Testing Event Generator Hadronization Models with Groomed Jet Mass

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in collaboration with

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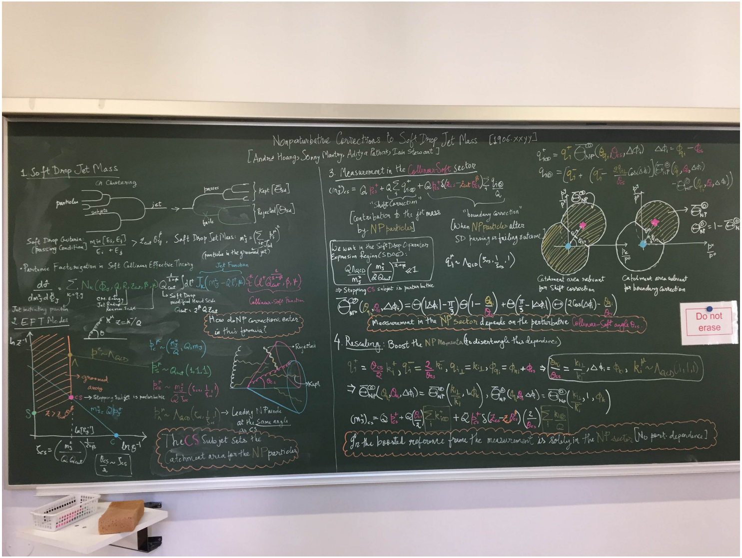
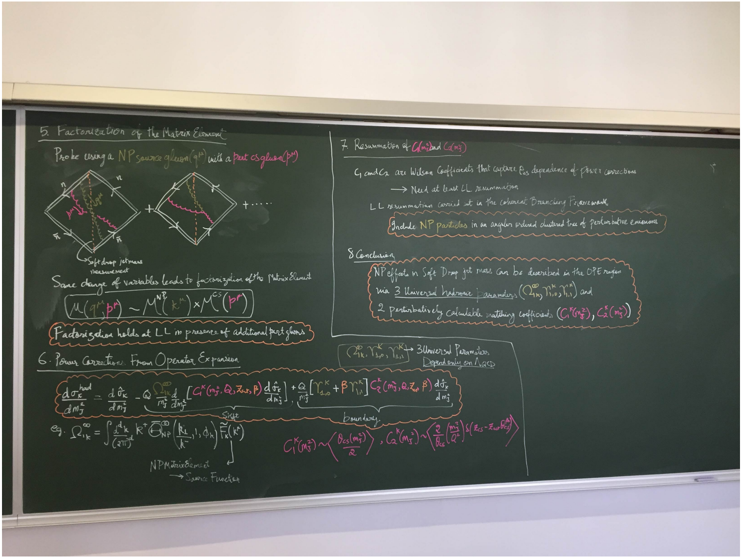
FWF Der Wissenschaftsfonds.

Outline

Theory Summary from the blackboard

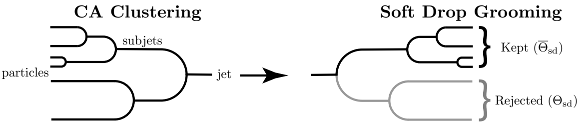


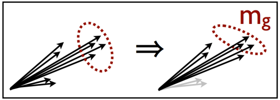
Theory Summary from the blackboard



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**.



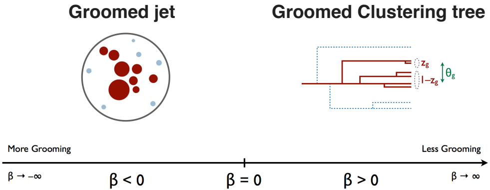


Soft drop grooming involves reclustering a jet with purely angular measure (CA clustering) and selectively throwing away the softer branches.

Soft Drop criteria:

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

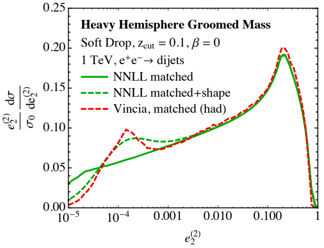
Larkoski, Marzani, Soyez, Thaler 2014



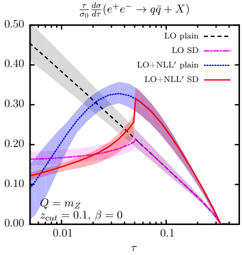
The criteria is IR safe for $\beta > 0$ and Sudakov safe for $\beta = 0$ (calculable after performing resummation)
Larkoski, Thaler 2013

How well do we understand the groomed spectrum in theory?

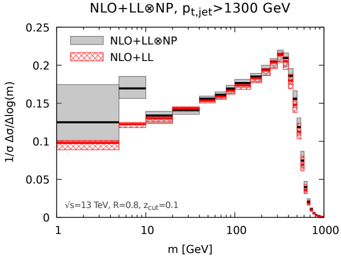
Partonic resummation of groomed jet mass is well understood:



Frye, Larkoski, Schwartz, Yan 2016



Baron et al. 1803.04719

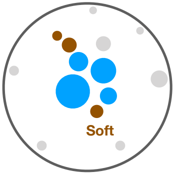


Marzani et al., JHEP07(2017)132

The fixed order corrections have also been evaluated at NNLO. [Kardos et al. 1807.11472].
See also [Larkoski, Moult, Neill 2017], [Lee, Shrivastava, Vaidya 2019], [Kang, Lee, Liu, Ringer 2018]

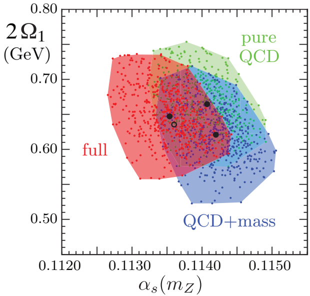
What about the power corrections in the groomed spectrum?

