Soft drop jet mass for precision top mass determination

Resummation, Evolution and Factorization 2021

DESY

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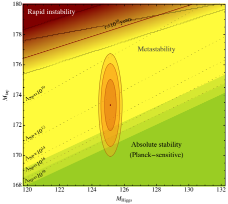
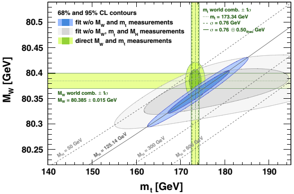
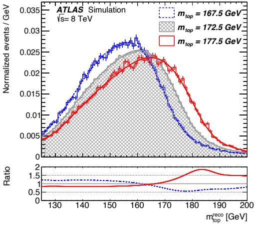
Top mass measurements

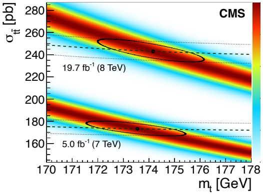
Top mass is *not* a physical observable, but a Lagrangian parameter and has to be defined through a well defined theoretical prescription: *a renormalization scheme*

- Top mass is an essential element in the consistency tests of the SM, indirect searches for BSM physics and electroweak precision fits.
  [Buttazzo, et al., 2013][Andreassen, et al. 2014]
  [M. Baak, et al. (Gfitter Group), 2014]
- Direct top mass the most precise but depends primarily on the MC parton shower and hadronization model:
  $m_t^{\rm MC} = 172.26 \pm 0.61$ GeV [CMS, 1812.10534],
  $m_t^{\rm MC} = 172.69 \pm 0.48$ GeV [ATLAS, 1810.01772],
  $m_t^{\rm MC} = 174.34 \pm 0.64$ GeV [Tevatron, 1407.2682]
  No field theoretic definition of $m_t^{\rm MC}$ exists
- Indirect cross section measurements not precise enough due to poor shape dependence:
  $m_t^{\rm pole} = 172.9^{+2.5}_{-2.6}$ GeV [ATLAS, 1406.5375]
  $m_t^{\rm pole} = 172.7^{+2.4}_{-2.7}$ GeV [CMS, 1701.06228]









Here we explore a first principles hadron-level prediction for a differential top mass sensitive observable.

Soft drop jet mass is robust and enables analytical calculations

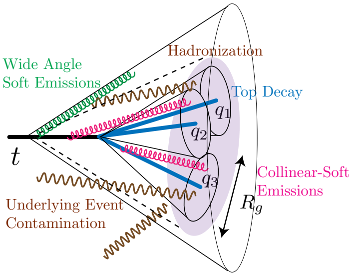
Considerations for groomed top jets: [Hoang, Mantry, AP, Stewart 1708.02586]

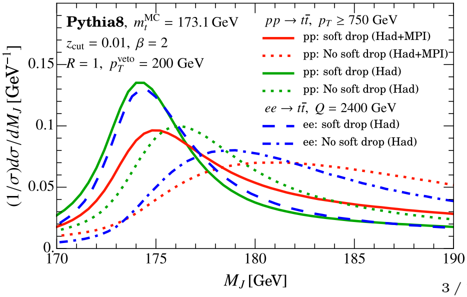
1. We need to be *inclusive over the top decay products* and achieve that by considering sufficiently boosted tops.
2. Need to *get rid of wide angle soft radiation* as much as possible: correlated with rest of the event, enhanced hadronization effects, underlying event.

