Jets and medium response

- Experiment

The 9th Asian Triangle Heavy-Ion Conference (ATHIC 2023)

Hiroshima, Japan

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Purpose of this talk

EPL 2011-2012

S. Aguero 93:20

Purpose of this talk

Title in 1968

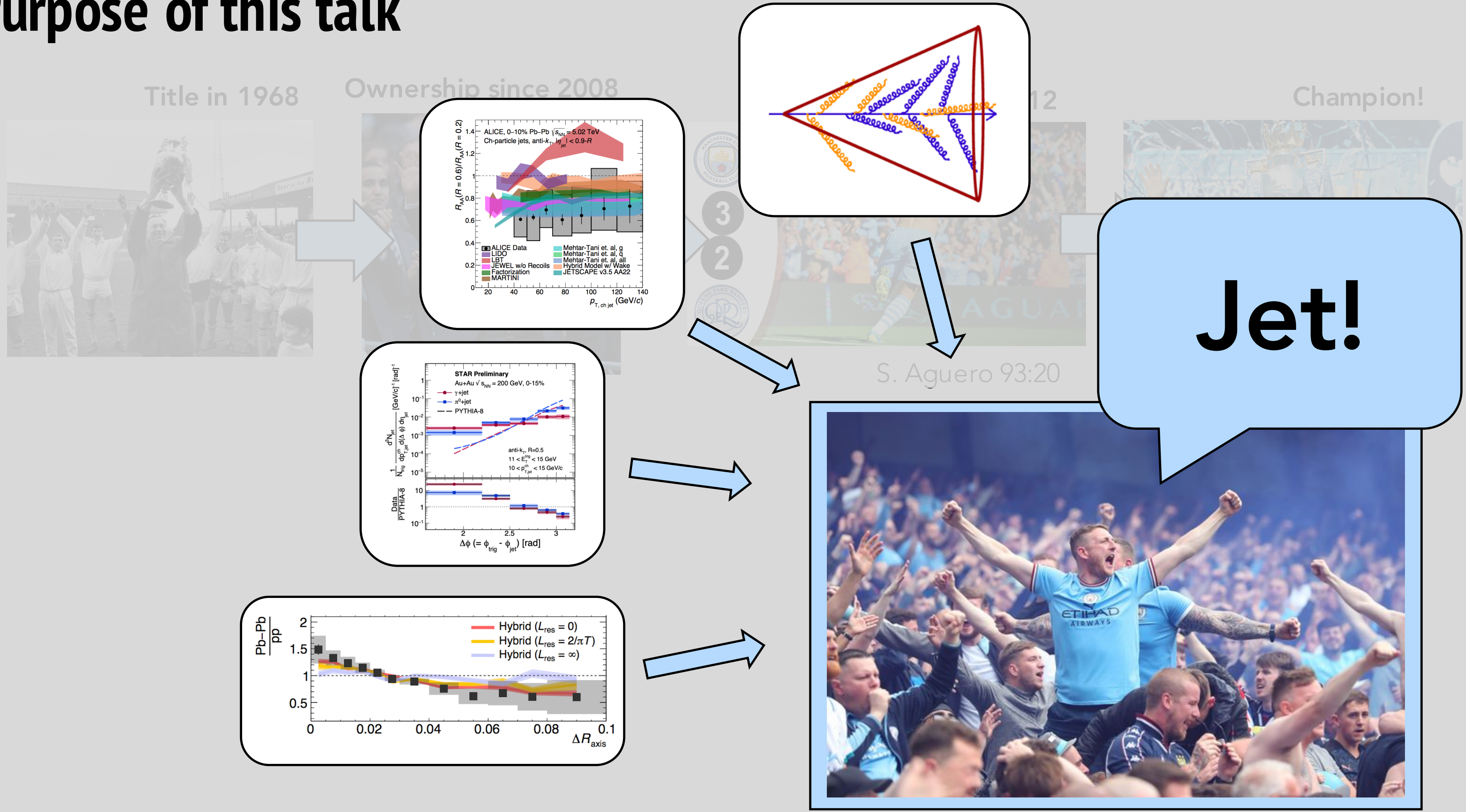
Ownership since 2008

EPL 2011-2012

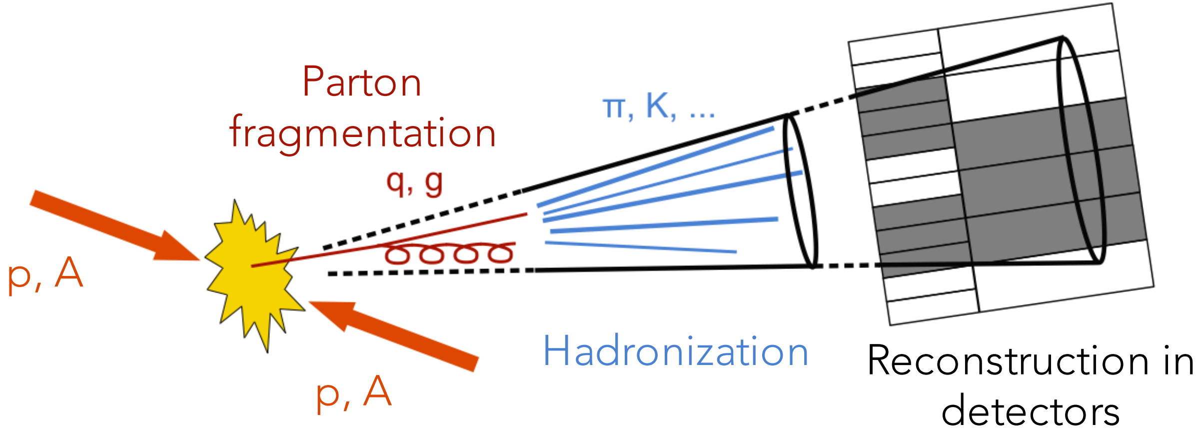
S. Aguero 93:20

Champion!

Purpose of this talk



Jets in QCD matter



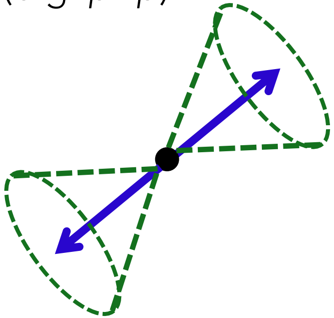
- **Jet**
  - Jets are multi-scale dynamic objects whose complex structure contains QCD information
  - Hard-scattered parton → Parton fragmentation → Hadronization → Algorithmic recombination into a jet

Jets in QCD matter

➢ **Jets in vacuum**

- Hard-scattered parton fragments into final state particles → Algorithmic recombination into a **Jet**
- Jets in vacuum are a useful tool to study QCD

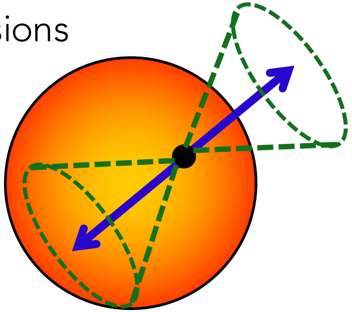
In vacuum (e.g. *p*+*p*)



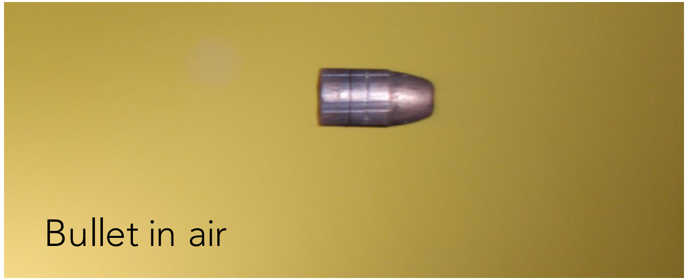
➢ **Jets in heavy-ion collisions**

- 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



Jets in QCD matter



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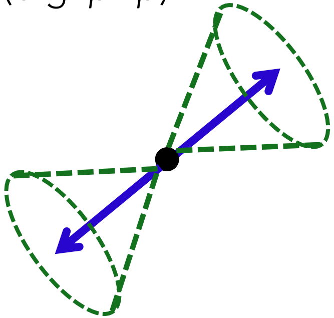

