Hadro-production of massive *b*-jets and associated dead-cone effects at the LHC

In collaboration with Prasanna Dhani, Andrea Ghira, Gregory Soyez and Simone Marzani.

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Exploring the Nature of Matter

Introduction and Motivation

- The jet substructure studies allows to test fundamental predictions of QCD.
- One of such predictions is a suppression of collinear radiation around massive relativistic quarks (the dead-cone effect).
- Theoretical predictions were made in early 1990s but direct observation was made by ALICE only in 2022 .
- The jet substructure observables are sensitive to collinear radiation and hence can be used to explore the dead-cone effect.
- The resummed predictions for jet angularities λ_α^1 at $\mathrm{NLO} + \mathrm{NLL}'$ accuracy level are available as a plugin to SHERPA
- We aim to reach $\mathrm{NLO} + \mathrm{NLL}'$ accuracy in for the massive quarks

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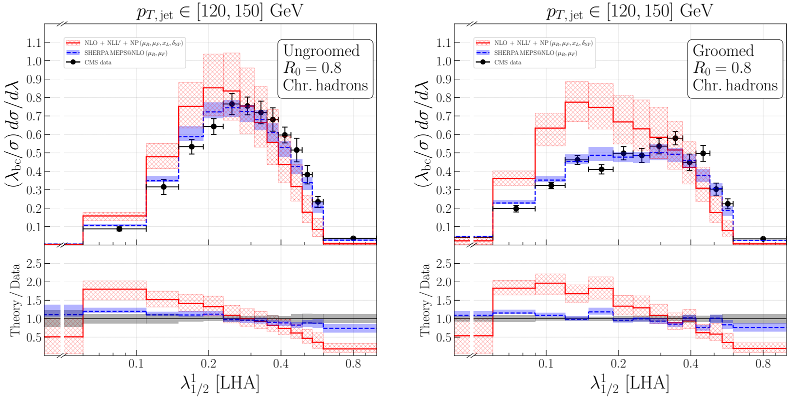
The $\mathrm{NLO} + \mathrm{NLL}'$ predictios for jet angularities in the approximation of massless partons were obtained in collaboration with S. Caletti, S. Marzani, D. Reichelt, S. Schumann, G. Soyez, V. Theeuwes, see 2112.09545, 2104.06920

Previous results for $\lambda_\alpha = \sum_i z_i \left(\frac{\Delta_{i,jet}}{R}\right)^\alpha$



Comparison against recent CMS data for the Jet Thrust angularity, $p_{T,\mathrm{jet}} \in [120, 150]$ GeV. Magenta band correspond to transfer matrix approach.

Theory: 2112.09545, 2104.06920 (in collaboration with S. Caletti, S. Marzani, D. Reichelt, S. Schumann, G. Soyez, V. Theeuwes); CMS: 2109.03340

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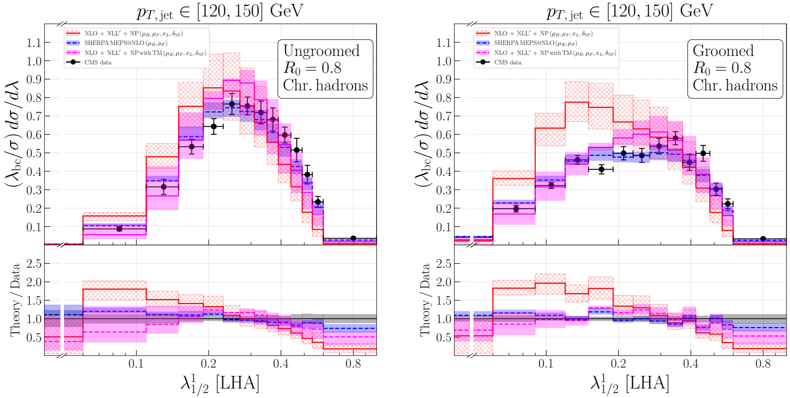

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We study two-point energy correlation functions

