Review on jets and preparation for the round table on onium in jets

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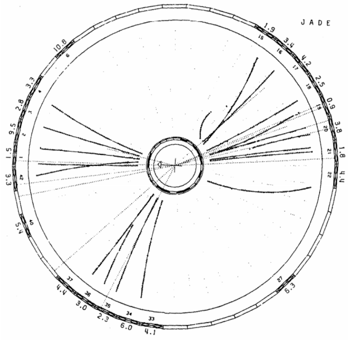
Quarkonia as Tools - January 6, 2025 - Aussois

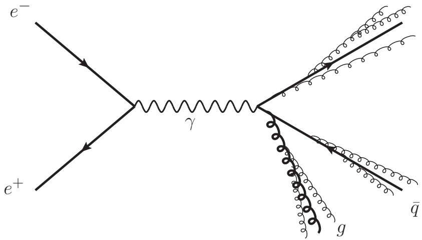
Outline of this talk

- Jet definition.
- Qualitative picture of a jet parton shower.
- Jet substructure.
- Selected topics on the connection between jets and heavy flavor physics
  - Quarkonia in jets
  - Open heavy flavor in jets
- Outlook

Final state parton evolution: QCD jets

- Jets are collimated spray of energetic hadrons.





- Jets result from successive collinear emissions from a virtual parton.
- How to properly define jets?

Jet definition via sequential recombination algorithms

- Popular jet definitions nowadays use sequential recombination algorithms.
  (Unlike cone-based jet definitions)
- Example with jets in e^+e^-: JADE, k_t algorithms,...
  JADE, Z.Phys.C 33 (1986), Catani, Dokshitzer, Olsson, Turnock, Webber, PLB 269, 432 (1991)
- Distance measure d_{ij} between particles i, j.
  Ex: $d_{ij} = M_{ij}^2/Q^2$ for JADE def.
- Sequential clustering of particles.
  - $\rightarrow$ For each pair of particles (i, j), work out the distance d_{ik}.
  - $\rightarrow$ Find the minimum of all d_{ij}.
  - $\rightarrow$ If the min is $< d_{\text{cut}}$, recombine i and j and repeat from step 1. Otherwise, terminate the iteration.

Jet algorithms in hadronic collisions

- Problem: initial state soft/collinear radiations. Need to distinguish between the beam remnant and high p_t jets.
- Idea: introduce particle-beam distance, d_{iB}, in addition to d_{ij}.

  Catani, Dokshitzer, Webber, PLB 285, 291 (1992)
- Sequential recombination algorithms widely used at the LHC: "generalized-k_t" algorithms.

$$d_{ij} = \min(p_{t,i}^{2k}, p_{t,j}^{2k})\frac{\Delta R_{ij}^2}{R^2}\,, \quad d_{iB} = p_{t,i}^{2k}$$

Catani, Dokshitzer, Seymour, Webber, NPB, 406 (1993), Cacciari, Salam, Soyez, JHEP 0804:063,2008

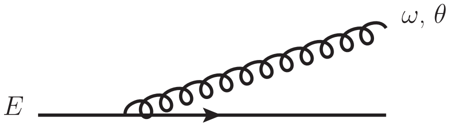
- The distance measure is longitudinally invariant $\Delta R_{ij}^2 = \Delta y_{ij}^2 + \Delta\phi_{ij}^2$.
- Same algorithm, but it stops when d_{iB} is the minimum among all d_{ij}, d_{iB}.

Jet evolution in vacuum

- Building block = Bremsstrahlung triggered by the virtuality of the parton from the hard process

$$d^2\mathcal{P}_{\mathcal{B}} \simeq \frac{\alpha_s C_R}{\pi} \frac{d\omega}{\omega} \frac{d\theta^2}{\theta^2}$$

- Includes soft and collinear divergences.



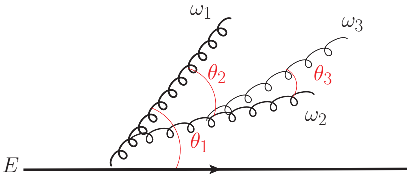
- Duration of the process: $t_f \sim 1/(\omega\theta^2)$.

