Soft drop jet mass for precision physics

Boost 2021

Aditya Pathak[1]

[1]University of Manchester

July 31, 2021

Outline

1. Soft drop jet mass for precision α_s
[Hannesdottir, AP, Schwartz, Stewart]

2. Soft drop jet mass for precision m_t
[Hoang, Mantry, AP, Stewart, ATLAS]

Soft drop jet mass cross section

Soft drop criteria: [Larkoski et al. 1402.2657]

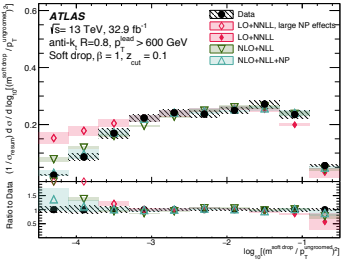
$$\frac{\min(p_{T_i}, p_{T_j})}{p_{T_i} + p_{T_j}} > z_{\rm cut} \left(\frac{\Delta R_{ij}}{R_0} \right)^{\beta}$$

Soft drop jet mass cross section:
[Frye, Larkoski, Schwartz, Yan JHEP 07 (2016) 064; Marzani et al., JHEP07(2017)132; Kardos, Larkoski, Trocsanyi 2002.00942; Kang, Lee, Liu, Ringer JHEP 10 (2018) 137; Anderle, Dasgupta, El-Menoufi, Helliwell, Guzzi Eur. Phys. J. C 80 (2020) 827; Baron Marzani, Theeeuwes, JHEP 08 (2018) 105]

$$\frac{d\sigma}{dm_J^2 d\Phi_J} = \sum_{\kappa=q,g} N_\kappa(\Phi_J, R, \mu) S_G^\kappa(Q_{\rm cut}, R, \beta)\, \Xi_G^\kappa\left(t[\mu_{sg}, \mu_N]\right) \frac{d\sigma_\kappa}{dm_J^2 d\Phi_J}$$

Studies on extraction of α_s using soft drop jet mass cross section have relied on either analytical or Monte Carlo hadronization models.
[Les Houches 2017 Report; Marzani, Reichelt, Schumann, Soyez, Theeuwes 2019]

What is the ultimate uncertainty on α_s without any assumptions about the hadronization model?

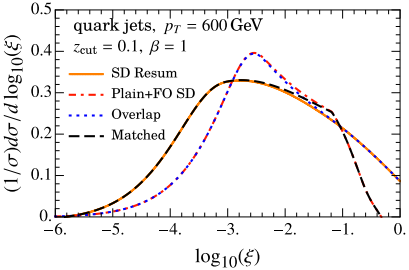


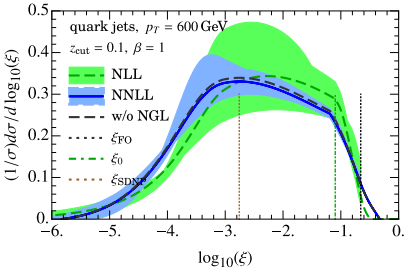
Soft drop jet mass cross section

Recipe for calculating the matched perturbative cross section:

$$\xi = \frac{m_J^2}{p_T^2 R^2}$$

$$d\sigma_{\text{match}} \equiv d\sigma_{\text{sd}}\Big|_{\mu_{\text{sd}\to\text{plain}}} + \Big(d\sigma_{\text{plain}} - d\sigma_{\text{sd}}\Big)\Big|_{\mu_{\text{plain}}} + \Big(d\sigma_{\text{FO}} - d\sigma_{\text{plain}}\Big)\Big|_{\mu_{\text{FO}}} .$$





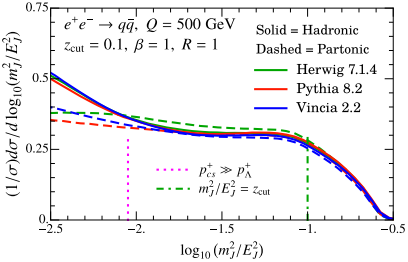
Field theoretic treatment of nonperturbative corrections

