中国高能核物理网络论坛
HIGH ENERGY NUCLEAR PHYSICS IN CHINA

Visualizing the Jet-induced diffusion wake in heavy-ion collisions

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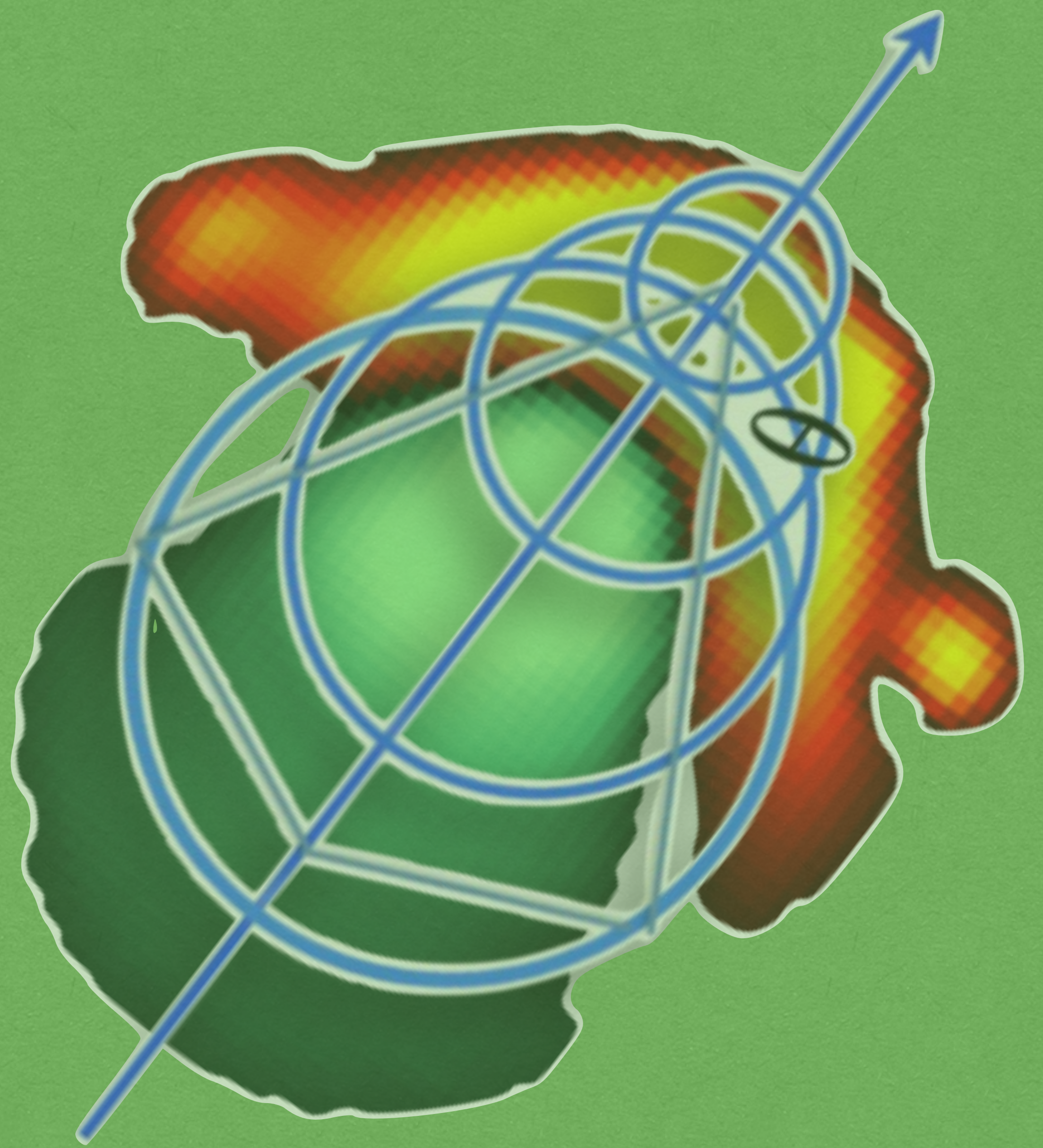
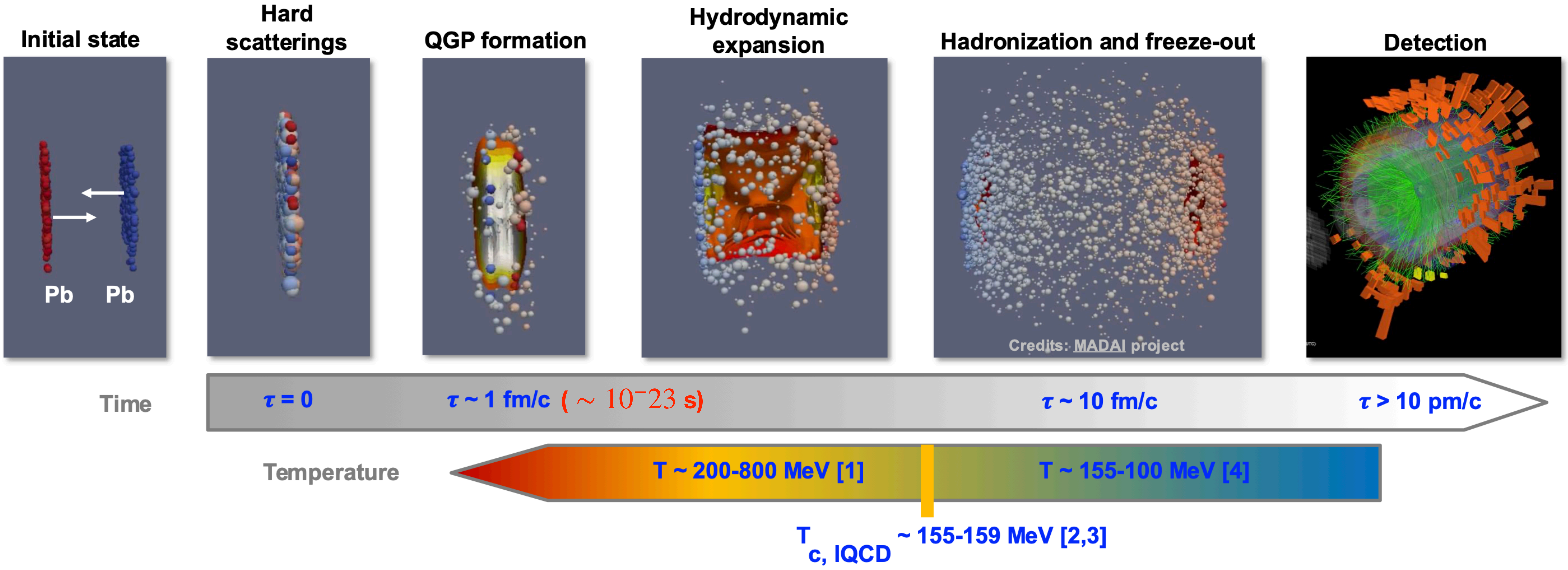
HENPIC

2025.11.27



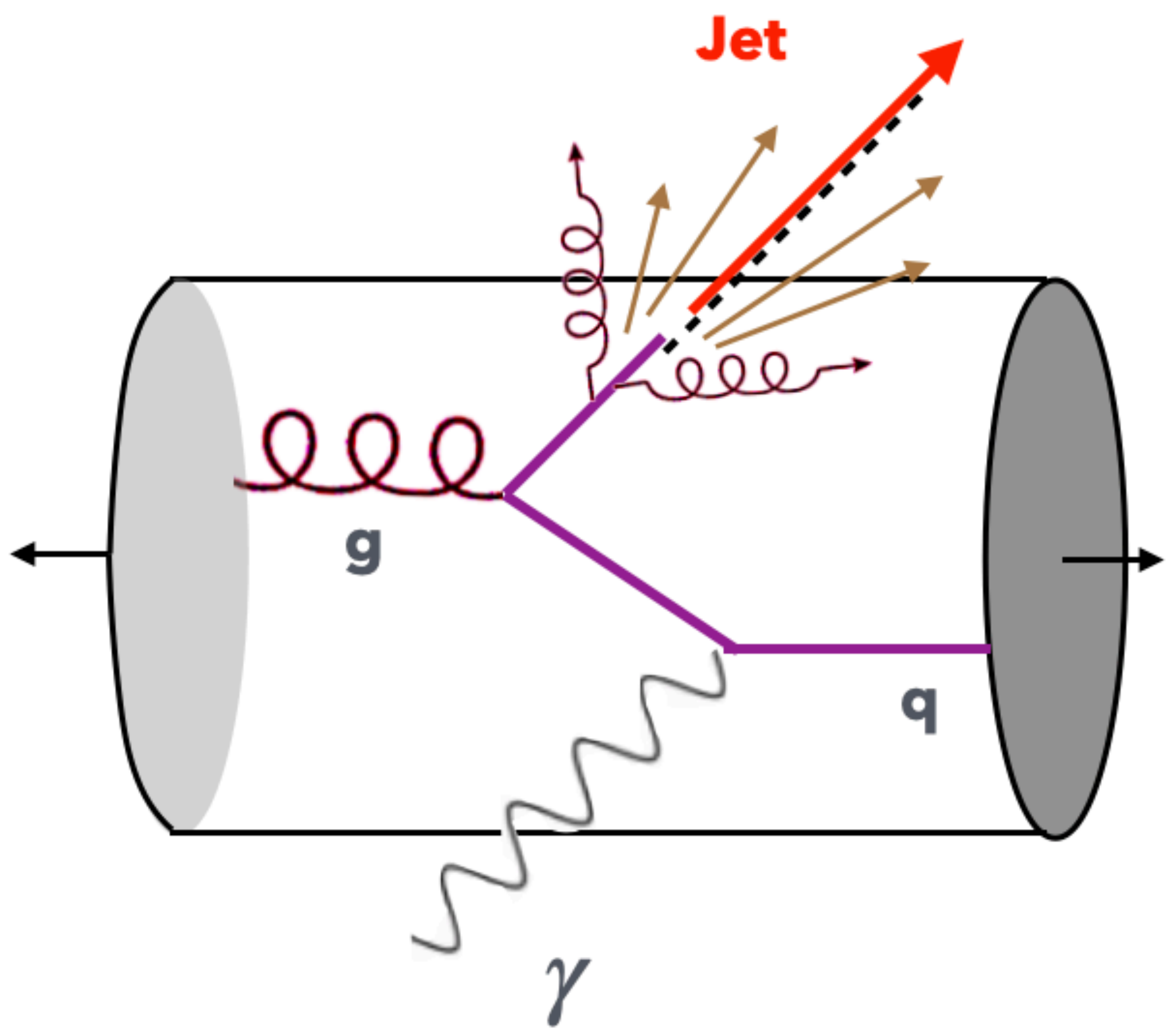
High-energy heavy-ion collisions

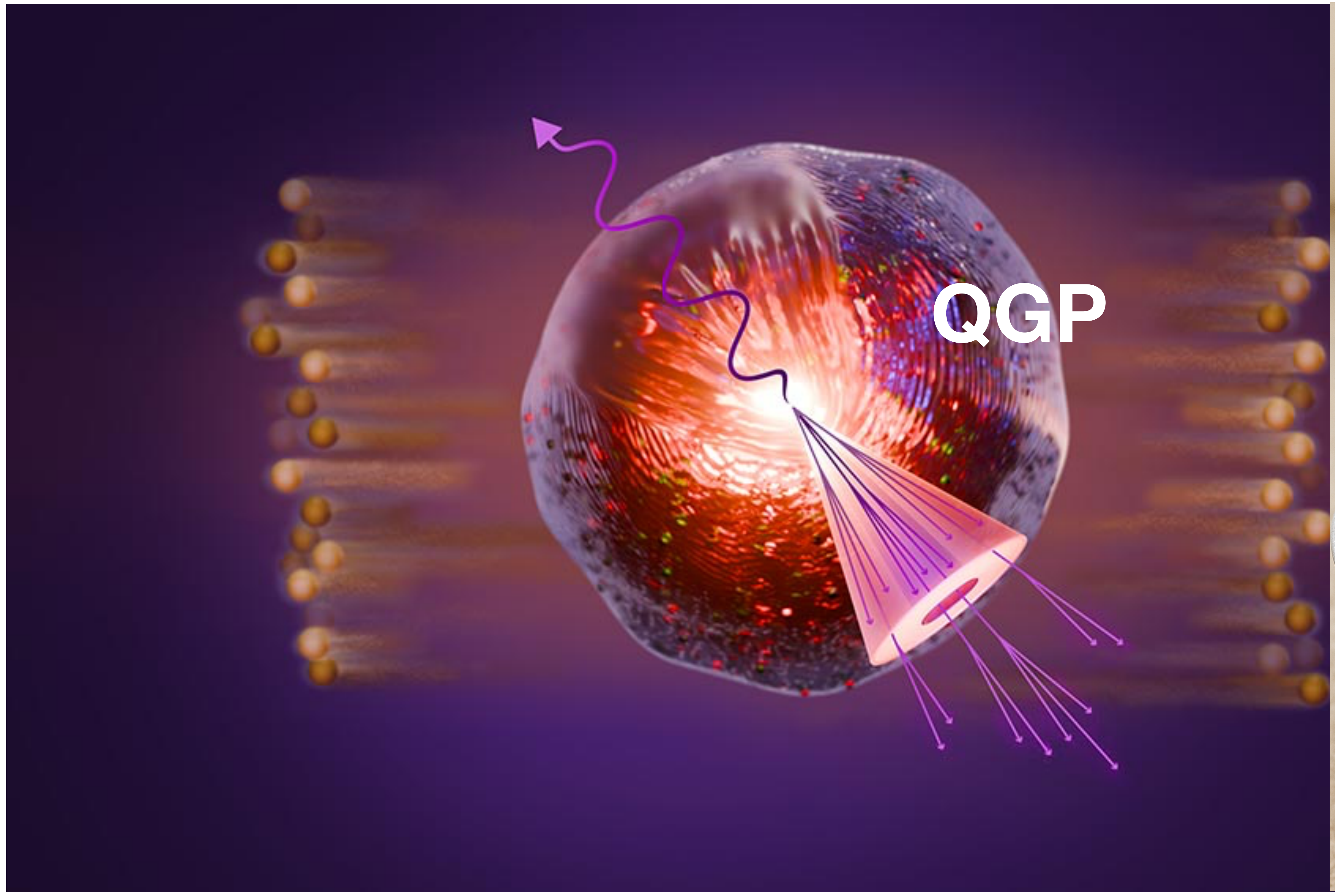
Ralf Averbeck, Quark Matter 2025



Jet quenching

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



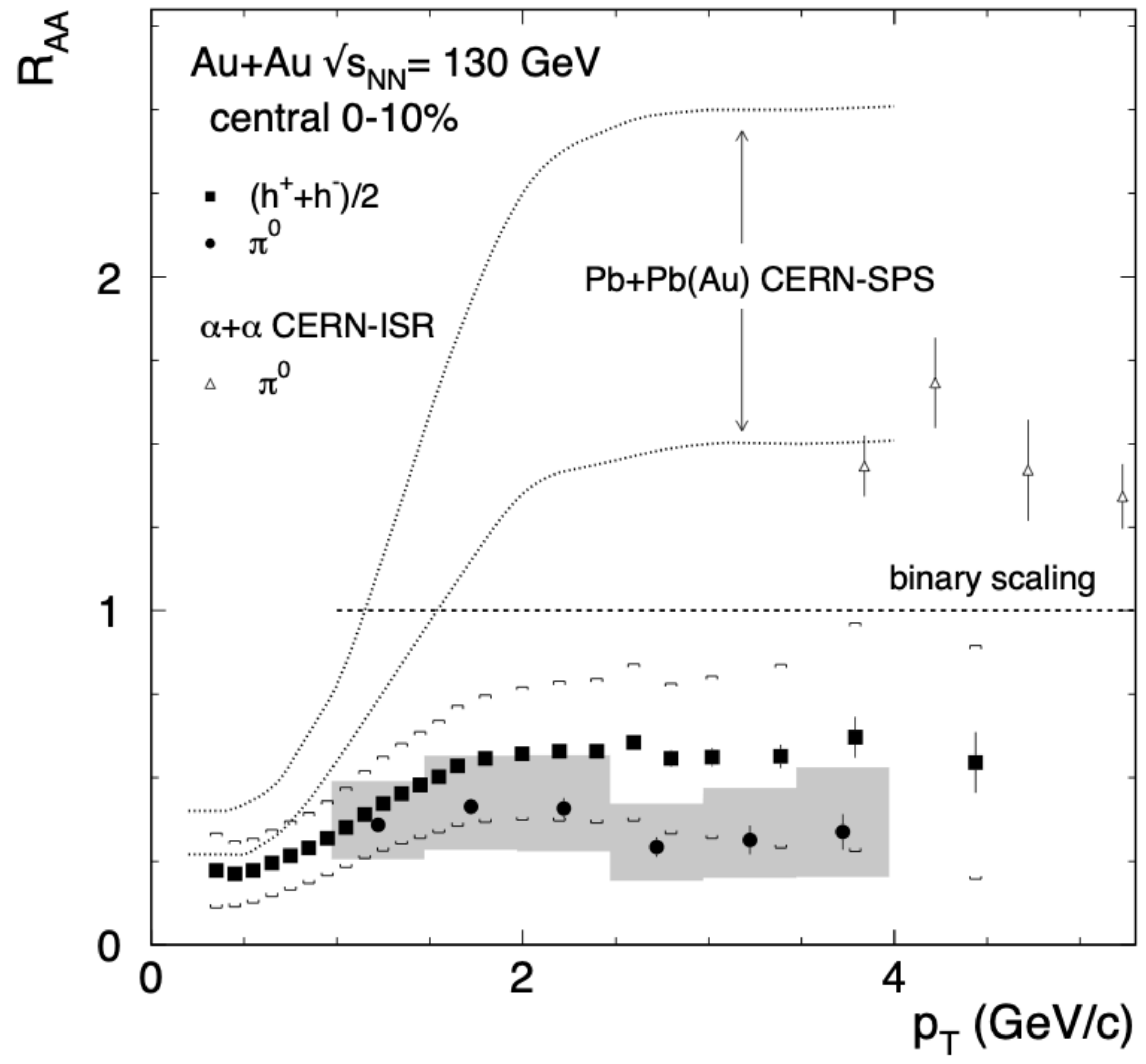


Jet quenching: jet energy loss due to interaction between jet and QGP.