Jet evolution in vacuum

- Building block = Bremsstrahlung triggered by the virtuality of the parton from the hard process

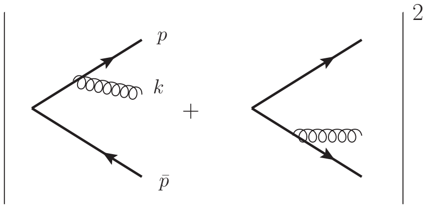
$$d^2\mathcal{P}_{\mathcal{B}} \simeq \frac{\alpha_s C_R}{\pi}\frac{d\omega}{\omega}\frac{d\theta^2}{\theta^2}$$

- Markovian process with angular ordering to account for **quantum** interferences.



$$\theta_1 \gg \theta_2 \gg \theta_3$$

Antenna radiation pattern



See e.g. Ellis, Stirling, Webber or Dokshitzer, Khoze, Mueller, Troyan books

- In the soft limit,

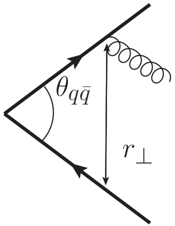
$$k^+ \frac{\mathrm{d}^3 N}{\mathrm{d}k^+ \mathrm{d}^2 \boldsymbol{k}_\perp} = \frac{\alpha_s C_F}{2\pi^2} \frac{p^\mu \bar{p}_\mu}{(p^\mu k_\mu)(\bar{p}^\mu k_\mu)}$$

- After averaging over the azimuthal angle of the gluon,

$$k^+ \frac{\mathrm{d}^2 N}{\mathrm{d}k^+ \mathrm{d}\theta_q} = \frac{\alpha_s C_F}{\pi} \frac{\sin(\theta_q)}{1 - \cos(\theta_q)} \Theta(\theta_{q\bar{q}} - \theta_q) + (q \leftrightarrow \bar{q})$$

What happens physically?

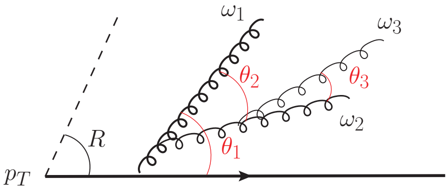
- Transverse wavelength of the gluon: $\lambda_\perp \sim 1/k_\perp \sim 1/(k^+\theta_q)$.
- Transverse size of the dipole at the gluon formation time $r_\perp \sim \theta_{q\bar{q}} t_f \sim \theta_{q\bar{q}}/(k^+\theta_q^2)$.
- The gluon does not resolve the color singlet dipole if $\lambda_\perp \gg r_\perp \Longrightarrow \theta_q \gg \theta_{q\bar{q}}$
- In this case, the gluon emission is suppressed.



DLA evolution of jets in vacuum

- Successive soft gluon emissions are angular ordered ⇒ "coherent branching algorithm"

  See e.g. Catani, Webber, Marchesini, 1991



$\theta_1 \gg \theta_2 \gg \theta_3$

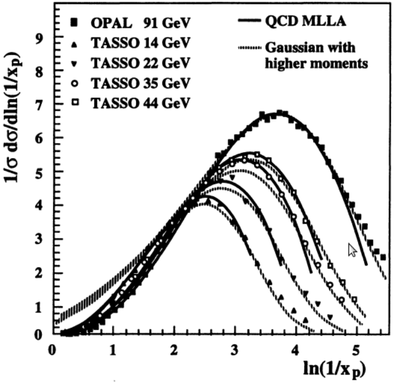
$\omega_1 \gg \omega_2 \gg \omega_3$

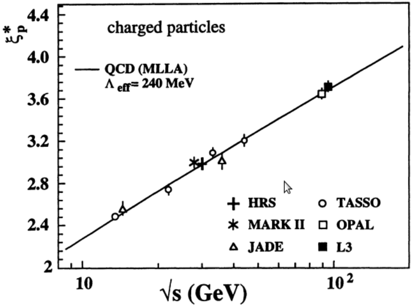
- E.g. double log resummation for parton intrajet multiplicity:

$$\omega\theta^2 \frac{\mathrm{d}^2 N}{\mathrm{d}\omega \mathrm{d}\theta^2} = \frac{\alpha_s C_R}{\pi} \mathrm{I}_0 \left(2\sqrt{\bar{\alpha}_s \ln\left(\frac{p_T}{\omega}\right) \ln\left(\frac{R^2}{\theta^2}\right)} \right)$$

Some phenomenological consequences

- Humped-back plateau in FF of jets in e^+e^- annihilation.

