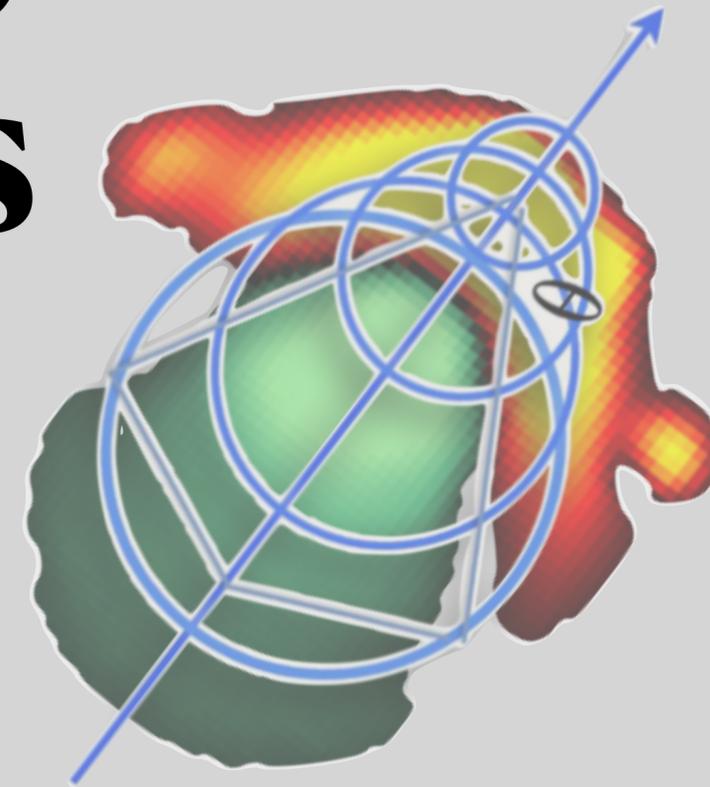# Theoretical overview of jets in heavy-ion collisions
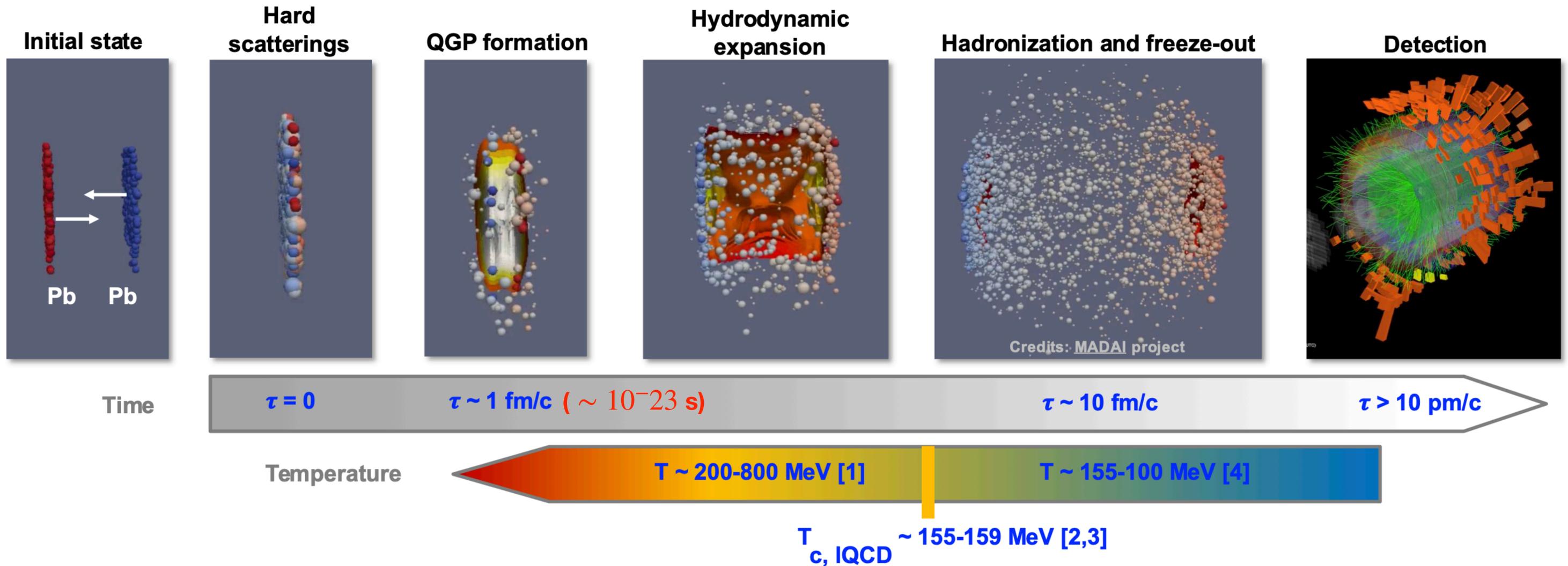
Zhong Yang

Vanderbilt University

01/23/2026~01/26/2026, JAQ, Wuhan

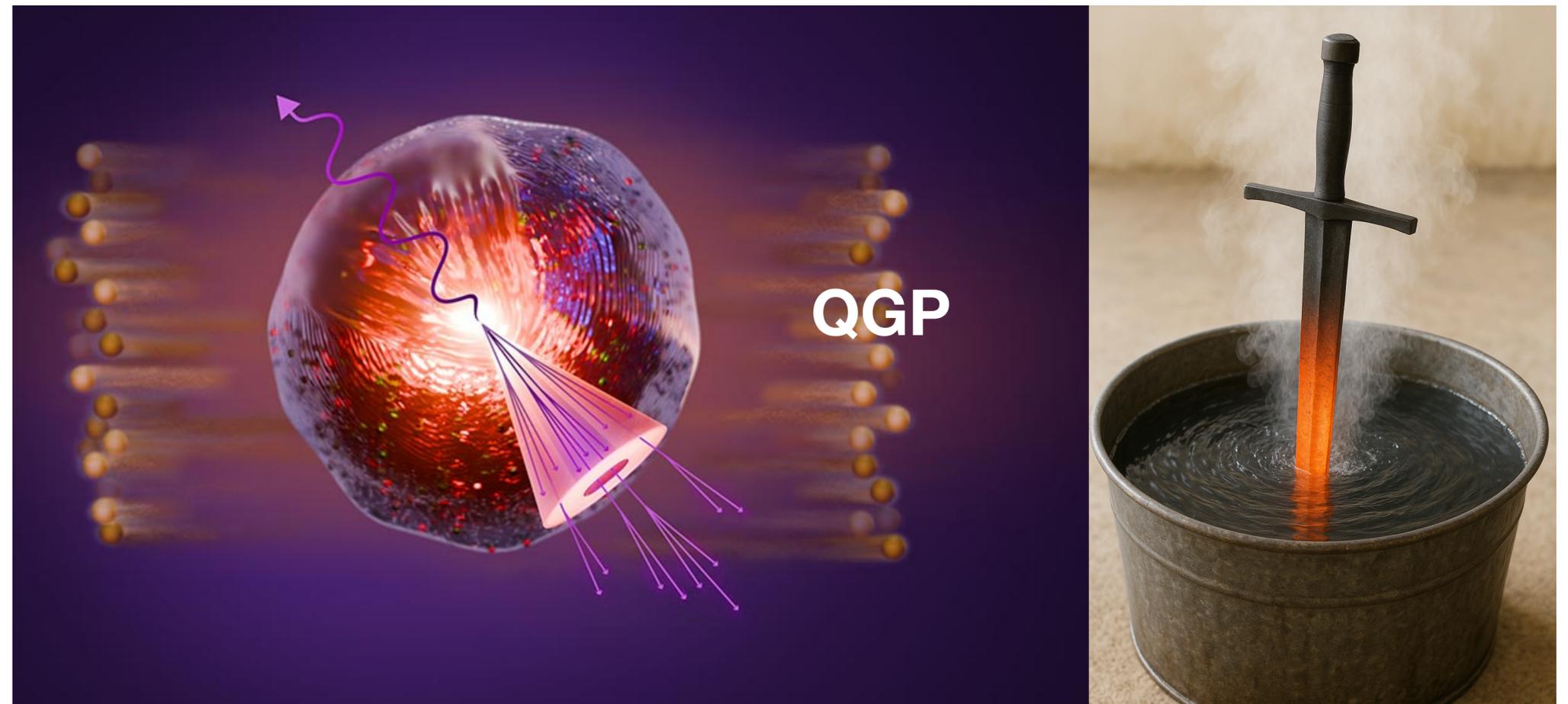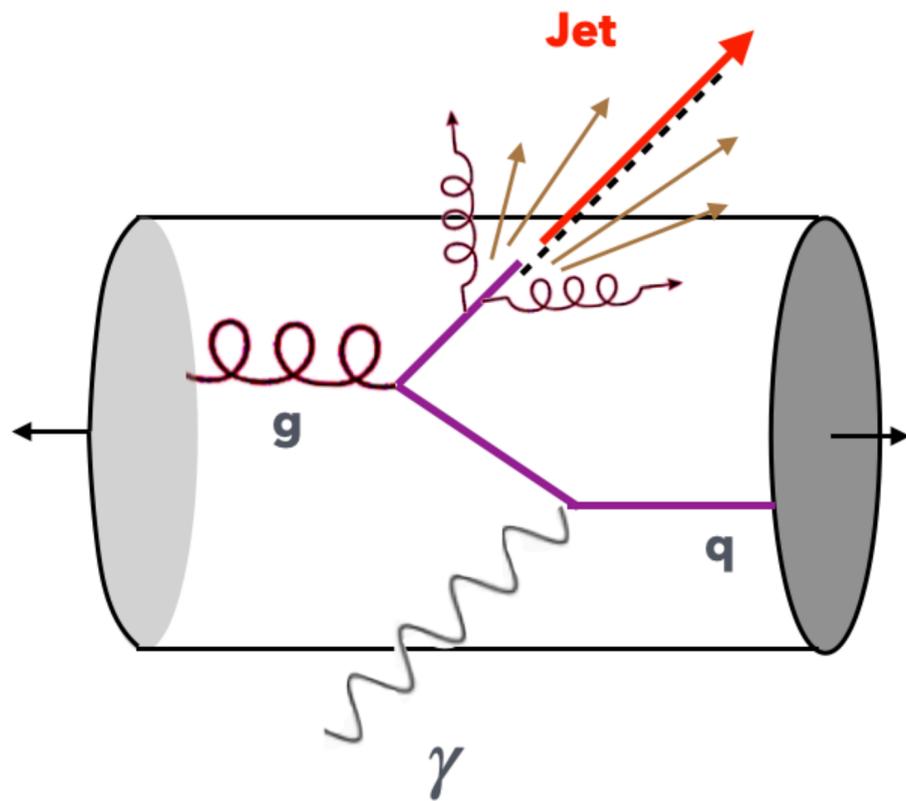# High-energy heavy-ion collisions

Ralf Averbeck, Quark Matter 2025

Initial state | **Hard scatterings** | **QGP formation** | **Hydrodynamic expansion** | **Hadronization and freeze-out** | **Detection**

Pb   Pb

Credits: MADAI project

Time $\tau = 0$ $\tau \sim 1$ fm/c ($\sim 10^{-23}$ s) $\tau \sim 10$ fm/c $\tau > 10$ pm/c

Temperature   T ~ 200-800 MeV [1]   T ~ 155-100 MeV [4]

$T_{c, lQCD}$ ~ 155-159 MeV [2,3]

Jet quenching

Jet is a cluster of energetic particles moving in the similar direction.

QGP

$$d\sigma_{\text{jet}} = \sum_{a,b,j,d} f_{a/p} \otimes f_{b/p} \otimes d\sigma_{ab \to jd} \otimes J_j$$

Jet quenching: jet energy loss due to interaction between jet and QGP.

Jet quenching

The observation of hadron RAA indicates the formation of quark-gluon plasma at high-energy heavy-ion collisions.[Phys. Rev. Lett., 2002, 88: 022301, Phys. Rev. Lett., 2002, 89: 202301,Phys.Lett.B 849 (2024) 138412, Phys.Lett.B 790 (2019) 108-128, JHEP 04 (2017) 039]