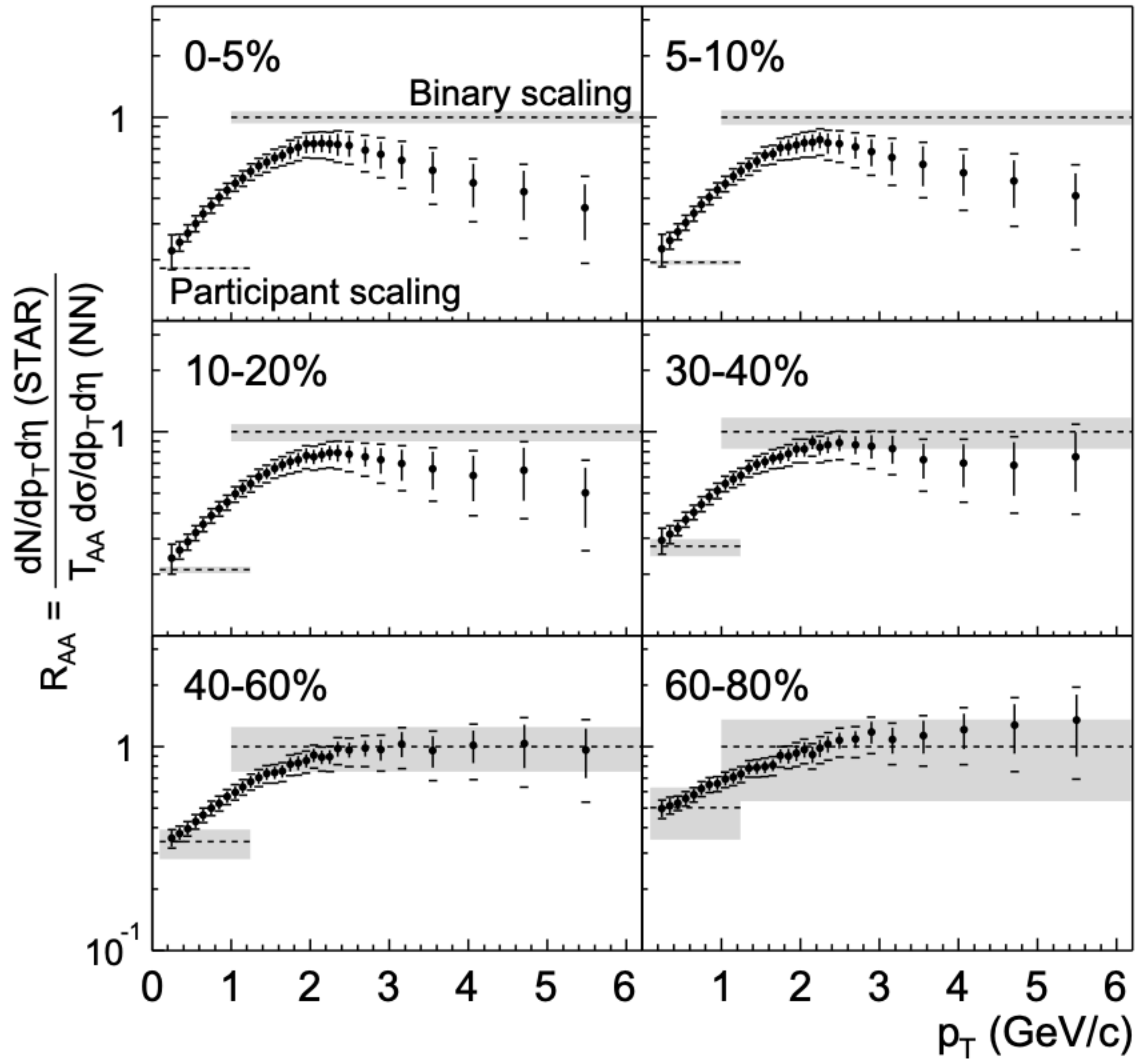
Jet quenching

The observation of hadron RAA from PHENIX and STAR indicates the formation of quark-gluon plasma at high-energy heavy-ion collisions.

Phys. Rev. Lett., 2002, 88: 022301

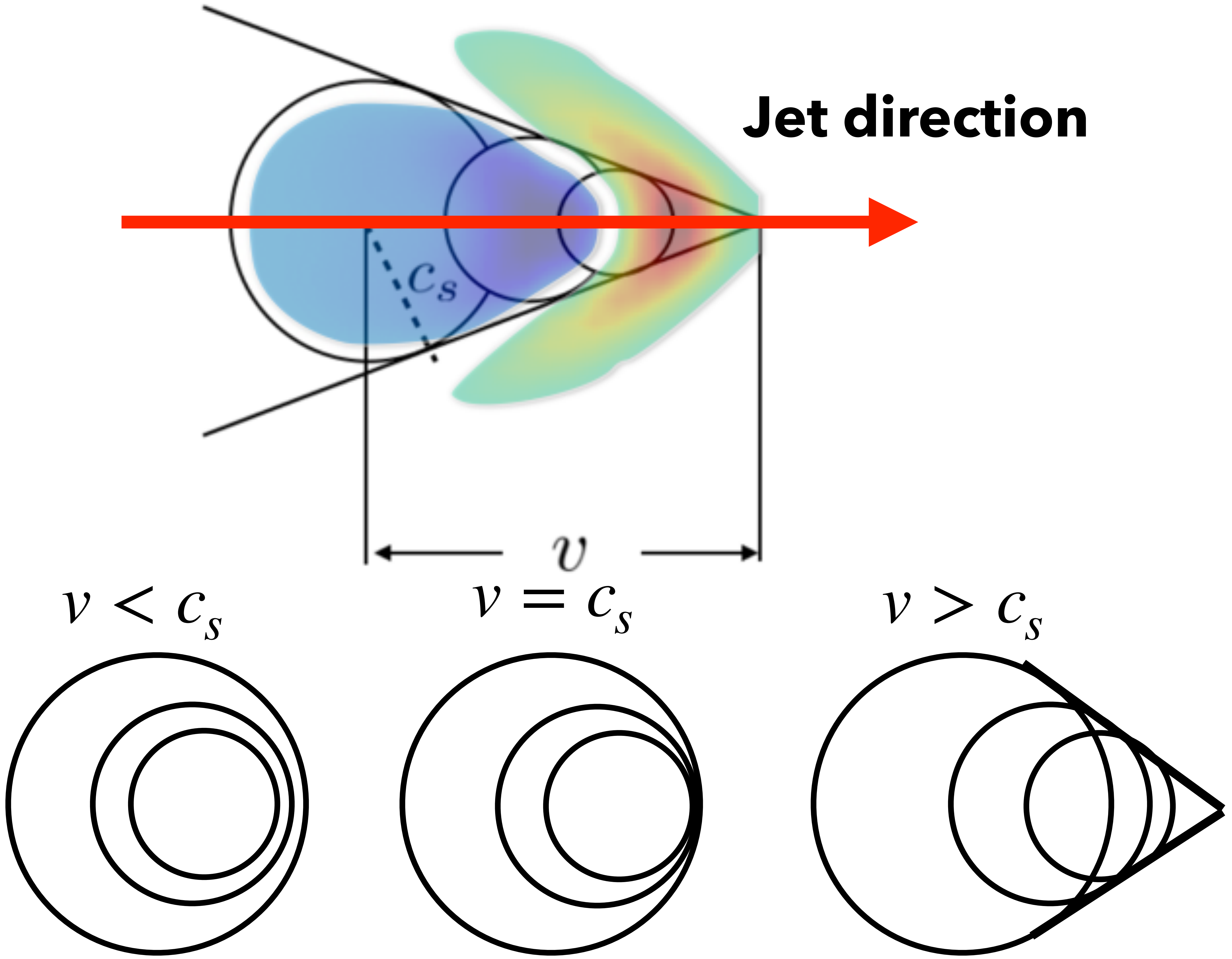


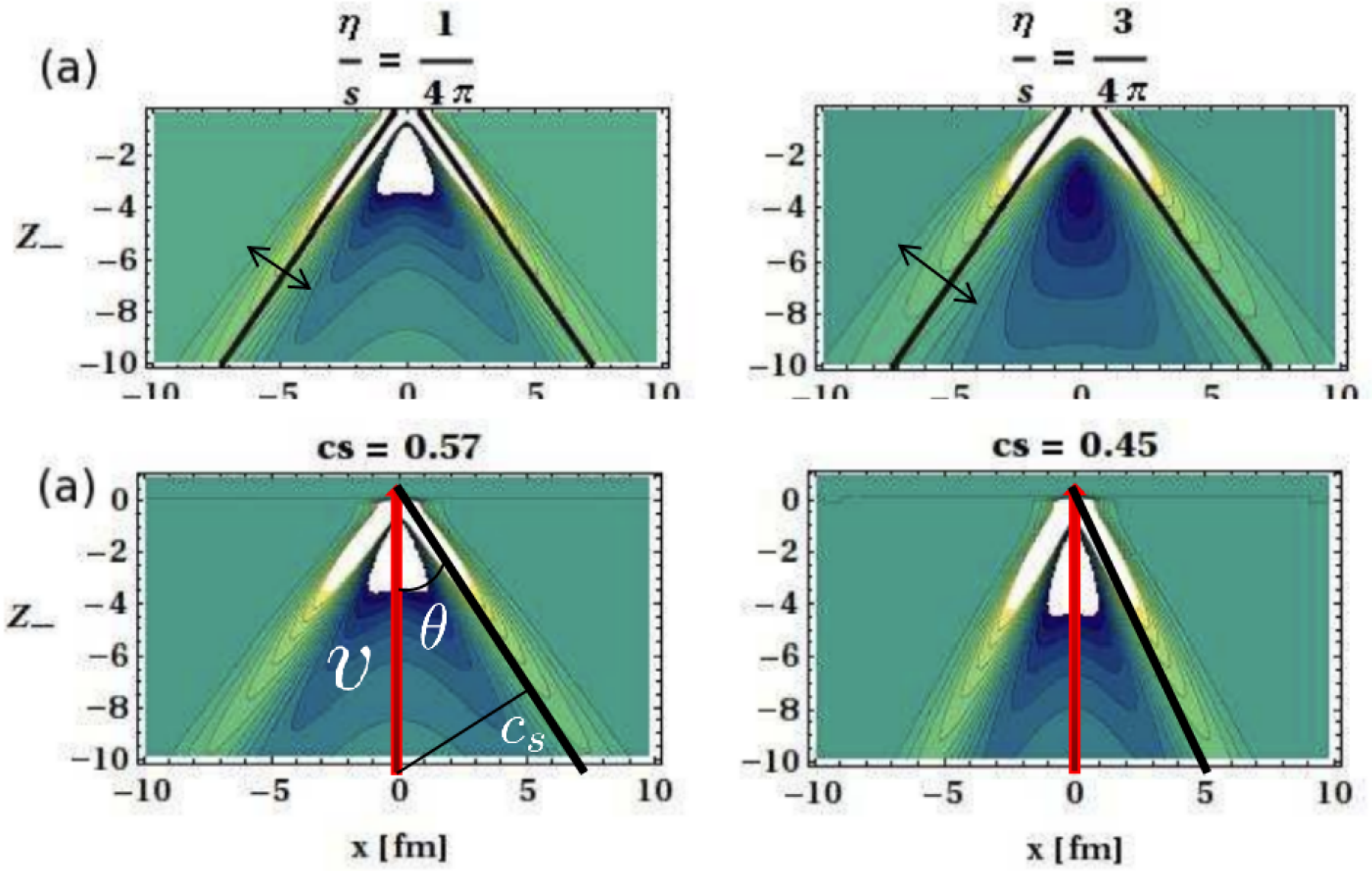
Phys. Rev. Lett., 2002, 89: 202301



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; …]

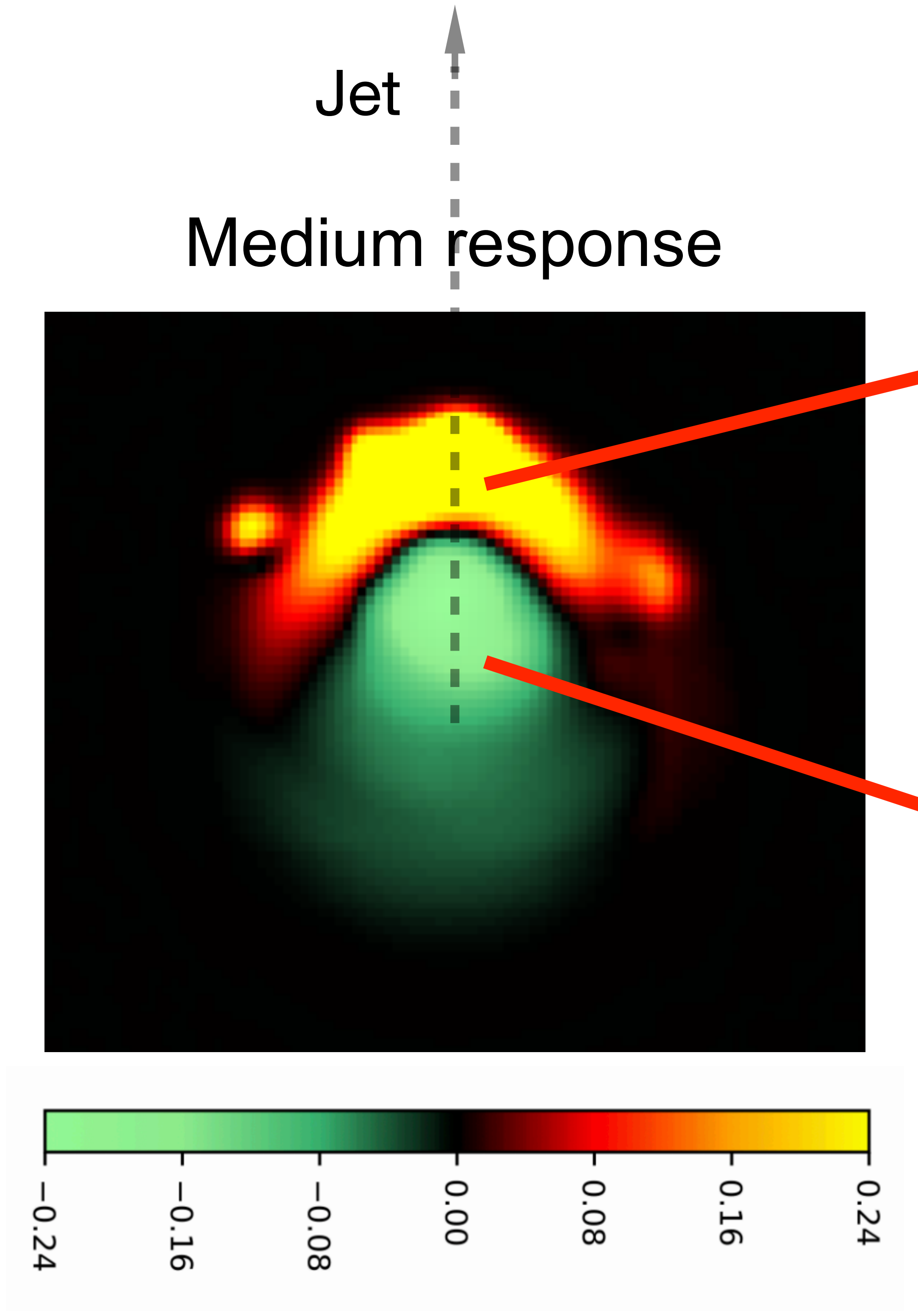


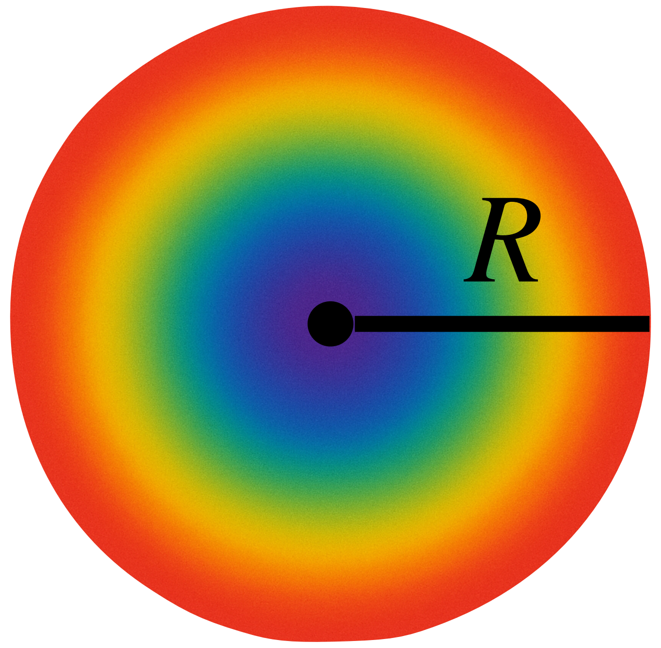


Phys.Rev.C 78 (2008) 041901

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

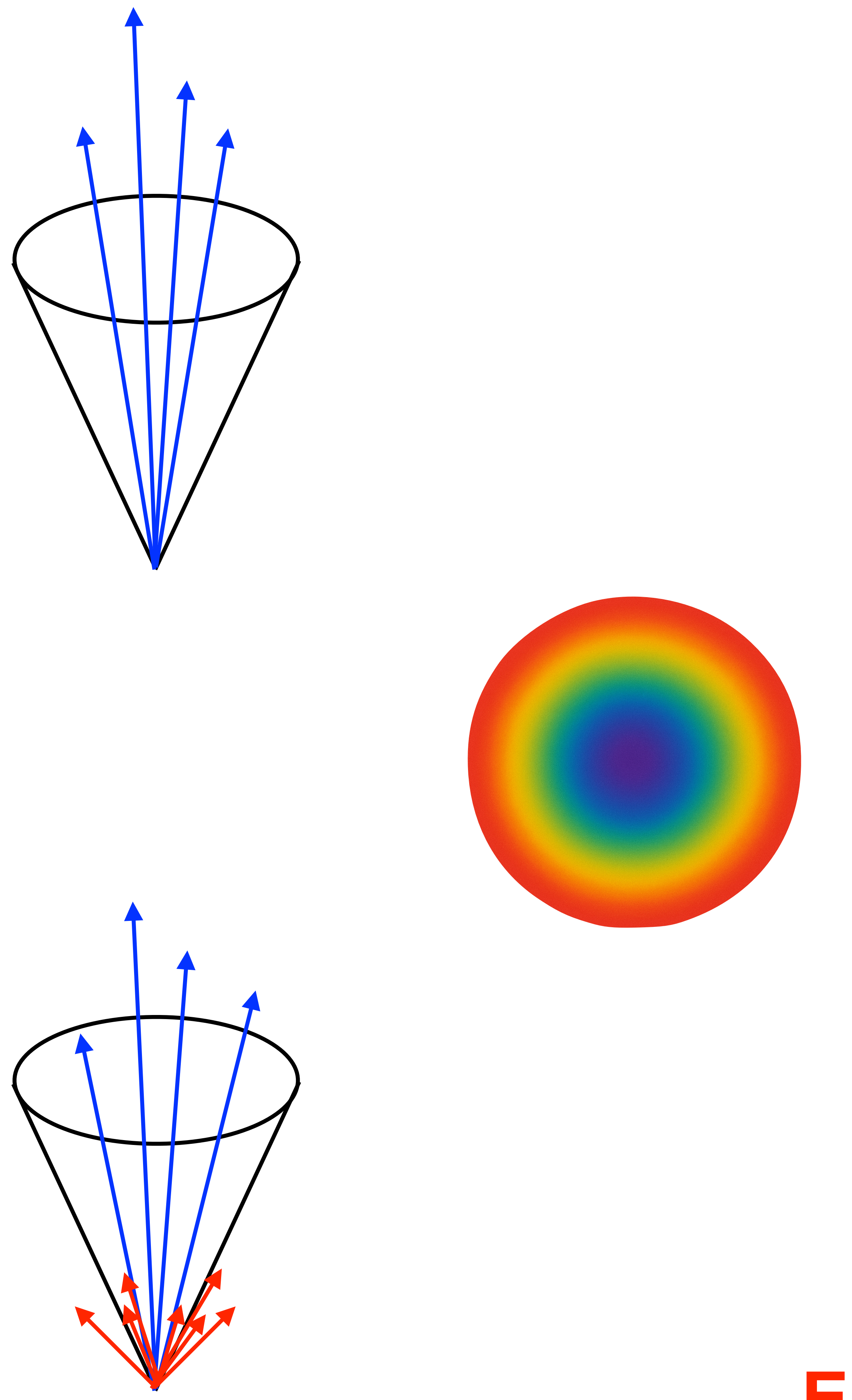
Negative: diffusion wake (against jet direction)

