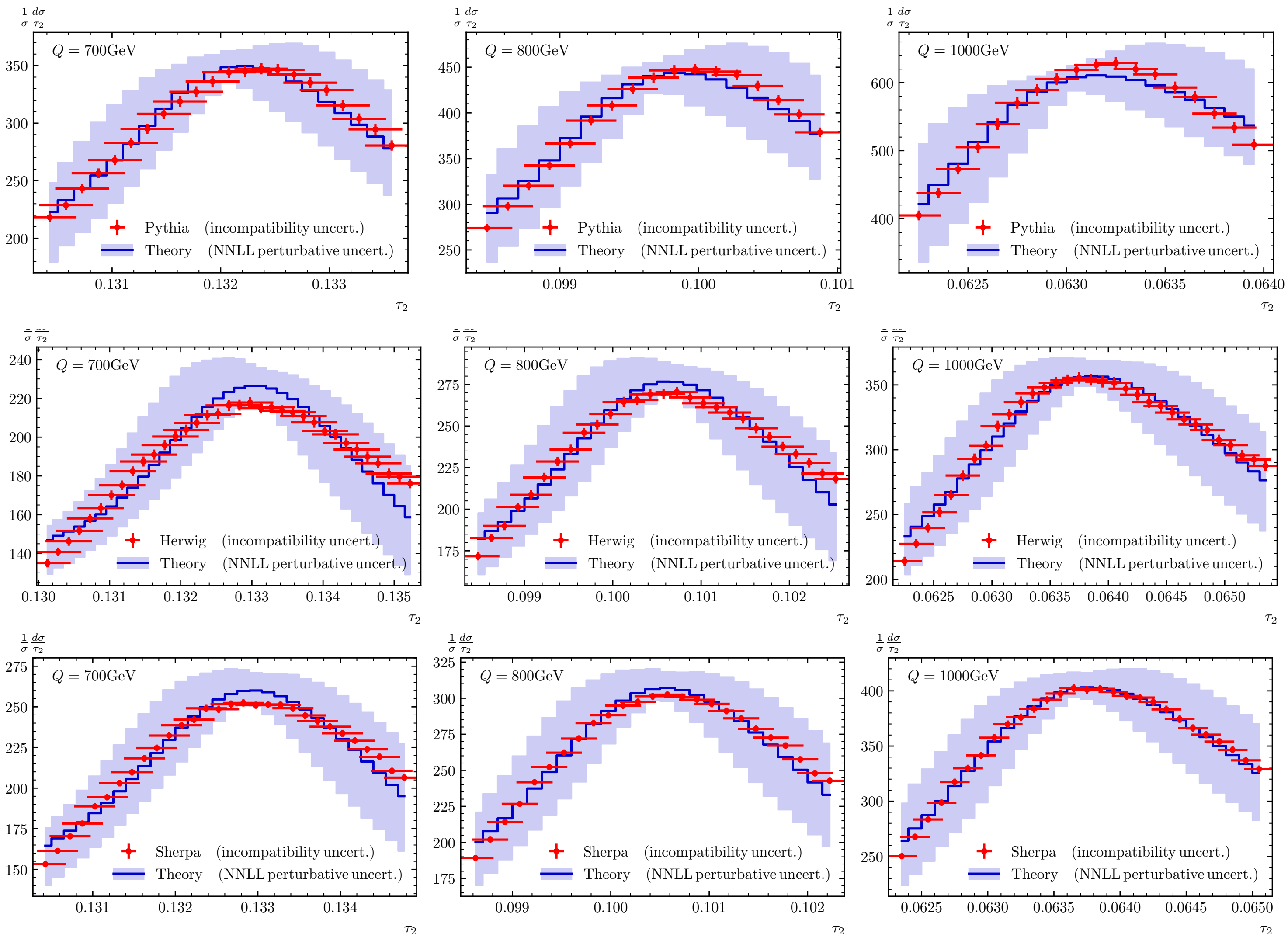
- Dynamical hadronization model in Herwig
  - Old default Herwig hadronization model interferes with meaning of m_t^{MC}
  - New dynamical hadronization model does not
  - Shower cutoff Q_0 as an IR factorization scale (invariance under Q_0 variations)
  - Control over m_t^{MC} through tuning
  - Calibration 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)

