Medium response to jet propagation in the QGP

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(Brookhaven National Laboratory)

On behalf of the
ALICE, ATLAS, and CMS collaborations

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3-7 June 2024
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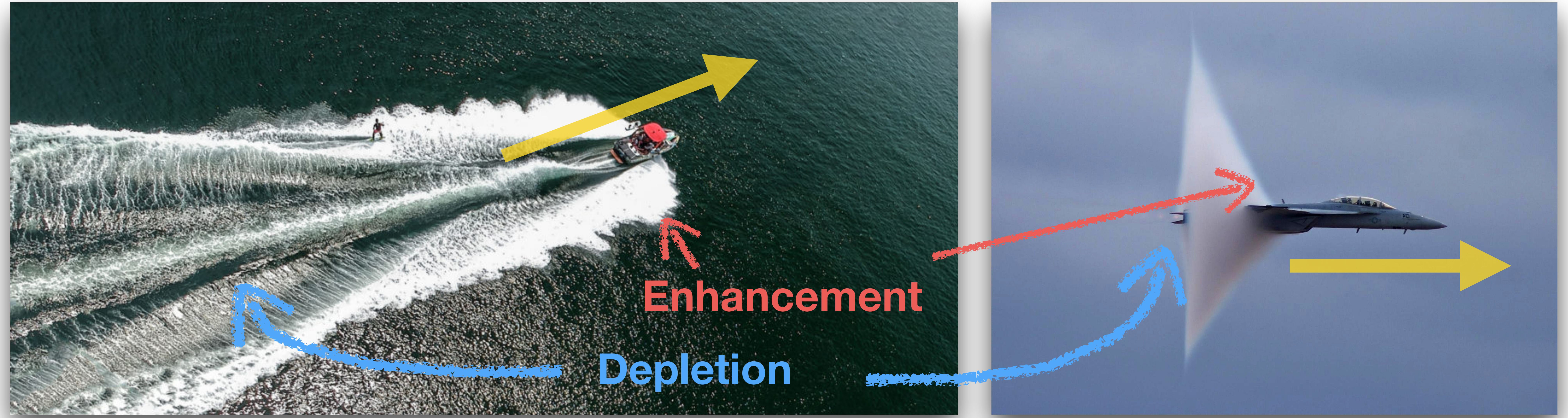
Brookhaven National Laboratory

U.S. DEPARTMENT OF ENERGY

Medium Response to Jet Propagation

- By energy and momentum conservation, lost jet energy goes into medium

- Typical form of medium response to jets
  ➡ enhancement in the jet direction
  ➡ depletion in the opposite direction



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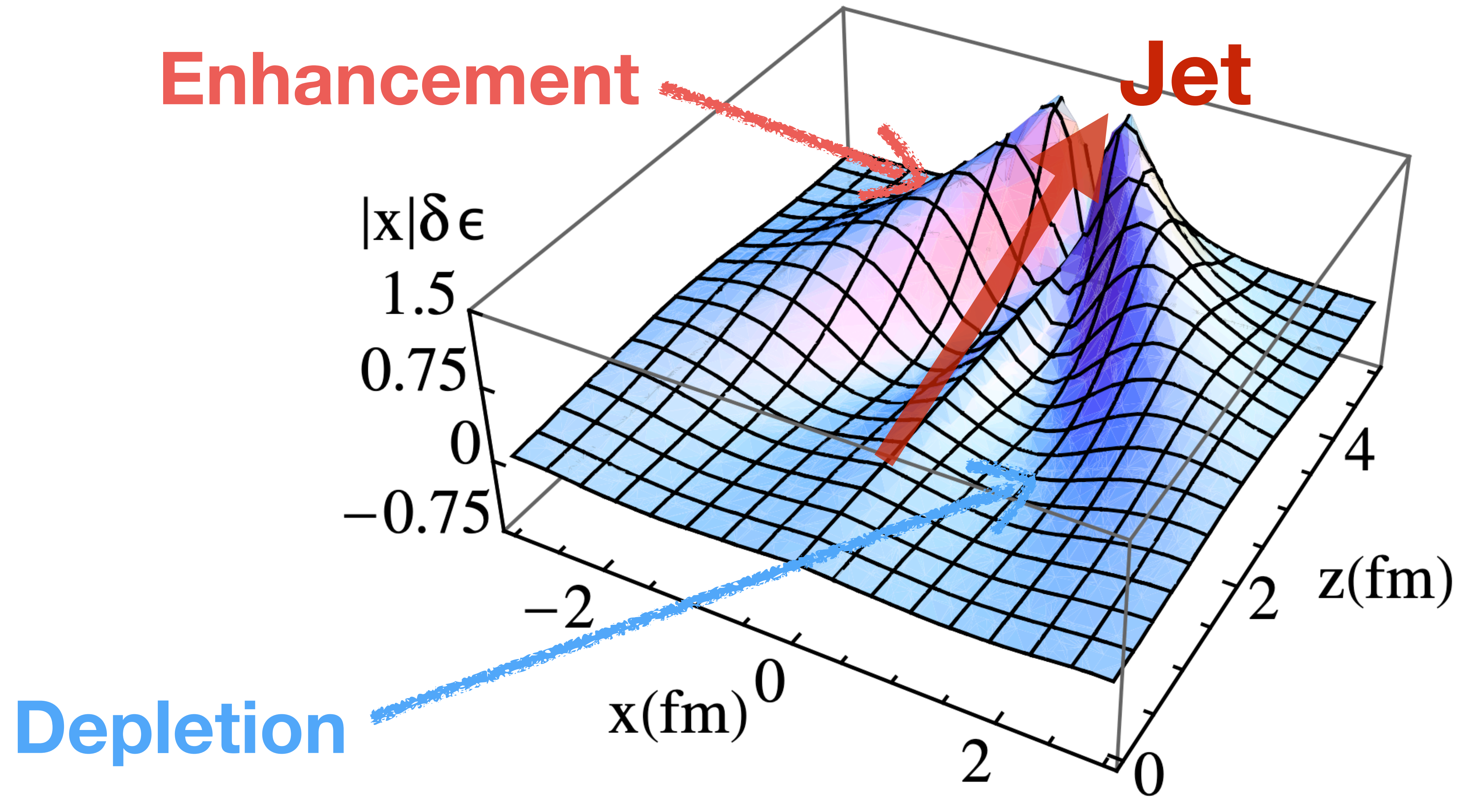
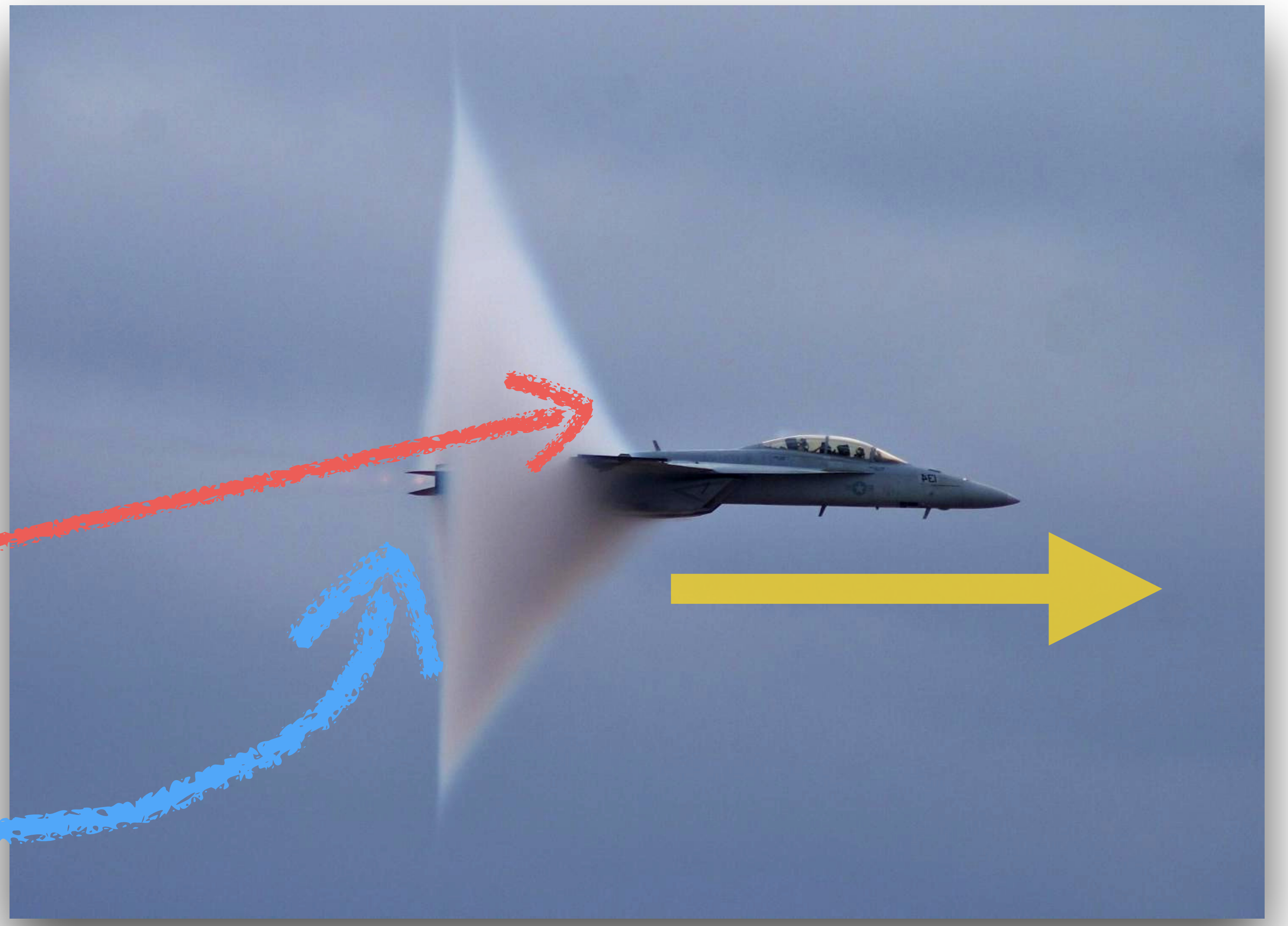


G.-Y. Qin et al, PRL 103, 152303 (2009)

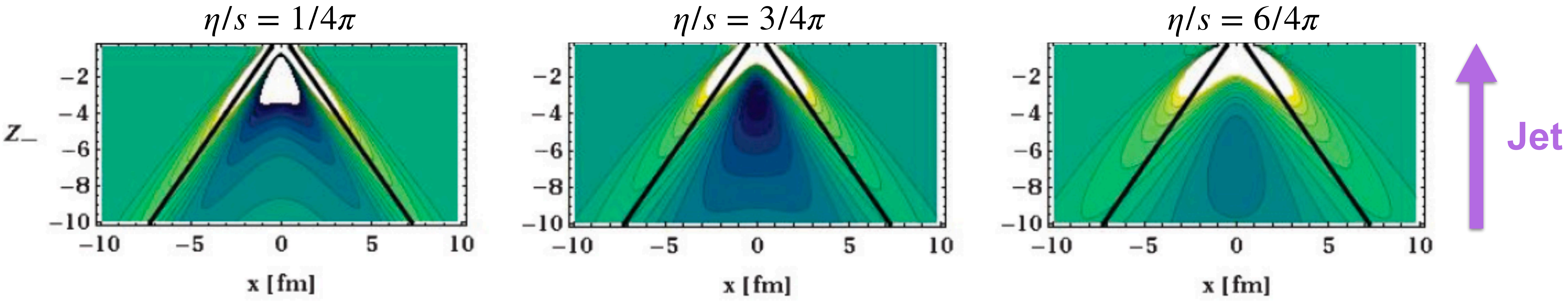


Why is medium response important to understand?

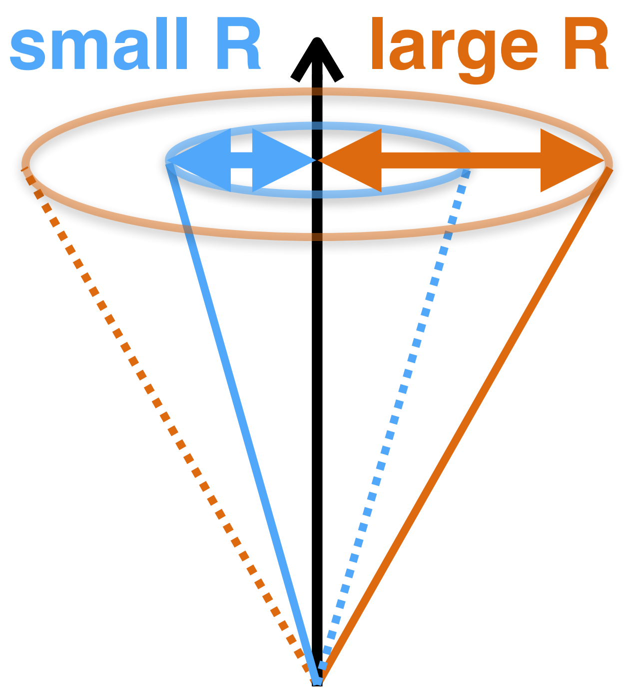
- Medium response changes the internal structure of jets
  e.g. jet shape, fragmentation function
  ➡ Essential to describe the jet (sub)structure precisely

- Medium excitation is directly related to the QGP properties
  ➡ e.g. η/s, jet transport coefficient, jet thermalization dynamics

R. B. Neufeld, PRC 79 (2009) 054909



Radius-dependent Jet R_{AA} at high-p_T

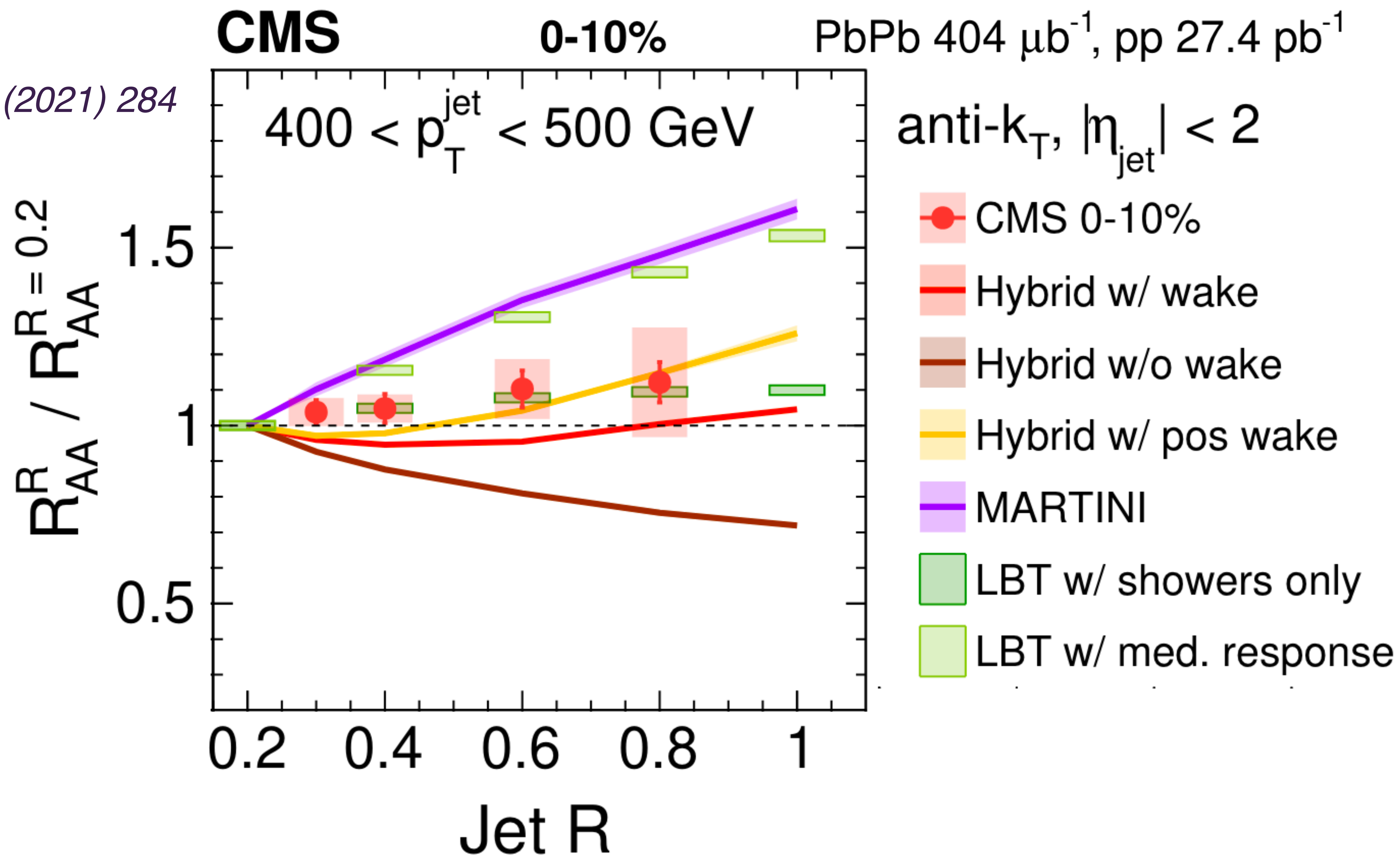


$R^{R}_{AA}/R^{R=0.2}_{AA}$

- ↑ medium response?
- ↑ recovery of out-of-cone soft radiation?
- ↓ larger suppression at large angle?

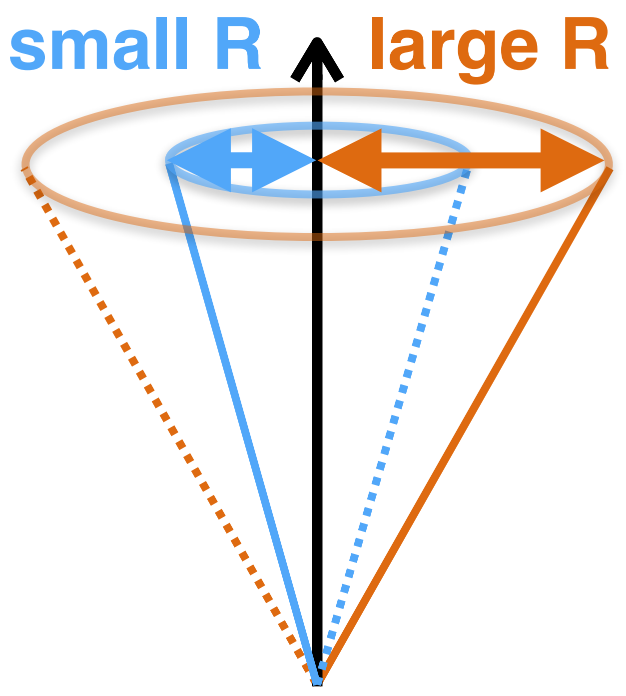
⋮

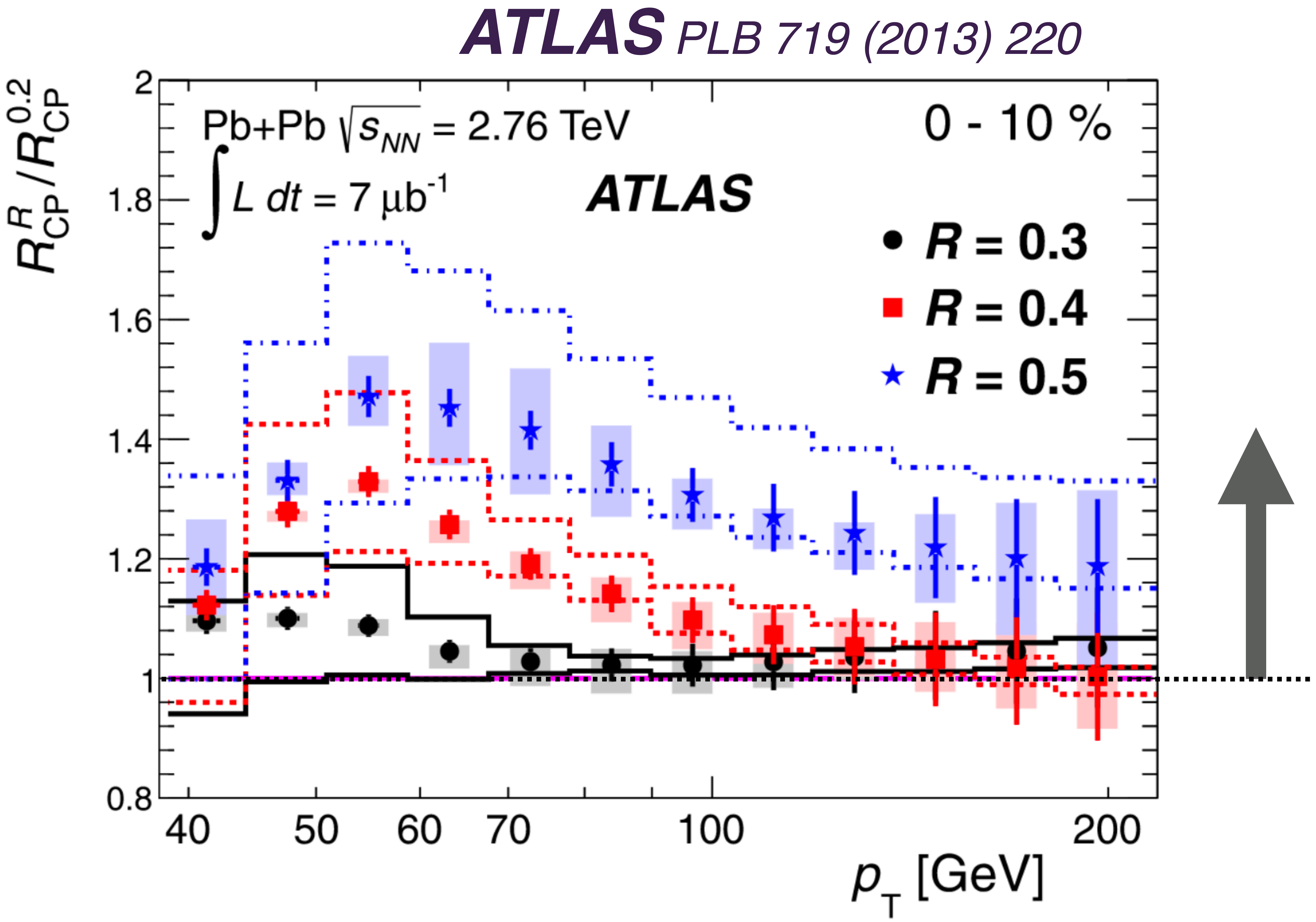
CMS *JHEP 05 (2021) 284*

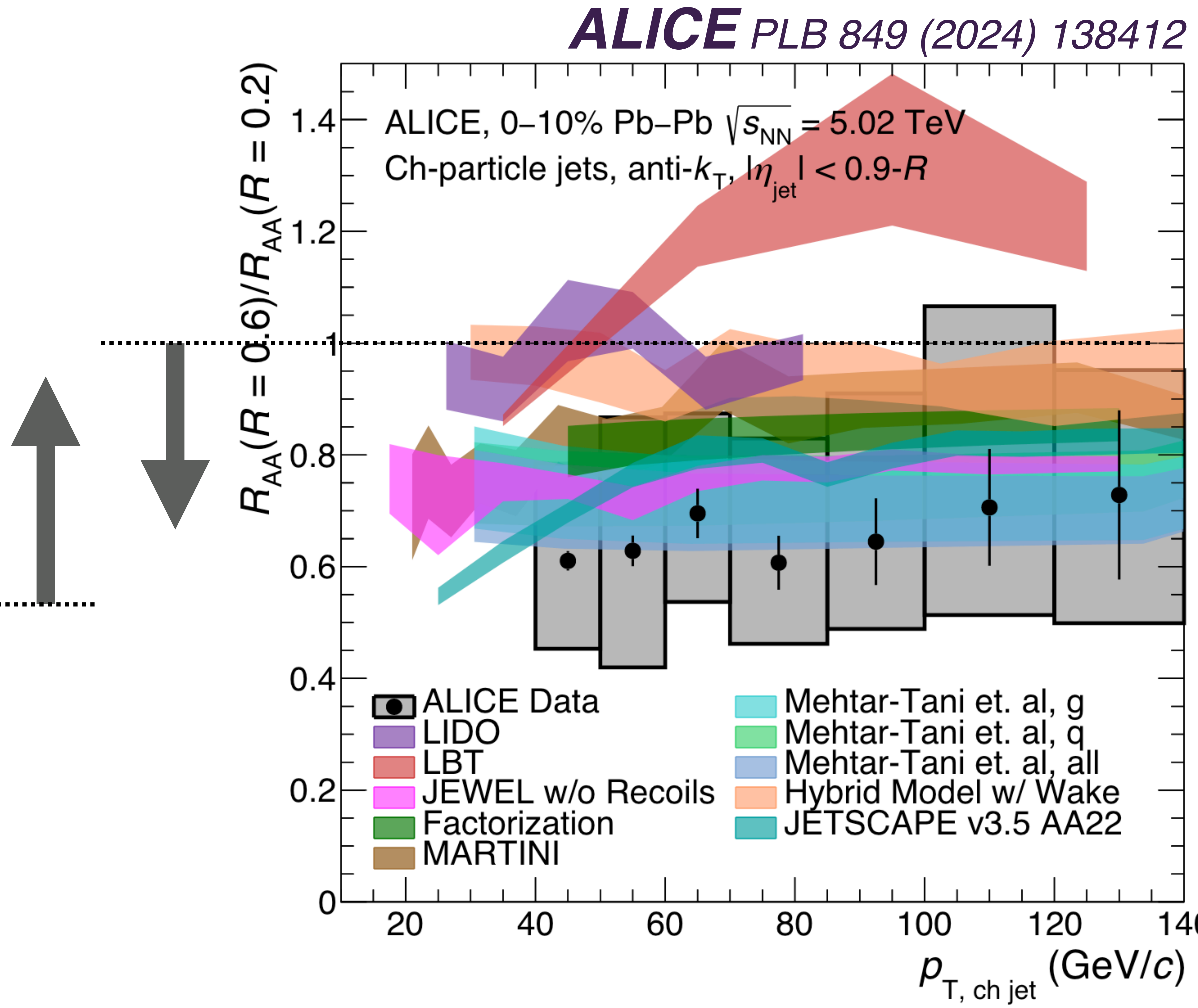


- At high jet p_T (400-500 GeV), relatively **small R-dependence** in data
- The trend between prediction w/ and w/o medium response for different models is the same; higher $R^{R}_{AA}/R^{R=0.2}_{AA}$ for models w/ medium response

Radius-dependent Jet R_{AA} at low-p_T

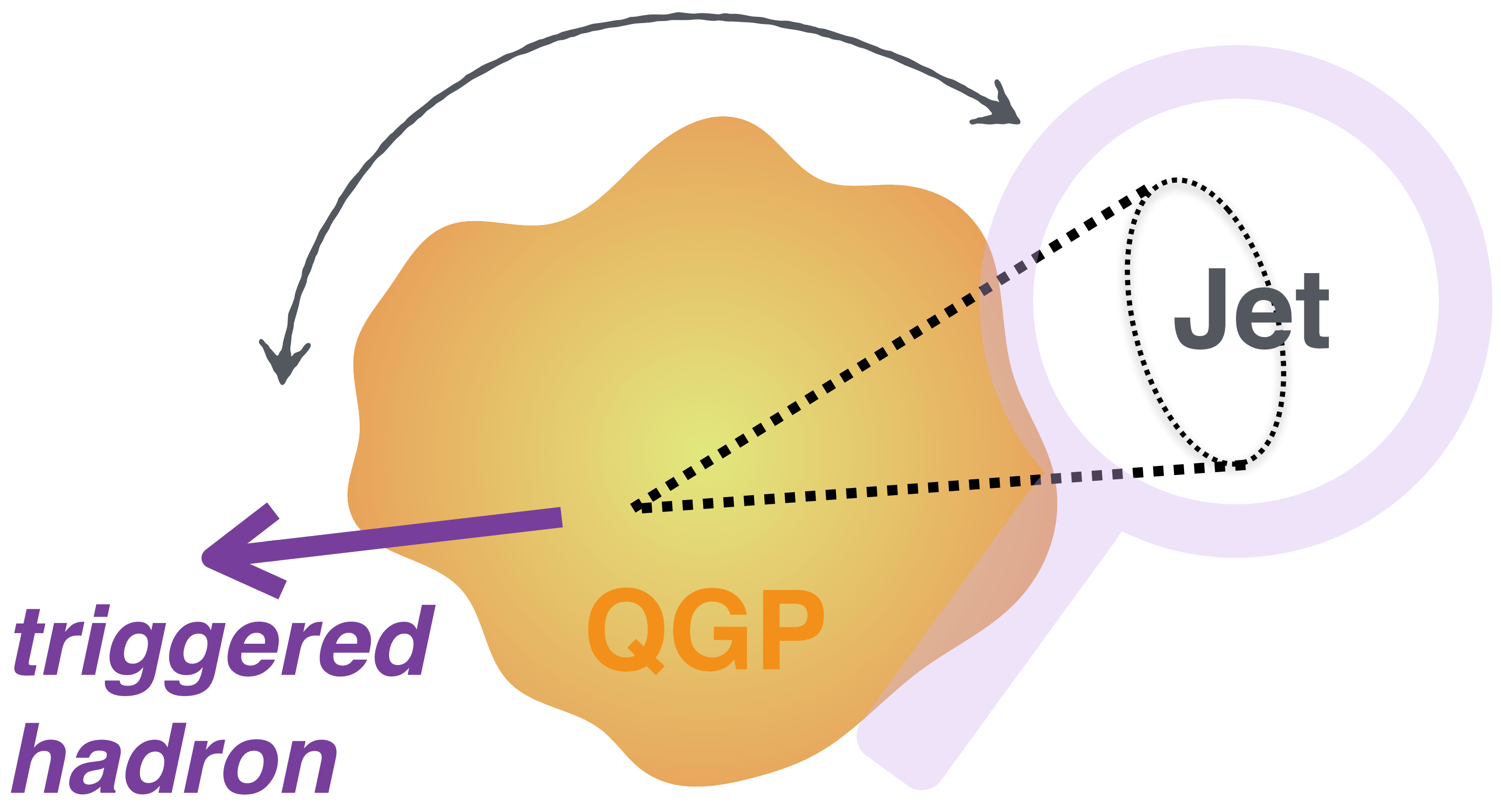






- **ATLAS** data shows R_{CP} (R=0.5) > R_{CP} (R=0.2)
- **ALICE** data shows R_{AA} (R=0.6) < R_{AA} (R=0.2)
- Tension between **ATLAS** and **ALICE**, but there are differences
  - full jet vs. charged-particle jet
  - η range → quark-jet fraction difference, p_T spectrum difference in pp