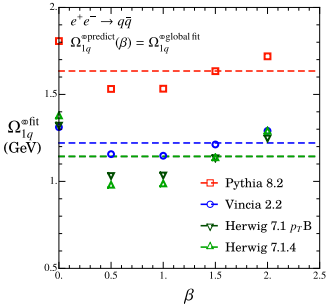
See my Boost 2018, 2019 talks

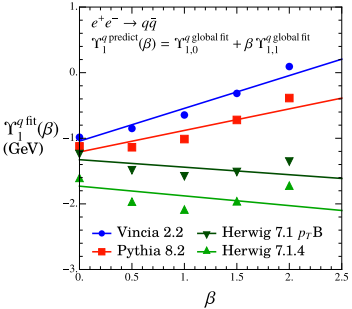
[Hoang, AP, Mantry, Stewart 1906.11843]

$$\frac{d\sigma_\kappa^{\rm had}}{dm_J^2} = \frac{d\hat\sigma^\kappa}{dm_J^2} - Q\,\Omega_{1\kappa}^{\infty}\,\frac{d}{dm_J^2}\left(C_1^\kappa(m_J^2,Q,z_{\rm cut},\beta,R)\,\frac{d\hat\sigma^\kappa}{dm_J^2}\right) + \frac{Q\left(\Upsilon_{1,0}^\kappa+\beta\,\Upsilon_{1,1}^\kappa\right)}{m_J^2}\,C_2^\kappa(m_J^2,Q,\,z_{\rm cut},\beta,R)\,\frac{d\hat\sigma^\kappa}{dm_J^2}$$

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







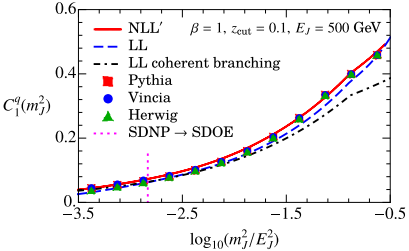
The formalism for NP corrections is based on field theory and model independent

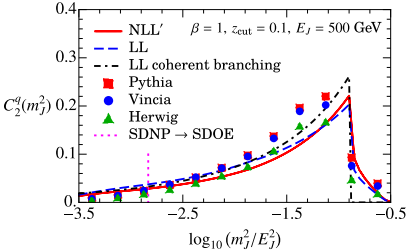
We can improve description of the *perturbative geometry*

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

$$M_1^\kappa(m_J^2, \Phi_J, z_{\rm cut}, \beta, R) \equiv \left(\frac{d\hat\sigma^\kappa}{dm_J^2}\right)^{-1} \int d\theta_g \, \frac{\theta_g}{2} \, \frac{d^2\hat\sigma^\kappa}{dm_J^2 d\theta_g} \,,$$

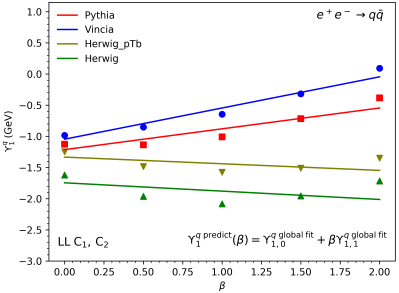
$$M_{-1}^{\kappa\circledcirc}(m_J^2, \Phi_J, z_{\rm cut}, \beta, R) \equiv \left(N_\kappa(\Phi_J, R, z_{\rm cut}, \beta) \frac{d\hat\sigma^\kappa}{dm_J^2}\right)^{-1} \int d\theta_g \, \frac{m_J^2}{Q^2} \, \frac{2}{\theta_g} \, \frac{d}{d\varepsilon} \left[N_\kappa(\Phi_J, R, z_{\rm cut}, \beta, \varepsilon)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

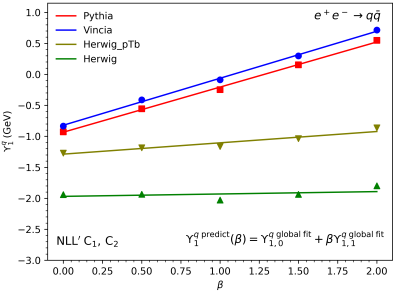




Improved description of hadronization and underlying event

Having an accurate calculation of the double differential cross section at hand we can improve the description of hadroniztion, [Ferdinand, Lee, AP (in progress)]





Impact of Hadronization corrections on α_s measurement

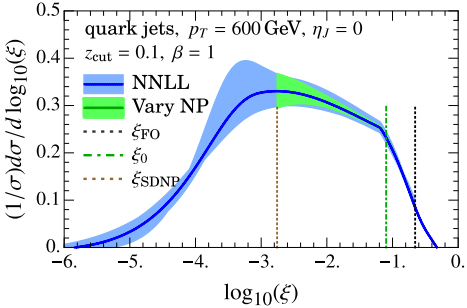
A precision measurement of α_s from soft drop jet mass data will ideally involve **fitting for 7 parameters (!)**:

$$\{\alpha_s(m_Z), \Omega_{1q}^{\infty}, \Upsilon_{1,0}^{1q}, \Upsilon_{1,1}^{1q}, \Omega_{1g}^{\infty}, \Upsilon_{1,0}^{1g}, \Upsilon_{1,1}^{1g}\}$$