The energy correlation function is defined as

$$e_2^{(\alpha)}\Big|_{e^+e^-} = \sum_{i<j} \frac{E_i}{E_J}\frac{E_j}{E_J}\left(\frac{\theta_{ij}}{R}\right)^{\alpha} \quad or \quad e_2^{(\alpha)}\Big|_{pp} = \sum_{i<j} \frac{p_{Ti}}{p_{T_J}}\frac{p_{Tj}}{p_{T_J}}\left(\frac{\Delta R_{ij}}{R}\right)^{\alpha}$$

SoftDrop groomer:

$$\frac{\min(E_i, E_j)}{E_i + E_j} > z_{\rm cut}\left(\frac{\theta_{ij}}{R}\right)^{\beta} \quad or \quad \frac{\min(p_{ti}, p_{tj})}{p_{ti} + p_{tj}} > z_{\rm cut}\left(\frac{\Delta R_{ij}}{R}\right)^{\beta}$$

- We are interested in the higher order large logarithmic contributions coming from the soft and collinear regions of the $Q(q_1) + \bar{Q}(q_2)$ production.
- The EFT (SCET_+ and bHQET) results were obtained by Lee *et al* in 1901.09095 for $\alpha < 1$ and $\beta = 0$.
- We aim to obtain results for all IRC safe combinations of α and β.

Dead-cone effect:

Consider $\gamma^*/Z^*(q) \to q(q_1) + \bar{q}(q_2) + g(k)$ process: if quarks are relativistic and emitted gluon is soft and quasi collinear then

$$d\sigma \approx C_F \frac{\alpha_S}{\pi} \frac{(2\sin\theta/2)^2 d(2\sin\theta/2)^2}{\left[(2\sin\theta/2)^2 + \theta_D^2\right]^2} \frac{dz}{z} \approx C_F \frac{\alpha_S}{\pi} \frac{\theta^2 d\theta^2}{\left[\theta^2 + \theta_D^2\right]^2} \frac{dz}{z}$$

Dead-cone is defined as

$$\theta_D = \lim_{E_g \to 0} (2m_Q/\sqrt{s}) = m_Q/E_Q$$

If $\theta \gg \theta_D$ we have di-log enhancement

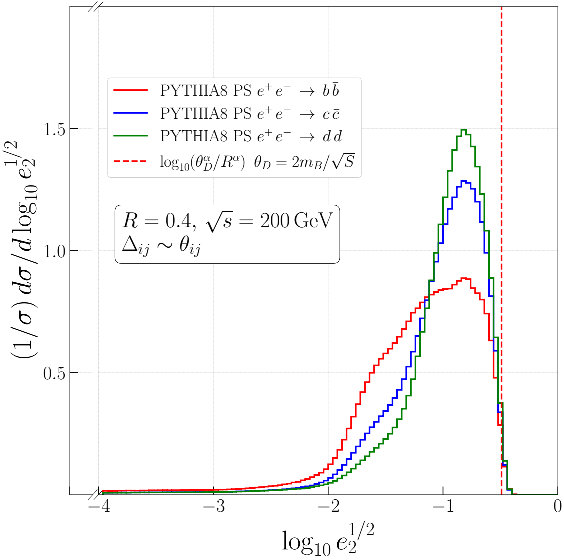
$$d\sigma \sim d(\log\theta^2)\, d(\log z)$$

If $\theta \ll \theta_D$ we have no collinear enhancement

$$d\sigma \sim \left(\frac{\theta}{\theta_D}\right)^2 d\left(\frac{\theta}{\theta_D}\right)^2 d(\log z)$$