Hadron-triggered Jets: p_T dependence



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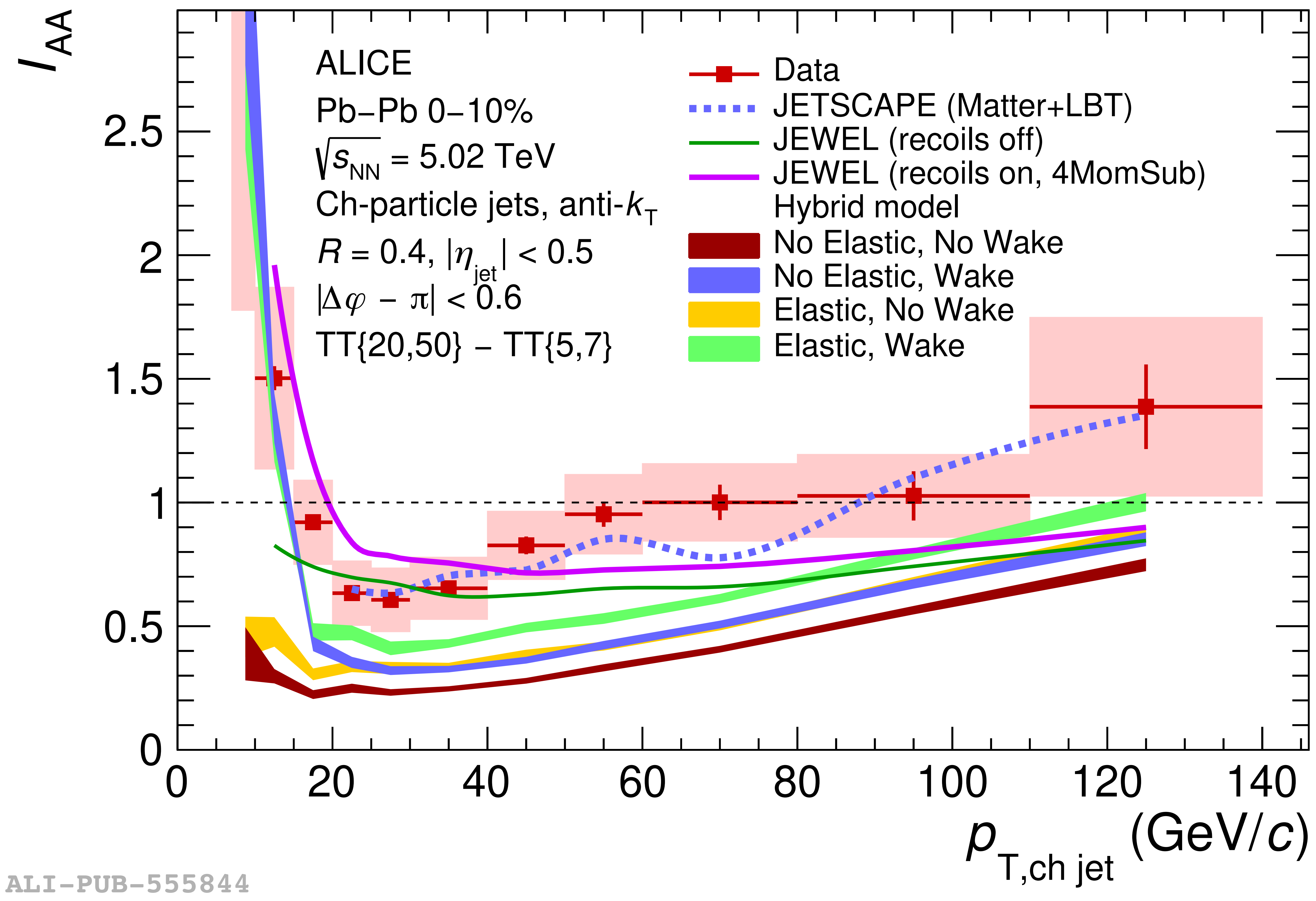
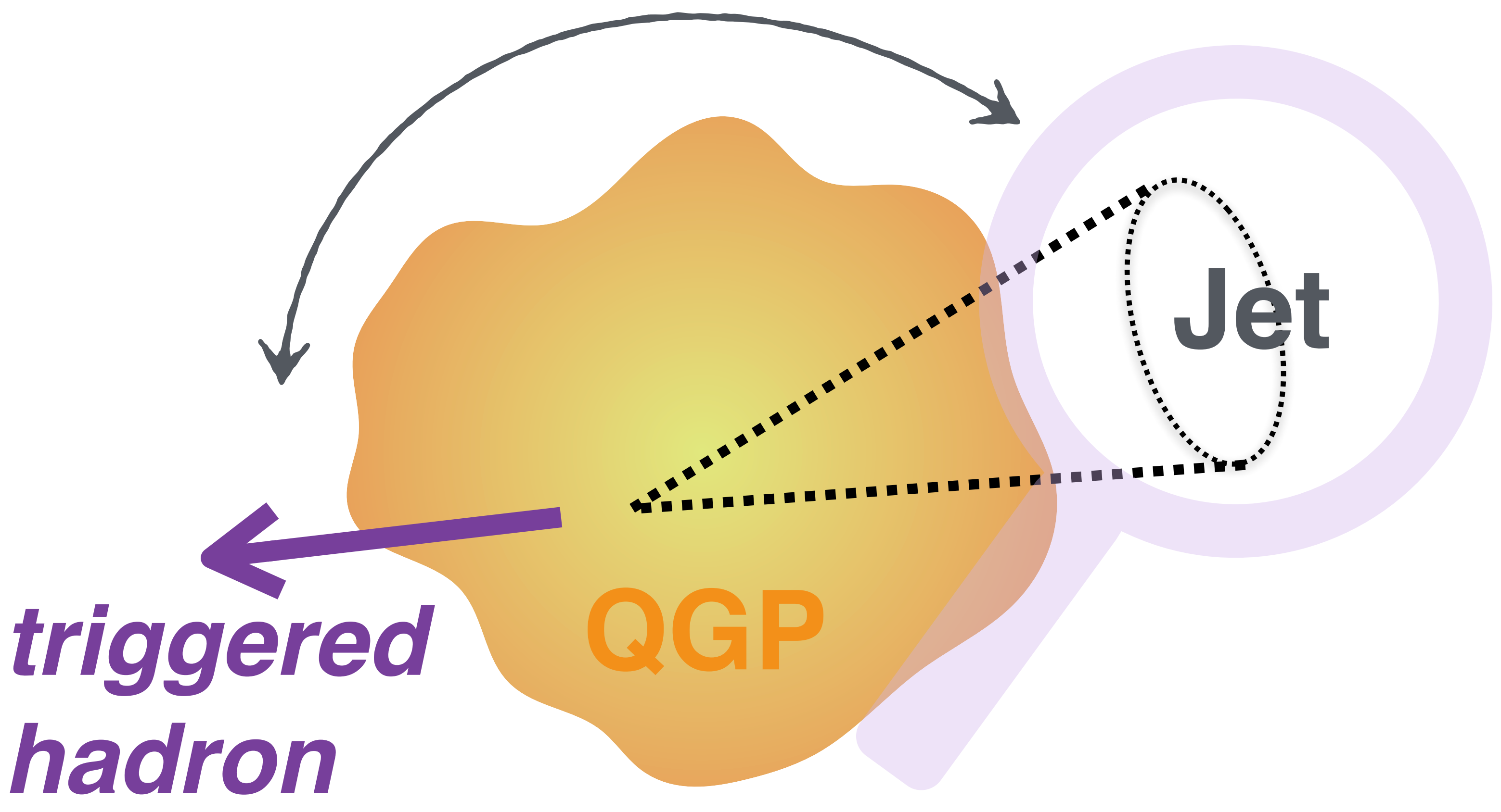


ALICE
arXiv:2308.16128
(accepted to PRC)

- **Low-p_T jet (10-20 GeV) enhancement**
  - ➡ significant difference between models w/ and w/o medium response
  - ➡ data described by models w/ medium response (**Hybrid w/ wake**, **JEWEL w/ recoil**)

Hadron-triggered Jets: p_T dependence

$\Delta\phi(\text{trig. hadron, jet}) > \pi - 0.6$



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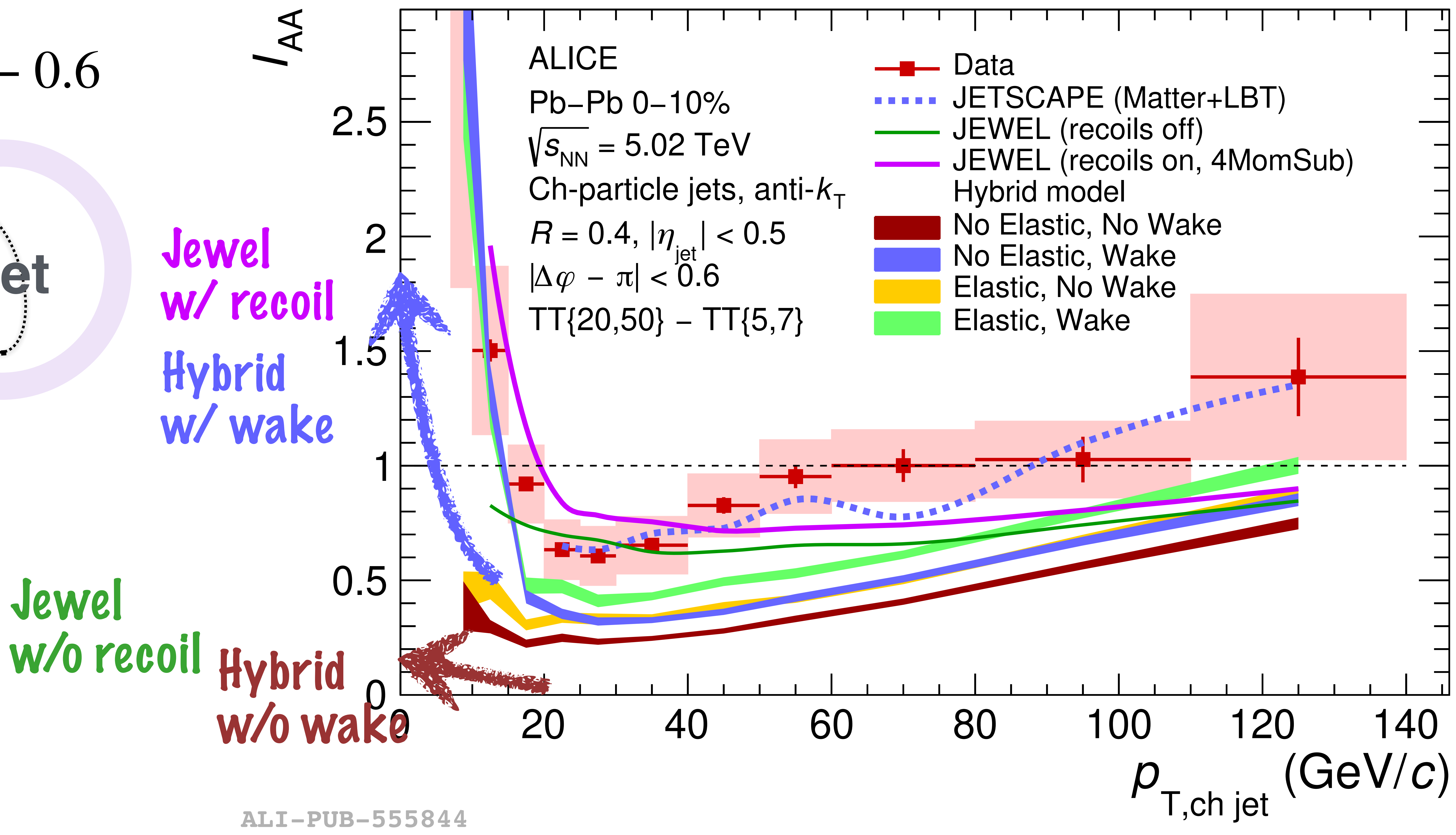

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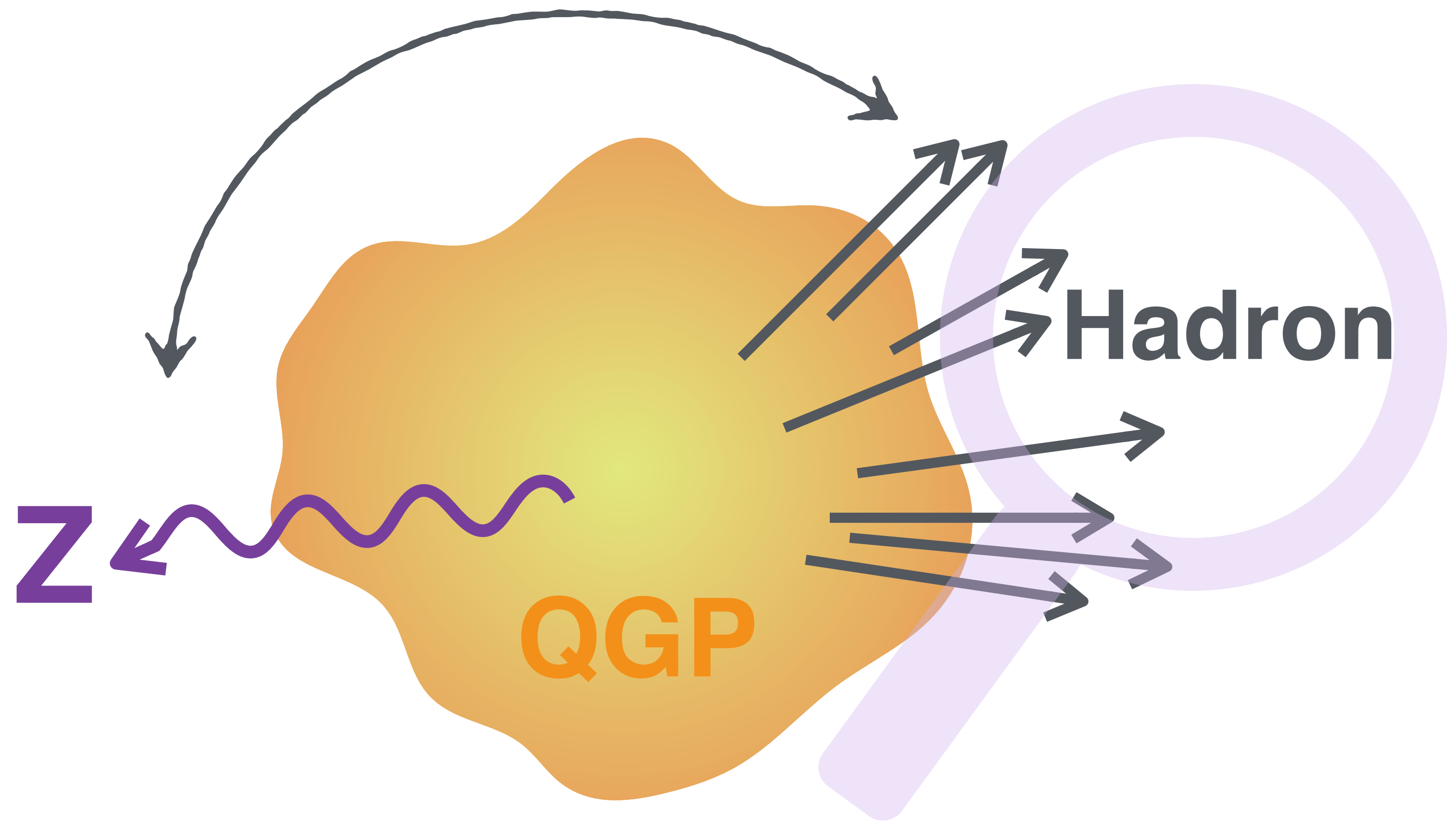
Z-triggered Hadrons: p_T dependence

$\Delta\phi(Z, \text{hadron}) > 3\pi/4$ or $7\pi/8$



$$I_{AA} = \frac{Y^{\text{hadron}}_{\text{Pb+Pb}} / N^{Z}_{\text{Pb+Pb}}}{Y^{\text{hadron}}_{pp} / N^{Z}_{pp}}$$

- Access to initial hard-scattering using electroweak bosons, e.g. Z

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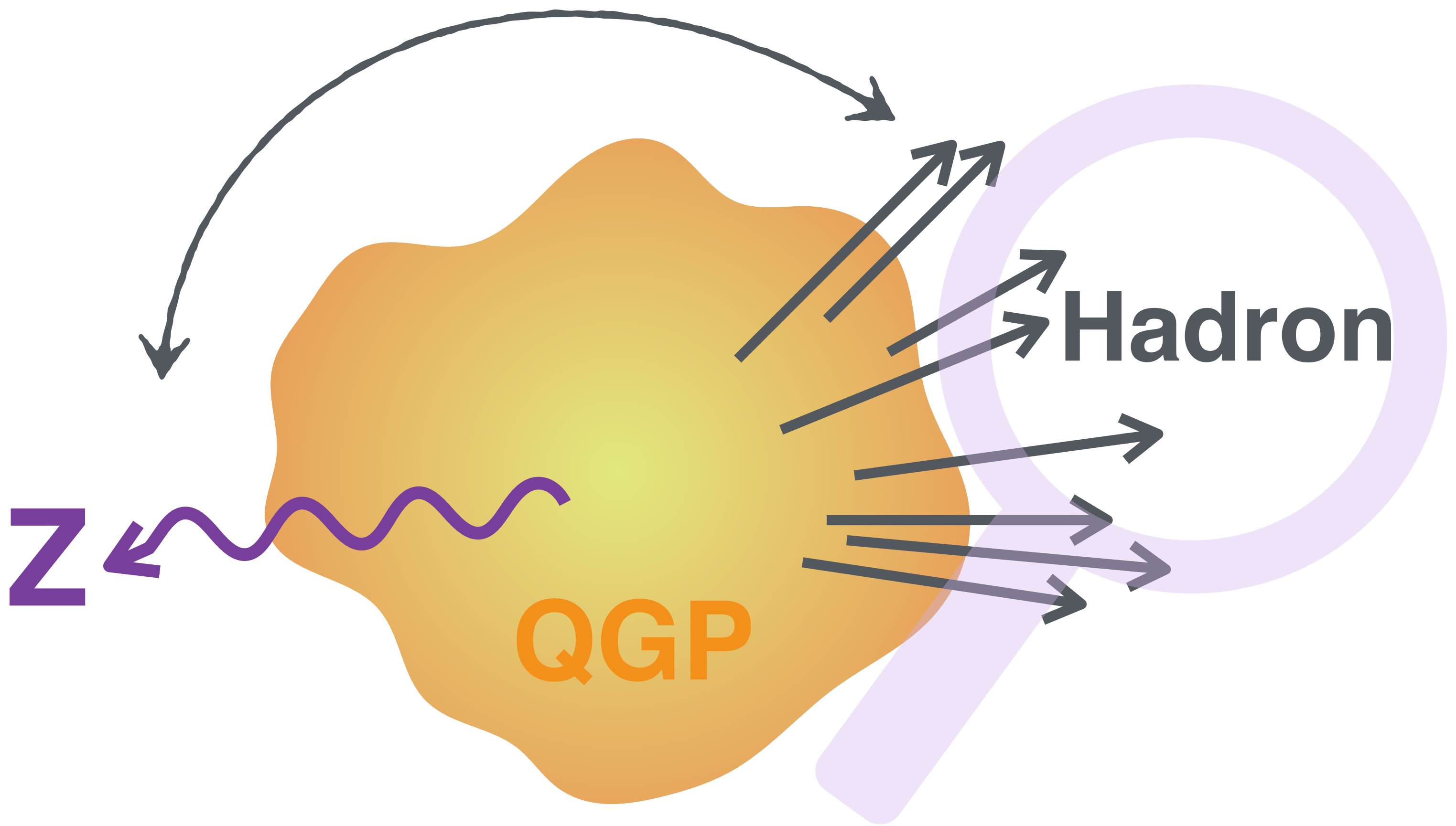

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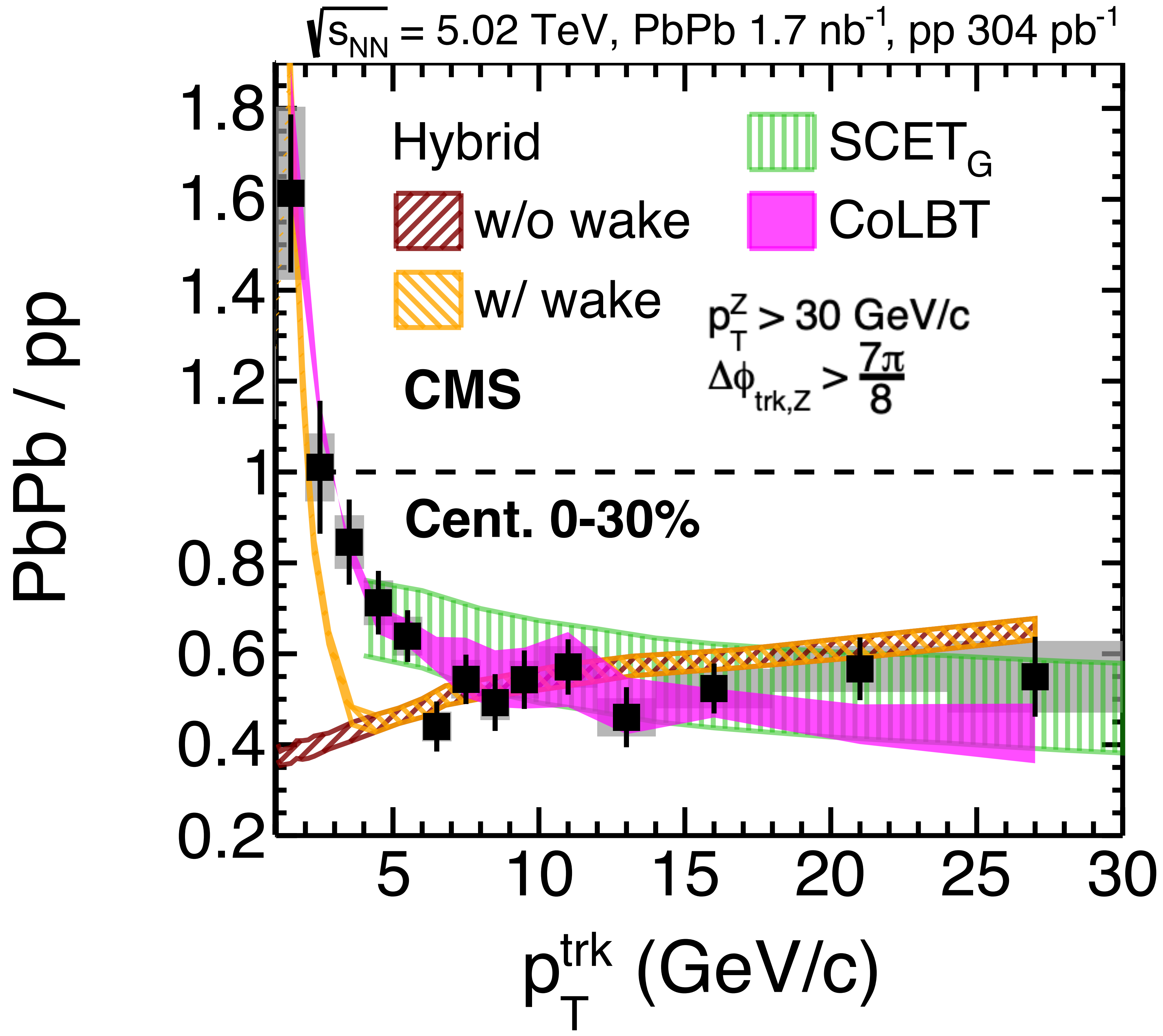
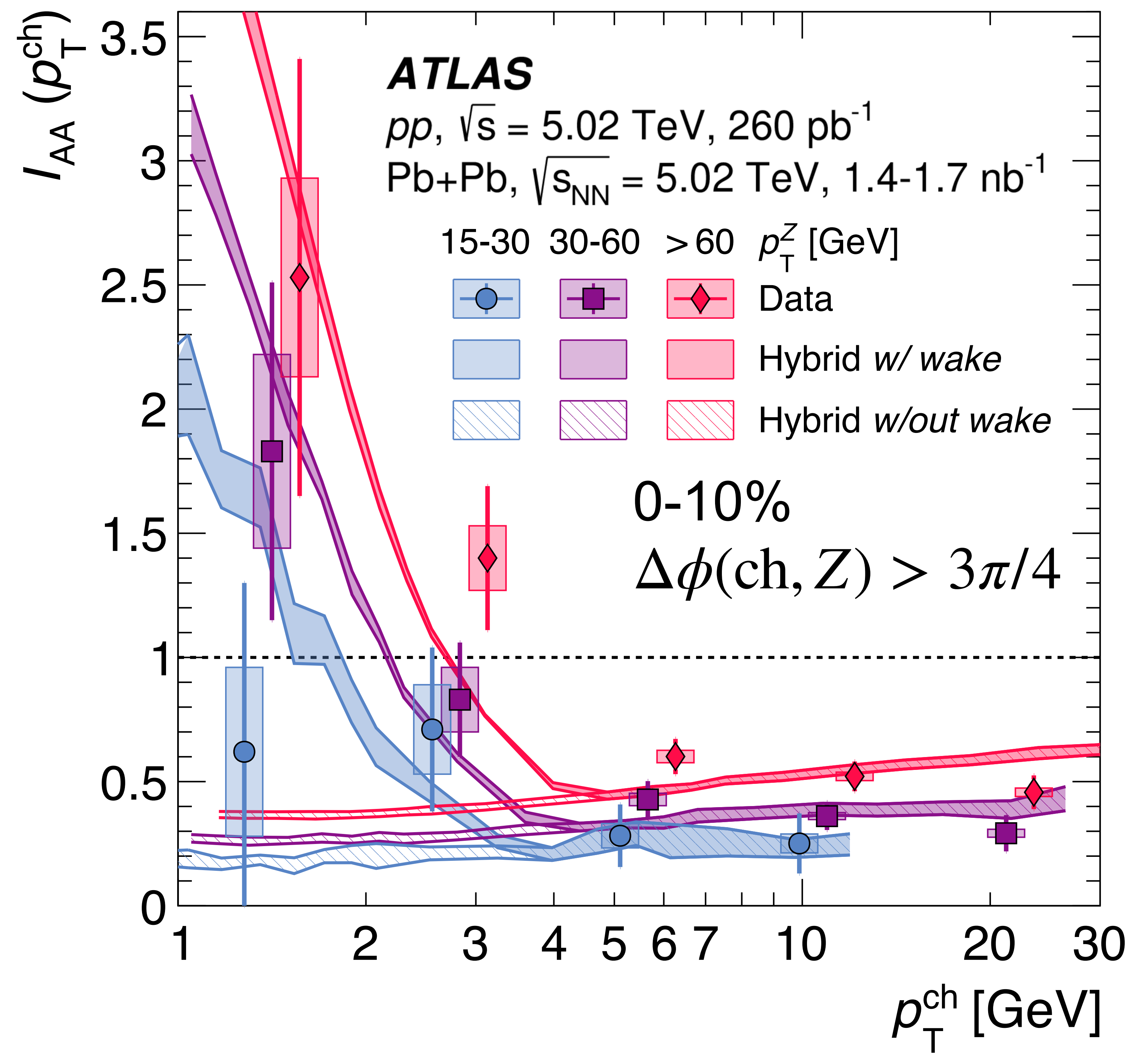
CMS *PRL 128 (2022) 122301*



ATLAS *PRL 126 (2021) 072301*



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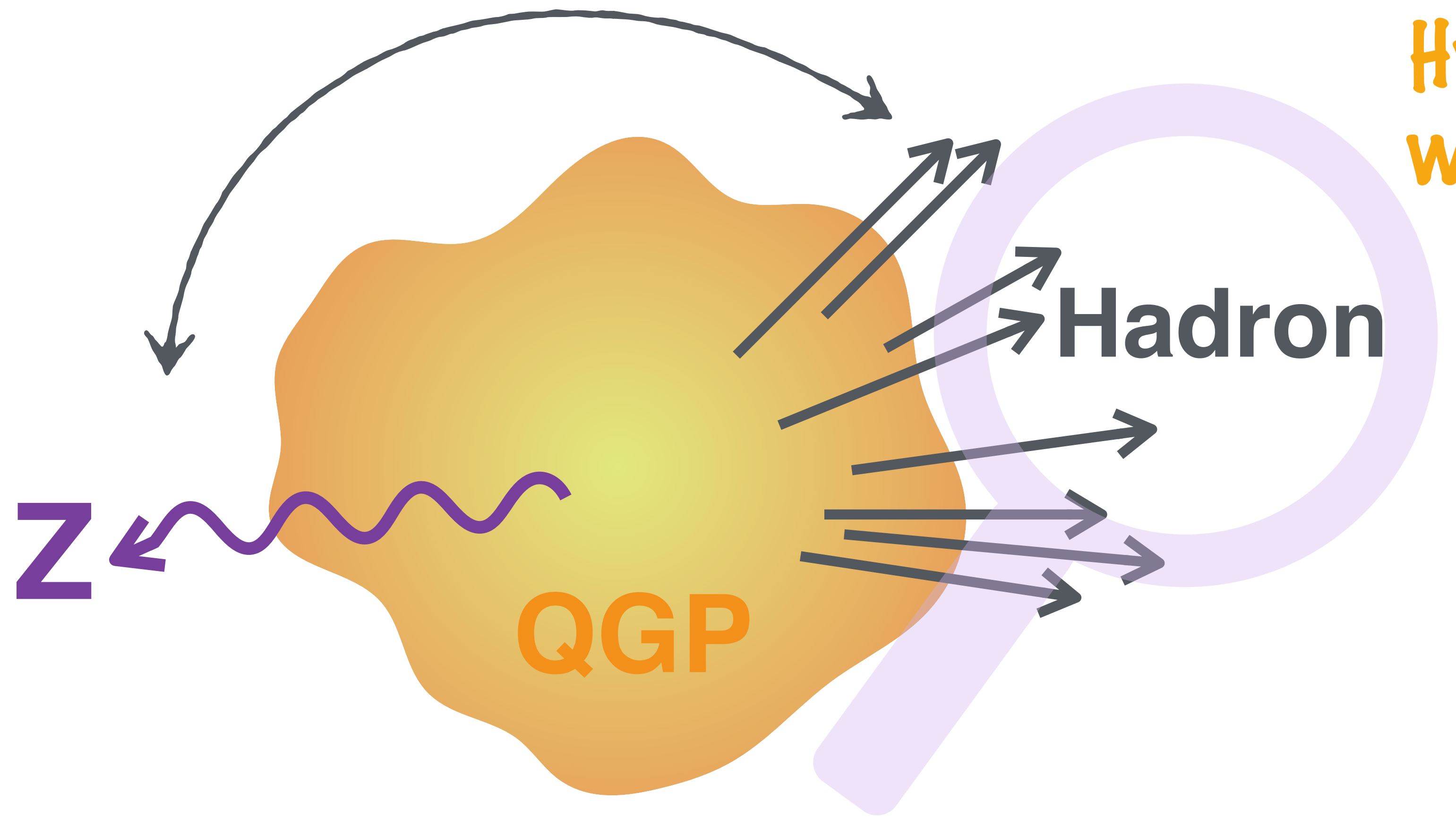

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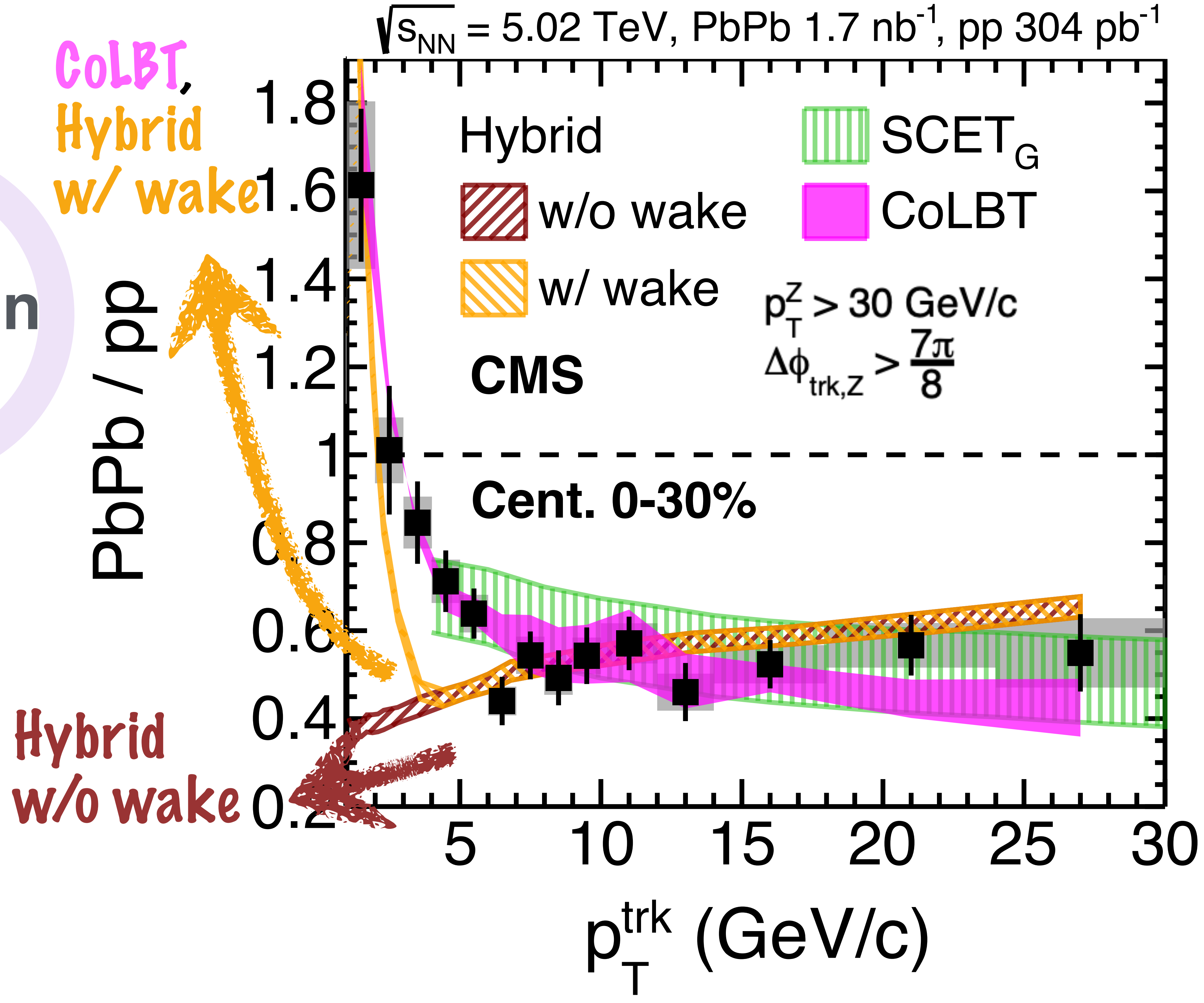
CMS *PRL 128 (2022) 122301*



