Uncovering the jet wake

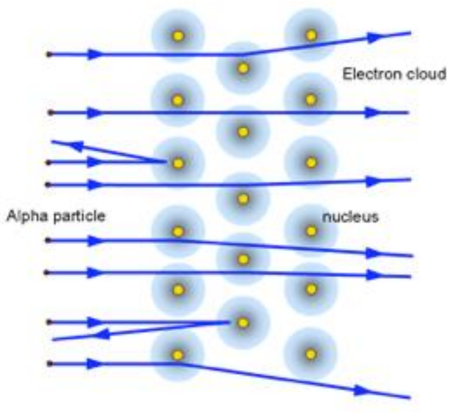
Peter Jacobs
Lawrence Berkeley National Laboratory
University of California, Berkeley

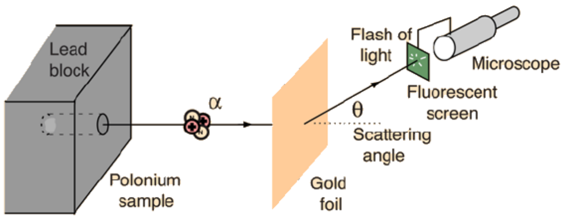
Jet Modification and Hard-Soft Correlations (SoftJet 2024)

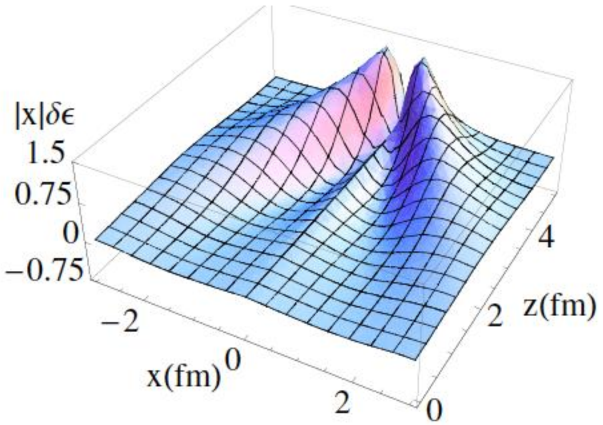
HP2024
~~NAGASAKI~~
TOKYO

What is the nature of the jet-QGP interaction?

Discrete scattering centers or
effectively continuous medium?







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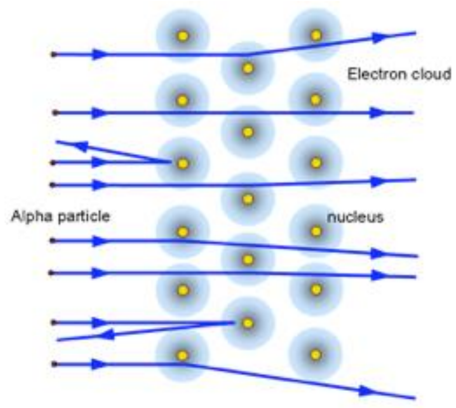
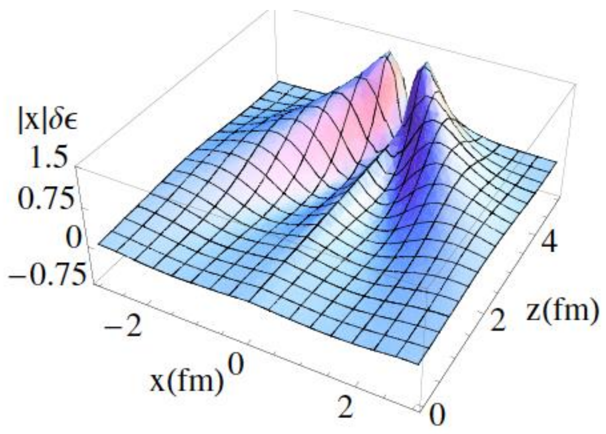
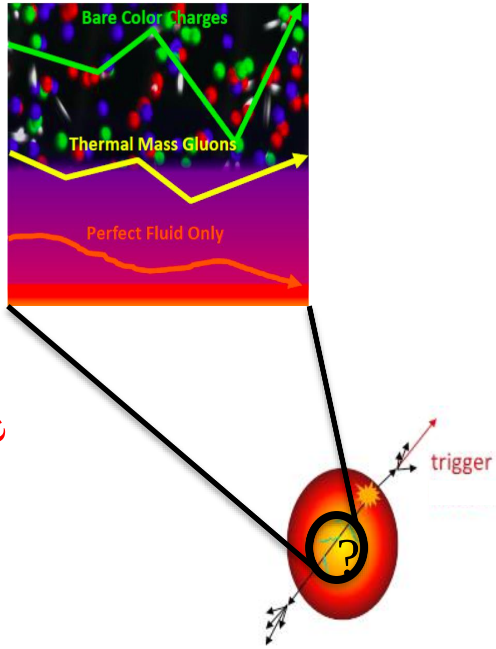
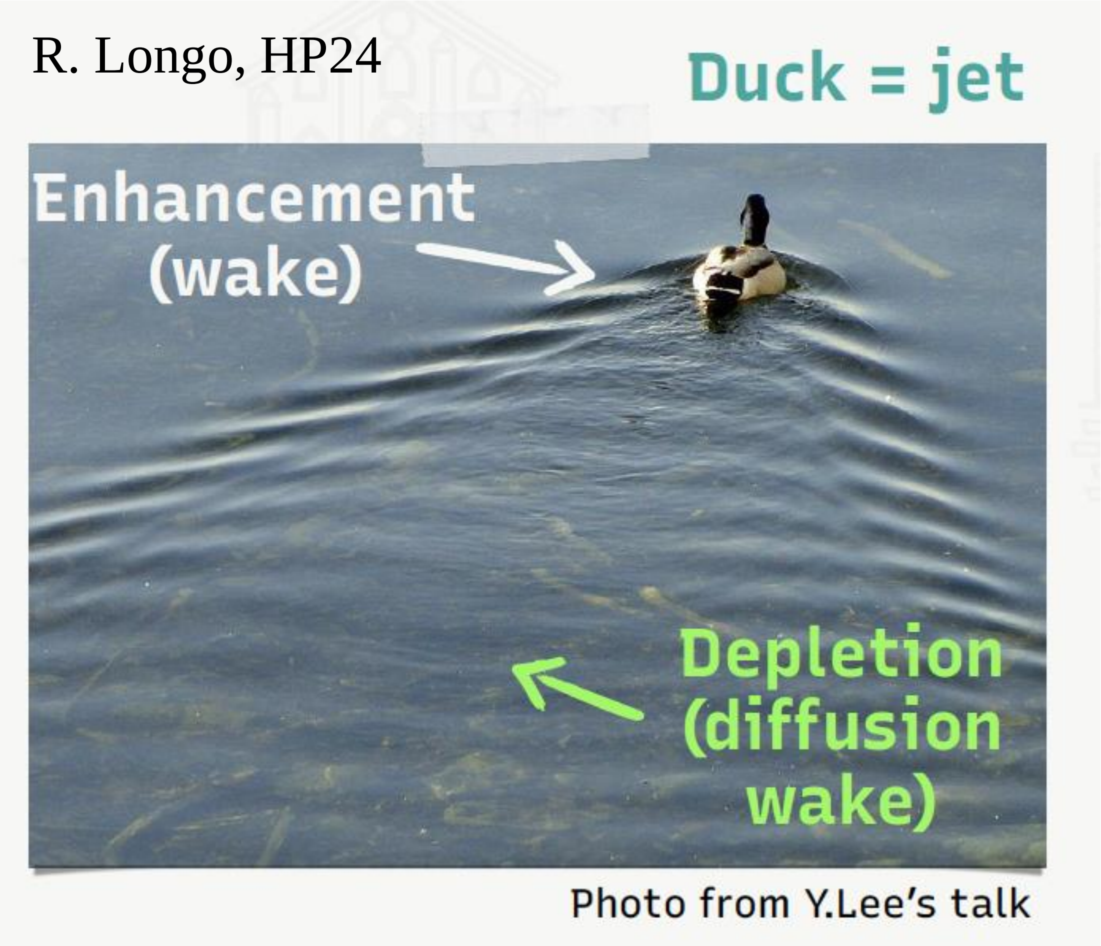




Are these pictures distinguishable conceptually?
Are they distinguishable in practice?

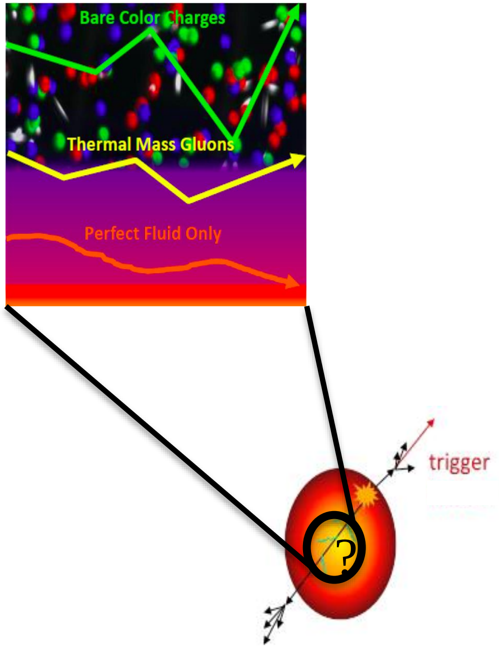


Tools:
- Substructure modification
- Yield modification
- Correlations
- Model comparisons



We are discussing two different wakes.

But they are two aspects of the same process:
to be successful a model must describe both accurately



Tools:

- Substructure modification
- Yield modification
- Correlations
- Model comparisons

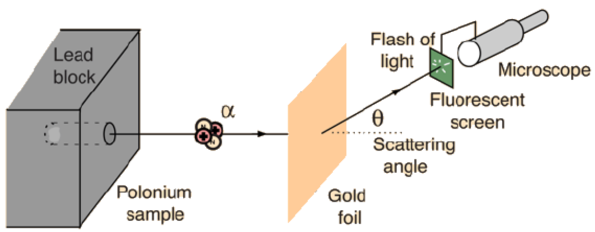
arXiv:2409.12837

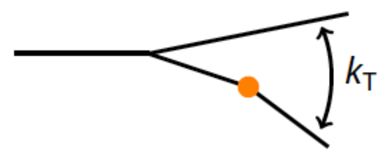
CERN-EP-2024-238
16 September 2024

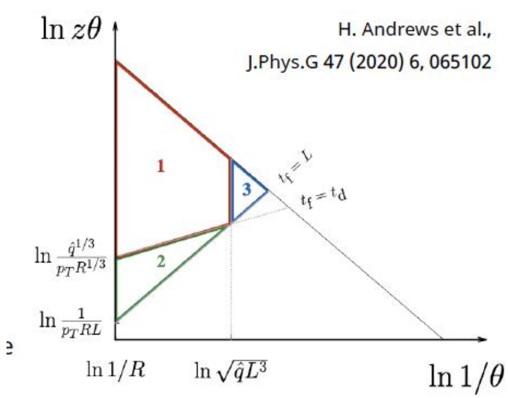
Search for quasi-particle scattering in the quark–gluon plasma with jet splittings in pp and Pb–Pb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV

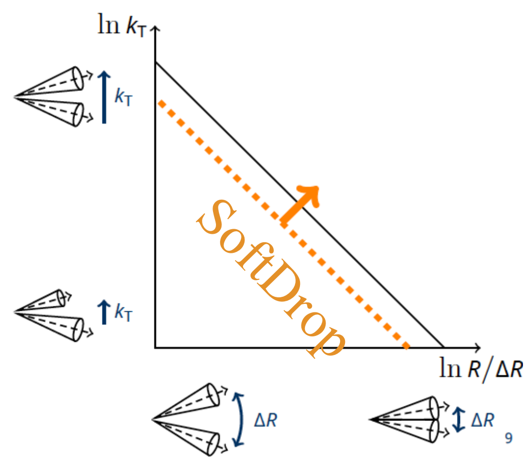
ALICE Collaboration*

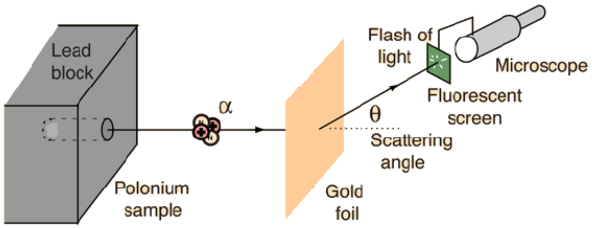
Use jet grooming to isolate hard k_T splittings → enhanced rate in Pb+Pb?





