Study of jet-induced diffusion wake in heavy-ion collisions

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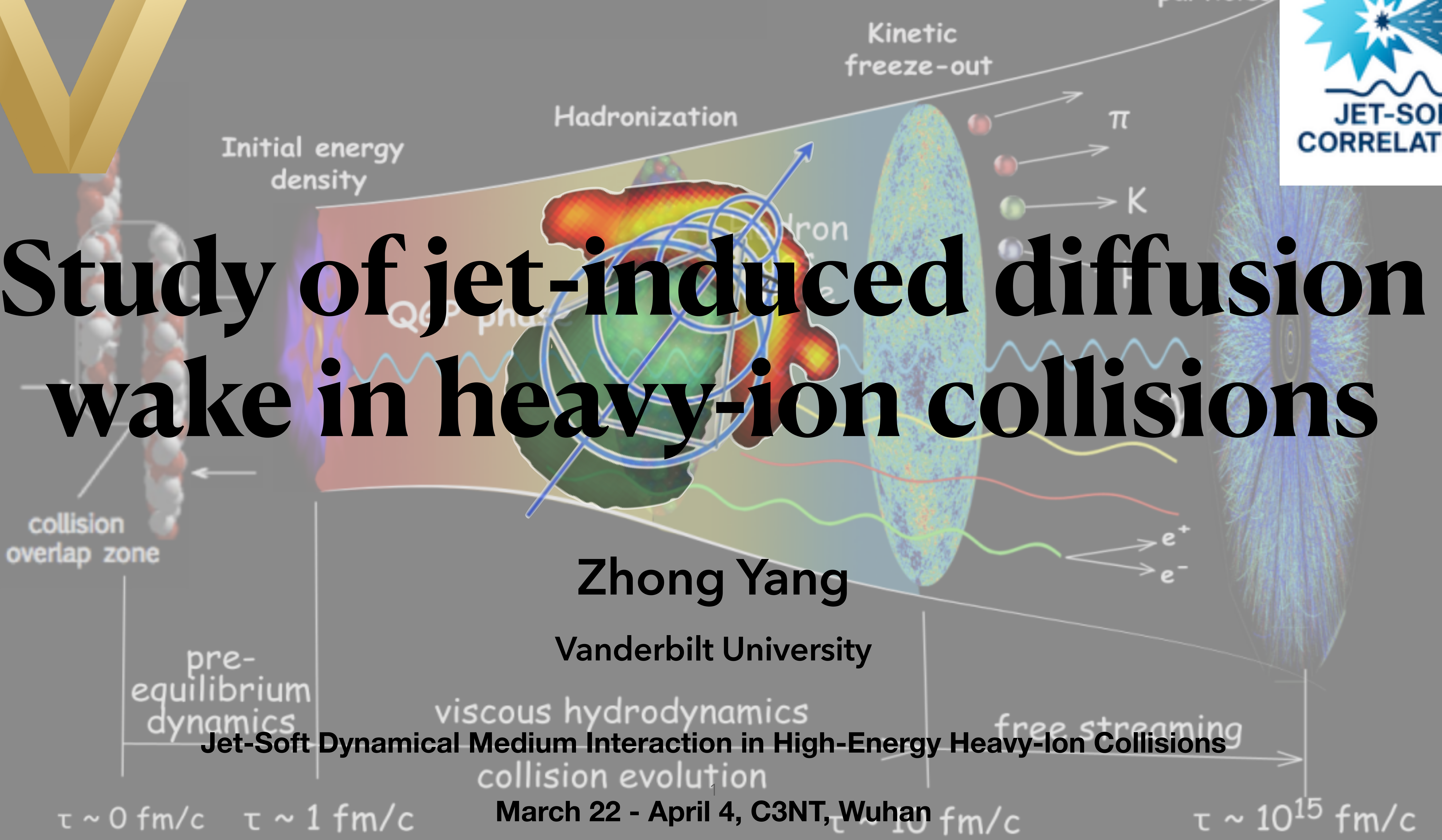
Vanderbilt University

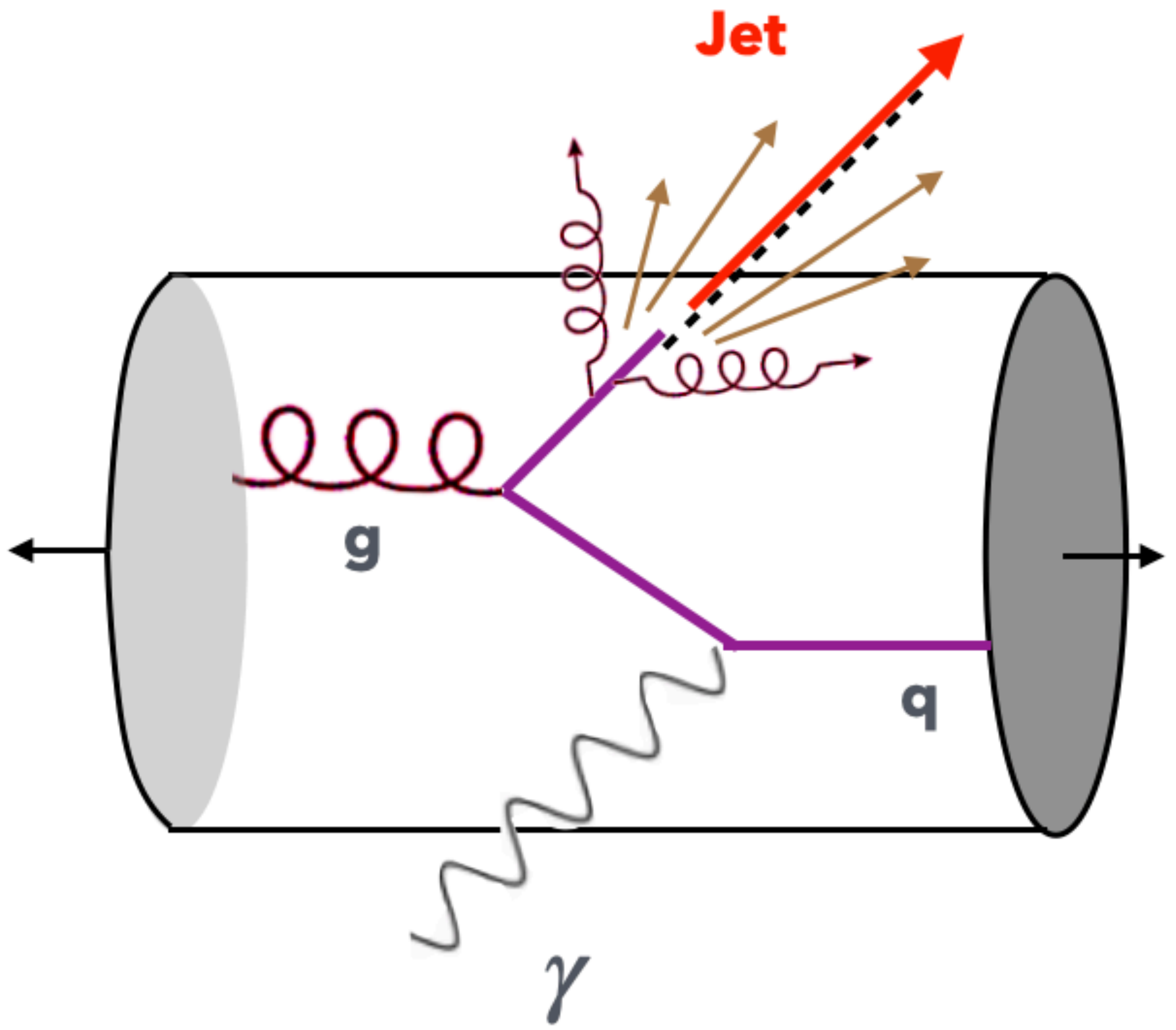
Jet-Soft Dynamical Medium Interaction in High-Energy Heavy-Ion Collisions

March 22 - April 4, C3NT, Wuhan

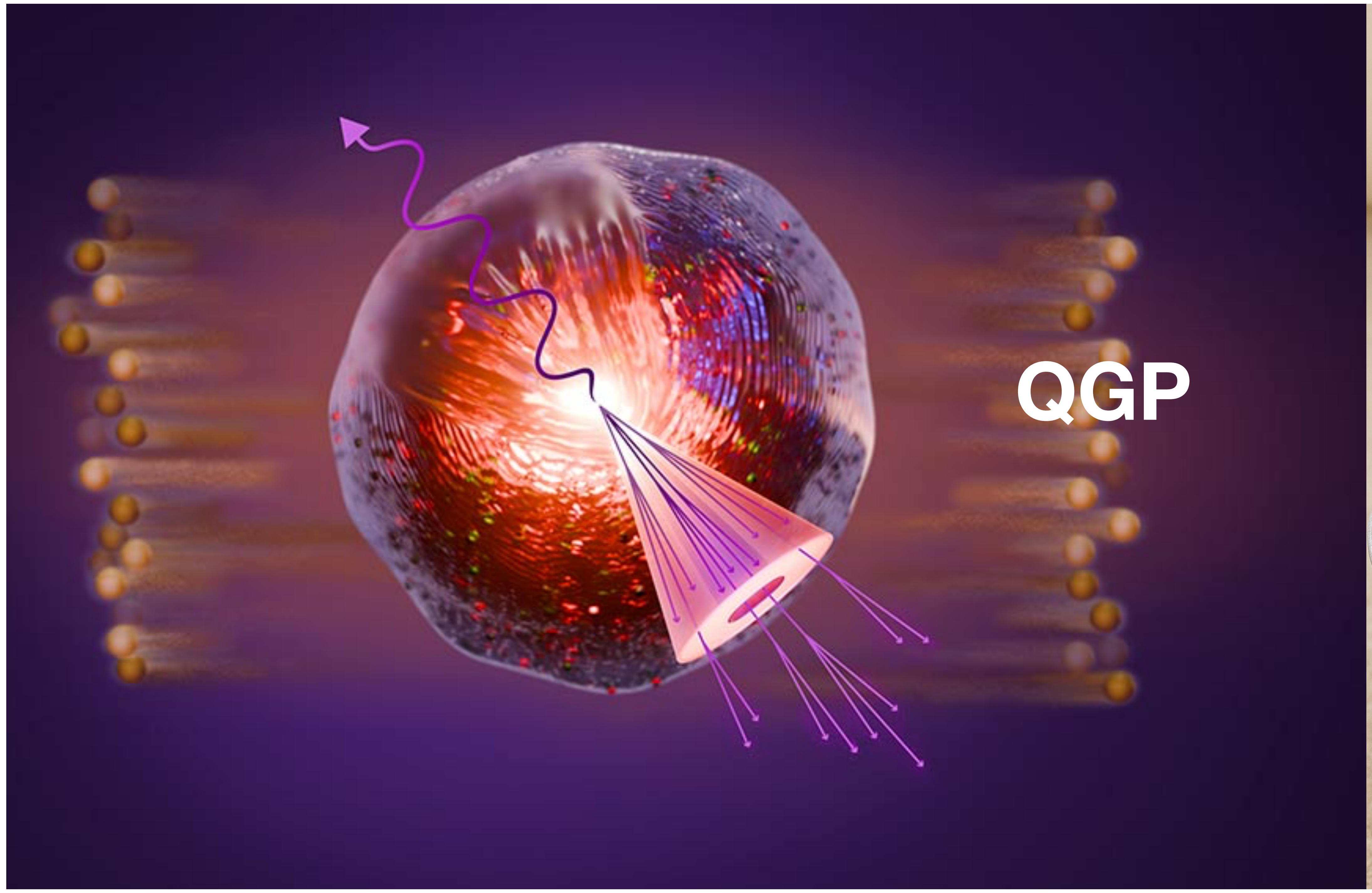


Jet quenching

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



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

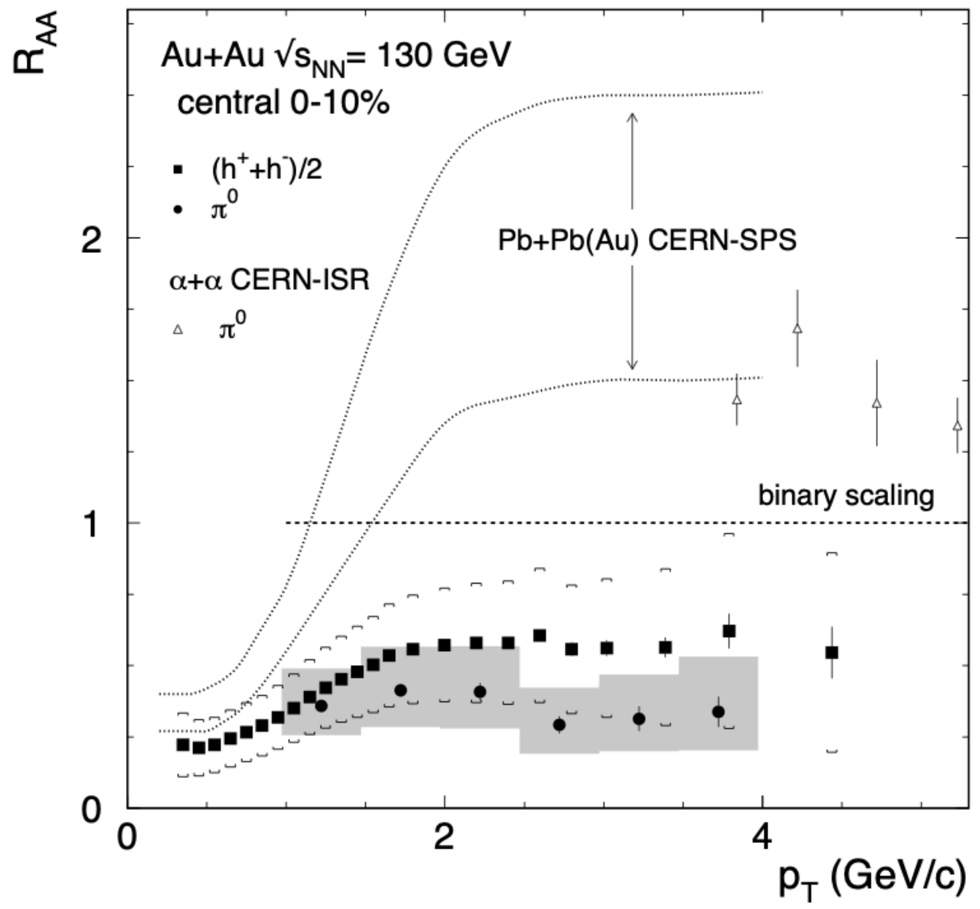


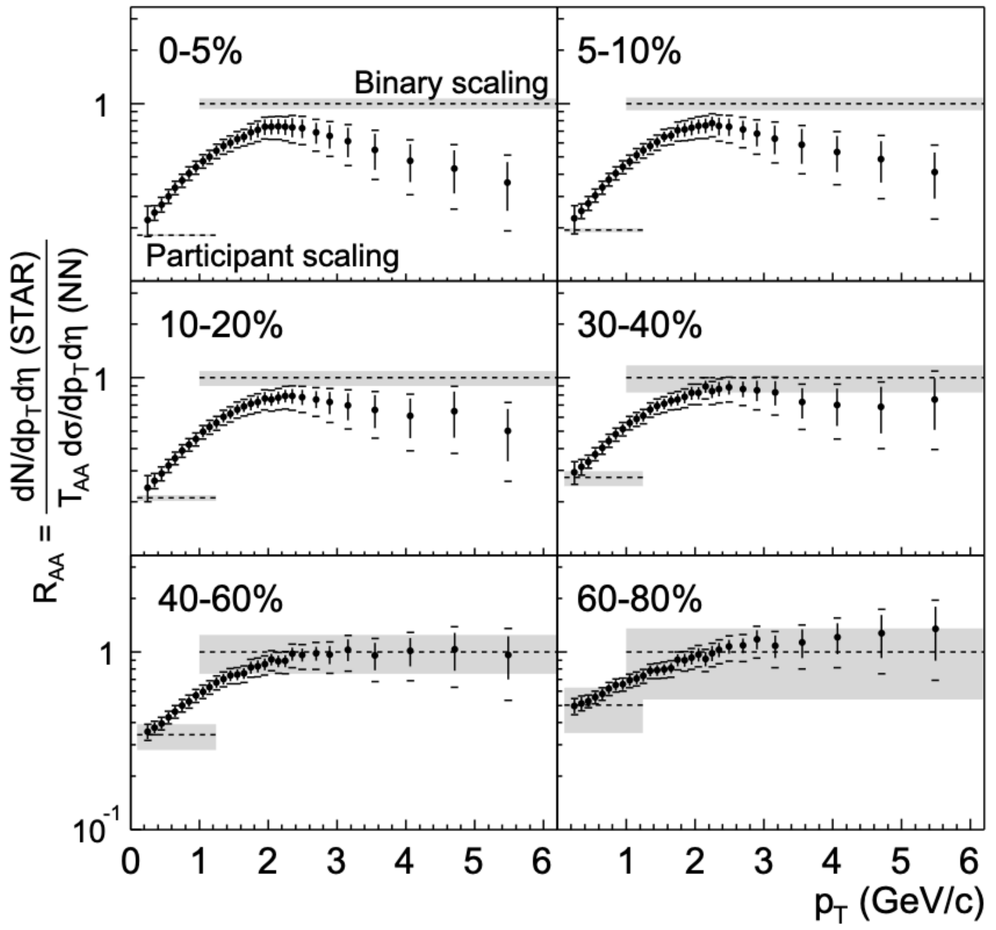
Jet quenching: jet energy loss due to interaction between jet and QGP.

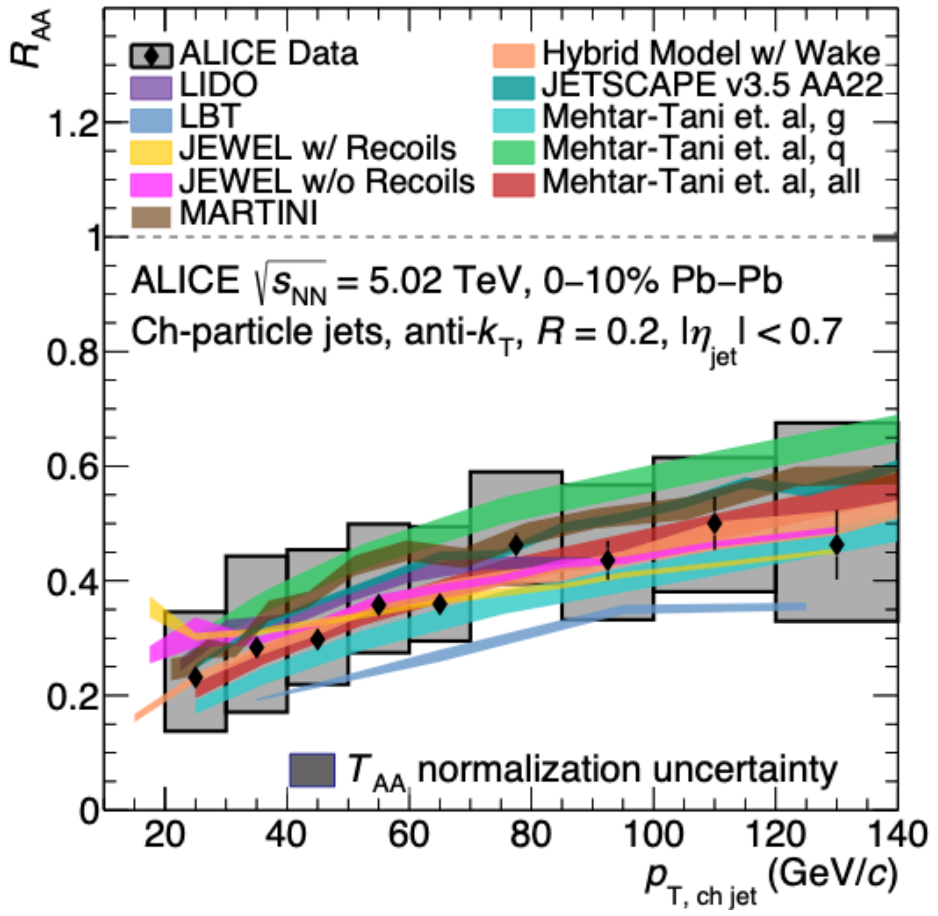
Jet quenching

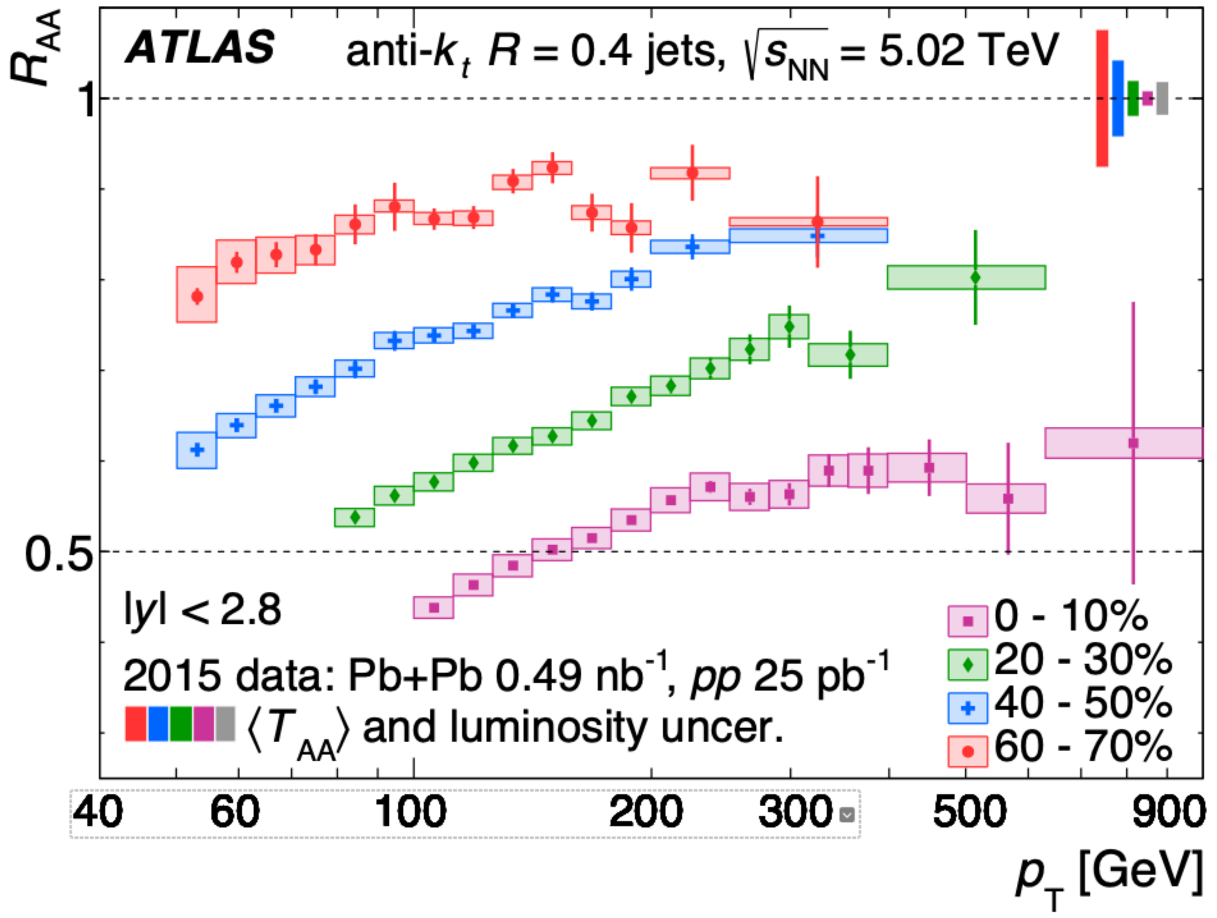
The observation of hadron RAA indicates the formation of quark-gluon plasma at high-energy heavy-ion collisions.[Phys. Rev. Lett., 2002, 88: 022301, Phys. Rev. Lett., 2002, 89: 202301,Phys.Lett.B 849 (2024) 138412, Phys.Lett.B 790 (2019) 108-128, JHEP 04 (2017) 039]

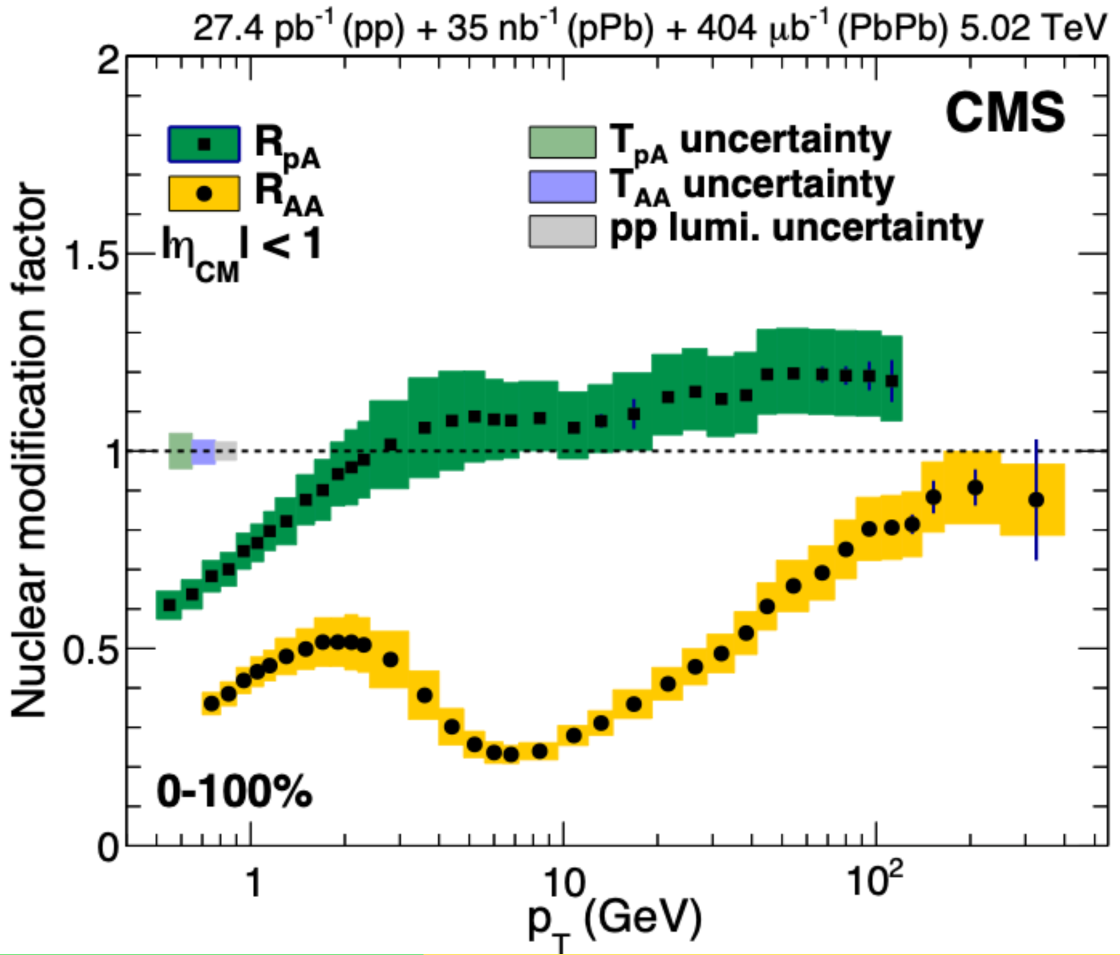
$$R_{AA} = \frac{dN_{AA}/dp_T}{\langle N_{\text{coll}} \rangle \, dN_{pp}/dp_T}$$