Although the hadronization effects are suppressed for groomed jet mass, in order to achieve the required accuracy of α_s we need to account for the left over soft particles.



Power corrections dictate the accuracy of precision measurements

α_s measurement from Thrust at LEP:



Abbate et al. 1006.3080

Power corrections are described via a nonperturbative shape function

$$\frac{d\sigma}{d\tau} = \int dk \frac{d\sigma^{\rm pert}}{d\tau}\left(\tau - \frac{k}{Q}\right) F\left(k - 2\overline{\Delta}\right)$$

Only the first moment Ω_1 is relevant.

$$\Omega_1 = \int dk\ k\ F(k)$$

Hoang Stewart 0709.3519

Field theory understanding of hadronization is important

SCET provides this understanding

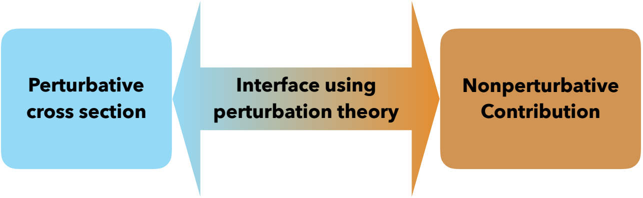
Ω_1 is a vacuum matrix element of soft Wilson lines:

$$\Omega_1 = \frac{1}{2N_c}\langle 0|{\rm tr}\overline{Y}_{\bar n}^T(0)Y_n(0)\hat{e}Y_n^\dagger(0)\overline{Y}_{\bar n}^*(0)|0\rangle$$

Power 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? R? Q? ...



Goal of this work is to deepen our understanding of the interface for groomed jet mass via field theory calculations

EFT modes for 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.

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

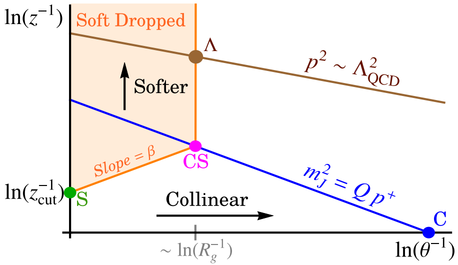
$$p_{\Lambda}^{\mu} \sim \Lambda_{\mathrm{QCD}}\left(\zeta,\, \frac{1}{\zeta},\, 1\right)$$

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

$$p_{CS}^{\mu} \sim \frac{m_J^2}{Q\,\zeta}\left(\zeta,\, \frac{1}{\zeta},\, 1\right) \qquad p_C^{\mu} \sim \left(\frac{m_J^2}{Q},\, Q,\, m_J\right)$$

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

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

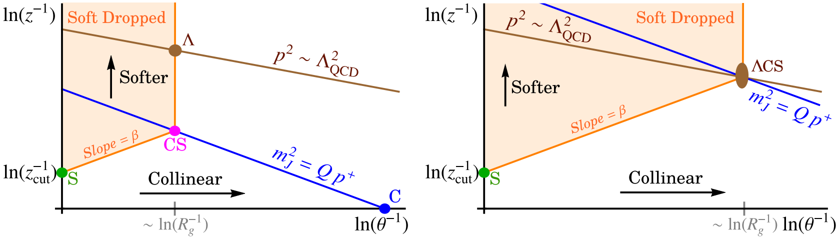


Soft Drop Nonperturbative and Operator Expansion Region

Distinguish two regions of the groomed jet mass spectrum:

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

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



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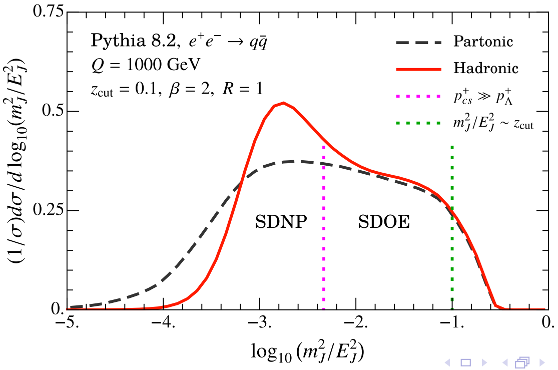
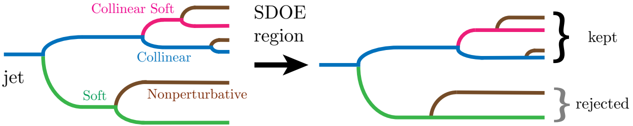
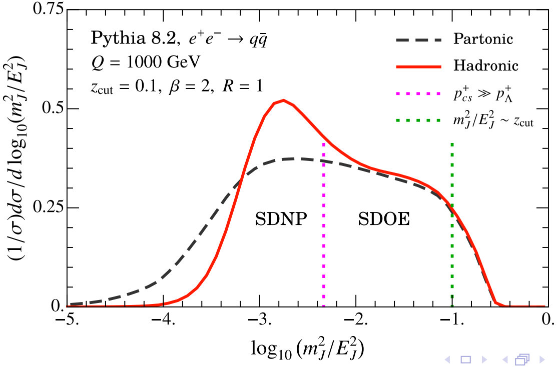
c) ungroomed resummation region: $\quad m_J^2 \gtrsim z_{\rm cut}\dfrac{Q^2}{4}\,.$



