Jet shape measurements in heavy-ion collisions

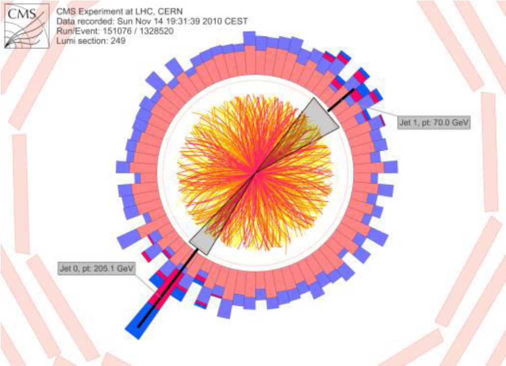
10th Asian Triangle Heavy-Ion Conference (ATHIC 2025)

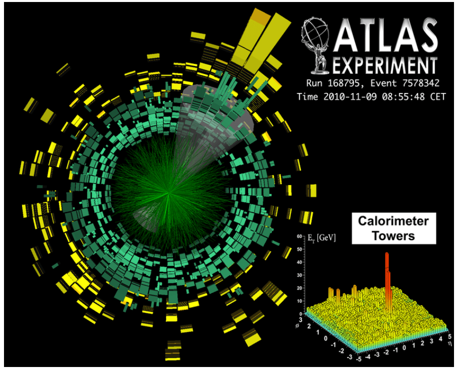
Gopalpur, India – January 14th, 2025

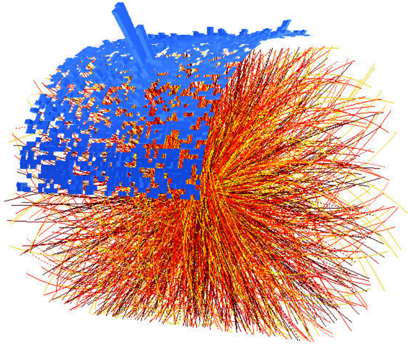
Saehanseul Oh (Sejong University, LBL)

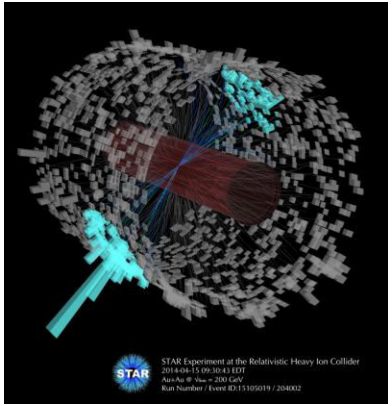
Introduction

Jets in heavy-ion collisions









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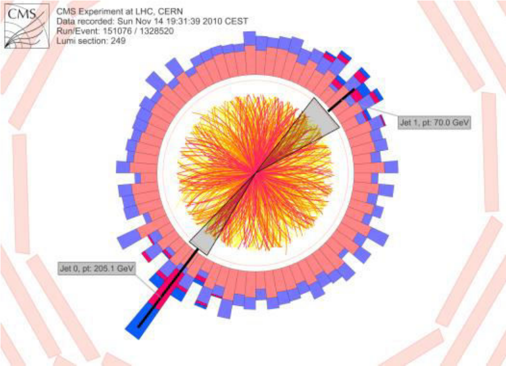
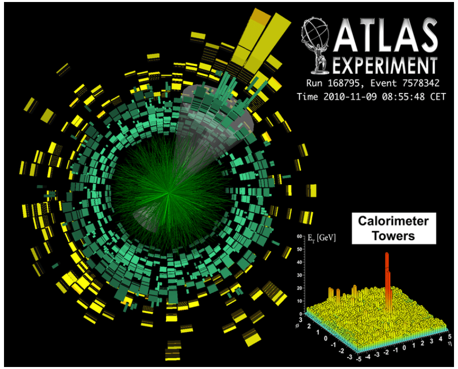
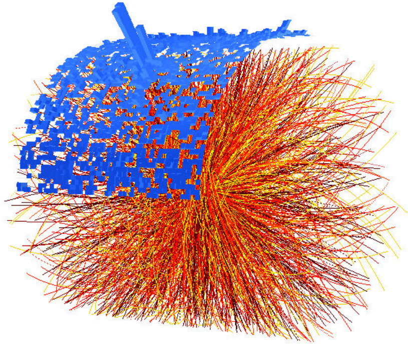
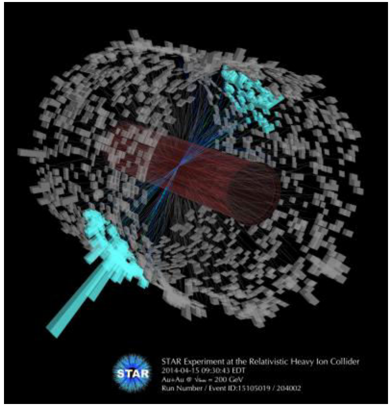


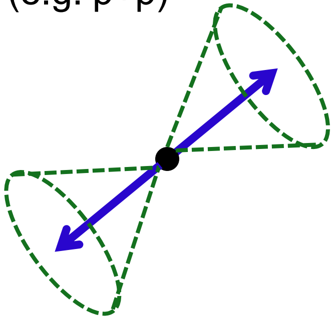






- Jets in vacuum
  - A hard-scattered parton fragments into final state particles → Algorithmic recombination into a Jet
  - Jets in vacuum are well understood in pQCD framework

In vacuum (e.g. p+p)