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

Enhancement from wake front

p+p

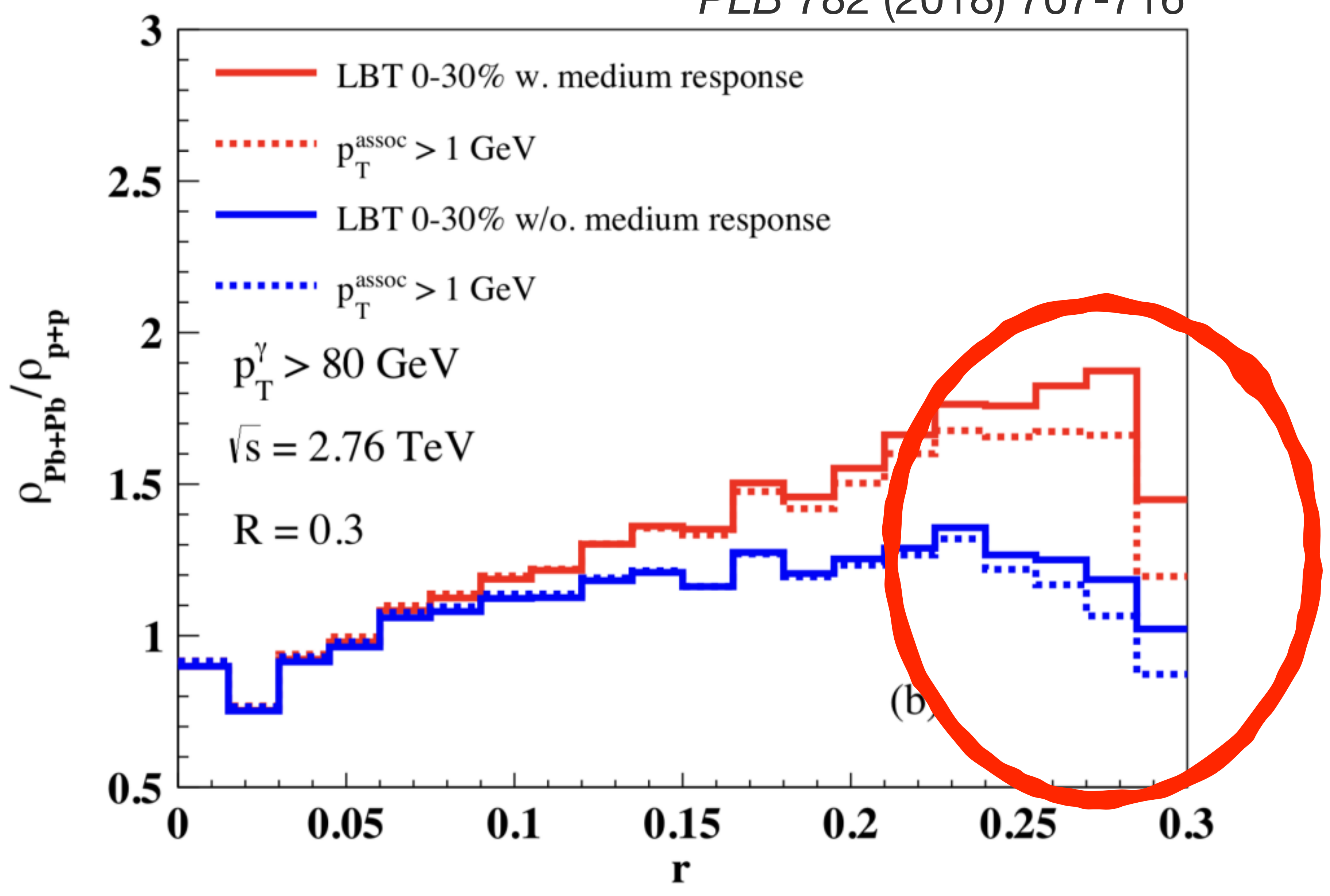
Pb+Pb



Jet shape: measure the p_T distribution inside jet

$$\rho(r) = \frac{1}{\delta r}\frac{\sum_{\text{jets}}\sum_{r<r_{\text{trk}}<r+\delta r}(p_T^{\text{trk}}/p_T^{\text{jet}})}{\sum_{\text{jets}}\sum_{r_{trk}<R}(p_T^{\text{trk}}/p_T^{\text{jet}})}$$

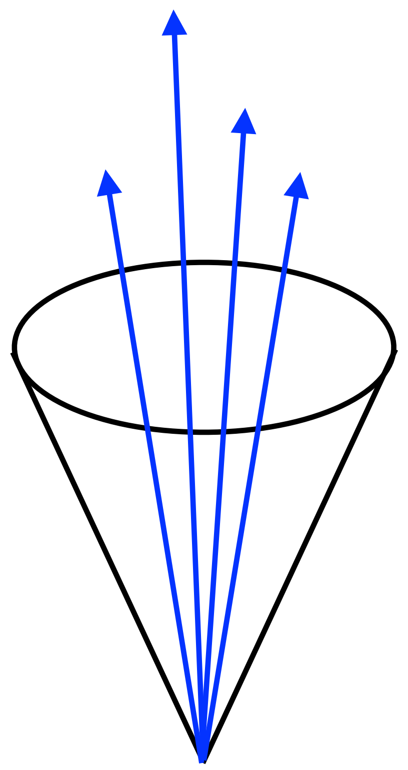
PLB 782 (2018) 707-716



Enhancement of soft hadrons due to medium response leads to clear enhancement of p_T at large angle inside jet

Enhancement from wake front

p+p

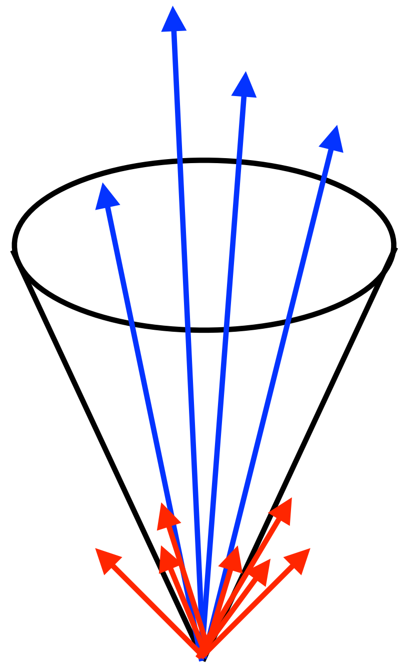


Jet fragmentation function

$$\frac{1}{N_{jet}}\frac{dN}{d\xi_T^{\gamma}}, \quad \xi_T^{\gamma} = \frac{-p_T^{\gamma 2}}{\vec{p}_T^{\gamma}\vec{p}_T^{h}}$$

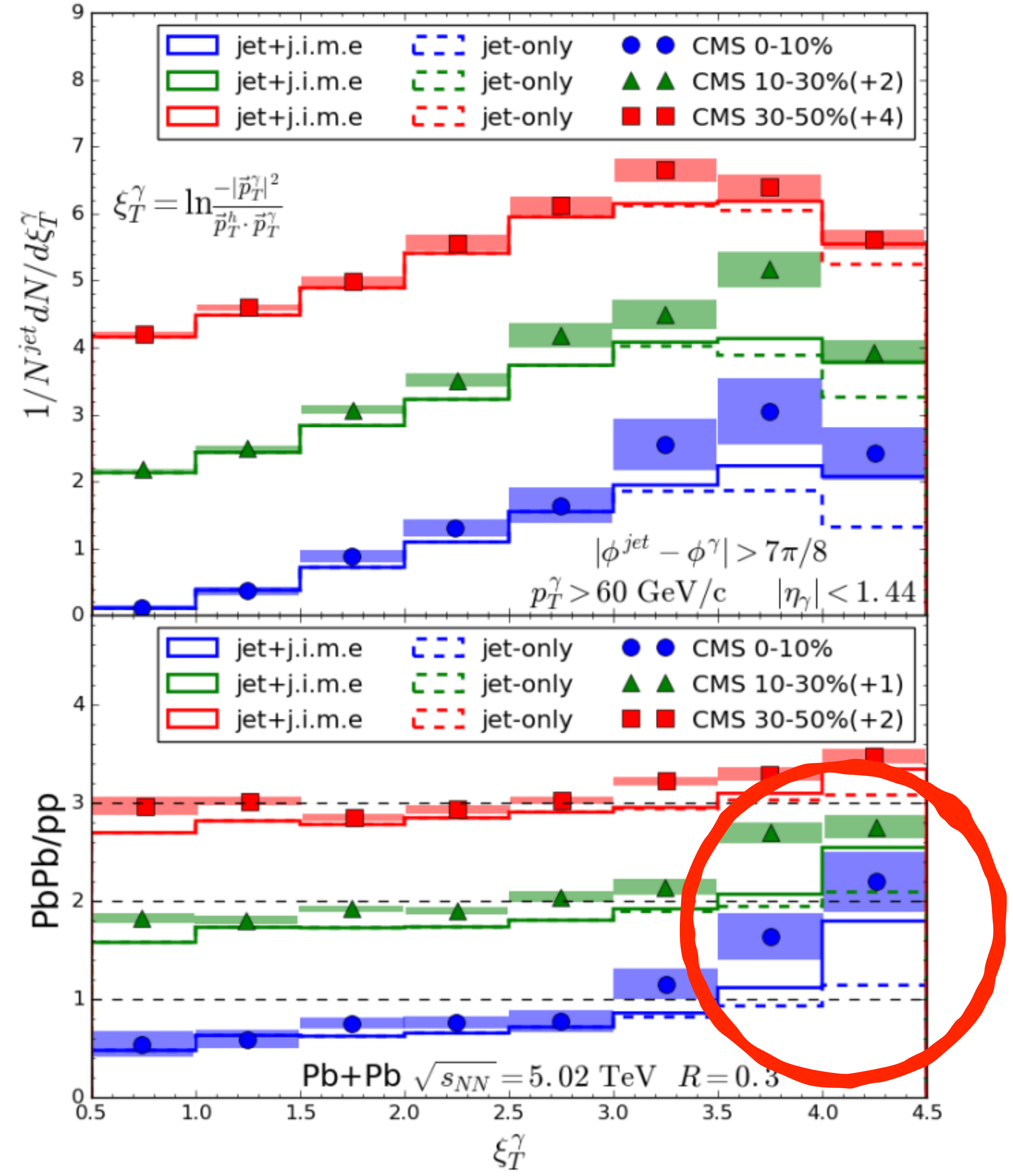
This observable reflects the soft and hard particles' distribution inside jet.

Pb+Pb



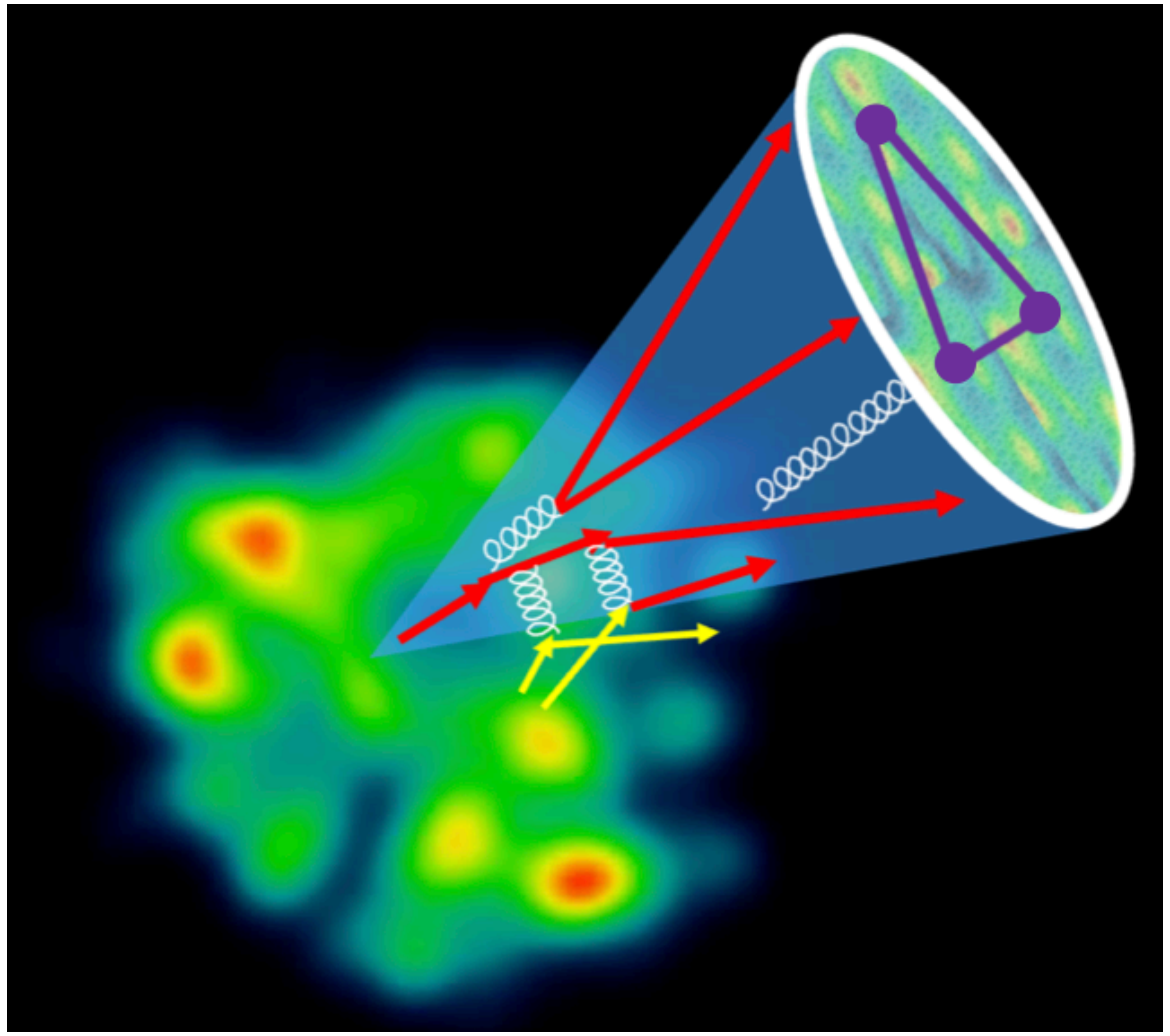
We successfully see the enhancement at large ξ_T^{γ}

