Precision Top Mass Determination at the LHC Using Jet Grooming

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in collaboration with

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arXiv:1906.11843

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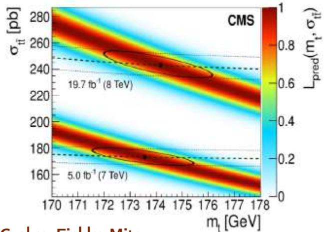
October 2, 2019

Der Wissenschaftsfonds.

There exist variety of ways for measuring m_t

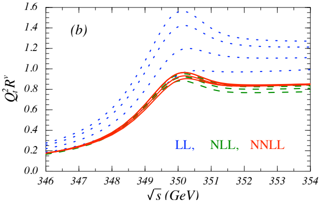
Top mass can be measured in a variety of ways. Some examples:

Total cross section:



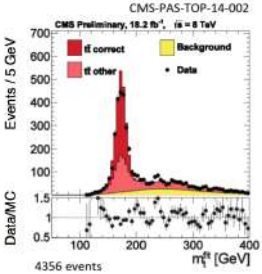
Czakon, Fielder, Mitov

Threshhold scan:



Fadin, Khoze; Peskin, Strassler; Hoang, Manohar, Stewart, Teubner; . . .

Kinematic reconstruction:



The top mass has been measured at the LHC at sub-percent accuracy via kinematic extractions:

- CMS @ 8 TeV (2016) : $m_t = 172.35 \pm 0.16$ (stat + JES) $\pm$ 0.48 (sys) GeV
  Phys. Rev. D 93 (2016)
- ATLAS @ 8 TeV (2017) : $m_t = 172.08 \pm 0.41$ (stat) $\pm$ 0.81 (sys) GeV
  ATLAS-CONF-2017-071

But, in what top mass scheme are we measuring this?

No field theoretic definition of Monte Carlo top mass parameter exists

Kinematic extractions:

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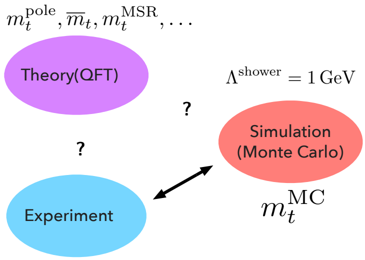
These extractions have relied on Monte Carlo simulations and lack a precise field theoretic interpretation.



Benchmark for this work:

- We need a kinematic observable that can be calculated in theory in a specified short distance mass scheme and has the required sensitivity to m_t.
- $m_t^{\rm MC}$ depends on the intrinsic details of parton shower [see Daniel Samitz's talk], hence we want minimal or no dependence on Monte Carlo.
- The observable must be robust against the nonperbative corrections from hadronization and contamination from the Underlying Event. (I trust my fellow experimentalists to deal with Pile-up).
- The observable must retain the sensitivity even after unfolding has been applied to the data.

We will use effective field theories and jet substructure tools to achieve these goals

Outline

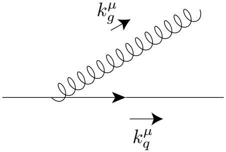
1. Plain light quark/gluon jet mass
2. Plain Top Jet Mass
3. Soft Drop Grooming
4. Light Grooming for Top Jets
5. Nonperturbative corrections to groomed light quark/gluon jet mass
6. Nonperturbative corrections to groomed top jet mass
7. Hadron Level Factorization for Groomed Top Jets
8. Monte Carlo Top Mass Calibration using Groomed Top Jet Mass
9. Conclusions

EFT modes for the Plain jet mass

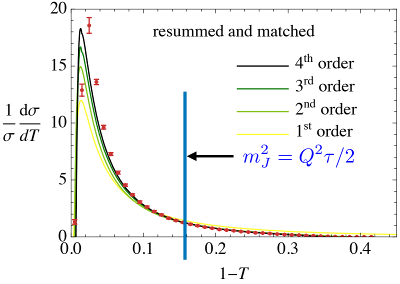
Consider a gluon emission off an energetic quark.

$$m_J^2 = (k_q + k_g)^2 = 2E_q E_g(1 - \cos\theta_{qg}) = Q p_g^+$$

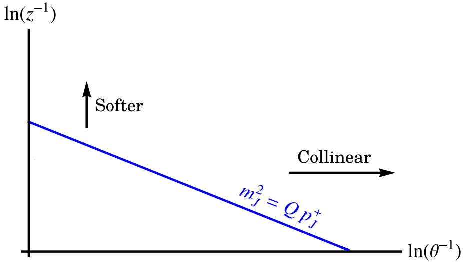
$$p^\pm = E \mp \vec{p}\cdot\vec{n}_{\rm jet}\,, \qquad z_i = E_i/E_J = p_i^-/Q$$



For a given jet mass m_J^2 the gluon will lie on the blue line



Becher, Schwartz 0803.0342



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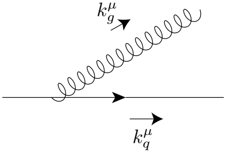
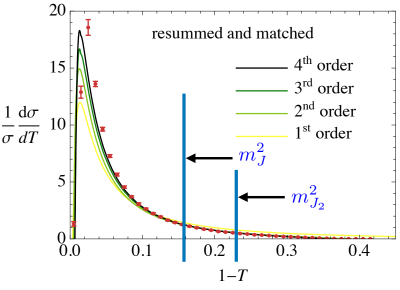


Moving further into the tail region moves the blue line down



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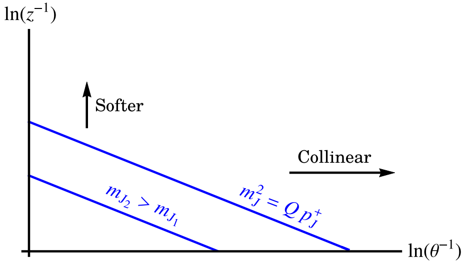

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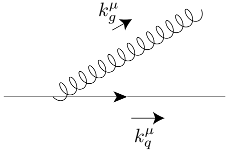
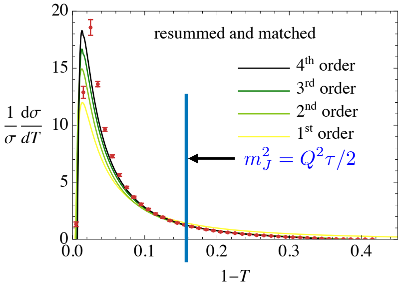


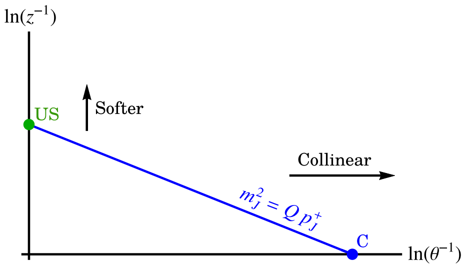
In the soft/collinear limit: $m_J^2 \simeq Q p^+_{\rm coll,\, usoft}$

$$z_{us} \sim \frac{m_J^2}{Q^2},\ \theta_{us} \sim 1 \qquad z_c \sim 1,\ \theta_c \sim \frac{m_J}{Q}$$



Becher, Schwartz 0803.0342

(Ultra-)Soft and collinear modes:



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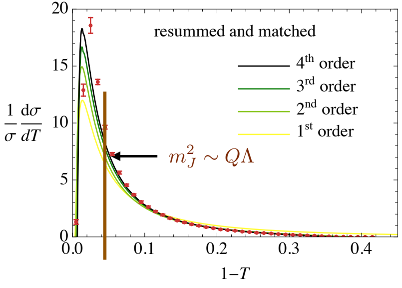


Becher, Schwartz 0803.0342

Now add a background of NP particles at all angles:

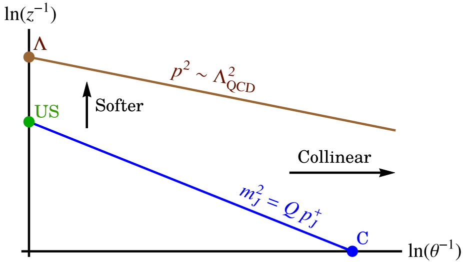
$$p_\Lambda^+ p_\Lambda^- - p_{\Lambda\perp}^2 \sim \Lambda^2_{\rm QCD}$$

$$\text{wide angle NP} \to \Lambda_{\rm QCD}\,(1,\ 1,\ 1)$$

$$\text{collinear NP} \to \Lambda_{\rm QCD}\left(\frac{\theta_\Lambda}{2},\ \frac{2}{\theta_\Lambda},\ 1\right)$$

$$z_\Lambda(\theta_\Lambda) = \frac{2\Lambda_{\rm QCD}}{Q\theta_\Lambda}$$

Dominant NP mode = Wide angle Λ mode



EFT modes for the Plain jet mass

In SCET this is captured by the factorization formula: **Becher, Schwartz 0803.0342**

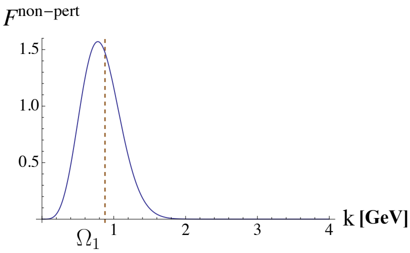
$$\frac{1}{\sigma_0}\frac{d\sigma}{d\tau} = H(Q^2,\mu)\int dp_L^2\, dp_R^2\, dk\, J(p_L^2,\mu)\, J(p_R^2,\mu)\, S_T(k,\mu)\, \delta\left(\tau - \frac{p_L^2+p_R^2}{Q^2} - \frac{k}{Q}\right)$$

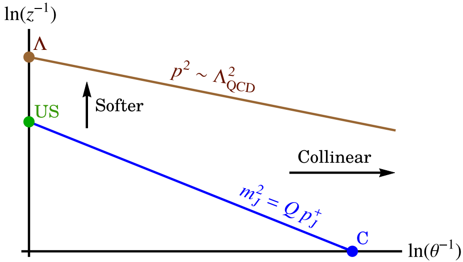
The Nonperturbative model function is then included in the Soft function:

$$S_T(\tau) = \int d\ell^+ d\ell^-\ \delta\left(\tau - \frac{\ell^+ + \ell^-}{Q}\right) S(\ell^+,\ell^-)\,,$$

where

$$S(\ell^+,\ell^-) = \int_{-\infty}^{\infty} dk^+ dk^-\, S_{\rm part}(\ell^+ - k^+, \ell^- - k^-)\, F(k^+,k^-)\,.$$