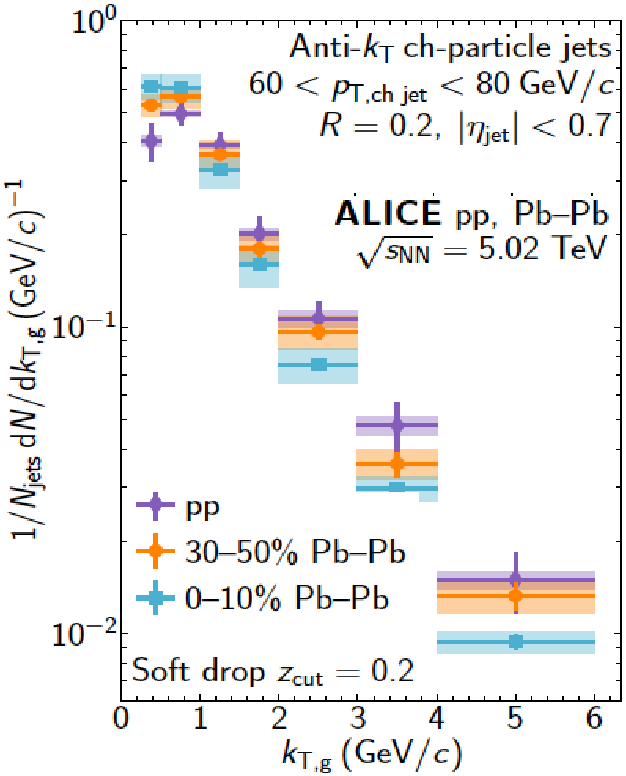


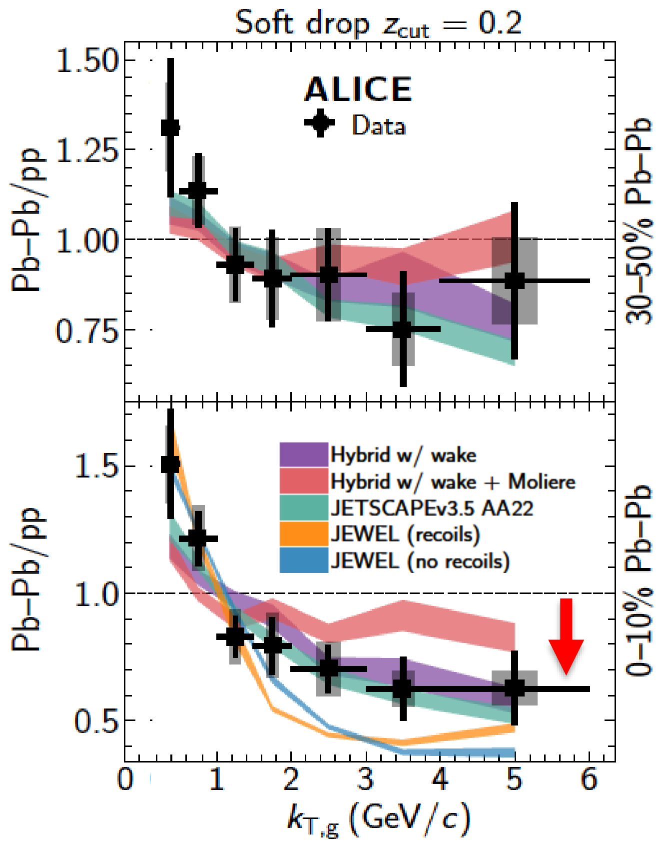




arXiv:2409.12837

Quasi-particle scattering: enhancement in high-k_T splitting rate





Data:

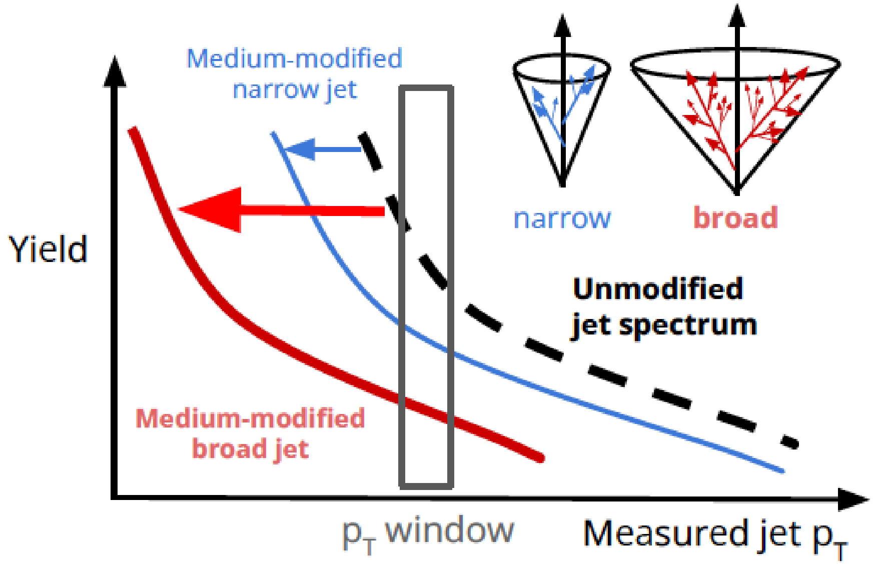
high k_T: suppression, not enhancement

no evidence for Moliere scattering

Model calculations:

- Hybrid w/Moliere does not describe data
- dominant effect is energy loss (survivor bias)

Interlude: survivor bias



CMS
arXiv:240502737

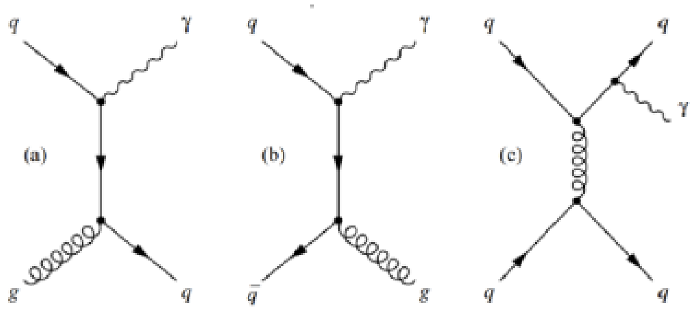
(+ numerous previous theory papers)

Figure 1: Schematic diagram of the potential selection bias due to jet energy loss that may occur when selecting jets based on the their p_T. Broader structures are expected to be more quenched (red line, thicker arrow), whereas narrower structures are expected to be quenched less (blue line, thinner arrow). Combined with the steeply falling jet p_T spectrum, this can lead to a preferential selection of narrow jets in a given jet p_T interval, as indicated by the vertical rectangular box. The dashed curve represents the jet p_T spectrum in the absence of medium-induced jet modifications.

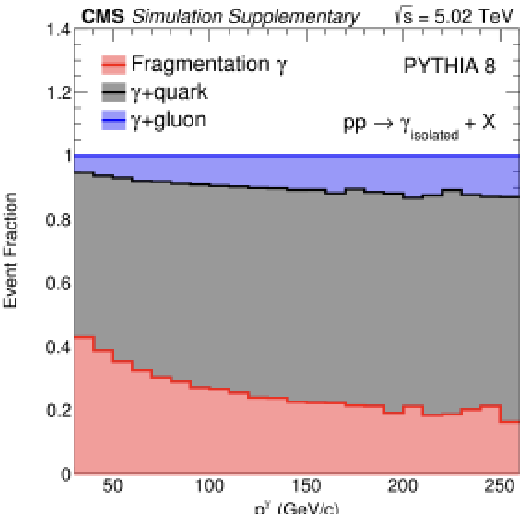
Survivor bias solution: γ/Z+jet?

M. Ngyuen, HP24

Photon-tagged jets



- "Prompt" photons produced at LO in pQCD via
  - Compton scattering: $qg \rightarrow q\gamma$
  - Quark annihilation: $q\bar{q} \rightarrow g\gamma$
  - ➡ Compton scattering dominates in pp collisions
- At NLO parton-to-photon fragmentation
  - ➡can reduced with photon isolation
- Large but reducible background from photonic decays of hadrons, e.g., $\pi^0 \rightarrow \gamma\gamma$

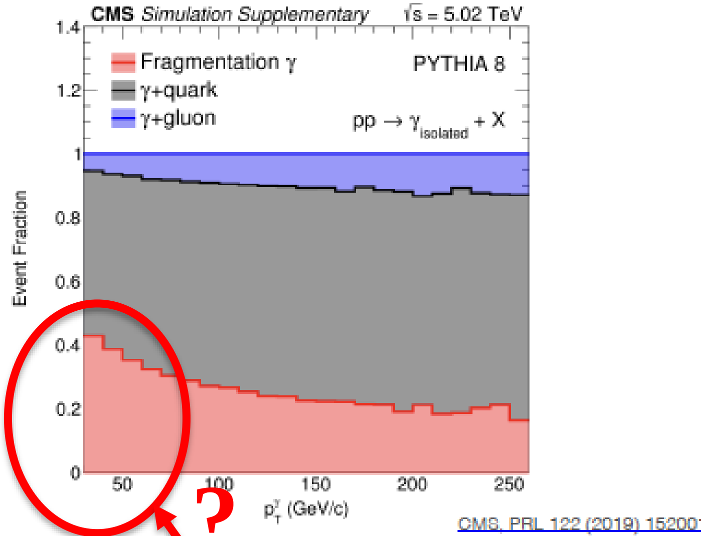


CMS, PRL 122 (2019) 152001

Benefits for jet quenching studies

- Photon fixes recoiling parton kinematics (prior to jet quenching)
- Relatively pure sample of quark jets