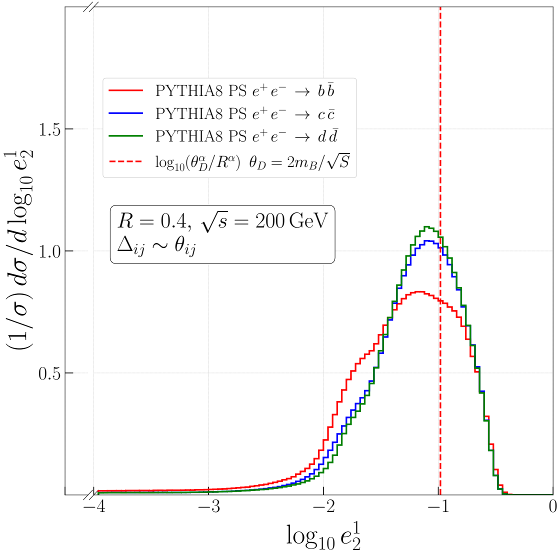
See Dokshitzer et all 91, Ellis et al 96 and recent ALICE measurements

MC predictions for $e_2^{1/2}$ at parton level (preliminary)



- PYTHIA8 takes into account qaurk masses in PS-evolution (partially accounts for dead-cone)
- We observe strong shape difference between b-jets and light-jets
- The difference between c-jets and light-jets is smaller
- If single hard emmision dominates $z_1 \gg \sum_{i=2}^{N} z_i$ then the dead-cone boundary is $\log_{10}(\theta_D^\alpha/R^\alpha)$

MC predictions for e_2^1 at parton level (preliminary)



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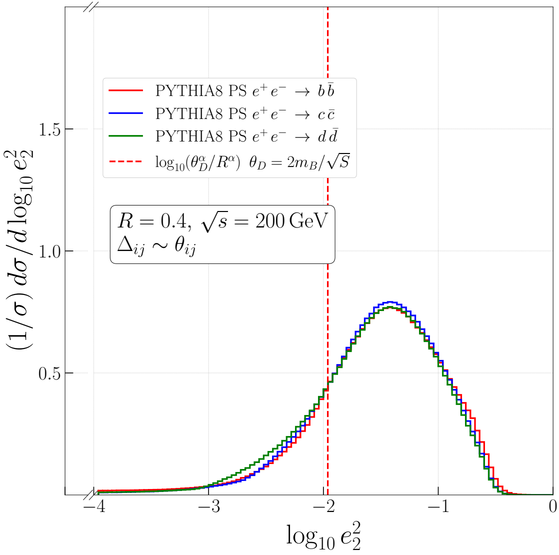
MC predictions for e_2^2 at parton level (preliminary)



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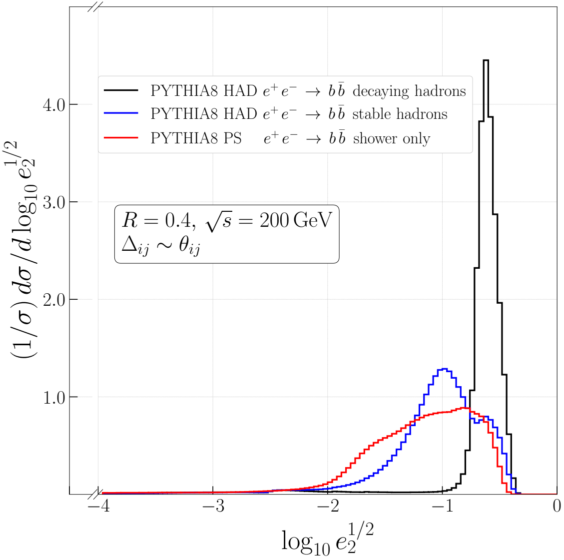
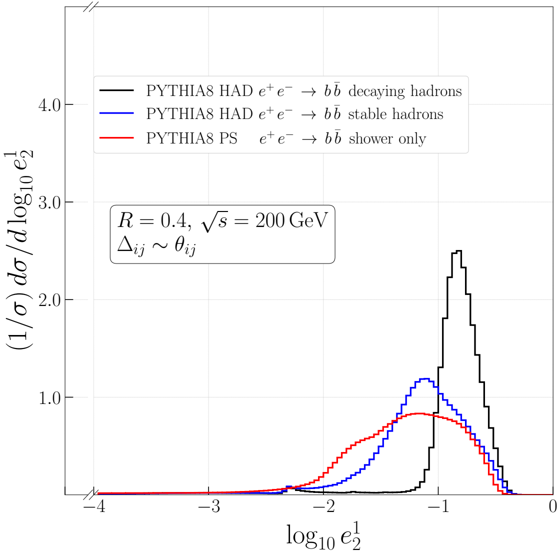
MC predictions for $e_2^{1/2}$ at hadron level (preliminary)