Achieve this via:

- Measure the jet mass of boosted groomed top jets in the peak region: $M_J^2 - m_t^2 \sim m_t \Gamma_t$
- Use soft drop. [Larkoski et al. 1402.2657]

$$\frac{\min(p_{T_i}, p_{T_j})}{p_{T_i} + p_{T_j}} > z_{\rm cut} \left(\frac{\Delta R_{ij}}{R_0} \right)^\beta$$

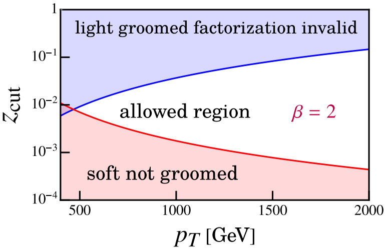




Parton level factorization formula

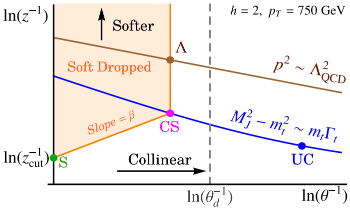
Factorization for top quarks derived using SCET and HQET:
[Hoang, Mantry, AP, Stewart 1708.02586]

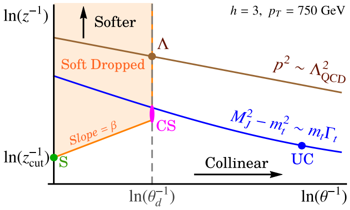
$$\frac{d\sigma^{\text{part.}}(\Phi_J)}{dM_J} = N(\Phi_J, z_{\text{cut}}, \beta, \mu) \int d\tilde{h}\; P\left(\tilde{h}, \frac{m_t}{Q}\right)$$
$$\times \int d\ell^+ \, J_B\left(\hat{s}_t - \frac{Q\ell^+}{m_t}, \delta m, \Gamma_t, \mu\right) S_c^{(d)}\left[\ell^+, Q_{\text{cut}}, \theta_d, \beta, \mu\right]$$
$$+ \text{Hadronization corrections}$$

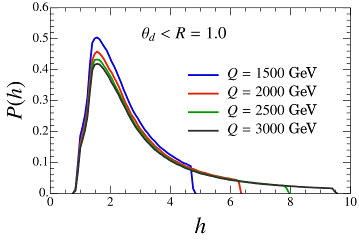


Depends on the angular separations of top decay products:

$$\tan\frac{\theta_d}{2} = \frac{m_t}{Q} h\left(\Phi_d^t, \frac{m_t}{Q}\right)$$

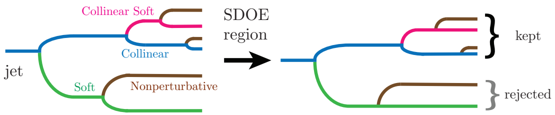


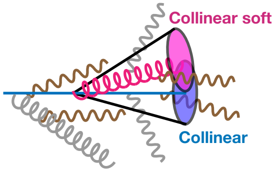




Field theoretic description of hadronization corrections

1. Hadronization corrections in the perturbative region depend sensitively on soft drop clustering:

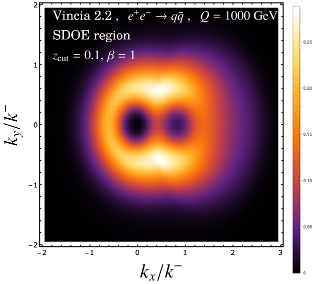




2. Factorization of leading nonperturbative corrections:
[Hoang, AP, Mantry, Stewart 1906.11843]

$$\frac{d\sigma^{\rm had}_{\kappa_i}}{dm_J^2} = \frac{d\hat\sigma^{\kappa_i}}{dm_J^2} - Q\,\Omega^{\circledcirc}_{1\kappa_i\kappa_j}\frac{d}{dm_J^2}\left(C_1^{\kappa_i}(m_J^2,Q,z_{\rm cut},\beta,R)\,\frac{d\hat\sigma^{\kappa_i}}{dm_J^2}\right) + \frac{Q\left(\Upsilon^{\kappa_i\kappa_j}_{1,0}+\beta\,\Upsilon^{\kappa_i\kappa_j}_{1,1}\right)}{m_J^2}\,C_2^{\kappa_i}(m_J^2,Q,\,z_{\rm cut},\beta,R)\,\frac{d\hat\sigma^{\kappa_i}}{dm_J^2}$$

Involves only three $\mathcal{O}(\Lambda_{\rm QCD})$ constants! Depends on the nature of parton κ_j stopping the soft drop groomer