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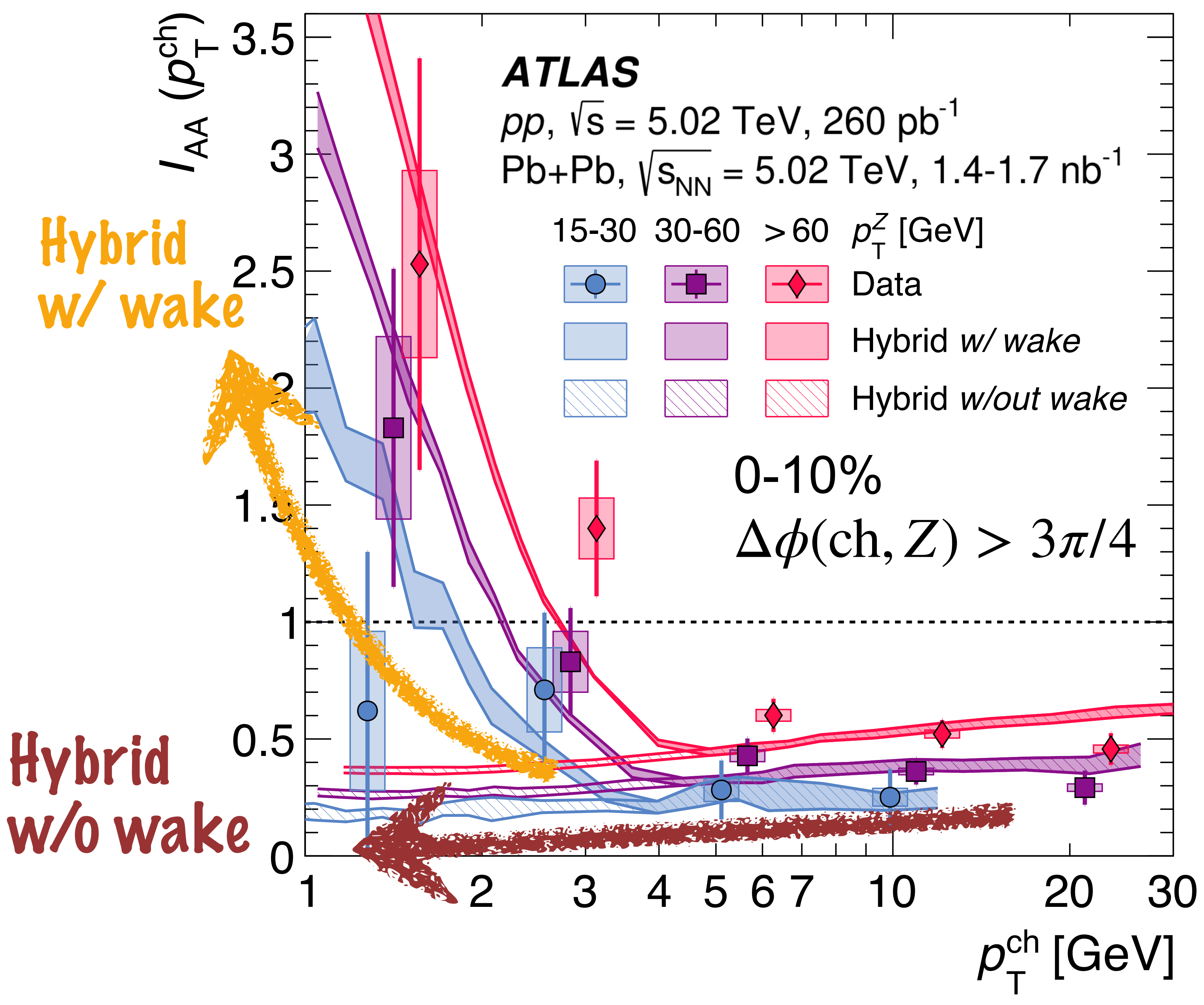
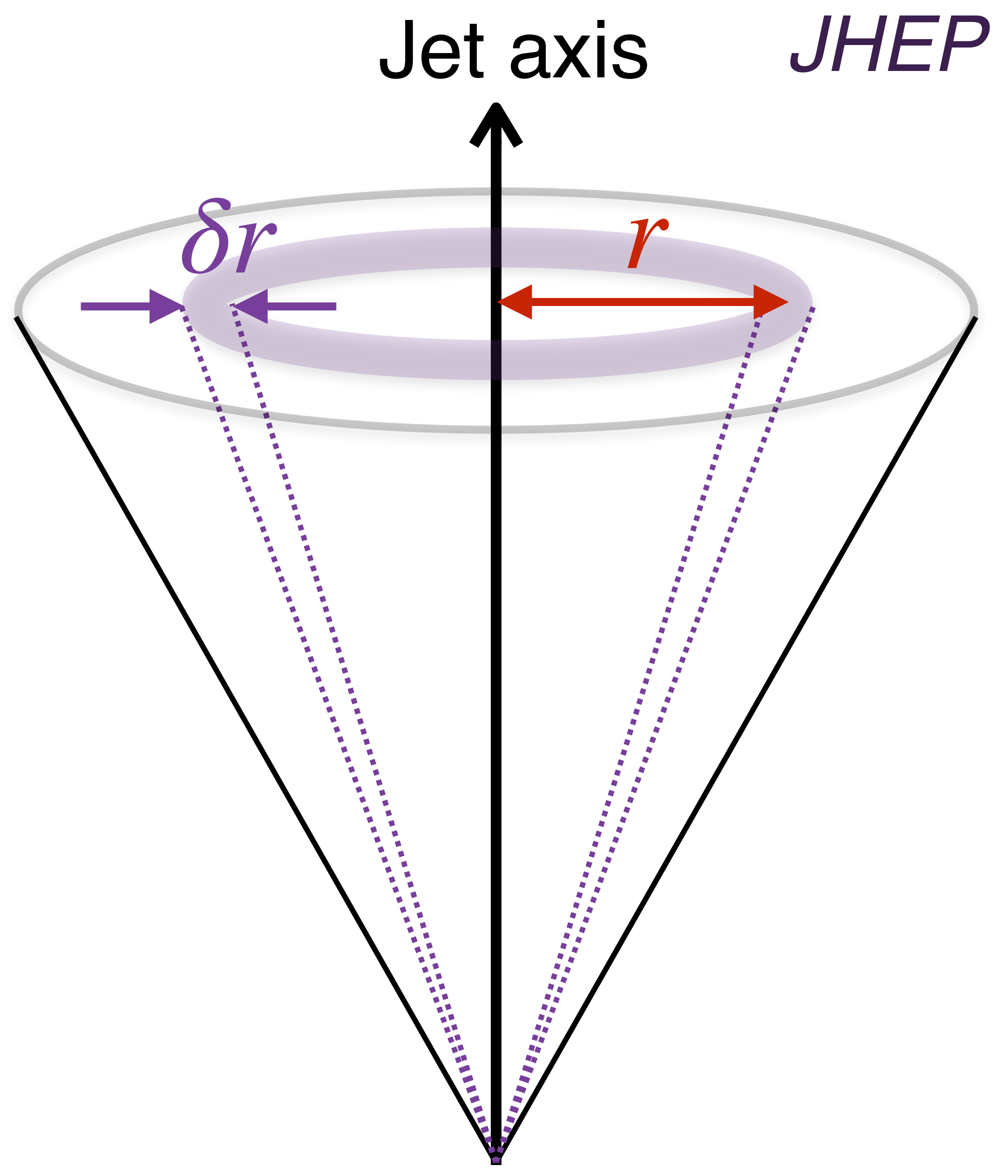
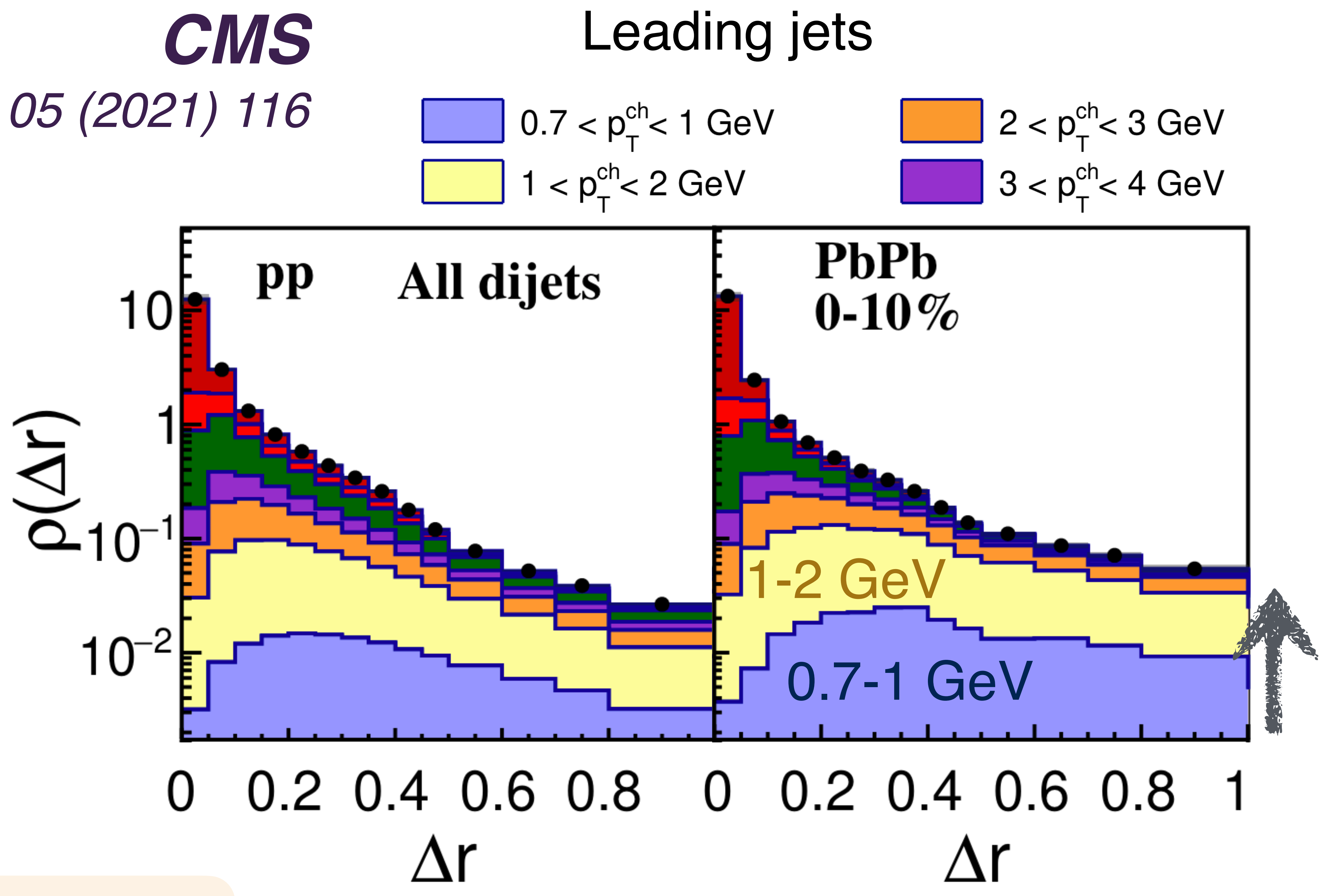


- Access to initial hard-scattering using electroweak bosons, e.g. Z
- **Low-p_T hadron enhancement**
  - ➡ models w/ medium response (**Hybrid w/ wake** and **CoLBT**) describe the data better

Jet Shape: Angular Distribution





$$\rho_{\mathrm{jet}}(r) = \frac{1}{N_{\mathrm{jet}}} \sum_{\mathrm{jet}} \left[\frac{1}{p_{\mathrm{T}}^{\mathrm{jet}}} \frac{\sum_{\mathrm{trk}\in(r-\delta r/2,\, r+\delta r/2)} p_{\mathrm{T}}^{\mathrm{trk}}}{\delta r} \right]$$

- Jet shapes have been measured for leading jets of dijets for different x_j
- At *large* angle, ***enhancement of low p_T particles at larger angles***

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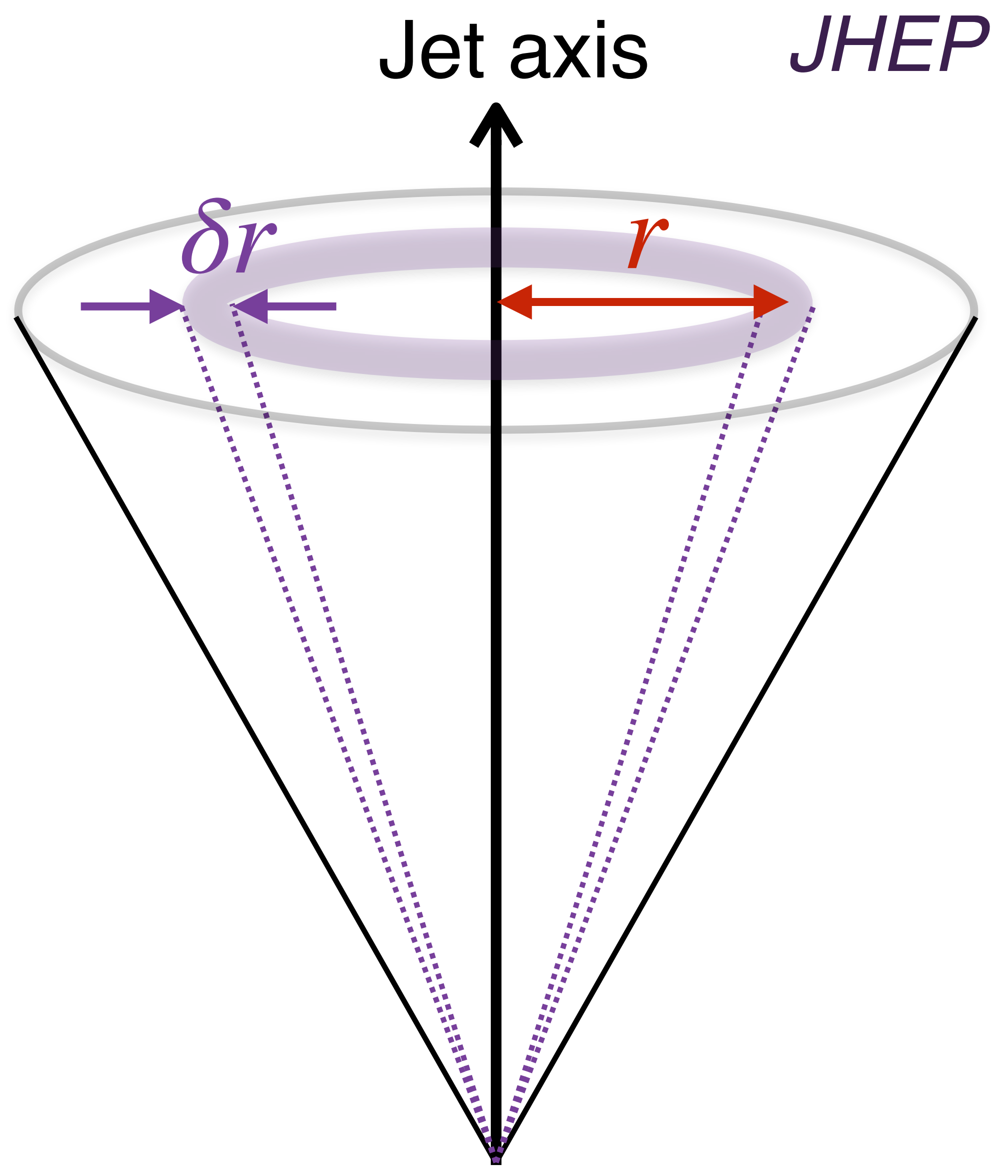

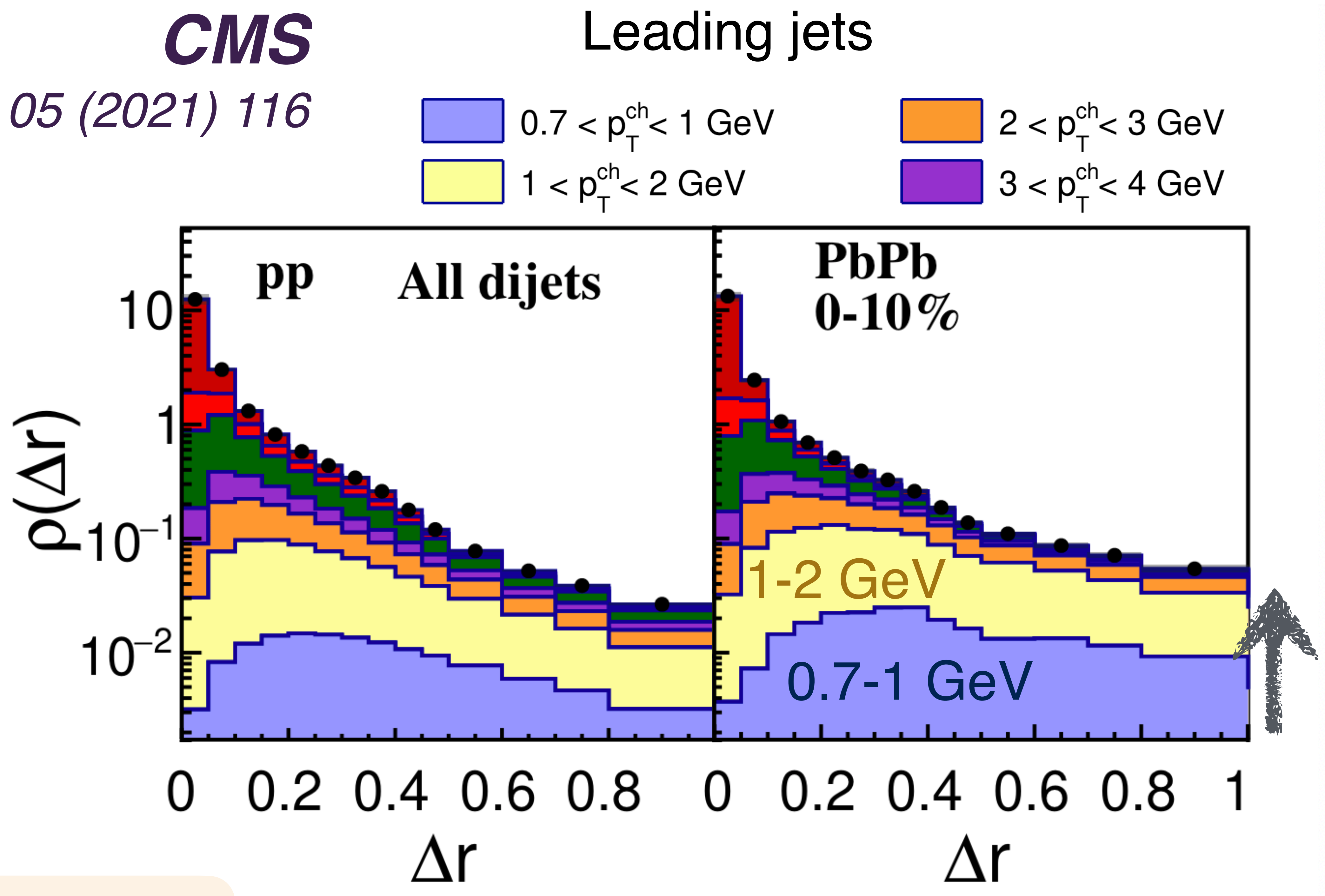

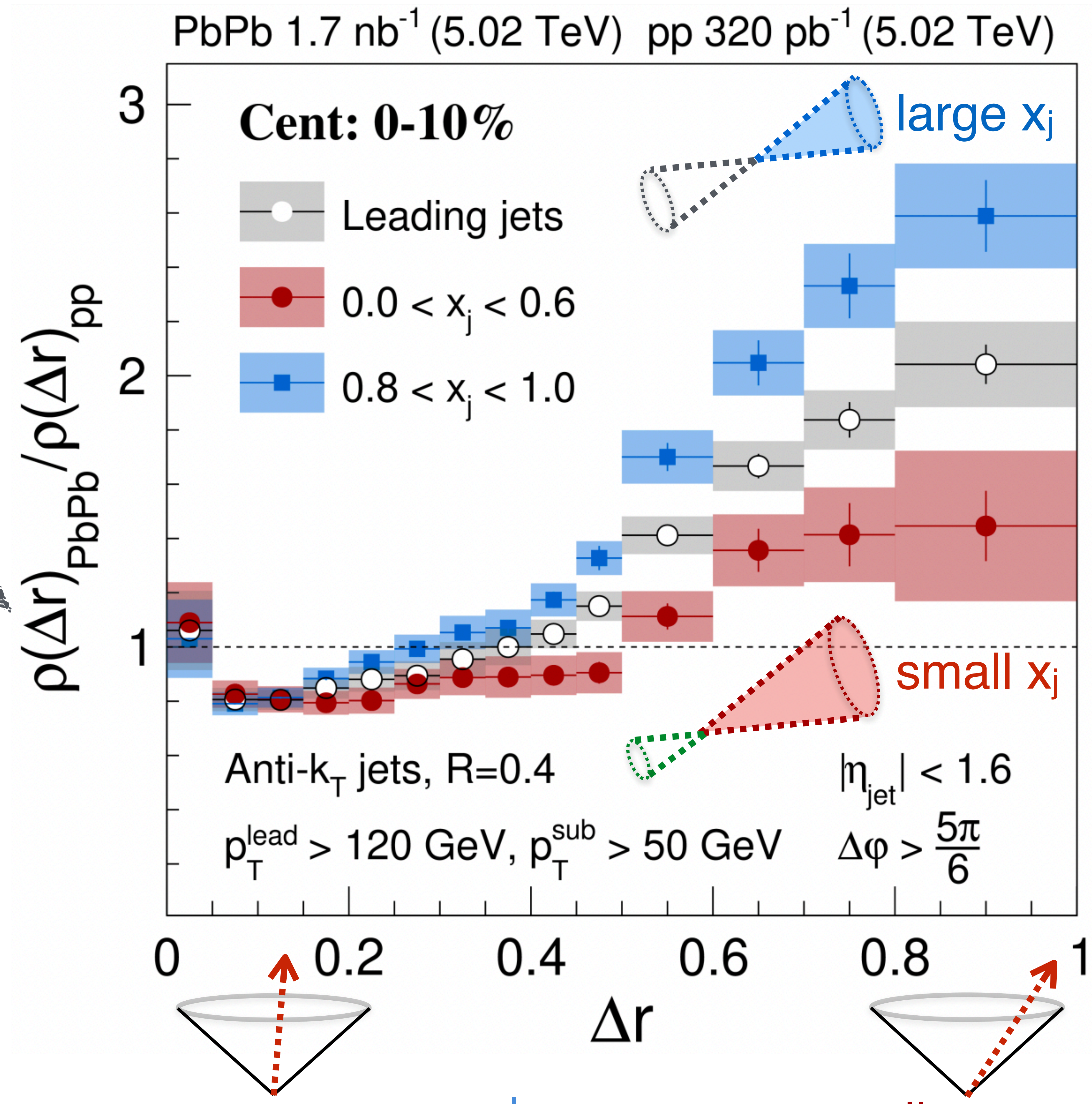

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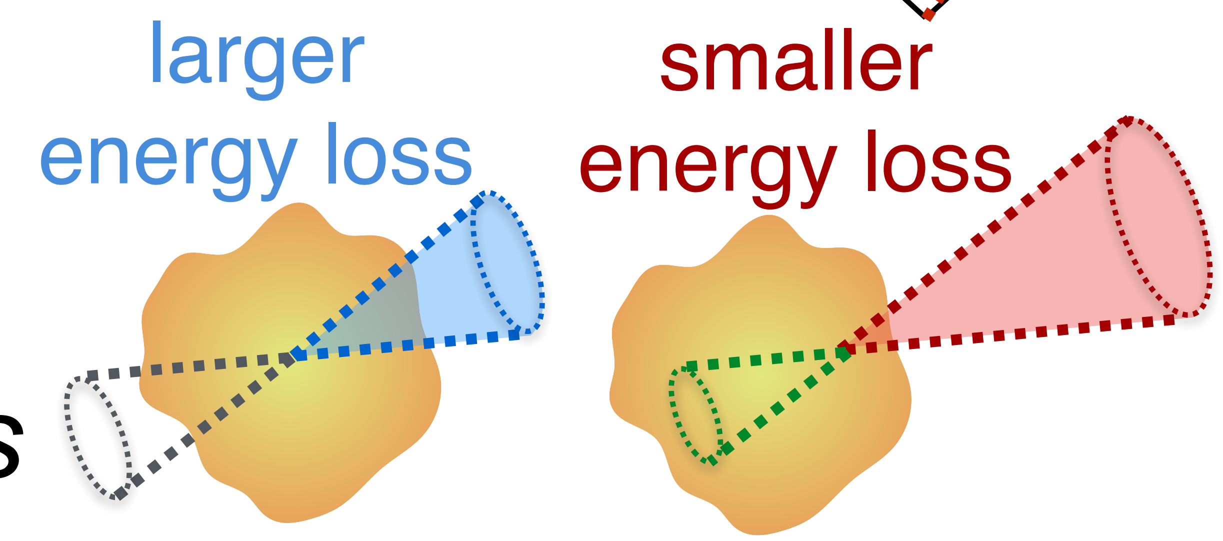

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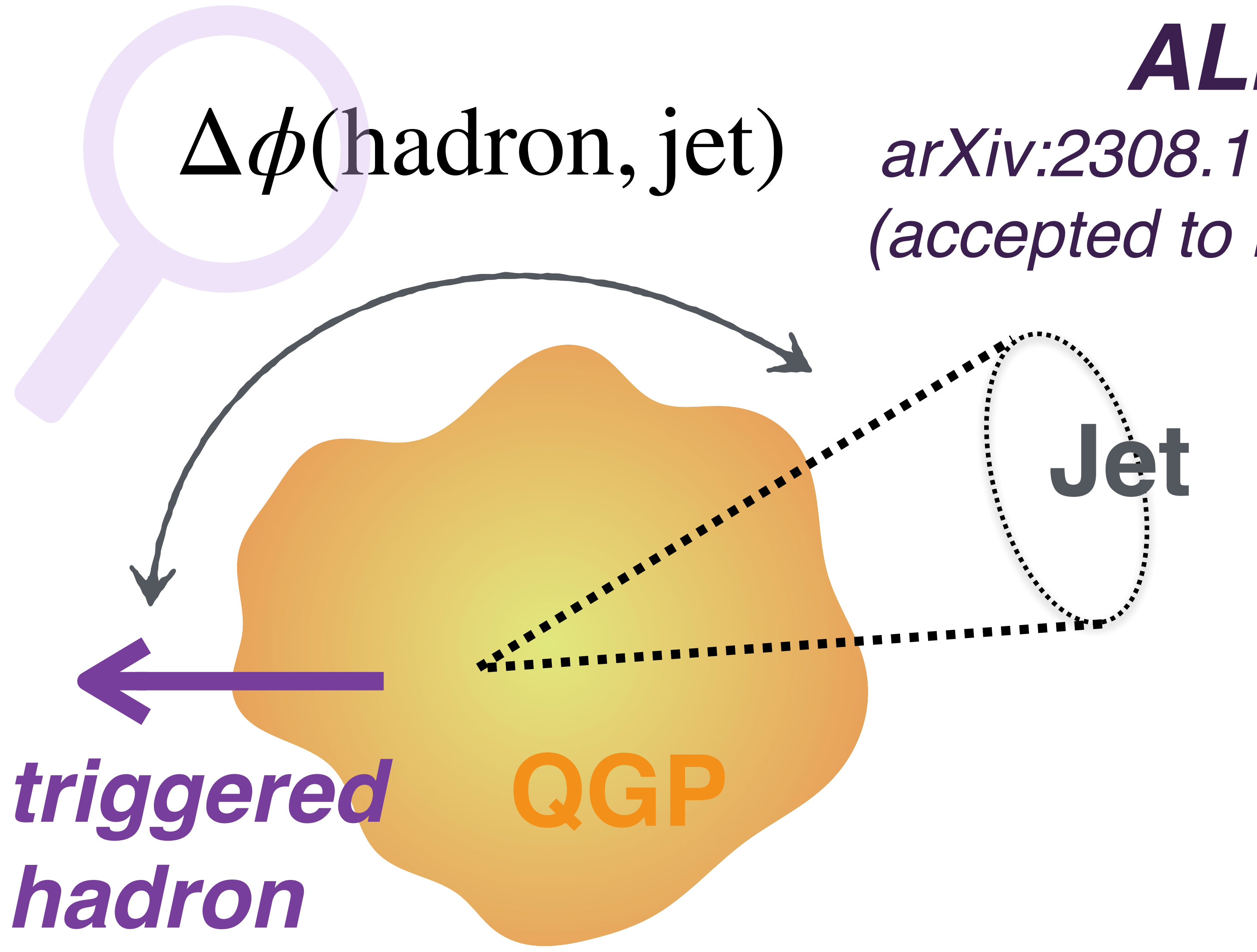
➡ *larger modification for more quenched jets i.e. unbalanced leading jets*