Heavy Quark Effective Theory for top quark

To connect the framework of light quark jet mass to top jets we isolate the top from the surrounding radiation using (boosted) HQET.

$$\mathcal{L}_{\rm pole} = \bar{h}_v\Big(iv\cdot D + \frac{i}{2}\Gamma_t\Big)h_v\,, \qquad v^\mu = \Big(\frac{m}{Q}, \frac{Q}{m}, \mathbf{0}_\perp\Big)$$

Here we integrated out the pole mass of the top. For other schemes where

$$m_t^{\rm pole} = m + \delta m$$

we have

$$\mathcal{L} = \bar{h}_v\Big(iv\cdot D + \frac{i}{2}\Gamma_t + \delta m\Big)h_v\,, \qquad \delta m \sim \Gamma_t$$

Assume a top quark produced close to mass shell:

$$p_t^\mu = m_t v^\mu + r^\mu\,, \qquad r^0 \ll p_t^0$$

$$M_J^2 = m_t^2 + 2m_t v\cdot r + \mathcal{O}(r^2/m_t^2)$$

A convenient variable for top quarks in the peak region:

$$\hat{s}_t = \frac{M_J^2 - m_t^2}{m_t} = 2v\cdot r\,, \qquad \hat{s}_t \sim \Gamma_t$$

Ultra collinear modes in HQET:

$$k_{uc} \sim \Gamma_t\Big(\frac{m_t}{Q}, \frac{Q}{m_t}, \mathbf{0}_\perp\Big)\,, \qquad k_{uc}^2 \sim \Gamma_t^2\,, \qquad z_{uc} \sim \frac{\Gamma_t}{m_t}\,, \qquad \theta_{uc} \sim 2\frac{m_t}{Q}\,.$$

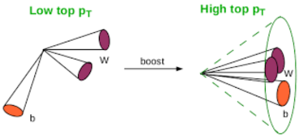
Heavy Quark Effective Theory for top quark

Hence the SCET jet function for top quark is modified to the bHQET jet function: **[Fleming et.al 2008]**, **[Jain et. al. 0801.0743]**

$$J(p^2, \mu) \to J_B(\hat{s}_t, \delta m, \Gamma_t, \mu)$$

One key assumption is that we are inclusive over the decay products. Hence use full decay width Γ_t:

$$J_B(\hat{s}_t, \Gamma_t, \delta m, \mu) = \int_{-\infty}^{\hat{s}_t} \mathrm{d}\hat{s}' \; J_B(\hat{s}_t - \hat{s}', \delta m, \mu) \frac{\Gamma_t}{\pi\left(\hat{s}'^{\,2} + \Gamma_t^2\right)}$$
$$= \int_{-\infty}^{\hat{s}_t} \mathrm{d}\hat{s}' \; J_B(\hat{s}_t - \hat{s}' - 2\delta m, \mu) \frac{\Gamma_t}{\pi\left(\hat{s}'^{\,2} + \Gamma_t^2\right)}$$



This leads to a factorization theorem for $e^+e^- \to t\bar{t}$ in the peak region and boosted regime **Fleming et.al 2008**

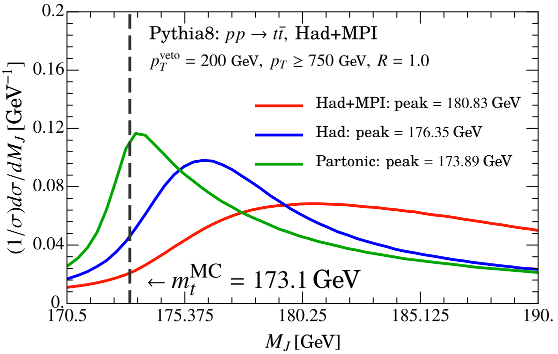
$$\frac{d\hat{\sigma}^{\rm plain}_{e^+e^-\to t\bar{t}}}{dM^2_{J_t}\, dM^2_{J_{\bar{t}}}} = \sigma_0 H_Q(Q, m_t, \mu)\, H_m\left(m_t, \frac{Q}{m_t}, \mu\right) \int_0^\infty d\ell^+ \int_0^\infty d\ell^- \, S^{\rm hemi}(\ell^+, \ell^-, \mu)$$
$$J_B\left(\hat{s}_t - \frac{Q}{m_t}\ell^+, \Gamma_t, \delta m_t, \mu\right) J_B\left(\hat{s}_{\bar{t}} - \frac{Q}{m_t}\ell^-, \Gamma_t, \delta m_t, \mu\right) + \mathcal{O}\left(\frac{m_t^2}{Q^2}, \frac{\Gamma_t, \hat{s}_t, \hat{s}_{\bar{t}}}{m_t}, \frac{\alpha_s m_t}{Q}\right),$$

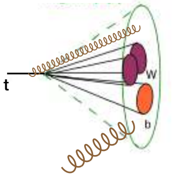
One has now ability to measure top mass in a specific short distance mass scheme (with $\delta m \sim \Gamma_t$) via jet mass of boosted tops. We employ MSR mass:

$$m_t^{\rm pole} = m_t^{\rm MSR}(R) + R \sum_{n=1}^{\infty} a_n^{\overline{\rm MS}}(n_l) \left(\frac{\alpha_s^{(n_l=5)}(R)}{4\pi}\right)^n, \qquad R \sim \Gamma_t$$

Challenges at a Hadron Collider

Very nice but not good enough for hadron colliders . . .



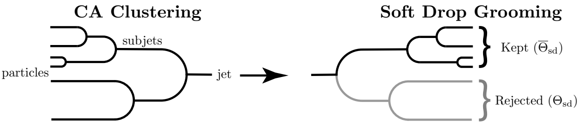


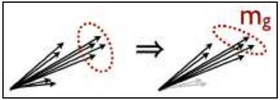
Hadronization and Underlying event have a significant effect on the spectrum. Peak position of the jet mass spectrum shifts by as much as 5 GeV.

The contamination lives in the soft sector (and spoils our beautiful physics in the collinear sector).

Reduce hadronization corrections using Soft Drop

Studies of boosted objects at the LHC and the need to reduce contamination from the underlying event and pile-up led to development of **jet grooming**.



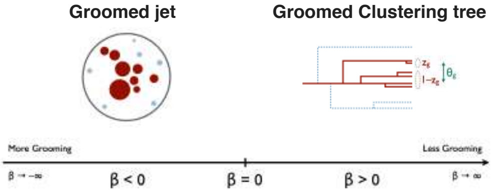


Soft drop grooming involves reclustering a jet with purely angular measure (CA clustering) and selectively throwing away the softer branches.

Soft Drop criteria:

$$\frac{\min[p_{Ti}, p_{Tj}]}{(p_{Ti} + p_{Tj})} > z_{\rm cut} \left(\frac{R_{ij}}{R_0}\right)^{\beta}$$

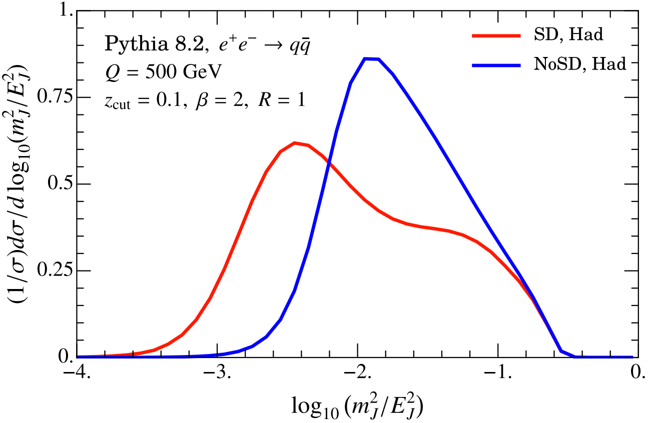
Larkoski, Marzani, Soyez, Thaler 2014



The criteria is IR safe for $\beta > 0$ and Sudakov safe for $\beta = 0$ (calculable after performing resummation)
Larkoski, Thaler 2013

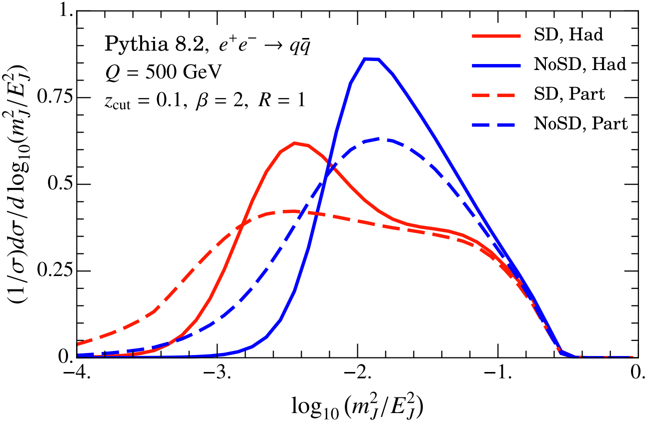
Groomed jet mass is less sensitive to hadronization corrections

Compare the groomed and ungroomed jet mass spectrum (for massless jets here):



Groomed jet mass is less sensitive to hadronization corrections

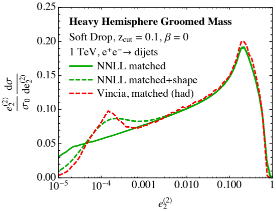
The nonperturbative corrections to the groomed jet mass become significant at much smaller jet masses compared to the ungroomed jet mass.



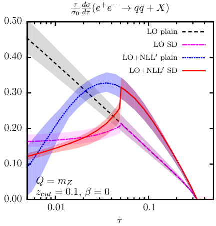
Hence the groomed jet mass spectrum is a desirable candidate for m_t measurement.