3. C_1 and C_2 capture the entire kinematic dependence:

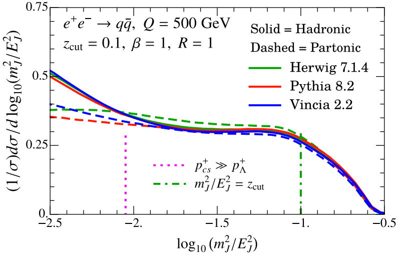
$$C_1^\kappa(m_J^2) = \frac{1}{\langle 1\rangle(m_J^2)}\left\langle\frac{\theta_g}{2}\right\rangle, \qquad C_2^\kappa(m_J^2) = \frac{m_J^2/Q^2}{\langle 1\rangle(m_J^2)}\left\langle\frac{2}{\theta_g}\,\delta\Big(z_g - z_{\rm cut}\theta_g^\beta\Big)\right\rangle$$

Calculation of the Wilson Coefficients

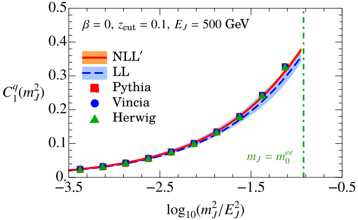
Calculate C_1 and C_2 moments from the double differential cross section:
[AP, Vaidya, Stewart, Zoppi 2020]

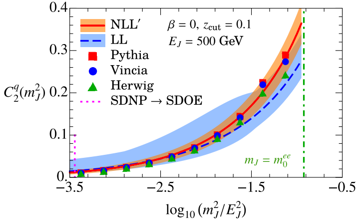
$$C_1^\kappa \equiv \left(\frac{d\hat{\sigma}^\kappa}{dm_J^2}\right)^{-1} \int d\theta_g \, \frac{\theta_g}{2} \, \frac{d^2\hat{\sigma}^\kappa}{dm_J^2 d\theta_g} \,,$$

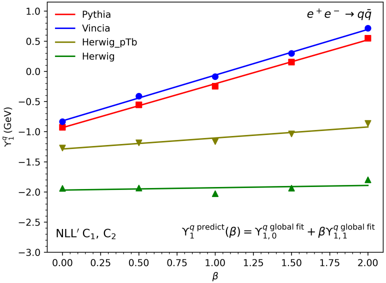
$$C_2^\kappa \equiv \left(N_\kappa \frac{d\hat{\sigma}^\kappa}{dm_J^2}\right)^{-1} \int d\theta_g \, \frac{m_J^2}{Q^2} \, \frac{2}{\theta_g} \, \frac{d}{d\varepsilon} \left[N_\kappa(\varepsilon) \frac{d^2\hat{\sigma}^\kappa(\varepsilon)}{dm_J^2 d\theta_g}\bigg|_{\theta_g \sim \theta_g^\star} \right]\bigg|_{\varepsilon\to 0} .$$



The doubly differential cross section allows us to achieve NLL′ accuracy for the Wilson coefficients:





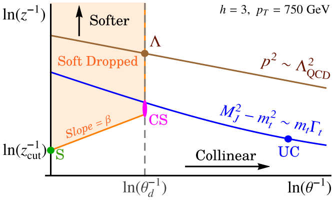


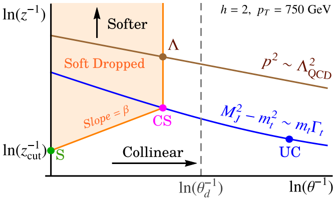
The framework can also be used to stress-test the MC hadronization models. [Ferdinand, Lee, AP (in progress)], and assess prospects for α_s measurements [Hannesdottir, AP, Schwartz, Stewart (in progress)].