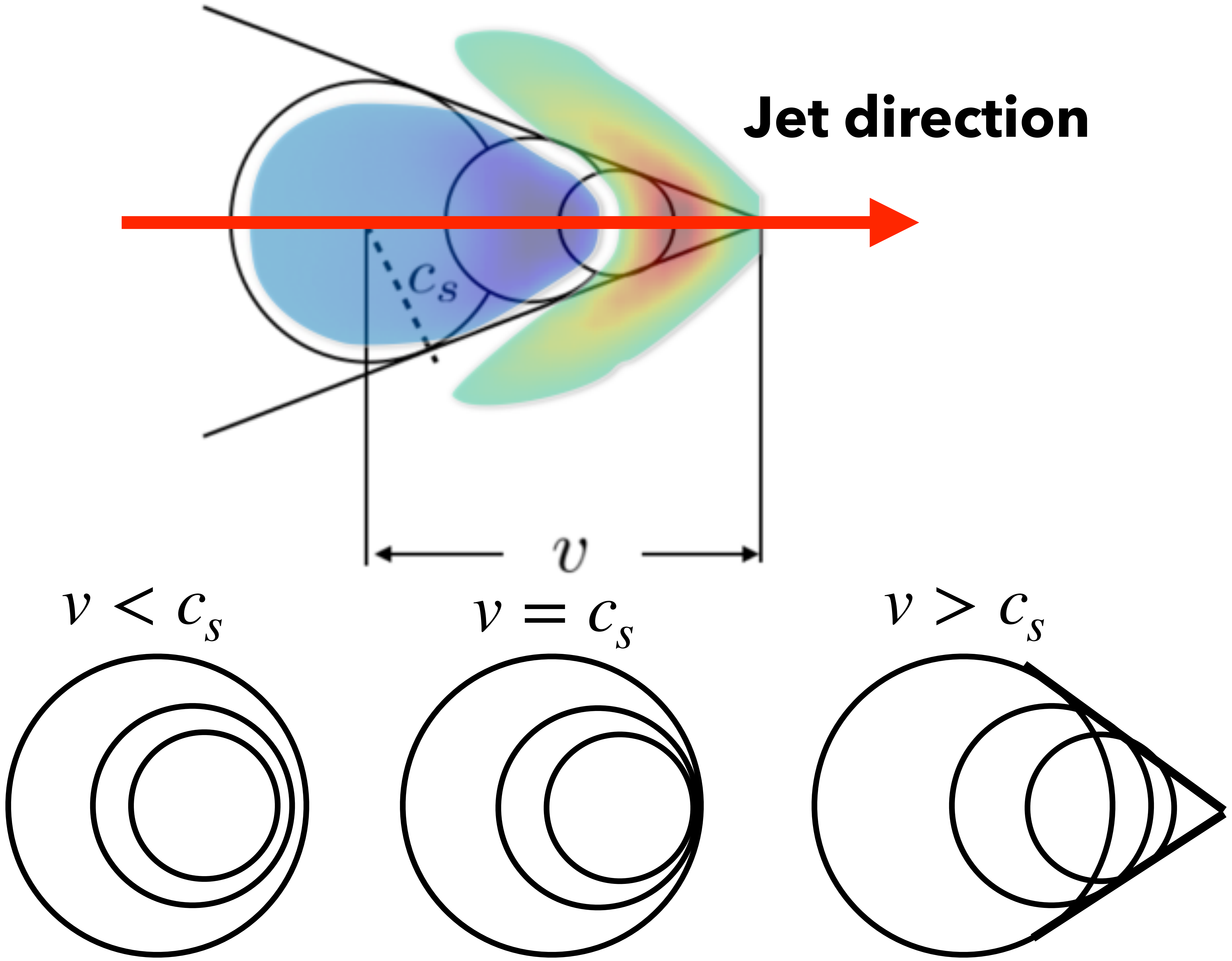


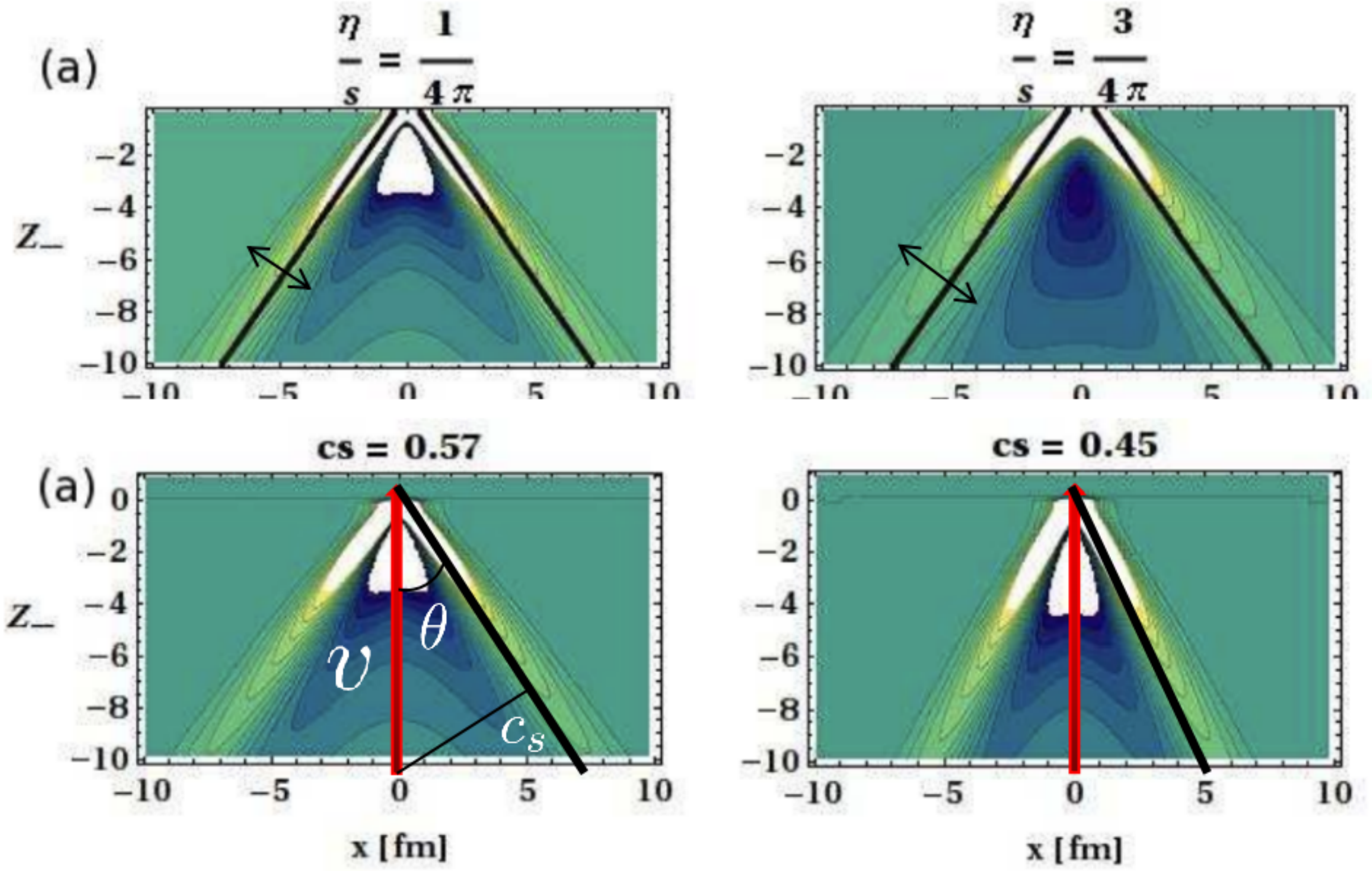




Jet-induced medium response

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; …]

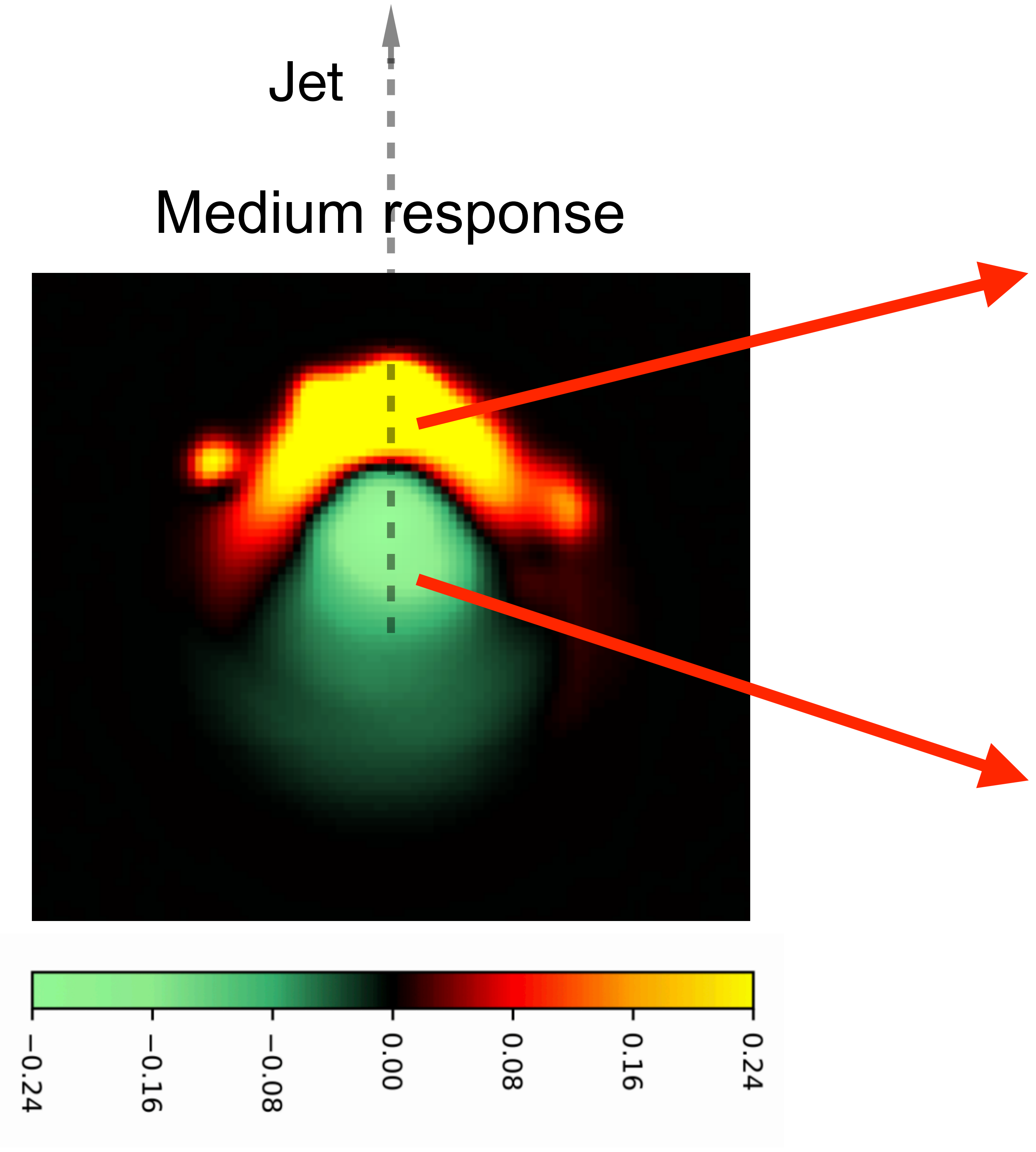


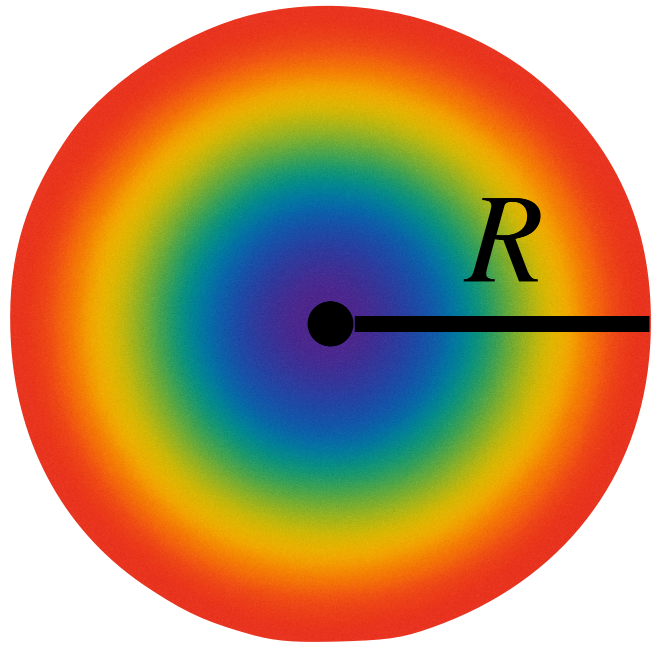


Phys.Rev.C 78 (2008) 041901

Jet-induced Mach-cone could extract the QGP properties

How to measure 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)

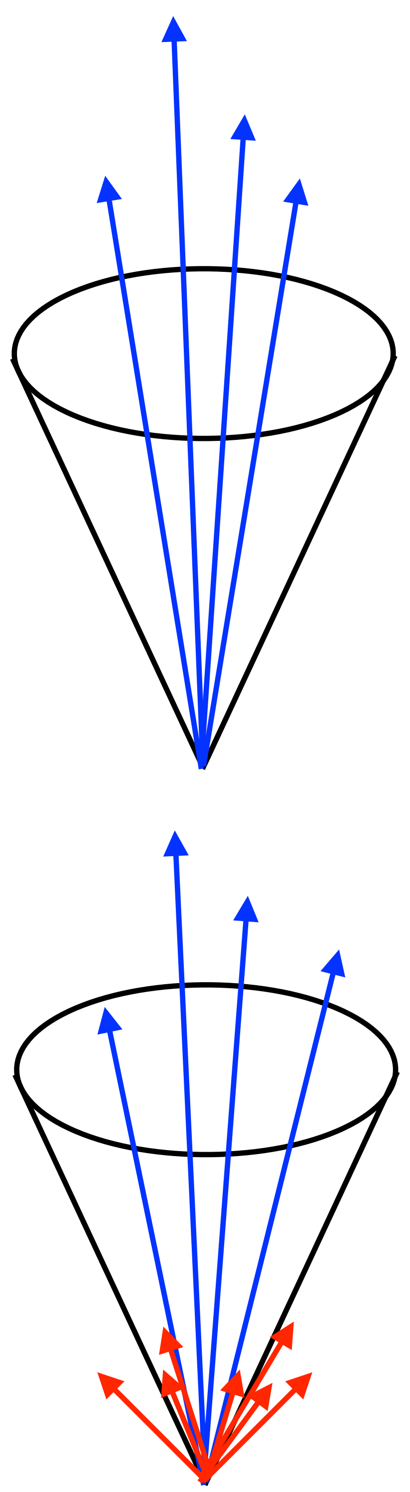
Leading to **depletion** of soft hadrons in opposite direction of jet

Enhancement from wake front

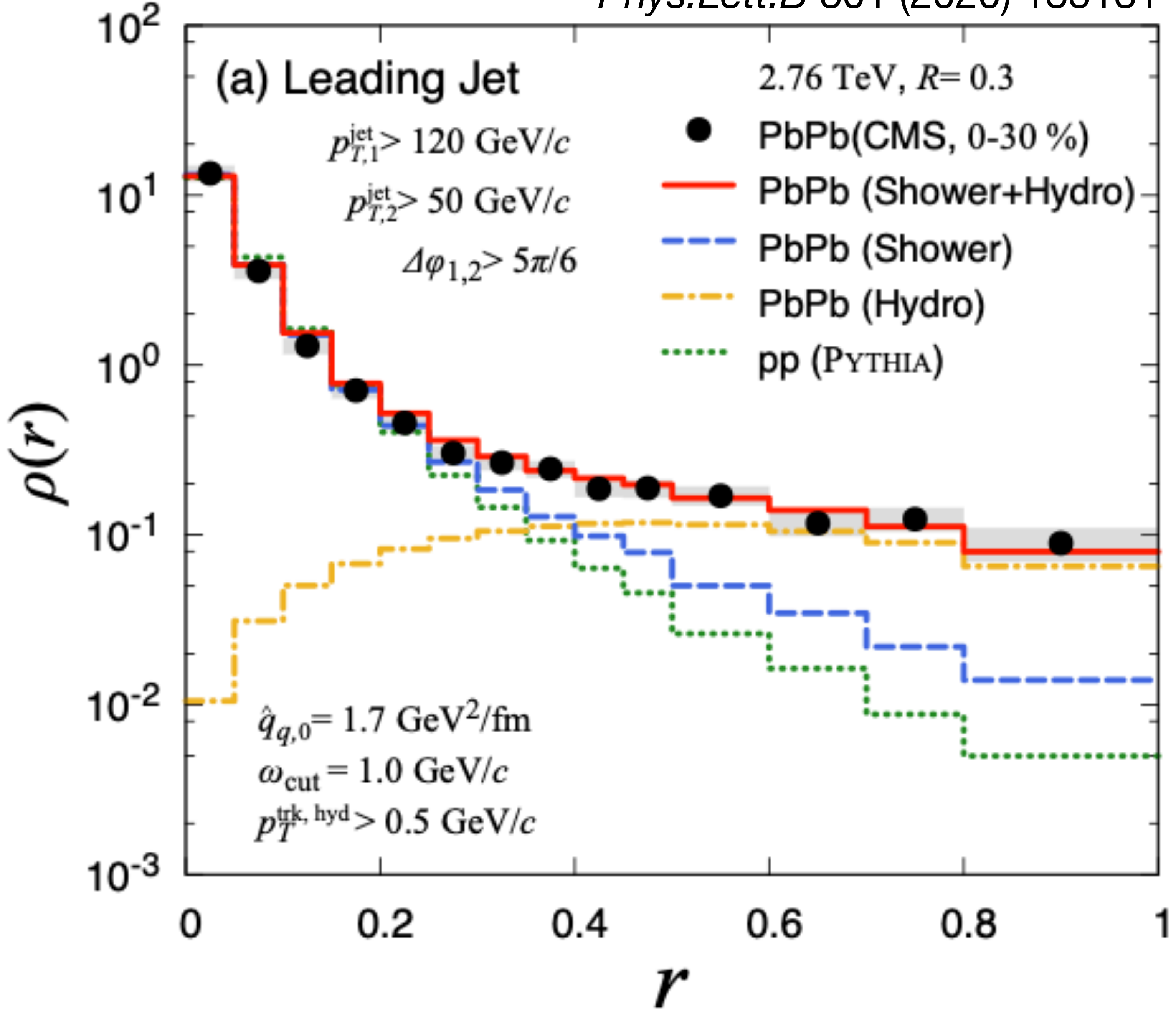
Enhancement of soft hadrons modifies jet substructure, highlighting the important role of medium response in heavy-ion collisions.