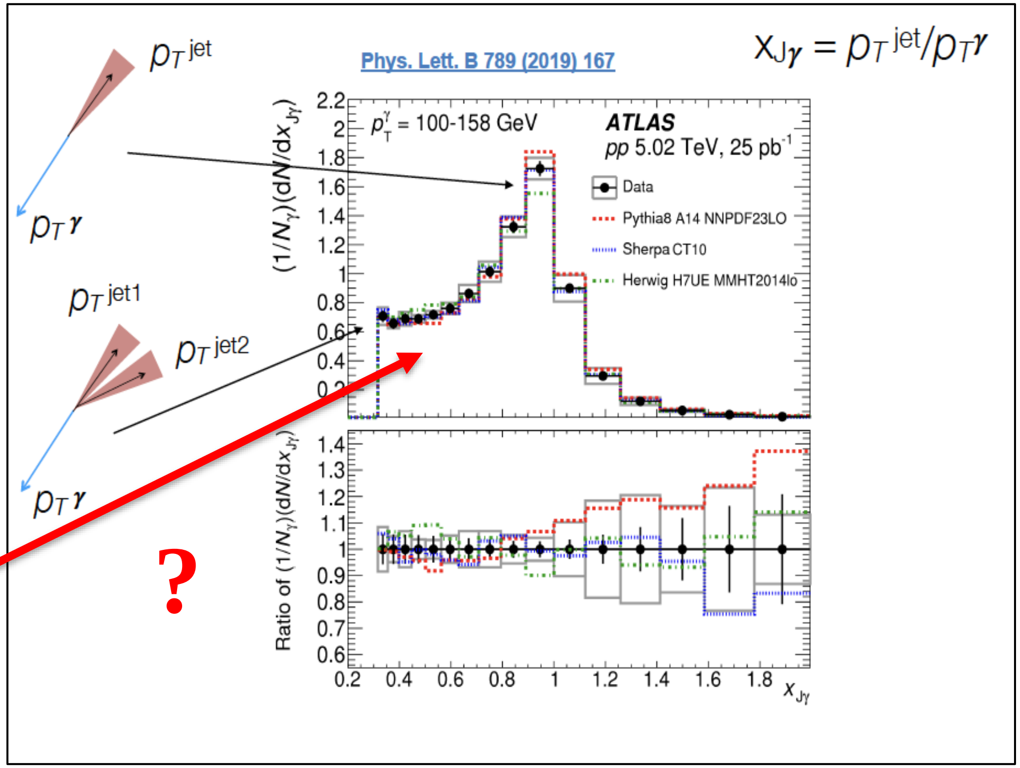
M. Ngyuen, HP24



Benefits for jet quenching studies

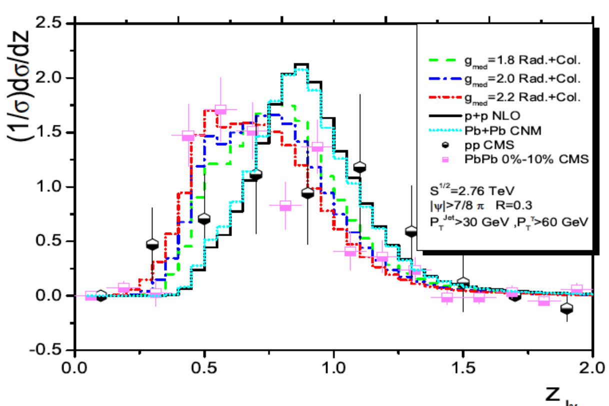
- Photon fixes recoiling parton kinematics (prior to jet quenching)

D. Derendarz, HP24



Large NLO corrections

Dai, Vitev and Zhang, PRL 110 **(2013)** 142001

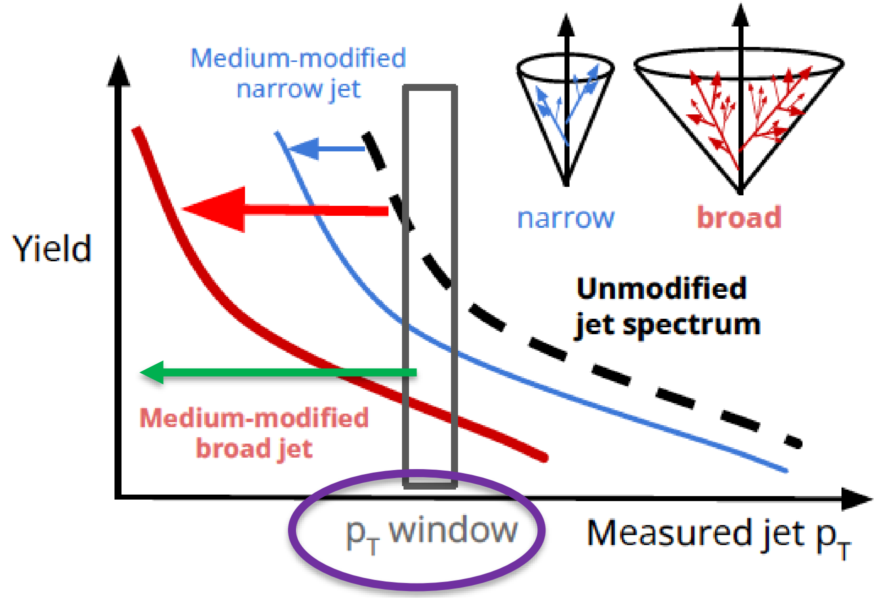


Similar for Z+jet

γ+jet: $x_{J\gamma}$ is not well-approximated by δ-fn
→ spectrum shape variation wrt inclusive is certainly valuable for systematic studies

But γ/Z+jet is not a comprehensive solution to survivor bias for precision measurements

Survivor bias: alternative solution



CMS
arXiv:240502737

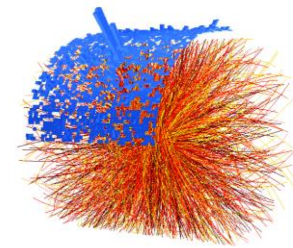
(+ numerous previous theory papers)

Survivor bias arises from the imposition of a p_T^{jet} threshold on a falling spectrum (+ energy loss)

ALICE/STAR solution: don’t do that.

Rather, use a statistical approach to measure the jet spectrum to (very) low p_T^{jet}, including large R. Then track the modification of observable X with p_T^{jet} .

What is the "statistical approach"?



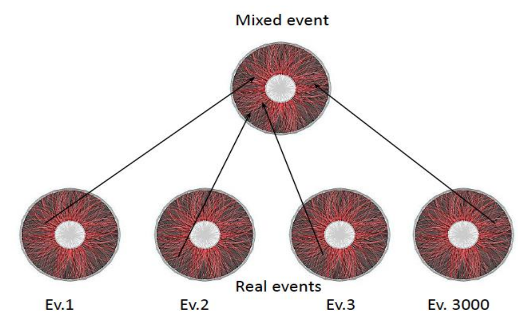
Low p_T^{jet}:

- huge background of uncorrelated particles
- large combinatorial (fake) jet rate: low $p_T^{jet} \rightarrow$ tiny S/B

Cannot model: correction must be fully data-driven

Example: Mixed Events

- Real event population ("SE") segregated into (thousands of) mixing bins: multiplicity, zvtx, Event Plane,…
- Only mix constituents within the same SE bin
- At most one track from each SE in an ME
- Sum over bins

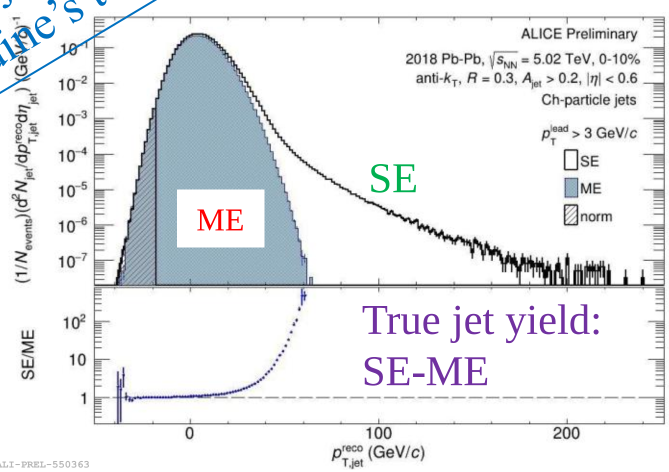


Destroys all multi-hadronic correlations, including jets

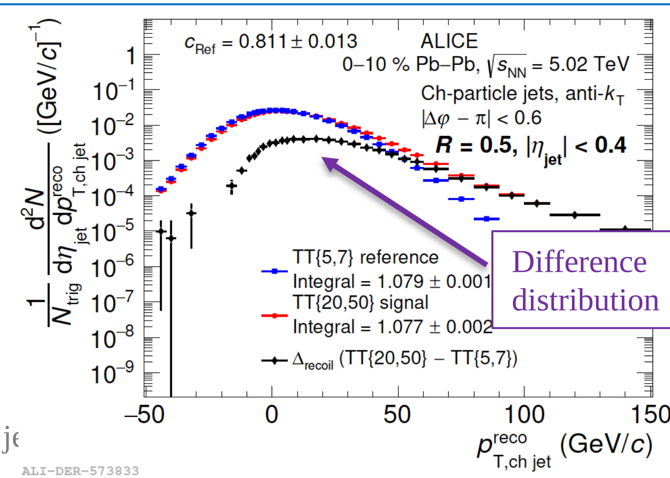
Run jet analysis on ME events

Correction at the level of distributions

Inclusive jets
See Nadine's talk



Related approach: h+jet trigger-differential



So … covering the je

Statistical correction: remarks

Two distinct corrections:

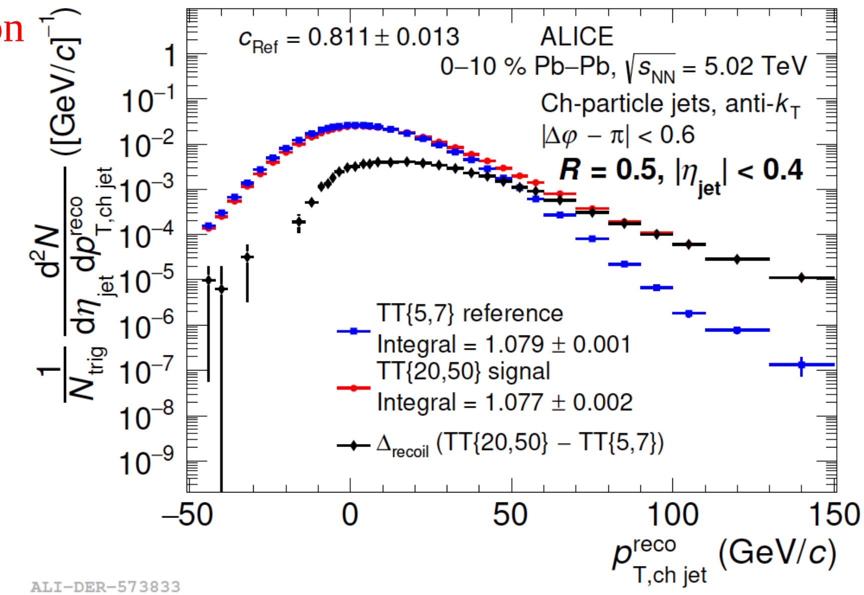
Bkgd yield

- must be entirely data-driven
- implementations: ME, trig-diff

p_T-smearing

- implementation: unfolding
- Some model dependence: Resp Matrix
- extensive systematic studies

Bkgd yield correction



p_T smearing correction

Enables corrected jet measurements at large R~0.5 down to very low p_T^{jet}

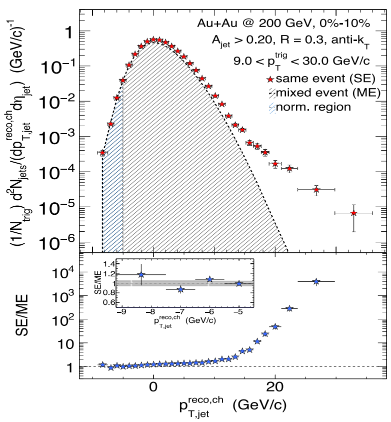
→ evade survivor bias effects

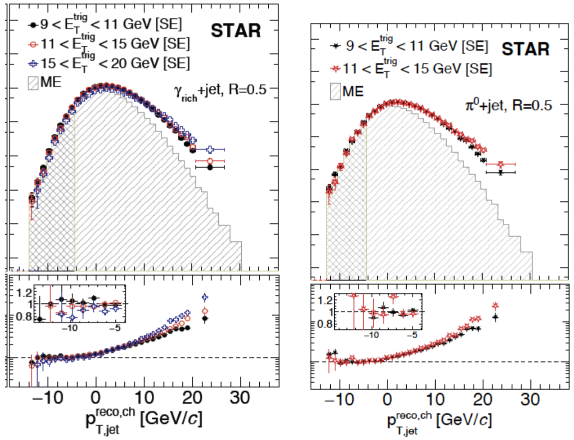
Uses jet reconstruction phenomenologically

