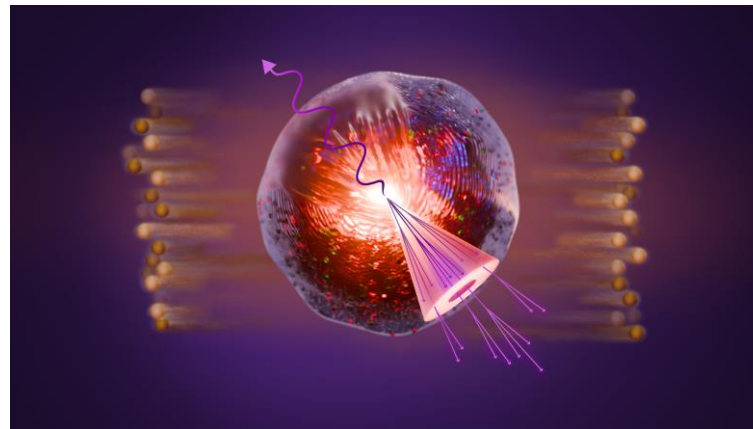


How to actually measure jet quenching in heavy-ion collisions

Peter Jacobs

Lawrence Berkeley National Laboratory

University of Liverpool

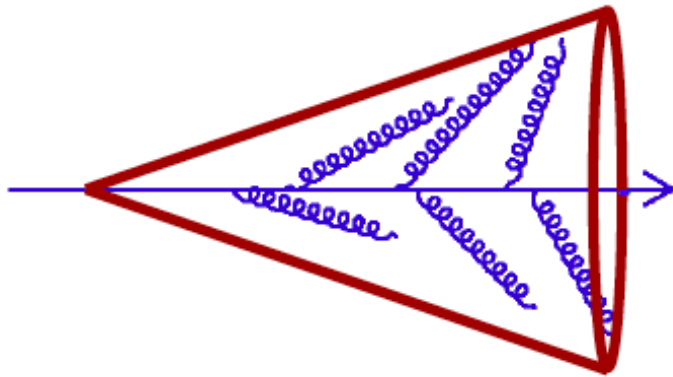


QCD@LHC 2026
University of Oxford

Jet quenching in one slide

Jet shower in-medium

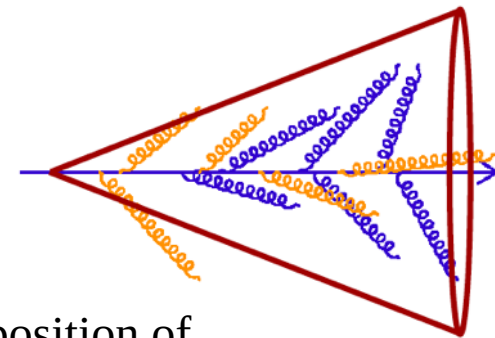
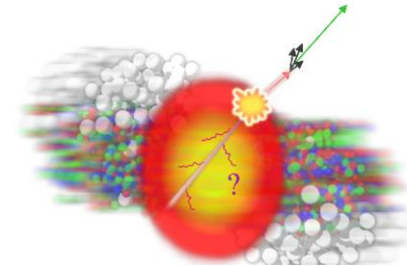
Jet shower in vacuum



Highly virtual parton evolves via gluon radiation

Quantum interference $\rightarrow$ angle-ordering

- hardest radiation is most collinear with jet axis
- Precise understanding in pQCD
- Accurately calculable with QCD-based Monte Carlo models



Superposition of

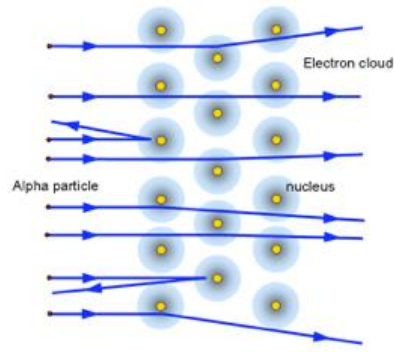
- vacuum shower
- medium-induced gluon emission

These processes happen simultaneously and interfere

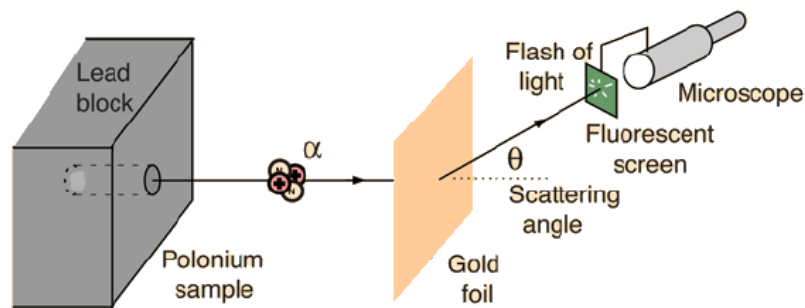
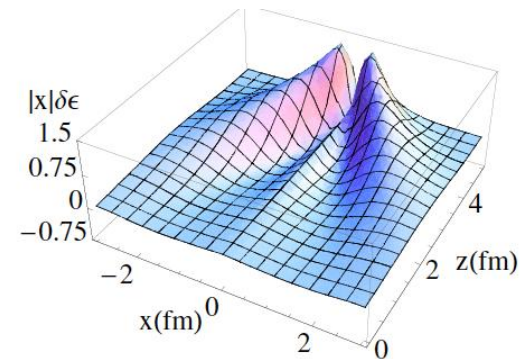
Angle-ordering is modified or destroyed

What can we learn about the Quark-Gluon Plasma from jet quenching ? Consider two limits...

Resolve discrete scattering centers: QGP quasi-particles



Excite a continuous medium and observe its response

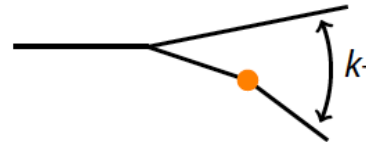
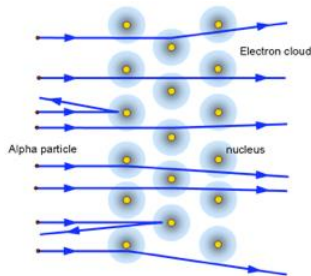


Search for quasi-particle scattering in the quark–gluon plasma with jet splittings in pp and Pb–Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV

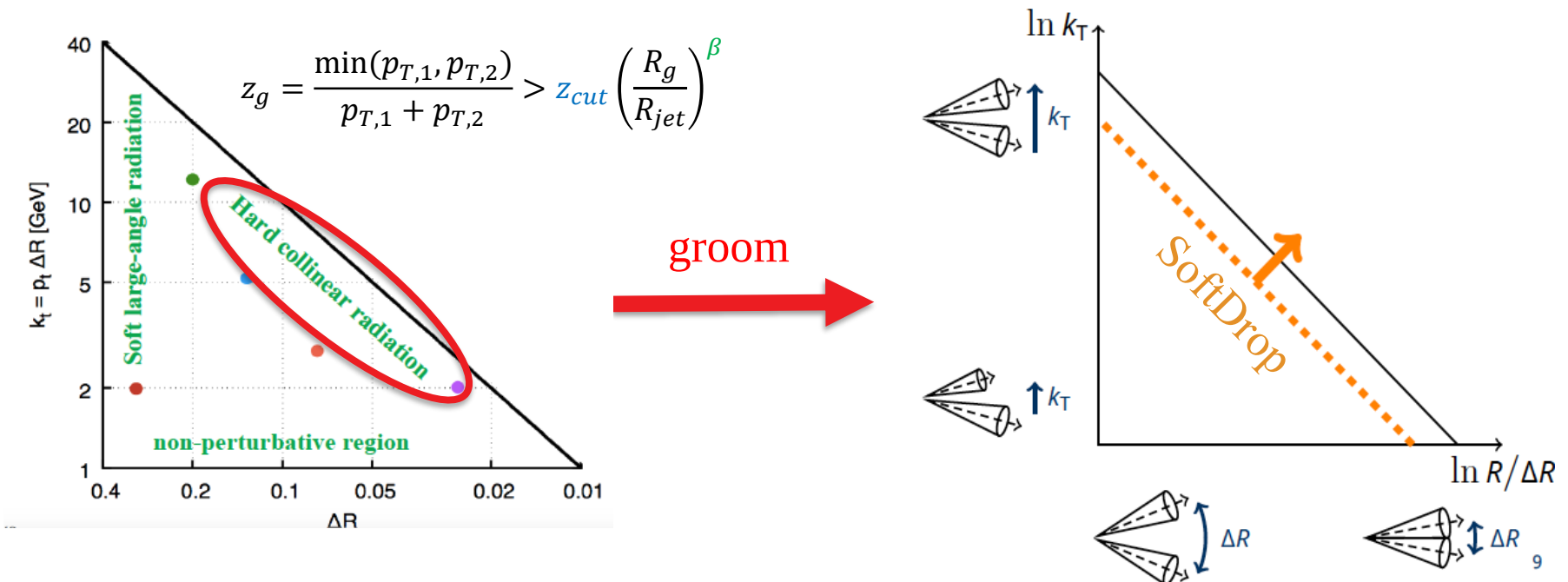
ALICE Collaboration*

Phys. Rev. Lett. 135 (2025) 031901

Quasi-particle scattering via jet splitting



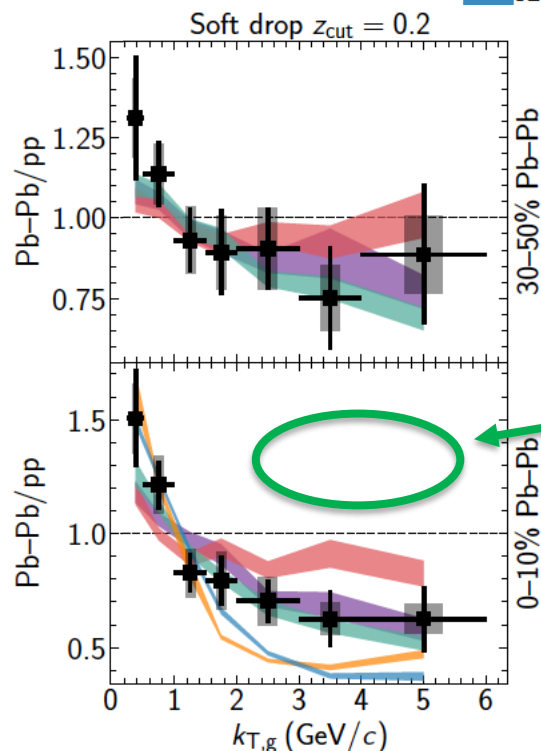
Use jet grooming to isolate hard k_T splittings
 → enhanced yield at high k_T in Pb+Pb?



