



Search for medium response through jet related correlations at LHC

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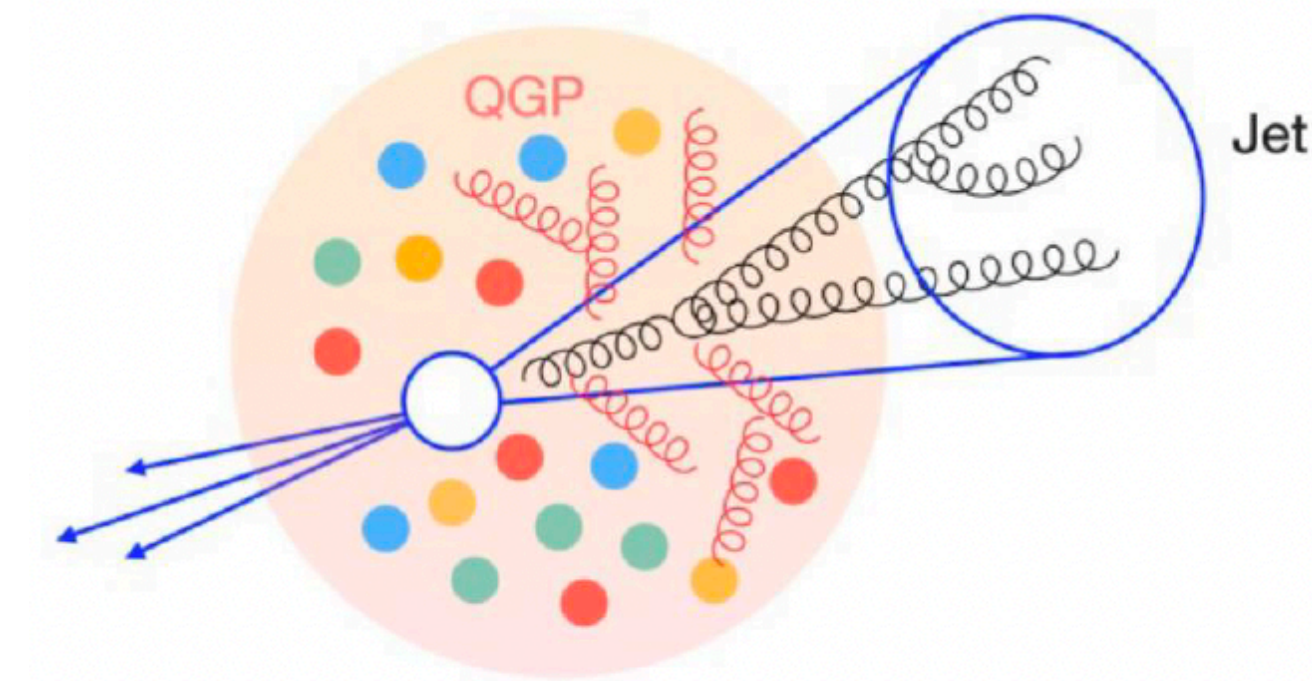
Central China Normal University
华中师范大学

第三届极端边缘碰撞物理学术研讨会
广州, 2025年11月21-24日



Jets as a probe of the quark-gluon plasma

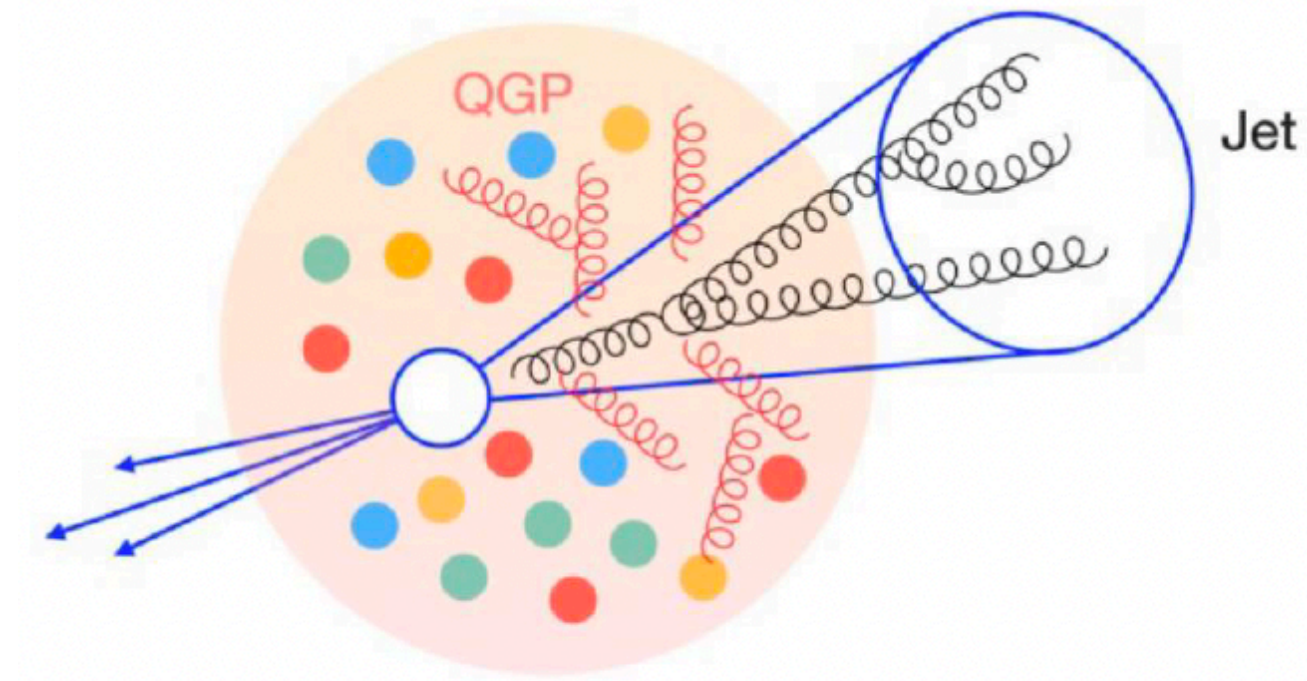
- Study structure of QGP by understanding jet modification from medium interaction (jet quenching)
- Several types of jet observables
 - Jet yields and constituents $\rightarrow$ suppression and energy redistribution
 - Jet reconstruction and declustering $\rightarrow$ jet substructure modification
 - Jet correlations and tagging $\rightarrow$ angular deflection and asymmetry



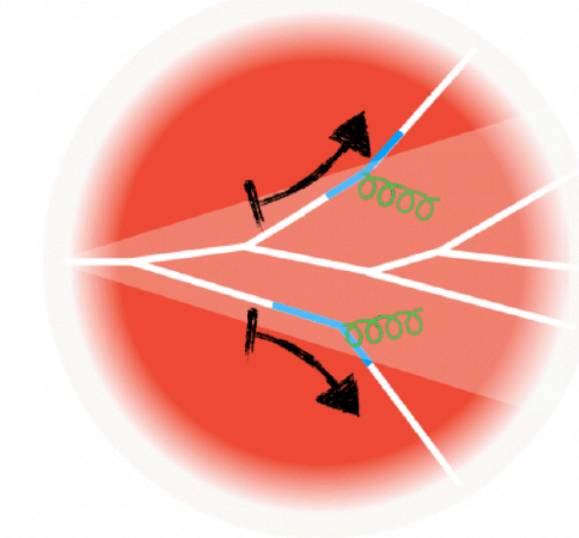
<https://www.int.washington.edu/node/776>

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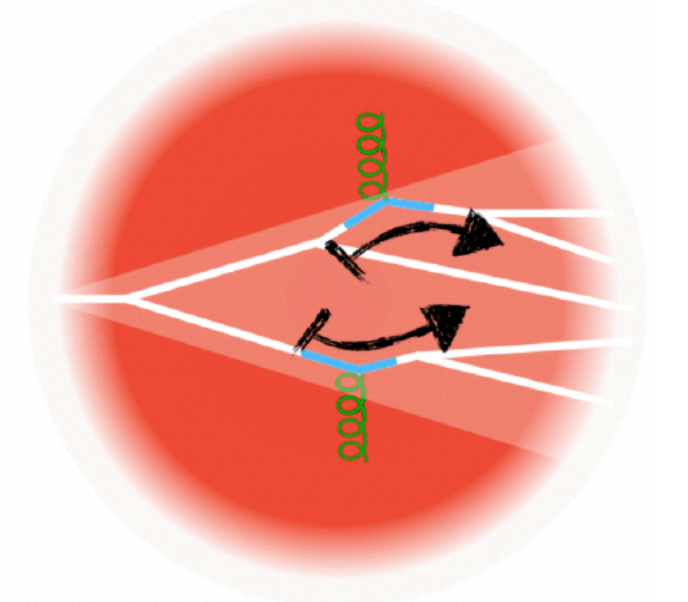
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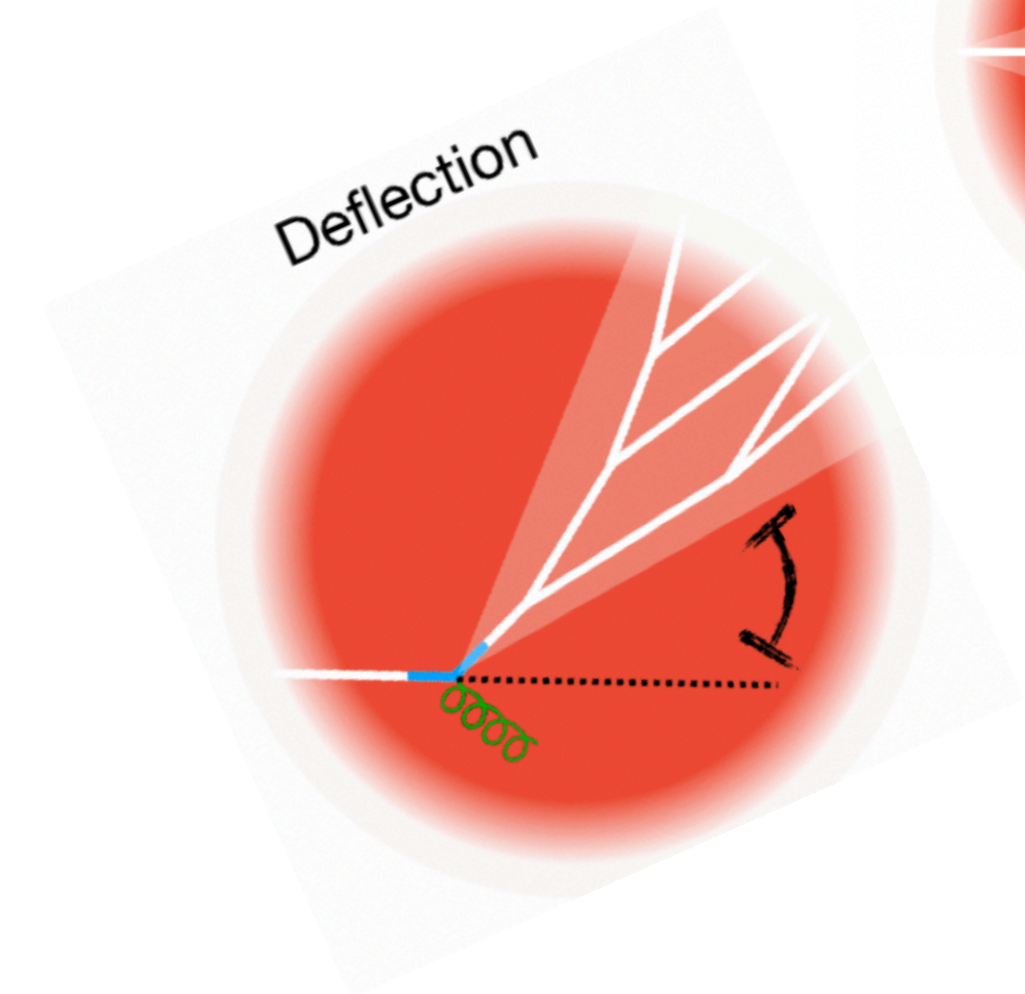
Energy Redistribution ("loss") ://www.int.washington.edu/node/776



Substructure modification

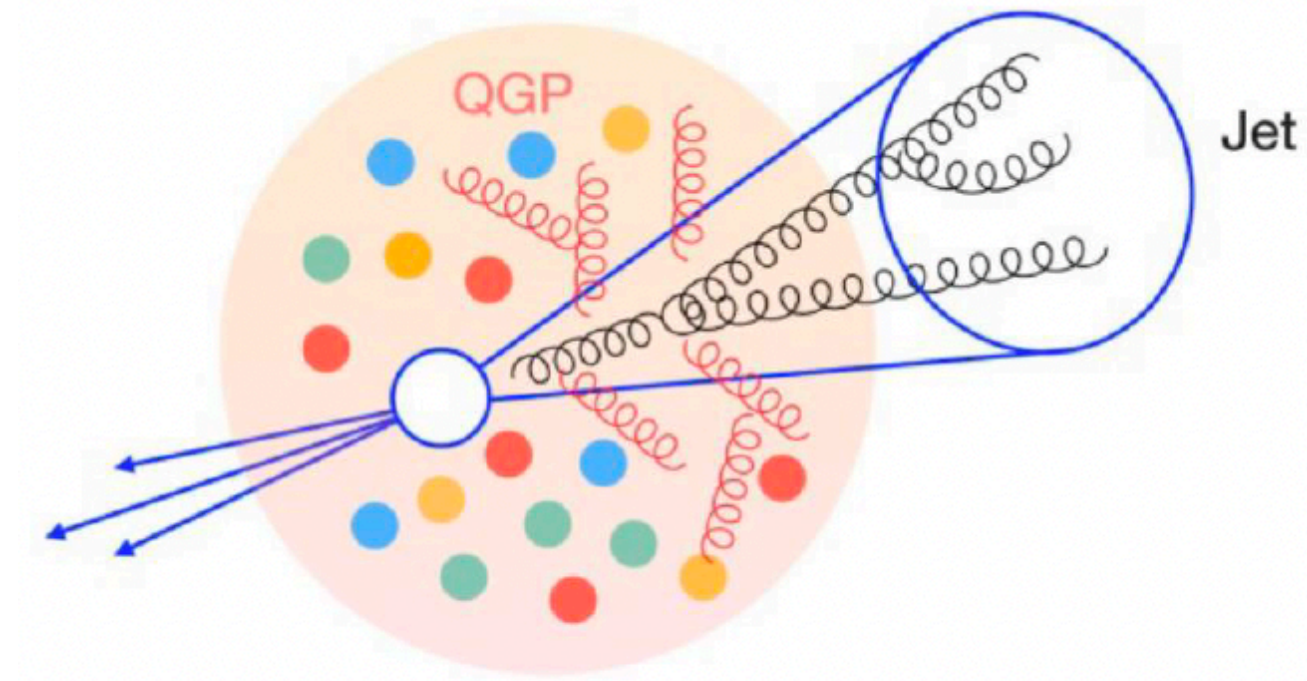


Deflection

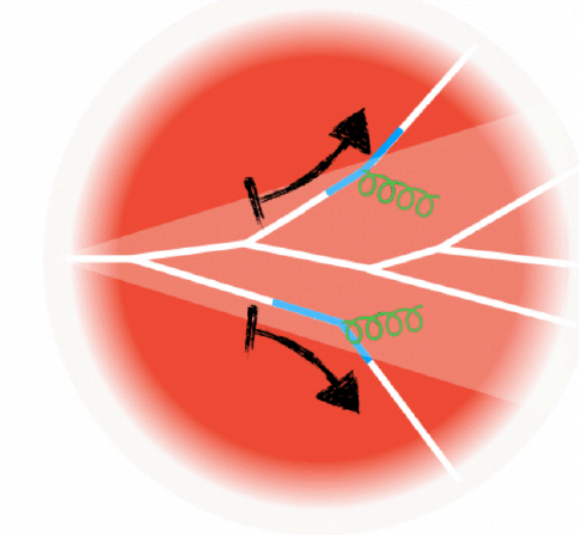


Jets as a probe of the quark-gluon plasma

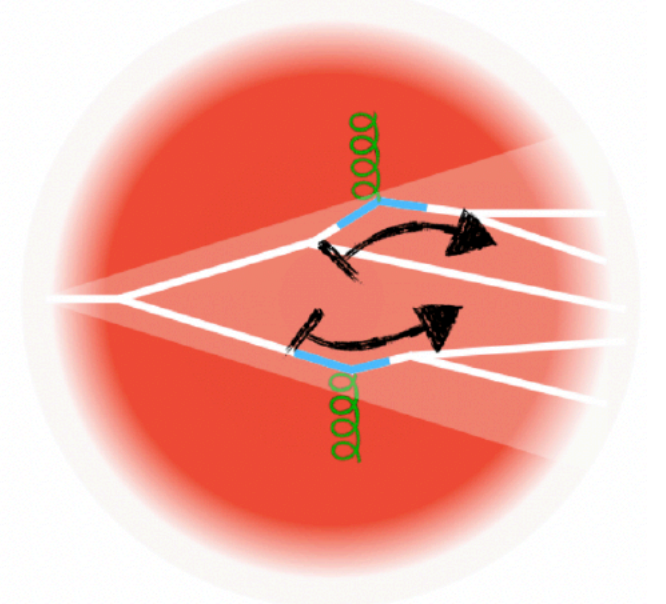
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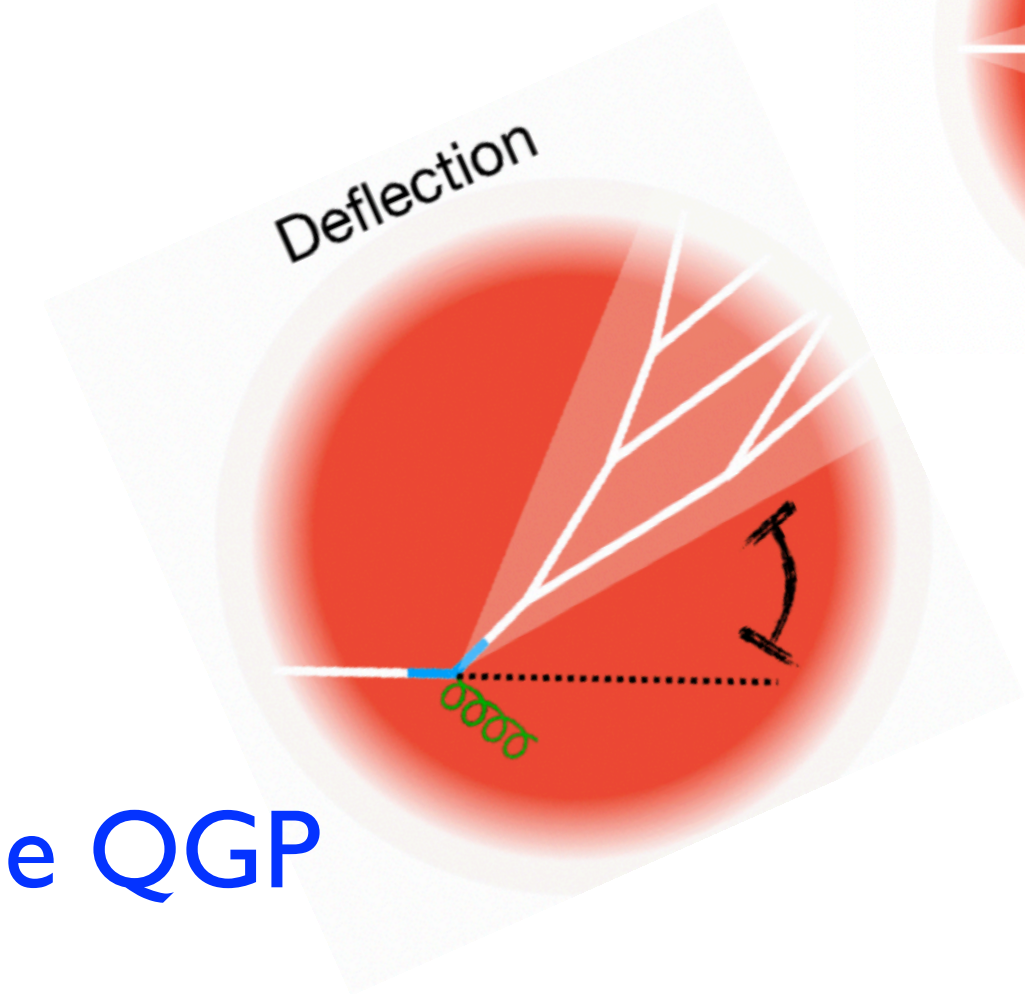
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Substructure modification



Deflection

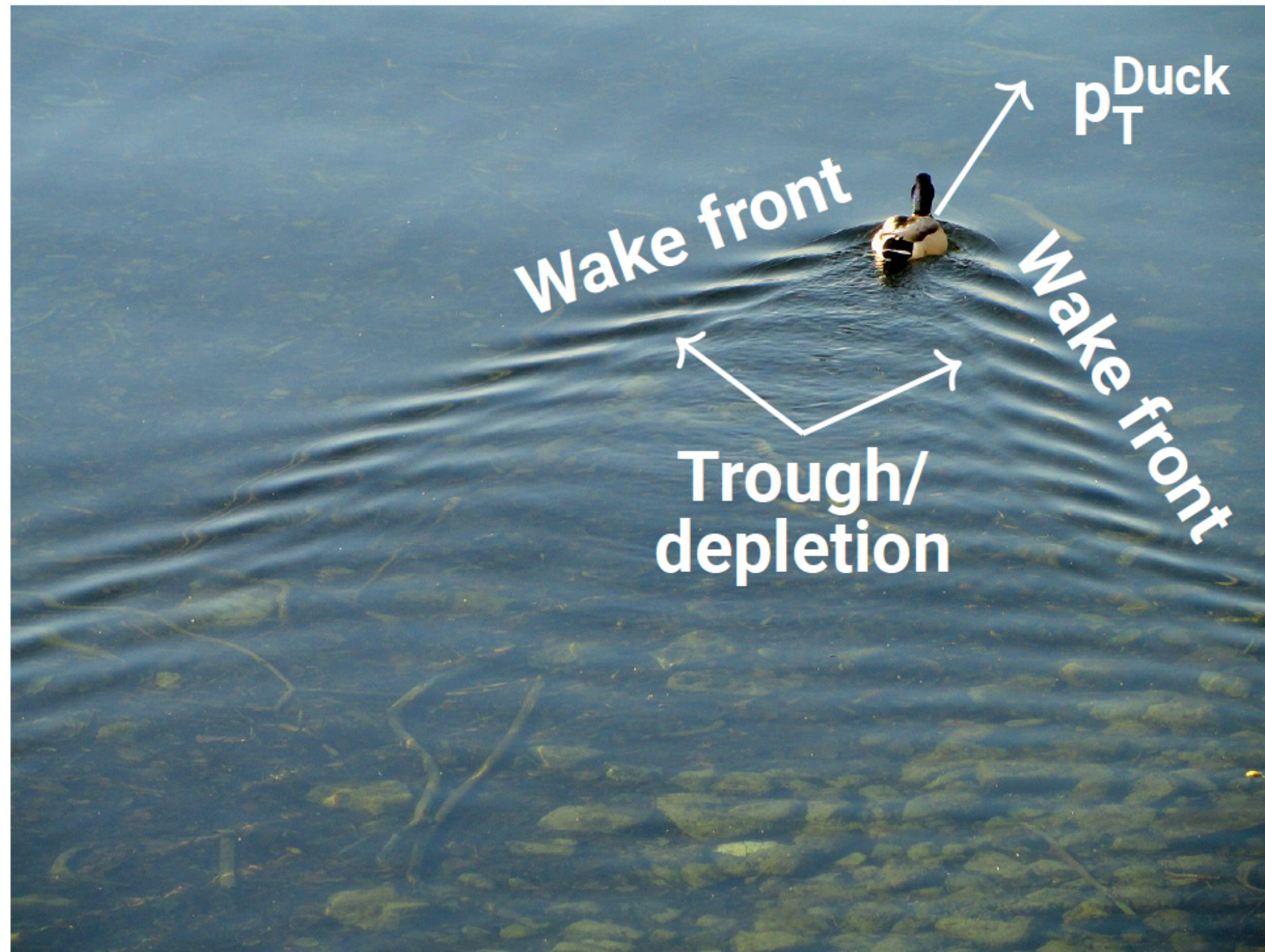


Goal: design observables to disentangle effects and extract properties of the QGP

Jet interaction with the medium

- Energetic objects traversing a medium induce excitations (a ‘response’)

Duck via [Wikimedia](#)

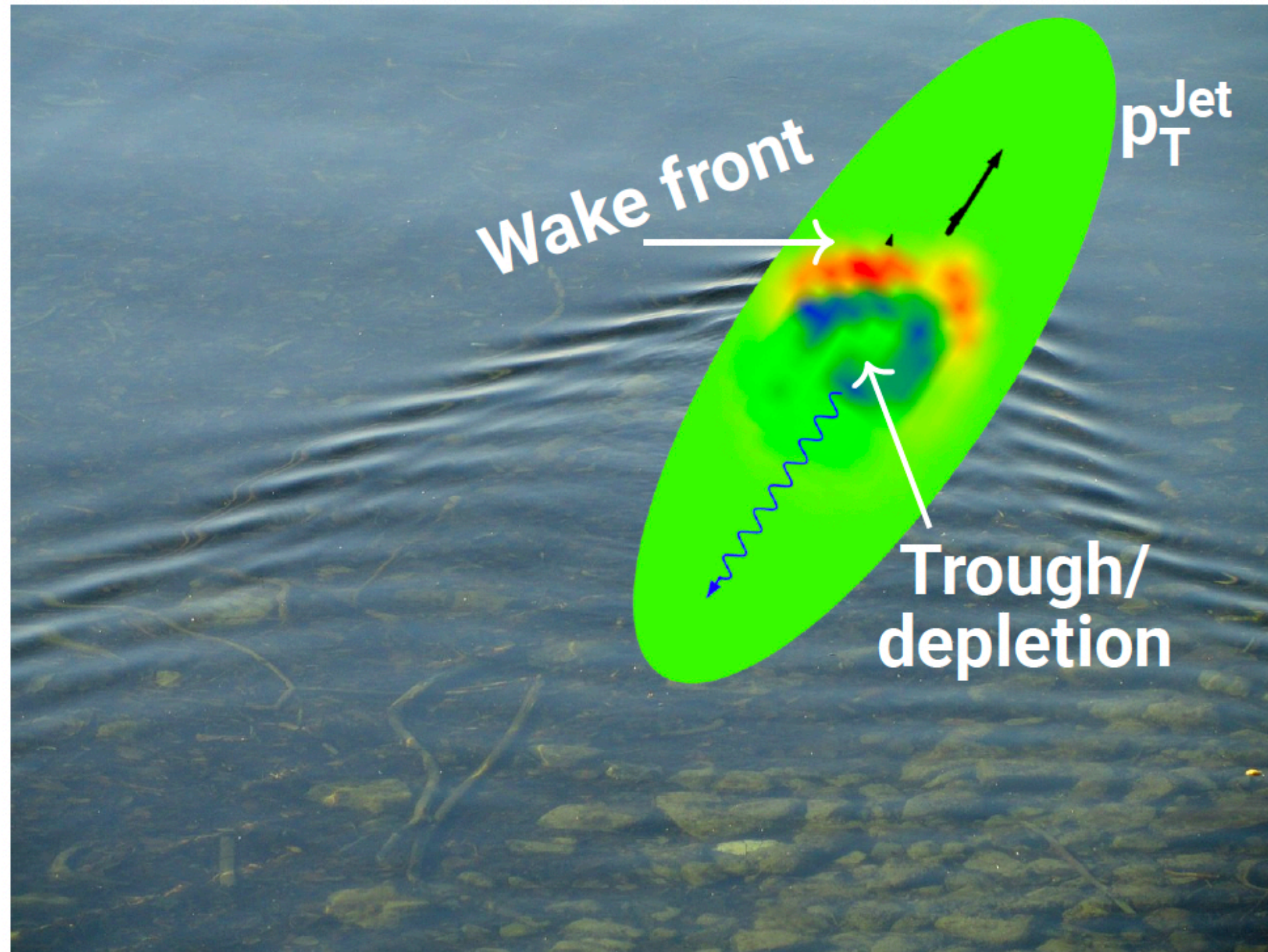


A duck in water induces a wake

Jet interaction with the medium

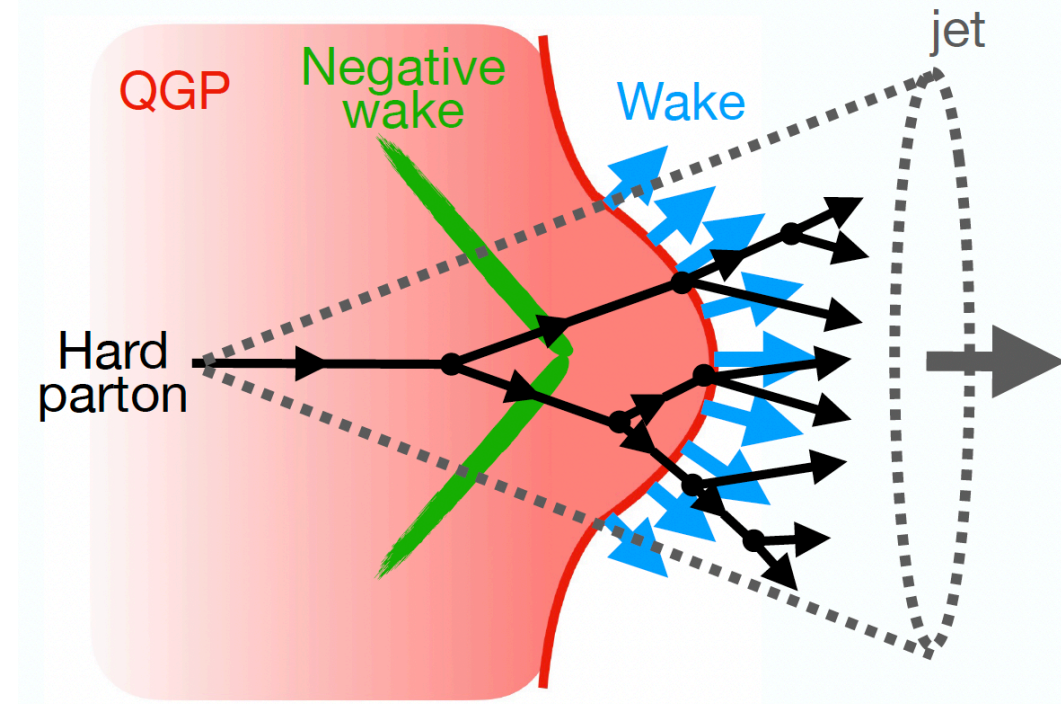
- Energetic objects traversing a medium induce excitations (a ‘response’)