p+p

Pb+Pb

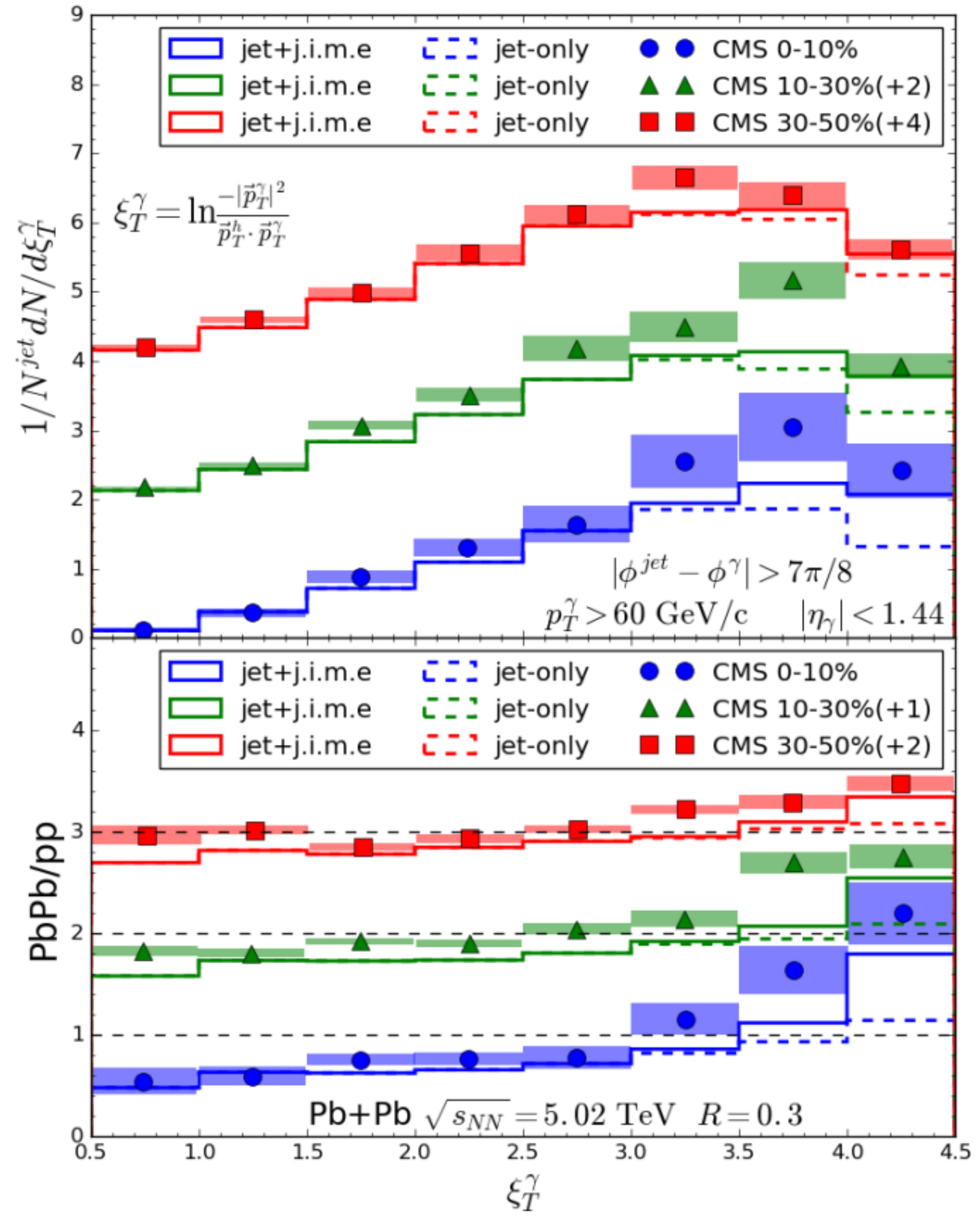


Phys.Lett.B 801 (2020) 135181



$$r = \sqrt{(\phi_h - \phi_{\rm jet})^2 + (\eta_h - \eta_{\rm jet})^2}$$

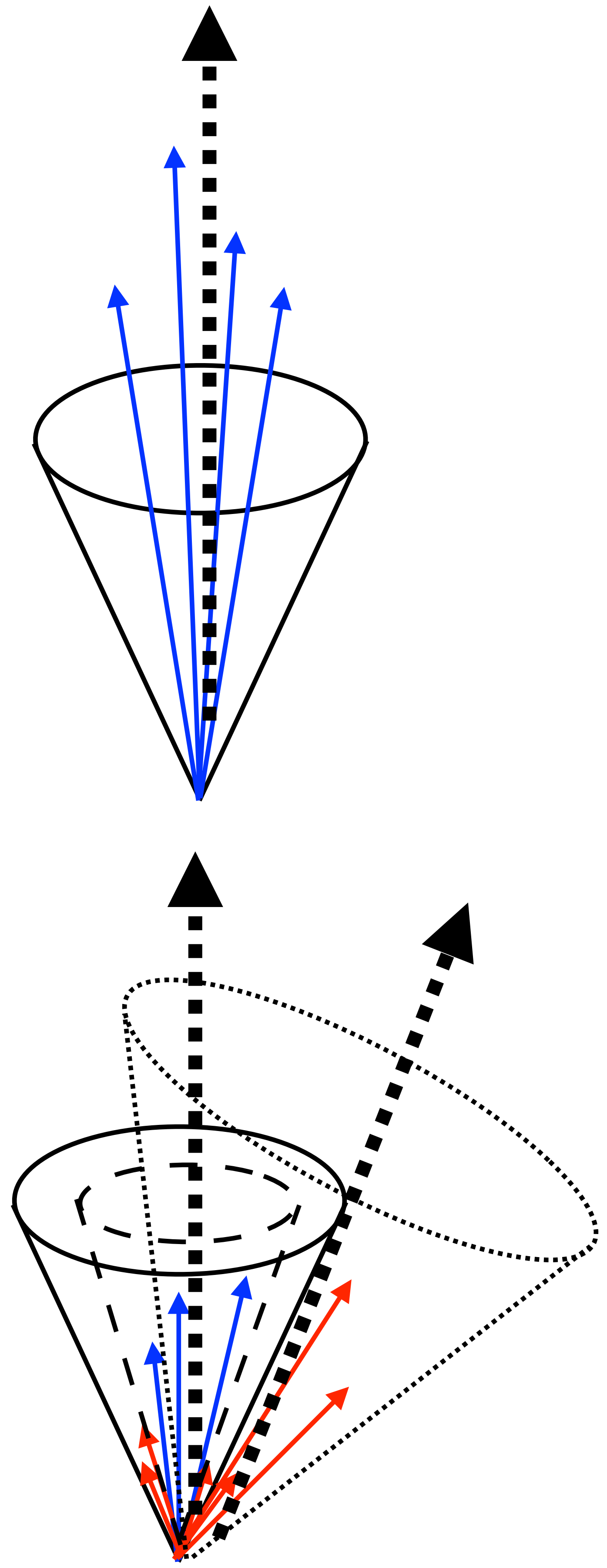
Phys.Lett.B 810 (2020) 135783



$$\xi_T^{\gamma} = \frac{-p_T^{\gamma 2}}{\vec{p}_T^{\gamma}\vec{p}_T^{h}}$$

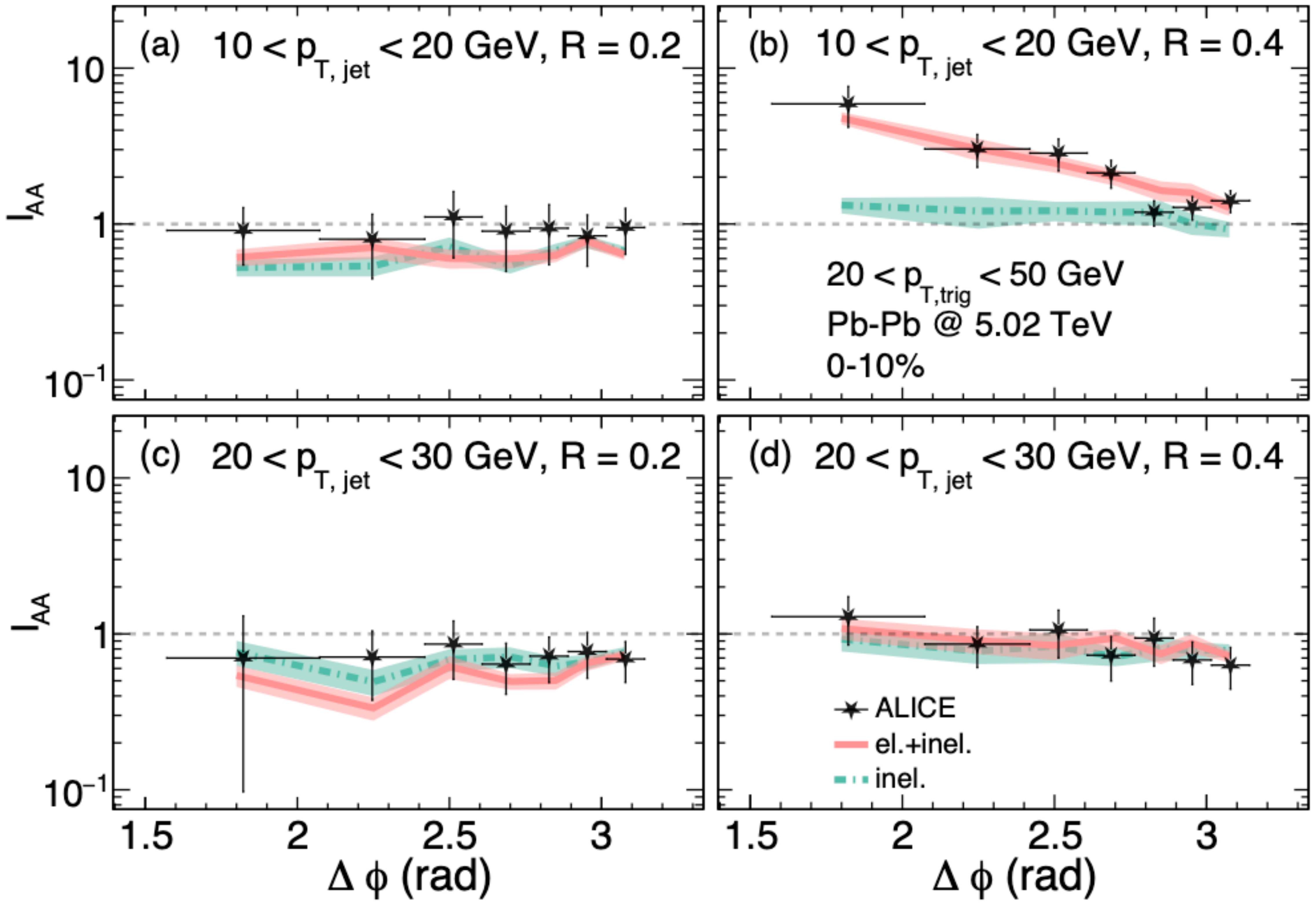
Emergence of recoil jets

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

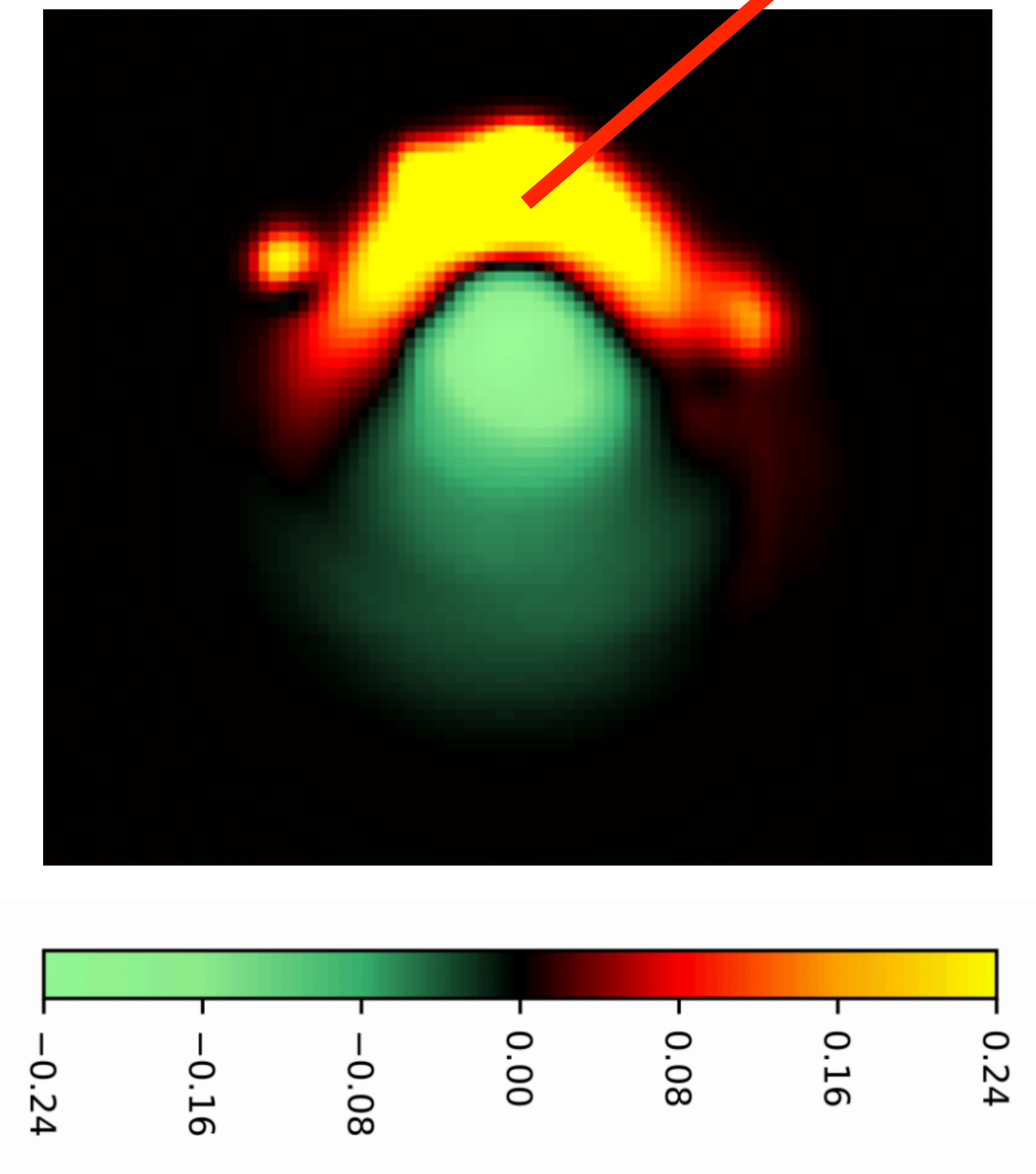
Phys.Rev.Lett. 133 (2024) 2, 022301



$$\Delta\phi = \phi_{\mathrm{jet}} - \phi_{trigger,h}$$

Effect of medium-induced gluon radiation

full hydrodynamic response



Positive: wake front (along jet direction)

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

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

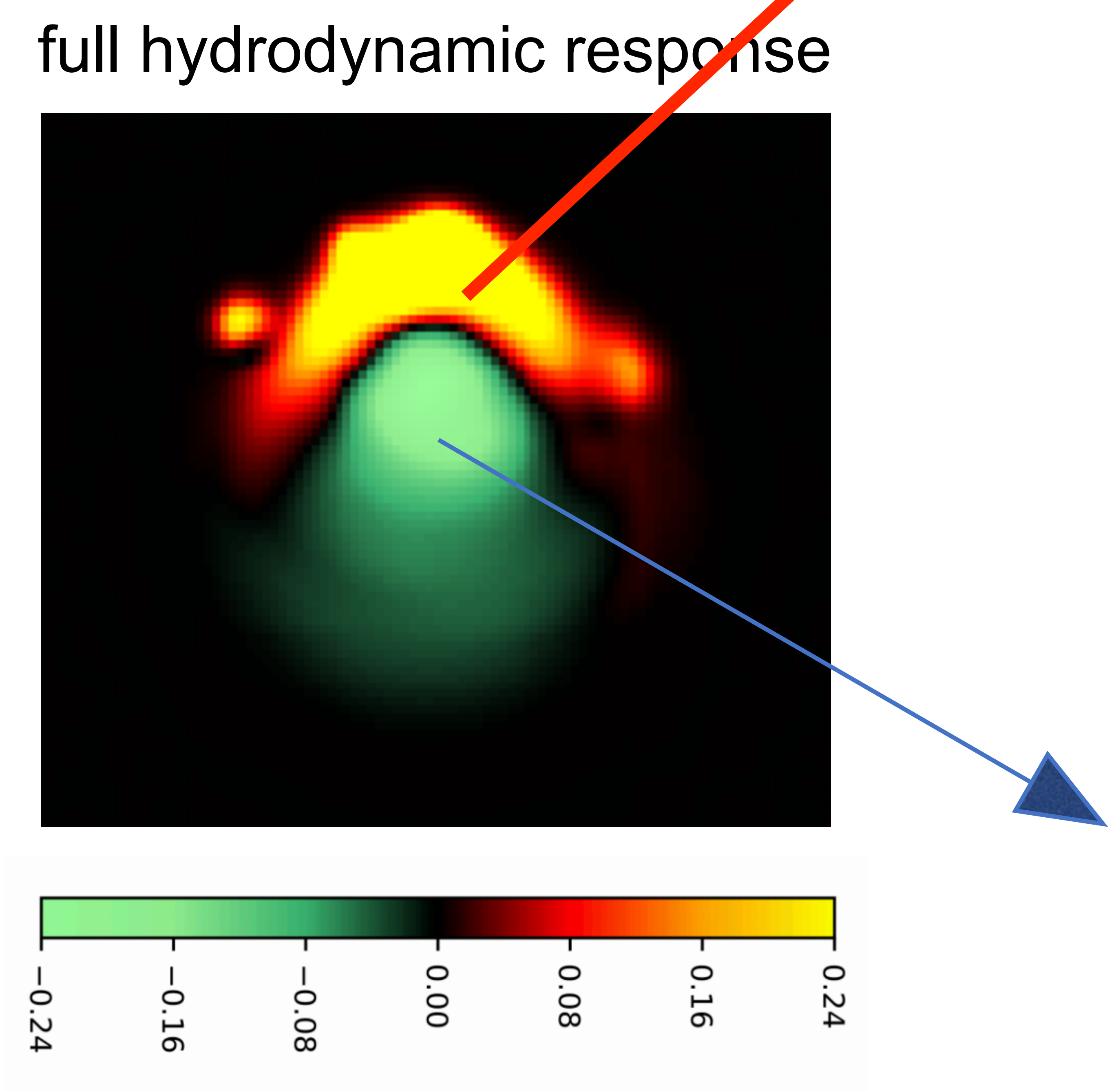
Mean-free-path limits the formation time: $\tau_f \leq \lambda \sim 1/T \qquad \hat{q} \sim T^3$

Medium-induced gluon radiation has the similar effect.

Jet-induced diffusion wake

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

Effect is unique

CoLBT-hydro model

LBT: Linear Boltzmann Transport Model

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

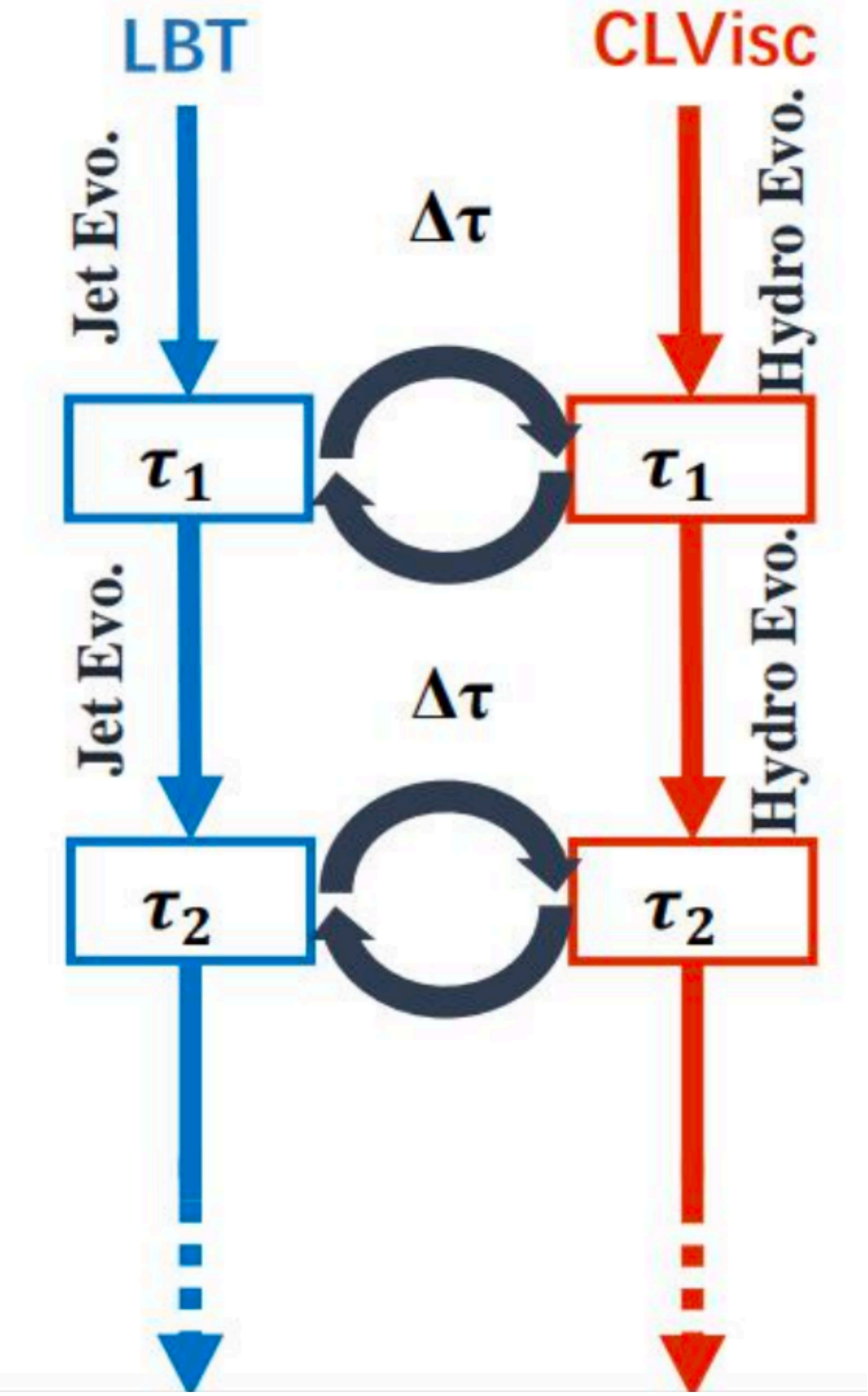
1. LBT for energetic partons(jet shower and recoil)

2. Hydrodynamic model for bulk and soft particles: CLVisc

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

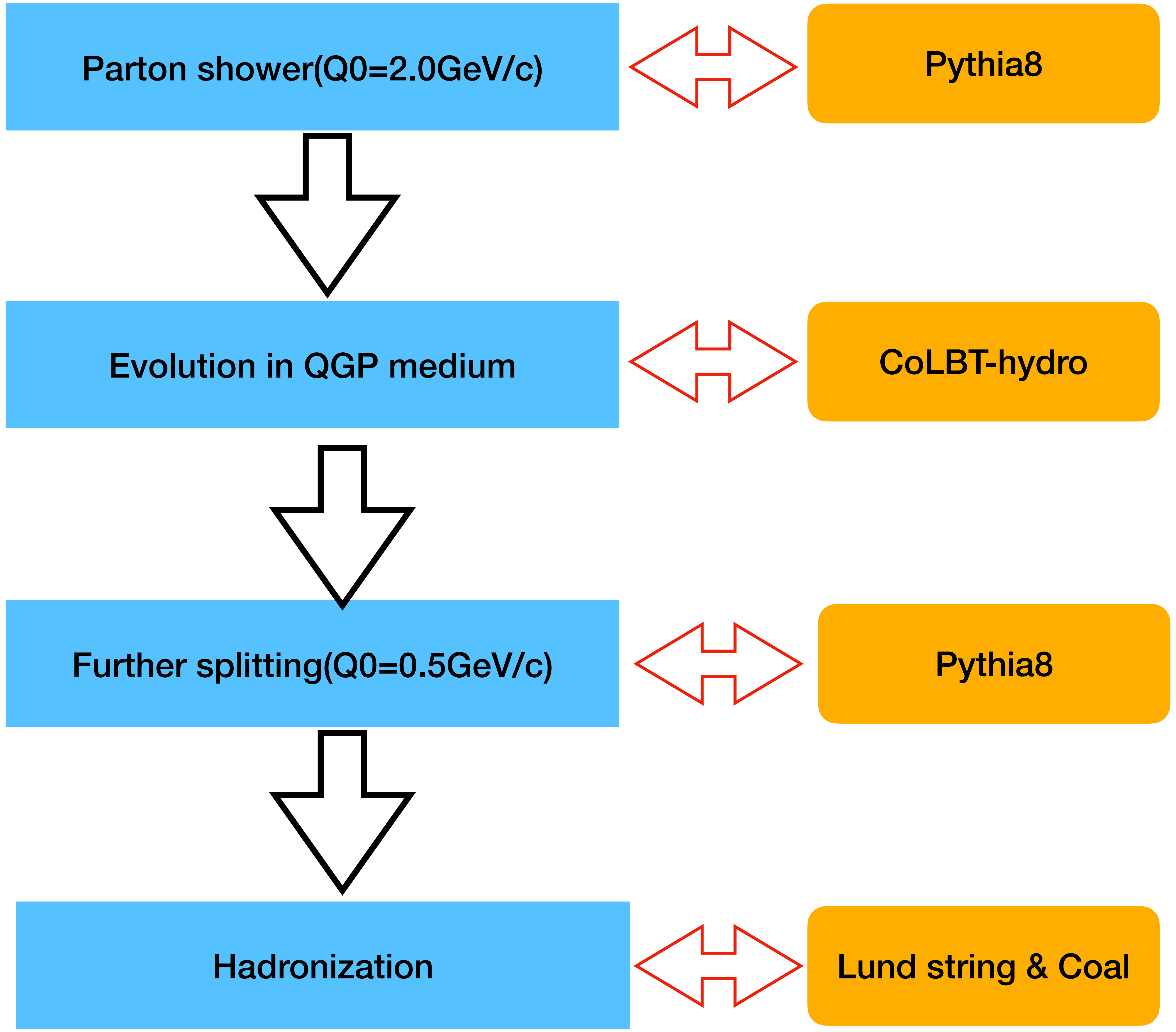
4. Updating medium information by solving the hydrodynamics equation with source term
$$\partial_\mu T^{\mu\nu} = j^\nu$$