Soft Drop Nonperturbative and Operator Expansion Region

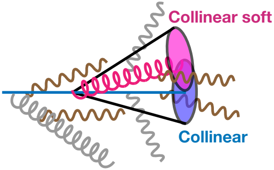
Changes to perturbative subjets on adding NP emissions are small:

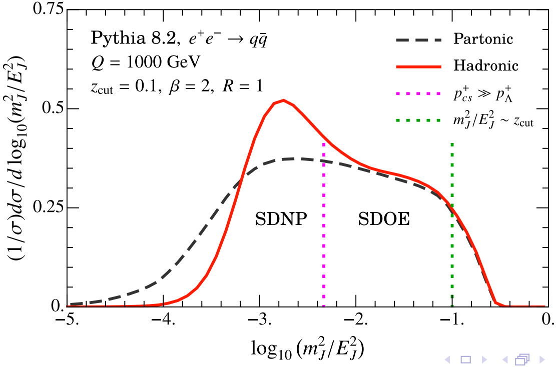




Soft Drop Nonperturbative and Operator Expansion Region

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





Measurement in the Collinear-Soft Sector

Measurement in the collinear-soft sector:

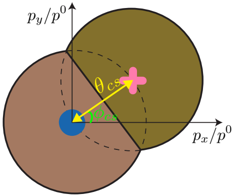
$$(m_J^2)_{cs} \overset{\text{SDOE}}{\simeq} Q\, p_{cs}^+ + Q \sum_i q_{i\infty}^+ + Q\, p_{cs}^+\, \delta\big(z_{cs} - z_{\rm cut}\,\theta_{cs}^\beta\big) \sum_i \frac{q_{i\circledcirc}}{Q}$$

nonperturbative corrections to the measurements involve two terms:

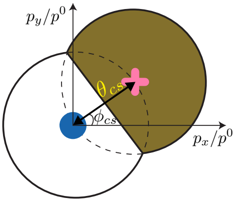
$$q_{i\infty}^+ \equiv q_i^+\, \overline{\Theta}_{\rm NP}^{\infty}(\theta_{q_i},\, \theta_{cs}, \Delta\phi_i)$$

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

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



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



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The projection operators only involve ratios of polar angles and difference of azimuthal angles:

$$\overline{\Theta}_{\rm NP}^{\infty}(\theta_{q_i},\, \theta_{cs}, \Delta\phi_i) \equiv \Theta\left(|\Delta\phi| - \frac{\pi}{3} \right) \Theta\left(1 - \frac{\theta_{q_i}}{\theta_{cs}} \right) + \Theta\left(\frac{\pi}{3} - |\Delta\phi| \right) \Theta\left(2\cos(\Delta\phi) - \frac{\theta_{q_i}}{\theta_{cs}} \right),$$

make the following rescaling:

$$q_i^+ = \frac{\theta_{cs}}{2} k_i^+ , \qquad q_i^- = \frac{2}{\theta_{cs}} k_i^- , \qquad q_{i\perp} = k_{i\perp} , \qquad \phi_{q_i} = \phi_{k_i} + \phi_{cs} \Rightarrow \frac{\theta_{q_i}}{\theta_{cs}} = \frac{k_\perp}{k^-}$$

Measurement in the Collinear-Soft Sector

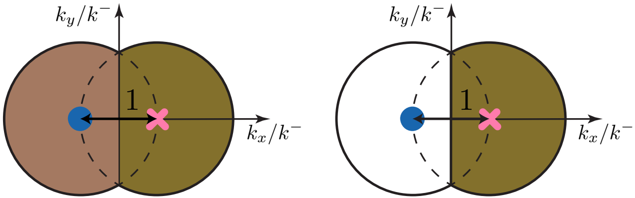
Measurement in the collinear-soft sector now factorizes

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

$$= Q\, p_{cs}^+ + Q \frac{\theta_{cs}}{2} \sum_i k_{i\infty}^+ + Q\, p_{cs}^+\, \delta\big(z_{cs} - z_{\rm cut}\theta_{cs}^\beta\big) \frac{2}{\theta_{cs}} \sum_i \frac{k_{i\circledcirc}}{Q}$$

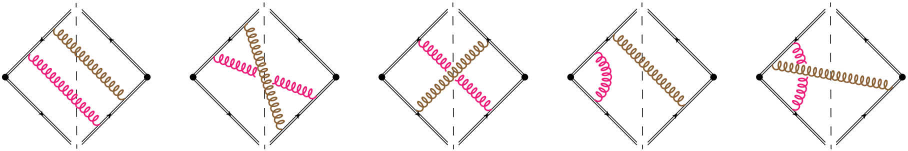
The projection operatos in k_∞^+ and $k_{i\circledcirc}$ are independent of θ_{cs}:

$$\overline{\Theta}_{\rm NP}^{\infty}\Big(\frac{k_{i\perp}}{k_i^-}, 1, \phi_k\Big) \equiv \Theta\Big(|\phi_{k_i}| - \frac{\pi}{3}\Big)\Theta\Big(1 - \frac{k_{i\perp}}{k_i^-}\Big) + \Theta\Big(\frac{\pi}{3} - |\phi_k|\Big)\Theta\Big(2\cos(\phi_{k_i}) - \frac{k_{i\perp}}{k_i^-}\Big),$$



Measurement now performed with unit radius projections

Factorization of the matrix element: Abelian graphs



Here we probe using a NP source gluon q^μ with a perturbative CS gluon p^μ.