PLB 810 (2020) 135783



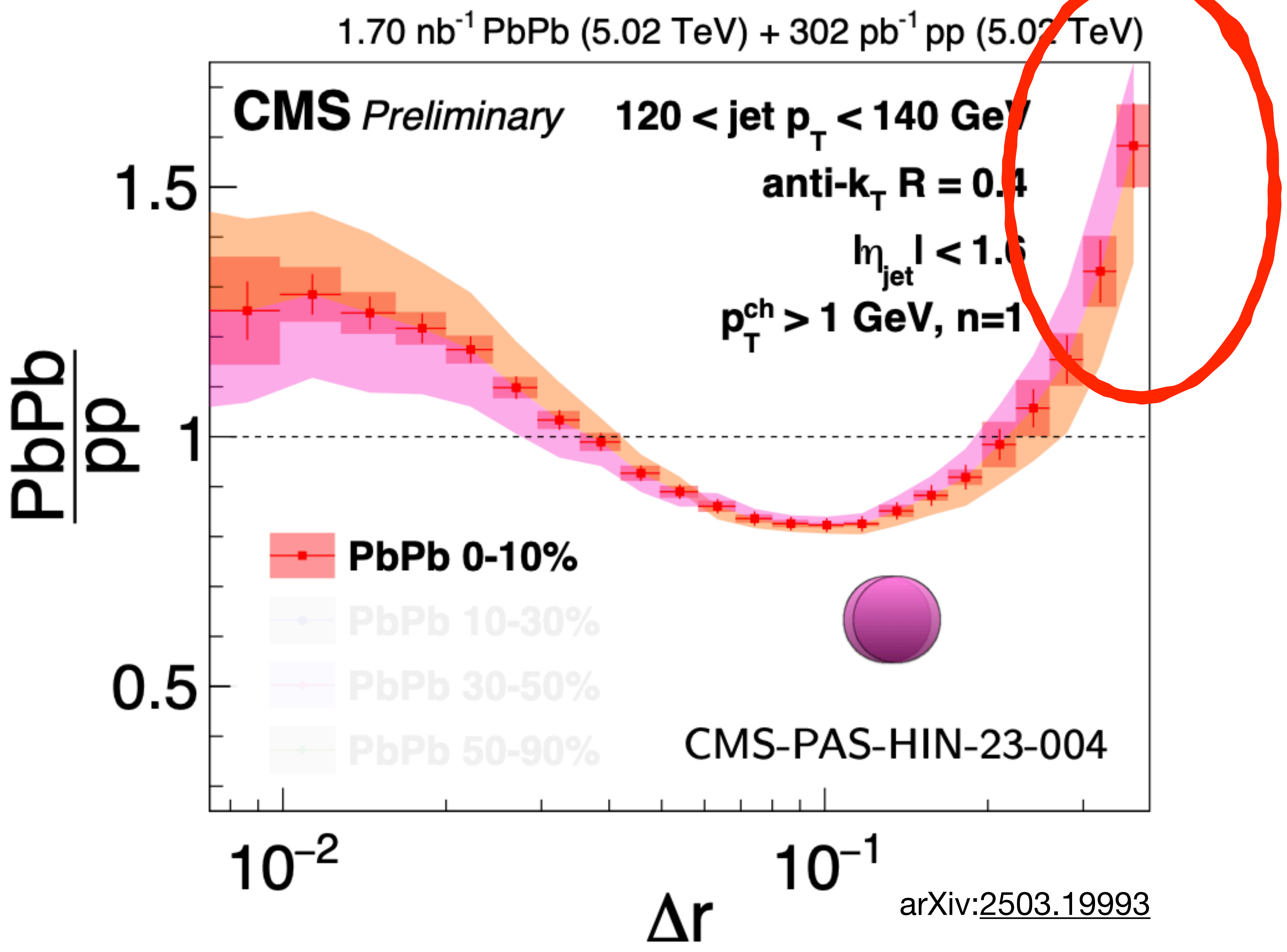
Enhancement from wake front

EEC: Energy-energy correlators



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

Jussi, Rithya, CMS group



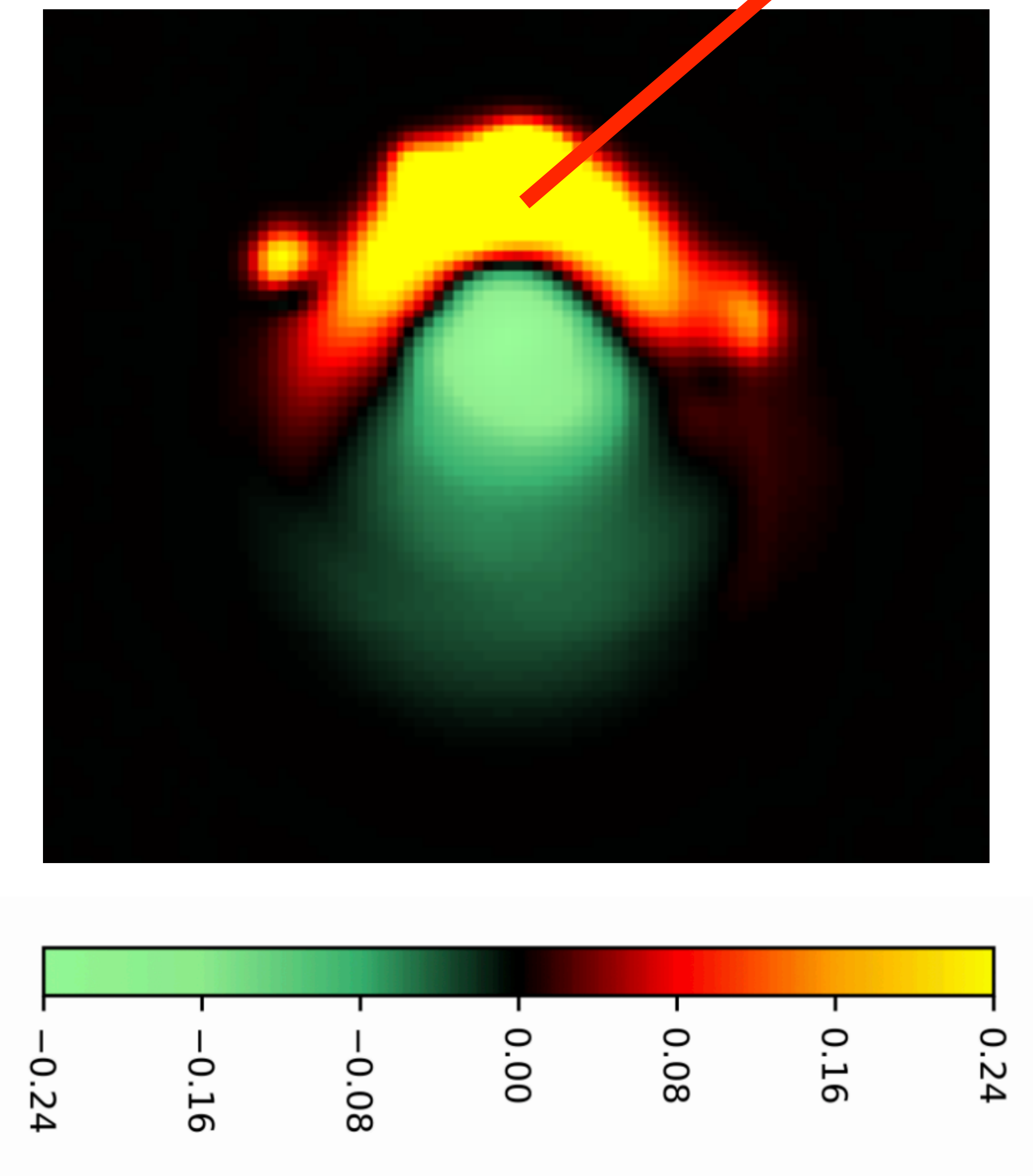
arXiv:2503.19993

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

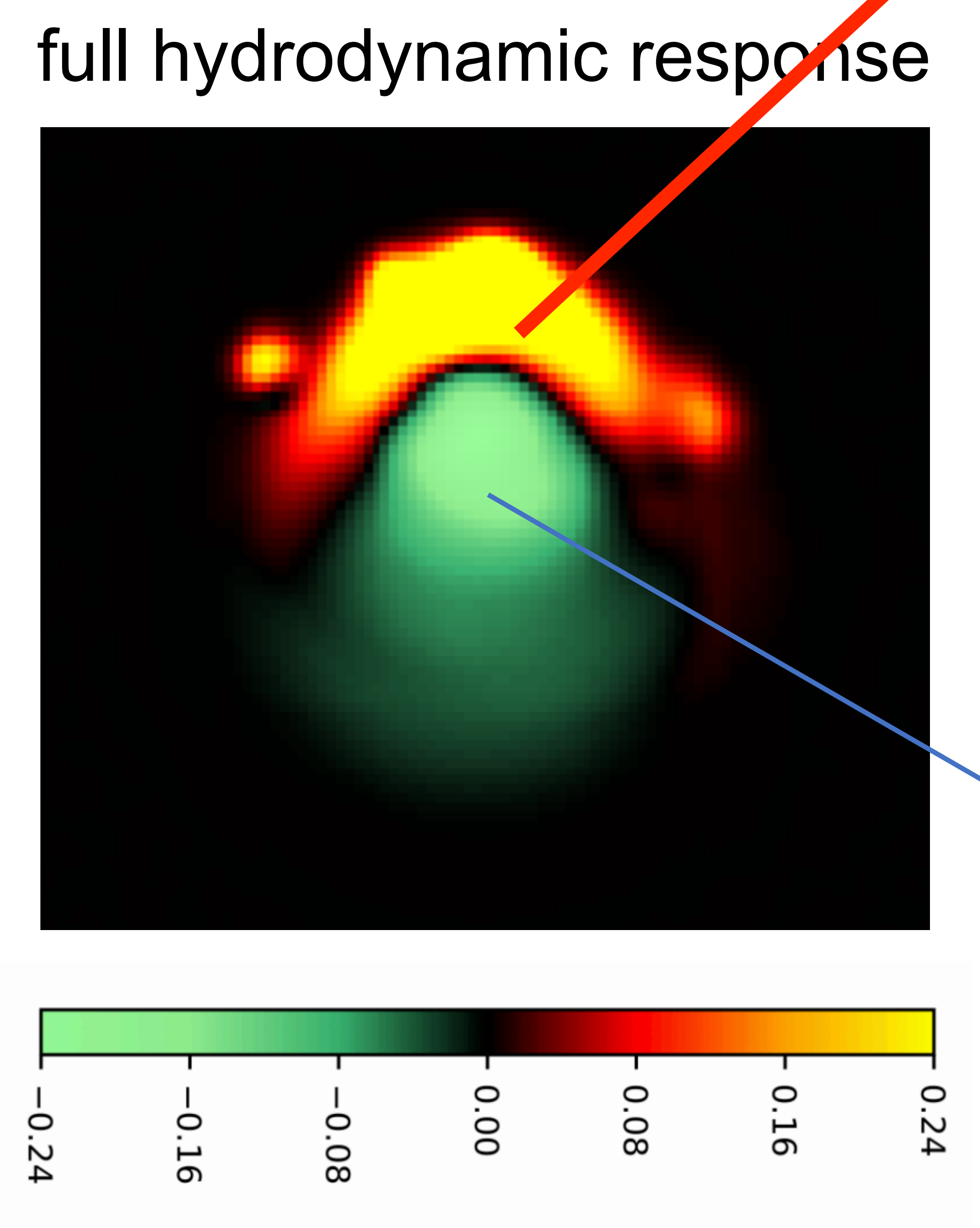
Mean-free-path limits the formation time: $\tau_f \leq \lambda \sim 1/T$ $\hat{q} \sim T^3$

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: $p\partial f(p) = -C(p) \quad (p \cdot u > p^0_{cut})$

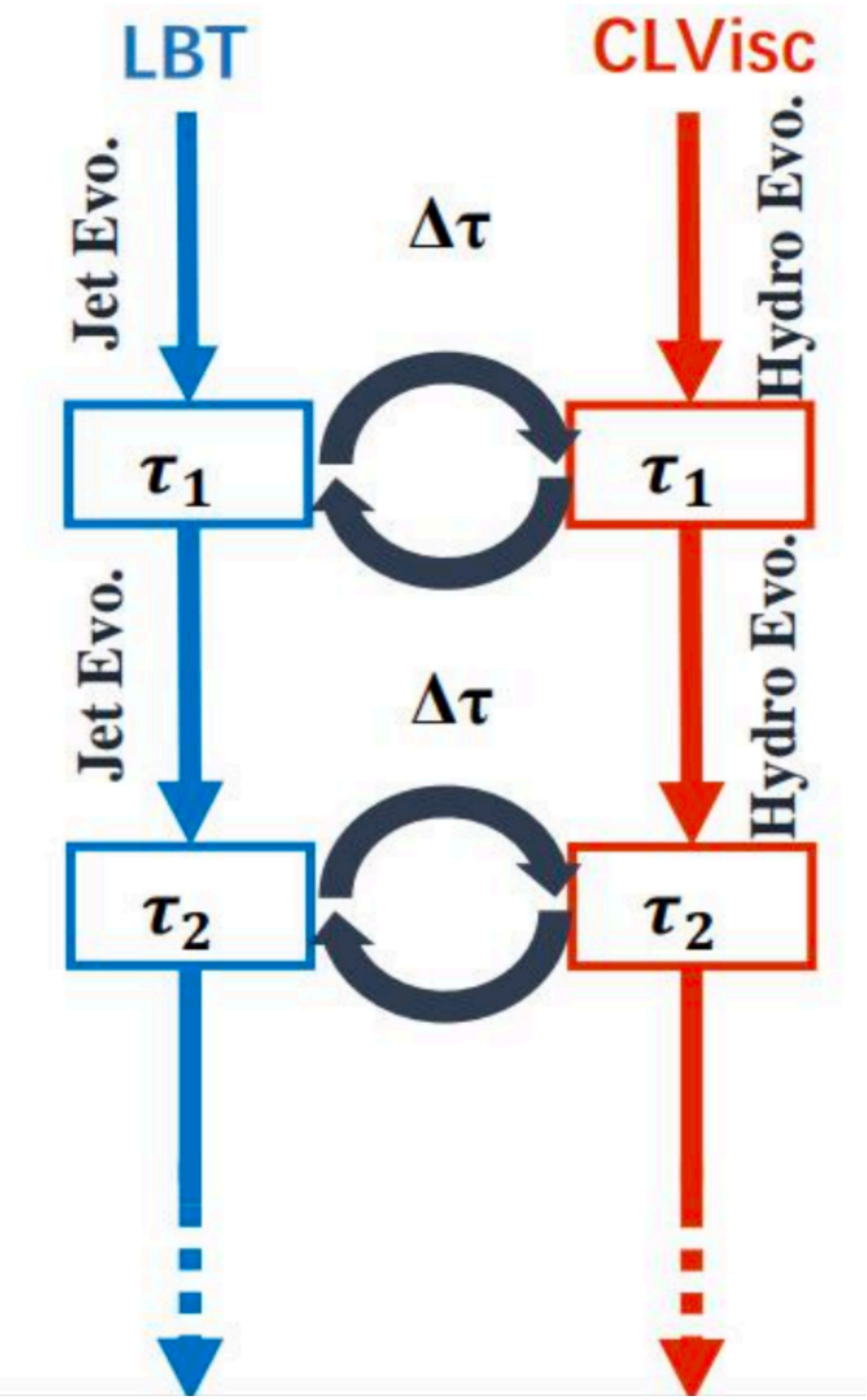
Soft and negative partons:

$$j^\nu = \sum_i p_i^\nu \delta^{(4)}(x - x_i)\theta(p^0_{cut} - p \cdot u)$$

4. Updating medium information by solving the hydrodynamics equation with source term

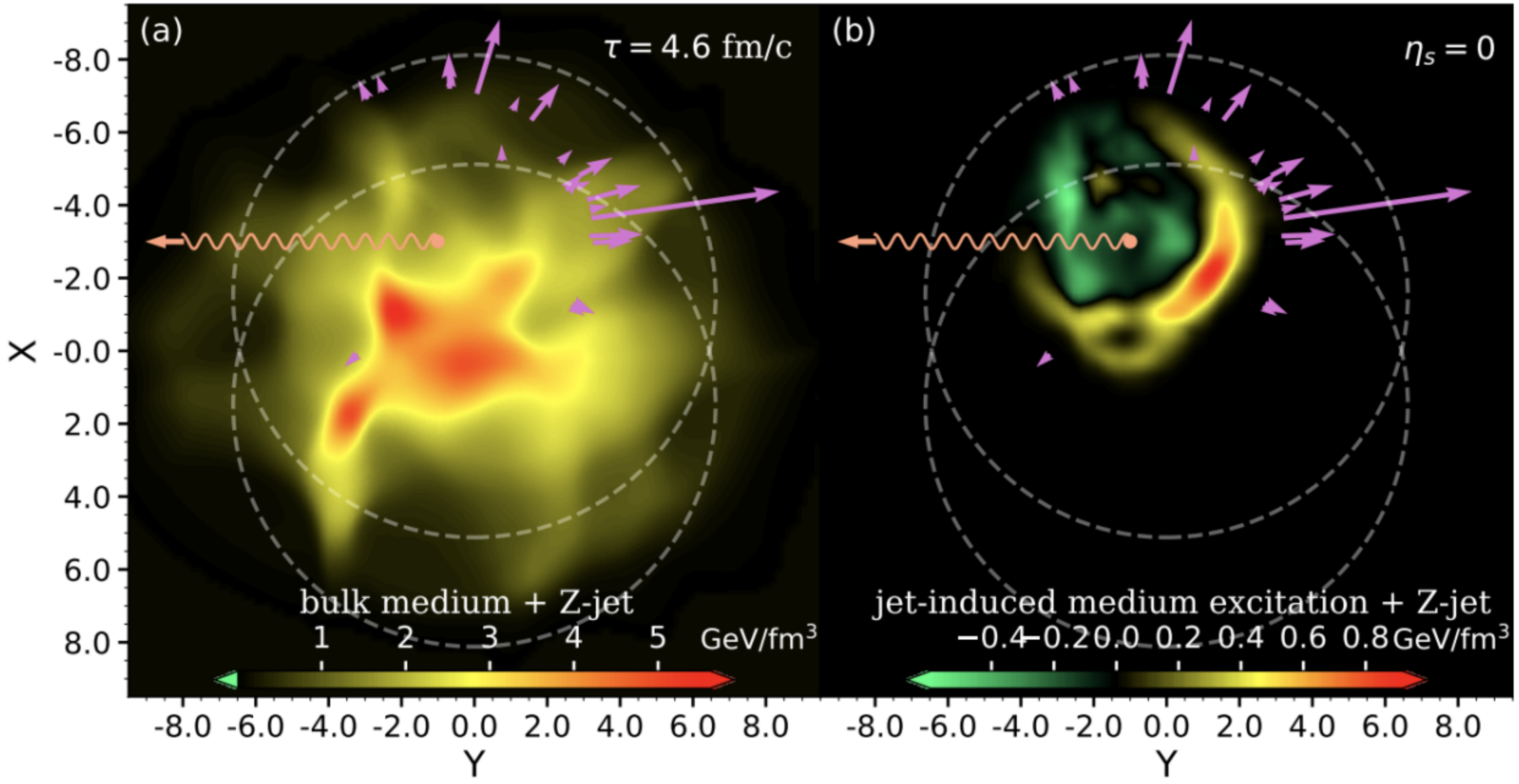
$$\partial_\mu T^{\mu\nu} = j^\nu$$

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



CoLBT-hydro model: Medium response

CoLBT-hydro model: **Hydro response**



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

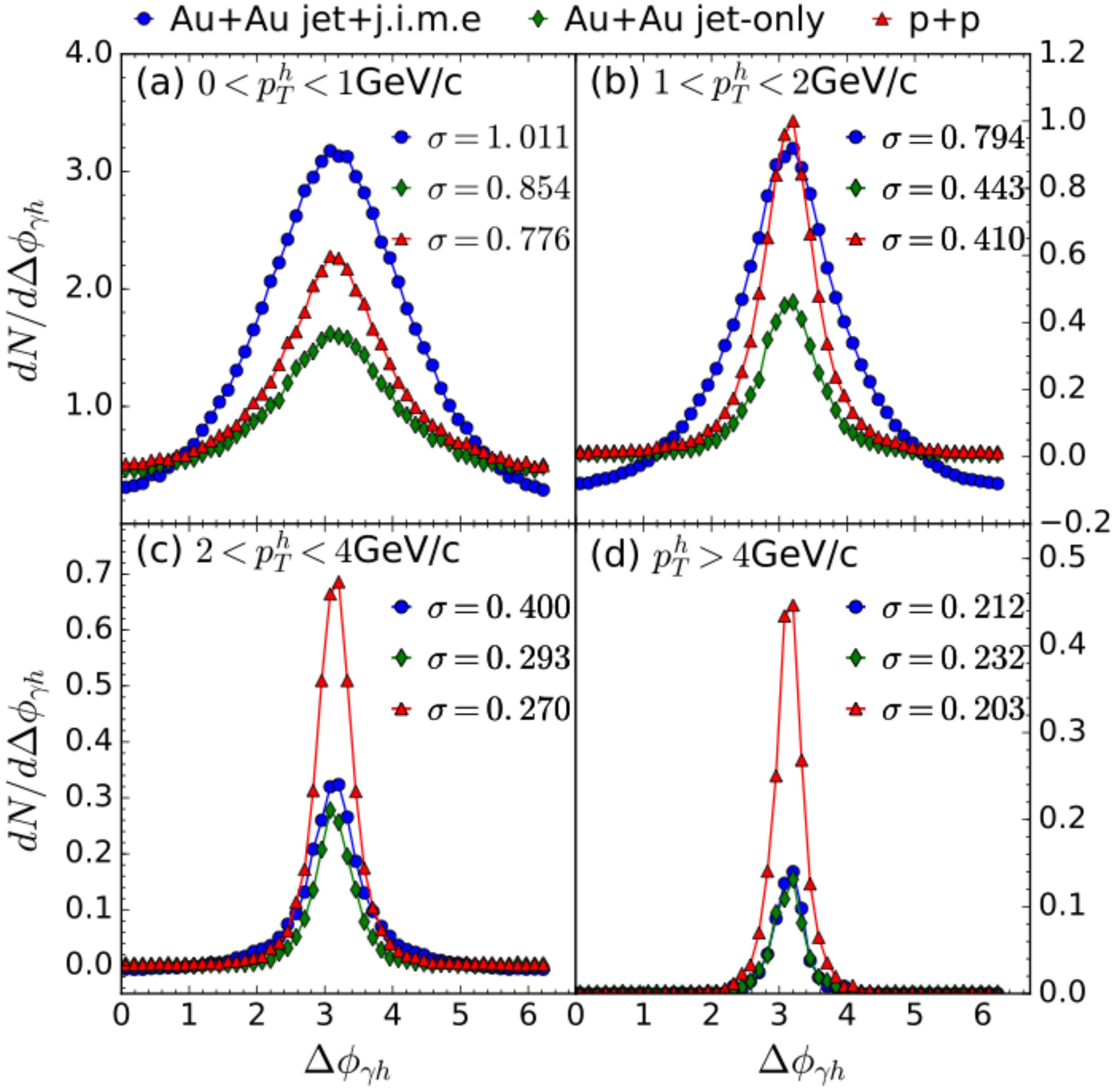
Theoretical background subtraction:

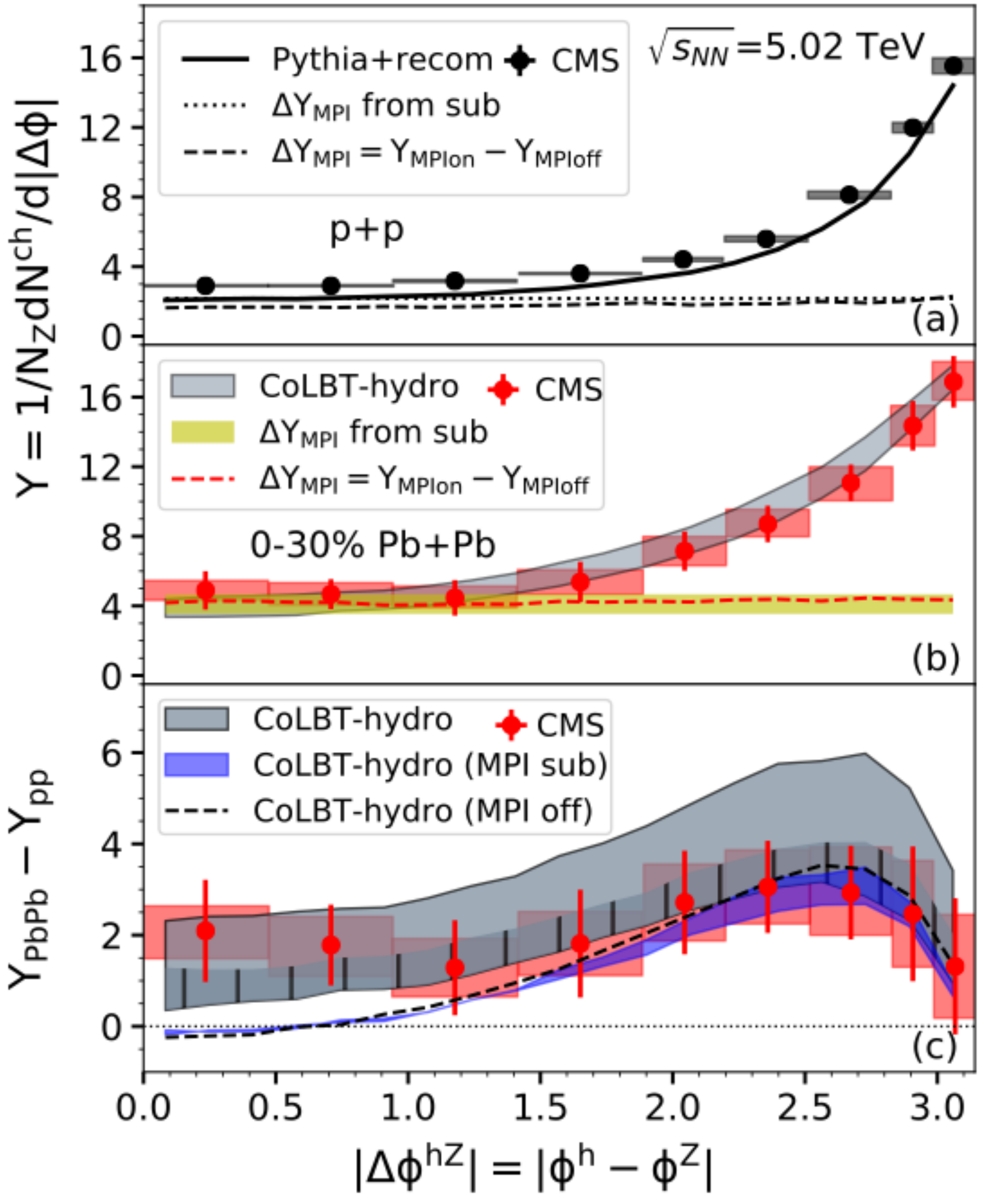
We run model twice with and without jet to subtract hydro background

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

Diffusion wake: depletion of soft hadrons

PLB 777 (2018) 86–90

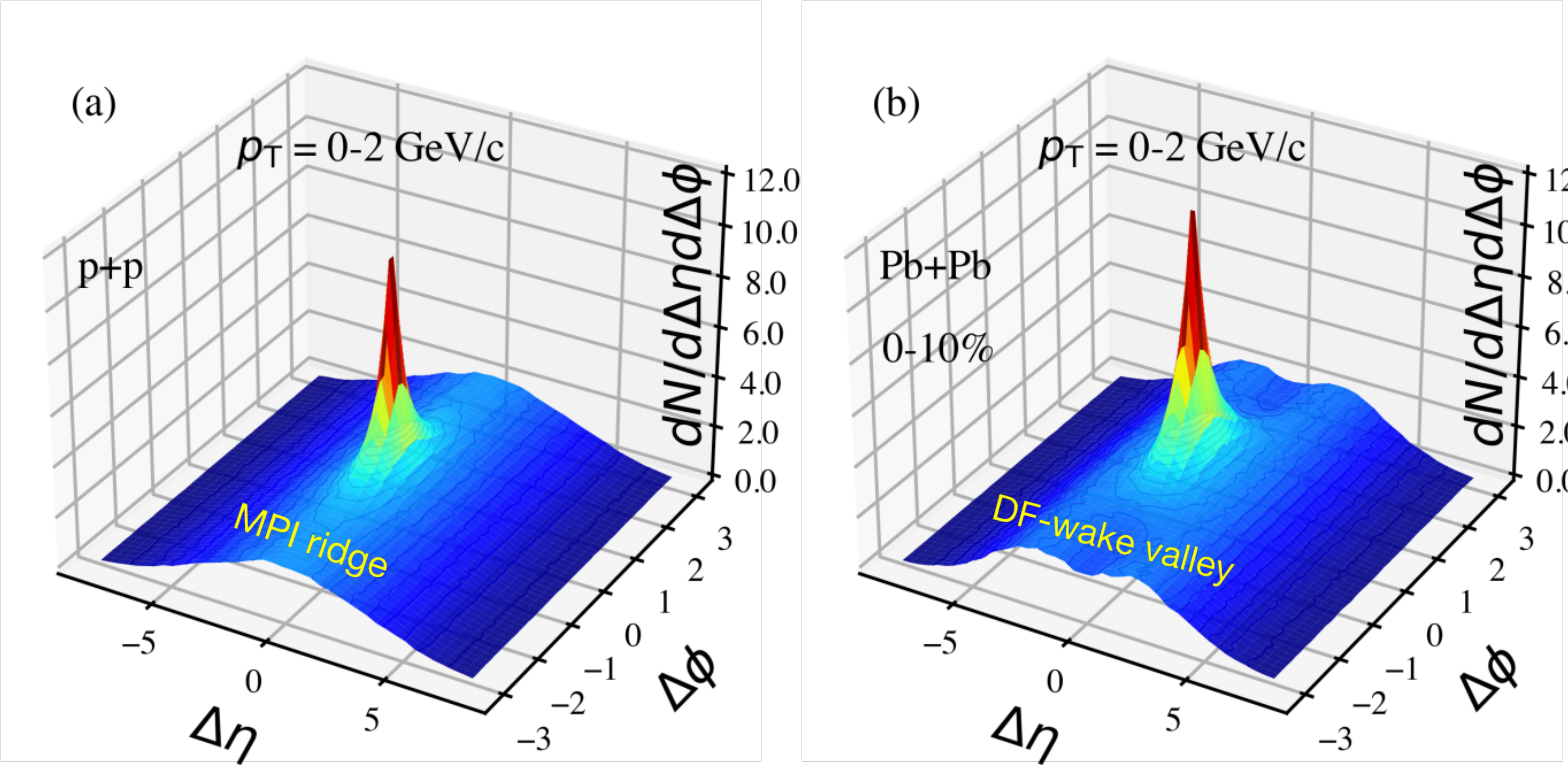




Initial multiple-parton interactions (MPI)

Diffusion wake: depletion of soft hadrons

γ-jet



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

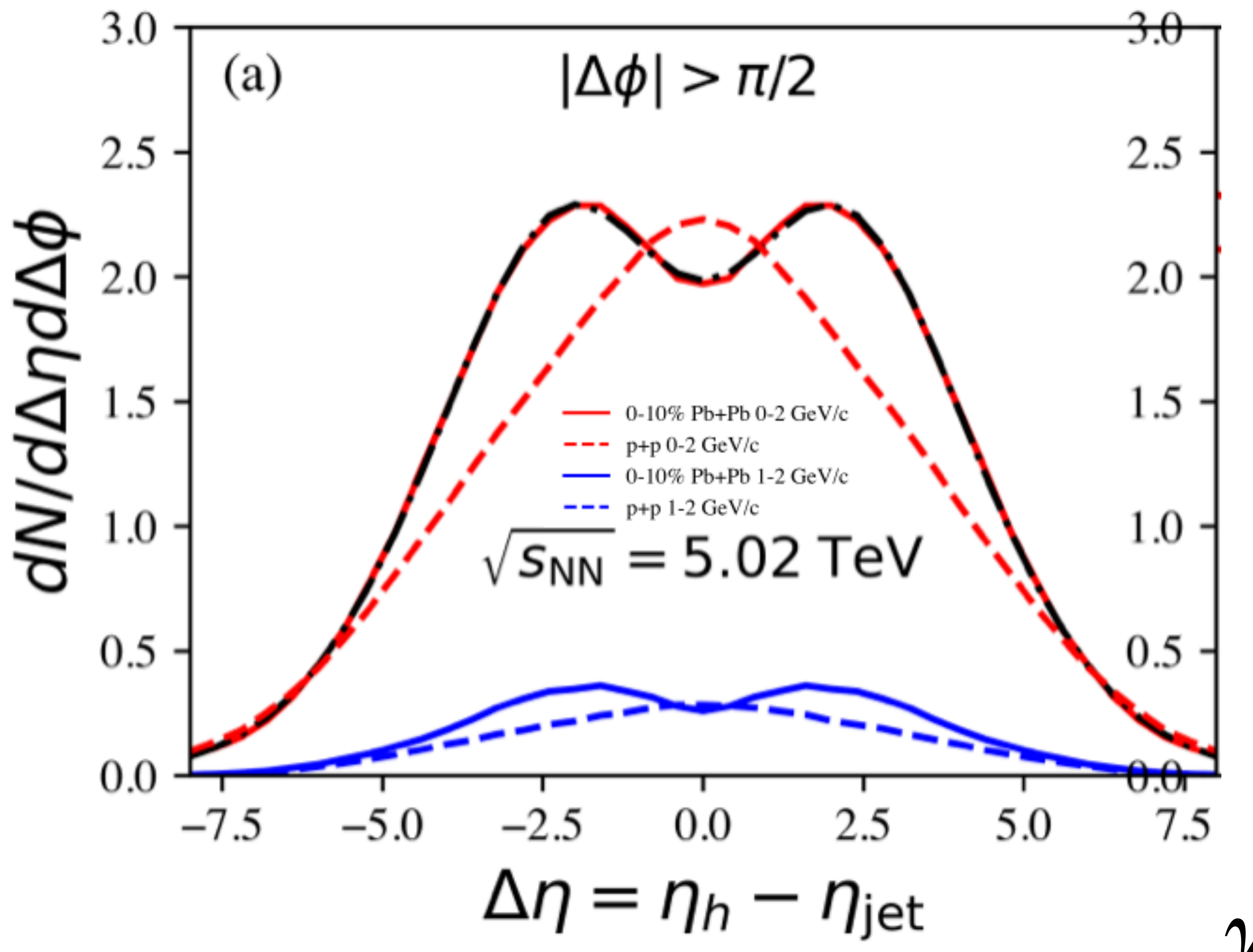
$$\Delta\phi = \phi_h - \phi_{\rm jet}$$

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

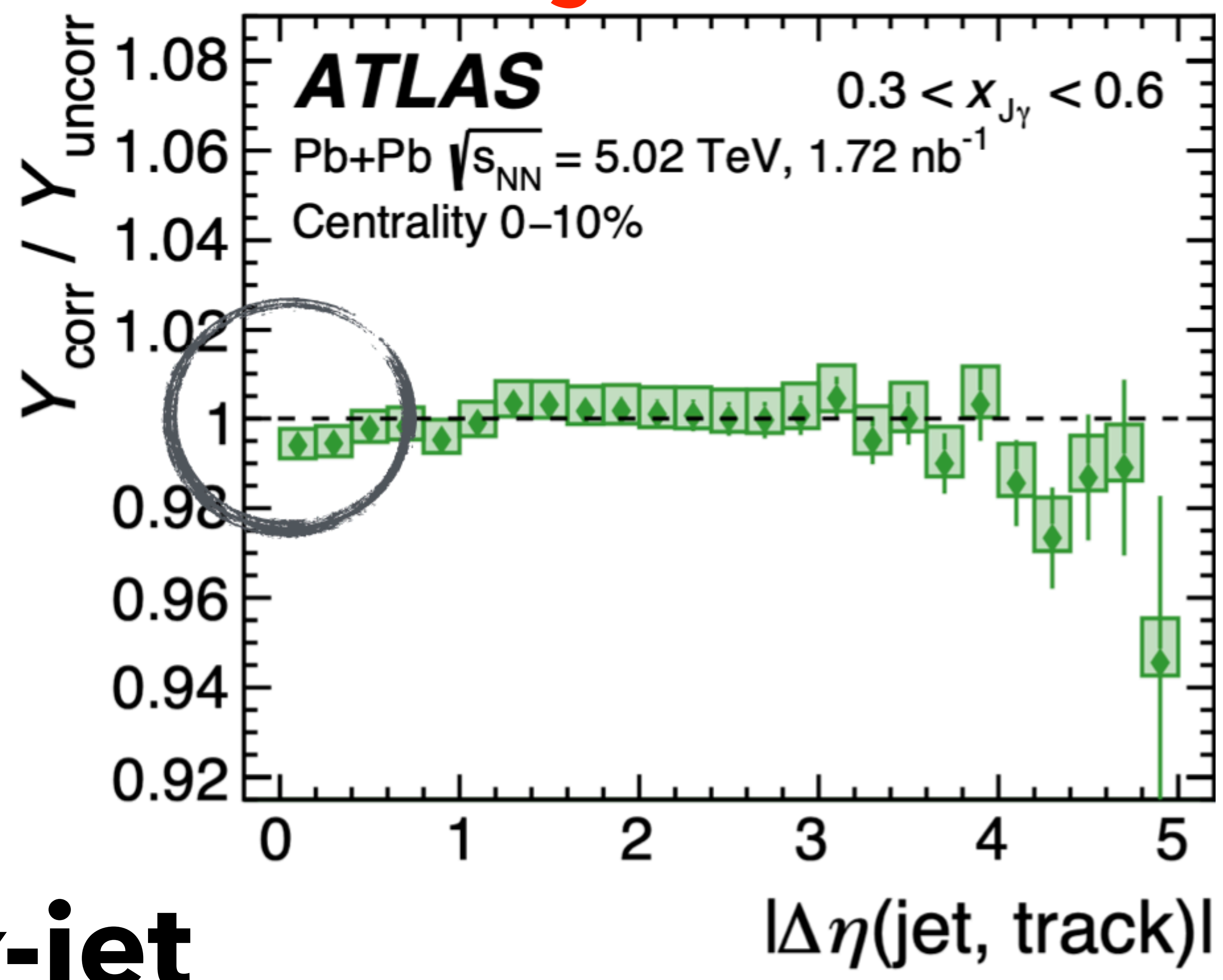
We project the two-dimensional distribution onto the rapidity direction.