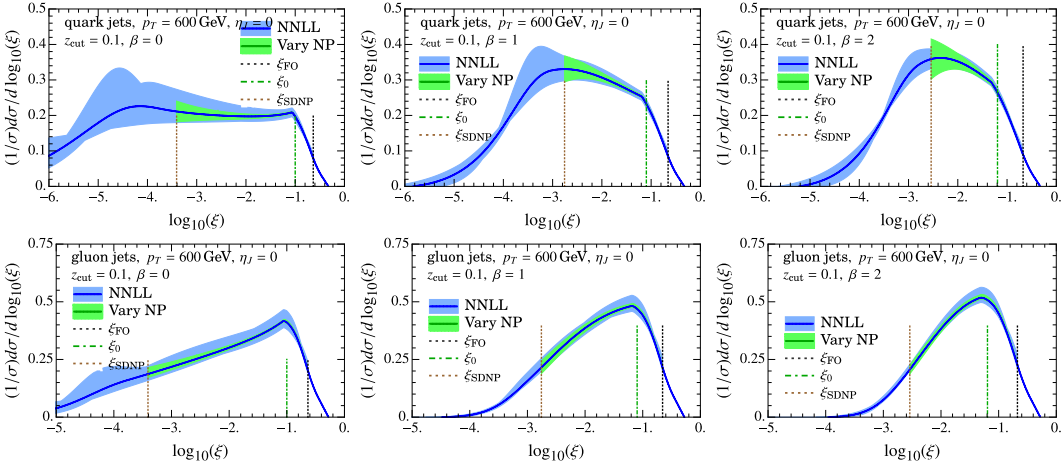
Let us assume that it's really hard to fit for 6 nonperturbative parameters (it's true!), and let their values float:

$$\Omega_{1q}^{\infty} \in [0,1]\text{GeV}\,, \qquad \Upsilon_{1,0}^{1q} \in [-1,1]\text{GeV}\,, \qquad \Upsilon_{1,1}^{1q} \in [-1,1]\text{GeV}$$
$$\Omega_{1g}^{\infty} \in [0,2]\text{GeV}\,, \qquad \Upsilon_{1,0}^{1g} \in [-2,2]\text{GeV}\,, \qquad \Upsilon_{1,1}^{1g} \in [-1,1]\text{GeV}$$

and include that as an uncertainty (and ignore UE for now):

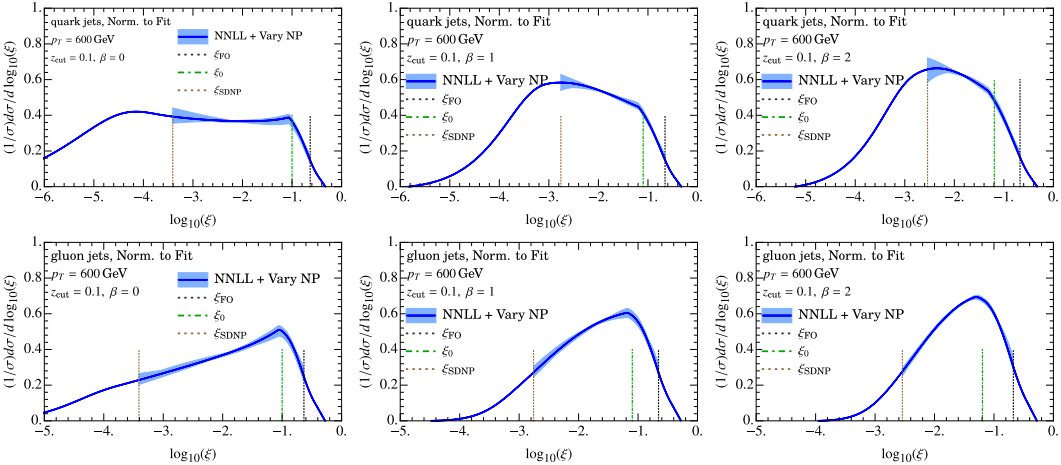


Impact of Hadronization corrections on α_s measurement



Sensitivity to α_s: Cross section normalized to the fit range

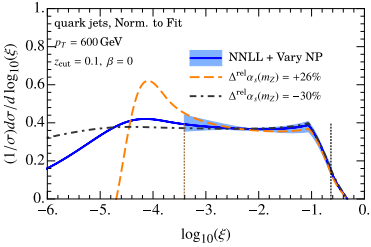
Looking at those curves we might as well normalize them in the fit range:

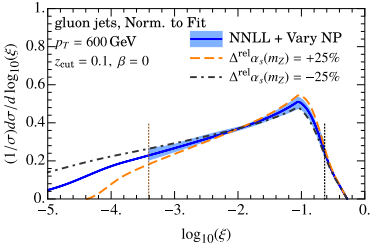


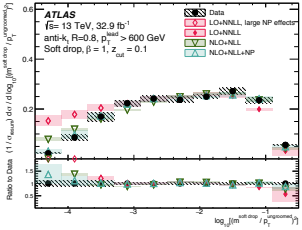
Very small uncertainties! No NGL's!

Sensitivity to α_s: Cross section normalized to the fit range

But, by normalizing to the fit range, we have essentially lost sensitivity to α_s:



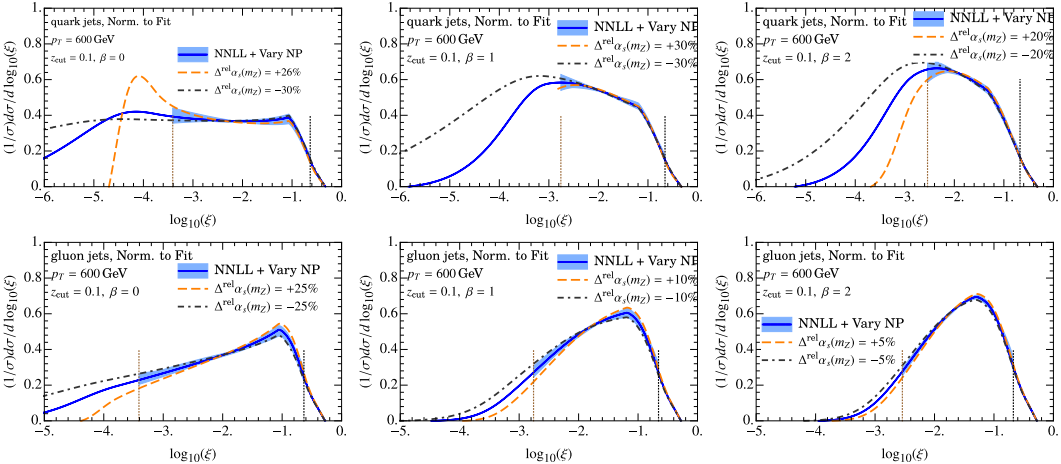




Interestingly the change due to variation α_s is only seen in the nonperturbative region!

Sensitivity to α_s: Cross section normalized to the fit range

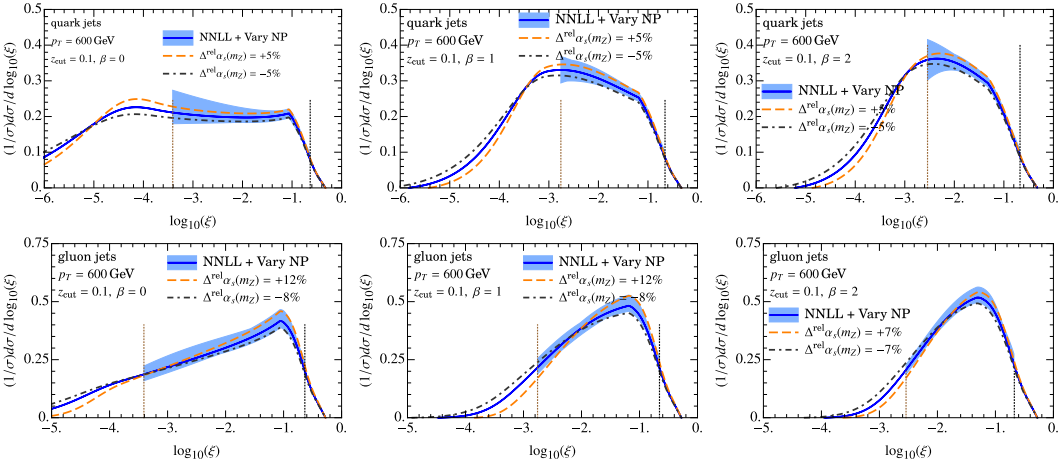
Sensitivity is recovered as grooming is reduced.