$$S_c^{\text{had, ab.}} = \frac{\alpha_s C_\kappa}{\pi} \frac{(\mu^2 e^{\gamma_E})^\epsilon}{\Gamma(1-\epsilon)} \int_0^\infty \frac{dp^+\, dp^-}{(p^+\, p^-)^{1+\epsilon}} \int \frac{d^d q}{(2\pi)^d} \frac{g^2\, (4C_\kappa - 2C_A)\, \tilde\mu^\epsilon\, \tilde{C}(q)}{q^+\, q^-} \left[\mathcal{M}^{p+q} - \mathcal{M}^q\right]$$

$$\tilde{F}^{\,\text{ab.}}(q^\mu) \equiv \frac{g^2\, (4C_\kappa - 2C_A)\, \tilde\mu^\epsilon\, \tilde{C}(q)}{q^+\, q^-}$$

Apply the rescaling to factorize the measurement $\mathcal{M}^{p+q} - \mathcal{M}^q$:

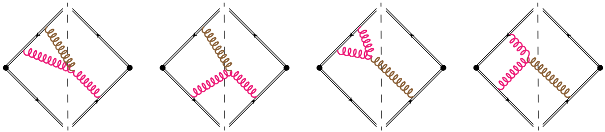
$$q^+ = \frac{\theta_p}{2}\, k^+ = \sqrt{\frac{p^+}{p^-}}\, k^+, \qquad q^- = \frac{2}{\theta_p}\, k^- = \sqrt{\frac{p^-}{p^+}}\, k^-, \qquad q_\perp = k_\perp, \qquad \Delta\phi = \phi_k$$

Note that the measure and the NP source are **already** invariant under boosts needed to factorize the measurement

$$\theta_q = \frac{2\, q_\perp}{q^-} = \theta_p \frac{k_\perp}{k^-}, \qquad \tilde{F}^{\,\text{ab.}}(q^\mu) = \frac{(4C_\kappa - 2C_A) g^2\, C_\kappa\, \tilde\mu^\epsilon\, \tilde{C}(q)}{q^+\, q^-} = \tilde{F}^{\,\text{ab.}}(k^\mu), \qquad d^d q = d^d k$$

Rescaling is essential for Nonperturbative factorization

Now consider the nonabelian graphs:



$$S_c^{\mathrm{had,\,n.a.}} = \frac{\alpha_s C_\kappa}{\pi}\frac{(\mu^2 e^{\gamma_E})^\epsilon}{\Gamma(1-\epsilon)}\int_0^\infty \frac{dp^+\,dp^-}{(p^+\,p^-)^{1+\epsilon}}\int\frac{d^dq}{(2\pi)^d}\,\frac{2\,g^2\,C_A\,\iota^\epsilon\,\tilde{C}(q)}{q^+\,q^-}$$
$$\times\left[\mathcal{M}^{p+q}-\mathcal{M}^{q}\right]\frac{q^+p^- + p^+q^-}{p^+q^- + q^+p^- - 2\sqrt{p^+p^-}\,|\vec{q}_\perp|\cos(\phi_q-\phi_{cs})}\,.$$

NOT invariant under boost of q^μ alone but factorizes in the rescaled coordinates

$$\frac{q^+p^- + p^+q^-}{p^+q^- + q^+p^- - 2\sqrt{p^+p^-}\,|\vec{q}_\perp|\cos(\phi_q-\phi_{cs})} = \frac{k^+ + k^-}{k^+ + k^- - 2\,|\vec{k}_\perp|\cos(\phi_k)}\,,$$

Obtain the full source function:

$$\tilde{F}(k^\mu) = 4g^2\,\tilde{\mu}^{2\epsilon}\,\tilde{C}(k)\left[\left(C_\kappa - \frac{C_A}{2}\right)\frac{1}{k^+\,k^-} + \frac{C_A}{2}\,\frac{1}{k^+\,k^-}\,\frac{k^+ + k^-}{k^+ + k^- - 2\,|\vec{k}_\perp|\cos(\phi_k)}\right]$$

Result holds at LL. Checked explicitly with an additional perturbative emission

Leading Power corrections to the groomed cross section

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

$$\frac{d\sigma_\kappa^{\rm had}}{dm_J^2} = \frac{d\hat{\sigma}_\kappa}{dm_J^2} - Q\,\Omega_1^{\circledcirc} \frac{d}{dm_J^2}\left(C_1(m_J^2, Q, z_{\rm cut}, \beta)\,\frac{d\hat{\sigma}_\kappa}{dm_J^2}\right) + \frac{Q\Upsilon_1^{\circledcirc}(\beta)}{m_J^2}\, C_2(m_J^2, Q;\, z_{\rm cut}, \beta)\,\frac{d\hat{\sigma}_\kappa}{dm_J^2}$$

$\Upsilon_1^{\circledcirc}(\beta)$ linear in β, hence two parameters:

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

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

Three parameters total, **only depending on** $\Lambda_{\rm QCD}$:

$$\Omega_1^{\circledcirc} \equiv \int \frac{d^d k}{(2\pi)^d}\, k^+\,\overline{\Theta}_{\rm NP}^{\circledcirc}\,\tilde{F}(k^\mu)$$

$$\Upsilon_{1,0}^{\circledcirc} \equiv \int \frac{d^d k}{(2\pi)^d}\, k^-\,\left(\overline{\Theta}_{\rm NP}^{\circledcirc} - \Theta_{\rm NP}^{\circledcirc}\right)\tilde{F}(k^\mu)$$

$$\Upsilon_{1,1}^{\circledcirc} \equiv \int \frac{d^d k}{(2\pi)^d}\left(k^- - k_\perp\,\cos(\phi_k)\right)\left(\overline{\Theta}_{\rm NP}^{\circledcirc} - \Theta_{\rm NP}^{\circledcirc}\right)\tilde{F}(k^\mu)$$

