

Jet-induced Medium Response

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(Goldhaber Distinguished Fellow)



Brookhaven
National Laboratory



U.S. DEPARTMENT OF
ENERGY



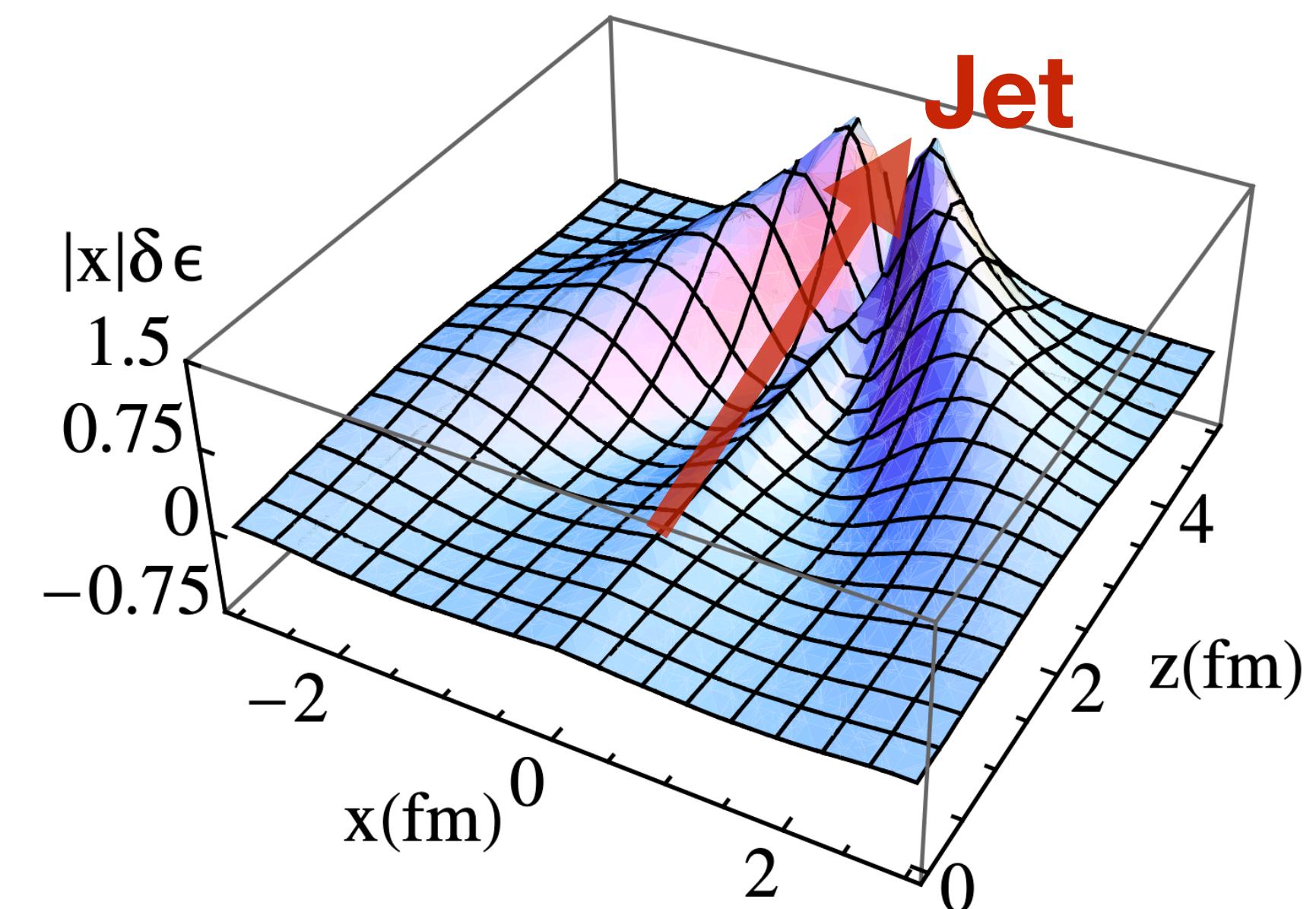
University of Colorado **Boulder**

Mutual Interaction : Medium \rightleftarrows Jets

- As jets are modified by medium, the medium is also affected by jets!



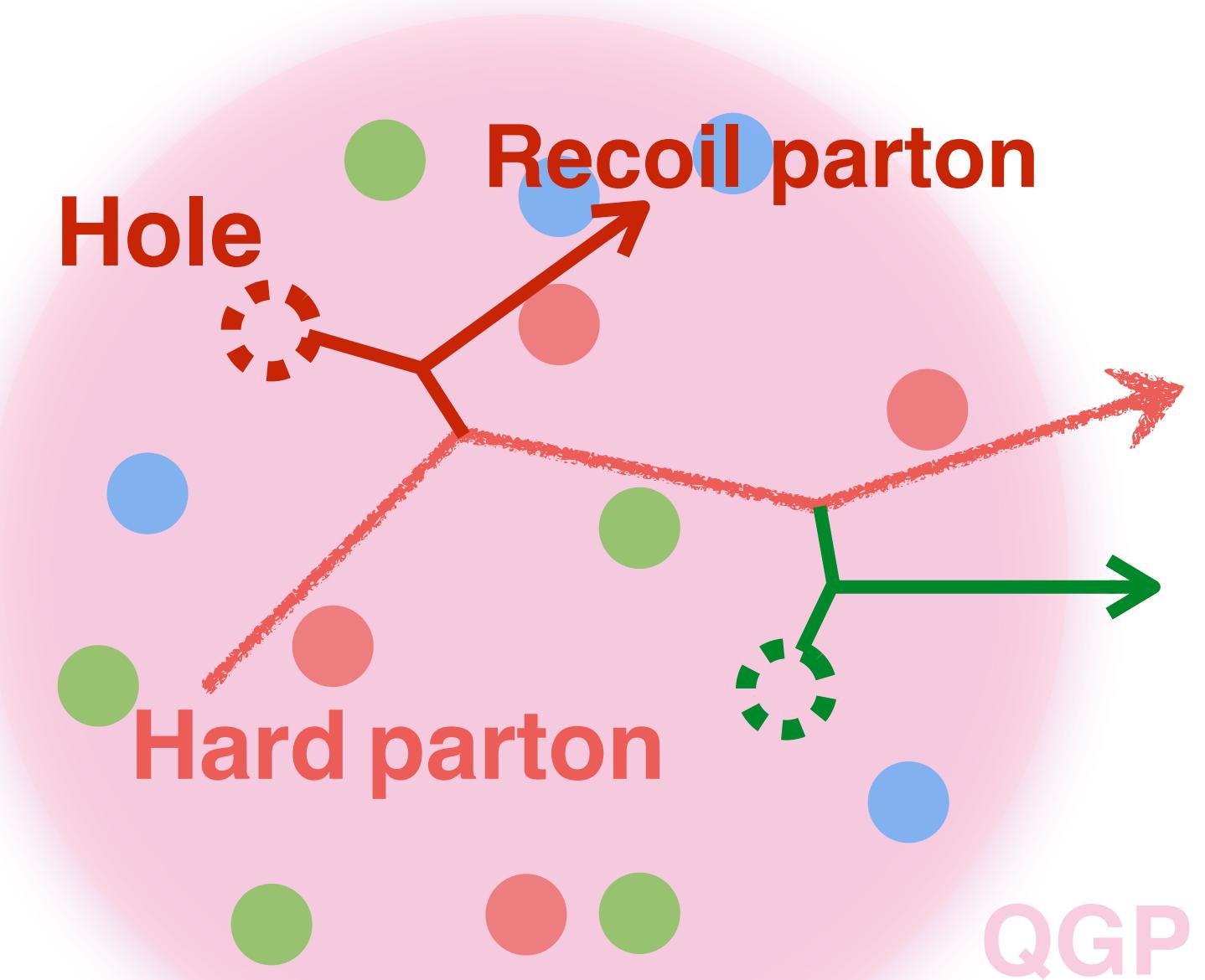
G.-Y. Qin et al, PRL 103, 152303 (2009)



- Structures formed; **Mach cone, sonic boom, shock wave, wake, diffusion wake, ...**
- By energy and momentum conservation, lost jet energy \rightarrow into medium

What is Medium Response?

- **Recoil** (Weakly-coupled approach, when $E > E_{\text{med}}$)
 - partons in medium scatter with hard parton
 - “hole” (or “negative”) of recoiled medium partons can be propagated and subtracted from the final parton spectra
- **Hydrodynamics** (Strongly-coupled approach, when $E \lesssim E_{\text{med}}$)
 - medium fluid with a source term from a jet; $\partial_\mu T_{\text{fluid}}^{\mu\nu} = J_{\text{jet}}^\nu$
- Medium response (medium excitation) \neq in-medium parton shower



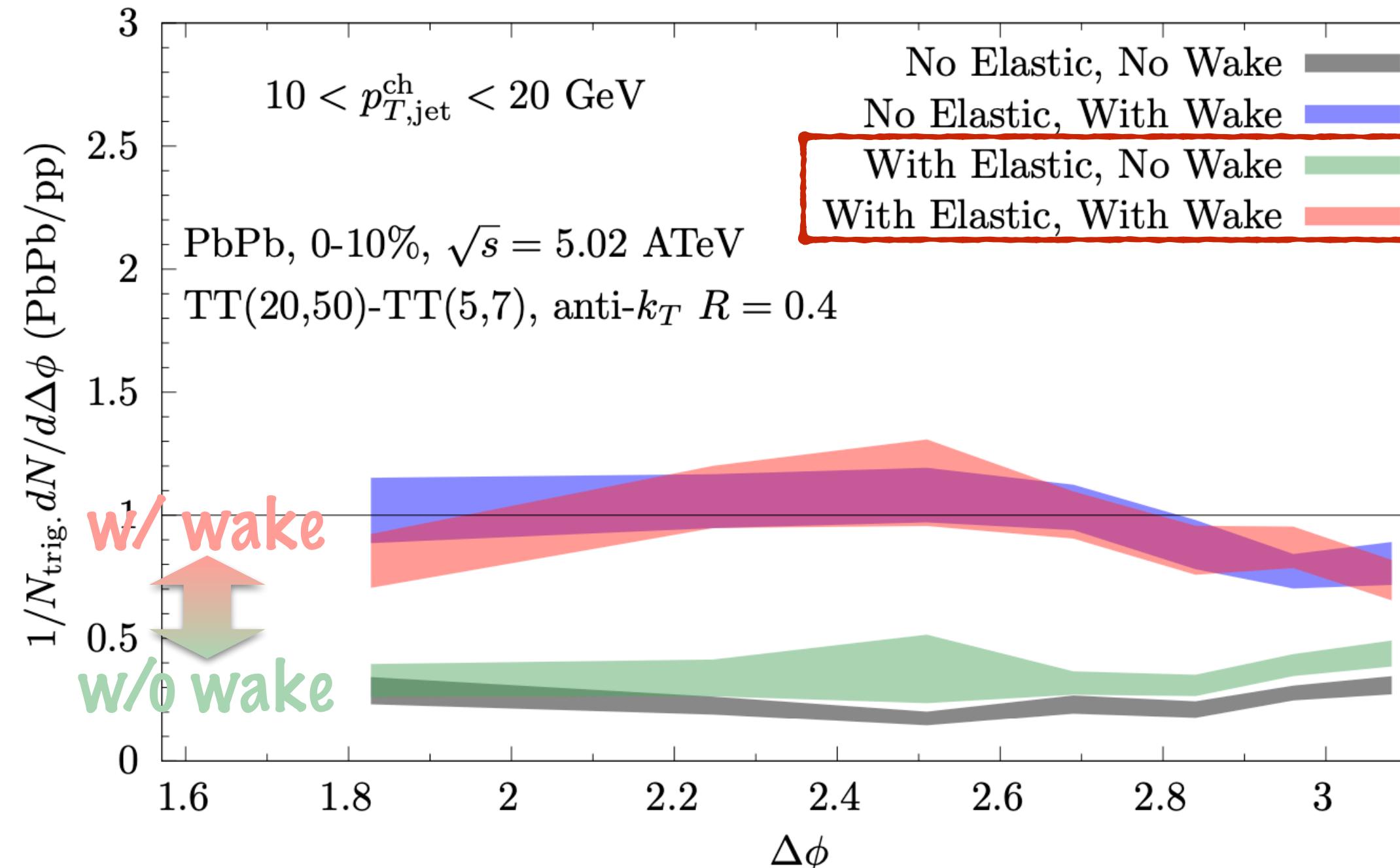
What Jet Observables to Investigate Medium Response?

- Jet quenching by (radiative energy loss + **medium response** + **Molière scattering** + ...)
- Hybrid strong/weak coupling model predict more sensitivity to
 - **wake effect** for jet shapes, fragmentation functions, boson (or jet)-hadron correlations, acoplanarity, ...
 - **Molière scattering** for groomed jet observables (e.g. R_g , z_g , girth, leading k_T) with small jet cone size, jet axes difference, ...

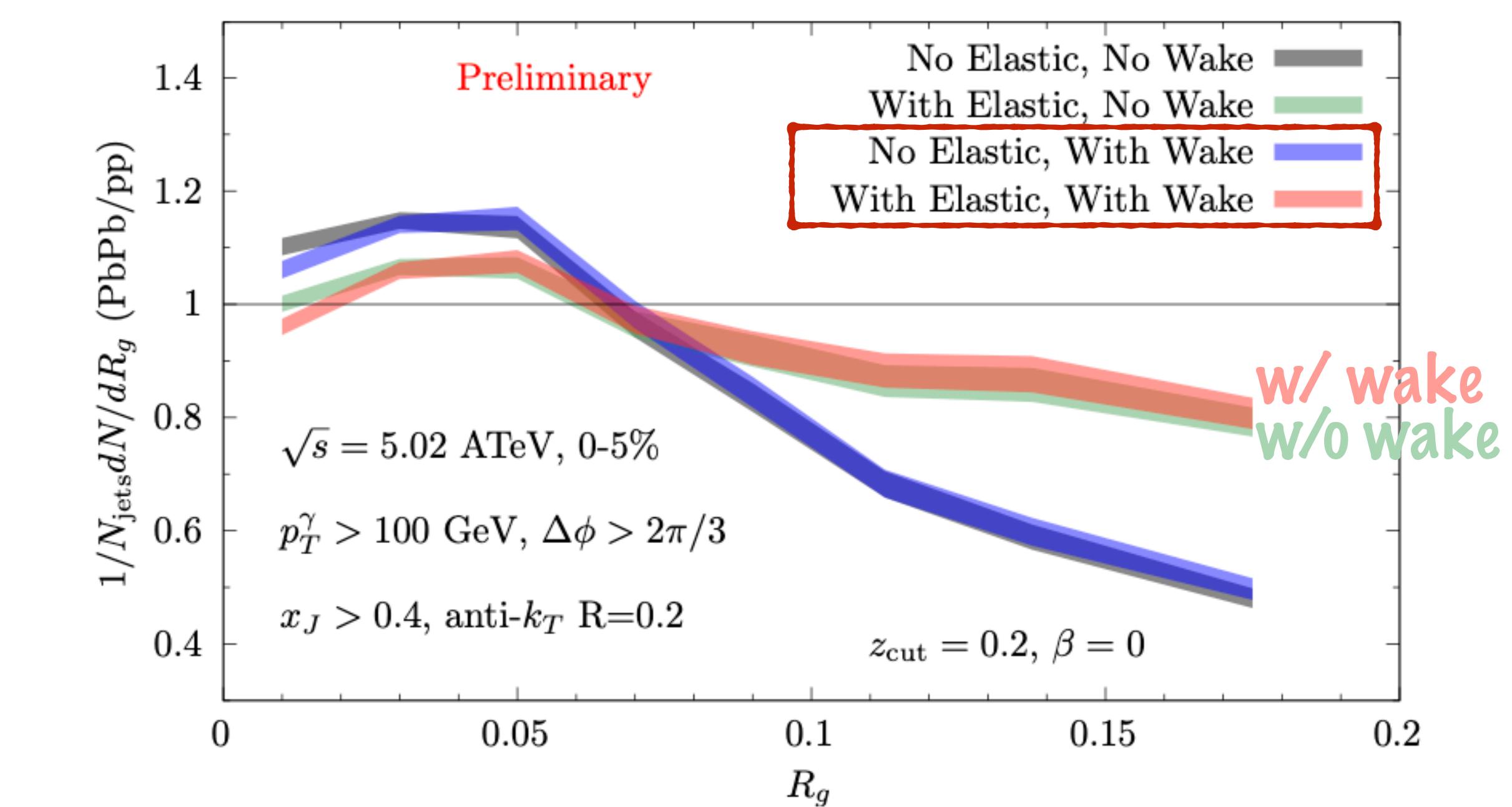
e.g.

[Talk by K. Rajagopal](#)

hadron-jet acoplanarity → **sensitive** to medium response

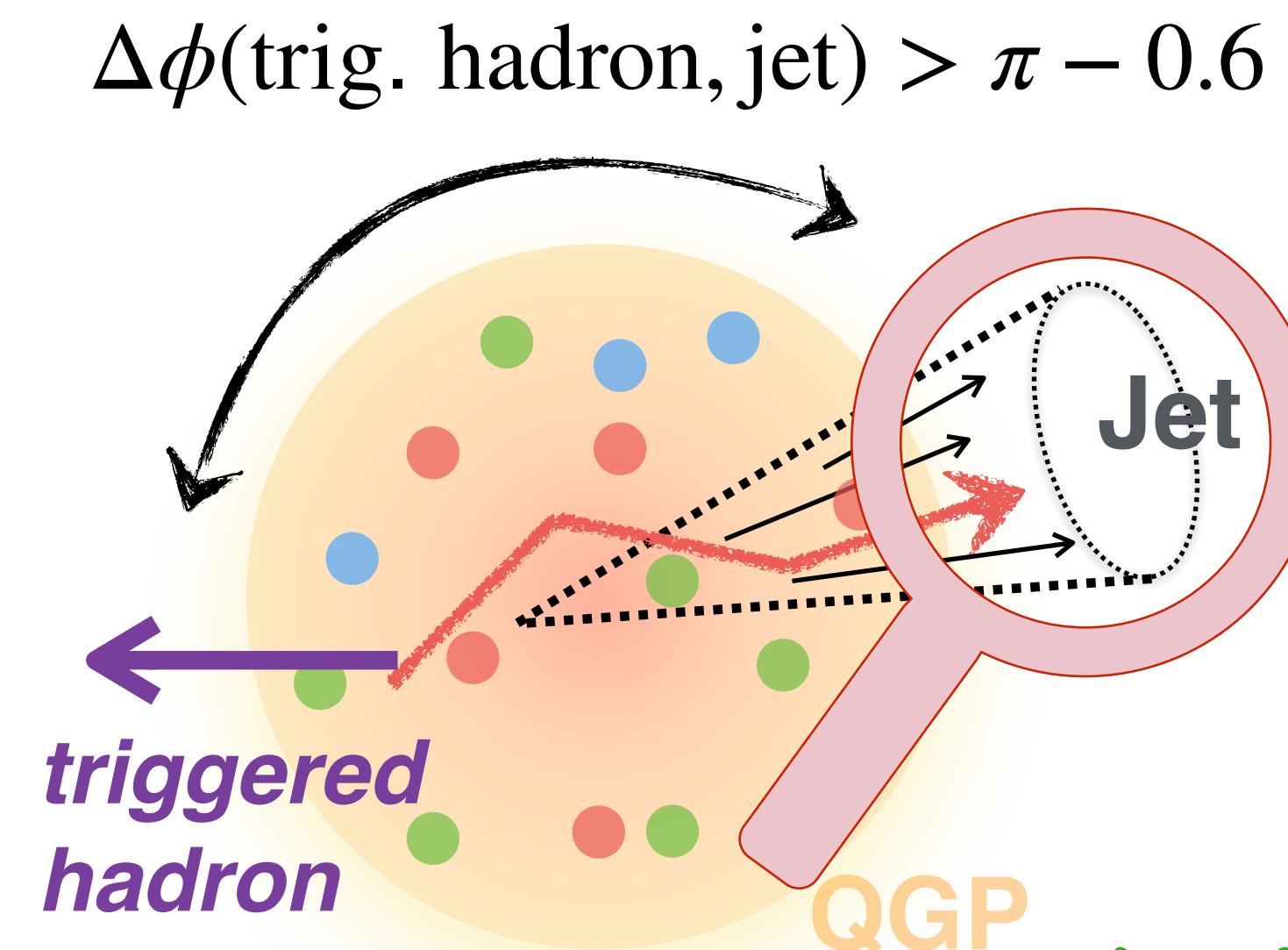


groomed γ -jet R_g w/ $R=0.2$ → **insensitive** to medium response

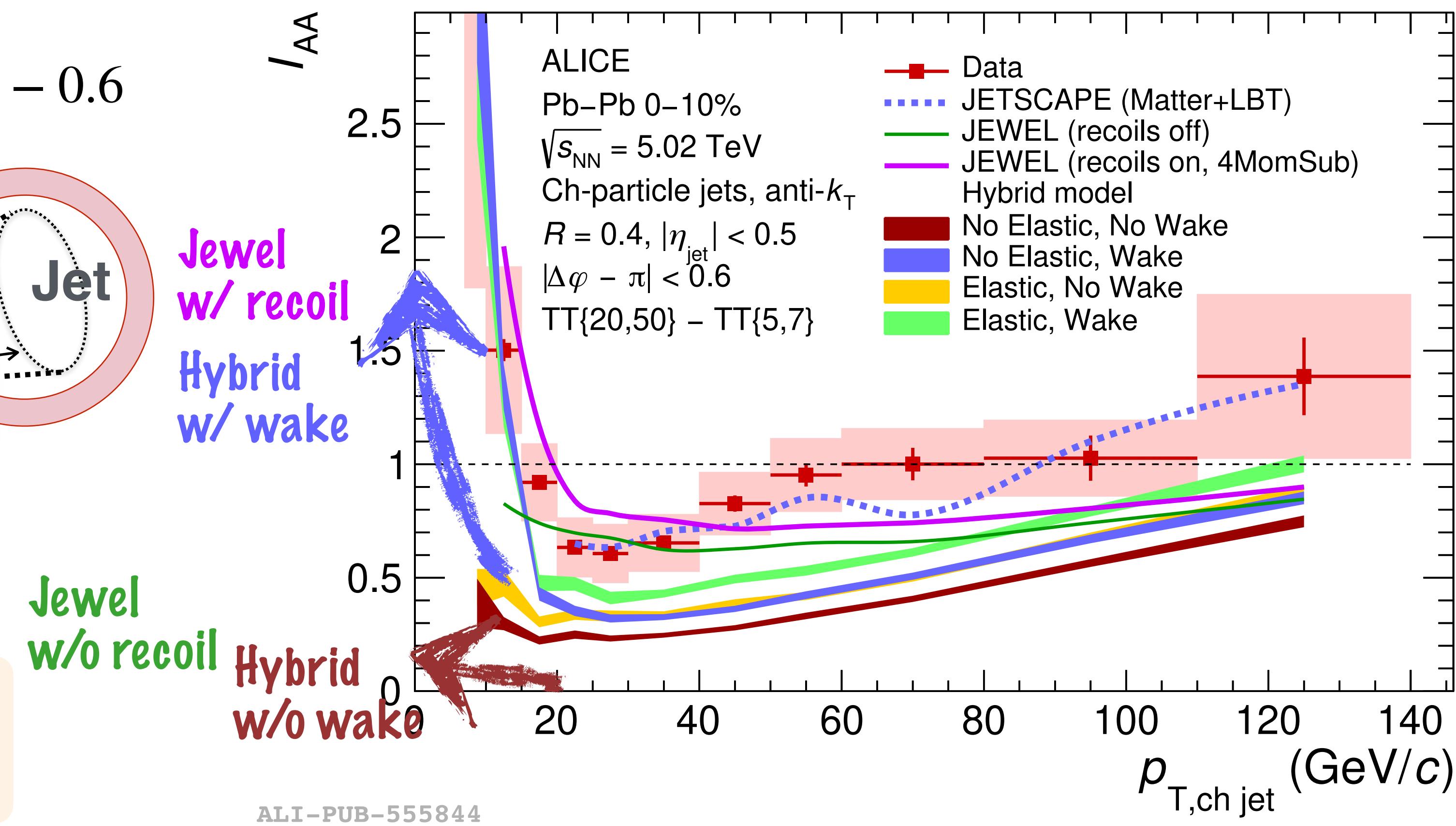


Experimental Results

Hadron-Jet Correlation at LHC: p_T dependence



$$I_{AA} = \frac{Y_{\text{Pb+Pb}}^{\text{jet}} / N_{\text{Pb+Pb}}^{\text{trig}}}{Y_{pp}^{\text{jet}} / N_{pp}^{\text{trig}}}$$

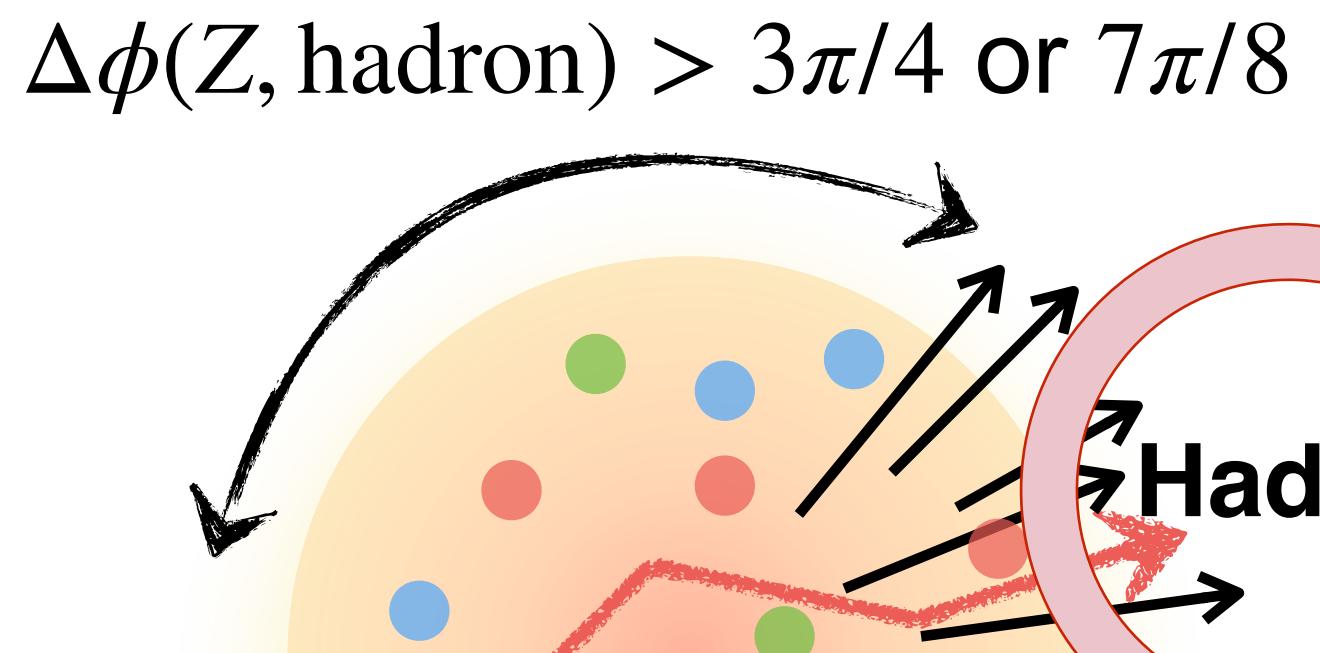


QM Finalized

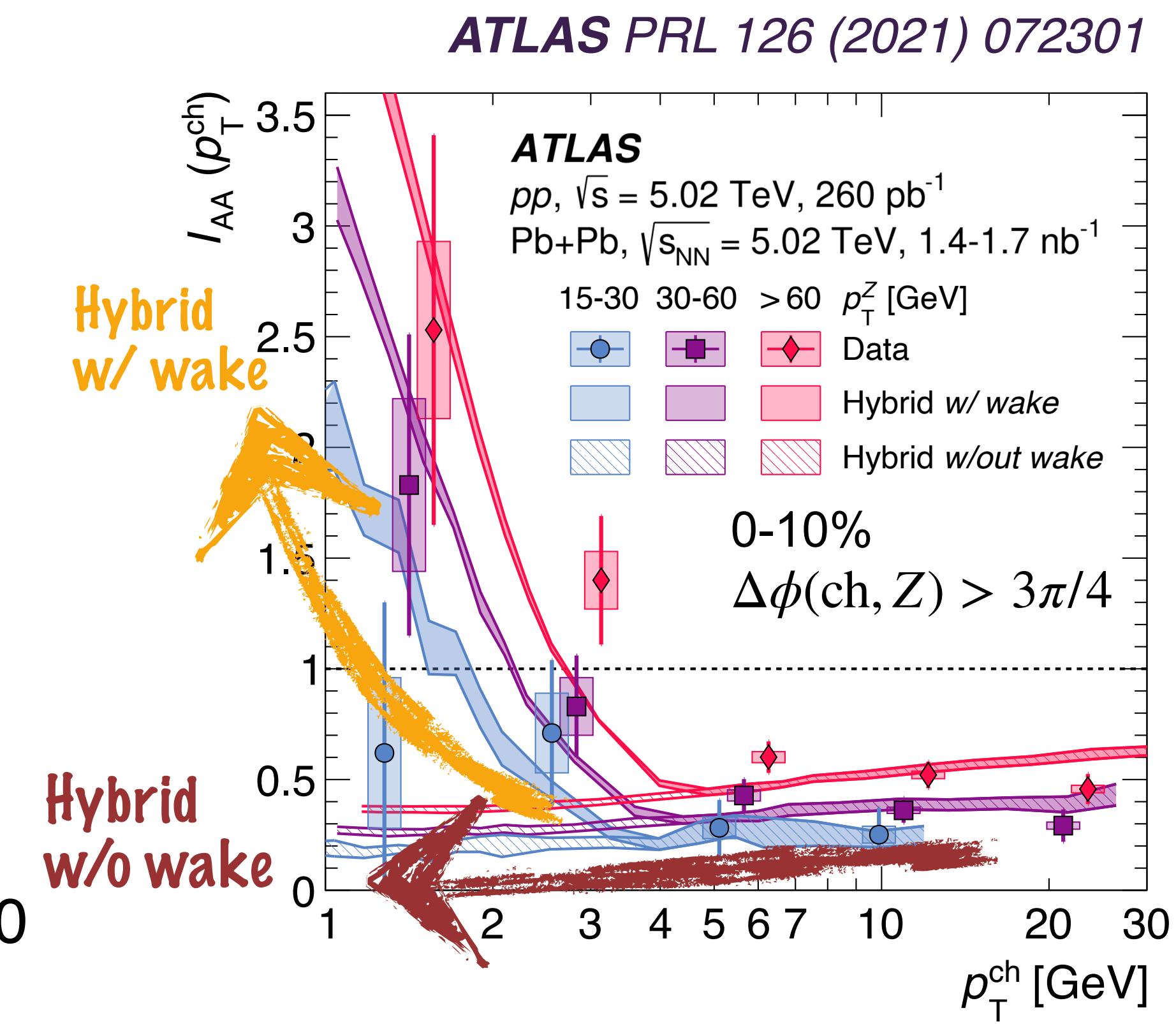
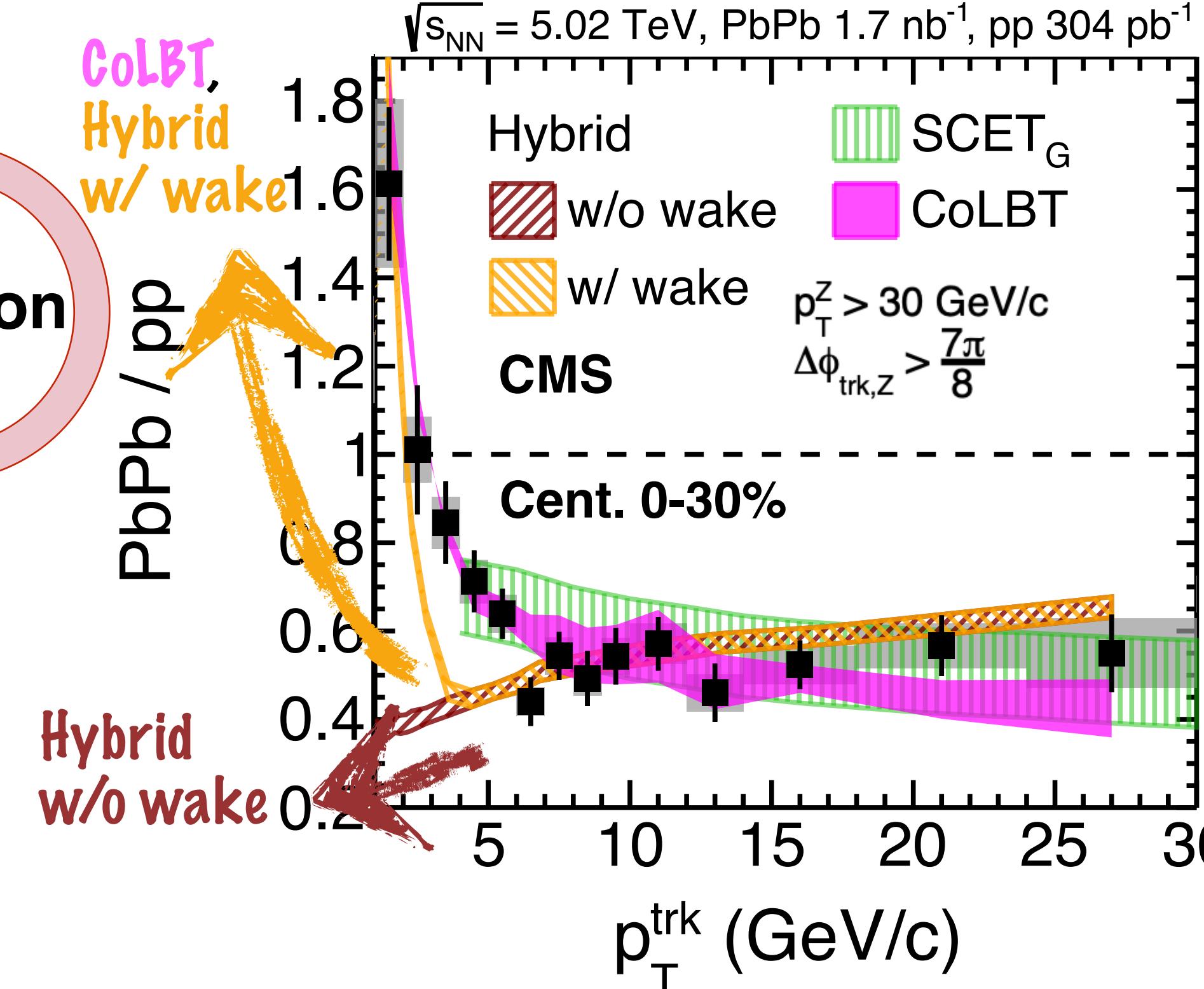
ALICE
[arXiv:2308.16128](https://arxiv.org/abs/2308.16128)
[arXiv:2308.16131](https://arxiv.org/abs/2308.16131)
[Talk by J. Norman](#)

- 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**)

Z-hadron Correlation at LHC: p_T dependence



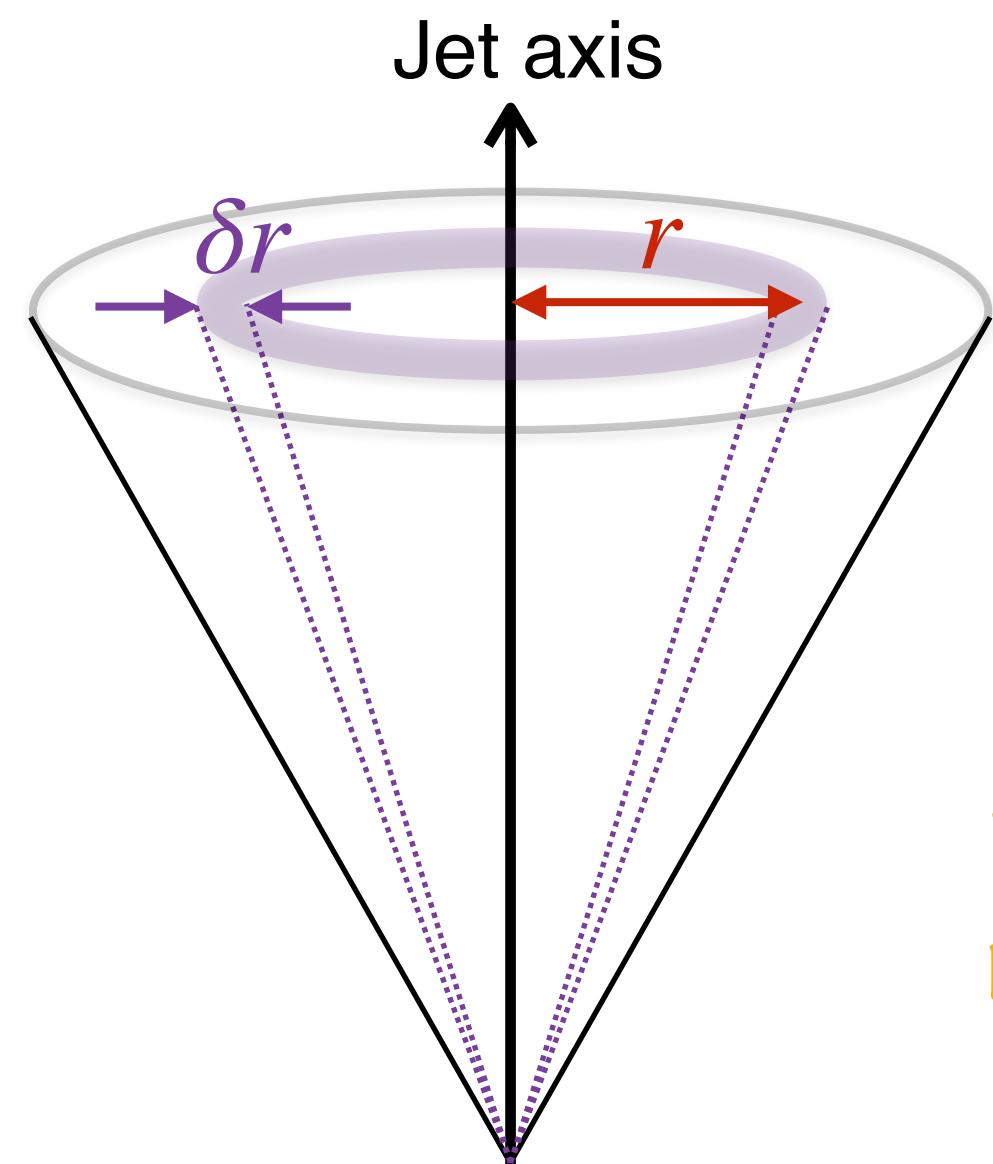
$$I_{AA} = \frac{Y_{\text{Pb+Pb}}^{\text{hadron}} / N_{\text{Pb+Pb}}^Z}{Y_{pp}^{\text{hadron}} / N_{pp}^Z}$$