Quasi-particle scattering via jet splitting

0-10%, 30-50% Pb-Pb, pp $\sqrt{s_{NN}} = 5.02$ TeV
Anti- k_T ch-particle jets, $R = 0.2$, $|\eta_{jet}| < 0.7$
 $60 < p_{T, ch jet} < 80$ GeV/c

Hybrid w/ wake
Hybrid w/ wake + Moliere
JETSCAPEv3.5 AA22
JEWEL (recoils)
JEWEL (no recoils)



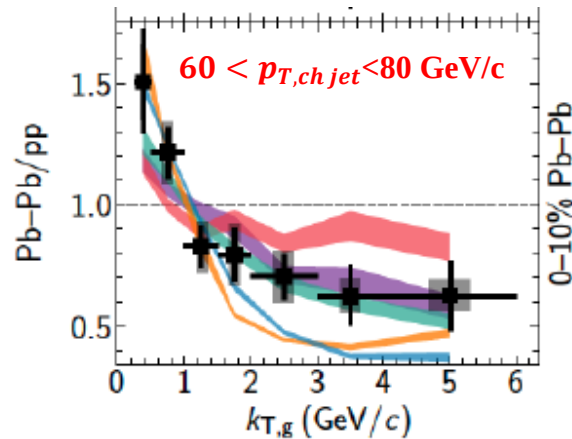
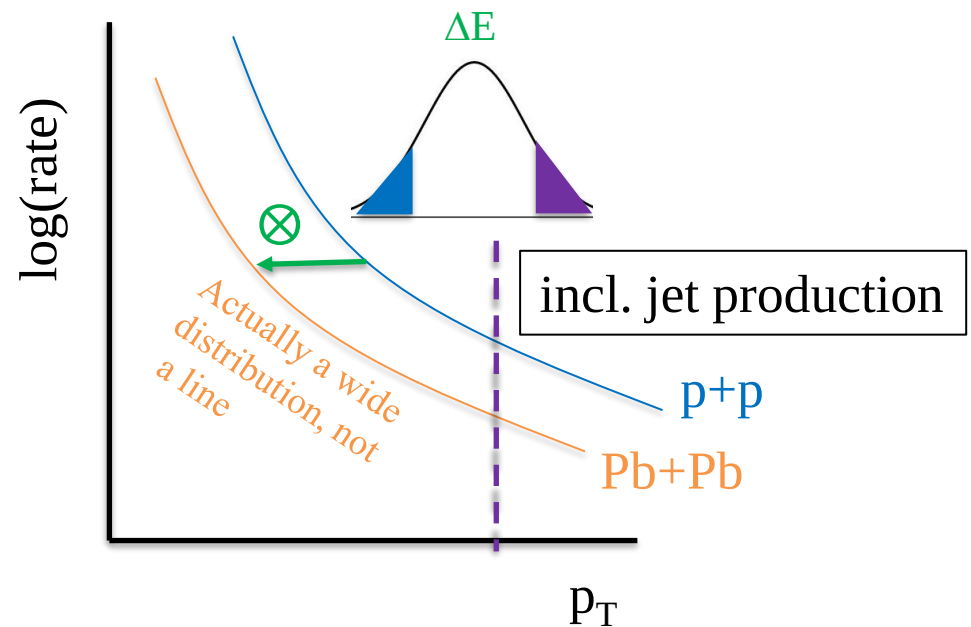
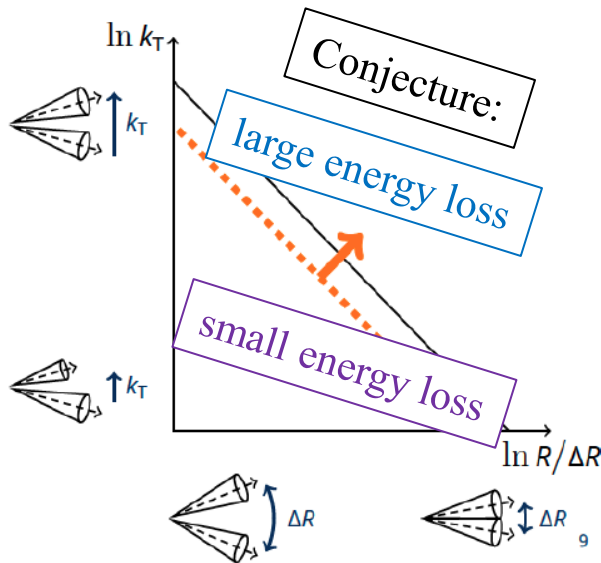
Quasi-particle scattering
corresponds to yield enhancement
at large k_T

??

Not seen. Why?

1. Wrong kinematics
2. Signal obscured by jet selection bias

Jet quenching → selection bias

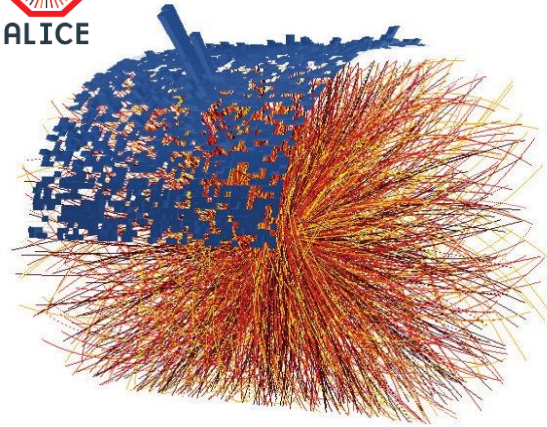
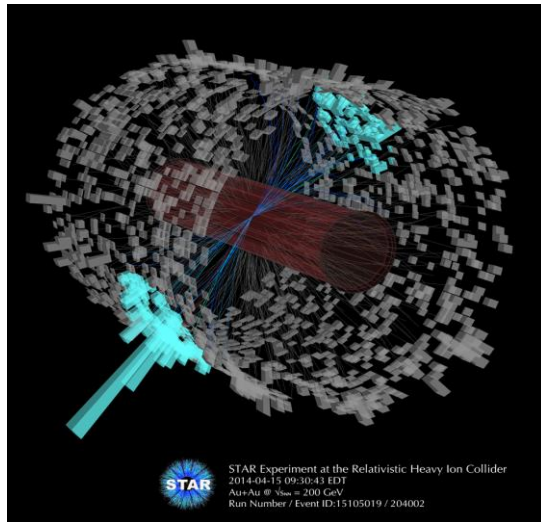


1. Energy loss due to quenching is a distribution
2. Jet spectrum falls with increasing p_T
3. We compare jets in Pb+Pb and p+p at the same value of observed p_T

Pb+Pb population at fixed p_T is **dominated by jets with small energy loss → selection bias against initial broad substructure**

The p_T threshold is the fundamental issue. Can we do this differently?

Step back: heavy-ion jet measurement challenge



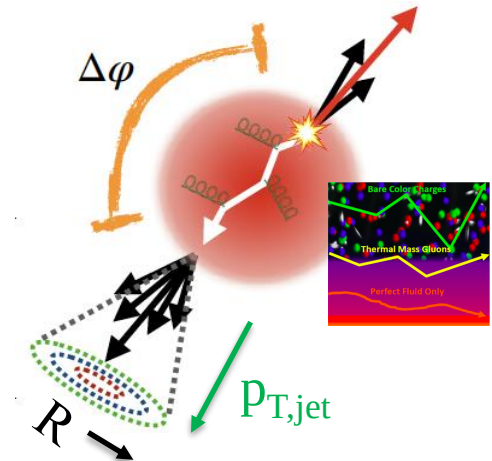
Very complex experimental environment

Huge background of particles not correlated with jet shower

Particles do not come labelled “jet” or “background”

Coincidence observables:

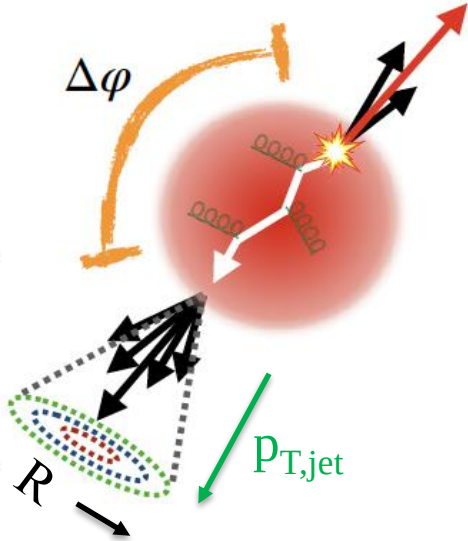
- cannot be certain that a given recoil hadron arises from the same high- Q^2 process as the trigger
- “uncorrelated background” strictly has meaning only for ensemble-averaged (“statistical”) distributions



Low p_T^{jet} /large R : tiny signal/background
→ requires “statistical” approach to uncorrelated background yield

Semi-inclusive measurement

Trigger: γ/Z , π^0 , ch hadron



Recoil jet

1. Event selection: hard processes trigger
 - γ/Z , π^0 , charged hadron (not jet, too messy)
2. Jet reconstruction on full event
3. Count number of recoil jets, normalize per trigger

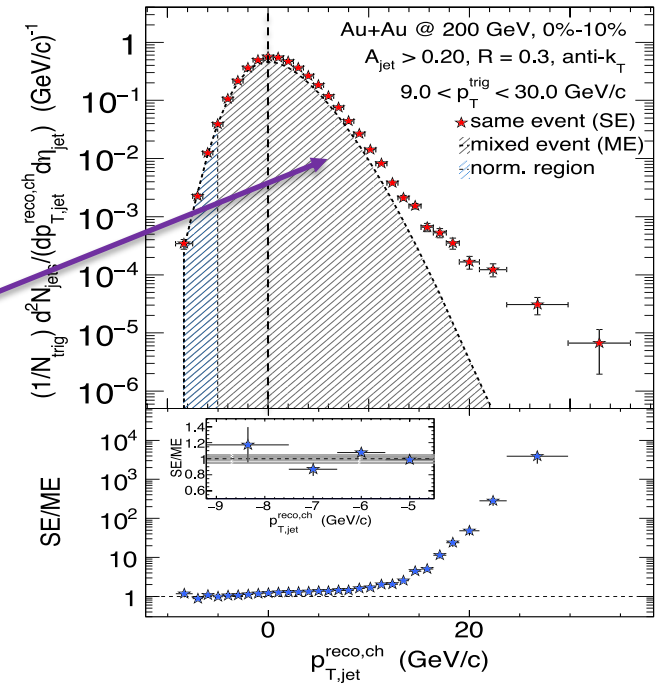
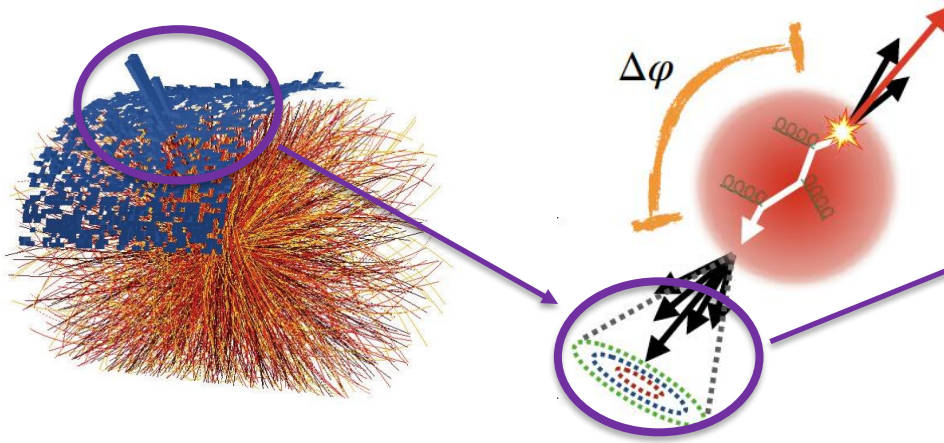
If no uncorrelated background $\rightarrow$ ratio of hard cross sections

$$\frac{1}{N_{trig}^{AA}} \frac{d^2 N_{jet}^{AA}}{dp_{T,jet} d\Delta\phi} = \frac{1}{\sigma^{AA \rightarrow trig+X}} \frac{d^2 \sigma^{AA \rightarrow trig+jet+X}}{dp_{T,jet} d\Delta\phi}$$

Recoil jet distribution: h+jet



Phys. Rev. C 96 (2017) 024905



No recoil jets are discarded. Two components:

- **Correlated:** arises from same high Q^2 interaction as trigger
- **Uncorrelated:**
 - MPI (different high Q^2 interaction)
 - Combinatorial (random association of tracks/towers)

$$p_{T, ch \, jet}^{reco} = p_{T, ch \, jet}^{raw} - \rho A$$

$$\rho = \text{median}_{\text{evt}} \left\{ \frac{p_{T, jet}^{raw, i}}{A_{jet}^i} \right\}$$

(first approx. to p_T -smearing, refined later by unfolding)