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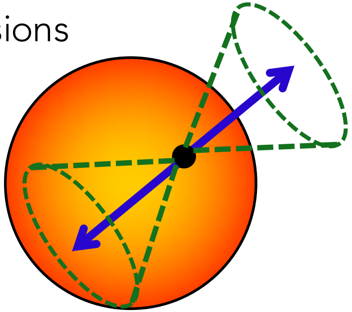
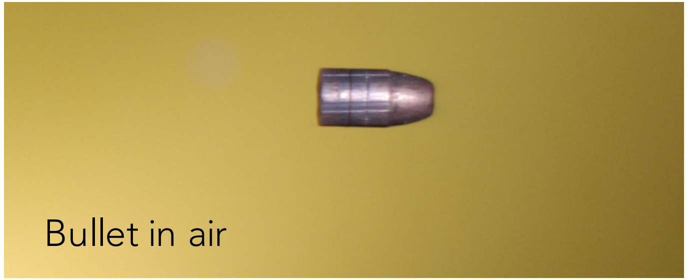
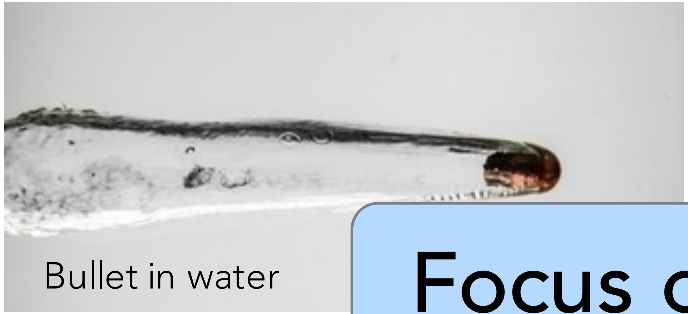
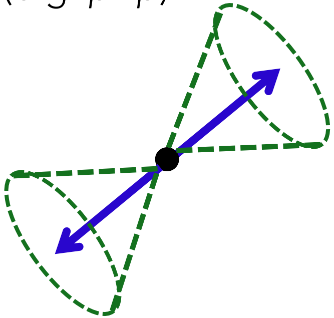


Jets in QCD matter





In vacuum (e.g. p+p)



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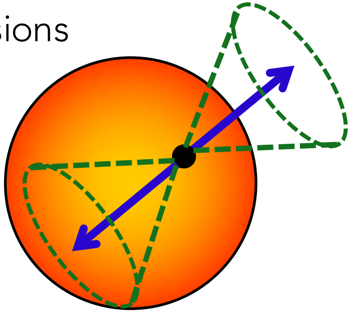
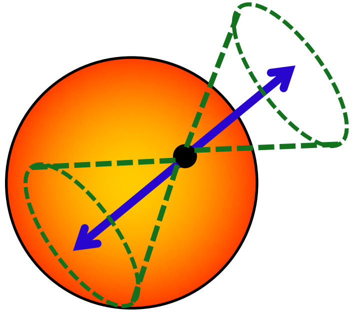


Focus of this talk

Jets in QCD matter

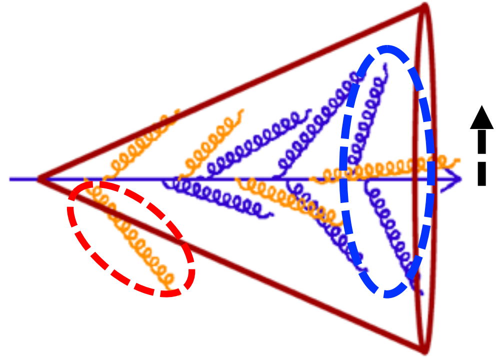
- What questions are we trying to answer?
  - How does QGP respond to the external out-of-equilibrium probe, e.g. jets?
  - How can we use jets to probe the microstructure of the QGP?
  - What is the resolution scale of the medium? How can we measure that?
  - What can we learn from the mass dependence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



Jets in QCD matter

What have we found so far?



- Jet energy redistribution (loss)
- Jet substructure modification
- Jet deflection

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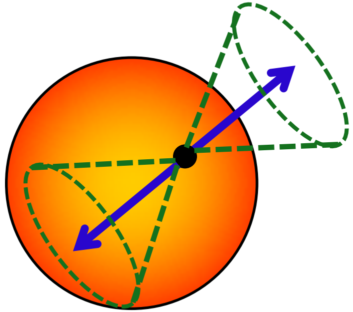

Jets in QCD matter

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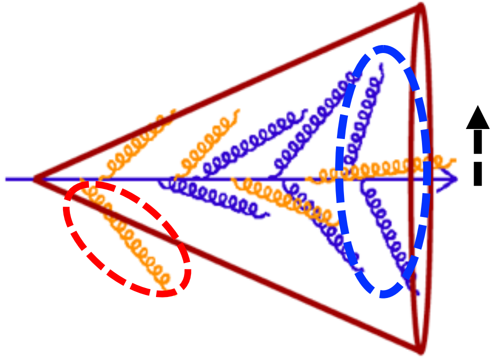

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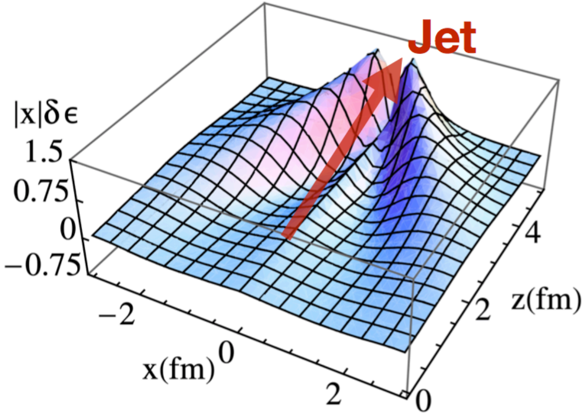

- Jets are modified by medium, and medium is influenced by jets
- Medium response is taken into account in models differently - Recoil (weakly-coupled approach), Hydrodynamics (Strongly-coupled approach), Hybrid, …

Experimental jet results in heavy-ion collisions

Inclusive jet spectra

- Jet energy redistribution (loss)
- Jet substructure modification
- Jet deflection

➢ How many jets do we see at a given jet p_T in heavy-ion collisions compared to pp collisions?

➢ Jet $R_{AA} = \frac{\frac{1}{N_{event}} \frac{d^2 N}{dp_{T,jet} d\eta_{jet}}\Big|_{AA}}{\langle T_{AA} \rangle \frac{d^2 \sigma}{dp_{T,jet} d\eta_{jet}}\Big|_{pp}}$ → Basic measurements of jet yield suppression

CMS, 2.76 TeV, PRC 96 (2017) 015202

ATLAS, 5.02 TeV, PLB 790 (2019) 108-128

ALICE, 5.02 TeV, PRC 101 (2020) 034911

- Most models reasonably describe data – more differential measurements needed

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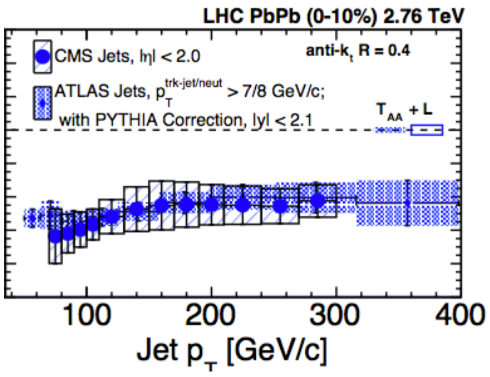