Duck via [Wikimedia](#), jet wake via [PLB 777 \(2018\) 86](#)



A jet in QGP induces a wake

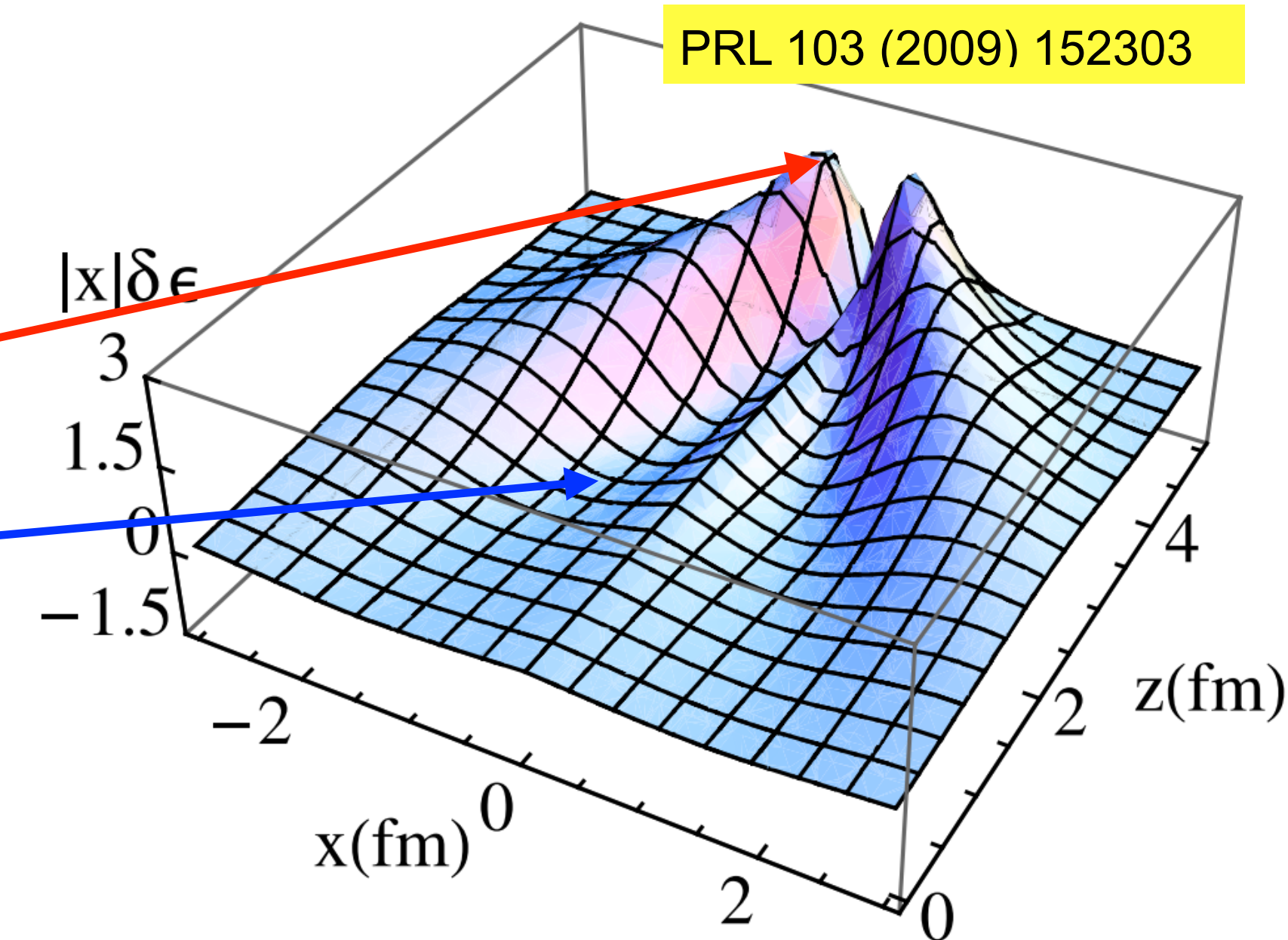
- Jet lose energy due to interaction with medium
 - ➡ jet fragmentation pattern changes
 - ➡ medium also modified by jets



Expectations: “wake effects”

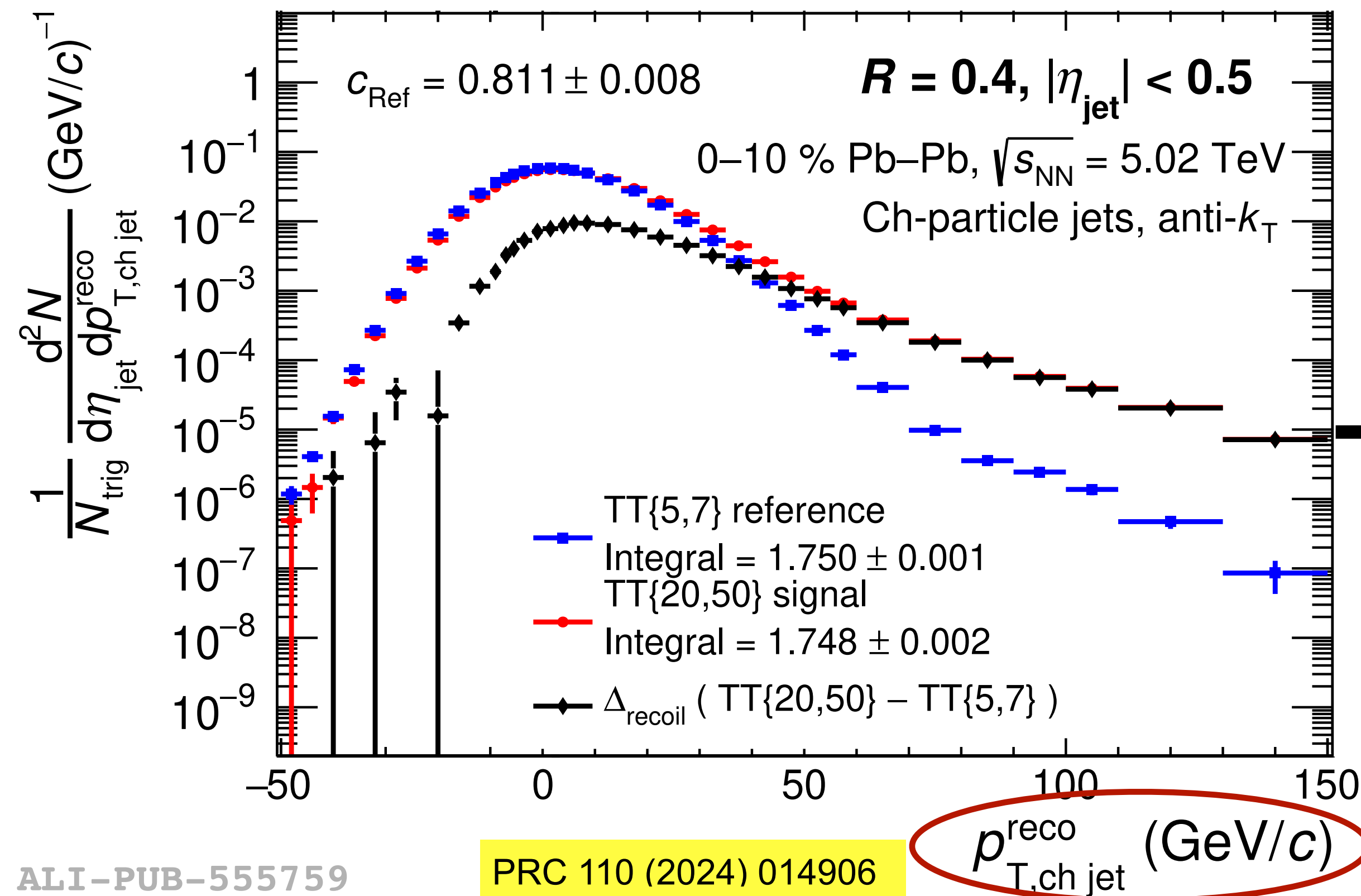
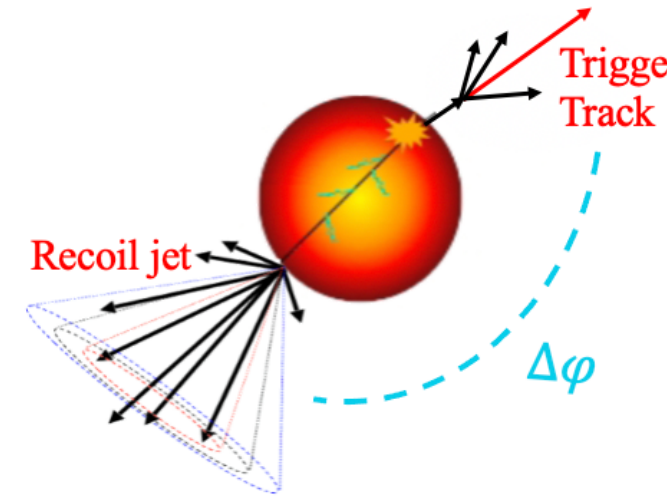
Enhancement around jet

Depletion opposite jet



Semi-inclusive jets recoiling from high- p_T hadrons

- Semi-inclusive jets recoiling from a high p_T hadron can push the kinematics down to very low p_T and large R
- Subtract uncorrelated background: yield difference between two exclusive trigger track-classed distributions: **‘signal’** and **‘reference’**:



TT_{sig}: $20 < p_{T,\text{trig}} < 50$ GeV/c

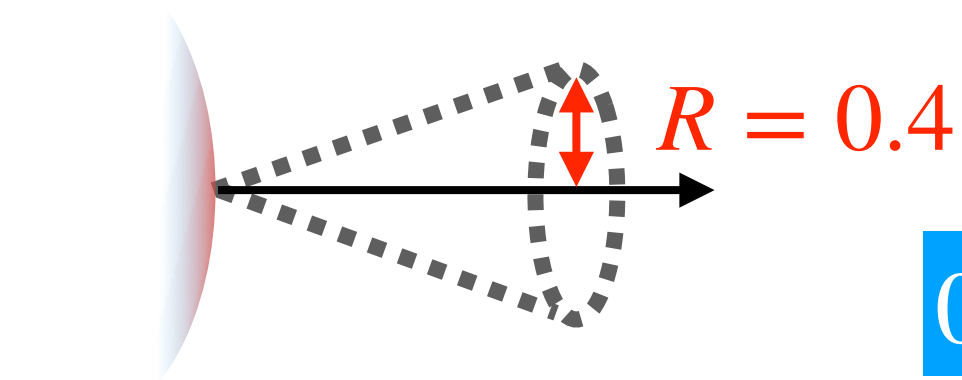
TT_{ref}: $5 < p_{T,\text{trig}} < 7$ GeV/c

$$\Delta_{\text{recoil}} = \frac{1}{N_{\text{trig}}^{\text{AA}}} \frac{d^3 N_{\text{jet}}^{\text{AA}}}{dp_{T,\text{jet}}^{\text{ch}} d\Delta\varphi d\eta_{\text{jet}}} \Big|_{p_{T,\text{trig}} \in \text{TT}_{\text{Sig}}} - c_{\text{Ref}} \cdot \frac{1}{N_{\text{trig}}^{\text{AA}}} \frac{d^3 N_{\text{jet}}^{\text{AA}}}{dp_{T,\text{jet}}^{\text{ch}} d\Delta\varphi d\eta_{\text{jet}}} \Big|_{p_{T,\text{trig}} \in \text{TT}_{\text{Ref}}}$$

ALI-PUB-555759

PRC 110 (2024) 014906

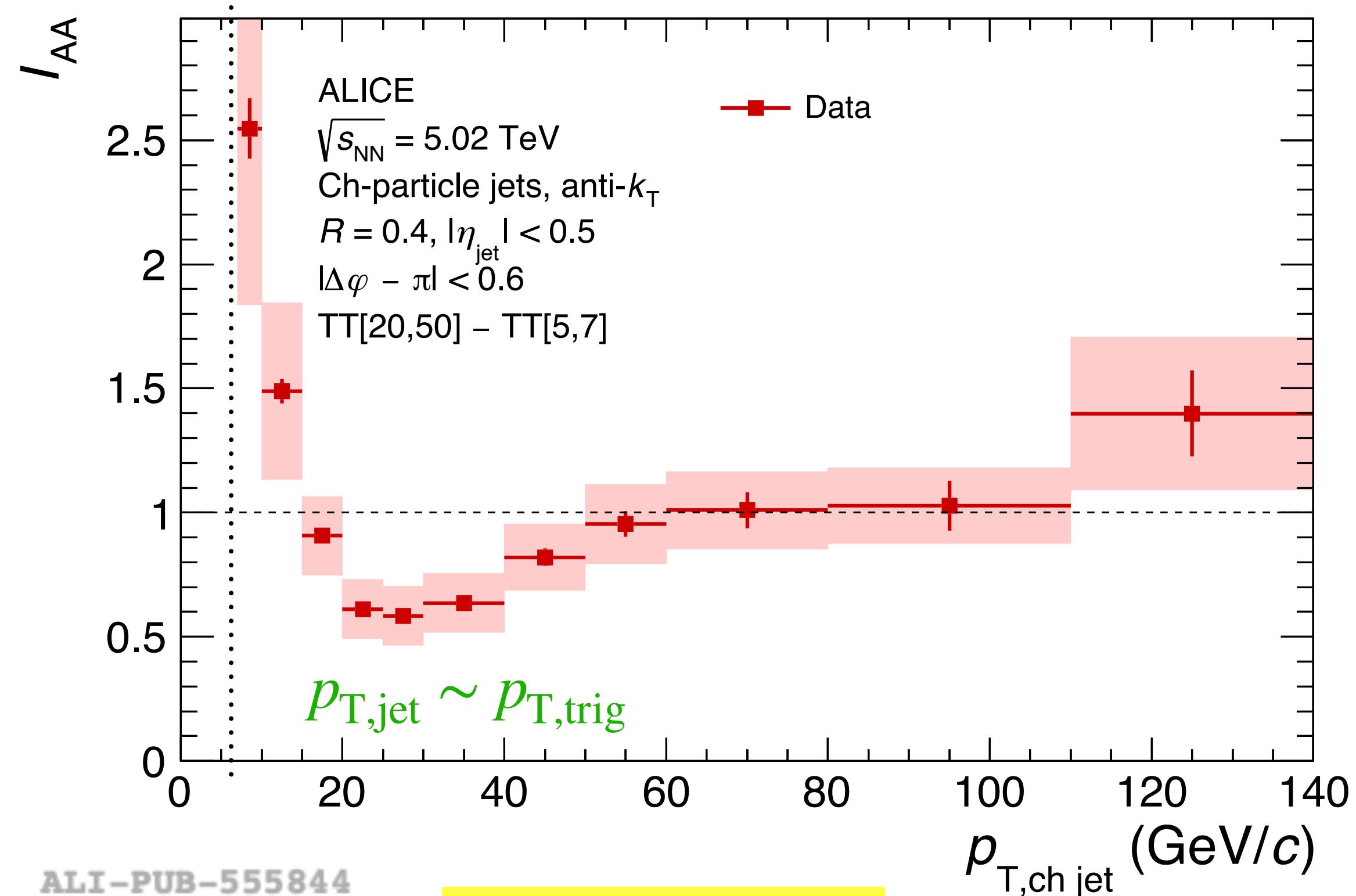
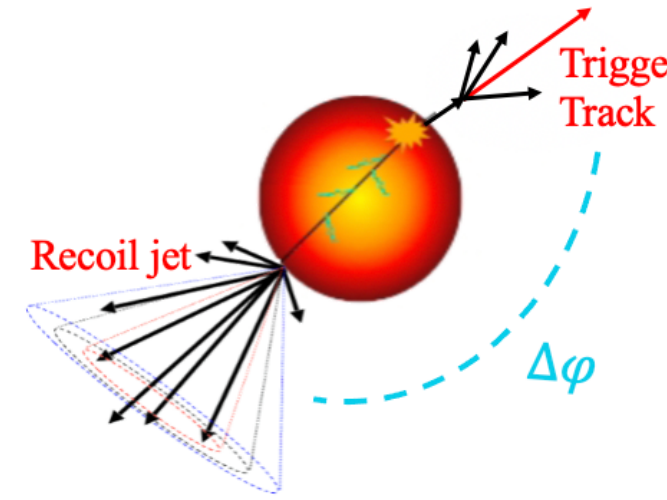
Semi-inclusive jet energy redistribution



0 – 10 %

$R = 0.4$

$$I_{AA} \equiv \frac{\Delta_{\text{recoil}}(p_T)_{AA}}{\Delta_{\text{recoil}}(p_T)_{pp}}$$

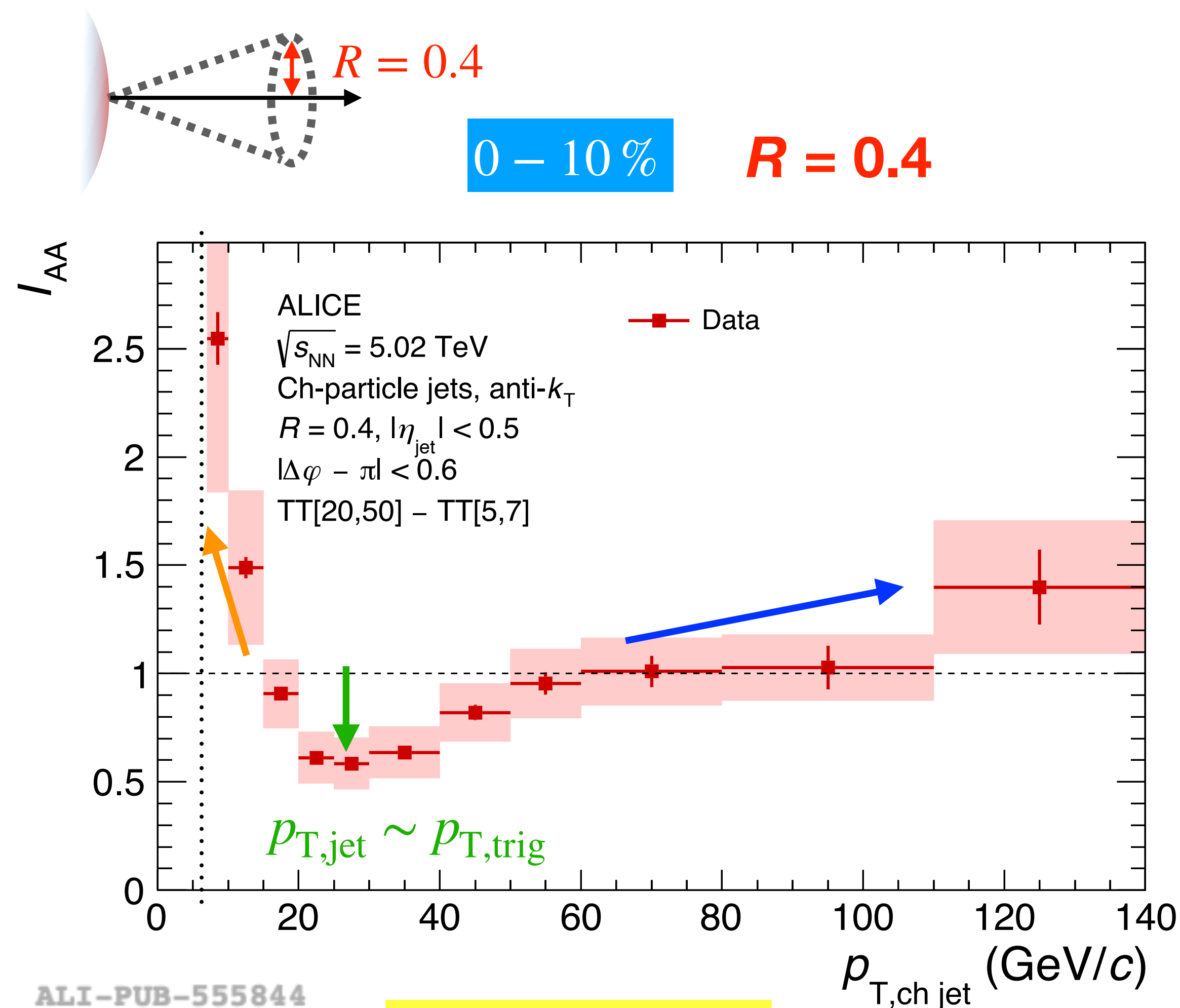


- First measurements of semi-inclusive recoil jet yields down to very low p_T (7 GeV/c) with ALICE

ALI-PUB-555844

PRC 110 (2024) 014906

Semi-inclusive jet energy redistribution



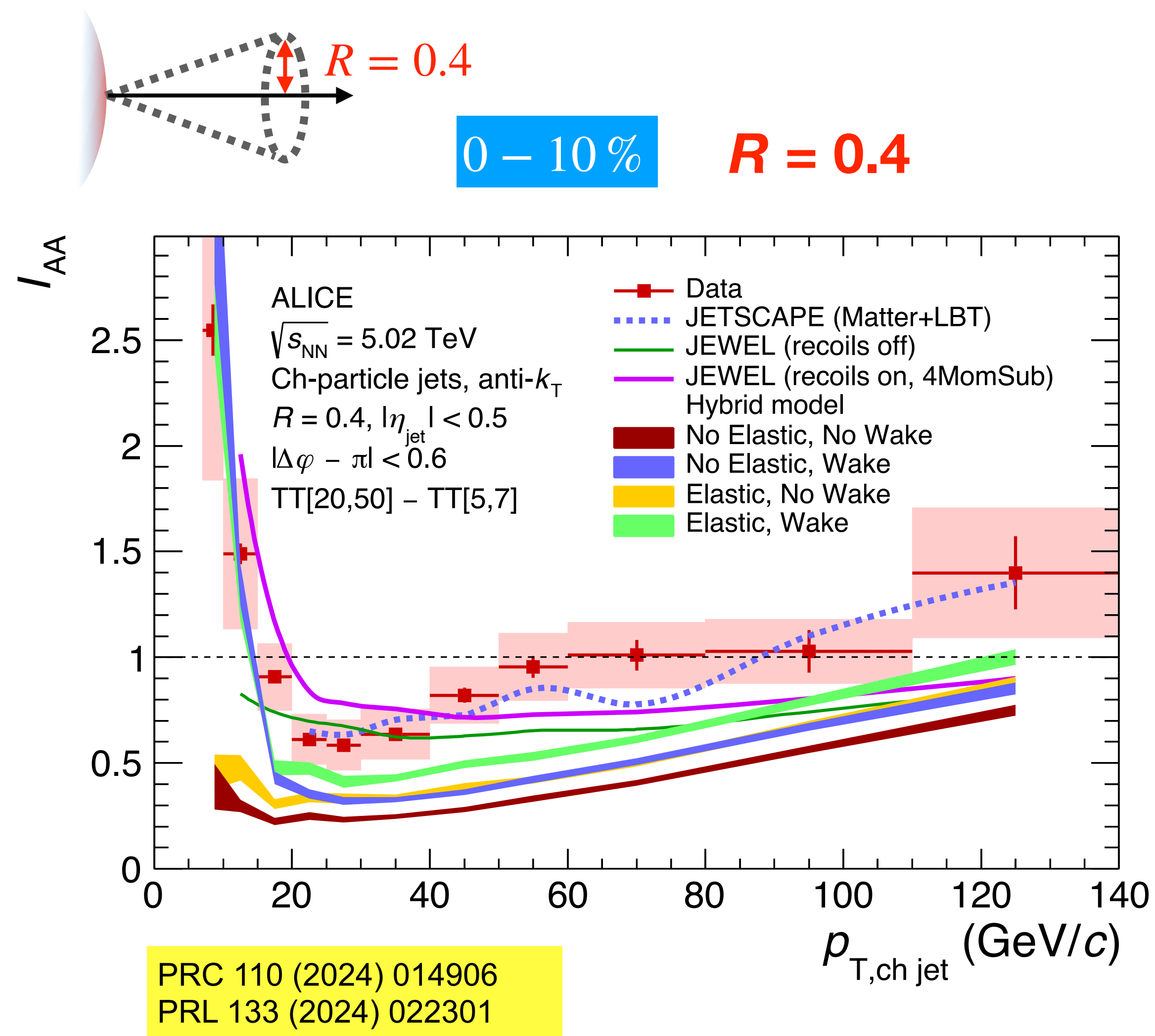
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- First measurements of semi-inclusive recoil jet yields down to very low p_T (7 GeV/c) with ALICE
- Jet yield enhancement at low $p_T \rightarrow$ hint of energy recovery in low p_T jets?
- Jet yield suppression at $20 < p_{T, \text{jet}} < 60 \text{ GeV/c}$ $\rightarrow$ Jet energy loss
- Rising trend with increasing jet $p_T \rightarrow$ Interplay of jet quenching and jet production

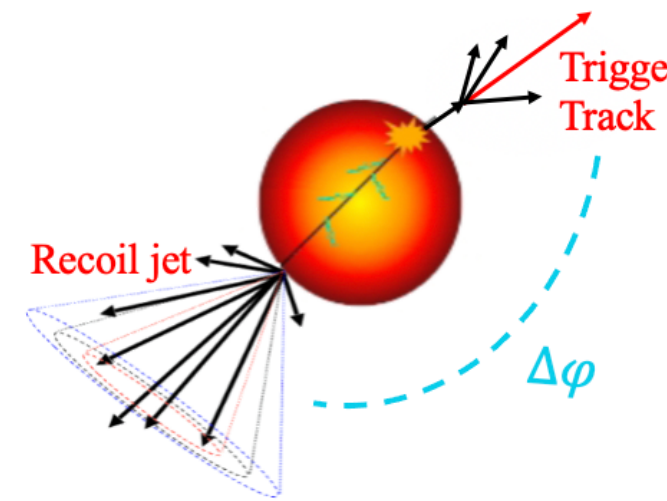
ALI-PUB-555844

PRC 110 (2024) 014906

Semi-inclusive jet energy redistribution: model comparison



$$I_{AA} \equiv \frac{\Delta_{\text{recoil}}(p_T)_{AA}}{\Delta_{\text{recoil}}(p_T)_{pp}}$$



- First measurements of semi-inclusive recoil jet yields down to very low p_T (7 GeV/c) with ALICE

JETSCAPE with Pb-Pb tune:

[1903.07706, Phys.Rev.C 107 \(2023\) 3](#)

Multi-stage energy loss MATTER+LBT

JEWEL:

[arXiv:1311.0048, https://jewel.hepforge.org/](#)

Includes collisional and radiative parton energy loss mechanisms in a pQCD approach.
 medium response effects via treatment of 'recoils'

Hybrid Model:

[JHEP 02 \(2022\) 175, JHEP01\(2019\)172](#)

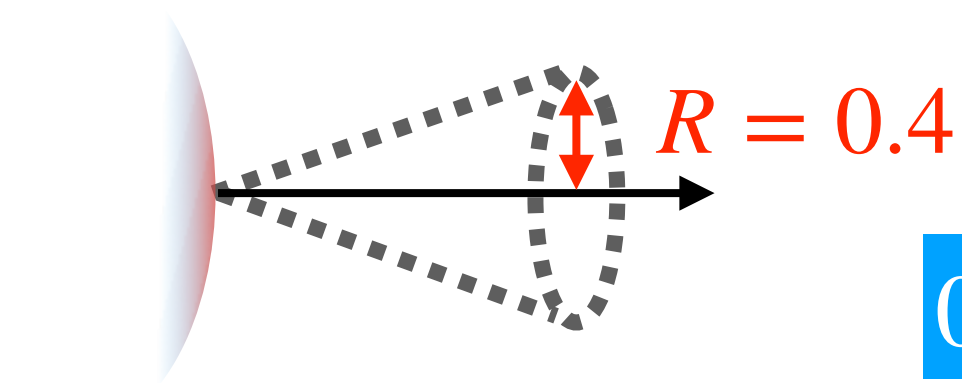
With/without elastic energy loss (i.e 'Moliere' scattering)
 medium response via with and without wake.

pQCD@LO + Sudakov broadening:

[Phys.Lett.B 773 \(2017\) 672](#)

Leading order pQCD, azimuthal broadening via jet transport coefficient

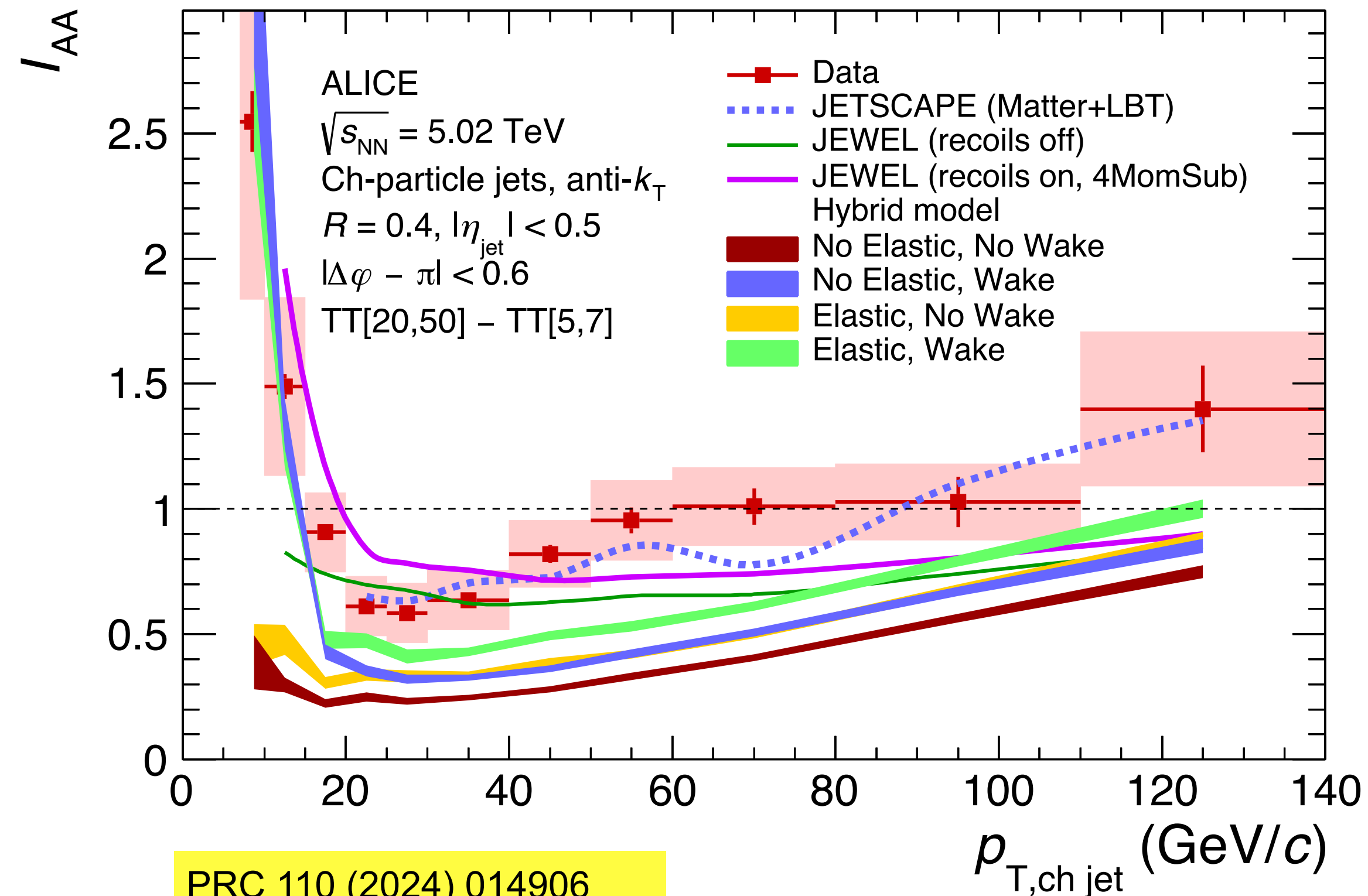
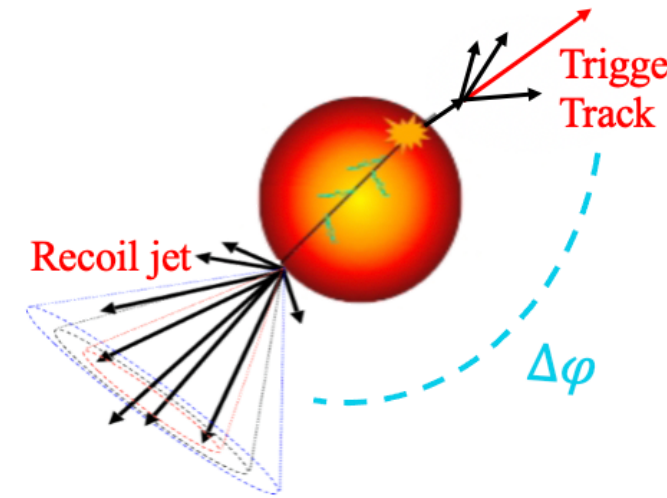
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0 – 10 %

$R = 0.4$

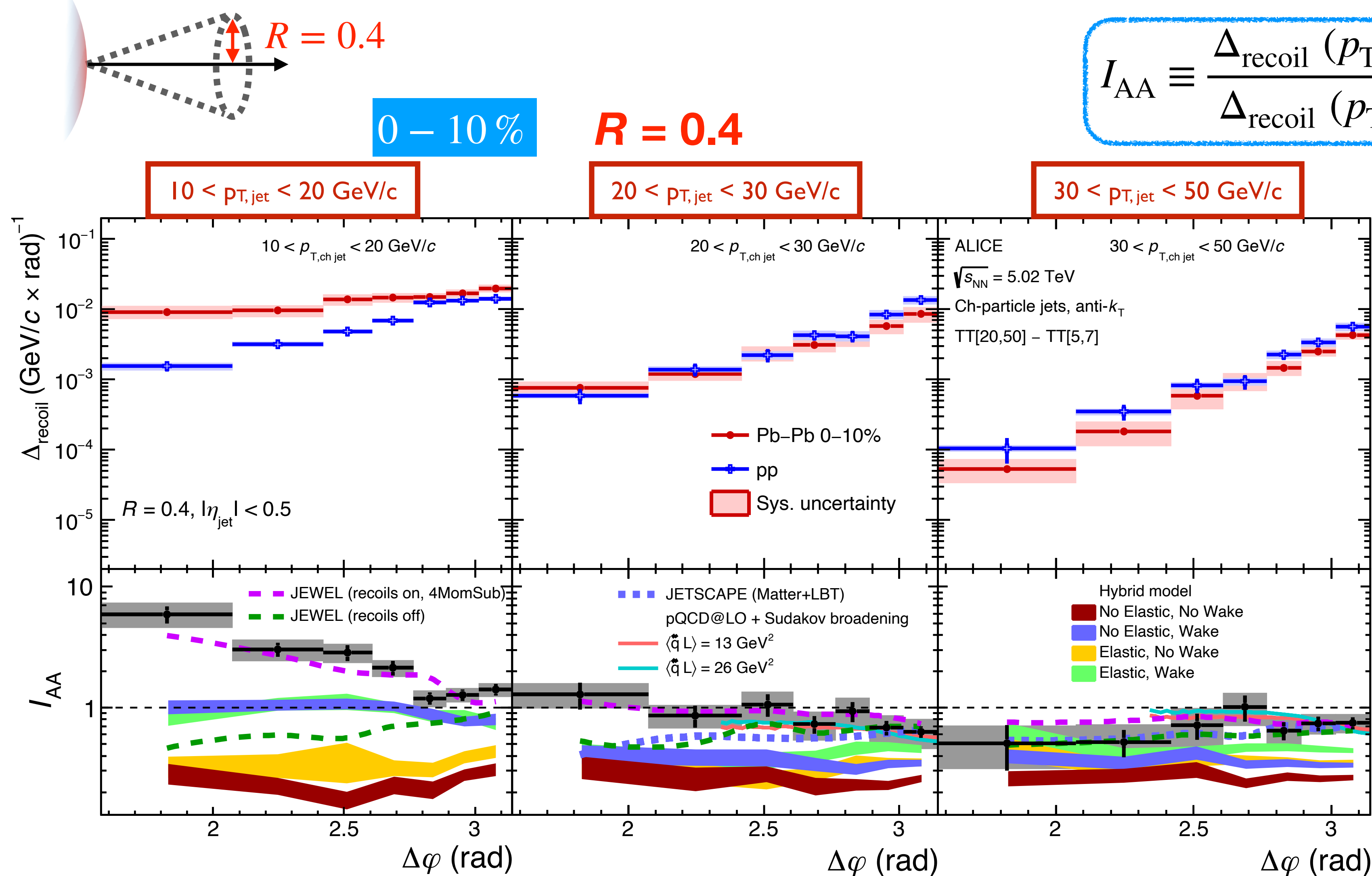
$$I_{AA} \equiv \frac{\Delta_{\text{recoil}}(p_T)_{AA}}{\Delta_{\text{recoil}}(p_T)_{pp}}$$



PRC 110 (2024) 014906
 PRL 133 (2024) 022301

- First measurements of semi-inclusive recoil jet yields down to very low p_T (7 GeV/c) with ALICE
- The **rising trend** is qualitatively described by all predications
- Hybrid model and JEWEL predictions overestimate the **suppression at high p_T**
- Hybrid model with wake effect and JEWEL with recoils on capture the **yield enhancement at low p_T** → Medium response could be responsible for enhancement

Recoil jet azimuthal modifications



PRL 133 (2024) 022301

JETSCAPE with Pb-Pb tune:

[1903.07706, Phys.Rev.C 107 \(2023\) 3](#)

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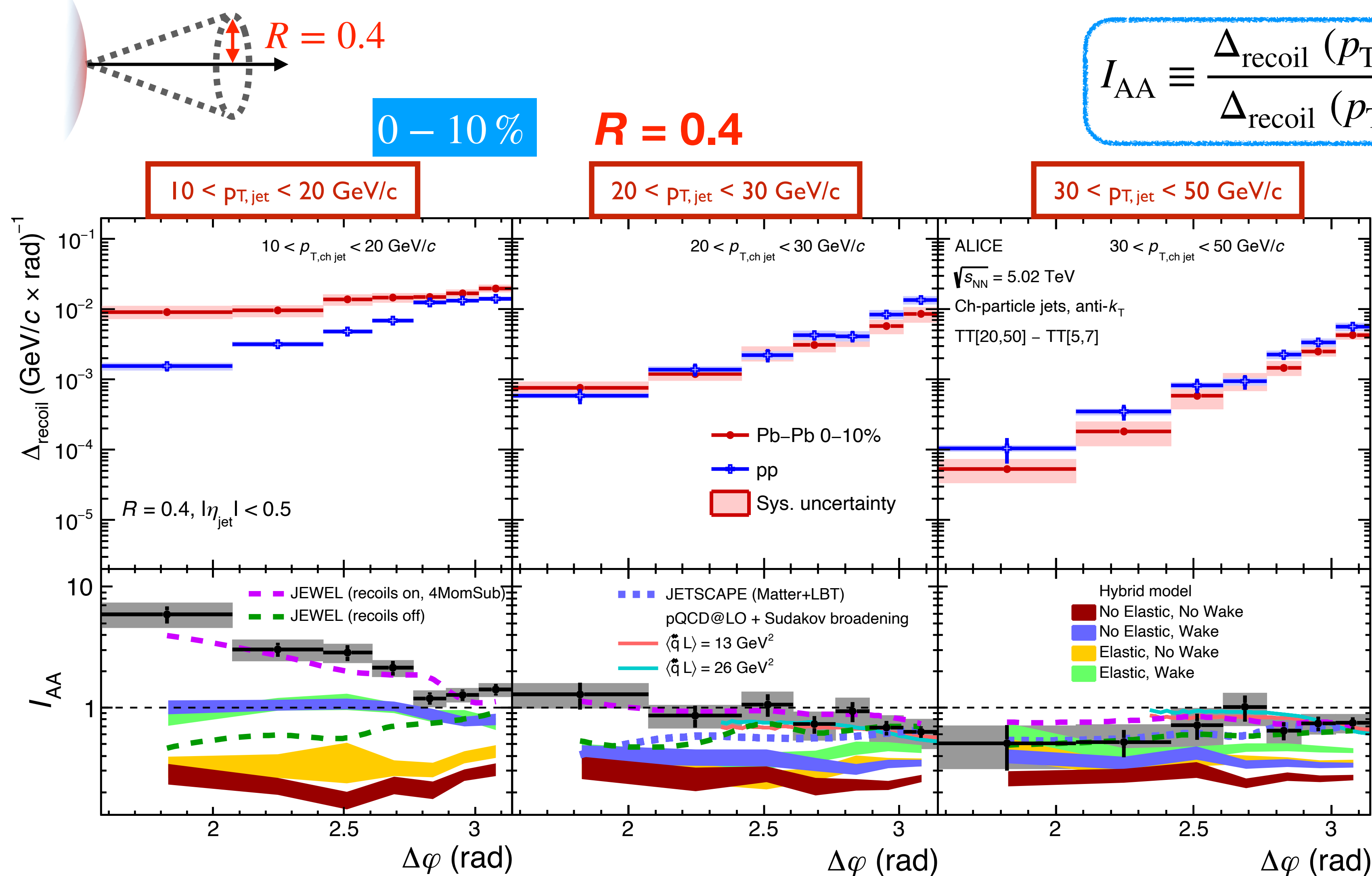
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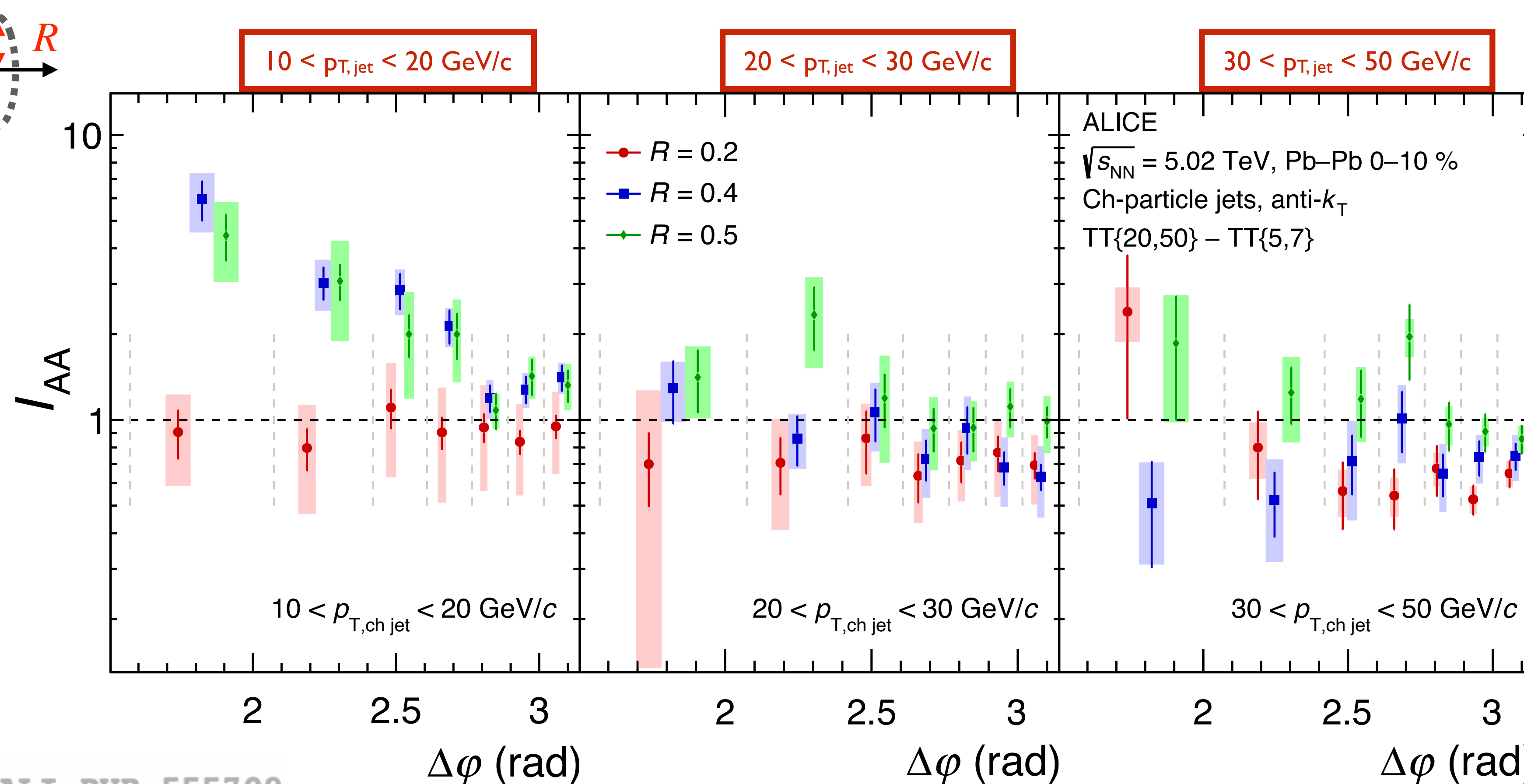
Recoil jet azimuthal modifications



PRL 133 (2024) 022301

- All predictions can reasonably describe the data trend
- JEWEL with recoils-on describes the I_{AA} in all p_T bins, including the broadening effect
- Hybrid model captures the **yield enhancement at low p_T** , but no broadening effect predicted even including elastic and wake component

Recoil jet azimuthal modifications: different R



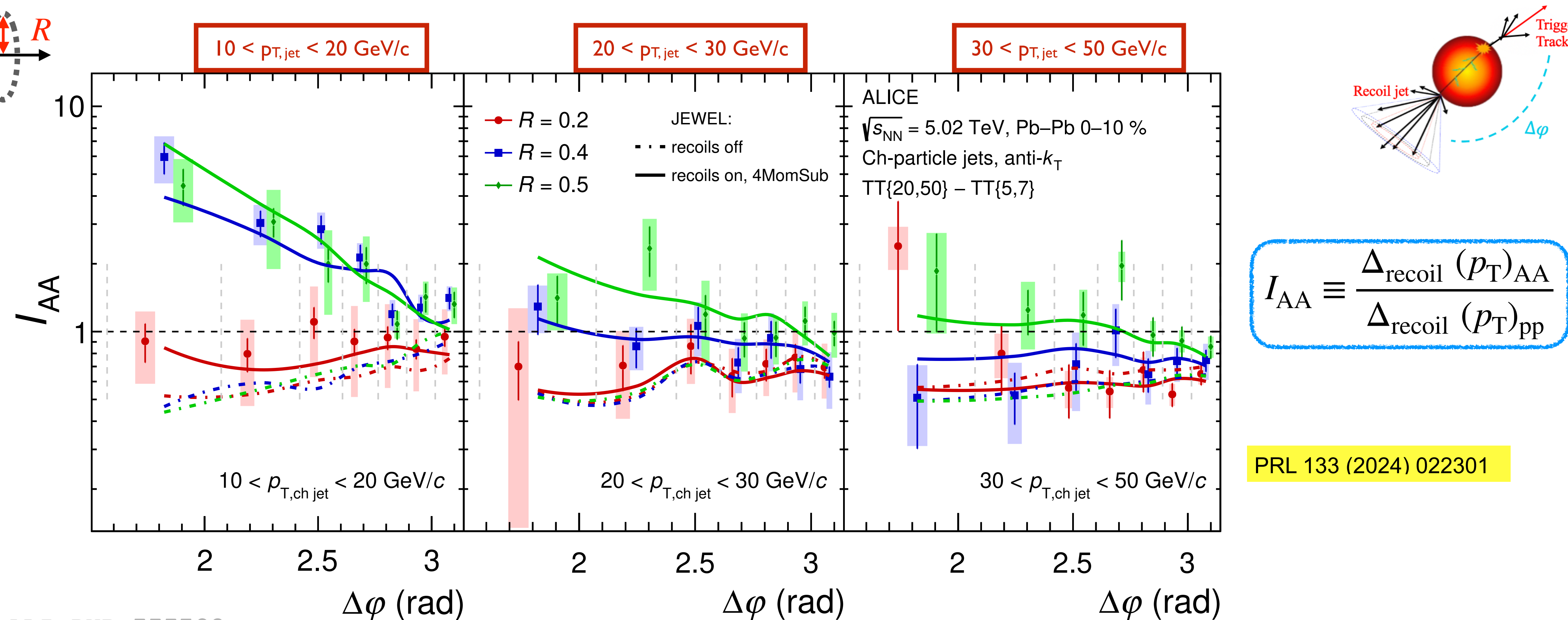
$$I_{AA} \equiv \frac{\Delta_{\text{recoil}}(p_T)_{AA}}{\Delta_{\text{recoil}}(p_T)_{pp}}$$

PRL 133 (2024) 022301

ALI-PUB-555709

- Transition to broadening from $R = 0.2$ to $R = 0.4$ for $10 < p_{T,ch jet} < 20$ GeV/c
- Characteristic of medium response
- soft radiation is recovered partially with increasing radius

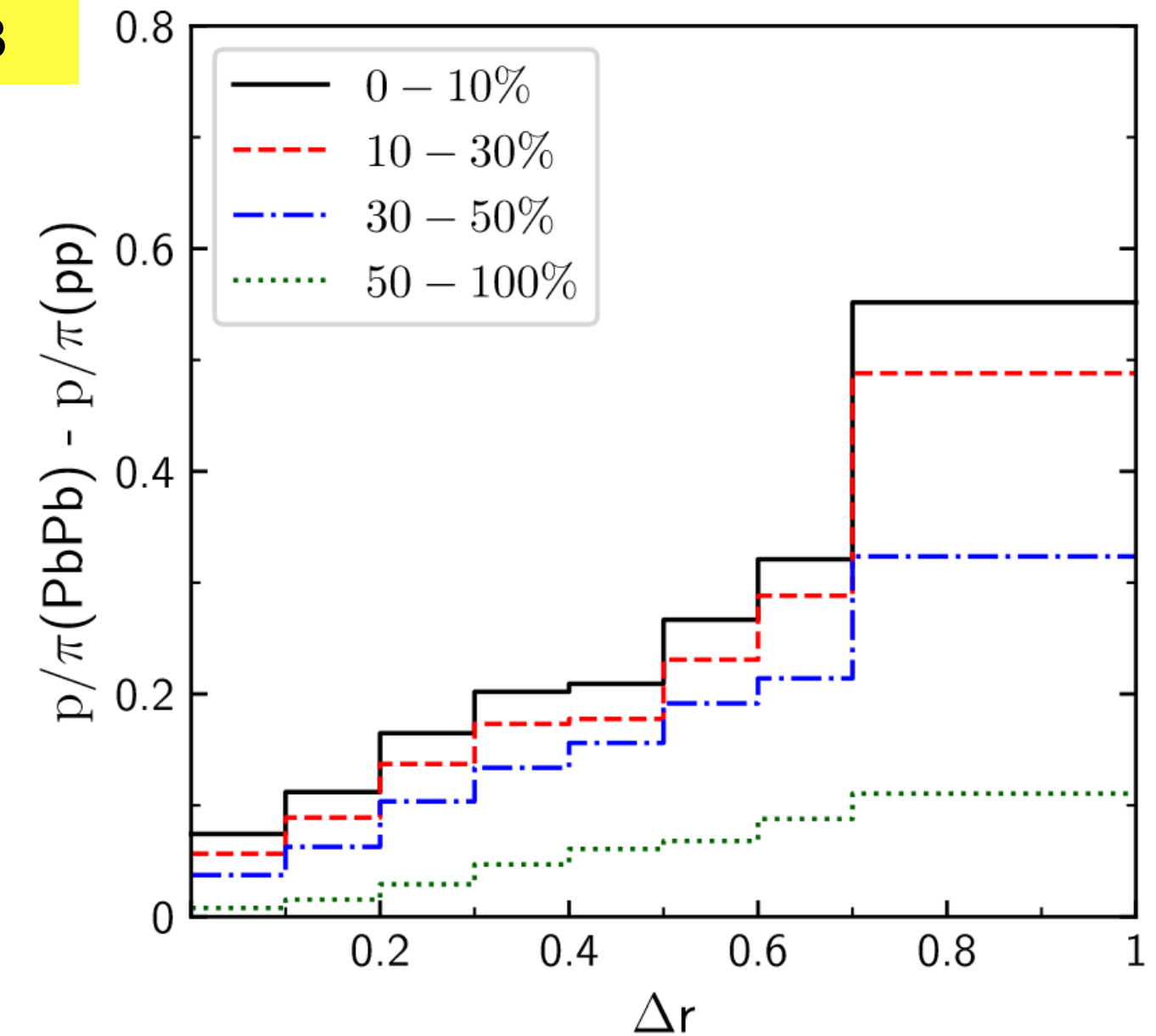
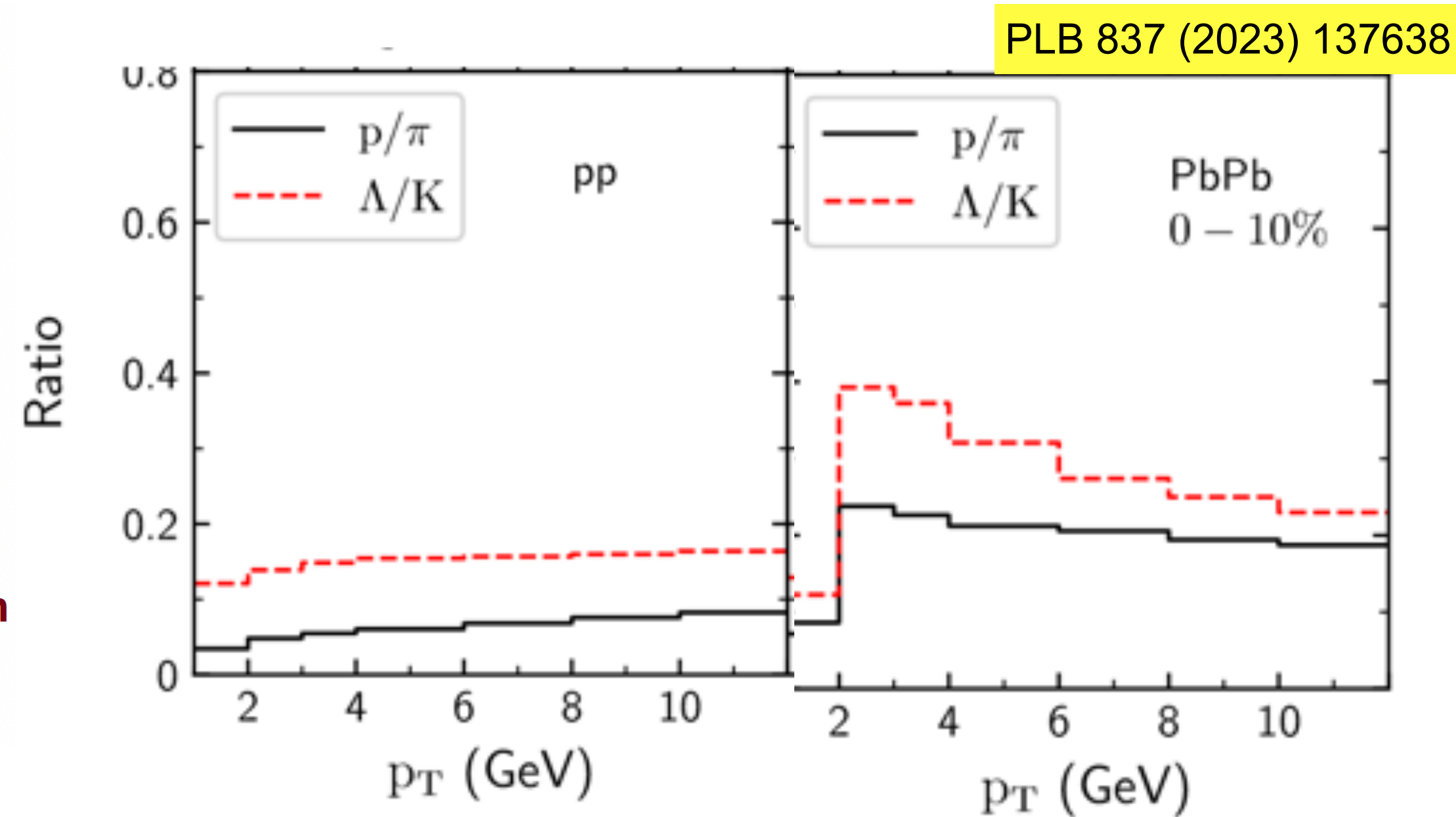
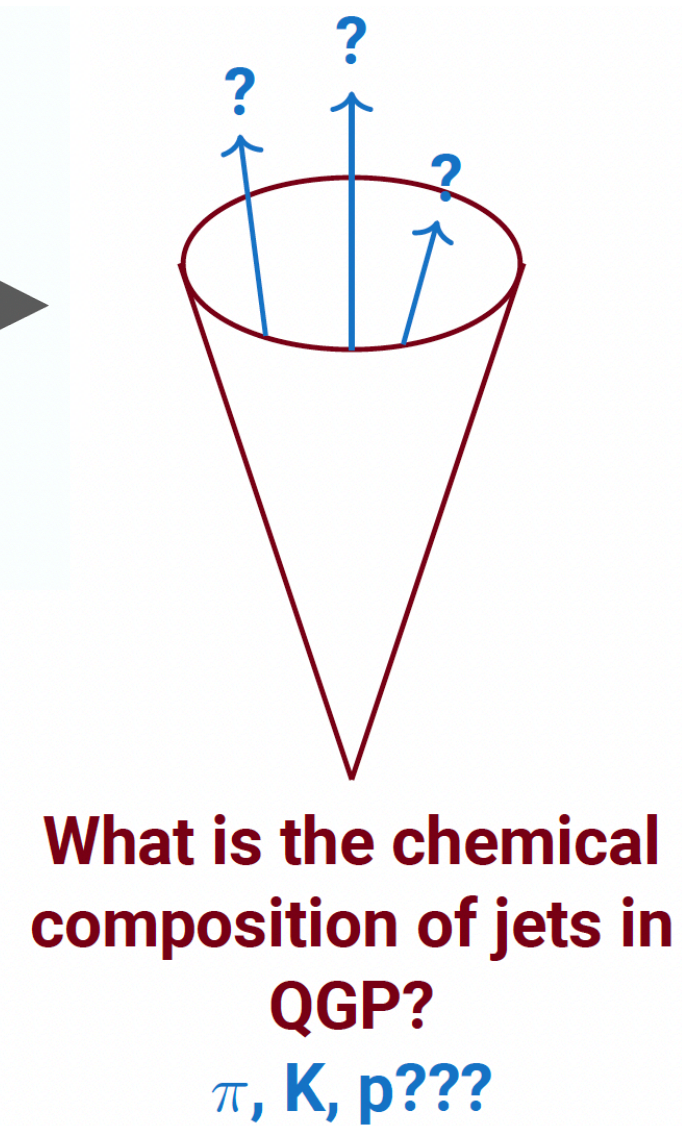
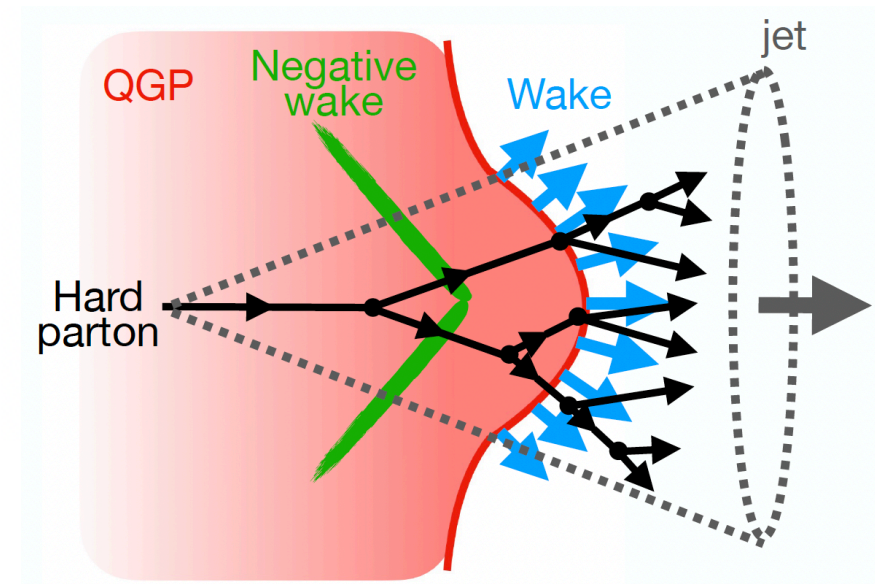
Recoil jet azimuthal modifications: model comparison