Constructing uncorrelated background via event mixing

STAR Collaboration,
Phys. Rev. C 96 (2017), 024905

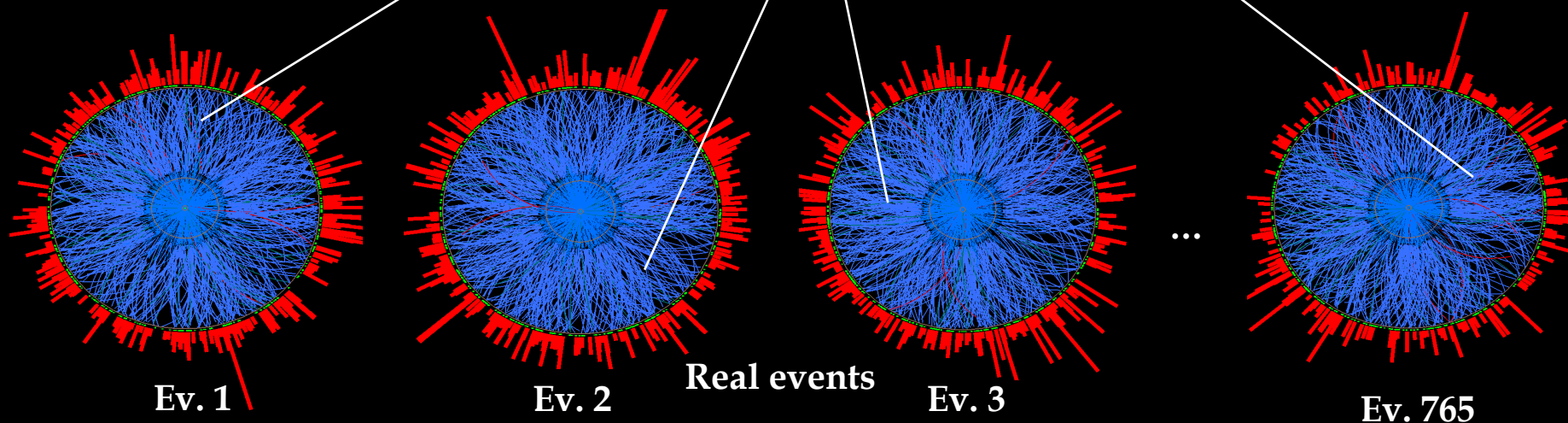
**Destroys all multi-hadronic
correlations, including jets**

Pick one random
track per real event
→ add to mixed
event

Mixed event

Mix only similar
centrality, Ψ_{EP} ,
z-vertex position

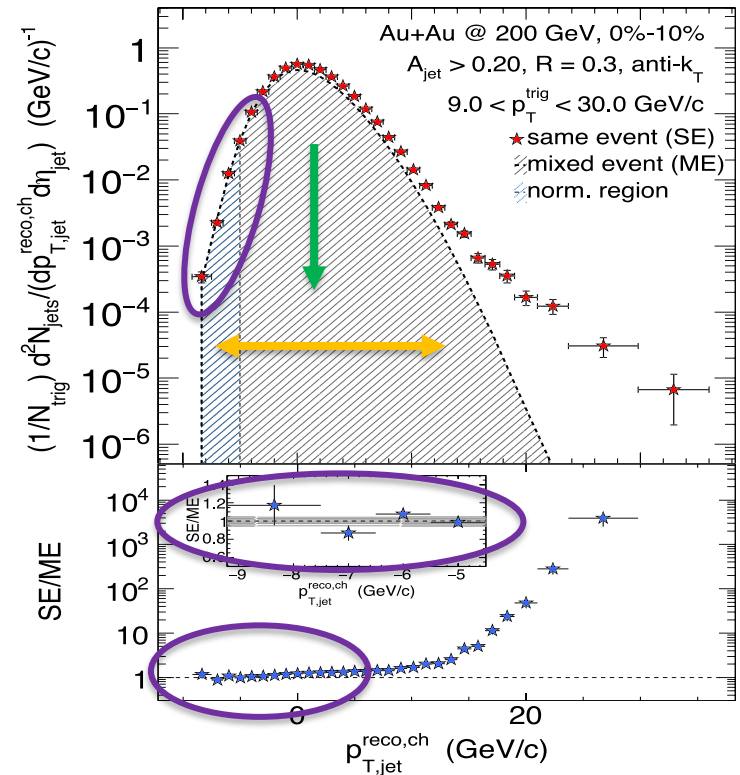
Carry out jet
reconstruction on
ensemble of mixed events



Background yield and p_T -smearing corrections

ME shape matches SE with precision in $p_{T,ch\,jet}^{reco} < 0$

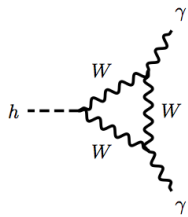
- region dominated by uncorrelated bkgd
- Data-driven validation of constructed bkgd distribution



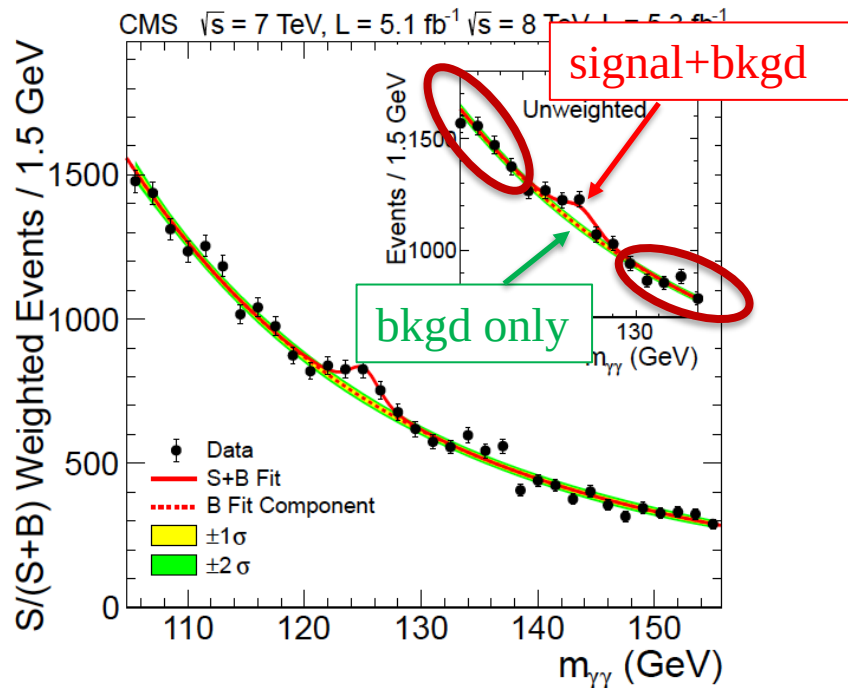
Two distinct corrections:

1. vertical: subtract uncorrelated recoil yield
2. horizontal: embedding/unfolding to correct residual p_T -smearing + JES

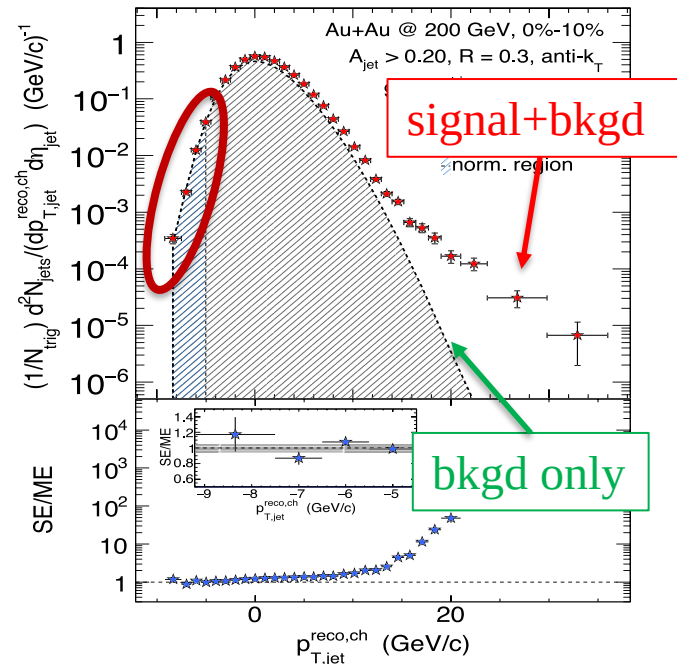
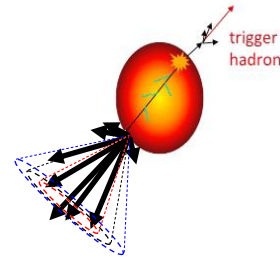
Statistical background correction



$$pp \rightarrow \text{Higgs} \rightarrow \gamma\gamma$$



$$\text{Au+Au} \rightarrow \text{hadron} + \text{jet}$$



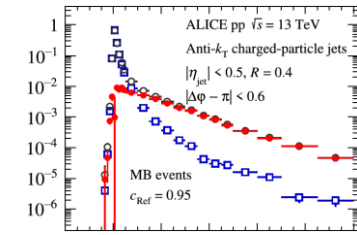
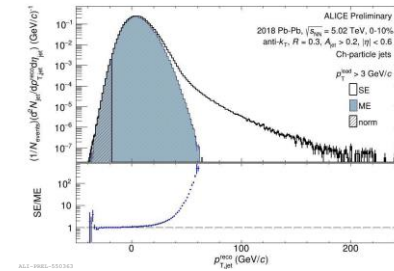
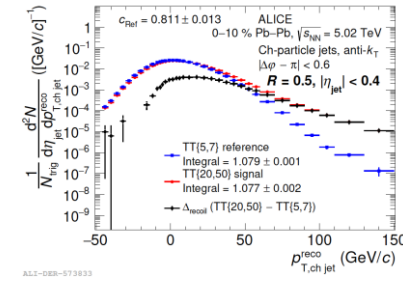
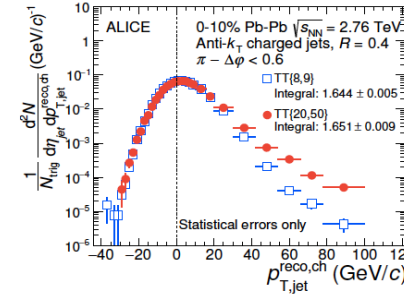
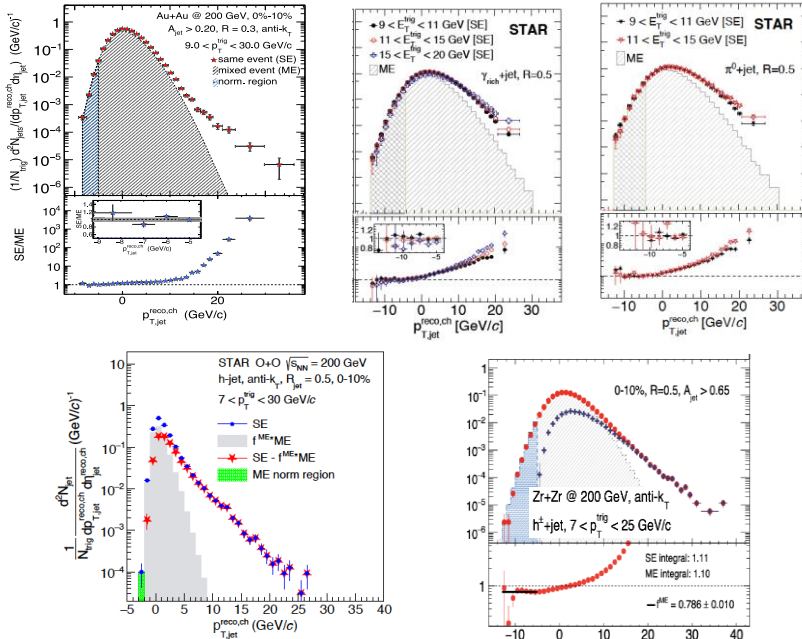
Two distributions:

- S+B: Signal + background
- B: Background only

Normalize in B-dominated region
→ Subtract B from S+B

Jets in A+A: precise (<0.1%) data-driven correction of uncorrelated bkgd yield over full jet p_T range w/ large R