Huge Interest in Understanding Groomed Observables

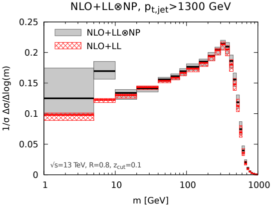
Partonic resummation of groomed jet mass is well understood:



Frye, Larkoski, Schwartz, Yan 2016

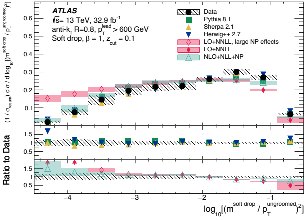


Baron et al. 1803.04719



Marzani et al., JHEP07(2017)132

Has been measured at the LHC:



ATLAS 1711.08341

More studies:

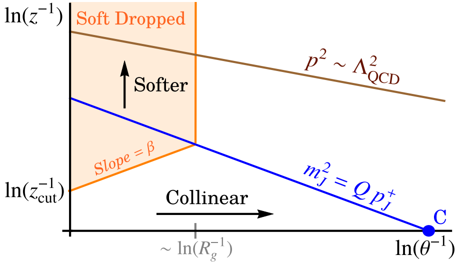
- Other observables: groomed D_2 [Larkoski, Moult, Neill 2017], groomed angularity for b-jets [Lee, Shrivastava, Vaidya 2019], Jet mass for inclusive jets and groomed angularities at the LHC [Kang, Lee, Liu, Ringer 2018].
- Fixed order pieces at NNLO: [Kardos et al. 1807.11472].
- Nonperturbative corrections: [Hoang, AP, Mantry, Stewart 2019]

EFT modes for the Groomed Jet Mass

We identify the relevant region for our analysis by considering the EFT modes for groomed jet mass measurement

- Turning on soft drop removes emissions in the shaded region.

$$z > z_{\rm cut}\theta^{\beta}$$



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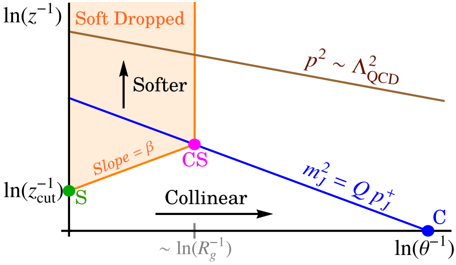
$$p^\mu_{CS} \sim \frac{m_J^2}{Q\,\zeta}\left(\zeta,\ \frac{1}{\zeta},\ 1\right) \qquad p^\mu_C \sim \left(\frac{m_J^2}{Q},\ Q,\ m_J\right)$$

$$\zeta \equiv \left(\frac{m_J^2}{Q\,Q_{\rm cut}}\right)^{\frac{1}{2+\beta}} \qquad Q_{\rm cut} \equiv 2^\beta Q z_{\rm cut}$$

$$\theta_{cs}/2 \sim \zeta$$



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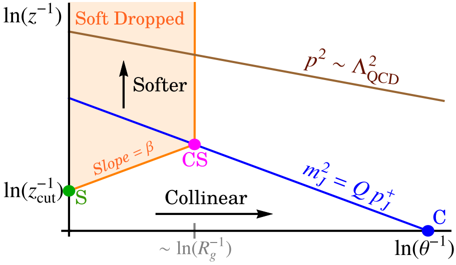
Parton level factorization formula

Frye, Larkoski, Schwartz, Yan 2016

$$\frac{d^2\hat\sigma}{dm_J^2 d\Phi_J} = \sum_{\kappa=q,g} N_\kappa(\Phi_J, R, z_{\rm cut}, \beta, \mu)$$

$$\times \int d\ell^+ J_\kappa\big(m_J^2 - Q\ell^+,\ \mu\big)\, Q_{\rm cut}^{\frac{1}{1+\beta}}\ S_c^{\kappa}\Big[\ell^+ Q_{\rm cut}^{\frac{1}{1+\beta}}, \beta, \mu\Big]\,.$$



- Same Jet function as in the case of ungroomed jets
- The Collinear soft function depends on $z_{\rm cut}$ and ℓ^+ only via the combination $\ell^+ Q_{\rm cut}^{\frac{1}{1+\beta}}$.

"Light grooming" is required for top quark jets

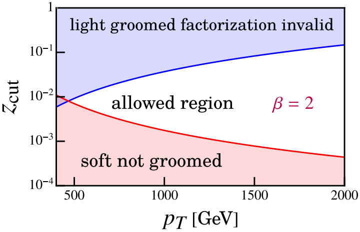
In order to retain the inclusive treatment of the decay products in the bHQET Jet function and also groom effectively at the same time we require the following:

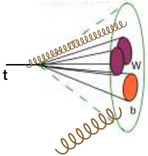
- Avoid grooming aggressively so as to not touch the decay products:

$$z_{\mathrm{cut}} \lesssim \frac{\Gamma_t}{h^{2+\beta} m_t}\left(\frac{p_T}{m_t}\right)^{\beta}, \qquad h \sim 2$$

- Groom enough so as to get rid of wide angle soft modes (where also the contamination from hadronization and UE lives):

$$z_{\mathrm{cut}}^{\frac{1}{2+\beta}} \gg \frac{1}{2}\left(\frac{\Gamma_t}{m_t}\frac{m_t^2}{p_T^2}\right)^{\frac{1}{2+\beta}}$$





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- Avoid grooming aggressively so as to not touch the decay products:

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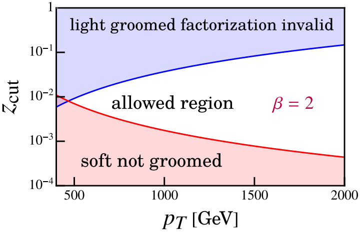
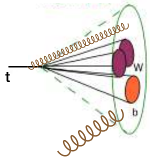
- Groom enough so as to get rid of wide angle soft modes (where also the contamination from hadronization and UE lives):

$$z_{\rm cut}^{\frac{1}{2+\beta}} \gg \frac{1}{2}\left(\frac{\Gamma_t}{m_t}\frac{m_t^2}{p_T^2}\right)^{\frac{1}{2+\beta}}$$





We then arrive at the following parton level factorization formula:

$$\frac{d\hat{\sigma}}{dM_J d\Phi_J} = N(\Phi_J, R, m_t, z_{\rm cut}, \beta, \mu) \times \int d\ell^+ \, J_B\left(\hat{s}_t - \frac{Q\ell^+}{m_t}, \delta m, \Gamma_t, \mu\right) S_c^q\left[\ell^+ Q_{\rm cut}^{\frac{1}{1+\beta}}, \beta, \mu\right]$$

- Same bHQET jet function J_B as in the ungroomed $t\bar{t}$ jets
- Same collinear soft function S_c^q as in the massless quark jets

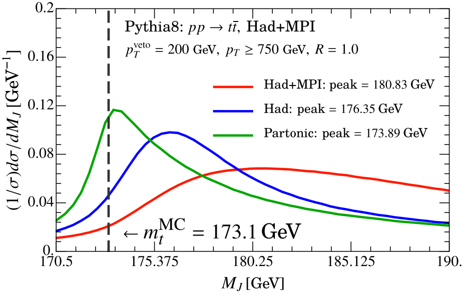
Light grooming is effective in the peak region

Light grooming achieves significant reduction of the contamination in the peak region

We take $z_{\rm cut} = 0.1$, $\beta = 2$ and $p_T \geq 750$ GeV for illustration.

Comparing jet mass spectrum at parton level, hadron level, and with MPI

No soft drop:



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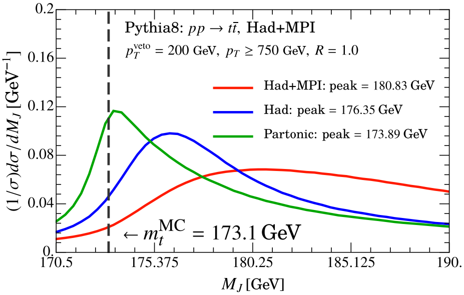
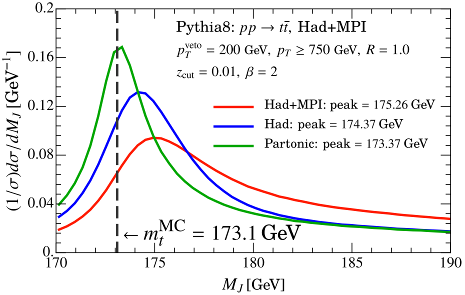


With soft drop:



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Comparing jet radius dependence

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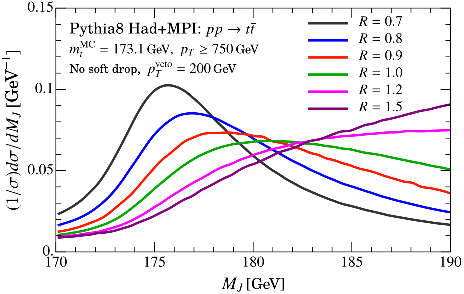

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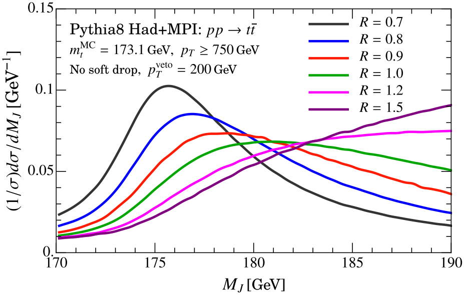

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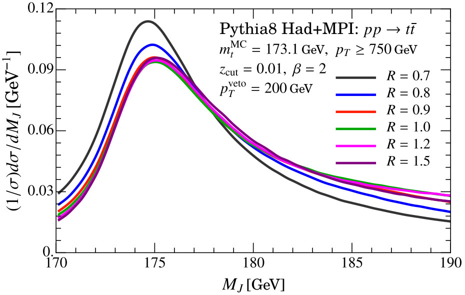

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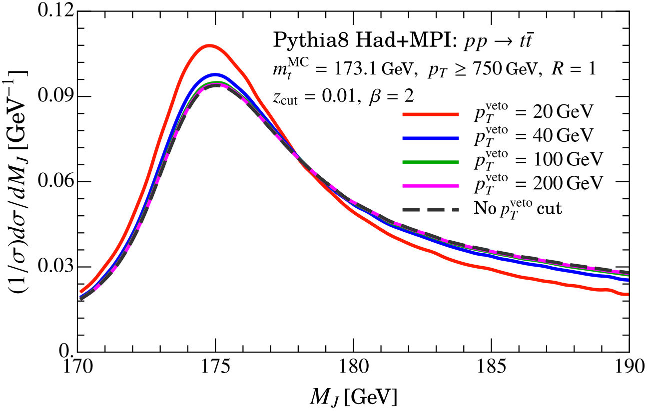
Light grooming achieves significant reduction of the contamination in the peak region

We take $z_{\rm cut} = 0.1$, $\beta = 2$ and $p_T \geq 750$ GeV for illustration.