$$R_{AA} = \frac{dN_{AA}/dp_T}{\langle N_{\text{coll}} \rangle \, dN_{pp}/dp_T}$$
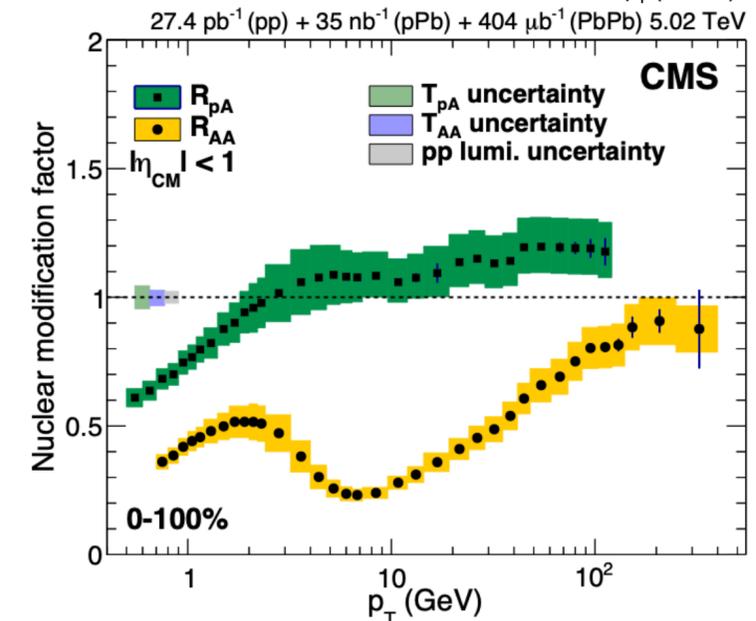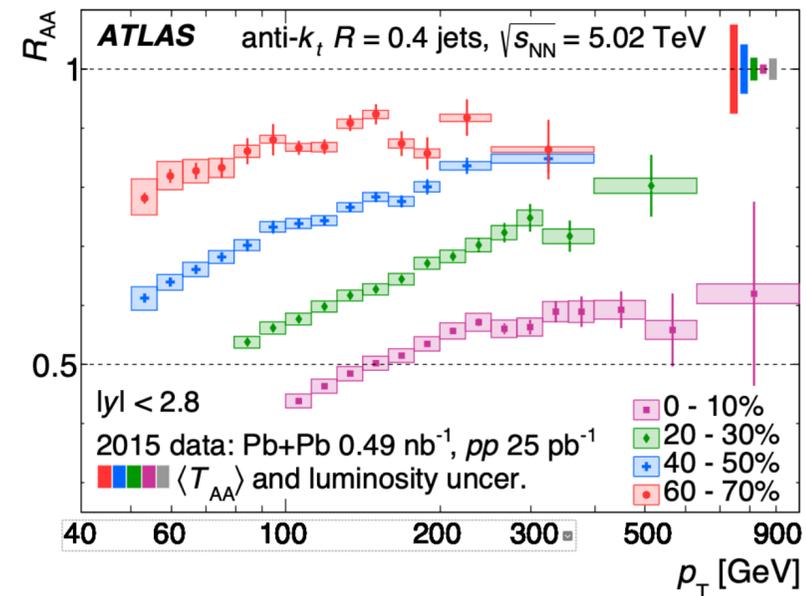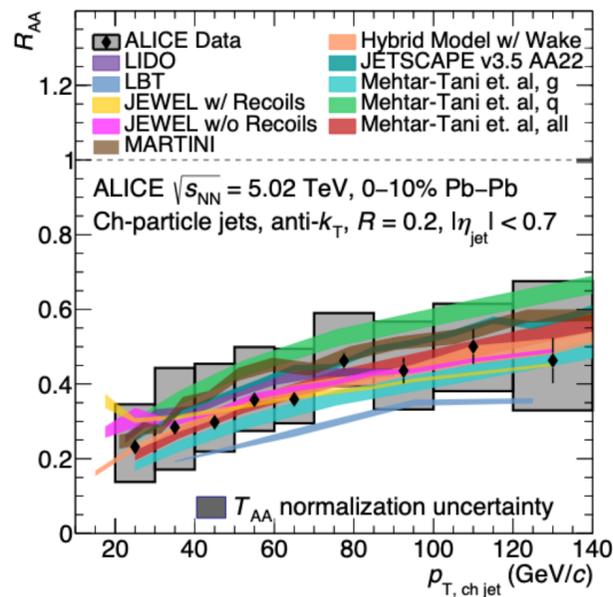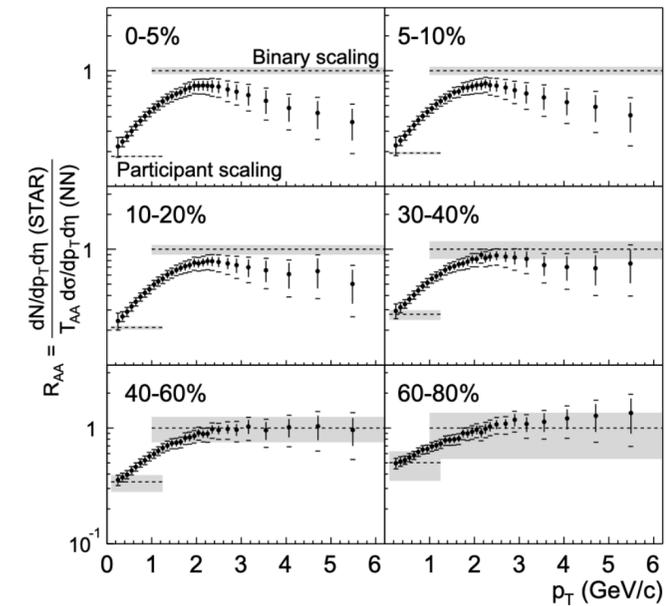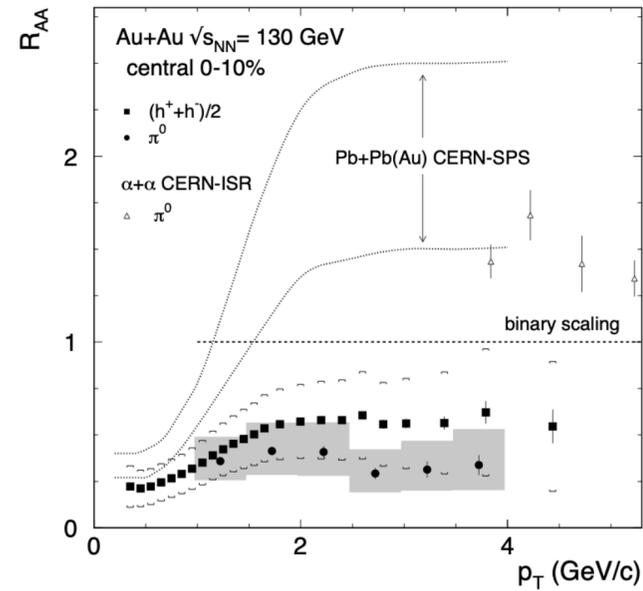
Jet-induced medium response
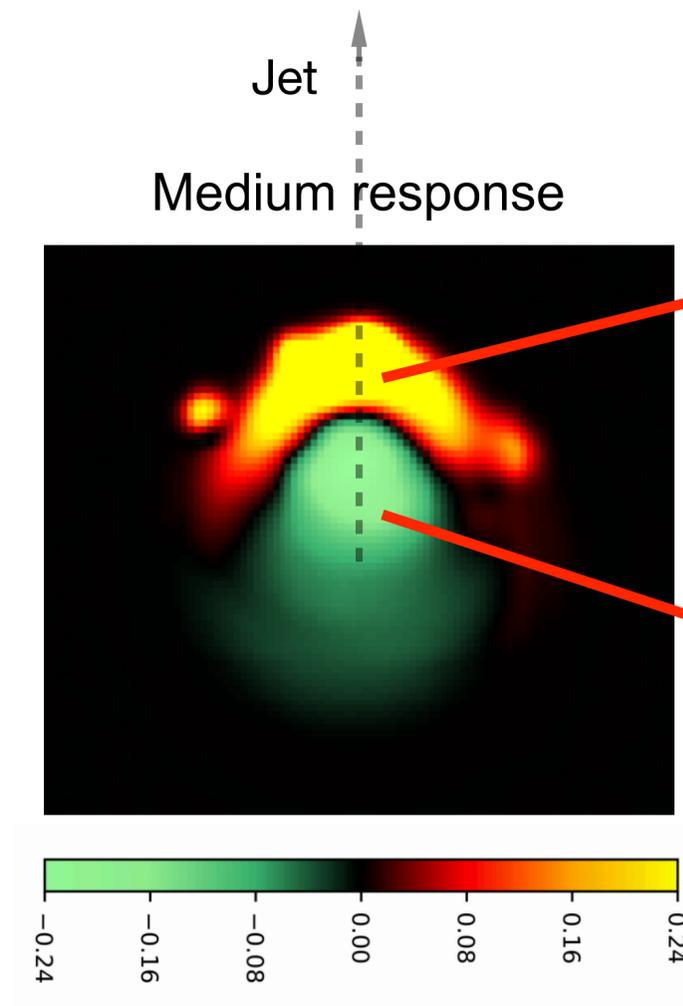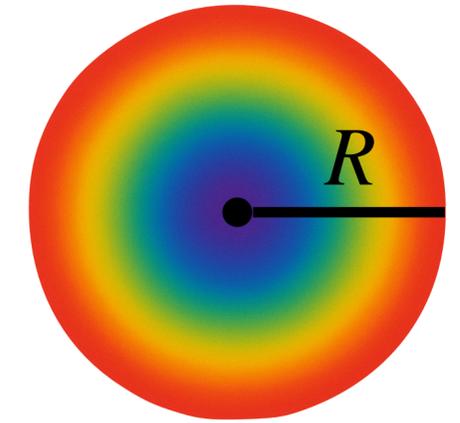
Jet-induced medium response in the form of Mach-cone-like excitation.[Casalderrey-Solana, Shuryak, Teaney, 2005; Ruppert, Muller, 2005; Gubser, Pufu, 2008; Qin, Majumder, Song, Heinz, 2009; Yan, Jean, Gale, 2017; …]

Jet direction

c_s

v

$v < c_s$ $v = c_s$ $v > c_s$
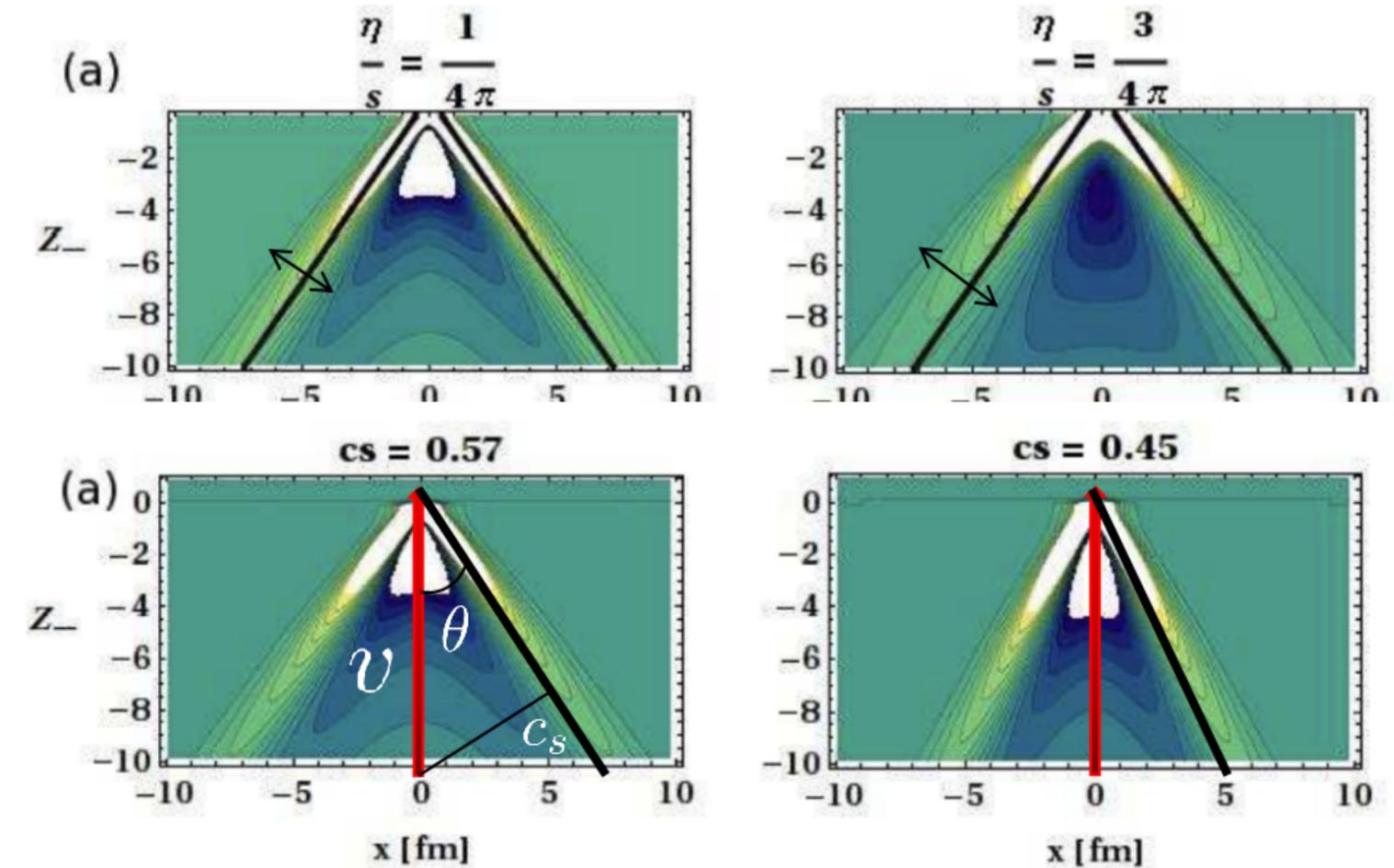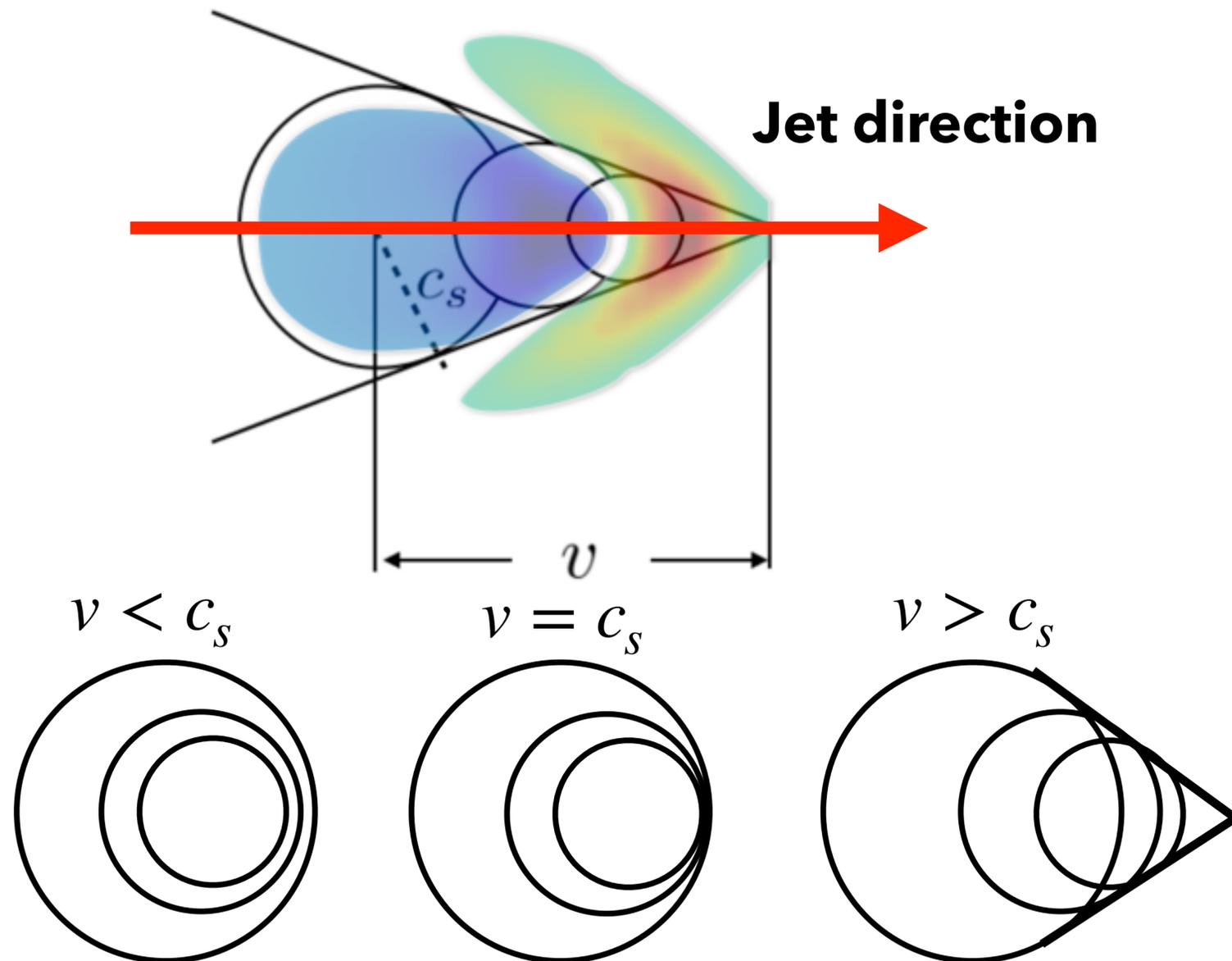
Phys.Rev.C 78 (2008) 041901

Jet-induced Mach-cone could extract the QGP properties

How to measure medium response

Jet

Medium response

Positive: wake front (along jet direction)

Leading to **enhancement** of soft hadrons at large angle inside jet

Negative: diffusion wake (against jet direction)

Leading to **depletion** of soft hadrons in opposite direction of jet

R

Enhancement of soft hadrons modifies jet substructure, highlighting the important role of medium response in heavy-ion collisions.