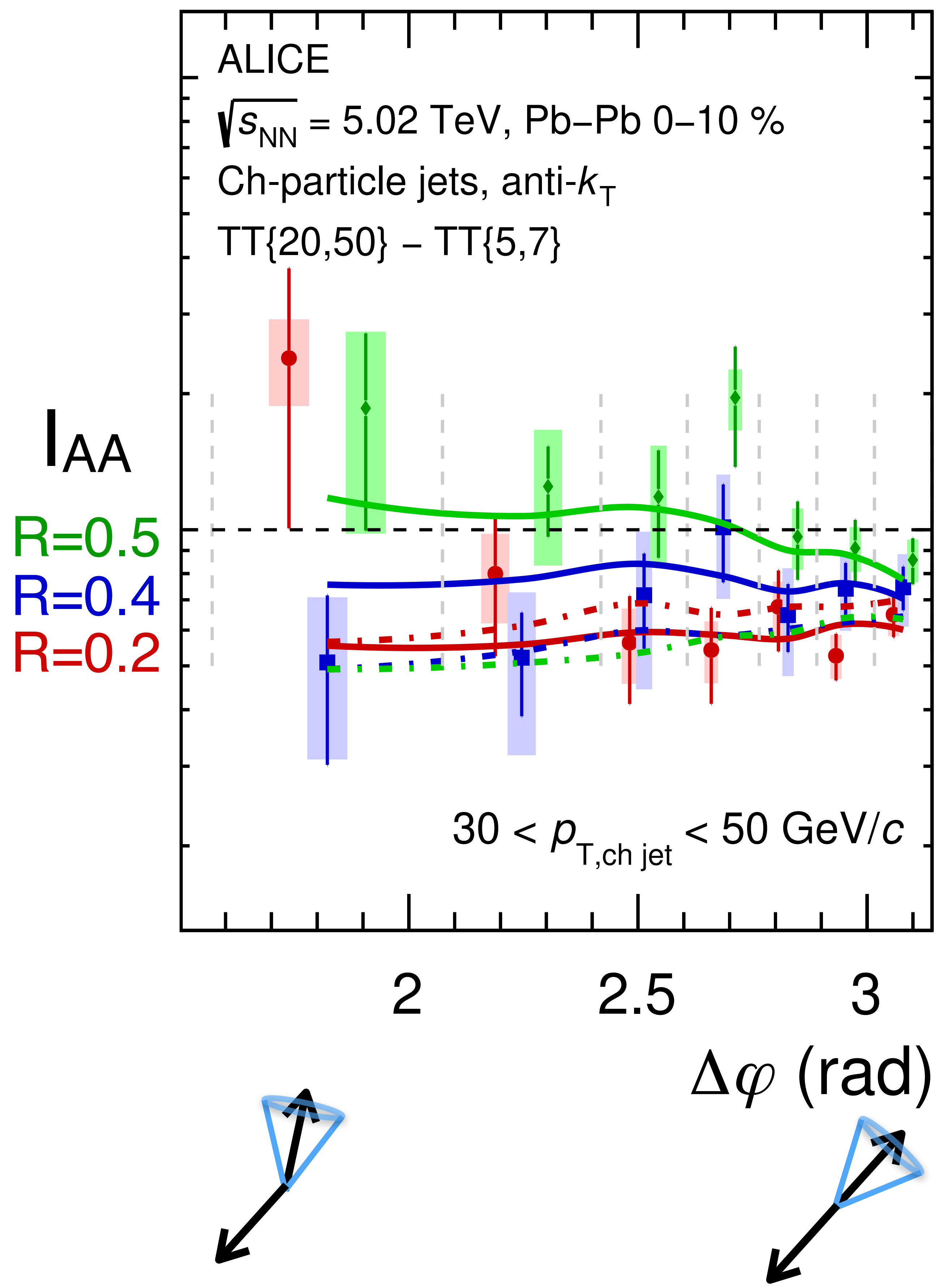
Hadron-Jet Angular Correlation



ALICE
arXiv:2308.16131
(accepted to PRL)

$$I_{AA} = \frac{Y^{\text{hadron}}_{\text{Pb+Pb}} / N^{\text{trig}}_{\text{Pb+Pb}}}{Y^{\text{hadron}}_{pp} / N^{\text{trig}}_{pp}}$$

$30 < p_T^{\text{jet}} < 50$ GeV



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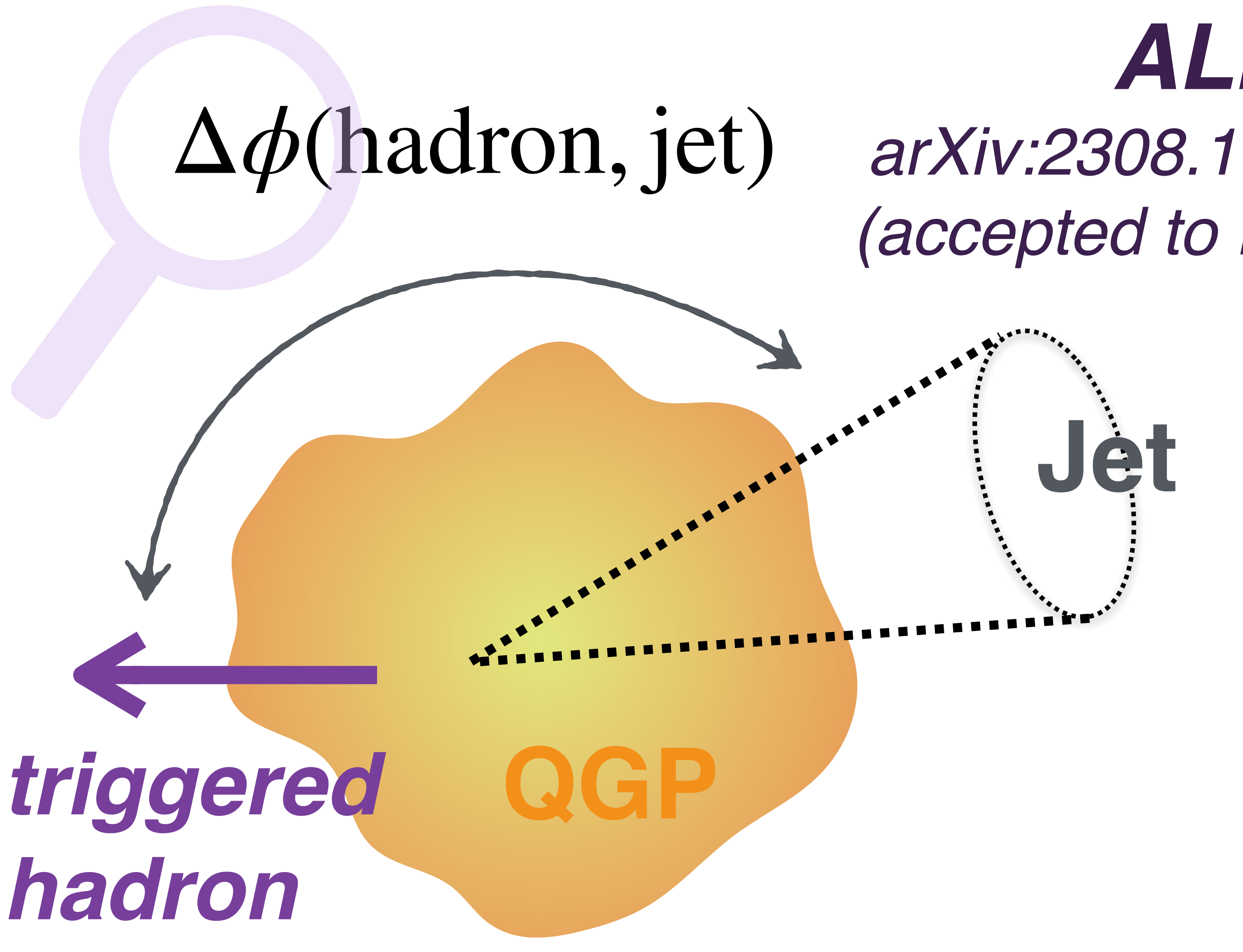

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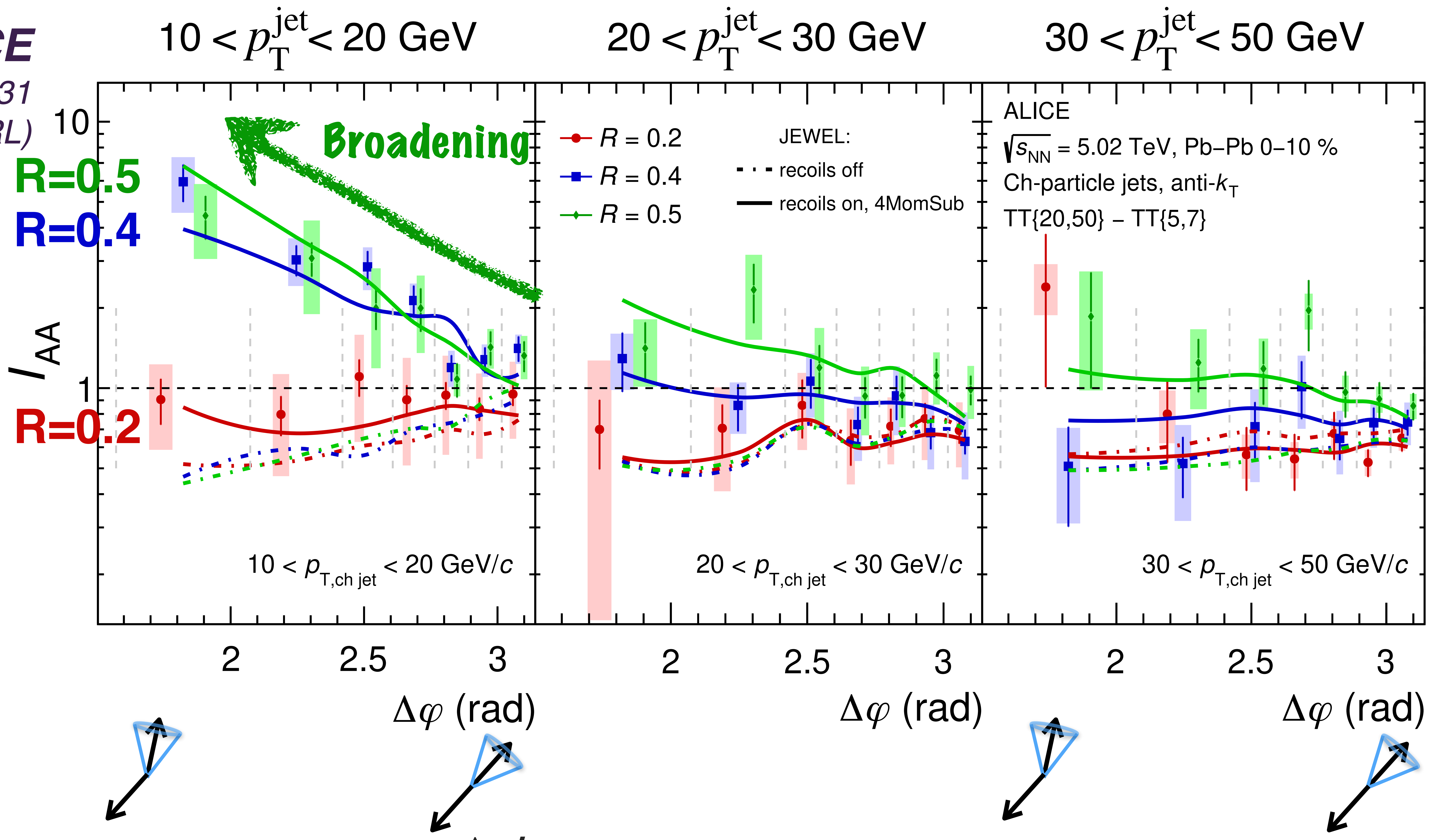

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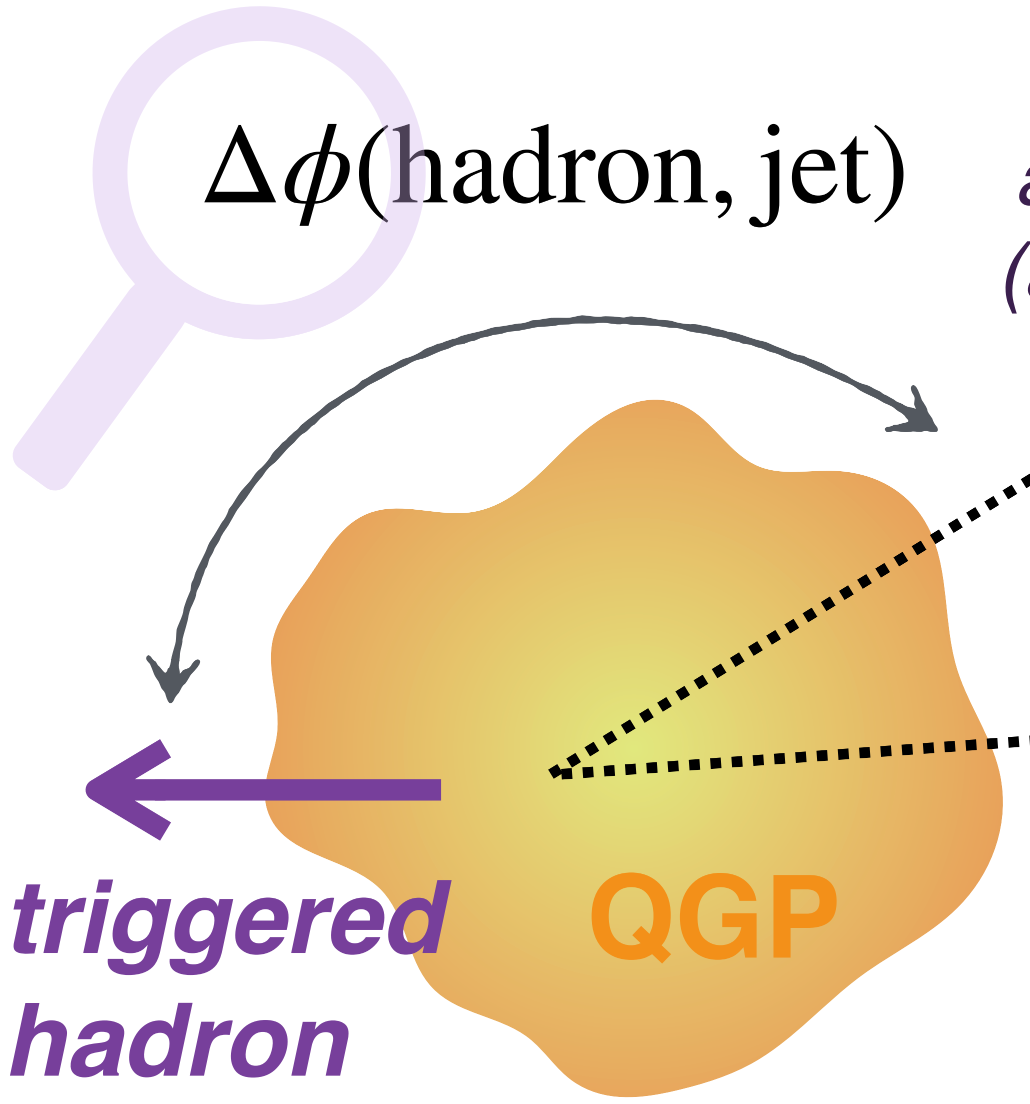

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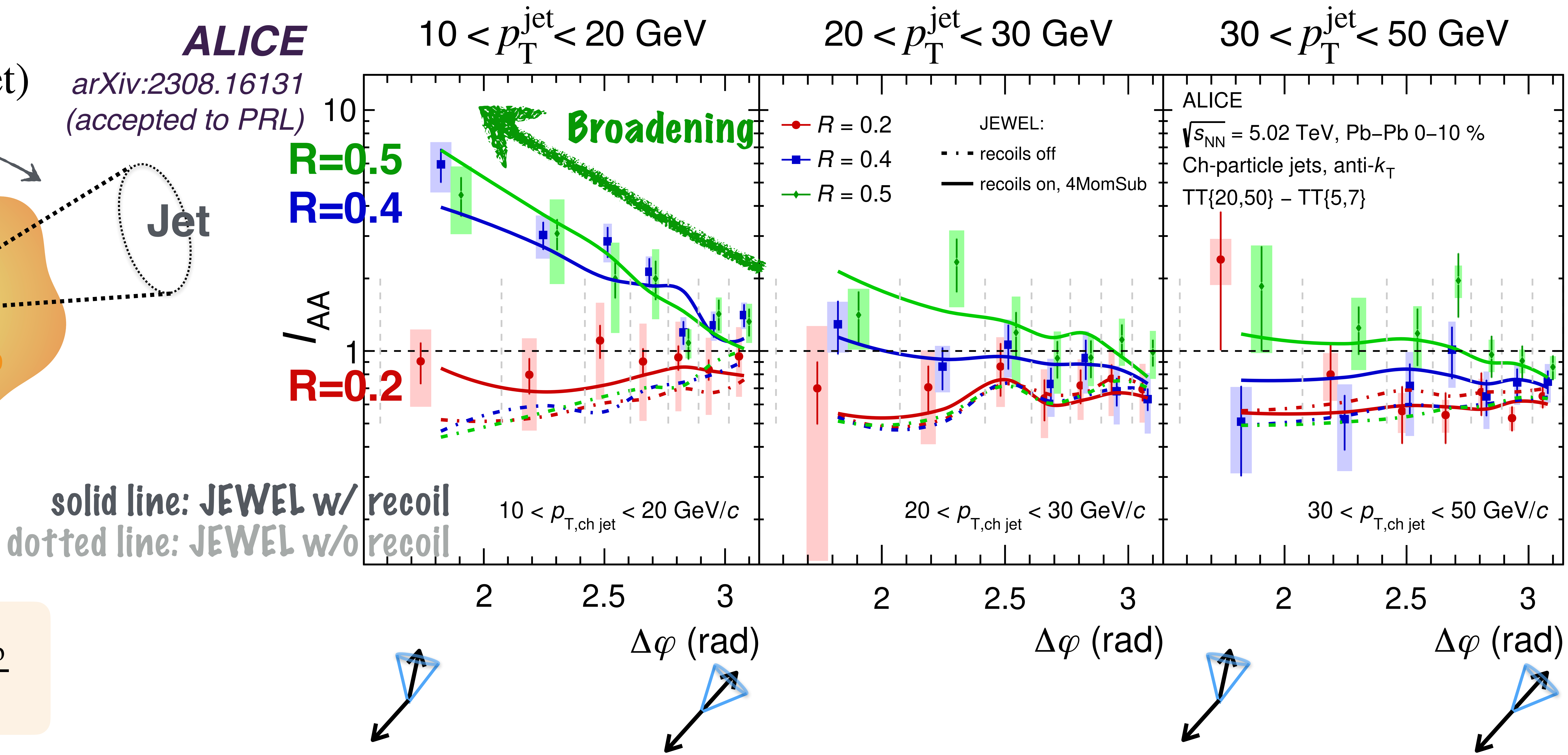

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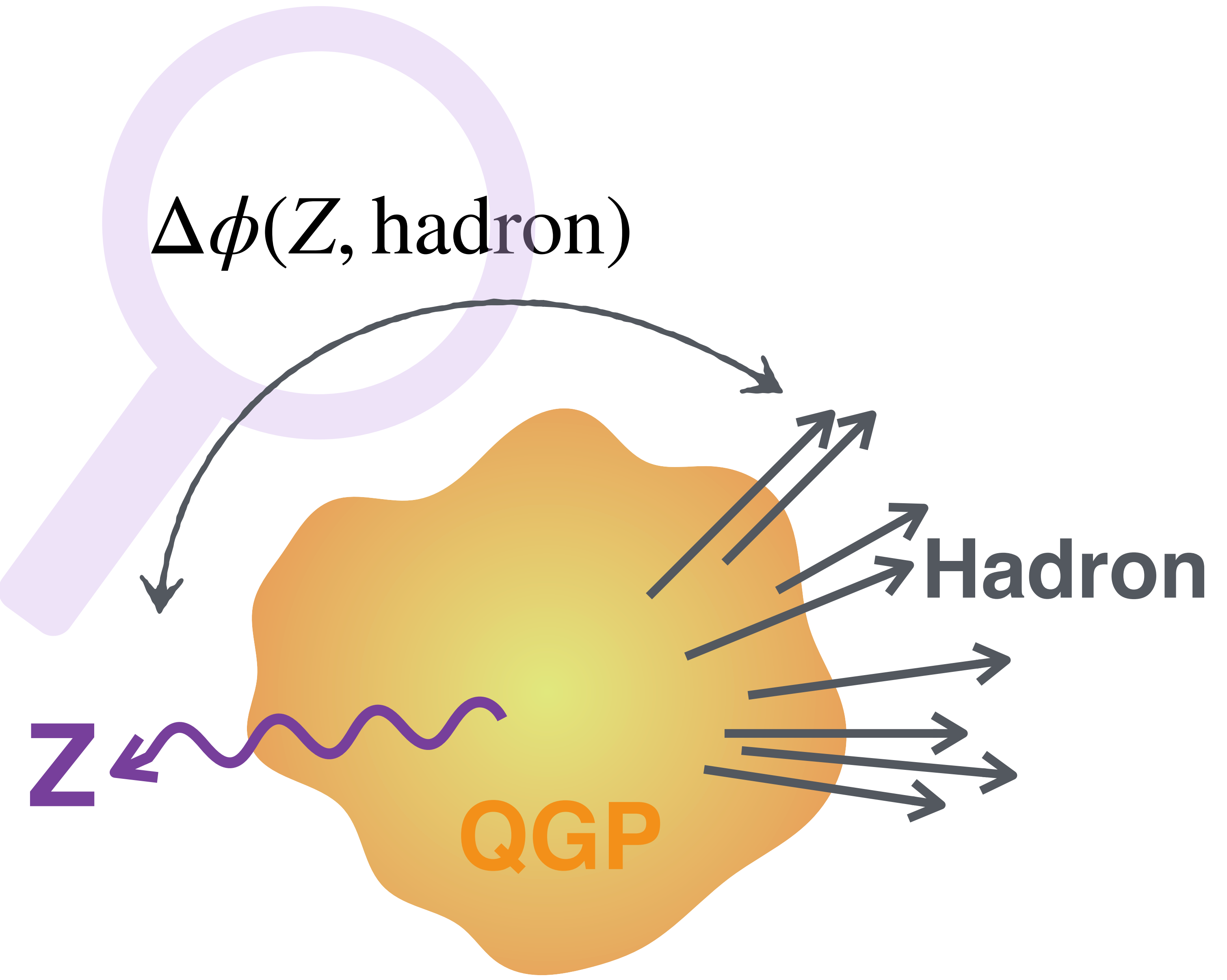
- Data described well by **JEWEL w/ medium response**

Z-hadron Angular Correlation



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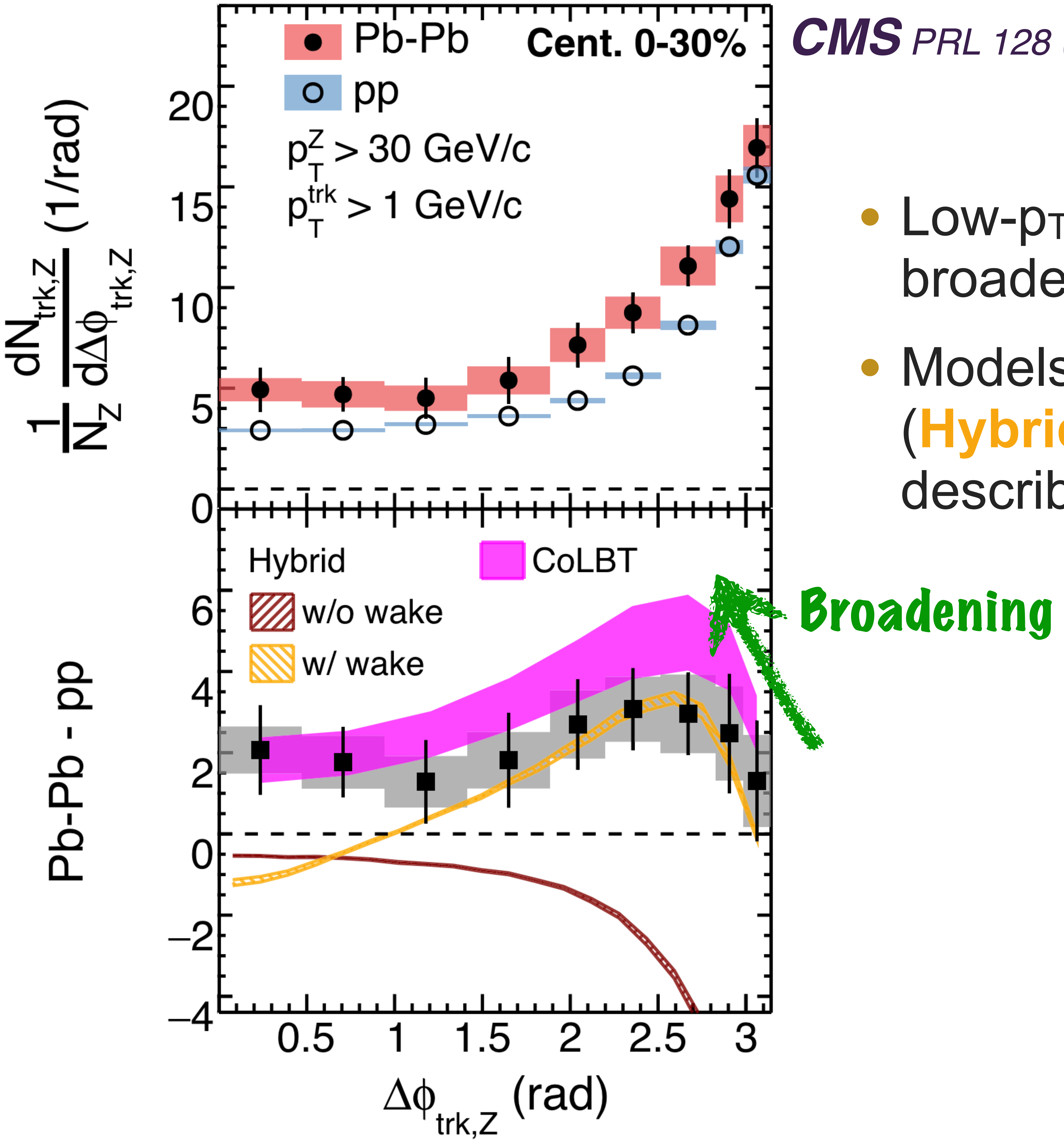

CMS *PRL 128 (2022) 122301*

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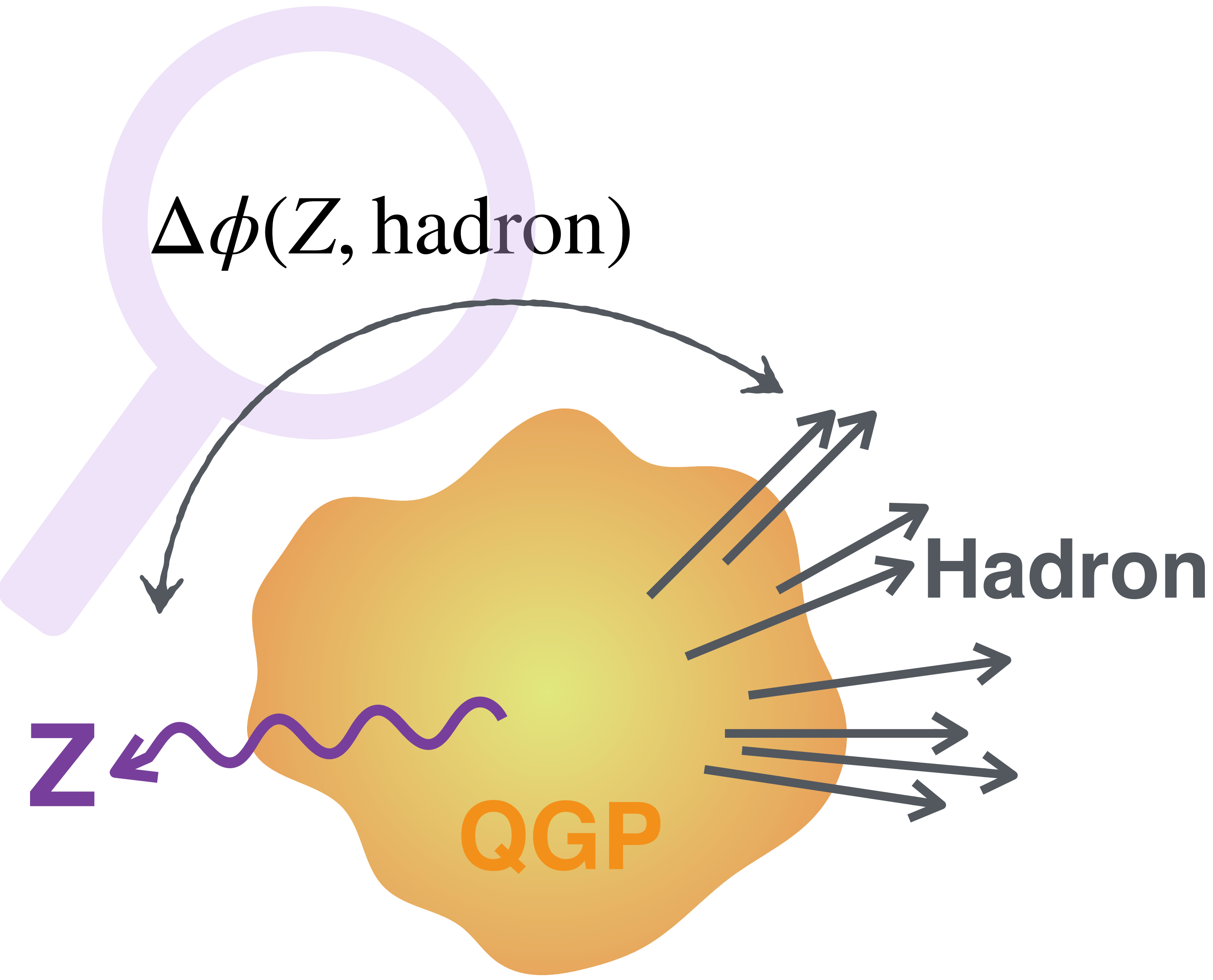