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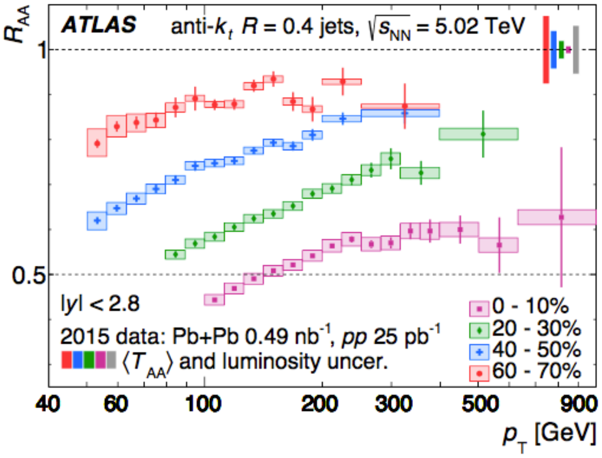
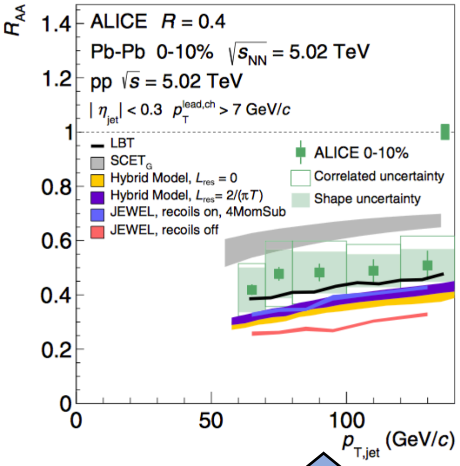


ALICE, 5.02 TeV, PRC 101 (2020) 034911



- Most models reasonably describe data – more differential measurements needed

Inclusive jet spectra

- Jet energy redistribution (loss)
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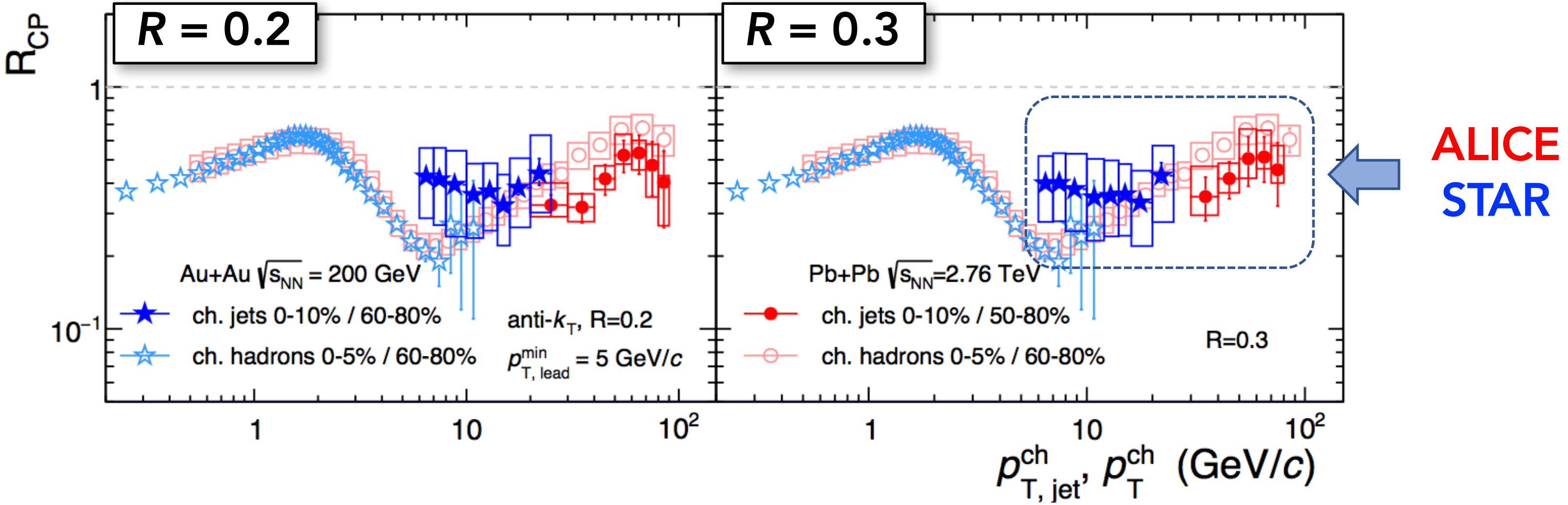
➢ Jet R_{CP} – Comparison between central and peripheral collisions

STAR, 0.2 TeV, PRC 102 (2020) 054913



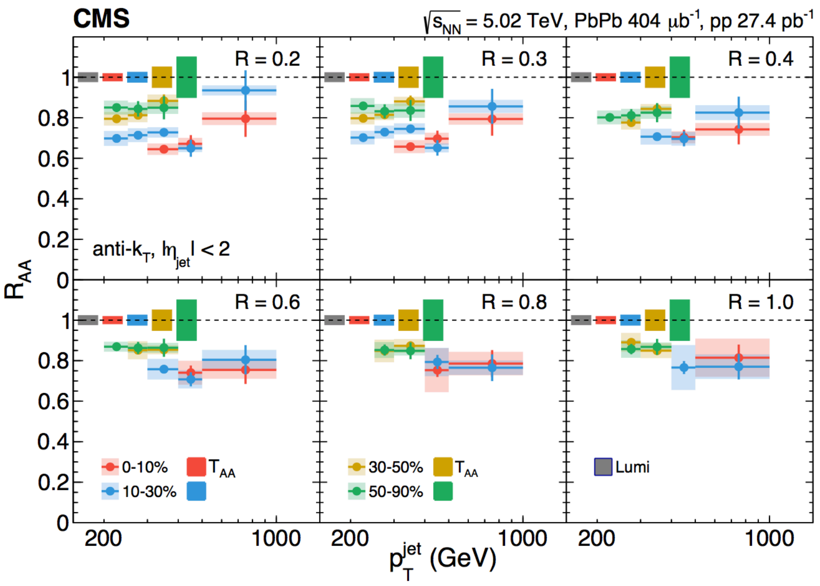
- Similar level of suppression between 200 GeV and 2.76 TeV, although their spectrum shapes are different

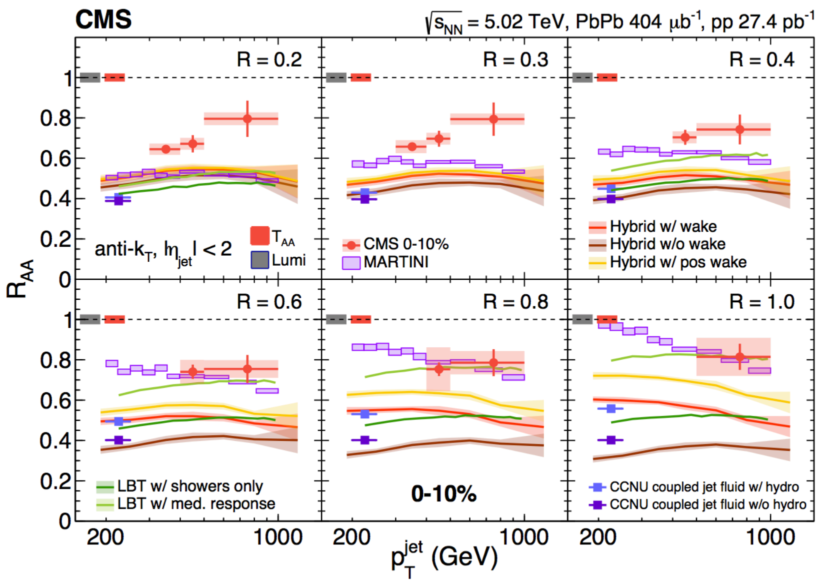
Inclusive jet spectra

- Jet energy redistribution (loss)
- Jet substructure modification
- Jet deflection

➢ Jet R_{AA} at higher jet R – Wider jets more suppressed? Quenched energy toward larger R?