p+p

Pb+Pb

Phys.Lett.B 801 (2020) 135181

Phys.Lett.B 810 (2020) 135783
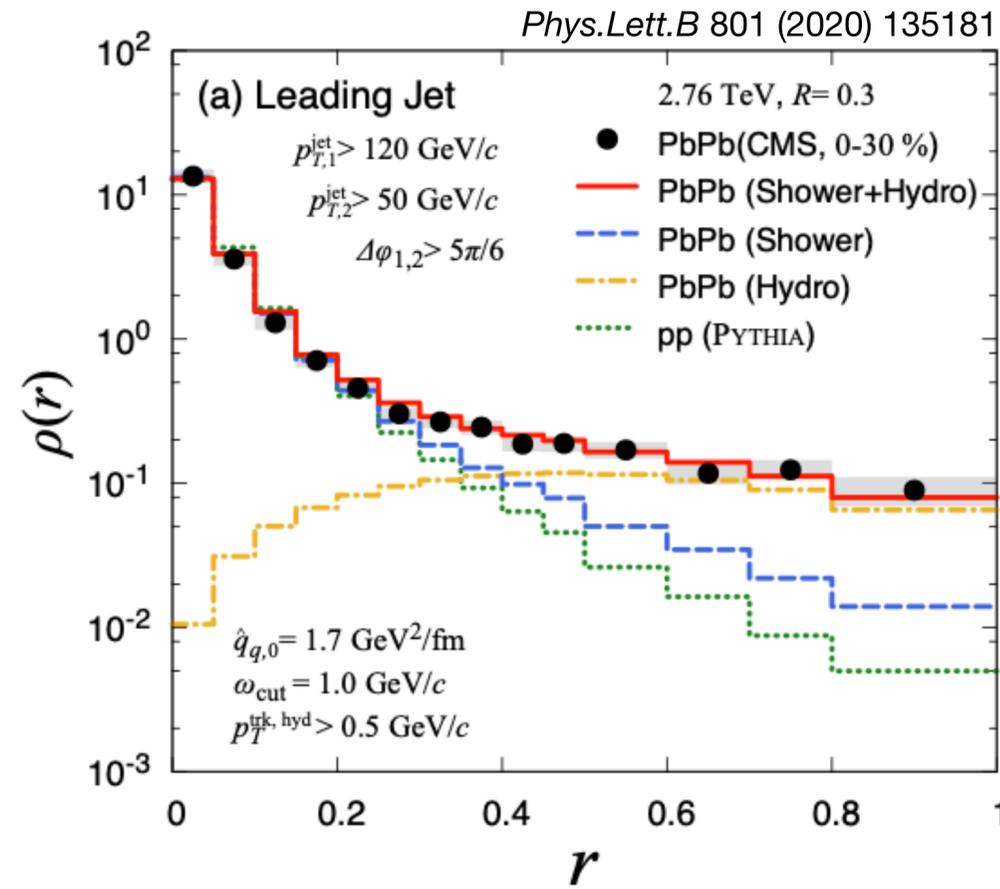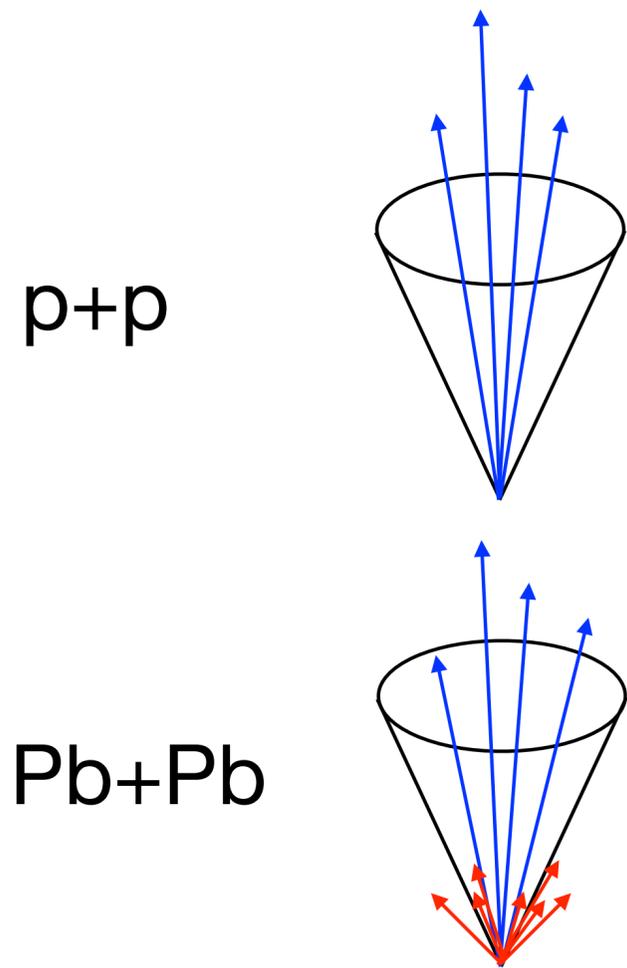
$$r = \sqrt{(\phi_h - \phi_{jet})^2 + (\eta_h - \eta_{jet})^2}$$
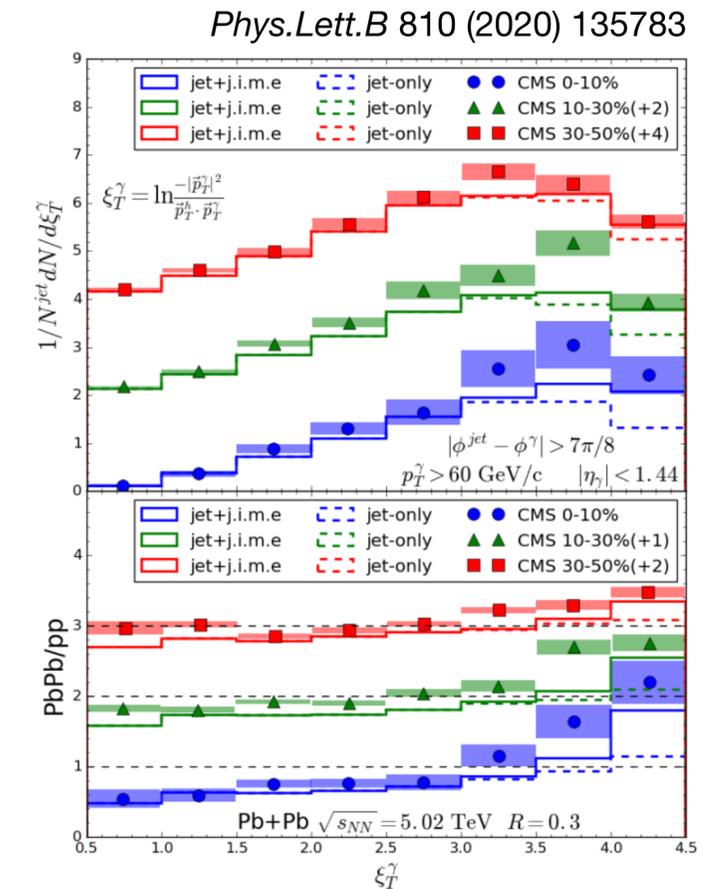
$$\xi_T^\gamma = \frac{-p_T^{\gamma 2}}{\vec{p}_T^\gamma \vec{p}_T^h}$$

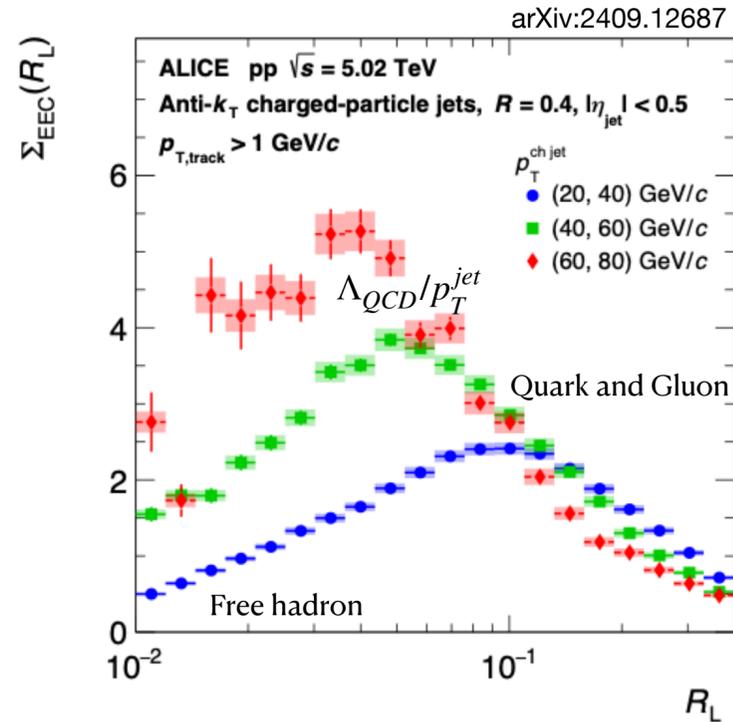Enhancement of energy-momentum at large angle inside jet, can be used to understand the enhancement of low-pt large radius jet in heavy-ion collisions.

arXiv:2512.12715
Phys.Rev.Lett. 133 (2024) 2, 022301

p+p

Pb+Pb
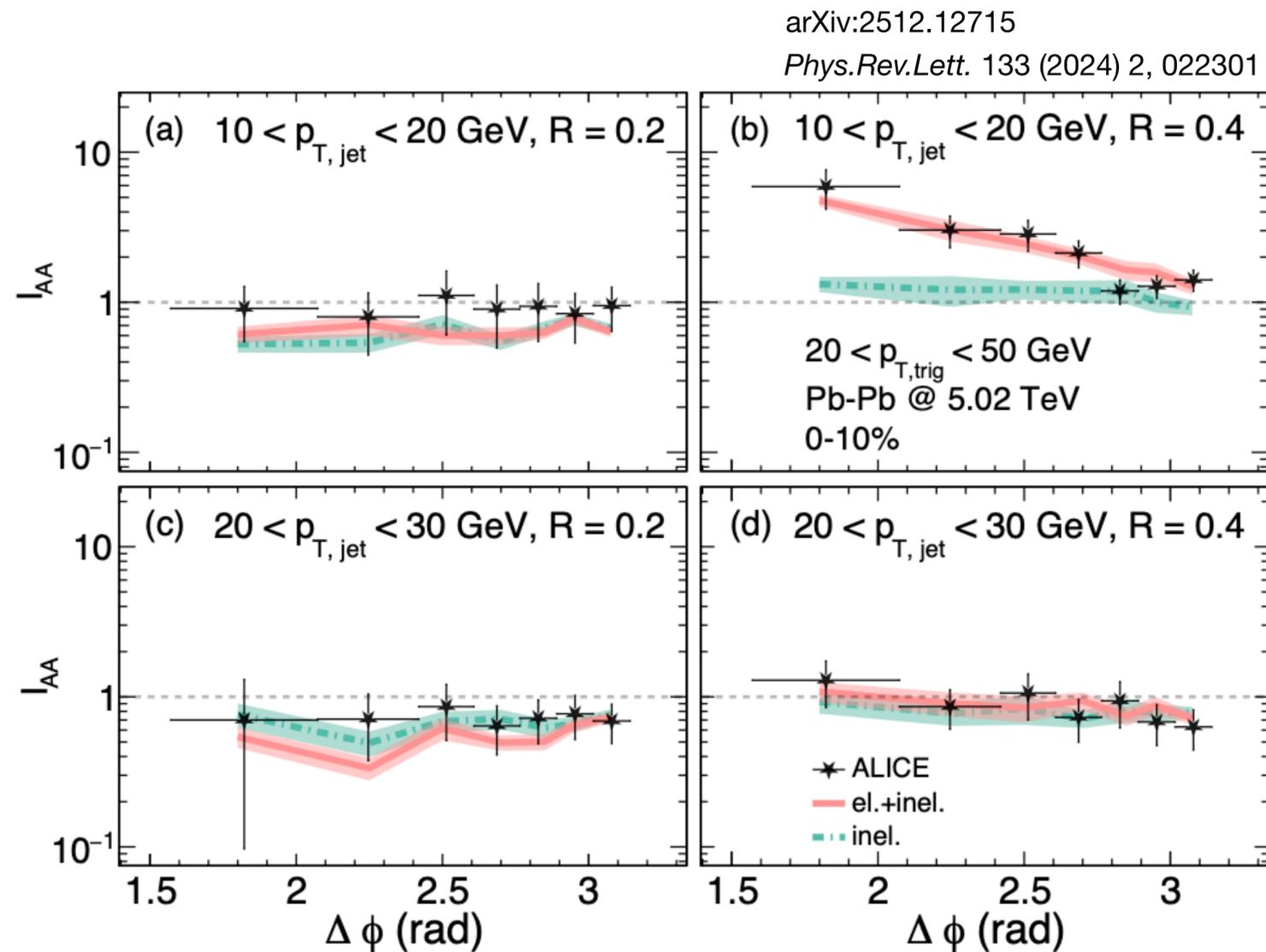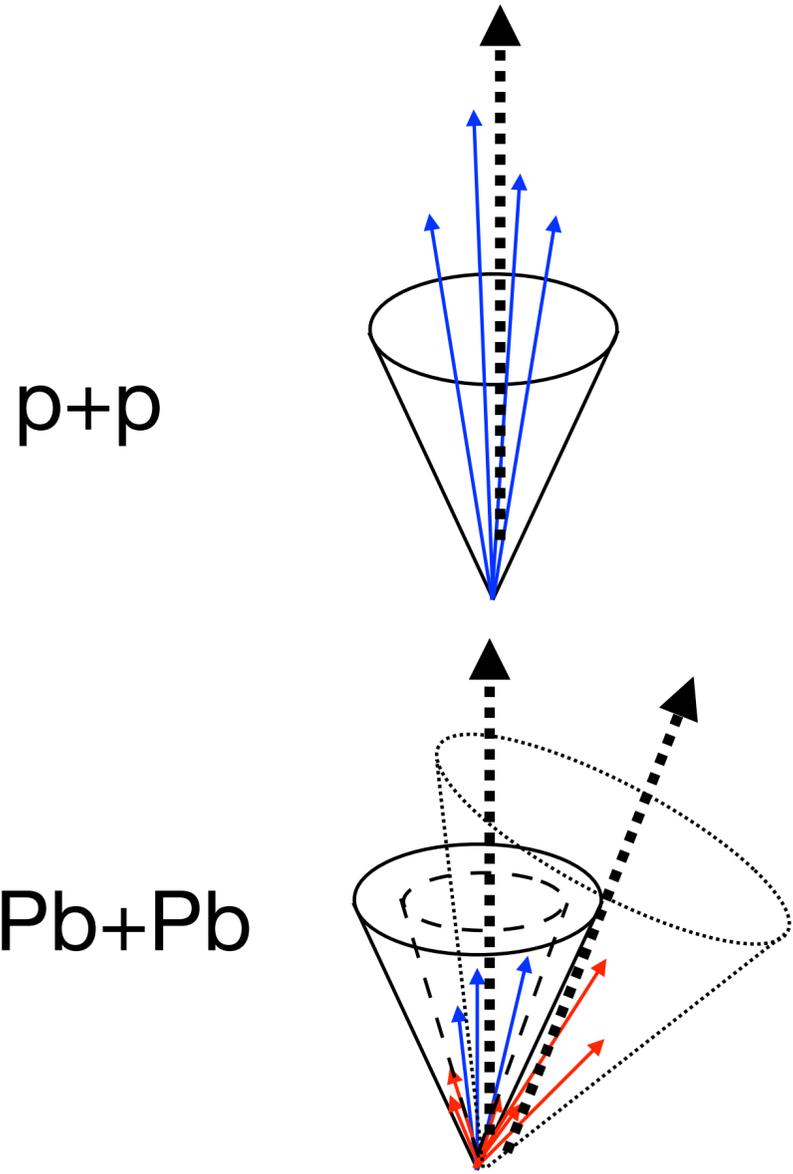
$$\Delta\phi = \phi_{\text{jet}} - \phi_{trigger,h}$$

Yi-Chao Dang
16:30, Sat

arXiv:2409.12687

ALICE   pp   √s = 5.02 TeV
Anti-k_T charged-particle jets, $R = 0.4$, $|\eta_{jet}| < 0.5$
$p_{T,track} > 1$ GeV/c

$p_T^{ch\ jet}$
● (20, 40) GeV/c
■ (40, 60) GeV/c
◆ (60, 80) GeV/c

Λ_{QCD}/p_T^{jet}

Quark and Gluon

Free hadron

$\Sigma_{EEC}(R_L)$

R_L

1.70 nb⁻¹ PbPb (5.02 TeV) + 302 pb⁻¹ pp (5.02 TeV)

CMS *Preliminary*   120 < jet p_T < 140 GeV
anti-k_T R = 0.4
$|\eta_{jet}| < 1.6$
$p_T^{ch} > 1$ GeV, n=1

$\frac{PbPb}{pp}$

■ PbPb 0-10%
PbPb 10-30%
PbPb 30-50%
PbPb 50-90%

CMS-PAS-HIN-23-004

Δr arXiv:2503.19993

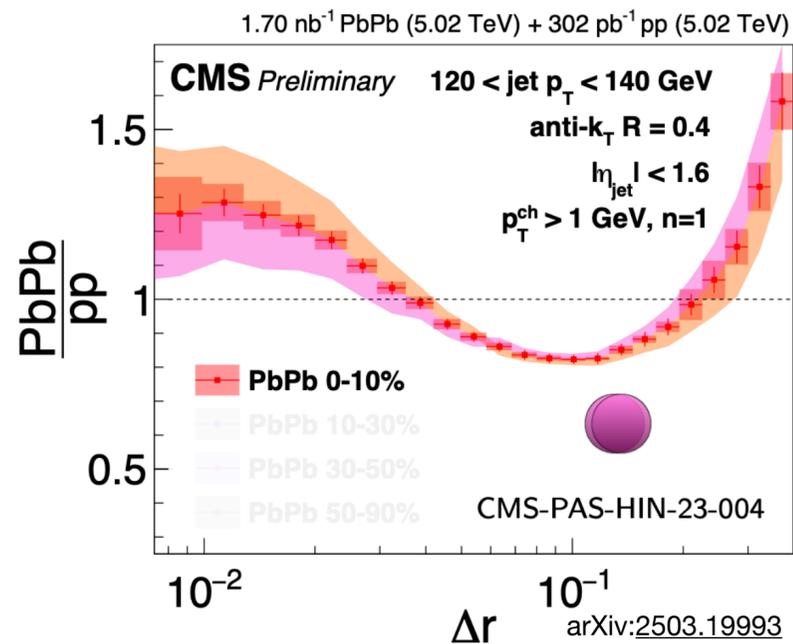$$\mathrm{EEC}(\Delta r) = \frac{1}{W_{pairs}} \frac{1}{\delta r} \sum_{jets \in [p_{T,1}, p_{T,2}]} \sum_{pairs \in [\Delta r_a, \Delta r_b]} (p_{T,i}\, p_{T,j})^n$$

In vacuum, the EEC presents a clear separation between the perturbative and non-perturbative regions.