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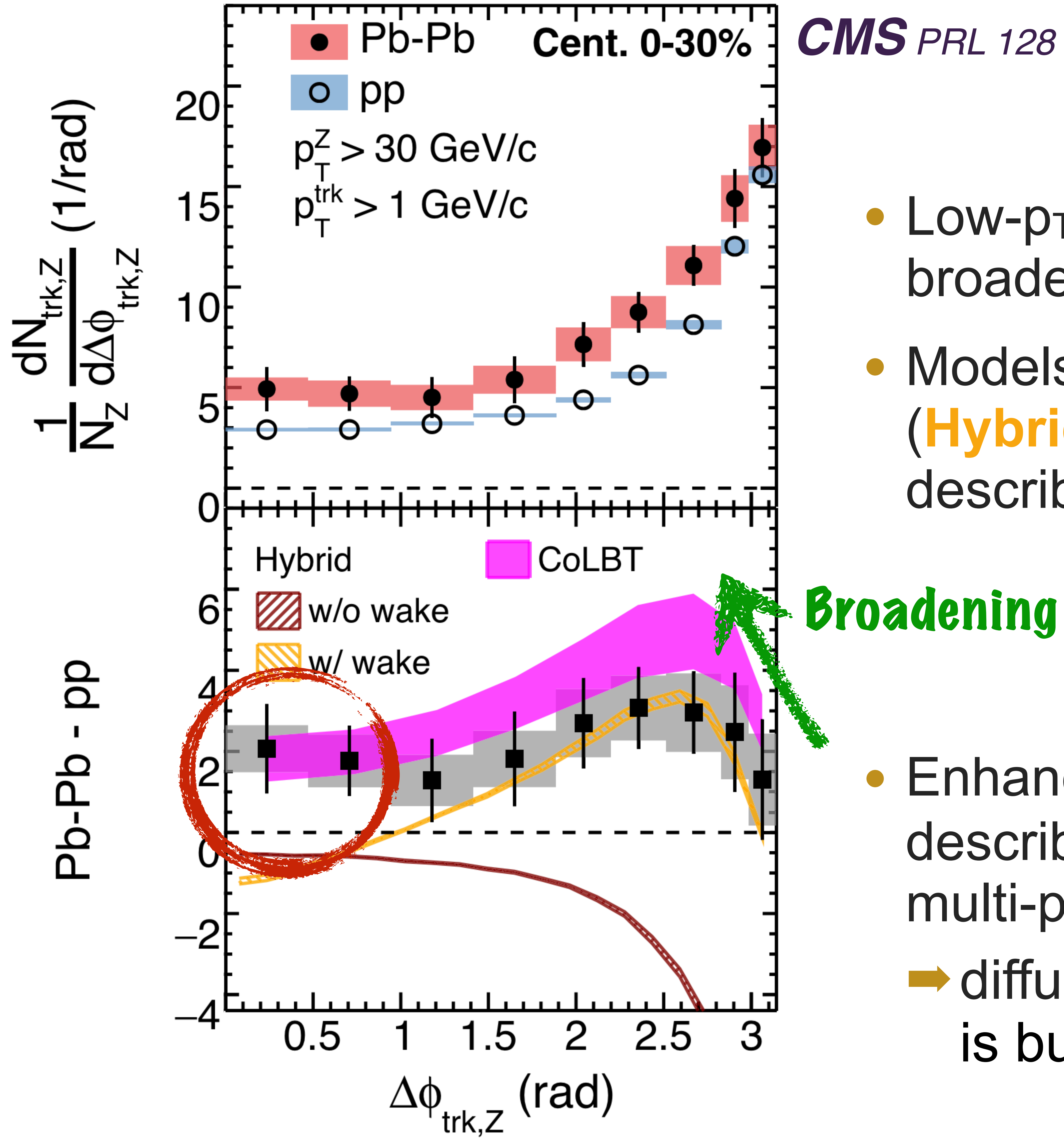
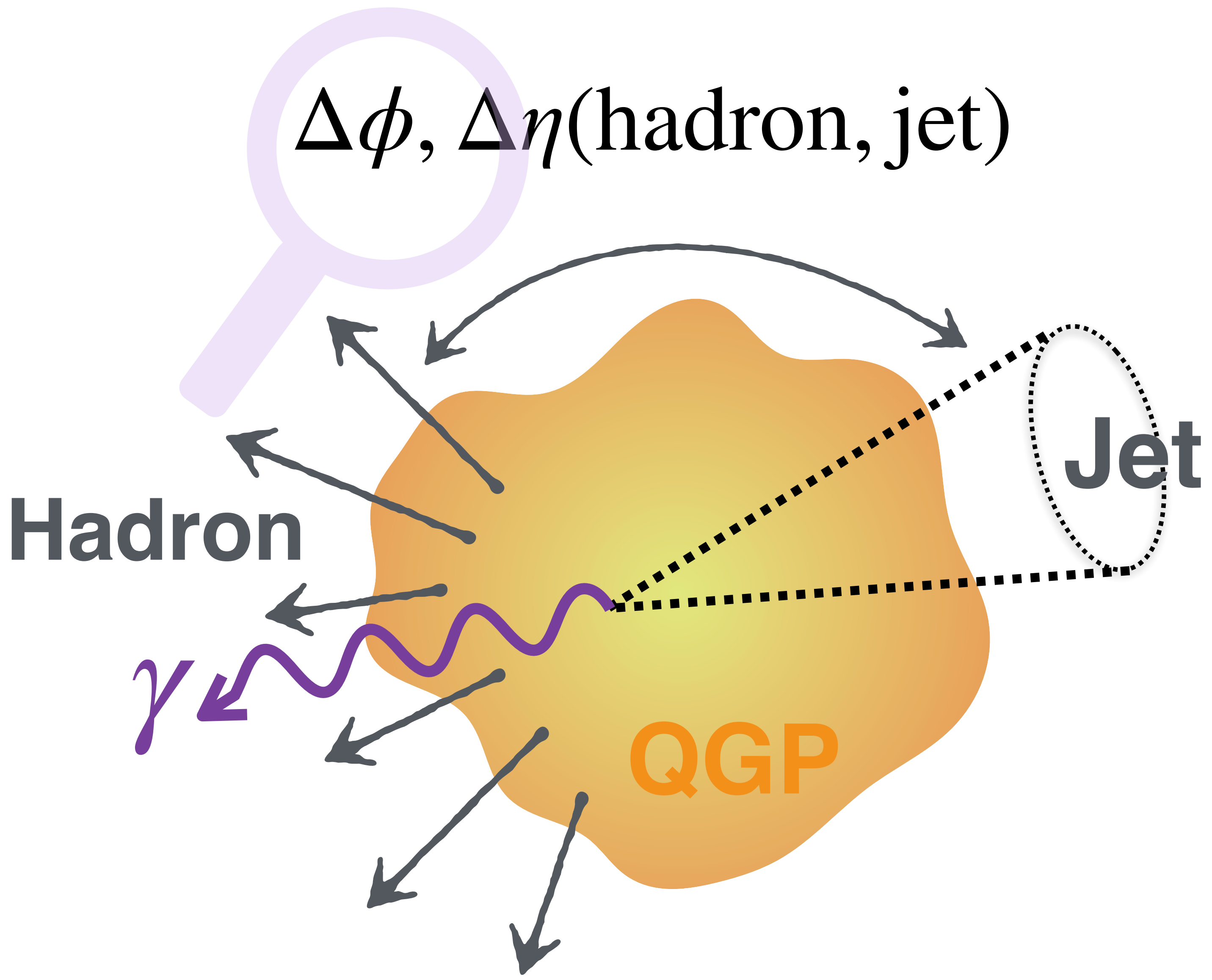


CMS *PRL 128 (2022) 122301*

- Low-p_T particles (~1 GeV) broaden towards larger angles
- Models w/ medium response (**Hybrid w/ wake** and **CoLBT**) describe the data better
- Enhancement at $\Delta\phi \sim 0$ is described by **CoLBT** with multi-parton interaction (MPI)
  - ➡ diffusion wake (depletion) is buried in MPI

Jet-Hadron Correlation in Photon-Jet Events



- Modifications in jet direction are convoluted with ***in-medium parton shower modification*** and ***medium response***
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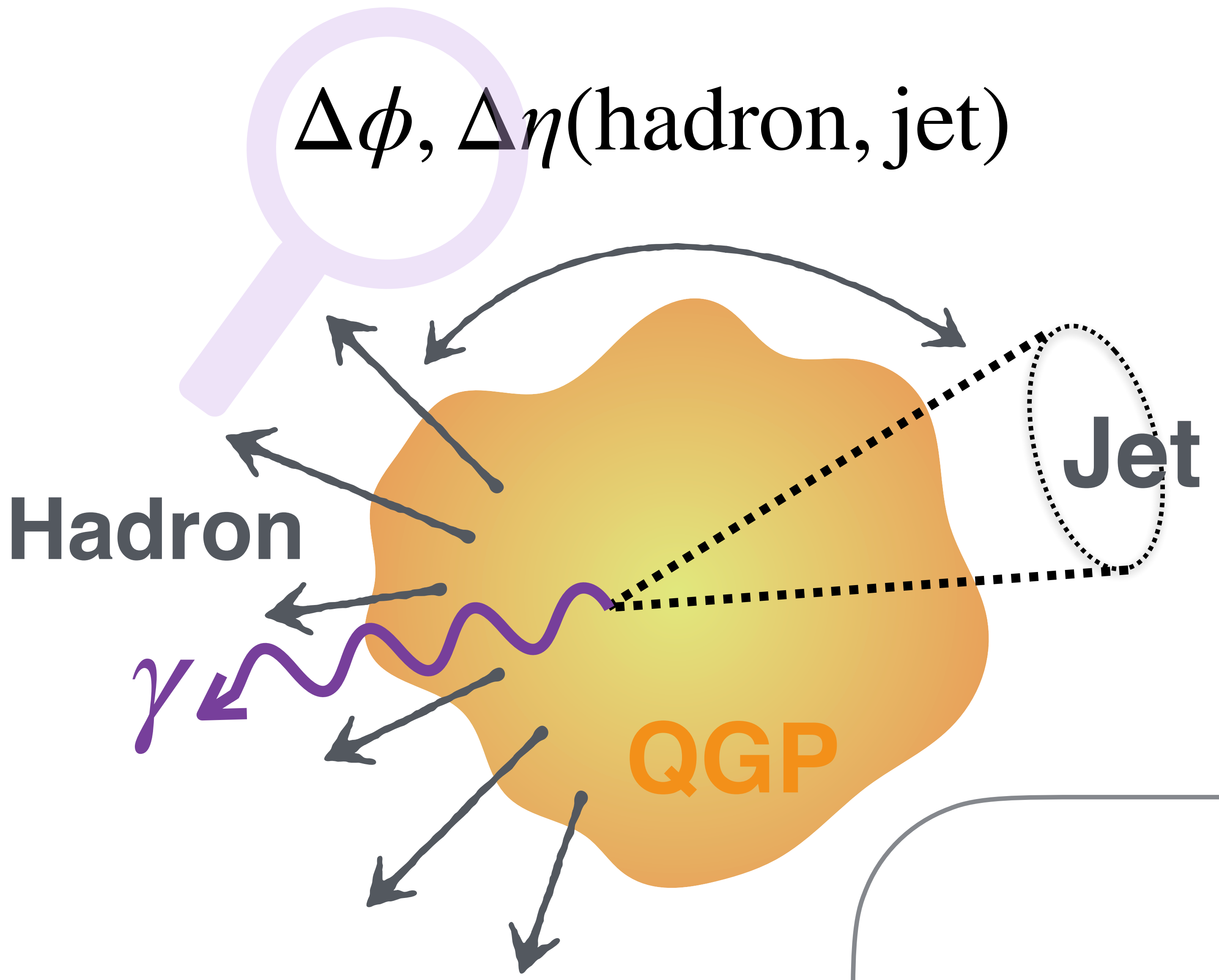

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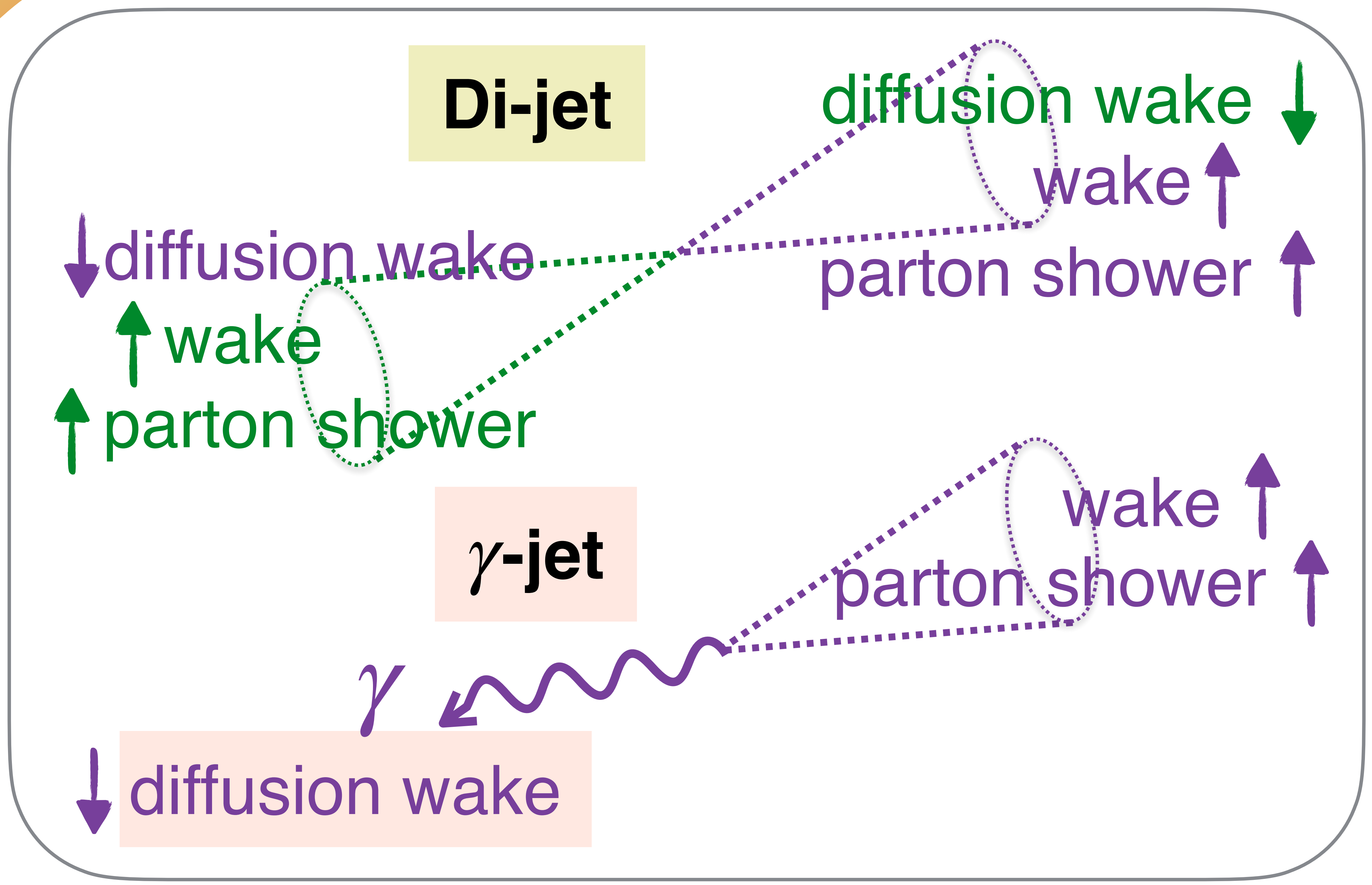
- Jet-hadron $(\Delta\phi, \Delta\eta) \sim (\pi, 0)$ in γ-jet events
  ➡ unambiguous diffusion wake signal



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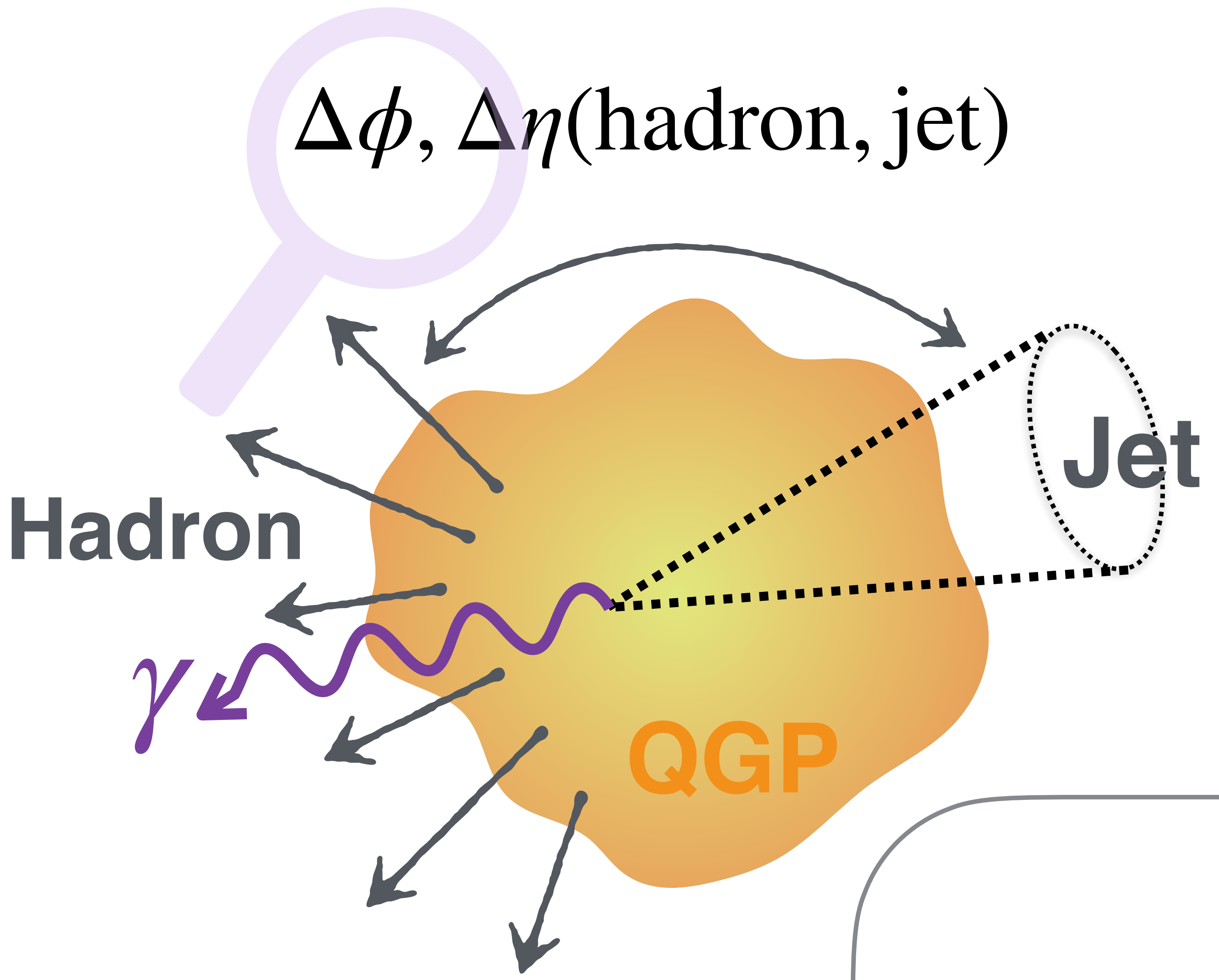

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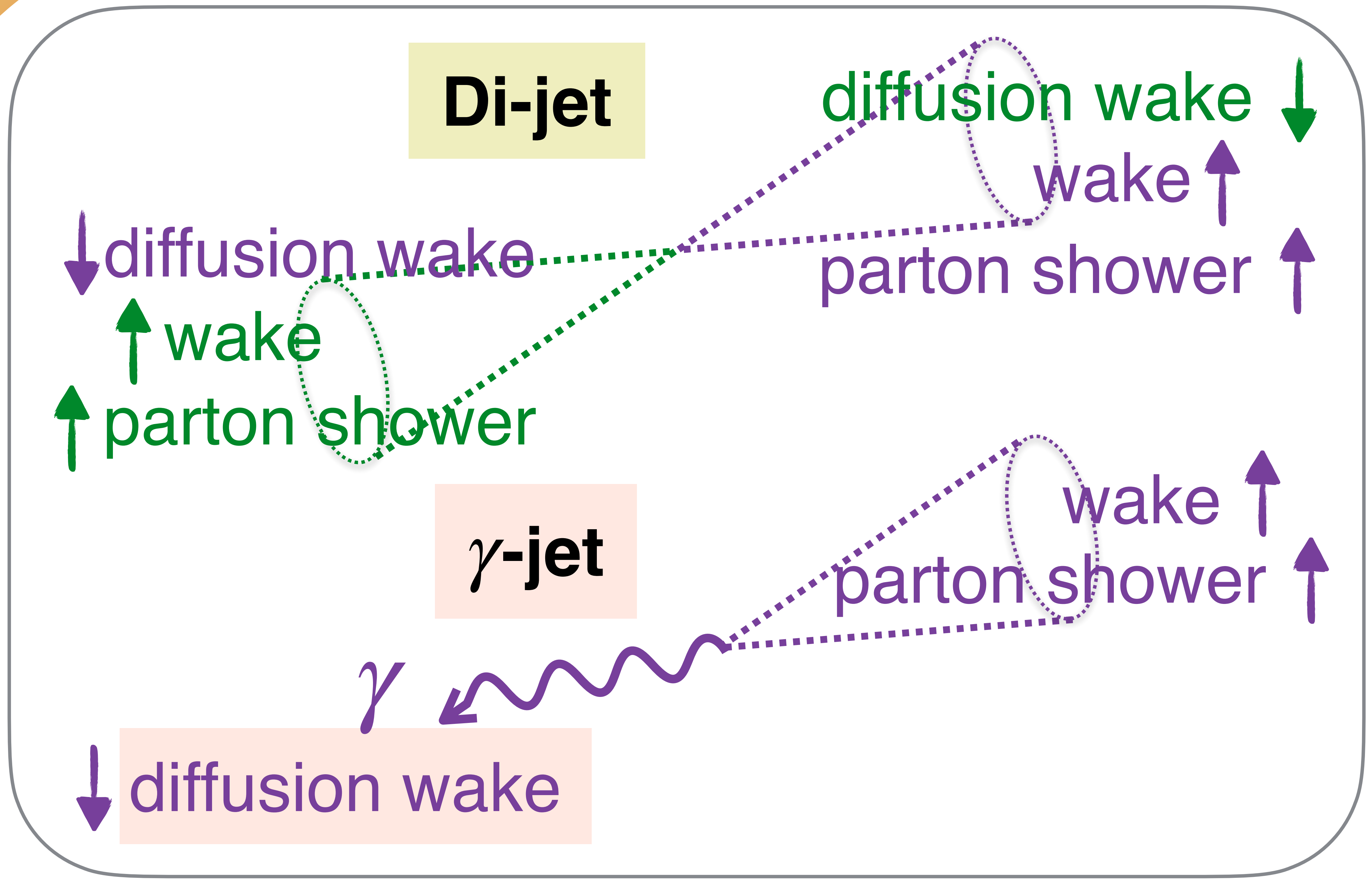
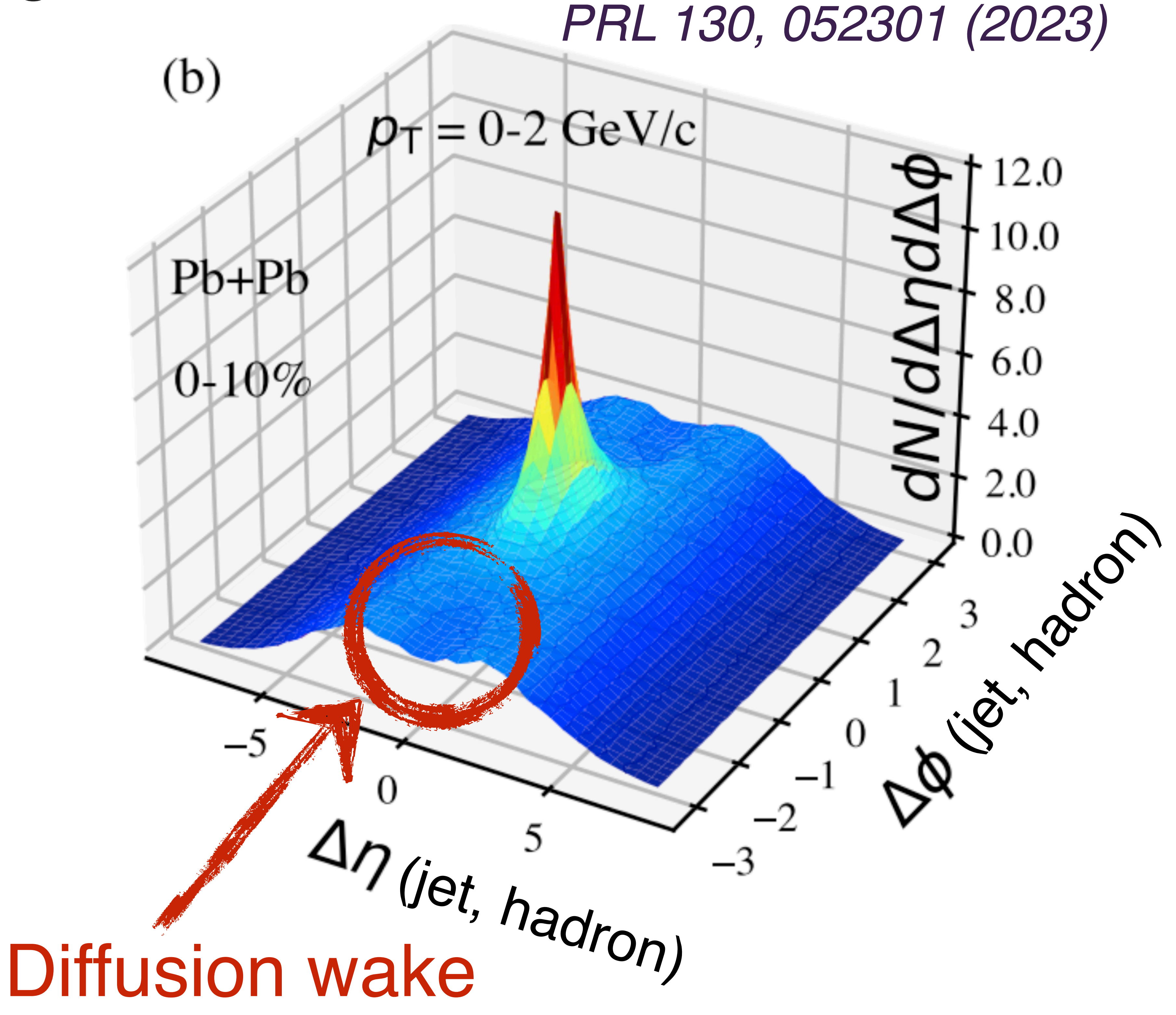


CoLBT
PRL 130, 052301 (2023)



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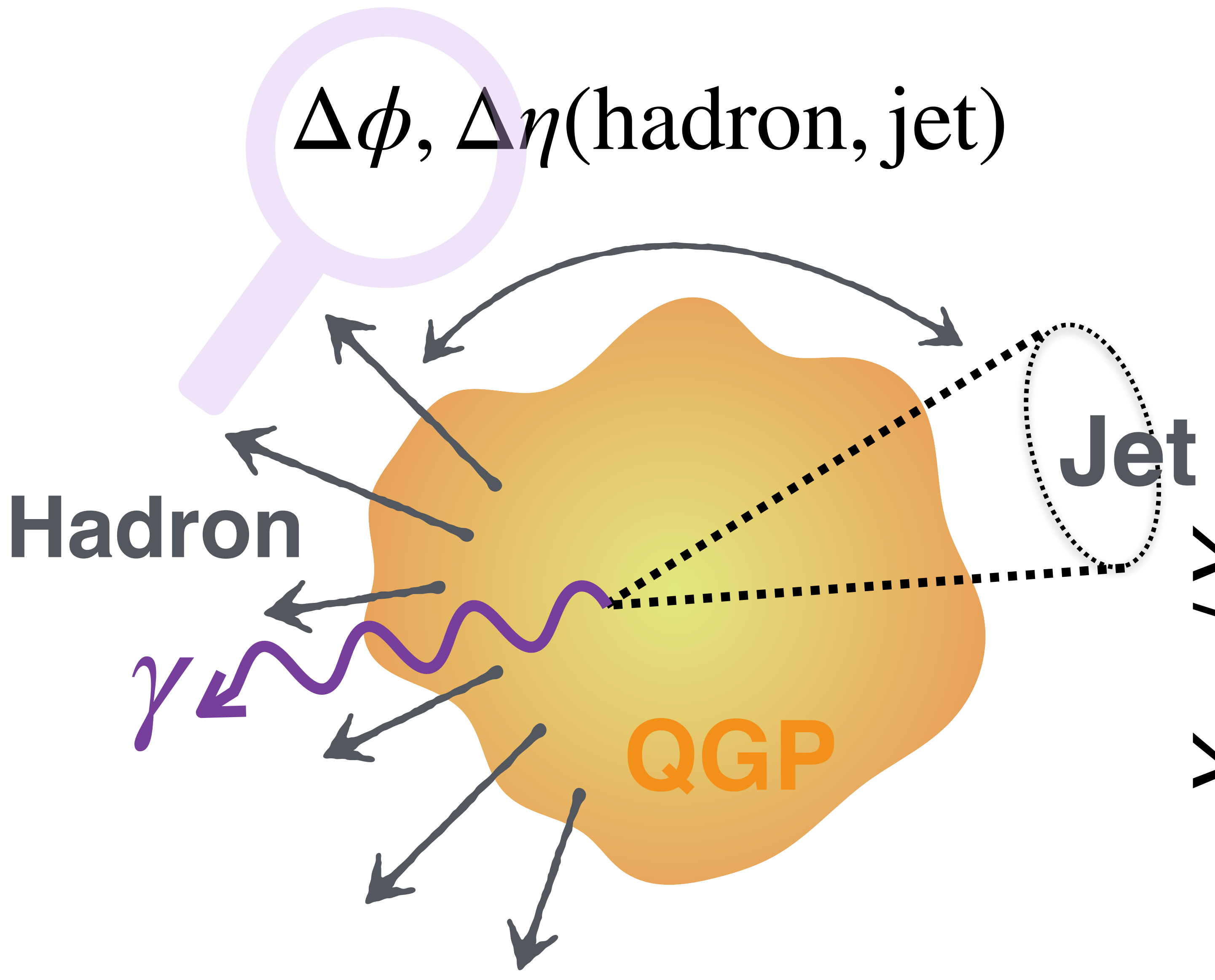
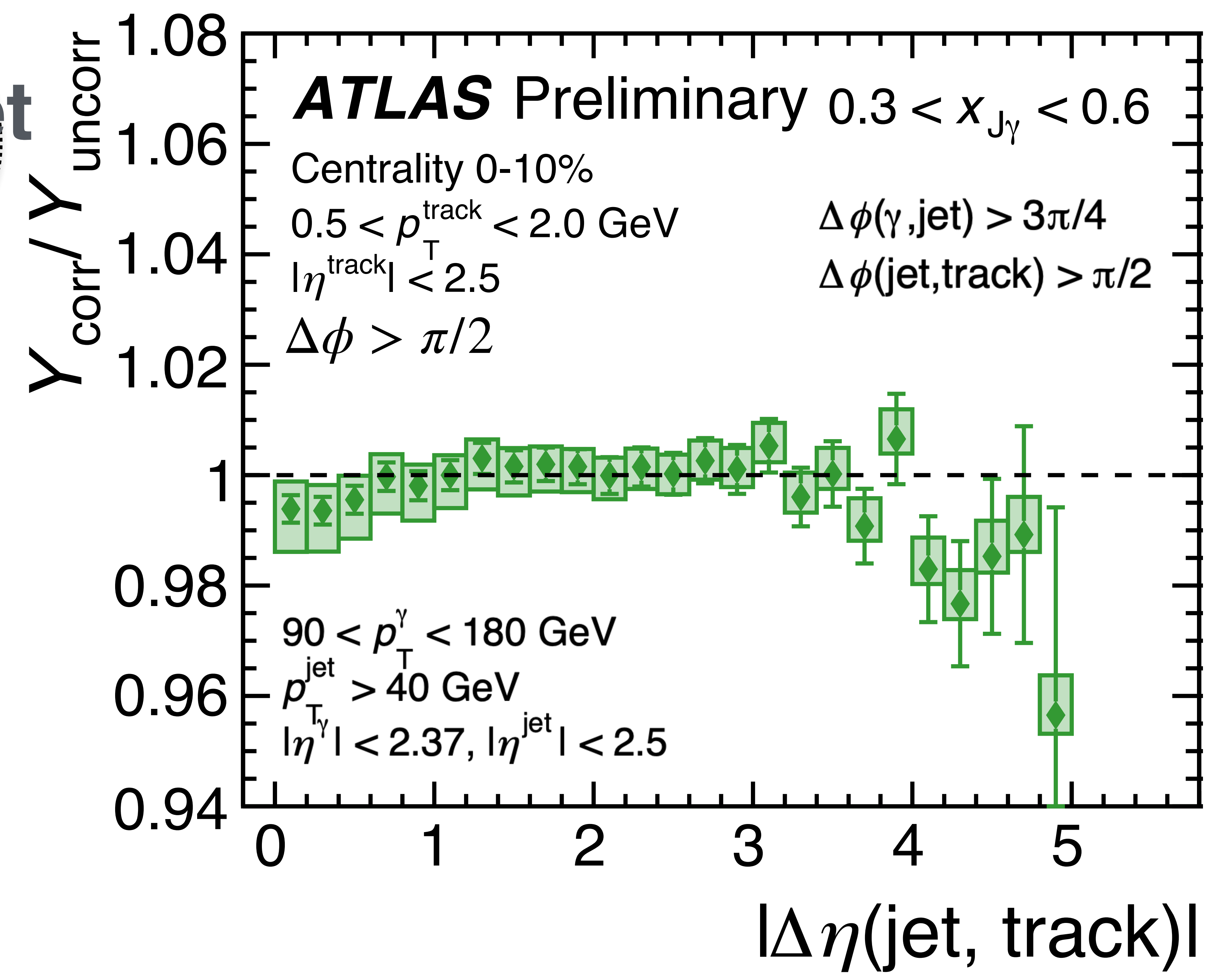