CMS – 5.02 TeV, JHEP 05 (2021) 284



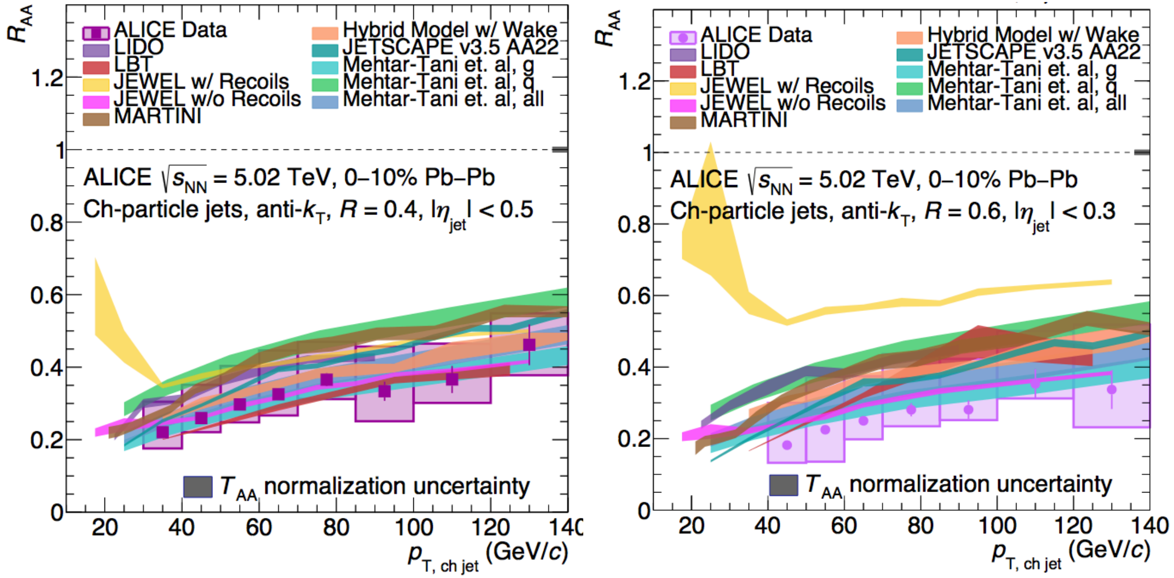


- No strong dependence on jet radius persists at large R (=1.0) and high $p_{\mathrm{T,jet}}$ (1 TeV/c)
- Significant tension between models – Further constraints on the underlying jet quenching mechanisms

Inclusive jet spectra

- Jet energy redistribution (loss)
- Jet substructure modification
- Jet deflection

ALICE – arXiv:2303.00592



Caveat

- Jets reported by different collaborations are not the same
  - ✓ Charged jet vs. full jet
  - ✓ How to deal with background
  - ✓ Different η ranges

- ➢ Machine-learning based correction for background (Haake, Loizides PRC 99, 064904 (2019))
- ➢ This enables measurements at lower jet p_T for large R

Inclusive jet spectra

- Jet energy redistribution (loss)
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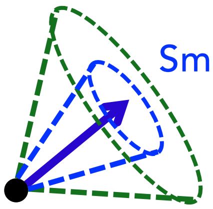

➢ Comparing R_{AA} for different R jets provides hints on jet substructure modification
  - ✓ Larger jet R_{AA} for wider jets – Recovery of energy?
  - ✓ Smaller jet R_{AA} for wider jets – Jets are narrowed in QGP?
  - ✓ (Larger R jets tends to have less quark to gluon fraction)

Inclusive jet spectra

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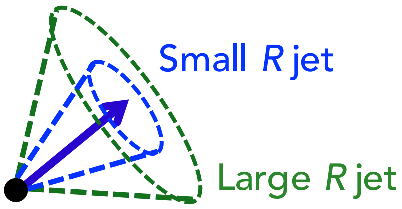

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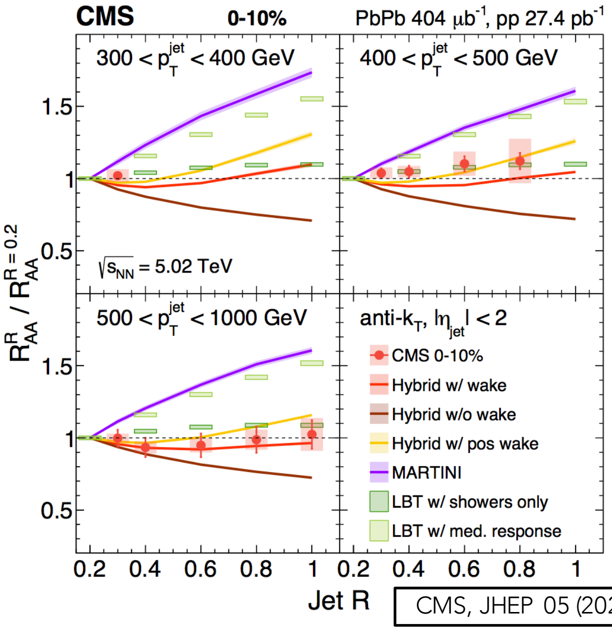

CMS, JHEP 05 (2021) 284

- No significant R dependence at high p_T
- Great discriminating power for models

Inclusive jet spectra

- Jet energy redistribution (loss)
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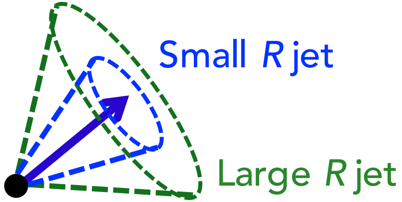
- Jet deflection



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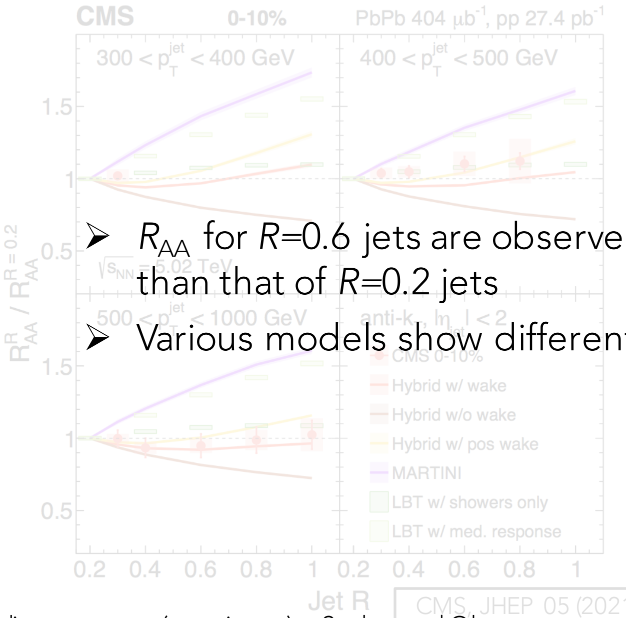
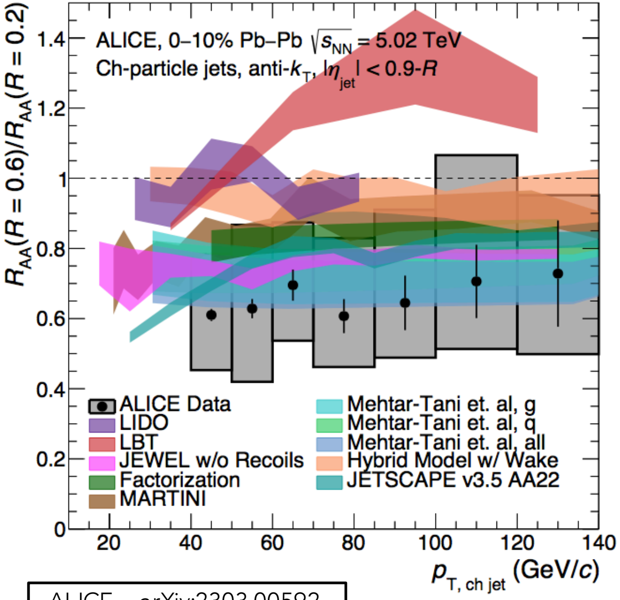