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

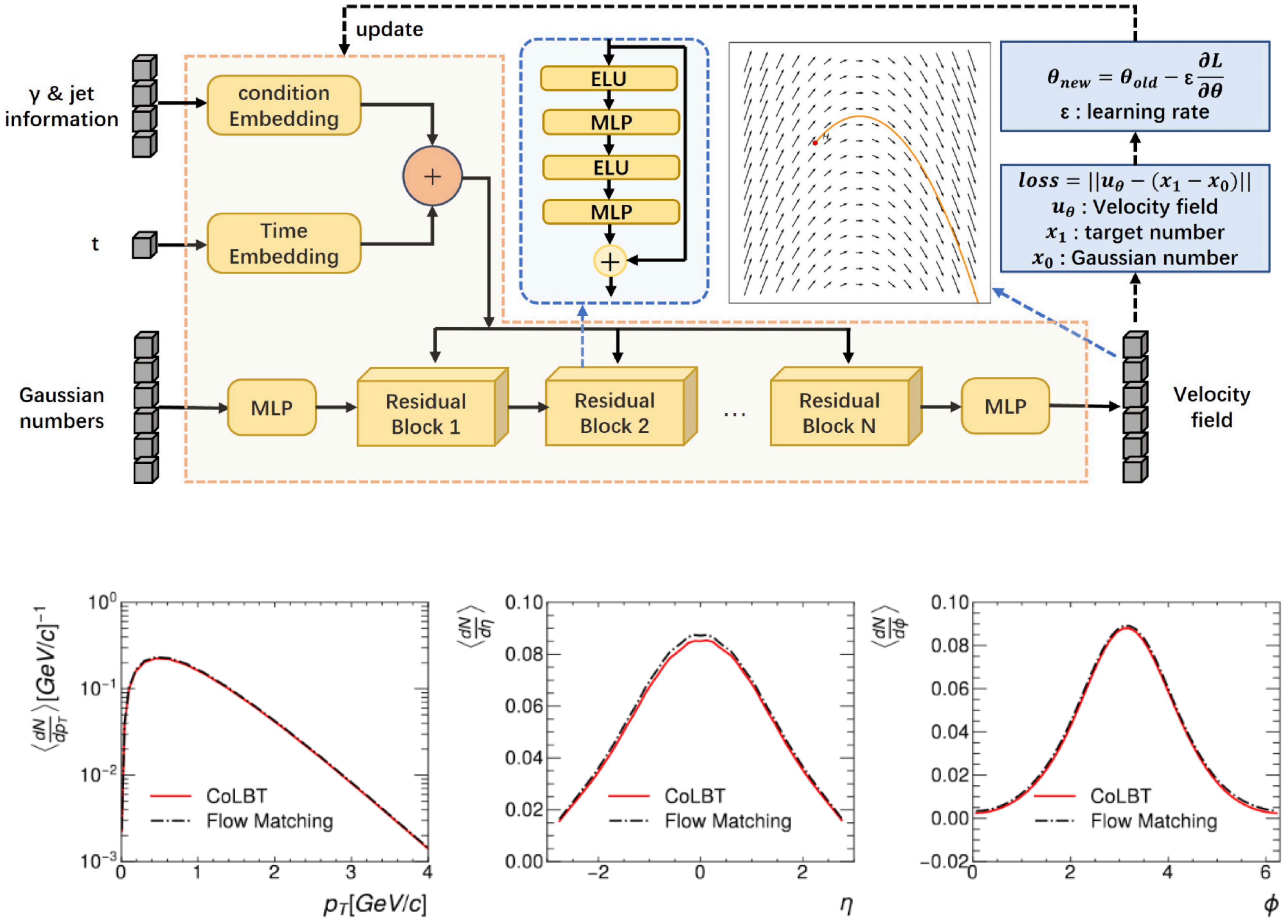


Development of CoLBT-hydro model

Merge vacuum splitting and medium evolution

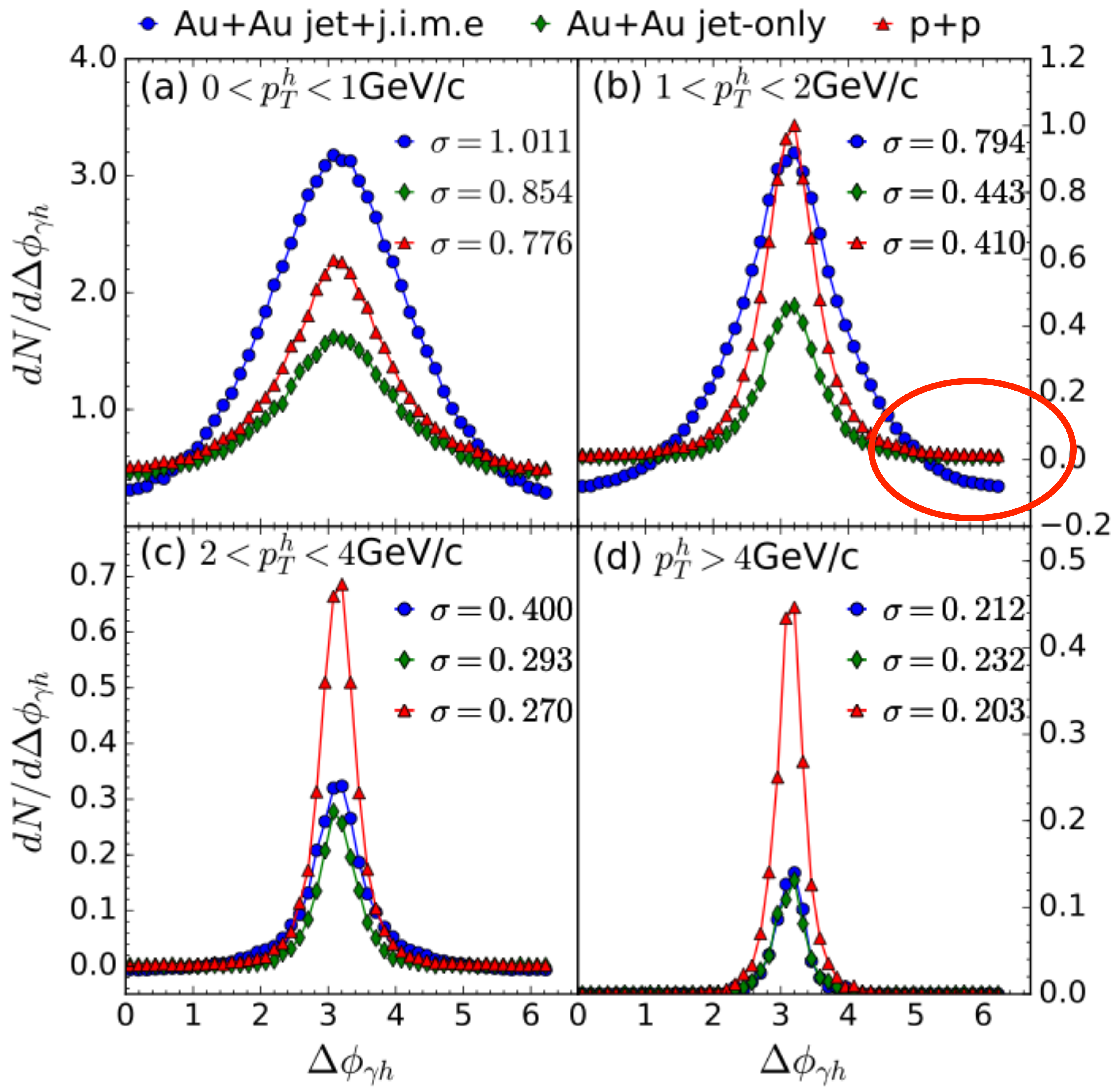


Speed simulation with ML

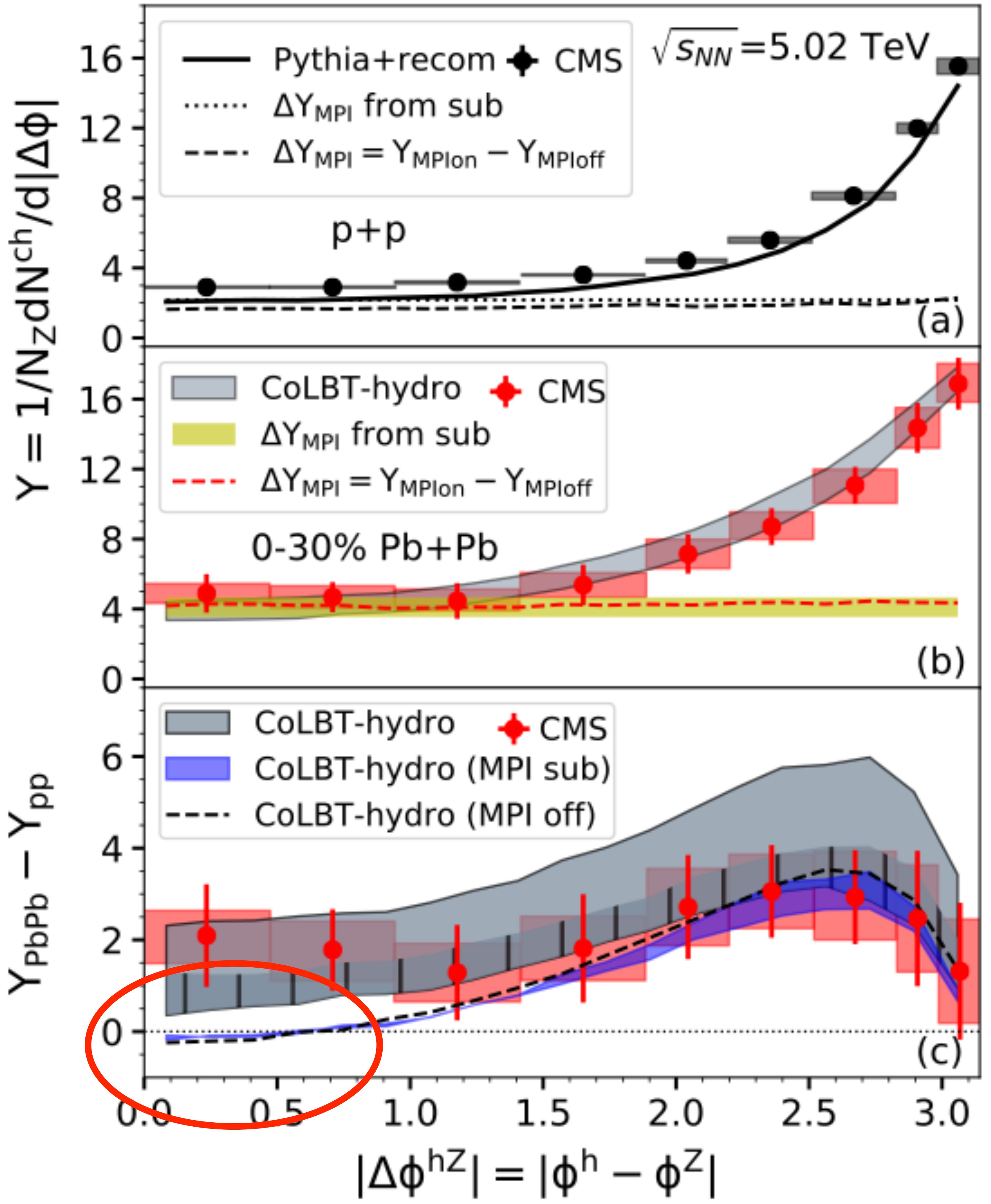


Kai-Yi Wu, ZY, Longgang Pang, Xin-Nian Wang, In preparation

Diffusion wake: depletion of soft hadrons



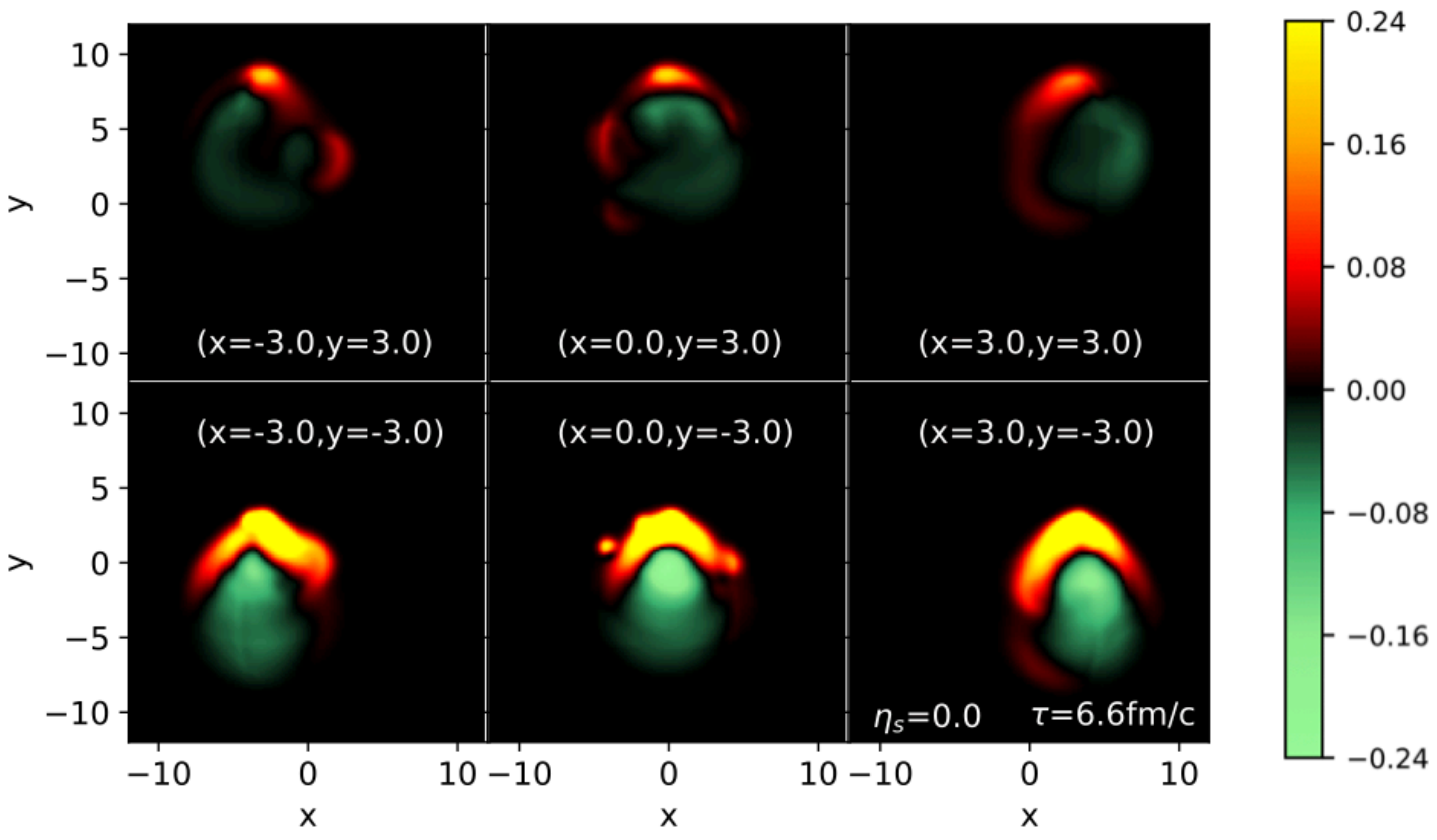
PLB 777 (2018) 86–90

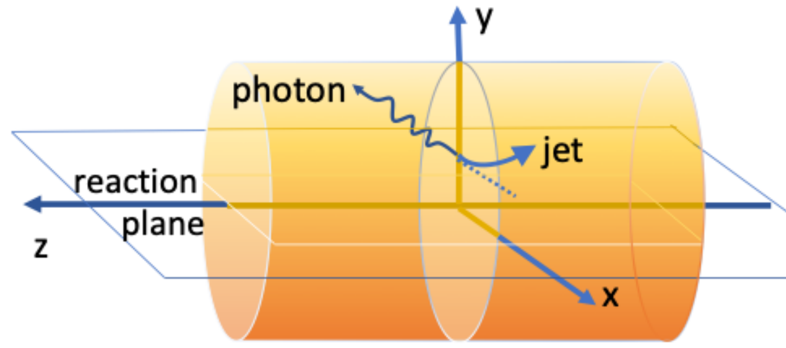


Initial multiple-parton interactions (MPI)

2D Jet tomography

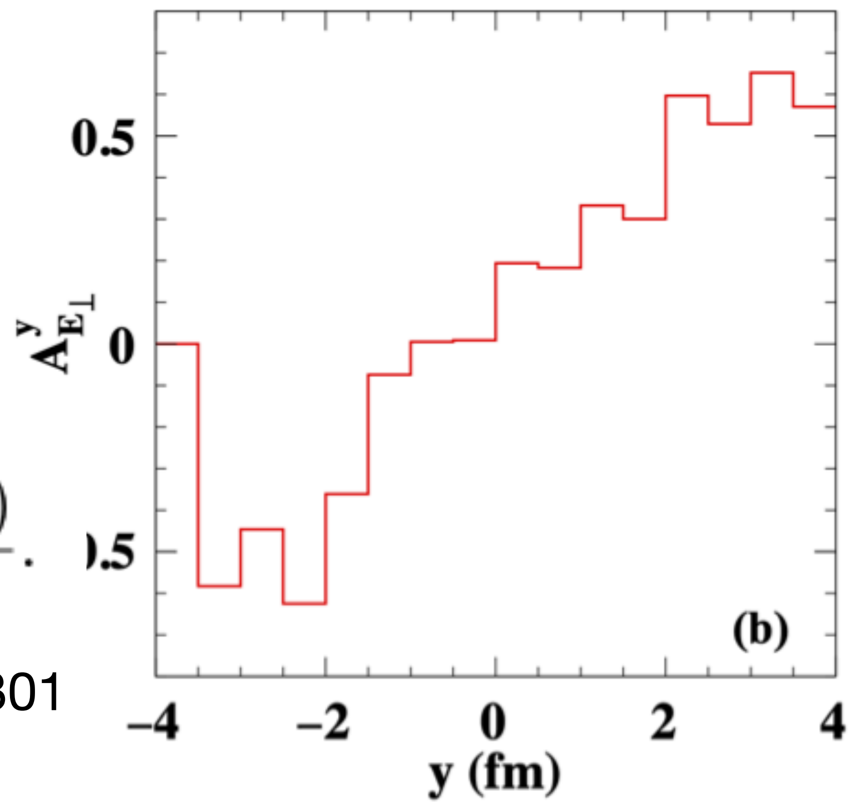
Jet-flow coupling distorted the jet-induced Mach cone, providing a unique opportunity to locate jet initial transverse position.

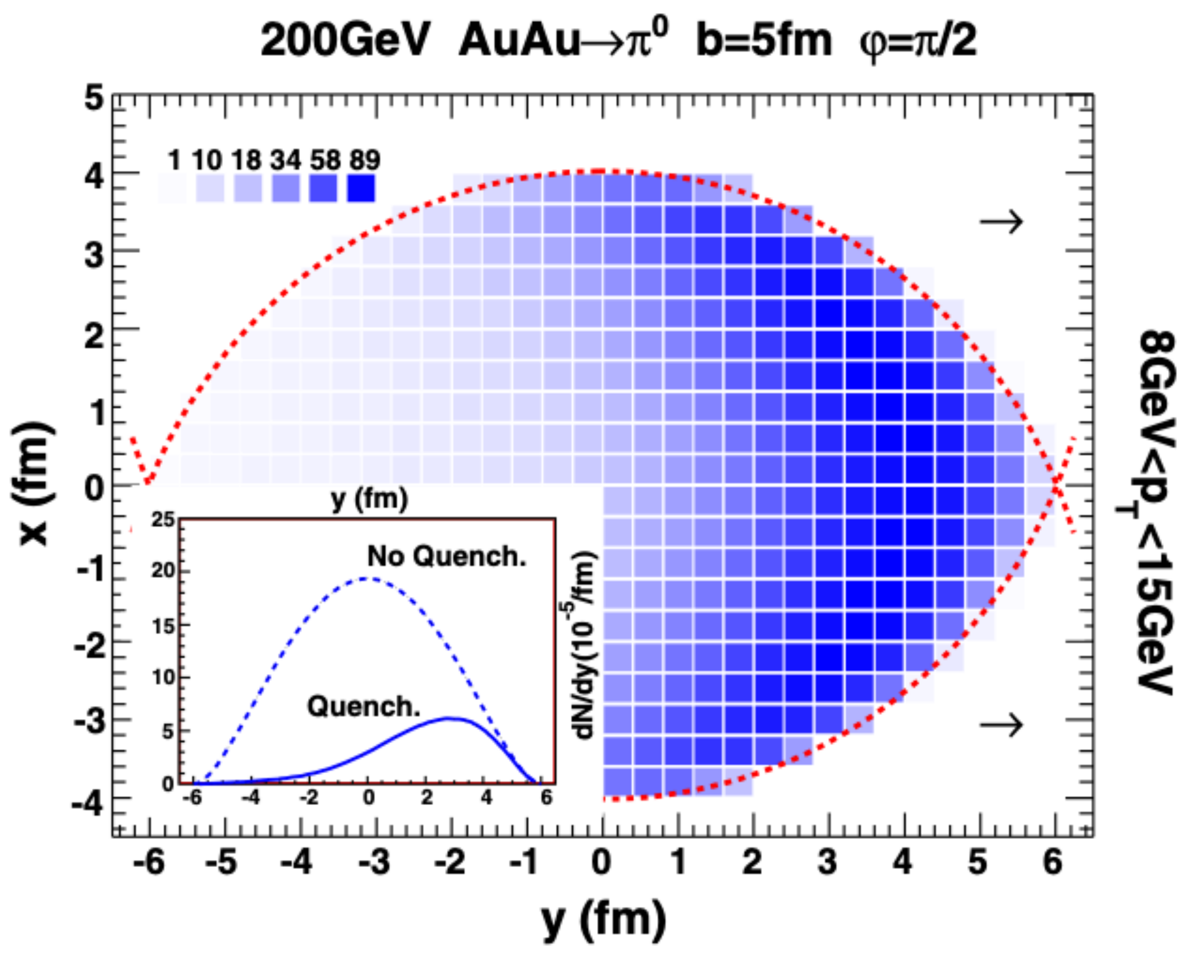




$$A_N^{\vec{n}} = \frac{\int d^3r d^3k f_a(\vec{k},\vec{r}) \mathrm{Sign}(\vec{k}\cdot\vec{n})}{\int d^3r d^3k f_a(\vec{k},\vec{r})}.$$

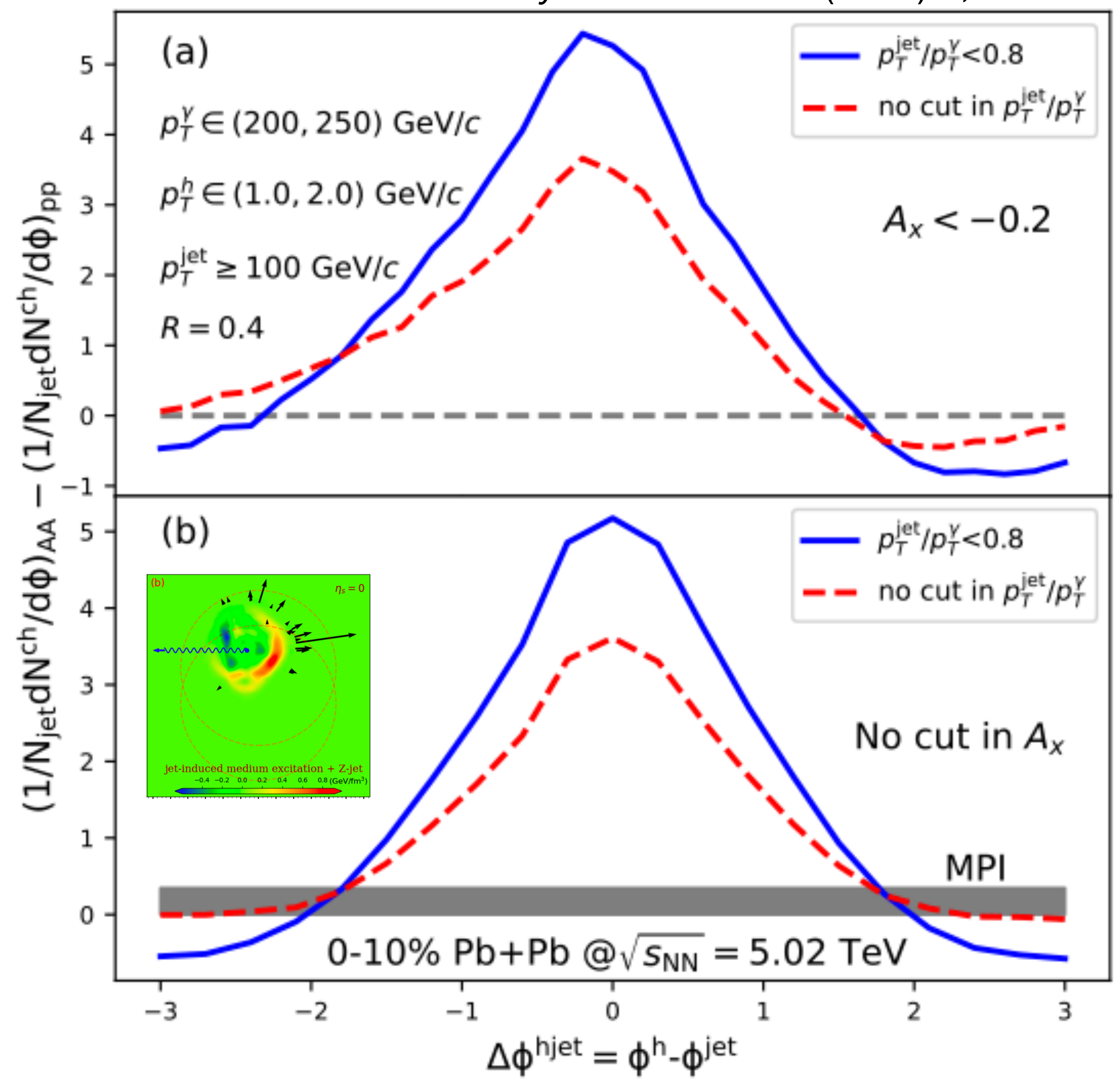
Phys.Rev.Lett. 125 (2020) 12, 122301





Phys.Rev.Lett. 103 (2009) 032302

Phys.Rev.Lett. 127 (2021) 8, 082301

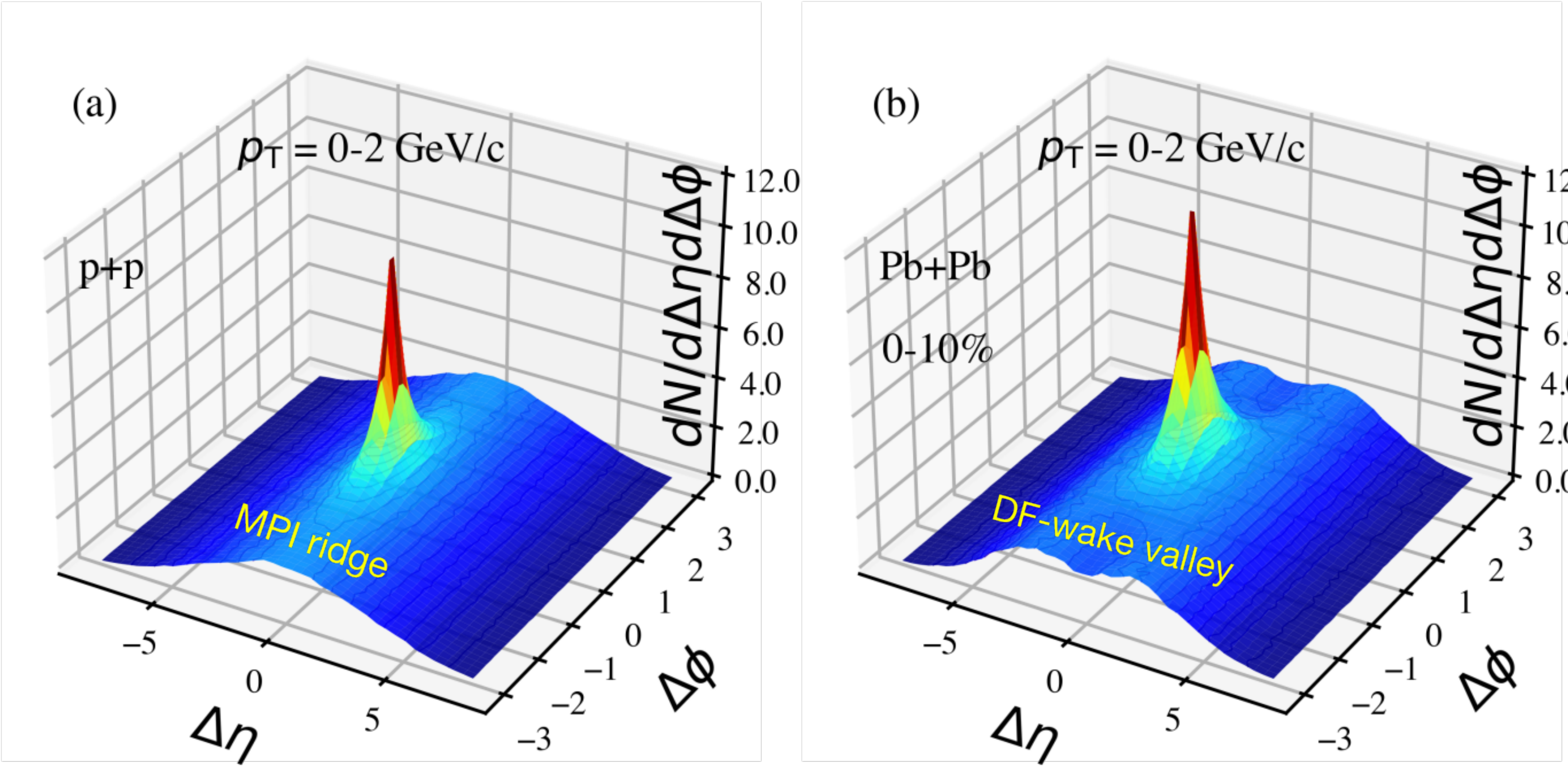


Longitudinal position $\propto$ $p_T^{h,\mathrm{jet}}/p_T^{trigger}$

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

Diffusion wake: depletion of soft hadrons

γ-jet



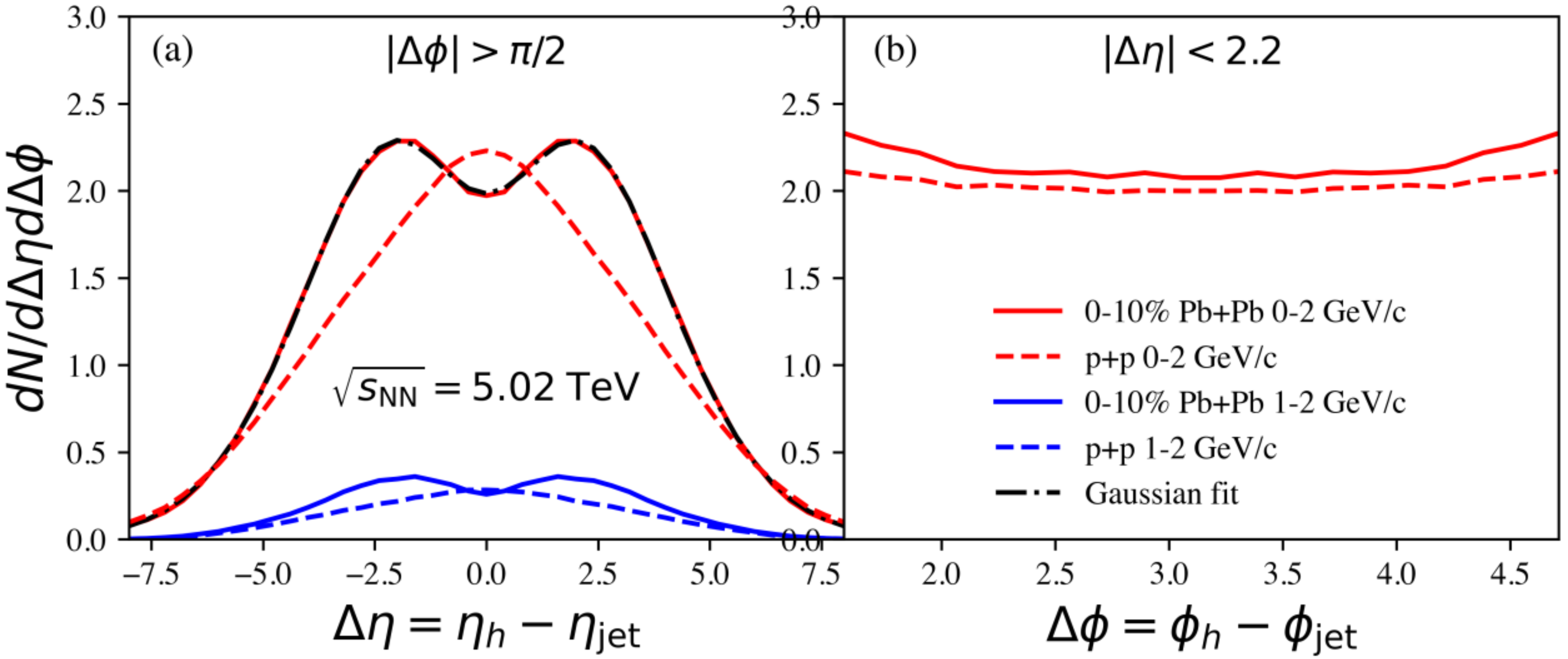
$$\Delta\eta = \eta_h - \eta_{\rm jet}$$

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

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.