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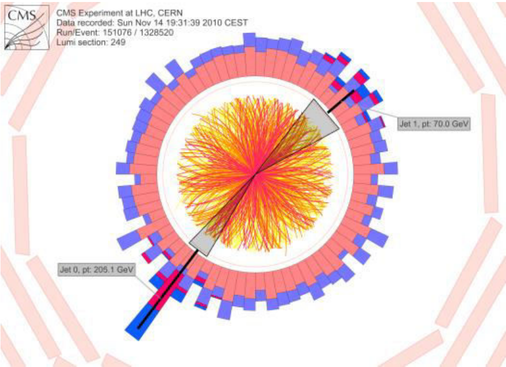
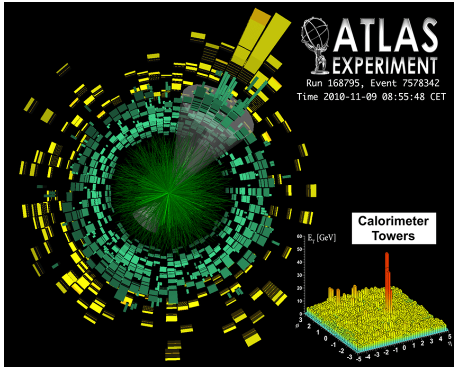
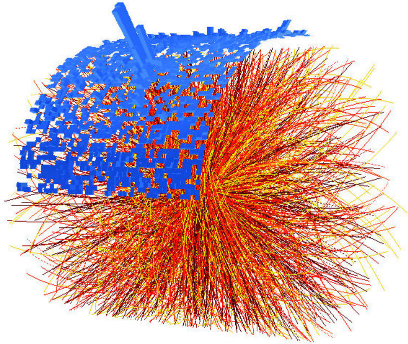
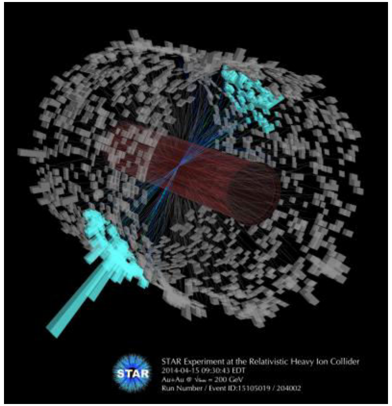


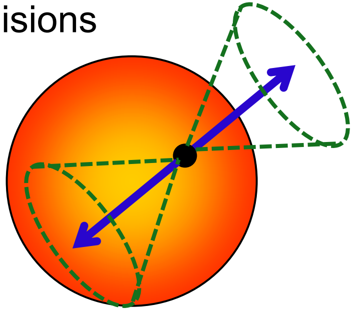






- Jets in heavy-ion collisions
  - Hard-scattered partons are produced at the very early stages of collisions → Interact with QGP as they traverse it
  - Any modifications to jet observables are due to the interaction with the QCD medium → Jet quenching

In A+A collisions



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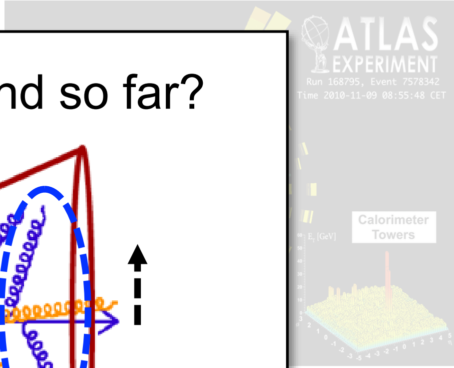
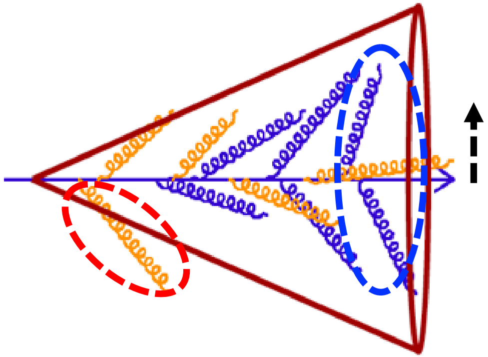
Jets in heavy-ion collisions



What have we found so far?



- Jet energy loss
- Jet substructure modification
- Jet deflection

In A+A collisions

Introduction

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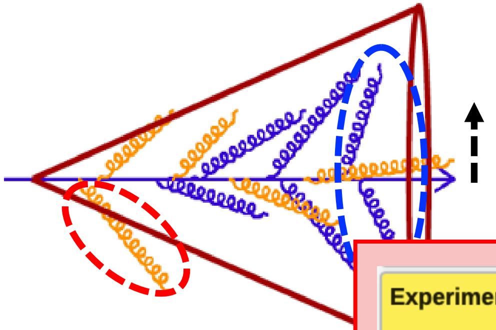

- Jet energy loss
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Experimental overview of recent jet measurements in relativistic heavy ion collisions *NIHAR RANJAN Sahoo*
16:35 - 17:00

Nihar’s talk at this conference

Introduction

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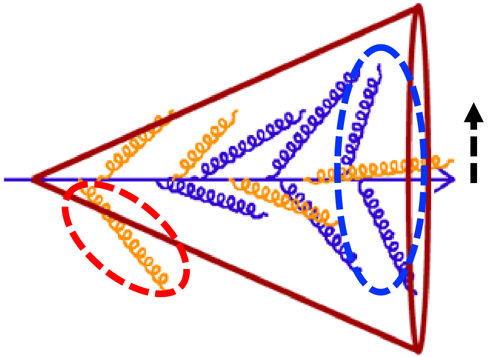

- Jet energy loss
- Jet substructure modification
- Jet deflection

- Jet fragmentation function
- Jet shape
- SoftDrop z_g, r_g
- Jet mass
- Jet axis
- Energy-energy correlator
- …

Introduction

We would like to invite you to attend ATHIC 2025 and deliver a plenary session presentation on the topic of 'jet shape measurements in relativistic heavy ion collisions'. The duration of the talk will be for 20 mins followed by 5 mins of discussions. We strongly hope that you will be able to attend the conference and deliver the plenary talk that will enh

Why does it matter?