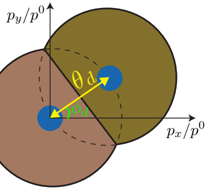
Nonperturbative power corrections for groomed top jets

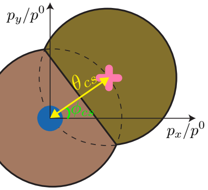
Nonperturbative power corrections for top quarks can be described via a more differential distribution: [Hoang, Mantry, Michel, AP, Stewart]

$$\frac{d\sigma^{\text{Had.}}(\Phi_J)}{dM_J} = \frac{d\sigma^{\text{Part.}}(\Phi_J)}{dM_J}$$
$$+ \int dk^+ d\theta_g dh \frac{k^+\theta_g}{2}\left(\frac{d\hat{\sigma}}{dM_J d\theta_g dh}\delta\left(\frac{2m_t h}{Q} - \theta_g\right) F^t_{\oplus}(k^+)\right.$$
$$\left. + \left[\Theta\left(\theta_g - \frac{2m_t}{Q}h\right)\frac{d\hat{\sigma}}{dM_J d\theta_g dh}\right]_+ F^{qg}_{\oplus}(k^+)\right)$$





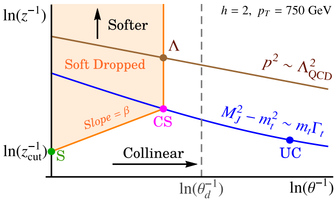


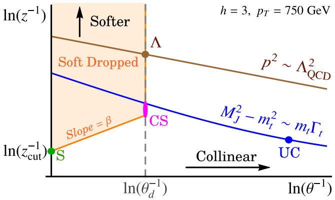


Hadron level cross section for groomed top jets

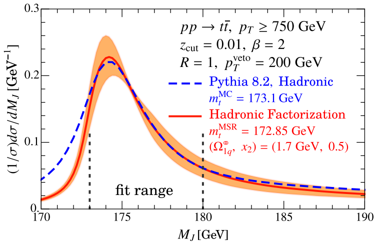
Assuming $\Omega^{\infty}_{1qg} \sim \Omega^{\infty}_{1t}$ we can write down a simplified form:

$$\frac{d\sigma^{\text{Had.}}(\Phi_J)}{dM_J} = N(\Phi_J, z_{\text{cut}}, \beta, \mu) \int d\tilde{h}\; P\Big(\tilde{h}, \frac{m_t}{Q}\Big) \int d\ell^+\, J_B\Big(\hat{s}_t - \frac{Q\ell^+}{m_t}, \delta m, \Gamma_t, \mu\Big)$$
$$\times \int dk^+\, S_c^q\Big[\Big(\ell^+ - \max\Big\{C_1^{q(pp)}(m_t\hat{s}_t), \frac{m_t\tilde{h}}{Q}\Big\}k^+\Big) Q_{\text{cut}}^{\frac{1}{1+\beta}}, \beta, \mu\Big]$$
$$\times F^q_{\infty}(k^+)\Big\{1 - \Theta\Big(C_1^{q(pp)}(m_t\hat{s}_t) - \frac{m_t\tilde{h}}{Q}\Big)\frac{Qk^+}{m_t}\frac{dC_1^{q(pp)}(m_t\hat{s}_t)}{d\hat{s}_t}\Big\}$$





NLL result:



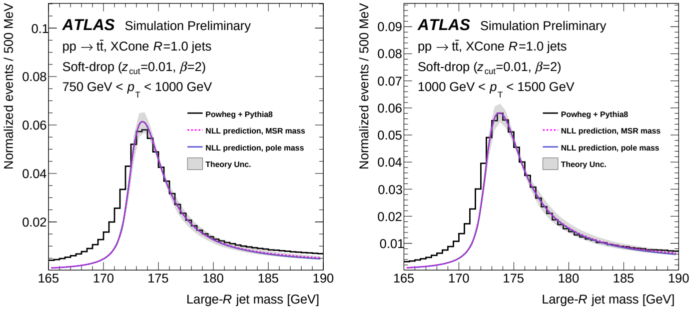
Precise Interpretation of MC top mass in ATLAS Monte Carlo