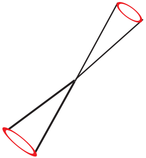




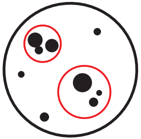
- In general, angular ordering is necessary to correctly resum leading soft logarithms.

Two classes of jet observables

- Global properties: differential cross-sections, thrust, dijet asymmetry, etc



- Inner structure = looking "inside" jets.



Jet physics involves a broad range of physical scales

- From the hard scattering scale $Q \sim$ few hundred of GeV, to the non-perturbative regime Λ_{QCD}.

- When building a substructure observable, one would like it to probe mainly the perturbative regime.

  $\Rightarrow$ non-perturbative effects power of Λ_{QCD}/Q suppressed.

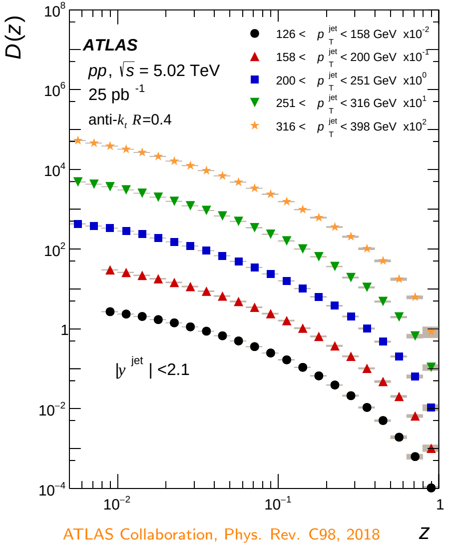
- IRC safe (or at least Sudakov safe).

Concrete counter-example: hadronic jet FF

- **"Standard" fragmentation function** = energy ($\simeq$ transverse momentum) distribution of hadrons within jets.

$$\mathcal{D}(x) = \frac{1}{N_{\text{jets}}} \frac{dN}{dx}$$

with $x \sim p_T / p_{T,\text{jet}}$

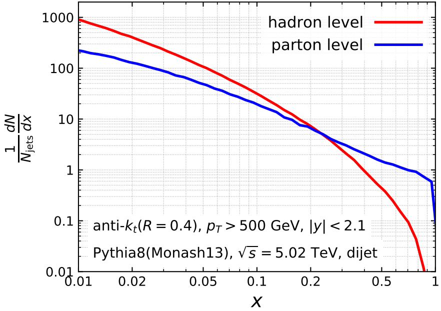


ATLAS Collaboration, Phys. Rev. C98, 2018

Concrete counter-example: hadronic jet FF

- **Standard FF is not IRC safe.**
- Simple LL estimate: $x\mathcal{D}_{\rm pp}(x) = 2\bar{\alpha}_s \int_{k_{\perp\rm min}/(xp_T)}^{R} \frac{d\theta}{\theta} \mathrm{I}_0\left(2\bar{\alpha}_s\sqrt{2\log(1/x)\log(R/\theta)}\right)$
  - $\Rightarrow$ **strong** dependence upon $k_{\perp\rm min}$.
  - $\Rightarrow$ very sensitive to hadronization modelling.
  - Not ideal if we want to probe the perturbative dynamics.