Dependence on p_T veto on additional jets is mild

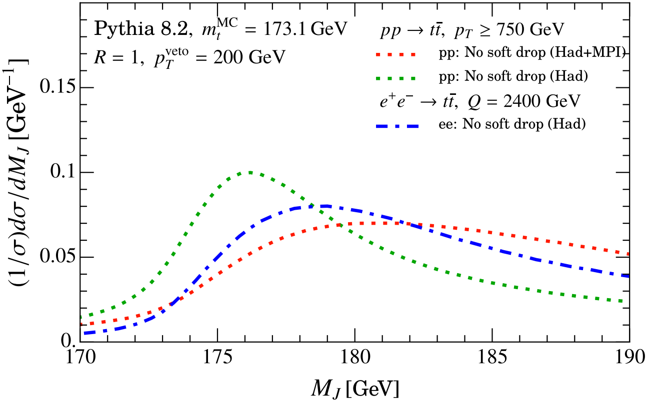


Light grooming is effective in the peak region

Light grooming achieves significant reduction of the contamination in the peak region

pp and e^+e^- spectra differ substantially without soft drop.

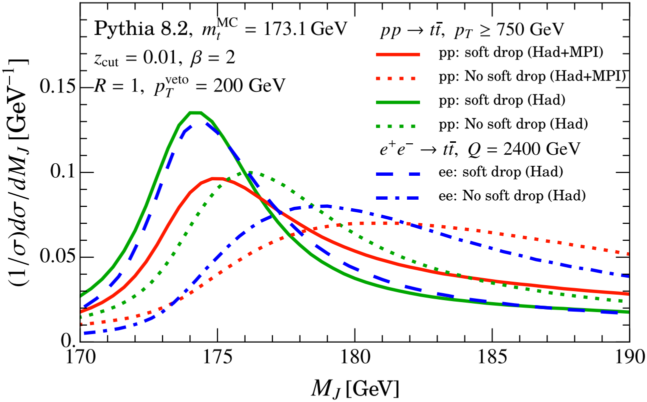
$$Q = 2400 \text{ GeV} \sim p_T \geq 750 \text{ GeV}\,,\ |\eta| \leq 2.5$$



Light grooming is effective in the peak region

Light grooming achieves significant reduction of the contamination in the peak region

pp and e^+e^- spectra agree very well with soft drop (at hadron level)

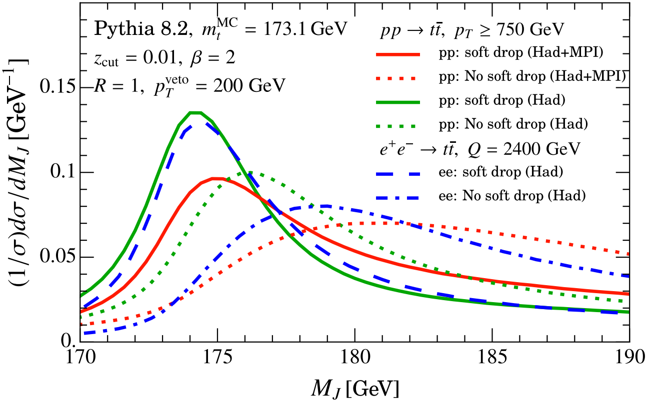


Light grooming is effective in the peak region

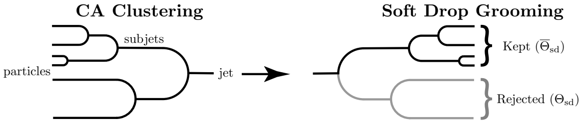
Light grooming achieves significant reduction of the contamination in the peak region

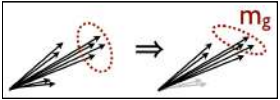
pp and e^+e^- spectra agree very well with soft drop (at hadron level)

All we need now is a hadron level factorization formula for light groomed top jets



Nonperturbative corrections to groomed jet mass are intricate



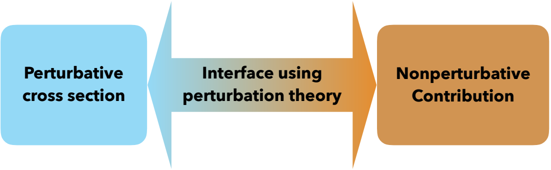


In what way is the groomed jet mass different?

- **C/A clustering:** NP corrections could depend on perturbative branching history. Not even obvious if a nonperturbative factorization is possible!
- **NP catchment area:** no longer determined by the jet radius, no fixed geometric region.
- **Universality:** dependence on $z_{\rm cut}$? β? Is there any connection between power corrections in groomed and ungroomed event shapes?

These questions can be answered within the framework of Effective field Theories

Hoang, AP, Mantry, Stewart 1906.11843



EFT modes for the Groomed Jet Mass

We identify the relevant region for our analysis by considering the EFT modes for groomed jet mass measurement

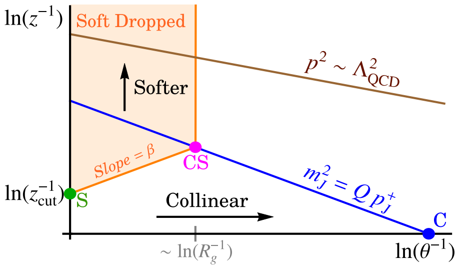
- Turning on soft drop removes emissions in the shaded region.
- CS denotes the emission at widest angle that satisfies the soft drop condition.

$$z > z_{\rm cut}\theta^{\beta}$$

$$p^{\mu}_{CS} \sim \frac{m_J^2}{Q\,\zeta}\Big(\zeta,\ \frac{1}{\zeta},\ 1\Big) \qquad p^{\mu}_{C} \sim \Big(\frac{m_J^2}{Q},\ Q,\ m_J\Big)$$

$$\zeta \equiv \Big(\frac{m_J^2}{Q\,Q_{\rm cut}}\Big)^{\frac{1}{2+\beta}} \qquad Q_{\rm cut} \equiv 2^{\beta}\,Q z_{\rm cut}$$

$$\theta_{cs}/2 \sim \zeta$$



EFT modes for the Groomed Jet Mass

We identify the relevant region for our analysis by considering the EFT modes for groomed jet mass measurement

- Turning on soft drop removes emissions in the shaded region.
- CS denotes the emission at widest angle that satisfies the soft drop condition.
- Leading non-perturbative corrections have the largest plus component - hence the same angle as the CS modes.

$$p_{cs}^{+} \gg p_{\Lambda}{}^{+}$$

$$p_{\Lambda}^{\mu} \sim \Lambda_{\rm QCD}\Big(\zeta,\ \frac{1}{\zeta},\ 1\Big)$$

The Λ mode slides with the CS mode.

$$z > z_{\rm cut}\theta^{\beta}$$

$$p_{CS}^{\mu} \sim \frac{m_J^2}{Q\,\zeta}\Big(\zeta,\ \frac{1}{\zeta},\ 1\Big) \qquad p_{C}^{\mu} \sim \Big(\frac{m_J^2}{Q},\ Q,\ m_J\Big)$$

$$\zeta \equiv \Big(\frac{m_J^2}{Q\,Q_{\rm cut}}\Big)^{\frac{1}{2+\beta}} \qquad Q_{\rm cut} \equiv 2^{\beta}\,Q z_{\rm cut}$$

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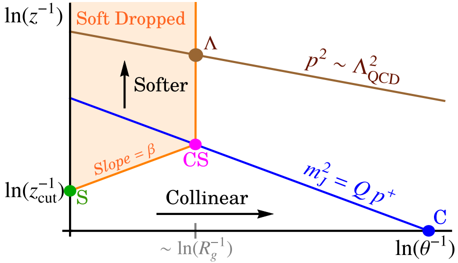
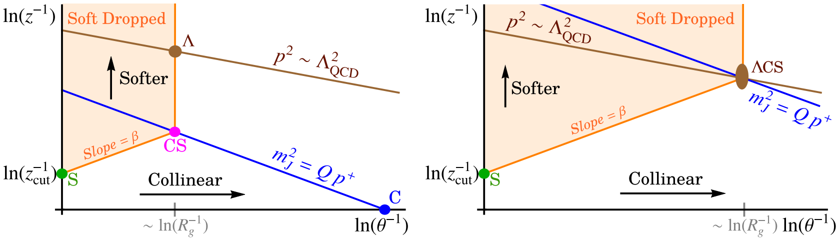


Soft Drop Nonperturbative and Operator Expansion Region

Distinguish two regions of the groomed jet mass spectrum:

a) soft drop operator expansion (SDOE) region, $p_{cs}^{+} \gg p_{\Lambda}^{+}$: $\quad \frac{Q\Lambda_{\rm QCD}}{m_J^2}\Big(\frac{m_J^2}{QQ_{\rm cut}}\Big)^{\frac{1}{2+\beta}} \ll 1\,,$

b) soft drop nonperturbative (SDNP) region, $p_{cs}^{+} \sim p_{\Lambda}^{+}$: $\quad m_J^2 \lesssim Q\Lambda_{\rm QCD}\,\Big(\frac{\Lambda_{\rm QCD}}{Q_{\rm cut}}\Big)^{\frac{1}{1+\beta}}\,.$



a) SDOE region $\qquad$ b) SDNP region

- In the SDNP region the Λ and CS mode come parametrically close merging into a single mode, Λ-CS.
- The nonperturbative corrections to the jet mass spectrum are $\mathcal{O}(1)$ in SDNP region.