Jet-hadron correlation in rapidity direction



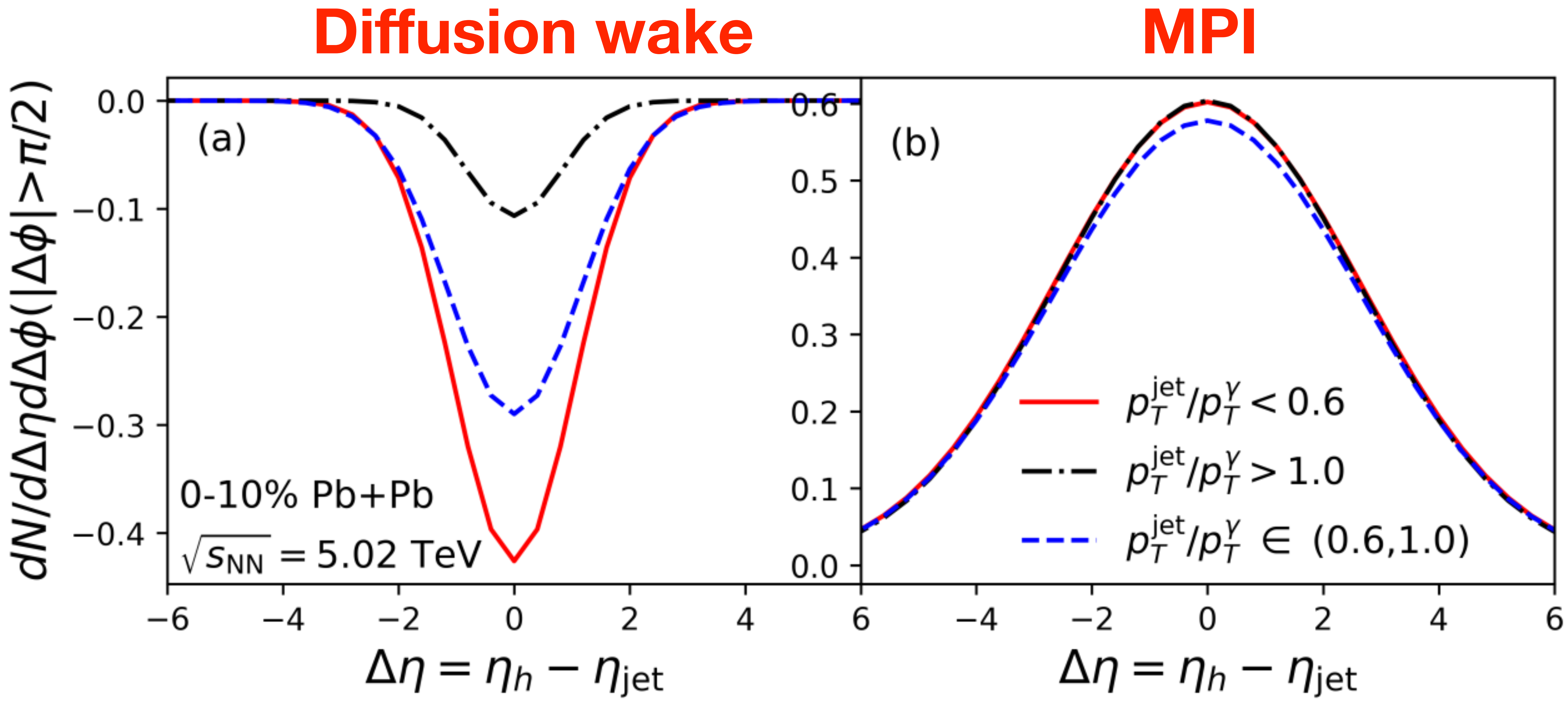
2-Gaussian fitting:

$$F(\Delta\eta) = \int_{\eta_{j1}}^{\eta_{j2}} d\eta_j F_3(\eta_j)(F_2(\Delta\eta, \eta_j) + F_1(\Delta\eta))$$

$$F_1(\Delta\eta) = A_1 e^{-\Delta\eta^2/\sigma_1^2}$$

$$F_2(\Delta\eta, \eta_j) = A_2 e^{-(\Delta\eta+\eta_j)^2/\sigma_2^2}$$

Extract diffusion wake: dependence on energy loss



Longer propagation length and larger jet energy loss leads to deeper DF-W valley.

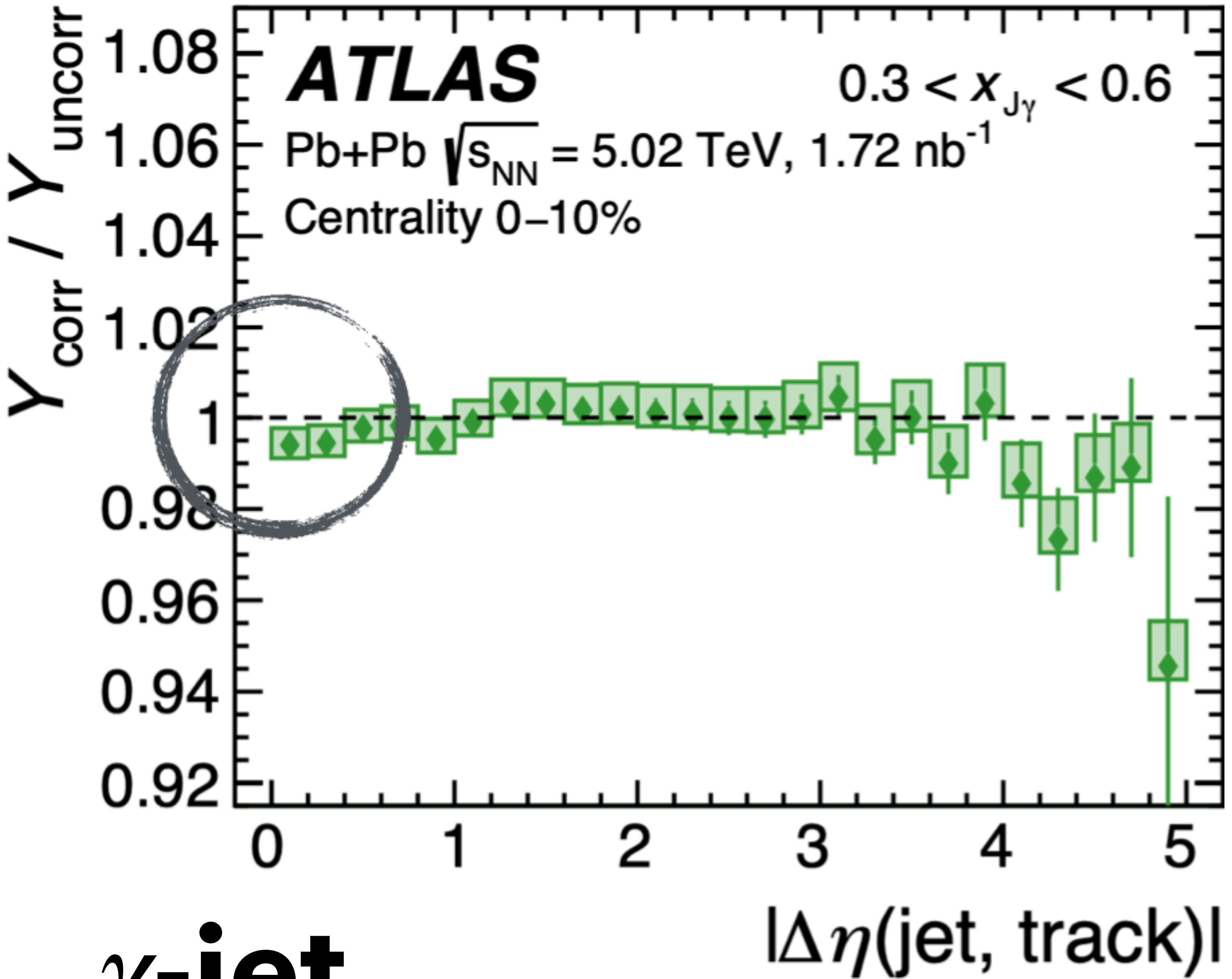
The MPI ridge has a very weak and non-monotonic dependence on $x_{j\gamma}$ due to the non-monotonic dependence of the propagation length on $x_{j\gamma}$ for mini-jets from MPI.

Jet-hadron correlation in rapidity direction

ATLAS

No background subtraction

$$Y_{\mathrm{corr}} = \frac{1}{N^{\gamma-\mathrm{jet}}} \frac{d^2 N^{\mathrm{jet-track}}}{d\Delta\eta d\Delta\phi}$$



γ-jet

Phys. Rev. C 111, 044909 (2025)

CMS

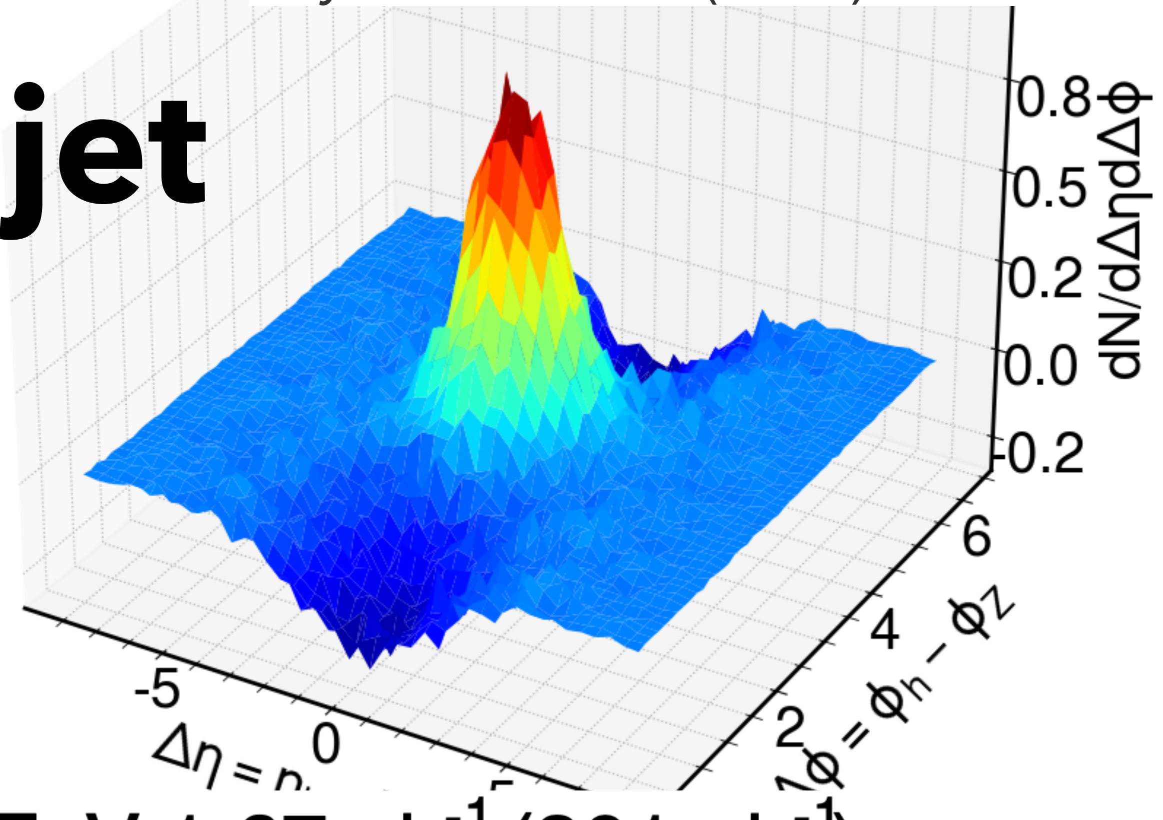
Mixed-event subtraction

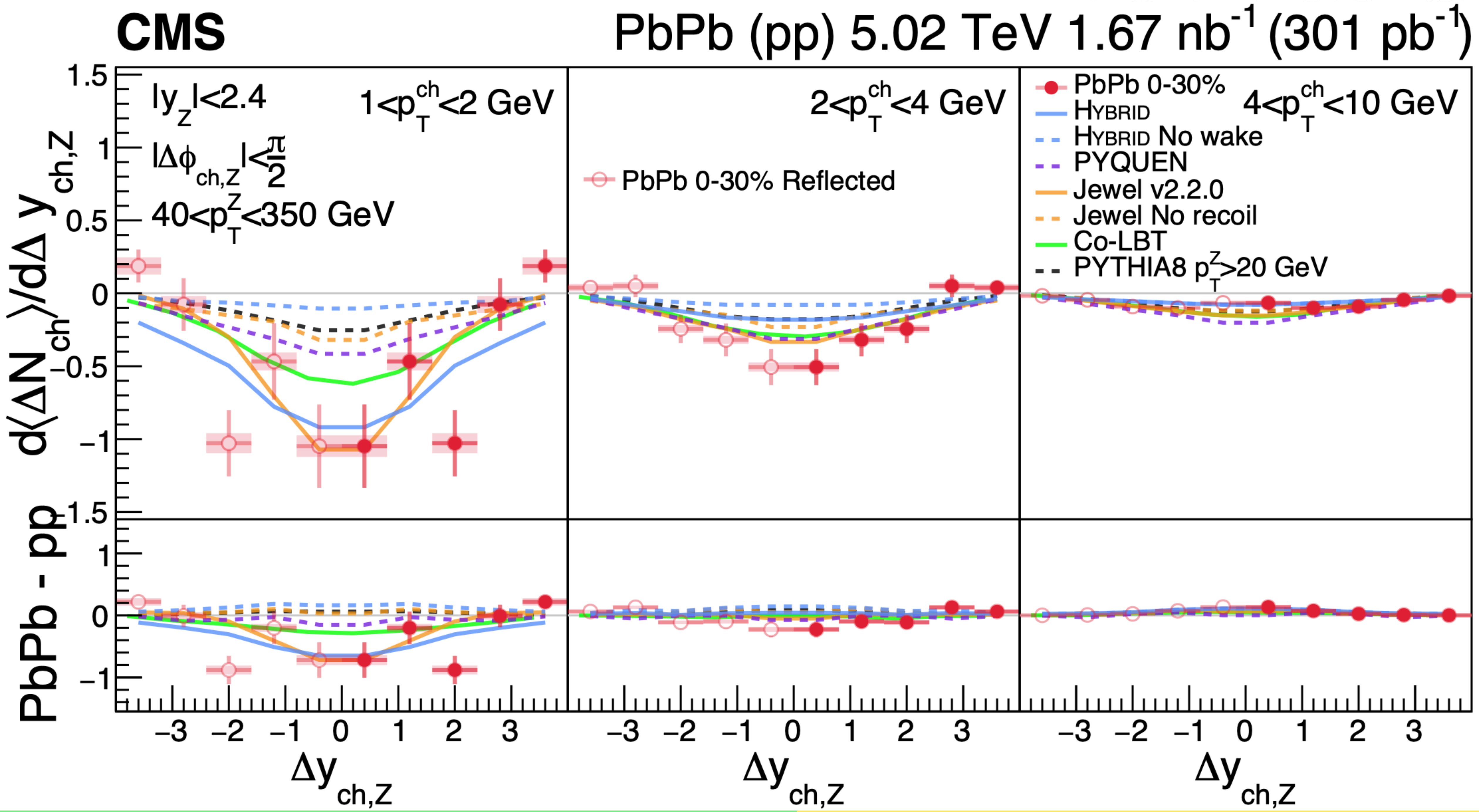
$$S(\Delta\phi_{ch,z}, \Delta y_{ch,z}) = \frac{1}{N_z} \frac{d^2 N^{same}}{d\Delta\phi_{ch,z} d\Delta y_{ch,z}}$$

$$B(\Delta\phi_{ch,z}, \Delta y_{ch,z}) = \frac{1}{N_z} \frac{d^2 N^{mix}}{d\Delta\phi_{ch,z} d\Delta y_{ch,z}}$$

Phys.Lett.B 874 (2026) 140120

Z-jet





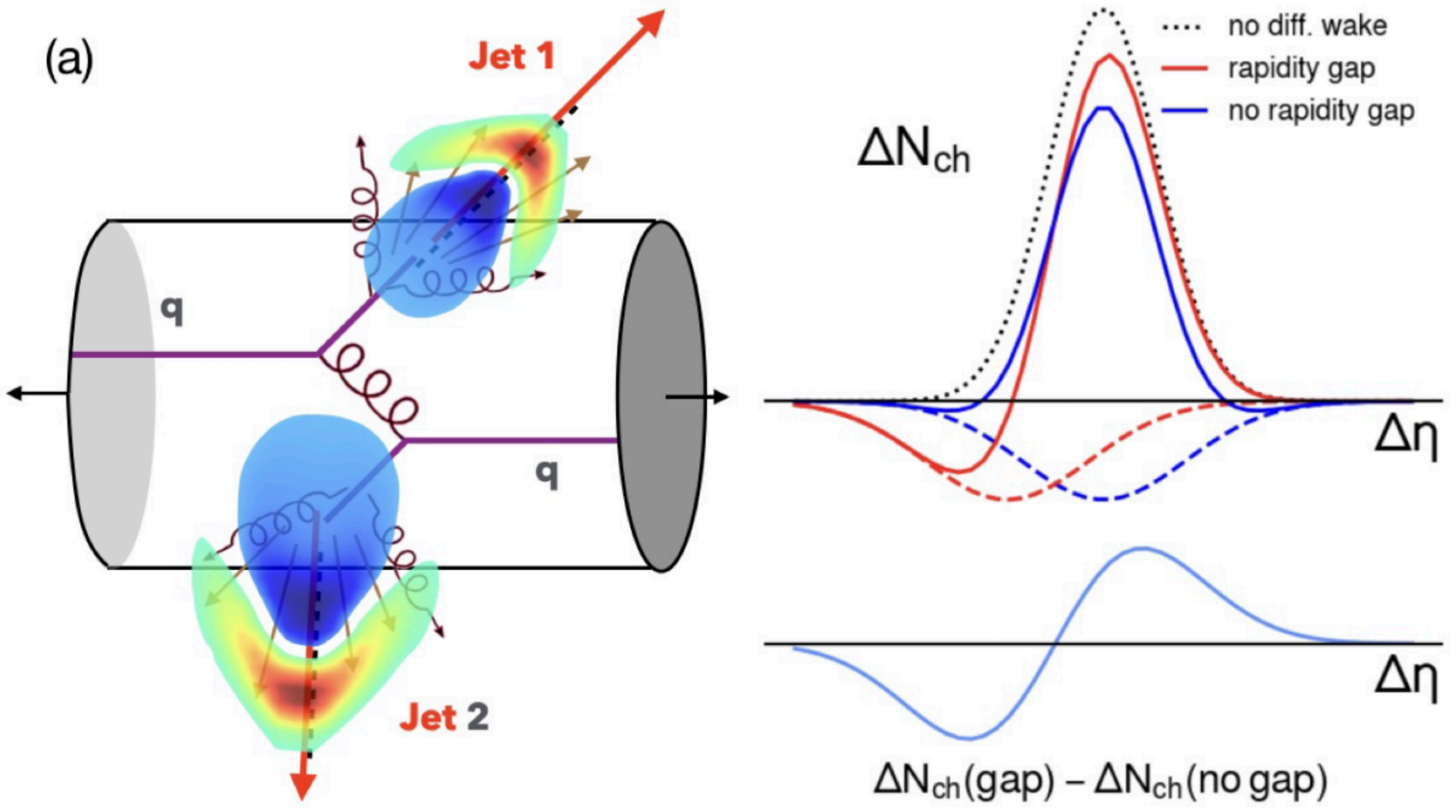
How to search for diffusion wake in di-jets

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

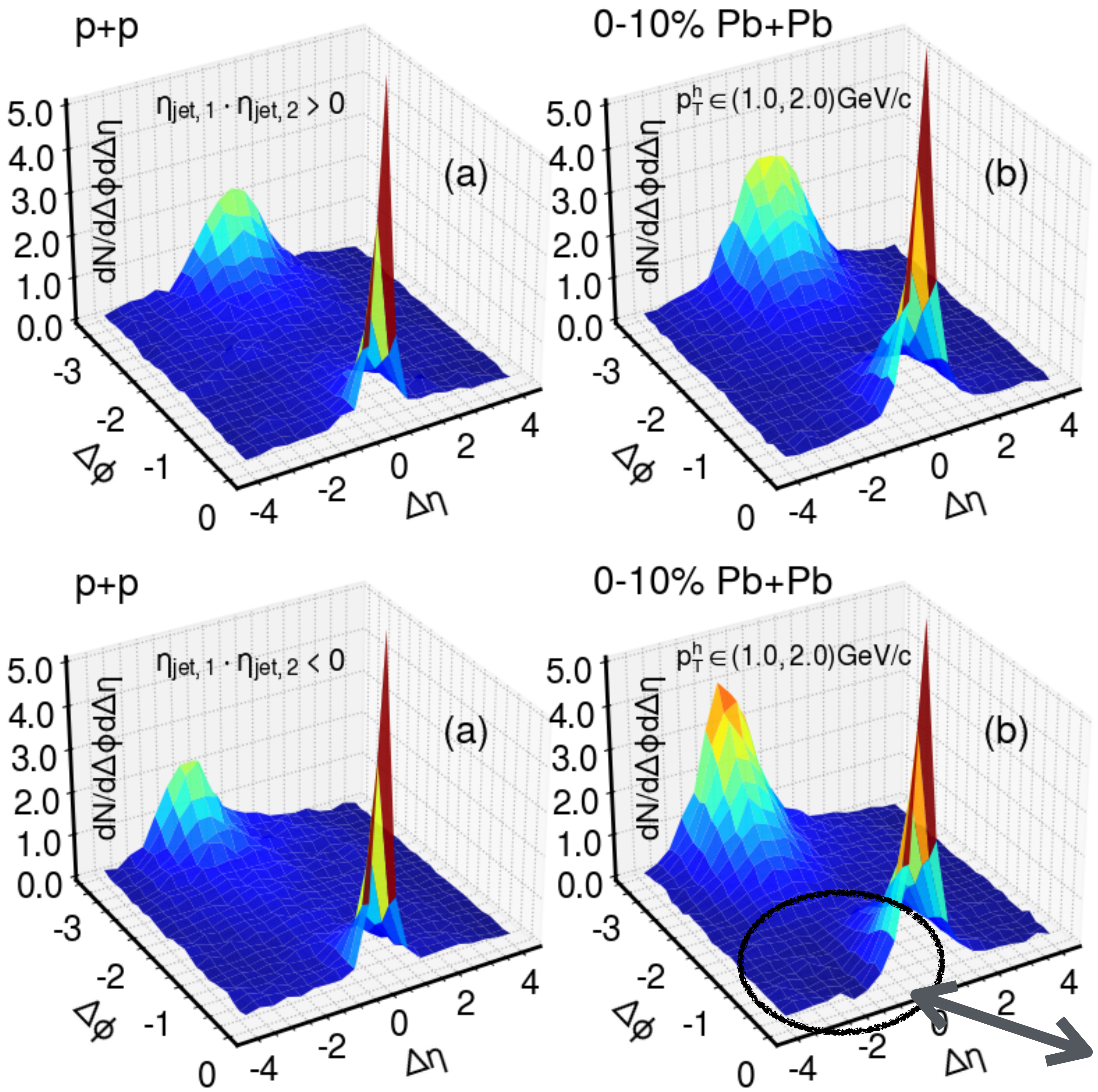
Eta	Phi
Same as jet	Opposite to jet



Challenge:

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

Diffusion wake induced by Di-jets



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

We use leading jet as reference to get 2D plots

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

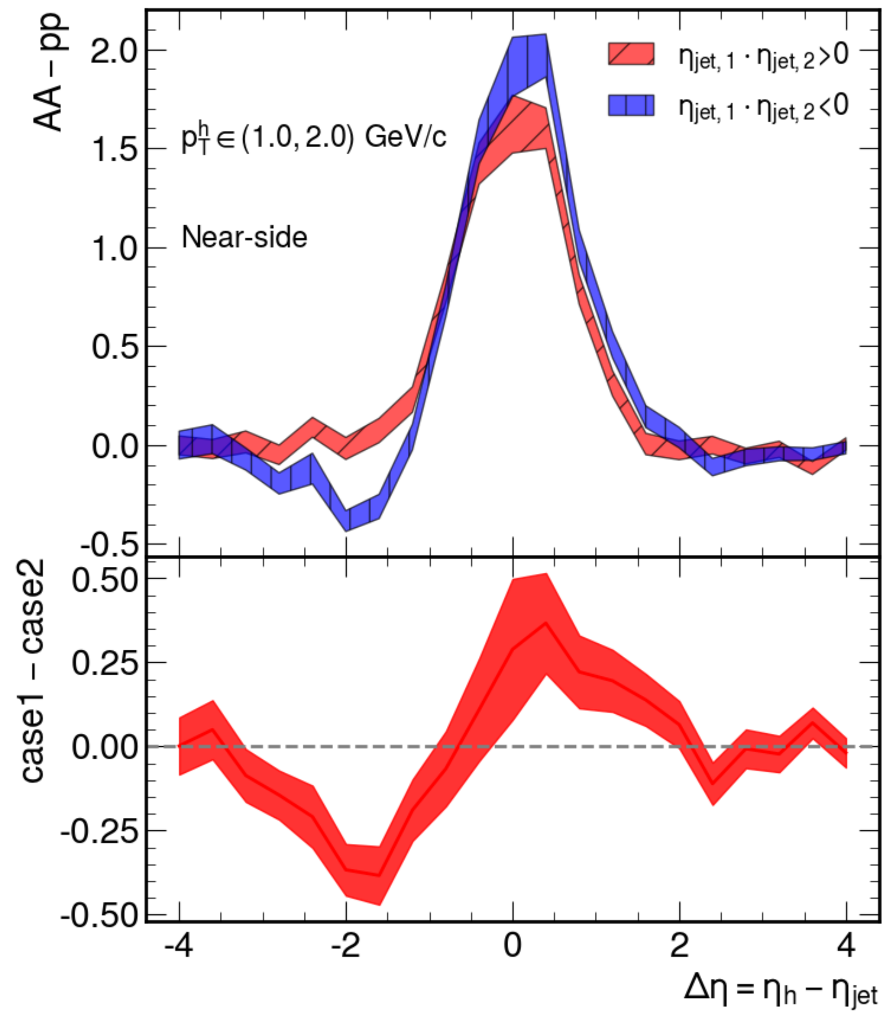
$$p_T^{sub-leading,jet} > 90\, GeV/c$$

Require leading jet with larger rapidity

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

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

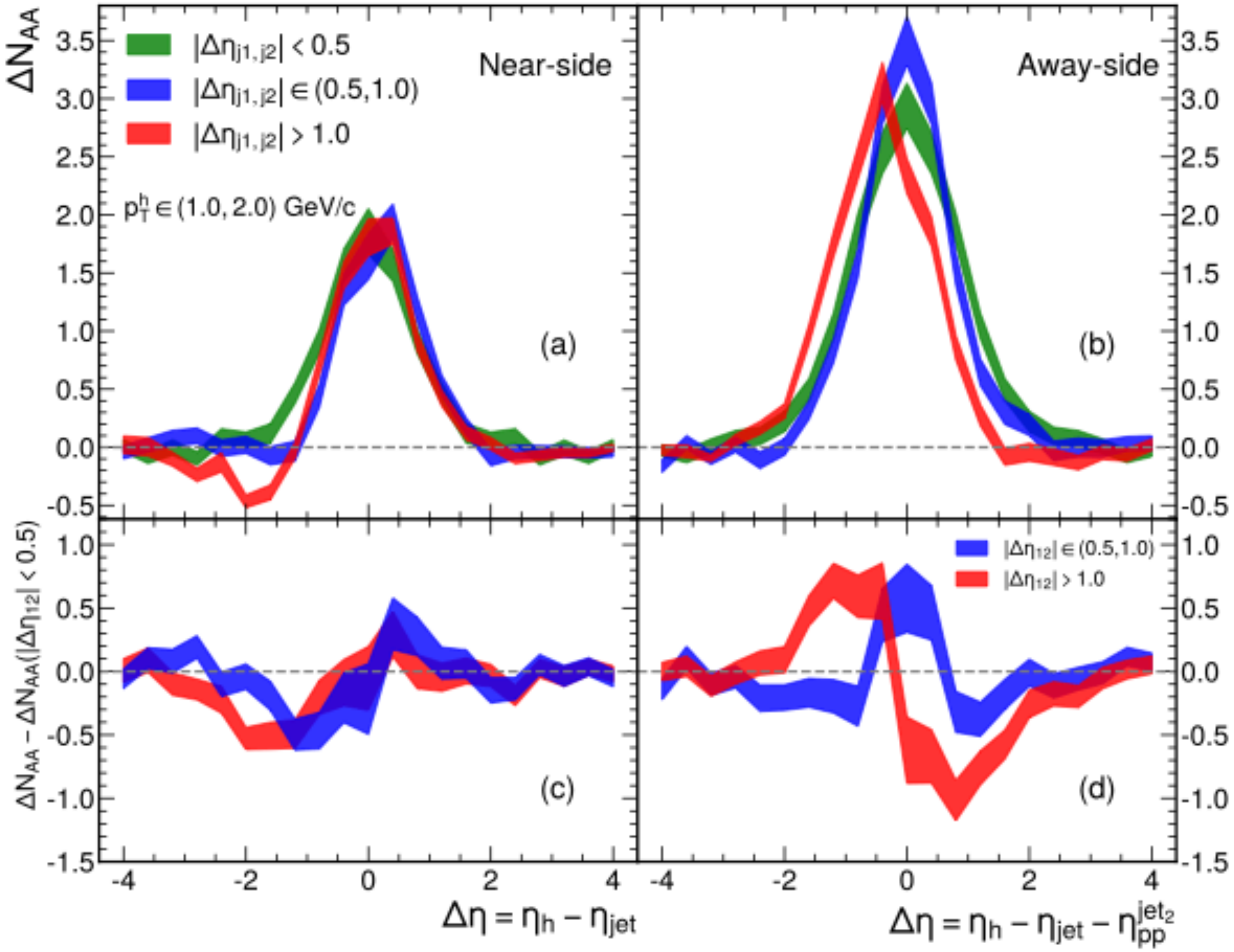
$$\eta_{jet,1} \cdot \eta_{jet,2} < 0\, (large\ gap)$$



Valley caused by diffusion wake

Rapidity asymmetry vs Rapidity gaps

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

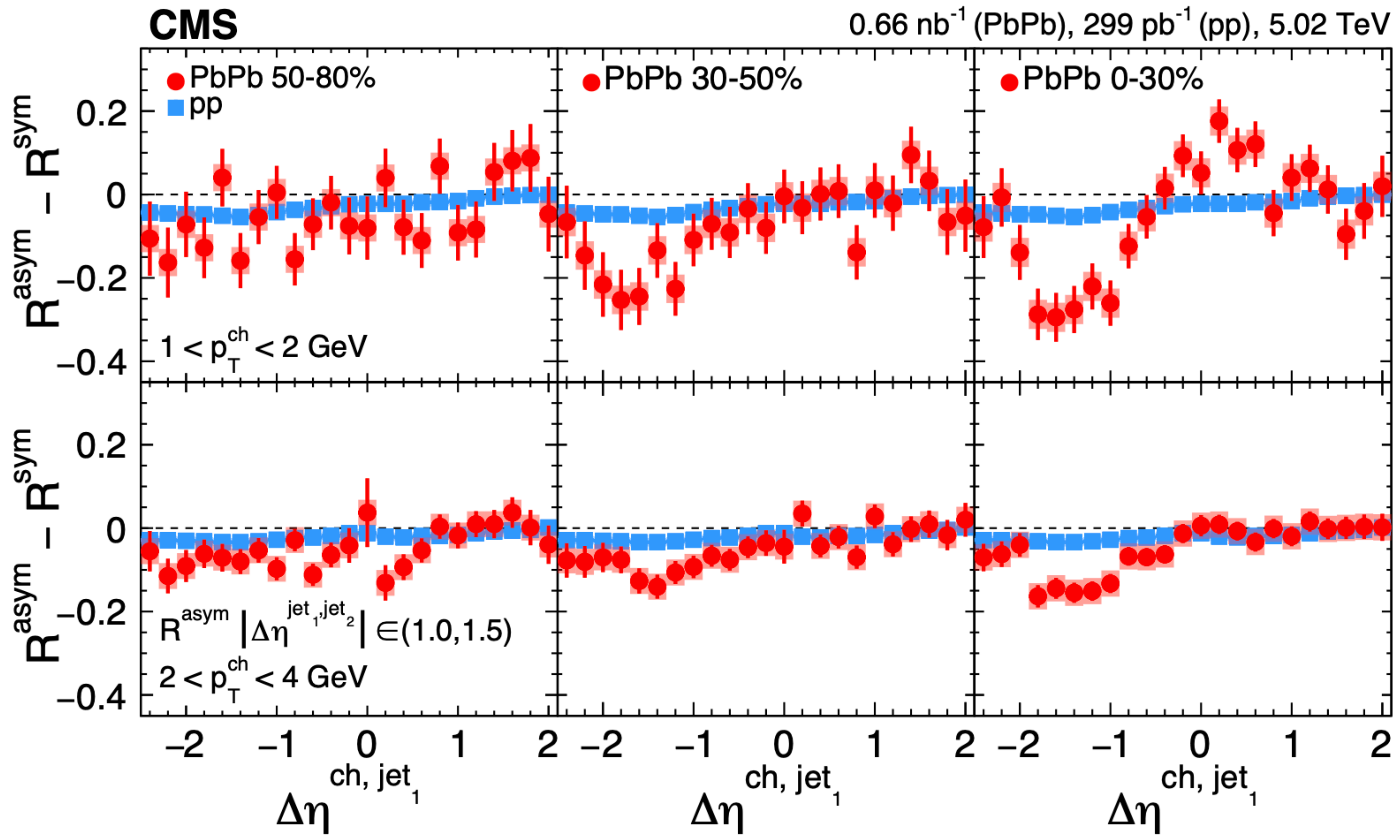
Away-side: $\Delta\phi_{j_1,h} > \pi/2$ (Shift by the peak in pp)

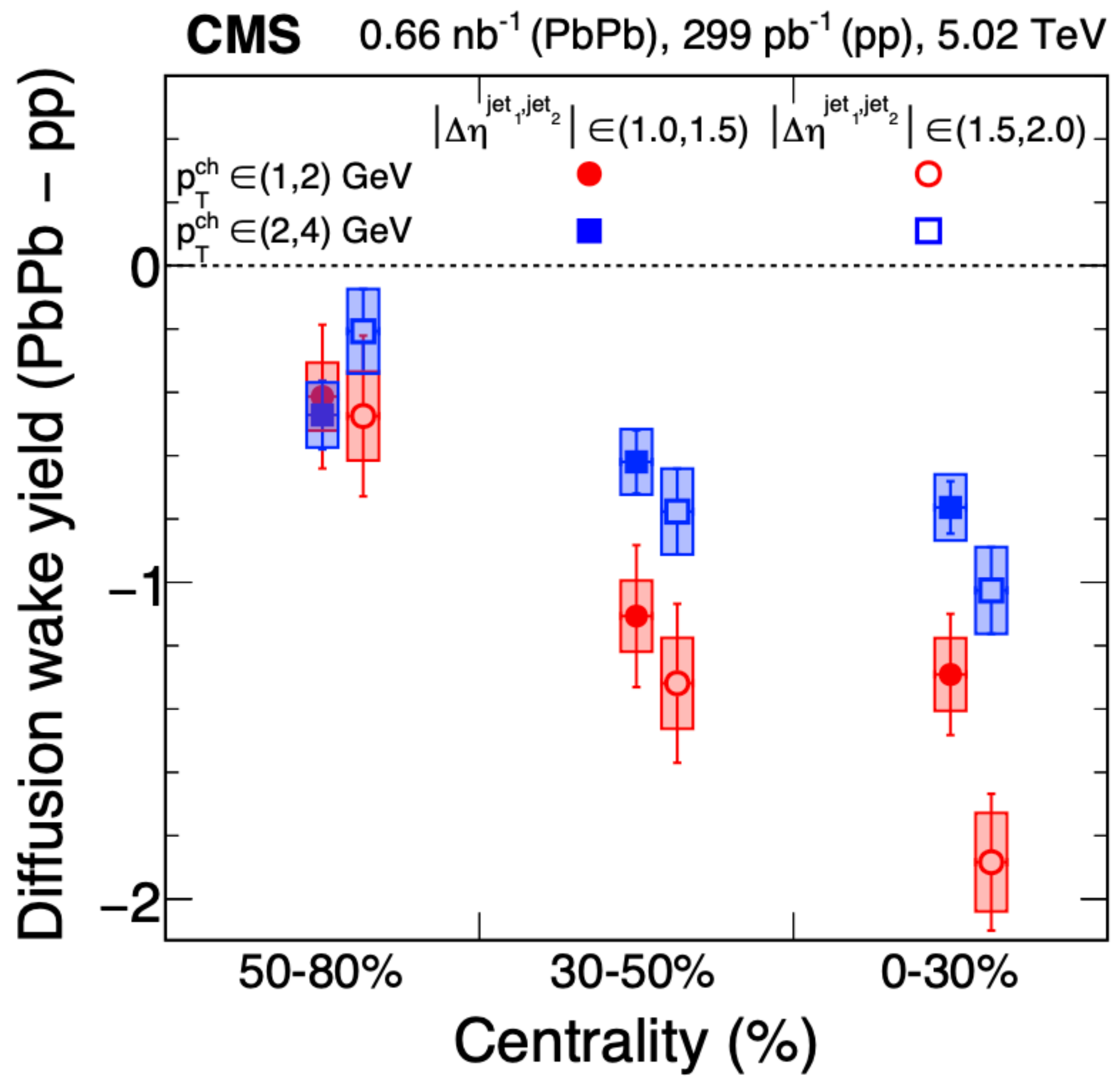
$$\Delta N_{\mathrm{AA}} = \int d\Delta\phi \left[\frac{dN_{\mathrm{AA}}}{d\Delta\phi d\Delta\eta} - \frac{dN_{\mathrm{pp}}}{d\Delta\phi d\Delta\eta}\right]$$

Observation of di-jet diffusion wake signal at CMS

CMS observed the first signal of diffusion wake of di-jets

arXiv: 2602.19431

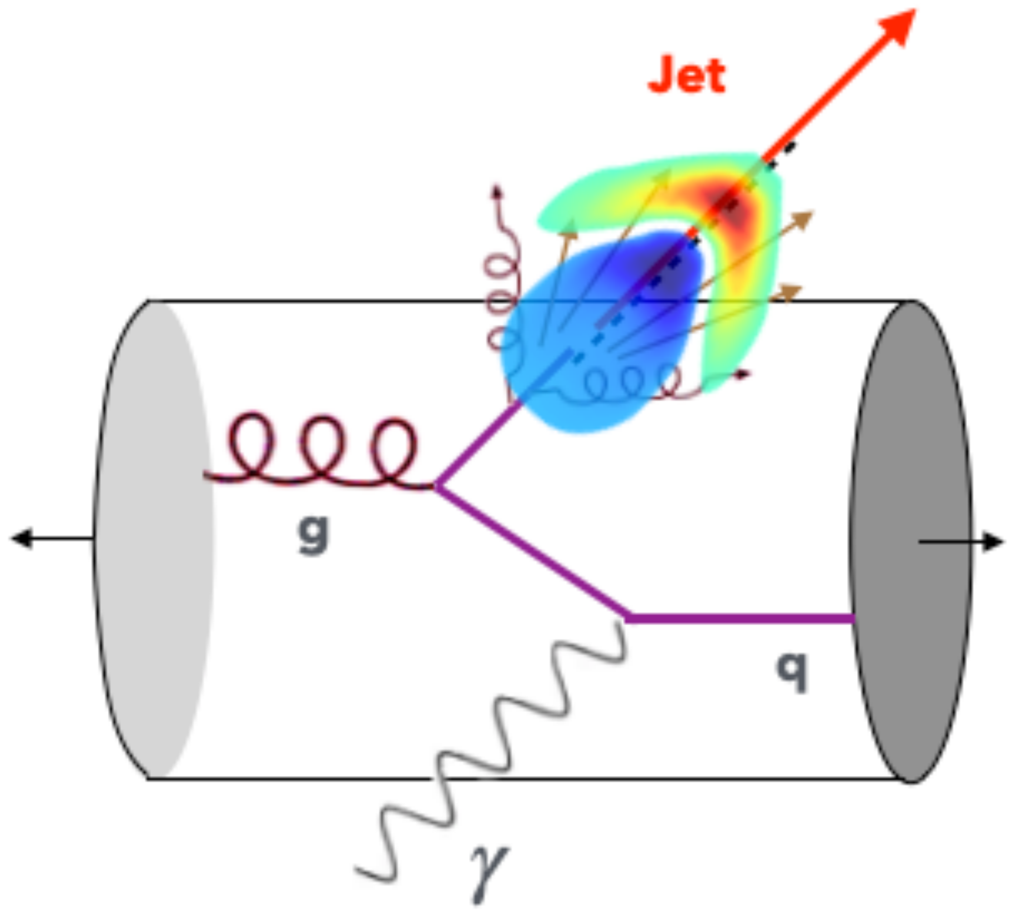




Background free signal of diffusion wake

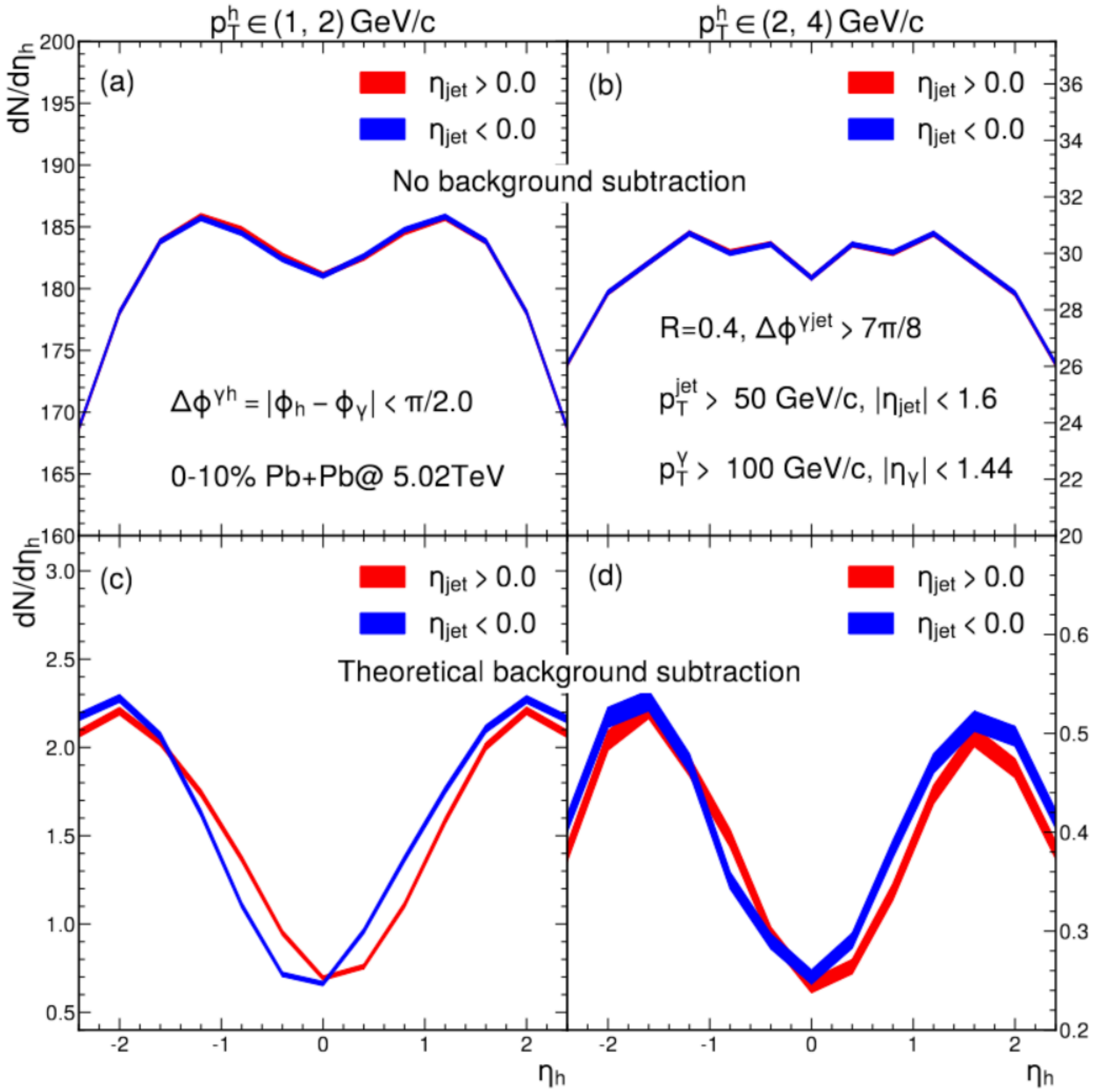
Using the η distribution instead of $\Delta\eta$ can remove rapidity dependence of track on jet.

We firstly focus on γ-jet



The signal of DW is clear in the γ direction

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



arXiv:2508.04194

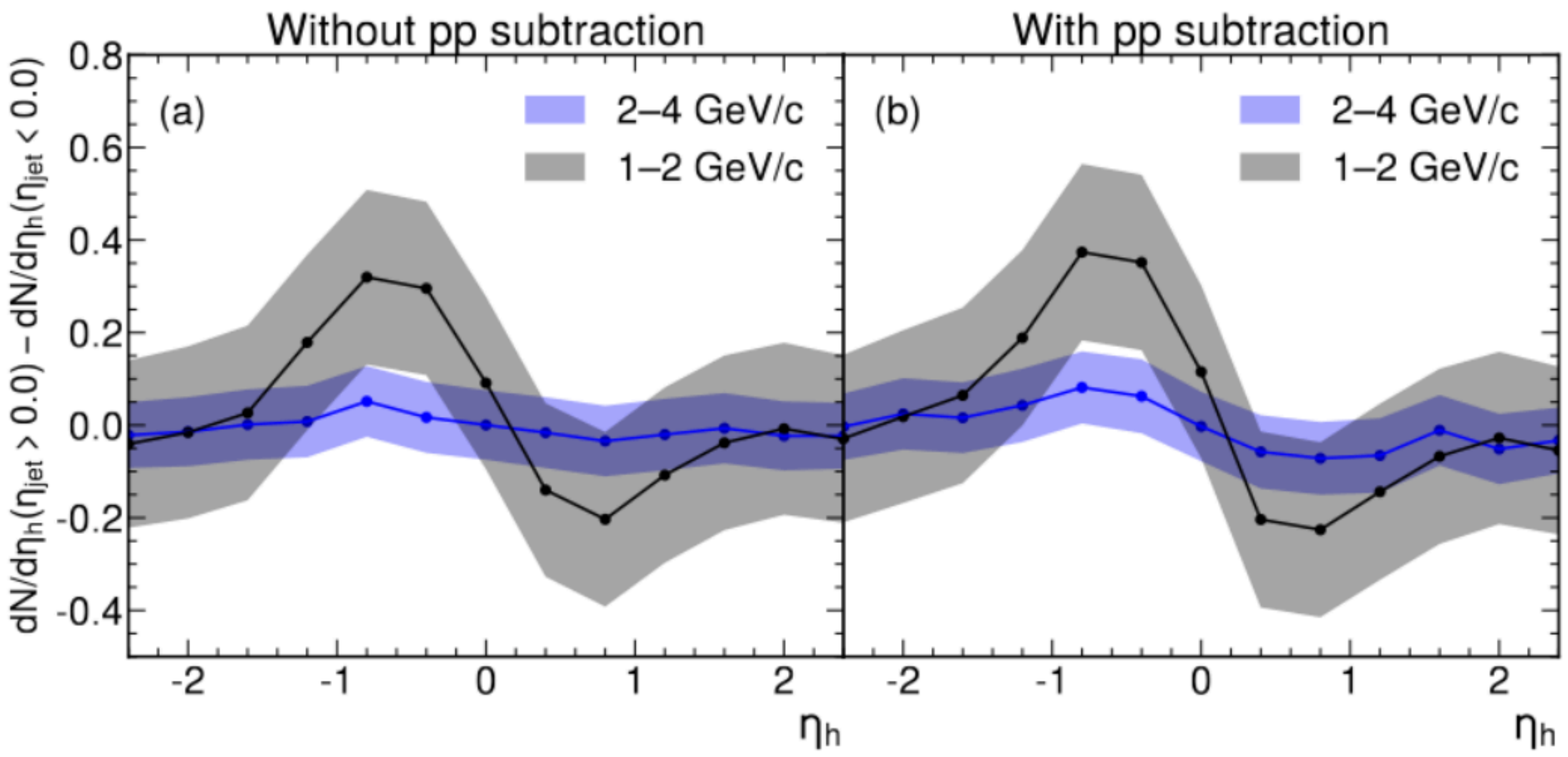
Pure distribution (including background)

Signal distribution (background subtracted)