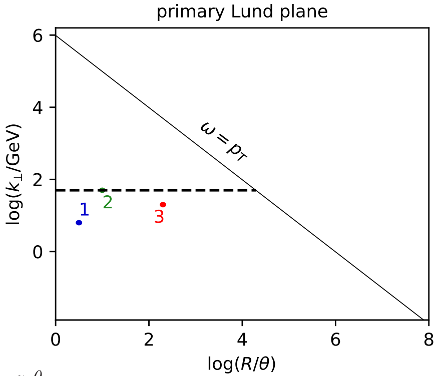
Standard FF: *pp* study

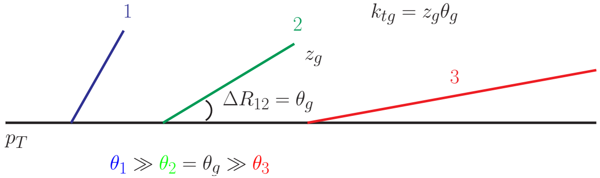


Usefool tool: the primary Lund jet plane

Definition

- Recluster jet constituents using C/A algorithm (angular ordered)
- Undo iteratively the clustering sequence.
- Then measure the kinematic $k_{tg} = z\Delta R/R$ or $\theta_g = \Delta R$ of each branching.





IRC safe fragmentation function: FF from subjets after grooming

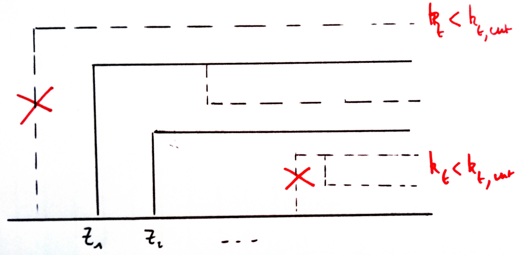
Definition

$$\mathcal{D}_{\rm sub}(z) = \frac{1}{N_{\rm jets}} \frac{dN_{\rm sub}}{dz}$$

$dN_{\rm sub}$ number of **primary subjets** with $k_\perp > k_{\perp\rm cut}$ found after an iterative C/A declustering.
PC, Iancu, Mueller, Soyez, 2020

$\Longrightarrow$ Similar to ISD multiplicity differential in z, or the primary Lund plane density $\rho(\theta, z)$ integrated over θ (with $k_\perp > k_{\perp,\rm cut}$). Frye, Larkoski, Thaler, Zhou, JHEP 09 (2017) 083 ; Dreyer, Salam, Soyez, JHEP 12 (2018) 064

$\Longrightarrow$ One can also define it fully recursively.



z is the *splitting fraction* (defined w.r.t. the parent subjet).

IRC safe fragmentation function: FF from subjets after grooming

Definition

$$\mathcal{D}_{\mathrm{sub}}(z) = \frac{1}{N_{\mathrm{jets}}} \frac{dN_{\mathrm{sub}}}{dz}$$

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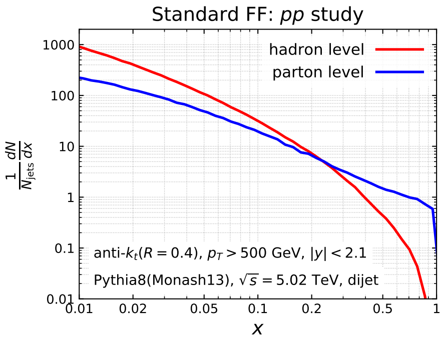
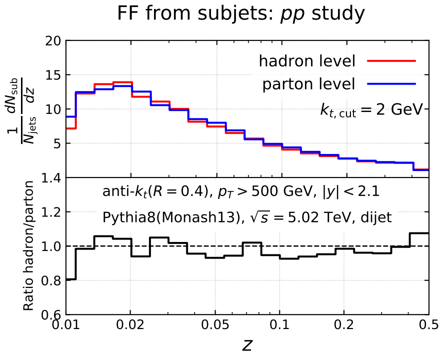
Leading log estimate:

$$\mathcal{D}^{pp}_{\mathrm{sub}}(z) \simeq \left[\int_0^R \frac{d\theta}{\theta} \frac{2\alpha_s(z\theta p_T)}{\pi z} \Theta(z\theta p_T - k_{\perp\mathrm{cut}})\right] \times \sum_{i=q,g} \frac{C_i \sigma_i(p_T)}{\sigma_q(p_T) + \sigma_g(p_T)}$$

Beyond LL, see e.g. Lifson, Salam, Soyez, JHEP 10 (2020) 170, Medves, Soto-Ontoso, Soyez, JHEP 10 (2022) 156

Sensitivity to hadronization: quick study in *pp* collisions with Pythia8





Comment

Improved resilience to hadronization compared to hadronic FF.