Soft Drop Nonperturbative and Operator Expansion Region

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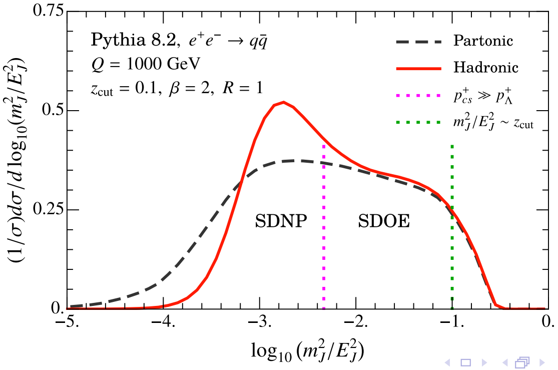
a) soft drop operator expansion (SDOE) region, $p^+_{cs} \gg p^+_\Lambda$: $\quad \frac{Q\Lambda_{\rm QCD}}{m_J^2}\Big(\frac{m_J^2}{QQ_{\rm cut}}\Big)^{\frac{1}{2+\beta}} \ll 1\,,$

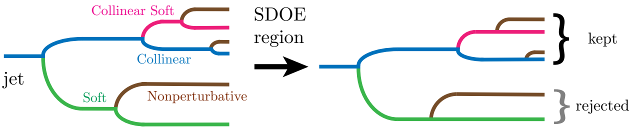
b) soft drop nonperturbative (SDNP) region, $p^+_{cs} \sim p^+_\Lambda$: $\quad m_J^2 \lesssim Q\Lambda_{\rm QCD}\Big(\frac{\Lambda_{\rm QCD}}{Q_{\rm cut}}\Big)^{\frac{1}{1+\beta}}\,,$

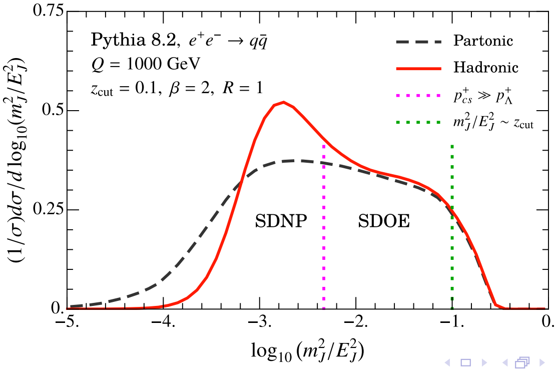
c) ungroomed resummation region: $\quad m_J^2 \gtrsim z_{\rm cut}\frac{Q^2}{4}\,.$



Soft Drop Nonperturbative and Operator Expansion Region

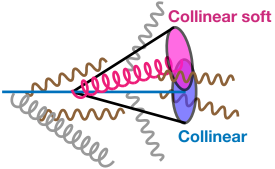
Changes to perturbative subjets on adding NP emissions are small:

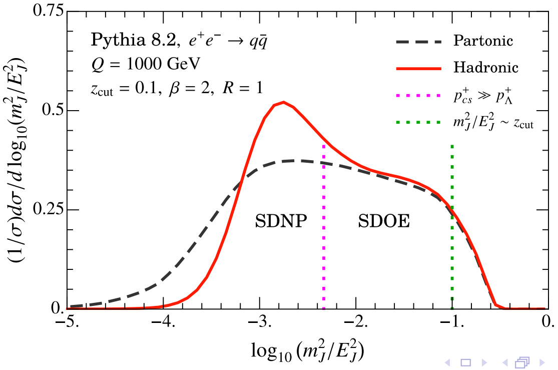




Soft Drop Nonperturbative and Operator Expansion Region

Catchment area determined by collinear and CS subjets (at LL):





Measurement in the Collinear-Soft Sector

Measurement in the collinear-soft sector:

$$(m_J^2)_{cs} \overset{\text{SDOE}}{\simeq} Q\, p_{cs}^+ + Q \sum_i q_{i\circledcirc}^+ + Q\, p_{cs}^+\, \delta\big(z_{cs} - z_{\text{cut}}\theta_{cs}^{\beta}\big) \sum_i \frac{q_{i\circledcirc}}{Q}$$

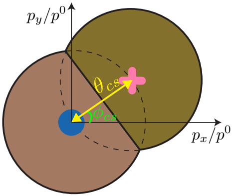
nonperturbative corrections to the measurements involve two terms:

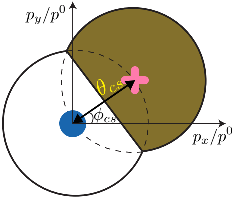
$$q_{i\circledcirc}^+ \equiv q_i^+\, \overline{\Theta}_{\text{NP}}^{\circledcirc}(\theta_{q_i}, \theta_{cs}, \Delta\phi_i)$$

$$q_{i\circledcirc} \equiv \left[q_i^- + \beta\left(q_i^- - \frac{2q_{i\perp}}{\theta_{cs}}\cos(\Delta\phi_i)\right)\right]\left(\overline{\Theta}_{\text{NP}}^{\circledcirc}(\theta_{q_i}, \theta_{cs}, \Delta\phi_i) - \Theta_{\text{NP}}^{\circledcirc}(\theta_{q_i}, \theta_{cs}, \Delta\phi_i)\right)$$

shift correction: CS emission sets the catchment area for the NP modes that are kept by soft drop: $\overline{\Theta}_{\text{NP}}^{\circledcirc} = 1$

boundary correction: change in the soft drop test for CS mode due to hadronization. Inside cs subjet: $\overline{\Theta}_{\text{NP}}^{\circledcirc} = 1$, $\Theta_{\text{NP}}^{\circledcirc} = 1 - \overline{\Theta}_{\text{NP}}^{\circledcirc}$





Leading Power corrections to the groomed cross section

Leading power corrections for the full cross section can be parameterized as

$$\frac{d\sigma_\kappa^{\mathrm{had}}}{dm_J^2} = \frac{d\hat{\sigma}_\kappa}{dm_J^2} - Q\,\Omega_{1\kappa}^{\infty}\,\frac{d}{dm_J^2}\left(C_1(m_J^2, Q, z_{\mathrm{cut}}, \beta)\,\frac{d\hat{\sigma}_\kappa}{dm_J^2}\right) + \frac{Q\Upsilon_1^\kappa(\beta)}{m_J^2}\,C_2(m_J^2, Q;\, z_{\mathrm{cut}}, \beta)\,\frac{d\hat{\sigma}_\kappa}{dm_J^2}$$

Hoang, AP, Mantry, Stewart 1906.11843

Nothing like standard shape function.

$\Upsilon_1^\kappa(\beta)$ linear in β, hence two parameters:

$$\Upsilon_1^\kappa(\beta) = \Upsilon_{1,0}^\kappa + \beta\,\Upsilon_{1,1}^\kappa$$

The Wilson coefficients $C_1(m_J^2, Q, z_{\mathrm{cut}}, \beta)$ and $C_2(m_J^2, Q, z_{\mathrm{cut}}, \beta)$ are not constants along the spectrum depend on both the grooming parameters, **but the hadronic power corrections themselves are universal:**

$\{\Omega_{1\kappa}^{\infty}, \Upsilon_{1,0}^\kappa, \Upsilon_{1,1}^\kappa\}$ only depend on Λ_{QCD} and the jet initiating parton $\kappa = q, g$

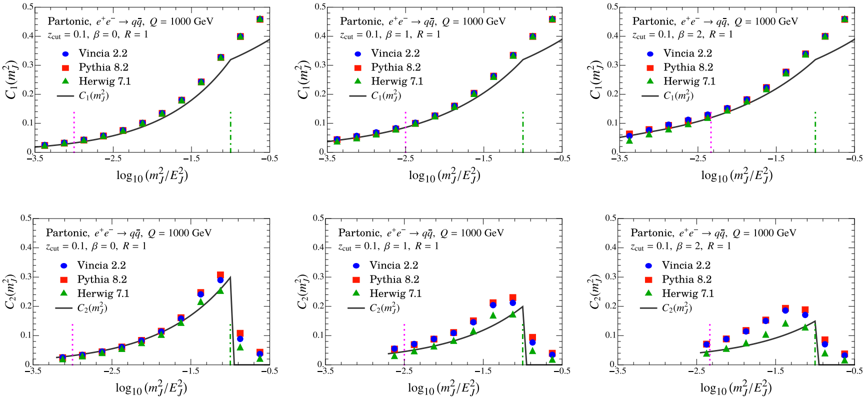
Wilson coefficients are perturbatively calculable and involve resummed averages of opening angles of stopping pair:

$$C_1(m_J^2, Q, z_{\mathrm{cut}}, \beta) \sim \left\langle \frac{\theta_{cs}(m_J^2)}{2} \right\rangle, \qquad C_2(m_J^2, Q;\, z_{\mathrm{cut}}, \beta) \sim \left\langle \frac{2}{\theta_{cs}(m_J^2)}\,\frac{m_J^2}{Q^2}\,\delta\!\left(z_{cs} - z_{\mathrm{cut}}\theta_{cs}^\beta\right) \right\rangle$$

All the dependence of the hadronization correction on $z_{\mathrm{cut}}, \beta, m_J, Q$ and R is perturbatively calculable via $C_{1,2}(m_J^2, Q;\, z_{\mathrm{cut}}, \beta)$

Comparing the shift correction matching coefficient with MC

LL result for $C_{\mathbf{1}}(m_J^{\mathbf{2}})$ compared with partonic Monte Carlo for $z_{\rm cut} = 0.1,\ \beta = 0, 1, 2$



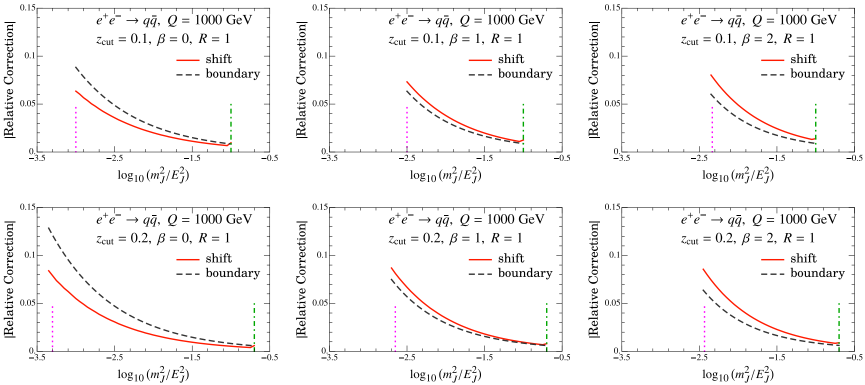
A LL calculation of $C_{\mathbf{1,2}}$ ($\sim$ 20% uncertainty) is sufficient for the precision we aim for, and agrees well with partonic Monte Carlo.