ALI-PUB-555709

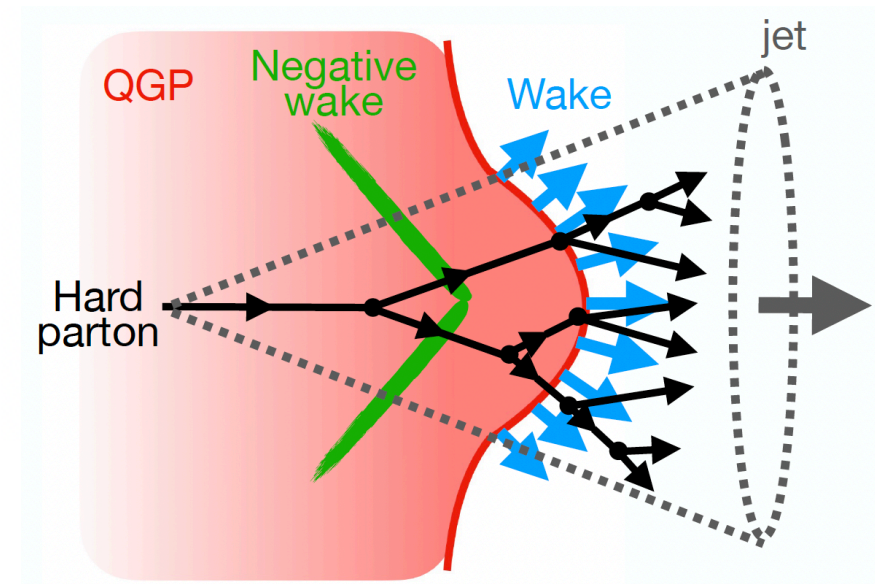
- All features of distribution **reproduced by JEWEL** with recoils on ...
 → Observed broadening consistent with medium response

Jet hadronchemistry to probe of medium response



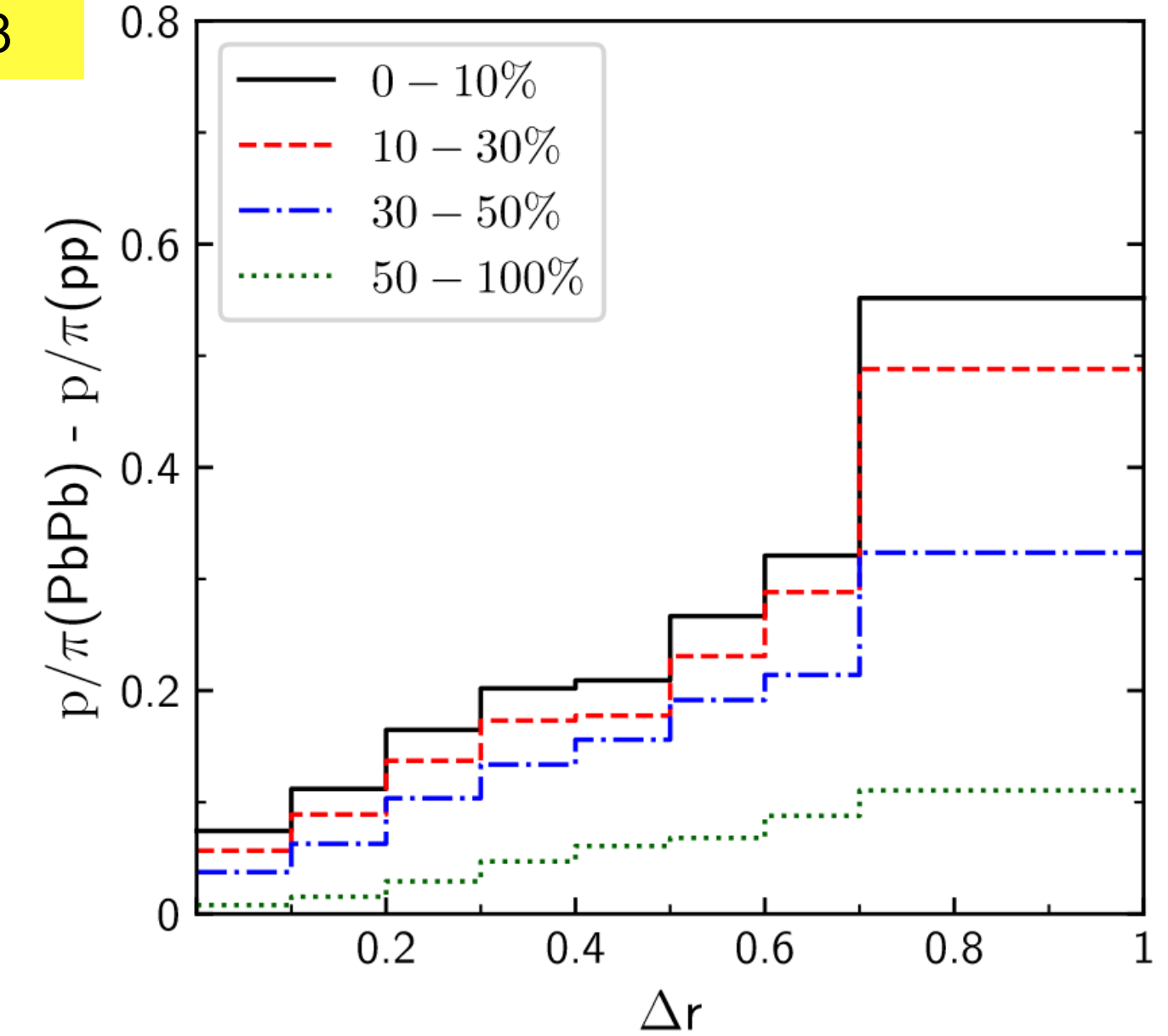
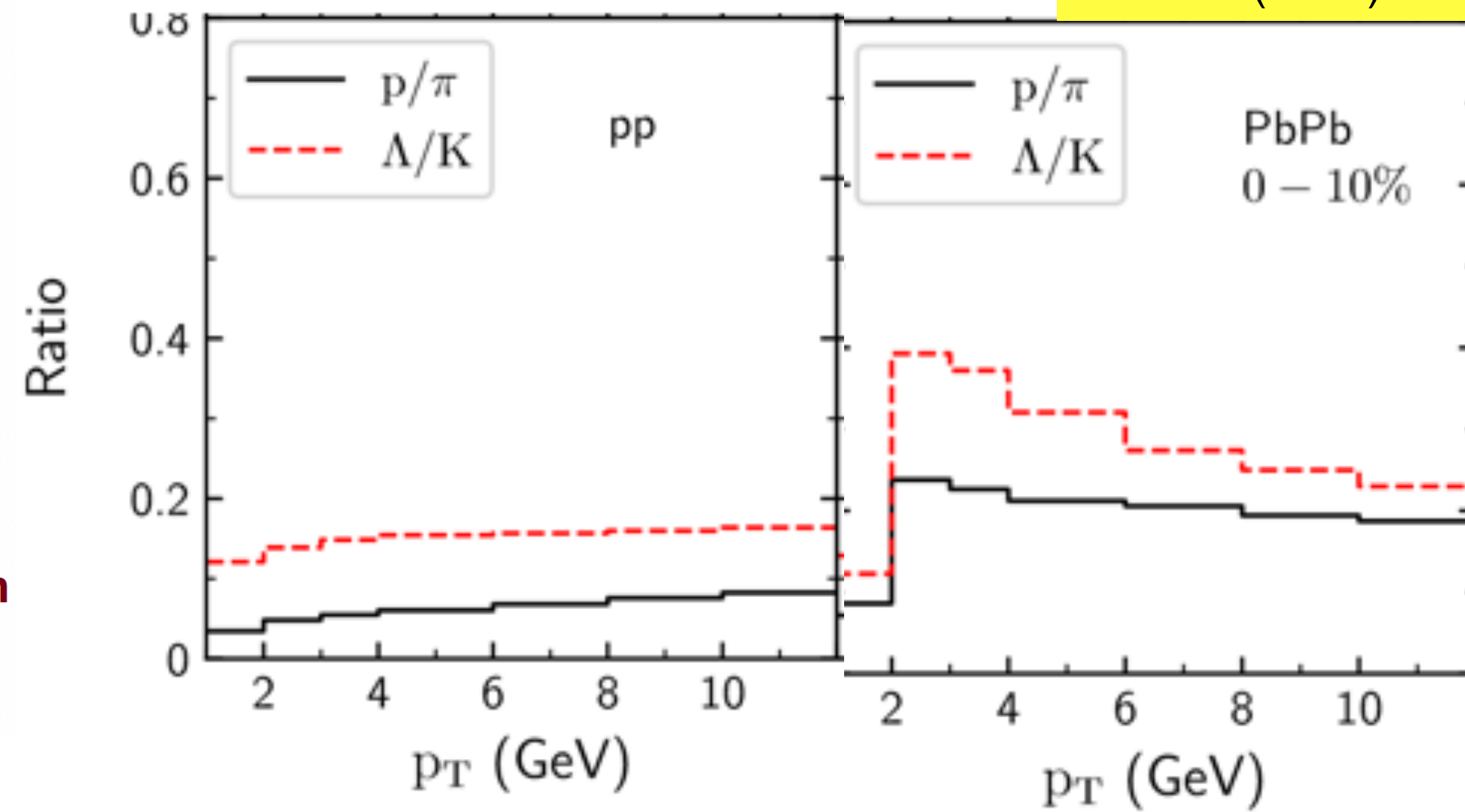
- Jet-medium interactions modify baryon-to-meson ratios
 - ➔ Enhancement of B/M ratios at intermediate p_T (2-6 GeV/c) for larger distance with respect to jet axis using jet-hadron correlations (explained by coalescence of medium excitations)

Jet hadronchemistry to probe of medium response

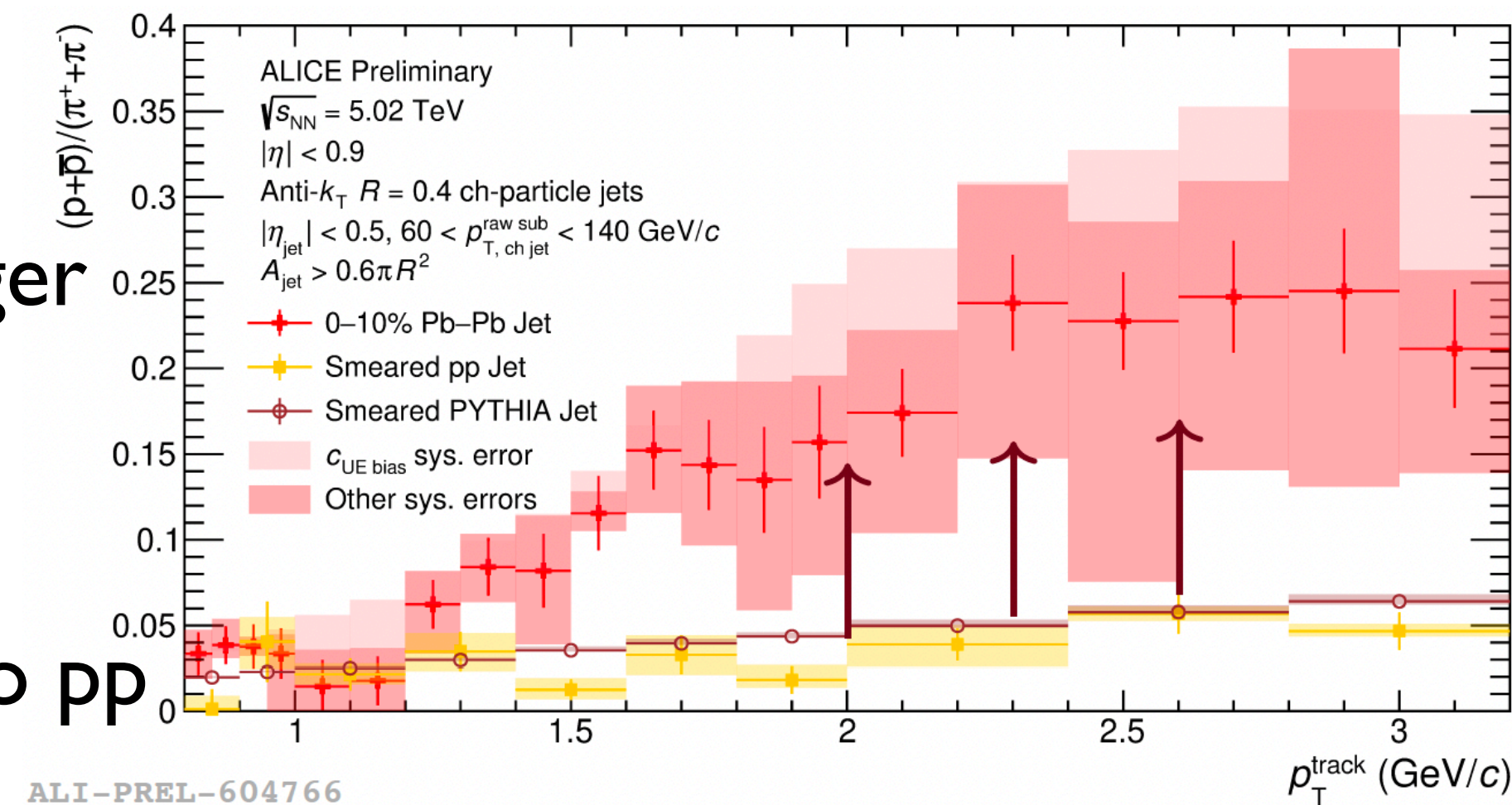


What is the chemical composition of jets in QGP?
 $\pi, K, p???$

PLB 837 (2023) 137638



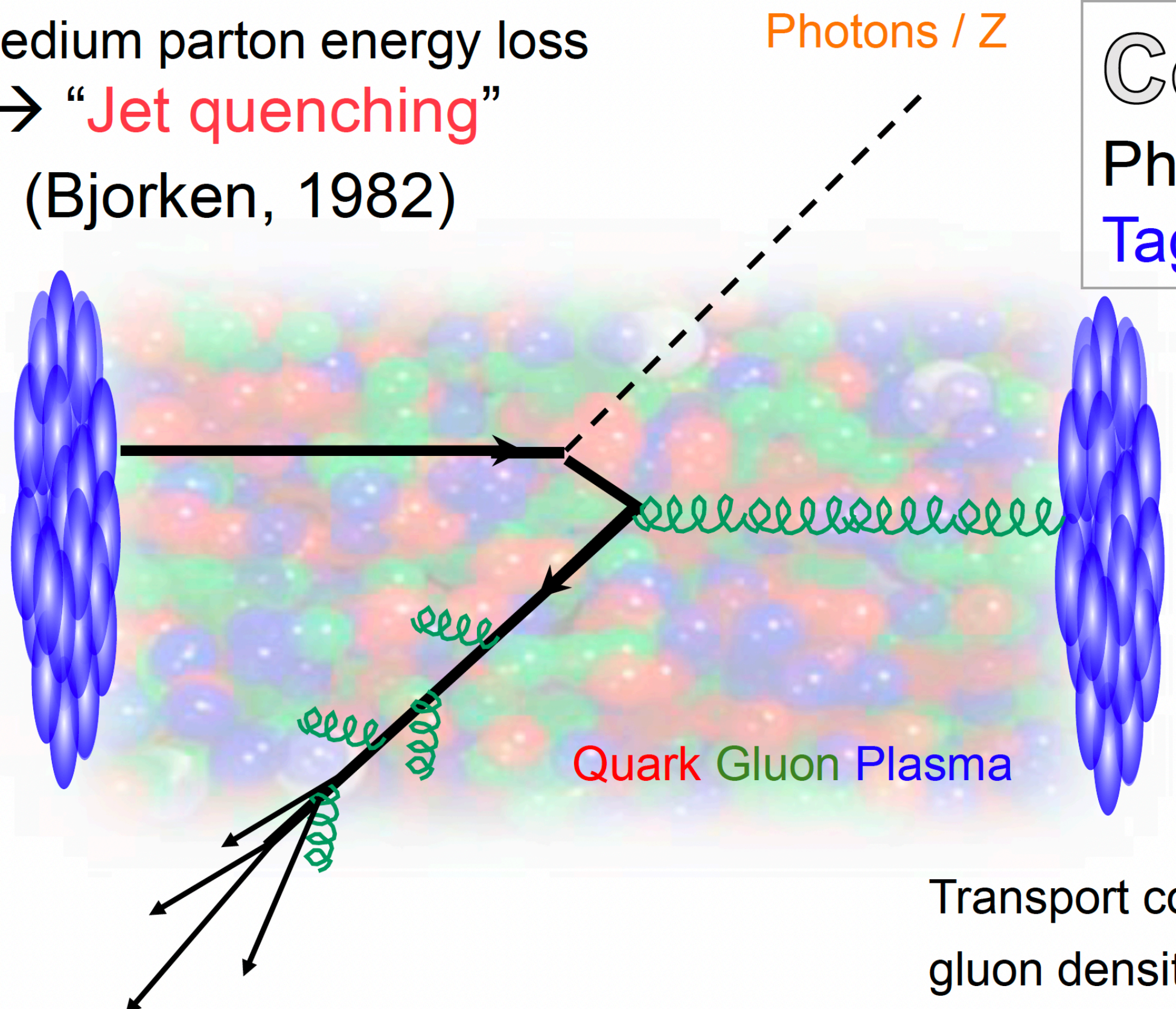
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 - ➔ Enhancement of B/M ratios at intermediate p_T (2-6 GeV/c) for larger distance with respect to jet axis using jet-hadron correlations (explained by coalescence of medium excitations)
- Hints of excess of in-jet p/π ratio in central Pb-Pb collision related to pp
 - ➔ Quantify distance dependent B/M ratio using jet-hadron correlations



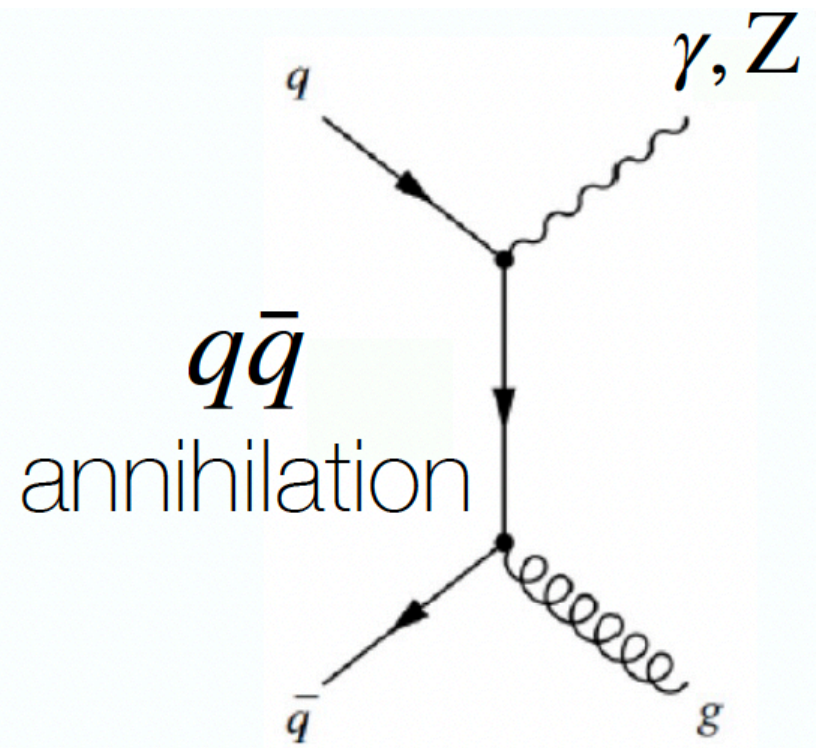
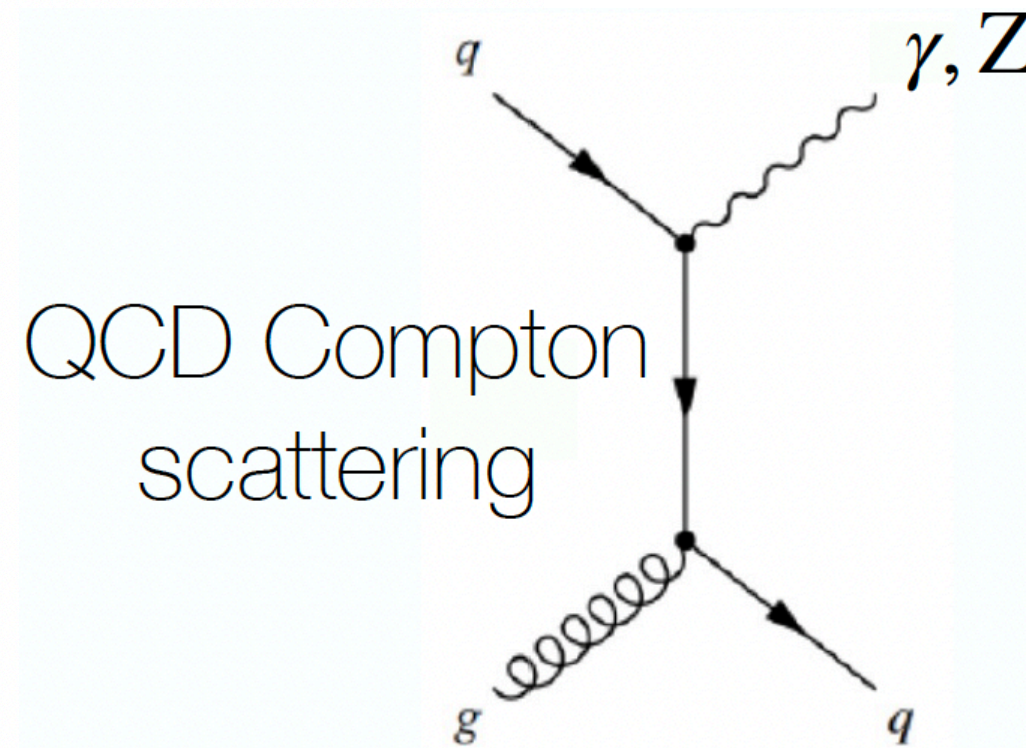
ALI-PREL-604766

Colorless probes

In medium parton energy loss
 → “**Jet quenching**”
 (Bjorken, 1982)