In heavy-ion collisions, the medium effect has clear modifications on EEC distribution at both small and large angles.

Small angle: pT selection bias, q/g jet fraction, parton shower algorithm, …
[*Phys.Rev.Lett.* 134 (2025) 8, 082303, *Phys.Rev.D* 112 (2025) 5, 054018, …]

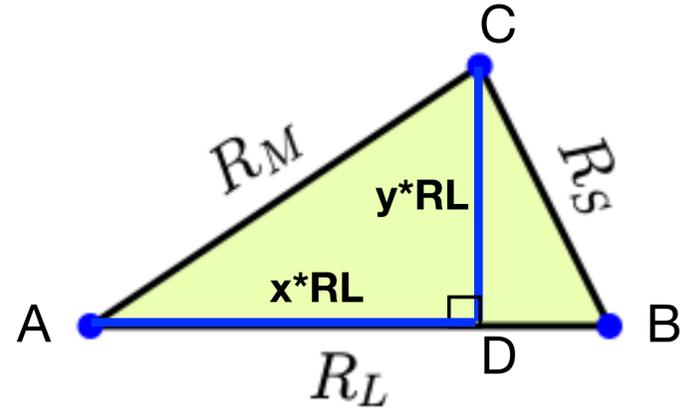Large angle: medium response, medium-induced gluon radiation.
[*Phys.Rev.Lett.* 130 (2023) 26, 262301, *Phys.Rev.Lett.* 132 (2024) 1, 1, …]

Medium effect on EEC has also been discussed in heavy-flavor jets and in small system.[*Phys.Rev.Lett.* 134 (2025) 5, 052301, *Phys.Rev.Lett.* 135 (2025) 3, 032301]
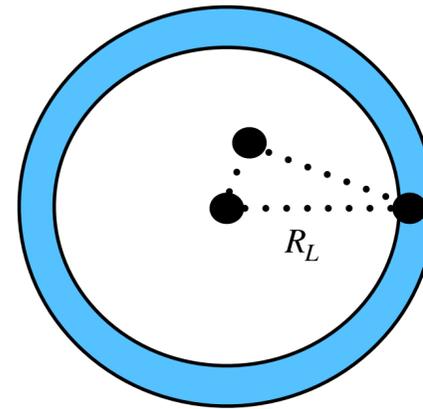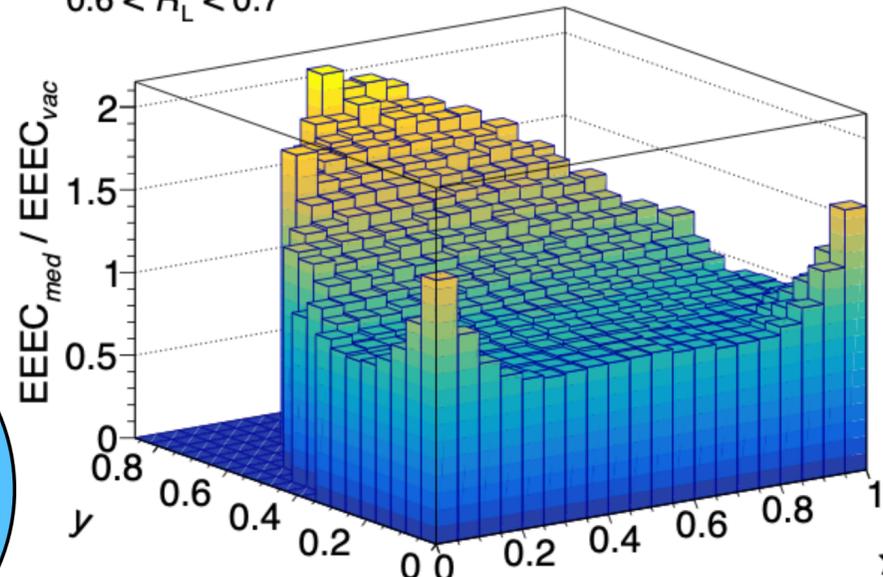
Wen-Jing Xing
09:00, Sun

E3C

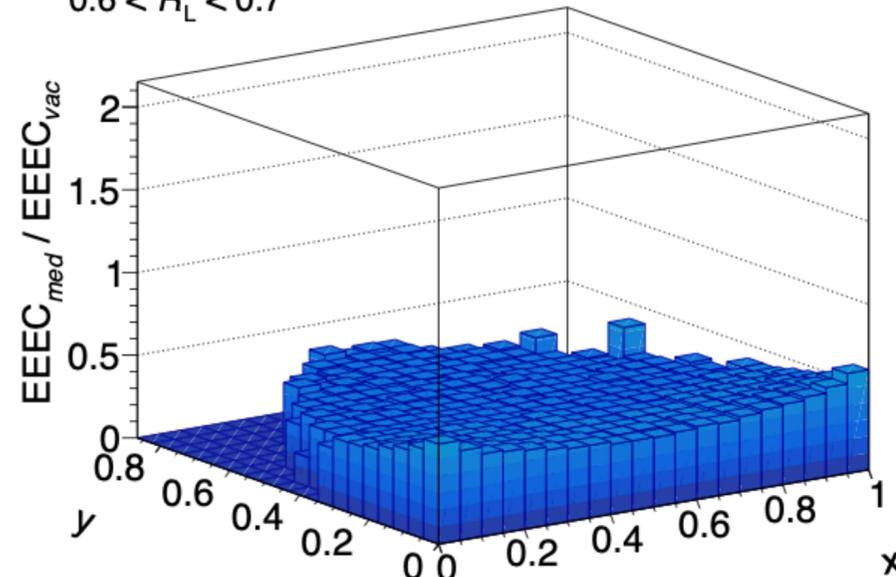$$x = \frac{L_{AD}}{L_{AB}} \qquad y = \frac{L_{CD}}{L_{AB}}$$

Requiring a large R_L enhances the contribution from the medium response

Wake = ON
$0.6 < R_L < 0.7$

$140 \text{ GeV}/c < p_{T,jet} < 240 \text{ GeV}/c$

Wake = OFF
$0.6 < R_L < 0.7$

$140 \text{ GeV}/c < p_{T,jet} < 240 \text{ GeV}/c$

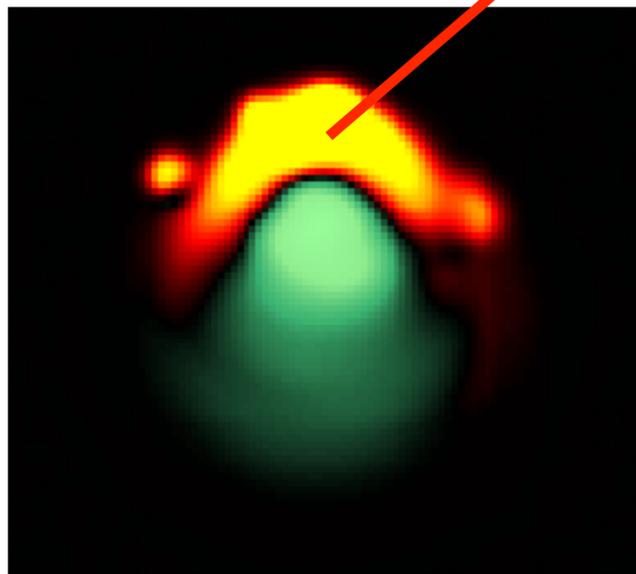**2D distribution of E3C shows strong sensitivity to medium modification, providing a novel method to probe jet wake.**

JHEP 12 (2024) 073

(a)

(b)

Effect of medium-induced gluon radiation

Positive: wake front (along jet direction)

Leading to **enhancement** of soft hadrons at large angle inside jet

full hydrodynamic response

Medium response: $\delta f(p) \sim e^{-p \cdot u/T}$

Medium induced gluon radiations: $\omega \approx \lambda^2 \hat{q}/2 \sim T$

Formation time: $\tau_f = \dfrac{2\omega}{k_T^2}$ $\quad k_T^2 = \hat{q}\tau_f \quad \tau_f \approx \sqrt{2\omega/\hat{q}}$

Mean-free-path limits the formation time: $\tau_f \leq \lambda \sim 1/T \qquad \hat{q} \sim T^3$
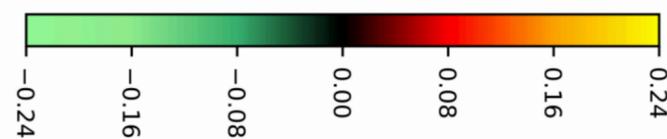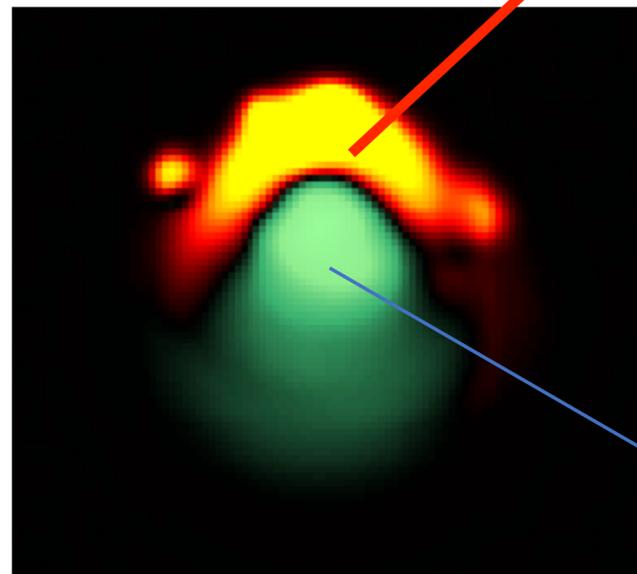
Medium-induced gluon radiation has the similar effect.

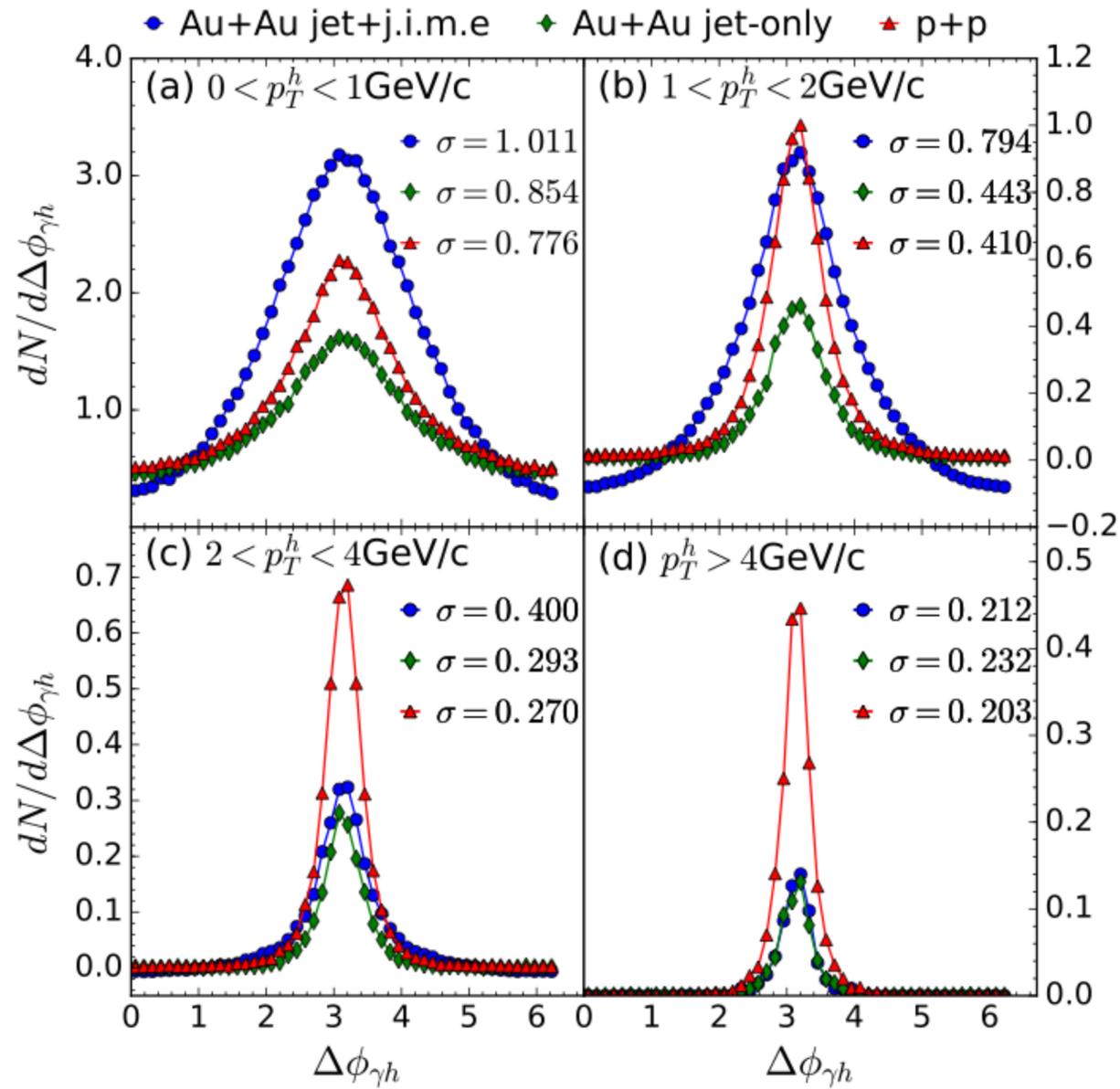# Jet-induced diffusion wake

full hydrodynamic response

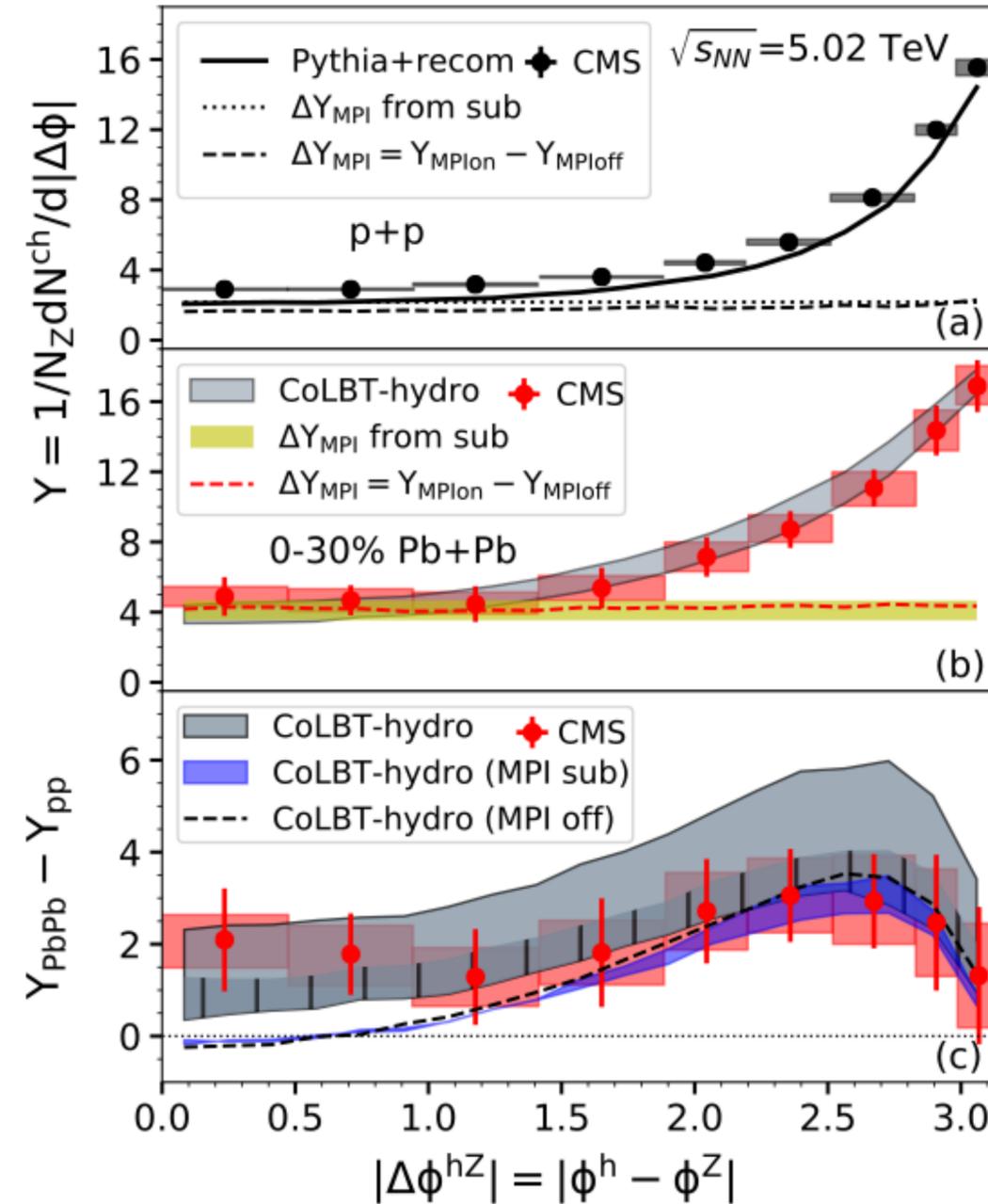**Negative: diffusion wake (against jet direction)**