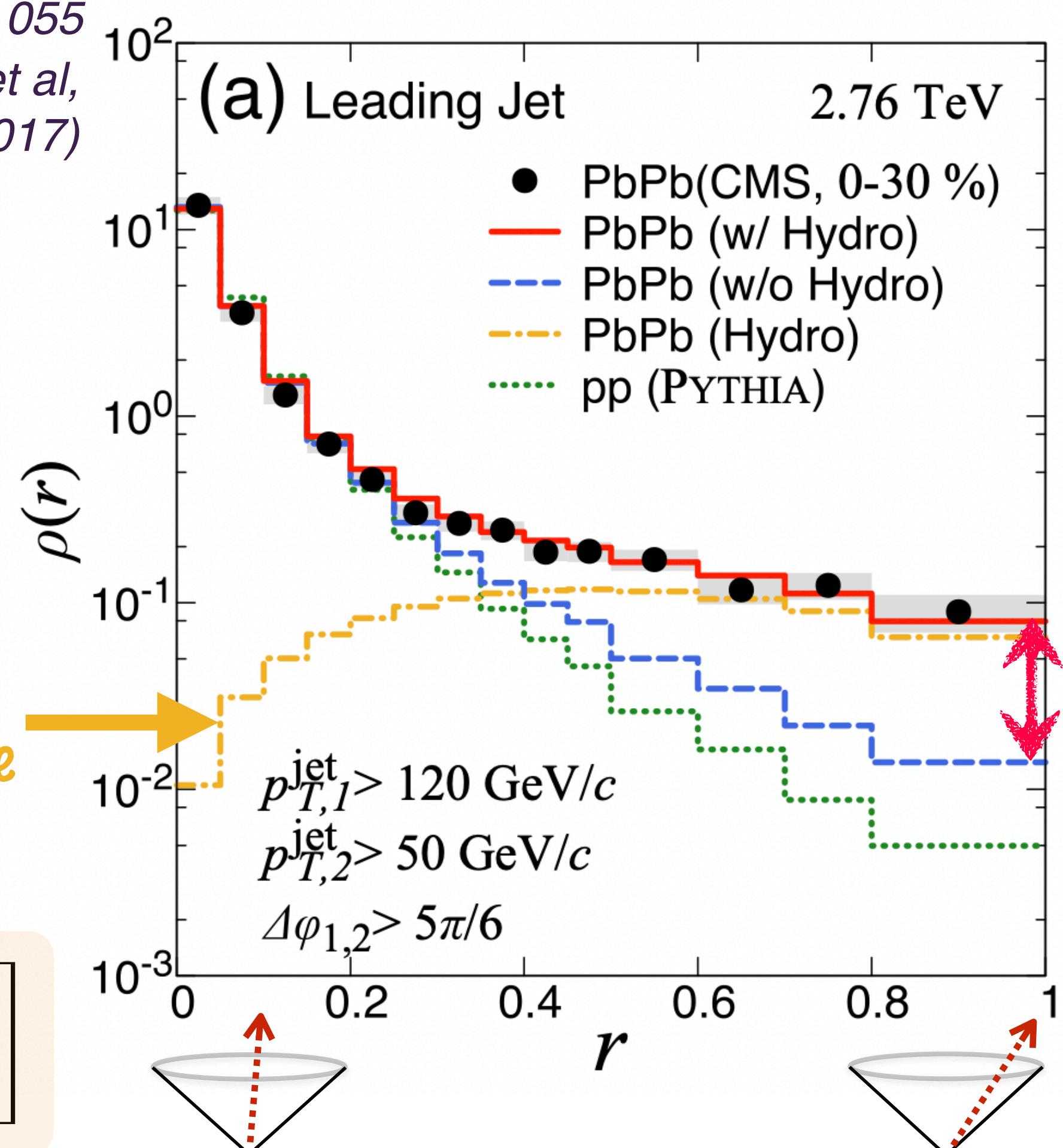
- Low p_T hadron enhancement
 - significant difference between w/ and w/o medium response
 - models w/ medium response (**Hybrid w/ wake** and **CoLBT**) describe the data better

Jet Shape at LHC: Angular Distribution

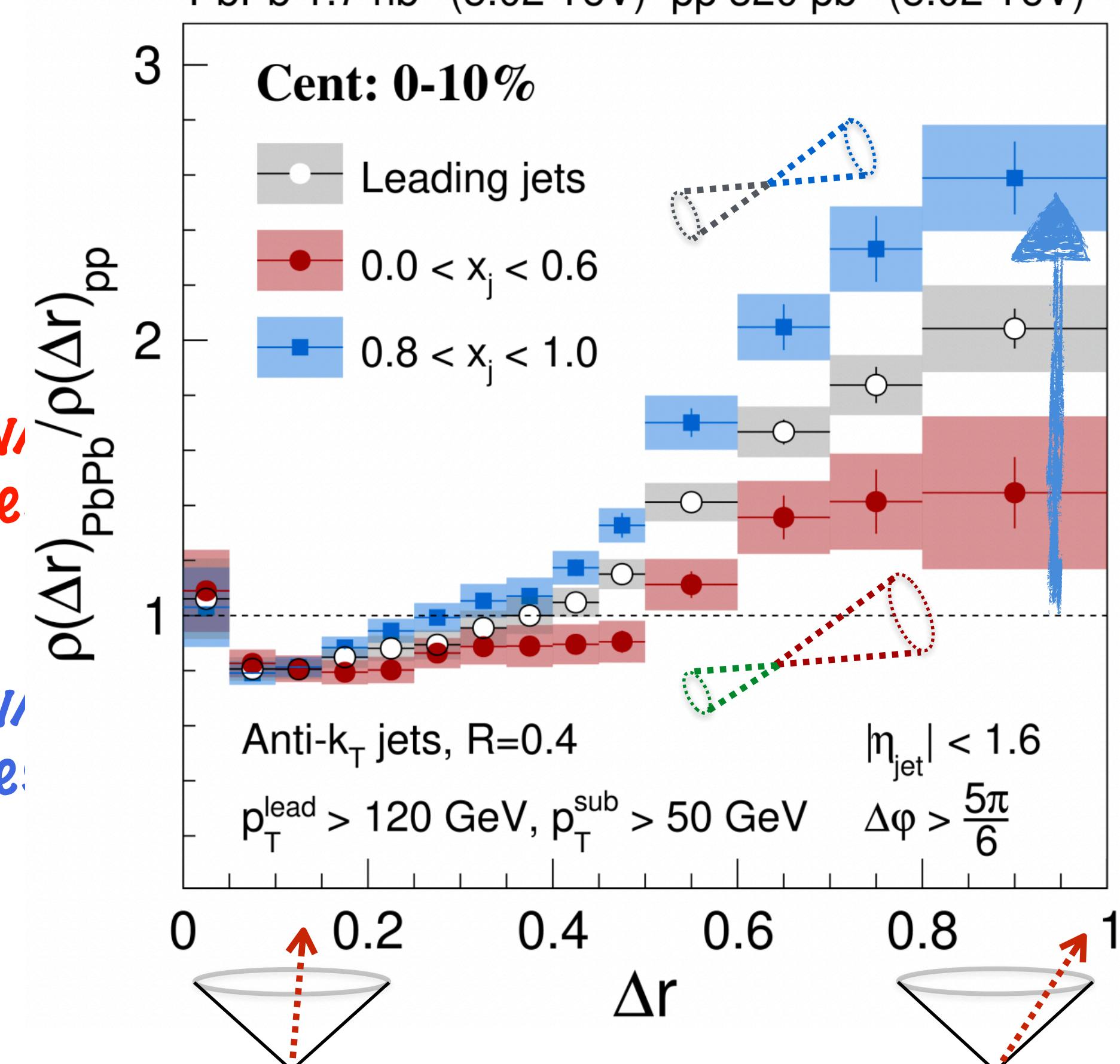
CMS JHEP 11 (2016) 055
 Y. Tachibana et al,
PRC 95, 044909 (2017)



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

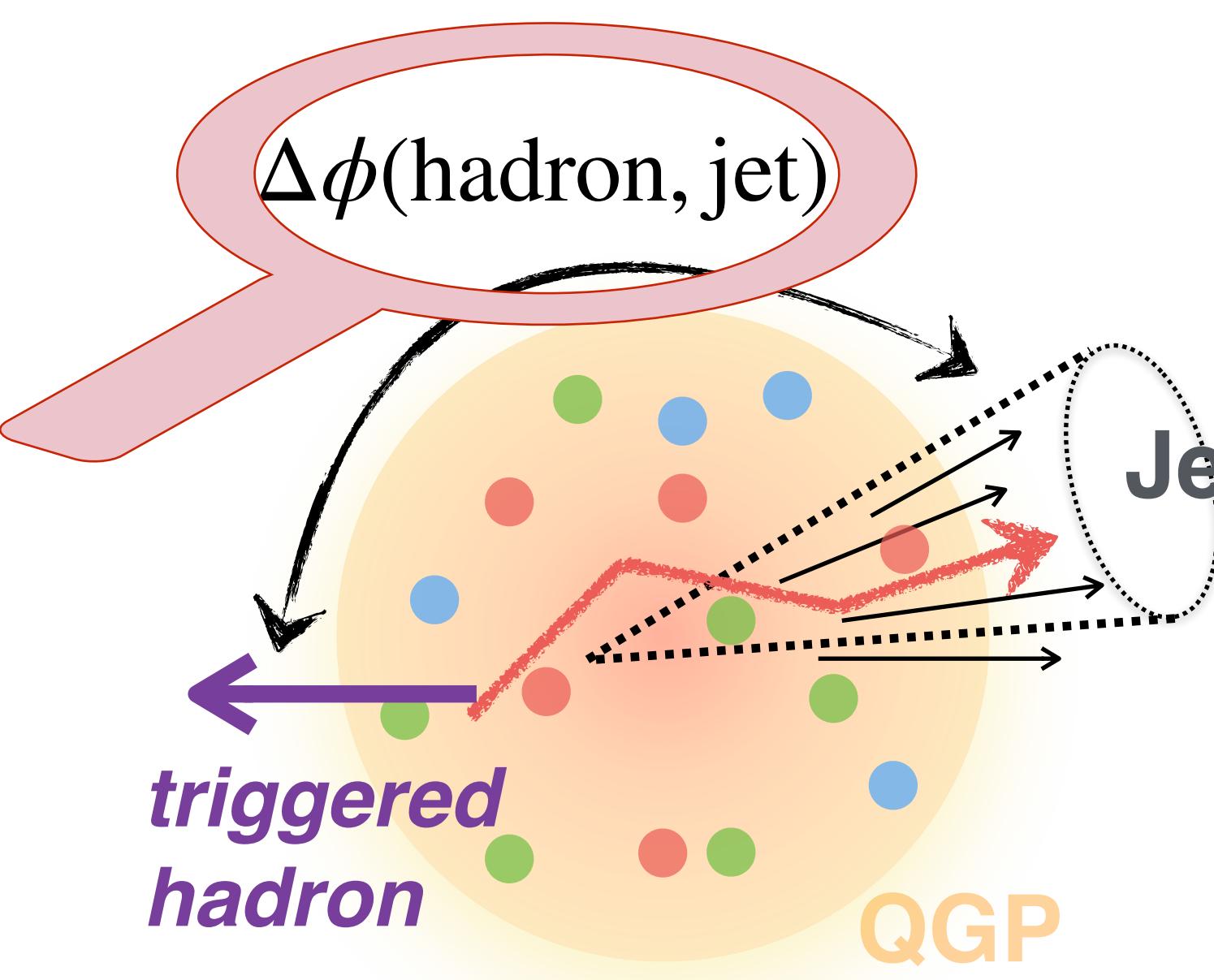


CMS JHEP 05 (2021) 116 [Talk by J. Viinikainen](#)
 PbPb 1.7 nb^{-1} (5.02 TeV) pp 320 pb^{-1} (5.02 TeV)



- At *small angle*, negligible effect of medium response by models
- At *large angle*, **enhancement**; explained by **medium response**

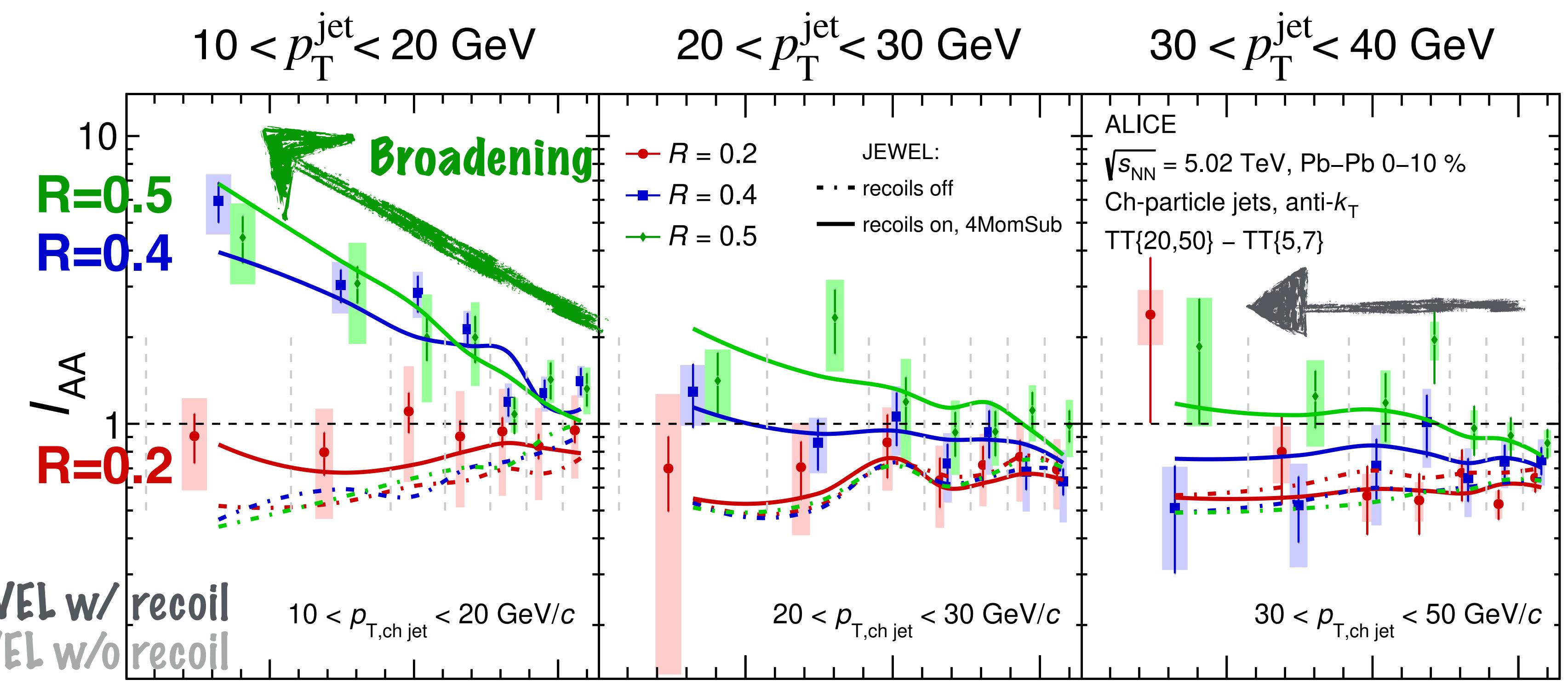
Hadron-Jet Correlation at LHC: Acoplanarity



QM Finalized

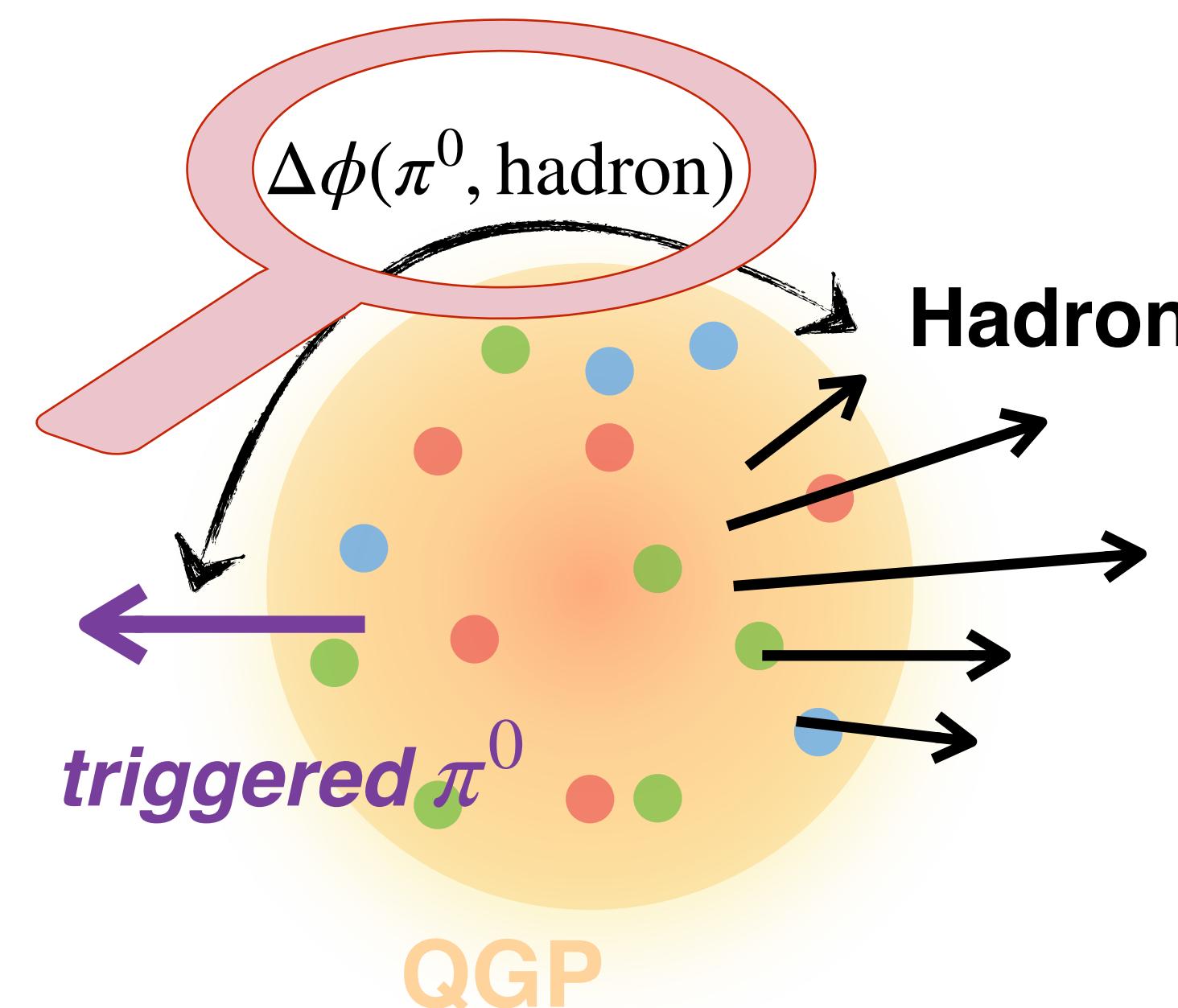
$$I_{AA} = \frac{Y_{\text{Pb+Pb}}^{\text{hadron}} / N_{\text{Pb+Pb}}^{\text{trig}}}{Y_{pp}^{\text{hadron}} / N_{pp}^{\text{trig}}}$$

ALICE arXiv:2308.16128
[Talk by J. Norman](#)



- Hadron-jet **acoplanarity broadening** particularly for *low- p_T* jets w/ **large R**
- Data described well by **JEWEL w/ medium response**

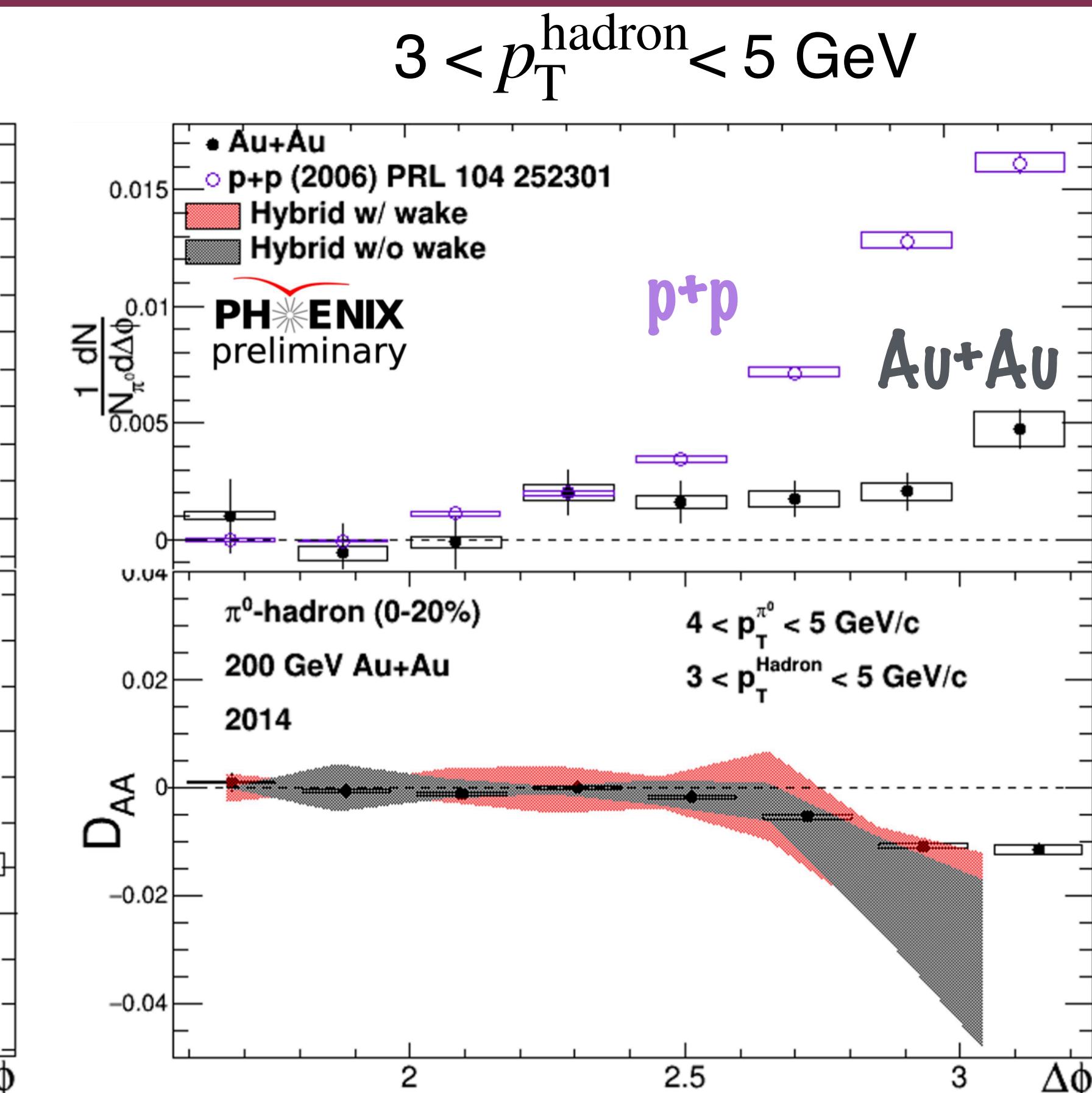
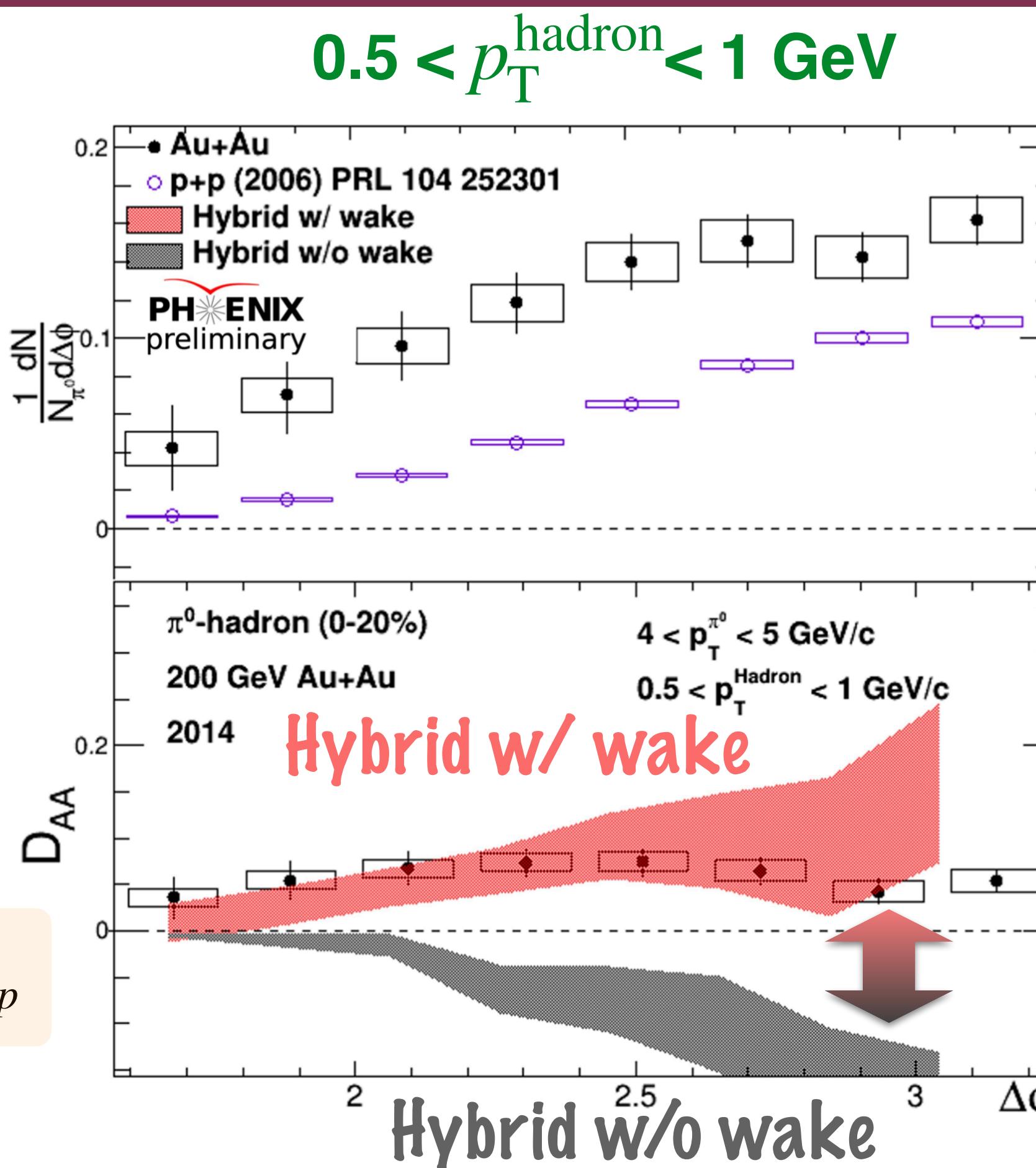
π^0 -Hadron Correlation at RHIC



PHENIX Preliminary

Talk by M. Connors

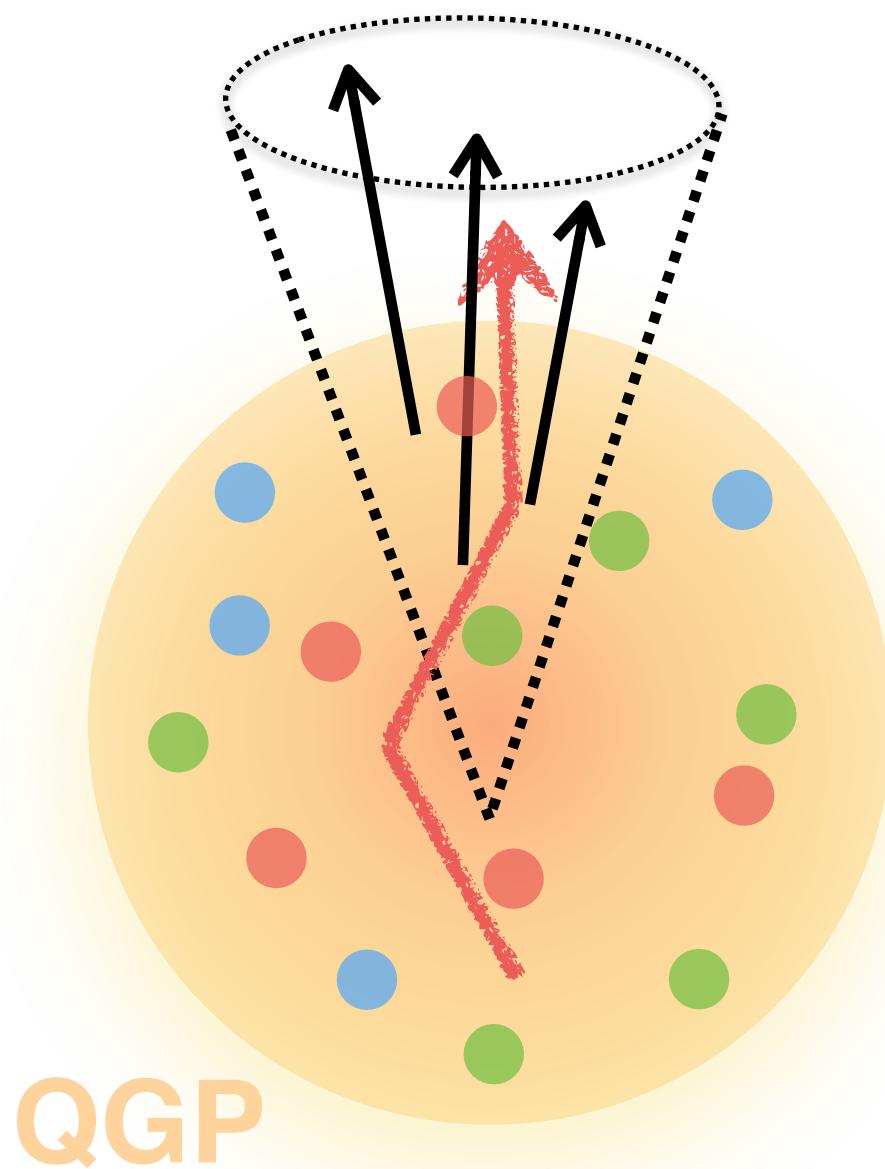
$$D_{AA} \equiv Y_{AA} - Y_{pp}$$



- Enhancement of low p_T hadrons
- Model with medium response (Hybrid w/ wake) describe the data better

Charged Jet Mass at LHC

Jet mass

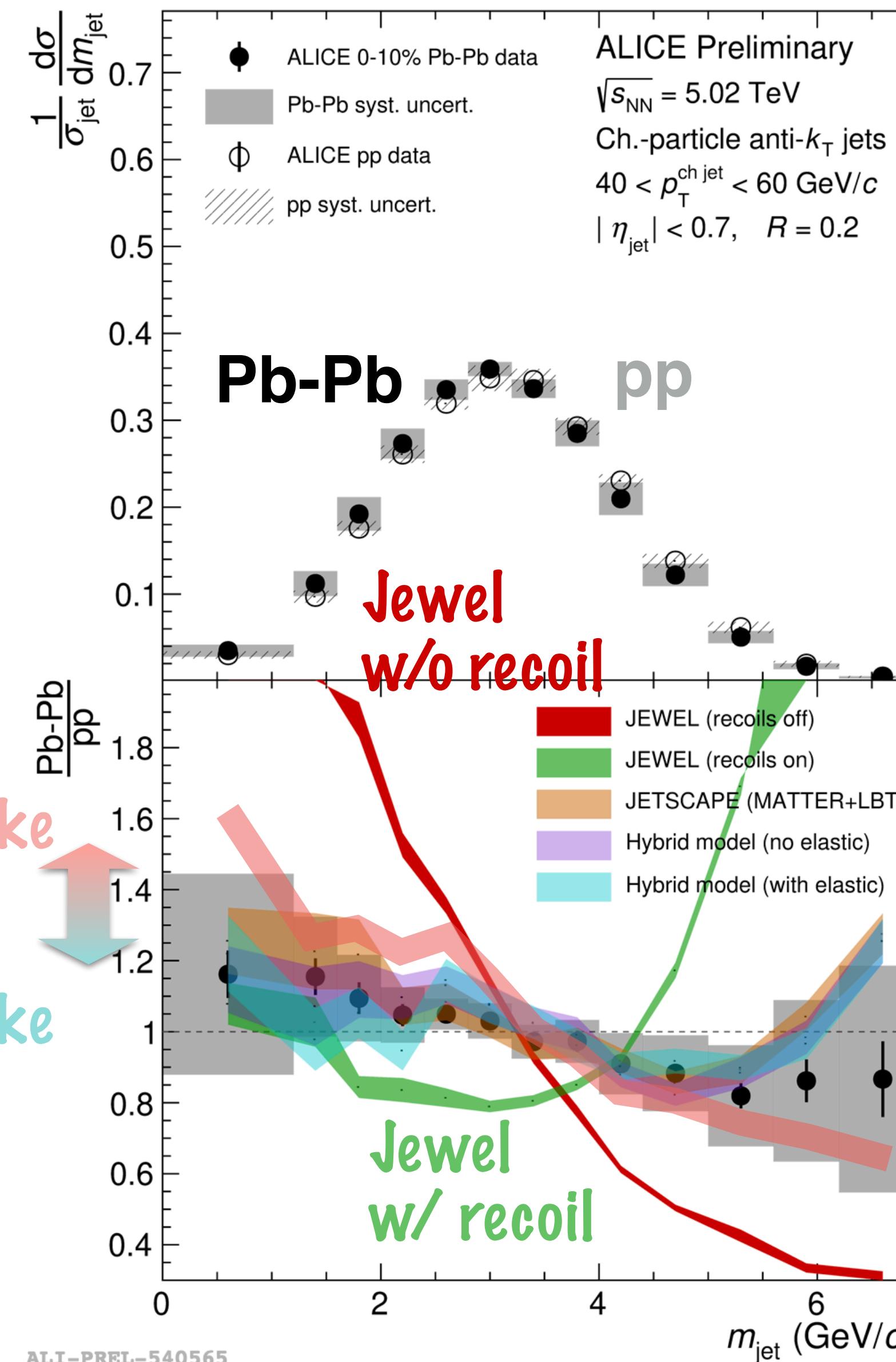


Hybrid
w/o wake

Hybrid
w/ wake

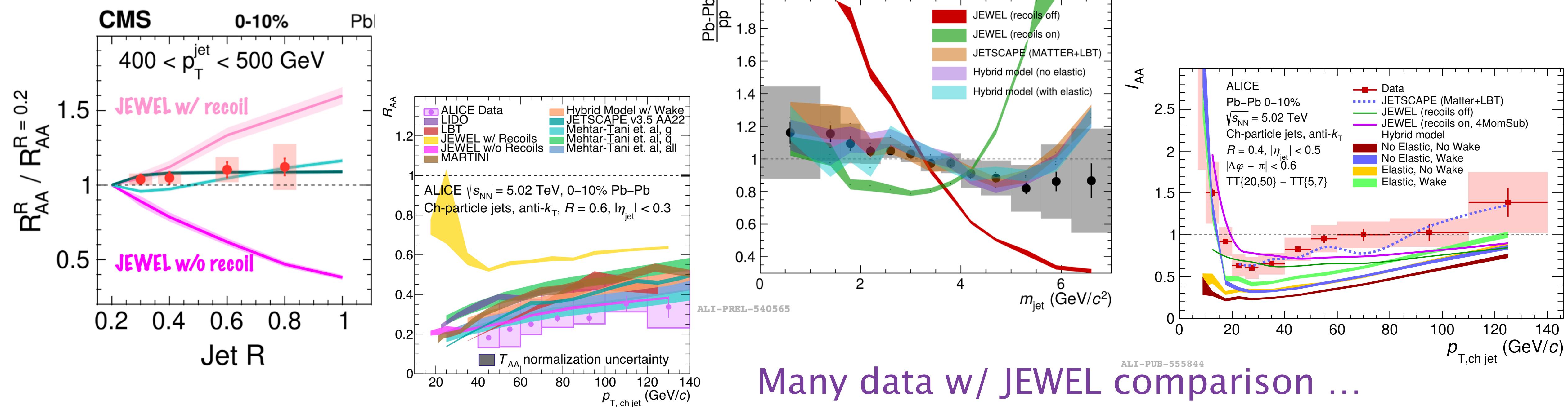
Talk by H. Bossi

ALICE ALI-PREL-540565



- **Ungroomed jet mass**
 - expected to be sensitive to medium response than *groomed* jet mass
- Hint of shift towards low mass in **Pb-Pb** compared to **pp**
- Data slightly favors **Hybrid w/ wake** than **Hybrid w/o wake**

JEWEL with Recoil



- JEWEL **w/o recoil**: not physical, energy-momentum not conserved
- JEWEL **w/ recoil w/o subtraction**: not compatible with background-subtracted jet data
 - important to subtract of thermal component of recoils
- JEWEL **w/ recoil w/ subtraction**:
 - important to use the up-to-date subtraction method: **constituent subtraction**
(*J. Milhano and K. Zapp arXiv:2207.14814*)

So far, we've learned ...