Statistical jet quenching analysis: current results



Au+Au; h+jet

- Phys. Rev. C 96 (2017) 024905

Au+Au, p+p; gamma/pi^0+jet

- Phys.Rev.Lett. 134 (2025) 232301

- Phys.Rev.C 111 (2025) 064907

- Phys.Rev.C 113 (2026) 014902

Zr+Zr, Ru+Ru; h+jet

- arXiv:2606.00973

O+O; h+jet

- arXiv:2604.13935

PbPb, pp; h+jet

- JHEP 09 (2015) 170

- Phys.Rev.Lett. 133 (2024) 2, 022301

- Phys.Rev.C 110 (2024) 1, 014906

Pb+Pb; inclusive jet

- EPJ Web Conf. 296 (2024) 11005

p+Pb, HM pp; h+jet

- JHEP 05 (2024) 229

- Phys.Lett.B 783 (2018) 95-113

O+O; h+jet

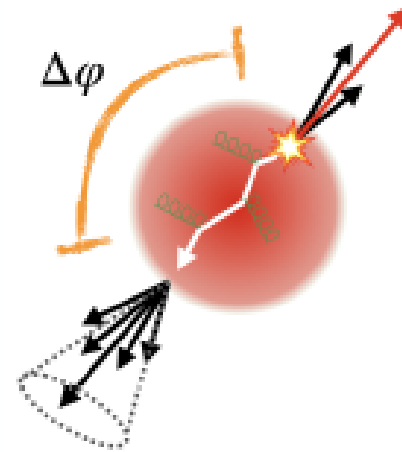
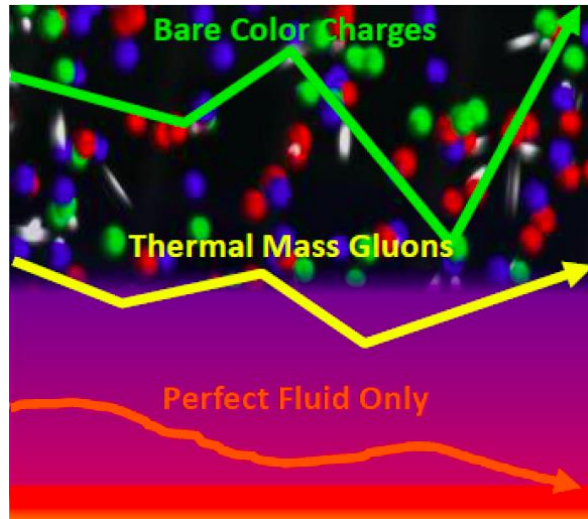
- in progress

In-medium jet scattering: acoplanarity



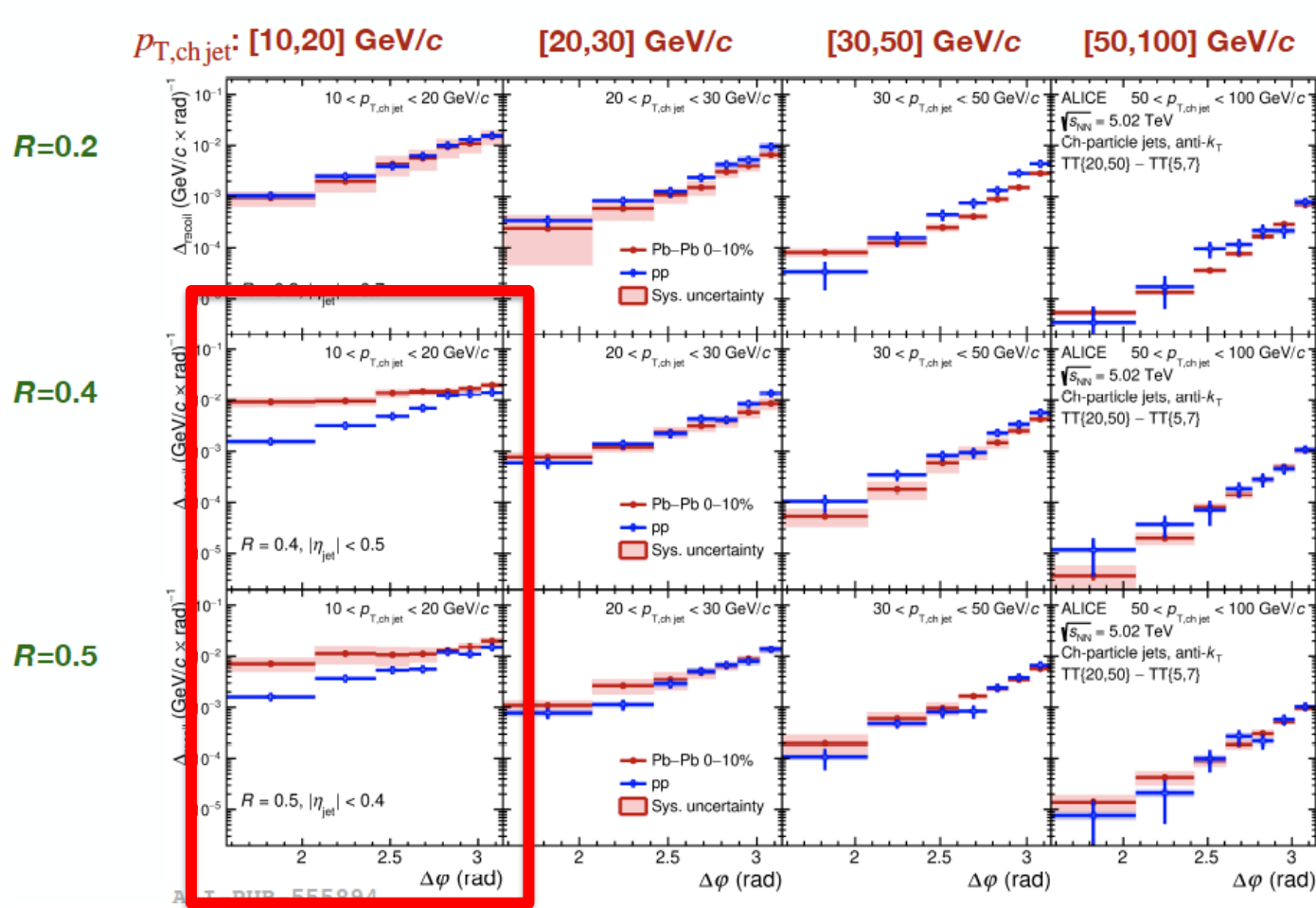
Phys.Rev.Lett. 133 (2024) 2 022301
Phys.Rev.C 110 (2024) 014906

$$\frac{1}{N_{trig}} \frac{dN_{jet}}{dp_{T,jet} d\Delta\varphi} = \frac{1}{\sigma^{AA \rightarrow h+X}} \frac{d\sigma^{AA \rightarrow h+jet+X}}{dp_{T,jet} d\Delta\varphi}$$



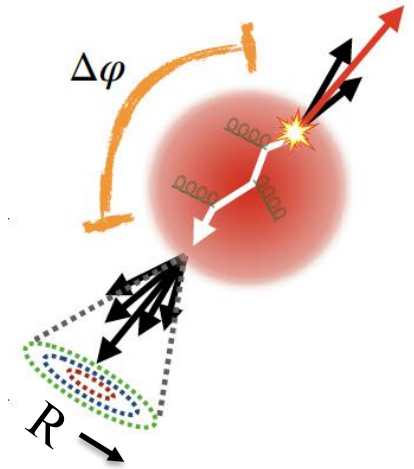
Expectation: scattering in the QGP broadens the acoplanarity distribution

Acoplanarity: h+jet in central Pb+Pb @ LHC



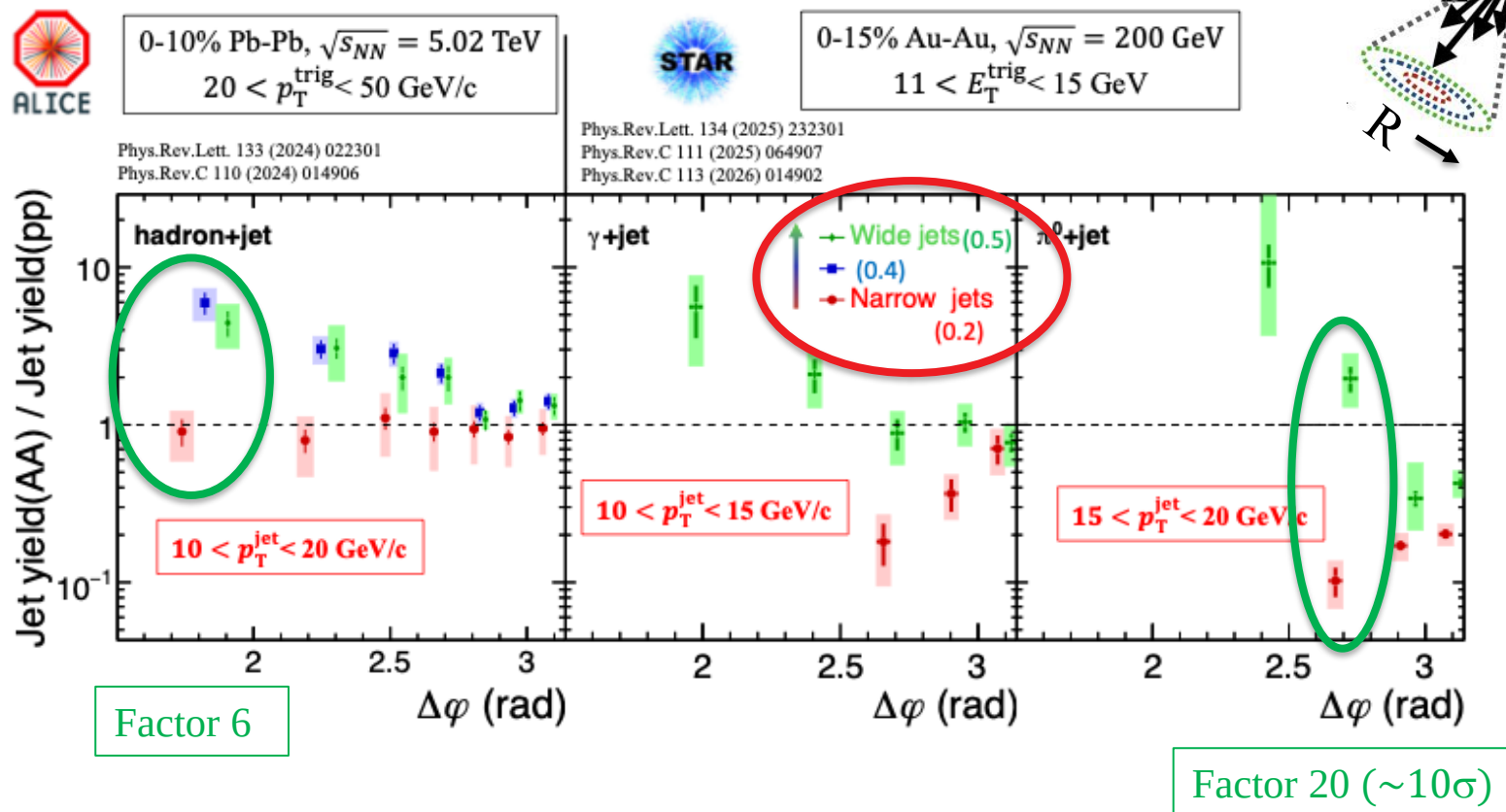
ALICE

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



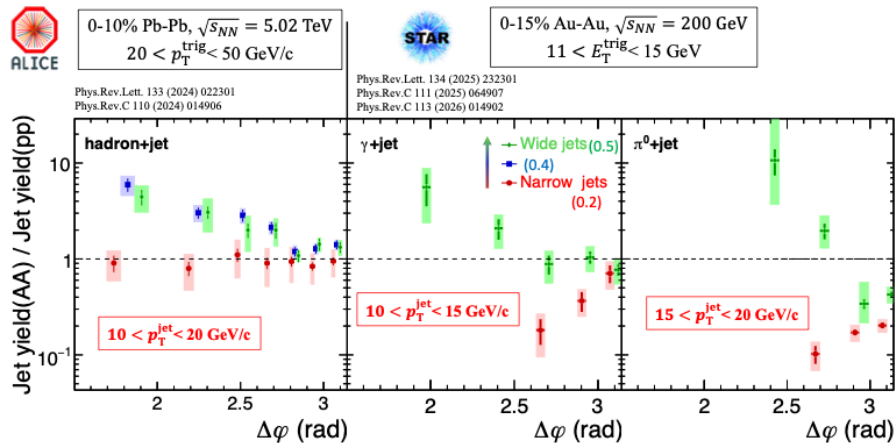
Large medium-induced azimuthal broadening
Only for large-aperture recoil jets at low $p_{T, \text{jet}}$

Medium-induced acoplanarity broadening at RHIC and the LHC



Large medium-induced azimuthal broadening
 Only for large-aperture recoil jets at low p_T^{jet}

What is a “jet” with $R=0.5$ at $p_T=10$ GeV/c?