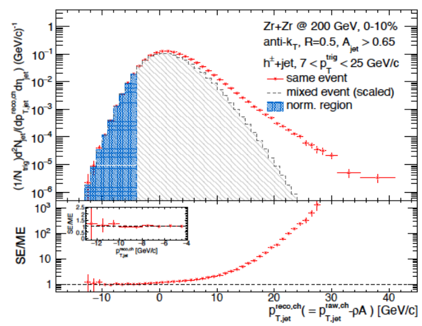
→ no requirement that full p_T^{jet} spectrum is interpretable perturbatively

→ track evolution from pert to non-pert regime, reveal e.g. wake effects

Statistical jet background approach: current analyses







Au+Au; h+jet

- Phys. Rev. C 96 (2017) 024905

Au+Au, p+p; γ/π⁰+jet

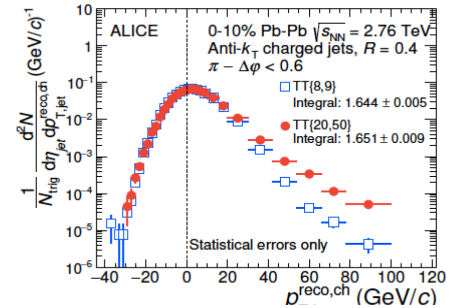
- arXiv:2309.00156
- arXiv:2309.00145

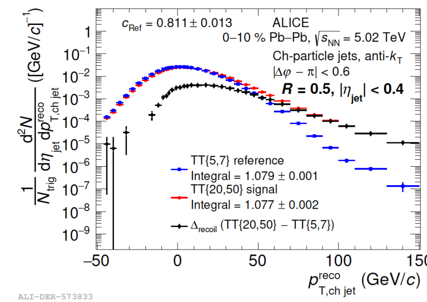
Zr+Zr, Ru+Ru; h+jet

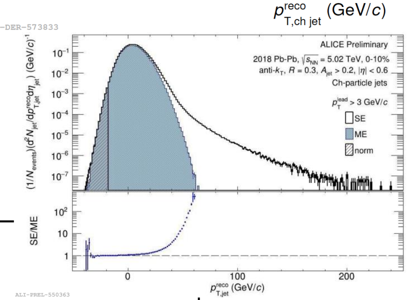
- PoS HardProbes2023 (2024) 174

Analyses in progress:

- inclusive jets (Nadine's talk)
- jet substructure (D. Jones HP24)
- EECs







PbPb, pp; h+jet

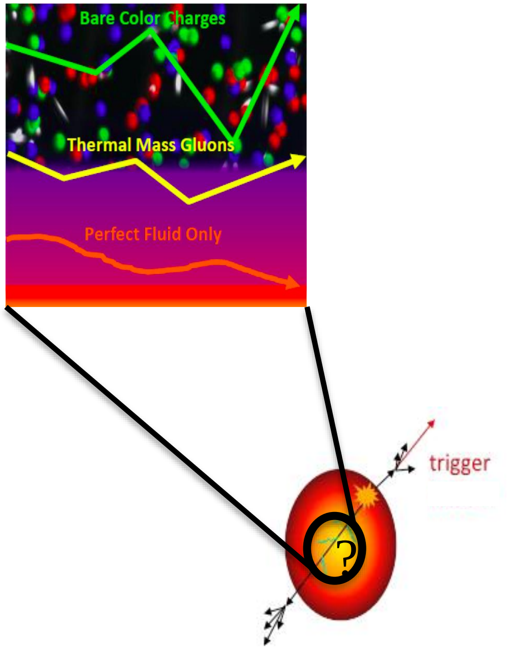
- JHEP 09 (2015) 170
- Phys.Rev.Lett. 133 (2024) 2, 022301
- Phys.Rev.C 110 (2024) 1, 014906

Pb+Pb; incl. jet

- EPJ Web Conf. 296 (2024) 11005

p+Pb, HM pp; h+jet

- JHEP 05 (2024) 229
- Phys.Lett.B 783 (2018) 95-113



Tools:

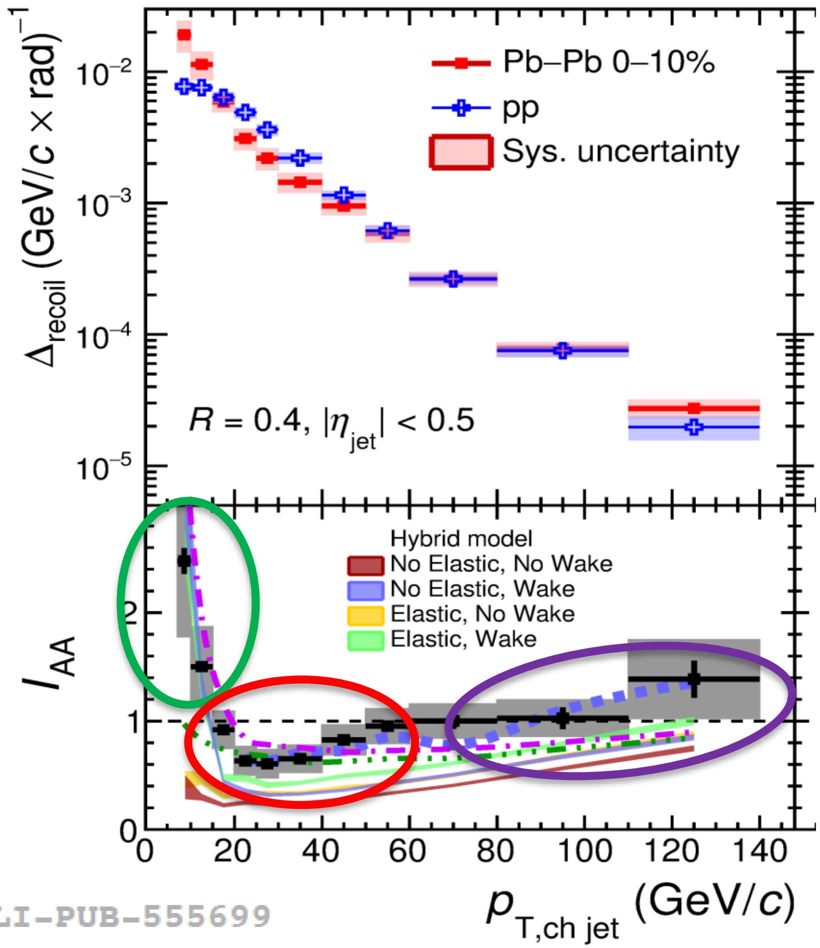
- Substructure modification
- Yield modification
- Correlations
- Model comparisons

Yield modification

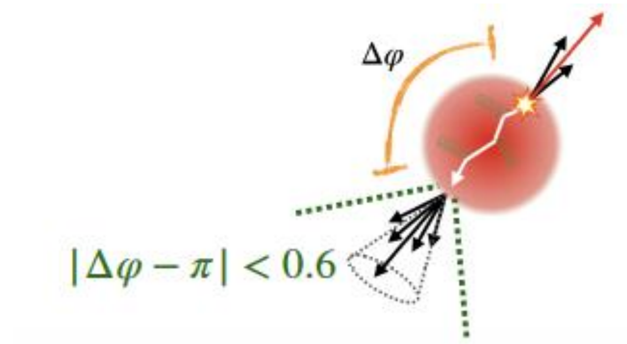
$$I_{AA} = \frac{\Delta_{\mathrm{recoil}}(\mathrm{Pb-Pb})}{\Delta_{\mathrm{recoil}}(\mathrm{pp})}$$

Phys.Rev.Lett. 133 (2024) 2, 022301
Phys.Rev.C 110 (2024) 1, 014906

(corrected)



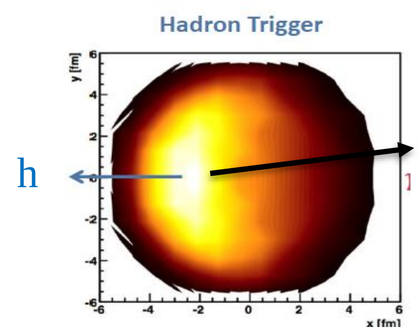
Semi-inclusive hadron+jet correlations



Energy loss

Energy recovery

Change in geometric bias (Y.He, HP24)

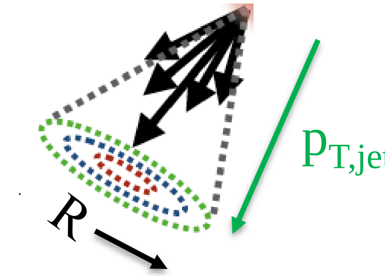


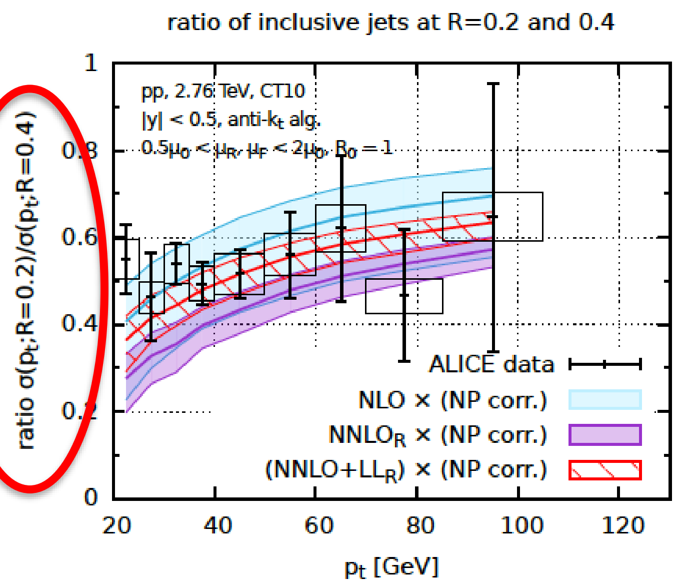
R-dependent jet yield ratios: robust jet shape observable

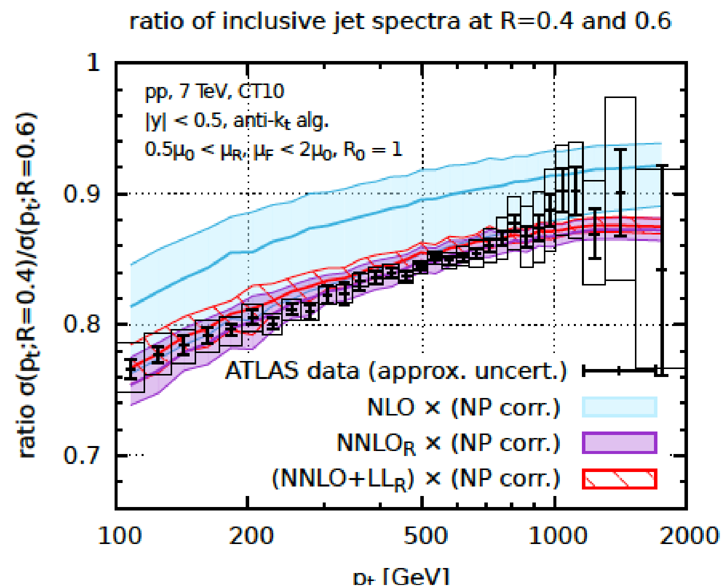
Inclusive jet spectrum for small-radius jets

Mrinal Dasgupta,[a] Frédéric A. Dreyer,[b,c,d] Gavin P. Salam,[d,*] and Gregory Soyez[e]