- We expect some low-momentum transfer effects $\sim \Lambda_{\mathrm{QCD}}$, however...
- Hadronization significantly change shape of e_2^{α}
- If we keep B-hadrons stable the changes are not so dramatic, see Lee *et al* in 1901.09095
- B-hadron reconstruction techniques should be applied

MC predictions for e_2^1 at hadron level (preliminary)



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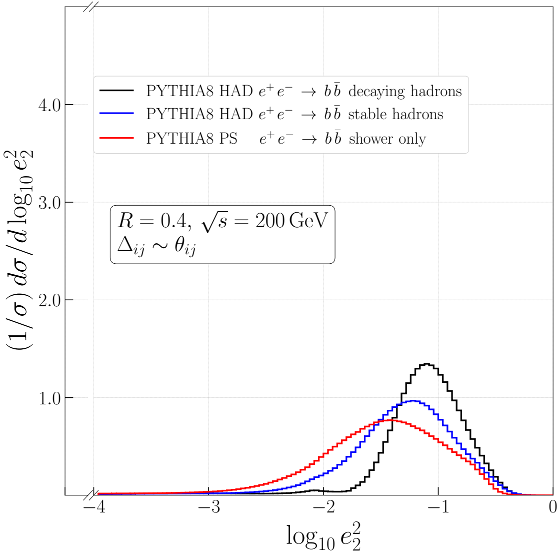

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Our workflow (general formalism)

We use Catani and Seymour approach

The squared amplitude factorization is given by

$$|\mathcal{M}_{g,a_1,\ldots,a_n}(k,q_1,\ldots,q_n)|^2 = -4\pi\alpha_{\mathrm{S}}^u\mu_0^{2\epsilon}\sum_{i,j=1}^{n}\mathrm{T}_i\cdot\mathrm{T}_j\,\frac{q_i q_j}{q_i k\; q_j k}\,|\mathcal{M}_{a_1,\ldots,a_n}(q_1,\ldots,q_n)|^2+\ldots,$$

$$|\mathcal{M}_{a_1,\ldots,a_m,\ldots}(q_1,\ldots,q_m,\ldots)|^2 = \left[\frac{8\pi\alpha_{\mathrm{S}}^u\mu_0^{2\epsilon}}{(q_1+\ldots+q_m)^2}\right]^{m-1}\mathcal{I}^{ss'}_{a,\ldots}(xp,\ldots)\,\widehat{P}^{ss'}_{a_1,\ldots,a_m}+\ldots$$

where the spin-averaged splitting kernels are given by

$$\widehat{P}^{\mathrm{TL}}_{QQ} = C_F\left[\frac{1+z^2}{1-z}-\epsilon(1-z)-\frac{m_Q^2}{p_Q p_g}\right], \qquad \widehat{P}^{\mathrm{TL}}_{Qg} = C_F\left[\frac{1+(1-z)^2}{z}-\epsilon z-\frac{m_Q^2}{p_Q p_g}\right],$$

$$\widehat{P}^{\mathrm{TL}}_{gQ} = T_R\left[1-\frac{2}{1-\epsilon}\left\{z(1-z)-\frac{m_Q^2}{(p_Q+p_{\bar{Q}})^2}\right\}\right], \quad \widehat{P}^{\mathrm{TL}}_{gg} = 2C_A\left[\frac{z}{1-z}+\frac{1-z}{z}+z(1-z)\right].$$

See Catani and Seymour and Catani et al.