So, let's not normalize to the fit range.

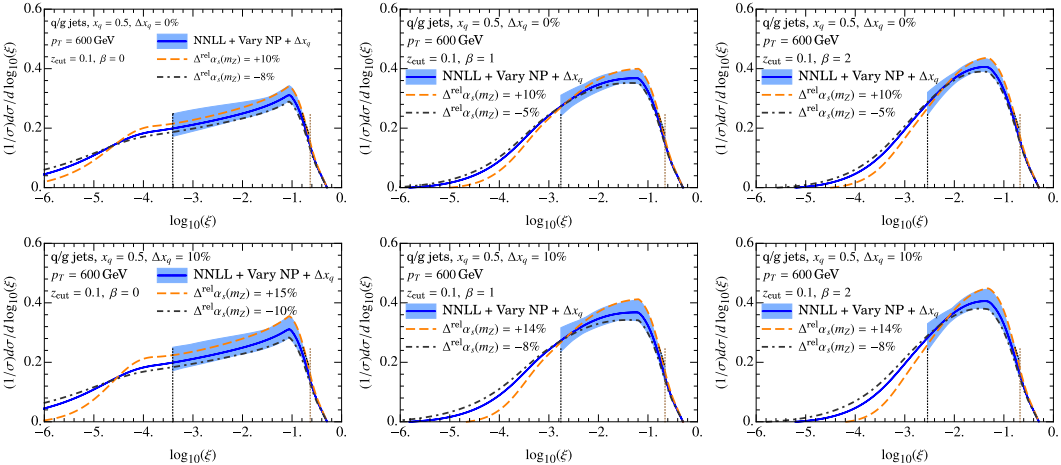
Sensitivity to α_s: Cross section NOT normalized to fig range

Instead, if we don't normalize we retain some sensitivity $\gtrsim 5\%$ for NNLL uncertainties:



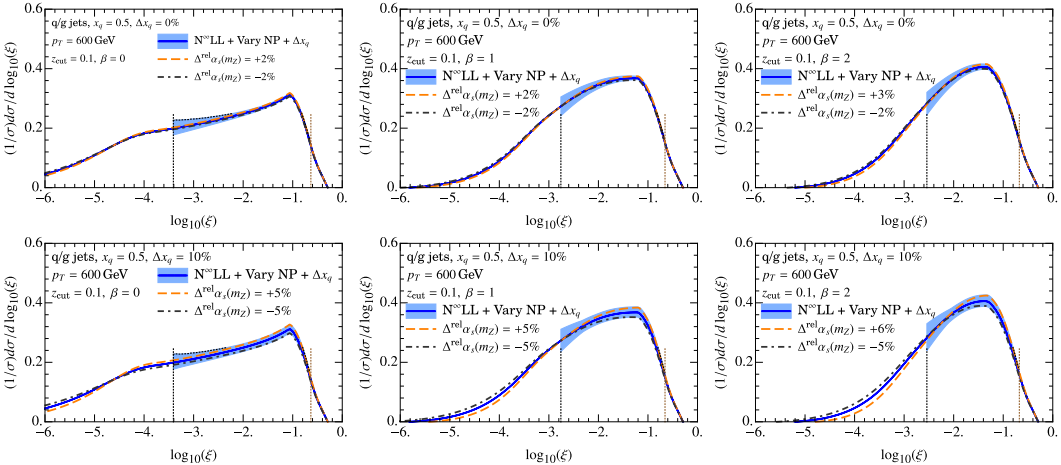
Sensitivity to α_s: Mixed quark and gluon samples

Pure quark/gluon samples are hard to obtain, so let us look at the sensitivity of mixed case for none and 10% q/g fraction uncertainty:



Ultimate Sensitivity to α_s: Mixed quark and gluon samples

If we only consider uncertainty from not knowing the NP parameters, we find **at best** 2% **sensitivity to** $\alpha_s(m_Z)$**.**



Soft drop jet mass for precision m_t

What does top mass measurement entail?