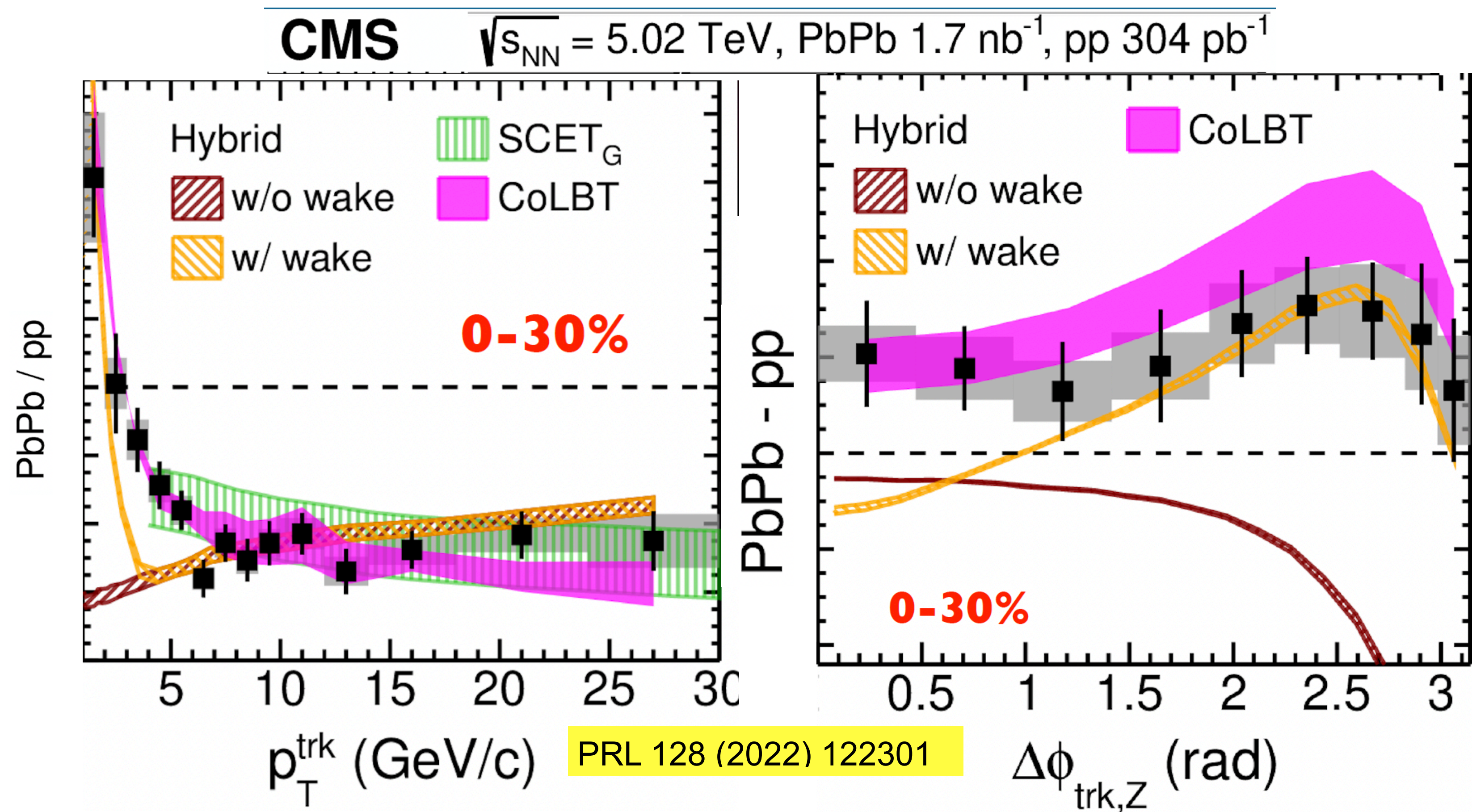
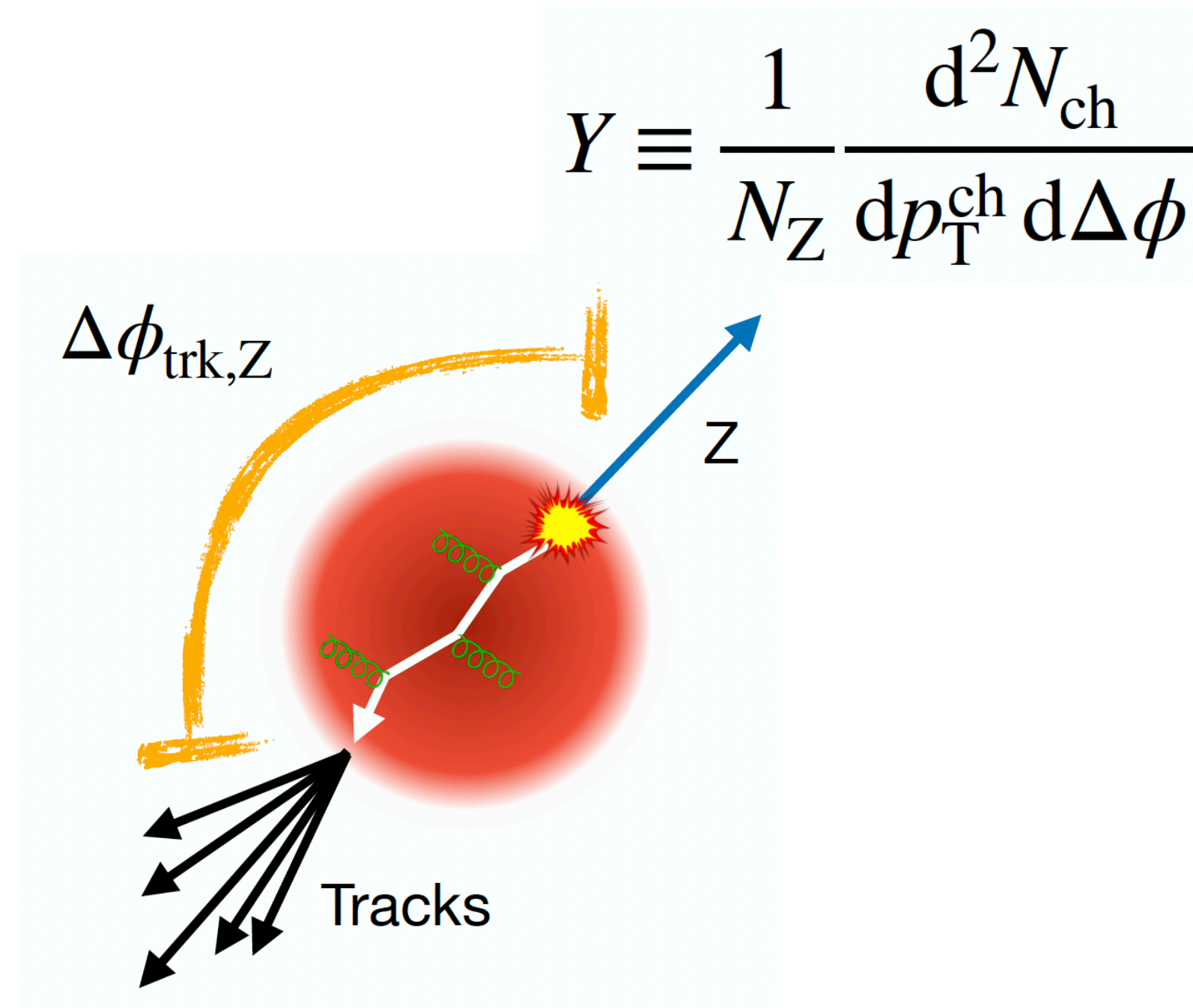
Colorless Probes
 Photons, electroweak bosons
 Tag the initial state



Tagging initial jet energy

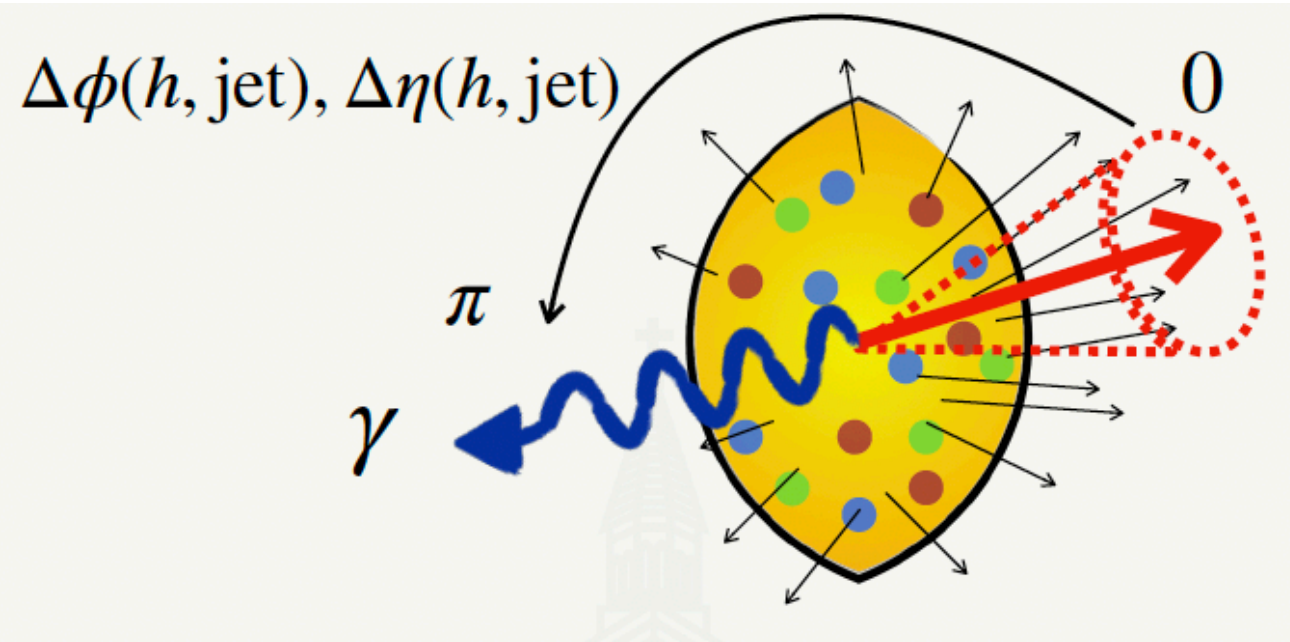
Colored Probes:
 high energy quarks and gluons, heavy quarks
 Studies of the medium properties

Charged particle yield recoiling from Z

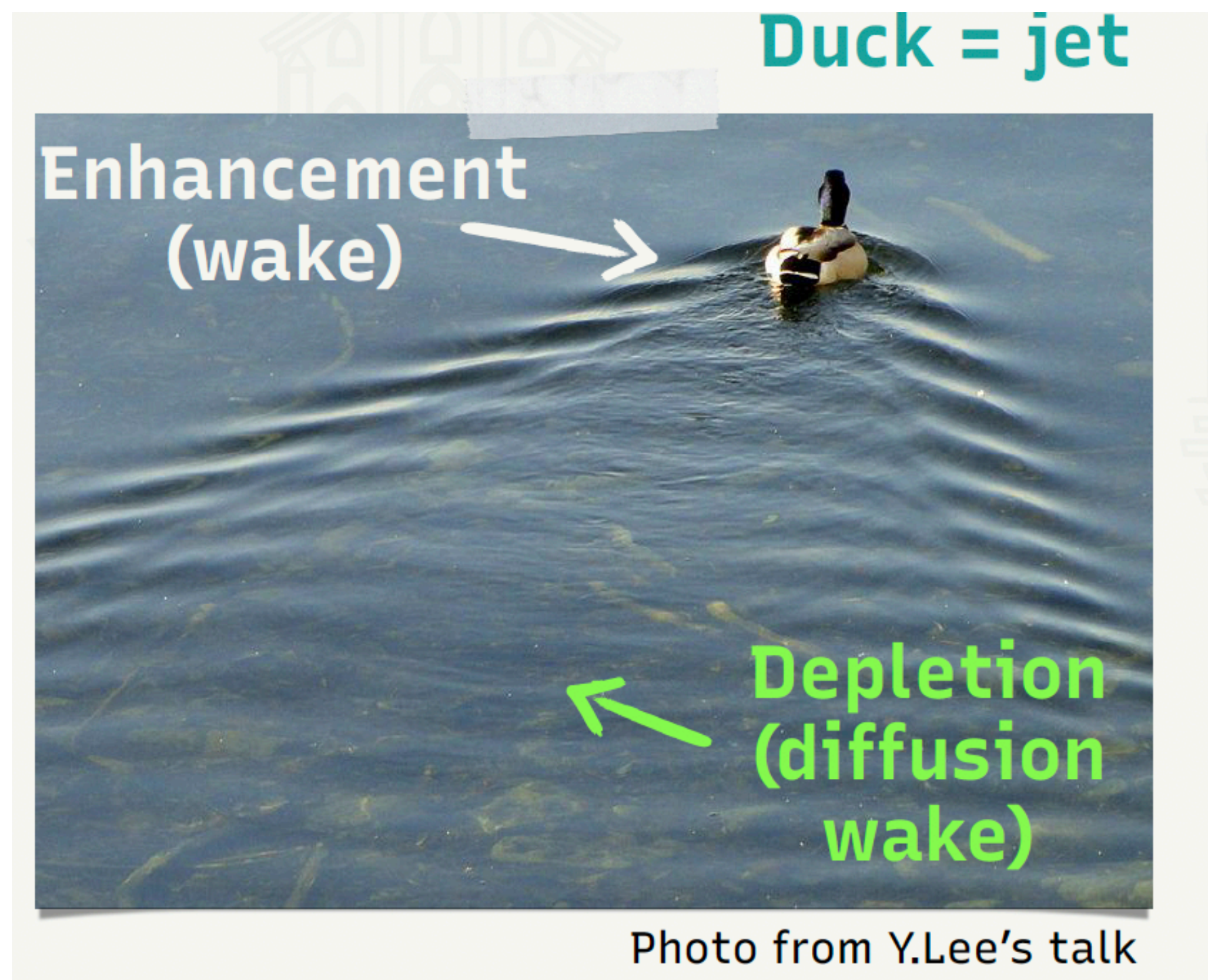


- Low p_T excess and high p_T suppression → energy redistribution due to quenching
- Excess of particle yields down to the $\phi^{trk} \approx \phi^Z$ in central PbPb collisions
 - quantitative agreement with models including medium response

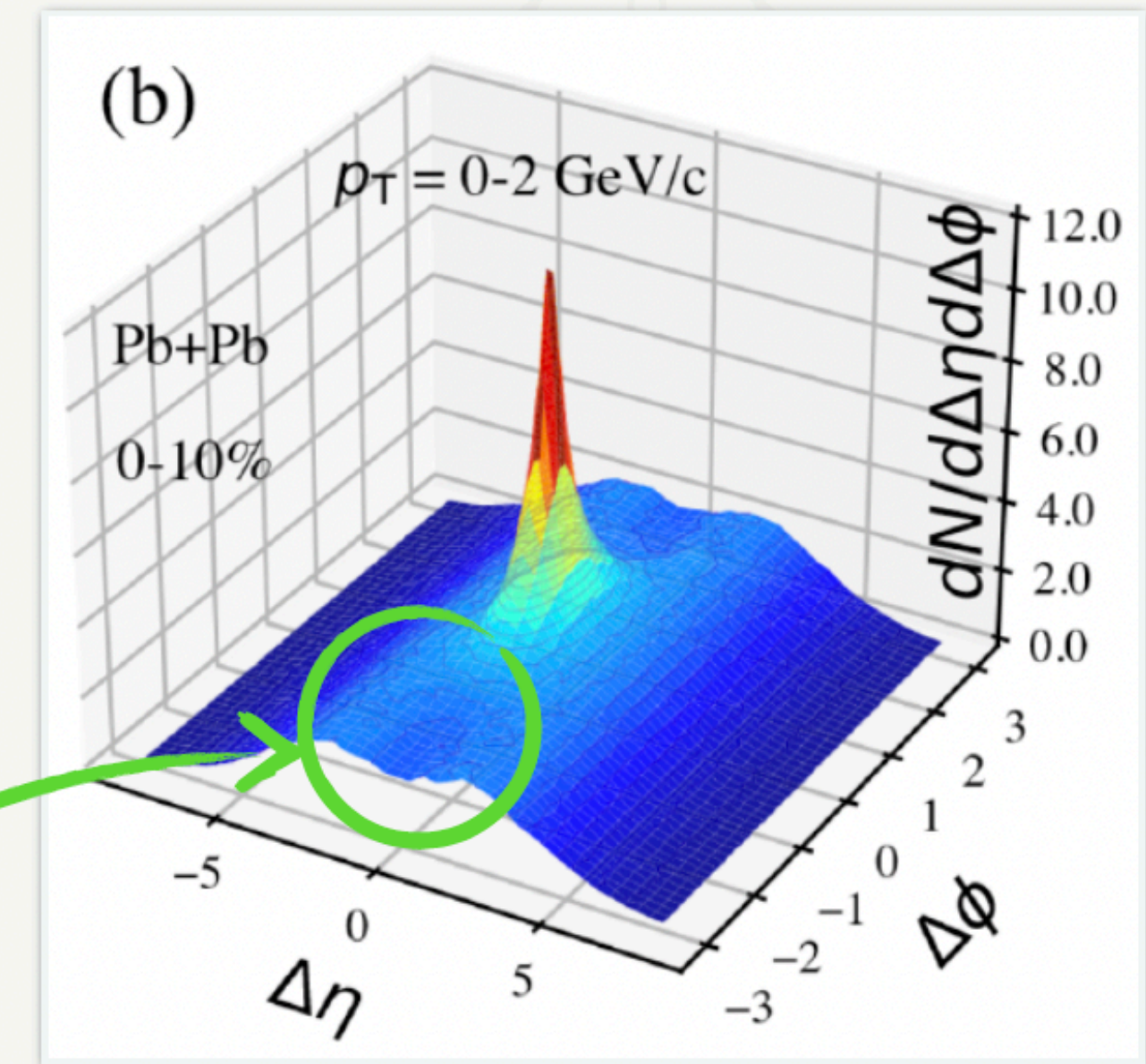
“Waking” the medium



- Experimental measurements with γ -tagged jets differential in $\Delta\phi$ and $\Delta\eta$

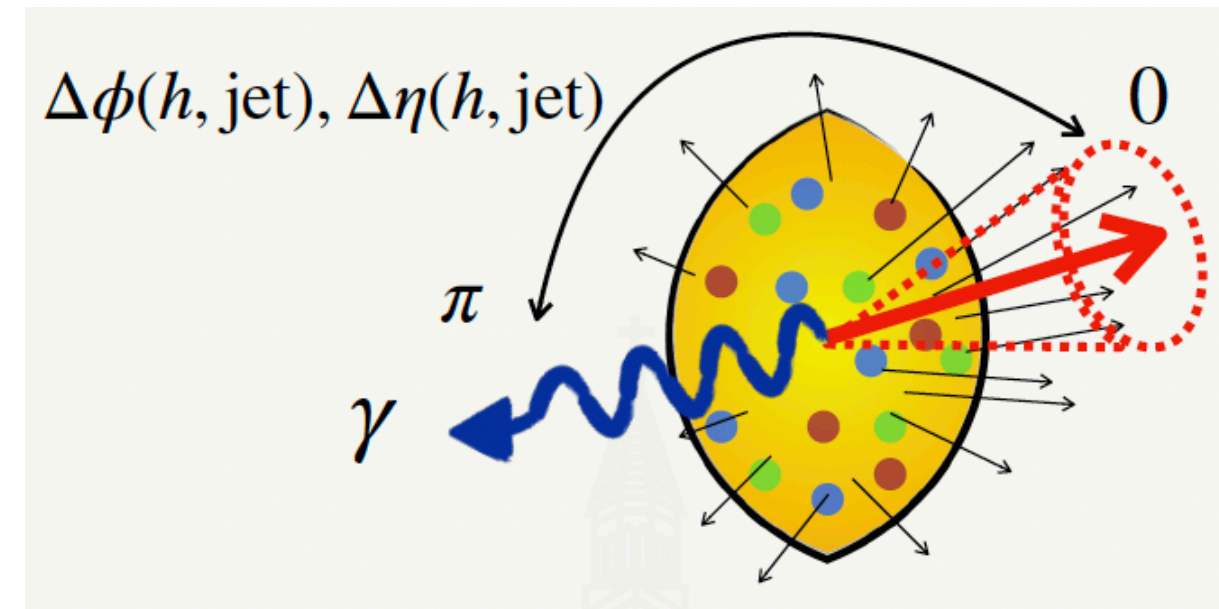


PRL 130, 052301
(2023), CoLBT

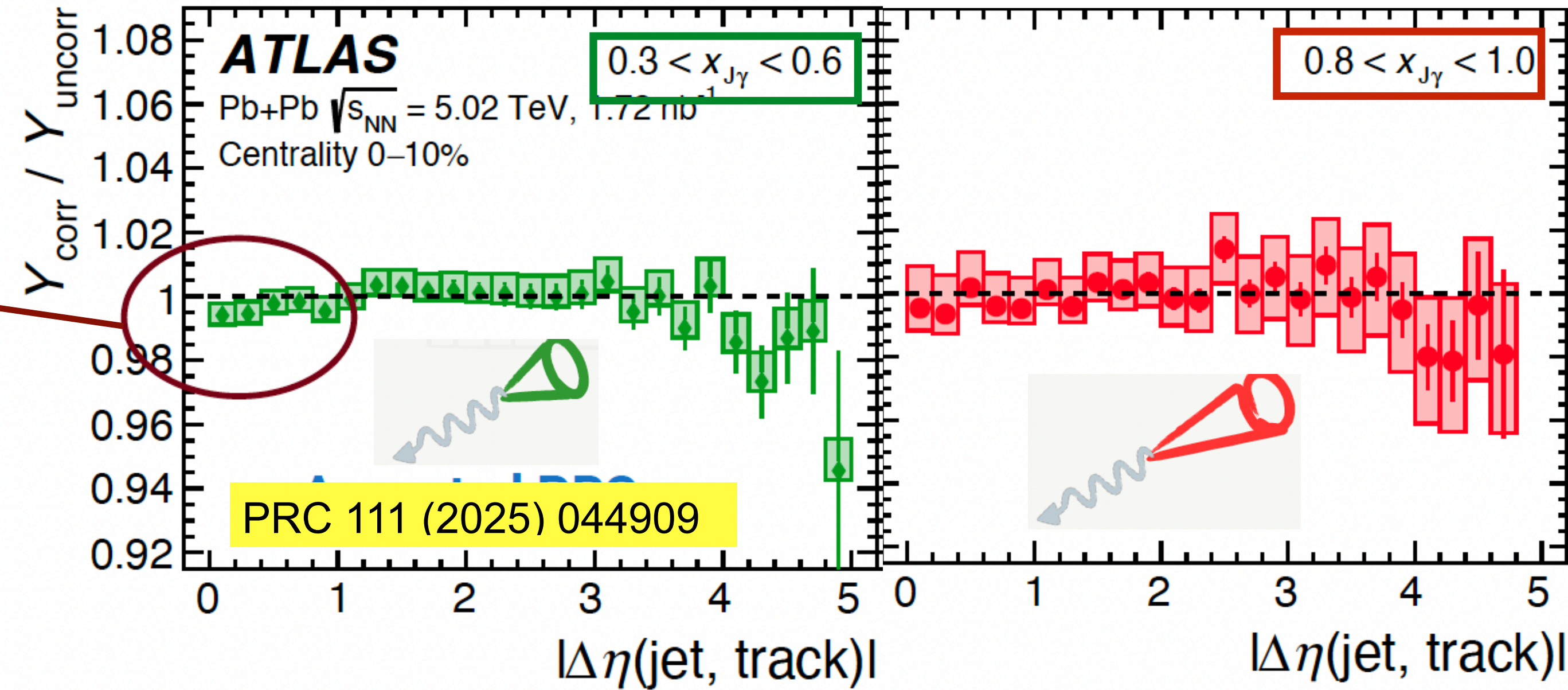
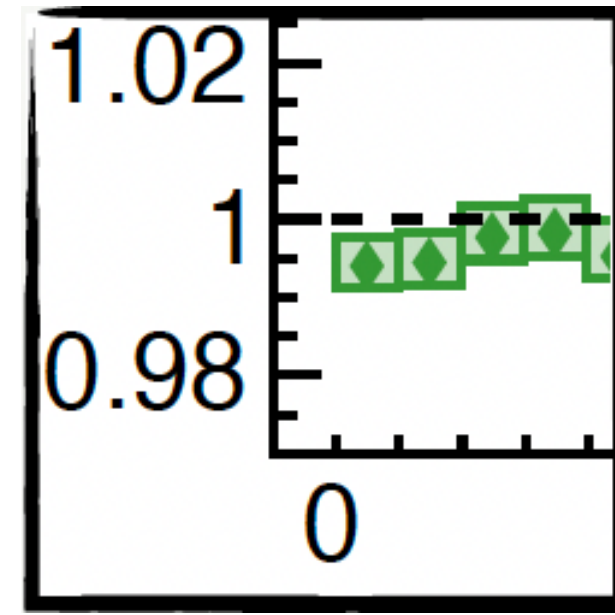


Diffusion wake signal expected at
 $\Delta\phi > \pi/2$ and $\Delta\eta \sim 0$

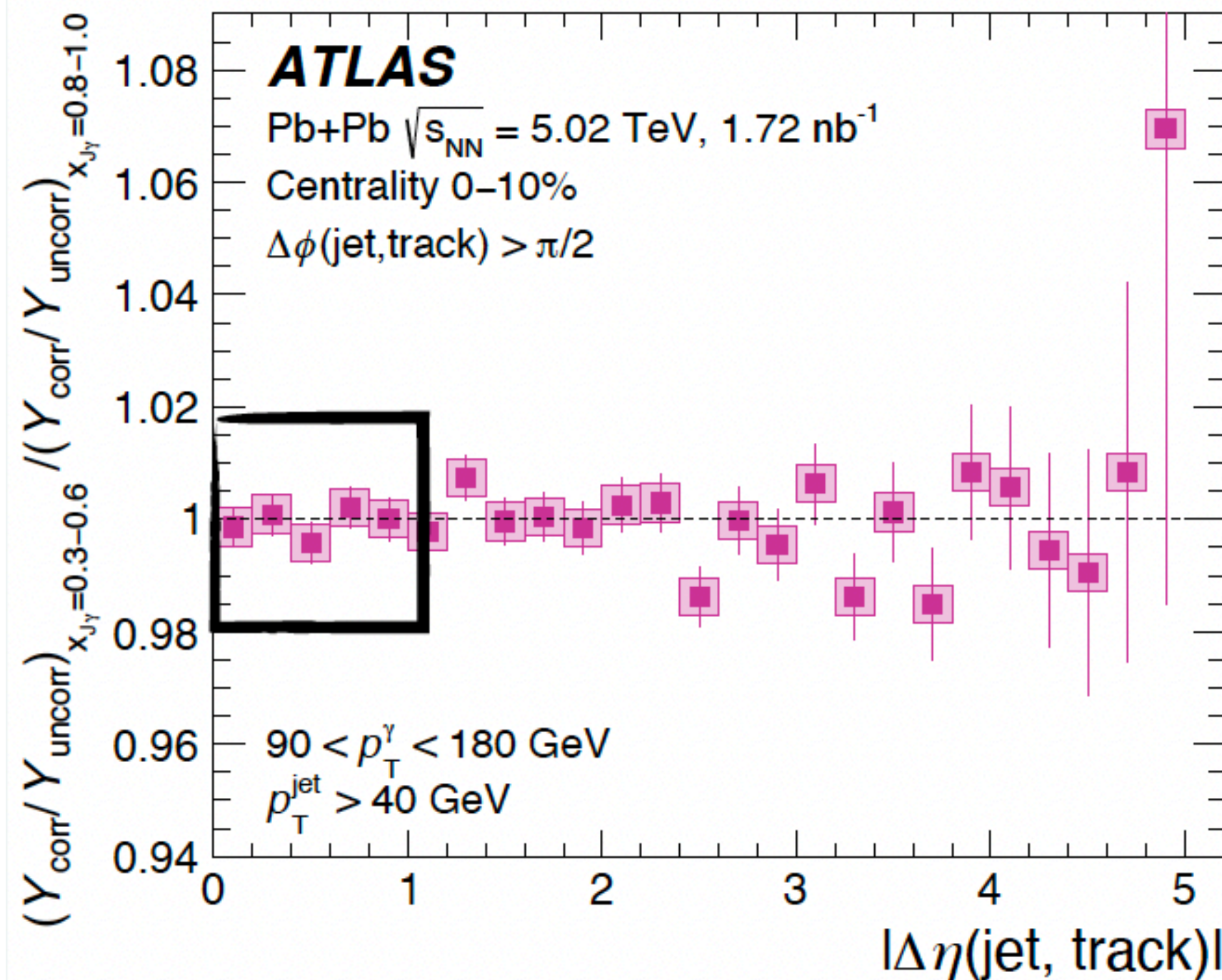
3D jet+tracks in γ +jet



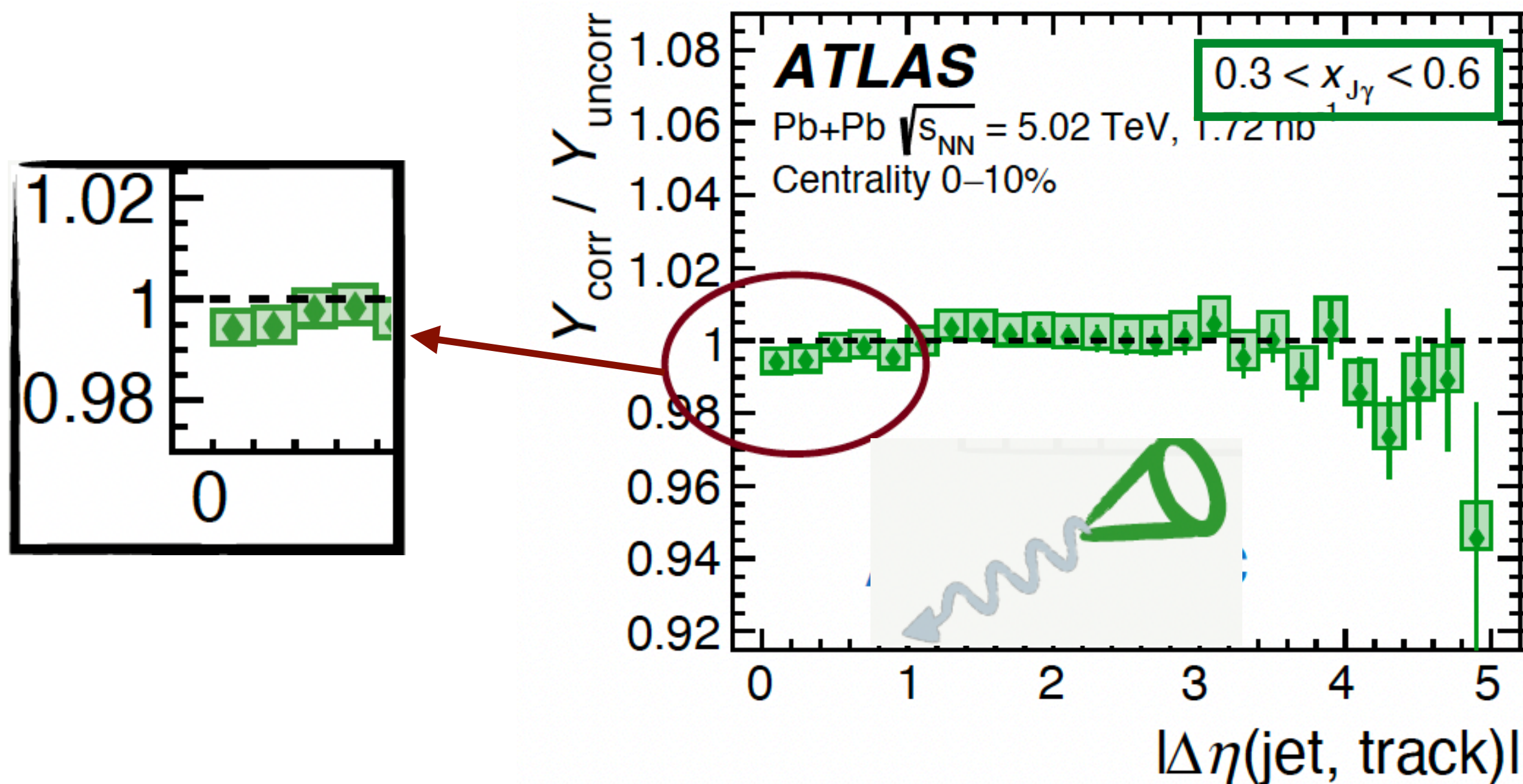
$$Y_{\text{corr}} \text{ or } Y_{\text{uncorr}} = \frac{1}{N_{\gamma\text{-jet}}} \frac{d^2 N_{\text{jet-track}}}{d\Delta\eta d\Delta\phi}$$