Our workflow (simple case of massless partons)

We use the "method of regions" to explore the log-structure

$$\frac{d\sigma^{\mathcal{R}_1}}{de_2^{(\alpha)}} = 2 \times \frac{(4\pi)^\epsilon}{16\pi^2\Gamma(1-\epsilon)} \int_{s_{qg}^{\min}}^{s_{qg}^{\max}} ds_{qg}\, s_{qg}^{-\epsilon} \int_{z_{\min}}^{z_{\max}} dz\, z^{-\epsilon}(1-z)^{-\epsilon} \times \left[\frac{8\pi\alpha_{\mathrm{S}}^u \mu_0^{2\epsilon}}{s_{qg}} \widehat{P}_{qq}^{\mathrm{TL}}\right] \times \delta\left(e_2^{(\alpha)} - z(1-z)\left(\frac{2q_1 k}{E_q E_g}\right)^{\frac{\alpha}{2}}\right),$$

$$\frac{d\sigma^{\mathcal{R}_2}}{de_2^{(\alpha)}} = \frac{\alpha_{\mathrm{S}}^u \mu_0^{2\epsilon}(2\pi)^{2\epsilon}}{\pi^2} C_F \int \frac{d^{d-1}\vec{k}}{|\vec{k}|} \frac{q_1 q_2}{q_1 k\, q_2 k} \delta\left(e_2^{(\alpha)} - \frac{E_q|\vec{k}|}{E_J^2}\left(\frac{2q_1 k}{E_q|\vec{k}|}\right)^{\frac{\alpha}{2}}\right),$$

$$\frac{d\sigma^{\mathcal{R}_1}}{de_2^{(\alpha)}} + \frac{d\sigma^{\mathcal{R}_2}}{de_2^{(\alpha)}} + \frac{d\sigma^{\mathcal{V}}}{de_2^{(\alpha)}} = \frac{\alpha_{\mathrm{S}} C_F}{\pi}\left\{-\frac{4}{\alpha}\left(\frac{\ln e_2^{(\alpha)}}{e_2^{(\alpha)}}\right)_+ + \left(\frac{1}{e_2^{(\alpha)}}\right)_+ \left[-\frac{3}{\alpha} + 4\ln 2\right] + \delta\left(e_2^{\alpha}\right)\left[-\frac{\pi^2}{3} + \frac{2}{3}\frac{\pi^2-9}{\alpha} + \frac{\alpha}{12}\left(\pi^2 - 24\ln^2 2\right) + \frac{1}{2}(5 + 6\ln 2)\right]\right\}.$$

Our workflow (massive partons and grooming)

We consider the most general SoftDrop case

$$
\begin{aligned}
&\mathcal{R}_1 : z_Q \equiv z \geq z_{\rm cut}\left(\frac{\theta^2_{Qg}}{R^2}\right)^{\frac{\beta}{2}} , \; z_g \equiv 1-z \geq z_{\rm cut}\left(\frac{\theta^2_{Qg}}{R^2}\right)^{\frac{\beta}{2}} , \\
&\mathcal{R}_2 : z_Q \equiv z \geq z_{\rm cut}\left(\frac{\theta^2_{Qg}}{R^2}\right)^{\frac{\beta}{2}} , \; z_g \equiv 1-z \leq z_{\rm cut}\left(\frac{\theta^2_{Qg}}{R^2}\right)^{\frac{\beta}{2}} \; \text{with} \cos R \leq \cos\theta \leq 1 , \\
&\mathcal{R}_2' : z_Q \equiv z \in [0,1], \qquad z_g \equiv 1-z \in [0,1], \qquad \text{with} \, 0 \leq \cos\theta \leq \cos R , \\
&\mathcal{R}_3 : z_Q \equiv z \leq z_{\rm cut}\left(\frac{\theta^2_{Qg}}{R^2}\right)^{\frac{\beta}{2}} , \; z_g \equiv 1-z \geq z_{\rm cut}\left(\frac{\theta^2_{Qg}}{R^2}\right)^{\frac{\beta}{2}} .
\end{aligned}
$$

where $\mathcal{R}_1$ and $\mathcal{R}_3$ are collinear regions while $\mathcal{R}_2$ and $\mathcal{R}_2'$ are soft regions.