- Enhancement of **low p_T** particles at **large angles** w.r.t jet axis
- Acoplanarity broadening
- Hint of lower jet mass

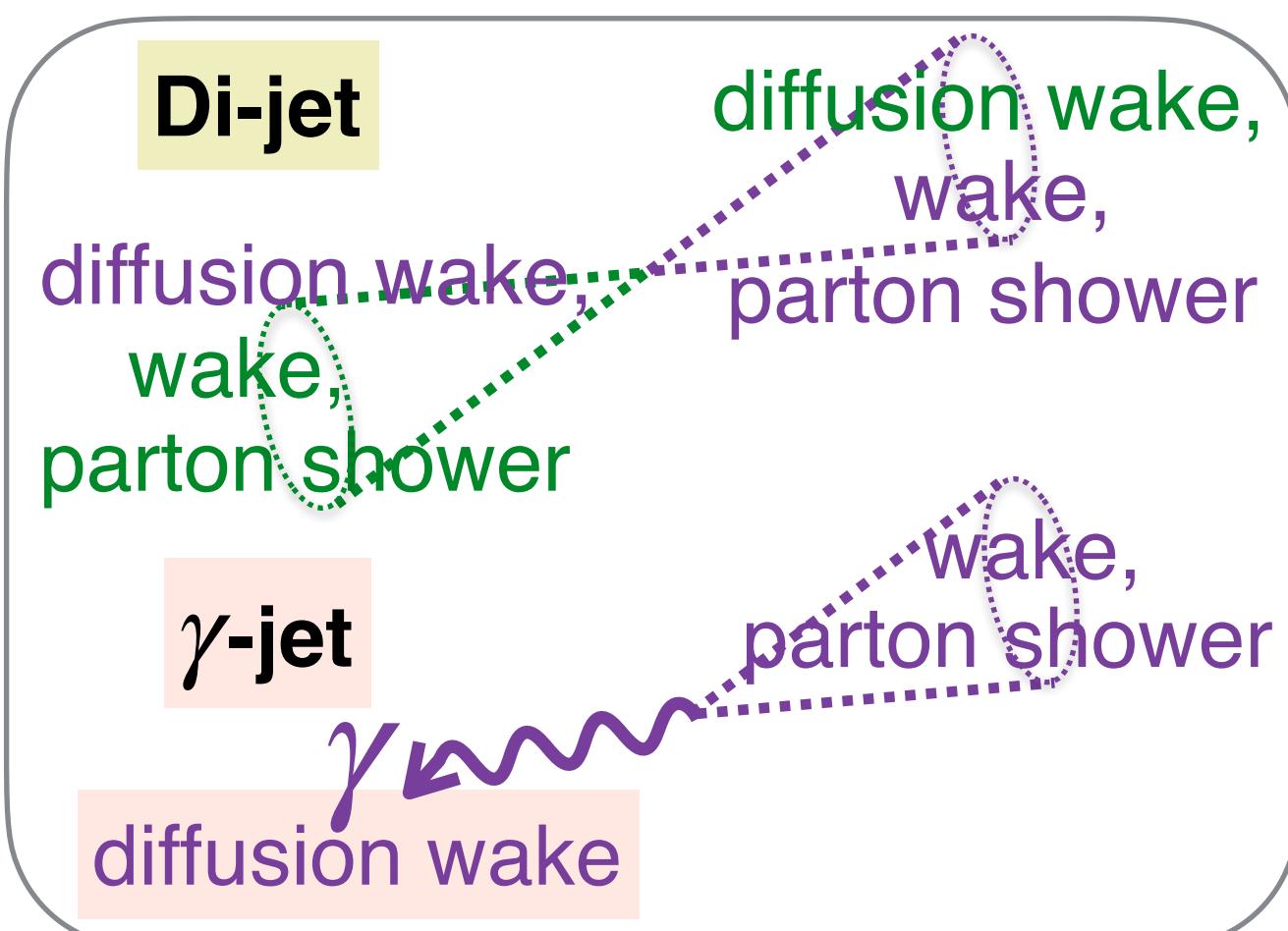
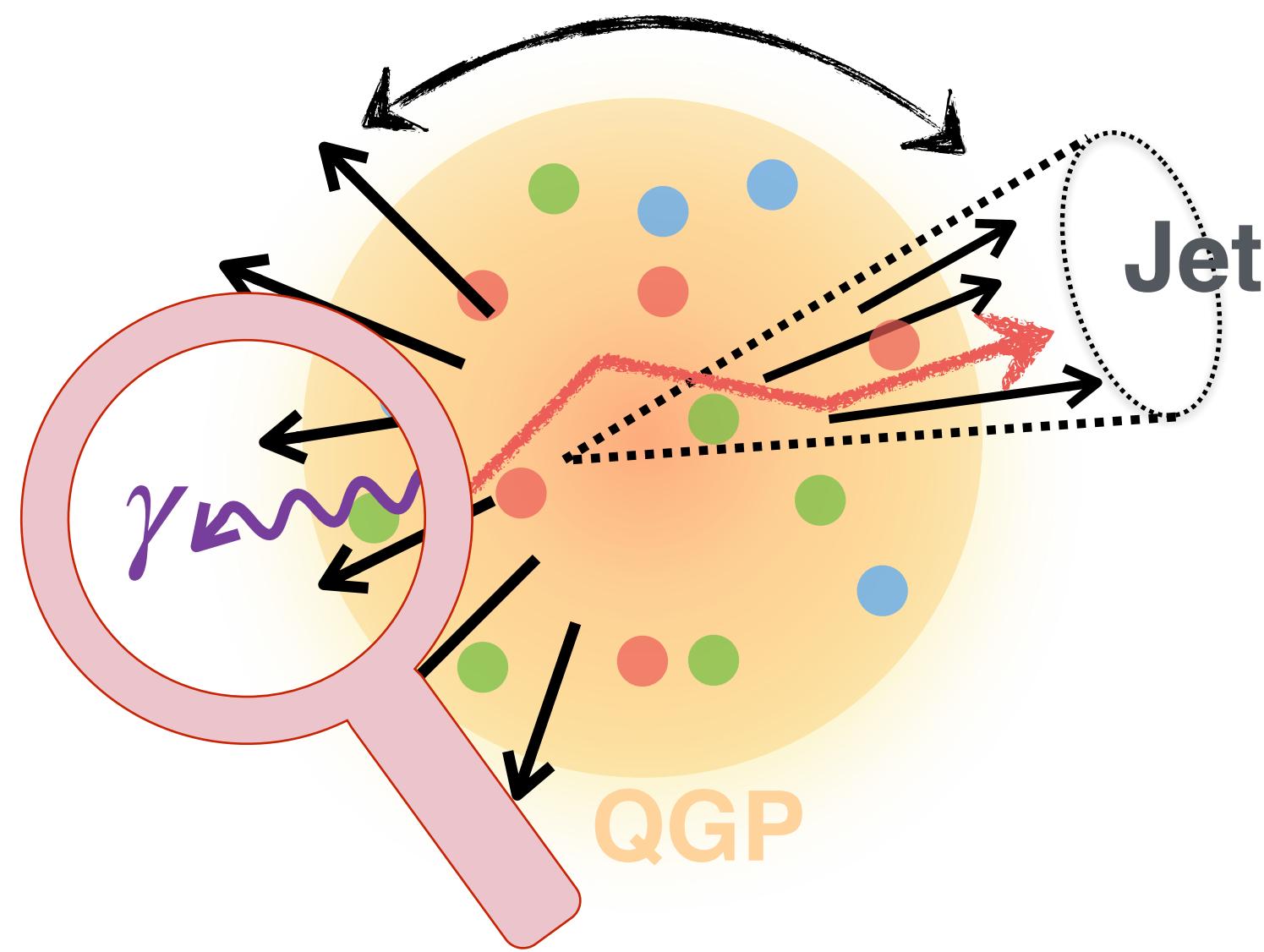


- Modification in the **jet direction**
 - How to disentangle
in-medium parton shower modification and
medium response experimentally?

One way ... Opposite jet direction, Diffusion wake !

Looking for Diffusion Wake

$$\Delta\phi, \Delta\eta(\text{hadron, jet})$$

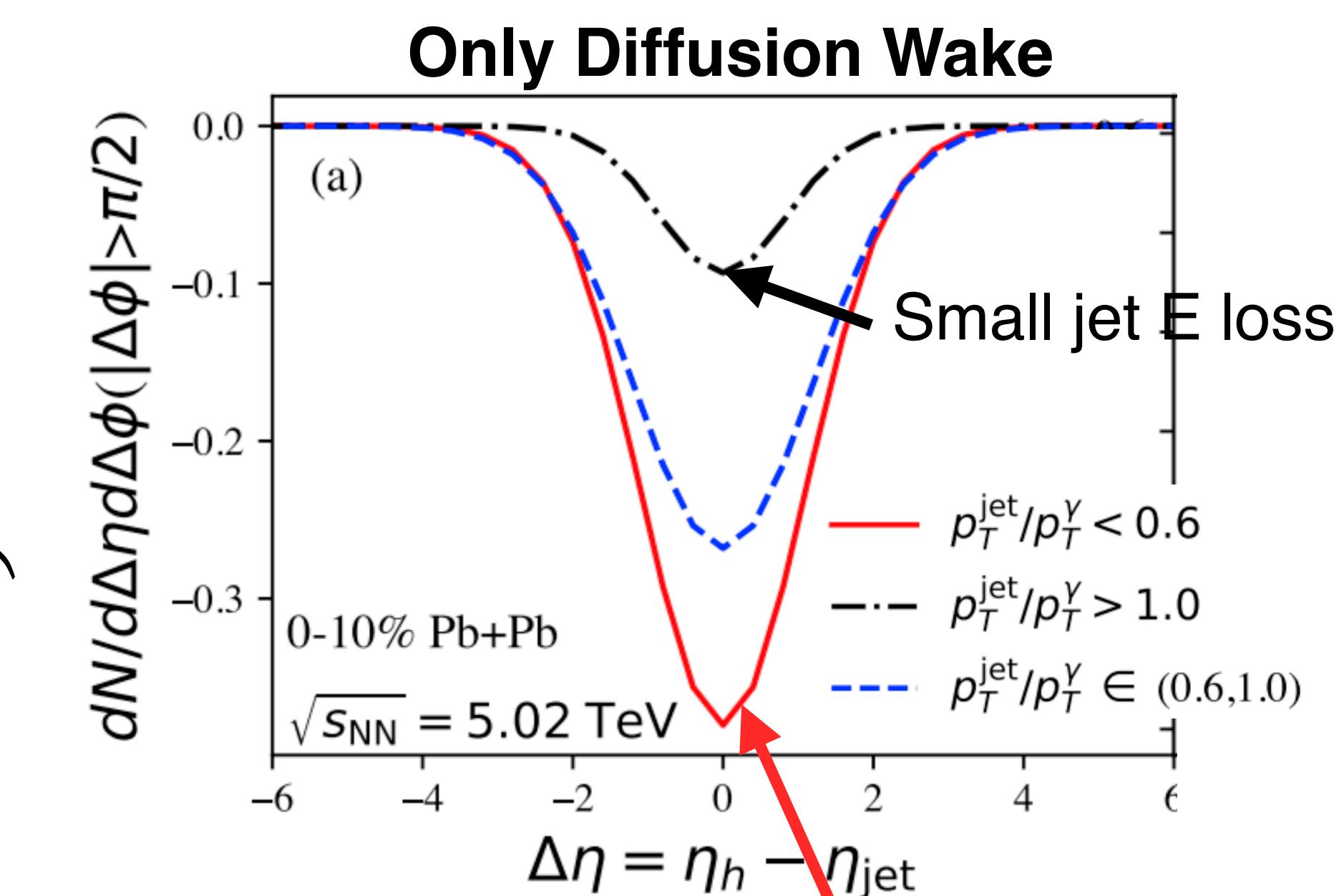
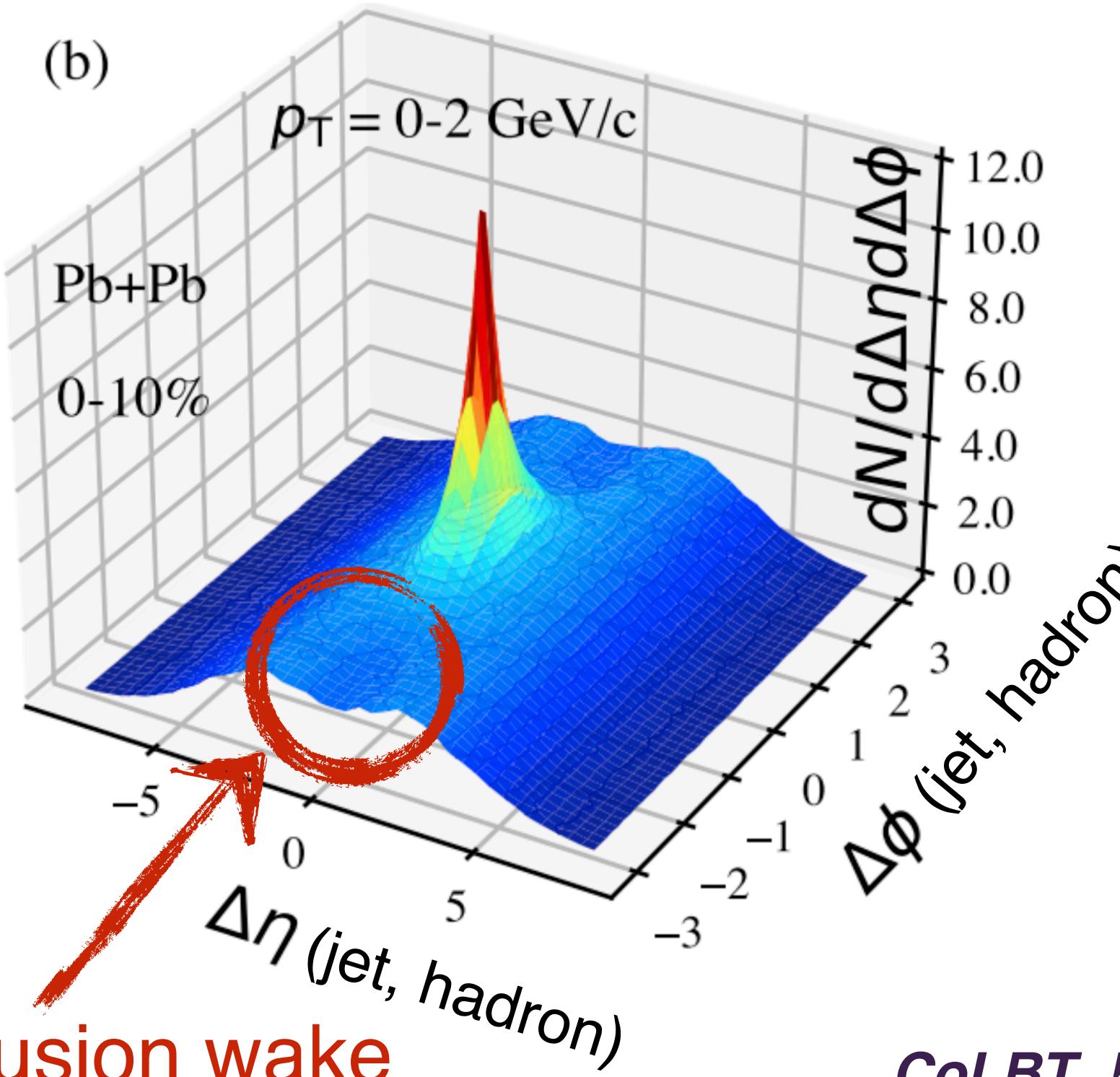


- Jet-hadron ($\Delta\phi, \Delta\eta$) $\sim (\pi, 0)$ in γ -jet events

→ unambiguous diffusion wake signal

- **CoLBT model**

→ diffusion wake amplitude \propto jet energy loss (smaller $p_T^{\text{jet}}/p_T^\gamma \equiv x_{J\gamma}$)

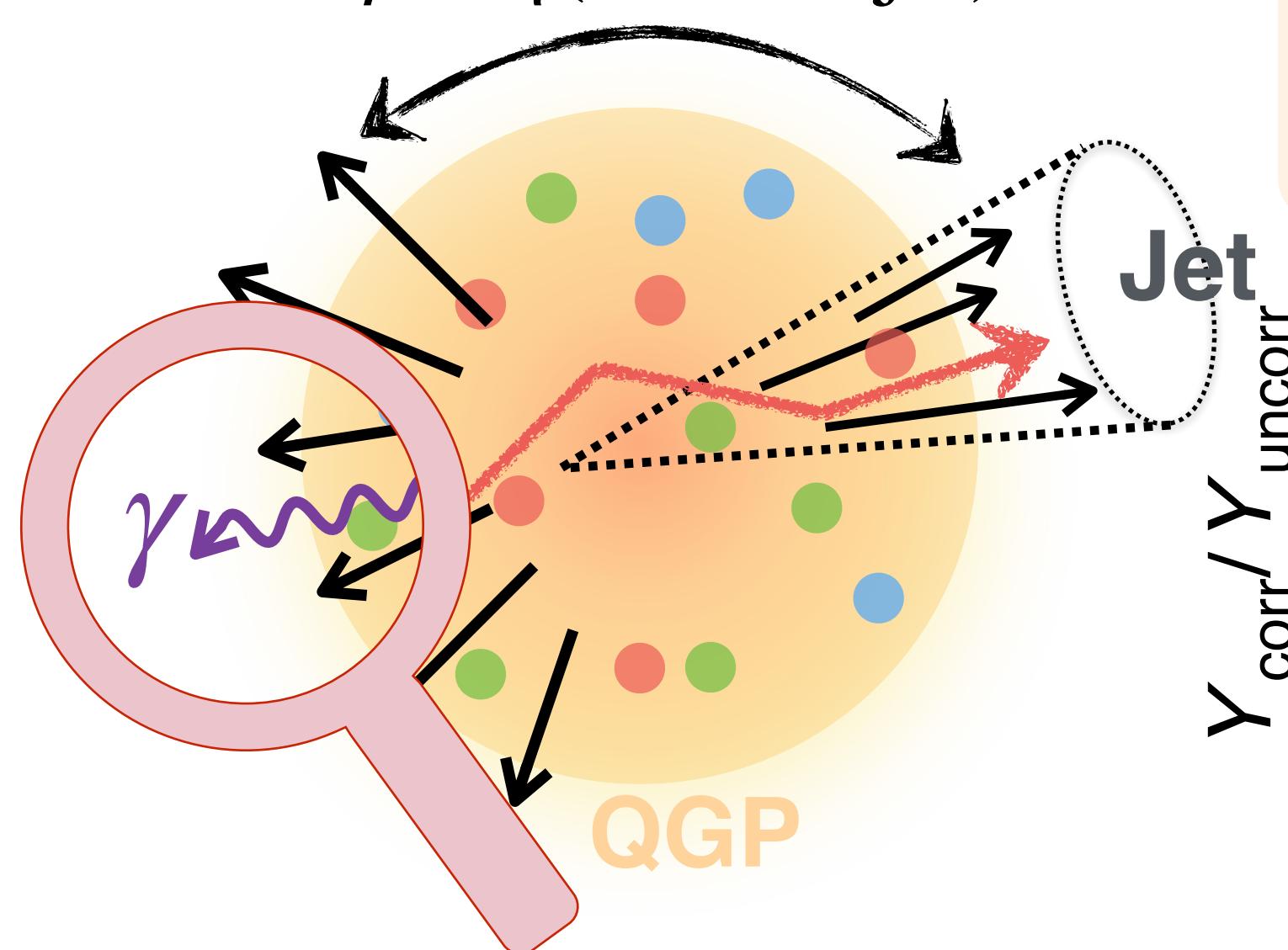


CoLBT, PRL 130, 052301 (2023)

[Poster by Z. Yang](#) [Talk by Z. Yang](#)

Jet-Hadron Correlation in Photon-Jet Events at LHC

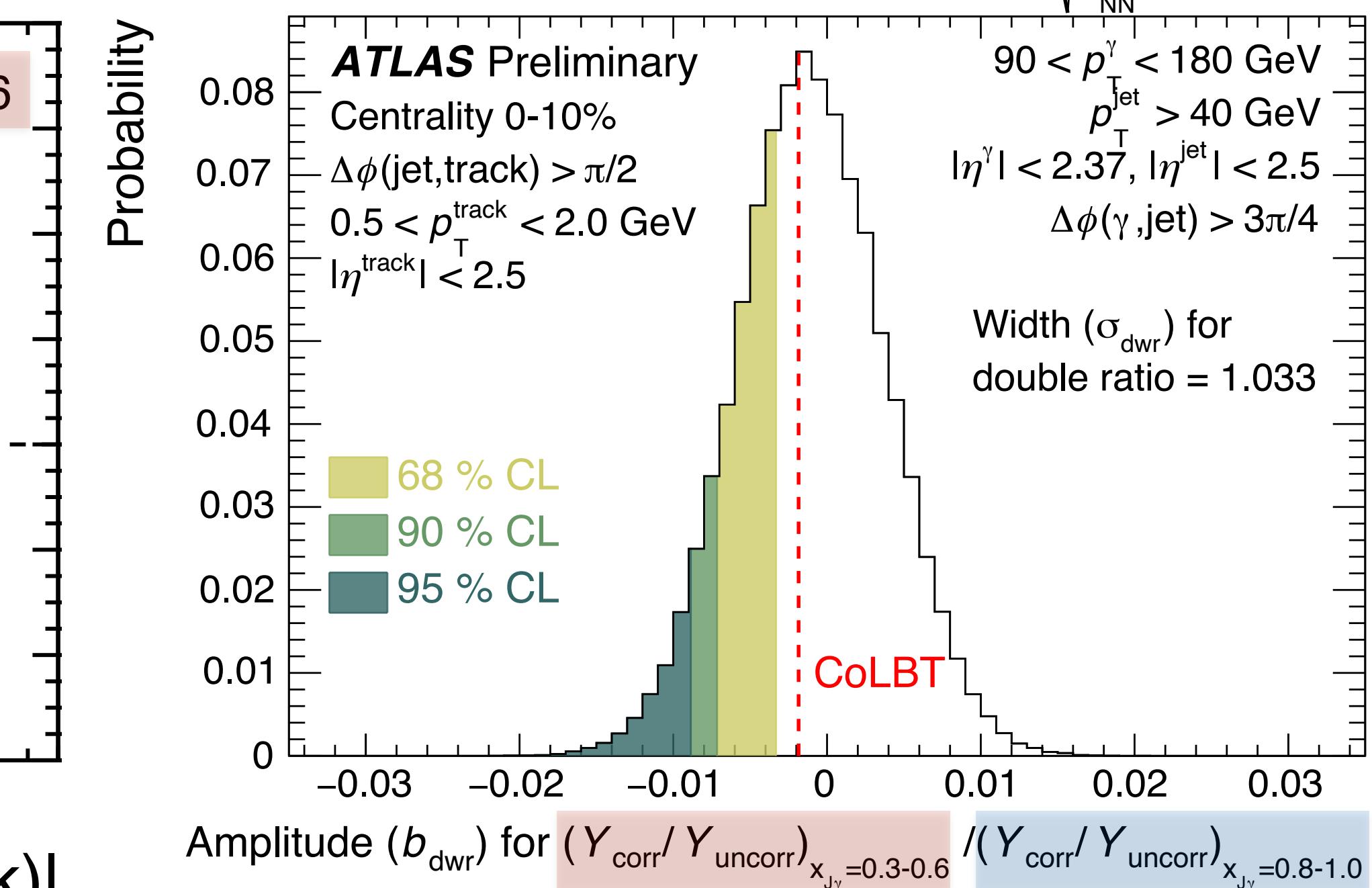
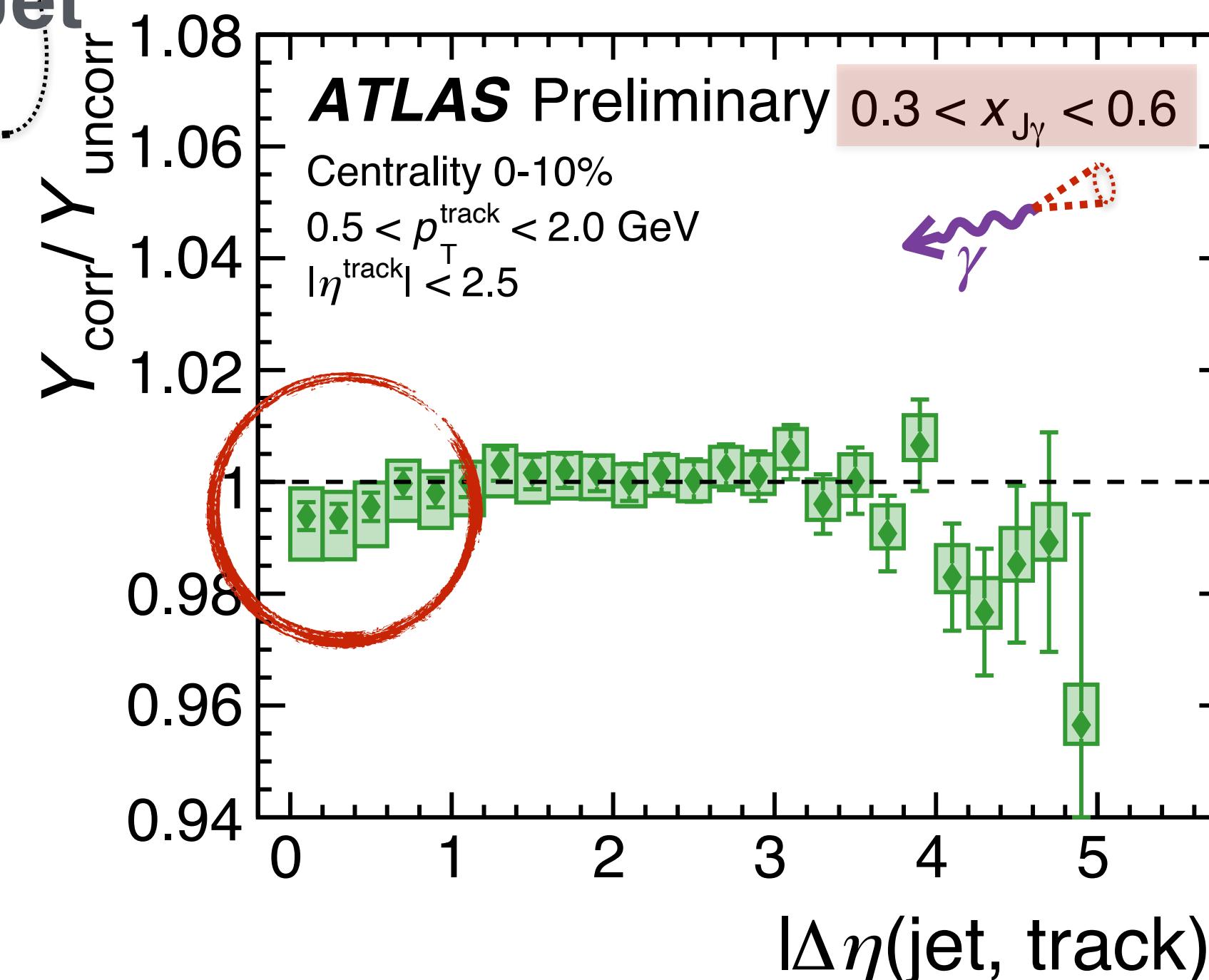
$\Delta\phi, \Delta\eta(\text{hadron, jet})$



QM Preliminary

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

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

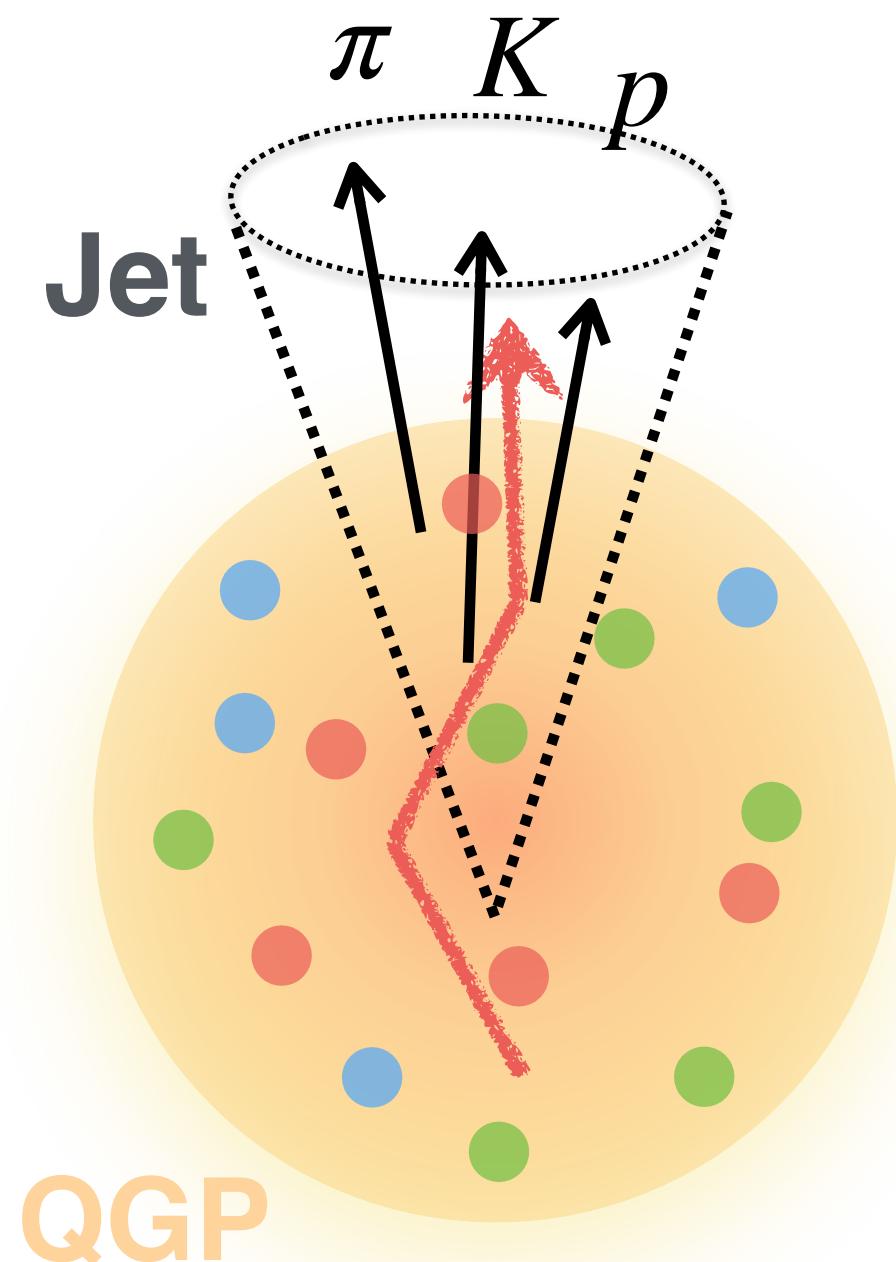


- No significant diffusion wake signal within the current sensitivity in data
- Data provides limits on double ratio amplitude
→ **95% CL upper limit** of **0.0095** does not rule out **CoLBT** prediction of **0.0018**
- Stat. uncert. dominates in probability distribution; more statistics in Run-3 would be valuable

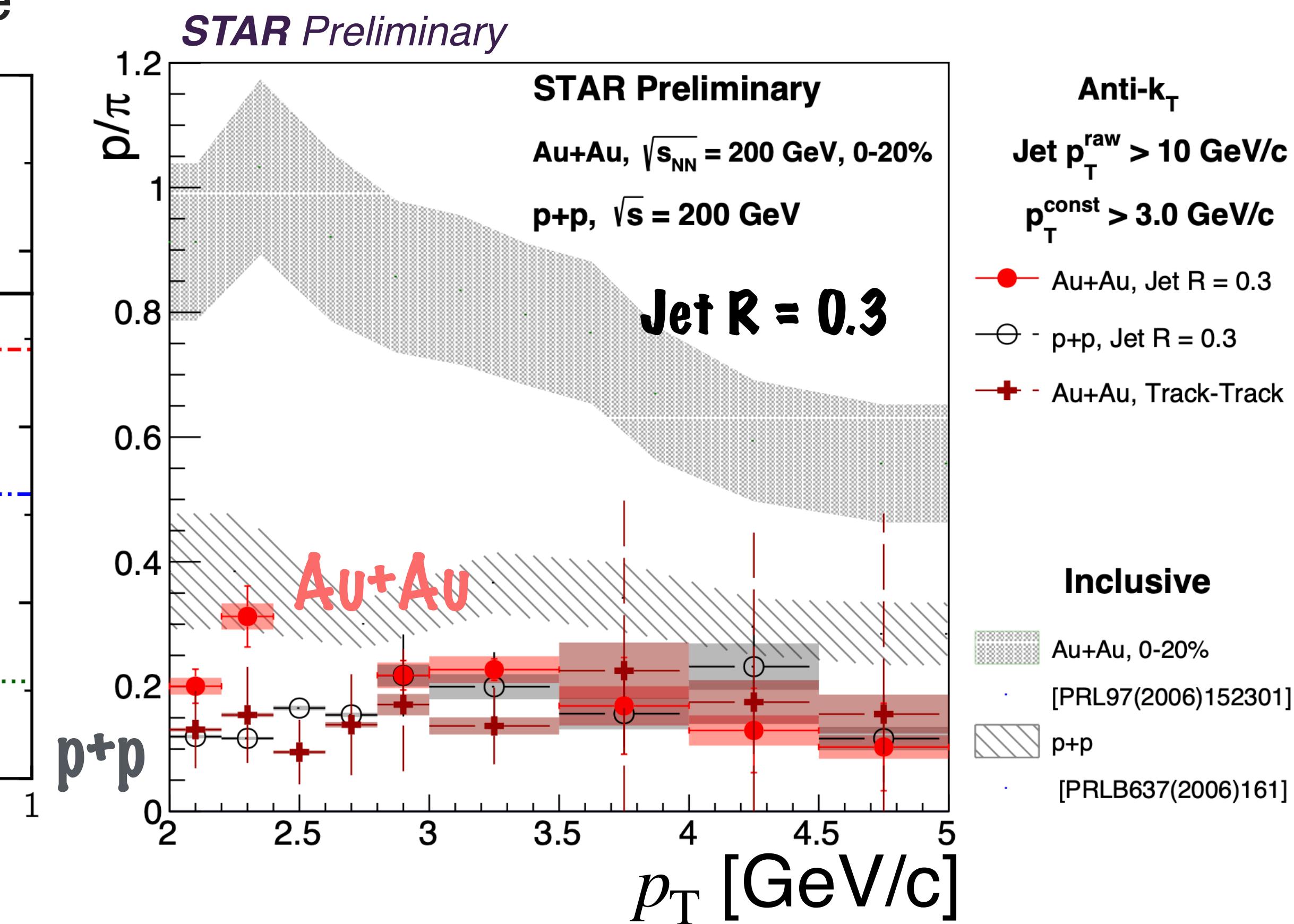
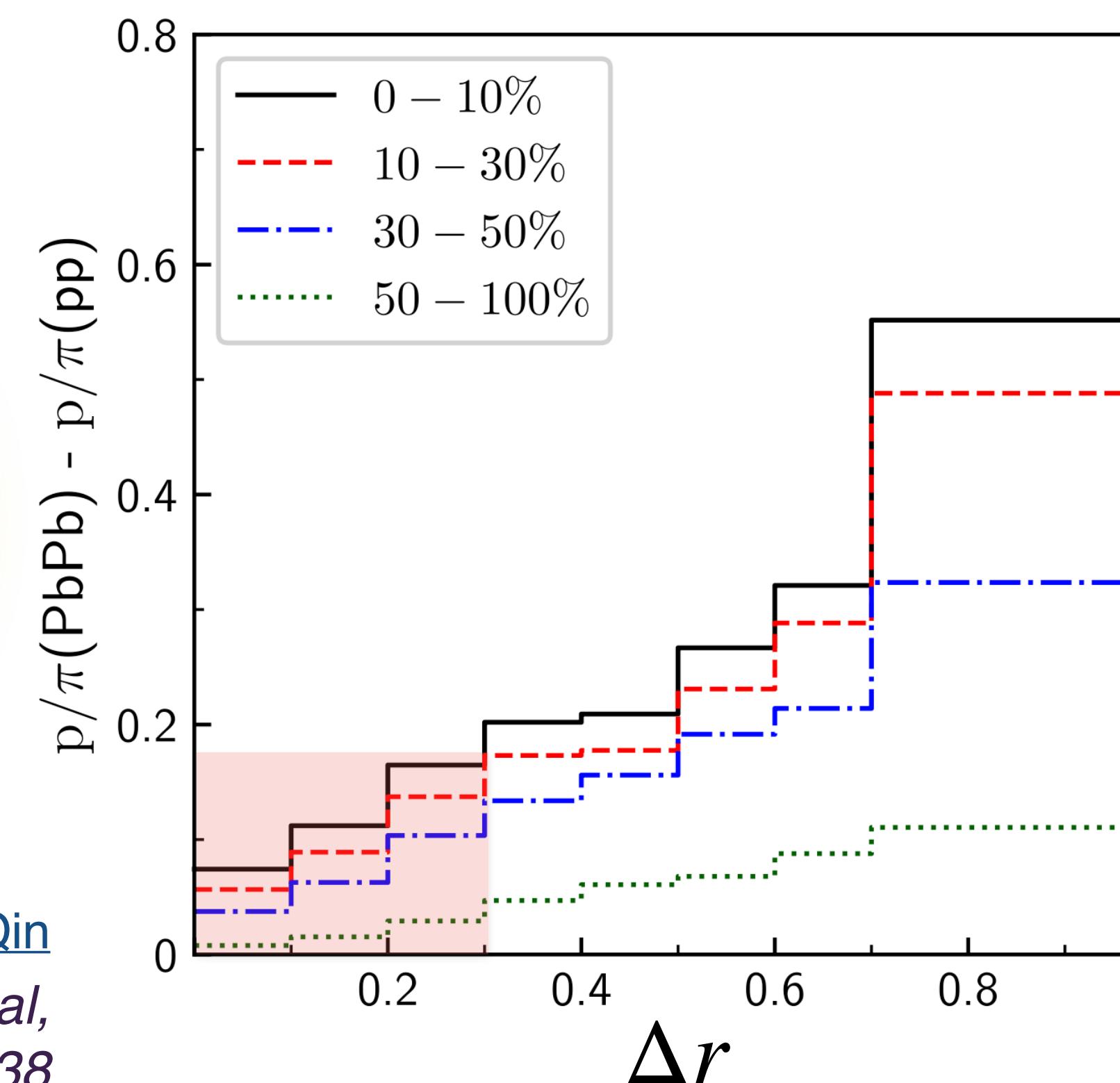