JHEP 06 (2016) 057







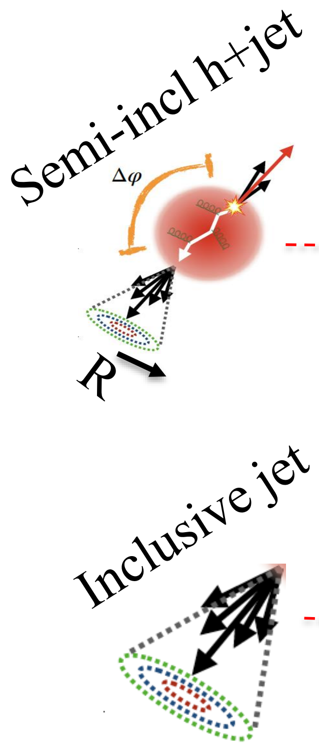
Probes transverse jet structure

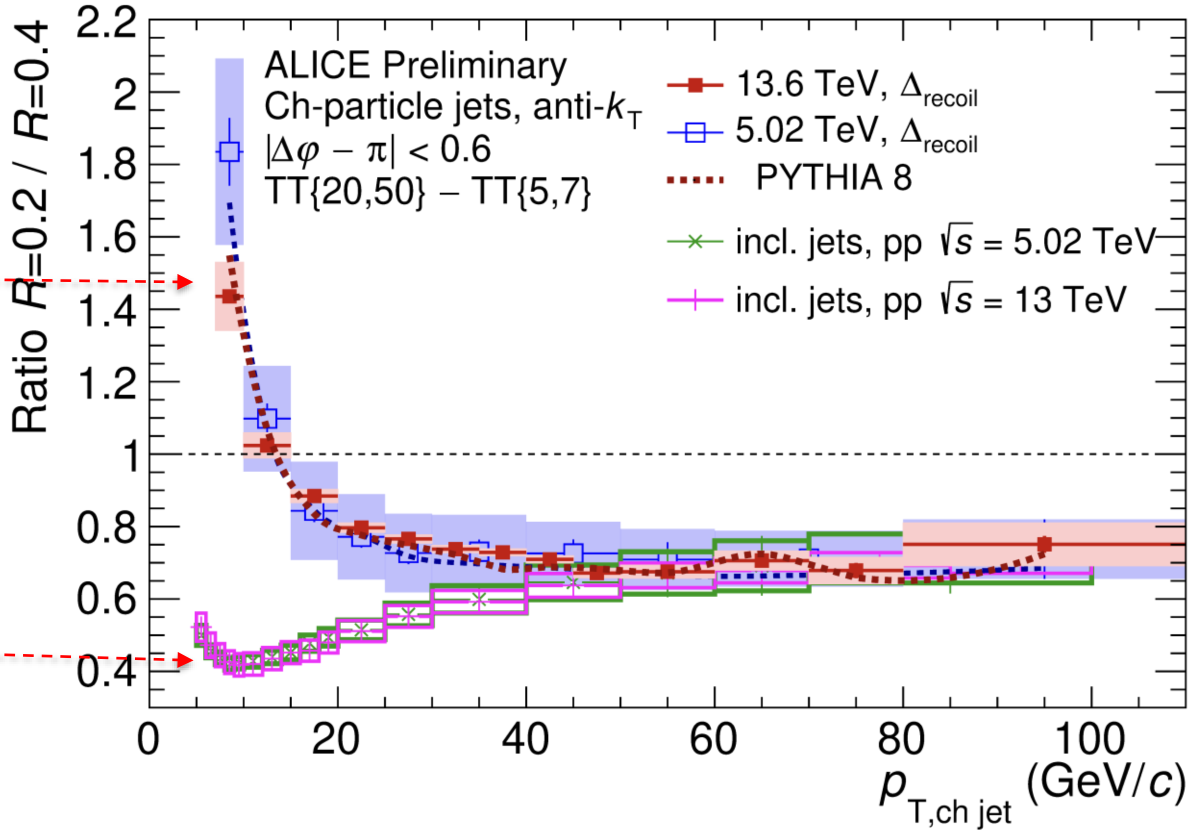
- p+p: calculable in pQCD to high perturbative order

A+A: measurable using statistical approach; no survivor bias! (zero)

R-dependent yield ratios: pp collisions

D. Jones, HP24

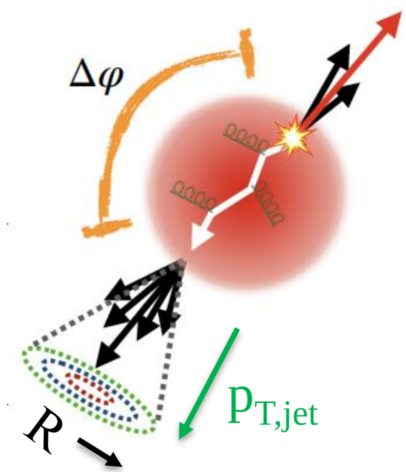


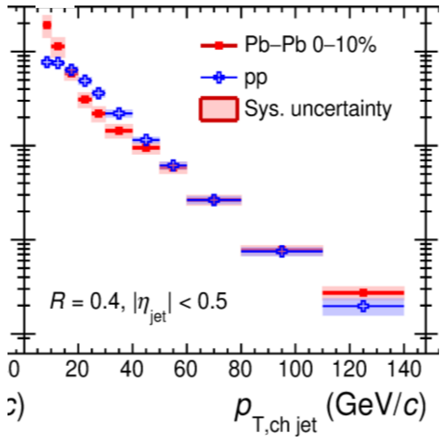


h+jet: $p_T^{jet} < p_T^{trigger}$ → LO production suppressed

→ QCD-based jet shape engineering

In-medium jet shape modification: yield(R=0.2)/yield(R=0.5)





Phys.Rev.Lett. 133 (2024) 2, 022301
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arXiv:2309.00156
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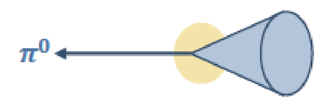
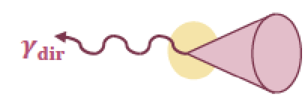
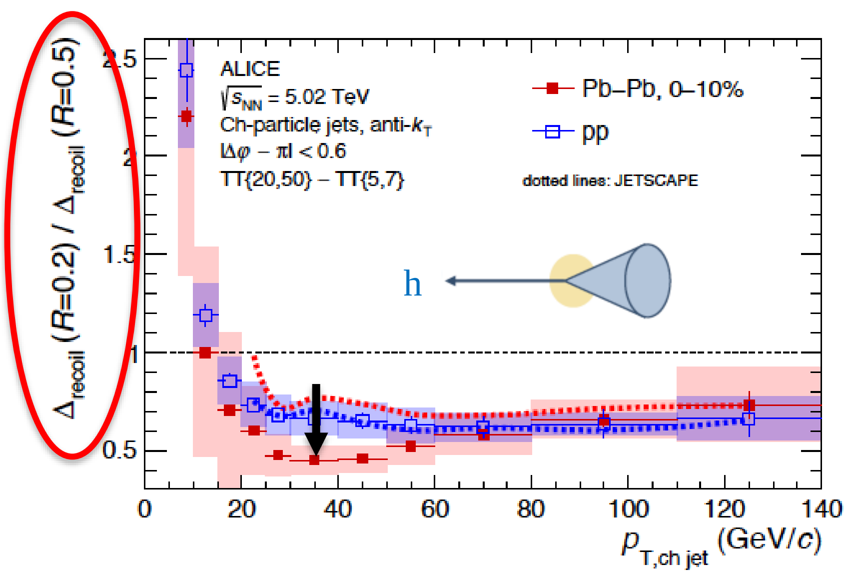
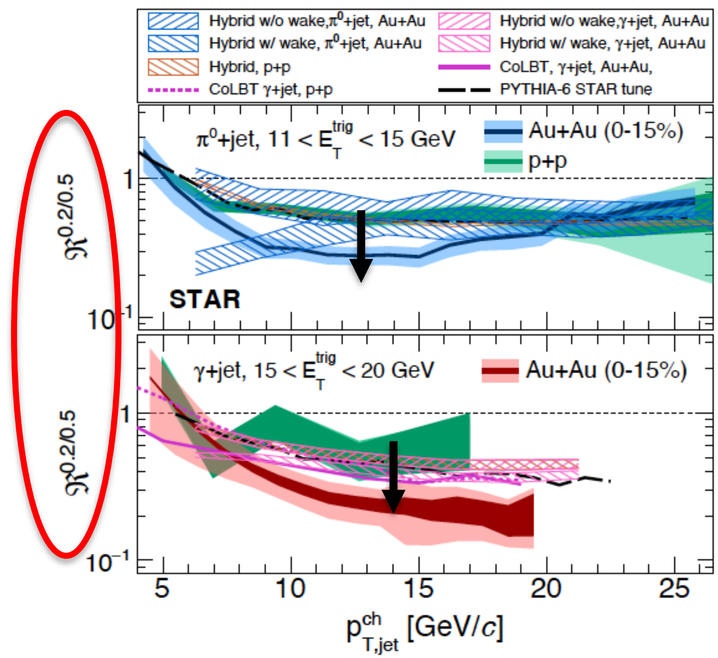
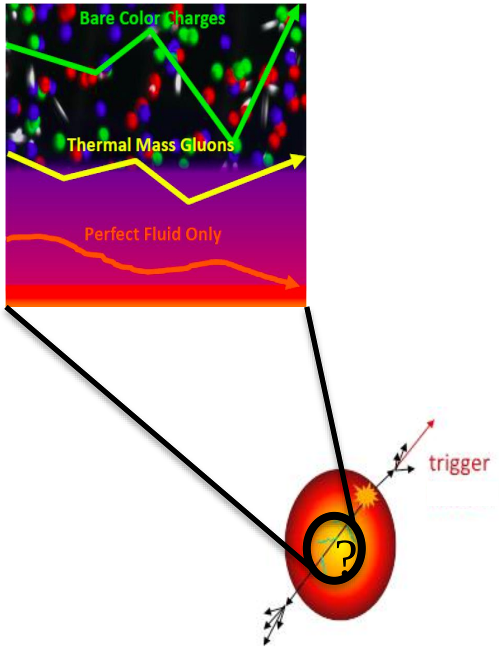








Medium-induced jet broadening in multiple channels at RHIC and LHC
- no survivor bias (zero)



Tools:

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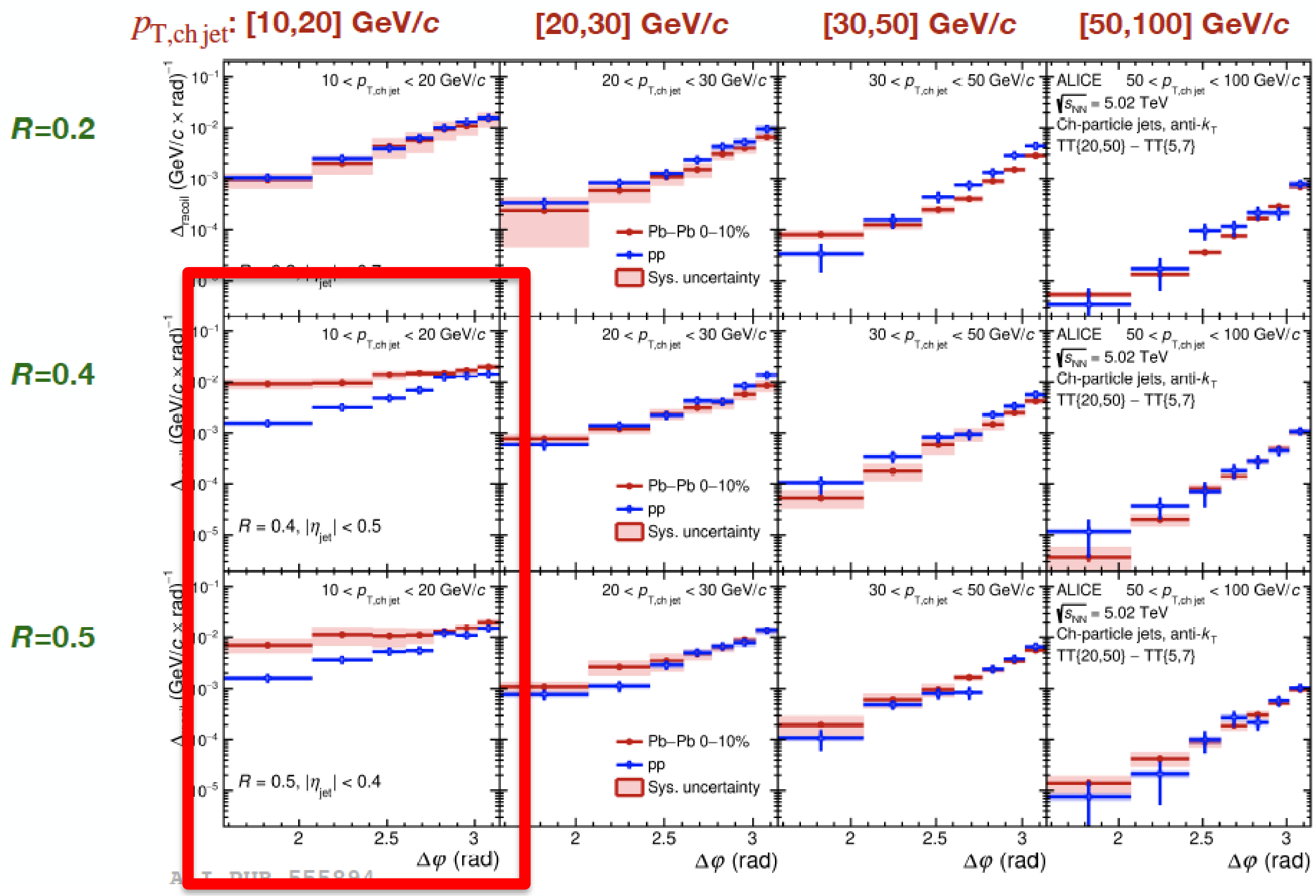
Semi-incl. jet quenching: angular dependence



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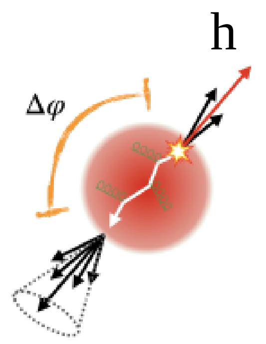
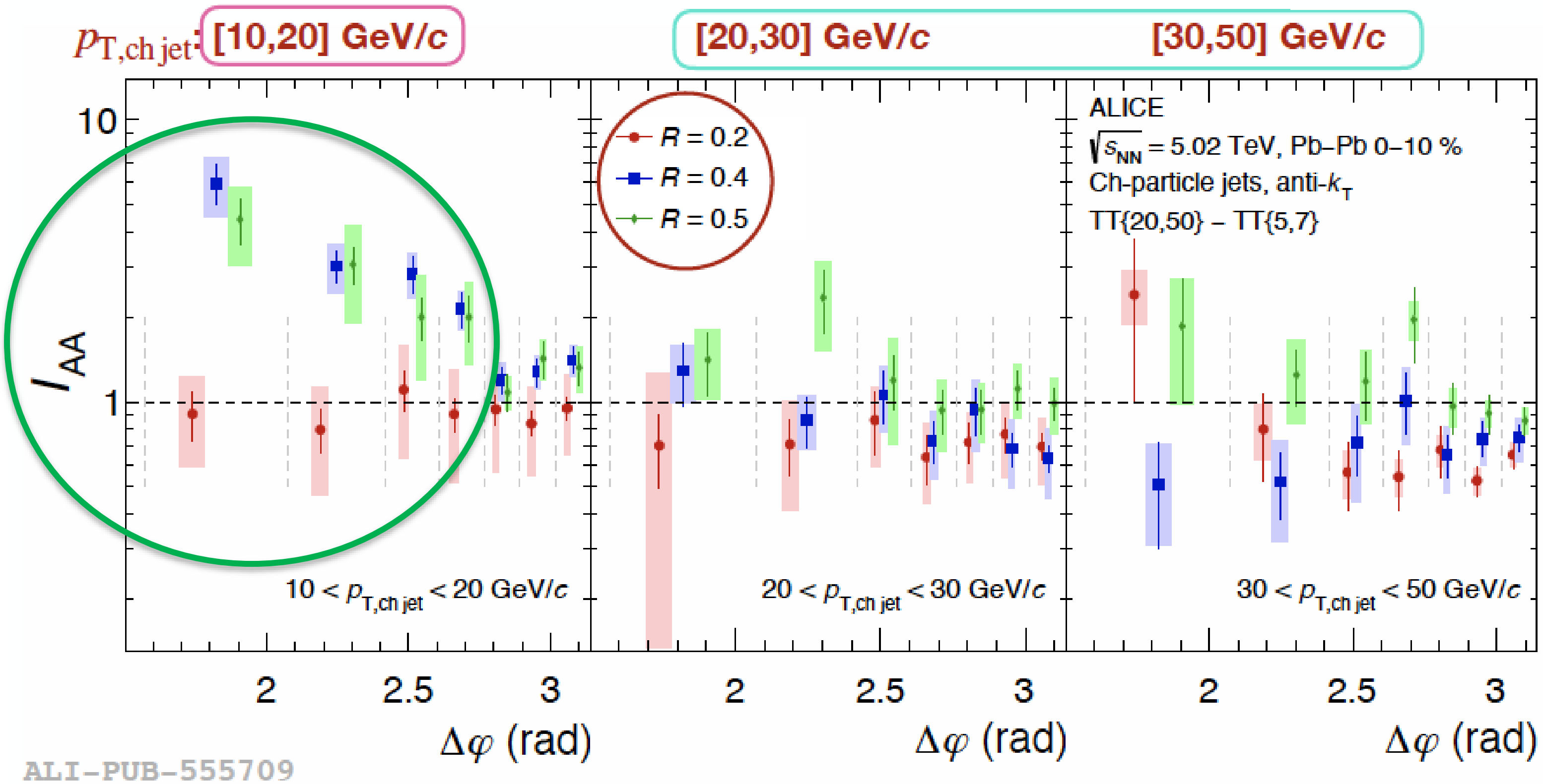


Large medium-induced azimuthal broadening for large-aperture “recoil jets” at low p_T^{jet} (!)

Semi-incl. jet quenching: angular and aperture (R) dependence

$$I_{AA} = \frac{\Delta_{recoil}(\text{Pb}-\text{Pb})}{\Delta_{recoil}(\text{pp})}$$

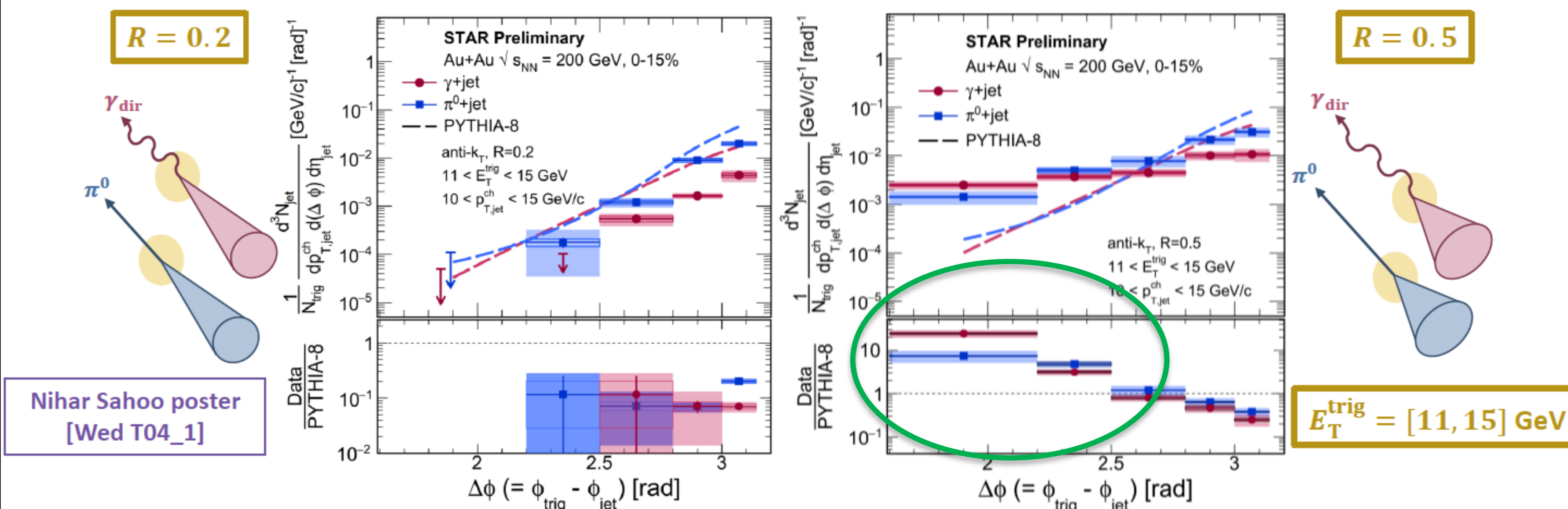


Large medium-induced azimuthal broadening

- **only** for large-aperture “recoil jets”
- **only** at low p_T^{jet}
- unexpected

Azimuthal broadening in γ/π^0+jet at RHIC

Corrected $\Delta\phi$ distributions in Au+Au collisions



- Corrected $\Delta\phi$ spectra in Au+Au compared **against smeared PYTHIA-8**
  - $\Rightarrow$ PYTHIA-8 validated against π^0+jet p+p data
- **Note:** $\Delta\phi$ integrated yield is I_{AA}
- **Highly significant medium-induced broadening of acoplanarity for $R = 0.5$**

$\Rightarrow$ Medium effects include

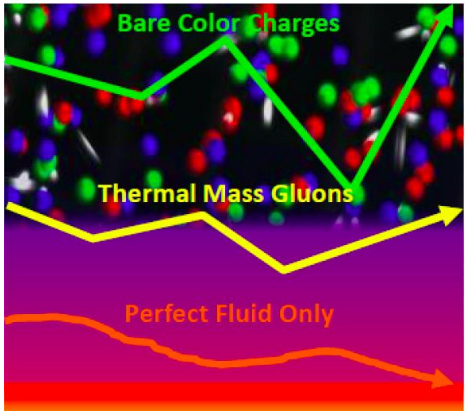
a) Scattering off QGP quasi-particles

b) Multiple soft scatters

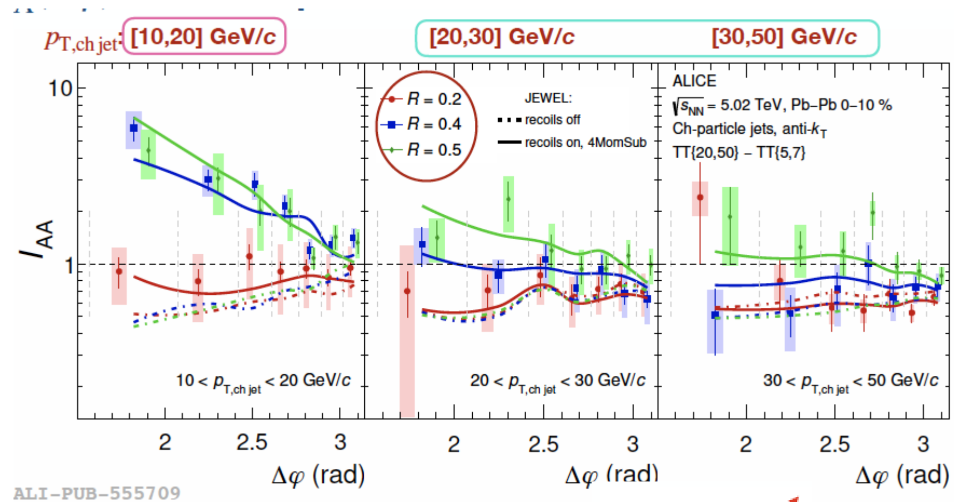
April 5th, 2022 Derek Anderson, QM 2022 19/21

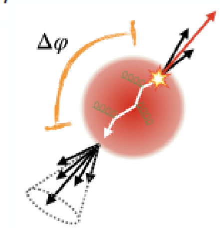
STAR sees similar medium-induced azimuthal broadening for large-aperture recoil jets (paper in progress)

Azimuthal broadening: interpretation



?