Relation between m_t^{MC} in nominal Powheg+Pythia8 and m_t^{MSR}:

$$m_t^{\mathrm{MSR}}(R = 1\,\mathrm{GeV}) = 172.42 \pm 0.1\,\mathrm{GeV}\,, \quad \Omega_{1q}^{\infty} = 1.49 \pm 0.03\,\mathrm{GeV}\,, \quad x_2 = 0.52 \pm 0.09$$

$$m_t^{\mathrm{MC}} = m_t^{\mathrm{MSR}}(R = 1\mathrm{GeV}) + 80^{+350}_{-400}\mathrm{MeV}$$

$$m_t^{\mathrm{MC}} = m_t^{\mathrm{Pole}} + 350^{+300}_{-360}\,\mathrm{MeV}$$



[ATL-PHYS-PUB-2021-034; ATLAS, STA's: Hoang, Mantry, AP, Stewart]

Precise Interpretation of MC top mass in ATLAS Monte Carlo

[ATL-PHYS-PUB-2021-034; ATLAS, STA's: Hoang, Mantry, AP, Stewart]

Uncertainty breakdown:

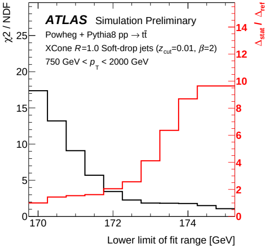
Source of Uncertainty	**size [MeV]**	**comment**
Theory	+ 230/-310	Envelope of NLL scale variations
Fit methodology	± 190	fit range, p_T bins
UE model	± 155	A14 eigentune variations, CR models
Observable definition	± 200	$z_{\rm cut} = 0.01, 0.005, 0.02,\ \beta = 1, 2,$ Anti-k$_t$ / XCone jets

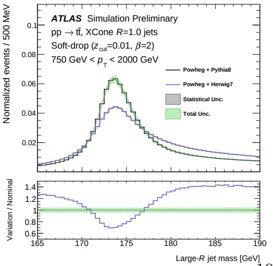
Calibration for POWHEG+HERWIG7 consistent with PYTHIA despite very different shapes!

$$m_t^{\rm MSR,P8}(R = 1\,{\rm GeV}) = 172.42 \pm 0.1\,{\rm GeV}$$

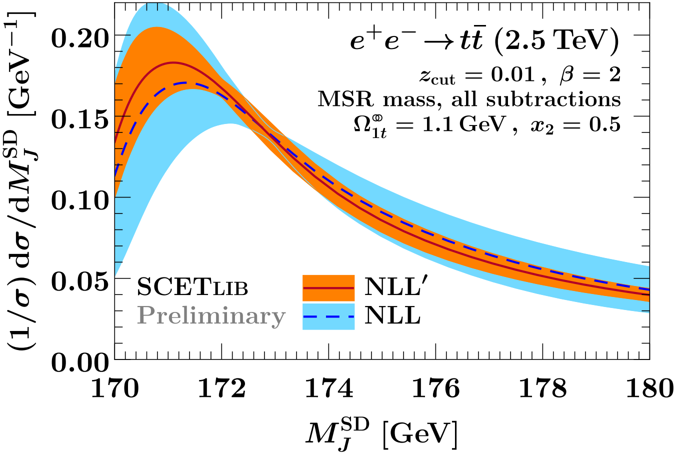
$$m_t^{\rm MSR,H7}(R = 1{\rm GeV}) = 172.27 \pm 0.09\,{\rm GeV}$$

$$\Omega_{1q}^{\circledcirc,\rm H7} = 1.9 \pm 0.07\,{\rm GeV}\,, \quad x_2^{\rm H7} = 0.98 \pm 0.12$$





Including the NLO perturbative ingredients brings down uncertainty to half the size.
[Hoang, Mantry, Michel, AP, Stewart]