Baryon-to-Meson Ratio around Jets

- Coupled jet fluid model
 - medium excitation → change the chemical composition of particles via parton coalescence



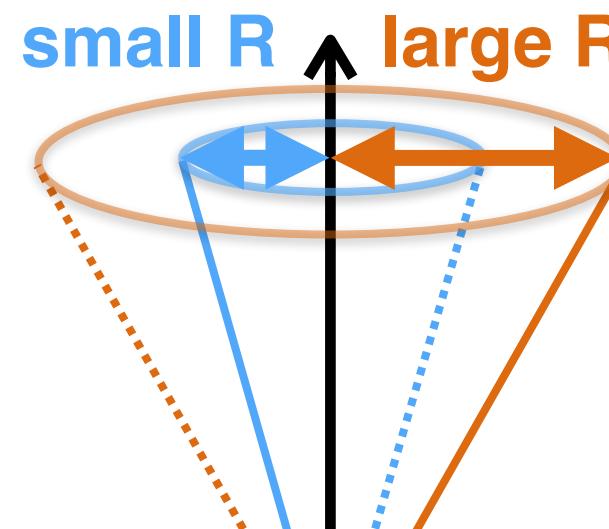
Talk by G-Y, Qin
Luo et al,
PLB 837 (2023) 137638



- No significant modification of p/π in Au+Au within uncertainties in data
 - larger datasets + larger radius would be valuable

R-dependence Measurements

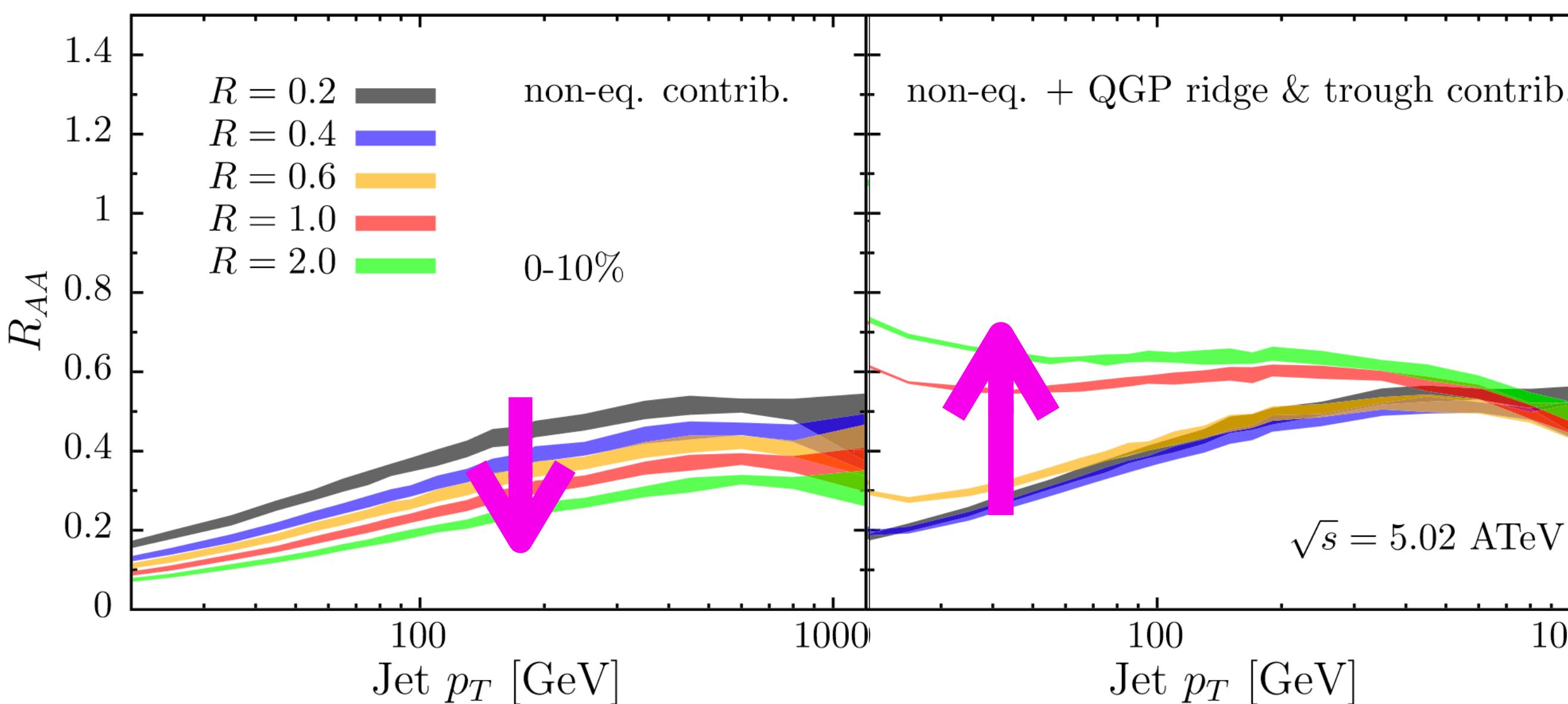
Radius-dependent Jet R_{AA}



with increasing R ...

Hybrid Strong/Weak Coupling

Daniel Pablos, PRL 124 (2020) 052301



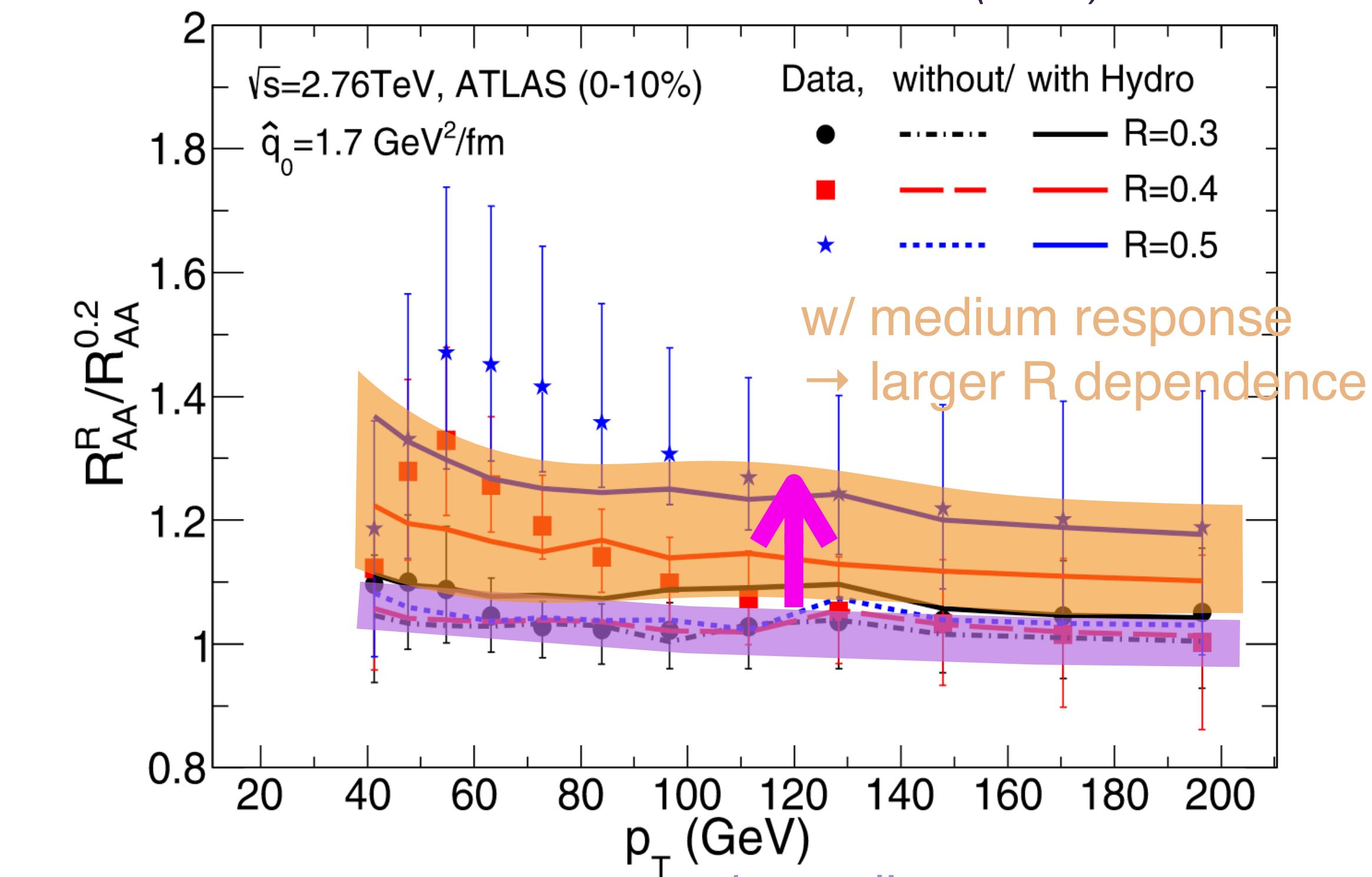
w/o medium response

w/ medium response

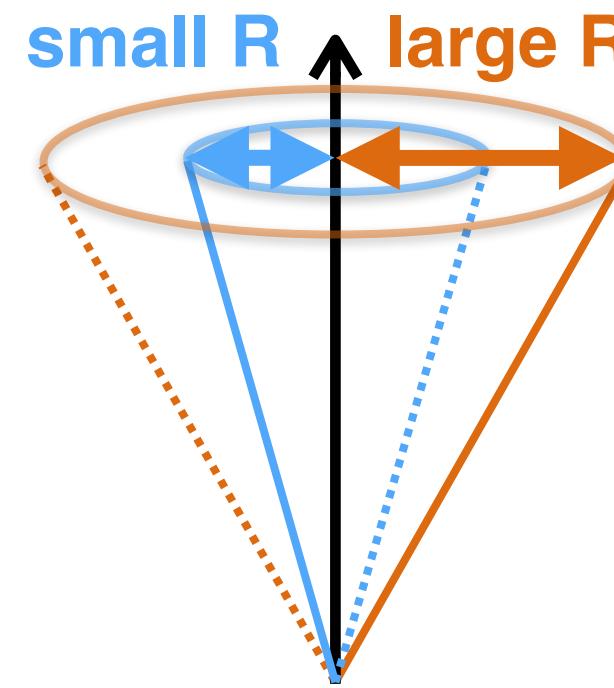
- Significantly different picture between w/o and w/ medium response in models

Coupled jet-fluid

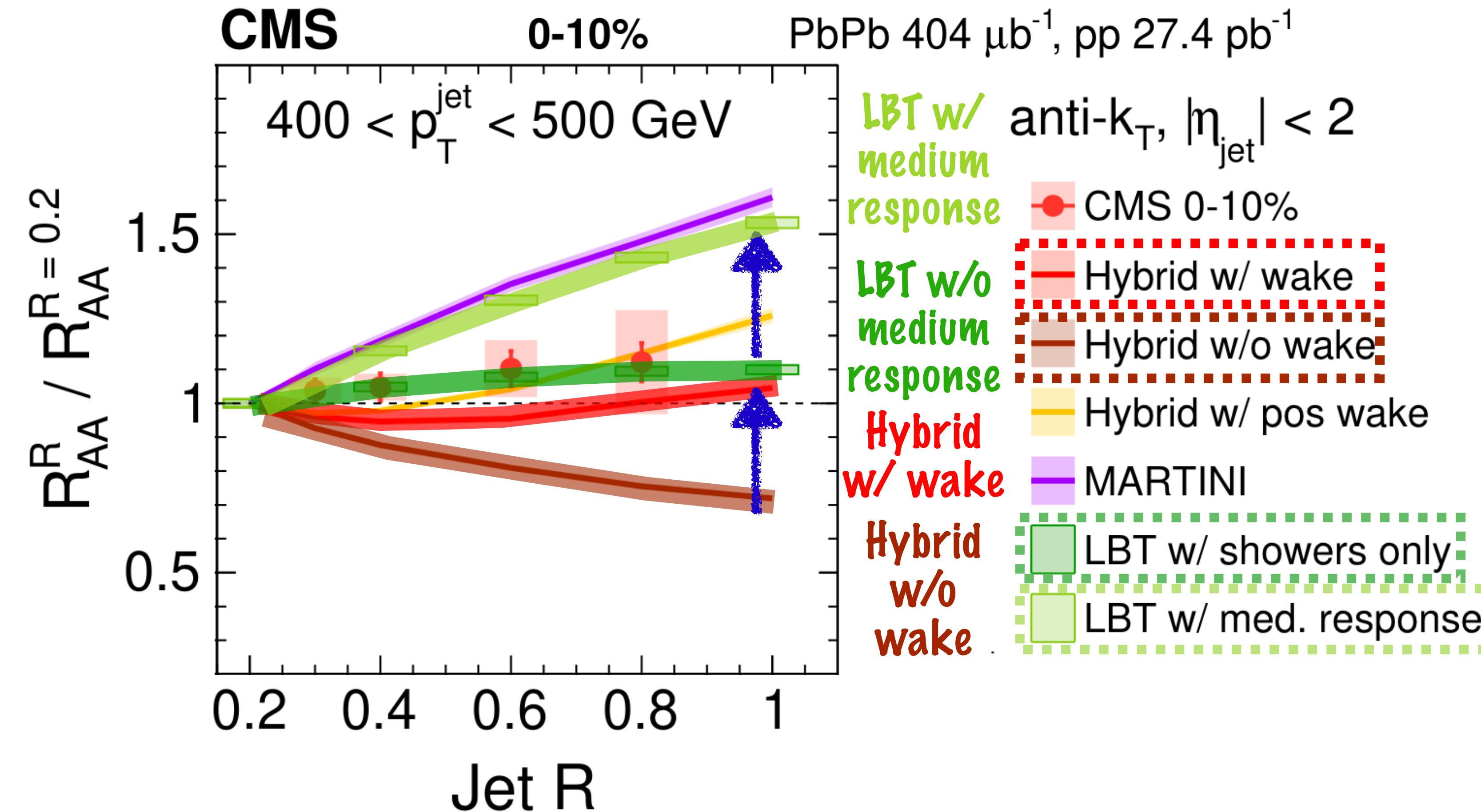
N.-B. Chang et al.
PLB 801 (2020) 135181



Radius-dependent Jet R_{AA}

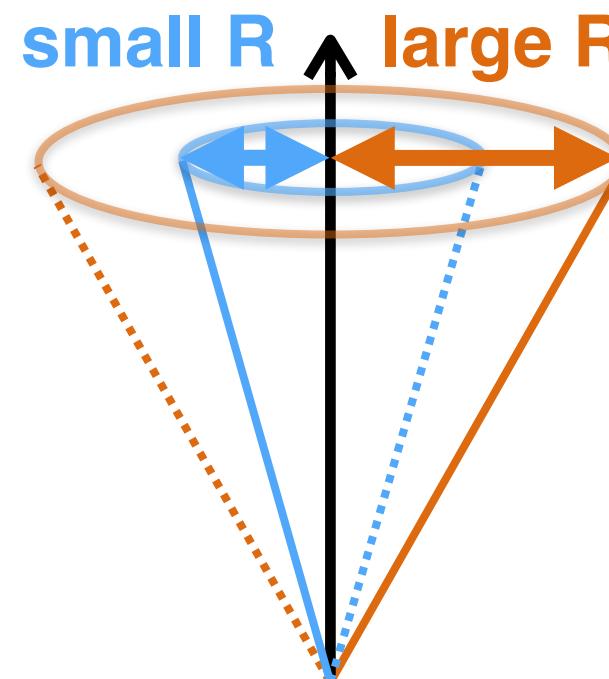


CMS JHEP 05 (2021) 284

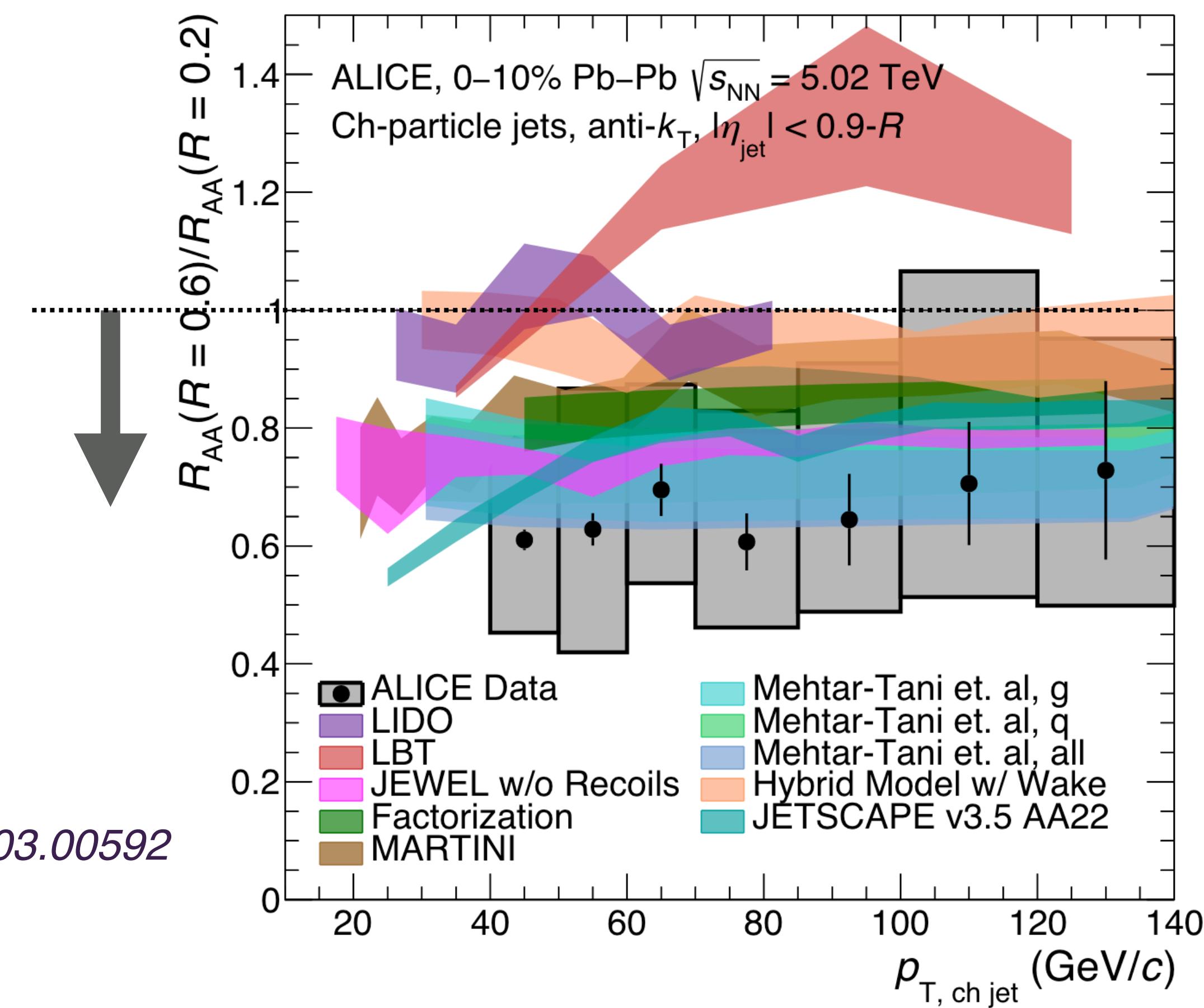


- At high jet p_T (400-500 GeV), relatively **small R-dependence** in data
- At **larger R**, higher $R_{\text{AA}}^R / R_{\text{AA}}^{R=0.2}$ for **models w/ medium response**

Radius-dependent Jet R_{AA}

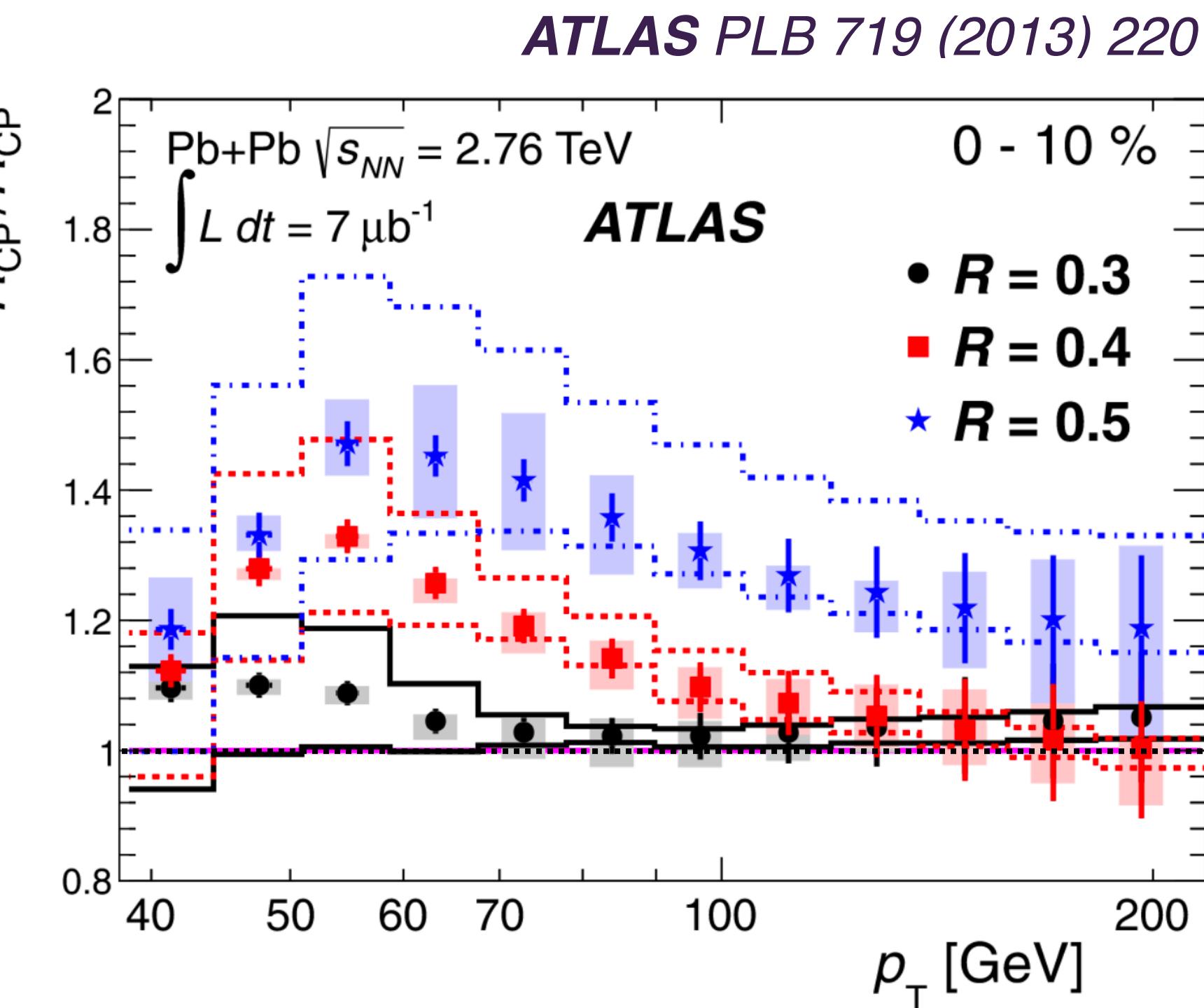
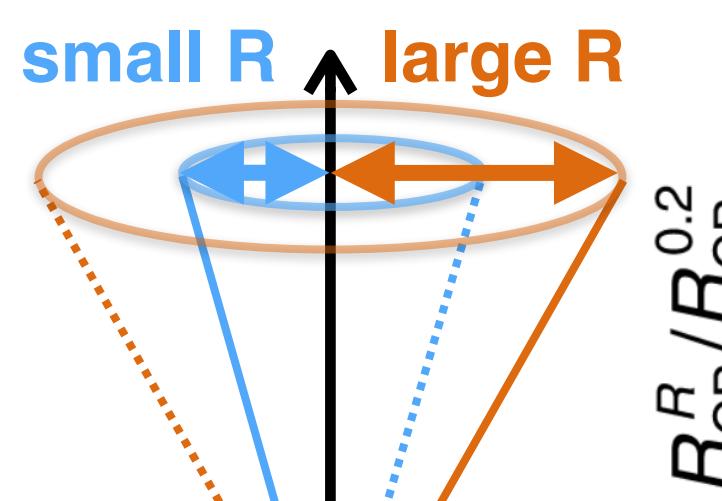


ALICE arXiv:2303.00592



- At low jet p_T (40-140 GeV), **ALICE** data shows $R_{AA}(R=0.6) < R_{AA}(R=0.2)$
- Various model (w/ and w/o medium response) *do* or *do not* describe data
→ detailed systematic study will be useful
e.g. baseline pp, recoil/hydro/other medium response, turn on/off medium response, ...

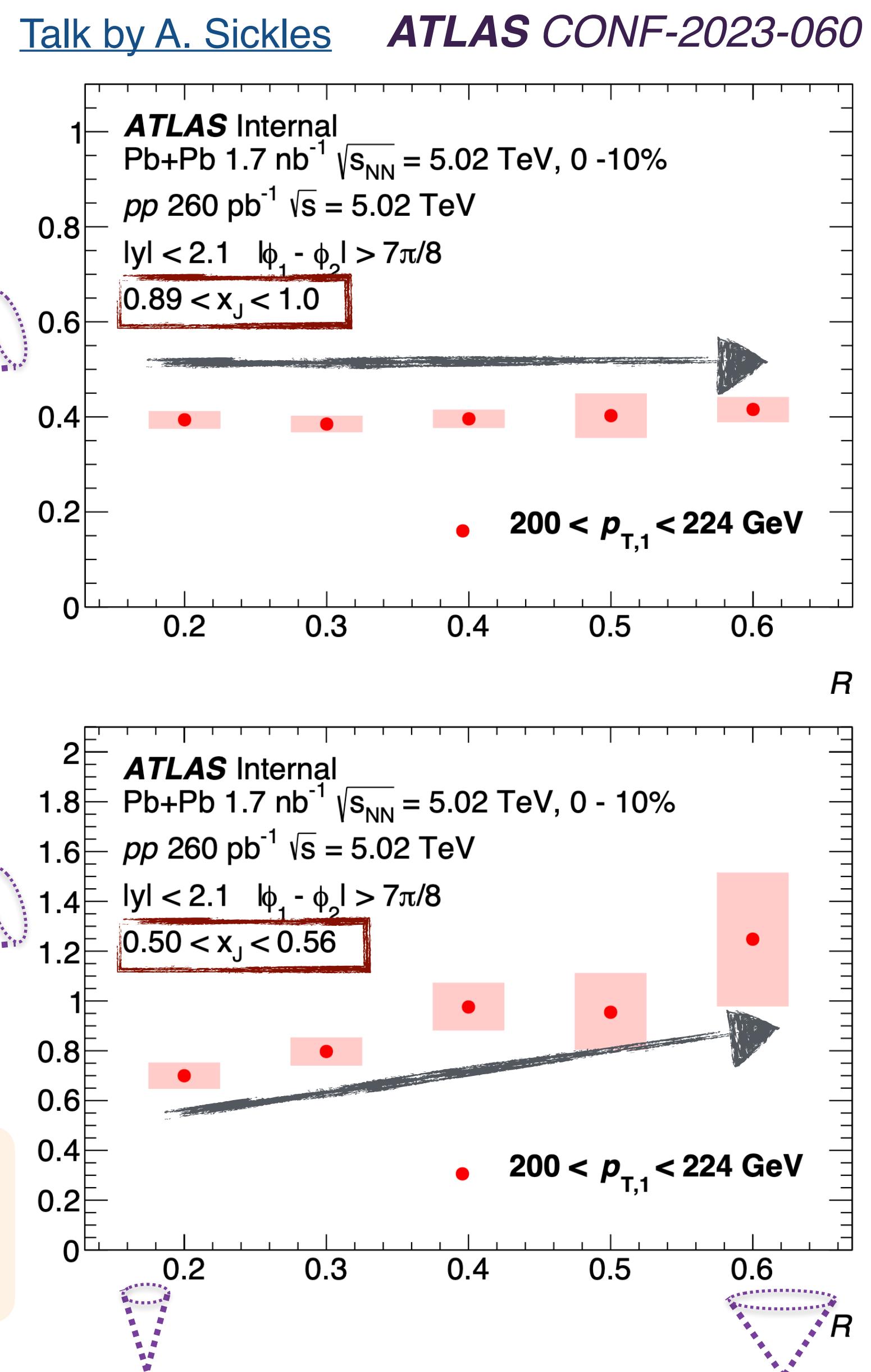
Radius-dependent Jet R_{AA}



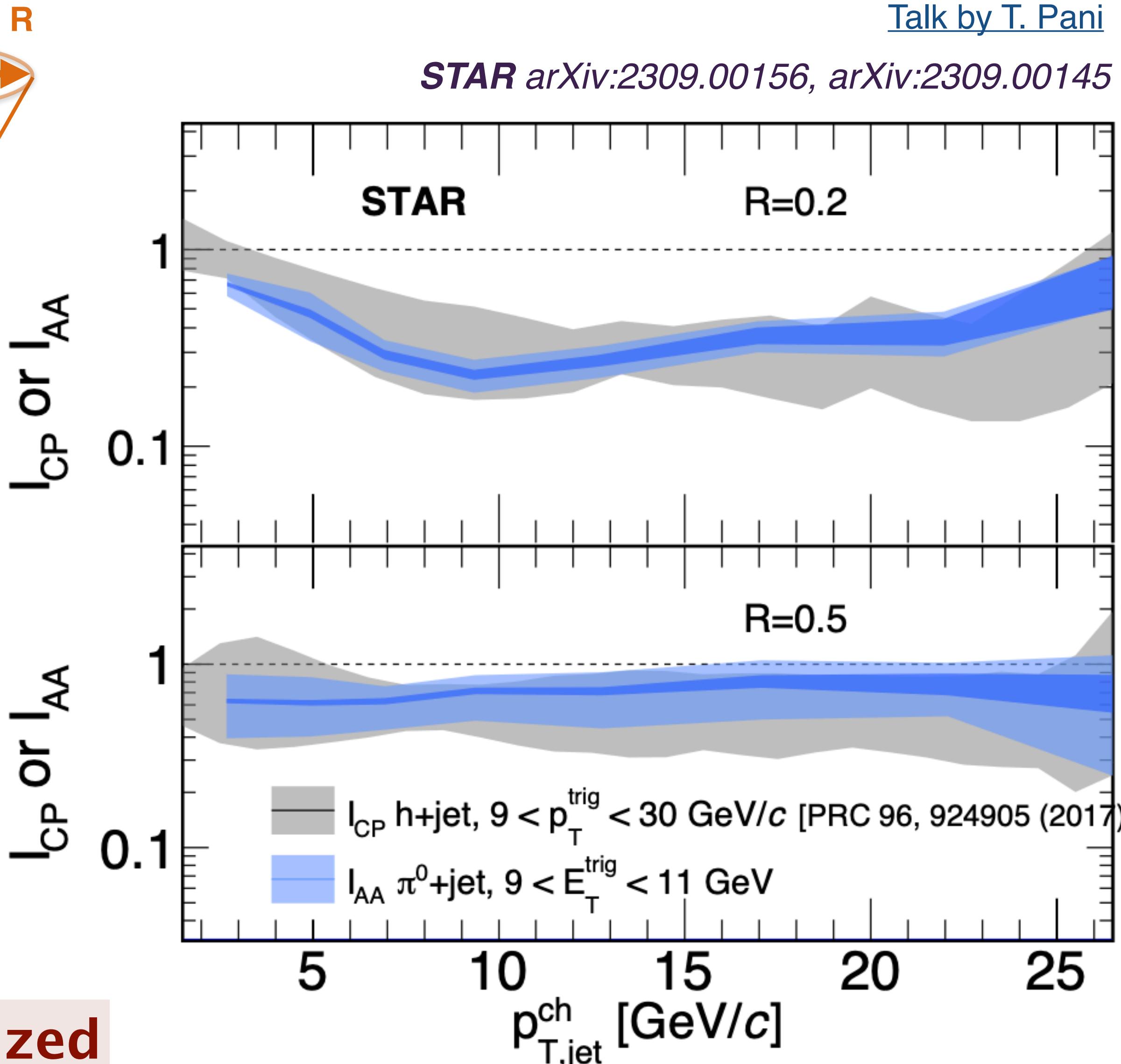
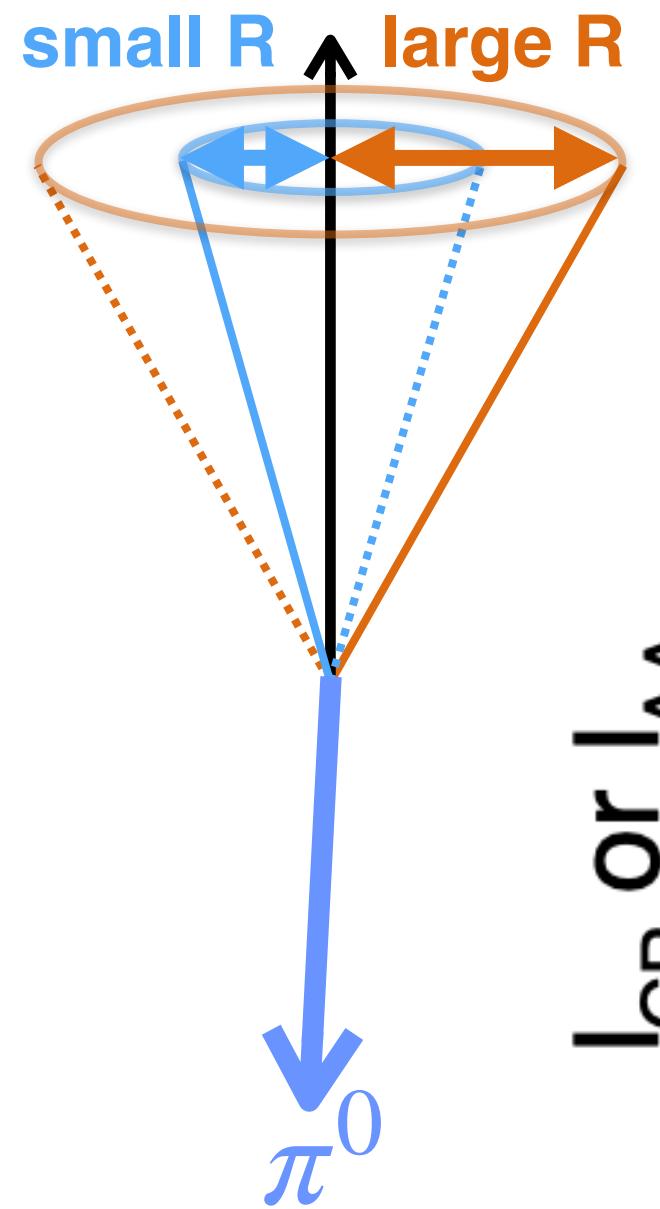
- At low jet p_T (40-200 GeV), **ATLAS** data shows $R_{\text{CP}} (R=0.5) > R_{\text{CP}} (R=0.2)$
- For di-jet pair, $J_{\text{AA}} (R=0.6) > J_{\text{AA}} (R=0.2)$
- tension between **ALICE** and **ATLAS**

$$J_{\text{AA}} \equiv \frac{1}{\langle T_{\text{AA}} \rangle N_{\text{evt}}^{\text{AA}}} \frac{dN_{\text{pair}}^{\text{AA}}}{dx_J} \Bigg/ \left(\frac{1}{L_{pp}} \frac{dN_{\text{pair}}^{pp}}{dx_J} \right)$$