CMS, JHEP 05 (2021) 284

➢ R_{AA} for R=0.6 jets are observed to be smaller than that of R=0.2 jets

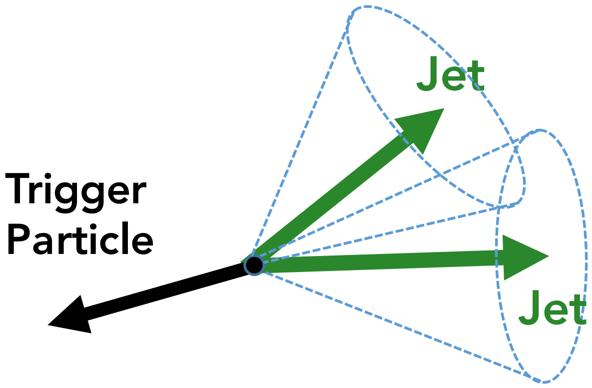
➢ Various models show different results



ALICE – arXiv:2303.00592

Semi-inclusive jet spectra

- Jet energy redistribution (loss)
- Jet substructure modification
- Jet deflection



➢ Semi-inclusive jet measurements

- Counting jets in the recoil region of high-p_{T} trigger particles
- Correlated vs. uncorrelated contributions with respect to the trigger particle → Effective removal of the latter
- Capability to access lower $p_{\mathrm{T,jet}}$

Semi-inclusive jet spectra

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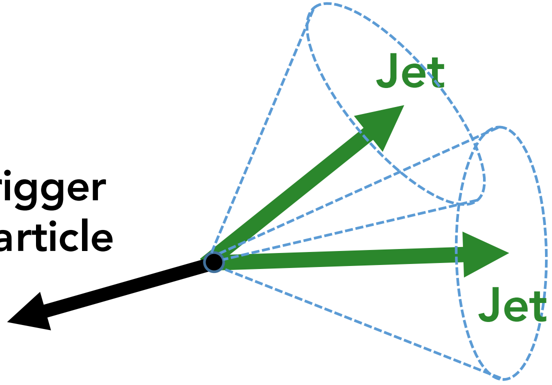
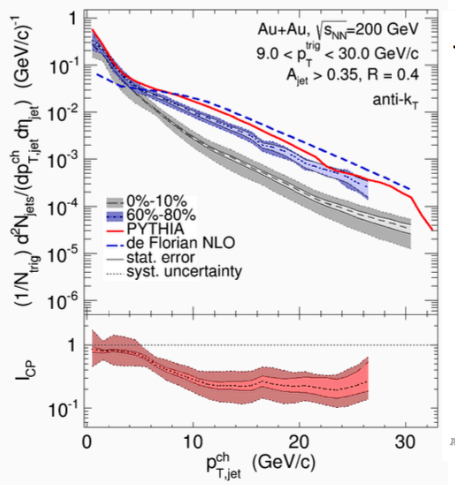
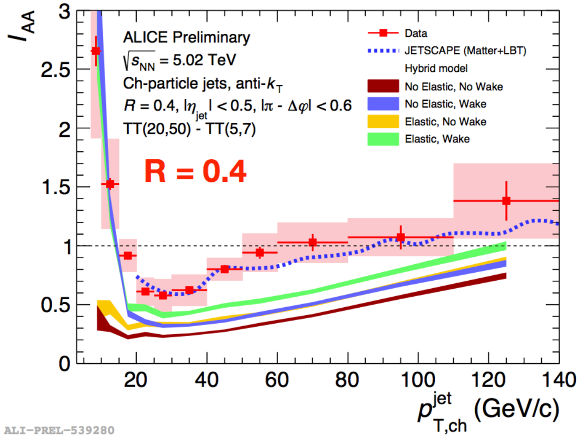


STAR, Phys. Rev. C 96 (2017) 24905



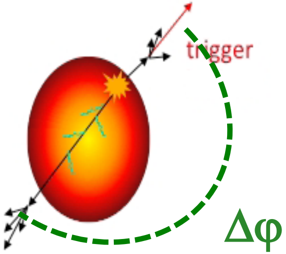


- Semi-inclusive jet measurements
  - Counting jets in the recoil region of high-p_T trigger particles
  - Correlated vs. uncorrelated contributions with respect to the trigger particle → Effective removal of the latter
  - Capability to access lower $p_{T,jet}$

- I_{CP} , I_{AA}= The ratio of recoil jet yields in central to peripheral or *pp* distributions
- Similar level of suppression via I_{CP} to charged-particle jet R_{CP} at 200 GeV
- Hint of energy recovery at low p_T jets at 5.02 TeV – Wake effect or medium response?

Jet acoplanarity

- Jet energy redistribution (loss)
- Jet substructure modification
- Jet deflection



- Δφ of the jet relative to the trigger particle
  → Direct measurement of jet deflection (acoplanarity)

Jet acoplanarity

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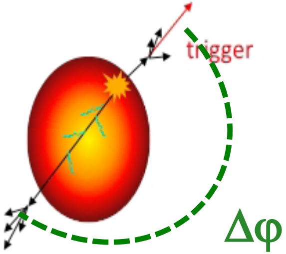
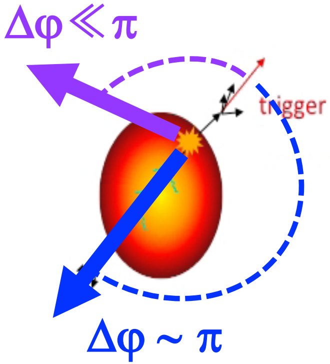


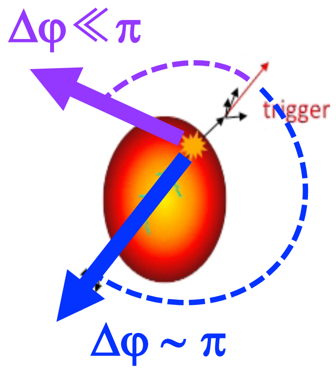


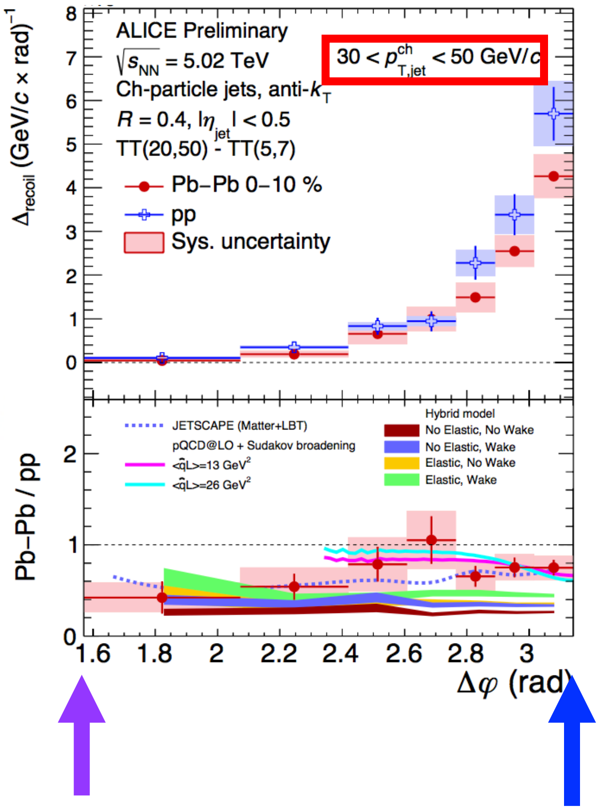
- Δφ of the jet relative to the trigger particle
  → Direct measurement of jet deflection (acoplanarity)