- 3D analysis of jet-track correlations ($x_{J\gamma}$, $\Delta\phi$ and $\Delta\eta$)
- Selecting different jet energy loss classes using $x_{J\gamma}$
- $Y_{\text{corr}}/Y_{\text{uncorr}}$ shows the relative modification of bulk medium
- No significant $x_{J\gamma}$ dependence of the diffusion wake

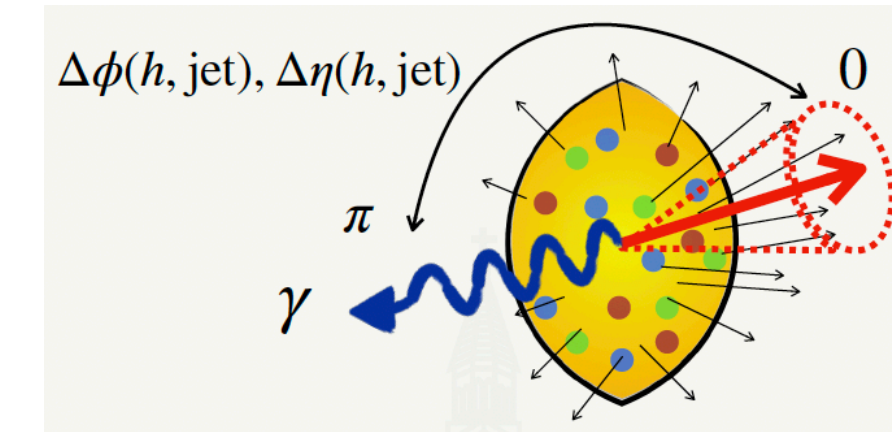


3D jet+tracks in γ +jet: wake constraints

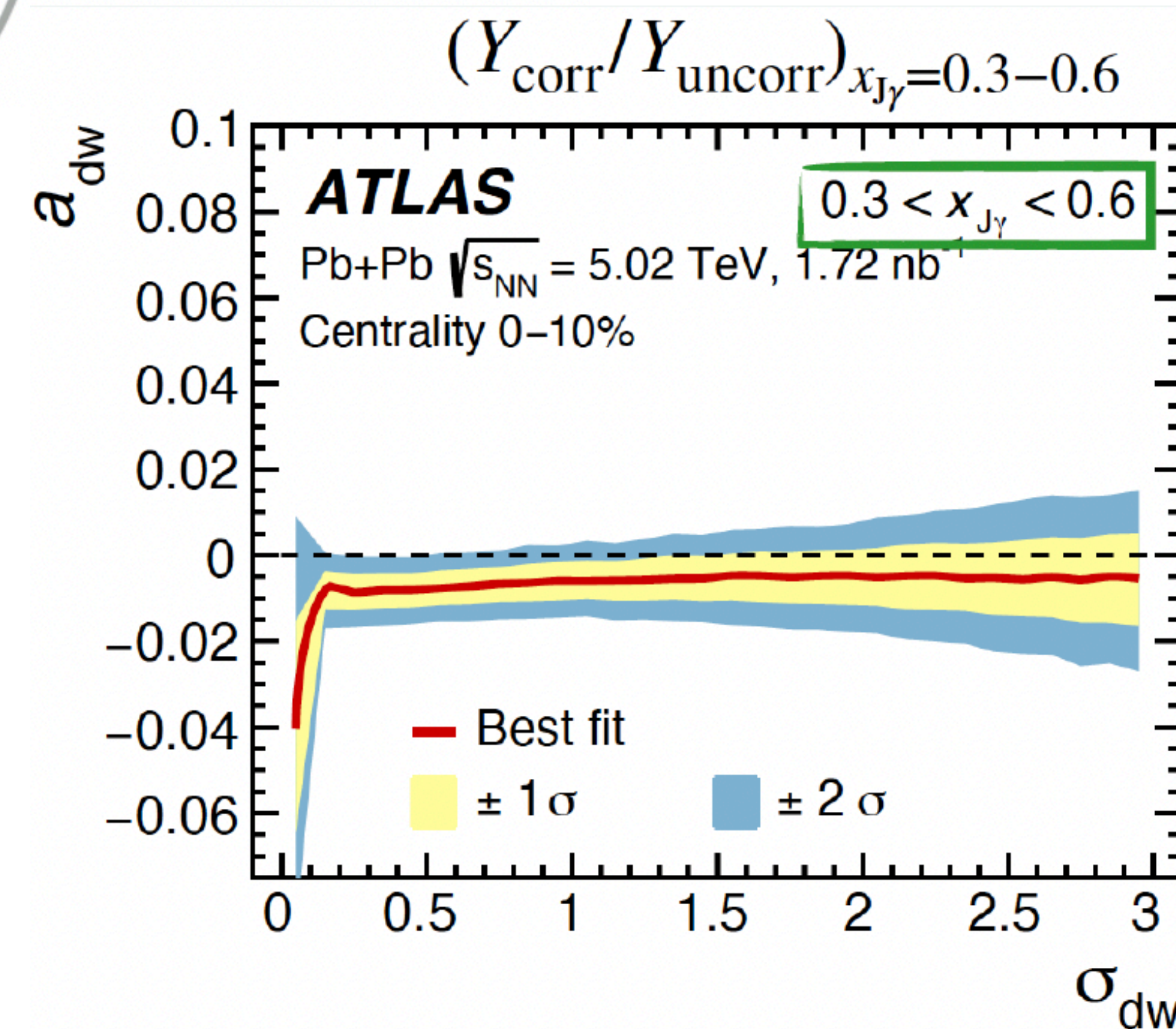
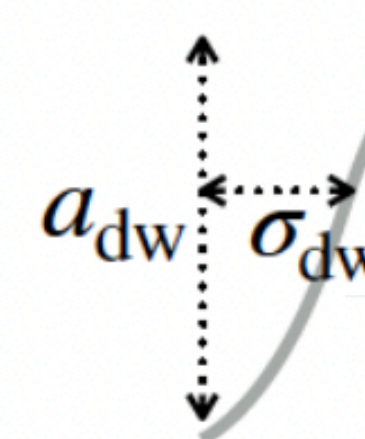


Diffusion Wake Amplitude Diffusion Wake Width

$$a_0 + a_{\text{dw}} \cdot e^{-|\Delta\eta(\text{jet, track})|^2 / (2\sigma_{\text{dw}}^2)}$$

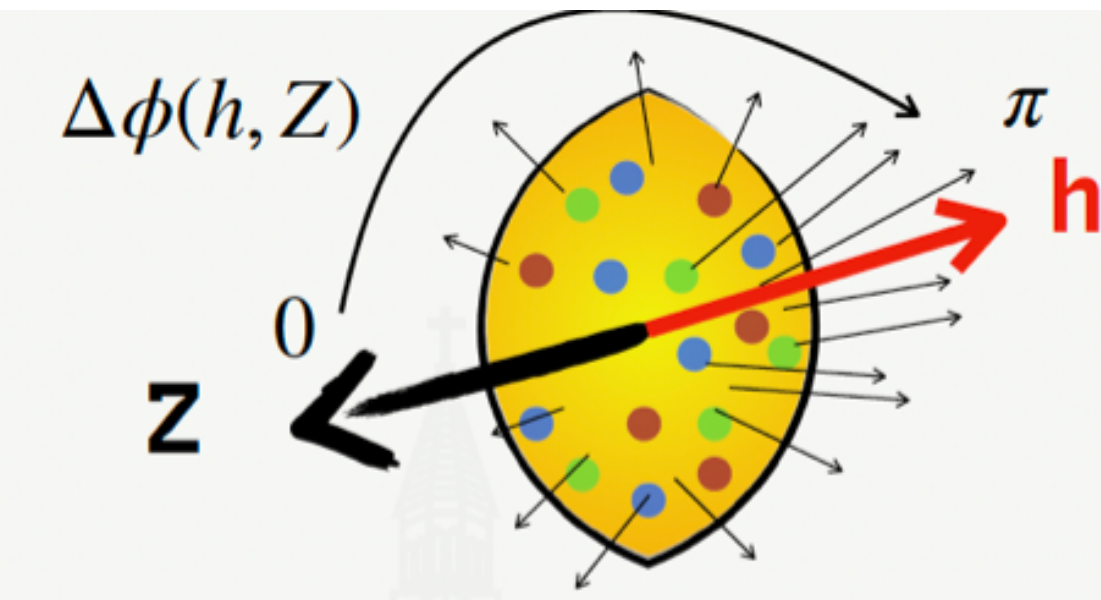


PRC 111 (2025) 044909



- The **best fit** of the **diffusion wake amplitude** for the lowest $x_{J\gamma}$ (highest energy deposition in the medium) is about **0.5-0.8%** for the diffusion wake width range of 0.5-1.0

Search for diffusion wake in Z-tagged events



- **No jet requirement** allows for contribution from very quenched jets ($x_{Jz} \ll 1$)
- Double differential absolute measurement of $\Delta N_{ch} = S - B$ in different selections of p_{T}^{ch}

CMS

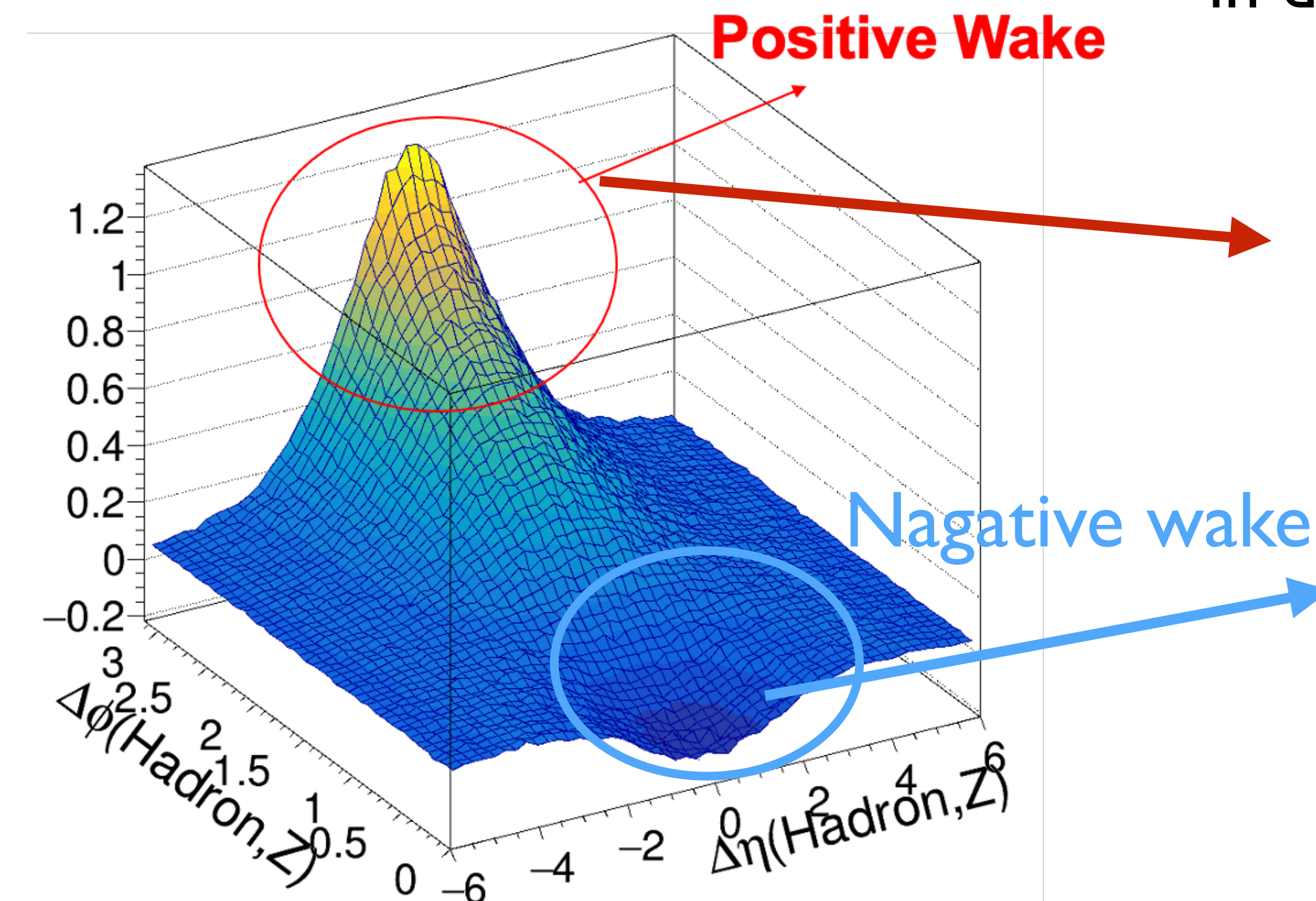
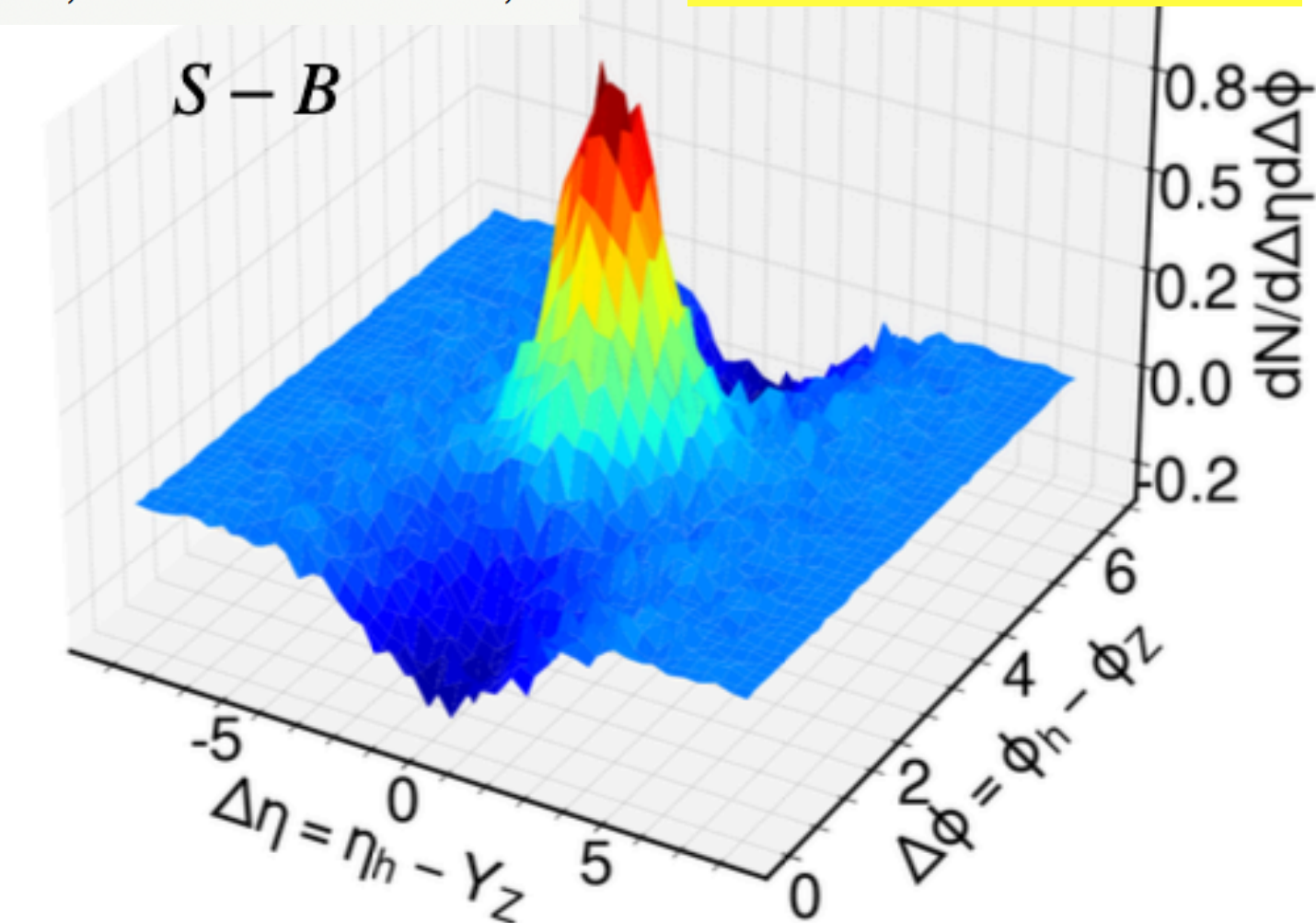
Z-hadron correlation

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

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

$$\frac{d\langle \Delta N_{ch} \rangle}{d\Delta\phi_{ch,Z}} \quad \text{or} \quad \frac{d\langle \Delta N_{ch} \rangle}{d\Delta y_{ch,Z}}$$

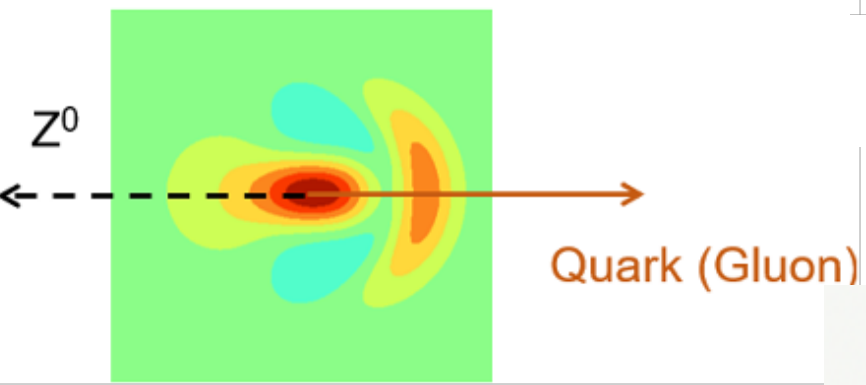
arXiv: 2507.09307



Note the different relative magnitudes of the two effects compared to γ -jet CoLBT due to different type of analysis

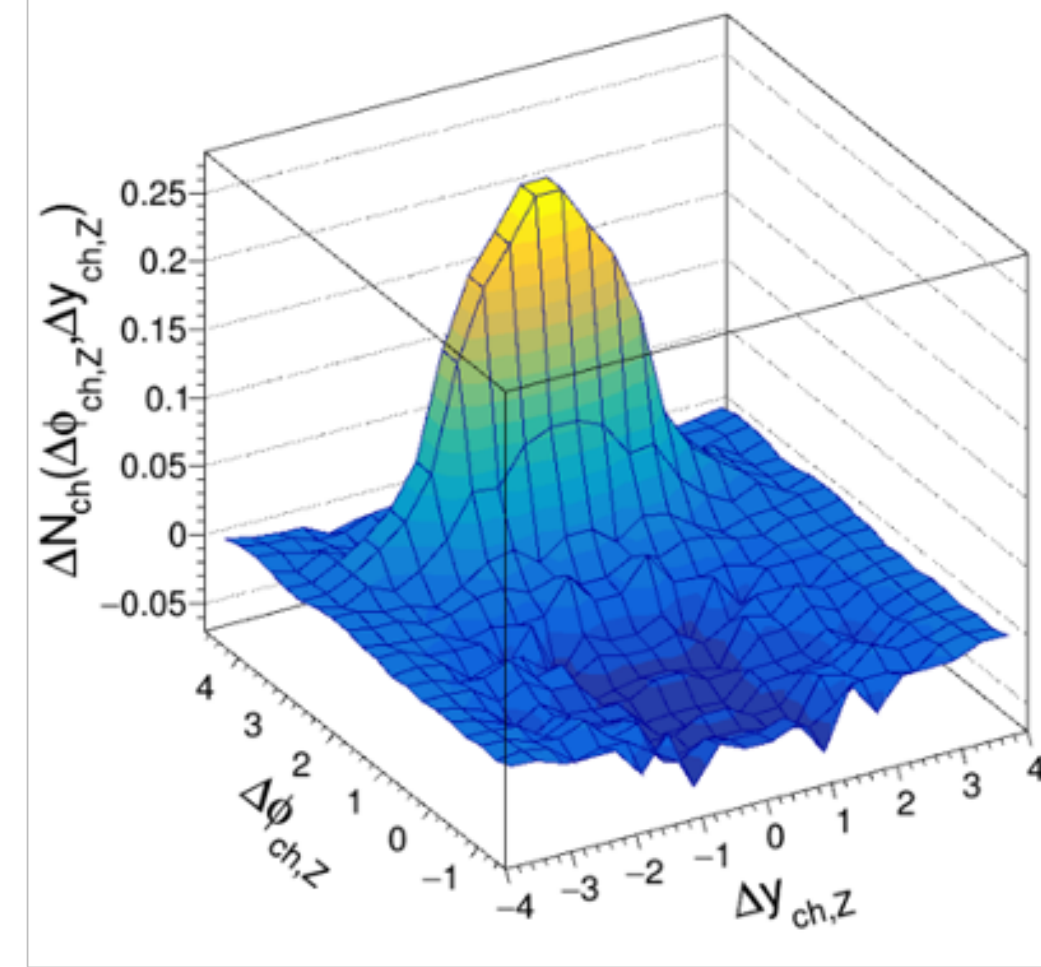
Z and Wake Hadron correlation in Hybrid model
Daniel Pablo, Krishna Rajagopal, Yen-Jee Lee

Diffusion wake via Z-jets: $\Delta\phi$

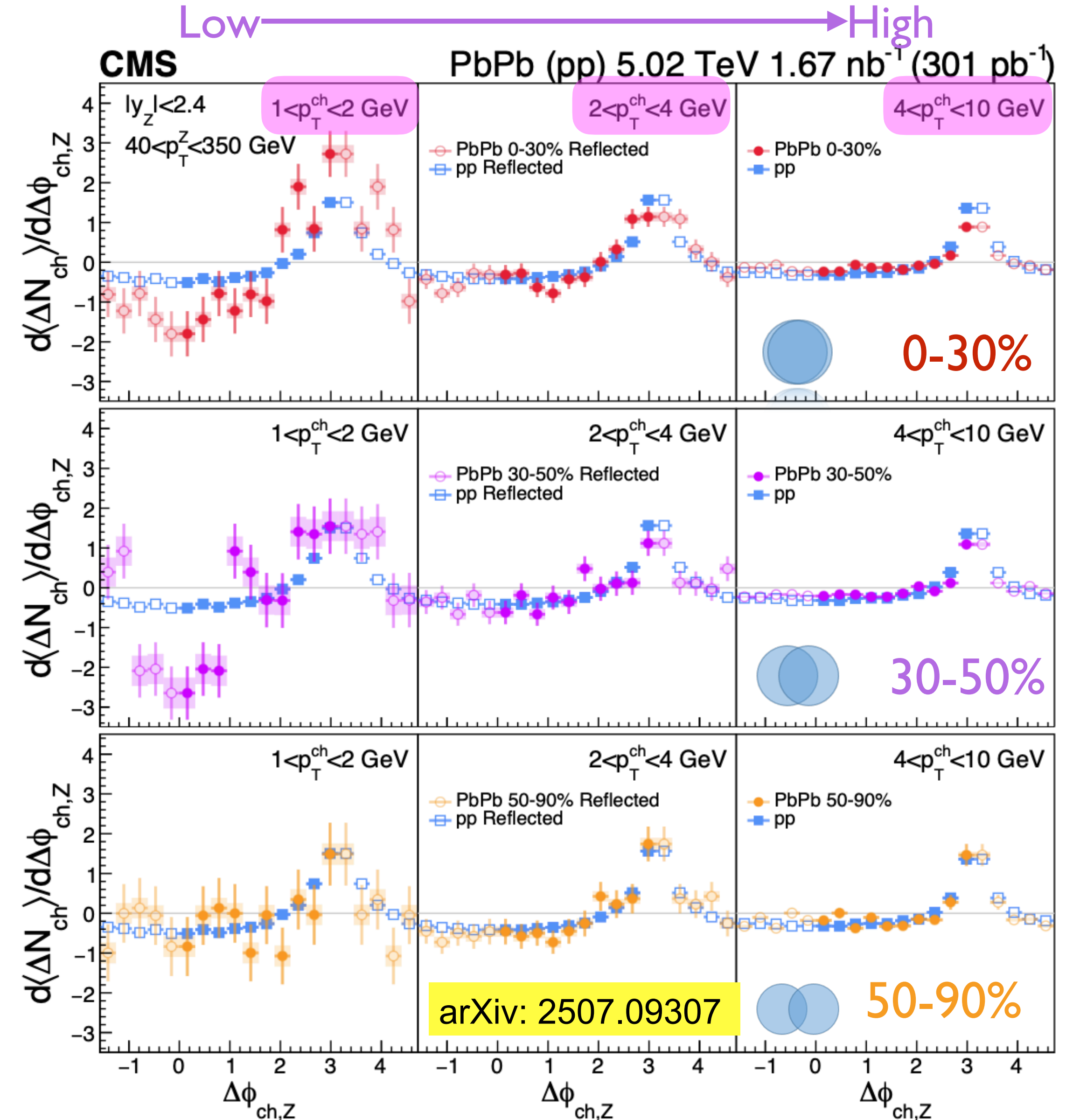


$$\Delta N_{ch} = S - B$$

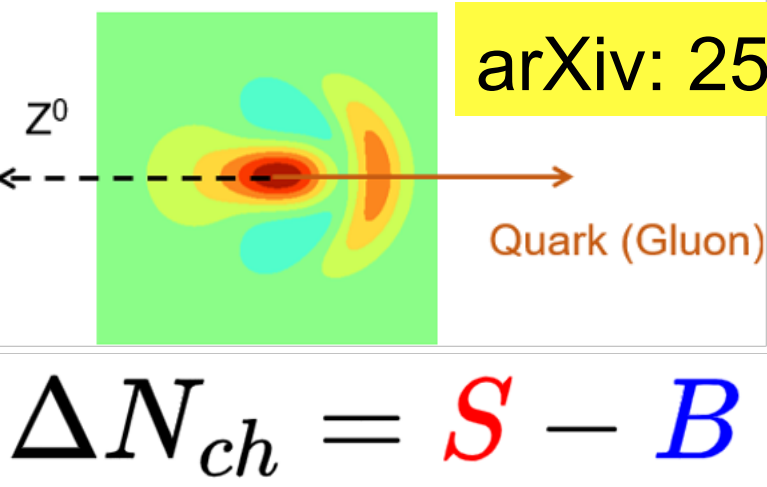
$$\frac{d\langle \Delta N_{ch} \rangle}{d\Delta\phi_{ch,Z}}$$