- Jet energy loss
- Jet substructure modification
- Jet deflection

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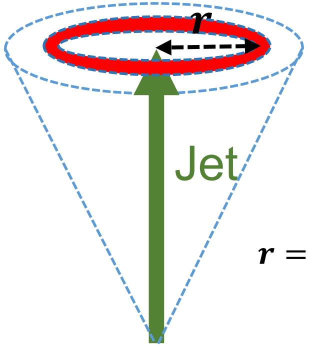
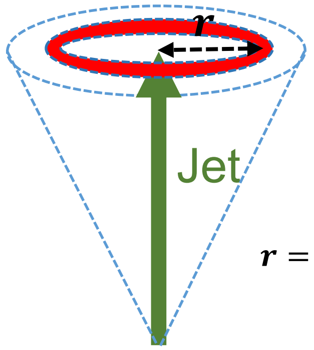
Jet shape



$$r = \sqrt{(\Delta\varphi)^2+(\Delta\eta)^2}$$

- $\rho(r) = \frac{1}{\delta r}\frac{1}{N_{\text{jet}}}\sum_{\text{jet}}\frac{\sum_{\text{track}\in(r-\delta r/2,\,r+\delta r/2)} p_{\text{T,track}}}{p_{\text{T,jet}}}$ (CMS, STAR)
- $D(p_{\text{T}}, r) = \frac{1}{N_{\text{jet}}}\frac{1}{2\pi r dr}\frac{dn_{\text{ch}}(p_{\text{T}},r)}{dp_{\text{T}}}$ (ATLAS)
- (Girth $g = \frac{\sum_{\text{track}\in\text{jet}} p_{\text{T,track}}\, r}{p_{\text{T,jet}}}$ (ALICE, STAR))
- Distribution of jet energy as a function of distance from the jet axis – Radial profile of jets

Jet shape



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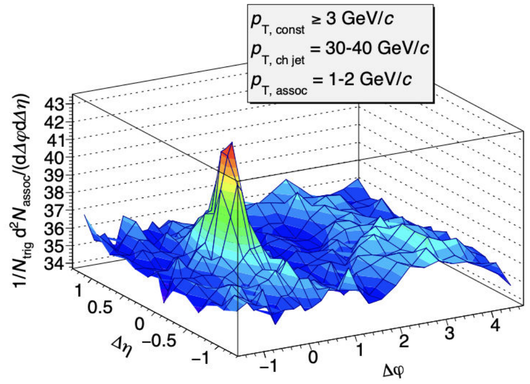
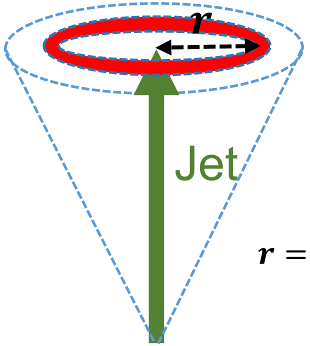


- Near side ((Δφ, Δη) ~ (0, 0)) of jet-hadron angular correlation
- Similar info can be extractable

Jet shape



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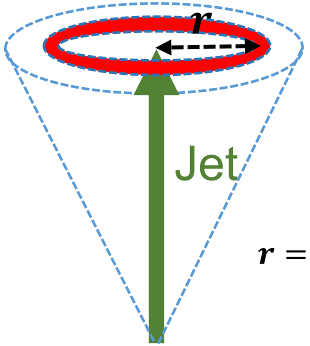
- One of the earliest publications regarding jets in heavy-ion collisions (CMS, Phys. Lett. B 730 (2014) 243)

Jet shape



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- Jet fragmentation function
- Jet shape
- SoftDrop z_g, r_g
- Jet mass
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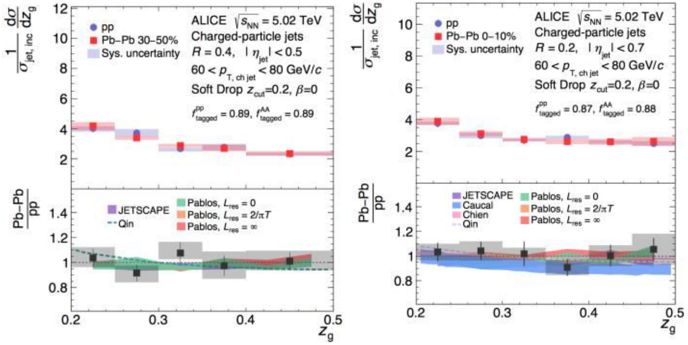
- …

- One of the earliest publications regarding jets in heavy-ion collisions (CMS, Phys. Lett. B 730 (2014) 243)
- There are observables that are difficult to measure due to large background in heavy-ion collisions

Jet shape

- E.g. SoftDrop z_g, R_g – incorrect splitting being identified by the grooming algorithm (Non-diagonal component in unfolding matrix) (Phys. Rev. C 102, 044913 (2020))



Smaller R jets, increased z_{cut} in SoftDrop, Semi-central events (ALICE, Phys. Rev. Lett. 128 (2022) 102001)

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…ion
…shape
- SoftDrop z_g, r_g
- Jet mass
- Jet axis
- Energy-energy correlator
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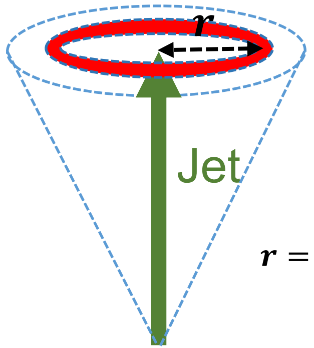
Jet shape



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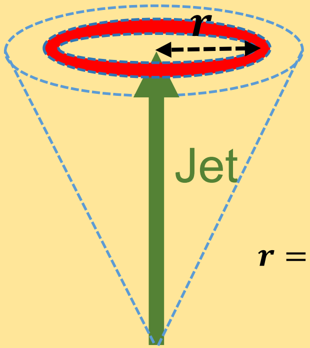
- There are observables that are
measure due to large backgrou
ion collisions

In experimental point of view, jet shape is a well-established/controlled observable