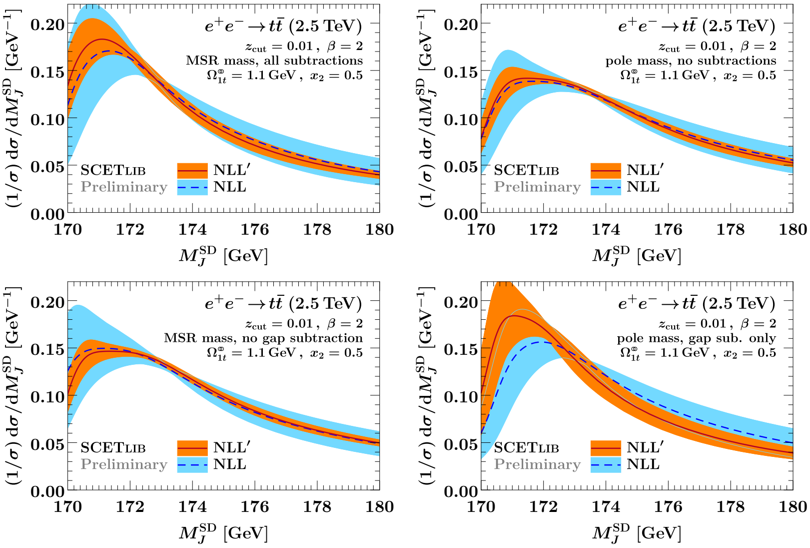
Conclusions

1. Hadron level prediction using only one extra parameter $\Omega_{1q}^{\circledcirc}$.
2. Calibration performed to hadron level MC: $\Omega_{1q}^{\circledcirc}$ properly absorbs all the nonperturbative physics
3. MC top mass compatible with $m_t^{\mathrm{MSR}}(R=1)$. Compatible m_t calibration between Pythia8 and Herwig7 despite very different shapes.
4. Future goals to explore cross section in bins of the decay angle.

Thank you

Backup slides

Impact of renormalon subtractions



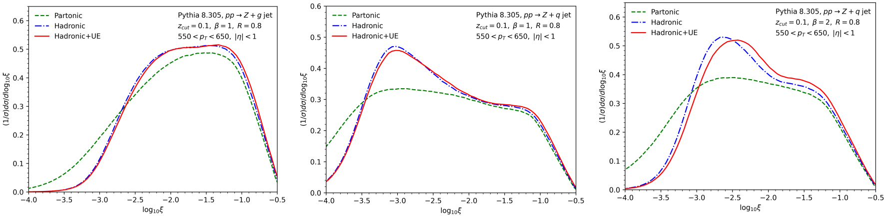
Accounting for the Underlying Event

Describe the underlying event in terms of radiation per unit area (and no shape function)

[Cacciari, Salam, Soyez, 2008], [Ferdinand, Lee, AP]

$$\frac{d\sigma_\kappa^{\mathrm{UE}}}{dm_J^2} = \frac{d\sigma_\kappa^{\mathrm{had}}}{dm_J^2} - \Omega_{1\mathrm{UE}}^{\infty} \frac{d}{dm_J^2}\left(C_1^{\kappa(2)}(m_J^2)\frac{d\hat{\sigma}_\kappa}{dm_J^2}\right) + (1+\beta)\frac{Q\Upsilon_{1\mathrm{UE}}^{-}}{m_J^2} C_2^{(2)\kappa}(m_J^2)\frac{d\hat{\sigma}_\kappa}{dm_J^2} - \beta\frac{Q\Upsilon_{1\mathrm{UE}}^{\perp}}{m_J^2} C_2^{(1)\kappa}(m_J^2)\frac{d\hat{\sigma}_\kappa}{dm_J^2}\,,$$

$$C_1^{\kappa(n)}(m_J^2) \equiv \frac{1}{\langle 1\rangle(m_J^2)}\left\langle\left(\frac{\theta_g}{2}\right)^n\right\rangle(m_J^2)\,, \qquad C_2^{\kappa(n)}(m_J^2) \equiv \frac{m_J^2}{Q^2}\frac{1}{\langle 1\rangle(m_J^2)}\left\langle\left(\frac{\theta_g}{2}\right)^n \delta(z_g - z_{\mathrm{cut}}\theta_g^\beta)\right\rangle(m_J^2)\,.$$



The various moments account for ALL the Φ_J, z_{cut}, β and R dependence of the UE.