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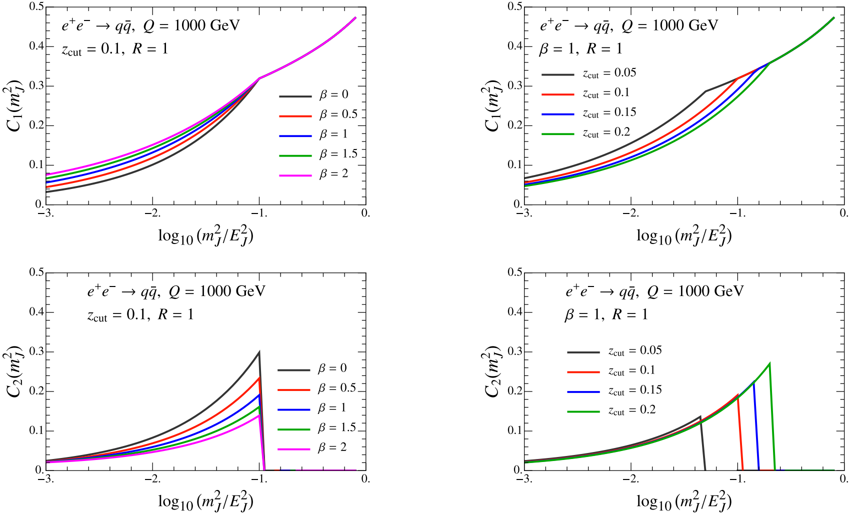
Wilson coefficients are perturbatively calculable and involve resummed averages of opening angles of stopping pair:

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

We calculate them in the coherent branching framework at LL.

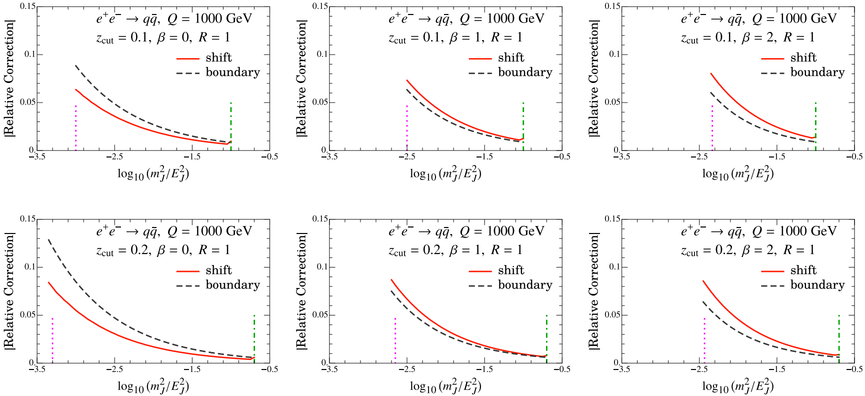
LL Resummed Wilson Coefficients



Wilson coefficients have nontrivial dependence on $z_{\rm cut}$ and β

Size of power corrections

Absolute value of the fractional power correction taking $\Omega_1^{\circledcirc} = 1.0$ GeV, $\Upsilon_{1,0} = 0.7$ GeV, $\Upsilon_{1,1} = 0.4$ GeV.

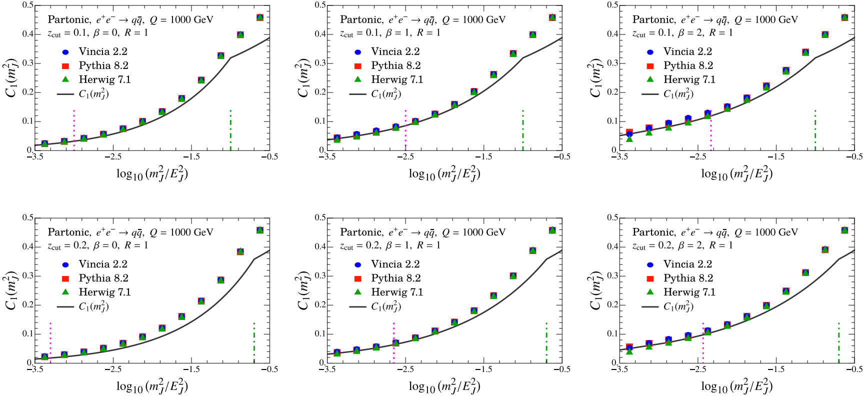


Shift and boundary power corrections have comparable size and grow from $\sim 1\%$ to $\sim 10\%$.

Dashed lines represent the extent of SDOE region.