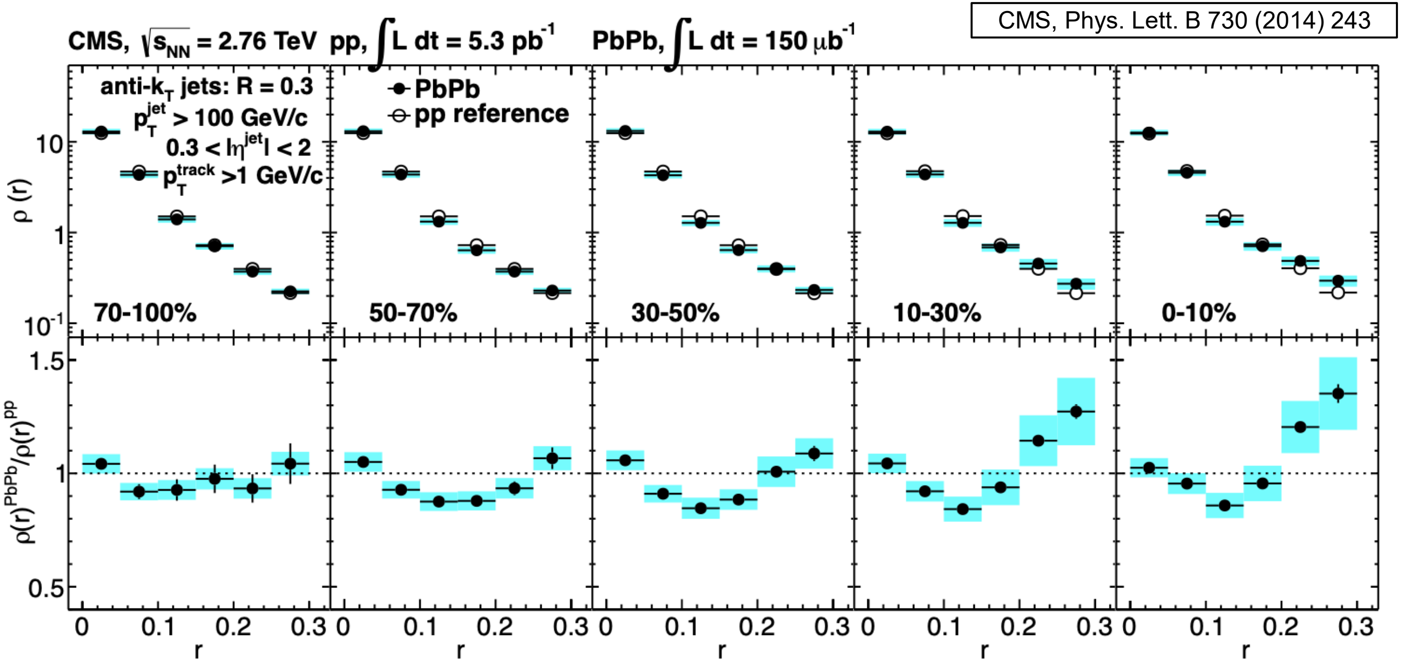
$$r = \sqrt{(\Delta\varphi)^2 + (\Delta\eta)^2}$$

(Some) Jet shape results

Results

$$\rho(r) = \frac{1}{\delta r}\frac{1}{N_{\text{jet}}}\sum_{\text{jet}}\frac{\sum_{\text{track}\in(r-\delta r/2,r+\delta r/2)} p_{\text{T,track}}}{p_{\text{T,jet}}}$$

CMS, Phys. Lett. B 730 (2014) 243

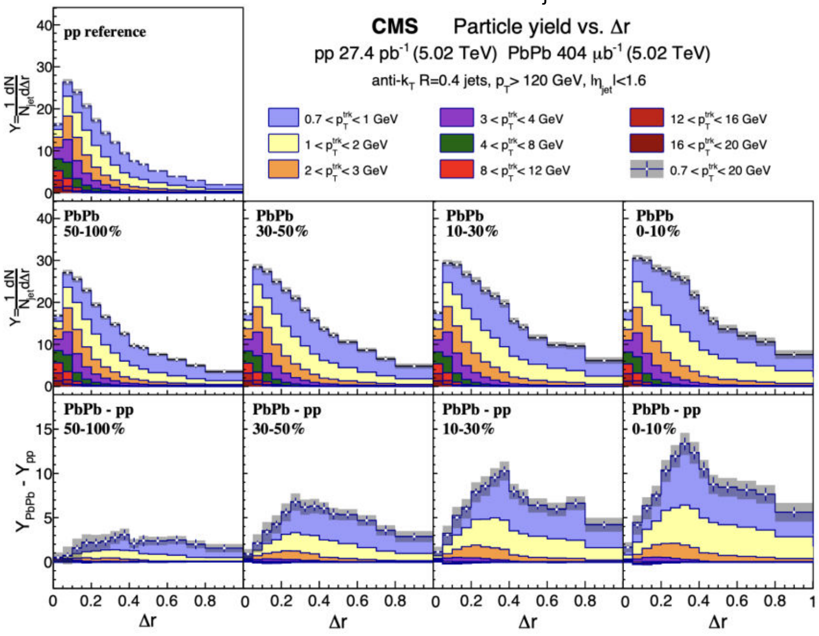


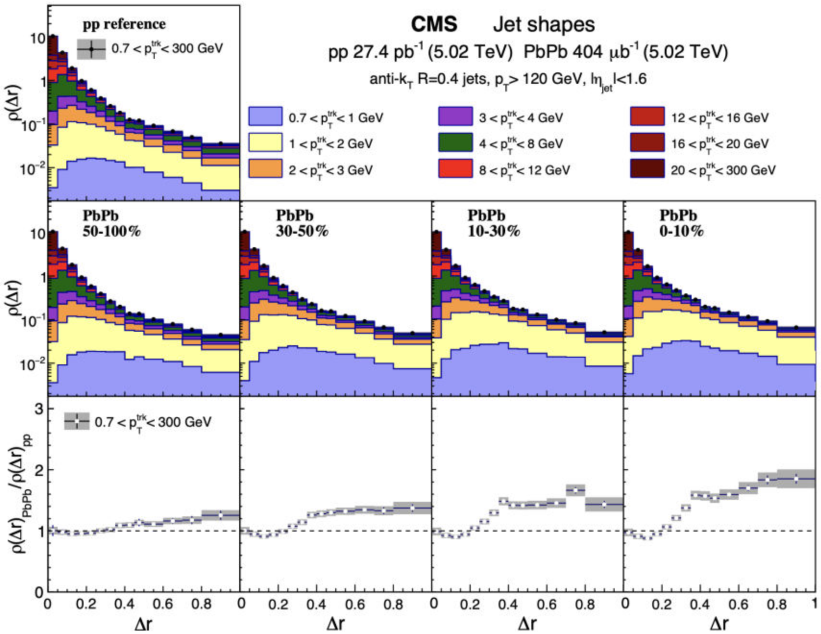
- $\sqrt{s_{\text{NN}}} = 2.76$ TeV with R = 0.3 jets, ρ up to r = 0.3
- Redistribution of the jet energy inside the cone – depletion at intermediate radii and excess at large radii