We get the double peak structure of rapidity correlation



γ-jet

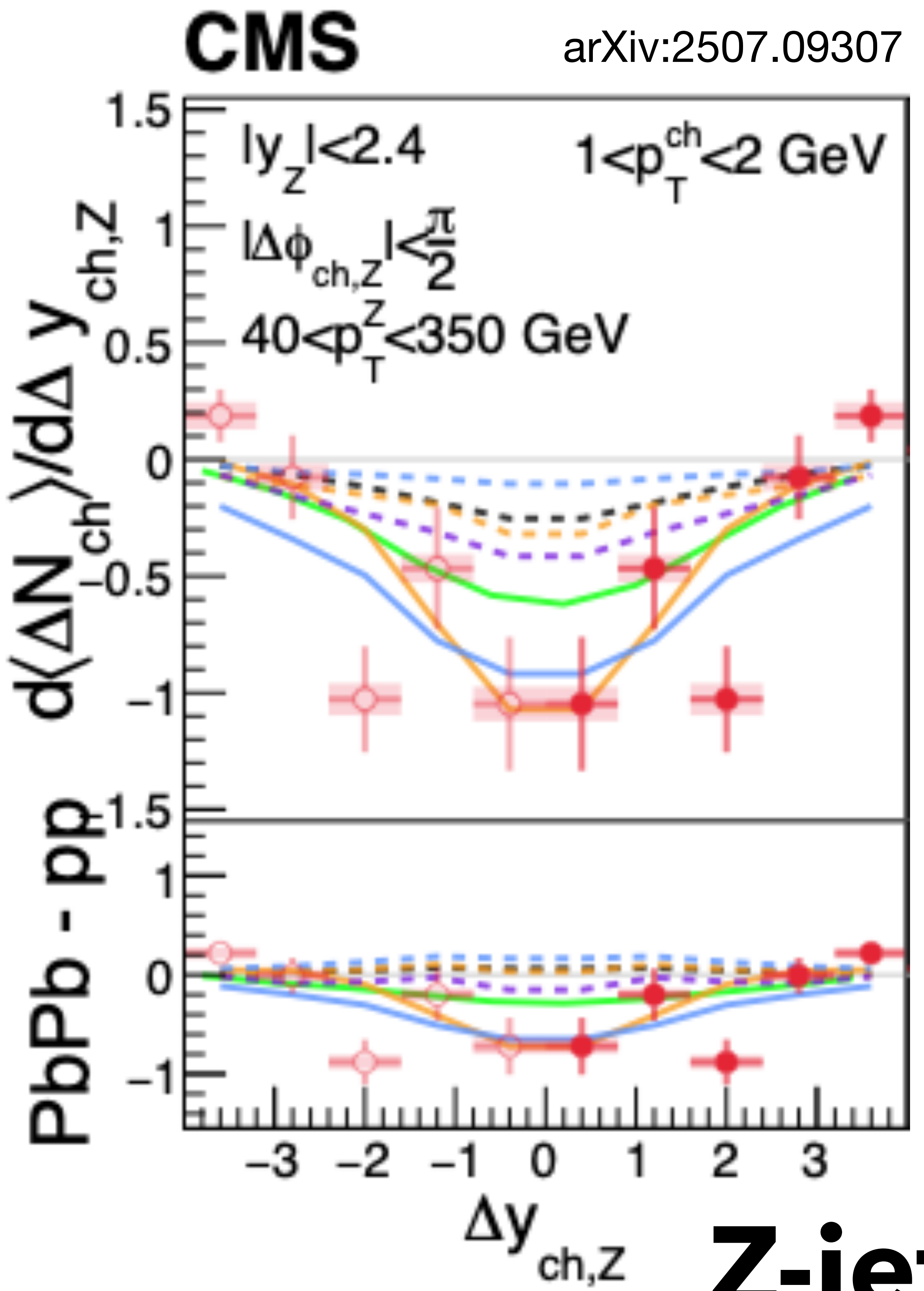
No background subtraction



Phys. Rev. C 111, 044909 (2025)

Mixed-event subtraction

arXiv:2507.09307



Z-jet

Diffusion wake in di-jets

Z/γ-jets events is relatively rare compared to single inclusive jet (or di-jet) events

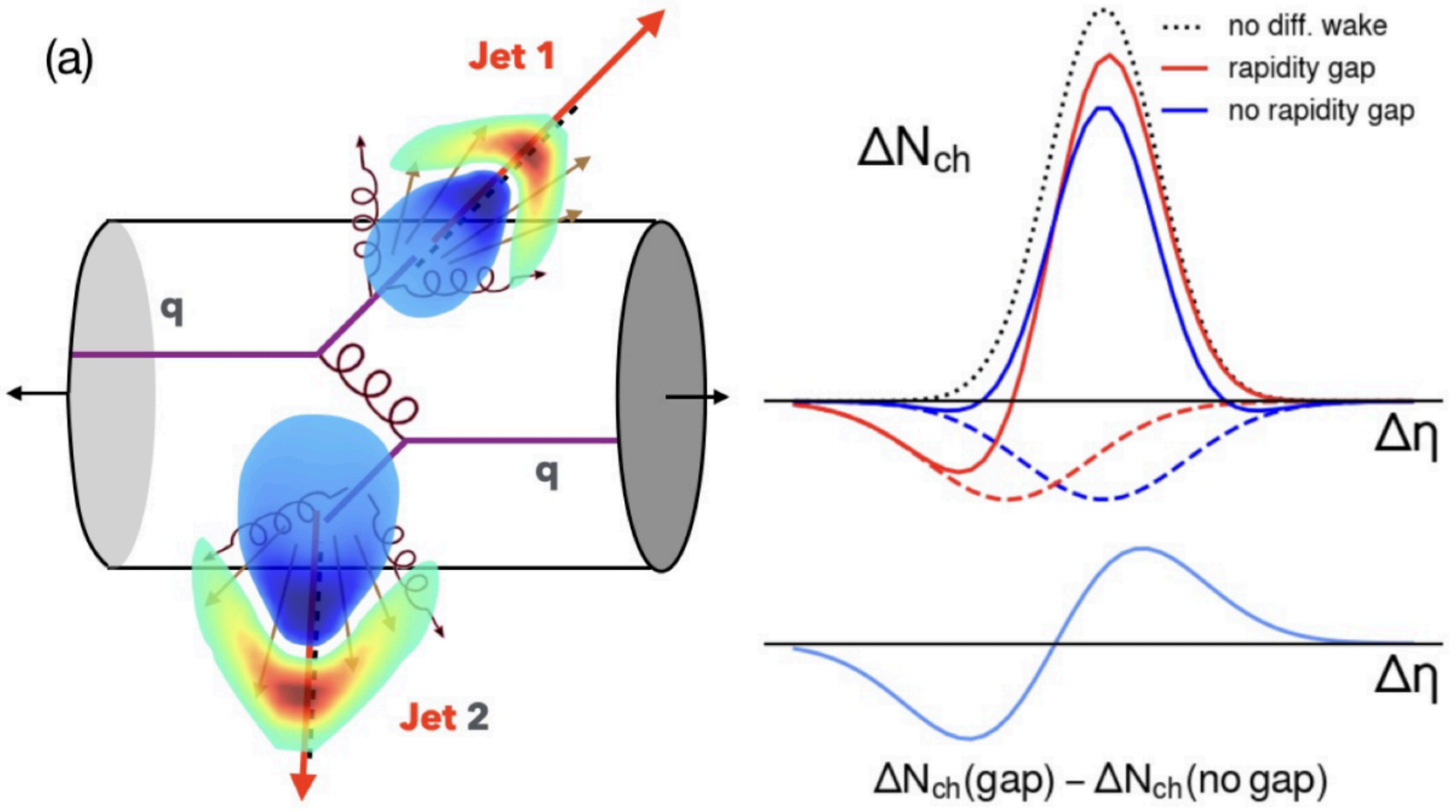
How to find signal of diffusion wake in di-jet events?

Relationship between diffusion wake and jet

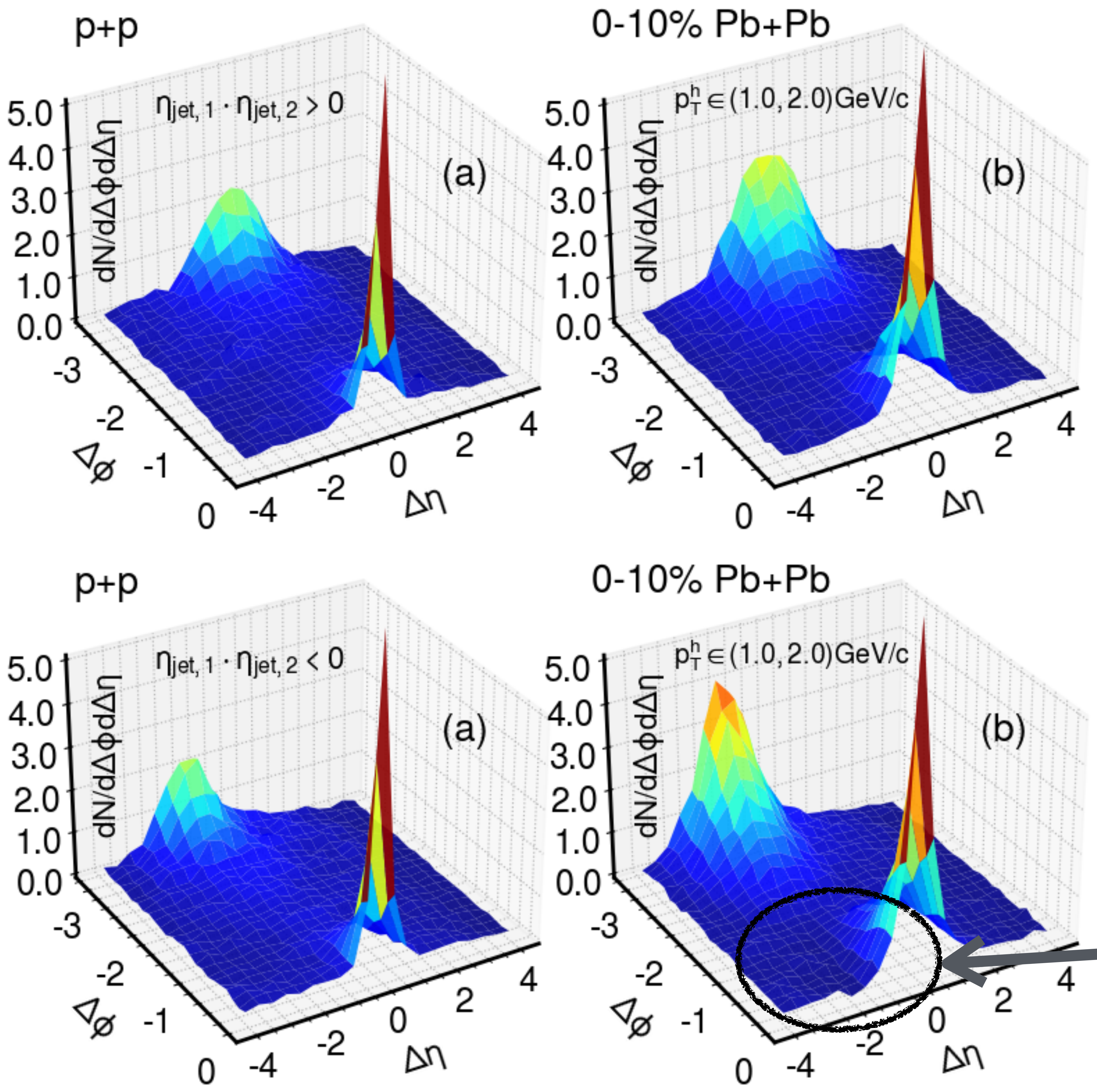
Eta	Phi
Same as jet	Opposite to jet

Challenge:

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



Jet-hadron 2D correlation



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

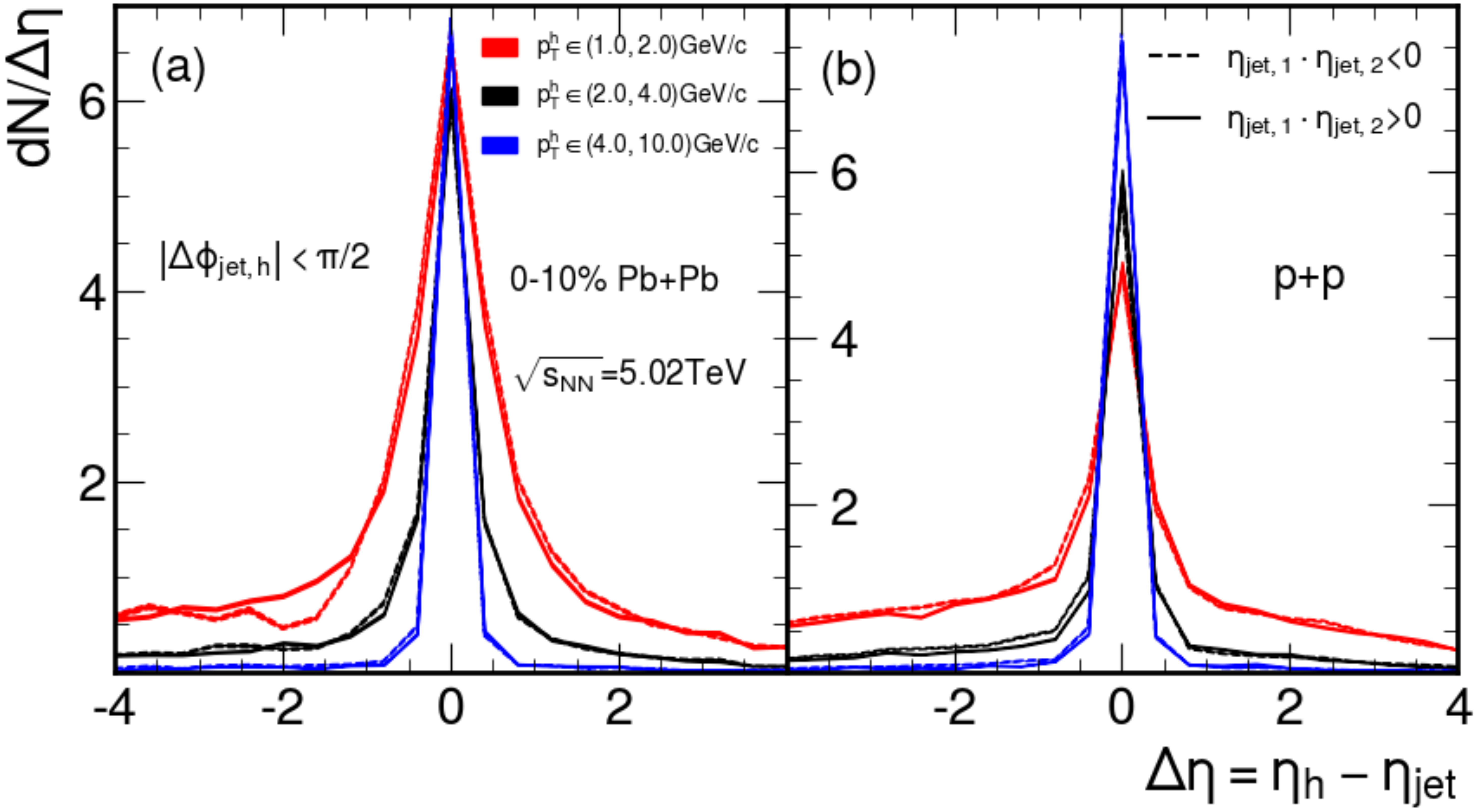
Dividing events by taking different rapidity relationship between leading jet and sub-leading jet

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

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

Valley caused by diffusion wake

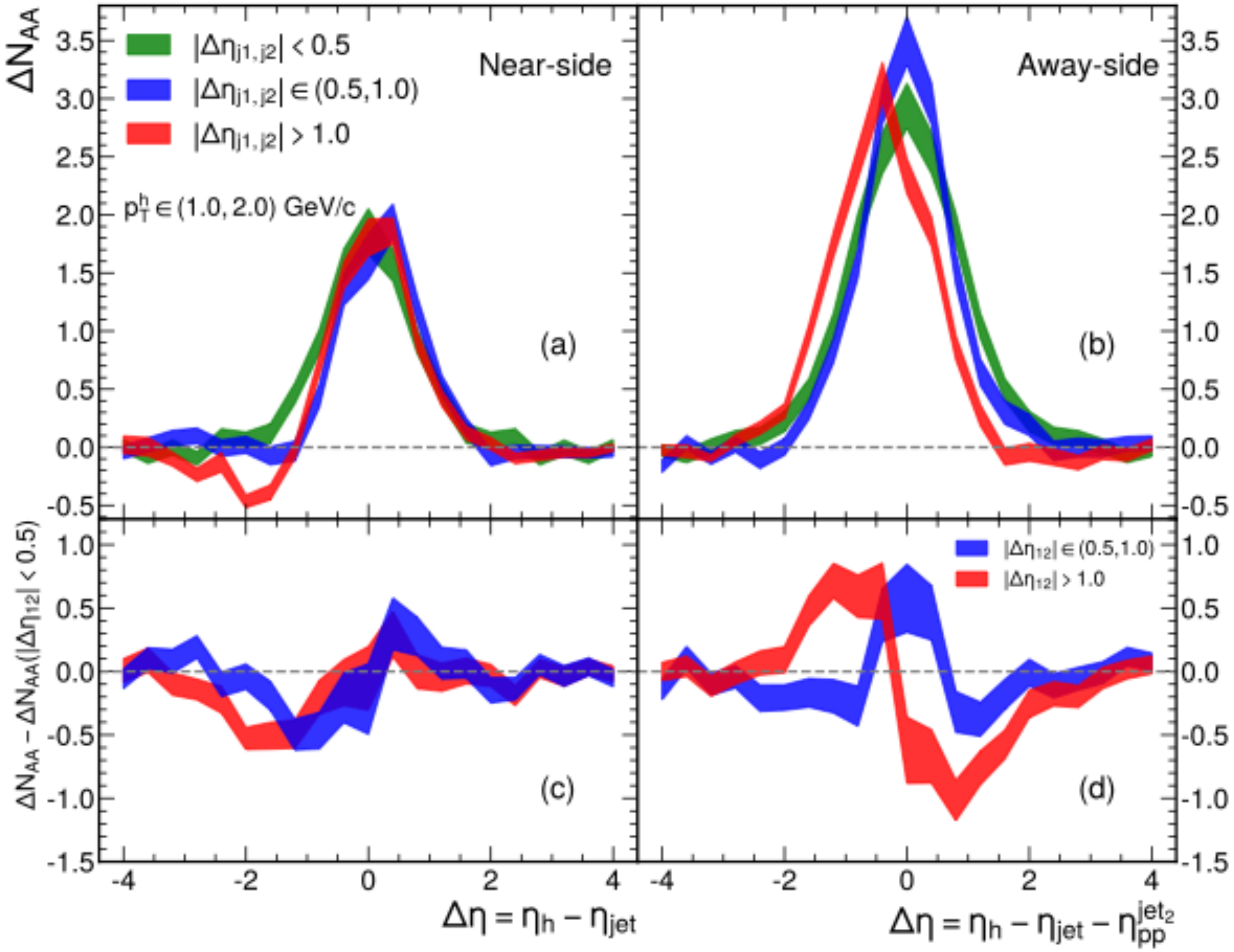
Jet-hadron correlation in rapidity direction



Diffusion wake leads to a clear asymmetry of jet hadron rapidity correlation at soft hadron p_T range.