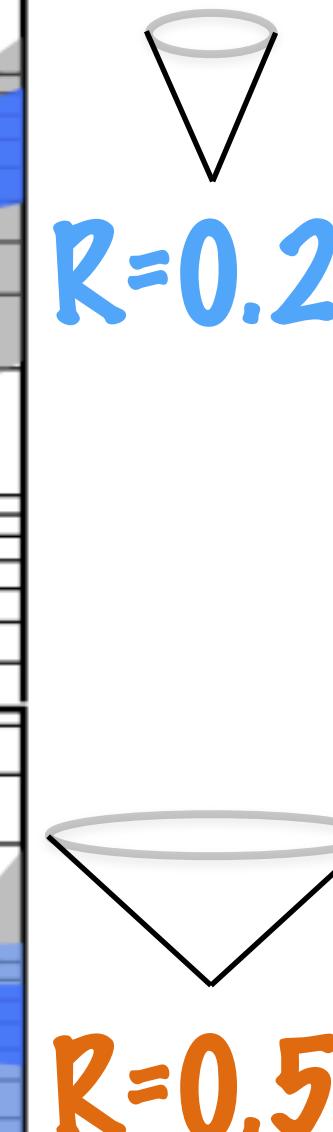
QM
Preliminary



Radius-dependent Jet Yield at RHIC



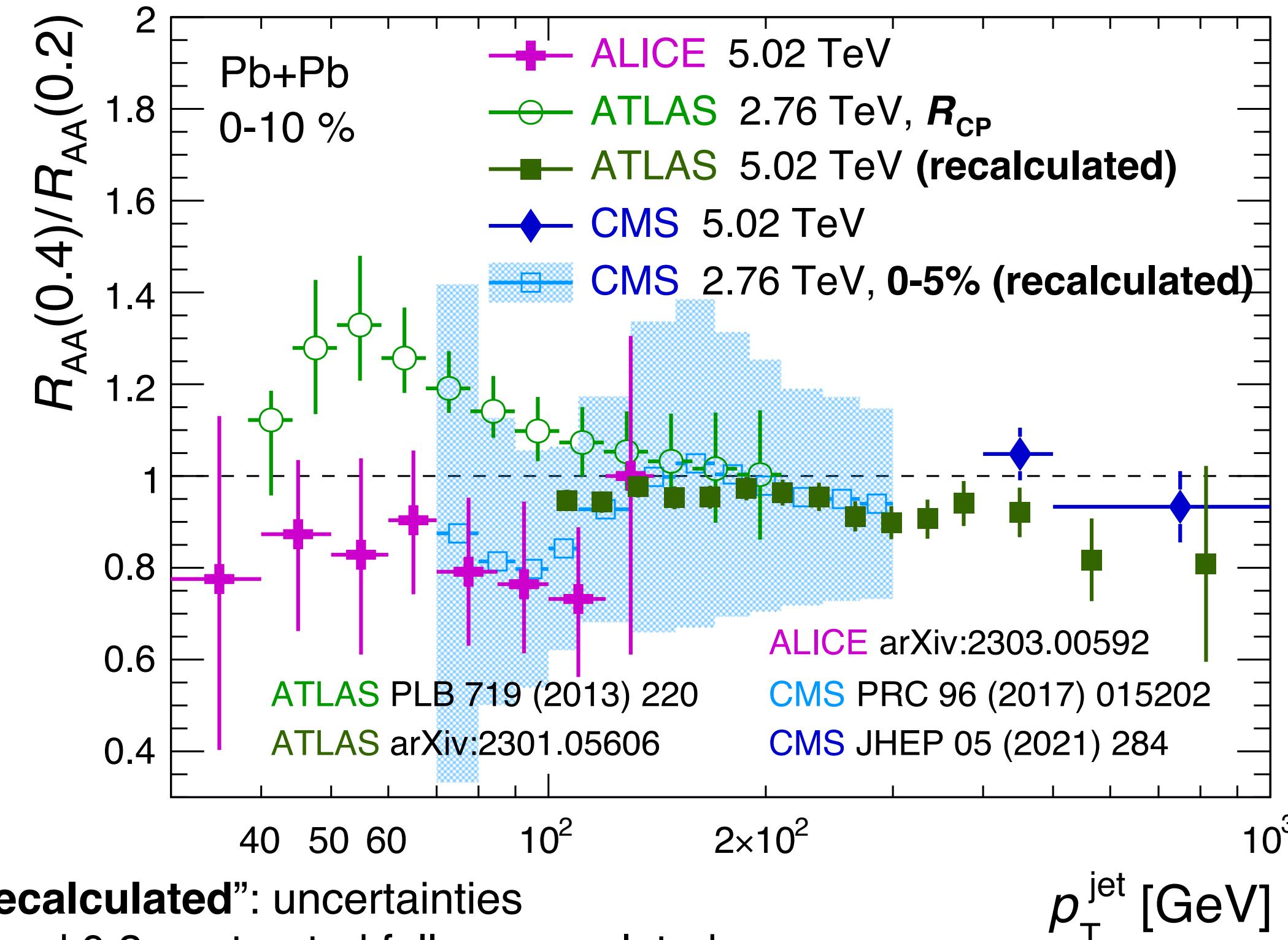
$$I_{AA} = \frac{Y_{\text{hadron}}^{\text{Pb+Pb}} / N_{\text{Pb+Pb}}^{\text{trig}}}{Y_{\text{hadron}} / N_{pp}^{\text{trig}}}$$



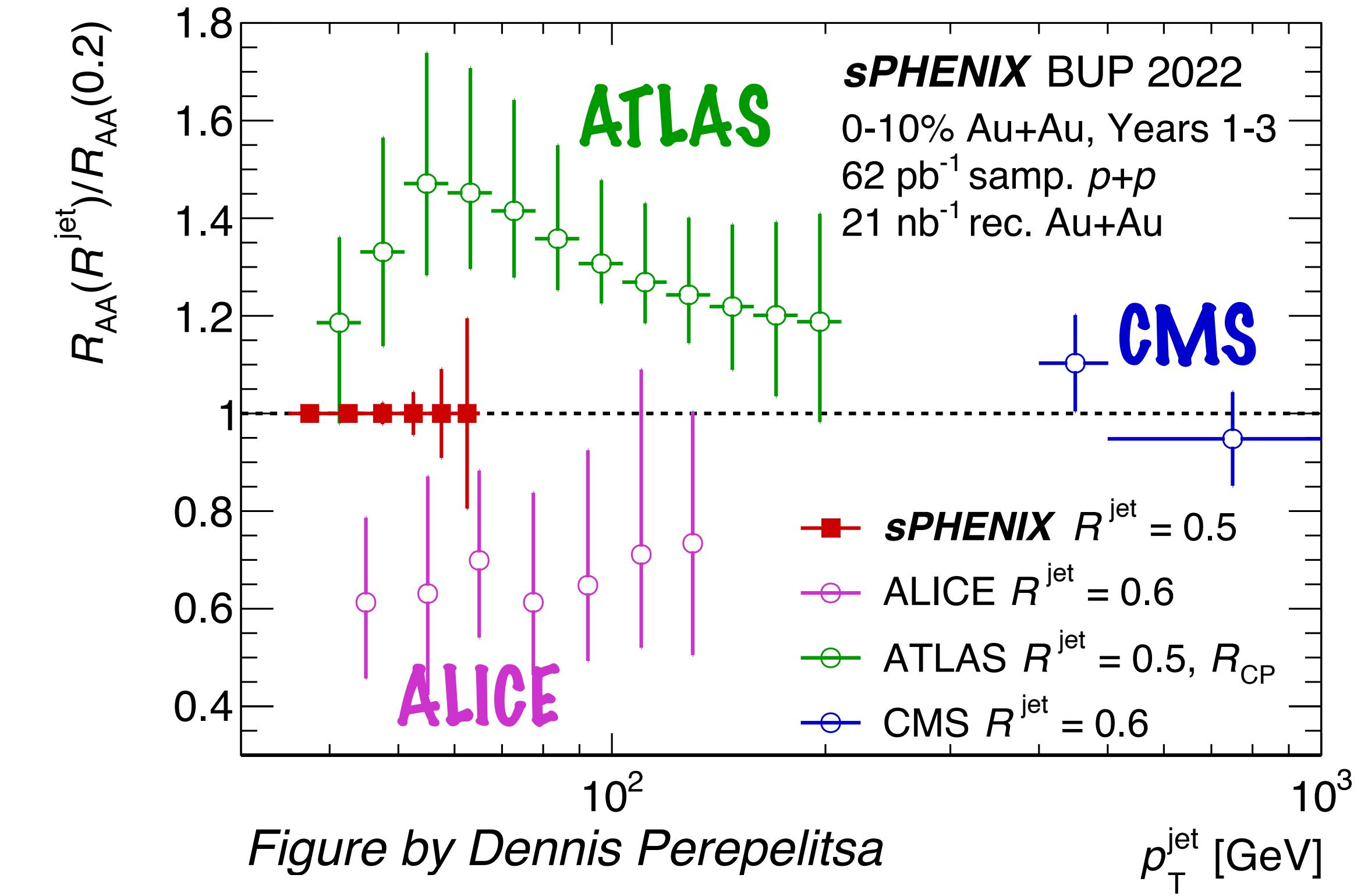
- $I_{AA}(0.5) > I_{AA}(0.2)$
 - Jets w/ **larger radius** are **less suppressed**
- $I_{AA}^{0.5} / I_{AA}^{0.2} > 1$
 - note) not directly comparable w/ LHC double R_{AA} ratio measurements

QM Finalized

Discussion: Radius-dependent Jet R_{AA}

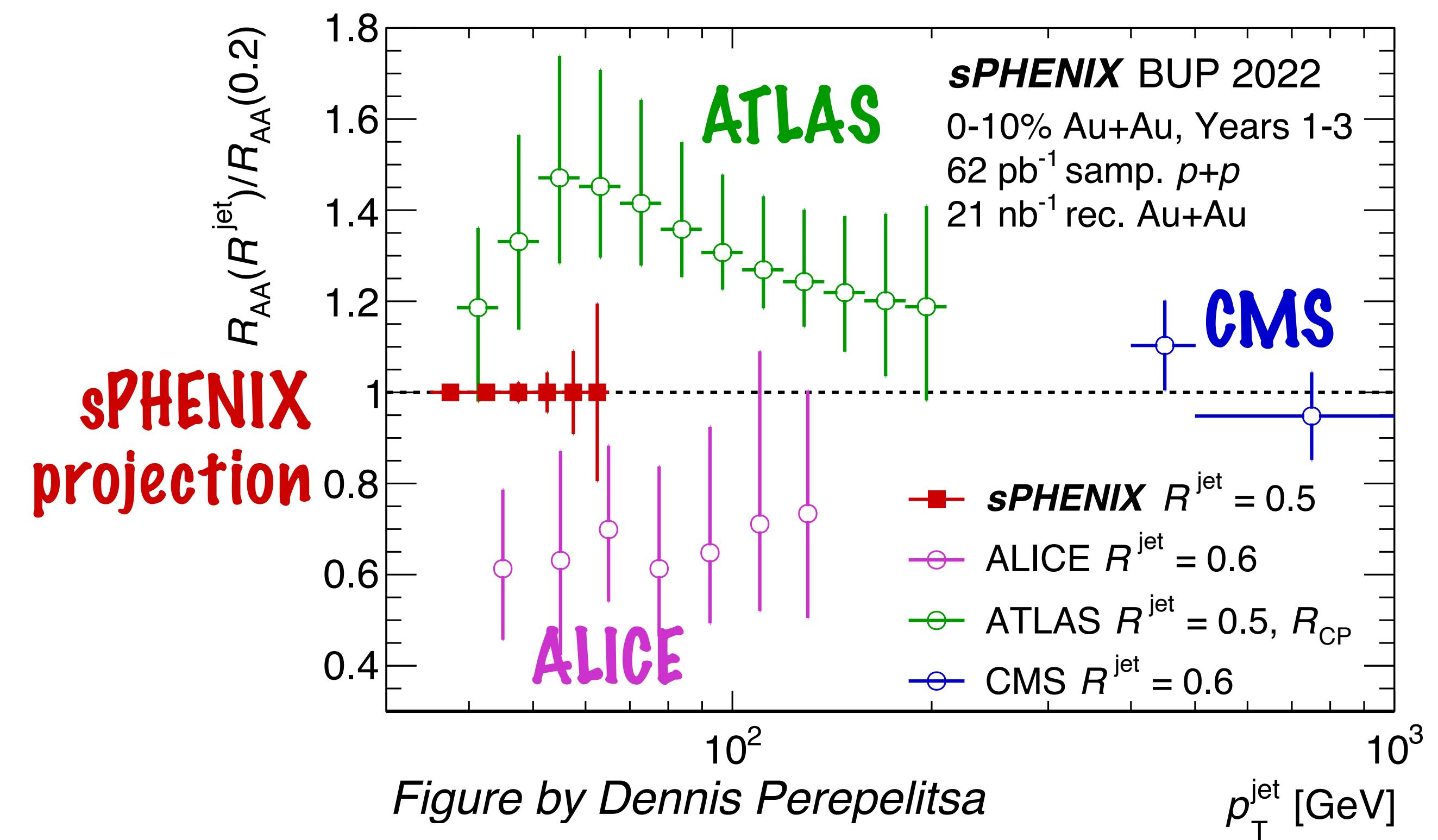
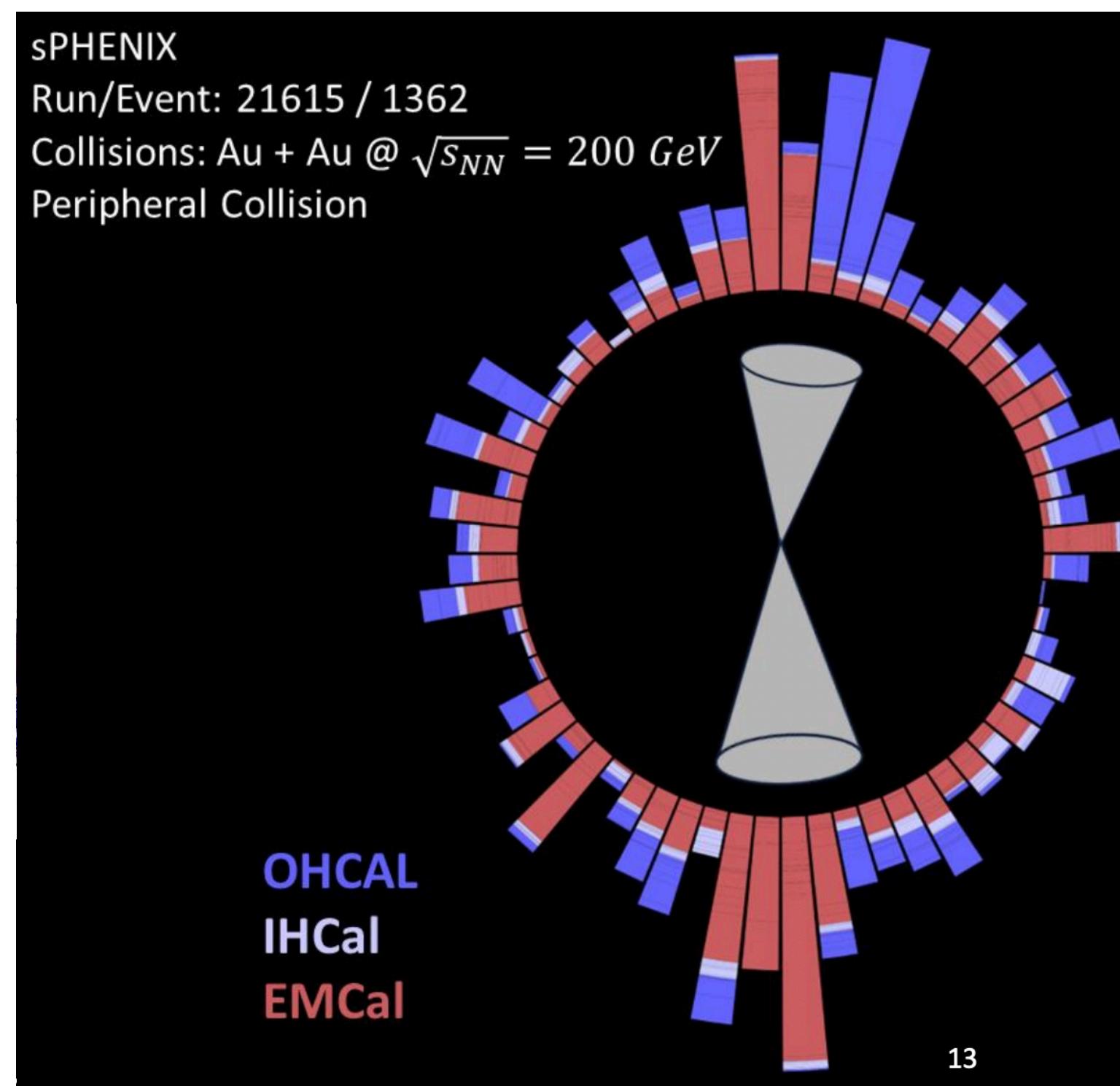


Note) “recalculated”: uncertainties
btw 0.4 and 0.2 are treated fully uncorrelated



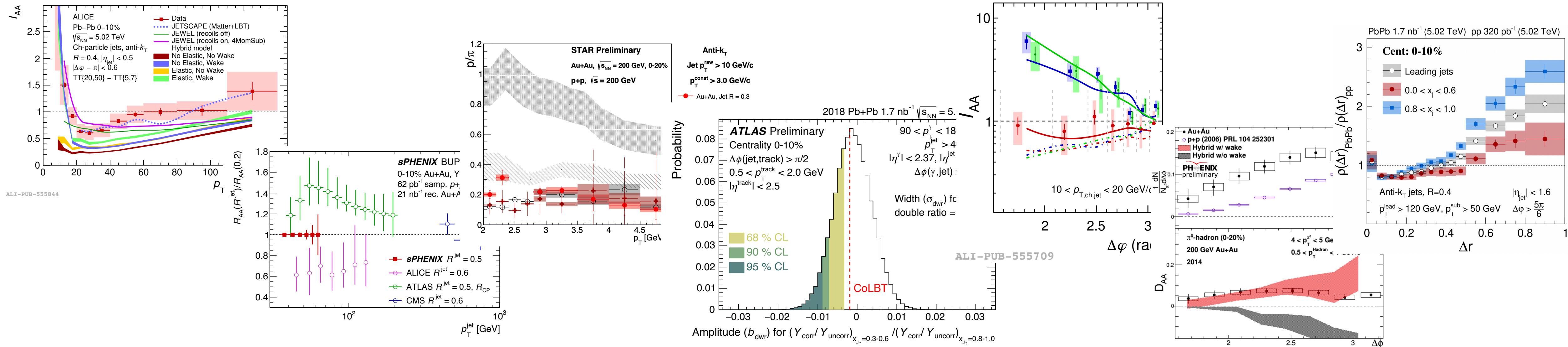
- At high p_T , mild R -dependence
- At low p_T , tension between data (**ATLAS** vs. **ALICE**), but there are *differences*
 - full jet vs. charged-particle jet
 - η range → quark-jet fraction difference, p_T spectrum difference in pp
 - ...

Discussion: Radius-dependent Jet R_{AA}



- Future beneficial jet measurements for medium response
 - R-dependence of **inclusive jets** at RHIC at low p_T (+ full jets w/ **sPHENIX**)
 - R-dependence of jets with higher **quark-initiated jet fraction** to disentangle **color-charge difference**
 - e.g. boson-tagged jets, jets at forward rapidity (*D. Pablos et al, arXiv:2210.07901*), ...

Summary

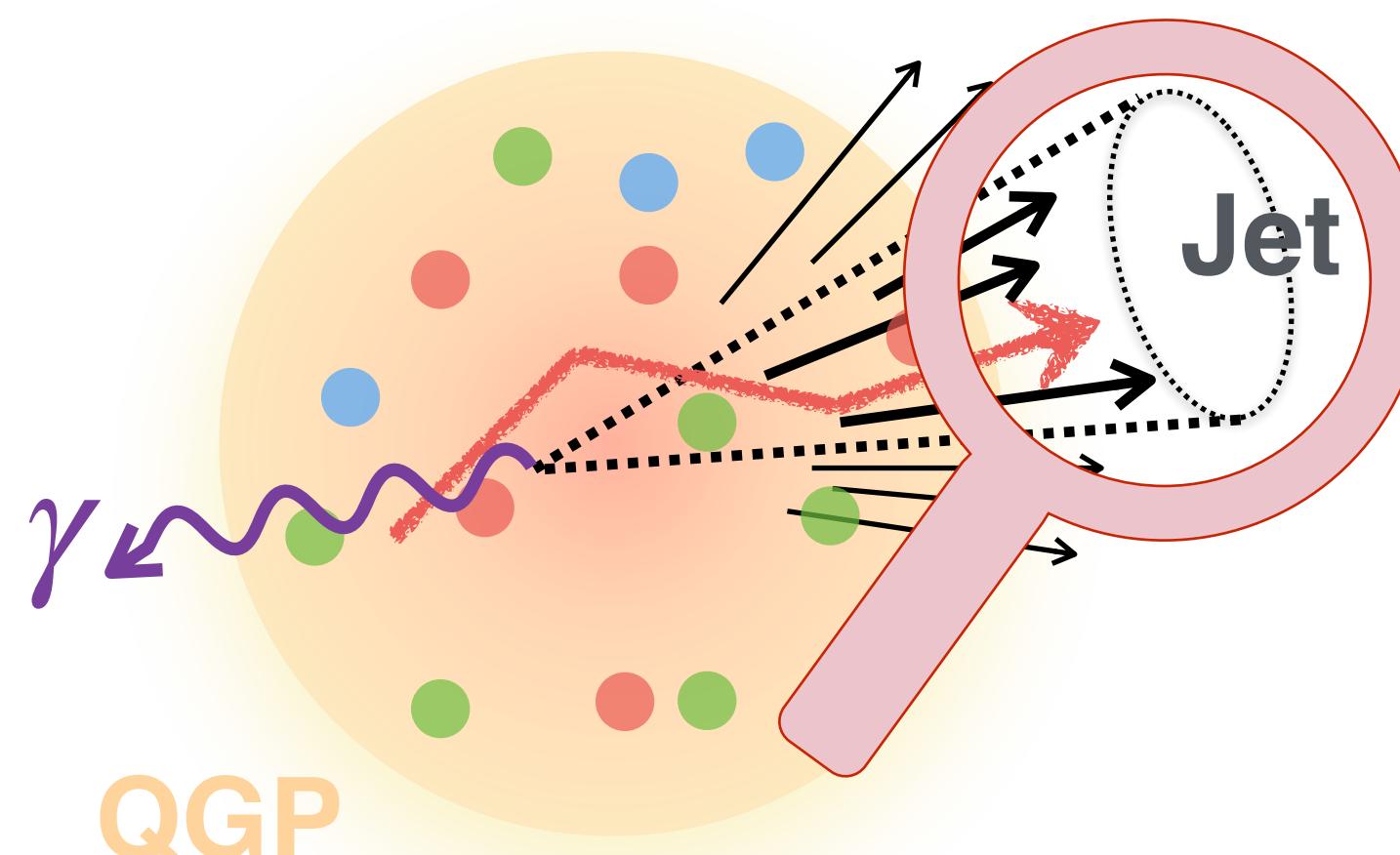


- Understanding medium response is important
 - for its own sake; e.g. extracting medium properties such as η/s , sound velocity
 - to reveal other effects; e.g. quasiparticle scattering
- More systematic studies between different models is crucial
- Precise experimental measurements with large statistics can help constraining models

Thank you!

BACK UP

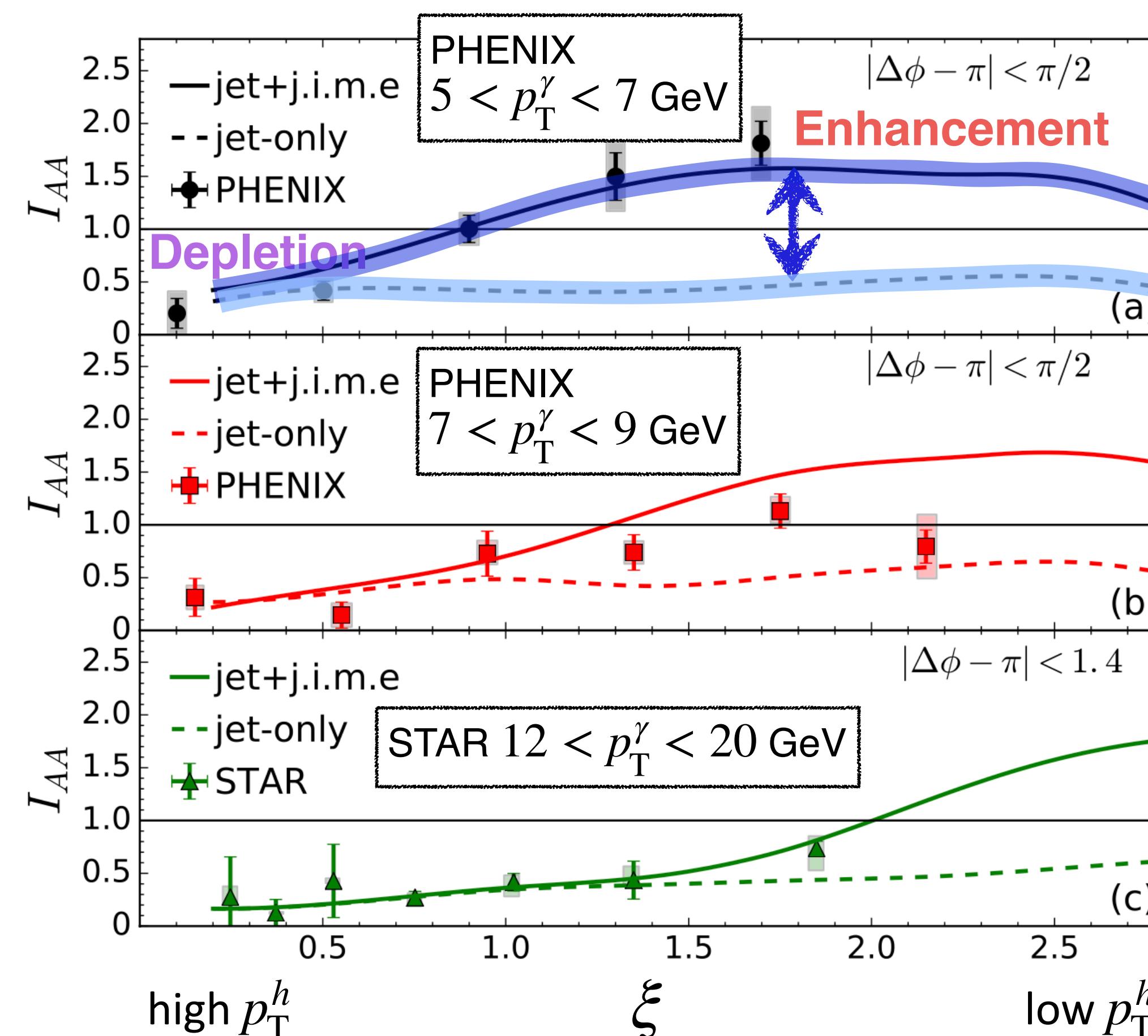
Fragmentation Function in γ -triggered Events at RHIC



$$z = p_T^h / p_T^\gamma$$

$$\xi = \ln(p_T^\gamma / p_T^h) = \ln(1/z)$$

$$I_{AA} = \frac{Y_{\text{Pb+Pb}}^{\text{hadron}} / N_{\text{Pb+Pb}}^\gamma}{Y_{pp}^{\text{hadron}} / N_{pp}^\gamma}$$



w/ medium response

w/o medium response

PHENIX PRC 102, 054910 (2020)

STAR PLB 760 (2016) 689

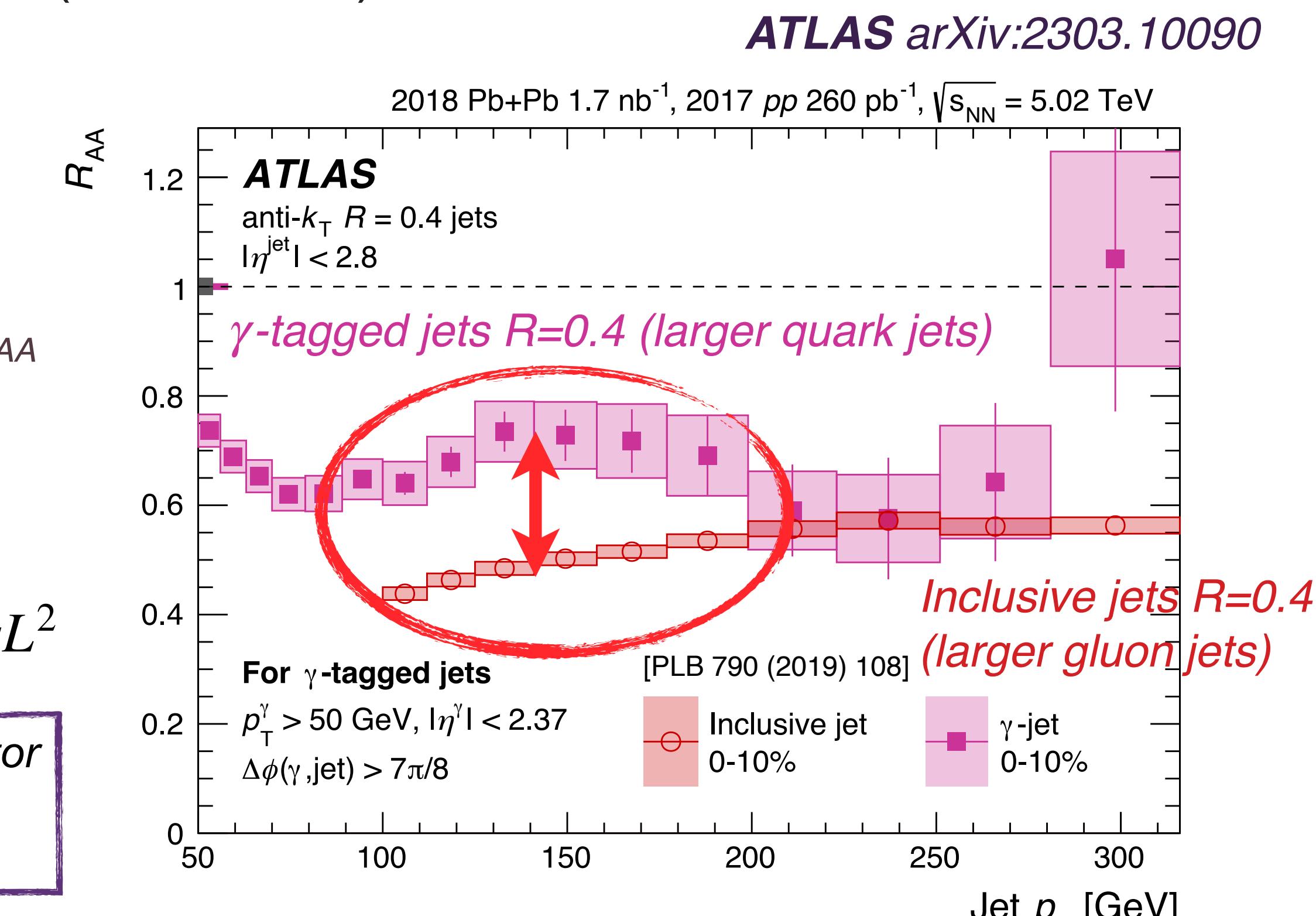
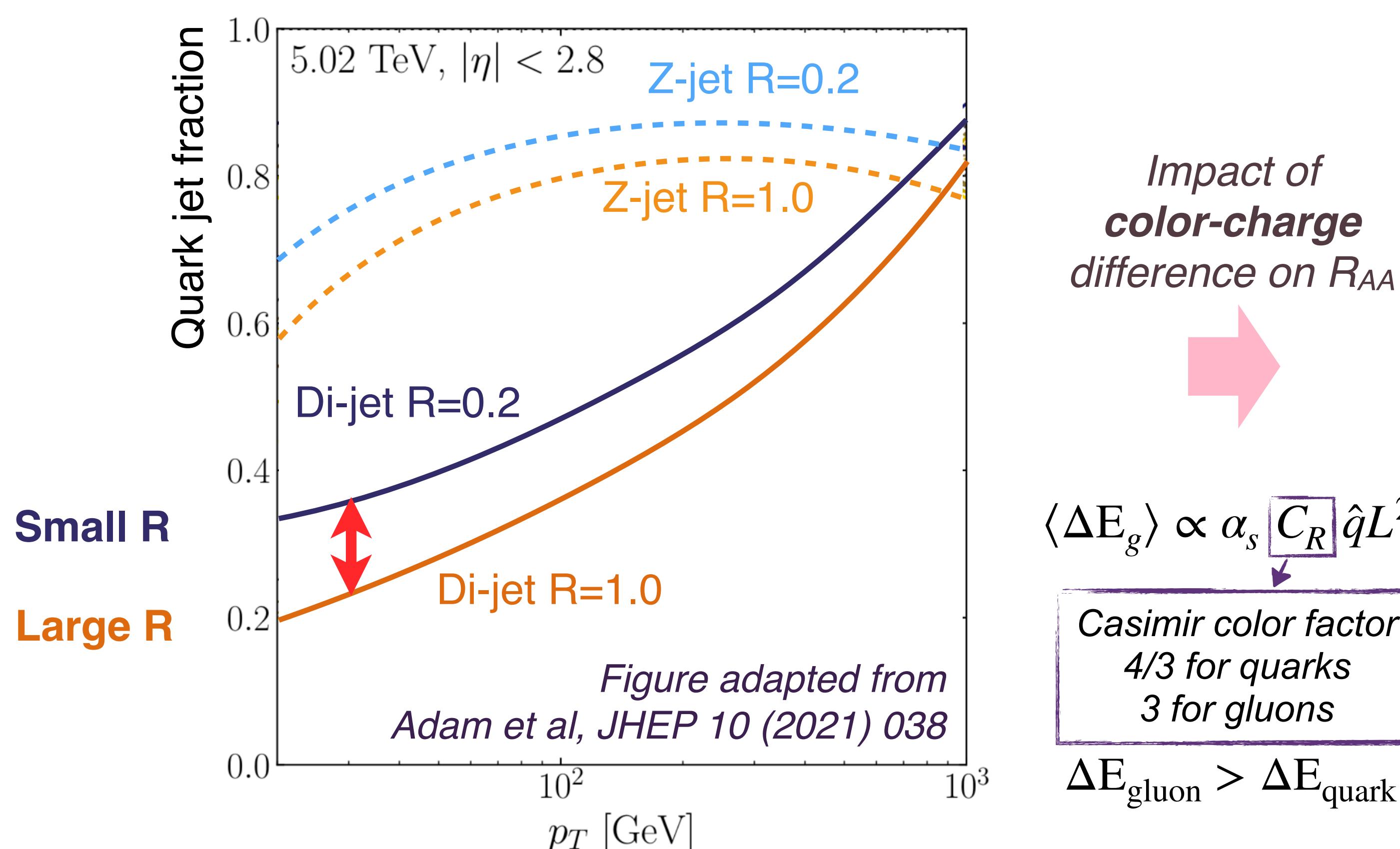
CoLBT-hydro

W. Chen et al, PLB 777 (2018) 86

- *Enhancement* of low- p_T hadrons, *depletion* of high- p_T hadrons
- Overall, **CoLBT-hydro with** jet induced medium excitations (**j.i.m.e**) describe the data better than the one *without* the medium response