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*

[Hoang AH. 2020. What is the top quark mass? Annu. Rev. Nucl. Part. Sci. 70]

Top mass measurement

$$\sigma^{\rm exp} = \hat{\sigma}(Q, m_t^X, \alpha_s(\mu), \mu; \delta m^X) + \sigma^{\rm NP}(Q, \Lambda_{\rm QCD})$$

Mass Scheme	**Comments**
Short distance mass: $m_t^{\overline{\rm MS}}$, $m_t^{\rm PS}$, $m_t^{\rm MSR}$	Involves a nonzero counter term that compensates for the linear IR sensitivity in $\hat{\sigma}$
Pole mass, $m_t^{\rm pole}$	leaves unphysical $\mathcal{O}(\Lambda_{\rm QCD})$ corrections uncancelled
Monte Carlo Mass $m_t^{\rm MC}$	A parameter in the MC simulation that is not $m_t^{\rm pole}$ [Hoang et al. 1807.06617]

Grooming boosted top quark jets

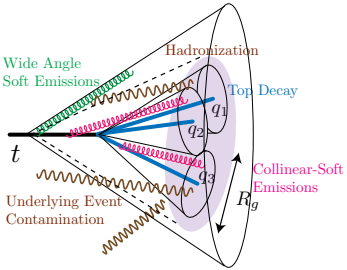
Factorization at NLL [Hoang, Mantry, AP, Stewart 1708.02586]

$$\frac{d\sigma^{\rm NLL}(\Phi_J)}{dM_J} = N(\Phi_J, z_{\rm cut}, \beta, \mu) \int d\tilde{h}\; P\Big(\tilde{h}, \frac{m_t}{Q}\Big) \int d\ell^+\; J_B\Big(\hat{s}_t - \frac{Q\ell^+}{m_t}, \delta m, \Gamma_t, \mu\Big)$$

$$\times \int dk^+\; S_c^q\Big[\Big(\ell^+ - \max\Big\{C_1^{q(pp)}(m_t\hat{s}_t), \frac{m_t\tilde{h}}{Q}\Big\} k^+\Big) Q_{\rm cut}^{\frac{1}{1+\beta}}, \beta, \mu\Big]$$

$$\times F_{\oplus}^q(k^+)\Big\{1 - \Theta\Big(C_1^{q(pp)}(m_t\hat{s}_t) - \frac{m_t\tilde{h}}{Q}\Big)\frac{Qk^+}{m_t}\frac{dC_1^{q(pp)}(m_t\hat{s}_t)}{d\hat{s}_t}\Big\}$$

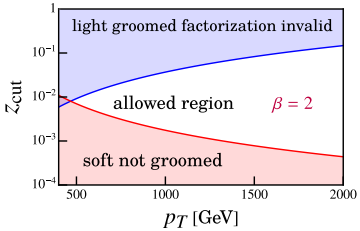
See my Boost 2017 talk



Jet grooming for fat top jets

- Reduces effects of underlying event, pile up and hadronization

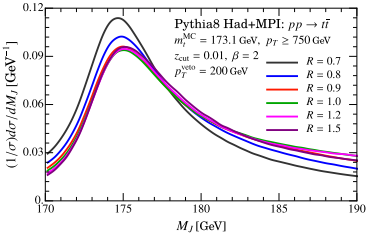
  [Hoang, Mantry, AP, Stewart 1708.02586]
- *Decouples* the jet from the rest of the event
- Complicates considerations of the inclusive treatment, but we can deal with that

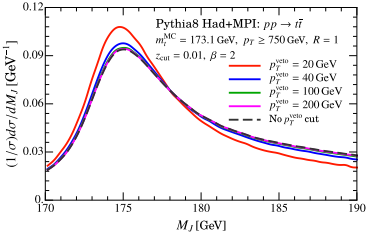


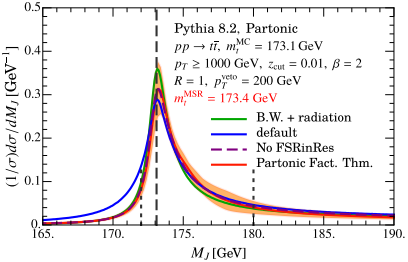
Soft drop jet mass is robust and enables analytical calculations

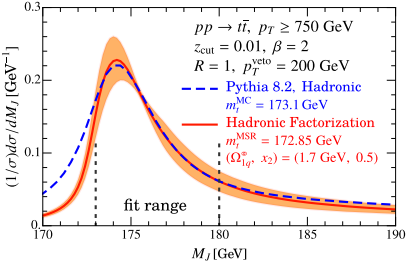
See my Boost 2017 talk

[Hoang, Mantry, AP, Stewart 1708.02586]