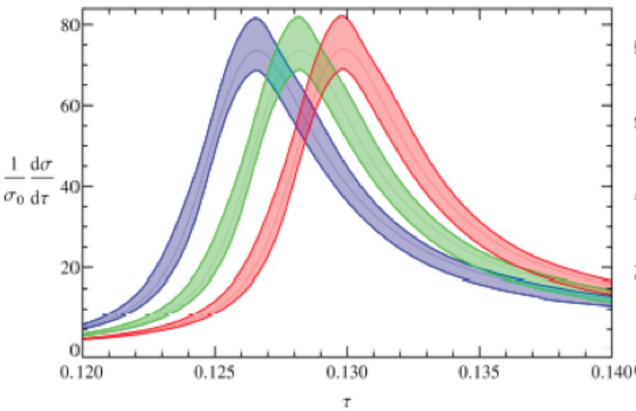


2-Jettiness for Top Production (QCD)

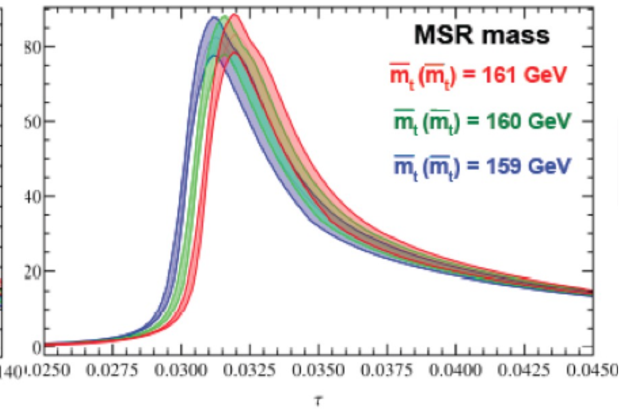
$$\frac{\mathrm{d}\sigma}{\mathrm{d}\tau_2} = f(\underbrace{m_t^{\mathrm{MSR}}(R)}_{\text{any scheme possible}}, \alpha_s(M_Z), \underbrace{\Omega_1, \Omega_2, \ldots}_{\text{Non-perturbative}}, \underbrace{\mu_h, \mu_j, \mu_s, \mu_m}_{\text{renorm. scales}}, R, \Gamma_t)$$

finite lifetime

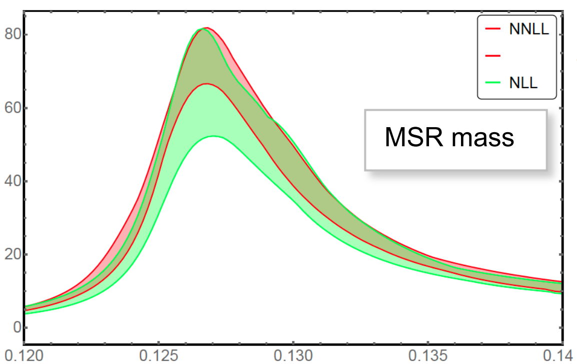
Q=700 GeV (p_T= 350 GeV)



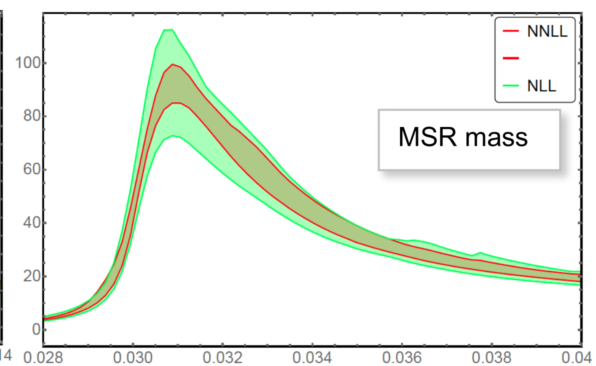
Q=1400 GeV (p_T = 700 GeV)



Q=700 GeV



Q=1400 GeV



- Higher mass sensitivity for lower Q (p_T)
- Finite lifetime effects included
- Dependence on non-perturbative parameters
- Convergence: $\Omega_{1,2,\ldots}$

- Good convergence
- Reduction of scale uncertainty (NLL to NNLL)
- Control over whole distribution