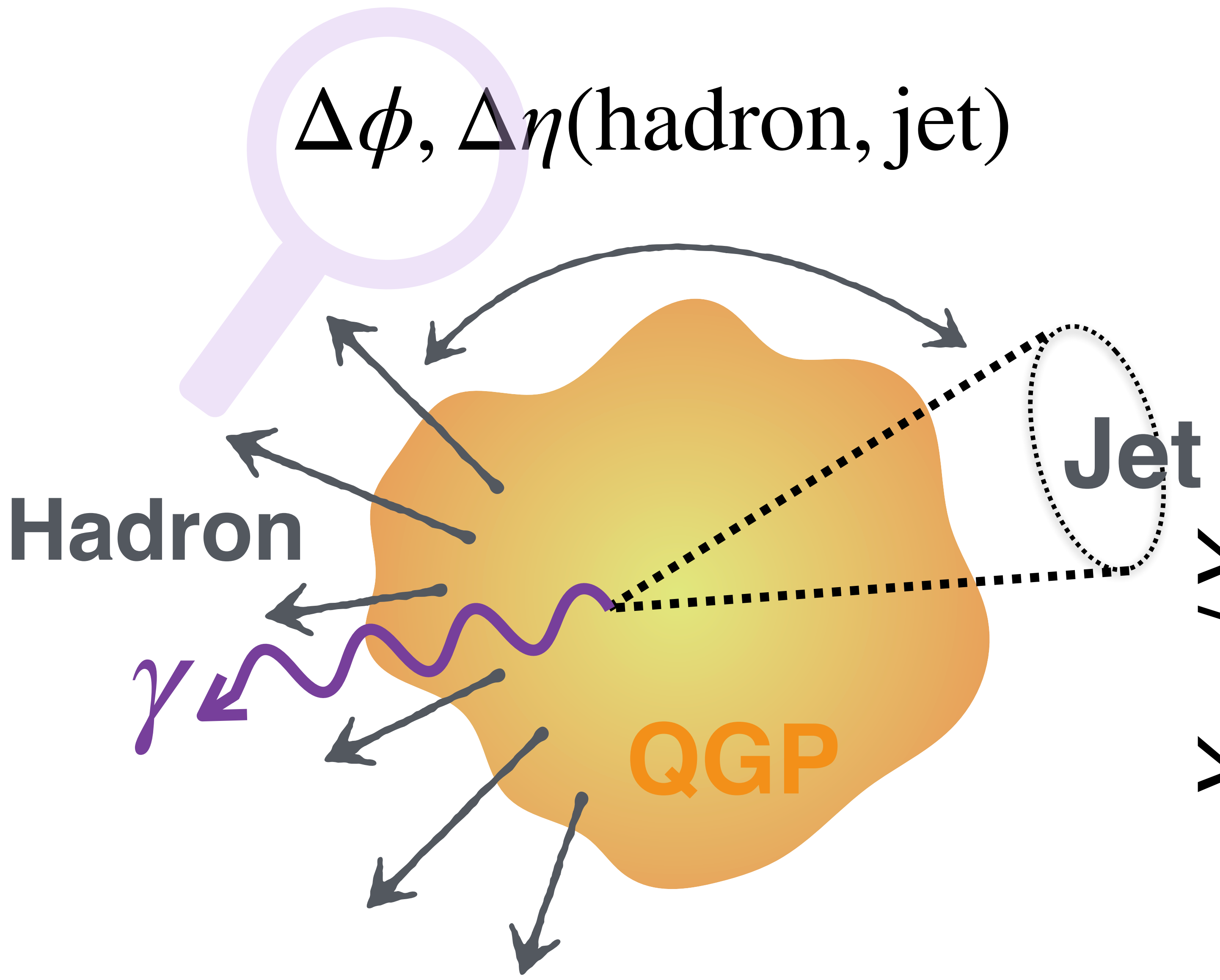
- Y_{corr}/Y_{uncorr}
  ➡ Relative yield ratio btw **signal** and **mixed** events

ATLAS
CONF-2023-054



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

Jet-Hadron Correlation in Photon-Jet Events



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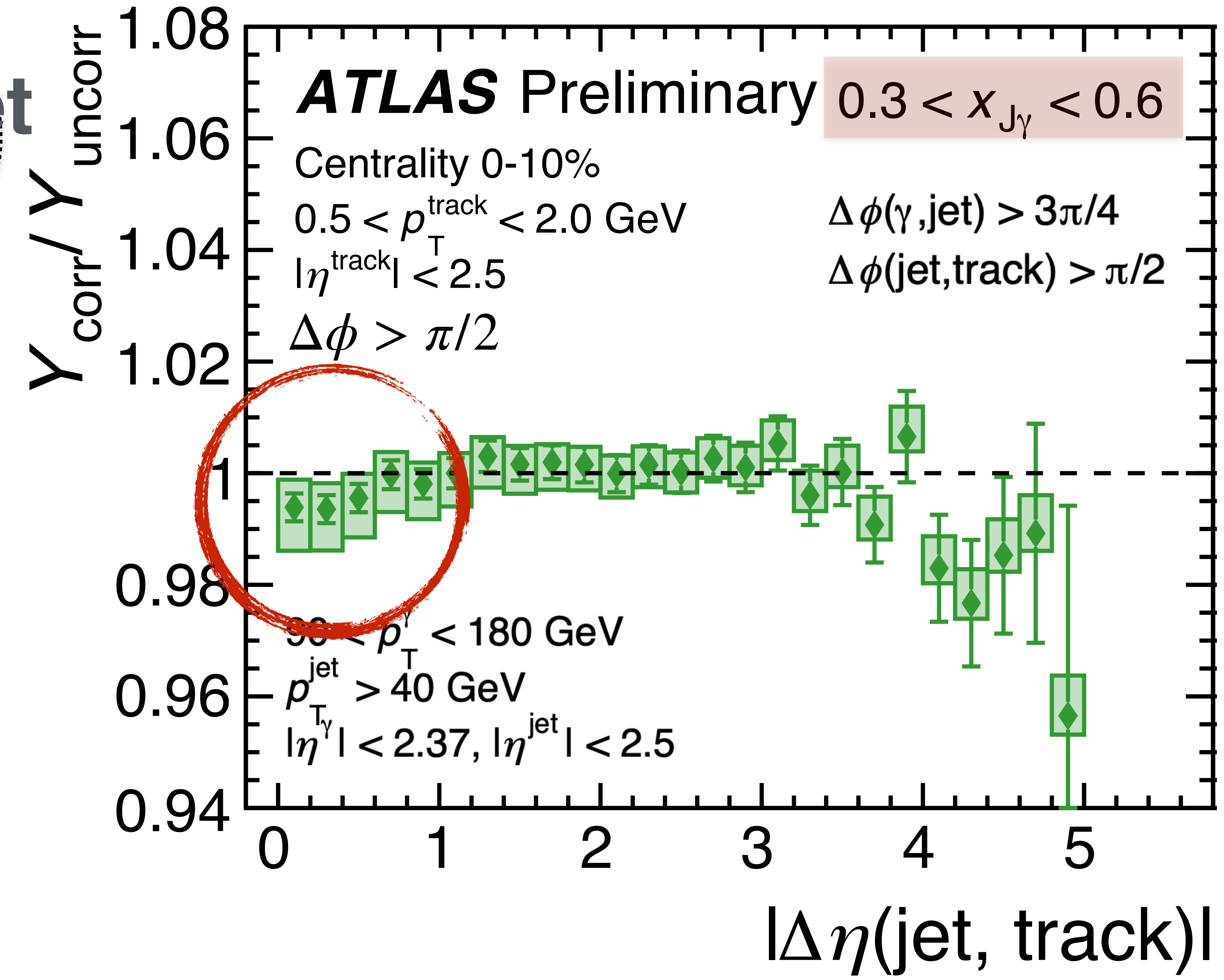

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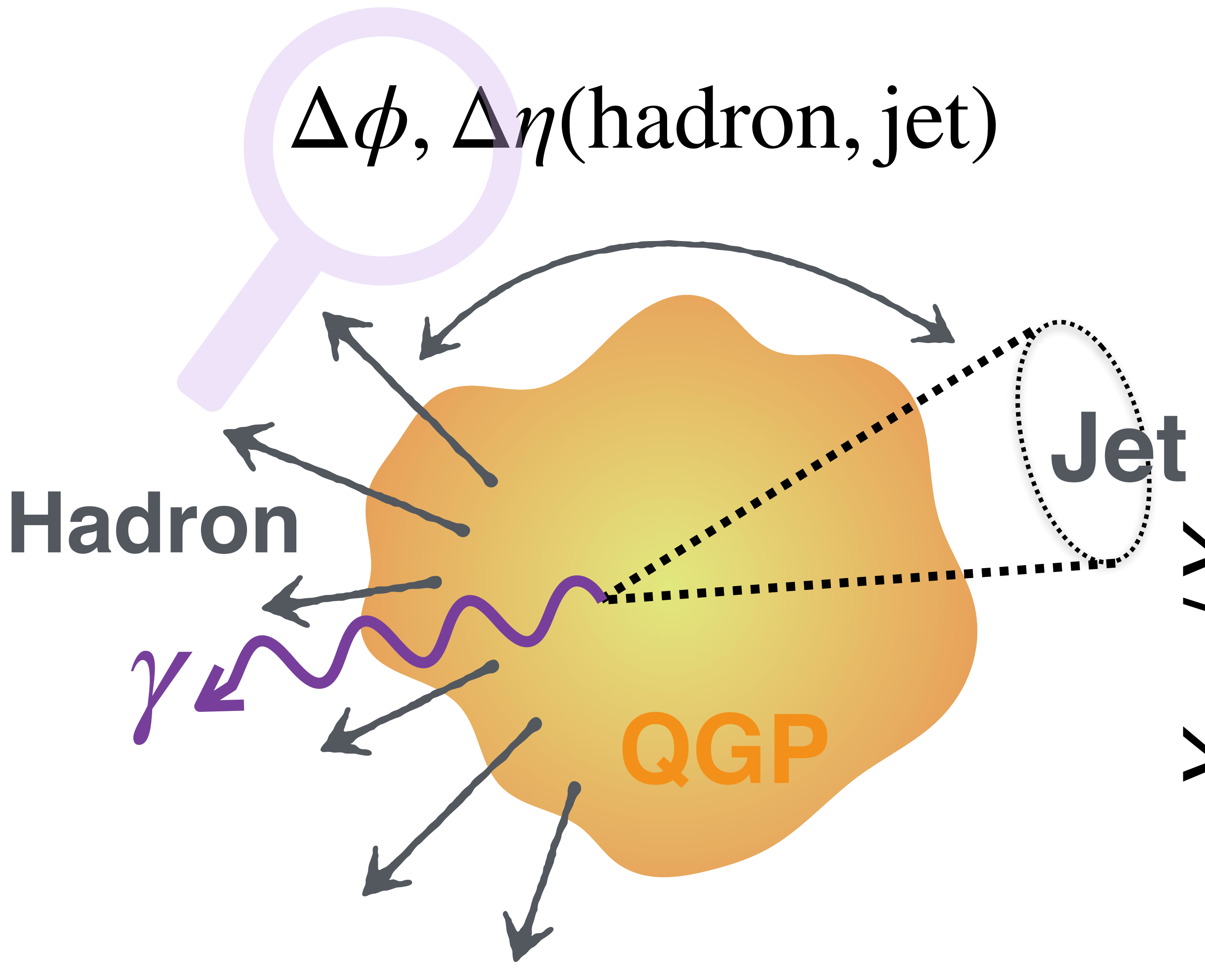

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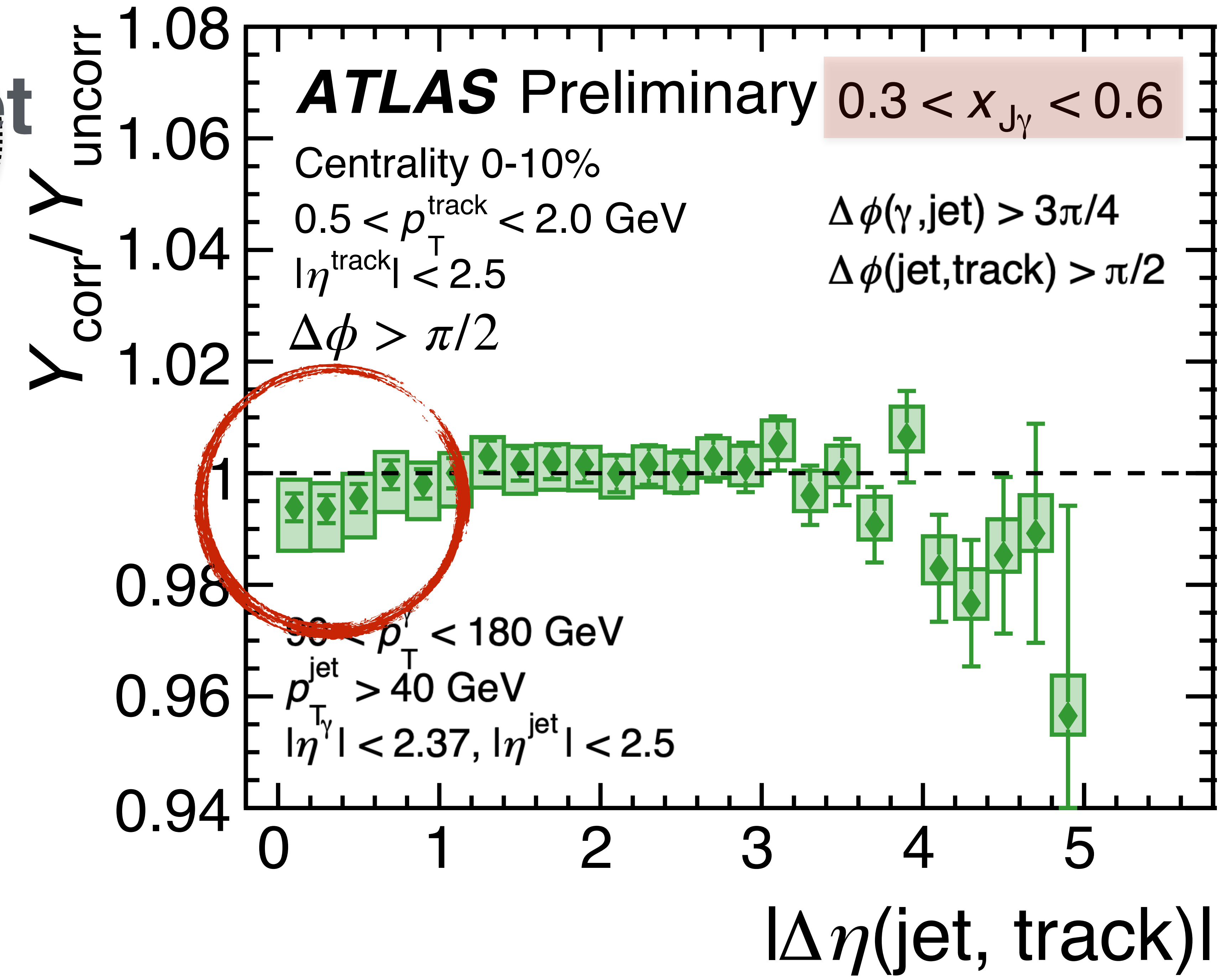
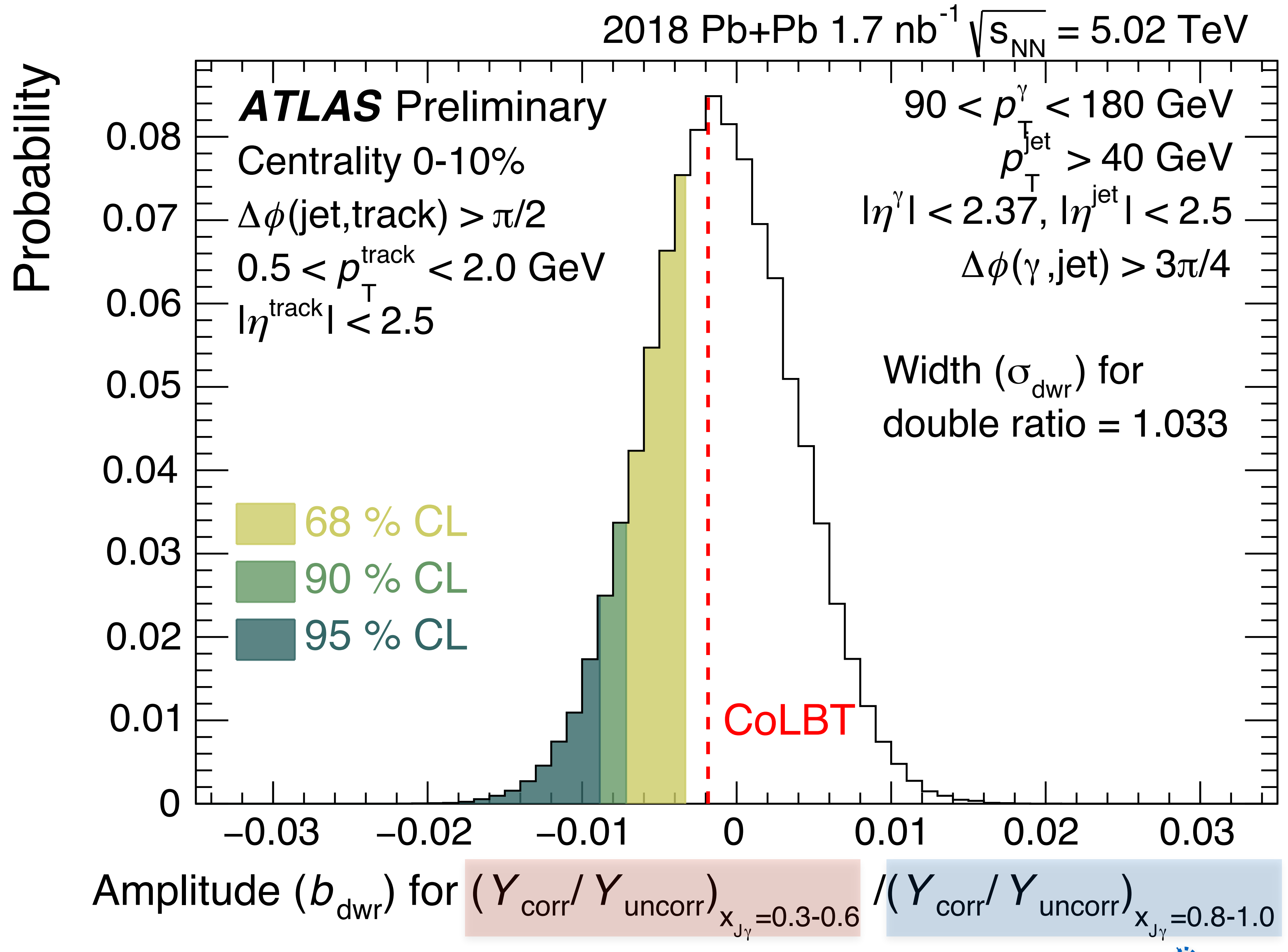
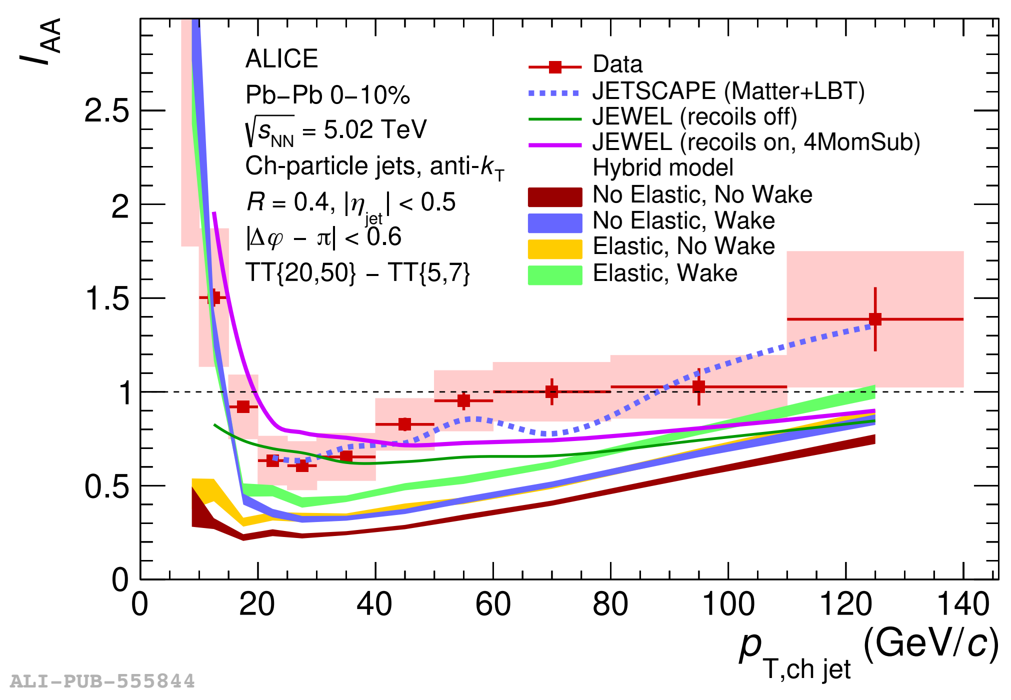
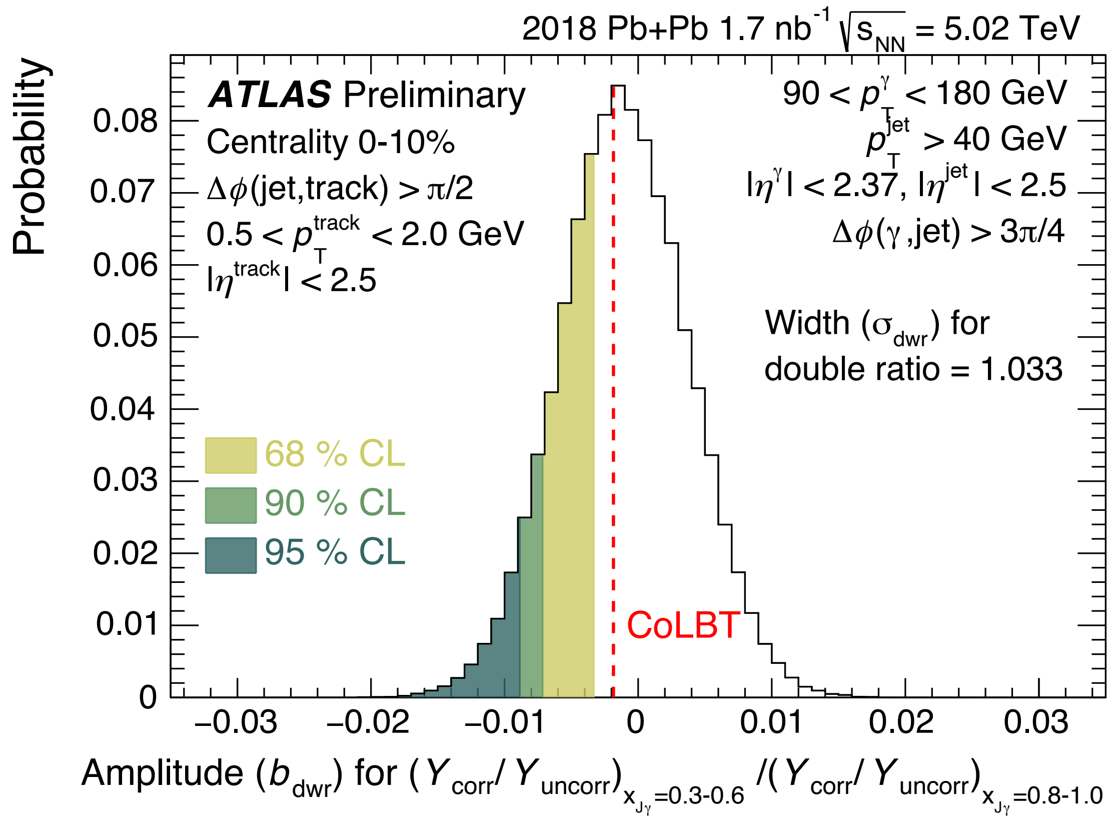


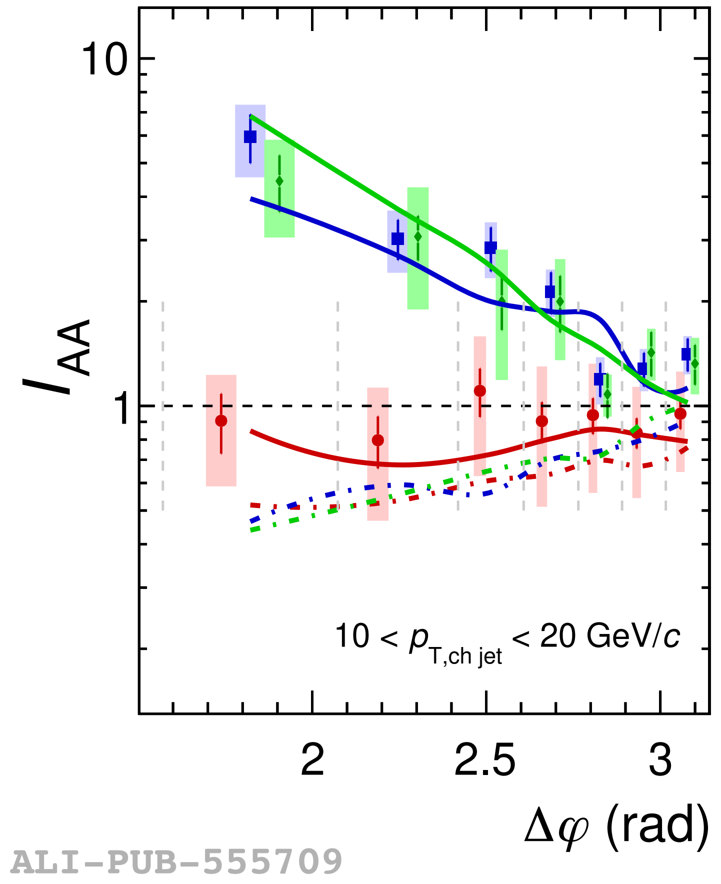


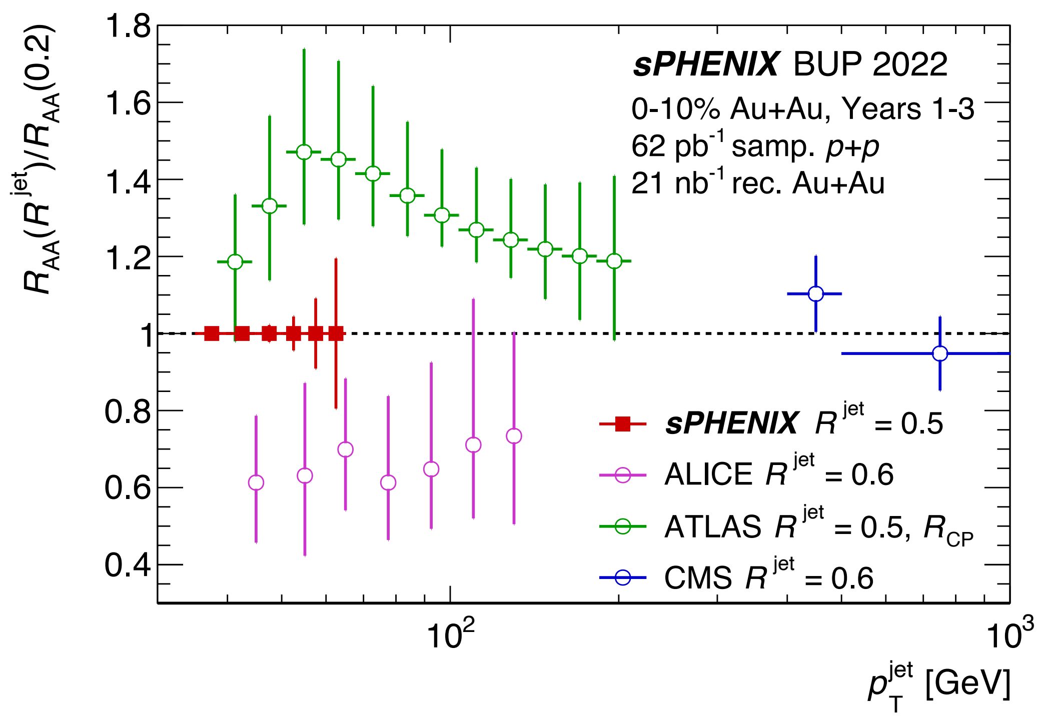
- **No significant diffusion wake signal** within the current sensitivity in data
- Data provides limits on double ratio amplitude
  ➡ **95% CL upper limit** of **0.0095** does not rule out CoLBT prediction of 0.0018
  ➡ Stat. uncert. dominates in probability distribution; more statistics would be valuable

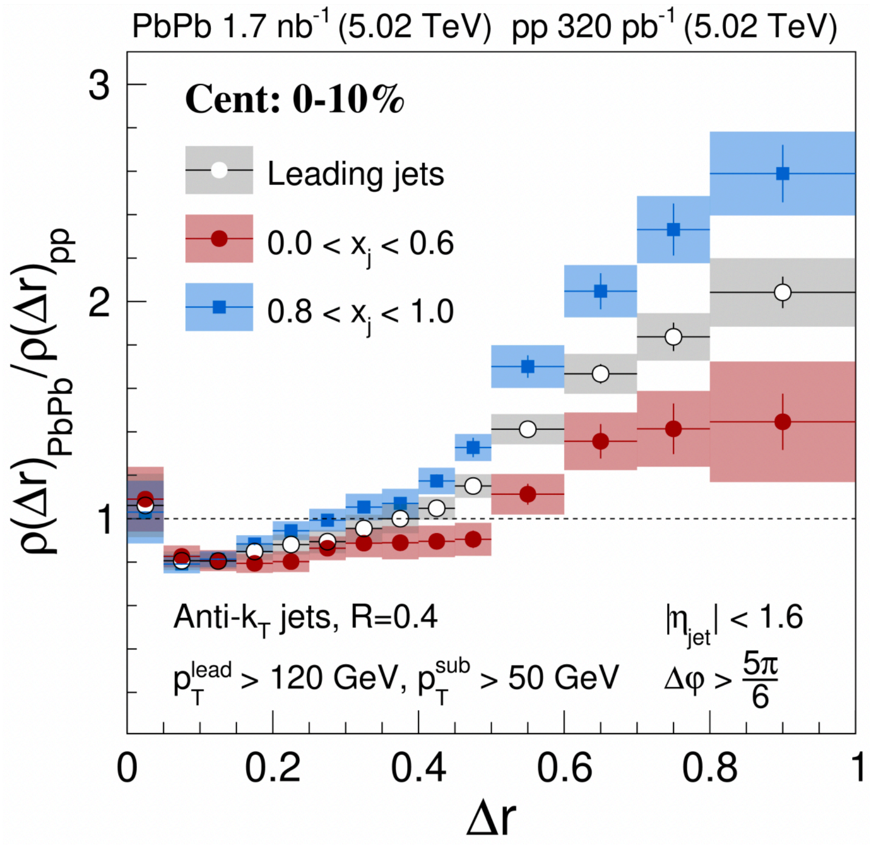
Summary


ALICE
Pb–Pb 0–10%
Ch-particle jets, anti-k_T
TT{20,50} – TT{5,7}
Data
JETSCAPE (Matter+LBT)
JEWEL (recoils off)
JEWEL (recoils on, 4MomSub)
Hybrid model
No Elastic, No Wake
No Elastic, Wake
Elastic, No Wake
Elastic, Wake
I_{AA}
$p_{T,ch\ jet}$ (GeV/c)
ALI-PUB-555844