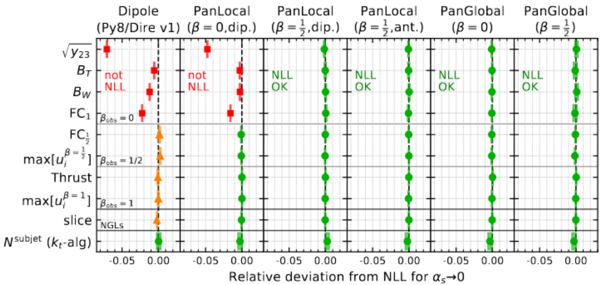
Towards NLL and N^{2}LL accurate parton shower

- IRC safe jet observable have a simple analytic resummation structure, e.g.

$$-\ln(\Sigma(v)) = \alpha_s^{-1} g_{\mathrm{LL}}(\alpha_s L) + g_{\mathrm{NLL}}(\alpha_s L) + \alpha_s g_{\mathrm{N^2LL}}(\alpha_s L) + \dots, \quad L = \ln(v) \gg 1$$

- Can be used to control the logarithmic accuracy of parton showers

$v = y_{\mathrm{cut}} \Rightarrow$



Dasgupta et al., PRL 125 (2020) & PanScales collaboration, 2406.02661

- Precision tests of QCD (α_s determination, etc).

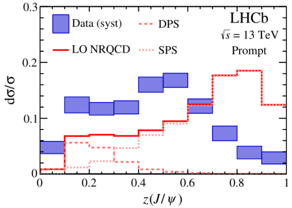
Quarkonia in jets

- General idea: correlate J/Ψ and jet production.
- Relevant at high p_T.
- To what extent high p_T J/Ψ are produced in isolation ?

Jet substructure with J/Ψ identification

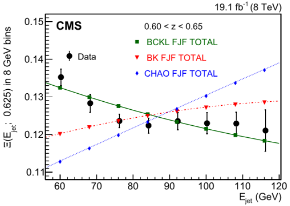
LHCb strategy LHCb, PRL 118 (2017)

- Reconstruct J/Ψ in the event using the dimuon decay channel.
- Then run the clustering algorithm with the J/Ψ treated as a final state particle.
- Compute $z_{J/\Psi} = p_T^{J/\Psi} / p_T^{\text{jet}}$.
(p_T^{jet} is the p_T of the jet containing the J/Ψ)



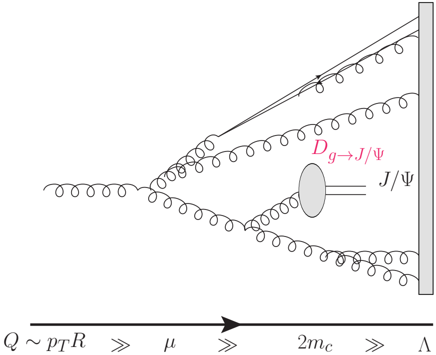
CMS strategy CMS, PLB 804 (2020)

- Run the clustering algorithm considering the muon pair as final state particles.
- Reconstruct the J/Ψ.
- If $\Delta R_{J/\Psi,jet} < 0.5$ **and** if both μ decay product are inside the same jet, then the J/Ψ is said to be part of the jet and $z_{J/\Psi} = p_T^{J/\Psi} / p_T^{\text{jet}}$ is computed.



Quarkonia in jets - formalism

- J/Ψ at high p_T is expected to predominantly come from jet fragmentation.
- Formalism based on the jet evolution outlined above + FF at the scale $\sim m_c$.



$$\frac{\mathrm{d}\sigma^{pp\to j_1+j_2(J/\Psi)+X}}{\mathrm{d}p_T\mathrm{d}z_{J/\Psi}} = H_{ab\to ij} \otimes f_a \otimes f_b \otimes J_j \otimes \mathcal{G}_i^{J/\Psi}(p_T, R, z, \mu)$$