Results

CMS, JHEP 05 (2018) 006

Jet-hadron angular correlations, N_{jet} normalized



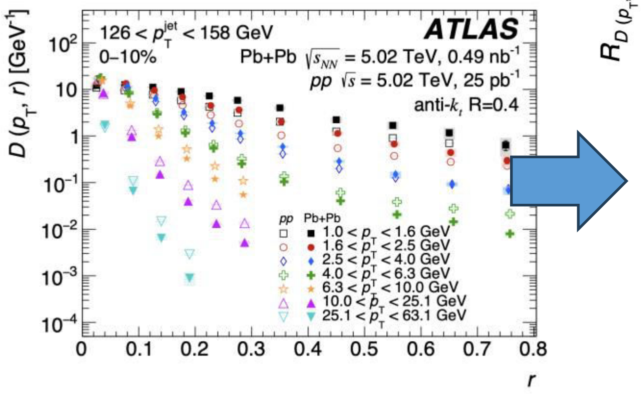


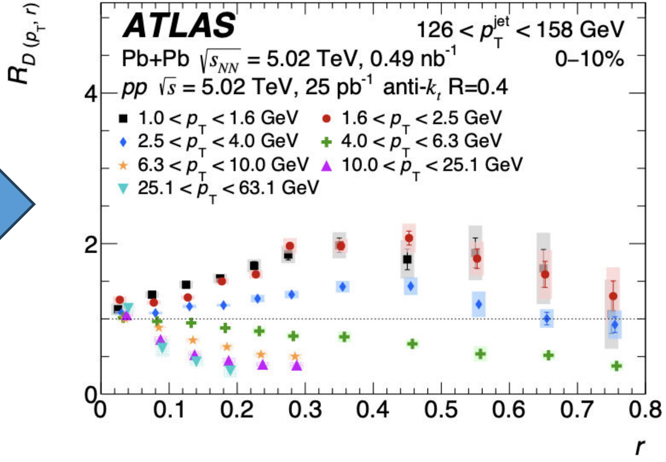
- $\sqrt{s_{\rm NN}} = 5.02$ TeV with *R* = 0.4 jets, ρ up to *r* = 1.0
- Enhancement of soft particles particularly at larger radii, and relative depletion of hard particles (Models with backreaction response of the medium to the jet agrees with the observation)

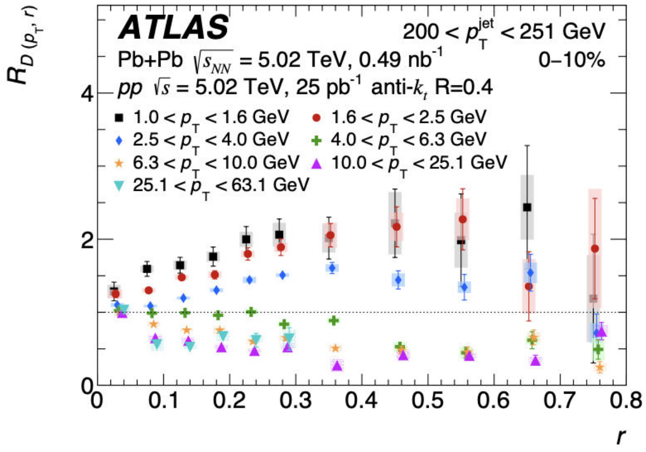
Results

ATLAS, Phys. Rev. C 100, 064901 (2019)

$$D(p_{\mathrm{T}}, r) = \frac{1}{N_{\mathrm{jet}}} \frac{1}{2\pi r dr} \frac{dn_{\mathrm{ch}}(p_{\mathrm{T}}, r)}{dp_{\mathrm{T}}}$$





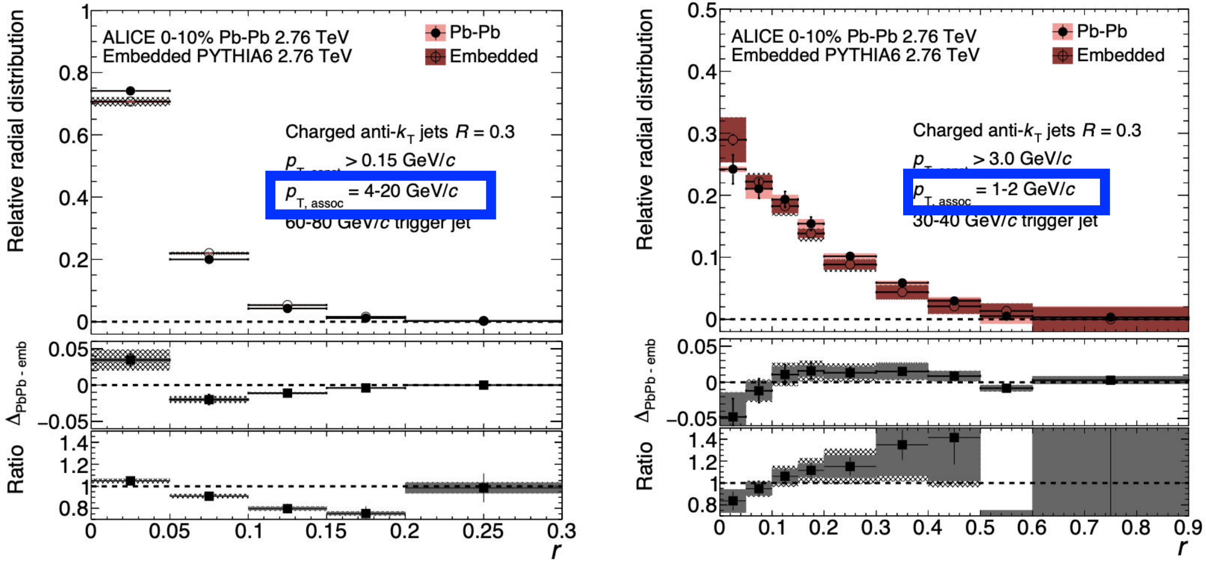


- $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV with *R* = 0.4 jets, *D* up to *r* = 0.8
- Enhancement of soft particles increasing with radius
- Depletion of hard particles especially outside the jet cone – Results consistent with CMS