Leading to **depletion** of soft hadrons in opposite direction of jet

Effect is unique

Diffusion wake: depletion of soft hadrons

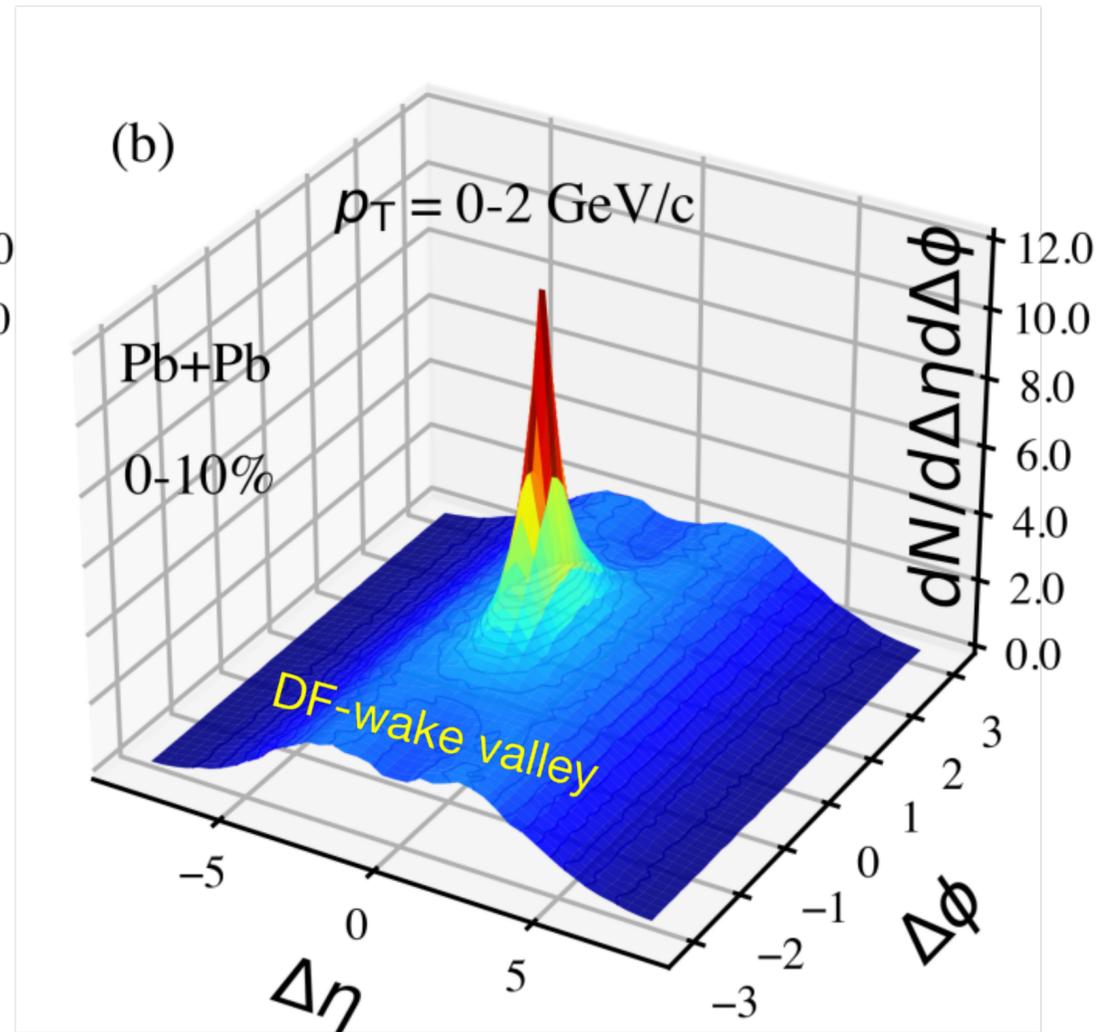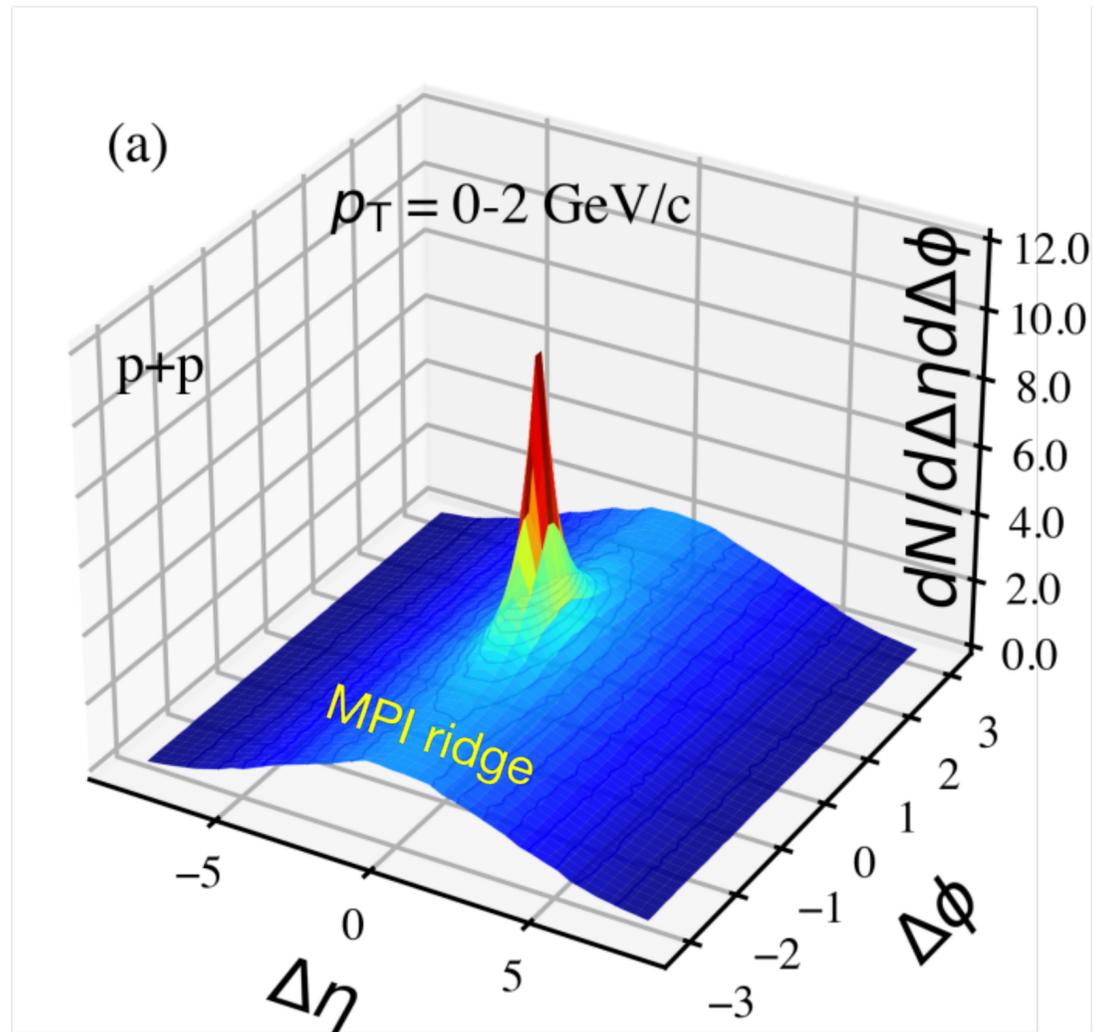PLB 777 (2018) 86–90

Initial multiple-parton interactions (MPI)

Diffusion wake: depletion of soft hadrons

γ-jet

$$\Delta\eta = \eta_h - \eta_{\text{jet}}$$

$$\Delta\phi = \phi_h - \phi_{\text{jet}}$$

Phys.Rev.Lett. 130 (2023) 5, 052301

Diffusion wake valley(DF-wake valley):a valley is formed on top of the MPI ridge due to the depletion of soft hadrons by jet-induced diffusion wake.

We project the two-dimensional distribution onto the rapidity direction.

We get the double peak structure of rapidity correlation
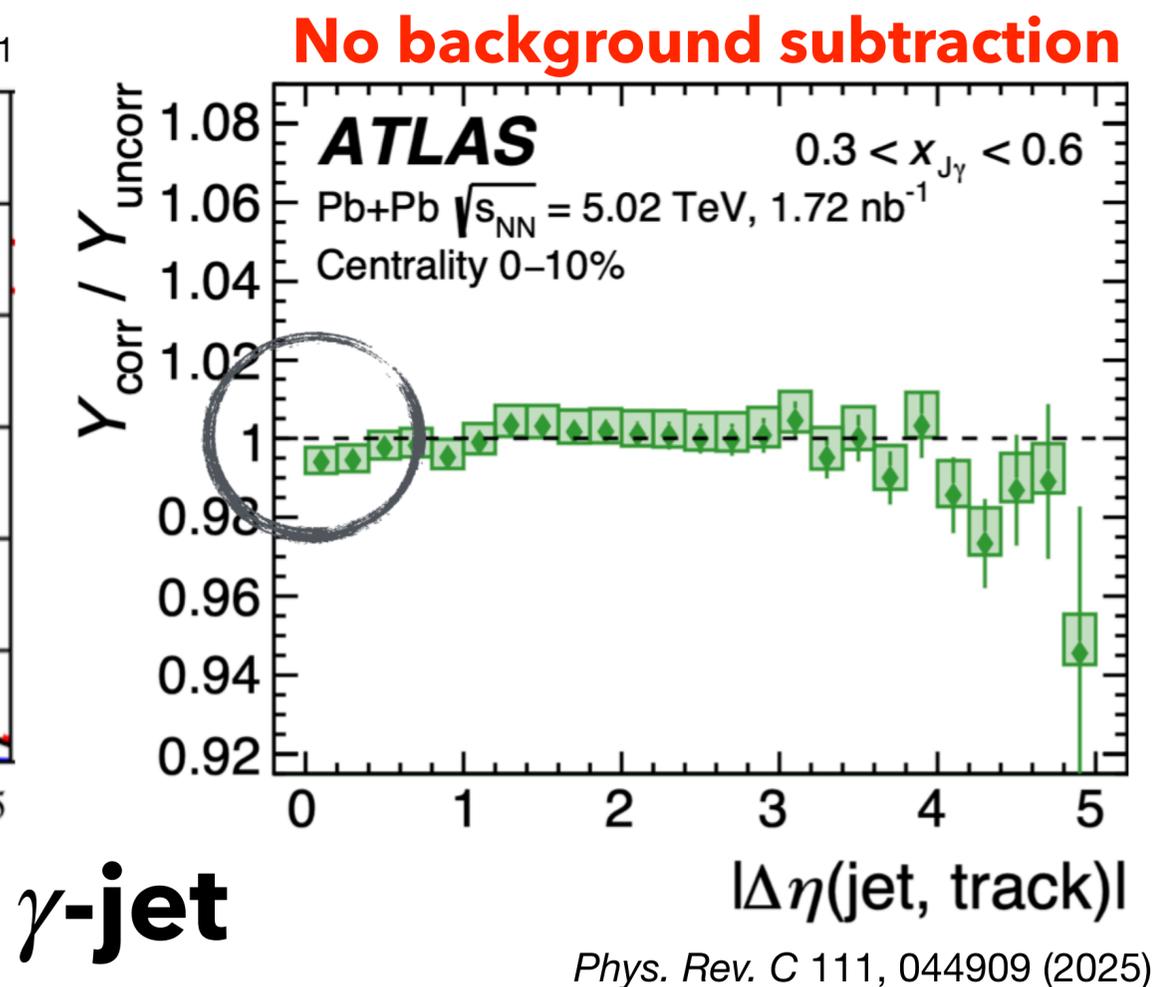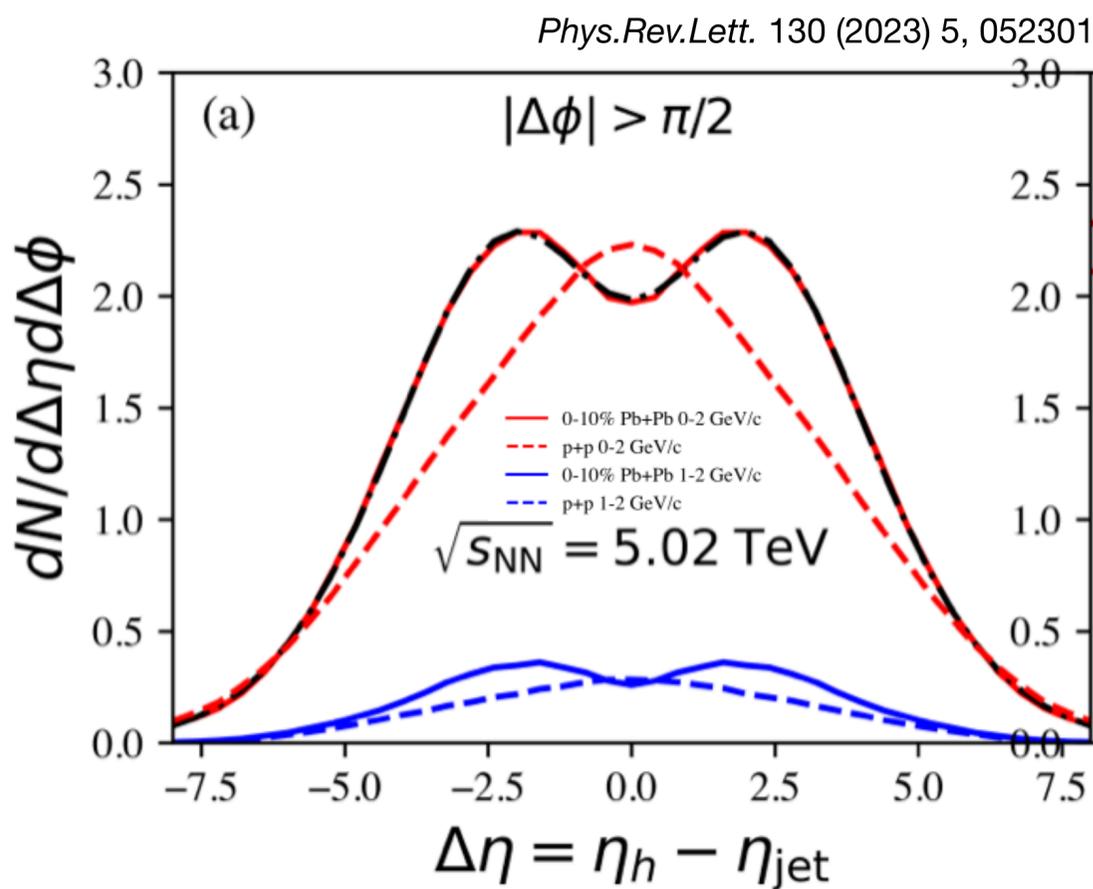
Mixed-event subtraction