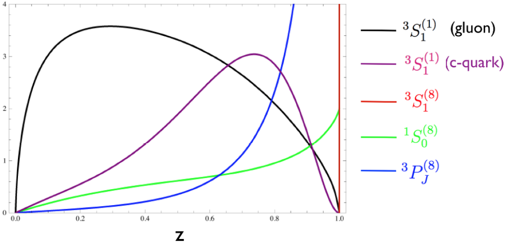
$$\mathcal{G}_i^{J/\Psi} \sim C_{ij}(p_T, R, \mu) \otimes K_{\mathrm{DGLAP}}\left[D_{j\to J/\Psi}(2m_c)\right]$$

State κ	${}^3S_1^{[1]}$	${}^3S_1^{[8]}$	${}^1S_0^{[8]}$	${}^3P_J^{[8]}$
$g \to c\bar{c}(\kappa)$	α_s^3	α_s	α_s^2	α_s^2
LDME $\langle O_\kappa^{J/\Psi}\rangle$	$(v/c)^3$	$(v/c)^7$	$(v/c)^7$	$(v/c)^7$

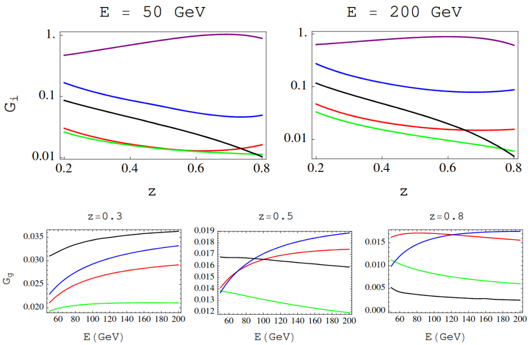
$\Rightarrow$ competing orders of magnitudes between $g \to c\bar{c}(\kappa)$ and LDME in NRQCD.

Quarkonia fragmenting jet function

- Probability to find a $c\bar{c}(\kappa)$ state with longitudinal momentum fraction z w.r.t. the jet with energy E.
- Sensitivity to LDME in NRQCD $\Rightarrow$ powerful constraints.



$\mu = 2m_c$



$\mu \sim ER$ with $R = 0.4$

Baumgart, Leibovich, Mehen, Rothstein, JHEP 11 (2024) 003

Complementary probe of LDME

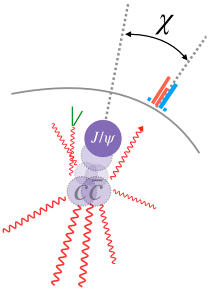
- High p_T J/Ψ primarily come from gluon fragmentation: dominance of the ${}^3S_1^{[8]}$ state leading to transversely polarised J/Ψ. Cho, Wise, hep-ph/9411303Braaten, Kniehl, Lee, hep-ph/9911436
  - Note that NLP contribution are sizeable, see Kang, Qiu, Sterman, PRL 108 (2012)
- However, data favors no J/Ψ polarisation at high p_T.

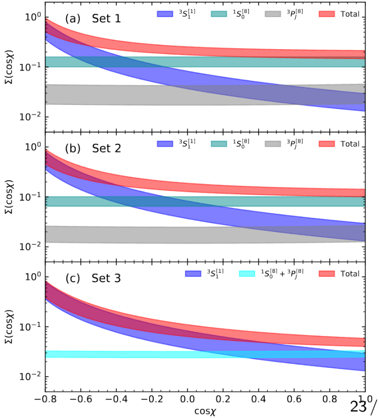
  $\Rightarrow$ larger $\langle O^{J/\Psi}_{{}^1S_0^{[8]}}\rangle$ value preferred and/or cancellation between ${}^3S_1^{[8]}$ and ${}^3P_J^{[8]}$ contributions in NLO fits within NRQCD.
- Since the $(z_{J/\Psi}, p_T^{\rm jet})$ double differential distribution is strongly sensitive to the $c\bar{c}$ state $\Rightarrow$ new constraints on the associated LDMEs.
- **Caveats:** $g, c \to J/\Psi$ FF only known at lowest order, so far only NLL resummation. Regime $z \to 1$ might need special resummation (threshold).