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

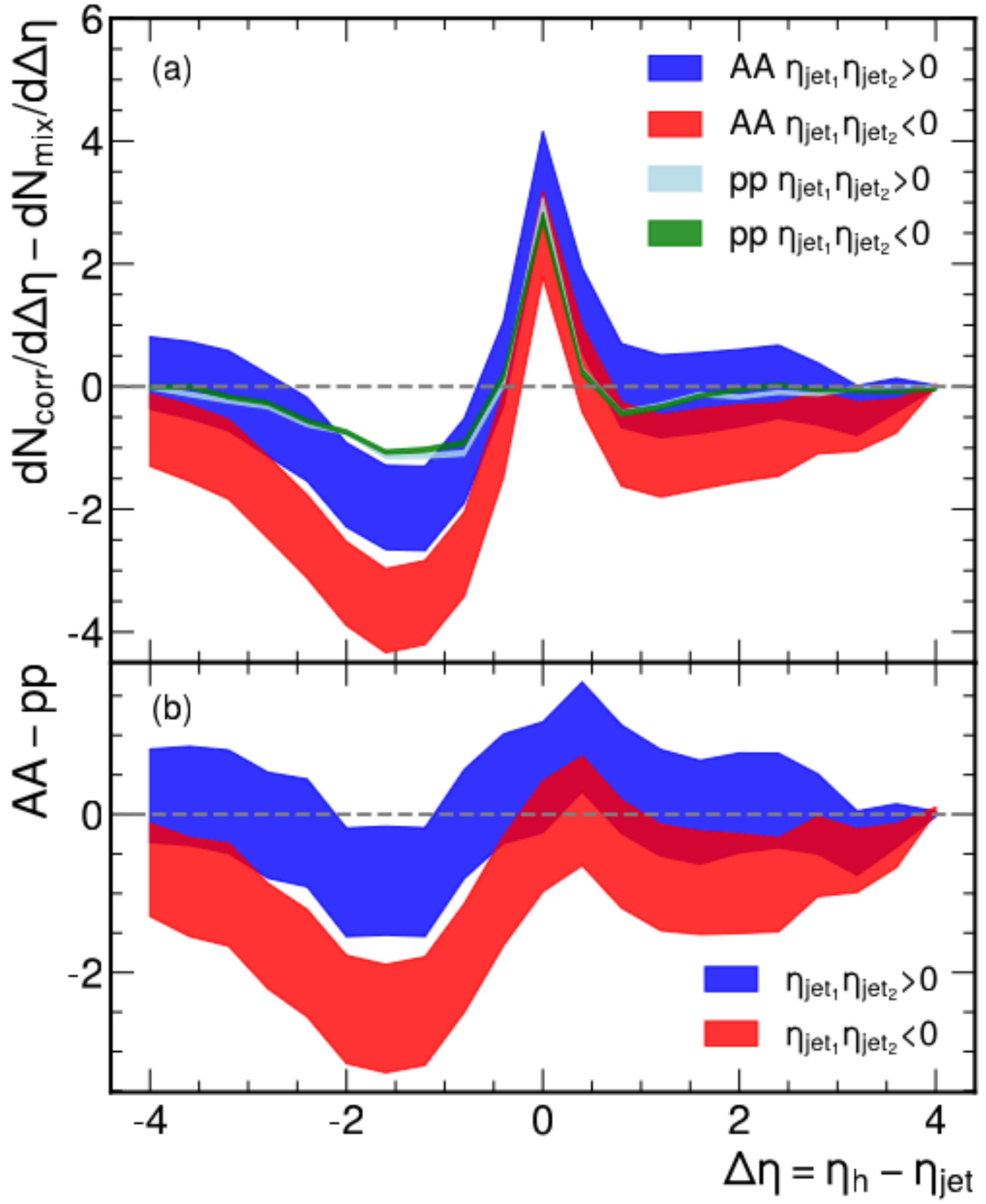
Away-side: $\Delta\phi_{j_1,h} > \pi/2$ (Shift by the peak in pp)

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

Mixed-event background subtraction

Mixed-event results

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



The previous is from theoretical background subtraction

Hard to realize in experimental measurement

Mixed-events

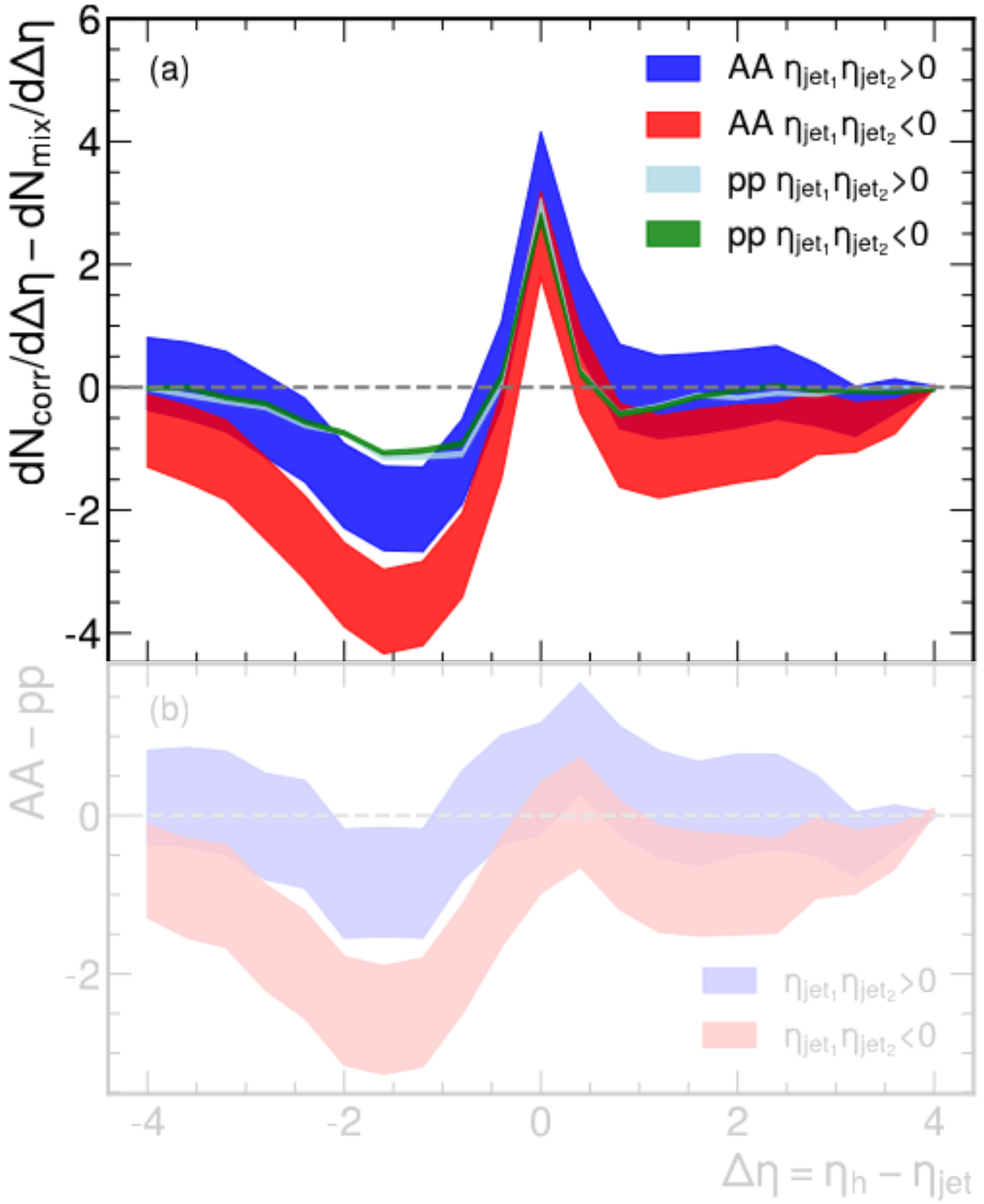
$dN_{corr}/d\Delta\eta$ (Jet hadron corr. in same event)

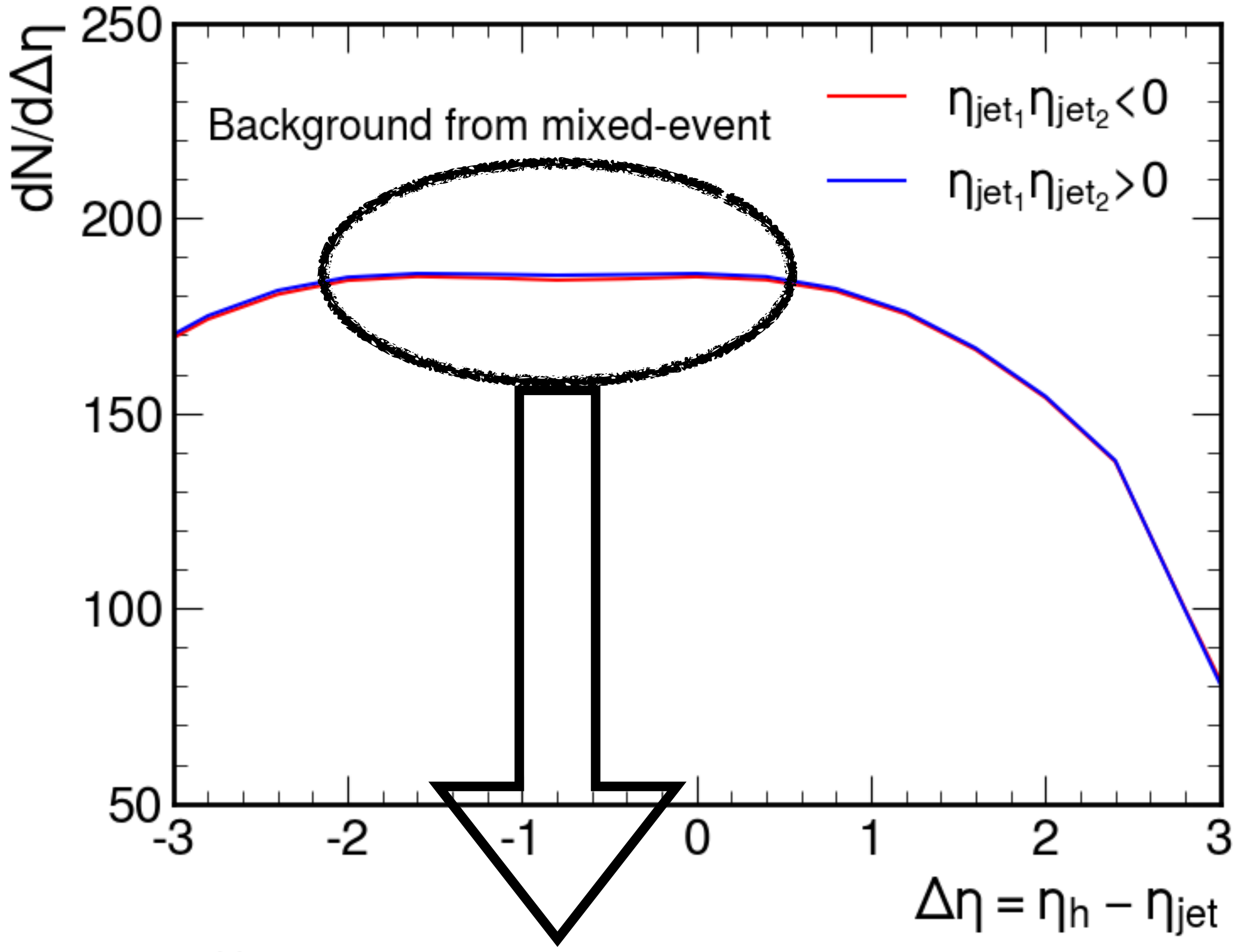
Medium modification

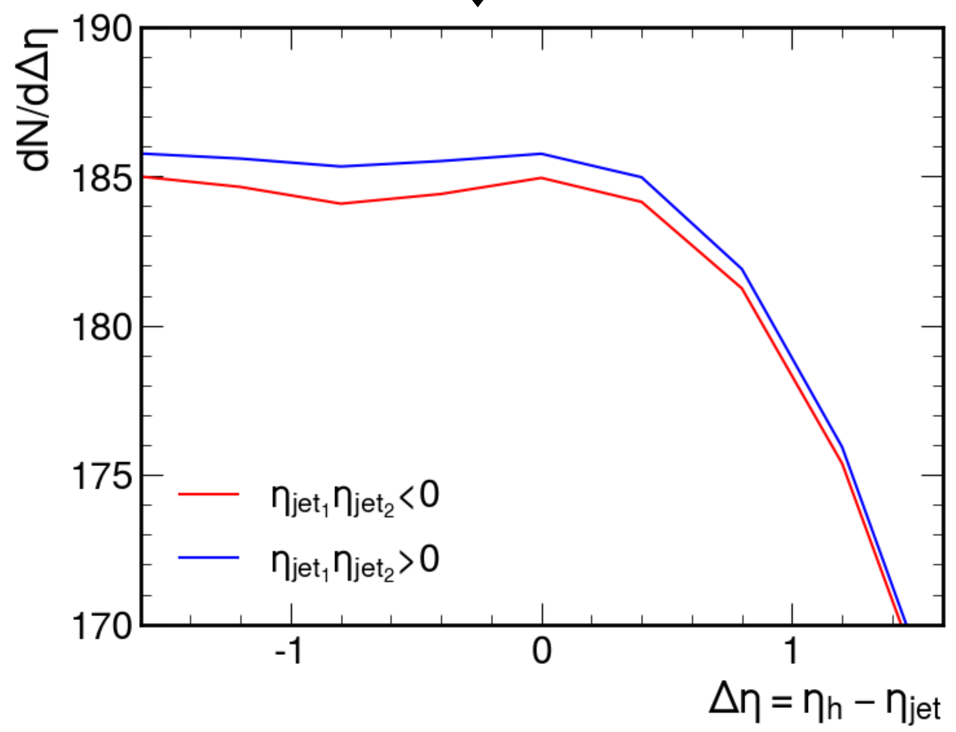
$dN_{mix}/d\Delta\eta$ (Jet hadron corr. in different event)

Background free signal

When we calculate the difference between red(large gap) and blue(small) band, if the mixed-event background is the same in both cases, does this mean that background subtraction is not necessary?







The background in two cases is indeed similar.

But still has clear difference which affect result.