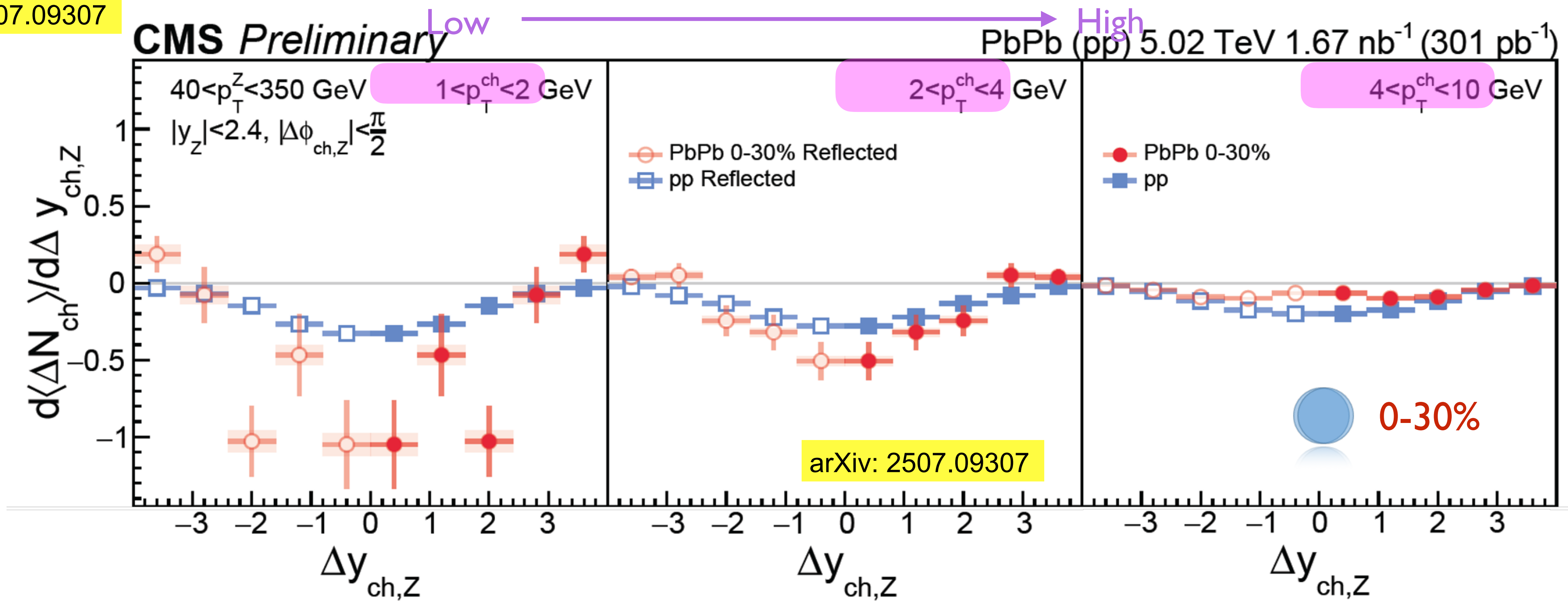
- Scan correlated hadrons with respect to Z^0 direction in different centrality and p_{T}^{ch} intervals
- Clear **depletion** observed for low p_{T}^{ch} hadrons around Z ($\Delta\phi \sim 0$) in central (0-50%) collisions
- Depletion vanished when going to high p_{T}^{ch} or peripheral events
- **Jet side peak** ($\Delta\phi = \pi$) reduced due to jet quenching at high hadron p_T



Diffusion wake via Z^0 -jets: Δy

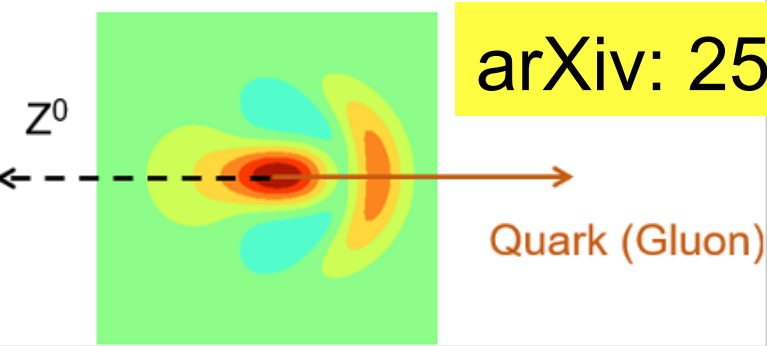


$$\frac{d\langle \Delta N_{ch} \rangle}{d\Delta y_{ch,Z}}$$



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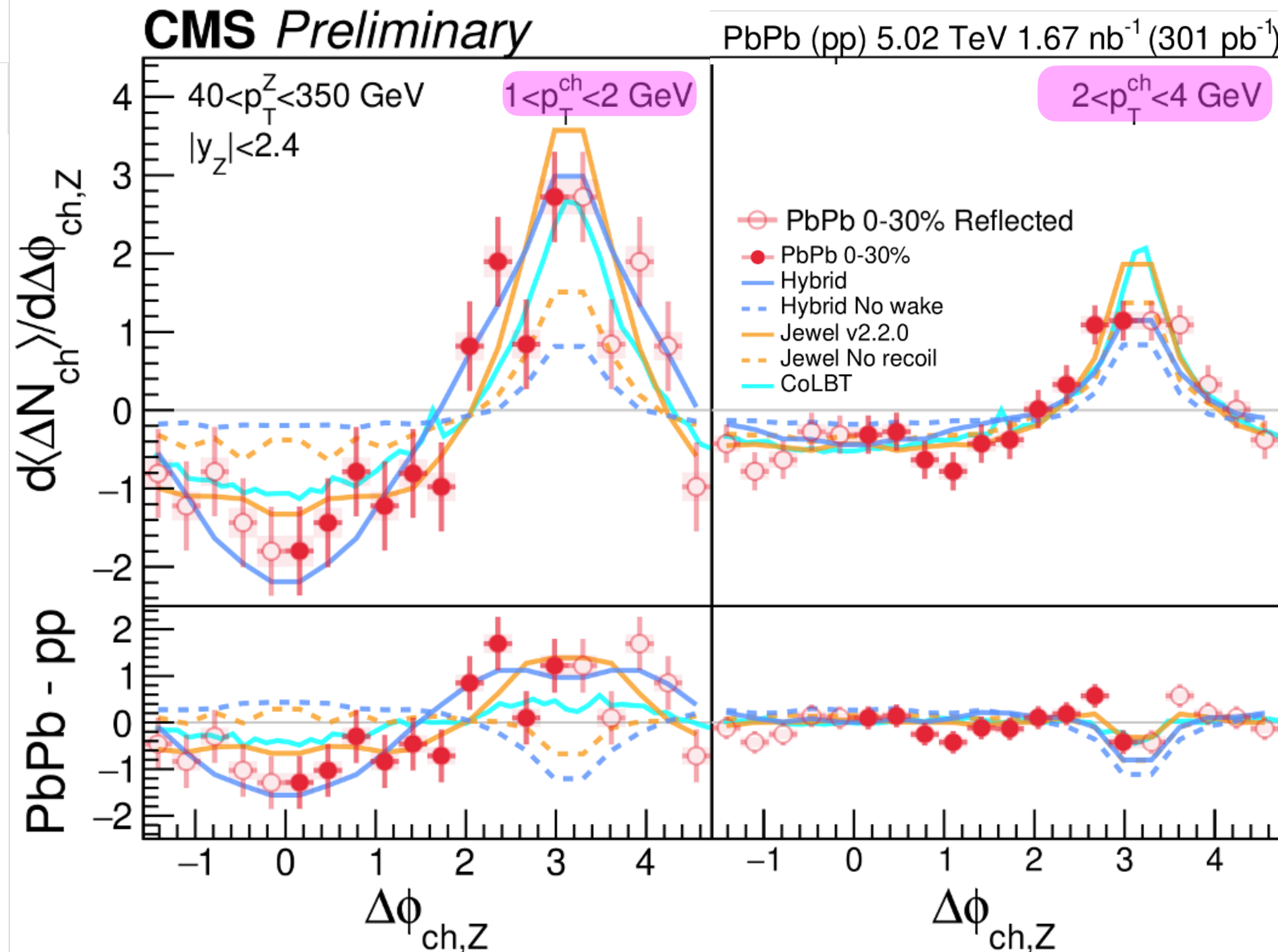
Comparison of diffusion wake with models



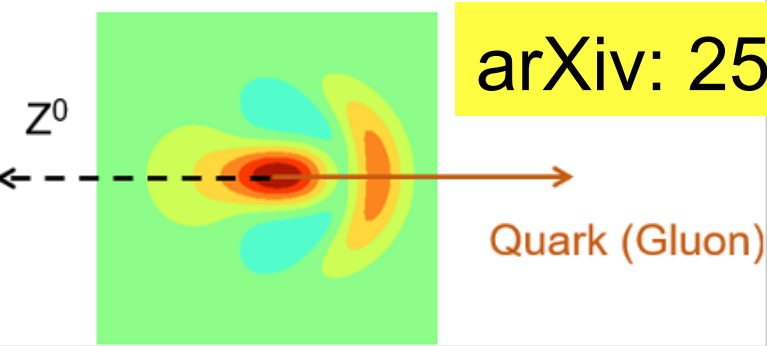
arXiv: 2507.09307

$$\Delta N_{ch} = \textcolor{red}{S} - \textcolor{blue}{B}$$

- Hybrid without wake and **Jewel without recoil** under-predict magnitude at low hadron p_T
- Hybrid with wake, **Jewel with recoil** and **CoLBT with wake** agree better with the data



Comparison of diffusion wake with models

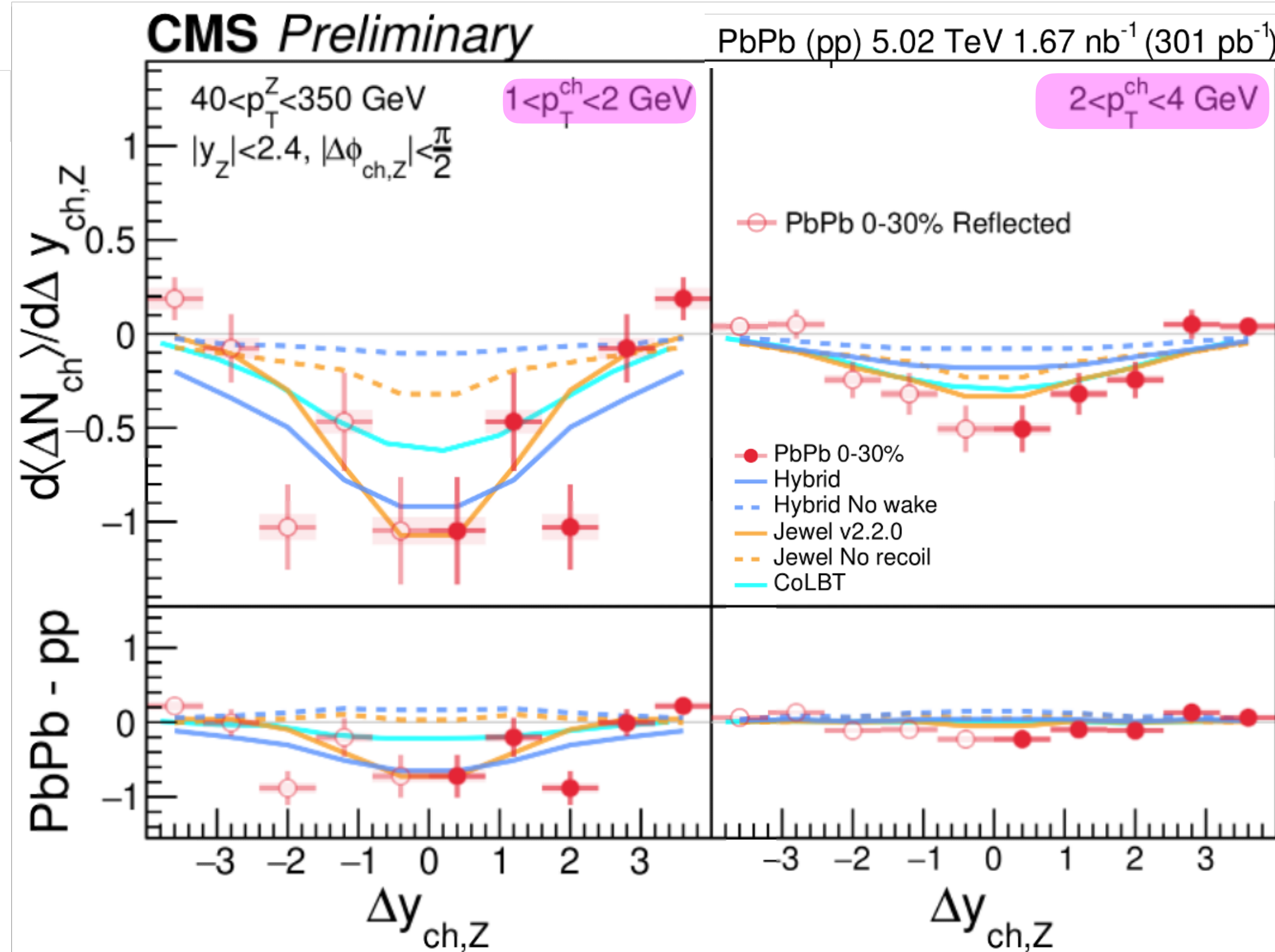


arXiv: 2507.09307

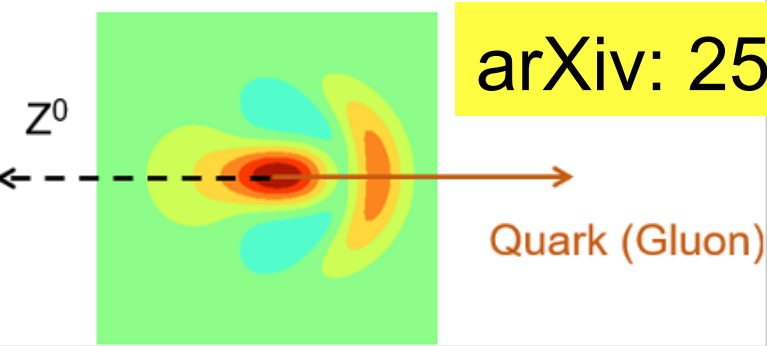
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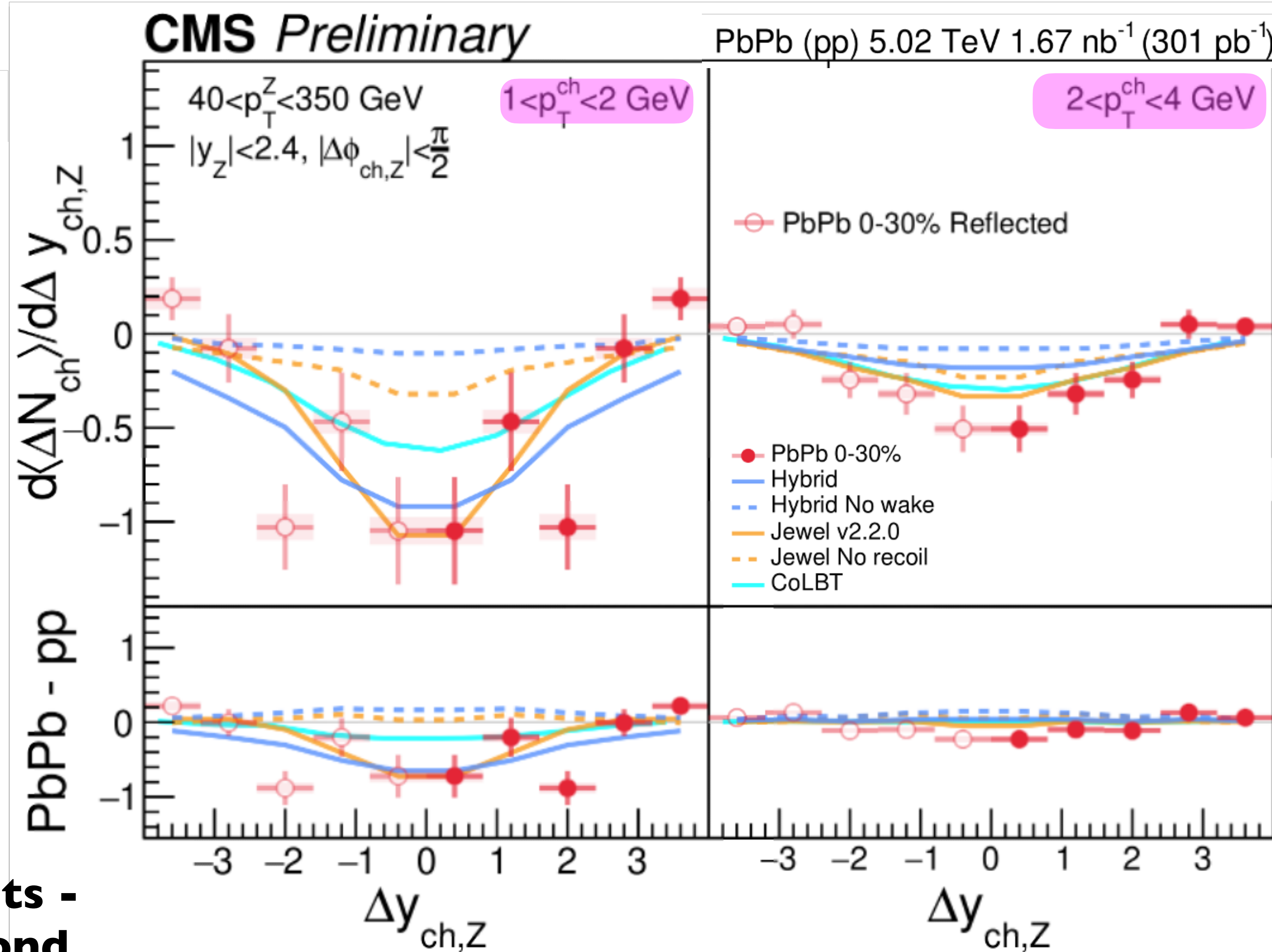
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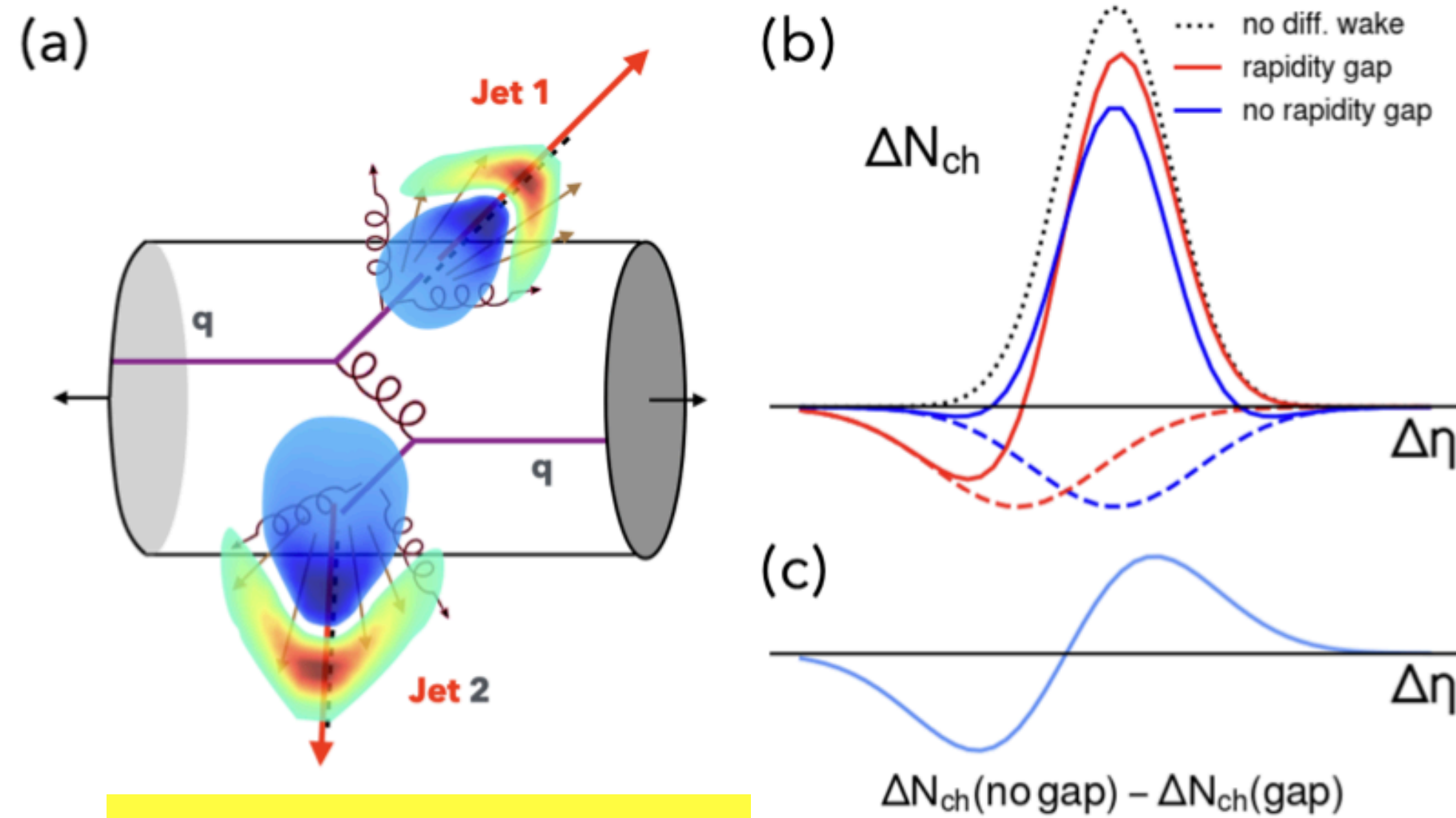
Statistically hungry measurements - more to come w/ Run 3 and beyond



New idea: diffusion wake searching using di-jets

Search diffusion wake using **jet-hadron correlations in di-jet events**

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



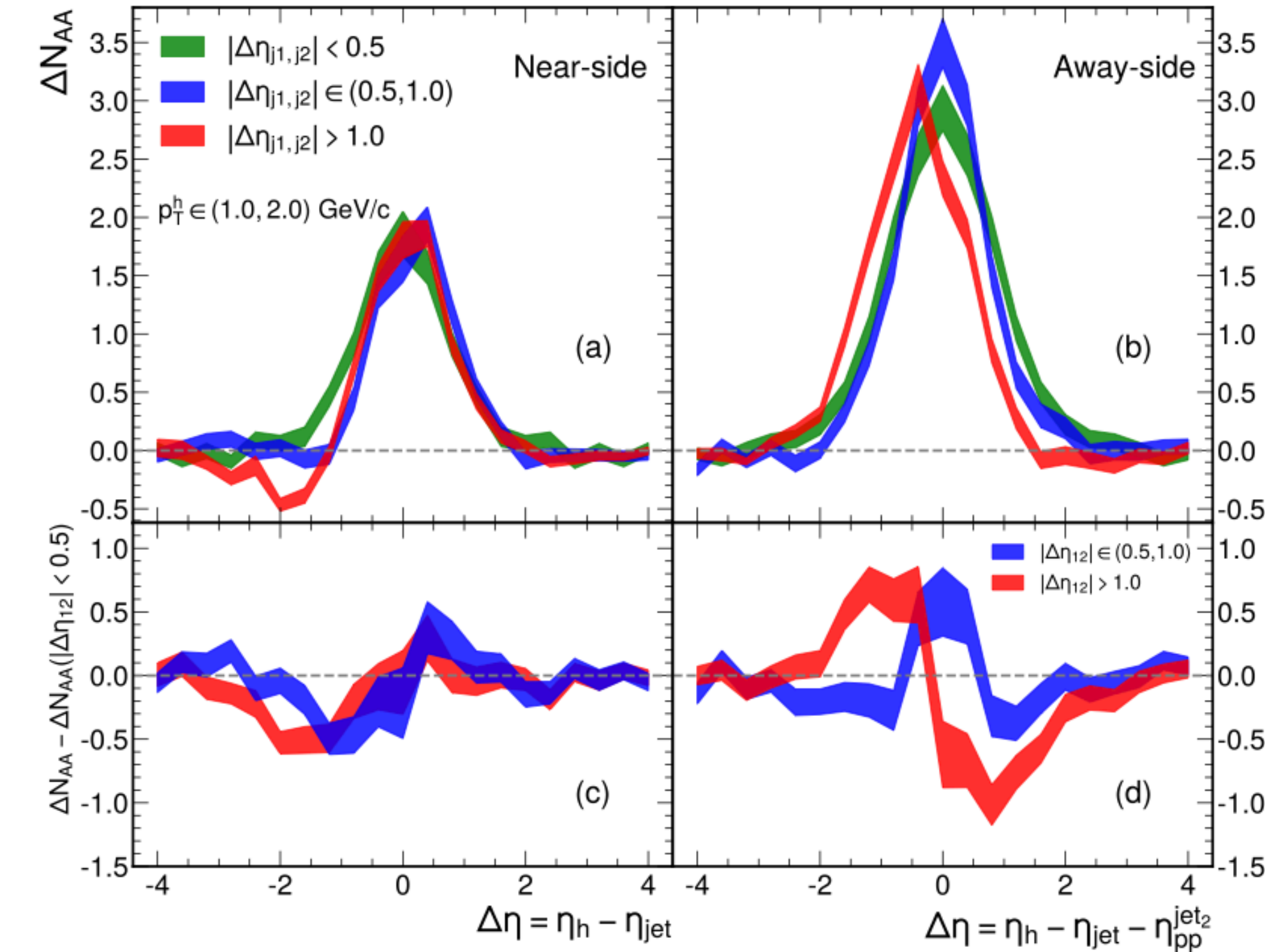
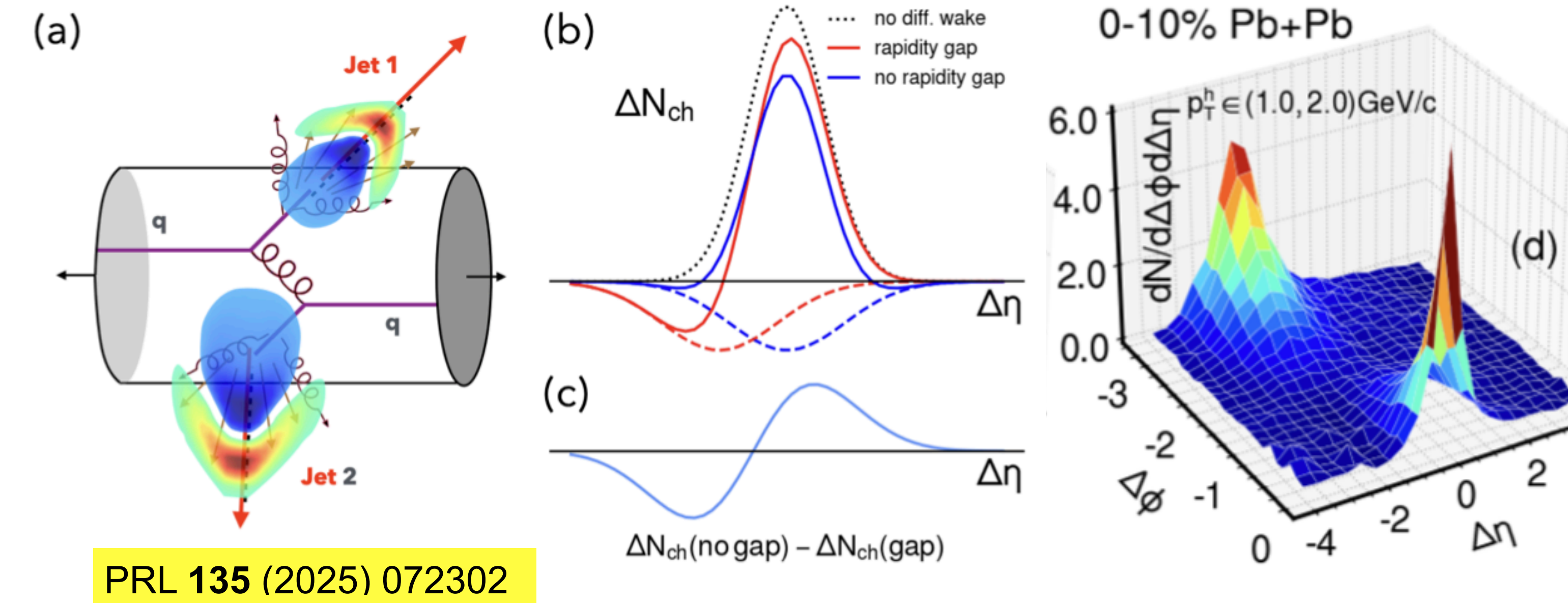
PRL 135 (2025) 072302