2018 Pb+Pb 1.7 nb^{-1} $\sqrt{s_{NN}}$ = 5.02 TeV
ATLAS Preliminary
Centrality 0-10%
$\Delta\phi$(jet,track) > π/2
0.5 < p_T^{track} < 2.0 GeV
$|\eta^{track}|$ < 2.5
90 < p_T^{γ} < 180 GeV
p_T^{jet} > 40 GeV
$|\eta^{\gamma}|$ < 2.37, $|\eta^{jet}|$ < 2.5
$\Delta\phi(\gamma$,jet) > 3π/4
Width (σ_{dwr}) for double ratio = 1.033
68 % CL
90 % CL
95 % CL
CoLBT
Probability
Amplitude (b_{dwr}) for (Y_{corr}/ Y_{uncorr})$_{x_{J\gamma}=0.3-0.6}$ /(Y_{corr}/ Y_{uncorr})$_{x_{J\gamma}=0.8-1.0}$

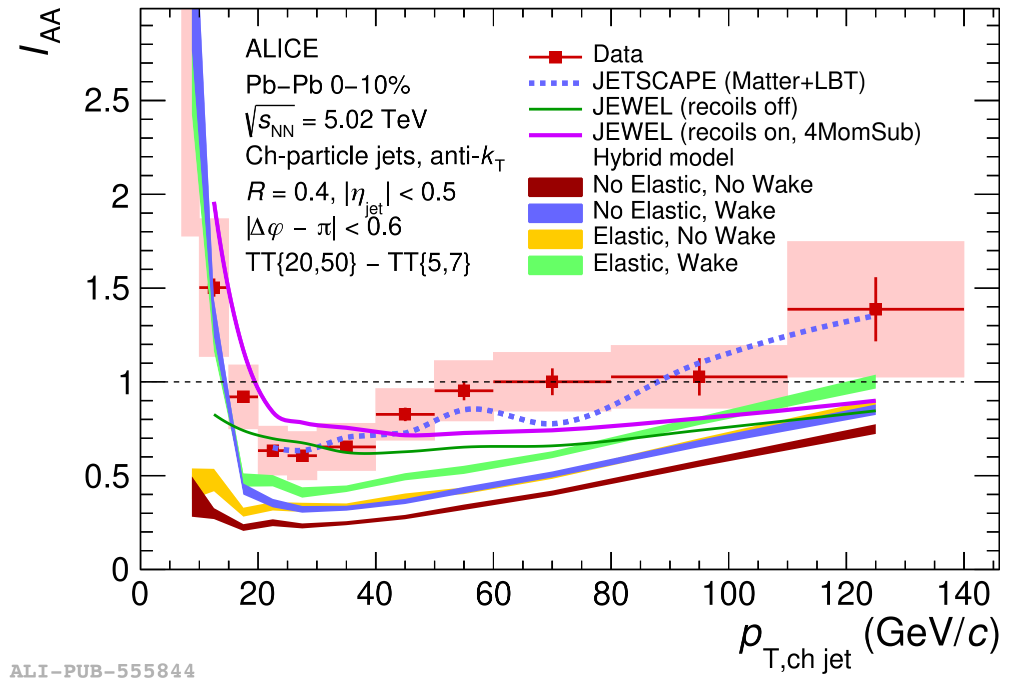

10 < $p_{T,ch\ jet}$ < 20 GeV/c
I_{AA}
$\Delta\varphi$ (rad)
ALI-PUB-555709

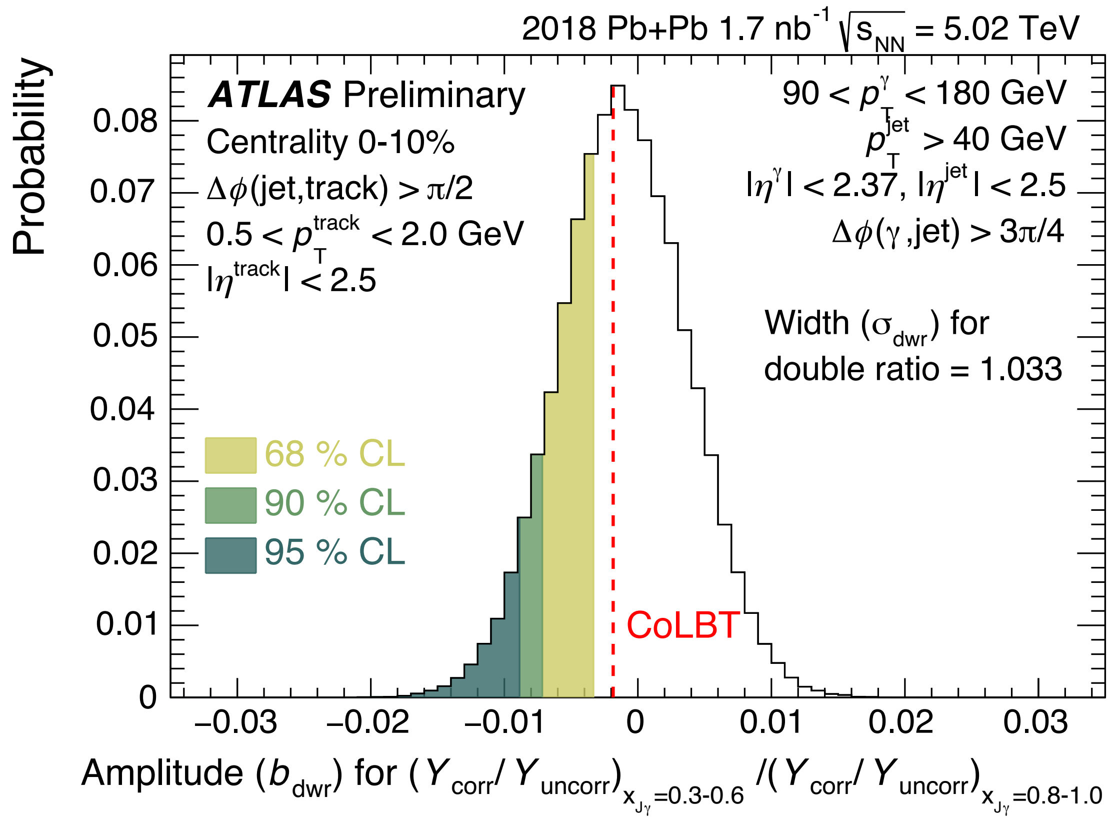

sPHENIX BUP 2022
0-10% Au+Au, Years 1-3
62 pb^{-1} samp. p+p
21 nb^{-1} rec. Au+Au
sPHENIX R^{jet} = 0.5
ALICE R^{jet} = 0.6
ATLAS R^{jet} = 0.5, R_{CP}
CMS R^{jet} = 0.6
$R_{AA}(R^{jet})/R_{AA}(0.2)$
p_T^{jet} [GeV]

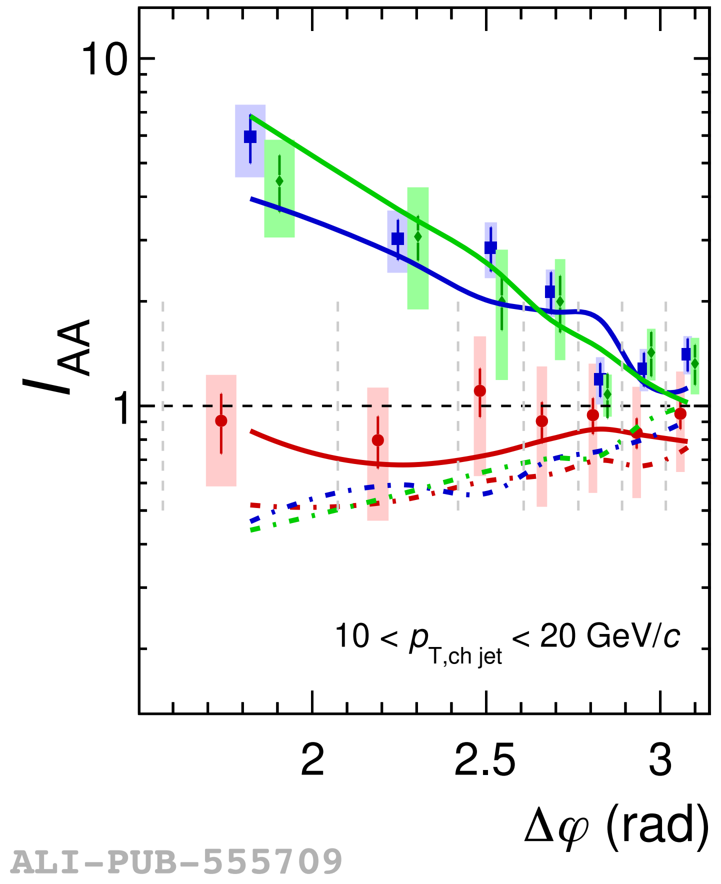

PbPb 1.7 nb^{-1} (5.02 TeV) pp 320 pb^{-1} (5.02 TeV)
Cent: 0-10%
Leading jets
0.0 < x_j < 0.6
0.8 < x_j < 1.0
Anti-k_T jets, R=0.4
p_T^{lead} > 120 GeV, p_T^{sub} > 50 GeV
$|\eta_{jet}|$ < 1.6
$\Delta\varphi$ > $\frac{5\pi}{6}$
$\rho(\Delta r)_{PbPb}/\rho(\Delta r)_{pp}$
Δr

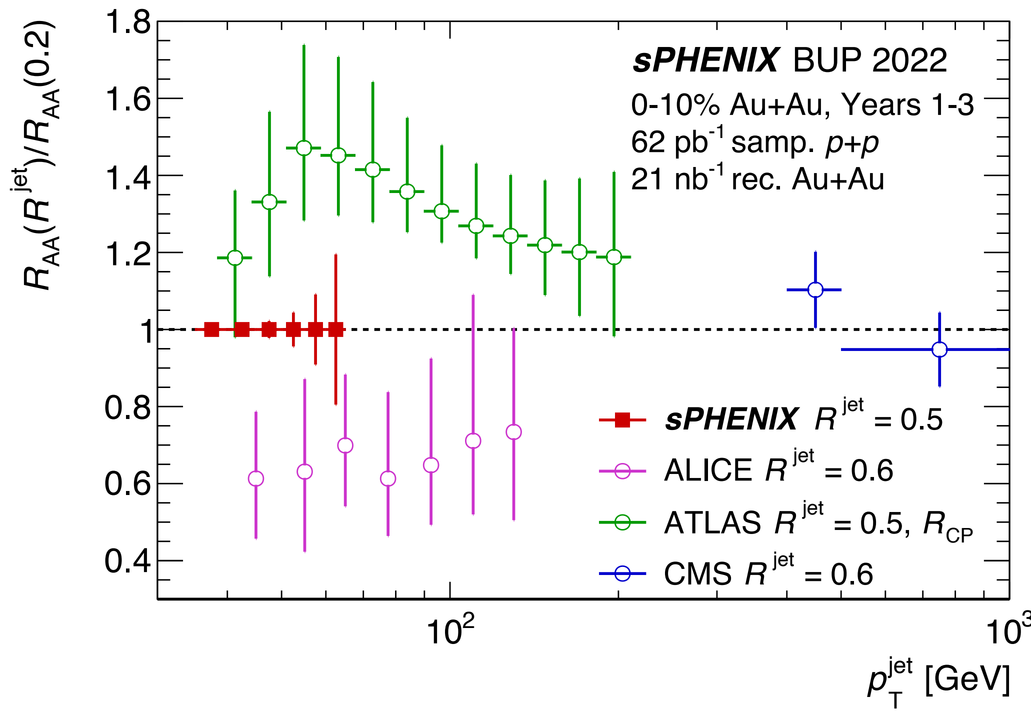
...

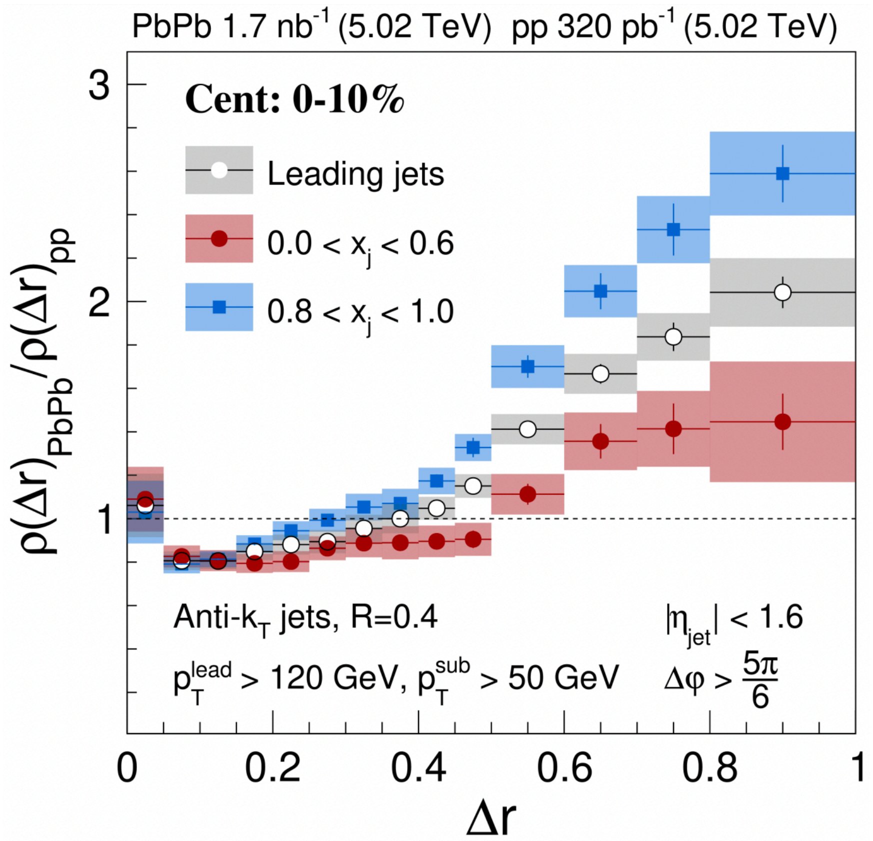
Summary











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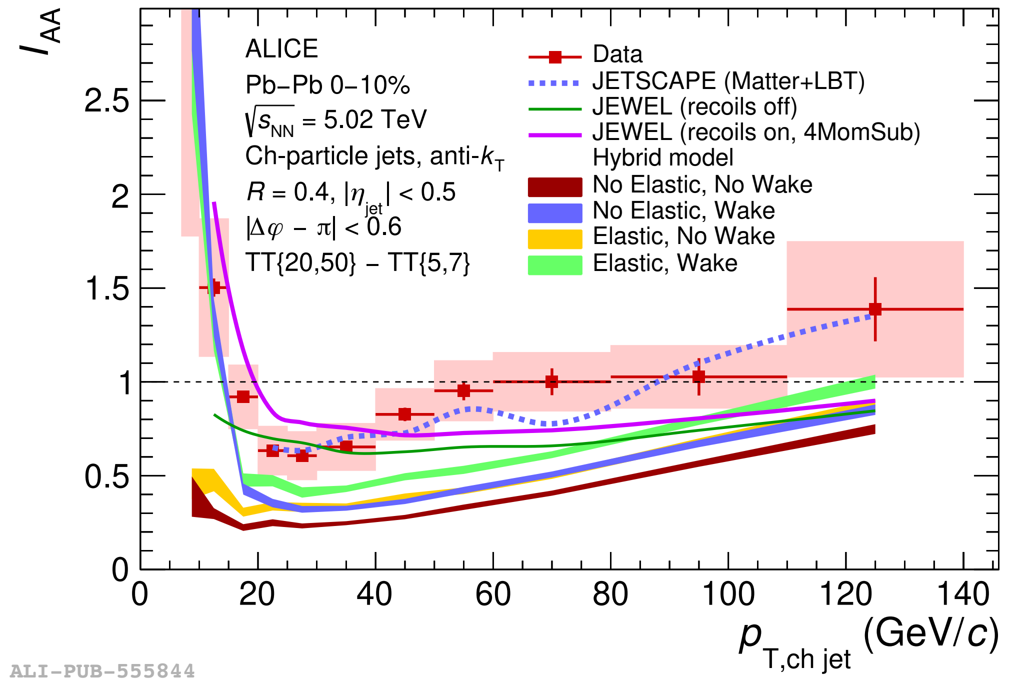
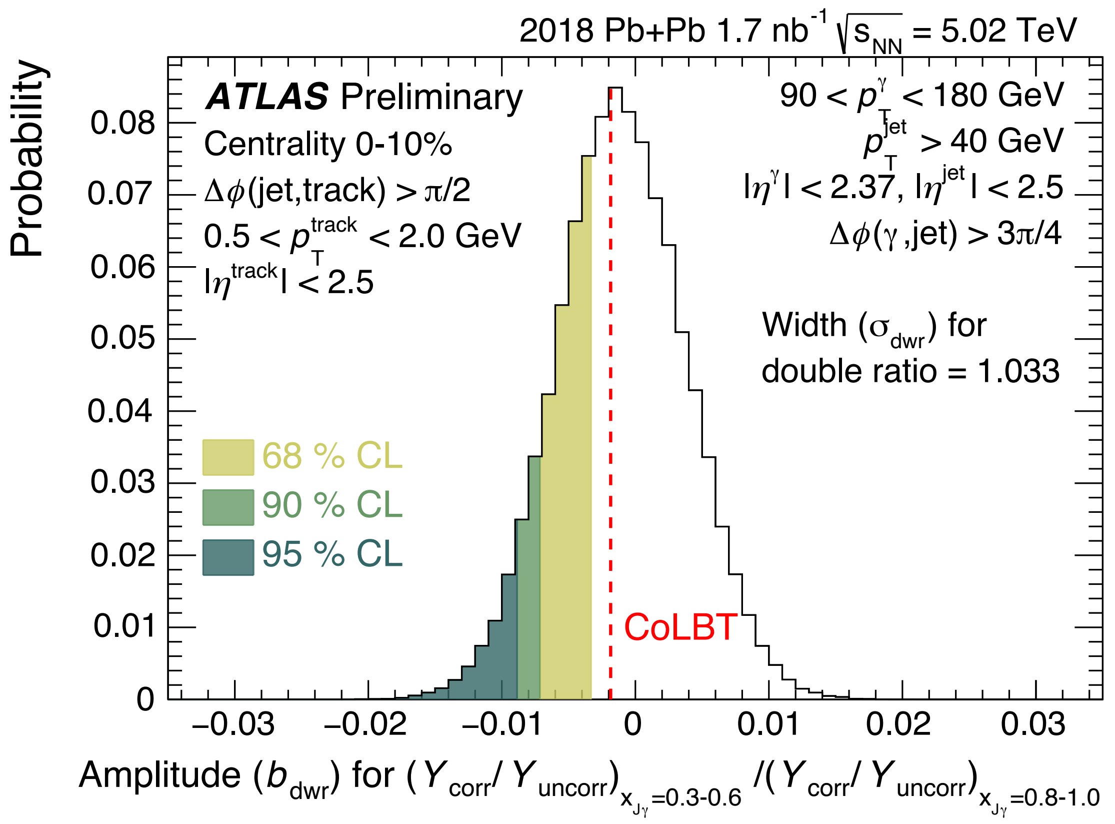
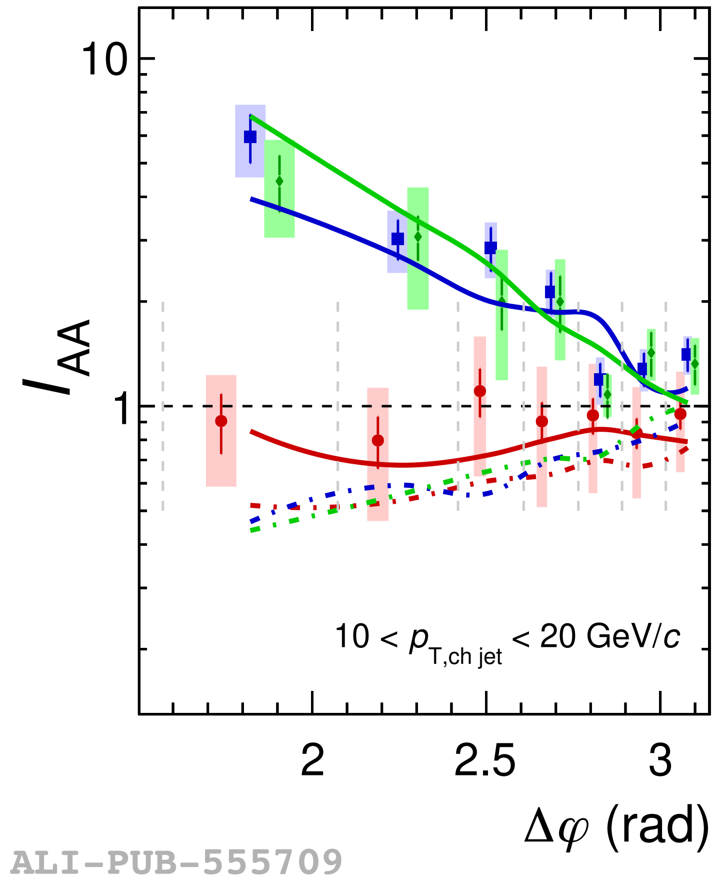
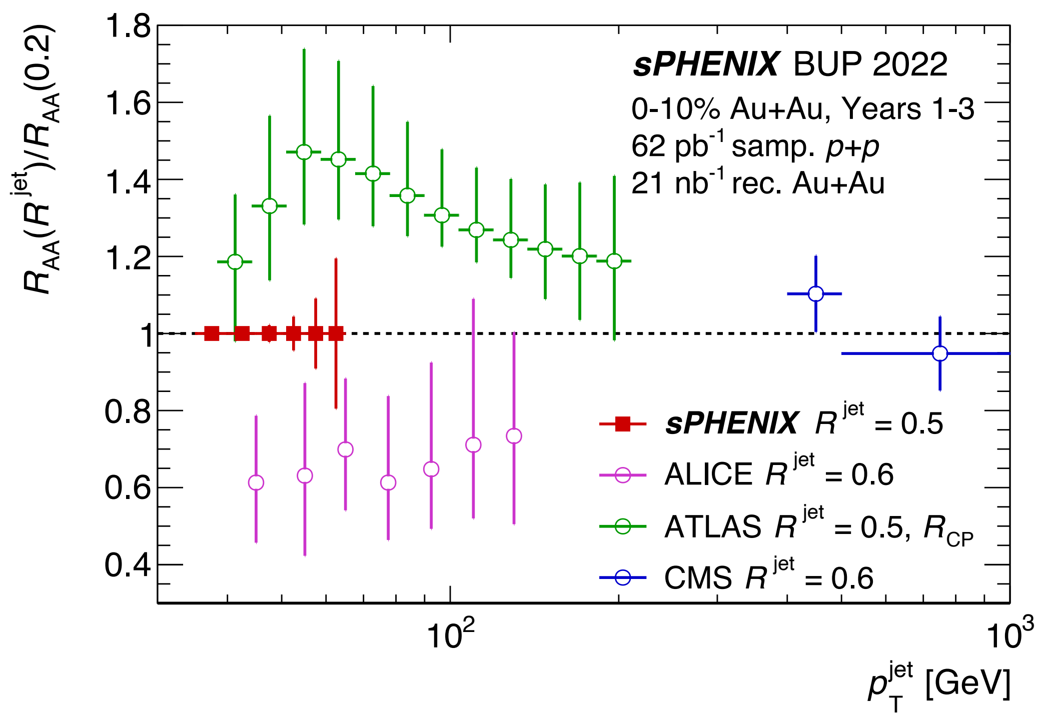
- Medium response is essential to precise jet measurements and allows direct access to QGP bulk properties

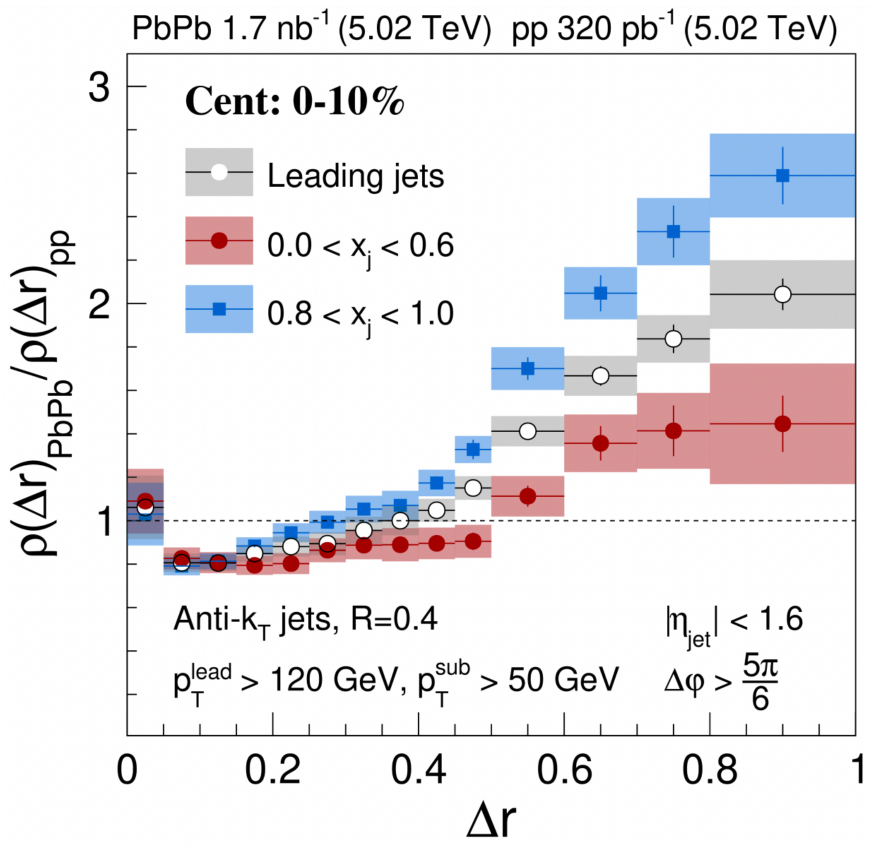
Summary











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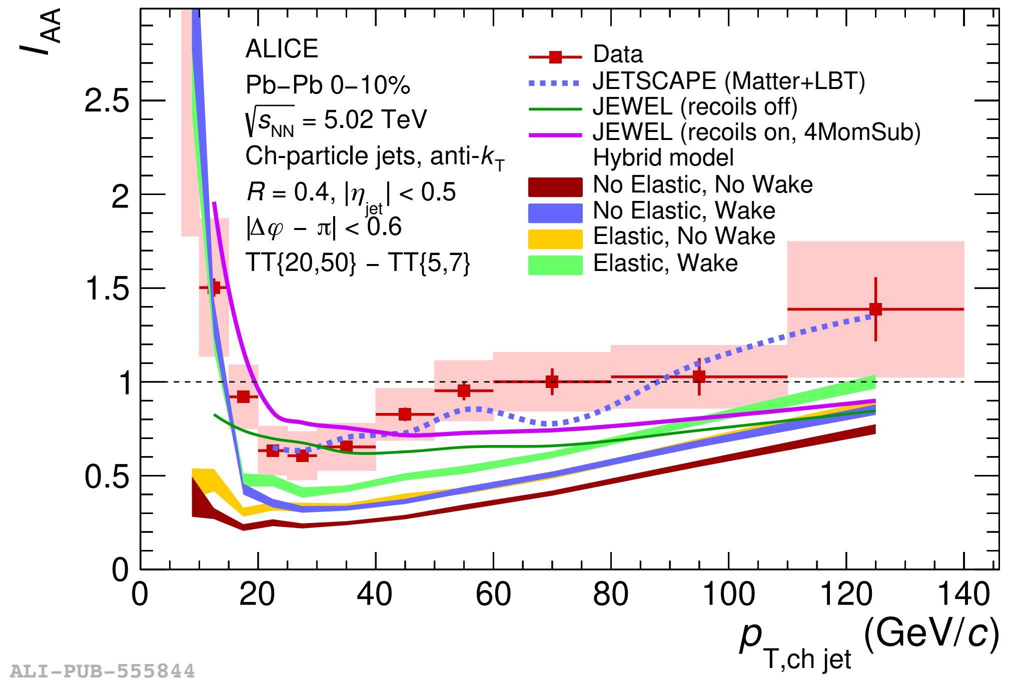
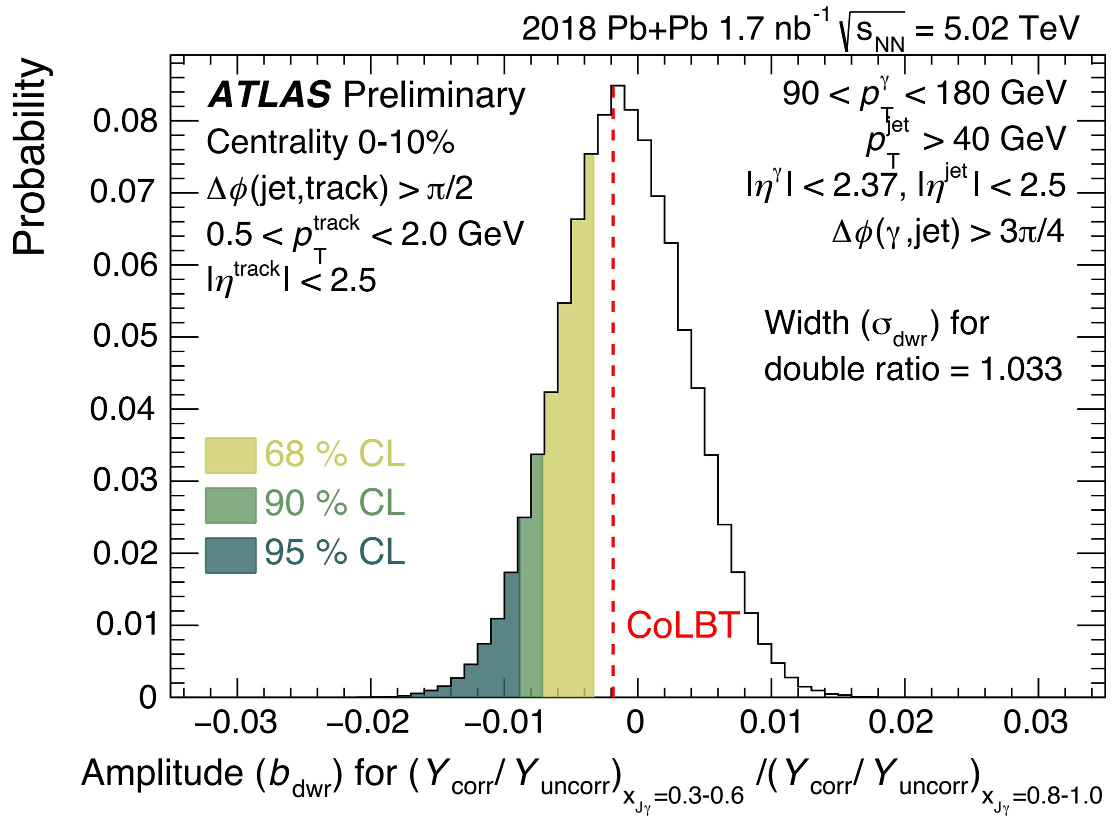
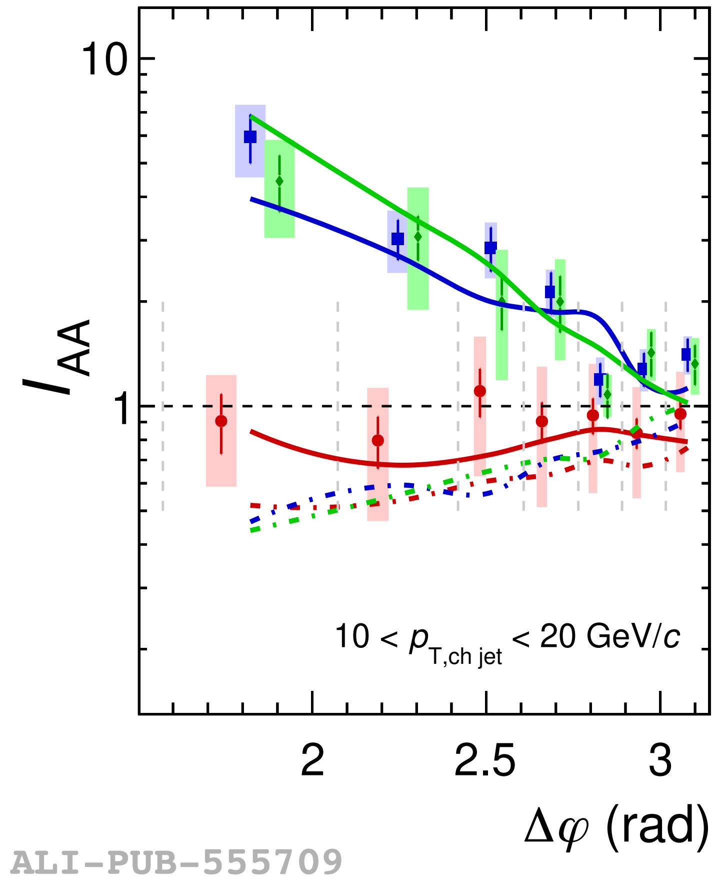
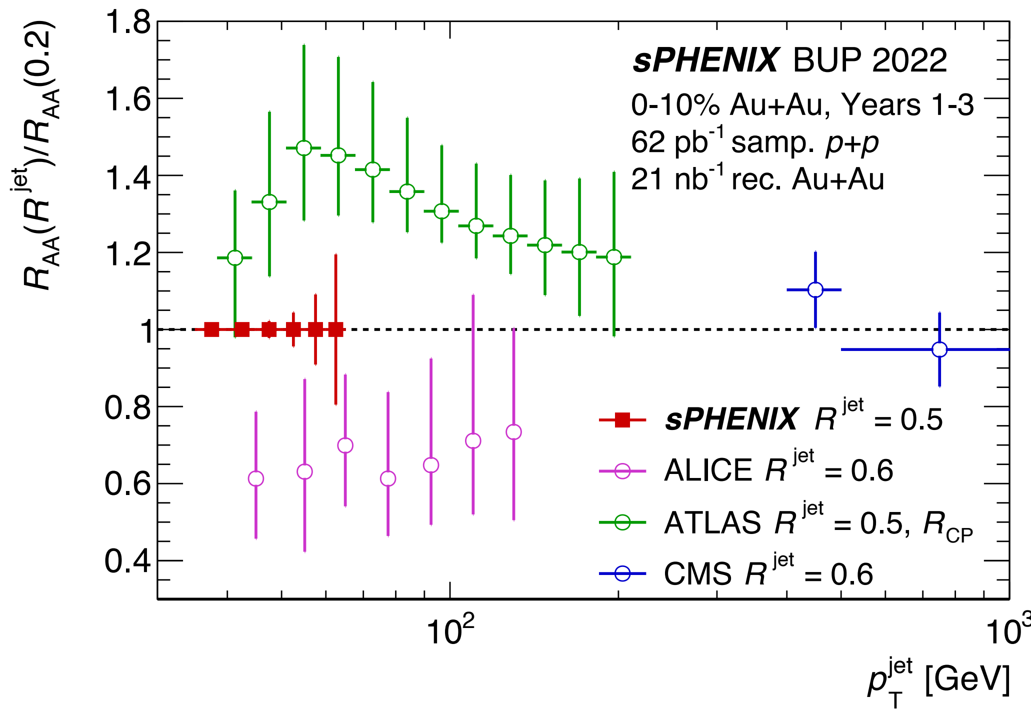
- LHC measurements on the medium response to jet propagation
  - ➡ *Enhancement of low p_T particles at large angles w.r.t jet axis*
  - ➡ *Acoplanarity broadening*
  - ➡ *Hint of diffusion wake signal*
  - ➡ *Mild R-dependence of jet R_{AA} at high-p_T, tension between experiments at low-p_T*