New avenue: quarkonium energy correlators

Chen, Liu, Ma, PRL 133 (2024)

- Measure energy-weighted angular correlations between produced particles and J/Ψ
- Angle defined in the J/Ψ rest frame.





$$\Sigma(\cos(\chi)) = \int \mathrm{d}\sigma_{ab\to J/\Psi+N} \sum_{i=1}^{N} \frac{E_i}{M_{\mathcal{Q}}} \delta(\cos(\chi) - \cos(\theta_i))$$

Heavy quark in jets: dead cone effect in pQCD

- Recall: branching probability $q \to q + g$ for a light quark:

$$\mathrm{d}^2\mathcal{P}_{\mathcal{B}} \simeq \frac{\alpha_s C_F}{\pi} \frac{\mathrm{d}\omega}{\omega} \frac{\mathrm{d}\theta^2}{\theta^2}$$

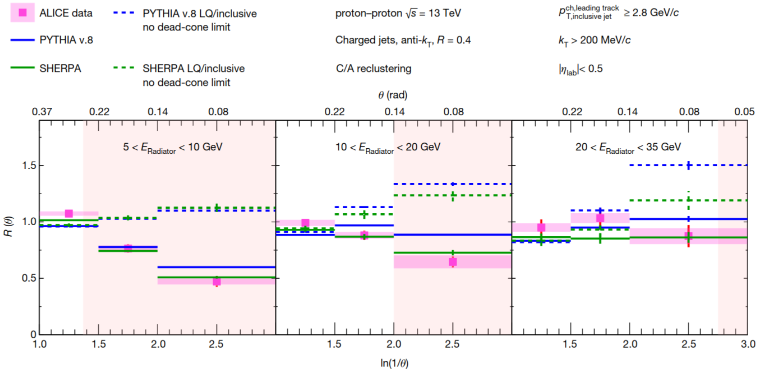
- For a heavy quark, mass regulates the collinear divergence

$$\mathrm{d}^2\mathcal{P}_{\mathcal{B}} \simeq \frac{\alpha_s C_F}{\pi} \frac{\mathrm{d}\omega}{\omega} \frac{\theta^3 \mathrm{d}\theta^2}{(\theta^2 + \frac{m^2}{E^2})^2}$$

- $\Rightarrow$ gluon radiation suppressed w.r.t light quarks for $\theta \leq \theta_0 \sim m/E$
- $\Rightarrow$ "dead cone" effect

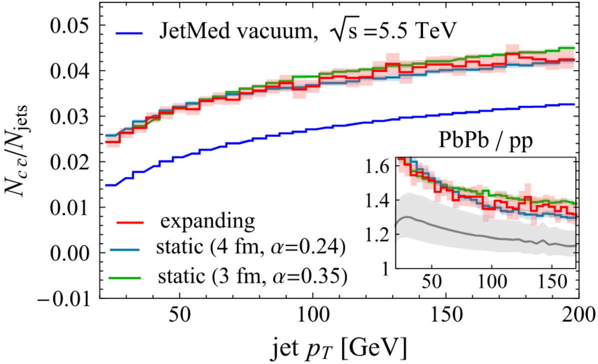
Dead cone measurement with jet substructure

- Idea of the ALICE measurement: measure the θ-differential subjet FF. (binned in terms of the energy of the parent subjet.) ALICE, Nature 605 (2022) 440-446
- Iteratively decluster the C/A sequence and record the angle of each splitting.
- Measurement performed for D^0 tagged and inclusive jets, then ratio is taken.



Heavy quark pair production in jets in AA

- $g \to c\bar{c}$ splitting are enhanced in a dense medium as compared to vacuum.
- This theory prediction should be confirmed by comparing the yield of $D^0\bar{D}^0$ tagged jets to inclusive jets in AA w.r.t. pp collisions.



Attems, Brewer, Innocenti, Mazeliauskas, Park, van der Schee, Soyez, Wiedemann, PRL 132 (2024)

Conclusion

- Overview on jets and jet substructure, with recent developments towards precision and new observables.
- More relevant to this workshop: overlap between jet and heavy quarks/quarkonia communities
  - ⇒ quarkonia isolation at high p_T.
  - ⇒ dead-cone effect in jets with open heavy flavor.
- Not discussed: quarkonia *with* jets. See e.g. next talk by Michael.
- Outlook: synergy between jet substructure observables and quarkonia isolation ?

THANK YOU!