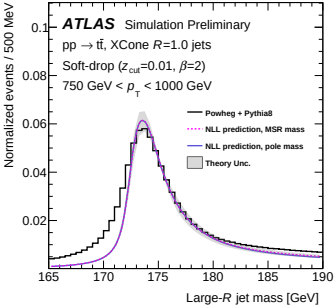
Precise Interpretation of MC top mass in ATLAS Monte Carlo

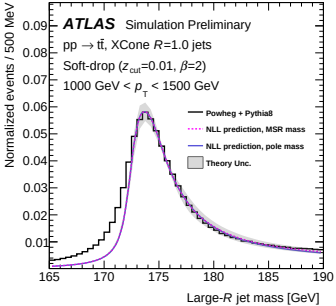
Relation between m_t^{MC} in nominal POWHEG+PYTHIA8 and m_t^{MSR}:

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

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

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





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

Precise Interpretation of MC top mass in ATLAS Monte Carlo

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

Uncertainty breakdown:

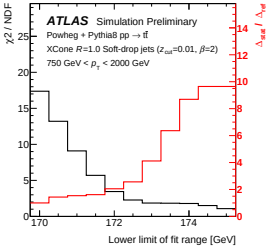
Source of Uncertainty	**size [MeV]**	**comment**
Theory	+ 230/-310	Envelope of NLL scale variations
Fit methodology	± 190	fit range, p_T bins
UE model	± 155	A14 eigentune variations, CR models
Observable definition	± 200	$z_{\rm cut} = 0.01, 0.005, 0.02,\ \beta = 1, 2,$ Anti-k$_t$ / XCone jets

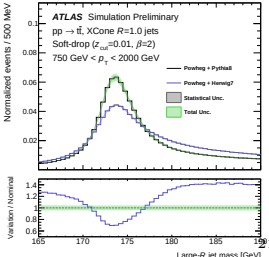
Calibration for POWHEG+HERWIG7 consistent with PYTHIA despite very different shapes!

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

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

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



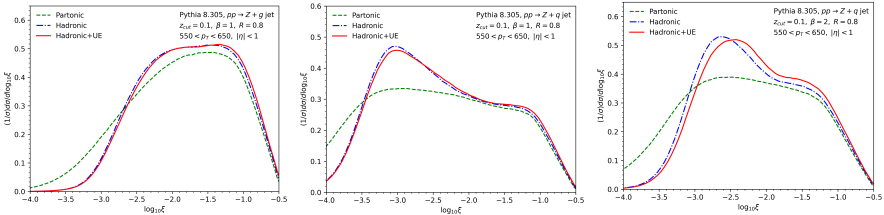


Future directions: Accounting for Underlying Event

Describe the underlying event in terms of radiation per unit area (and no shape function)
[Ferdinand, Lee, AP], [Cacciari, Salam, Soyez, 2008]

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

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



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

Future directions: Accounting for Underlying Event

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

Hadronization corrections

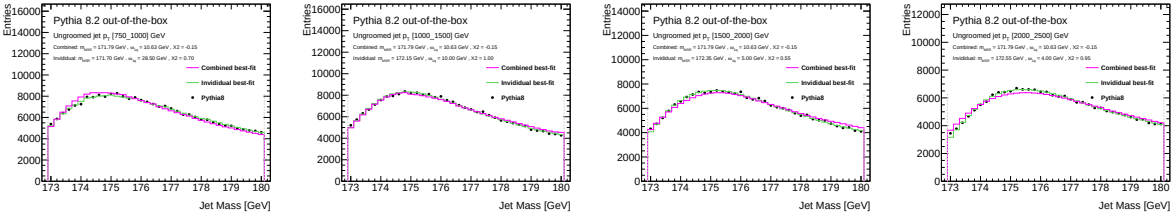
$$\frac{d\sigma_\kappa^{\rm had}}{dm_J^2} = \frac{d\hat{\sigma}_\kappa}{dm_J^2} - Q\,\Omega_{1\kappa}^{\infty}\,\frac{d}{dm_J^2}\left(C_1^\kappa(m_J^2)\,\frac{d\hat{\sigma}_\kappa}{dm_J^2}\right)$$

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

Underlying event contribution

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

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



- 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.