Comparing the shift correction matching coefficient with MC

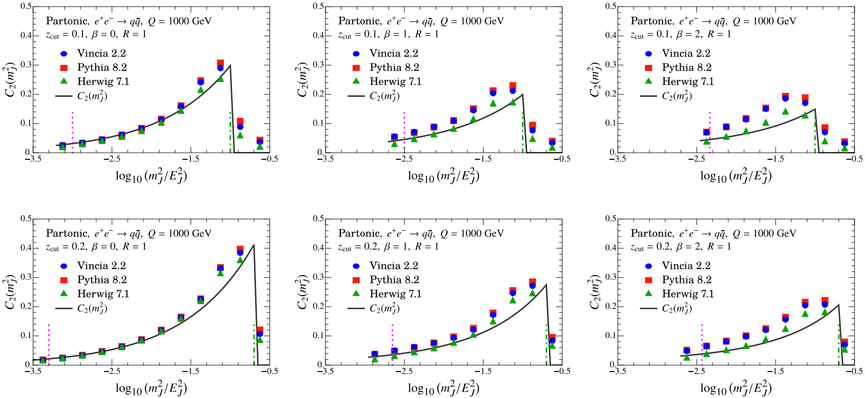
Comparing our computation of $C_1(m_J^2)$ with partonic Monte Carlo for $z_{\mathrm{cut}} = 0.1, 0.2$ (rows), $\beta = 0, 1, 2$ (columns)



All the MC do equally well

Comparing the boundary correction matching coefficient with MC

Comparing our computation of $C_2(m_J^2)$ with partonic Monte Carlo for $z_{\rm cut} = 0.1, 0.2$ (rows), $\beta = 0, 1, 2$ (columns)



calculate using

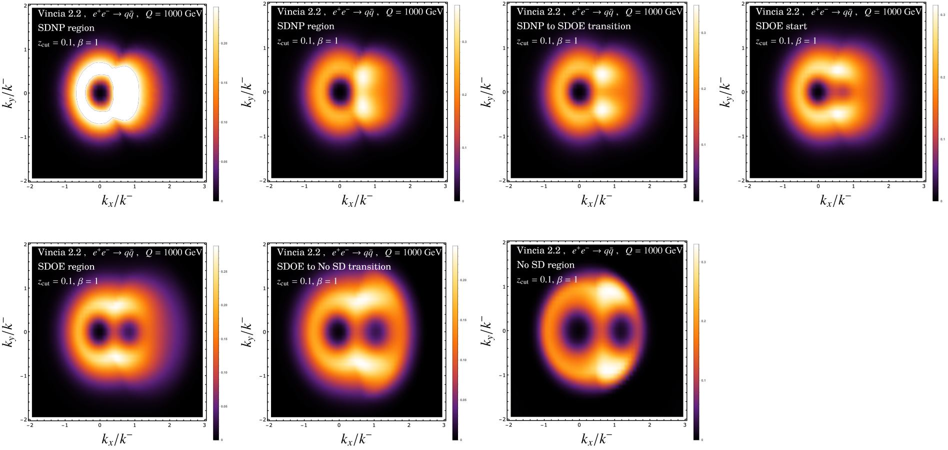
$$\Theta\left(z - z_{\rm cut}\theta^\beta\right) \to \Theta\left(z - z_{\rm cut}\theta^\beta + \frac{2}{\theta}\,\epsilon\right)$$

Relatively better agreement of LL calculation with Herwig

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 $R \sim 1$

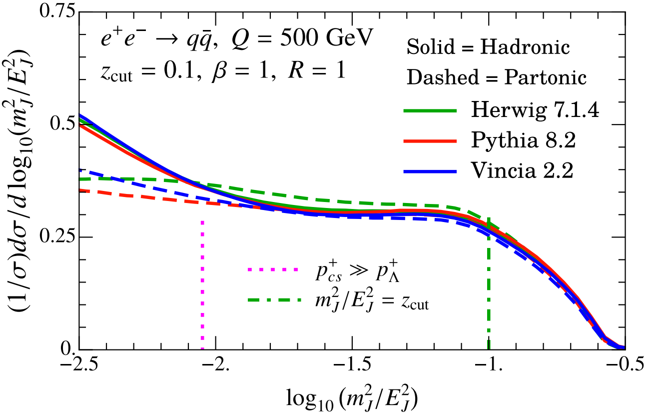


Fitting for the power corrections in Monte Carlo

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

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

Take 0.05 units as the difference between partonic and hadronic normalized cross section. Error defined as 10% uncertainty on this number.



Fitting for the power corrections in Monte Carlo

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

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

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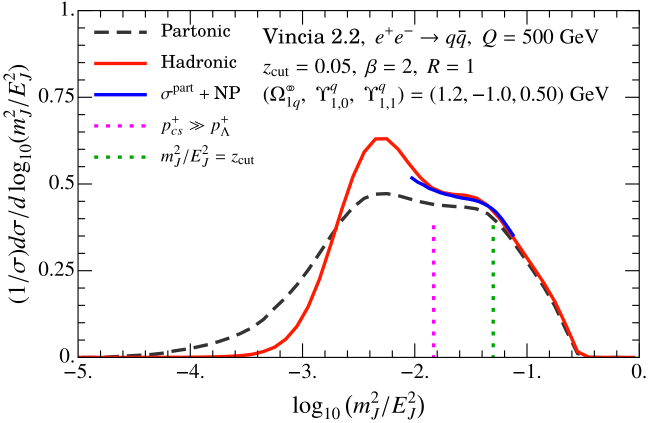


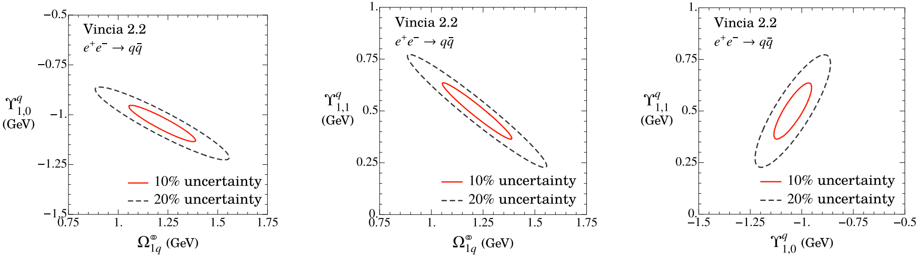
Fitting for the power corrections in Monte Carlo