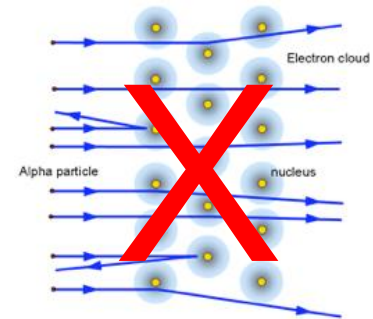
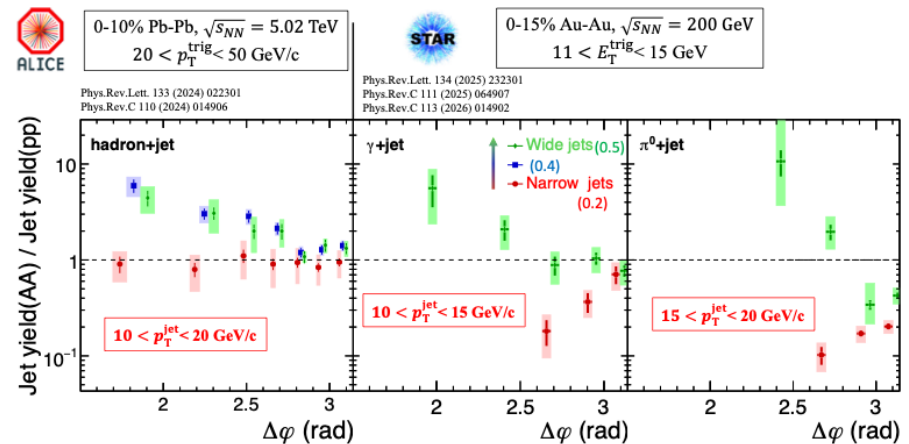
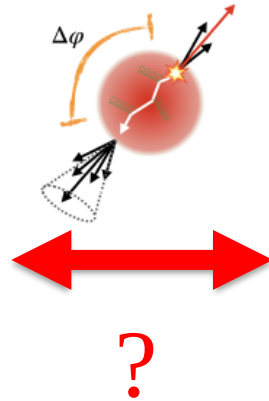
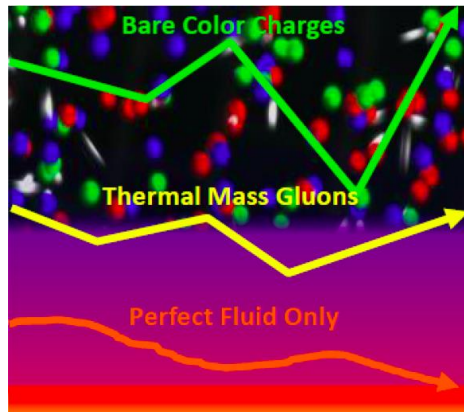
Anti- k_T used operationally as clusterizer - no reference to physical origin

Low p_T : may not be a “jet” in the perturbative sense, with angle-ordered substructure

- rather: just correlated energy-momentum flow within the aperture

Analysis procedure smoothly tracks the fate of jets in the QGP, from out-of-equilibrium at high p_T to partial or complete thermalization at low p_T

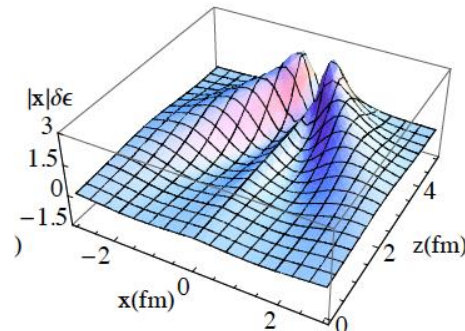
Acoplanarity broadening: interpretation



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 excited by the passage of an energetic recoil (“jet” $p_T \sim R^2$)



Probes QGP response to jet excitation

Emergence of thermal recoil jets in high-energy heavy-ion collisions

Peng Jing,¹ Yichao Dang,¹ Yang He,² Shanshan Cao,^{1,*} Li Yi,^{1,†} and Xin-Nian Wang^{3,‡}

¹*Institute of Frontier and Interdisciplinary Science,*

Shandong University, Qingdao, Shandong 266237, China

²*Department of Modern Physics, University of Science and Technology of China, Anhui 230026, China*

³*Institute of Particle Physics and Key Laboratory of Quark and Lepton Physics (MOE),*

Central China Normal University, Wuhan, 430079, China

(Dated: January 21, 2026)

In the established paradigm of jet quenching in relativistic heavy-ion collisions, jets from initial hard parton scatterings are suppressed due to their interaction with the quark-gluon plasma (QGP) as they traverse the hot medium, serving as crucial tomographic probes of QGP properties. The QGP is also capable of absorbing and reprocessing energy deposited by the hard jets into emergent jet-like objects, providing a novel production mechanism of thermal recoil jets. These emergent thermal recoil jets exhibit distinct transverse momentum (p_T) and jet-size (R) dependencies different from the hard jets, and naturally explain the puzzling observation of the enhanced yields of hadron or photon triggered jets at large azimuthal angle and solely at small p_T and large R . These thermal recoil jets are predicted to have unique substructures, such as their jet shape that increases with the radius and the thermal-like distribution of their constituents, which can be verified in future experimental analyses.

Emergence of thermal recoil jets in high-energy heavy-ion collisions

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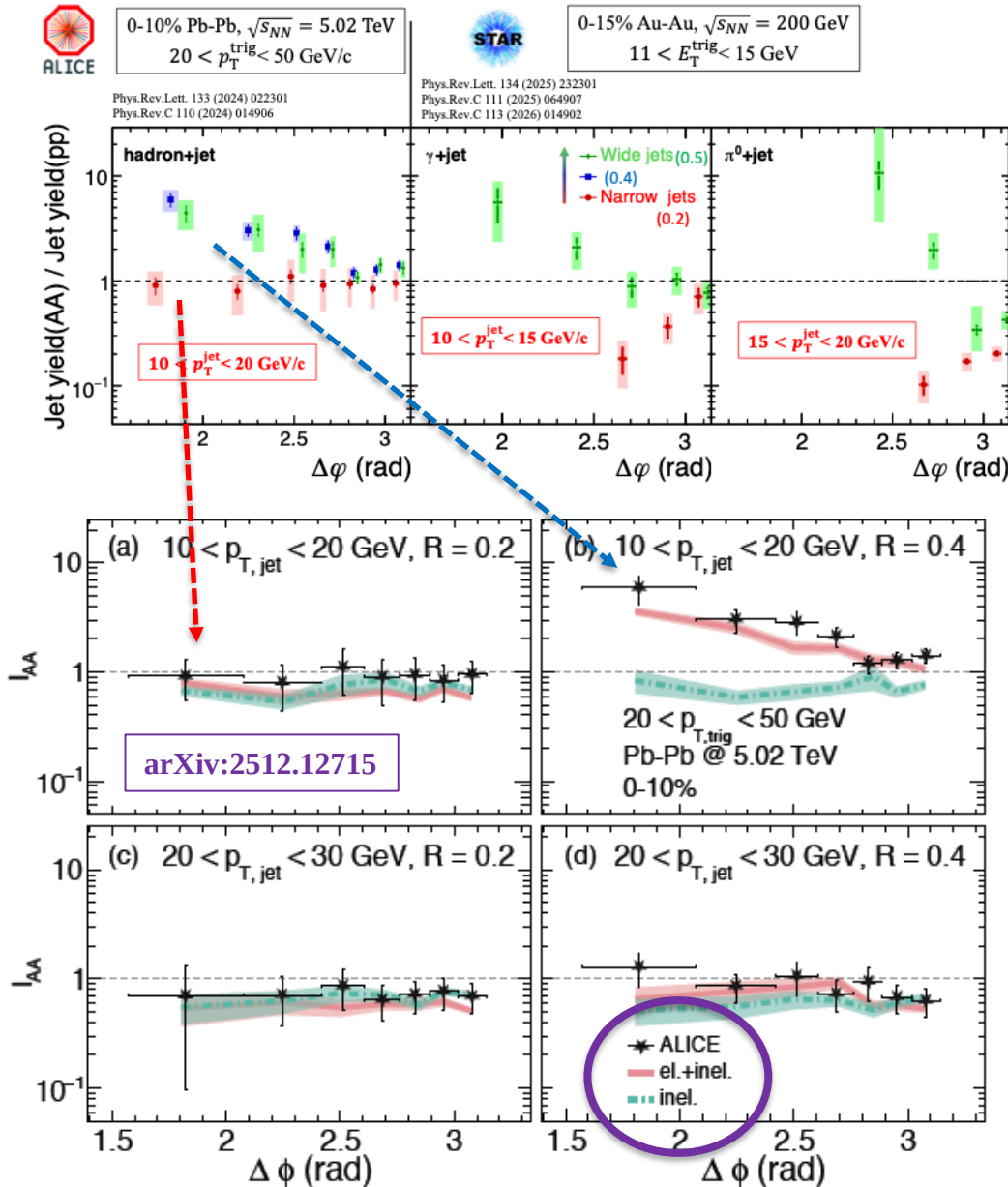
Central China Normal University, Wuhan, 430079, China

(Dated: January 21, 2026)

Linear Boltzmann Transport (LBT) model

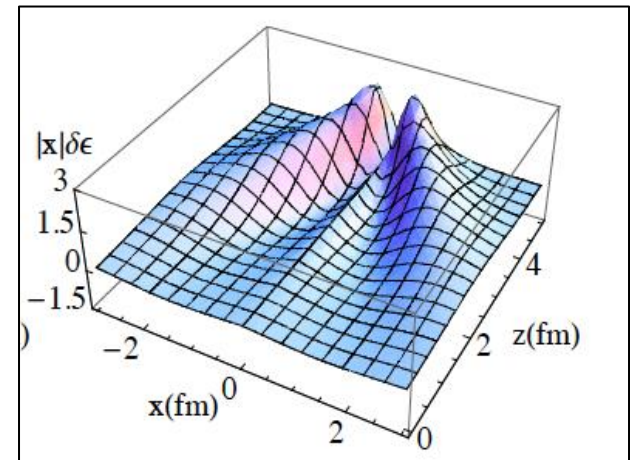
- 3+1 dimensional hydrodynamics
- elastic and inelastic jet-medium scattering in Higher Twist (HT) approach
- generation of radiative and thermal recoil partons; further scattering and QGP back-reaction