Results

Jet-hadron angular correlations, self normalized

ALICE, Phys. Lett. B796 (2019) 204

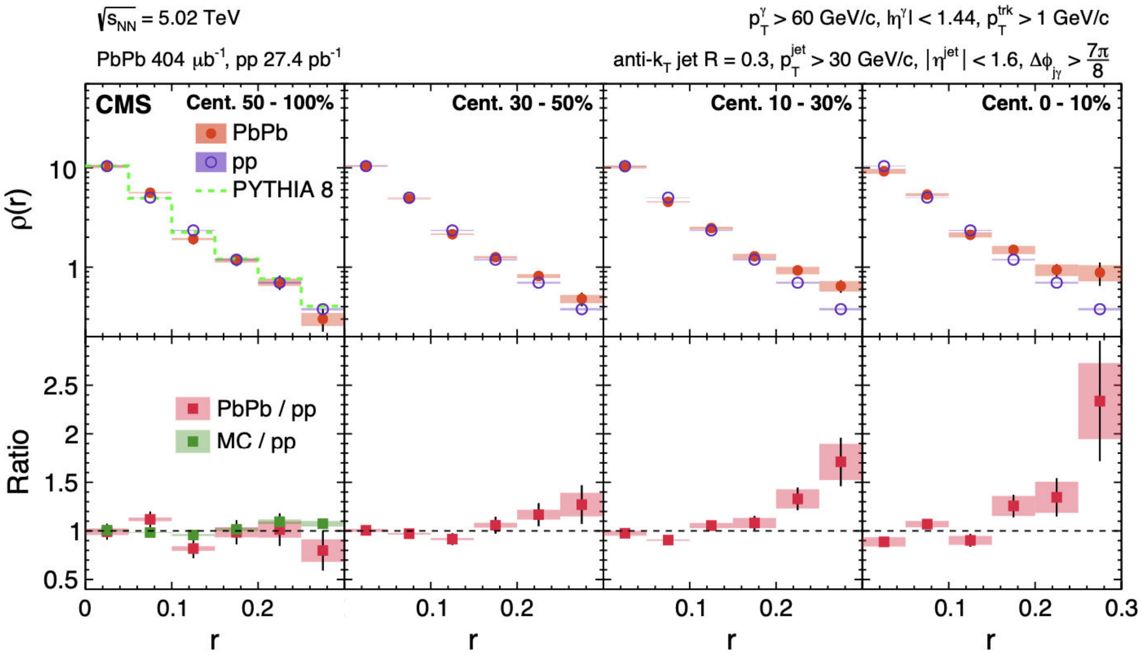


- $\sqrt{s_{NN}} = 2.76$ TeV with R = 0.3 jets
- Large uncertainty, lower jet transverse momenta
- (Hint of) broadening with soft particles, slightly more collimation of hard particles – Consistent with CMS/ATLAS

Results – Isolated photon-tagged jet

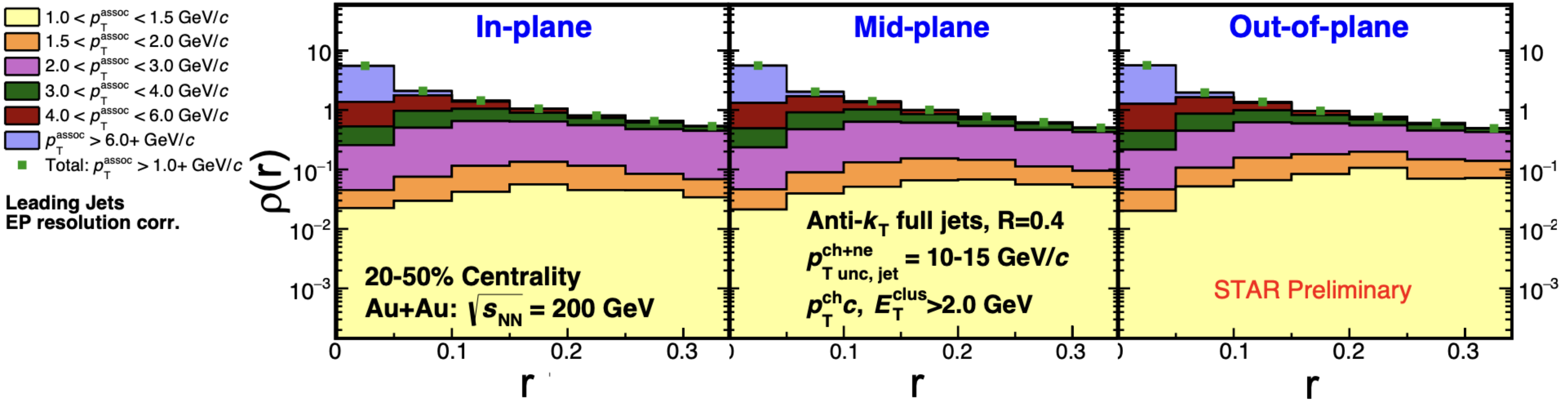
CMS, Phys. Rev. Lett. 122, 152001 (2019)

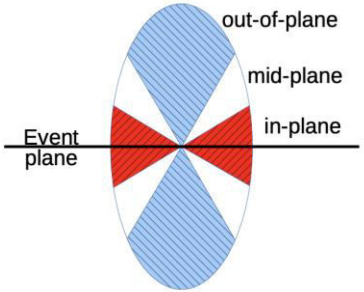
- Isolated photon-tagged jets
  - More likely quark jets
  - Different surface bias to inclusive jets



- Larger fraction of jet energy is at large distances from the axis in Pb-Pb with the similar level of modification to inclusive jet shape
- No significant depletion at intermediate *r* – Due to quark jet fraction? Low $p_{T,jet}$ (>30 GeV/c) range? (Previously, 100 GeV/c)