Size of power corrections

Absolute value of the fractional power correction:

$$\text{shift} = \left| -Q\Omega_{1\kappa}^{\infty} \frac{d}{dm_J^2}\left(C_1(m_J^2)\frac{d\hat{\sigma}_\kappa}{dm_J^2}\right) \bigg/ \frac{d\hat{\sigma}_\kappa}{dm_J^2} \right|, \qquad |\text{boundary}| = \left| \frac{Q\Upsilon_1^\kappa(\beta)}{m_J^2} C_2(m_J^2)\frac{d\hat{\sigma}_\kappa}{dm_J^2} \bigg/ \frac{d\hat{\sigma}_\kappa}{dm_J^2} \right|$$

Take $\Omega_1^{\infty} = 1.0$ GeV, $\Upsilon_{1,0} = 0.7$ GeV, $\Upsilon_{1,1} = 0.4$ GeV

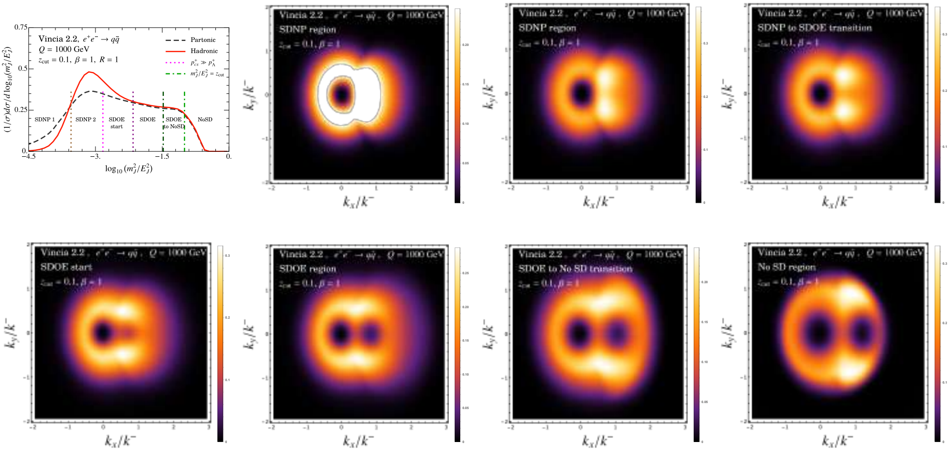


Shift and boundary power corrections have comparable size and grow from $\sim 1\%$ to $\sim 10\%$.

Visualizing the angular distribution of NP subjets

Tag an NP subjet with $E \lesssim 1$ GeV in the CA clustering tree of the groomed jet and apply the rescaling.

In the OPE region we find the expected geometry with $R \sim 1$

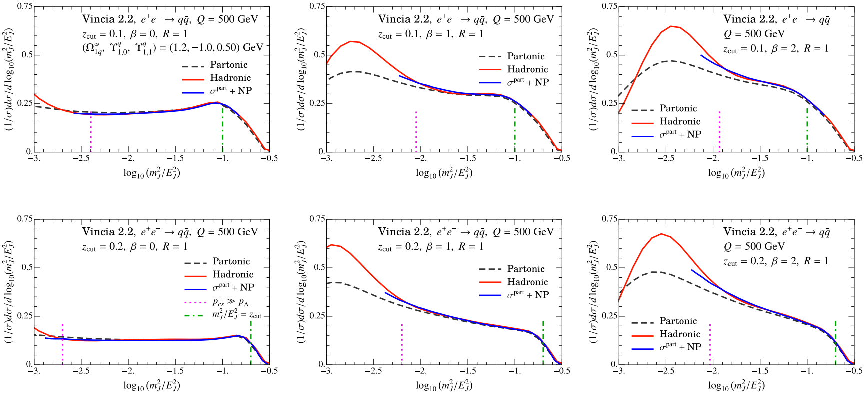


Fitting for the power corrections in Monte Carlo

Fit for the three hadronic parameters for the following grid in the SDOE region:

$$Q = 500, 1000 \text{ GeV}, \; z_{\rm cut} = \{0.05, 0.1, 0.15, 0.2\}, \; \beta = \{0, 0.5, 1.0, 1.5, 2.0\}$$

3 universal parameters fit the whole grid well



Hadronization corrections to the groomed top jet mass

To recap -

- Light grooming ensures an inclusive treatment of the decay products at parton level (for jet mass)
- Top mass schemes with $m_{\rm pole} - m = \delta m \sim \Gamma_t$ can be implemented in the factorized cross section.
- Hadronization corrections in soft drop depend on the opening angle of the stopping pair θ_{cs}.

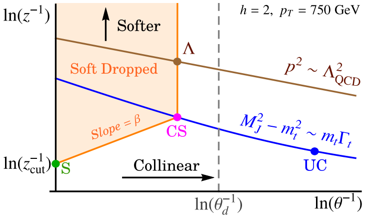
Hadronization corrections to the groomed top jet mass

To recap -

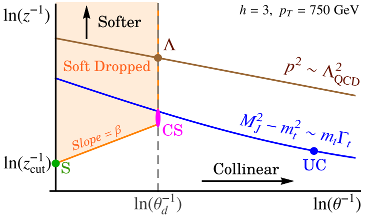
- Light grooming ensures an inclusive treatment of the decay products at parton level (for jet mass)
- Top mass schemes with $m_{\text{pole}} - m = \delta m \sim \Gamma_t$ can be implemented in the factorized cross section.
- Hadronization corrections in soft drop depend on the opening angle of the stopping pair θ_{cs}.

However, hadronic corrections can not be treated while being inclusive over the decay products!

"high-p_T" scenario:



"decay" scenario:



In the second case a decay product at an angle θ_d is seen first by the groomer and determines the location of the Λ mode.

Hadronization corrections to the groomed top jet mass

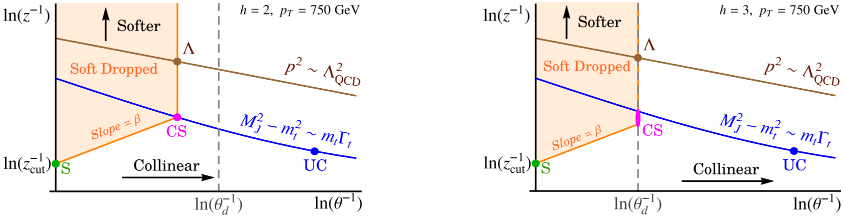
$$\theta_d \equiv \max\Big(\tilde\theta_{(xy)t}, \tilde\theta_{zt}\Big)\,, \qquad \tilde\theta_{xy} = \min\Big(\tilde\theta_{q\bar q'}, \tilde\theta_{qb}, \tilde\theta_{\bar q' b}\Big)$$

Parameterize θ_d in terms of h (useful later):

$$\theta_d = \theta_d\Big(\Phi_d, \frac{m_t}{Q}\Big)\,, \qquad \tan\Big(\frac{\theta_d}{2}\Big) = \frac{m_t}{Q} h\Big(\Phi_d, \frac{m_t}{Q}\Big)$$

Φ_d is 5 dimensional top decay $t \to bq\bar q'$ phase space in the rest frame. m_t/Q is the boost factor.

$$d_t\Big(\Phi_d, \frac{m_t}{Q}\Big) = \frac{1}{\Gamma^{\mathcal{J}}_{t\to bq\bar q'}} \frac{d\Gamma_{t\to bq\bar q'}}{d\Phi_d}\,, \qquad P\Big(\tilde h, \frac{m_t}{Q}\Big) = \int_{\mathcal{J}} d\Phi_d\, d_t\big(\Phi_d, \frac{m_t}{Q}\big)\, \delta\Big(\tilde h - h(\Phi_d, \frac{m_t}{Q})\Big)$$



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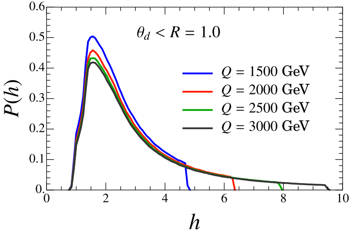
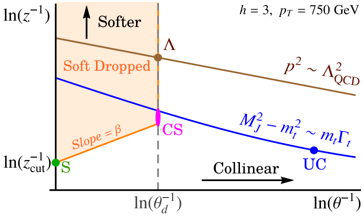




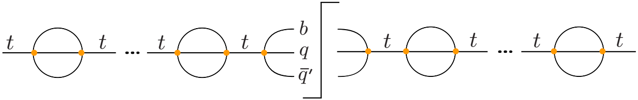
$P(h)$ gives us the probability of the event where a decay product stops soft drop and determines the leading nonperturbative Λ mode.