Future directions: Accounting for Underlying Event

[J. Aparisi Pozo, Le Blanc, AP, M. Vos]

Hadronization corrections

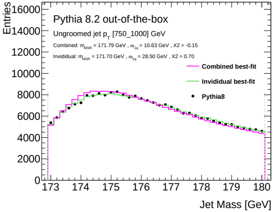
$$\frac{d\sigma_\kappa^{\rm had}}{dm_J^2} = \frac{d\hat\sigma_\kappa}{dm_J^2} - Q\,\Omega_{1\kappa}^{\circledcirc}\,\frac{d}{dm_J^2}\left(C_1^\kappa(m_J^2)\,\frac{d\hat\sigma_\kappa}{dm_J^2}\right)$$

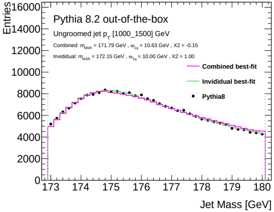
$$C_1^\kappa(m_J^2) \sim \left\langle \theta_g(m_J^2)/2 \right\rangle$$

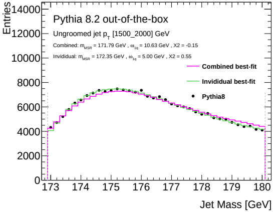
Underlying event contribution

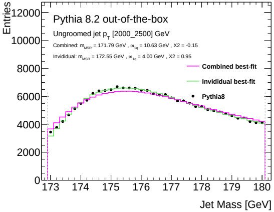
$$\frac{d\Delta\sigma^{\rm UE}}{dm_J^2} = \frac{-Q\Omega_1^{\circledcirc\,\rm UE}}{m_J^2}\,\frac{d}{dm_J^2}\left(C_1^{\kappa(2)}(m_J^2)\,\frac{d\hat\sigma_\kappa}{dm_J^2}\right)$$

$$C_1^{\kappa(2)}(m_J^2) \sim \left\langle \theta_g^2(m_J^2)/4 \right\rangle$$



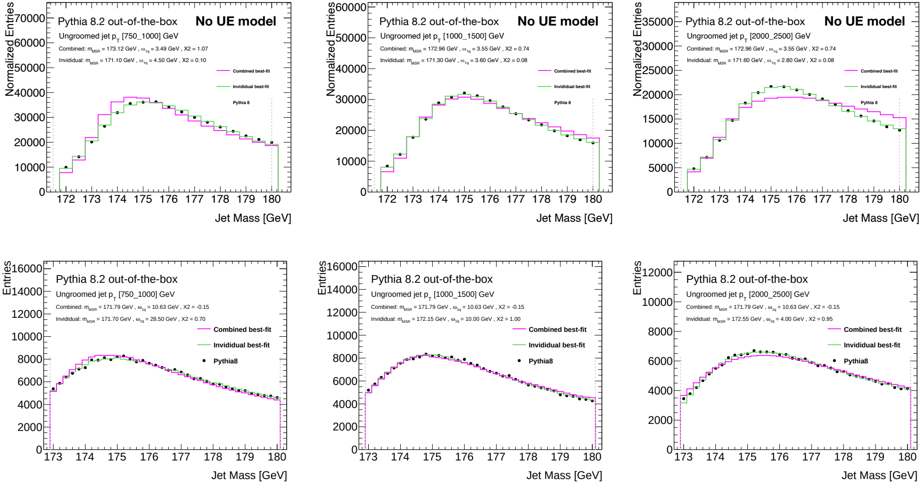






- Consistently describes the p_T dependence of the Underlying Event
- One extra parameter
- Can be constrained from b jets in the large R top jets.

Cannot simply extend the prescription for hadronization to account for UE:



$C_1^{(2)}$ **coefficient consistently describes the p_T dependence of the Underlying Event.**