Results – Event-plane dependent jet shape



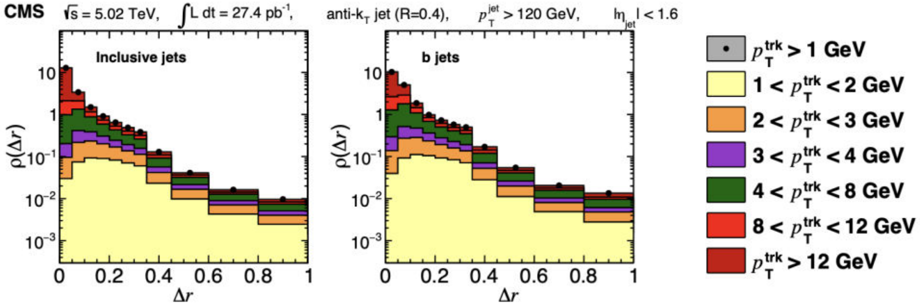


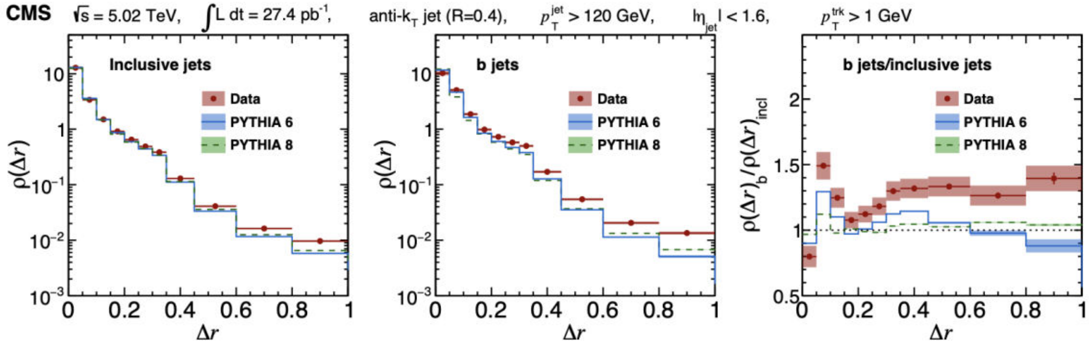
- Low-p_T tracks are pushed toward farther distances in the out-of-plane direction relative to the in-plane direction
- Larger yields of low-p_T tracks in the out-of-plane direction

→ Larger effects in the out-of-plane direction due to longer in-medium path-length?

Results – b-jet shape in pp

CMS, JHEP 05 (2021) 054

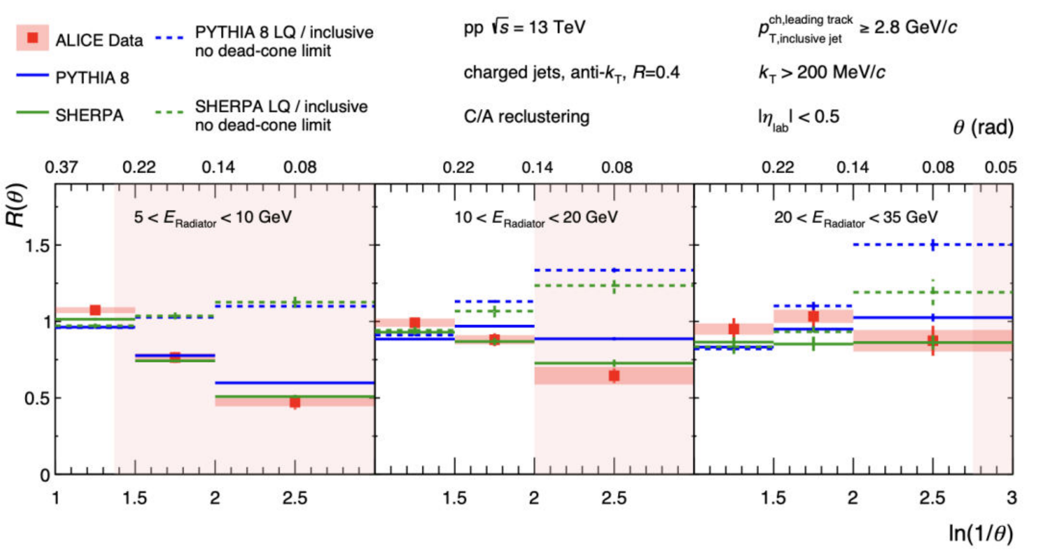




- Flavor-dependent jet quenching if we measure in AA
- In pp, comparison with PYTHIA → Smaller soft radiative contribution in models
- b/inclusive ratio
  - Shift of transverse momenta from small to larger Δr → Dead-cone effect?

Results – b-jet shape in pp

Direct observation of dead-cone effects from ALICE (Nature 605 (2022) 440)



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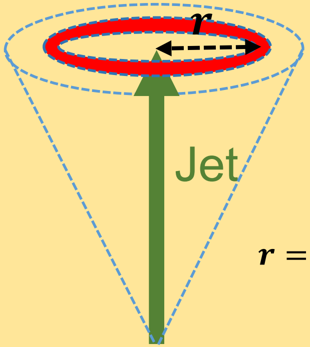
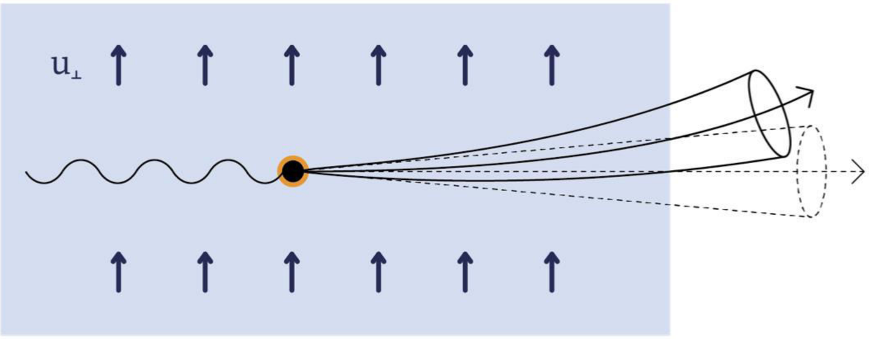