Our workflow (massive partons and grooming)

SoftDrop condition restrict the phase space

For example, for the soft region $\mathcal{R}_2$

$$\frac{d\sigma^{\mathcal{R}_2}}{de_2^{(\alpha)}} \sim \int \frac{d^d k}{(2\pi)^{d-1}} \delta_+(k^2) \left\{ \text{... some eikonal terms ...} \right\} \delta\left(e_2^{(\alpha)}\right)$$
$$\times \Theta\left(z \geq z_{\rm cut} \left(\frac{\theta_{Qg}^2}{R^2} \right)^{\frac{\beta}{2}} \right) \Theta\left(1 - z \leq z_{\rm cut} \left(\frac{\theta_{Qg}^2}{R^2} \right)^{\frac{\beta}{2}} \right) \Theta\left(\cos R \leq \cos\theta \leq 1 \right)$$

the result is given by

$$\frac{d\sigma^{\mathcal{R}_2}}{de_2^{(\alpha)}} = \frac{\alpha_{\rm S} C_F}{\pi} \delta\left(e_2^{(\alpha)}\right) \left\{ \left[-\frac{1}{2\epsilon} + \ln\left(z_{\rm cut} \left(\frac{2}{R^2} \right)^{\frac{\beta}{2}} \right) \right] \left[(1+\beta_m^2)\left(\mathcal{I}_1[\epsilon^0] + \mathcal{I}_2[\epsilon^0]\right) \right. \right.$$
$$\left. - \frac{m^2}{E_J^2}\left(\mathcal{I}_3[\epsilon^0] + \mathcal{I}_4[\epsilon^0]\right) \right] - \frac{1}{2}\left[(1+\beta_m^2)\left(\mathcal{I}_1[\epsilon] + \mathcal{I}_2[\epsilon]\right) - \frac{m^2}{E_J^2}\left(\mathcal{I}_3[\epsilon] + \mathcal{I}_4[\epsilon]\right) \right]$$
$$\left. - 2 z_{\rm cut} \left(\frac{2}{R^2} \right)^{\frac{\beta}{2}} \mathcal{I}_5[\epsilon^0] + \frac{z_{\rm cut}^2}{2} \left(\frac{2}{R^2} \right)^{\beta} \mathcal{I}_6[\epsilon^0] \right\} + \mathcal{O}(\epsilon)\,.$$

Our workflow (massive partons and grooming)

$$\frac{d\sigma^{\mathcal{R}_2}}{de_2^{(\alpha)}} = \frac{\alpha_{\mathrm{S}} C_F}{\pi}\delta\left(e_2^{(\alpha)}\right)\Bigg\{\left[-\frac{1}{2\epsilon} + \ln\left(z_{\mathrm{cut}}\left(\frac{2}{R^2}\right)^{\frac{\beta}{2}}\right)\right]\Big[(1+\beta_m^2)\Big(\mathcal{I}_1[\epsilon^0] + \mathcal{I}_2[\epsilon^0]\Big)$$
$$- \frac{m^2}{E_J^2}\Big(\mathcal{I}_3[\epsilon^0] + \mathcal{I}_4[\epsilon^0]\Big)\Big] - \frac{1}{2}\Big[(1+\beta_m^2)\Big(\mathcal{I}_1[\epsilon] + \mathcal{I}_2[\epsilon]\Big) - \frac{m^2}{E_J^2}\Big(\mathcal{I}_3[\epsilon] + \mathcal{I}_4[\epsilon]\Big)\Big]$$
$$- 2z_{\mathrm{cut}}\left(\frac{2}{R^2}\right)^{\frac{\beta}{2}}\mathcal{I}_5[\epsilon^0] + \frac{z_{\mathrm{cut}}^2}{2}\left(\frac{2}{R^2}\right)^{\beta}\mathcal{I}_6[\epsilon^0]\Bigg\} + \mathcal{O}(\epsilon)\,.$$

The integrals $\mathcal{I}_i$ lead to log-structures proportional to

$$\ln\left(\frac{1\pm\beta_m}{1\mp\beta_m}\right), \quad \ln(1\pm\cos R), \quad \ln\left(\frac{1\pm\beta_m\cos R}{1\pm\beta_m}\right), \quad \ln(1-\beta_m),$$

where $\beta_m = \sqrt{1-\frac{4m^2}{Q^2}}$.