Radius-dependent Jet R_{AA}: Discussion

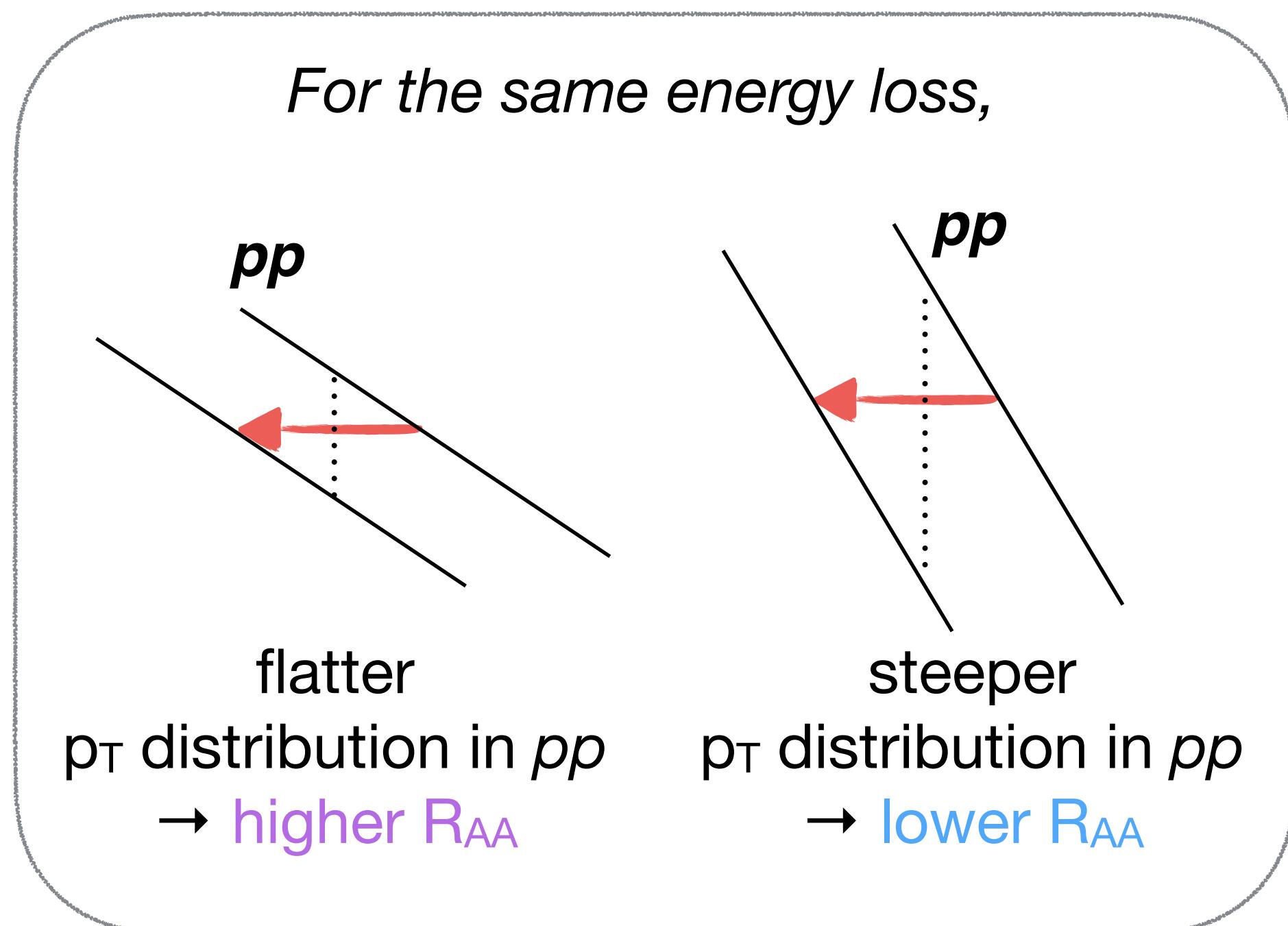
- Quark/gluon fraction difference in different R
→ Larger R → less quark (more gluon) fraction → more E-loss (Lower R_{AA})



- Forward rapidity** → more quark (less gluon) fraction → less E-loss (Higher R_{AA}) D. Pablos arXiv:2210.07901
- One could utilize **RAA of boson-tagged jets** or **jets at forward rapidity** (dominated by quark-jets) to de-weight the *color-charge dependent E-loss effect* in the double R_{AA} ratio

Radius-dependent Jet R_{AA}: Discussion

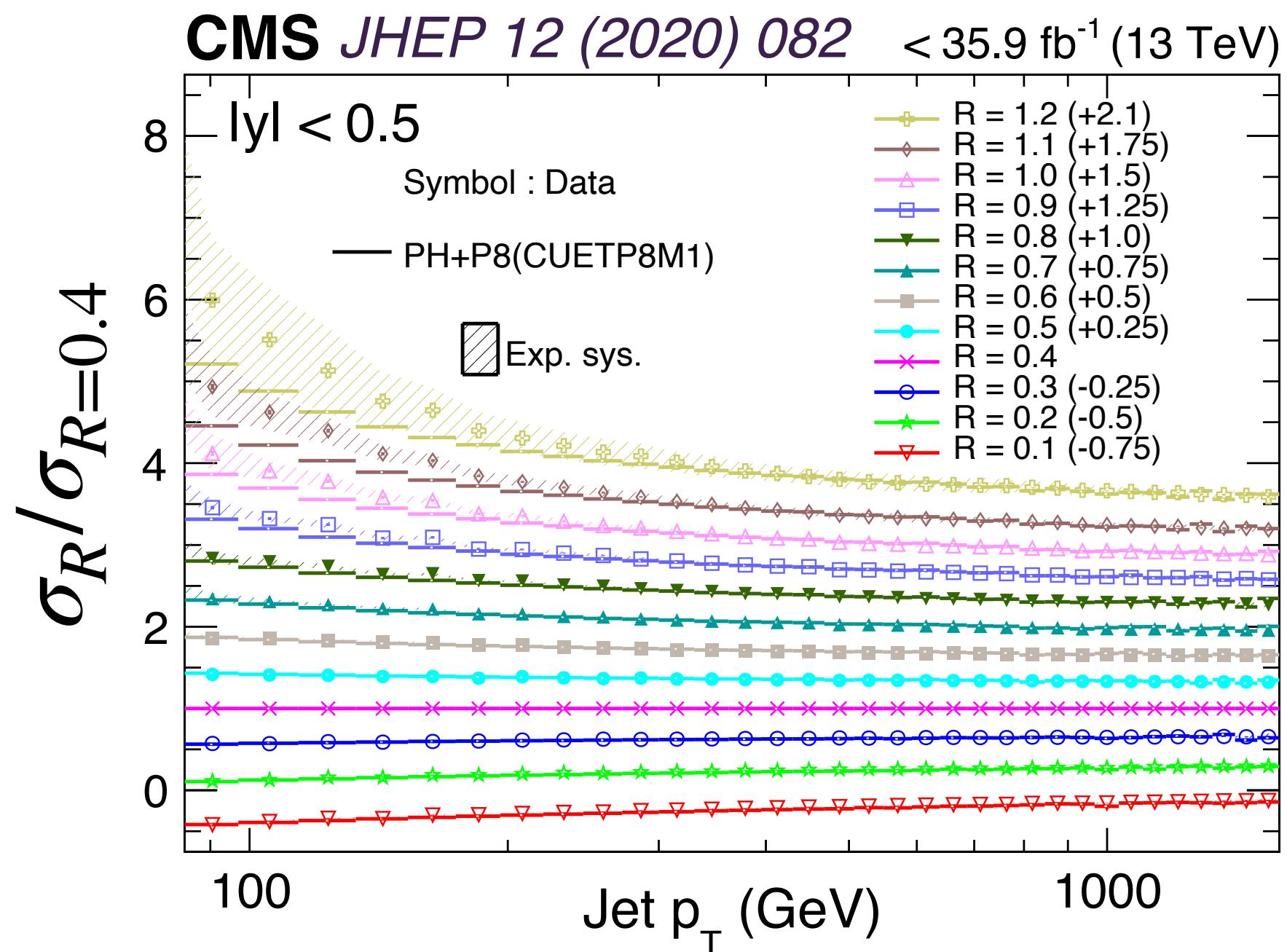
- In pp collisions, different p_T slope results in different R_{AA}
 - **steeper p_T distribution** → **Lower R_{AA}**



Radius-dependent Jet R_{AA}: Discussion

J. Brewer et al, PRL122 (2019) 222301

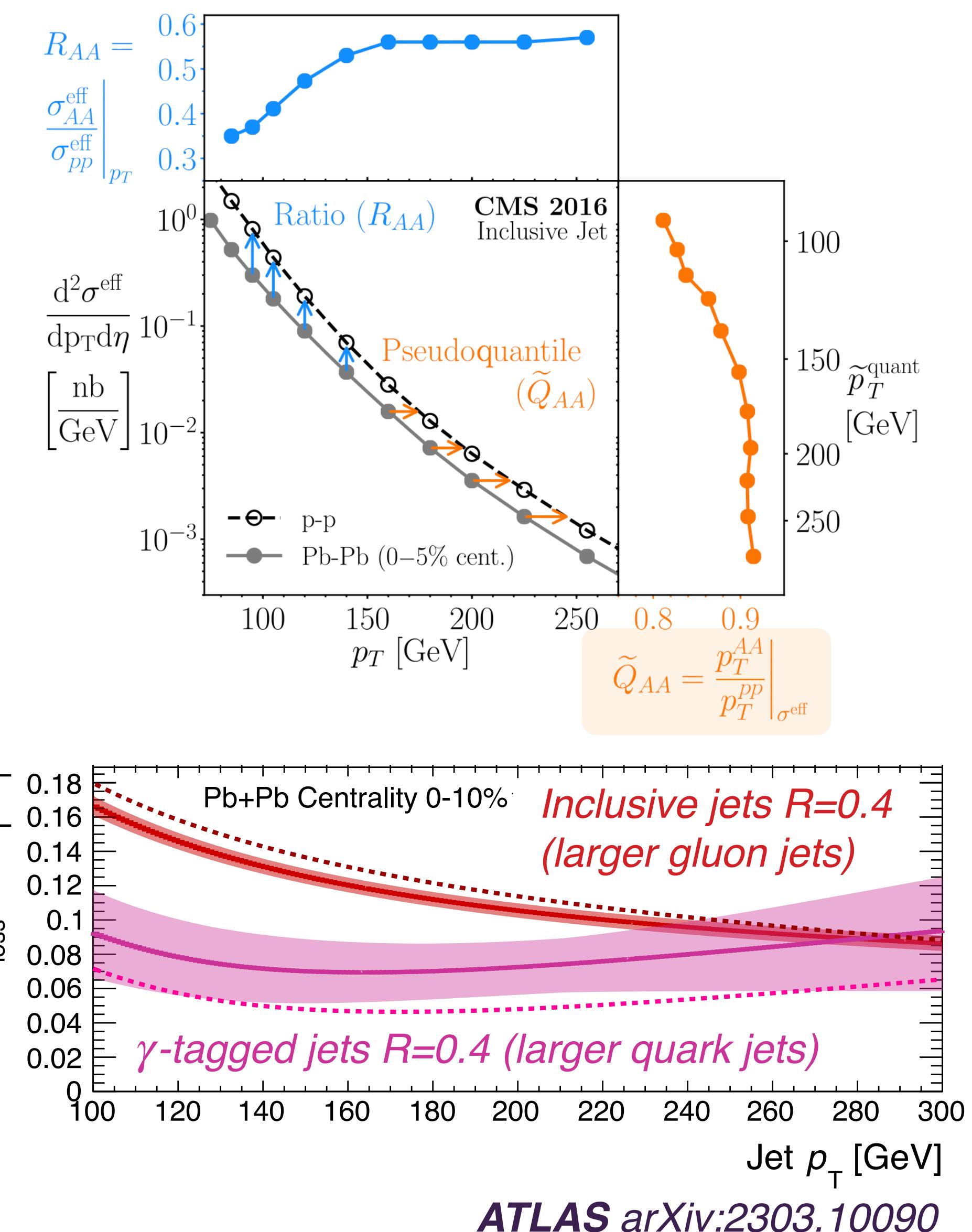
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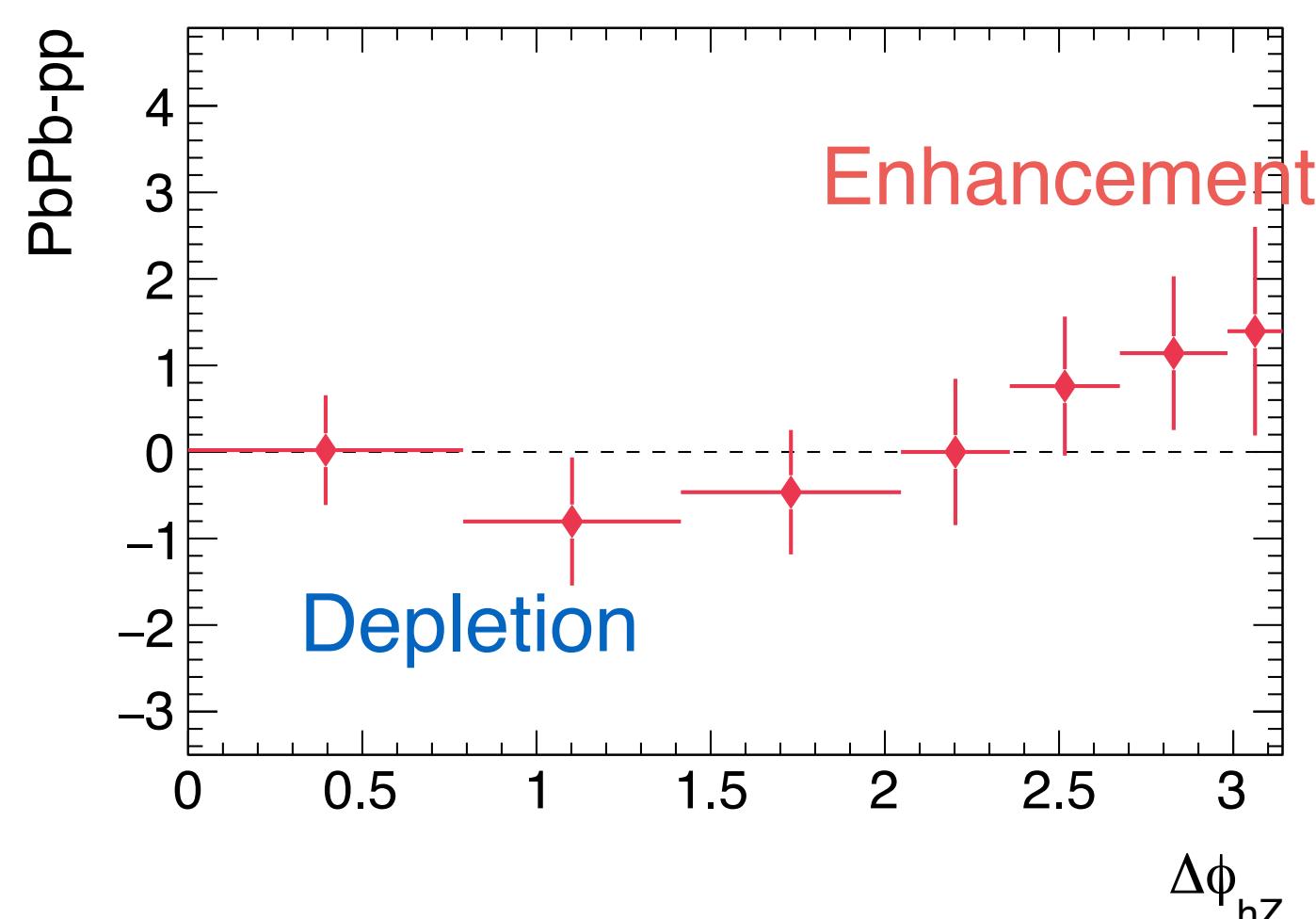
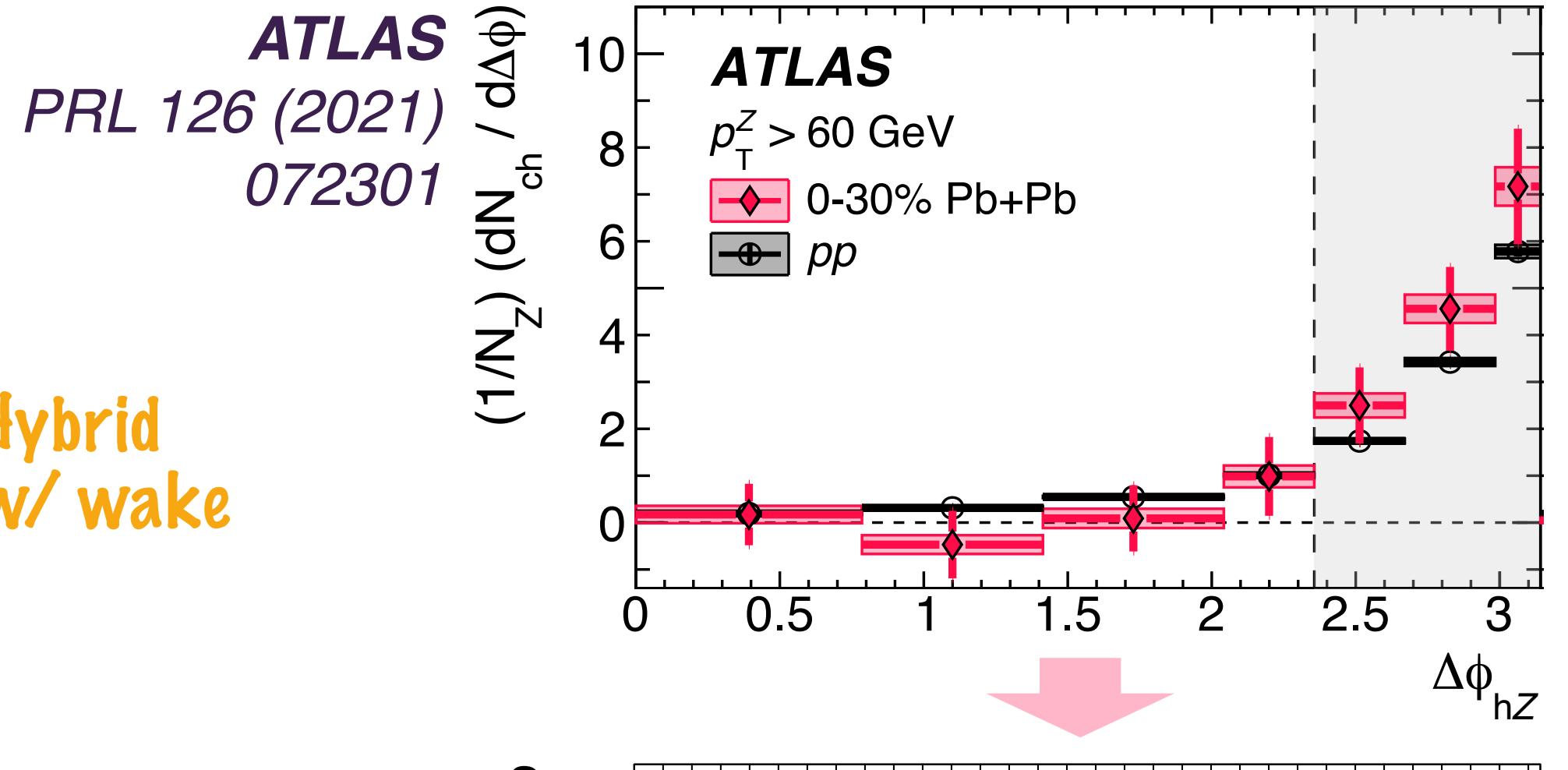
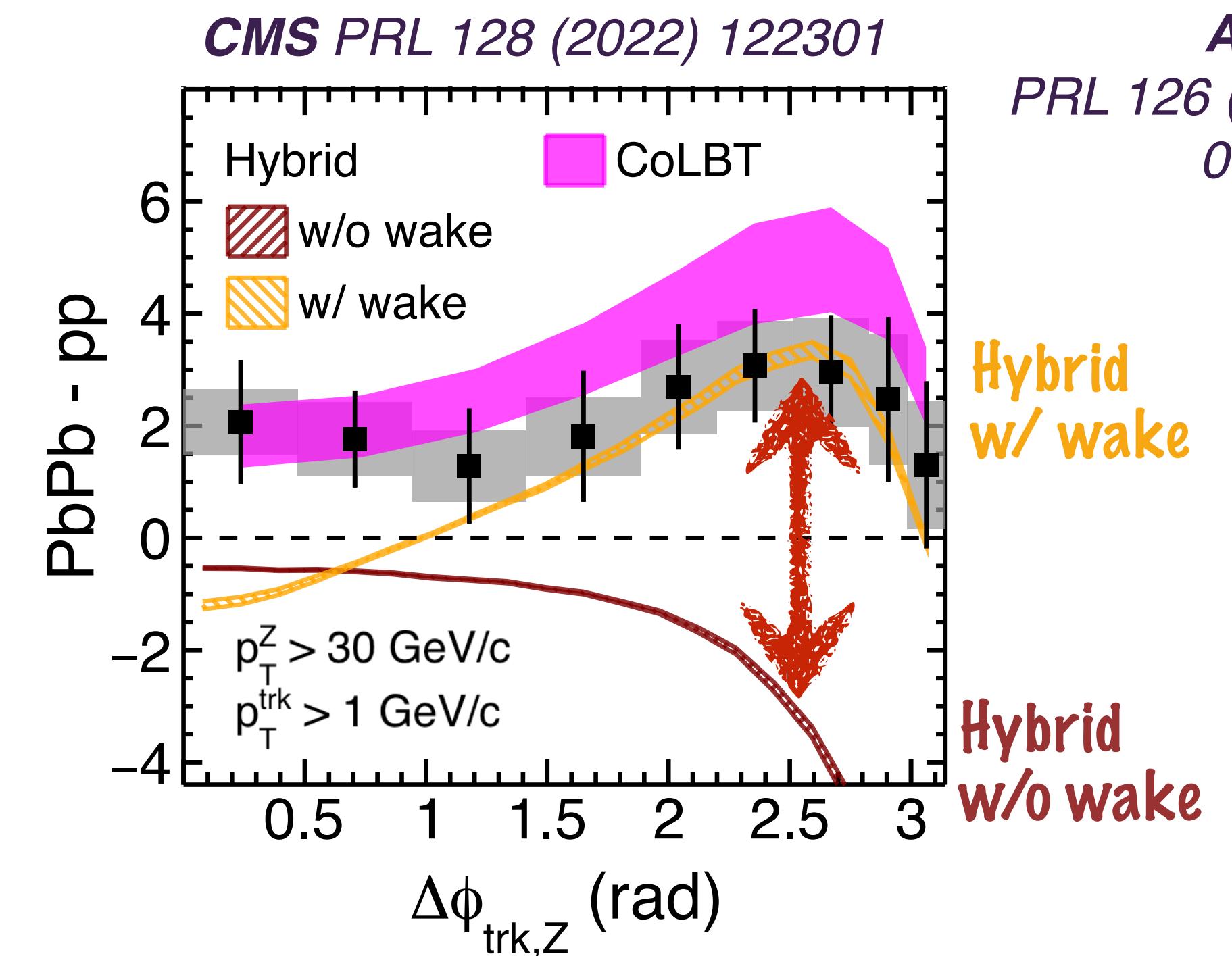
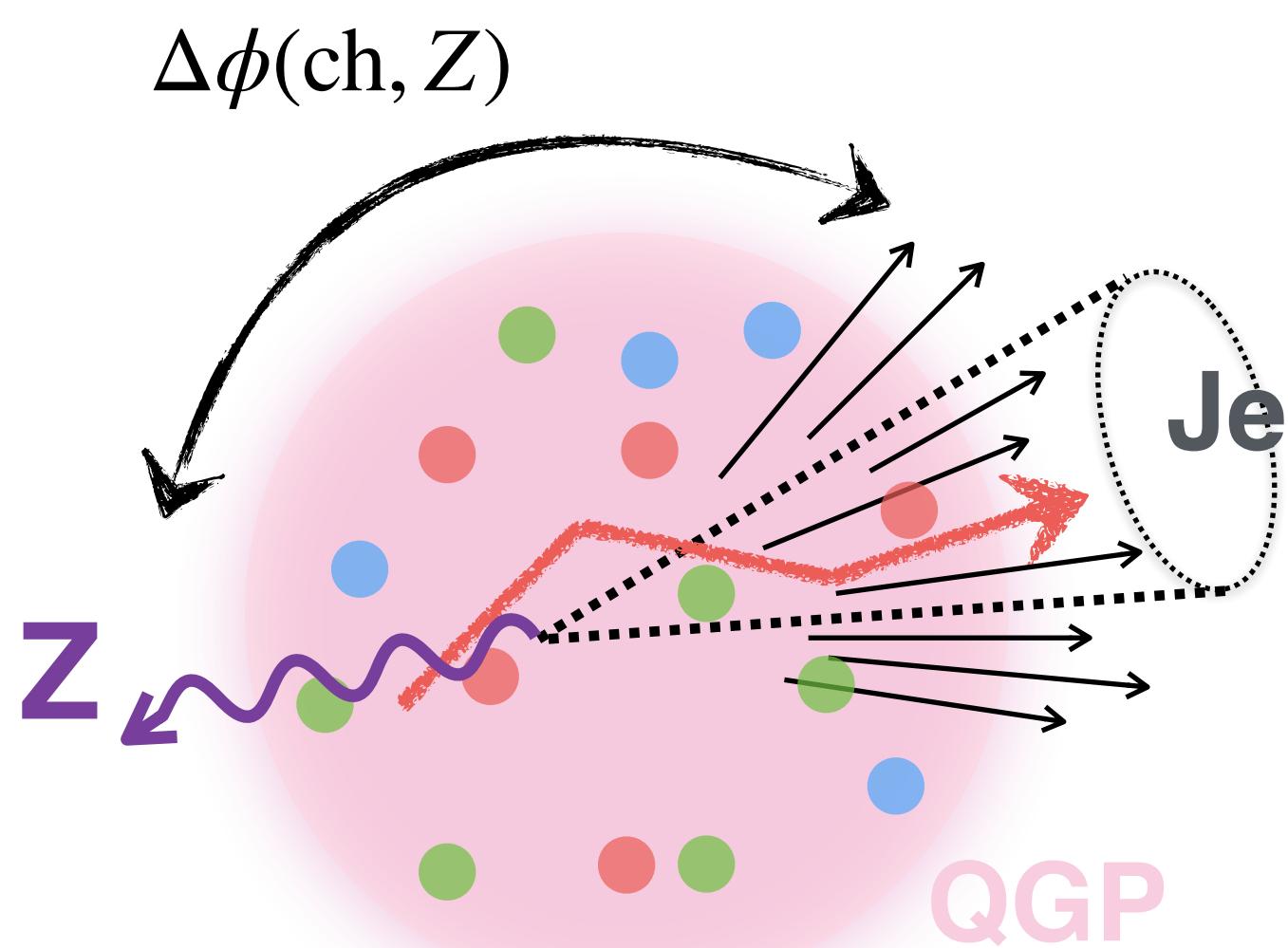
S_{loss} or Q_{AA}
to mitigate the
effect from p_T
slope difference

$$S_{\text{loss}} \equiv \frac{(p_T^{\text{pp}} - p_T^{\text{PbPb}})}{p_T}$$

- Different R have different p_T slope in pp collisions
- Instead of R_{AA} , other observables (e.g. S_{loss} , Q_{AA}) can be measured to de-weight the p_T slope effect



Z-hadron Correlation at LHC: $\Delta\phi$ dependence

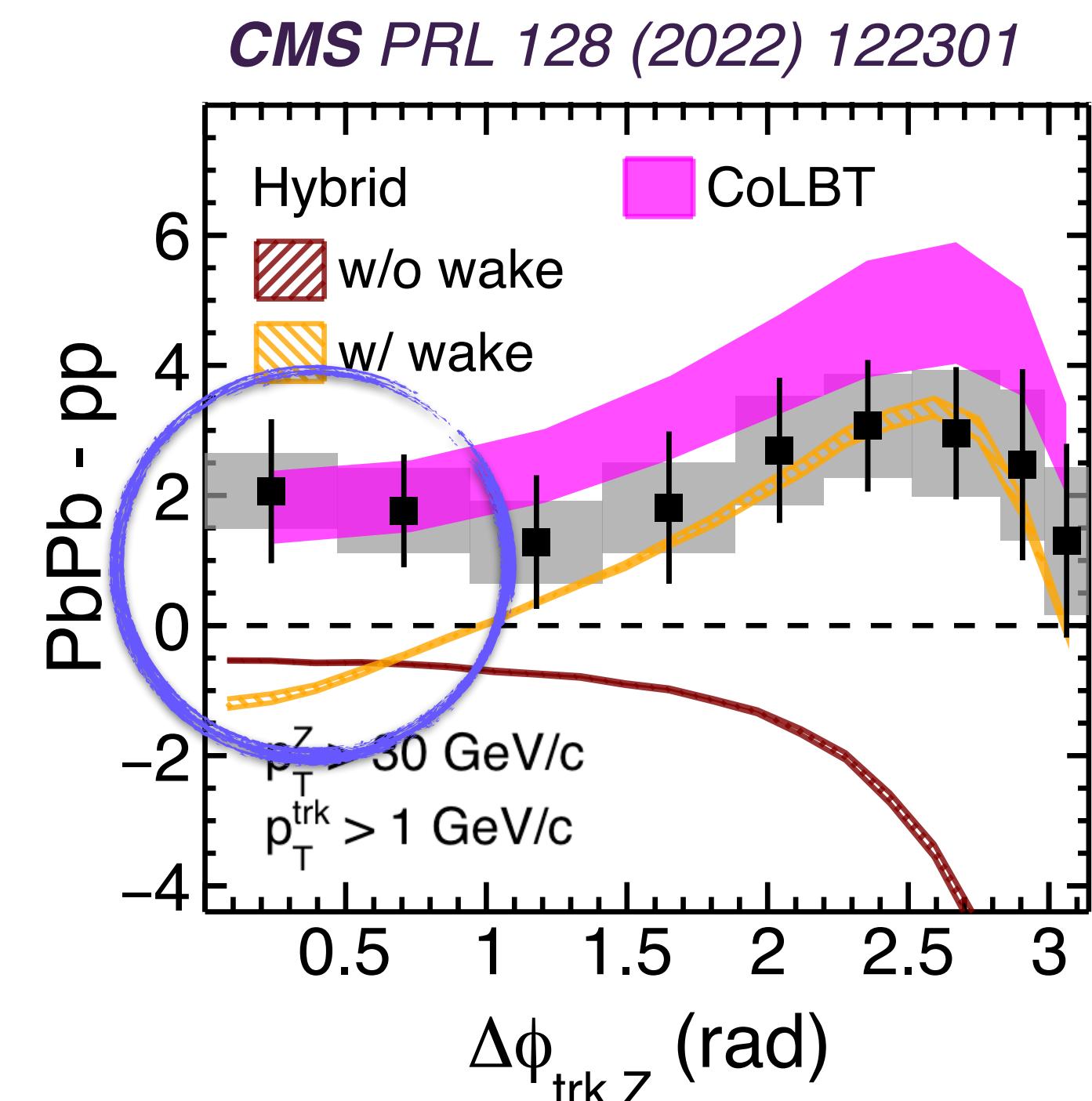
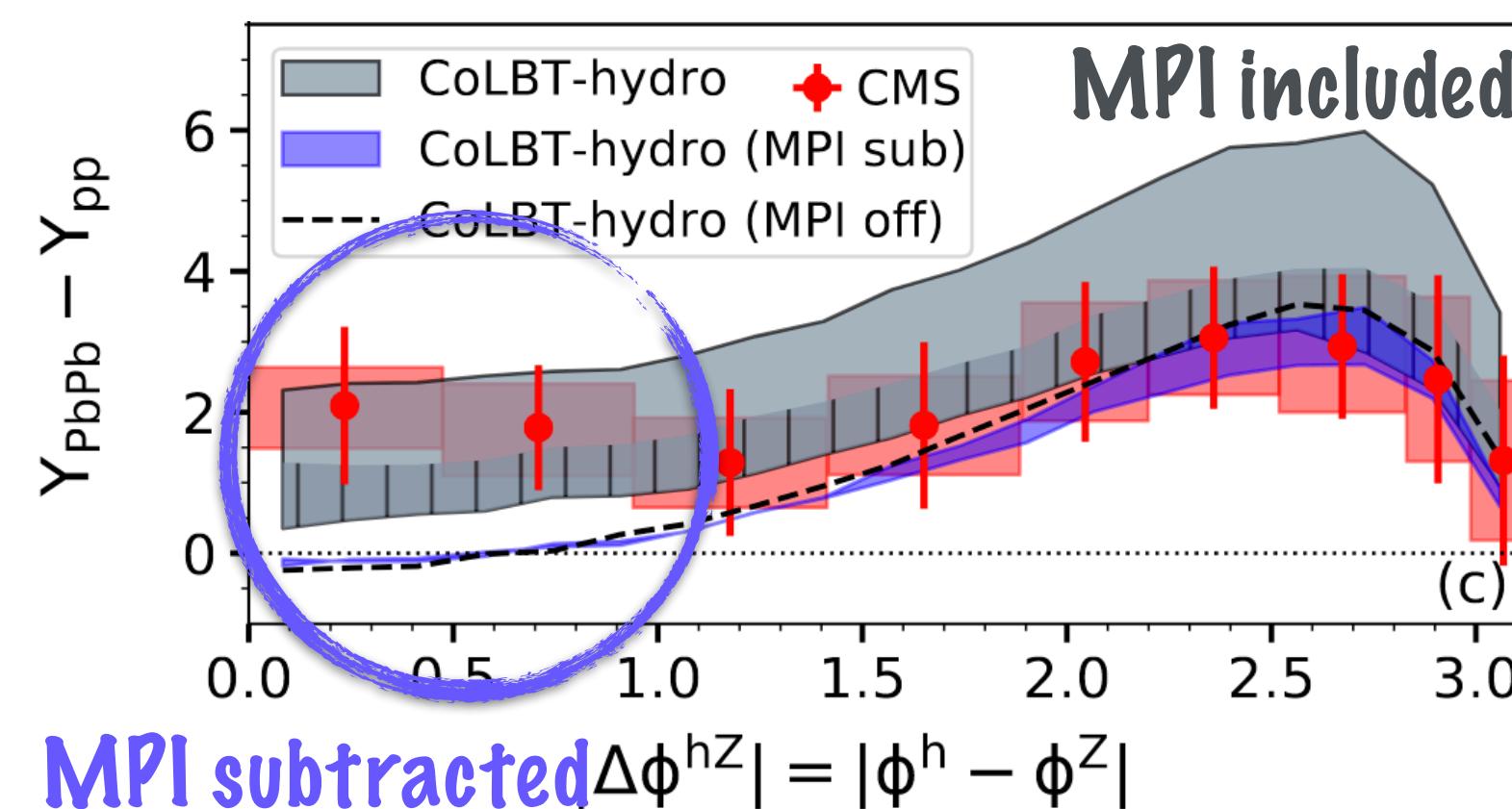


- Enhancement of hadrons in jet direction; **medium response!**
- Differences between **ATLAS** and **CMS** measurements
 - (1) different background subtraction method
 - (2) **ATLAS** $2 < p_T^h < 4 \text{ GeV}$, **CMS** $p_T^h > 1 \text{ GeV}$
- In **Z**-boson direction, **ATLAS** shows hint of **diffusion wake**