Most comprehensive model of QGP response to jet excitation



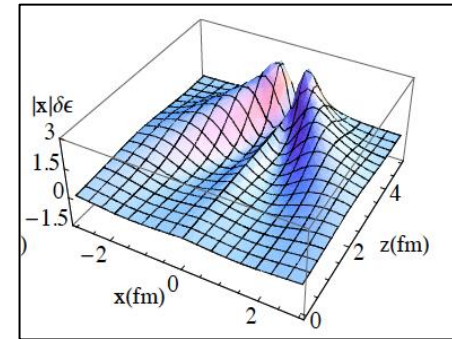
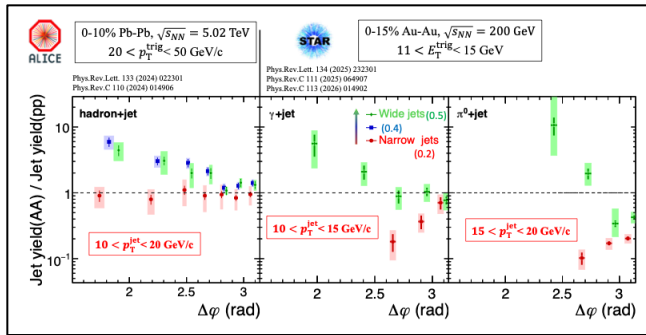
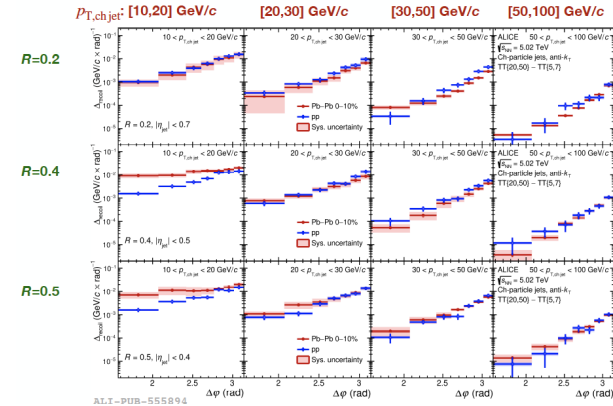
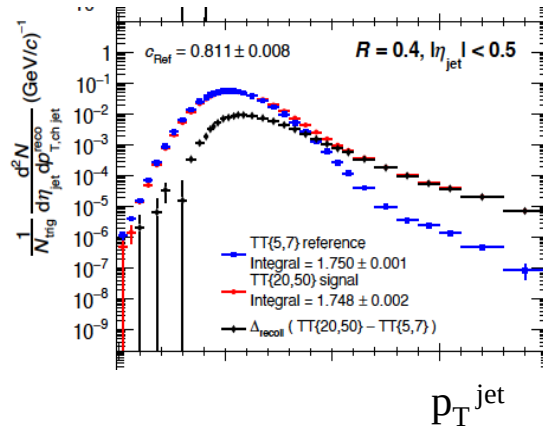
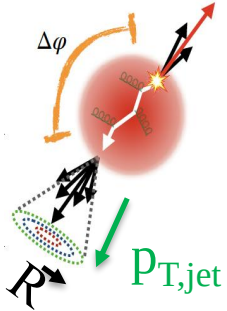
Calculations reproduce measurements, but only if “medium response” is included

Additional evidence for “thermal jets” or jet wake



Summary

How to characterize a new material? Excite it and see how it responds



First direct measurement of the jet wake in the Quark-Gluon Plasma

- requires statistical approach to measure low $p_{T,jet}$ /large R , where the signal lies

Extra slides

Comment on ρ and biases

$$p_{T,ch\ jet}^{reco} = p_{T,ch\ jet}^{raw} - \rho A$$

$$\rho = \text{median}_{\text{evt}} \left\{ \frac{p_{T,jet}^{raw,i}}{A_{jet}^i} \right\}$$

Definition of ρ (and similar factors) is arbitrary:

- why exclude some specific number of jets?
- why median and not some other metric?

No unique definition $\rightarrow$ not a physical quantity

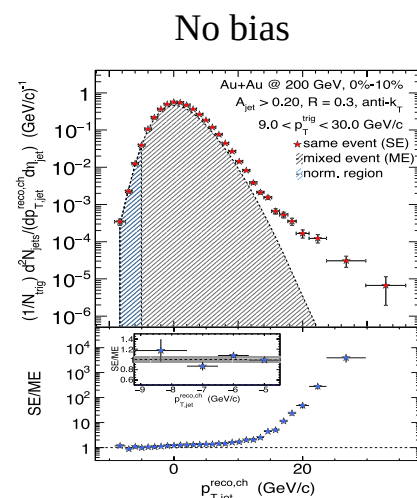
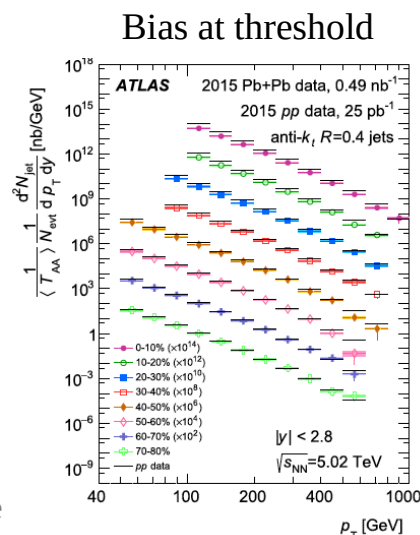
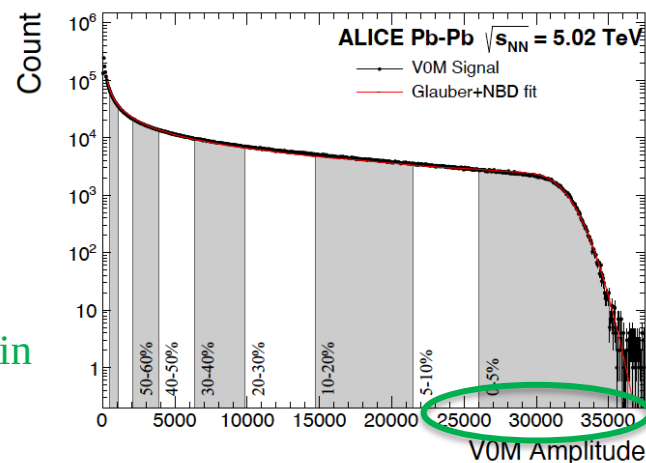
But still very useful:

- E-by-e estimate of multiplicity variation in a given centrality bin
- Reduces the challenge to the unfolding task
 $\rightarrow$ only needs to correct residual fluctuations

However: beware any cut on p_T^{reco}

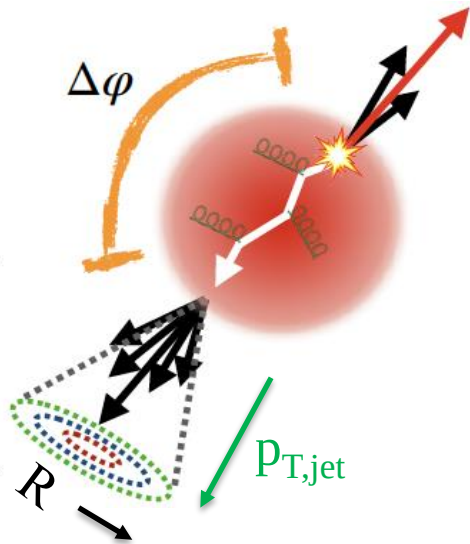
- bakes in arbitrary ρ definition
- biases the jet population near threshold
 $\rightarrow$ large effects!

Theorem: if no p_T^{reco} cut, effects of arbitrary choices in definition of ρ are precisely undone by embedding/unfolding
 $\rightarrow$ **no bias**



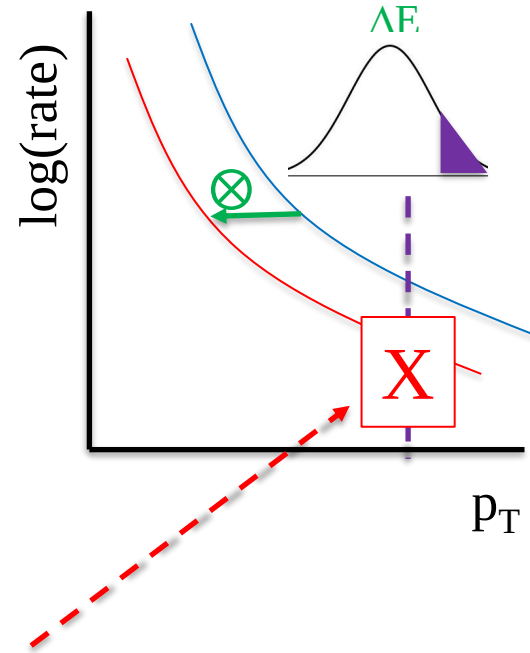
Semi-inclusive approach mitigates selection bias

Trigger: γ , π^0 , ch hadron



Recoil jet

1. Select for hard-process trigger
2. Count number of recoil jets



No requirements on p_T^{jet}

No selection bias $\rightarrow$ unbiased recoil jet distributions

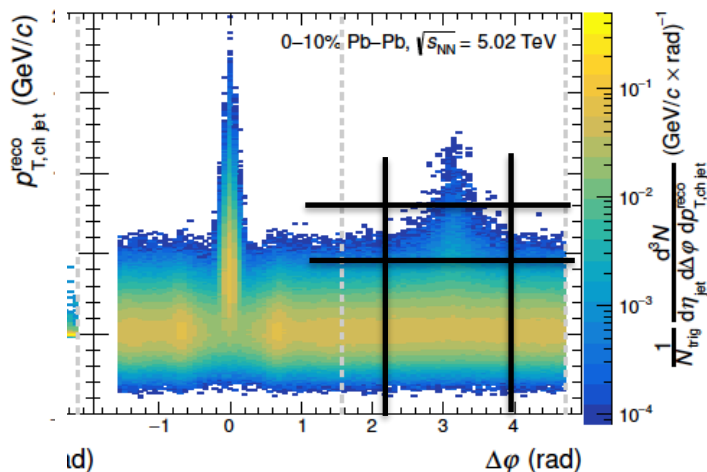
Semi-inclusive hadron+jet measurements



Phys.Rev.Lett. 133 (2024) 2 022301

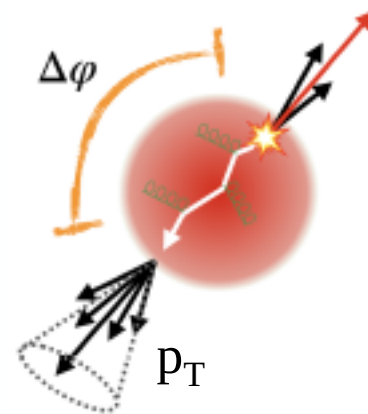
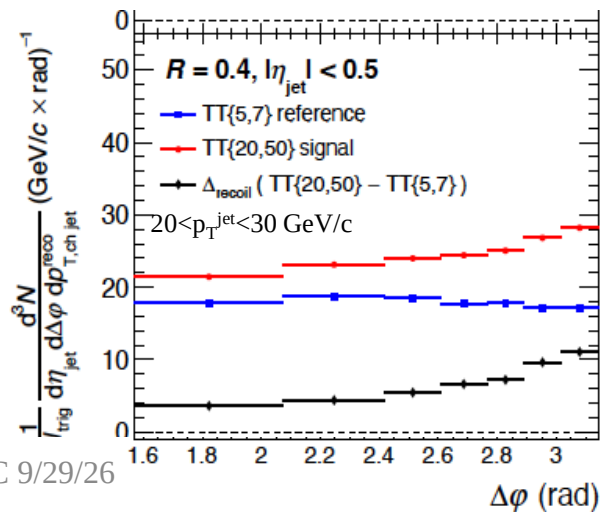
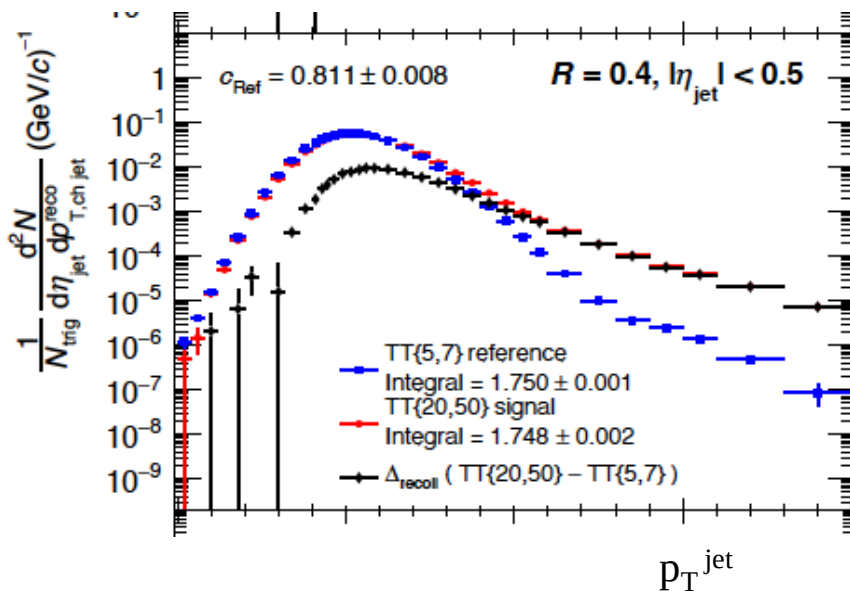
Phys.Rev.C 110 (2024) 014906

$$\frac{1}{N_{trig}} \frac{dN_{jet}}{dp_{T,jet} d\Delta\varphi} = \frac{1}{\sigma^{AA \rightarrow h+X}} \frac{d\sigma^{AA \rightarrow h+jet+X}}{dp_{T,jet} d\Delta\varphi}$$



id)