Phys.Rev.Lett. 130 (2023) 5, 052301

No background subtraction

arXiv:2507.09307

Phys. Rev. C 111, 044909 (2025)

γ-jet

Z-jet
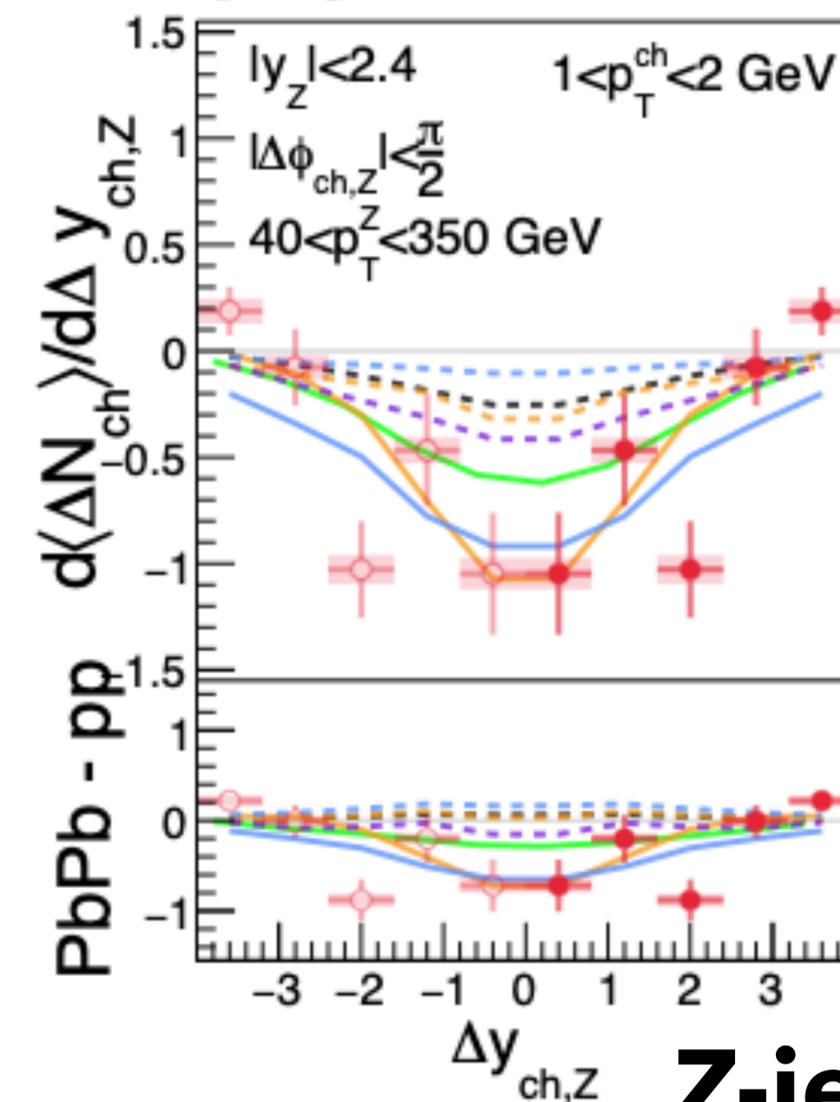
Diffusion wake induced by Di-jets

p+p

0-10% Pb+Pb

$p_T^h \in (1.0, 2.0) \, GeV/c$

p+p

0-10% Pb+Pb

$p_T^h \in (1.0, 2.0) \, GeV/c$

Valley caused by diffusion wake

Phys.Rev.Lett. 135 (2025) 7, 072302
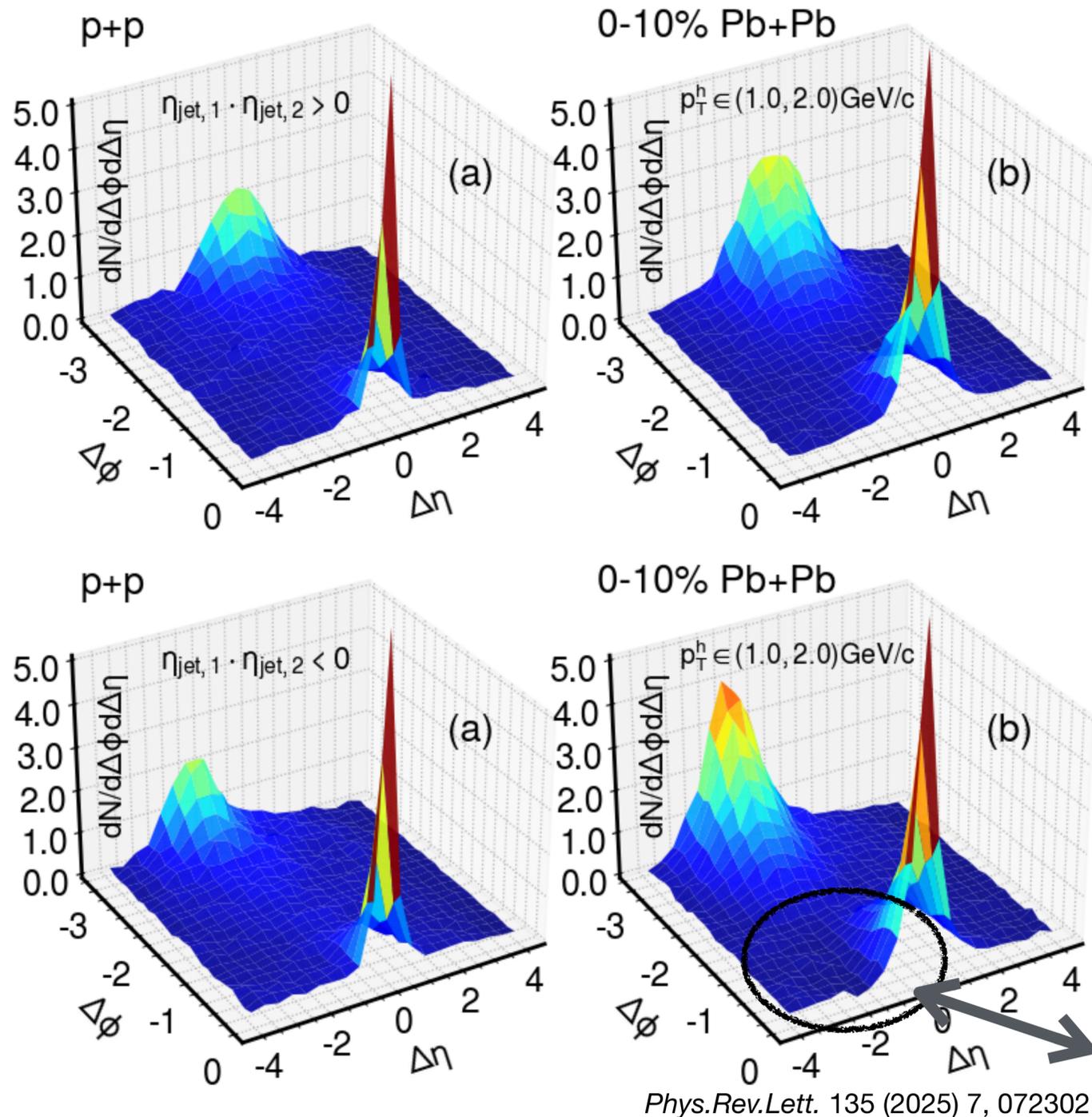
We use leading jet as reference to get 2D plots

$$p_T^{leading,jet} > 120 \, GeV/c$$

$$p_T^{sub-leading,jet} > 90 \, GeV/c$$

Require leading jet with larger rapidity

Dividing events by taking different rapidity relationship between leading jet and sub-leading jet

$$\eta_{jet,1} \cdot \eta_{jet,2} > 0 \, (small \, gap)$$

$$\eta_{jet,1} \cdot \eta_{jet,2} < 0 \, (large \, gap)$$

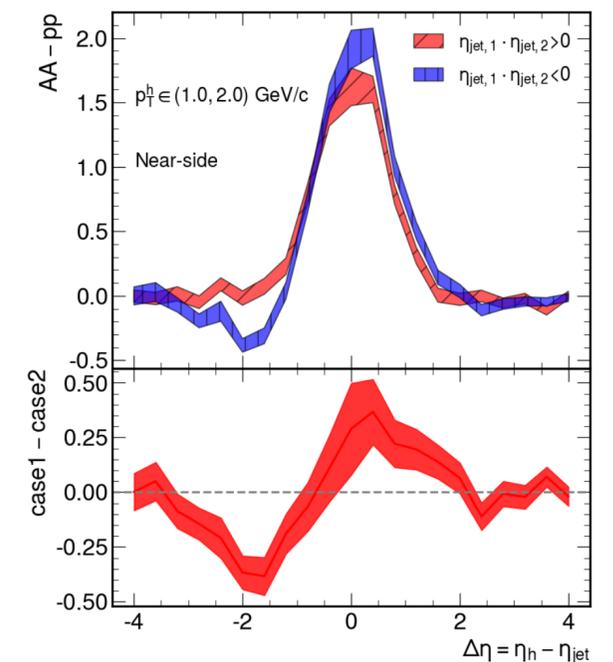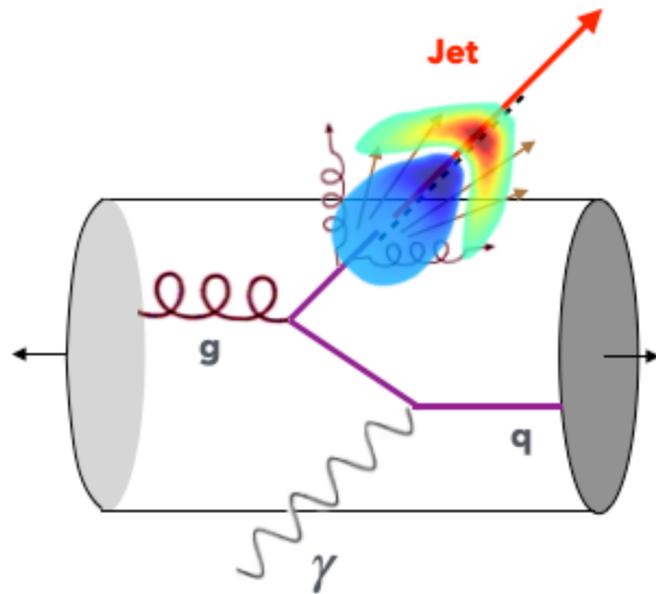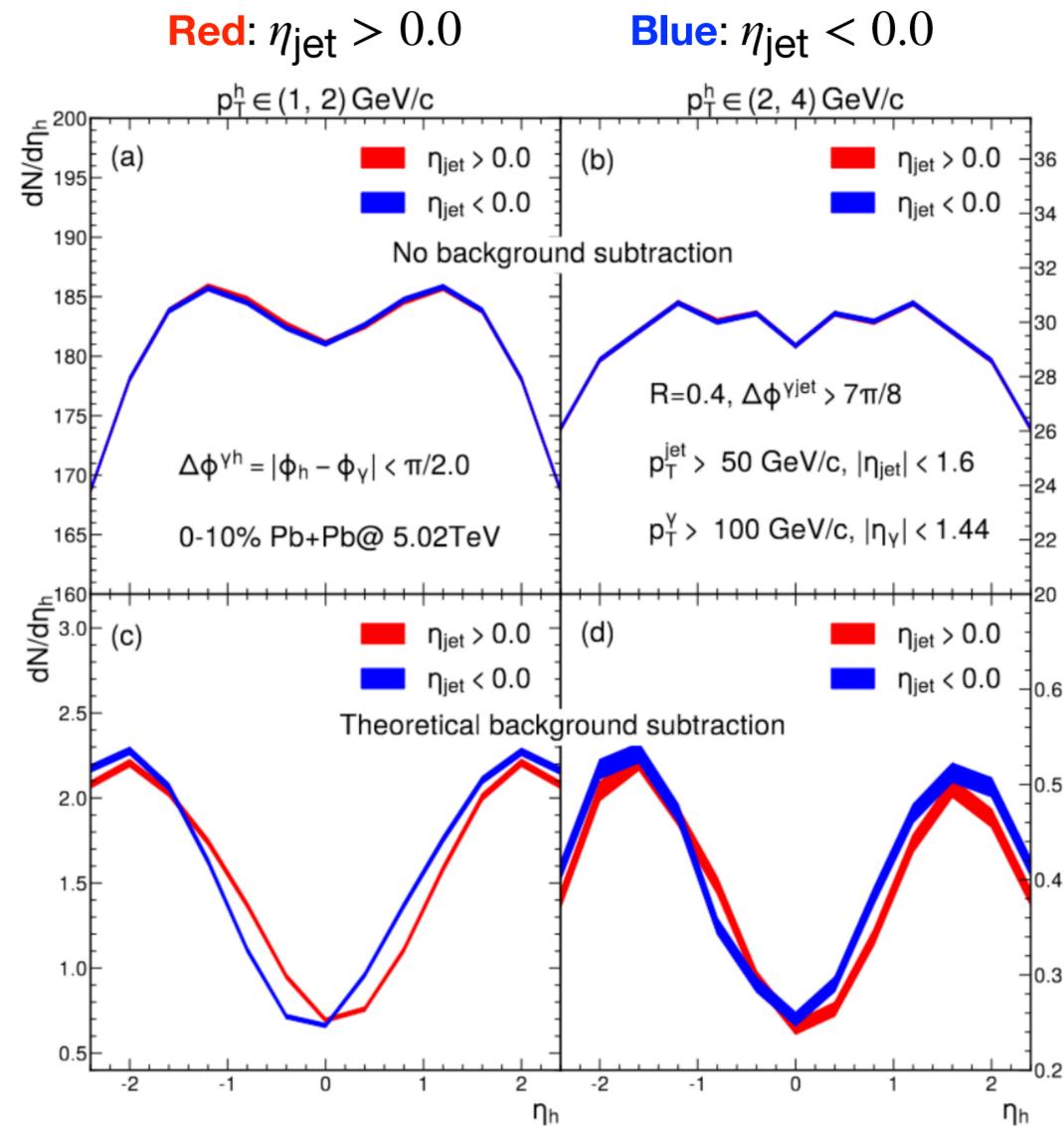# Background free signal

Using the η distribution instead of $\Delta\eta$ can remove rapidity dependence of track on jet.