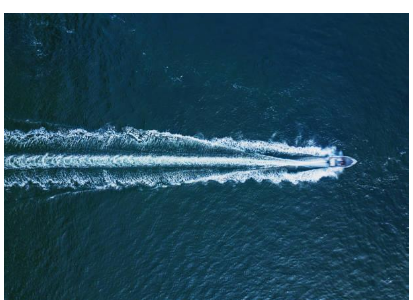


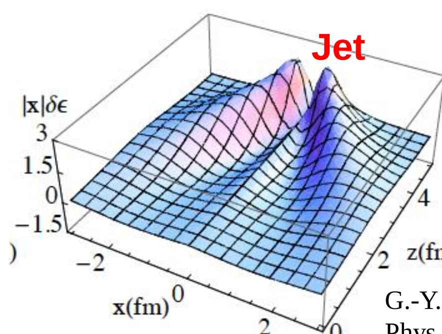


Why broadening only for large aperture recoil jets?

- not compatible with Rutherford scattering (should also affect small R jets)

Rather: characteristic of diffuse large-angle flow of QGP fluid excited by the passage of an energetic recoil





G.-Y. Qin, A. Majum
Phys.Rev.Lett. 103 (2

Conjecture at low p_T^{jet}:
not perturbative "jets" but rather only correlated energy/momentum flow of soft particles

→ $p_T^{jet} \sim R^2$

→ first direct evidence of jet wake in QGP

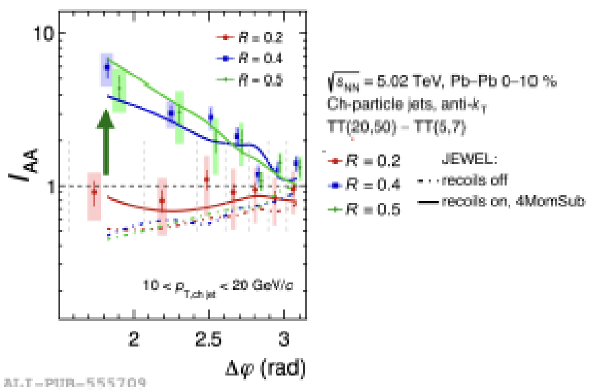
Acoplanarity: next steps

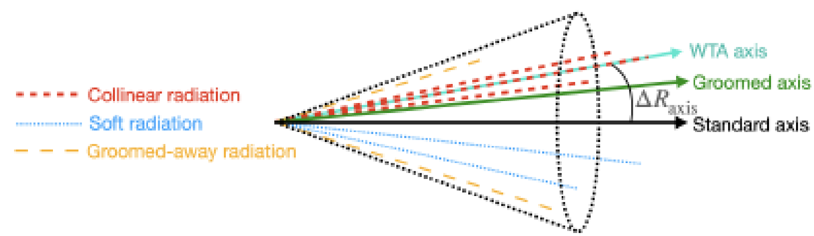
How do we verify this picture?

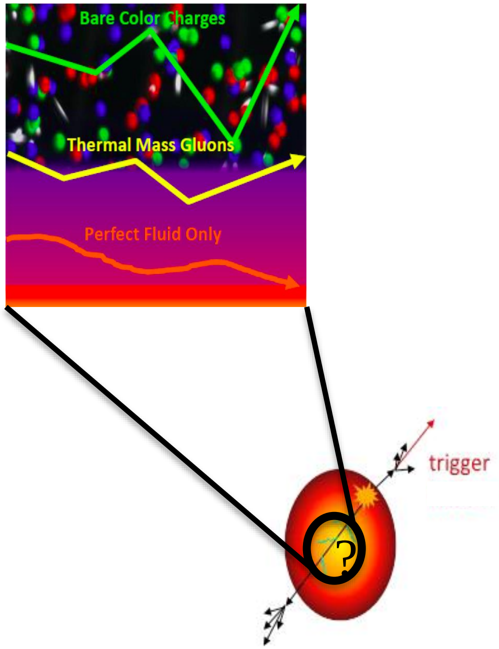
D. Jones, HP24

- **Introduce an observable to look at recoil jet substructure: ΔR_{axis}**
  - Utilise the statistical approach - the first application to jet substructure
- **Begin Pb-Pb analysis!**
  - What is the origin of the acoplanarity broadening?

JHEP 07 (2023) 201



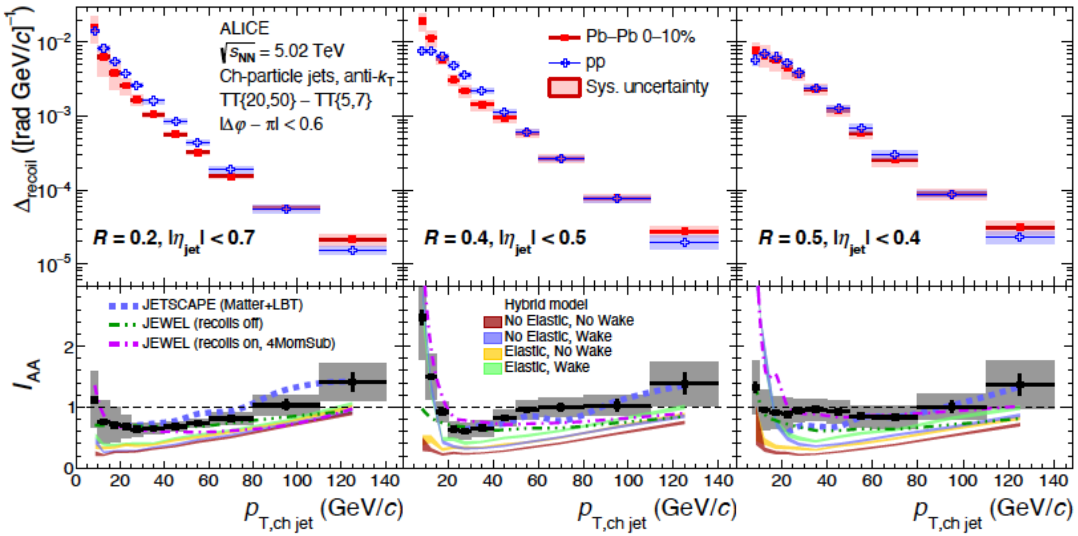




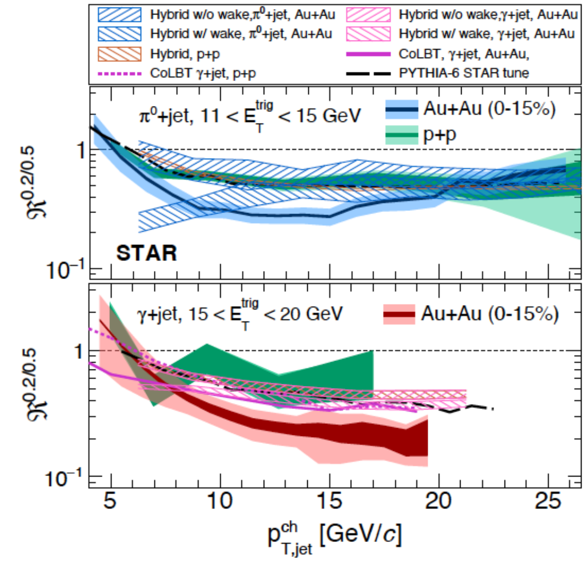
Tools:

- Substructure modification
- Yield modification
- Correlations
- Model comparisons