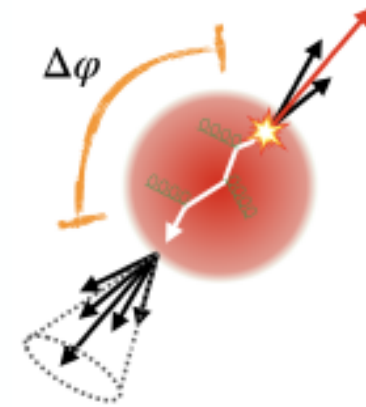
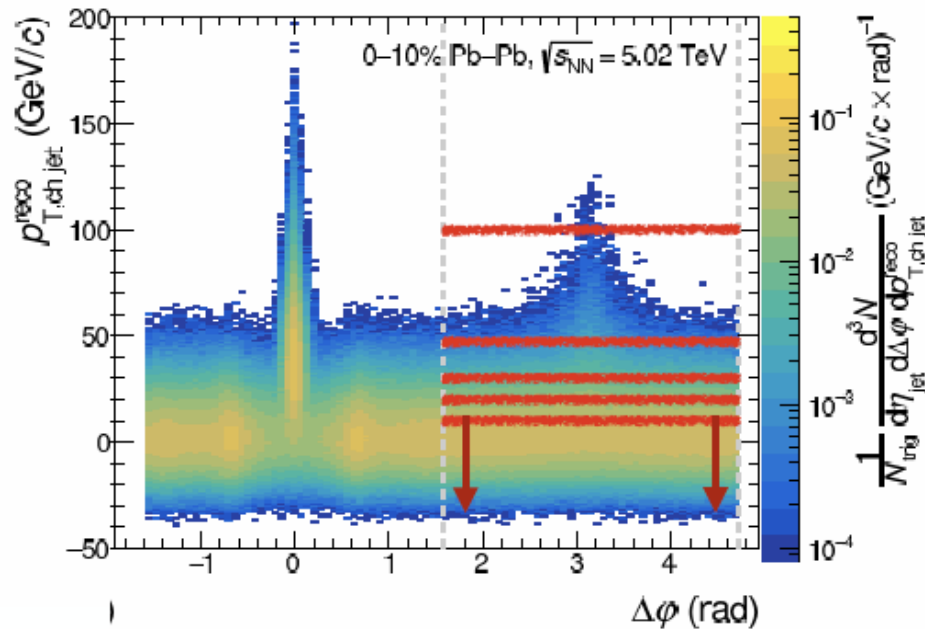
$\Delta\varphi$ (rad)



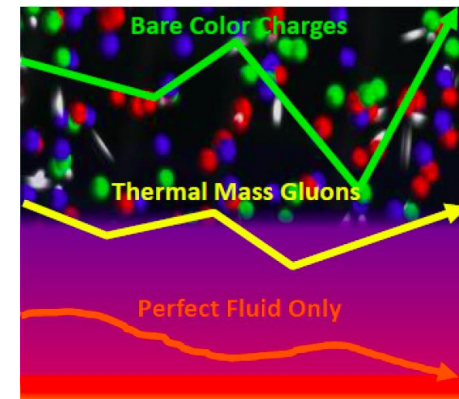
In-medium acoplanarity: what do we expect?



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

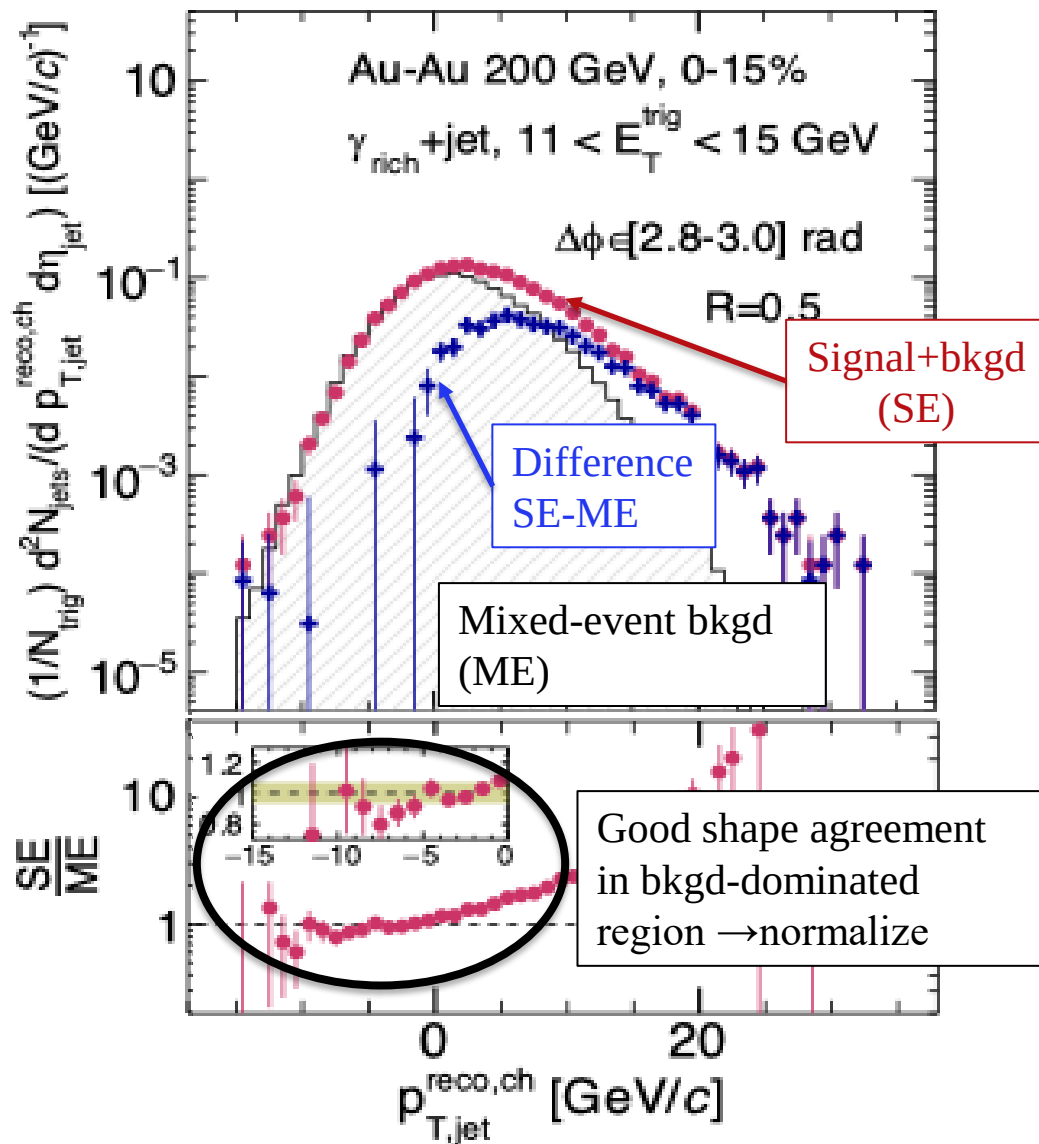


Expectation: scattering in the QGP should broaden the azimuthal acoplanarity distribution