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*



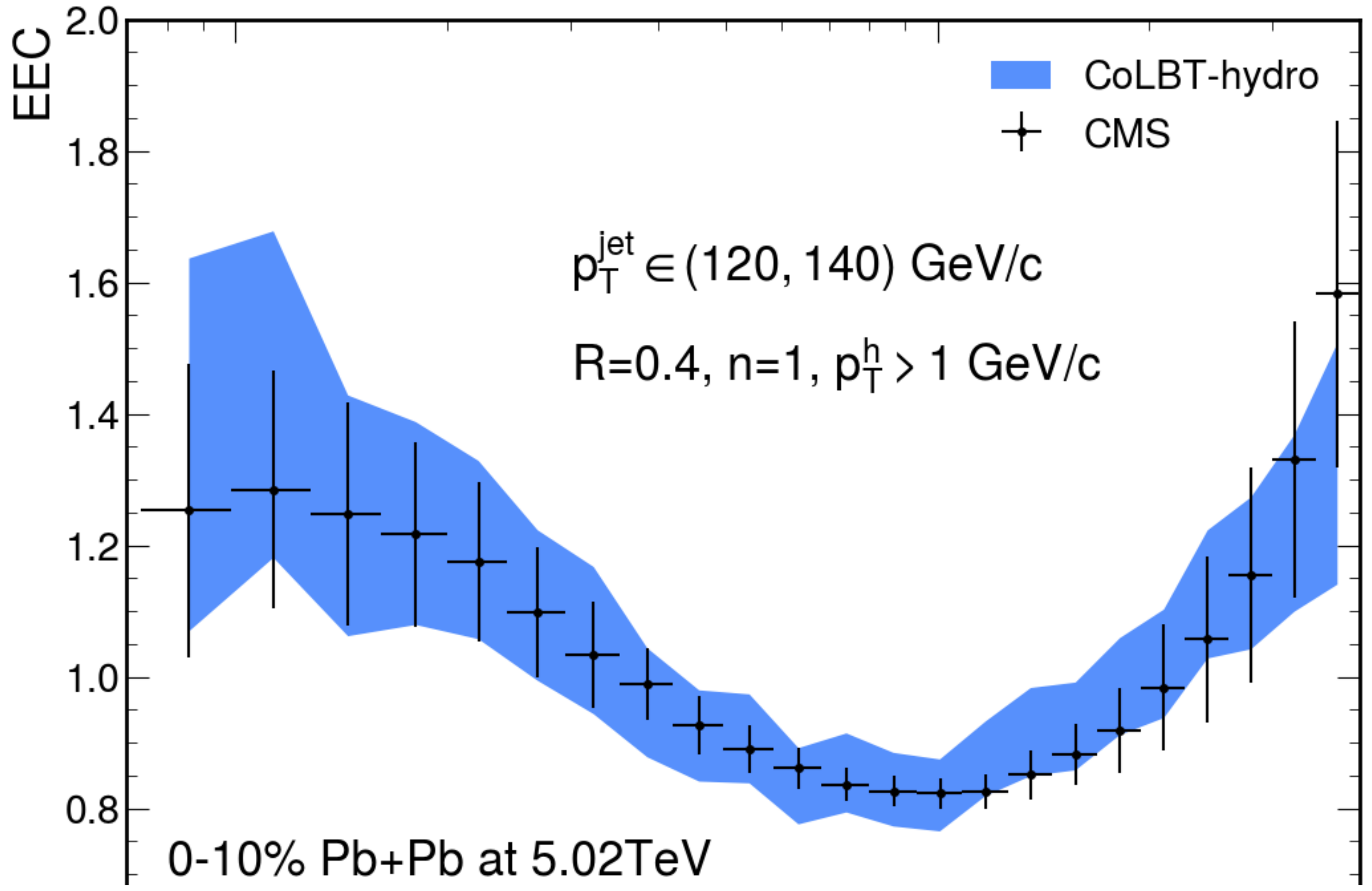
arXiv:2508.04194

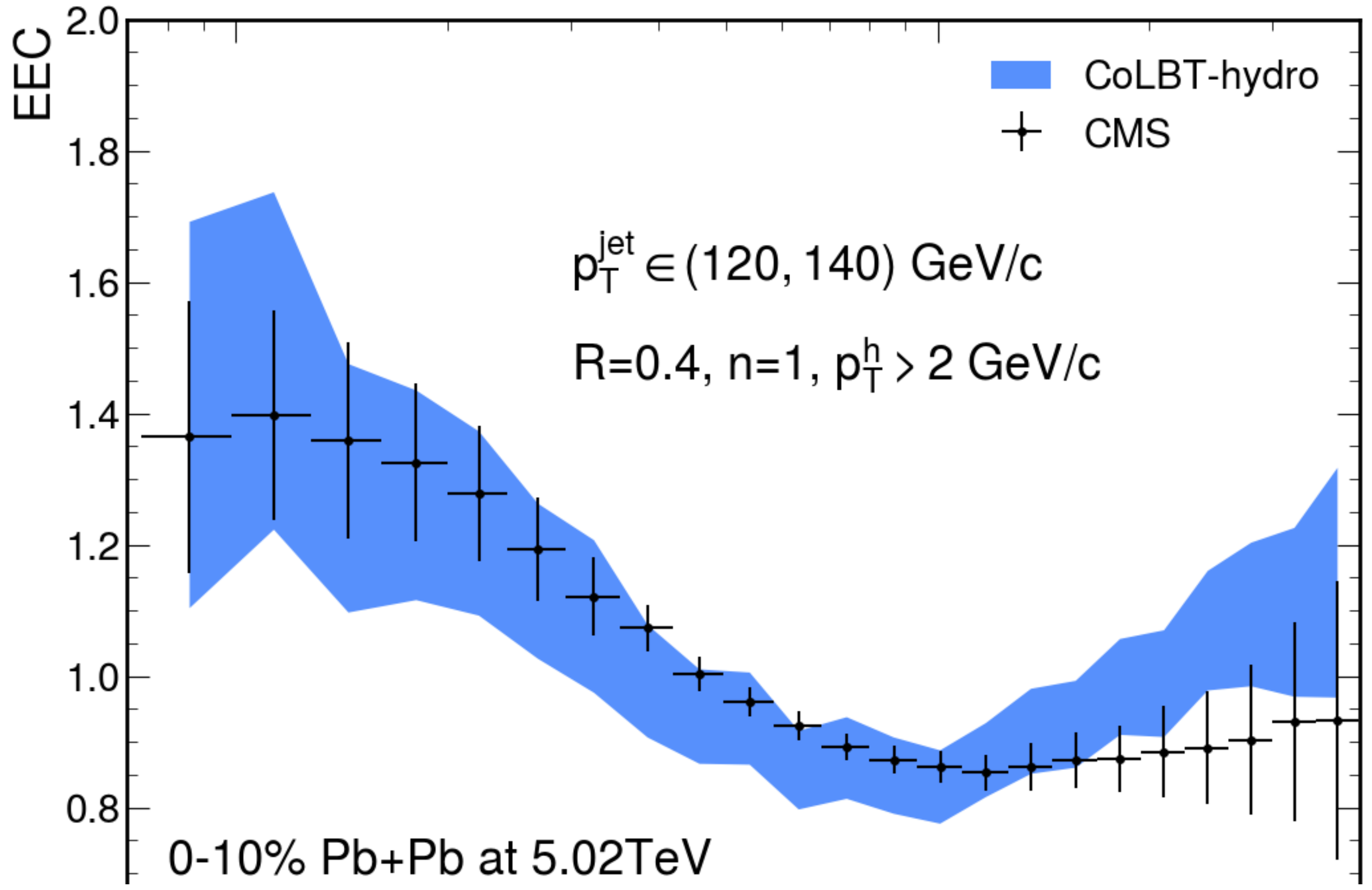
- ★ Background cancel automatically
- ★ Rapidity asymmetry in low hadron p_T
- ★ PP baseline is not important

Effect of diffusion wake on E2C

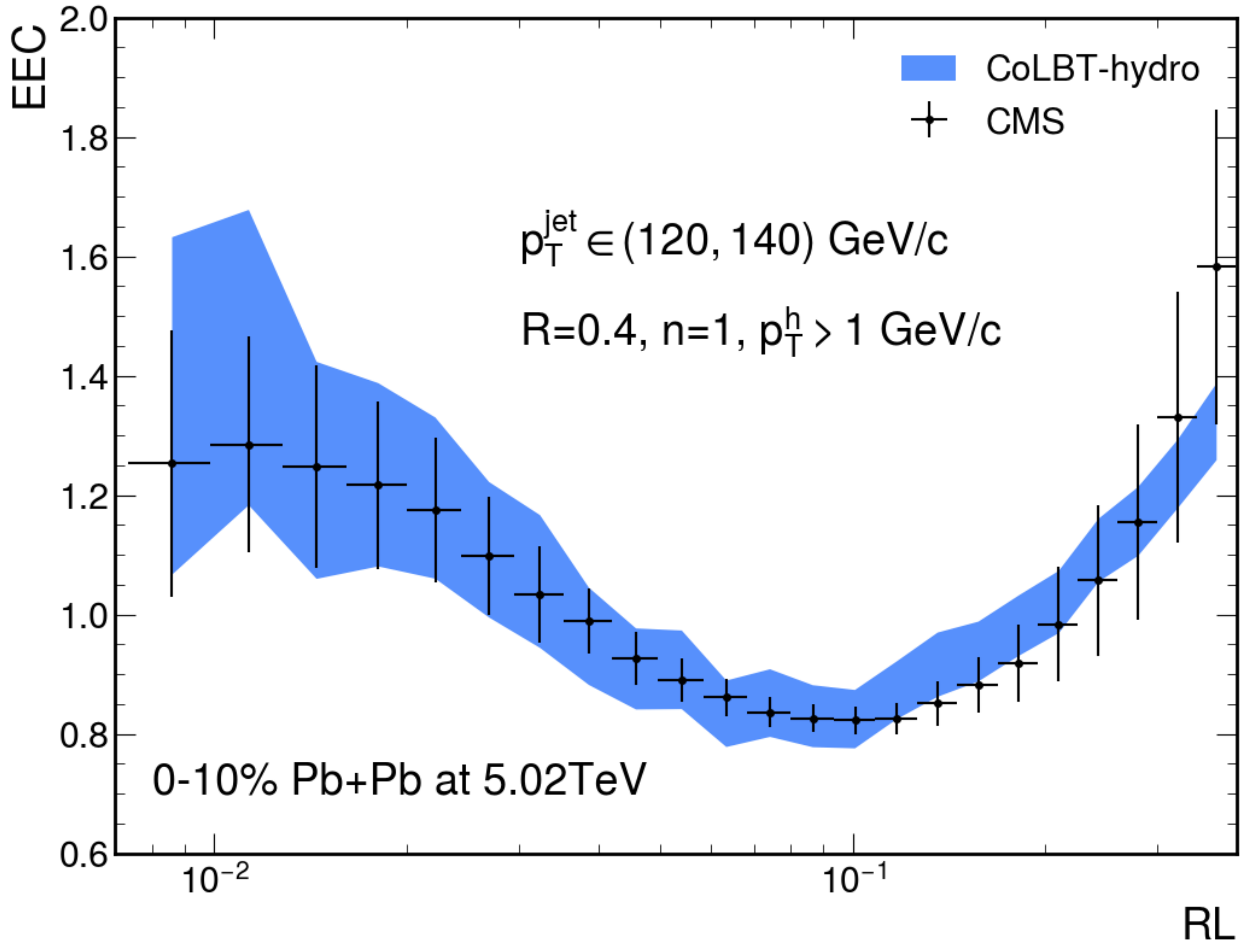
Do we have a measurable effect of diffusion wake on E2C?