We firstly focus on γ-jet

The signal of DW is clear in the γ direction

Red: $\eta_{\text{jet}} > 0.0$ **Blue**: $\eta_{\text{jet}} < 0.0$

Pure distribution
(including background)
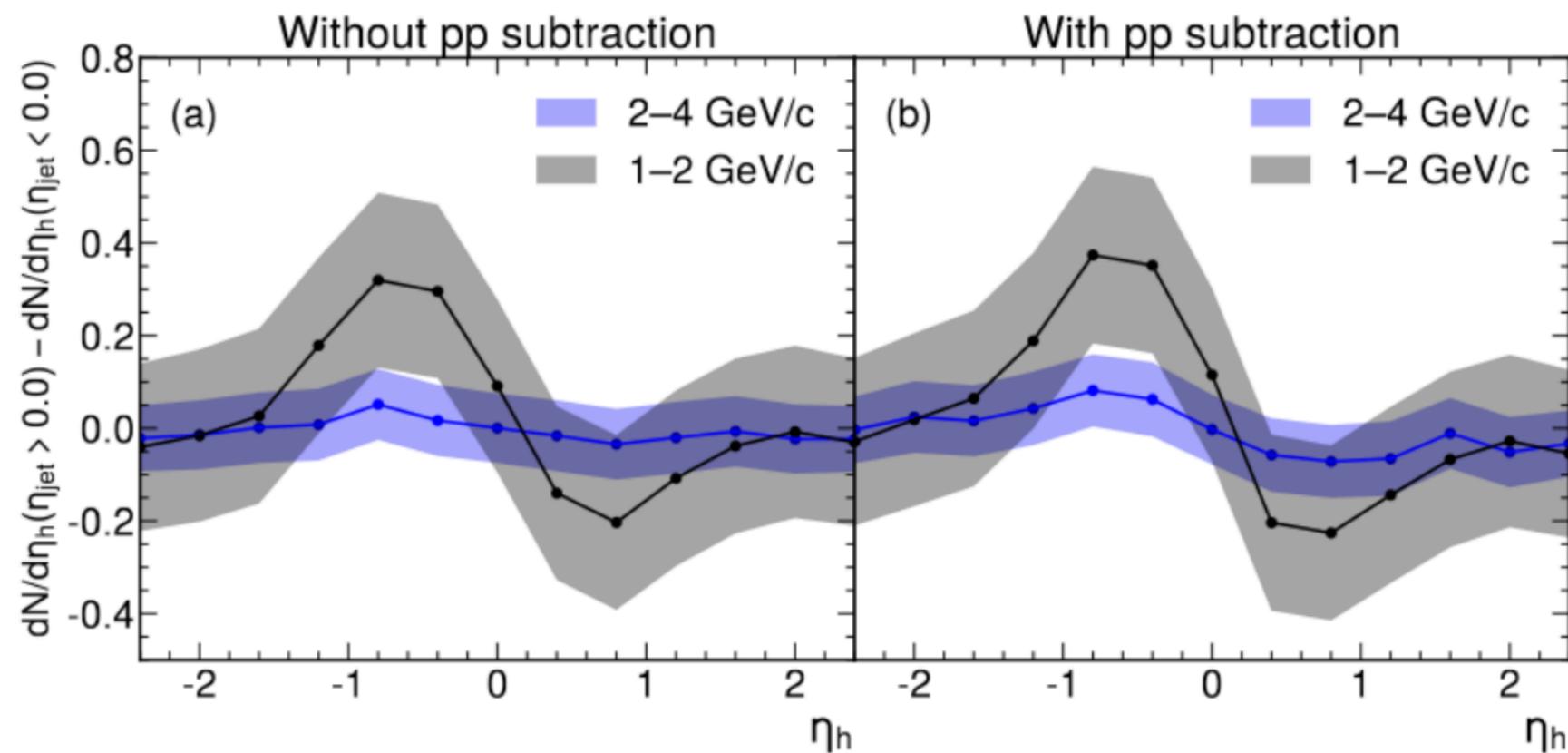
Signal distribution
(background subtracted)

arXiv:2508.04194

Rapidity asymmetry in gamma-jets

We calculate the difference of rapidity distribution between large jet rapidity and central jet rapidity.

$$\Delta\phi_{jet,h} > \pi/2.0$$

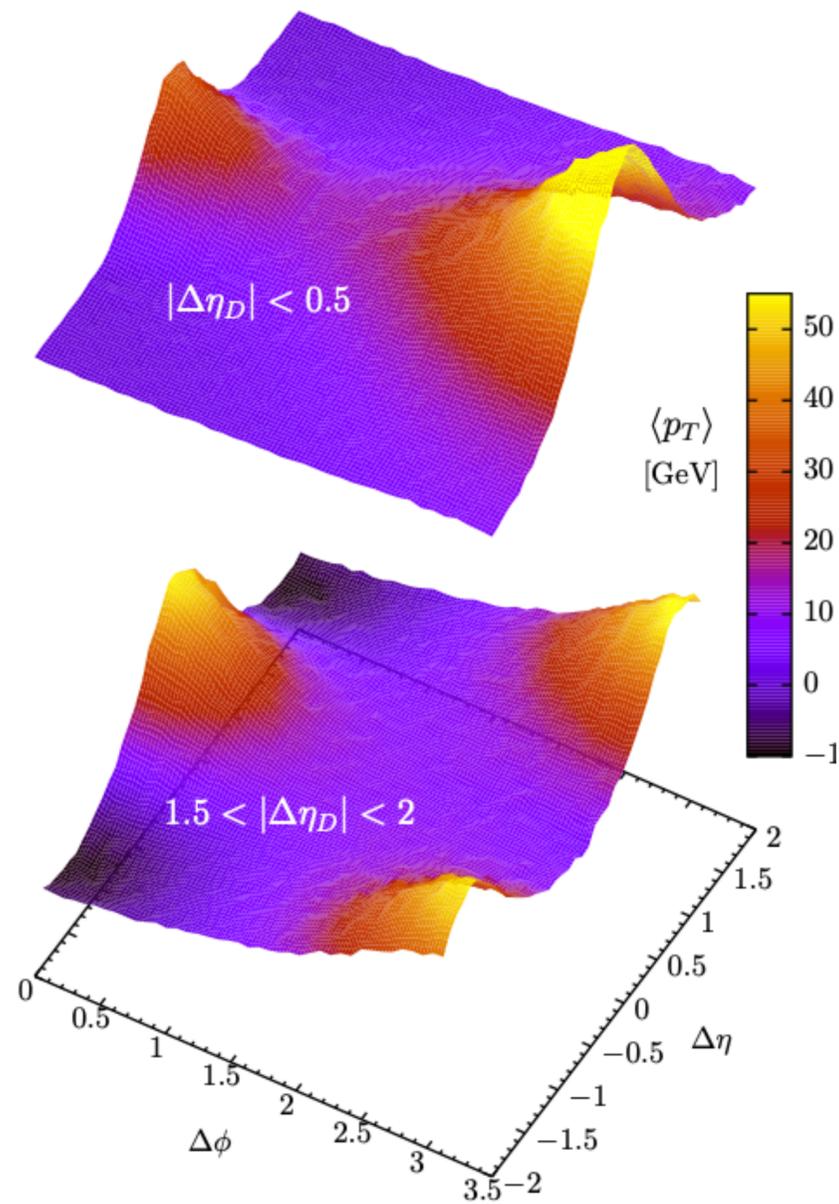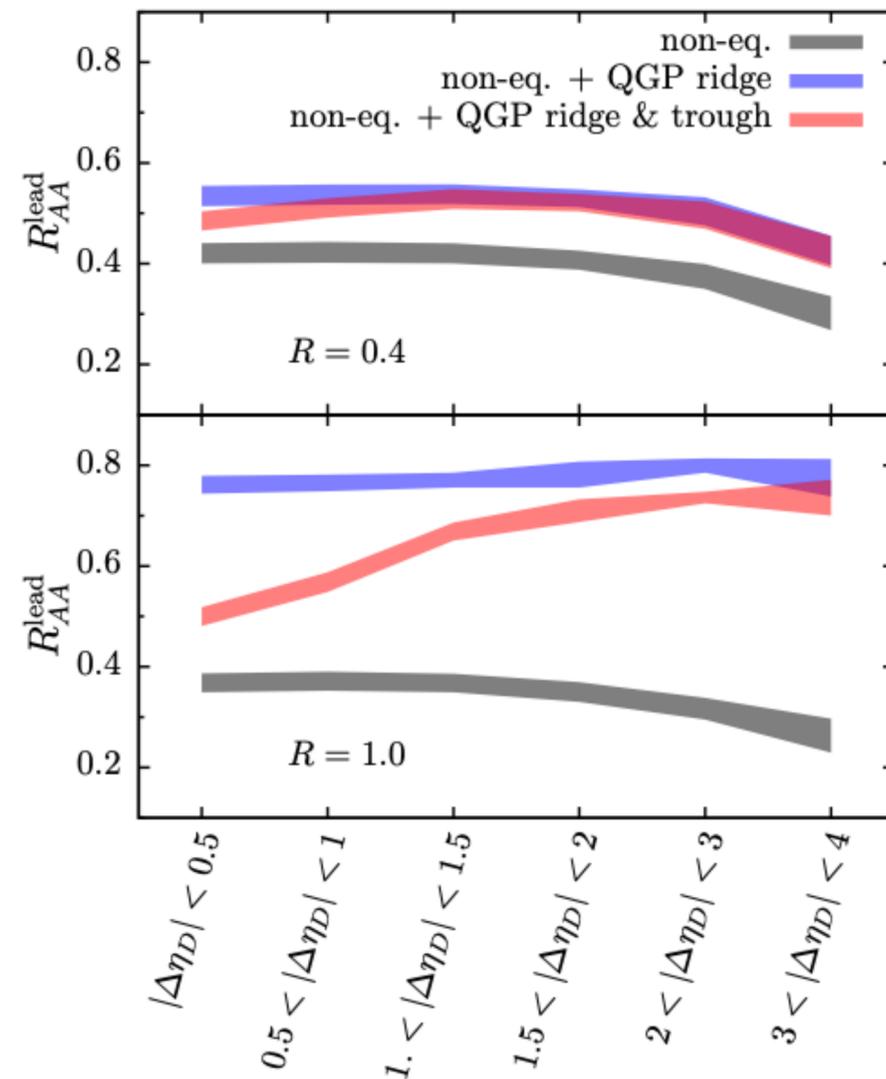*Jet as the reference*

⭐ Background cancel automatically

⭐ Rapidity asymmetry in low hadron p_T

⭐ PP baseline is not important

arXiv:2508.04194

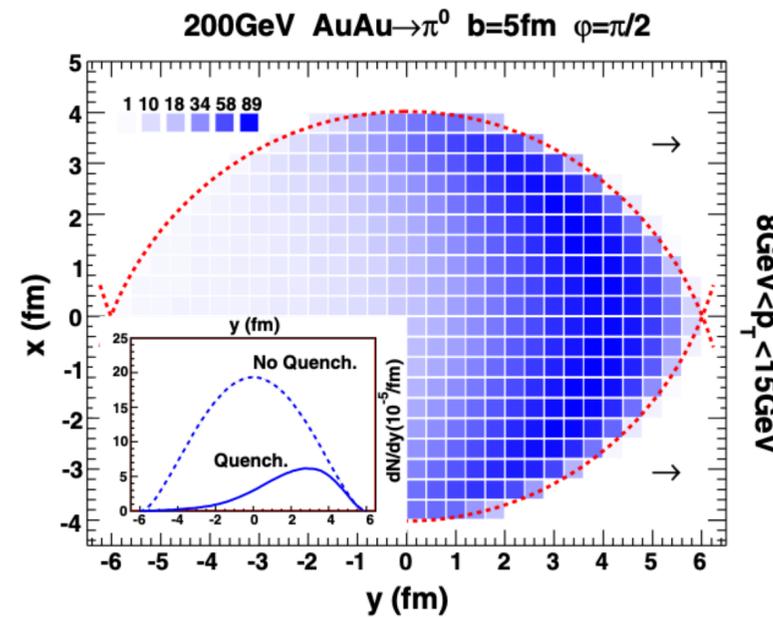# Visualize diffusion wake through jet RAA

Phys. Rev. Lett. 124, 052301 (2020)

Jet R_{AA} with large R is sensitive to the di-jet rapidity gaps, providing a novel method to search for the signal of jet-induced diffusion wake

Jet-flow coupling

Jet-flow coupling distorted the jet-induced Mach cone, providing a unique opportunity to locate jet initial transverse position.

Phys.Rev.Lett. 127 (2021) 8, 082301
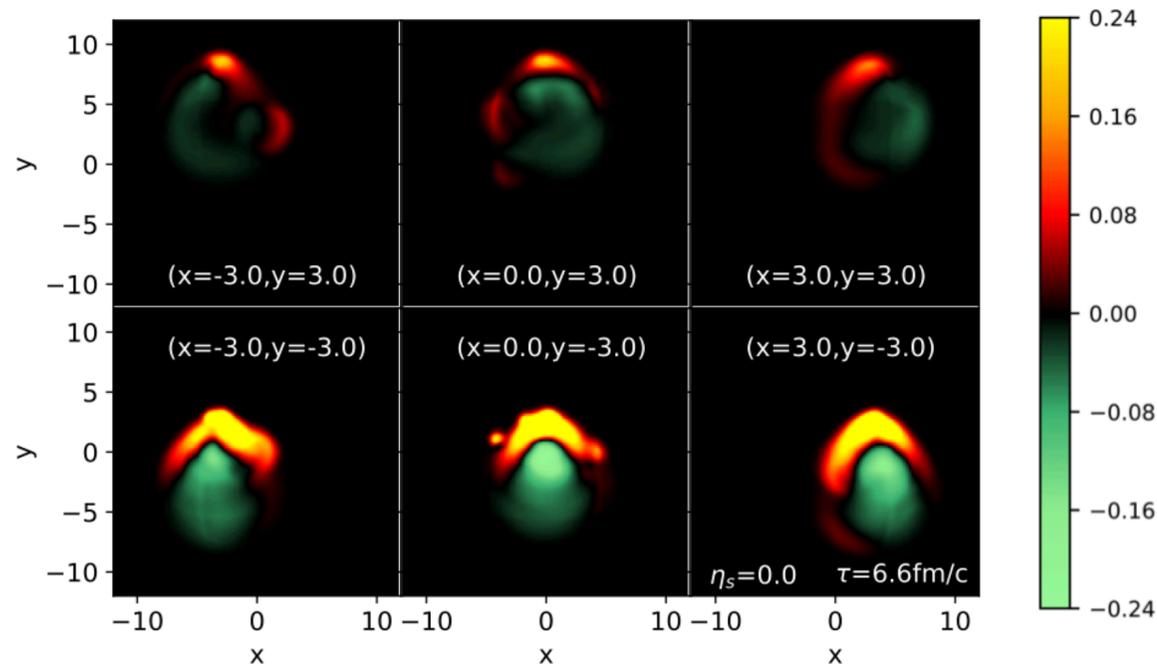
Phys.Rev.Lett. 103 (2009) 032302

$$A_N^{\vec{n}} = \frac{\int d^3r d^3k f_a(\vec{k}, \vec{r}) \mathrm{Sign}(\vec{k} \cdot \vec{n})}{\int d^3r d^3k f_a(\vec{k}, \vec{r})}.$$

Phys.Rev.Lett. 125 (2020) 12, 122301

Longitudinal position $\propto$ $p_T^{h,\mathrm{jet}}/p_T^{trigger}$

The position prediction provides a completely new approach for our study of Mach-cone signals.

Tan Luo
09:35, Sat

Summary

- Energy lost by jets deposits into the QGP will induce medium response in the form of Mach-cone-like excitation.

- Medium response modifies soft hadrons distribution inside jet and reflects on the jet substructure observables.

- Jet-induced diffusion wake is a unique signal of medium response. It leads to a double-bump structure of jet-hadron rapidity correlation which has been observed by experimental measurements.

- Rapidity asymmetry is a robust signal of diffusion wake in dijets events. We further explore a signal of diffusion wake based on it which is background free.

- Jet–fluid coupling provides a new framework for investigating jet–medium interactions.