- Novel method to **identify diffusion wake signal** from dijets **with finite rapidity gap**

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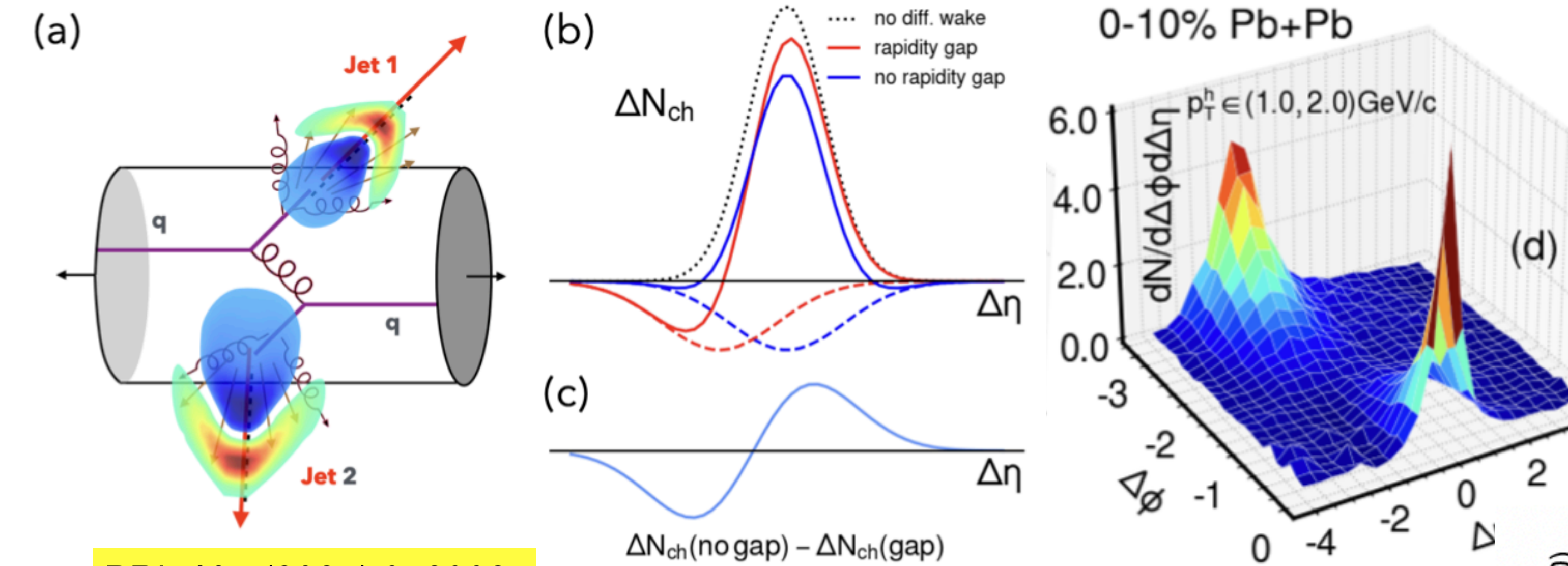


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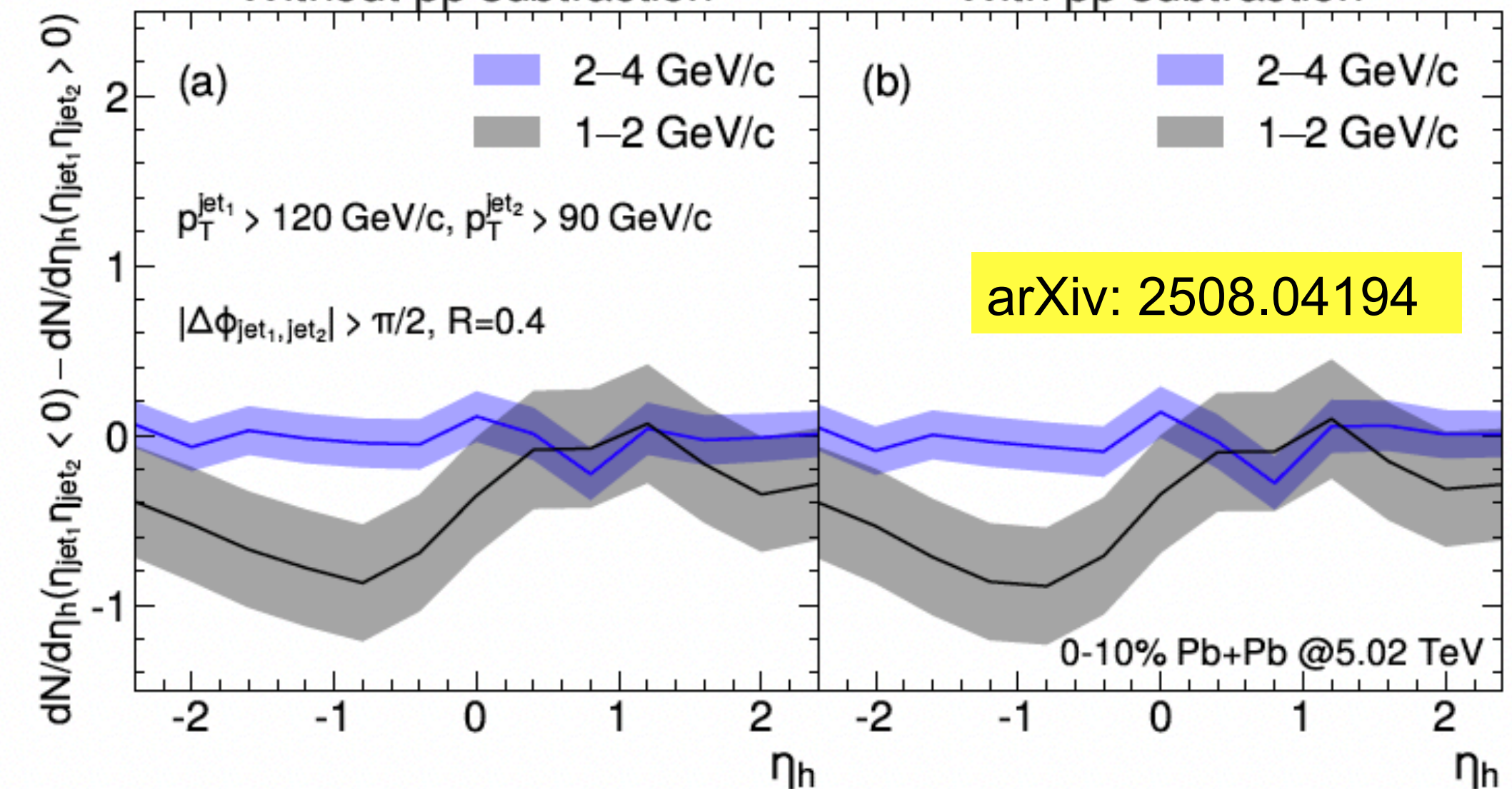
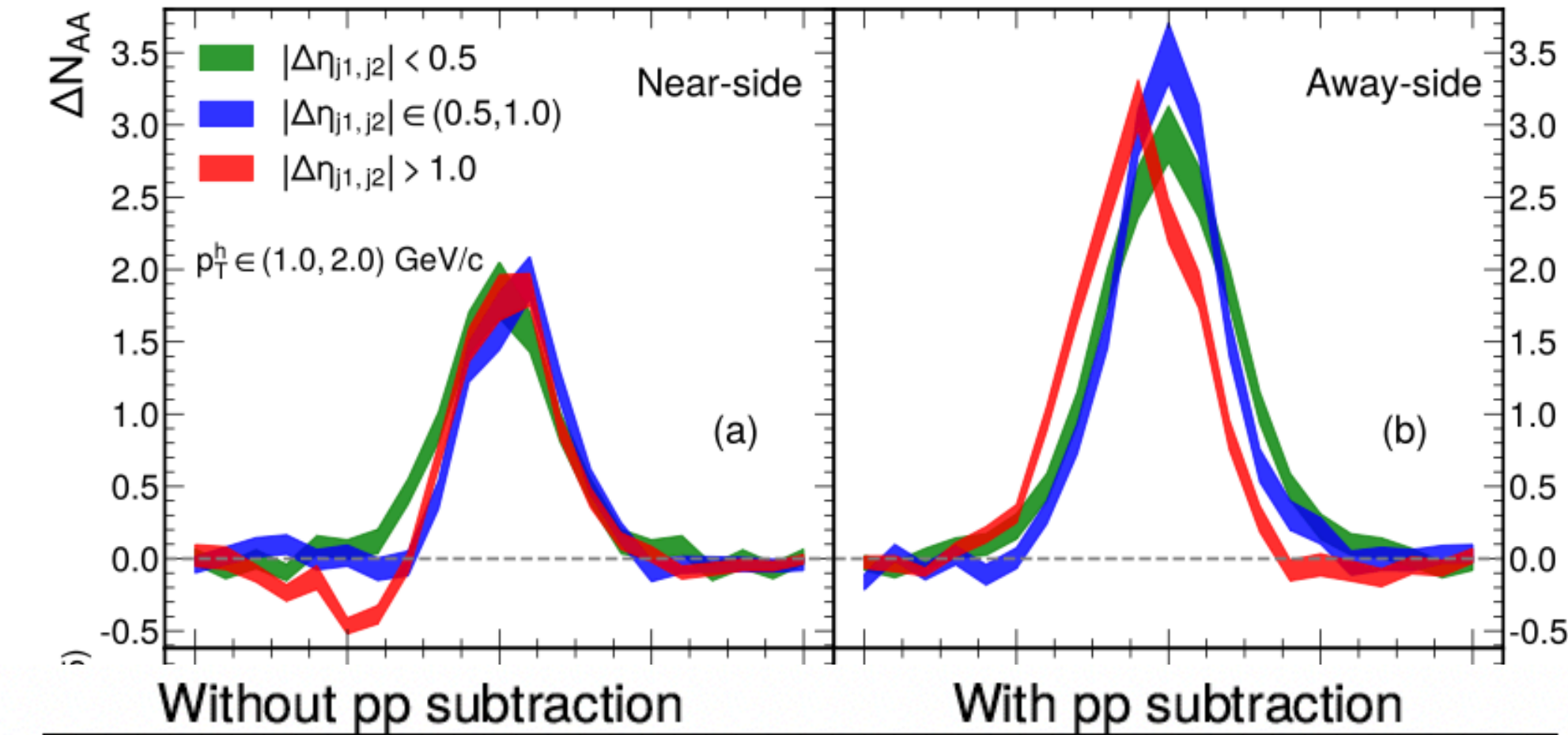
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PRL 135 (2025) 072302

- Novel method to **identify diffusion wake signal** from dijets **with finite rapidity gap**
- **Background-free** → simplifies experimental measurements



arXiv: 2508.04194

Diffusion wake search with ALICE

Search diffusion wake using **jet-hadron correlations in di-jet events**

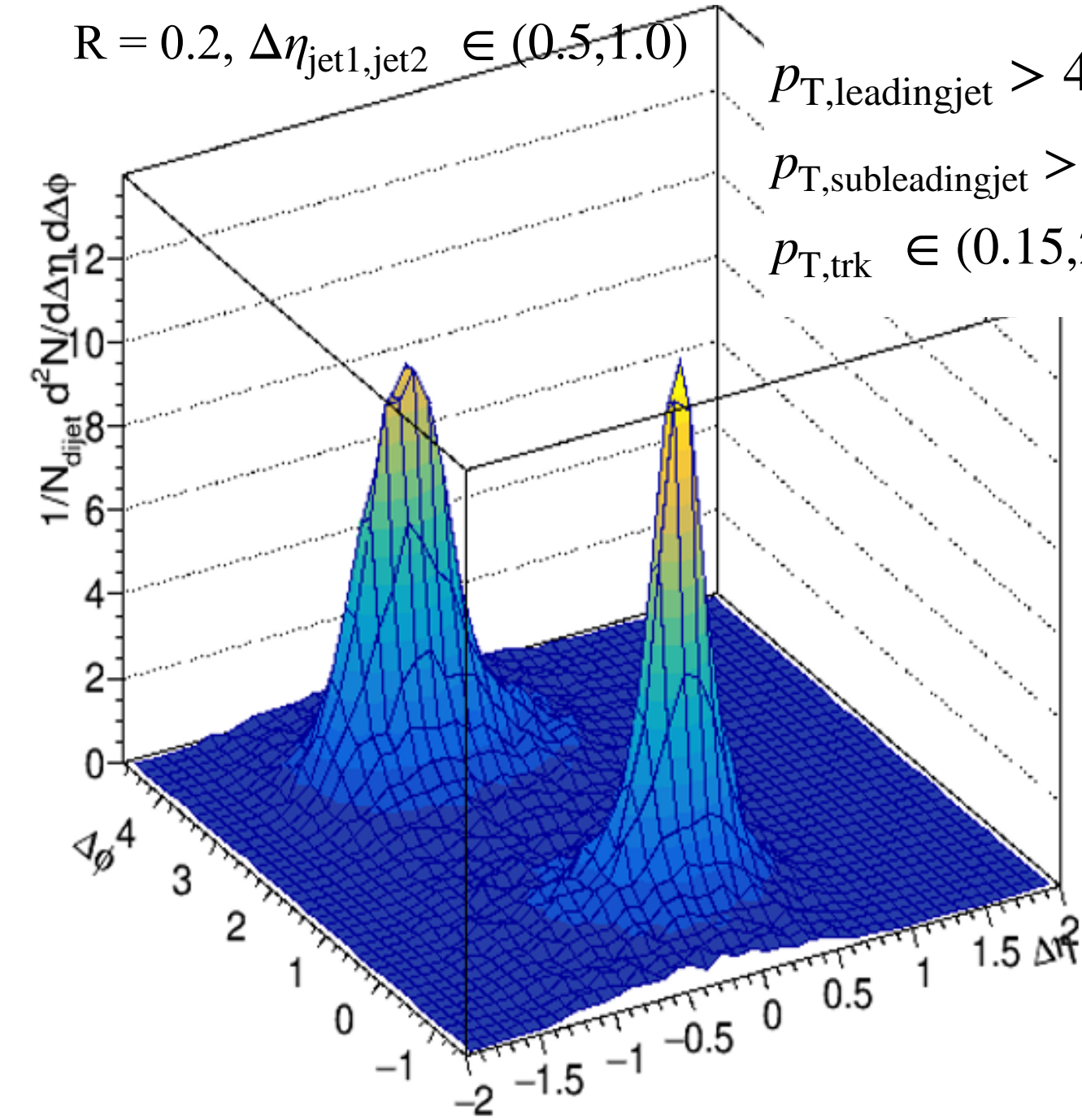
PYTHIA8 simulations: pp 5.35 TeV

$R = 0.2, \Delta\eta_{\text{jet1, jet2}} \in (0.5, 1.0)$

$p_{T, \text{leadingjet}} > 40 \text{ GeV}/c$

$p_{T, \text{subleadingjet}} > 20 \text{ GeV}/c$

$p_{T, \text{trk}} \in (0.15, 2.0) \text{ GeV}/c$



ALICE pp $\sqrt{s} = 5.36 \text{ TeV}, R = 0.2$

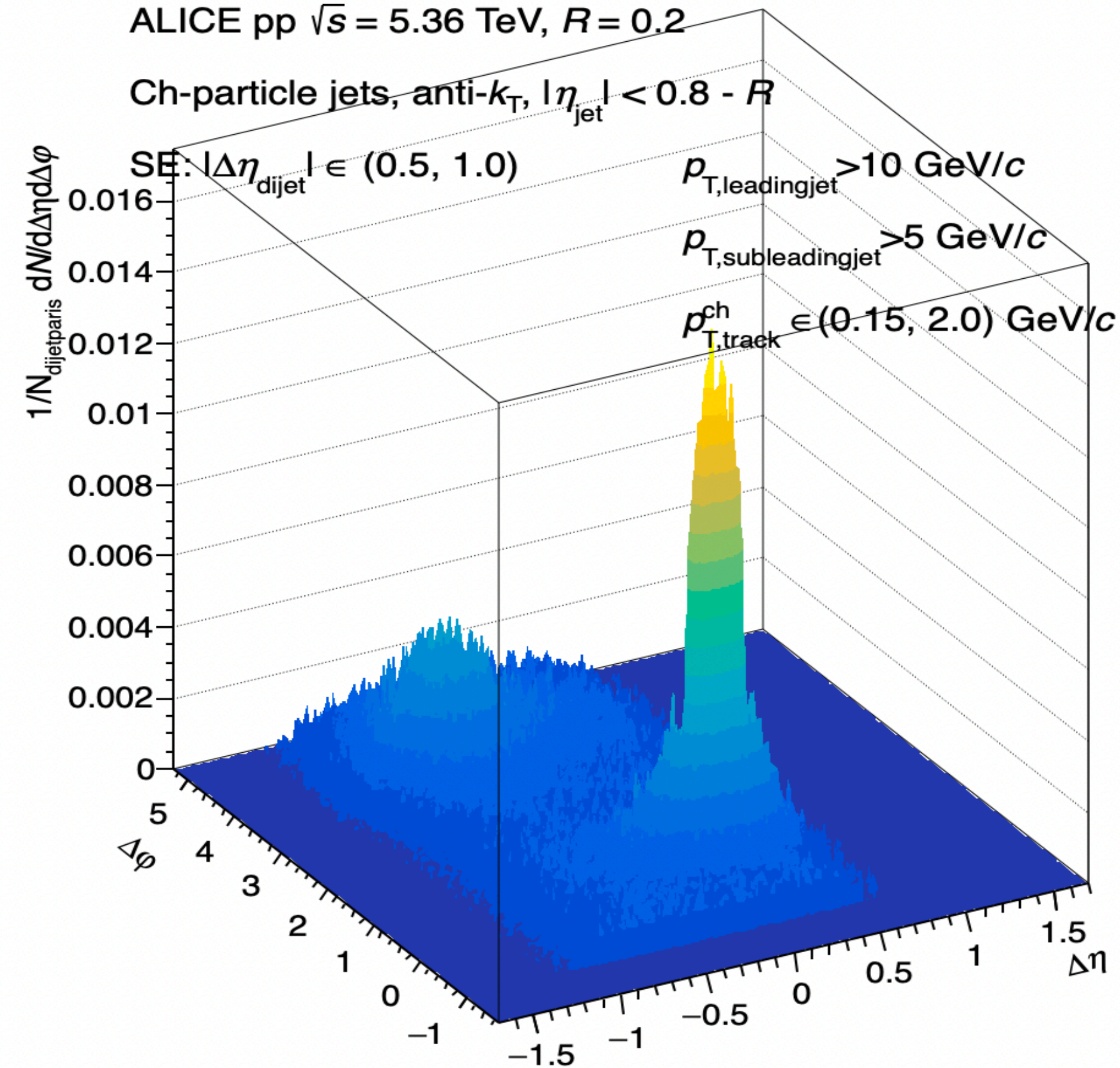
Ch-particle jets, anti- $k_T, |\eta_{\text{jet}}| < 0.8 - R$

SE: $|\Delta\eta_{\text{dijet}}| \in (0.5, 1.0)$

$p_{T, \text{leadingjet}} > 10 \text{ GeV}/c$

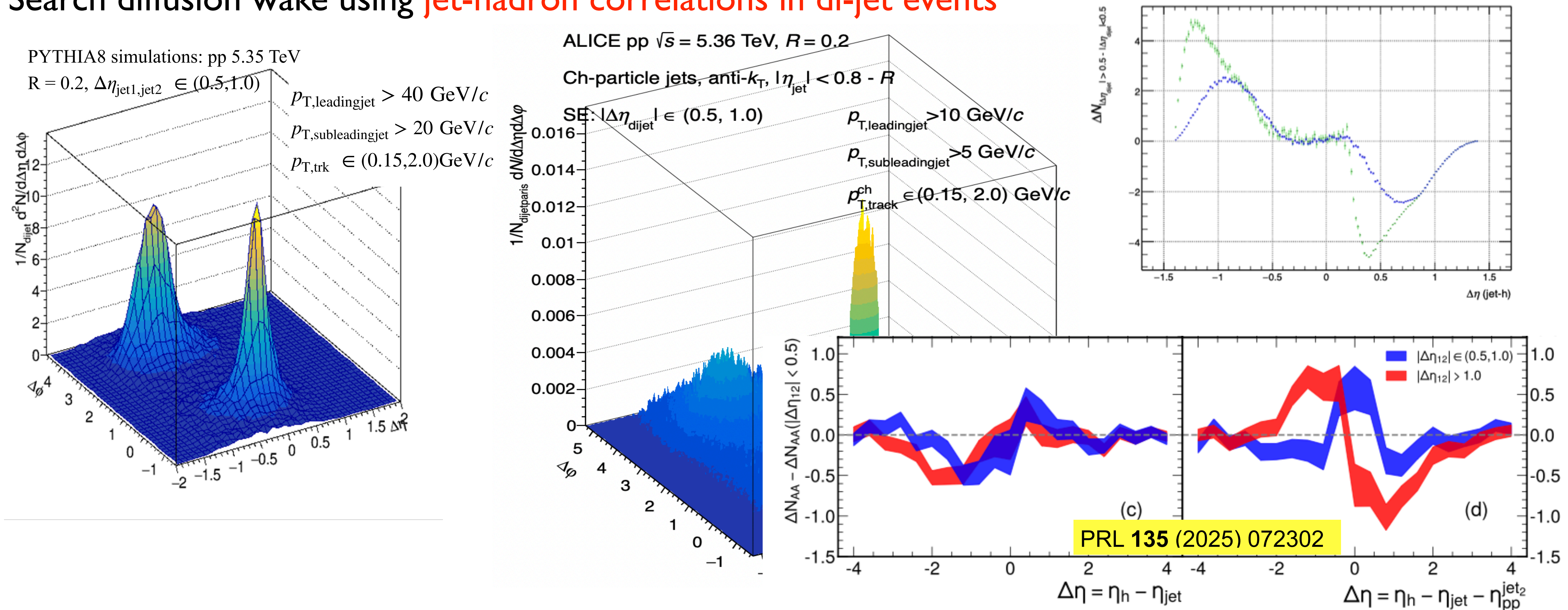
$p_{T, \text{subleadingjet}} > 5 \text{ GeV}/c$

$p_{T, \text{trk}}^{\text{ch}} \in (0.15, 2.0) \text{ GeV}/c$



Diffusion wake search with ALICE

Search diffusion wake using **jet-hadron correlations in di-jet events**



- First attempt on ALICE RUN3 data show interesting behavior!
 → Caution: no correction yet and di-jet selection is not optimized yet!

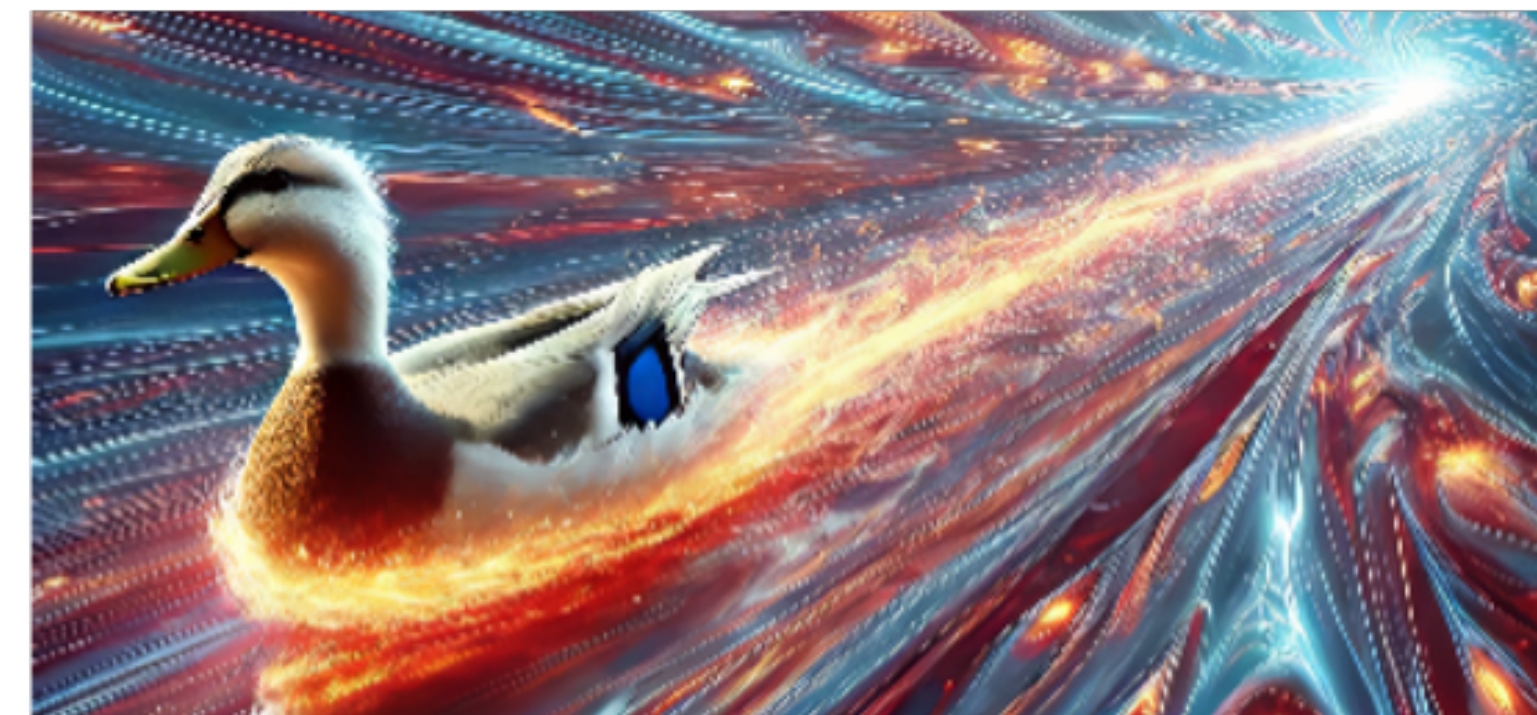
Summary

- **Enhanced yields** and **azimuthal broadening** of low- p_T particles/jets indicate medium response in the jet direction.
- ATLAS has measured jet-track correlations in γ -jet events to investigate possible **diffusion wake signal**
 - ➡ **Small diffusion wake signal** in the asymmetric γ -jet events (lowest $x_{J\gamma}$)
- Z^0 -hadron correlations in azimuthal angle and rapidity, measured differentially in p_T and centrality intervals with CMS
 - ➡ **First direct evidence of medium response in QGP**
- Theorists proposed **a new rapidity-asymmetry method** as **diffusion wake search** in di-jets
 - ➡ Motivating further explorations in LHC Runs 3 and 4

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Stay tuned! Thank you for your attention!



Backup