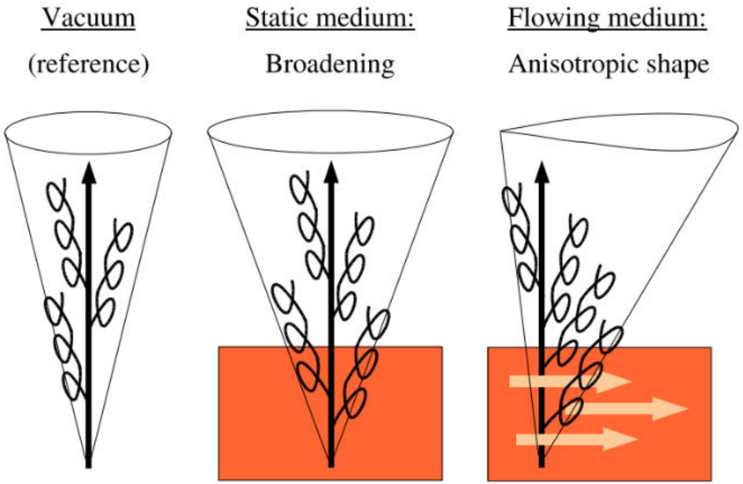
$$r = \sqrt{(\Delta\varphi)^2 + (\Delta\eta)^2}$$

(One of) Future jet shape results

Jet drift

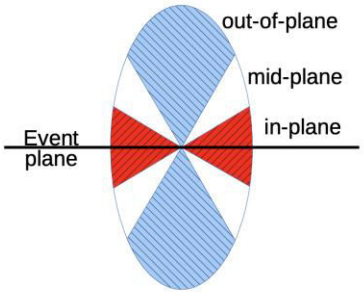
- Hard probe tomography requires new precision perturbative calculations and calculation inputs



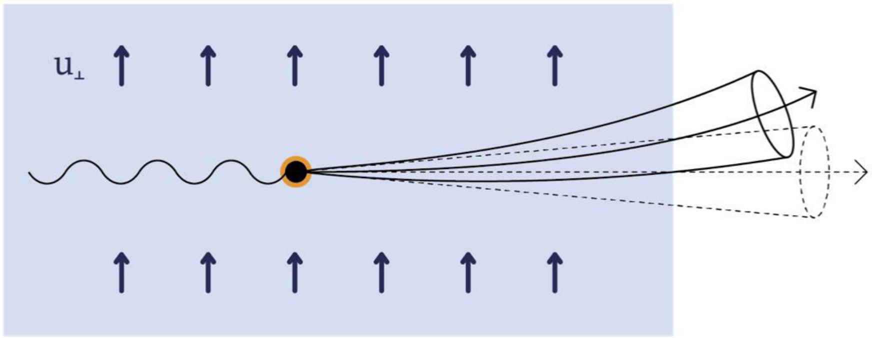


- Jet drift – Anisotropic broadening in direction of medium flow (particle couples to anisotropic flow) (Phys. Rev. D 104, 094044, Eur.Phys.J.C 84 (2024) 2, 174, Hard Probes 2024 J. Bahder, A. Sadofyev, R. J. Fries, X. Lopez, D. Pablos, and many more)

Jet drift



- Previous event-plane dependent jet measurements in ALICE (Phys. Rev. C 101, 064901 (2020)) and STAR (arXiv:2307.13891)
  - ✓ How to deal with event-plane resolution effects
  - ✓ More statistics in RHIC Run 2023-2025, LHC Run 3

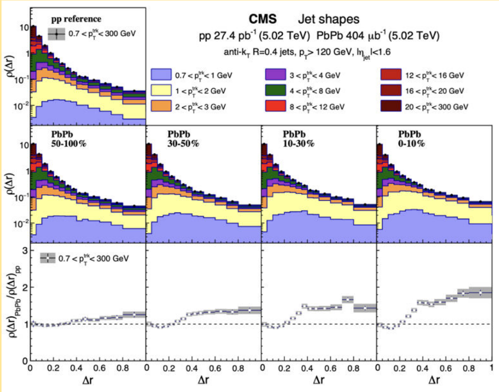


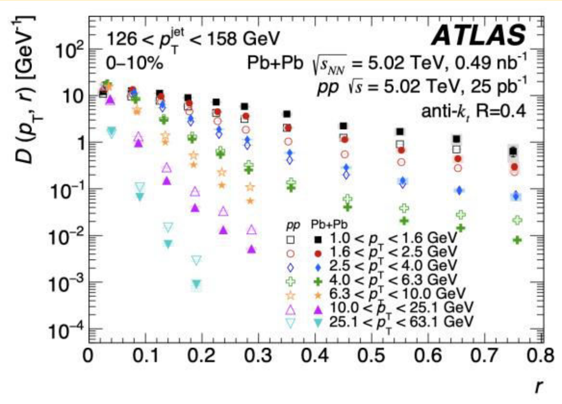
- Event-plane dependent jet shape can be a candidate to test the jet drift → Jet-shape-like observables in azimuthal angle, not in r?

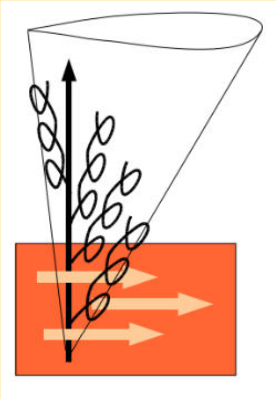
Summary

- Jet shape is a well-established observable showing the radial profile of a jet
  - In heavy-ion collisions, enhancement of soft particles particularly at larger radii has been commonly observed

- Jet shape can be used further to explore jet quenching phenomena
  - Flavor-dependent jet quenching, jet drift with EP-dependent jet shape








Thank you
धन्यवाद
감사합니다
ありがとう
谢谢

Back-up – Jets in QCD matter

- What questions are we trying to answer?
  - How does QGP respond to the external out-of-equilibrium probe, e.g. jets?
  - How can we use jets to probe the microstructure of the QGP?
  - What is the resolution scale of the medium? How can we measure that?
  - What can we learn from the mass dependence of jet quenching?
  - …

- Jet observables
  - Each jet observable is connected to one or multiple questions – We can probe different aspects of jet quenching
  - We measure the same physics in multiple ways – Consistency