THANK YOU

CoLBT-hydro model

LBT: Linear Boltzmann Transport Model

CLVisc: CCNU-LBNL (3+1)D Viscous hydro model

1. LBT for energetic partons(jet shower and recoil)

2. Hydrodynamic model for bulk and soft particles: CLVisc

3. Sorting jet and recoil partons according to a cut-off parameter p_{cut}^0 (2 GeV)
   Hard partons: $p\partial f(p) = -C(p)$ $(p \cdot u > p_{cut}^0)$
   Soft and negative partons:
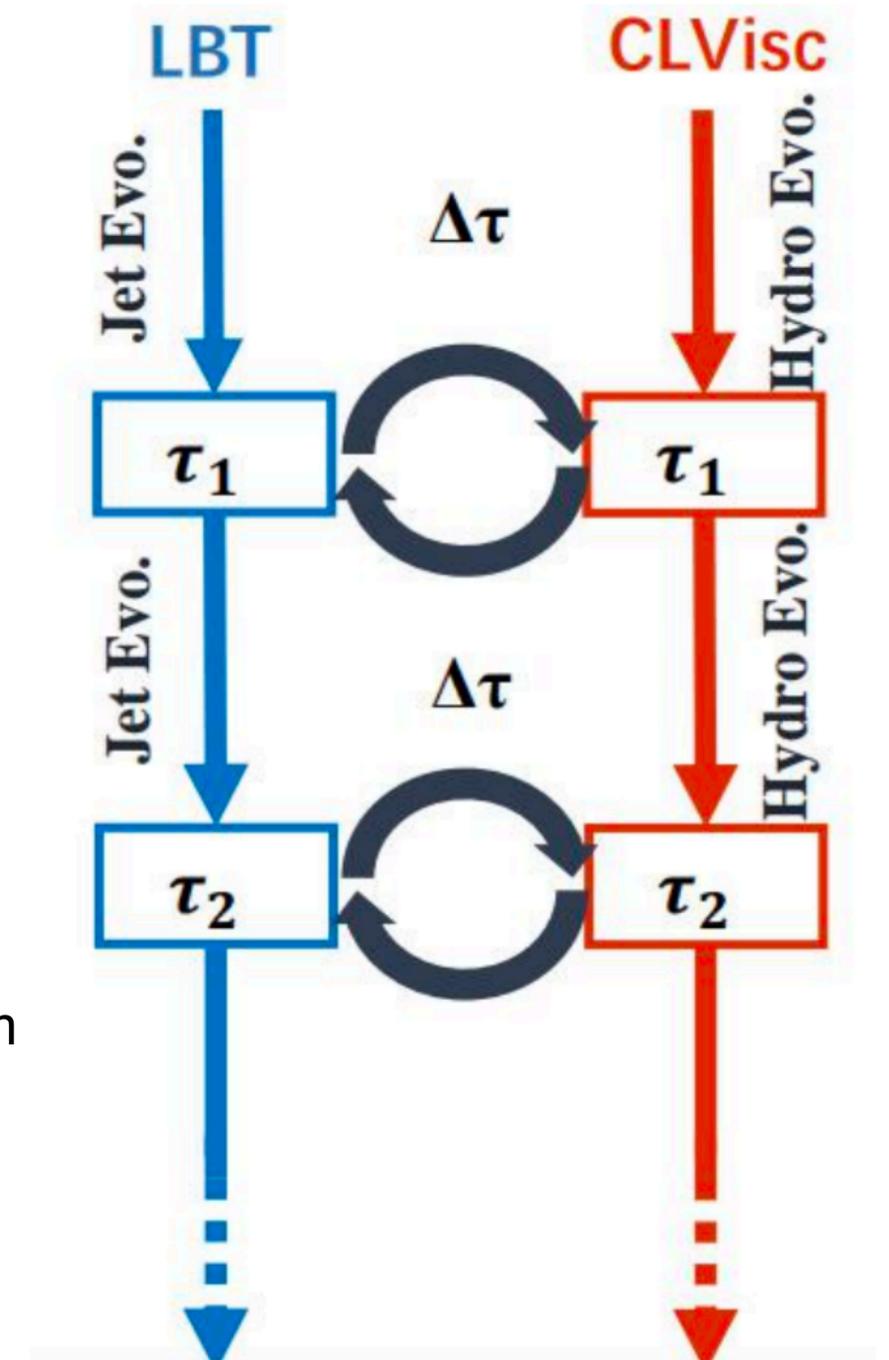 $$j^\nu = \sum_i p_i^\nu \delta^{(4)}(x - x_i)\theta(p_{cut}^0 - p \cdot u)$$

4. Updating medium information by solving the hydrodynamics equation with source term
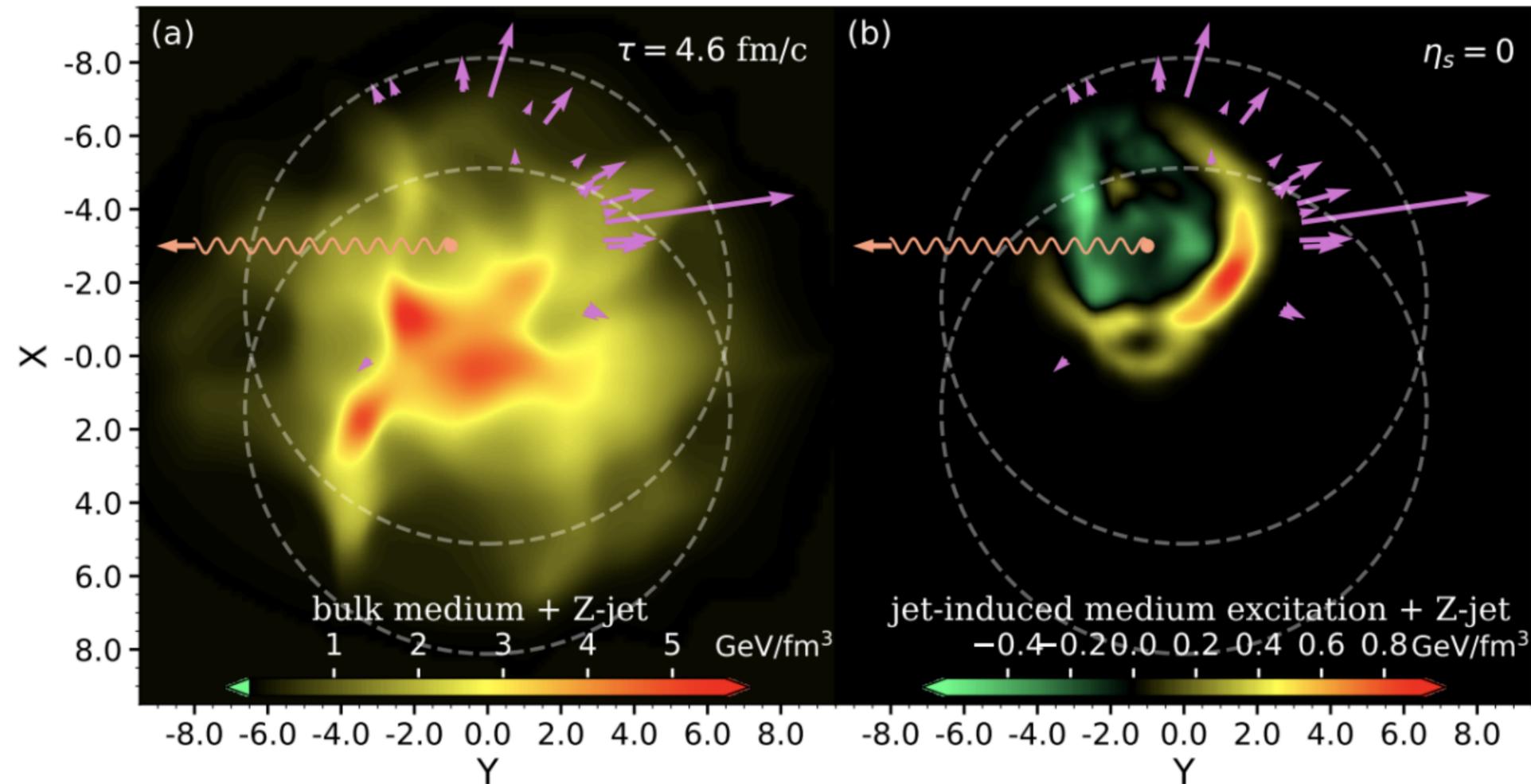 $$\partial_\mu T^{\mu\nu} = j^\nu$$

5. The final hadron spectra:
   (1) hadronization of hard partons within a parton recombination model
   (2) jet-induced hydro response via Cooper-Frye freeze-out

CoLBT-hydro model: **Hydro response**

Chen, Yang, He, Ke, Pang and Wang, PRL 127 (2021) 8, 082301

Theoretical background subtraction:

We run model twice with and without jet to subtract hydro background

The Mach-cone-like jet-induced medium response including the diffusion wake is clearly seen in the right panel.

Diffusion wake in di-jets

Z/γ-jets events is relatively rare compared to single inclusive jet (or di-jet) events
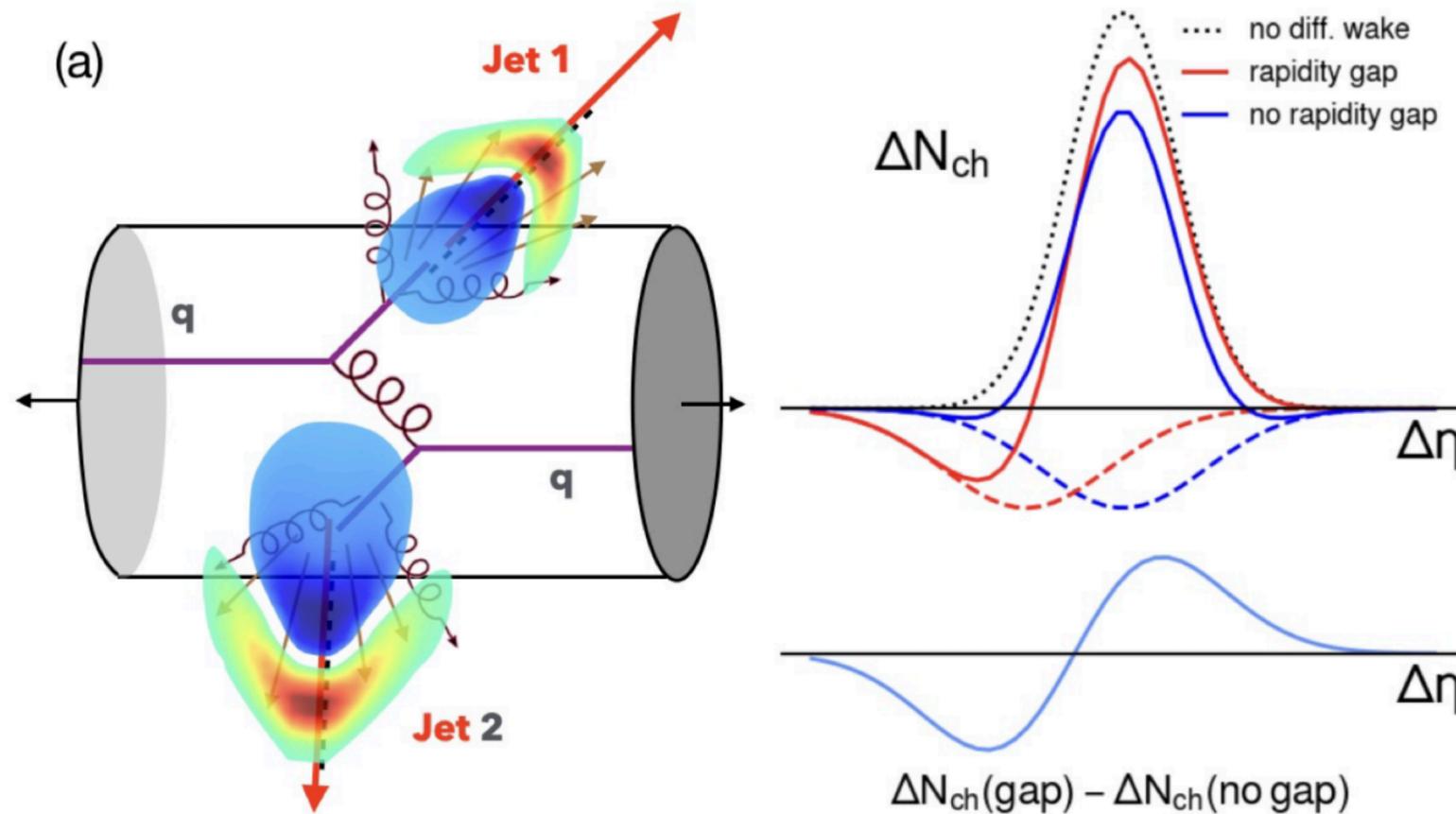
How to find signal of diffusion wake in di-jet events?

Relationship between diffusion wake and jet
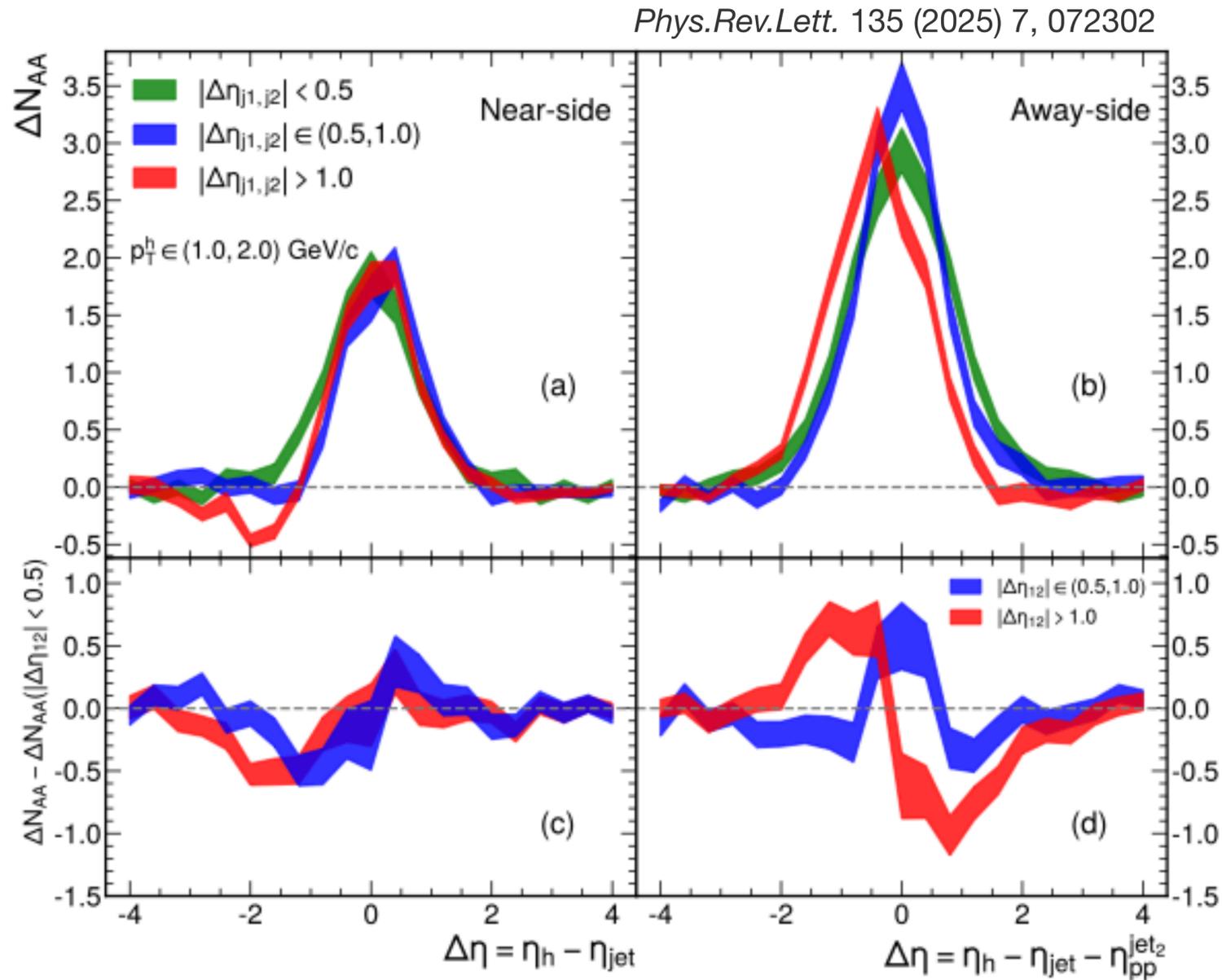
Eta	Phi
Same as jet	Opposite to jet

Challenge:

Diffusion wake caused by one jet will be overlapped by wake front of another jet, unless di-jets have a clear rapidity gap!

Rapidity asymmetry

Phys.Rev.Lett. 135 (2025) 7, 072302

New category

(1) $|\Delta\eta_{j_1,j_2}| < 0.5,$ symmetrize distributions

(2) $0.5 < |\Delta\eta_{j_1,j_2}| < 1.0$

(3) $|\Delta\eta_{j_1,j_2}| > 1.0$

Near-side: $\Delta\phi_{j_1,h} < \pi/2$

Away-side: $\Delta\phi_{j_1,h} > \pi/2$ (Shift by the peak in pp)

$$\Delta N_{\mathrm{AA}} = \int d\Delta\phi \left[\frac{dN_{\mathrm{AA}}}{d\Delta\phi d\Delta\eta} - \frac{dN_{\mathrm{pp}}}{d\Delta\phi d\Delta\eta} \right]$$