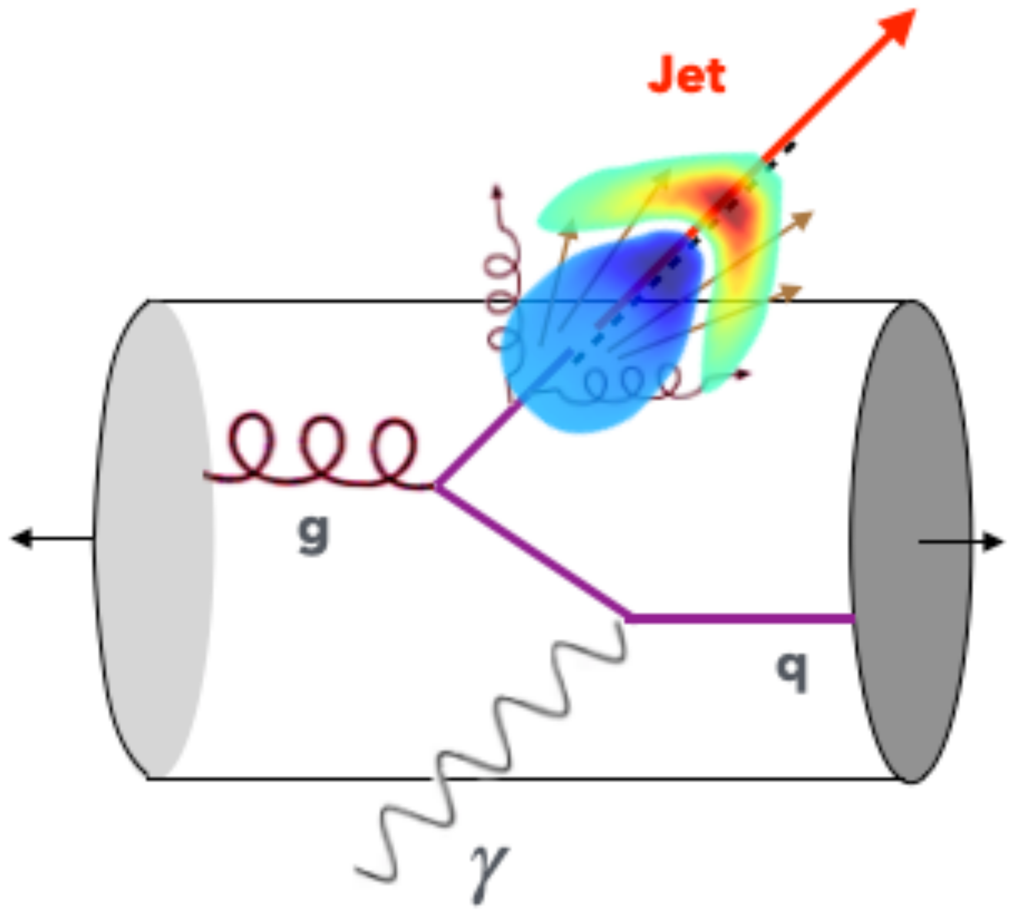
Close to background free

Since it is $\Delta\eta$ distribution, the back depends on jet rapidity, which brings challenges to experimental correction. And since we require $\eta_{j1} > \eta_{j2}$, the dependence on the jet rapidity could be little different in cases.

Background free signal

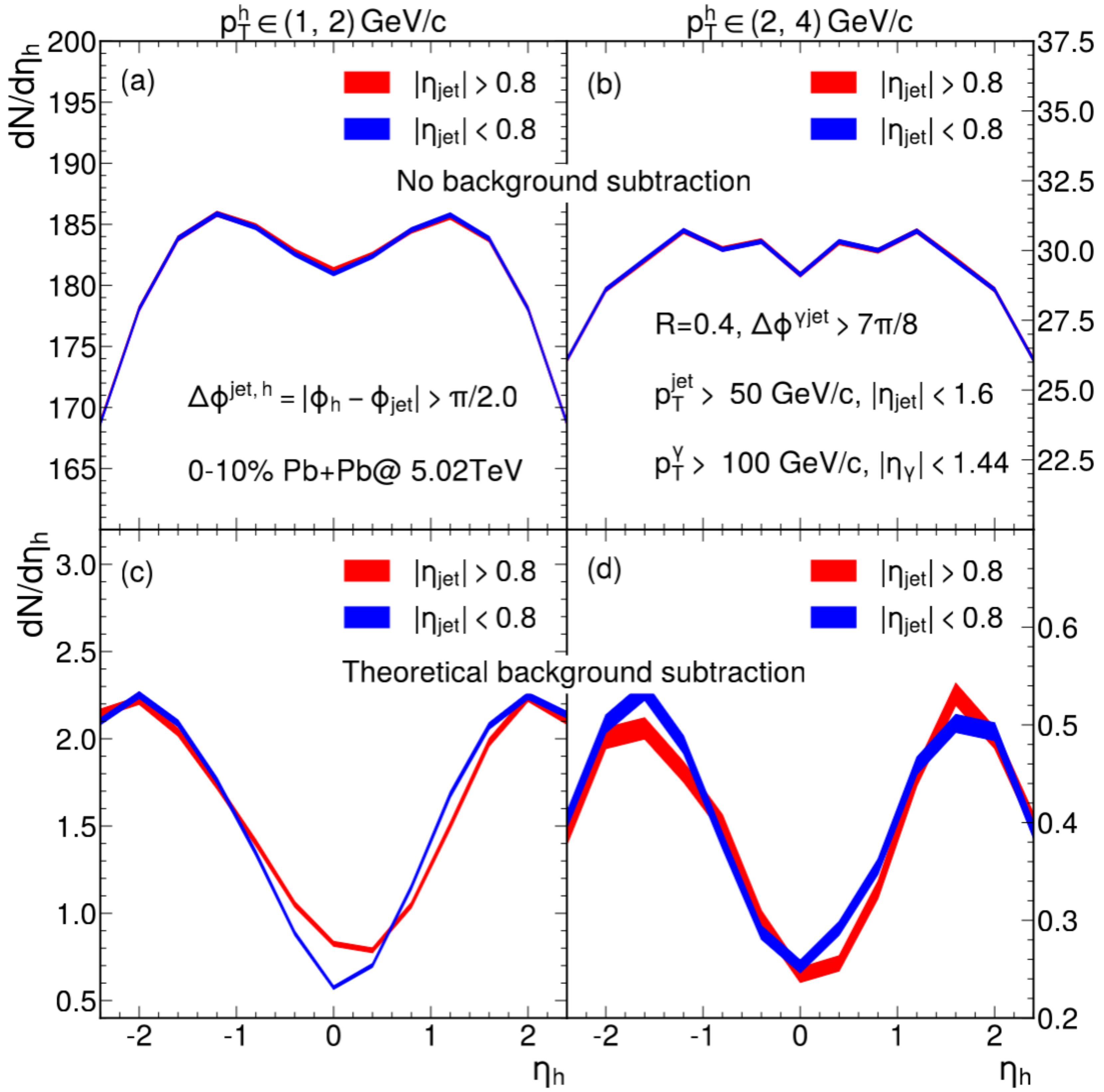
Since the background in previous studies depends on jet rapidity. We use the η distribution instead of $\Delta\eta$

We firstly focus on γ-jet



The signal of DW is clear in the γ direction

Red: $|\eta_{\text{jet}}| > 0.8$ **Blue**: $|\eta_{\text{jet}}| < 0.8$



arXiv:2508.04194

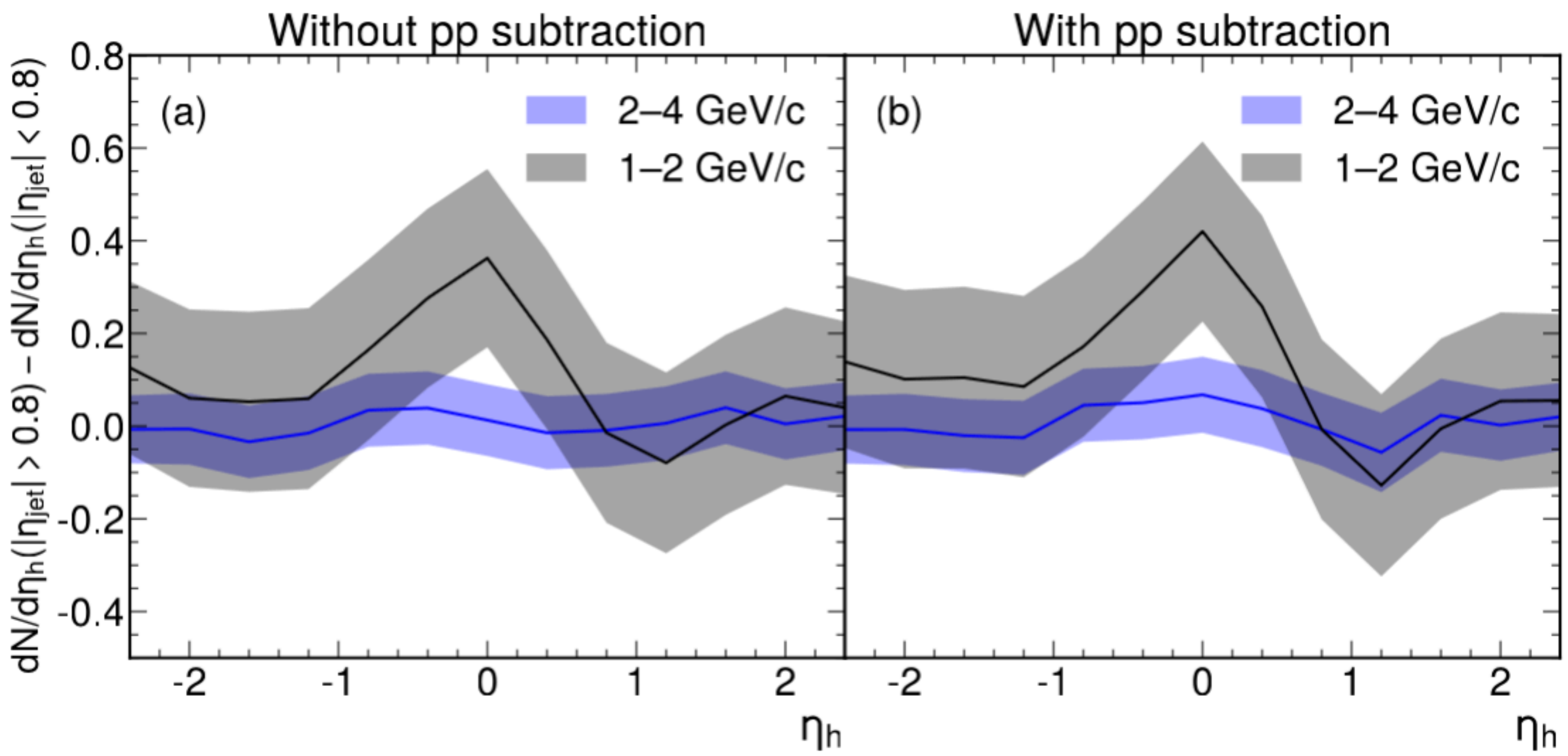
Pure distribution (including background)

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*



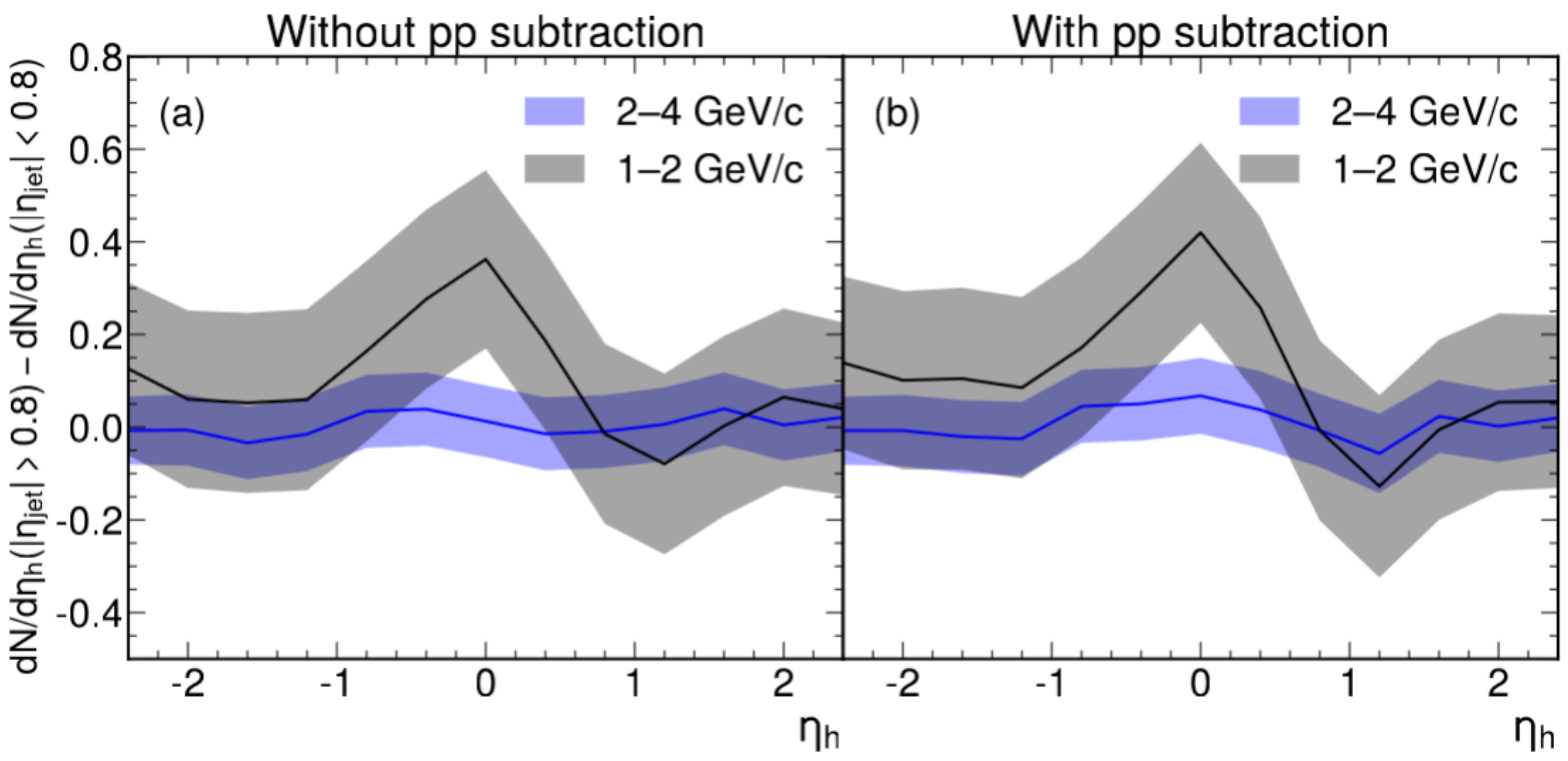
arXiv:2508.04194

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

Rapidity asymmetry in gamma-jets

We choose gamma as reference instead of jet.

$\Delta\phi_{\gamma,h} < \pi/2.0$ 　 *γ as the reference*



- ★ Background cancel automatically
- ★ R… ron p_T
- ★ PP baseline is not important

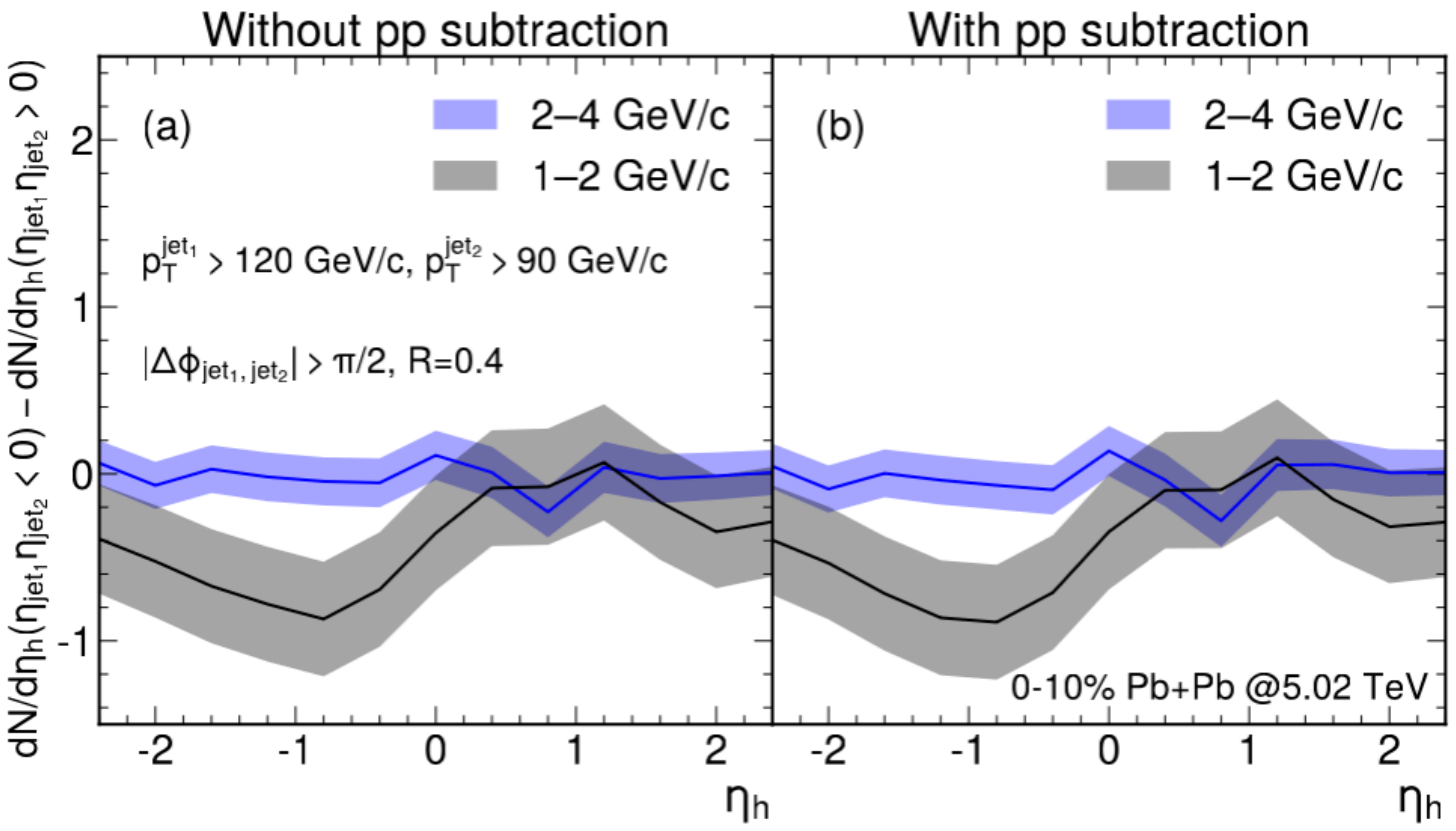
Conclusion is the same!

Background free signal in di-jets

This background free observable can also be calculated in di-jet events.

The same di-jets as we used before.

Focus on near-side of leading jet: $\Delta\phi_{jet_1,h} < \pi/2.0$



Events classification:

(1) $\eta_{\text{jet}_1}\eta_{\text{jet}_2} > 0$; (2) $\eta_{\text{jet}_1}\eta_{\text{jet}_2} < 0$

We require: $\eta_{\text{jet}_1} > 0$

(Suppress enhancement from medium modifications)

This new result is totally free of background.

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 and verified by experimental measurements.
- Diffusion wake 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 di-jets events and it provides background free signal of diffusion wake both in gamma-jet and di-jet events.

THANK YOU