Summary and next steps:

Current results

- Preliminary MC simulations with PYTHIA8 show strong dependence on the quark mass and non-perturbative effect (hadronization and decay of B-hadrons).
- We have identified all regions corresponding to soft and collinear. divergencies
- We have performed corresponding phase space integration and identified. related logarithmic contributions
- We also take into account logs due to the running coupling.

It is work in progress, so our next steps would be:

- Analytical results should be merged together and turned into computer program.
- Ideally, resummed predictions should be matched to fixed-order results to reach $\mathrm{NLO} + \mathrm{NLL}'$ accuracy level.
- Similar computation can be made for primary Lund plane projection.

Thank you for your attention!

Next steps: CAESAR formalism

The cumulative cross section for a generic observable v can be written as a sum over partonic channels δ:

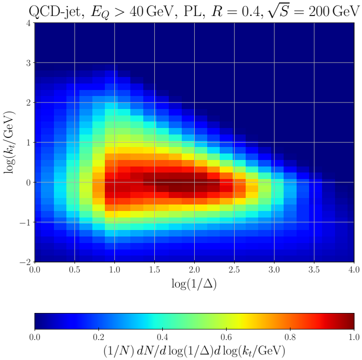
$$\Sigma_{\mathrm{res}}(v) = \sum_{\delta} \Sigma_{\mathrm{res}}^{\delta}(v)\,,\ \text{with}$$

$$\Sigma_{\mathrm{res}}^{\delta}(v) = \int d\mathcal{B}_{\delta} \frac{d\sigma_{\delta}}{d\mathcal{B}_{\delta}} \exp\left[-\sum_{l\in\delta} R_{l}^{\mathcal{B}_{\delta}}(L)\right] \mathcal{P}^{\mathcal{B}_{\delta}}(L) \mathcal{S}^{\mathcal{B}_{\delta}}(L) \mathcal{F}^{\mathcal{B}_{\delta}}(L) \mathcal{H}^{\delta}(\mathcal{B}_{\delta})\,,$$

where $L = -\ln(v)$, $\frac{d\sigma_{\delta}}{d\mathcal{B}_{\delta}}$ is the differential Born cross section, R_l is the collinear radiator for the hard legs l, $\mathcal{P}$ is the ratio of PDFs, $\mathcal{S}$ is the soft function, $\mathcal{F}$ is the multiple emission function and $\mathcal{H}$ stands for the corresponding kinematic cuts on the Born process.

For CAESAR implementation of jet angularities for $Z + jet$ and $jet + jet$ production see 2104.06920 and 2112.09545.

Next steps: what about primary Lund plane?



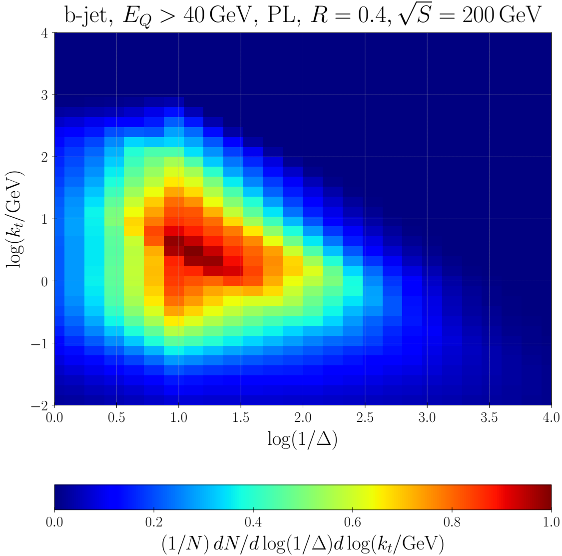
To build a Lund plane:

- Recluster your jet using CA algorithm
- Then compute:

$$\Delta_{ab} \equiv \sqrt{(y_a - y_b)^2 + (\phi_a - \phi_b)^2},$$
$$k_t \equiv p_{Tb}\,\Delta_{ab}.$$

- Discard softest branch and repeat.