- Δφ ~ π
  - ✓ Jet angle broadening – vacuum Sudakov radiation
  - ✓ Multiple soft scatterings further broaden Δφ
  - ✓ Negative radiative correction – reduction of Δφ broadening (Zakharov, EPJC 81 (2021) 57)
- Δφ≪π
  - ✓ Large-angle deflection of hard partons (Moliere scattering)
  - ✓ Probe of weakly coupled short-distance quark and gluon particles in the strongly coupled QGP

Jet acoplanarity

- Jet energy redistribution (loss)
- Jet substructure modification
- Jet deflection





- Recoil jets are suppressed at high-p_T
- No observable signature of Moliere effect

Jet acoplanarity

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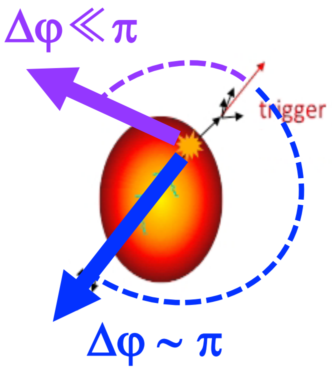
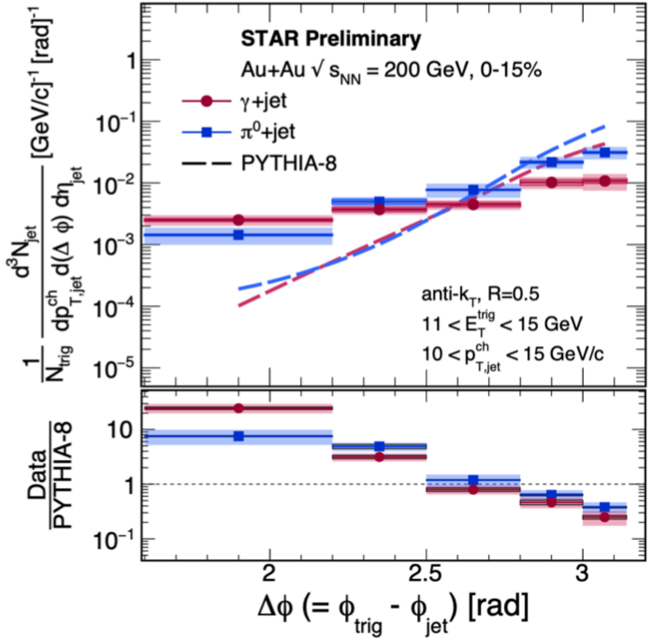
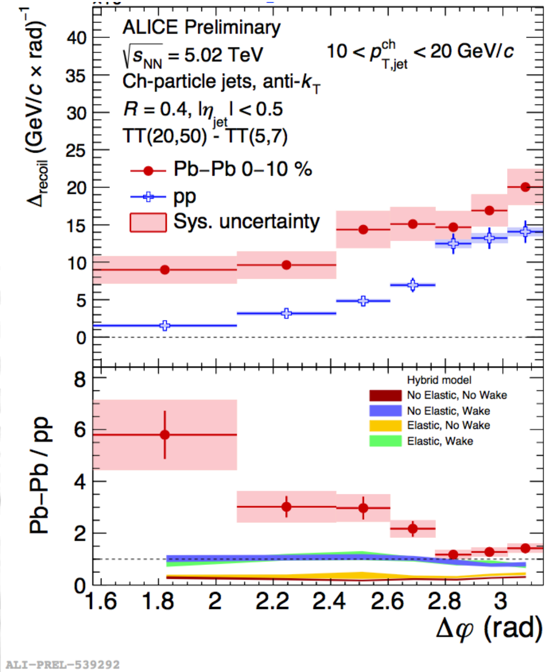
- Jet substructure modification
- Jet deflection



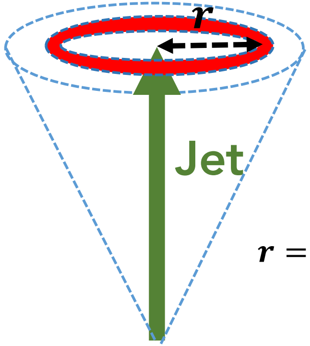




- Δφ broadening at low jet p_T in both RHIC and LHC energies → In-medium hard scattering? Multiple soft scattering? Medium response?
- Models do not show broadening effects, nor any sensitivity to Moliere scattering (Elastic)

Jet shape

- Jet energy redistribution (loss)
- Jet substructure modification
- Jet deflection



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

- Instead of counting number of jets, let's look at energy distribution within each jet as a function of distance from the jet axis

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

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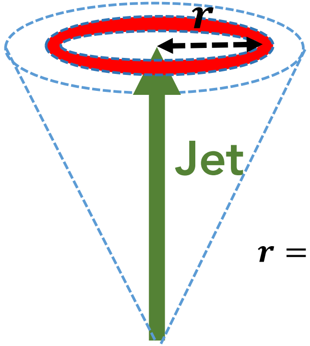

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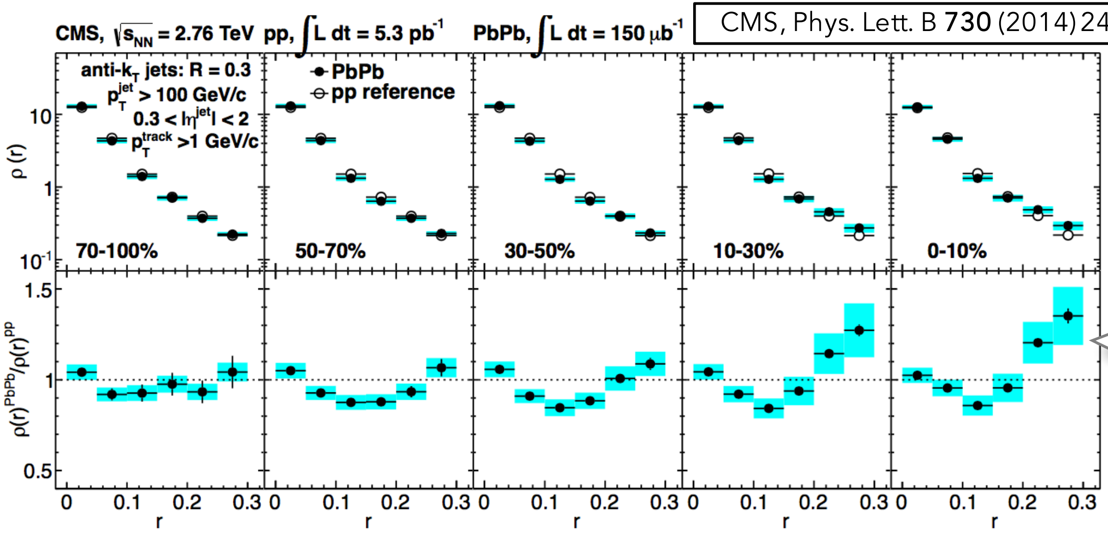
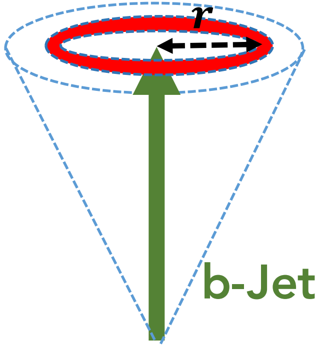
CMS, Phys. Lett. B **730** (2014) 243



- Narrowing of jet core
- Excess of transverse momentum fraction at large radius in most central collisions → Broadening within jets