Sensitivity to the decay product phase space at hadron level is not problematic

The inclusive treatment of bHQET Jet function remains valid at hadron level. The Breit-Wigner is now replaced by

$$D_t\Big(\hat{s}', \Phi_d, \frac{m_t}{Q}\Big) = \frac{\Gamma_t}{\pi(\hat{s}'^{\,2}+\Gamma_t^2)}\, d_t\Big(\Phi_d, \frac{m_t}{Q}\Big)\Big[1+\mathcal{O}\Big(\frac{\hat{s}'}{m_t}\Big)\Big]\,, \qquad \int_{\mathcal{J}} d\Phi_d\; d_t\Big(\Phi_d, \frac{m_t}{Q}\Big) = 1$$

- Φ_d dependence of θ_d determined at the m_t scale and does not affect the dynamics of the ultracollinear modes
- Description of UC modes still based on the inclusive bHQET jet function $J_B(\hat{s}, \delta m, \mu)$



Keep the full top width in the non cut bubbles

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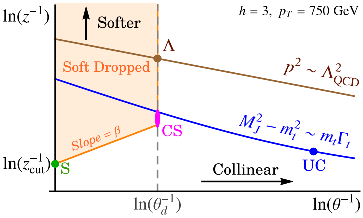
- Description of UC modes still based on the inclusive bHQET jet function $J_B(\hat{s}, \delta m, \mu)$

The collinear soft function needs to account for the angular infomration of the decay products. At NLO we have

$$\begin{aligned} S_c^{(d)}(\ell^+, Q_{\rm cut}, \beta, \theta_d, \mu) &= S_c^q\Big(\ell^+ Q_{\rm cut}^{\frac{1}{1+\beta}}, \beta, \mu\Big) \\ &- \frac{\alpha_s(\mu) C_F}{(2+\beta)\pi}\, \frac{2^{3+\beta}}{Q_{\rm cut}\theta_d^{2+\beta}}\, \mathcal{L}_1\Big(\frac{\ell^+}{Q_{\rm cut}}\frac{2^{2+\beta}}{\theta_d^{2+\beta}}\Big)\Theta\Big[\frac{Q_{\rm cut}\theta_d^{2+\beta}}{2^{2+\beta}} - \ell^+\Big] \\ &+ \mathcal{O}(\alpha_s^2)\,, \end{aligned}$$



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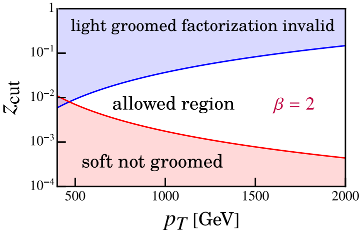
$$S_c^{(d)}(\ell^+, Q_{\rm cut}, \beta, \theta_d, \mu) = S_c^q\Big(\ell^+ Q_{\rm cut}^{\frac{1}{1+\beta}}, \beta, \mu\Big) - \frac{\alpha_s(\mu)C_F}{(2+\beta)\pi}\frac{2^{3+\beta}}{Q_{\rm cut}\theta_d^{2+\beta}}\mathcal{L}_1\Big(\frac{\ell^+}{Q_{\rm cut}}\frac{2^{2+\beta}}{\theta_d^{2+\beta}}\Big)\Theta\Big[\frac{Q_{\rm cut}\theta_d^{2+\beta}}{2^{2+\beta}} - \ell^+\Big] + \mathcal{O}(\alpha_s^2)\,,$$

Not a large log in the light grooming region

$$S_c^{(d)}(\ell^+, Q_{\rm cut}, \beta, \theta_d, \mu)\Big|_{\rm NLL} = S_c^q\Big(\ell^+ Q_{\rm cut}^{\frac{1}{1+\beta}}, \beta, \mu\Big)\Big|_{\rm NLL}$$



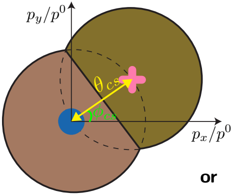
$$z_{\rm cut} \lesssim \frac{\Gamma_t}{h^{2+\beta} m_t}\Big(\frac{p_T}{m_t}\Big)^\beta$$

Shift Correction for Light Groomed Top Jets

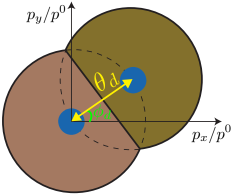
The leading hadronization effects depend on the angle of the soft drop stopping subjet

- The winning scenario between "decay" and "high-p_T" factorizations depends on the comparison between θ_d and θ_{cs}

$$|\text{shift}| = \left| -\frac{Q\Omega_{1q}^{\circledcirc}}{m_t}\frac{d}{d\hat{s}_t}\left(\frac{\theta_{\text{stop}}}{2}\frac{d\hat{\sigma}_\kappa}{d\hat{s}_t}\right)\Big/\frac{d\hat{\sigma}_\kappa}{d\hat{s}_t}\right|, \qquad \theta_{\text{stop}}\left(\hat{s}_t, \Phi_d, \frac{m_t}{Q}\right) = \max\left\{\hat{\theta}_{cs}(\hat{s}_t), \theta_d\left(\Phi_d, \frac{m_t}{Q}\right)\right\}$$



or



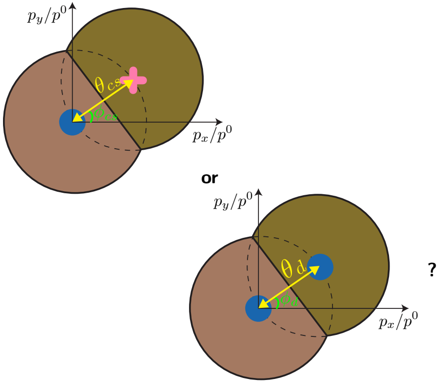
?

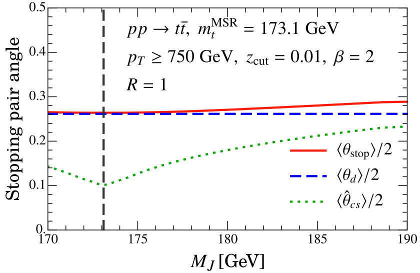
Shift Correction for Light Groomed Top Jets

The leading hadronization effects depend on the angle of the soft drop stopping subjet

- The winning scenario between "decay" and "high-p_T" factorizations depends on the comparison between θ_d and θ_{cs}
- Pick a kinematic phase space region allowed by light grooming constraints

$$|\mathrm{shift}| = \left| -\frac{Q\Omega_{1q}^{\circledcirc}}{m_t}\frac{d}{d\hat{s}_t}\left(\frac{\theta_{\rm stop}}{2}\frac{d\hat{\sigma}_\kappa}{d\hat{s}_t}\right)\Big/\frac{d\hat{\sigma}_\kappa}{d\hat{s}_t}\right|, \qquad \theta_{\rm stop}\left(\hat{s}_t,\Phi_d,\frac{m_t}{Q}\right) = \max\left\{\hat{\theta}_{cs}(\hat{s}_t),\theta_d\left(\Phi_d,\frac{m_t}{Q}\right)\right\}$$





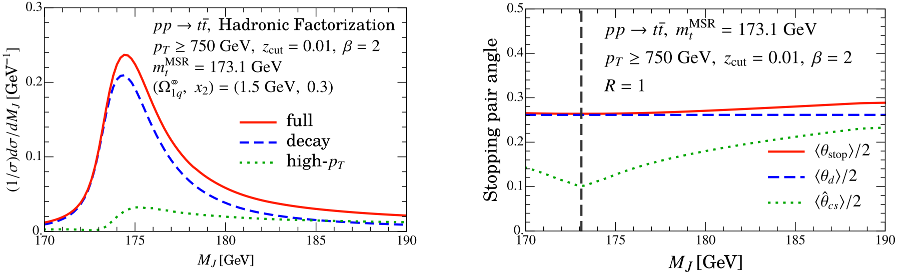
Shift Correction for Light Groomed Top Jets

The leading hadronization effects depend on the angle of the soft drop stopping subjet

- The winning scenario between "decay" and "high-p_T" factorizations depends on the comparison between θ_d and θ_{cs}
- "decay" scenario dominant in the peak region

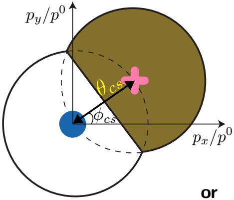
$$|\text{shift}| = \left| -\frac{Q\Omega_{1q}^{\infty}}{m_t}\frac{d}{d\hat{s}_t}\left(\frac{\theta_{\rm stop}}{2}\frac{d\hat{\sigma}_\kappa}{d\hat{s}_t}\right)\Big/\frac{d\hat{\sigma}_\kappa}{d\hat{s}_t}\right|, \qquad \theta_{\rm stop}\left(\hat{s}_t, \Phi_d, \frac{m_t}{Q}\right) = \max\left\{\hat{\theta}_{cs}(\hat{s}_t), \theta_d\left(\Phi_d, \frac{m_t}{Q}\right)\right\}$$

Decay and high-p_T components of the factorization theorem (coming up):



Boundary Correction for Light Groomed Top Jets

The boundary correction is only relevant for the case when a QCD radiation stops soft drop



or

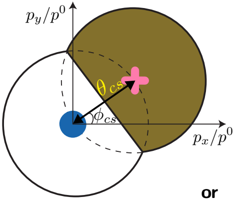
None?

Boundary Correction for Light Groomed Top Jets

The boundary correction is only relevant for the case when a QCD radiation stops soft drop

- The net correction gets reduced by this fraction of high-p_T events in the peak region.

$$|\text{boundary}| = \left| \left(\frac{Q \Upsilon_1^q(\beta)}{m_t \hat{s}_t} C_2(\hat{s}_t) \frac{d\hat{\sigma}_\kappa}{d\hat{s}_t} \right) \Big/ \frac{d\hat{\sigma}_\kappa}{d\hat{s}_t} \right| \times \frac{\sigma^{\text{high}-p_T}(M_J)}{\sigma(M_J)}$$



or

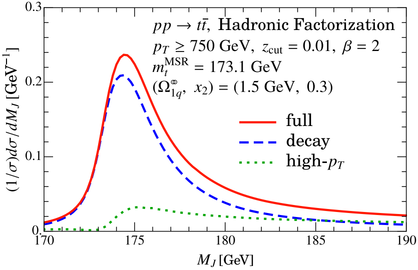
None?