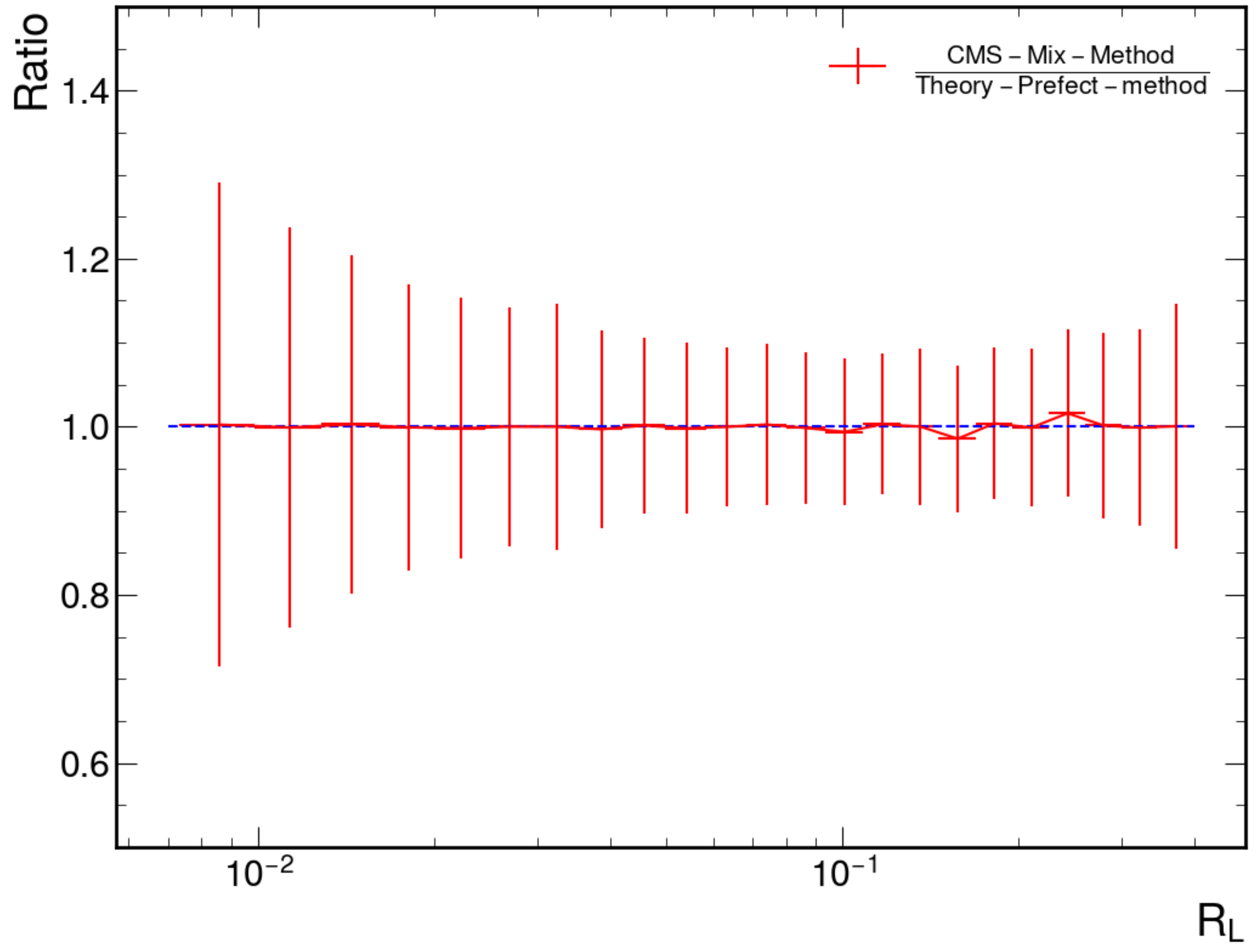
Mixed-event subtraction





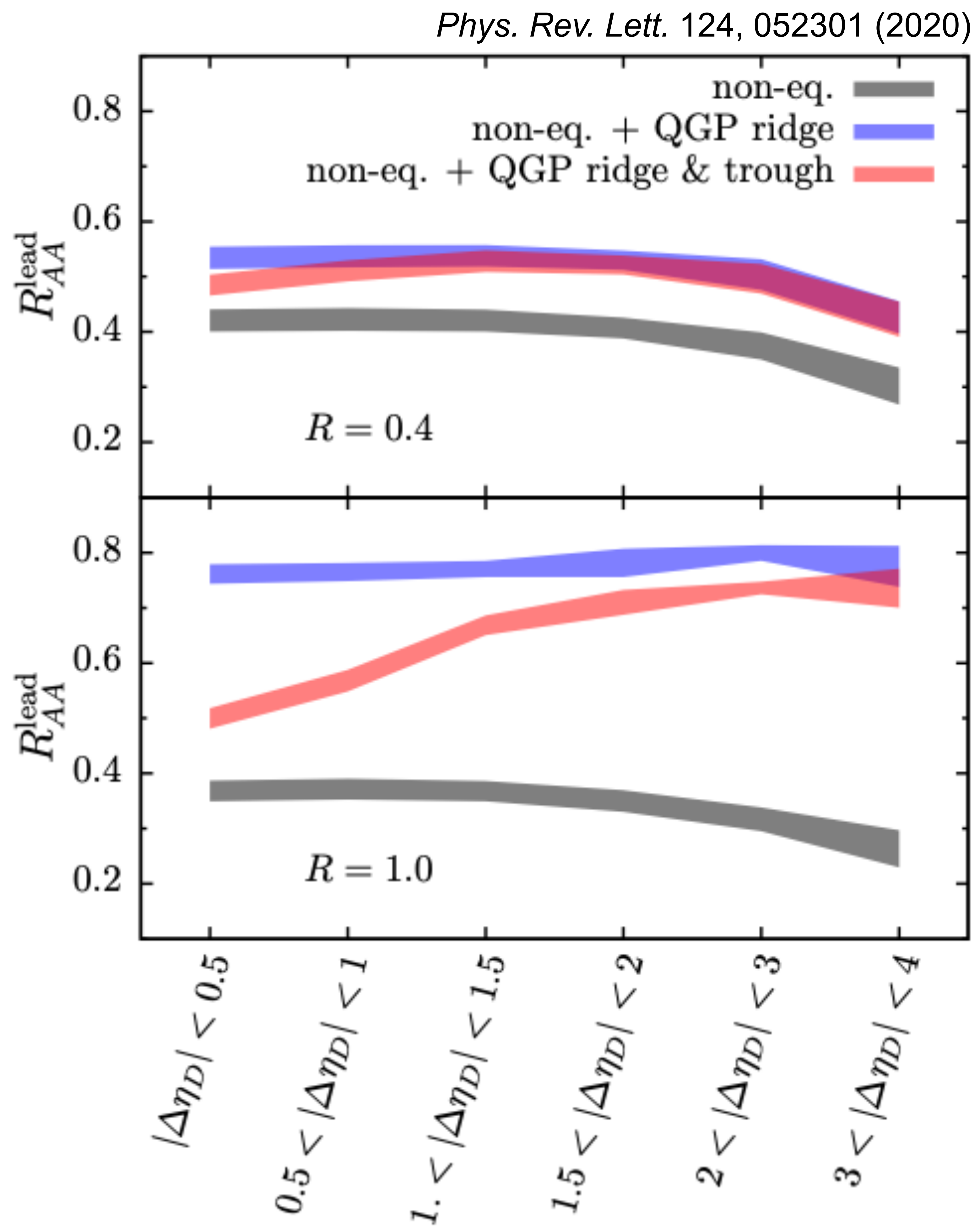
Theoretical subtraction

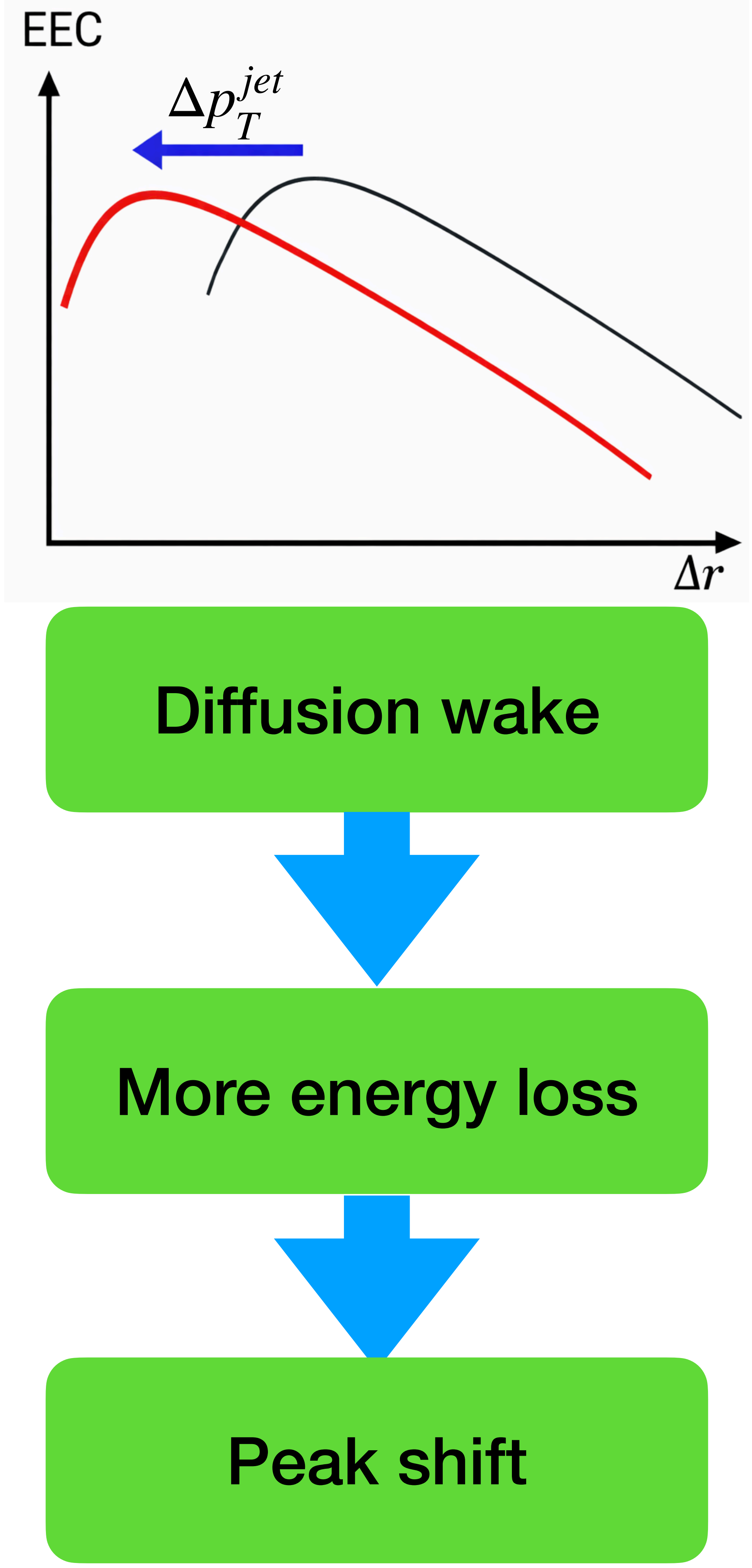


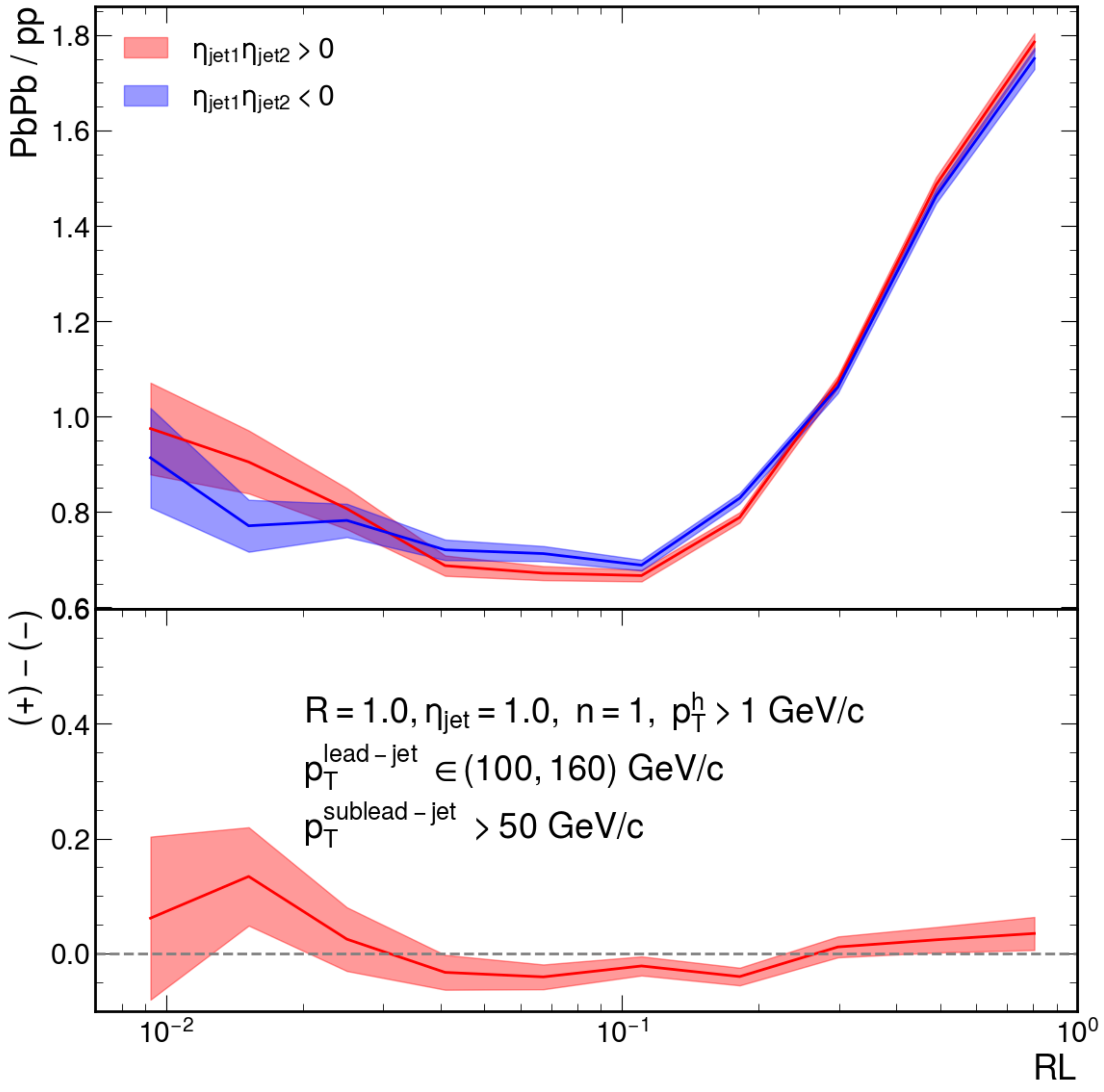


Effect of diffusion wake on E2C

We can use the ideal in di-jet diffusion wake to classify our di-jet events

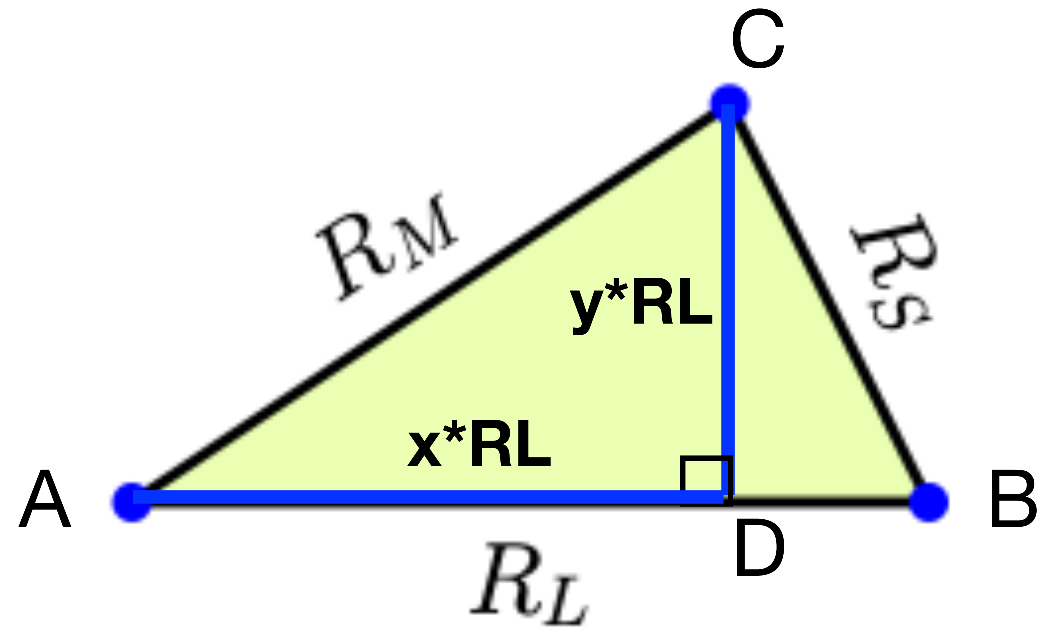




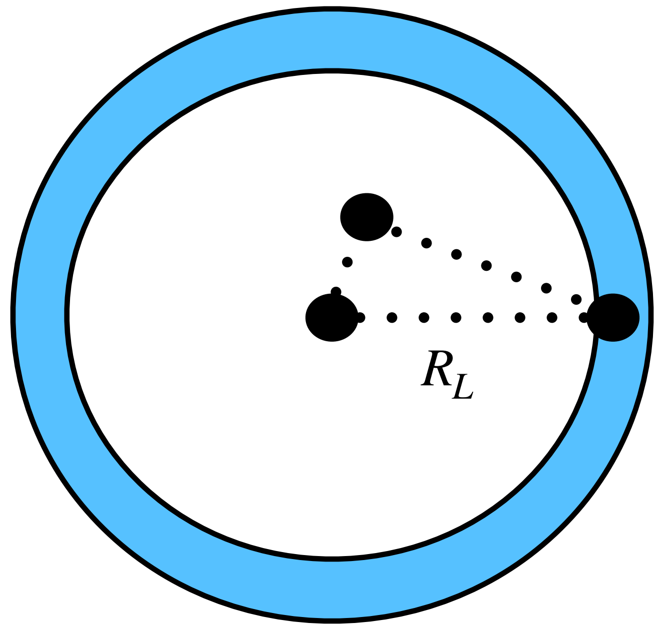


Medium effect on E3C

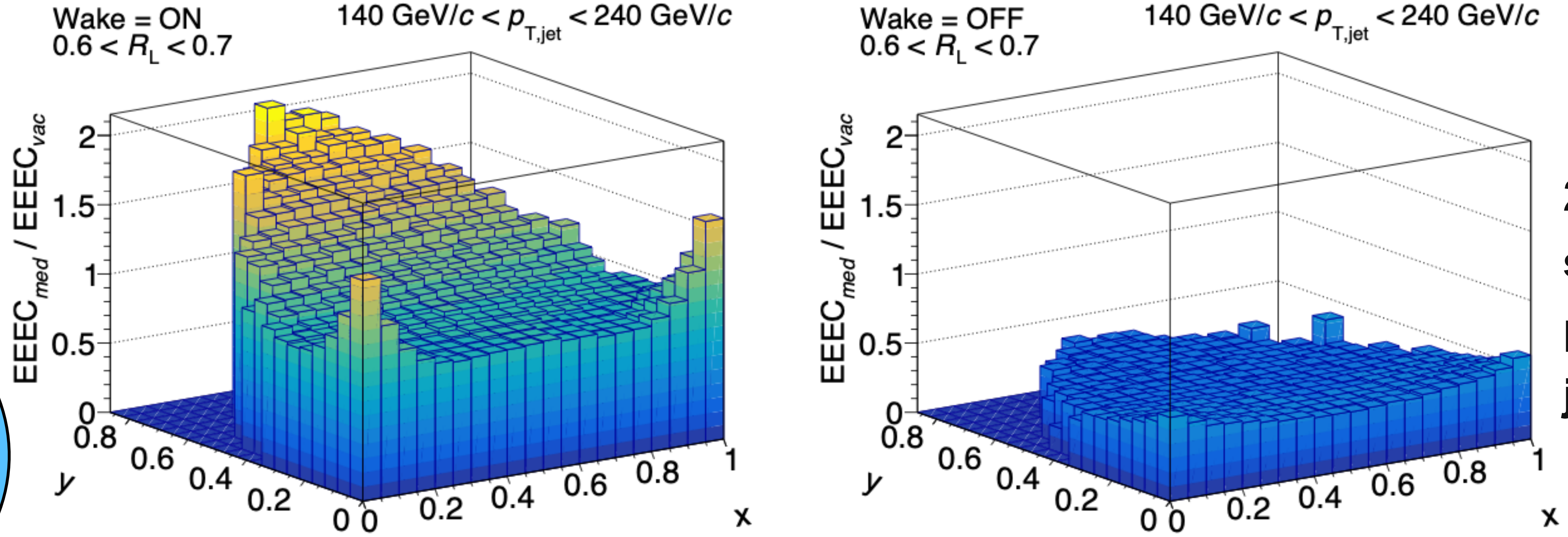
E3C



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



Requiring a large R_L enhances the contribution from the medium response



(a) (b)

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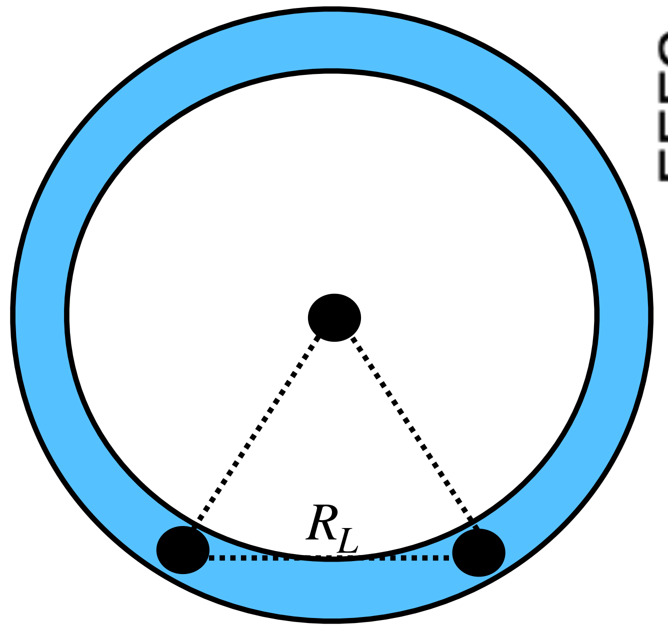
2D distribution of E3C shows strong sensitivity to medium modification, providing a novel method to probe jet wake.



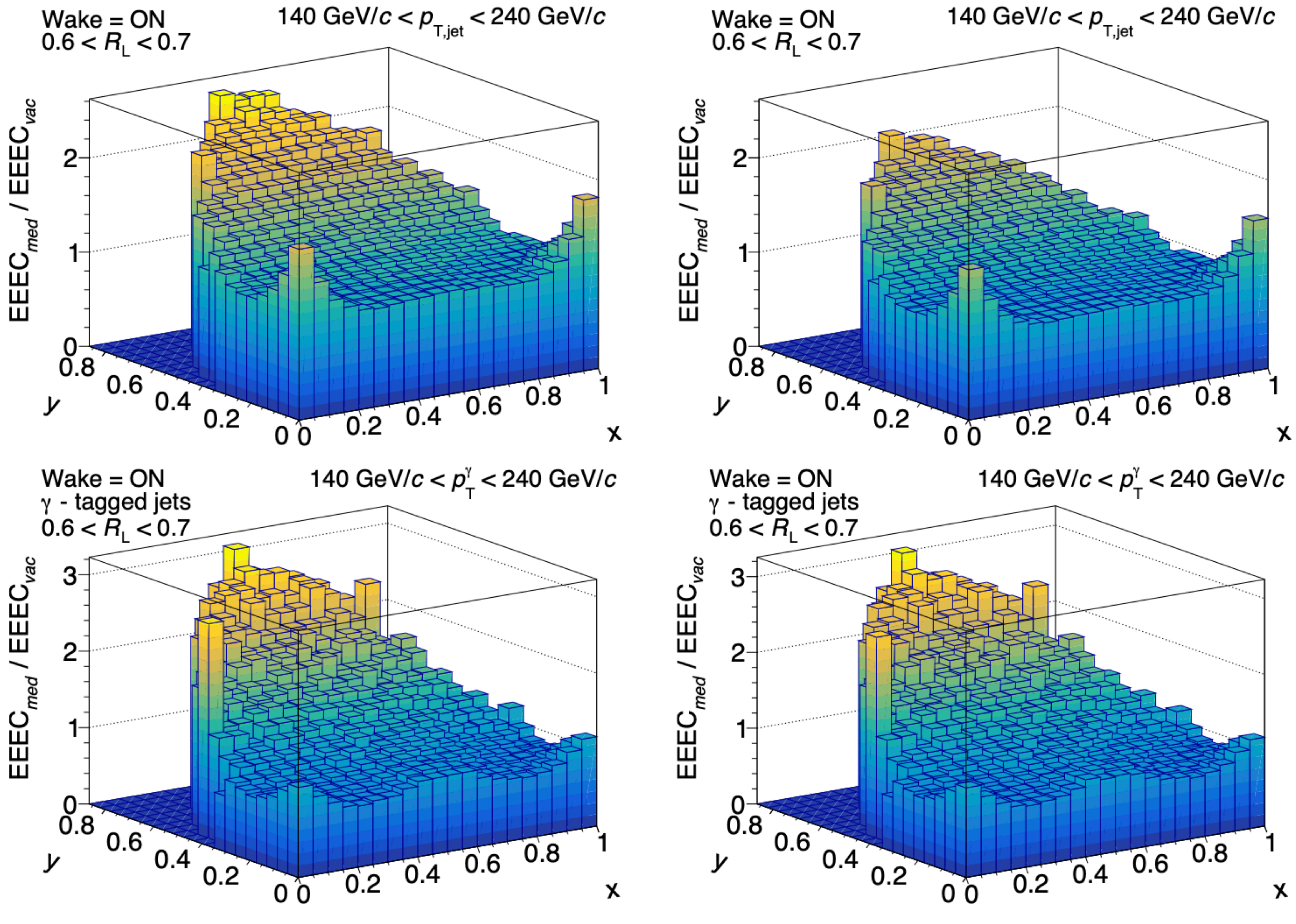
Effect of diffusion wake on E3C

Single inclusive jets

noticeable effect of DW

Gamma-jets

Negligible effect of DW



(a) Ignoring negative wake particles (b) Subtracting negative wake particles

Summary

Now:

- Jet-induced diffusion wake is a unique signal of medium response. It shows potential to study medium properties.
- The signal of diffusion wake has been confirmed by both theoretical and experimental studies now.

Outlook:

- Study of diffusion wake at different collision energy(RHIC) and system(OO)
- Looking for signal of wake front and build connection between it and QGP properties.

THANK YOU

Jet-induced medium response

Where does the energy go?

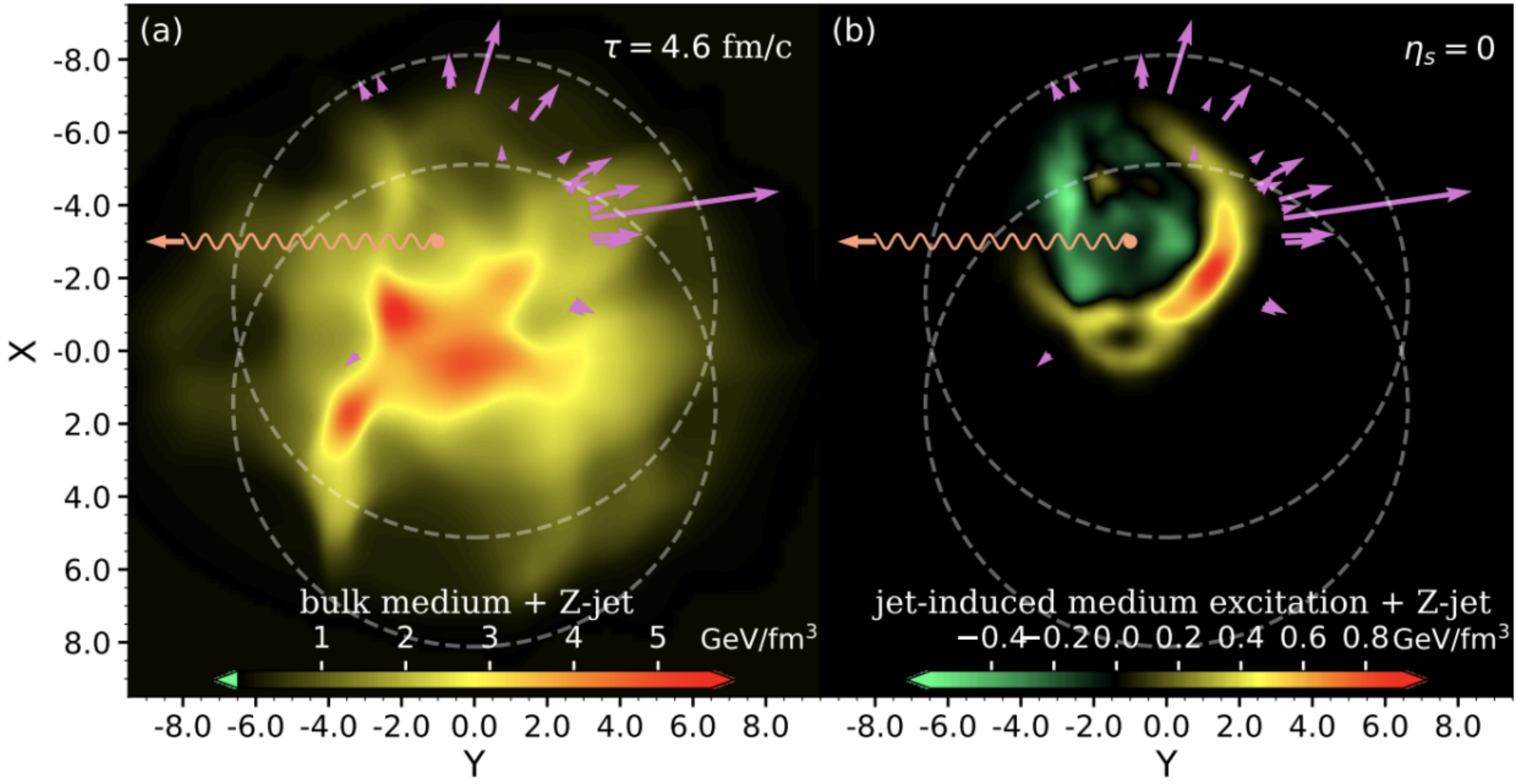
$$\partial_\mu T^{\mu\nu} = 0$$

$$\partial_\mu \delta T^{\mu\nu} = J^\nu$$

J^ν is generated by the energy-momentum lost by hard particle or jets, acting as the source term of hydro.

CoLBT-hydro model: Medium response

CoLBT-hydro model: Hydro response



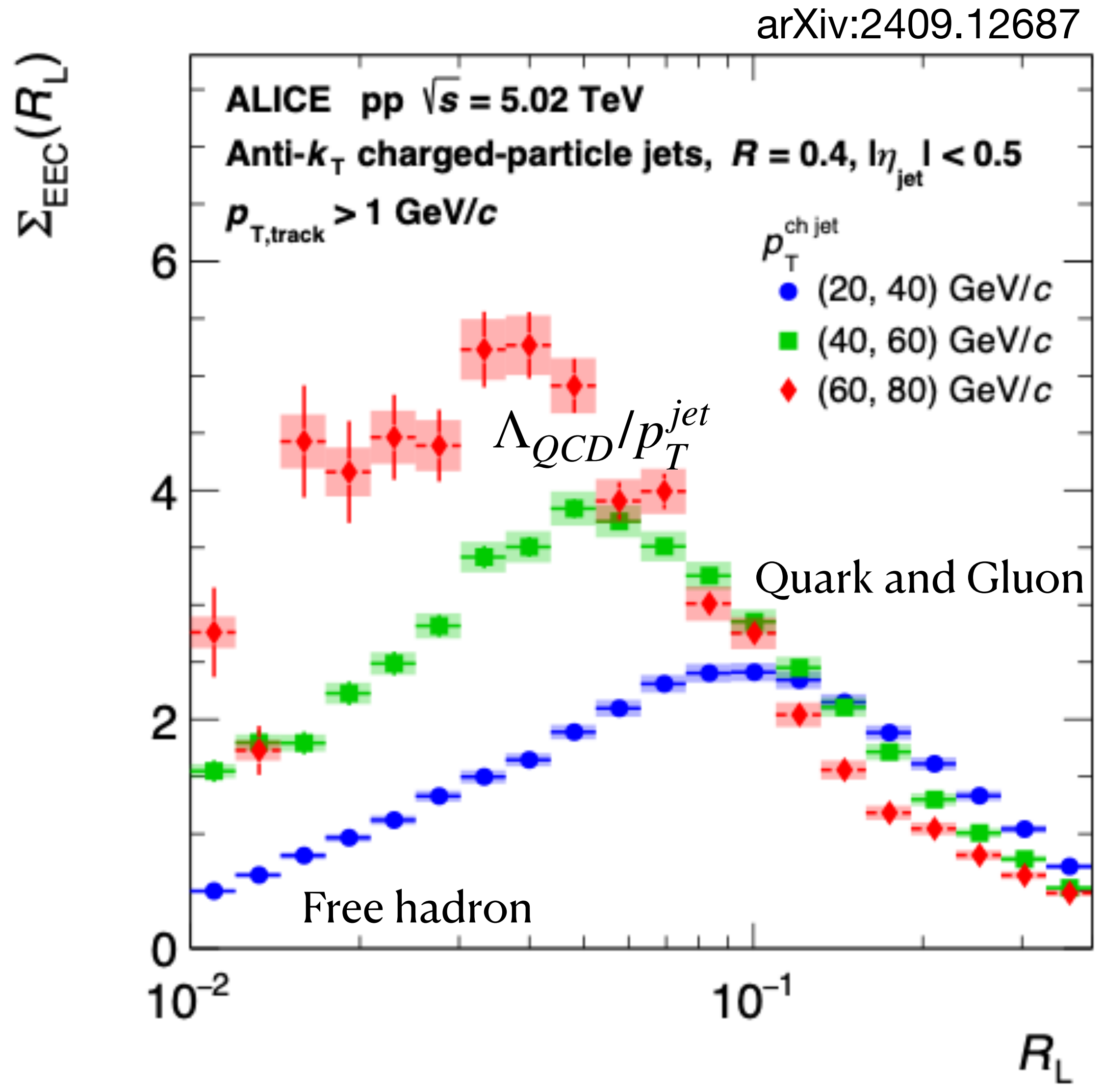
Chen, Yang, He, Ke, Pang and Wang, PRL 127 (2021) 8, 082301

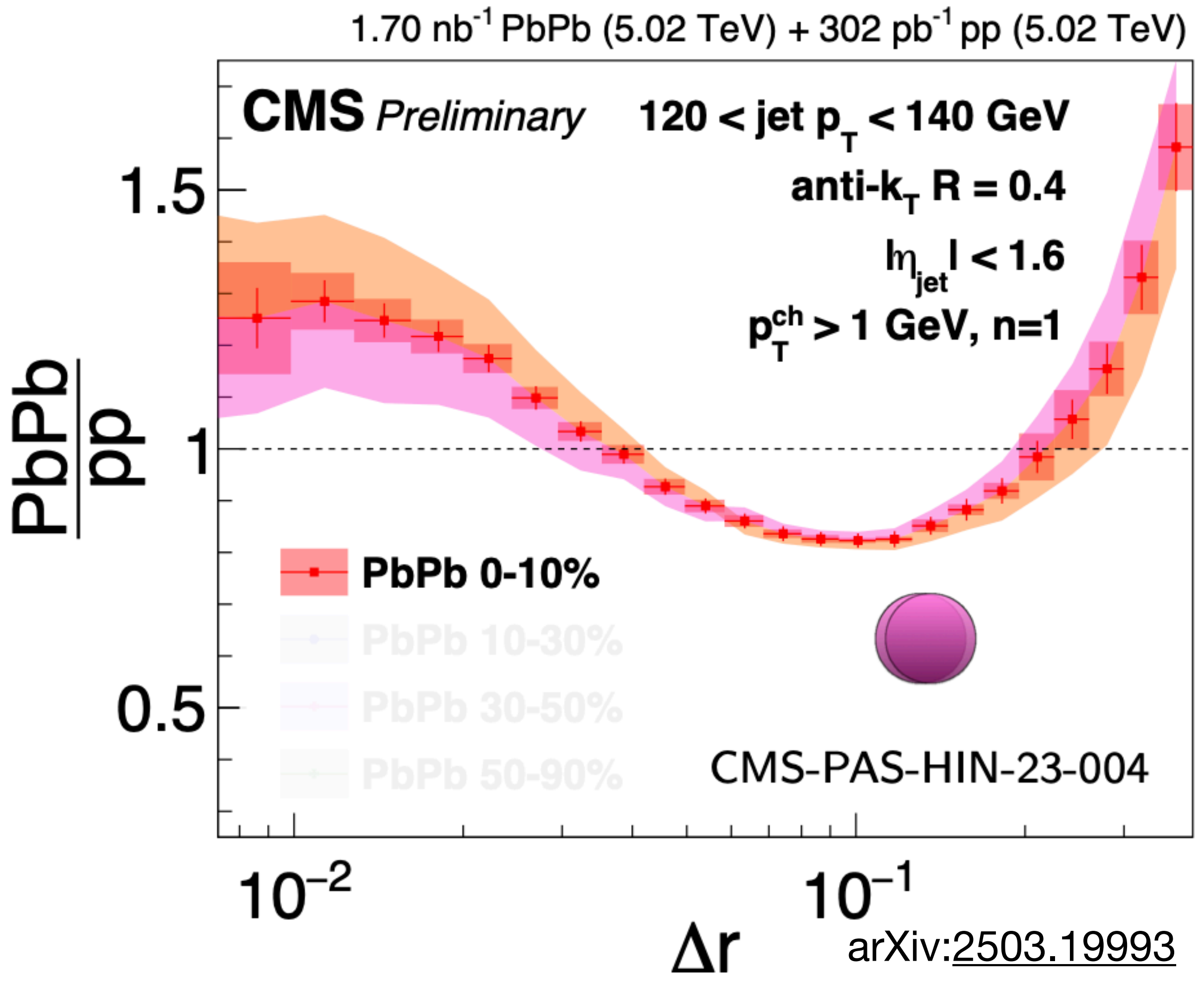
Theoretical background subtraction:

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.

Energy-energy correlators





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

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

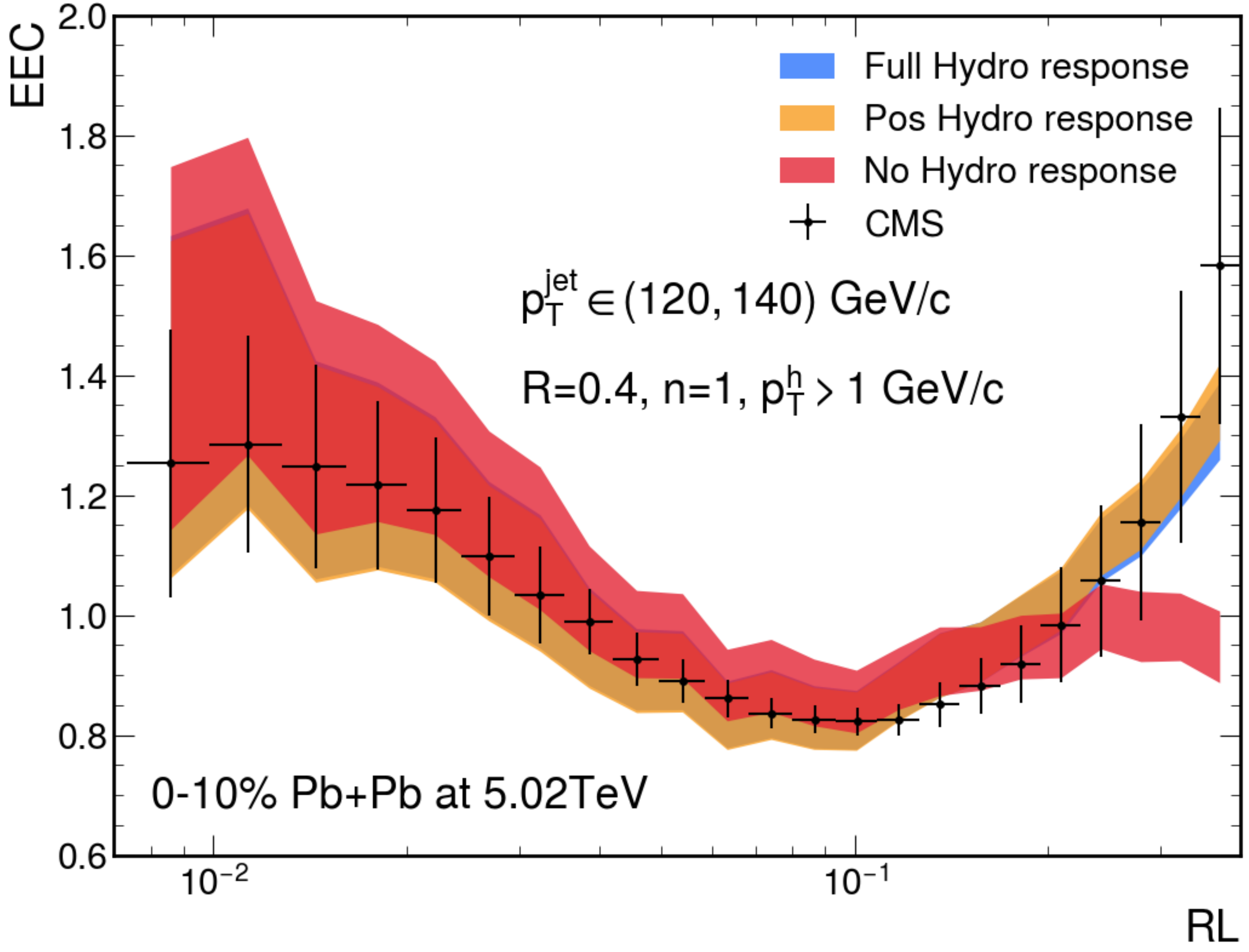
In heavy-ion collisions, the medium effect has clear modifications on EEC distribution at both small and large angles.

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]

Effect of diffusion wake on E2C



Medium response play an important role

Effect of negative parton is negligible