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

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

Event Generator	Ω_{1q}^{∞} (GeV)	$\Upsilon_{1,0}^{q}$ (GeV)	$\Upsilon_{1,1}^{q}$ (GeV)	χ^2/dof
Pythia 8.235	1.63	-1.21	0.33	0.96
Vincia 2.2	1.22	-1.04	0.50	0.84
Herwig 7.1.4 (default)	1.14	-1.73	-0.15	2.53
Herwig 7.1 (p_TB)	1.14	-1.32	-0.11	0.77

The parameters are correlated but have very small uncertainty



Fitting for the power corrections in Monte Carlo

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

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

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More studies with Herwig:

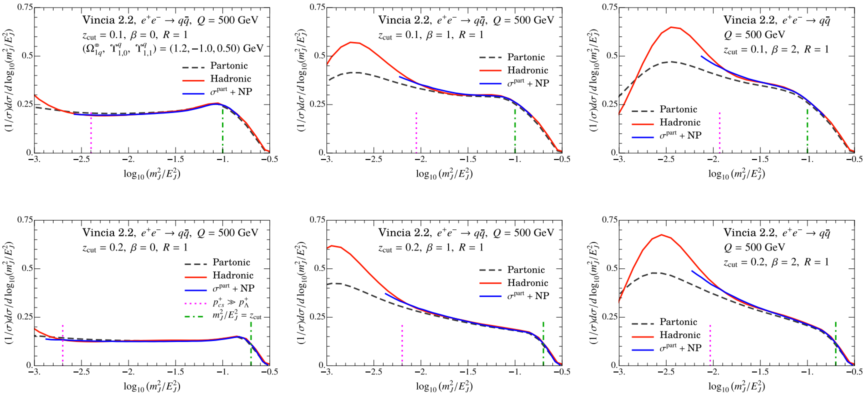
- Included p_TB tune in Herwig to probe poor χ^2 of default Herwig [Reichelt et. al. 1708.01491]
- q^2 preserving kinematic reconstruction in default Herwig vs. p_T preserving in p_TB tune (originally proposed in [Gieseke, Stephens, Webber 2003])
- We use the same $\alpha_s^{\rm CMW} = 0.127$ in the p_TB tune. Using the prescribed $\alpha_s^{\rm CMW} = 0.1087$ failed to produce reasonable fits (with $\chi^2/\text{dof} > 10$). More plots in backup.

Fitting for the power corrections in Monte Carlo

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

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

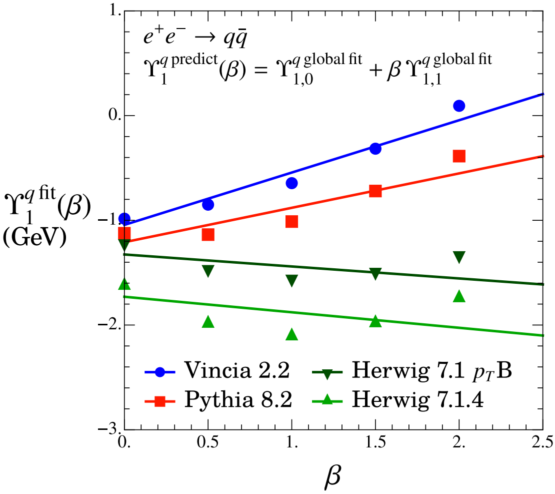
3 universal parameters fit the whole grid well



Plots for Herwig and Pythia in backup

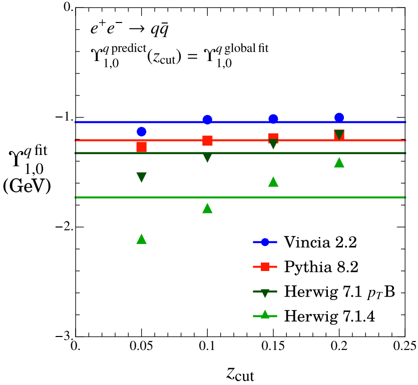
Linear behavior of boundary correction

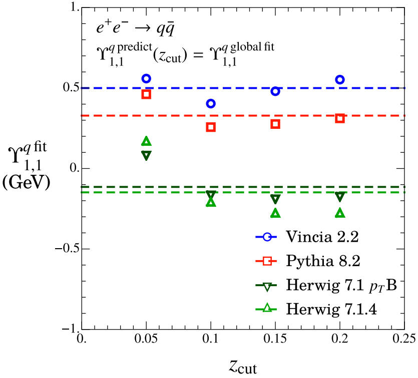
Fit for individual β's using the $\Omega_{\mathbf{1}}^{\varpi}$ from the global fit. **Fits agree with prediction**.