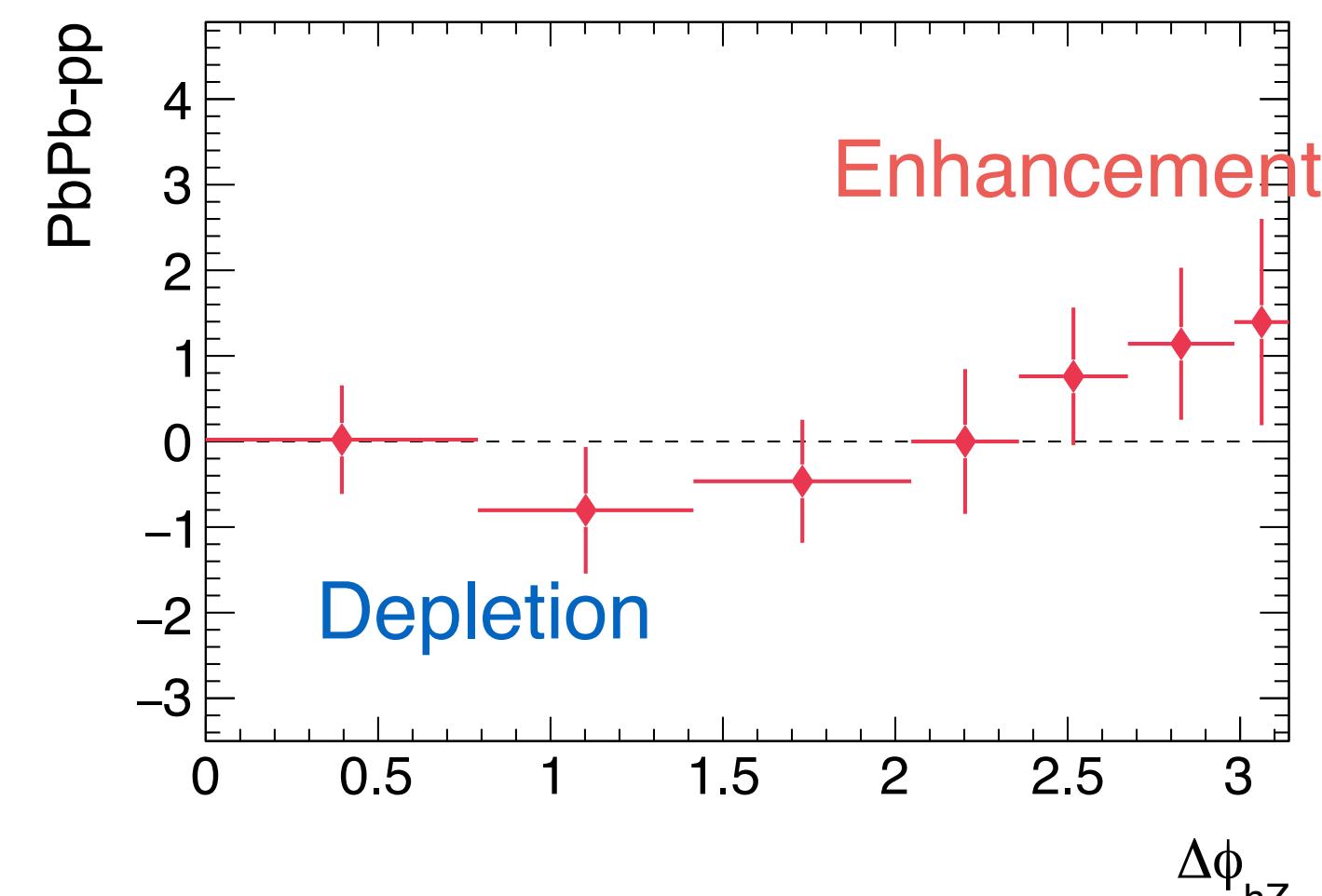
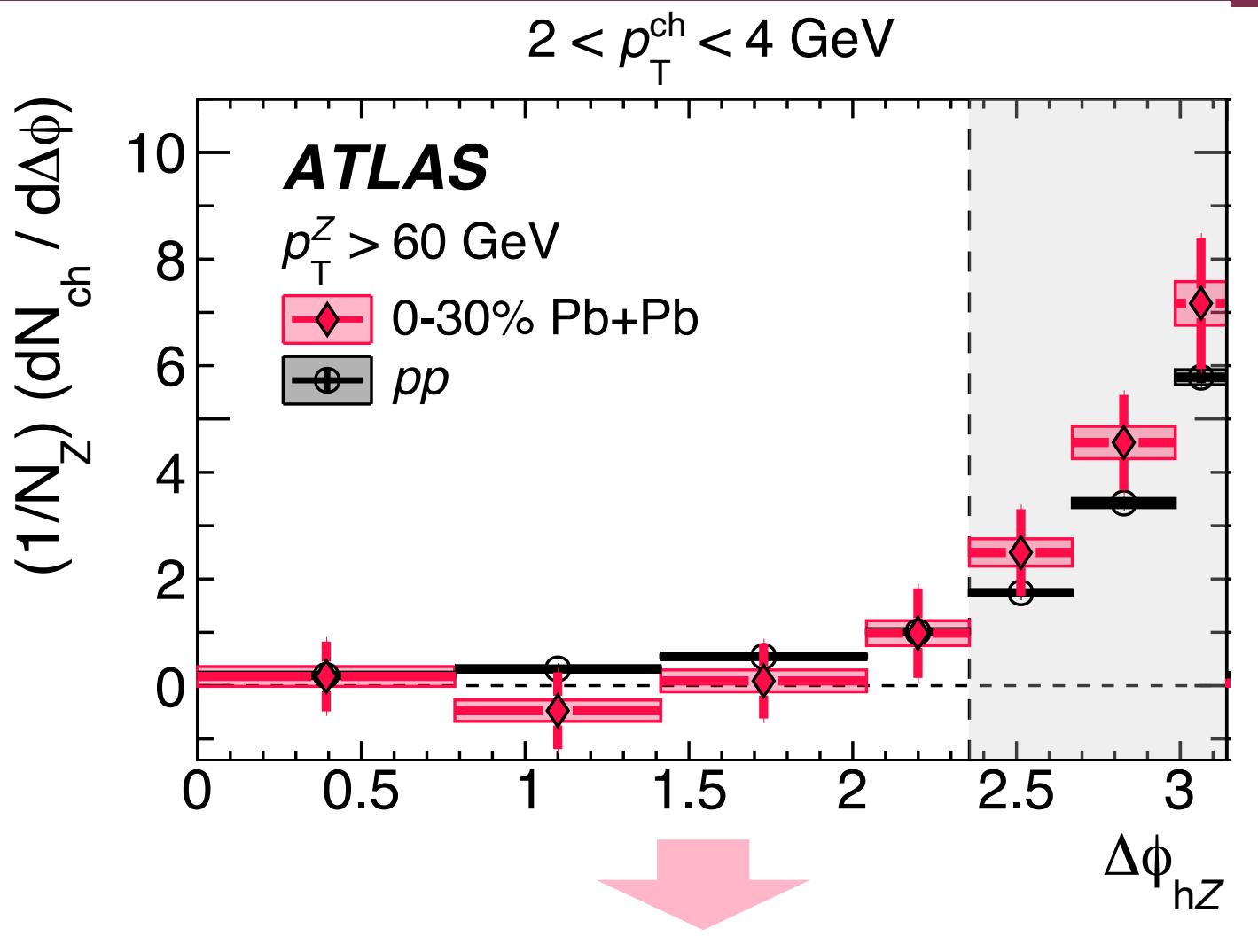
Z-hadron Correlation at LHC: $\Delta\phi$ dependence

Wei Chen, PRL 127 (2021) 082301

CoLBT-hydro



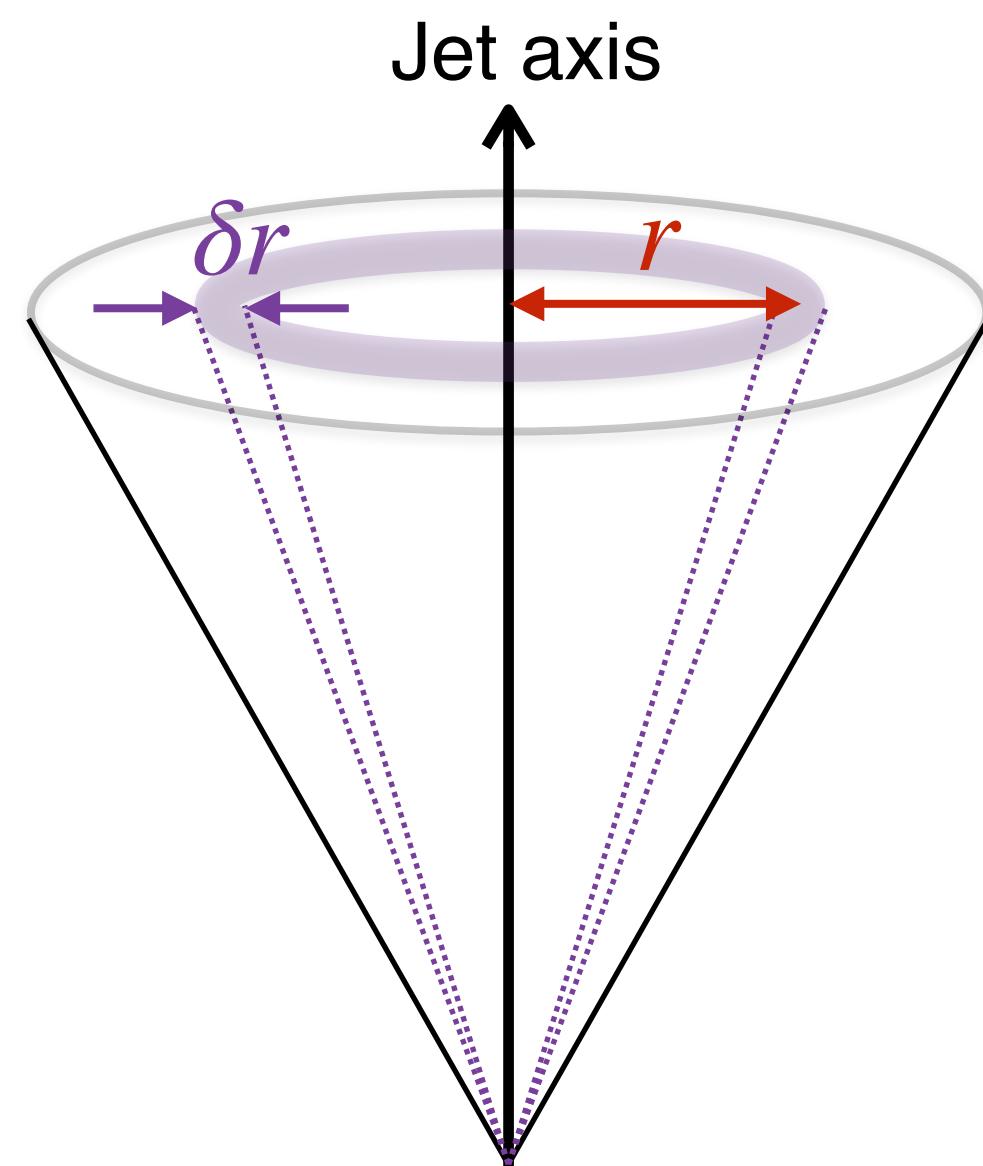
ATLAS
PRL 126 (2021)
072301



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CMS and **CoLBT** shows enhancement by **multi-parton interaction (MPI)**

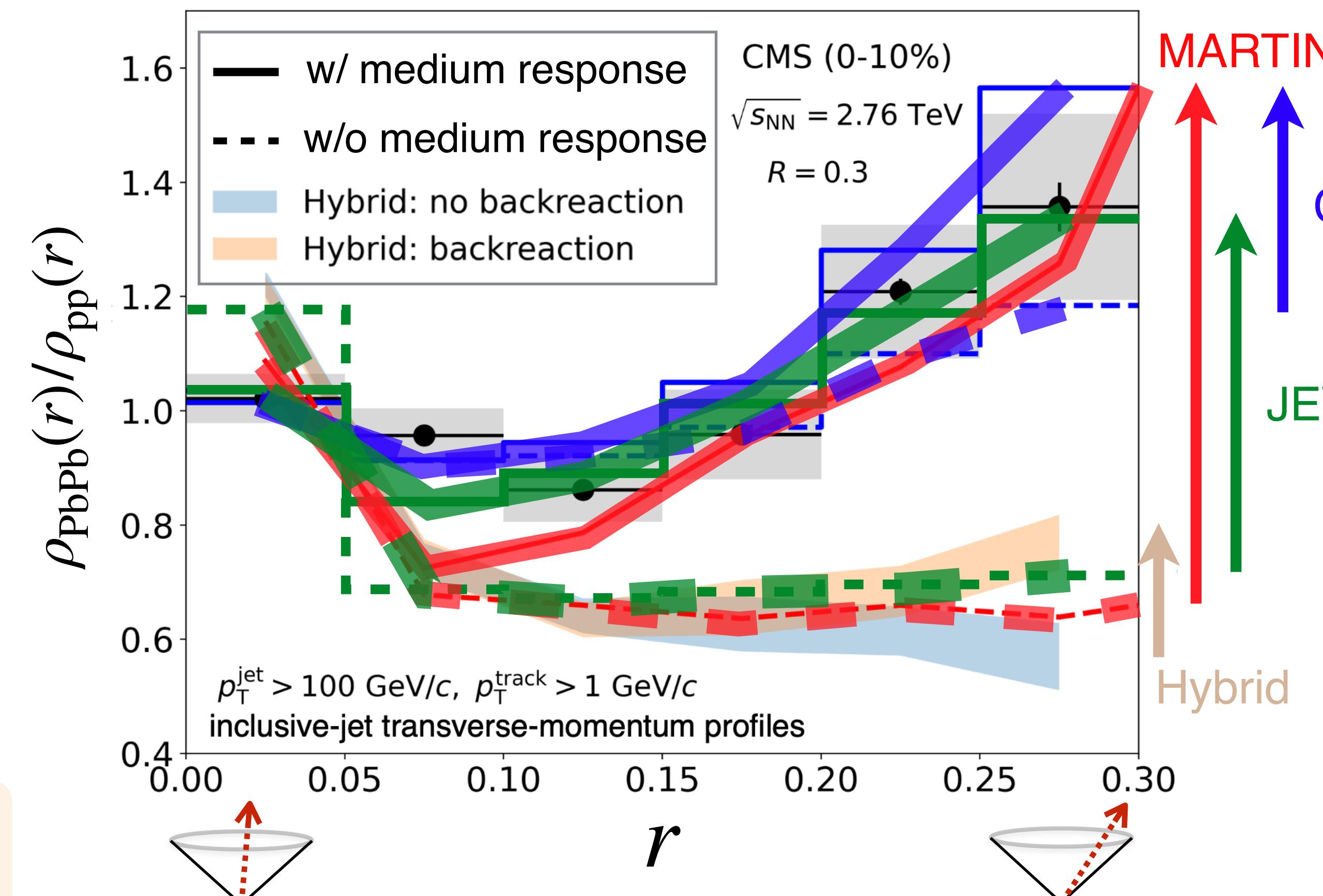
Jet Shape

CMS, PLB 730 (2014) 243



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

- At large angle, all models predict **enhancement** by medium response



MARTINI, NPA 982 (2019) 643

JEWEL, JHEP 1707 (2017) 141

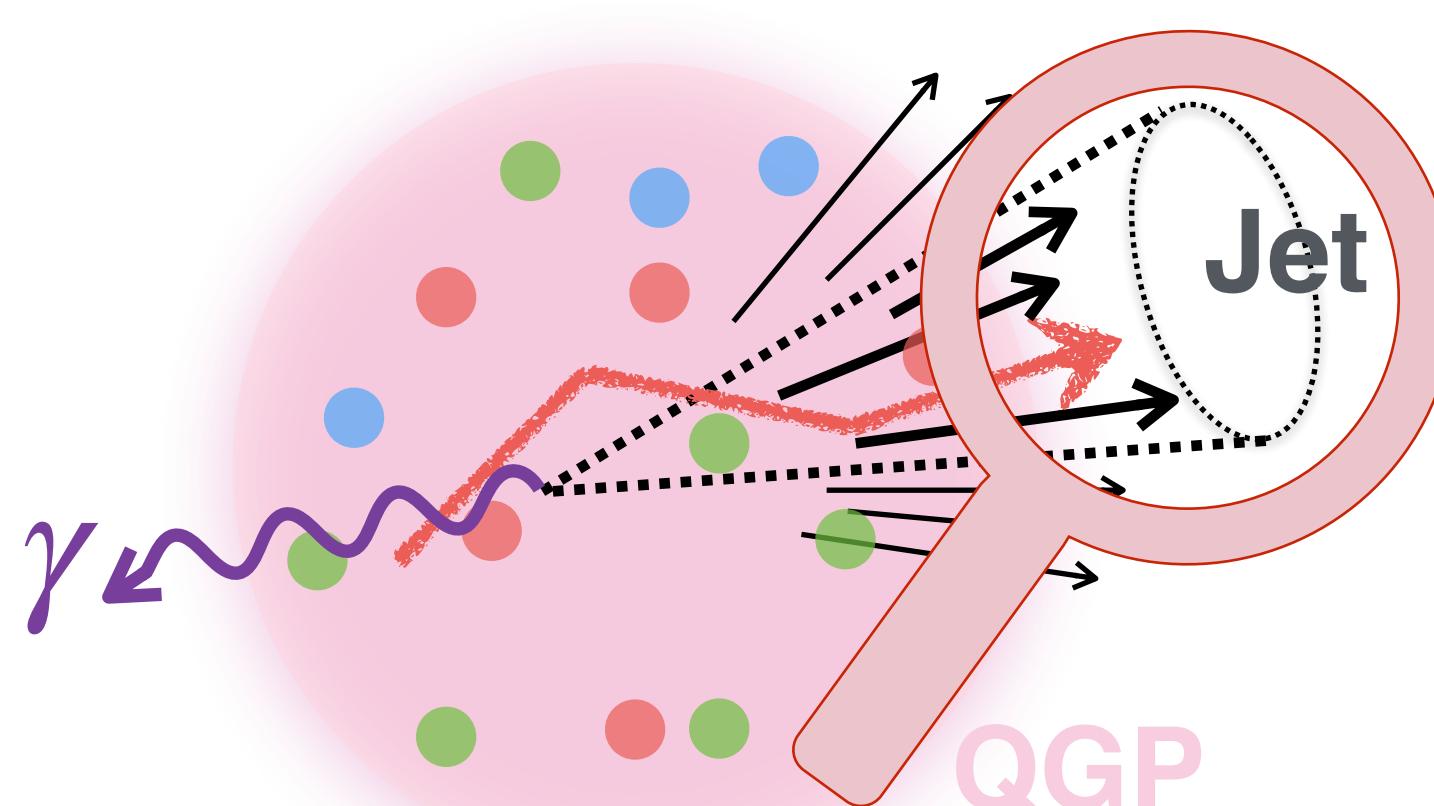
Coupled jet-fluid, PRC 95 (2017) 044909

Figure adapted from [Rey Cruz-Torres' slides](#)

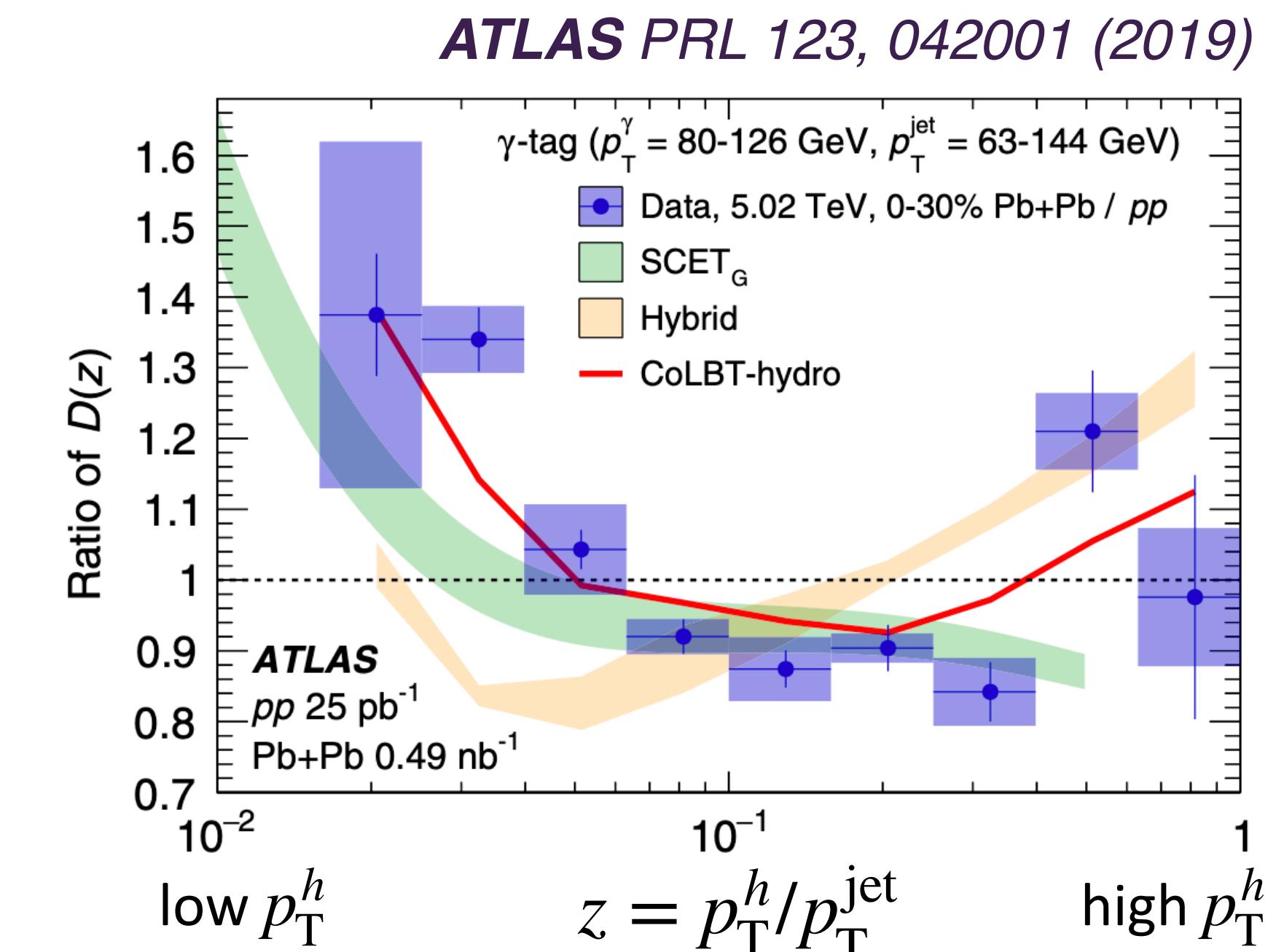
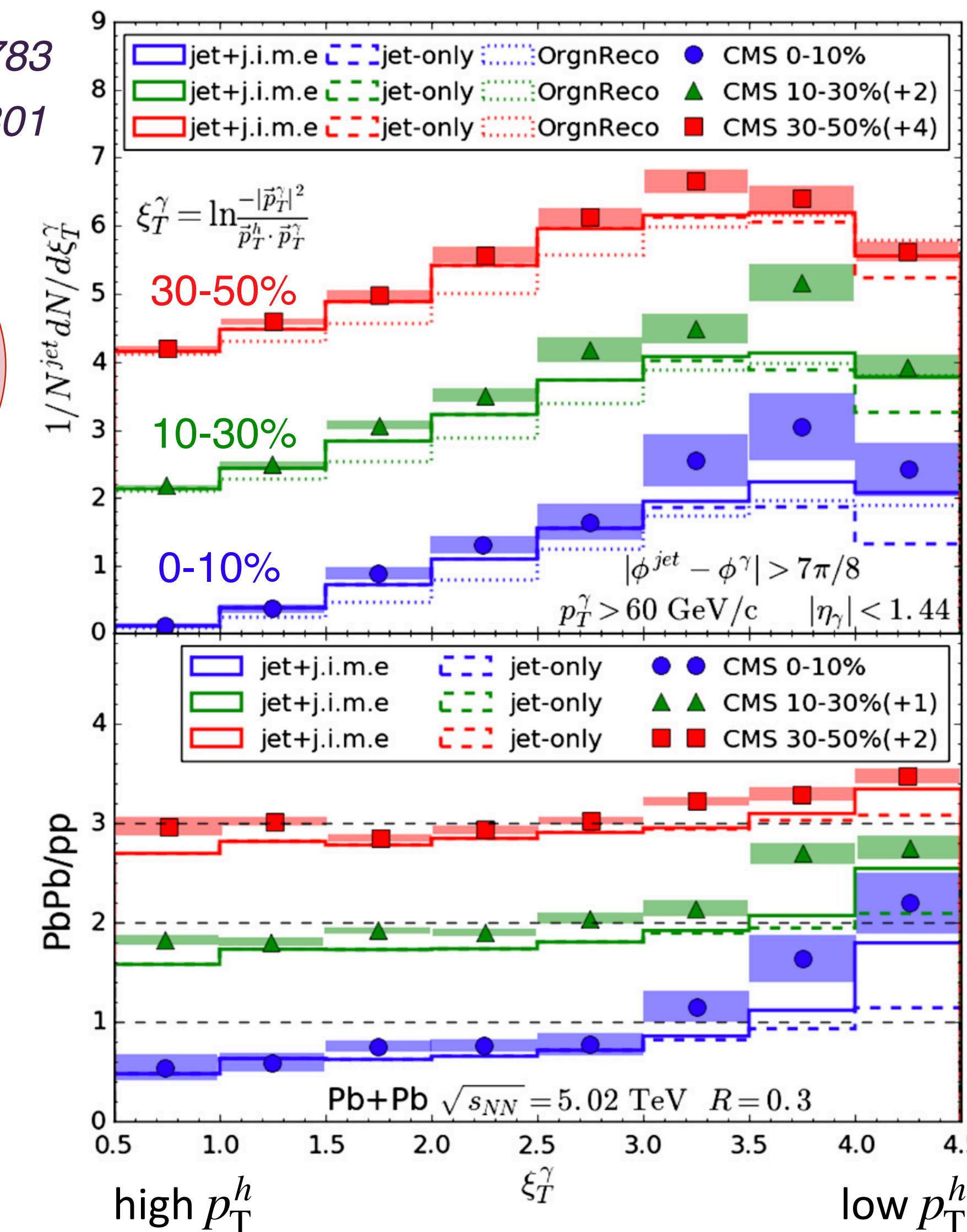
γ -Jet Fragmentation Function at LHC

Wei Chen et al., PLB 810 (2020) 135783

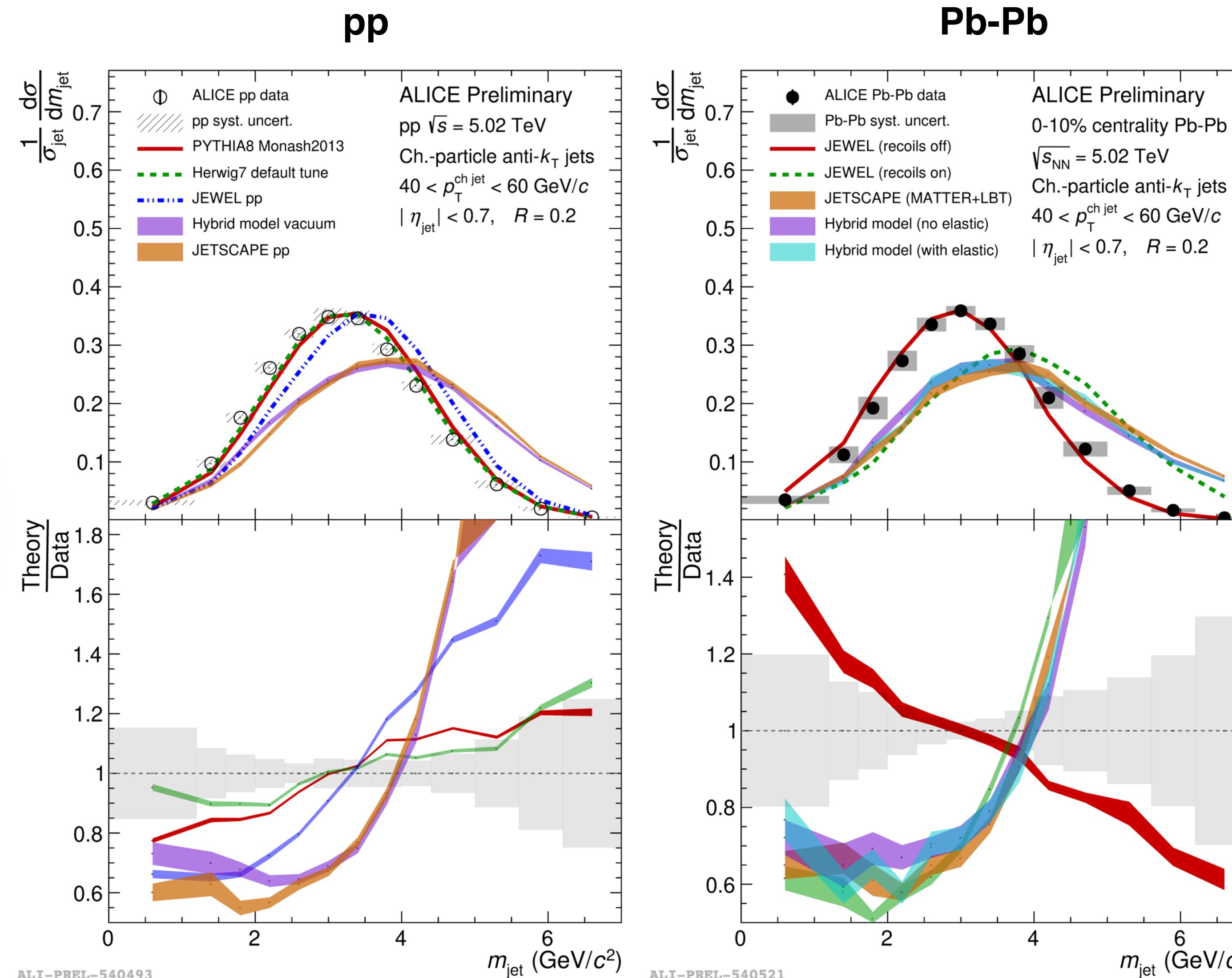
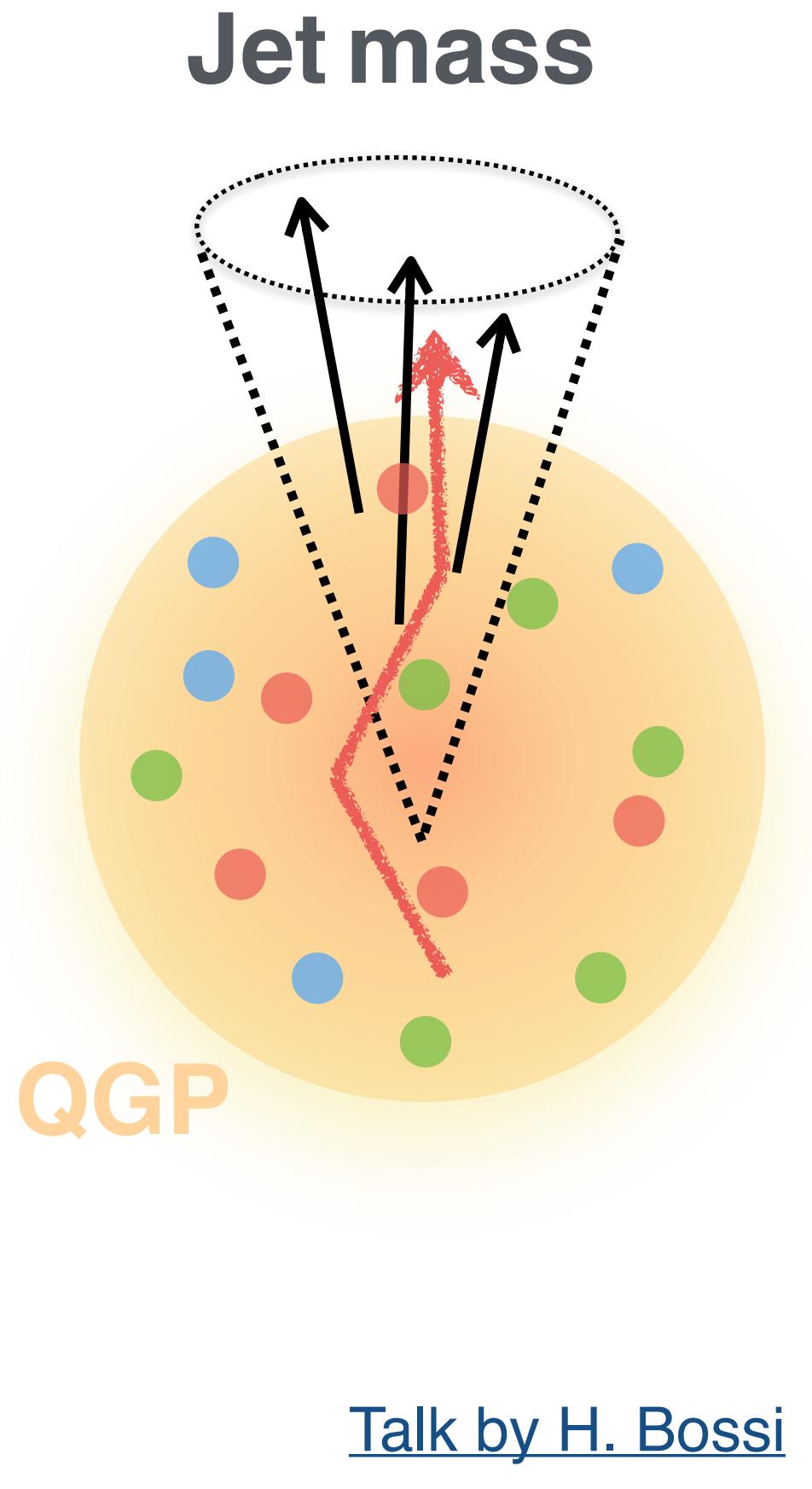
CMS PRL 121 (2018) 242301



$$\xi_T^\gamma = \ln \frac{-|\vec{p}_T^\gamma|^2}{\vec{p}_T^h \cdot \vec{p}_T^\gamma}$$

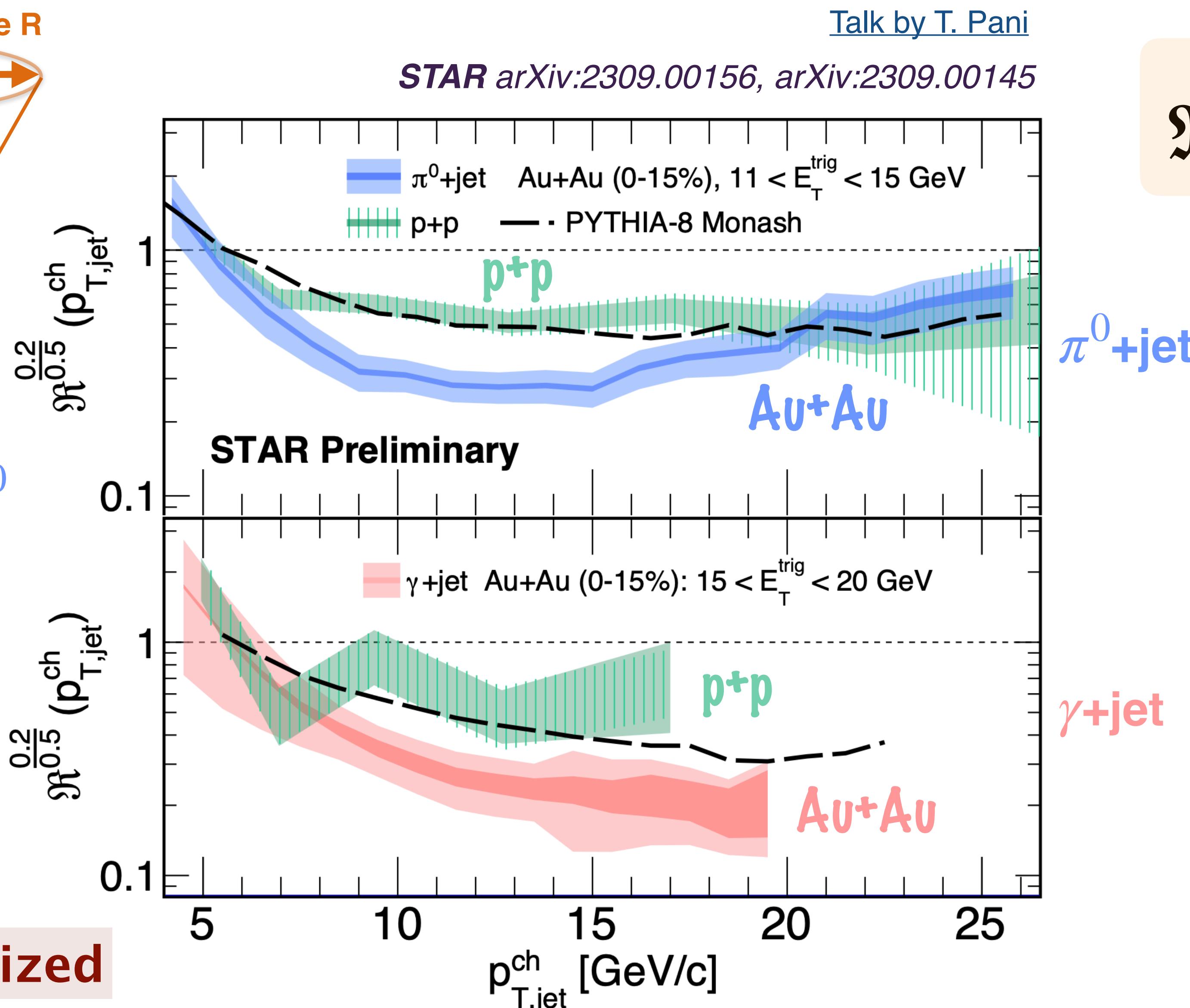
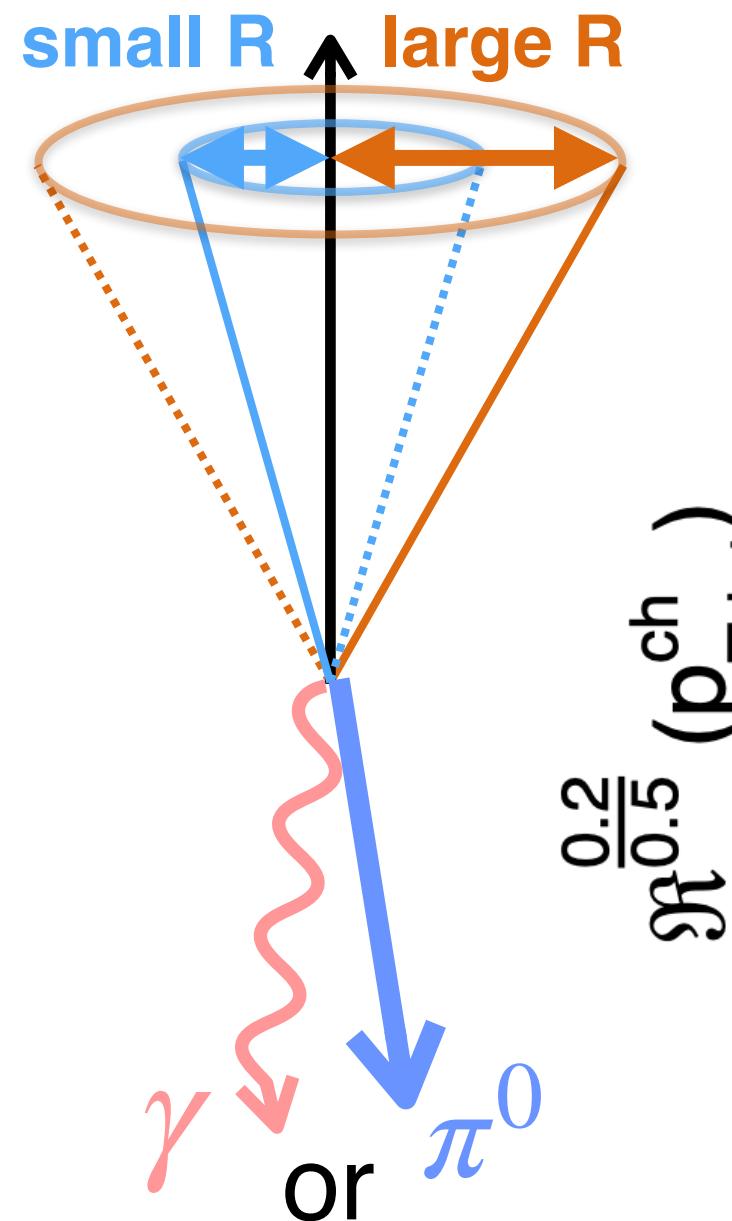