Next steps: what about primary Lund plane? (preliminary)



b-jet production with Pythia8

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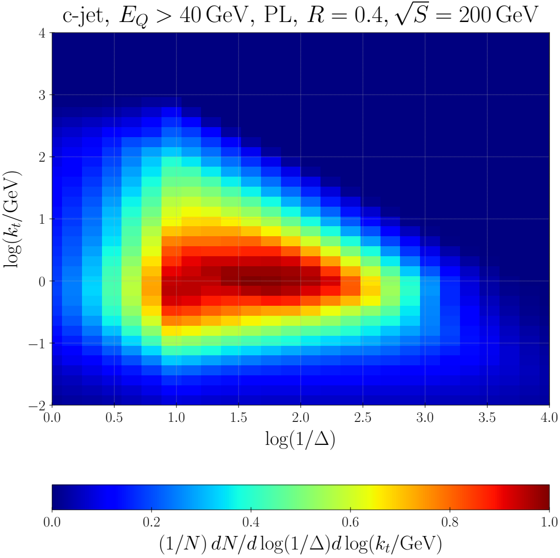

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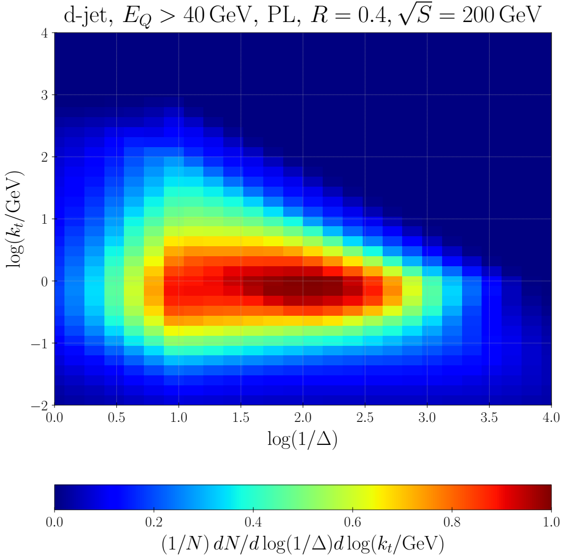
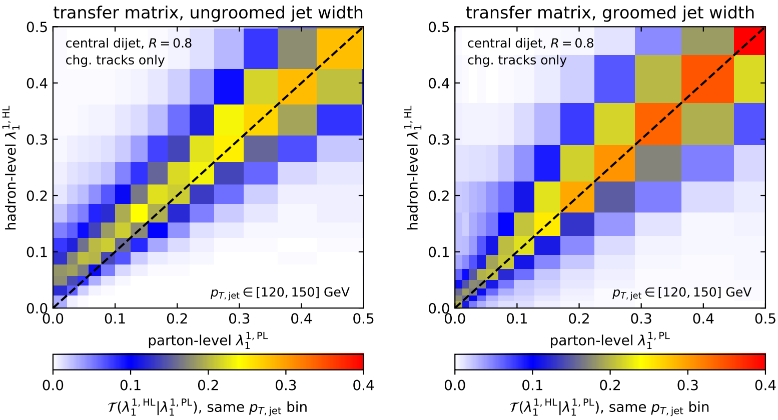


b-jet production with Pythia8

Parton to hadron level transition; credits G. Soyez



Transfer matrix $\mathcal{T}(\lambda_1^{1,\mathrm{HL}}|\lambda_1^{1,\mathrm{PL}})$ for the jet-width angularity for central dijet events with $R = 0.8$ and $p_{T,\mathrm{jet}} \in [120, 150]$ GeV.

From 2112.09545