Testing $z_{\rm cut}$ independence of $\Upsilon^q_{1,0}$ and $\Upsilon^q_{1,1}$

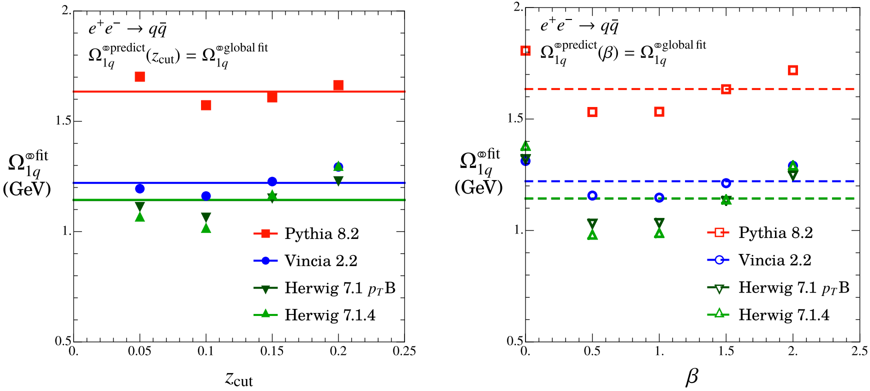
Fit for individual $z_{\rm cut}$ values and compare against the global fit





Testing $z_{\rm cut}$ and β independence of $\Omega_{1q}^{\circledcirc}$

Fit for individual $z_{\rm cut}$ and β values and compare against the global fit



Conclusion

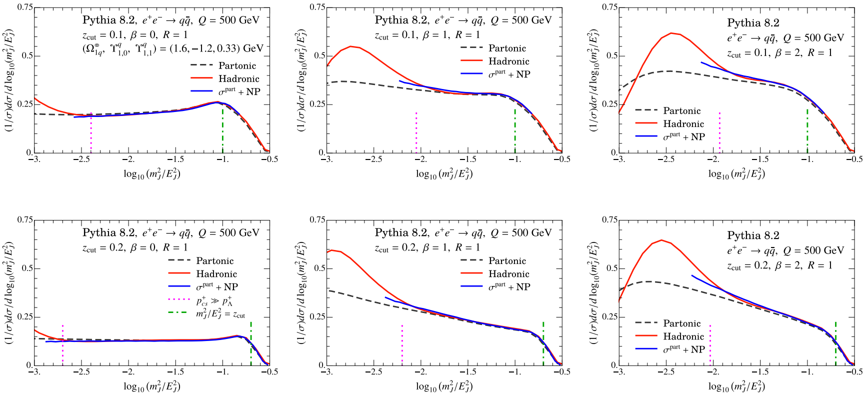
- QFT based treatment of power corrections to groomed observables. 3 Universal parameters
- Calculate the shape dependence of power corrections via Wilson Coefficients determined with Coherent Branching at LL
- Enables precision measurements for α_s and m_t involving direct comparison of data with theory, or m_t calibration in Monte Carlos.
- Interesting test of hadronization models of Monte Carlos
- Future applications to collinear drop

Thank you.

Fits in the SDOE region for Pythia

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

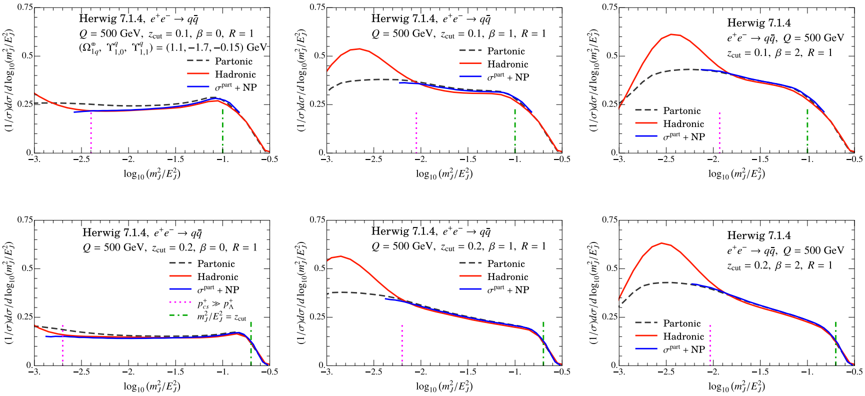
$$Q = 500, 1000 \text{ GeV}, \; z_{\text{cut}} = \{0.05, 0.1, 0.15, 0.2\}, \; \beta = \{0, 0.5, 1.0, 1.5, 2.0\}$$



Fits in the SDOE region for Herwig (default)

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

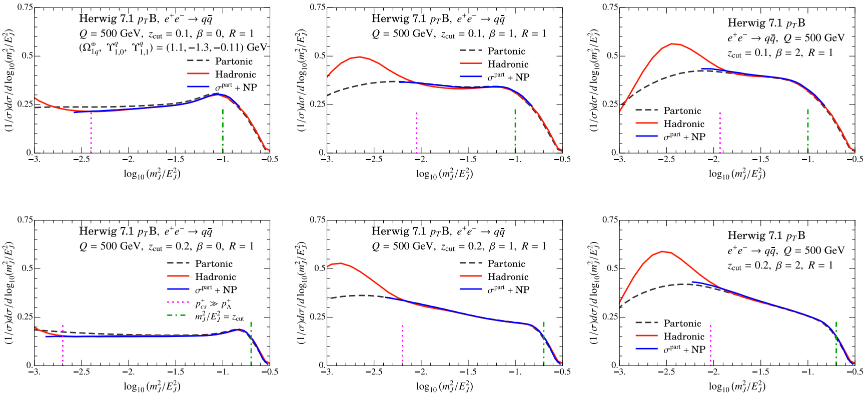
$$Q = 500, 1000 \text{ GeV}, \; z_{\text{cut}} = \{0.05, 0.1, 0.15, 0.2\}, \; \beta = \{0, 0.5, 1.0, 1.5, 2.0\}$$



Fits in the SDOE region for Herwig (p_TB tune, same $\alpha_s^{\rm CMW} = 0.127$)

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

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



Fits in the SDOE region for Herwig (p_TB tune, $\alpha_s^{\rm CMW} = 0.1087$)

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

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