Conclusion

Sensitivity to α_s: discussion

1. Quark and gluon jets have different sensitivities to α_s.
2. NNLL uncertainty compatible with uncertainties from floating 6 nonperturbative parameters.
3. Not normalizing the cross section to the fit range, we can achieve 5-10% uncertainty, with any further uncertainty in q/g-jets fraction adding up.
4. If not deciding to fit for NP parameters, the ultimate possible uncertainty is $\sim 2\%$.
5. The groomed jet mass cross section when normalized in a fit range is essentially independent of α_s. Note that the location of the cusp does depend on the fixed order matching [Larkoski 2006.14680].
6. For $z_{\rm cut} = 0.1$, effects of Underlying event significant for $\beta = 2$, but less so for $\beta = 0$ and $\beta = 1$.

MC top mass calibration:

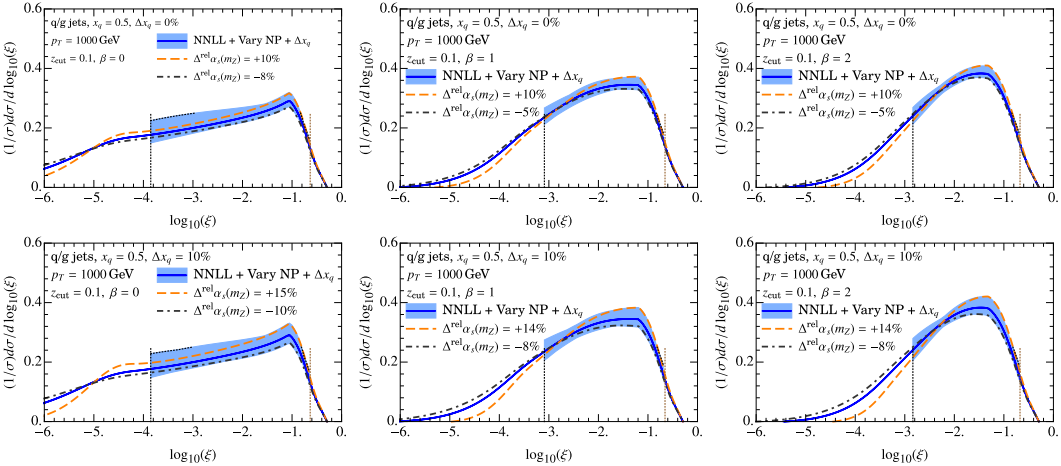
1. Calibration performed to hadron level MC
2. MC top mass compatible with $m_t^{\rm MSR}(R = 1)$.
3. Future goals to improve perturbative precision and include Underlying Event.

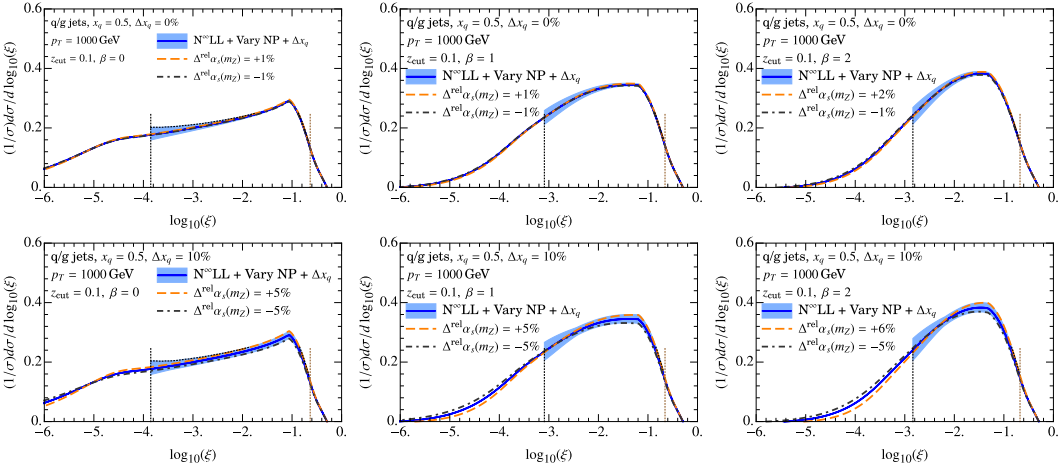
Thanks

Backup

Sensitivity to α_s: Mixed quark and gluon samples

Here we show plots for $p_T = 1$ TeV.



Ultimate Sensitivity to α_s: Mixed quark and gluon samples

Here we show plots for $p_T = 1$ TeV.