Charged Jet Mass



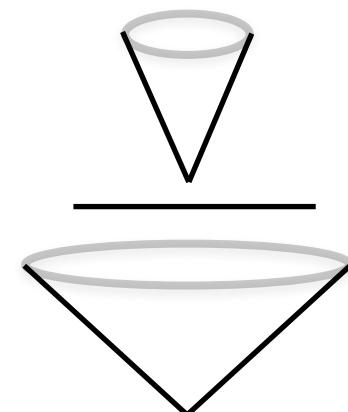
- For pp as baseline, there are discrepancies between data and models
- need to consider this when interpreting comparisons between data and models in Pb-Pb collisions

Radius-dependent Jet Yield at RHIC

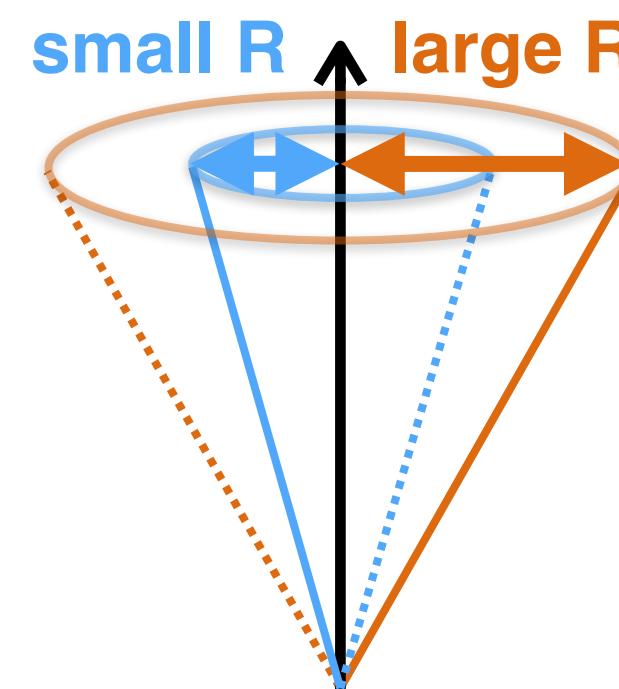


QM Finalized

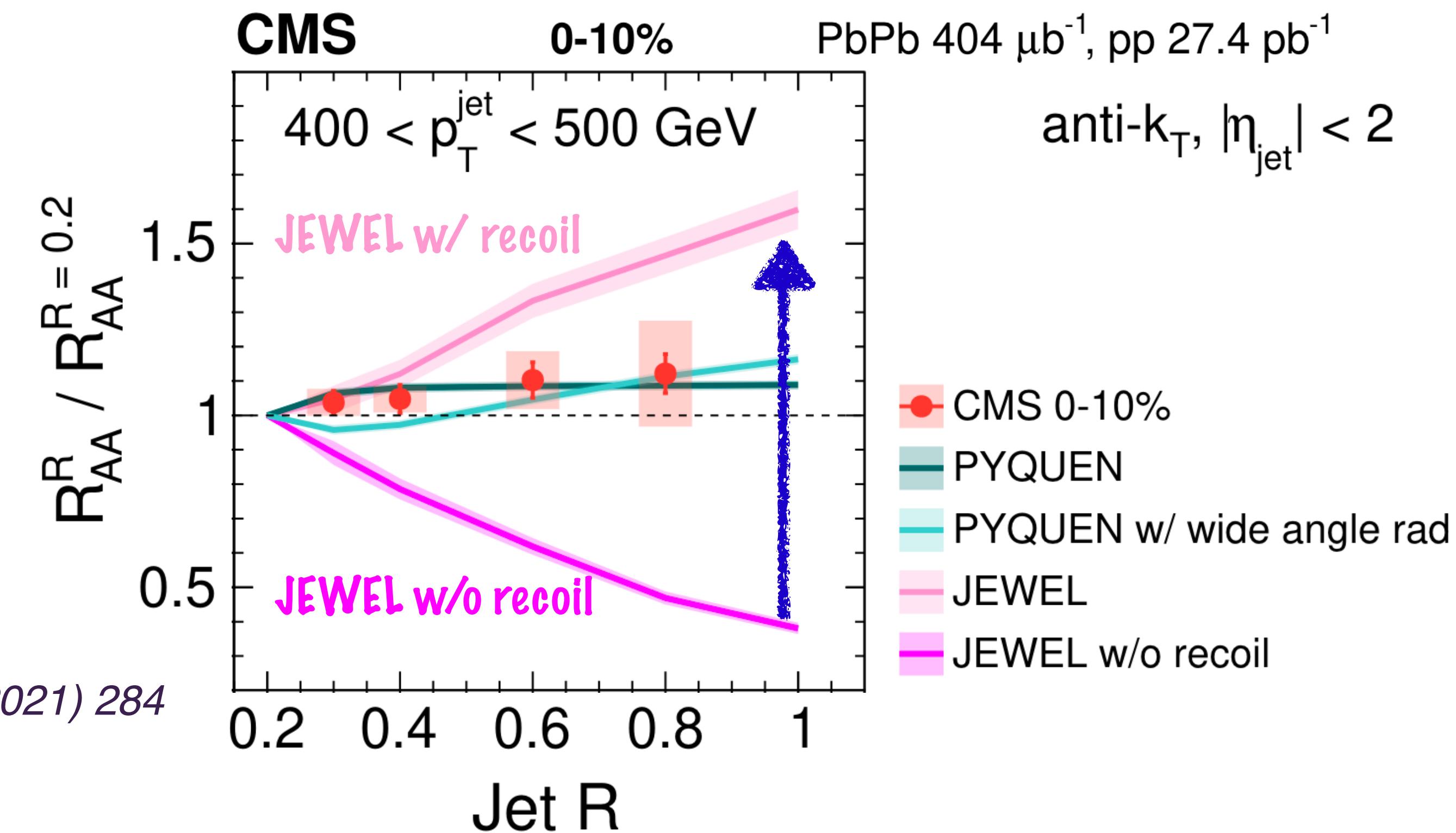
- Relative yield ratio between different radius
- Jets w/ **larger radius** are **less suppressed**
- $\mathfrak{R}^{\frac{0.2}{0.5}} / \mathfrak{R}^{\frac{0.2}{0.5}} \sim R_{AA}^{0.5} / R_{AA}^{0.2}$
 - larger than unity
 - note) not inclusive jets
e.g. more quark-initiated jets in γ -jet



Radius-dependent Jet R_{AA}



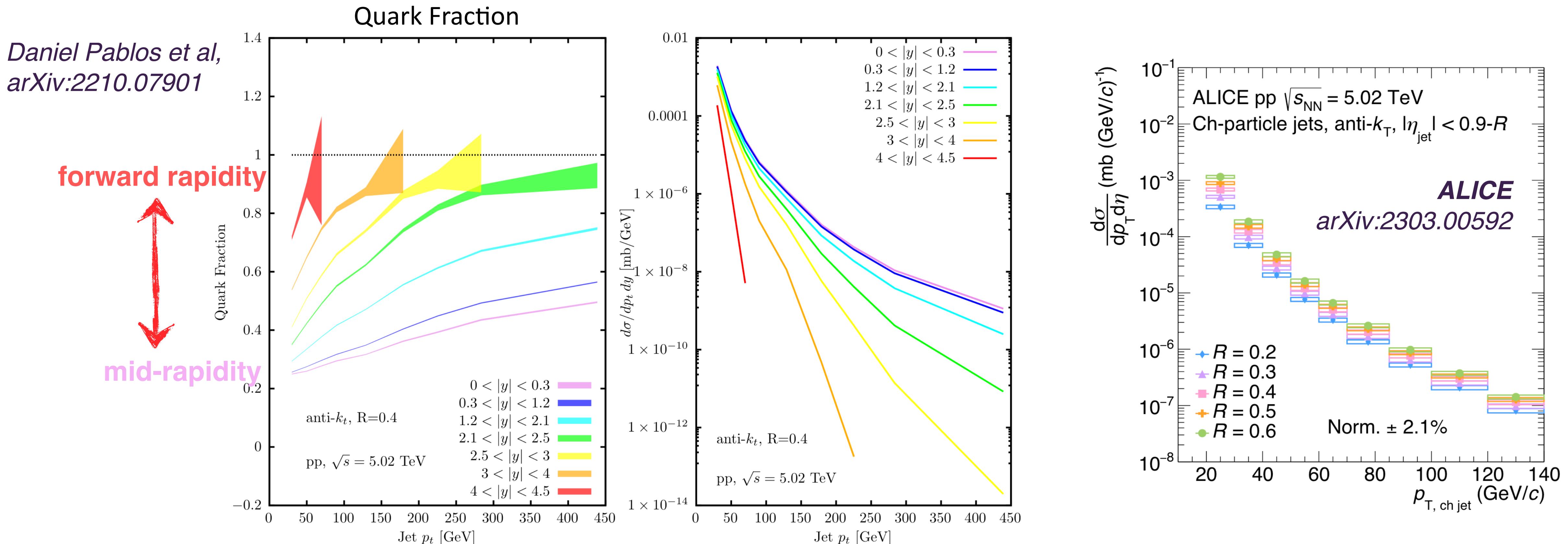
CMS JHEP 05 (2021) 284



- At high jet p_T (400-500 GeV), relatively **small R-dependence** in data
- Medium response increases $R_{\text{AA}}^R / R_{\text{AA}}^{R=0.2}$ for most models (**Hybrid**, **LBT**, **JEWEL**)

Radius-dependent Jet R_{AA}: Discussion

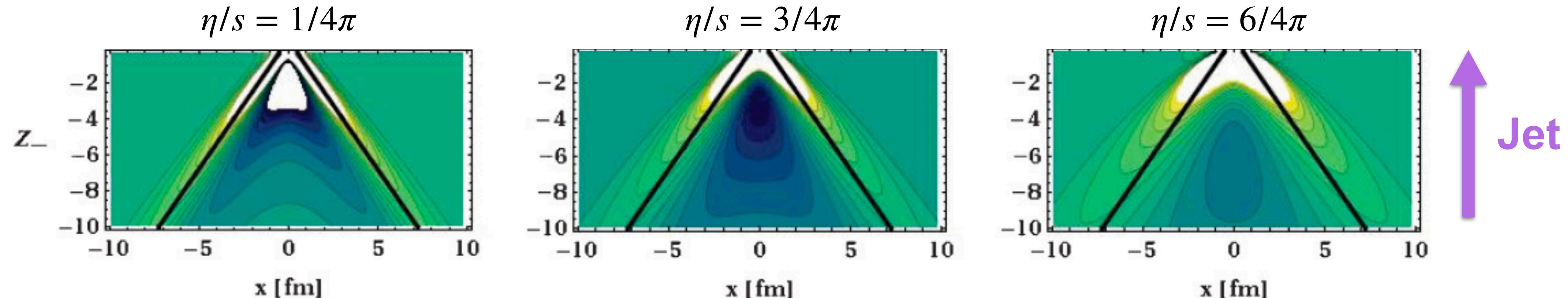
- Rapidity difference in different R
 - **Forward rapidity** → more quark (less gluon) fraction → less E-loss (**Higher R_{AA}**)



Why is medium response important to understand?

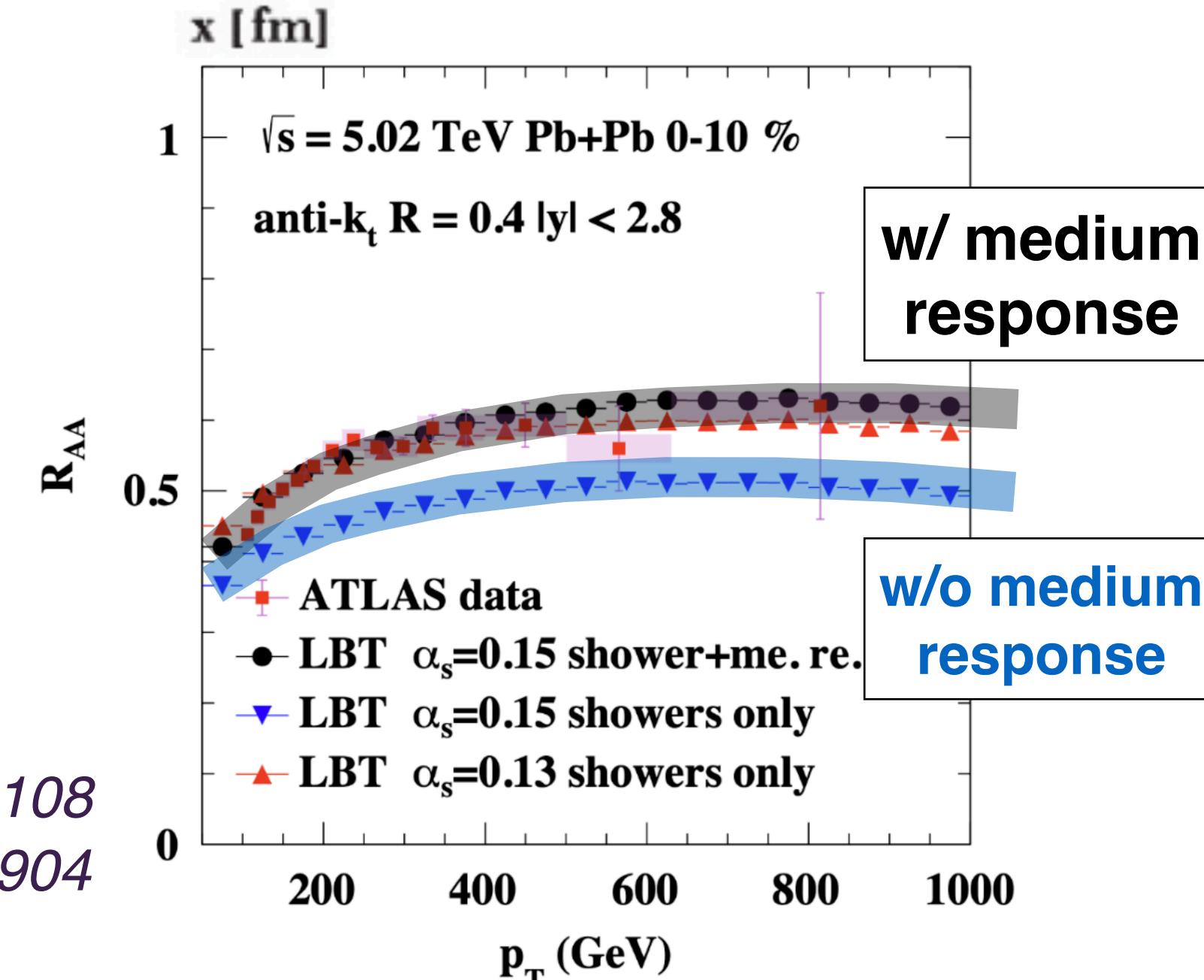
- Essential to describe the jet (sub)structure precisely
- Understanding in **QGP bulk properties** e.g. η/s , sound velocity

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



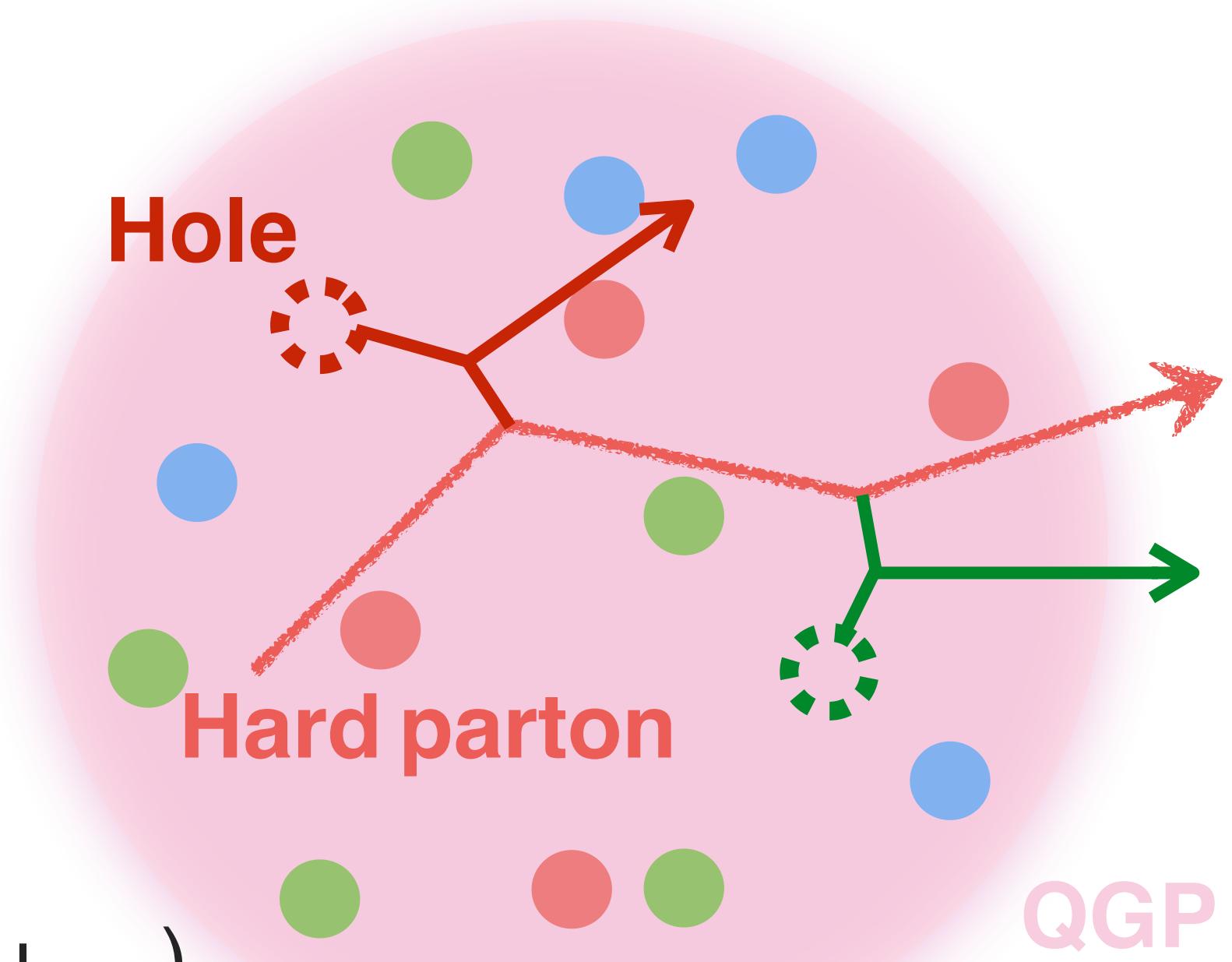
- **In-medium thermalization** information e.g. E_{med} , D_{diff} , τ_{th}
- Medium response affects the extraction of **jet transport coefficient**
 - can be related to local gluon density distribution of the medium

ATLAS, PLB 790 (2019) 108
Yayun He et al, PRC 106 (2022) 044904



Medium Response in Various Models: (1) Recoil

- Different models have different medium response implementation
- **Recoil (Weakly-coupled approach, when $E > E_{\text{med}}$)**
 - partons in medium scatter with hard parton
 - “hole” (or “negative”) of recoiled medium partons can be propagated and subtracted from the final parton spectra
- **Models with recoil**
 - **LBT** (T. Luo, S. Cao, Y. He, X.-N. Wang, S.-L. Zhang, G.-Y. Qin, Y. Zhu, ...)
 - low virtuality
 - **MARTINI** (C. Park, S. Jeon, C. Gale, B. Schenke, ...)
 - low virtuality
 - **MATTER** (A. Majumder, S. Cao, G. Vujanovic, M. Kordell, ...)
 - high virtuality
 - **JEWEL** (K. C. Zapp, R. Kunnnawalkam Elayavalli, J. G. Milhano, U. A. Wiedemann, ...)
 - re-scatterings of recoil partons with the medium are not implemented yet



Medium Response in Various Models: (2) Hydro

- **Hydrodynamics (Strongly-coupled approach, when $E \lesssim E_{\text{med}}$)**
 - medium fluid with a source term from a jet; $\partial_\mu T_{\text{fluid}}^{\mu\nu} = J_{\text{jet}}^\nu$
- **Models with hydrodynamics**
 - **Coupled Jet-Fluid** (Y. Tachibana, N.-B. Chang, G.-Y. Qin, ...)
 - Ideal hydro
 - **EPOS3-HQ** (I. Karpenko, M. Rohrmoser, J. Aichelin, P. Gossiaux, K. Werner, ...)
 - viscous hydro (vHLL)
 - source term thermalizes after τ_{th}

Medium Response in Various Models: (3) Hybrid

- **Hybrid (Recoil+Hydrodynamics)**

- **(Co)LBT-hydro** (W. Chen, T. Luo, S. Cao, L.-G. Pang, X.-N. Wang, ...)

- LBT + viscous hydro (CLVisc)

- **JETSCAPE** (JETSCAPE)

- e.g. MATTER + LBT/MARTINI + viscous hydro (MUSIC)

- Other models

- **Hybrid Strong/Weak Coupling (+ Linearized Hydro)**

- (D. Pablos, Z. Hulcher, J. Casalderrey-Solana, K. Rajagopal, J. G. Milhano D. C. Gulhan, ...)

- **AMPT** (G.-L. Ma, X.-N. Wang, Z. Gao, A. Luo, H.-Z. Zhang, G.-Y. Qin, ...)

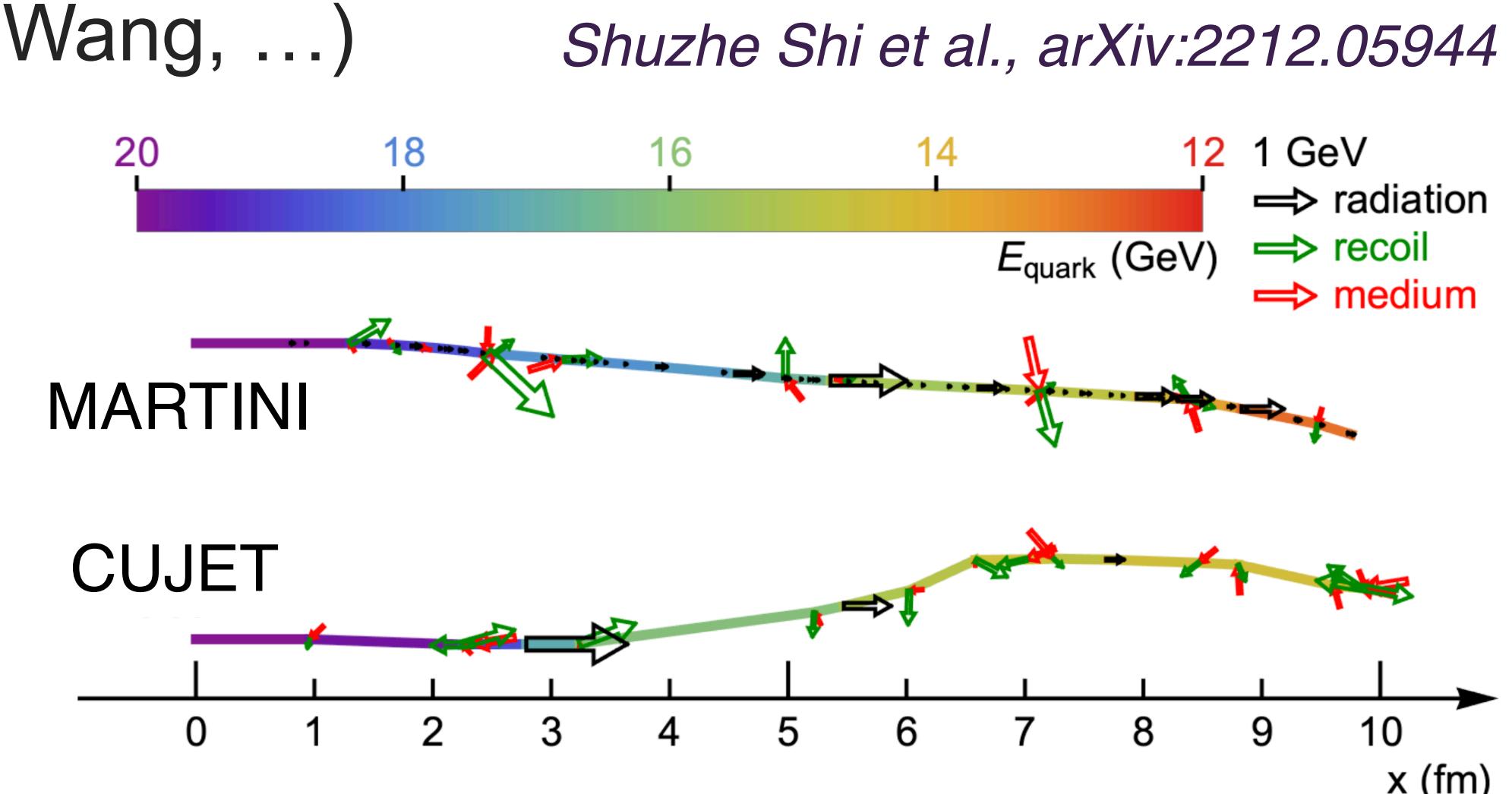
- Boltzmann equation based approach

- **BAMPS** (I. Bouras, Z. Xu, C. Greiner, B. Betz, ...)

- Boltzmann equation based approach

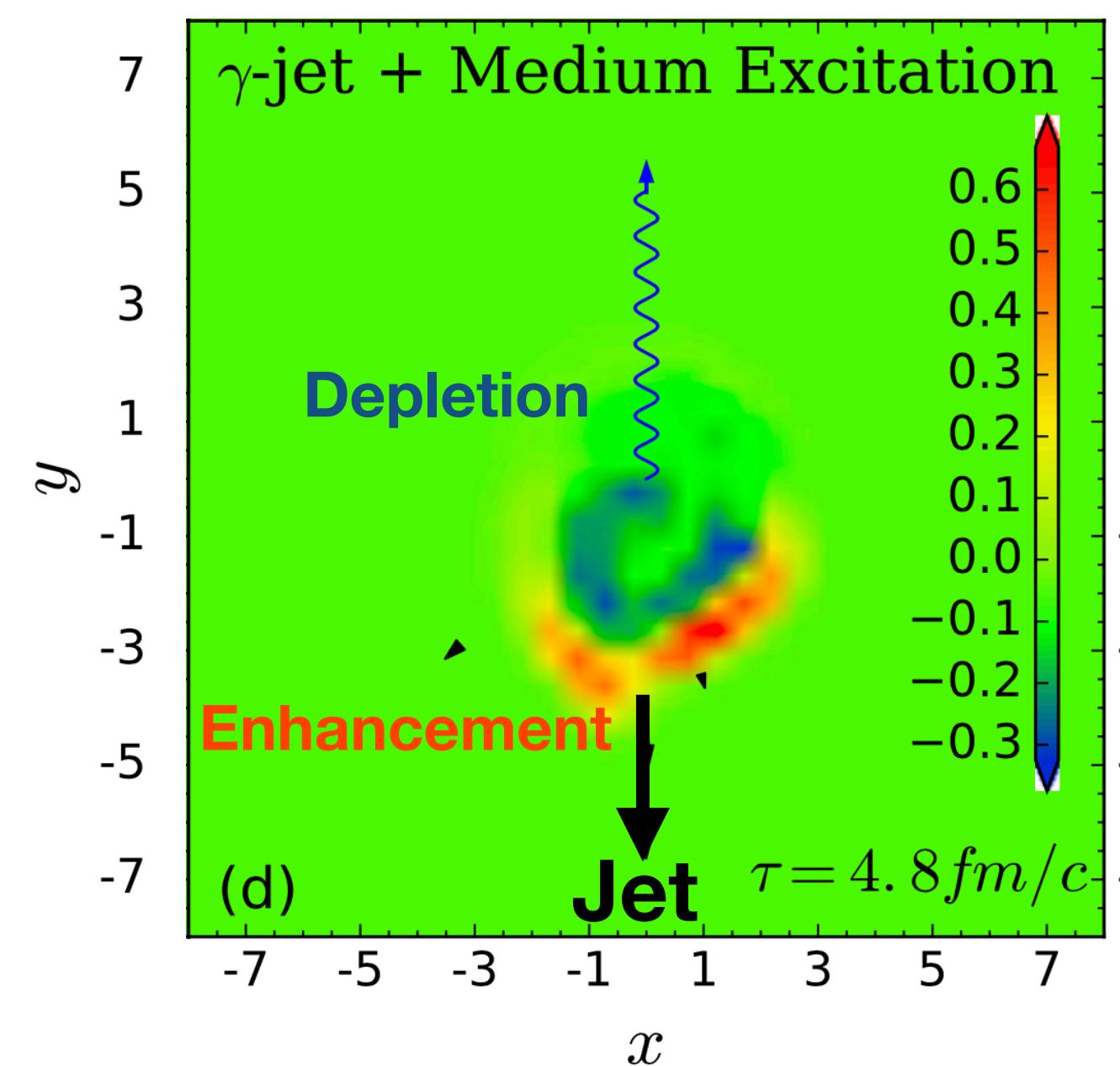
- **MARTINI + Causal diffusion** (S. Ryu, S. McDonald, C. Shen S. Jeon, C. Gale)

- ...



Structure formed from Medium Response in Models

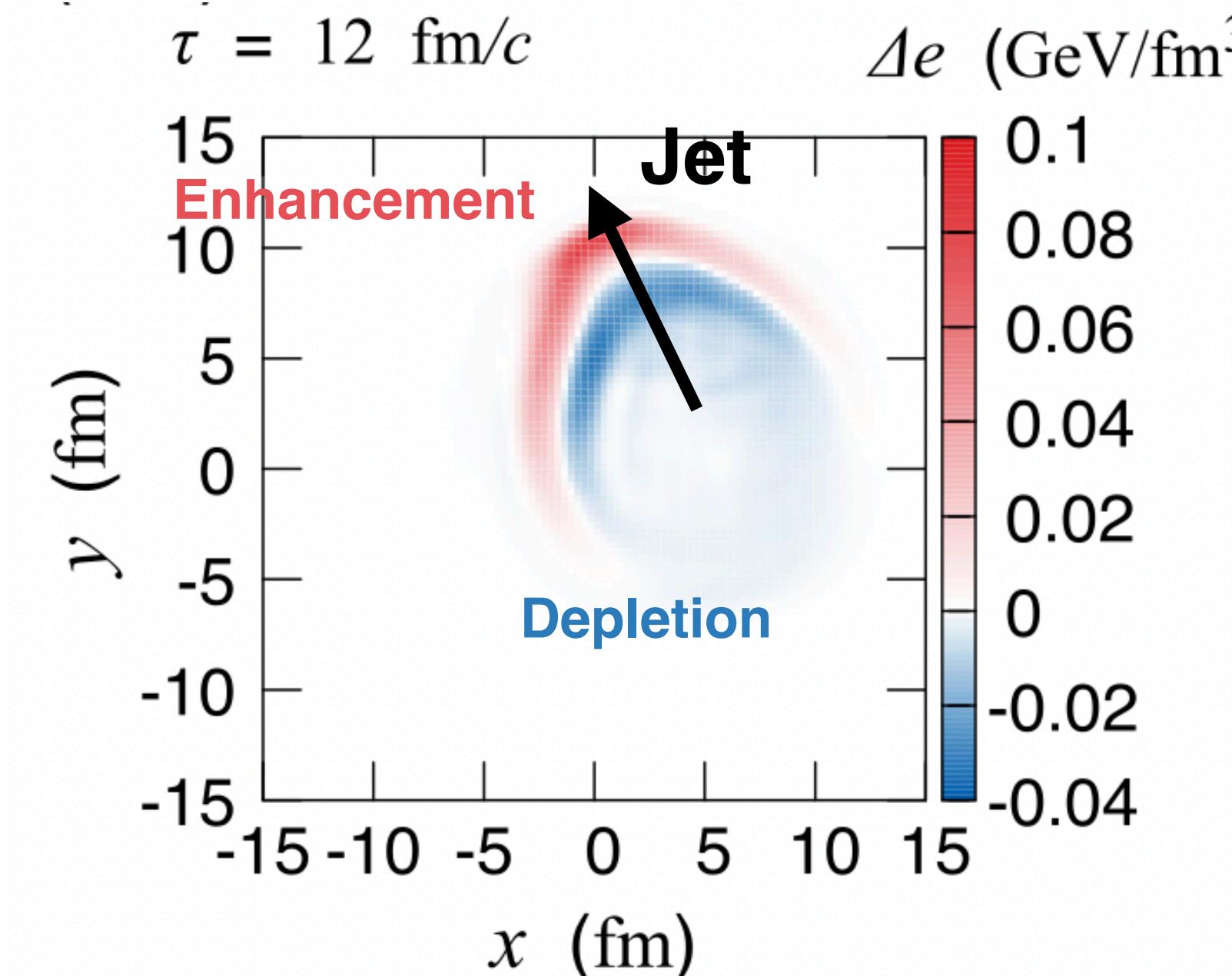
$(\gamma\text{-jet} + \text{Medium} + \text{Medium Excitation}) - (\gamma\text{-jet} + \text{Medium})$



CoLBT-hydro (Recoil+Hydro)

W. Chen et al. PLB 777 (2018) 86

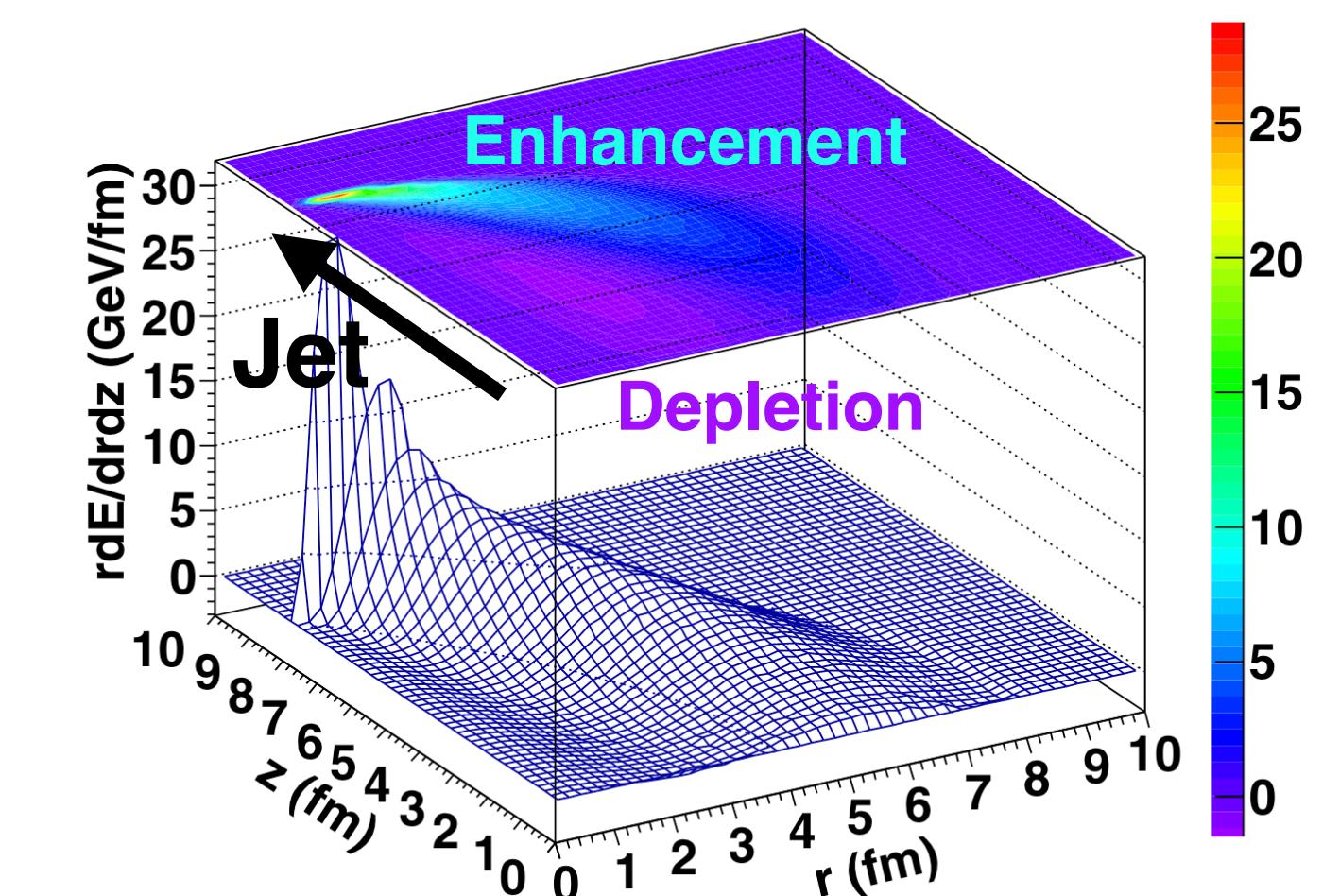
(Whole medium energy density) – (medium w/o jet)



Coupled Jet-Fluid (Hydro)

Y. Tachibana et al. PRC 95, 044909 (2017)

(b) $t=8 \text{ fm}/c$



LBT (Recoil)

Y. He et al. PRC 91, 054908 (2015)

- Enhancement in jet direction; Mach-cone like structure
- Depletion in the opposite direction of jet; diffusion wake