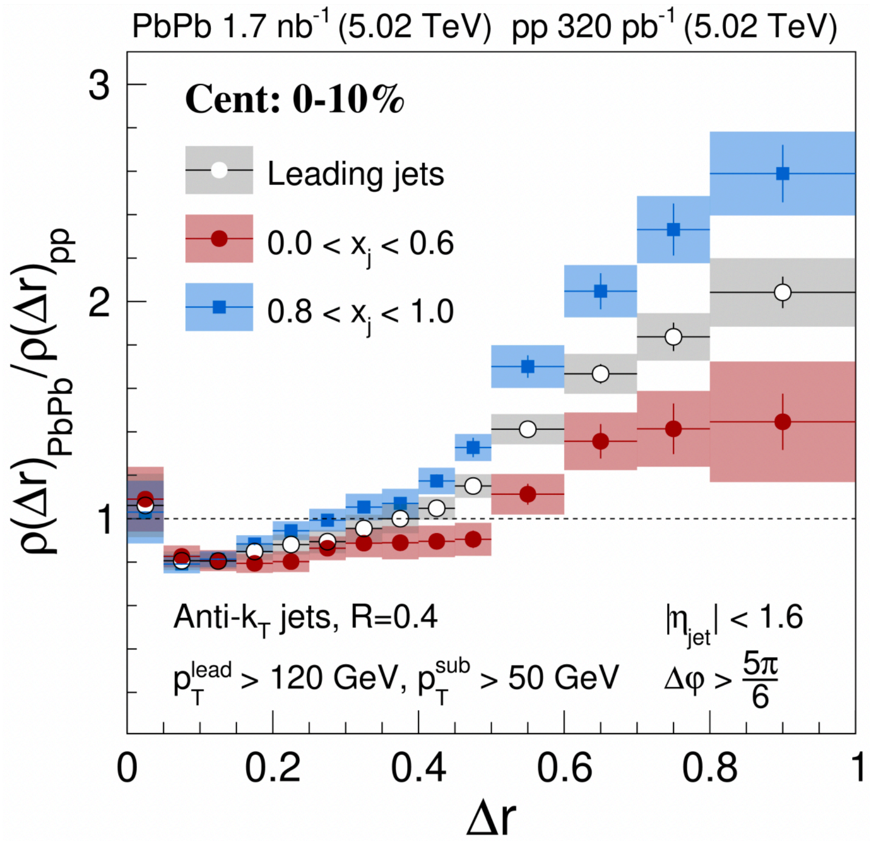
Summary











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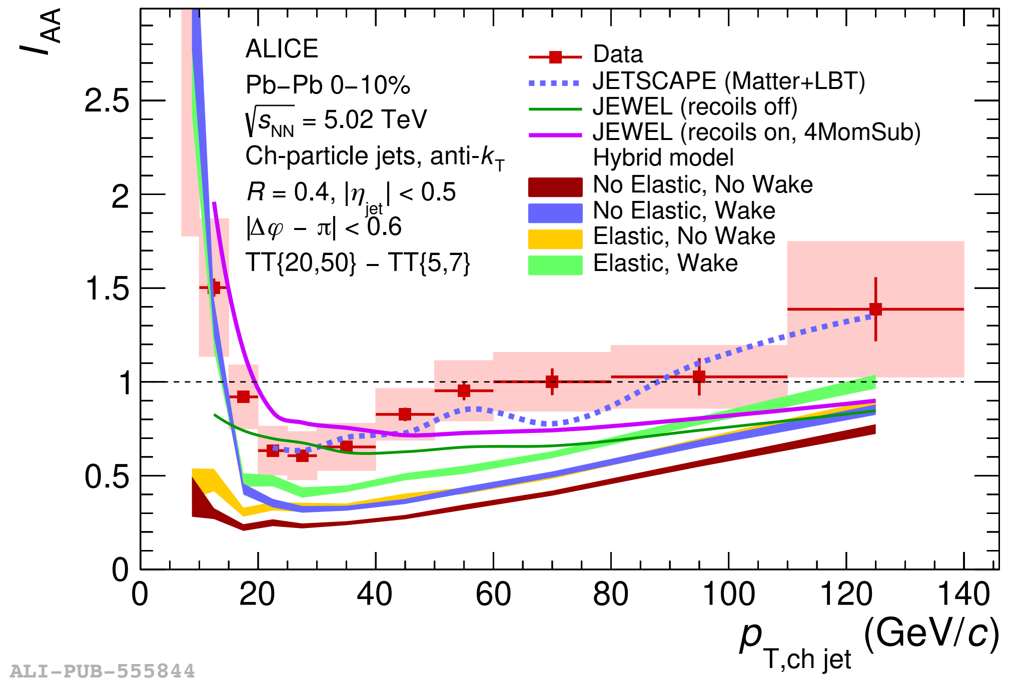

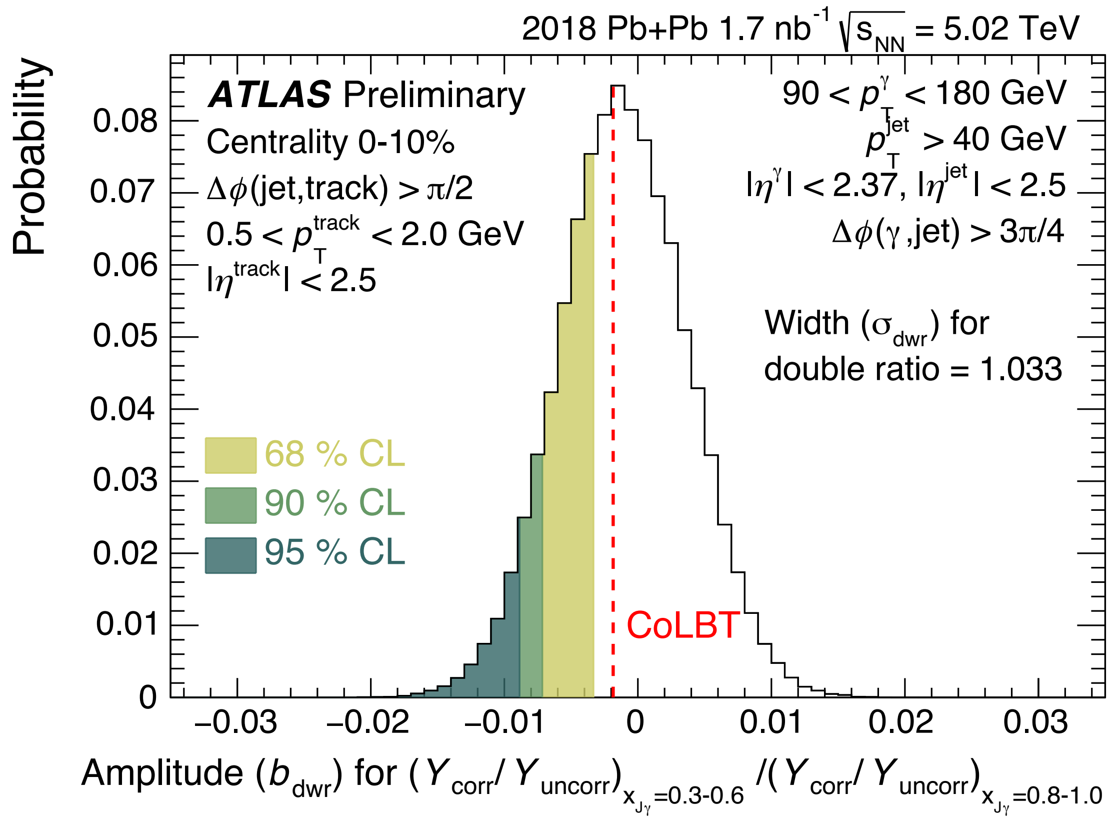

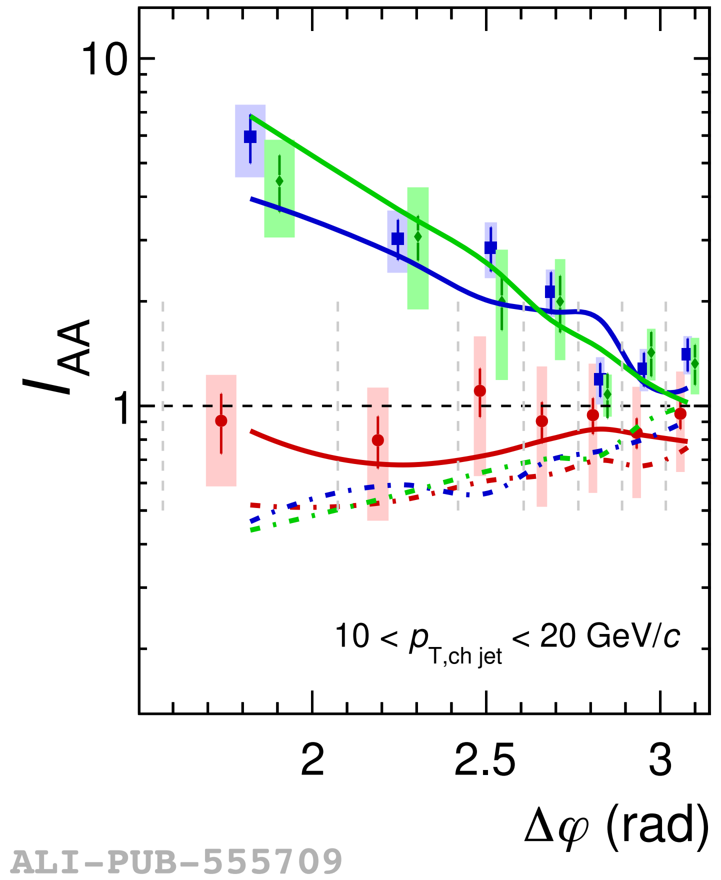

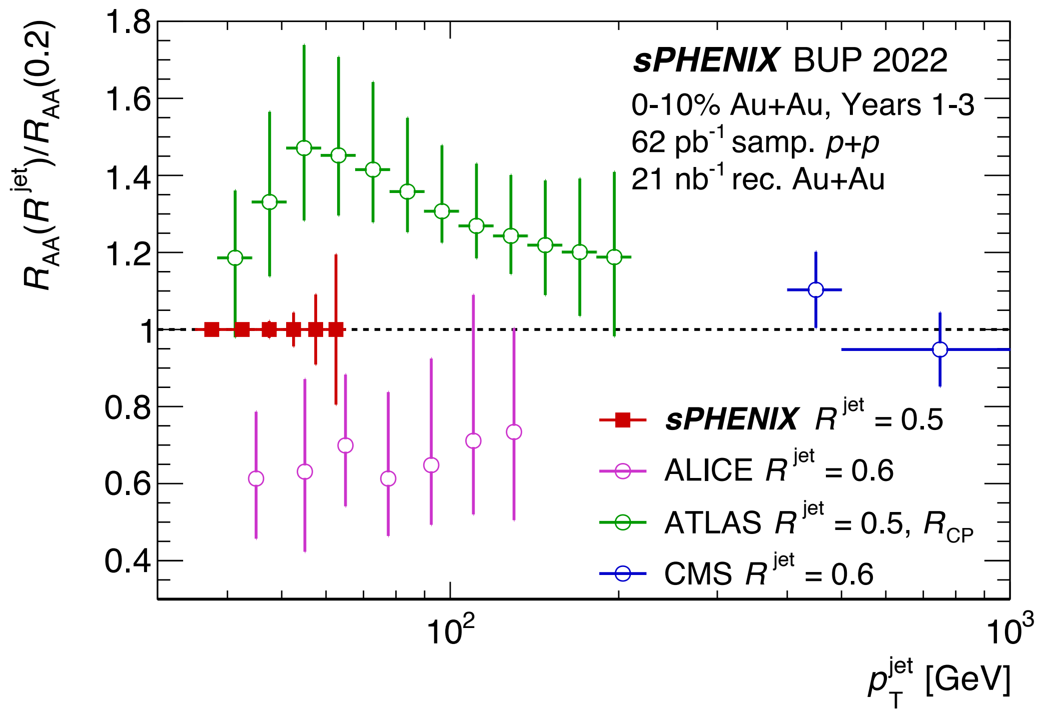

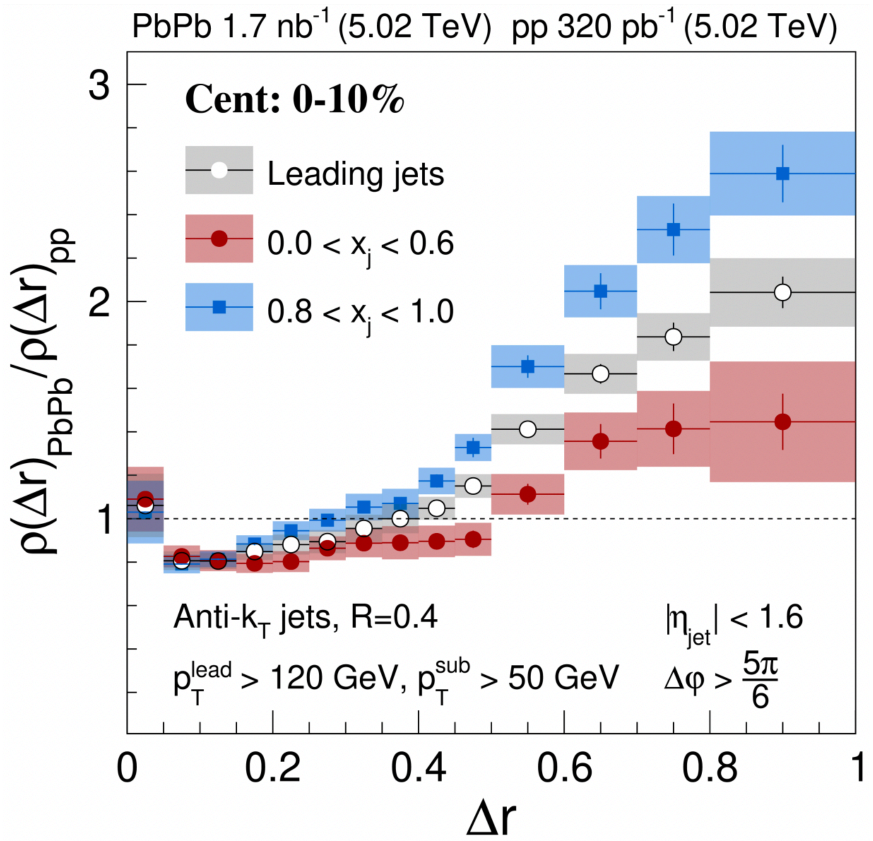

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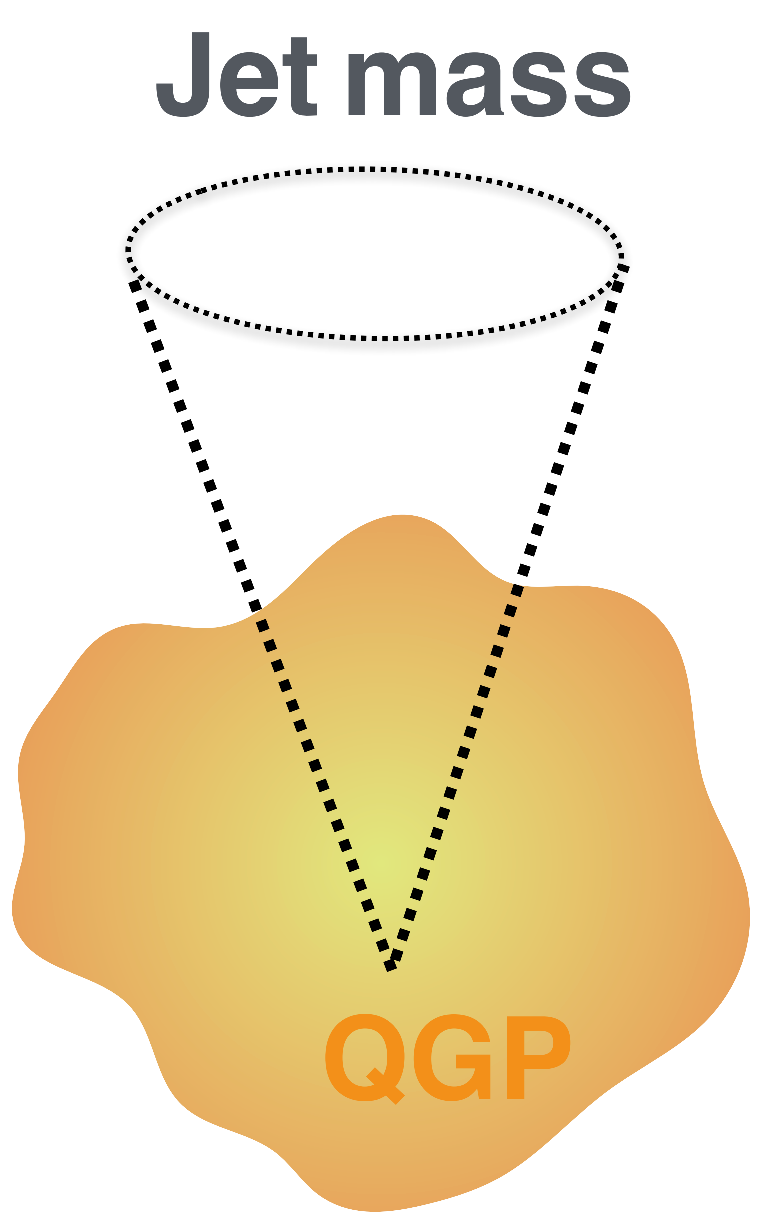
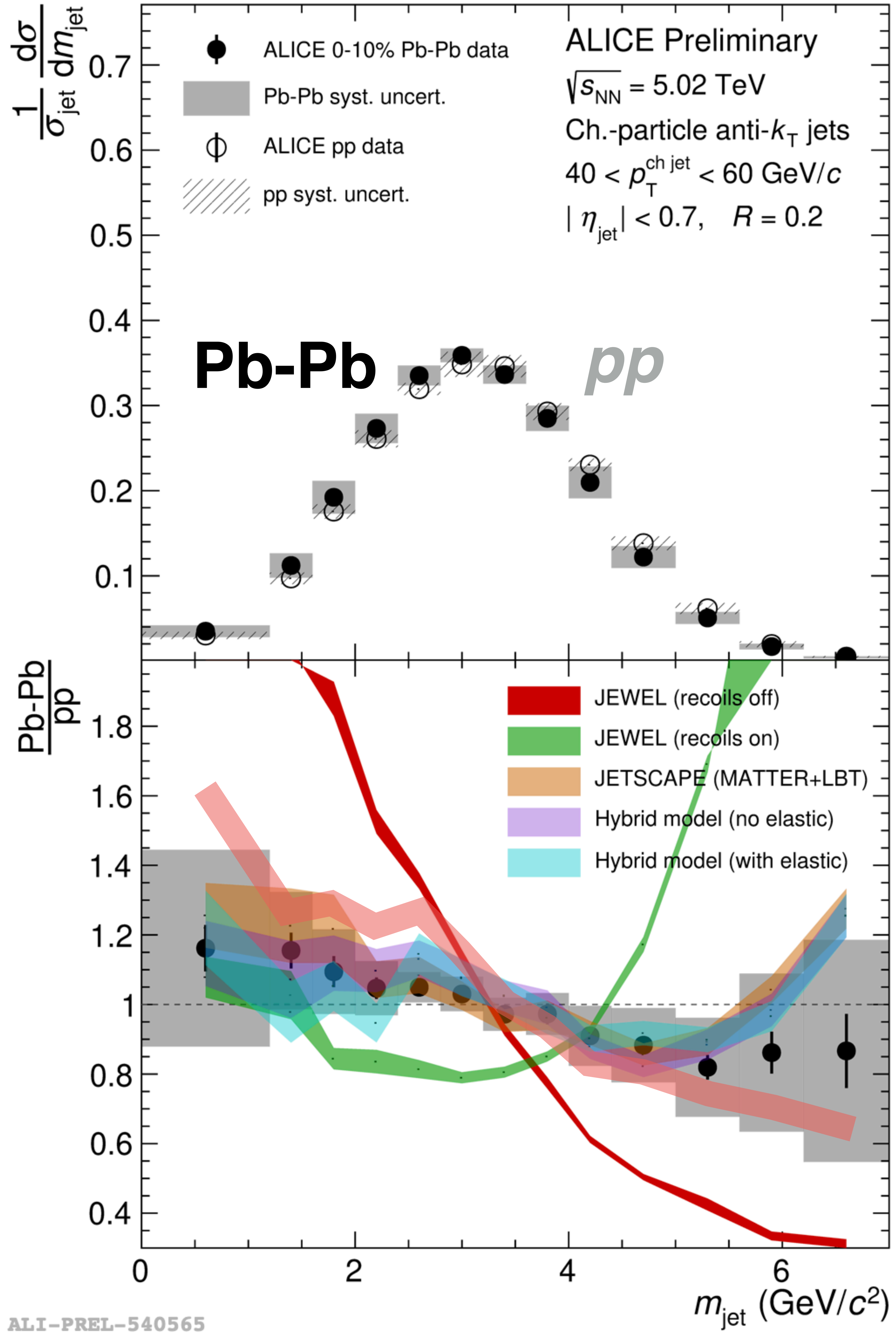
Thank you!

BACK UP

Ungroomed Charged Jet Mass

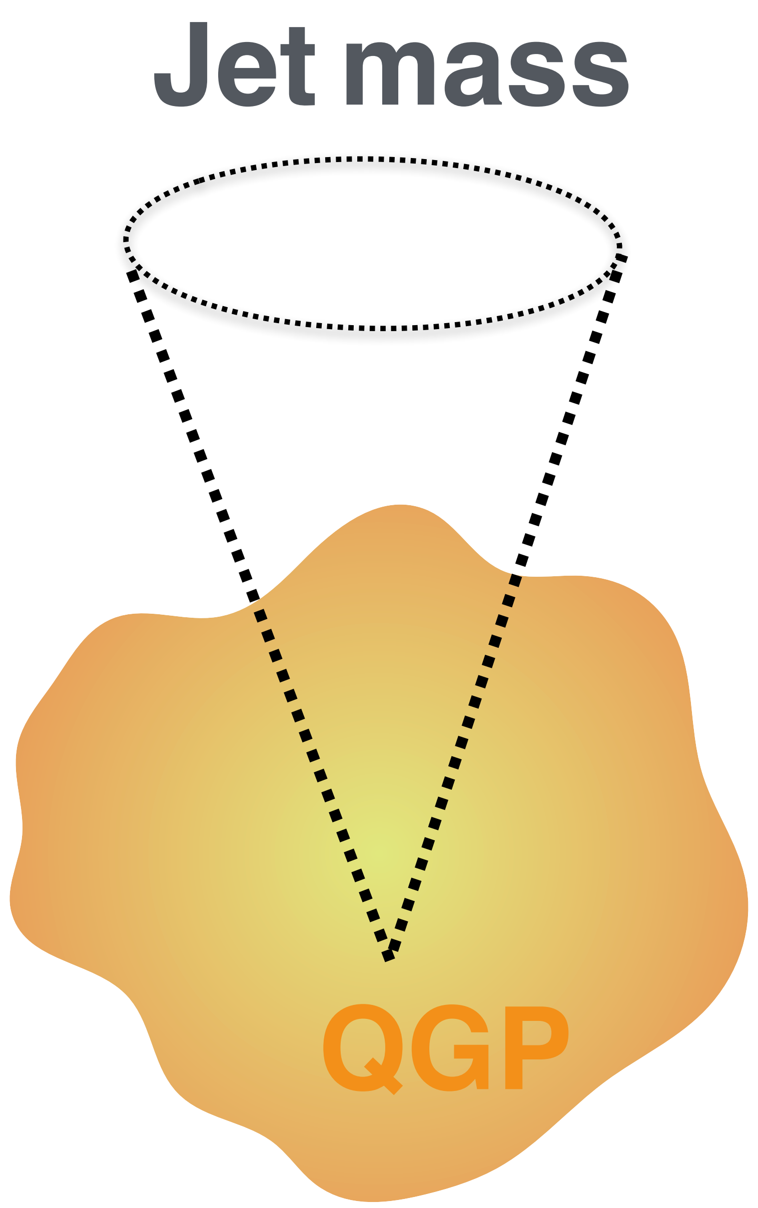


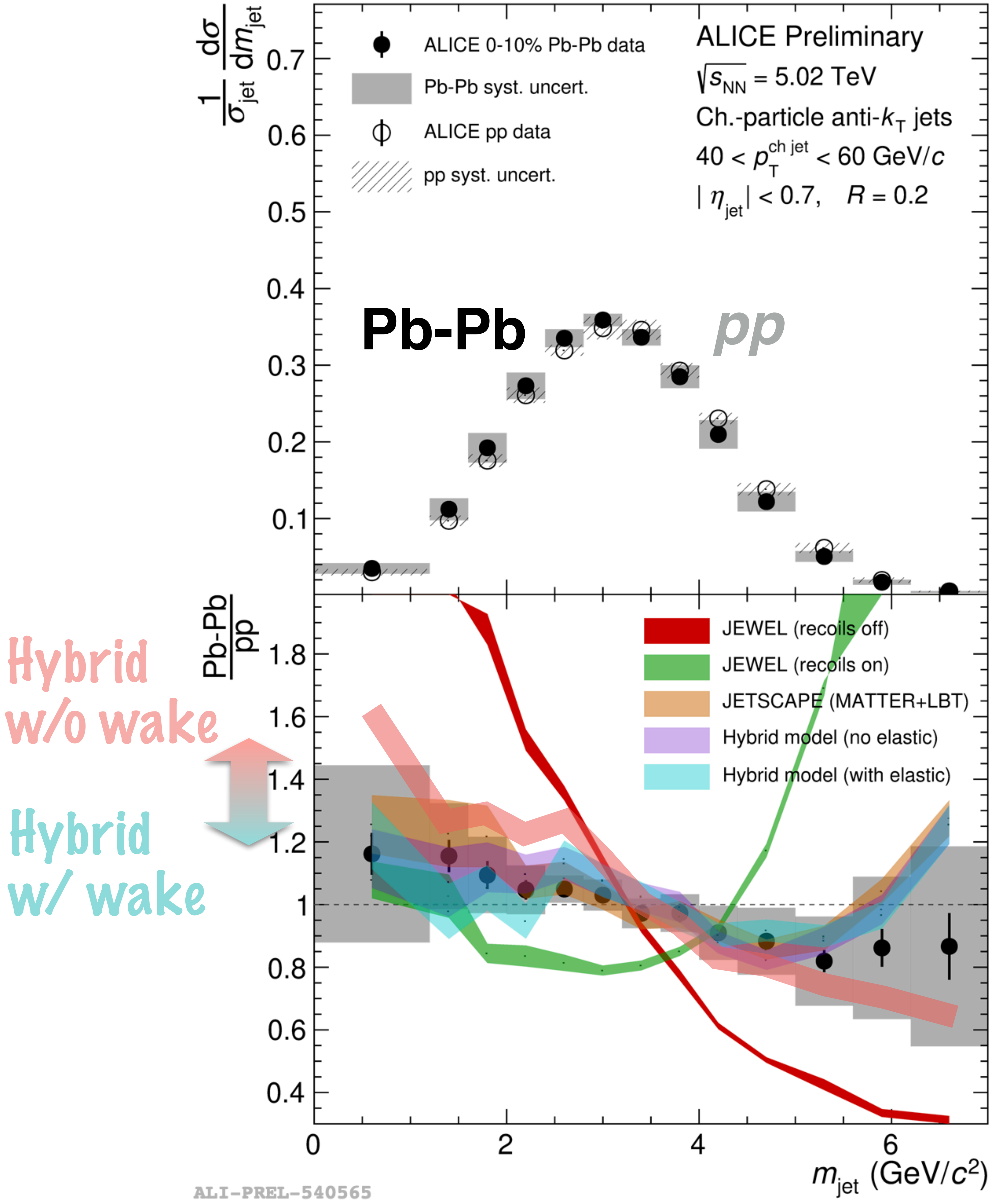


ALICE *ALI-PREL-540565*

- ***Ungroomed* vs *Groomed***
  - ➡ *Ungroomed* jets; sensitive to medium response
- Hint of shift towards low mass in **Pb-Pb** compared to ***pp***

Ungroomed Charged Jet Mass





***ALICE** ALI-PREL-540565*

- ***Ungroomed* vs *Groomed***
  - ➡ *Ungroomed* jets; sensitive to medium response
- Hint of shift towards low mass in **Pb-Pb** compared to ***pp***
- Data slightly favors **Hybrid w/ wake** than Hybrid w/o wake