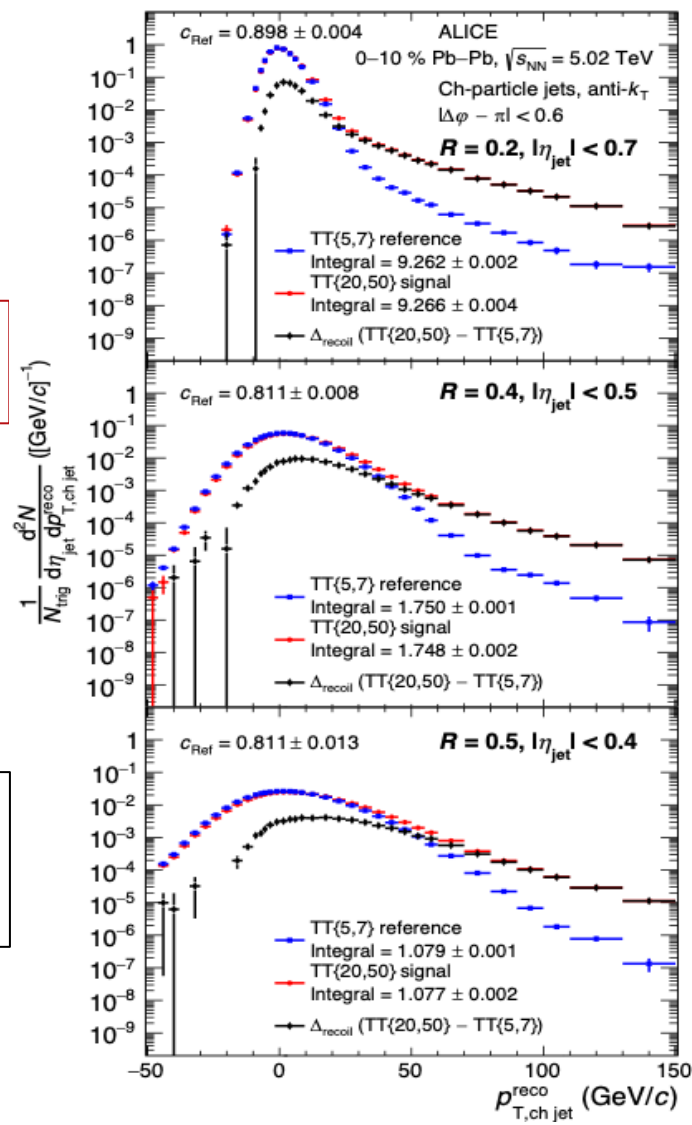
STAR: event-mixed bkgd

STAR Phys.Rev.C 111 (2025) 6, 064907

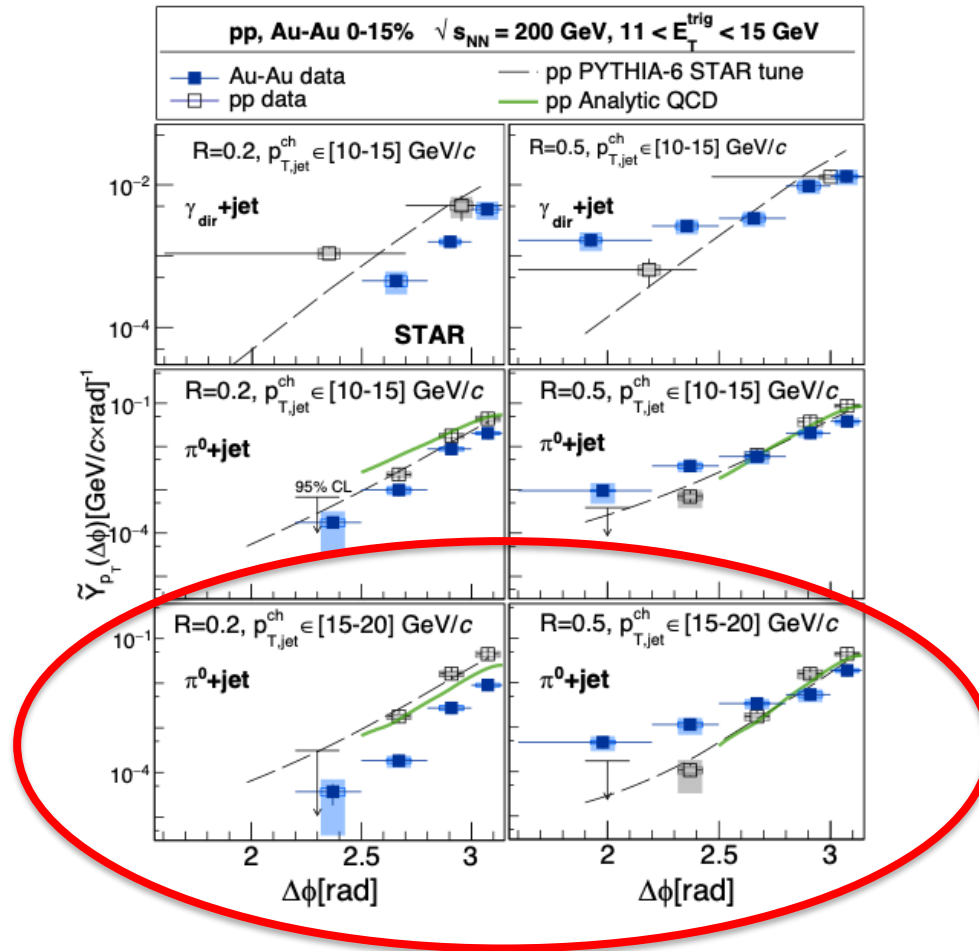


ALICE: trigger-difference bkgd

ALICE Phys.Rev.C 110 (2024) 1, 014906



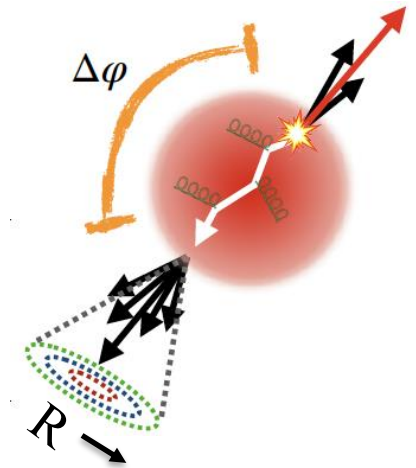
Acoplanarity: γ/π^0 +jet in central Au+Au @ RHIC



Phys.Rev.Lett. 134 (2025) 232301

Phys.Rev.C 111 (2025) 064907

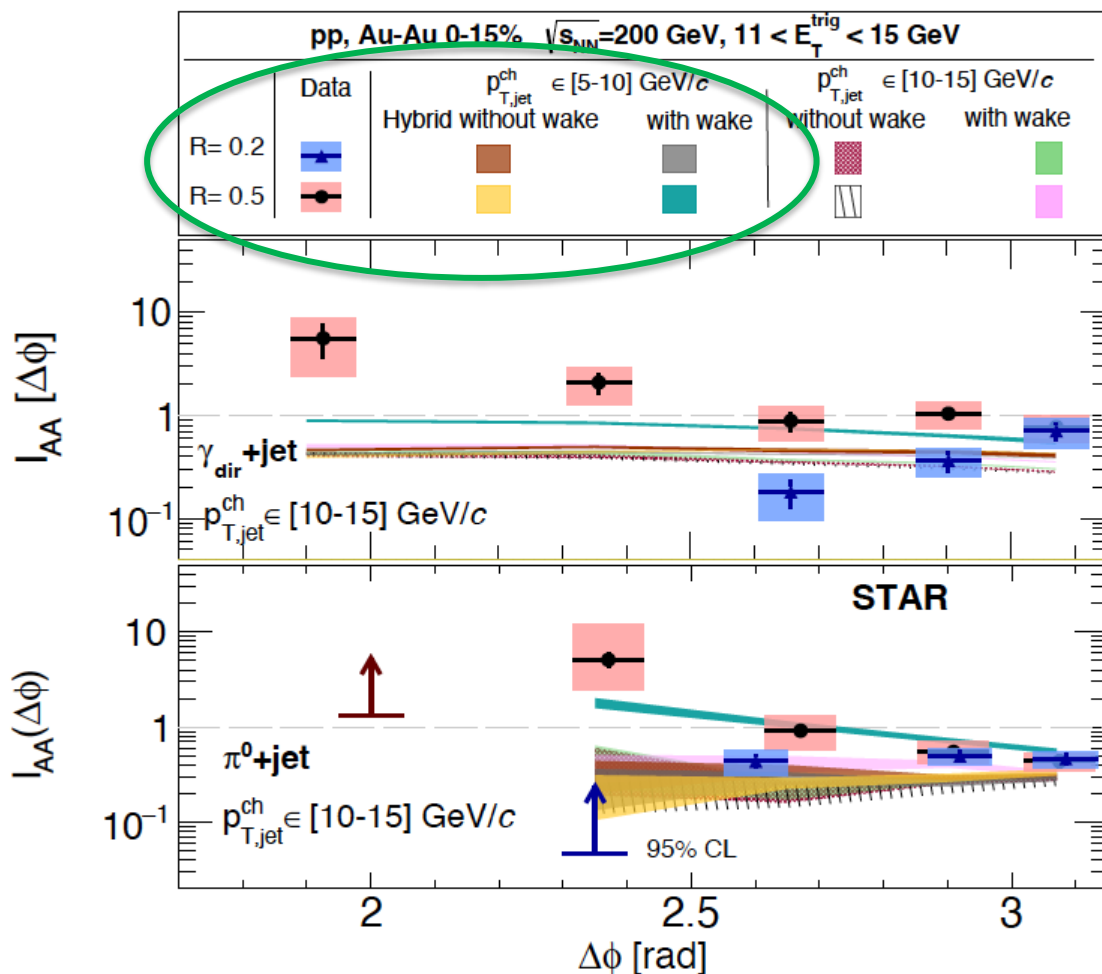
Phys.Rev.C 113 (2026) 014902



Large medium-induced azimuthal broadening
Only for large-aperture recoil jets at low p_T^{jet}

Hybrid model predictions

Appendix of STAR paper:
Phys.Rev.C 113 (2026) 014902



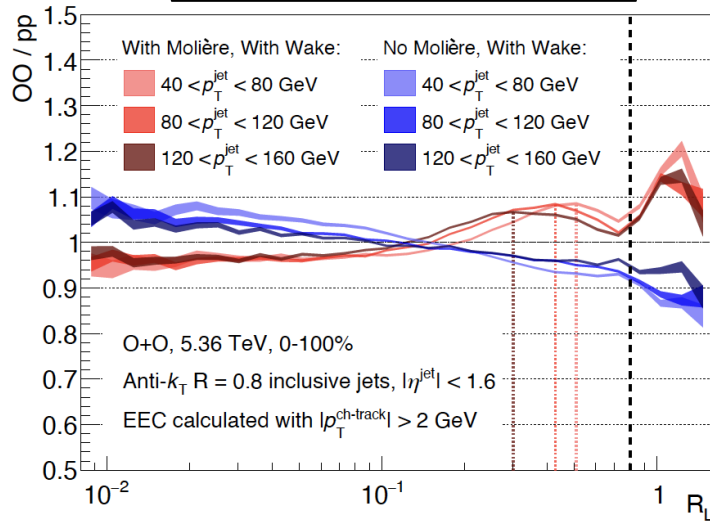
Qualitatively: predicts the large-R enhancement seen in data but only with wake switched on

Quantitatively: only for lower $p_{T,jet}$, smaller effects than in data

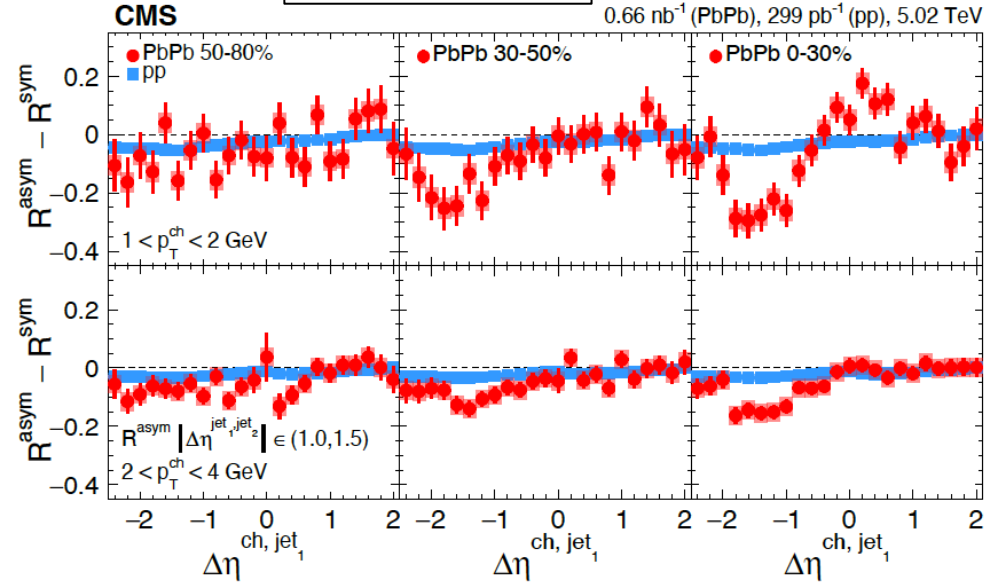
Effect is present, model needs tuning

Outlook

Kudinoor et al., 2603.23596



CMS 2602.19431



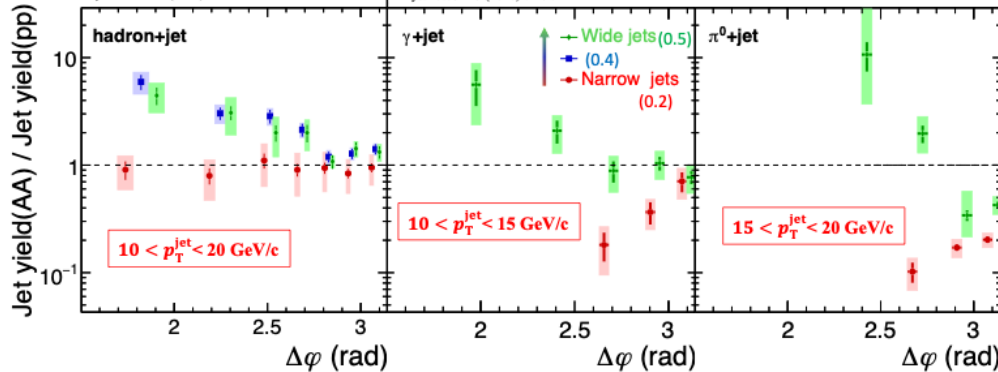
0-10% Pb-Pb, $\sqrt{s_{NN}} = 5.02$ TeV
 $20 < p_T^{\text{trig}} < 50$ GeV/c



0-15% Au-Au, $\sqrt{s_{NN}} = 200$ GeV
 $11 < E_T^{\text{trig}} < 15$ GeV

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 Phys.Rev.C 113 (2026) 014902



We now have the tools to disentangle QGP responses to jet excitation:

- primary wake
- diffusion wake
- Molière scattering