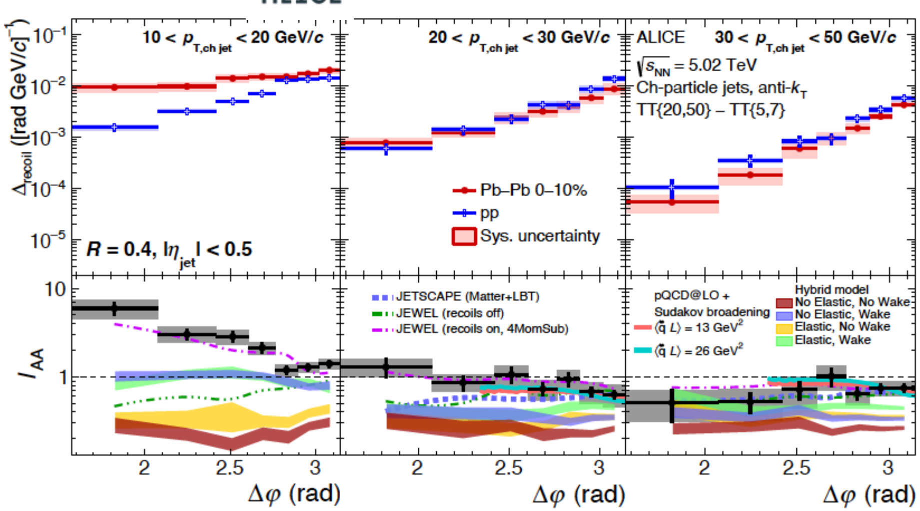
h+jet I_{AA}



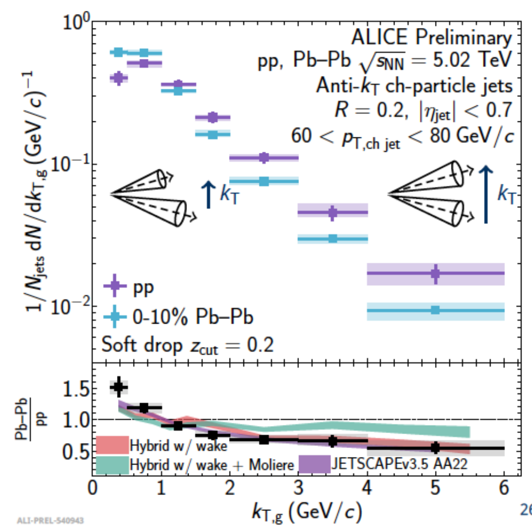
γ/π^0 recoil R=0.2/R=0.5



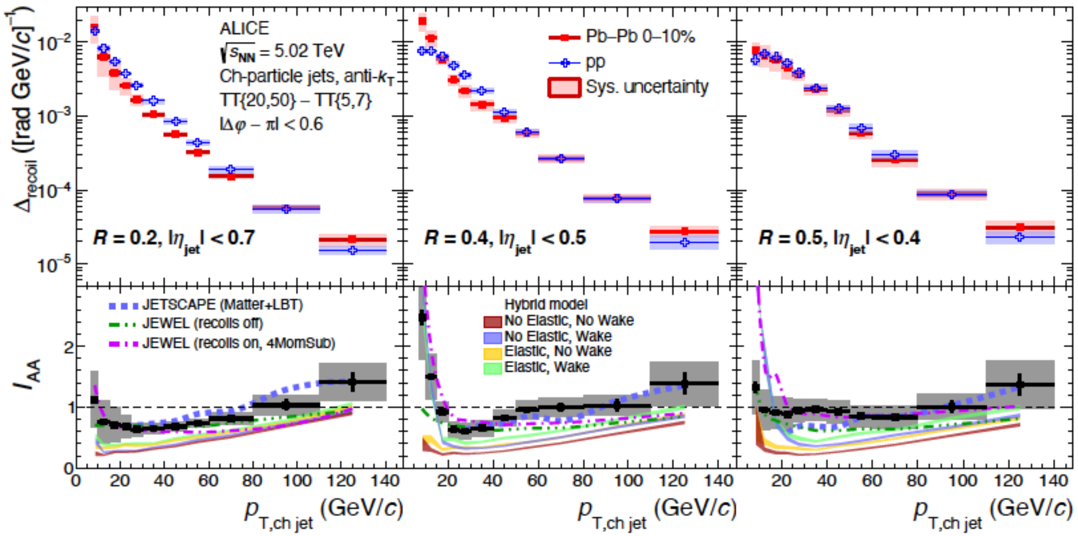
h+jet $\Delta\varphi$



Hardest k_T



h+jet I_{AA}



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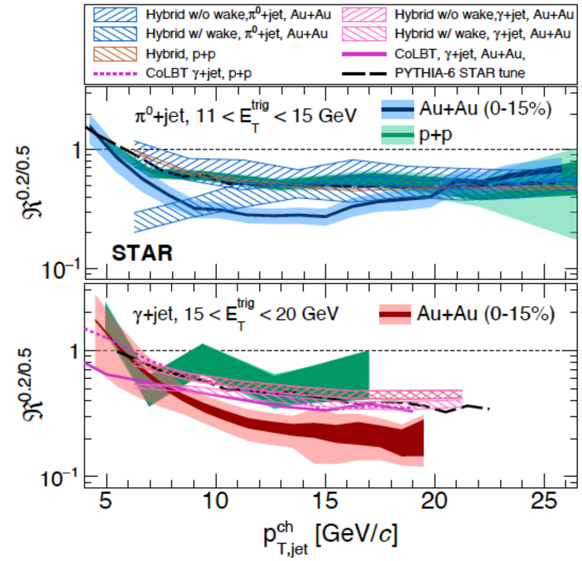
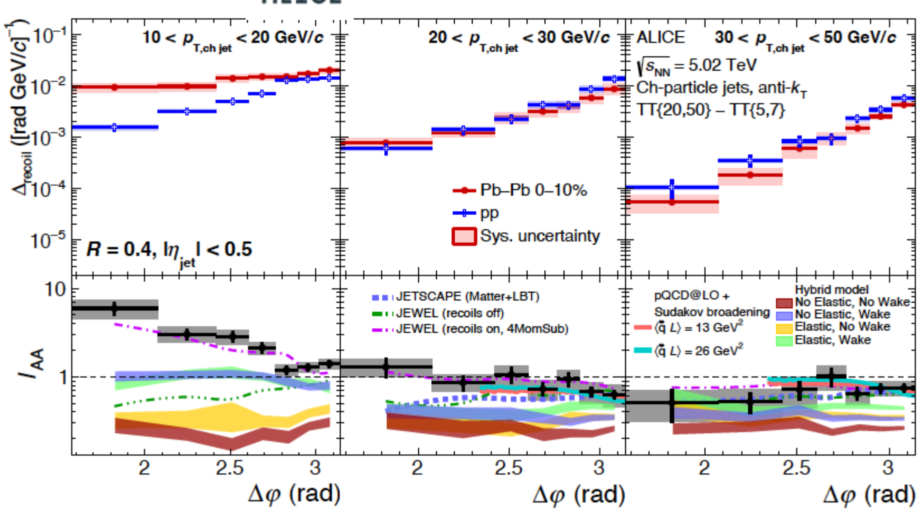


h+jet Δφ



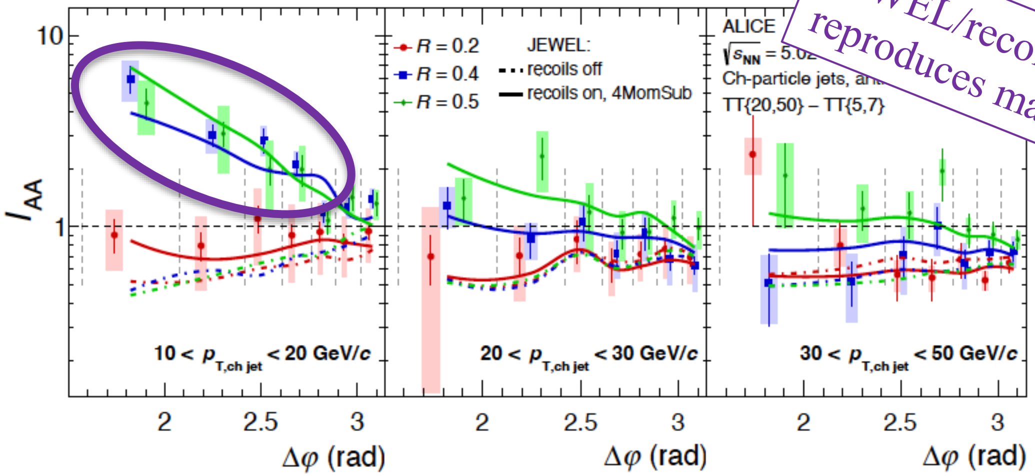
Semi-incl. yields:

- Models qualitatively ~OK but miss quantitatively

Acoplanarity:

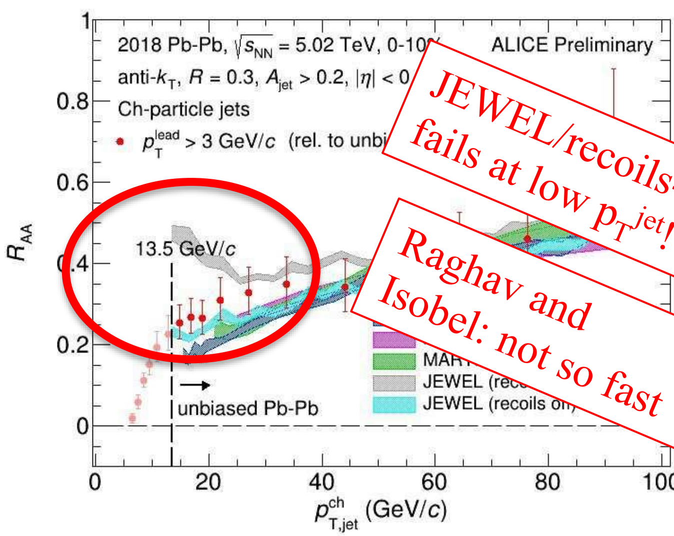
- most models fail
- only Jewel/recoils-on reproduces observations

h+jet $\Delta\varphi$



JEWEL/recoils-on reproduces main features

Incl. jet R_{AA} (Nadine's talk)



JEWEL/recoils-on fails at low p_T^{jet}!

Raghav and Isobel: not so fast

No current model (?) successfully describes all unbiased measurements of medium-induced modification at low p_T^{jet}

Predictions for other observables (EECs, diffusion wake,…) are compromised?

Summary

Moliere scattering:

- no clear evidence to date
- may be masked by wake effects; no clear path forward for direct observation

Heavy-ion jet measurements: statistical approach to background mitigation

- enables precise jet measurements over the full phase space
- scope expanding beyond coincidence channels: inclusive, sub-structure
    - under discussion: EECs

Multiple measurements of medium-induced jet broadening at low to intermediate p_T^{jet}

Striking medium-induced acoplanarity: phenomena consistent with jet wake

- substructure measurements in progress to verify

No current model incorporating medium response correctly describes all these data

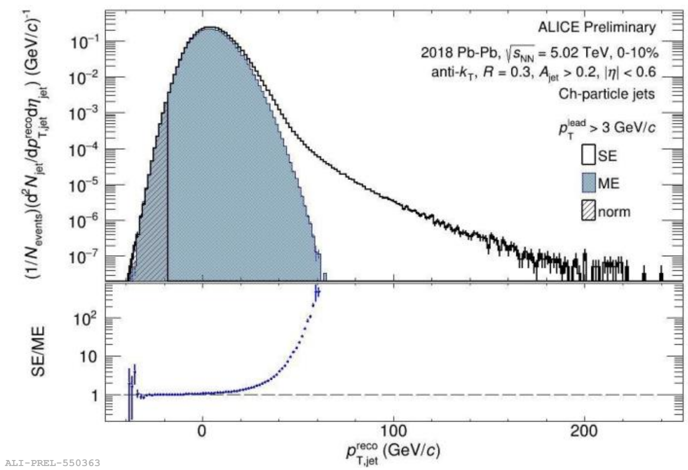
- unclear what predictions of other observables mean
- need to re-assess modeling approaches

Extra slides

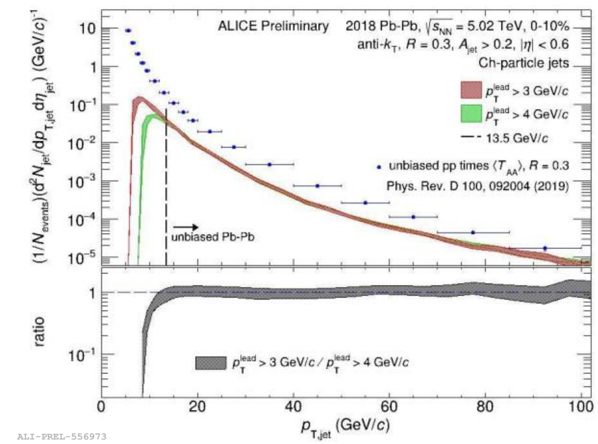
Inclusive jets: R_{AA} at very low p_T^{jet}

First application of ME to inclusive jet measurements

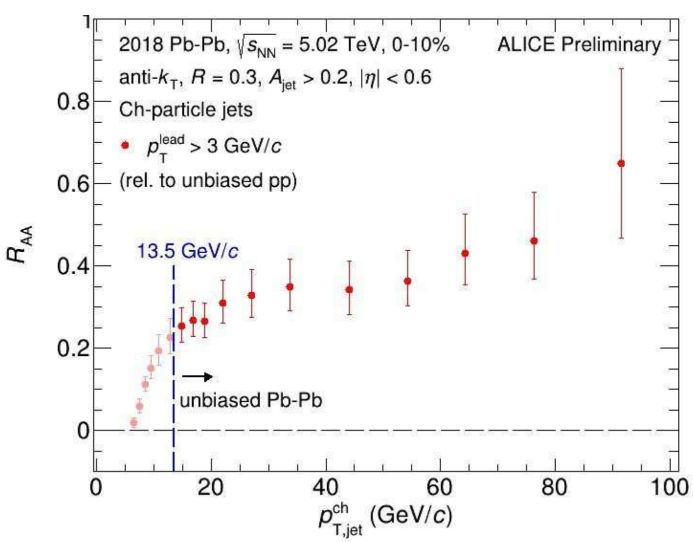
SE/ME



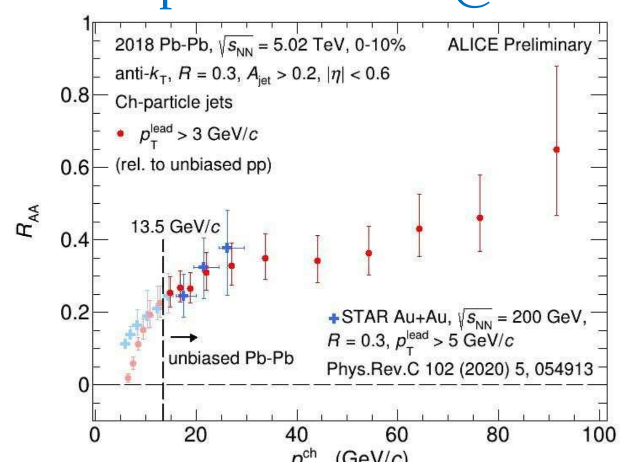
Corrected spectrum



R_{AA}



Compare to STAR@RHIC



Similar suppression at RHIC and LHC
LHC: harder spectrum → larger E-loss