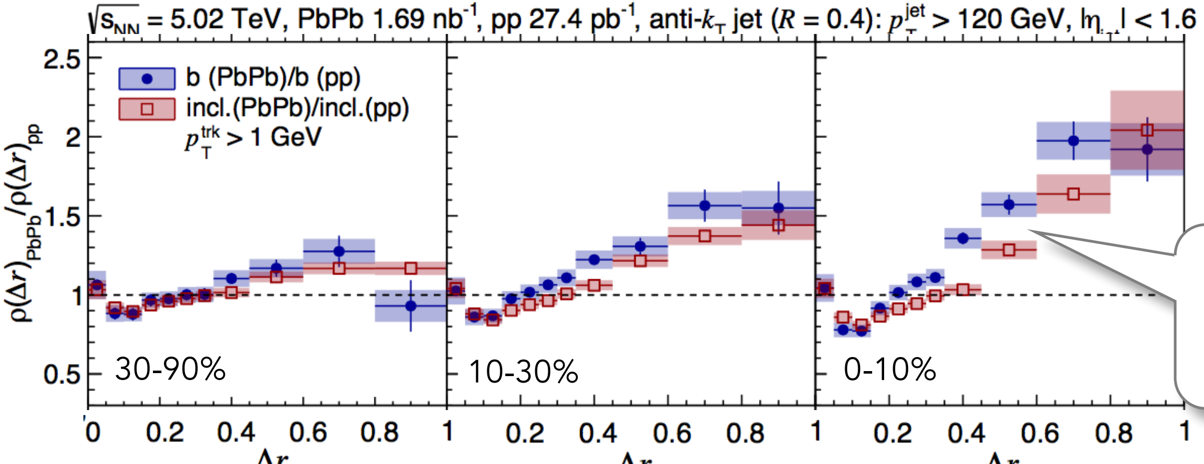
Jet shape – b-jet

- Jet energy redistribution (loss)
- Jet substructure modification
- Jet deflection



- Different fragmentation and hadronization
- b-hadron decay kinematics

CMS, arXiv:2210.08547



Increased large angle enhancement for b-jets

Jet shape – b-jet

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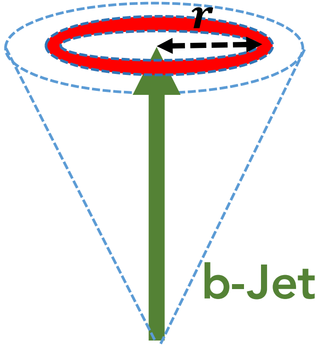

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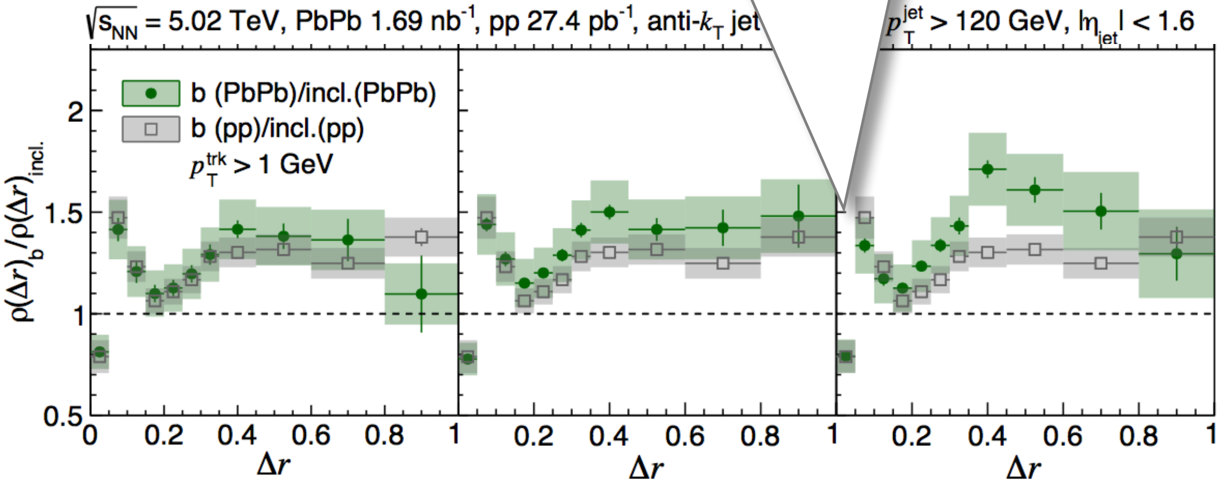
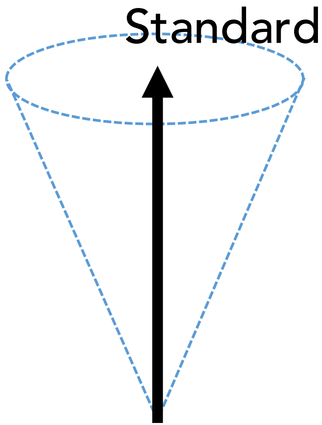
Depletion at small radial distance both in pp and Pb+Pb collisions
→ Dead-cone effect

CMS, arXiv:2210.08547



Dead cone effect – Suppression of gluon emission within a cone of angular size $\theta < m_q/E_q$

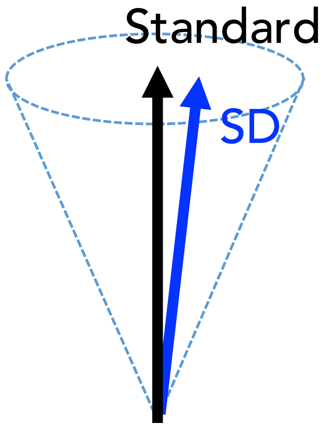
Jet-axis differences



- Jets have multiple axes
  - ✓ **Standard axis** – From anti-k_T algorithm

Jet-axis differences

- Jet energy redistribution (loss)
- Jet substructure modification
- Jet deflection



➢ Jets have multiple axes
  - ✓ **Standard axis** – From anti-k_T algorithm
  - ✓ **Groomed axis** – Soft large angle radiation contributions removed (groomed) via SoftDrop algorithm

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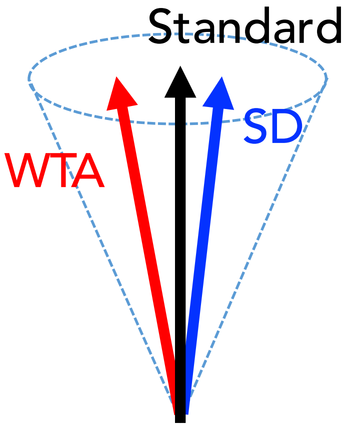

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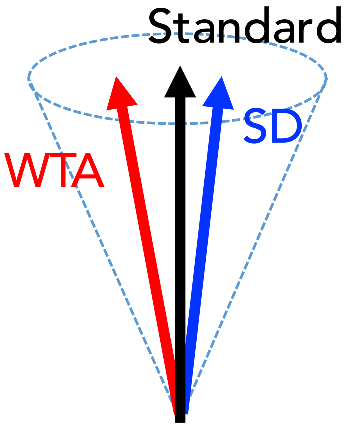

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- Distance ΔR between axes are sensitive to
  - ✓ How coherent energy loss is in QGP
  - ✓ q/g jet fraction in AA
  - ✓ Interplay between competing effects in QGP, e.g. medium-induced gluon radiation vs. multiple scattering-like p_T broadening