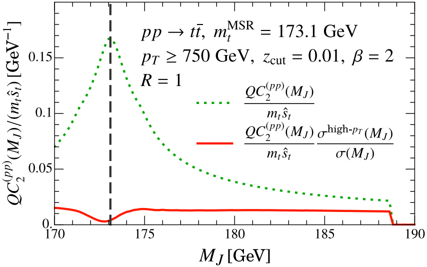
Boundary Correction for Light Groomed Top Jets

The boundary correction is only relevant for the case when a QCD radiation stops soft drop

- The net correction gets reduced by this fraction of high-p_T events in the peak region.
- For the light grooming region boundary correction from high-p_T component is negligible in the peak region
- Boundary correction is negligible in the peak region

$$|\text{boundary}| = \left| \left(\frac{Q\Upsilon_1^q(\beta)}{m_t \hat{s}_t} C_2(\hat{s}_t) \frac{d\hat{\sigma}_\kappa}{d\hat{s}_t} \right) \Big/ \frac{d\hat{\sigma}_\kappa}{d\hat{s}_t} \right| \times \frac{\sigma^{\text{high}-p_T}(M_J)}{\sigma(M_J)}$$



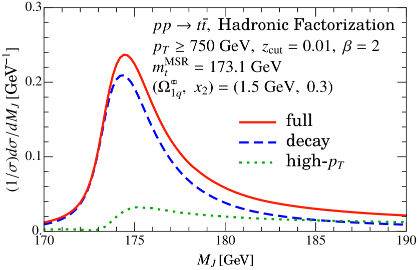


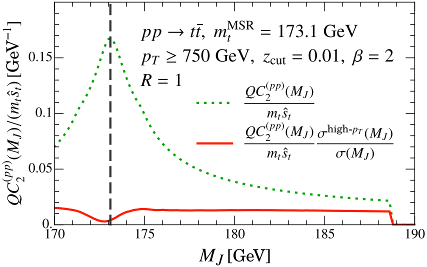
Boundary Correction for Light Groomed Top Jets

The boundary correction is only relevant for the case when a QCD radiation stops soft drop

- The net correction gets reduced by this fraction of high-p_T events in the peak region.
- For the light grooming region boundary correction from high-p_T component is negligible in the peak region
- Only the shift hadronic parameter Ω_1^{∞} is relevant for NP corrections.
- As a nuisance parameter we also consider the second moment of a shape function whose first moment is constrained by Ω_1^{∞}:

$$\int_0^\infty dk\, k\, F_{\infty}^q(k) = \Omega_{1q}^{\infty} \quad \to \quad \Omega_{nq}^{\infty} \equiv \int_0^\infty dk\, k^n\, F_{\infty}^q(k)\,, \qquad x_2 \equiv \frac{\Omega_{2q}^{\infty}}{(\Omega_{1q}^{\infty})^2} - 1$$



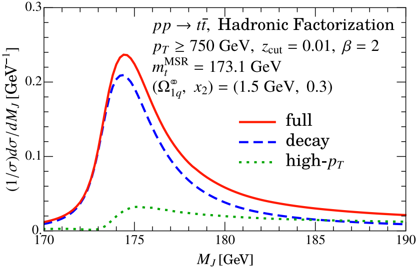


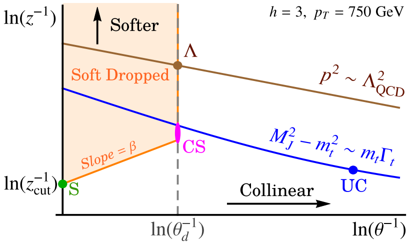
Hadron level factorization for groomed top jets

We now arrive at the final hadron level factorization formula for light groomed top jets:

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

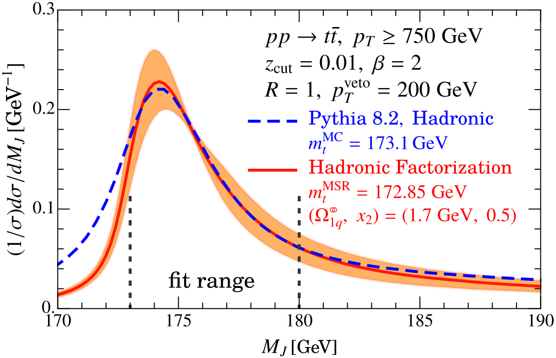
The non perturbative corrections are incorporated by comparing $\theta_d/2$ and $\theta_{cs}/2 = C_1^q(m_t\hat{s}_t)$
$\hat{s}_t = (M_J^2 - m_t^2)/m_t$





Calibrating m_t^{MC} in Pythia 8

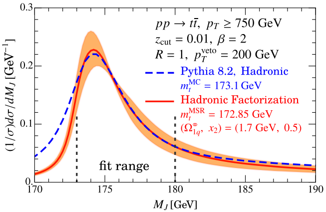
Fit for the top mass in MSR scheme $m_t^{\mathrm{MSR}}(R_m = 1)$ with $m_t^{\mathrm{MC}} = 173.1$ GeV and hadronic parameters $\Omega_1^{\circledcirc}$ and x_2 in the peak region.

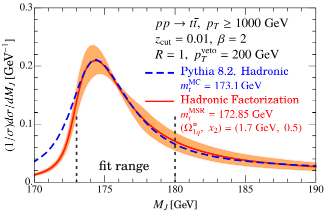


Calibrating $m_t^{\rm MC}$ in Pythia 8

Fit for the top mass in MSR scheme $m_t^{\rm MSR}(R_m = 1)$ with $m_t^{\rm MC} = 173.1$ GeV and hadronic parameters $\Omega_1^{\circledcirc}$ and x_2 in the peak region.

- Fit for two different p_T bins to break degeneracy between m_t and $\Omega_1^{\circledcirc}$





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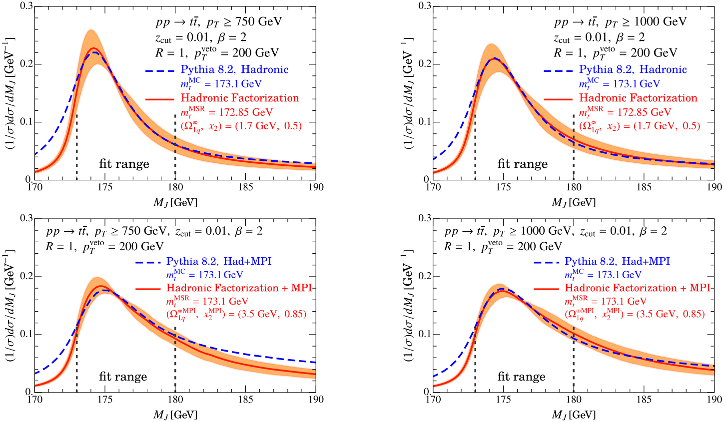
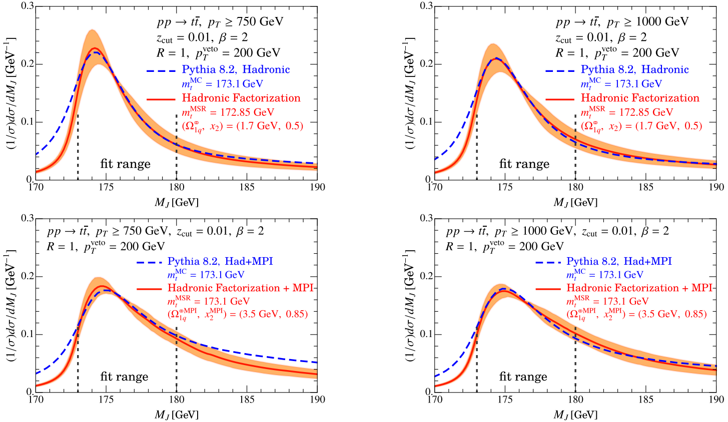
- Fit for two different p_T bins to break degeneracy between m_t and $\Omega_1^{\circledcirc}$
- Compare the fit results with and without underlying event



Calibrating m_t^{MC} in Pythia 8

Results:

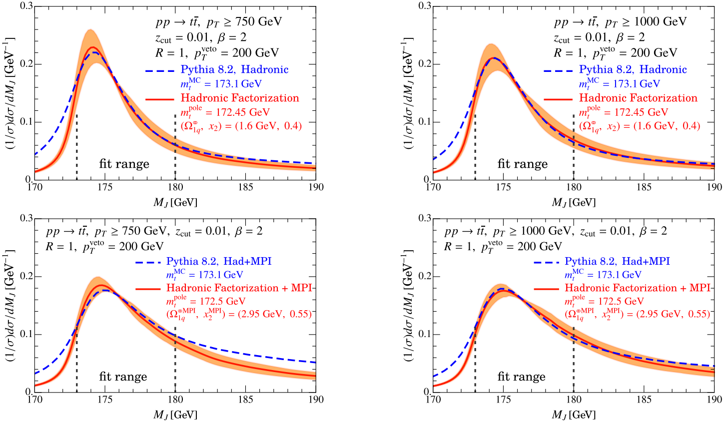
- m_t^{MSR} remains stable, UE effects absorbed in $\Omega_1^{\circledcirc}$ and x_2
- Result compatible with e^+e^- calibration result in [Butenschoen et. al, 1608.01318]: supports universality of m_t^{MC} calibration fits for pp groomed or e^+e^- ungroomed even with UE



Fits for pole mass

Comparing the fits with MSR scheme we see $m_t^{\rm pole}$ fit values are 0.4-0.6 GeV lower than $m_t^{\rm MSR}$

- difference related to R evolution between the reference scale $R_m = 1$ and scale probed by the bHQET jet function in the peak region $R_m = \mu_{J_b} \sim 5$ GeV.
- compatible with e^+e^- calibration in [Butenschoen et. al, 1608.01318]



Conclusions

- We used EFT and jet substructure tools to achieve a hadron level observable for kinematic extraction of short distance top mass at the LHC.
- The power corrections to the groomed jet mass are universal, and their dependence on kinematic and grooming parameters $\{z_{\rm cut}, \beta, Q, R\}$ can be calculated perturbatively.
- Our preliminary calibration of pp with groomed top quark jets in presence of underlying event is compatible with e^+e^- calibration [Butenschoen et. al, 1608.01318] with ungroomed top quark jets.
- Given our systematically improvable approach we anticipate the perturbative and hadronization uncertainties on m_t extraction using this observable to eventually go down below a GeV.
- Universality allows $\Omega_{1q}^{\circledcirc}$ to be determined from fits to light or b quark soft drop jets, and can be further used as a handle.

Thank you