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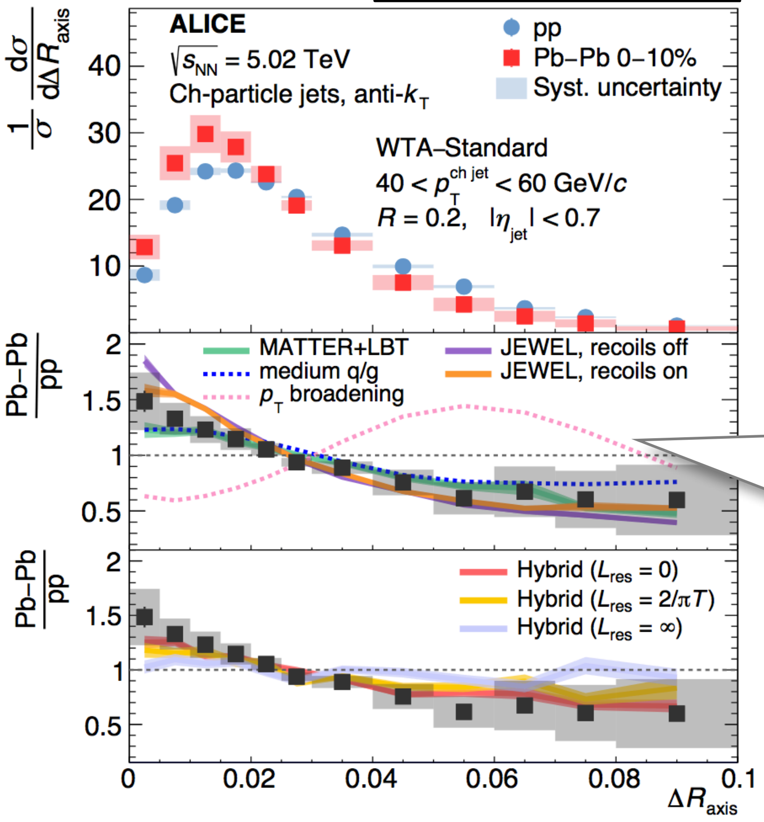
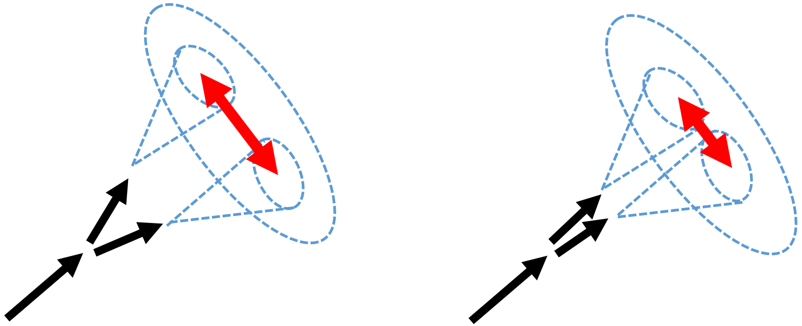
ALICE, arXiv:2303.13347



- Narrower distribution in Pb+Pb collisions for WTA-Standard axes distance
- Insensitivity to grooming - WTA-SD results are more or less the same with WTA-Standard results (Not shown)

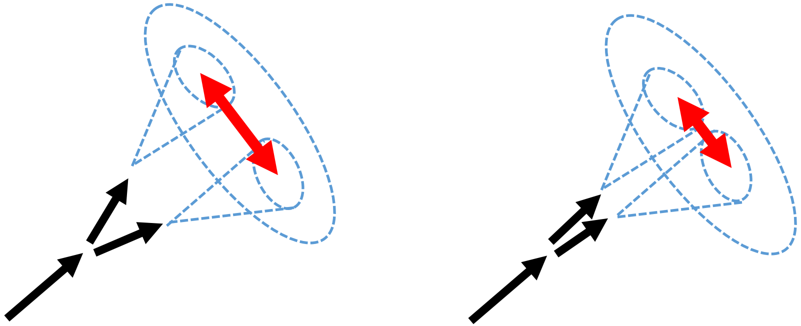
Model with "Modified q/g fraction" + "p_T broadening due to incoherent multiple scattering with the medium parton" disagrees with the data (PLB 808 (2020) 135634)

Jet-axis differences



- Do these jets quench differently in QCD medium?
→ It depends on medium resolution length, L_{res}

Jet-axis differences



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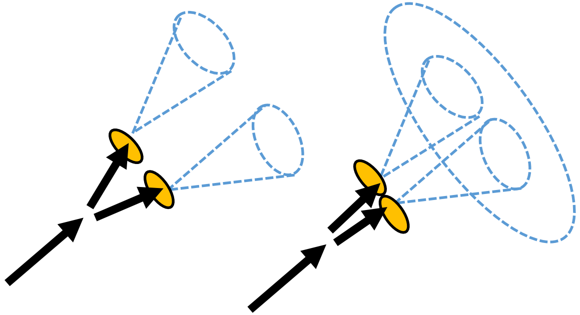
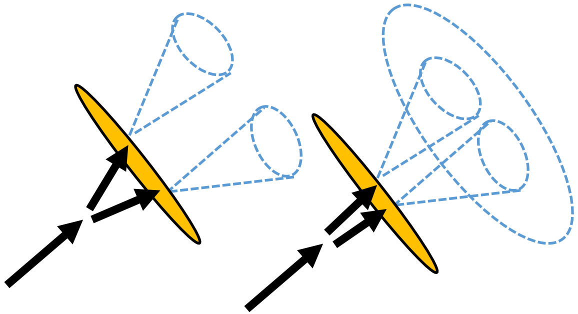


$L_{res} = 0$ → Fully incoherent energy loss

Intermediate L_{res}



$L_{res} = \infty$ → Fully coherent energy loss
(Medium does not resolve splitting)

Jet-axis differences

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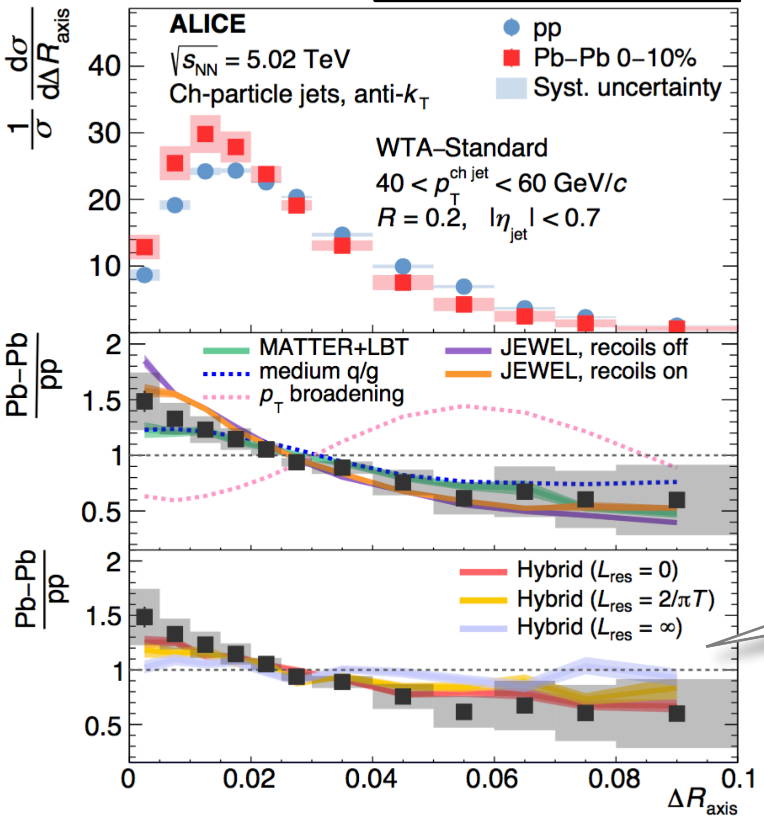
- Jet substructure modification
- Jet deflection

ALICE, arXiv:2303.13347



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Data favors incoherent energy loss picture in the hybrid model (L_{res} = 0)

Summary

- Jets provide unique tools to study hot dense QCD medium
  - Broad kinematic reach: probe the medium over a wide range in scale
  - Complex structure: many complementary observables that probe similar physics – require consistent picture
  - (Some) Observables are challenging to measure experimentally due to large background in heavy-ion collisions

- Experimental jet results reveal various aspects of QGP, such as resolution scale, microstructure of the medium, transport properties

- Further results expected to be presented at QM 2023, and more data coming with LHC Run 3, and RHIC 2023-2025 run with advanced detectors