Probing Jet Energy Loss and Medium Modifications in Photon-Jet Events in Heavy Ion Collisions with ATLAS

Yeonju Go
Brookhaven National Laboratory

Nuclear Physics Seminars
Brookhaven National Laboratory, NY, USA (Hybrid)
2023 Oct. 10

Brookhaven National Laboratory

Outline

1. Study of **Color-charge-dependent Jet Quenching** using Photon-tagged Jet
   - [PLB 846 (2023) 138154]

2. Searching for **Diffusion Wake** using Jet-Hadron Correlations in Photon-Jet events
   - [ATLAS-CONF-2023-054]

Physics Letters B 846 (2023) 138154

Contents lists available at ScienceDirect

Physics Letters B

journal homepage: www.elsevier.com/locate/physletb

ELSEVIER

PHYSICS LETTERS B

Comparison of inclusive and photon-tagged jet suppression in 5.02 TeV Pb+Pb collisions with ATLAS

Check for updates

The ATLAS Collaboration *

A R T I C L E I N F O

Article history:
Received 29 March 2023
Received in revised form 21 July 2023
Accepted 23 August 2023
Available online 29 August 2023
Editor: M. Doser

Dataset link: https://hepdata.cedar.ac.uk

A B S T R A C T

Parton energy loss in the quark–gluon plasma (QGP) is studied with a measurement of photon-tagged jet production in 1.7 nb^{-1} of Pb+Pb data and 260 pb^{-1} of pp data, both at $\sqrt{s_{NN}} = 5.02$ TeV, with the ATLAS detector. The process $pp \to \gamma$+jet+X and its analogue in Pb+Pb collisions is measured in events containing an isolated photon with transverse momentum (p_T) above 50 GeV and reported as a function of jet p_T. This selection results in a sample of jets with a steeply falling p_T distribution that are mostly initiated by the showering of quarks. The pp and Pb+Pb measurements are used to report the nuclear modification factor, R_{AA}, and the fractional energy loss, S_{loss}, for photon-tagged jets. In addition, the results are compared with the analogous ones for inclusive jets, which have a significantly smaller quark-initiated fraction. The R_{AA} and S_{loss} values are found to be significantly different between those for photon-tagged jets and inclusive jets, demonstrating that energy loss in the QGP is sensitive to the colour-charge of the initiating parton. The results are also compared with a variety of theoretical models of colour-charge-dependent energy loss.

ATLAS EXPERIMENT

ATLAS CONF Note

ATLAS-CONF-2023-054

30th August 2023

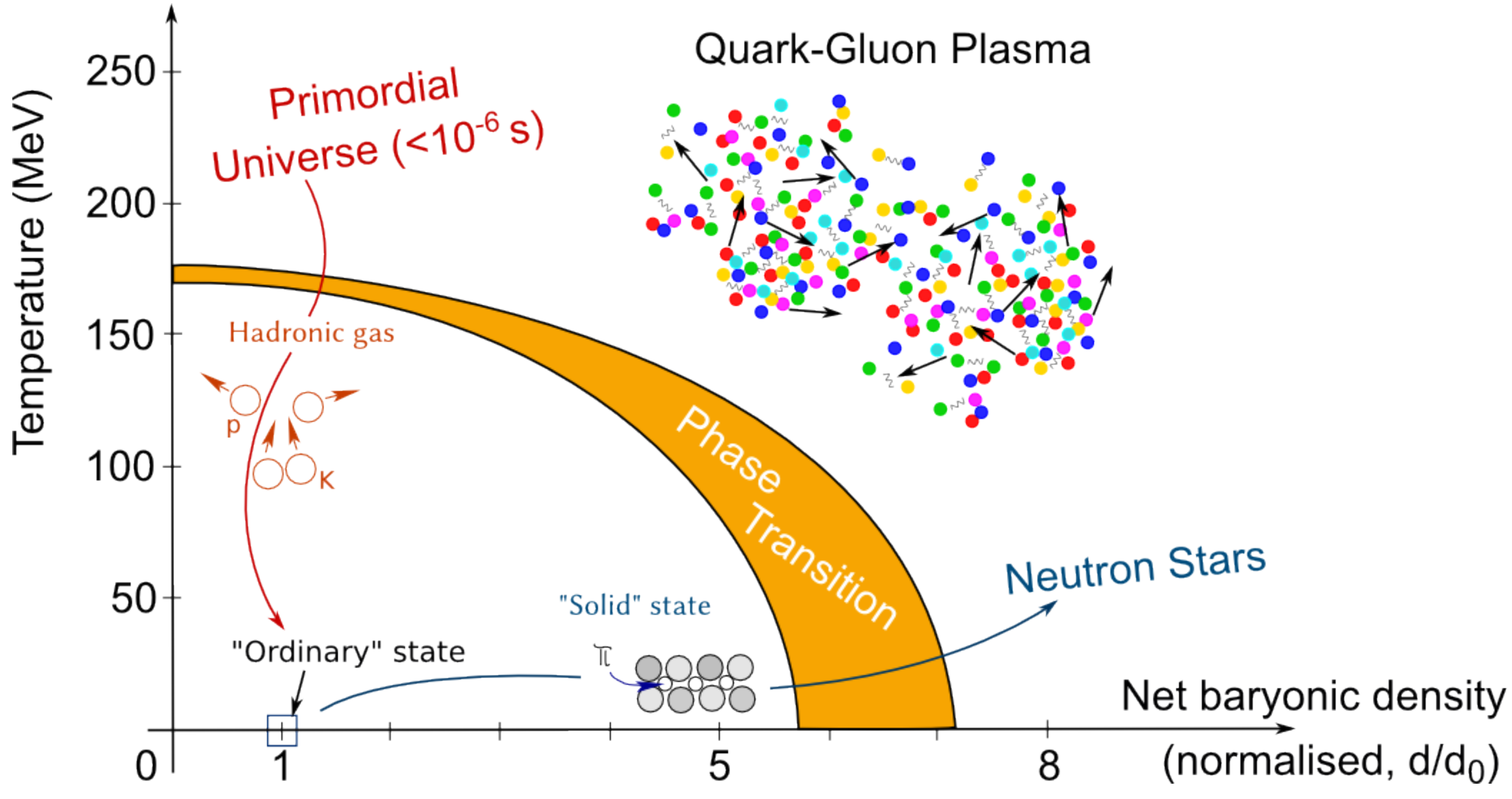
CERN

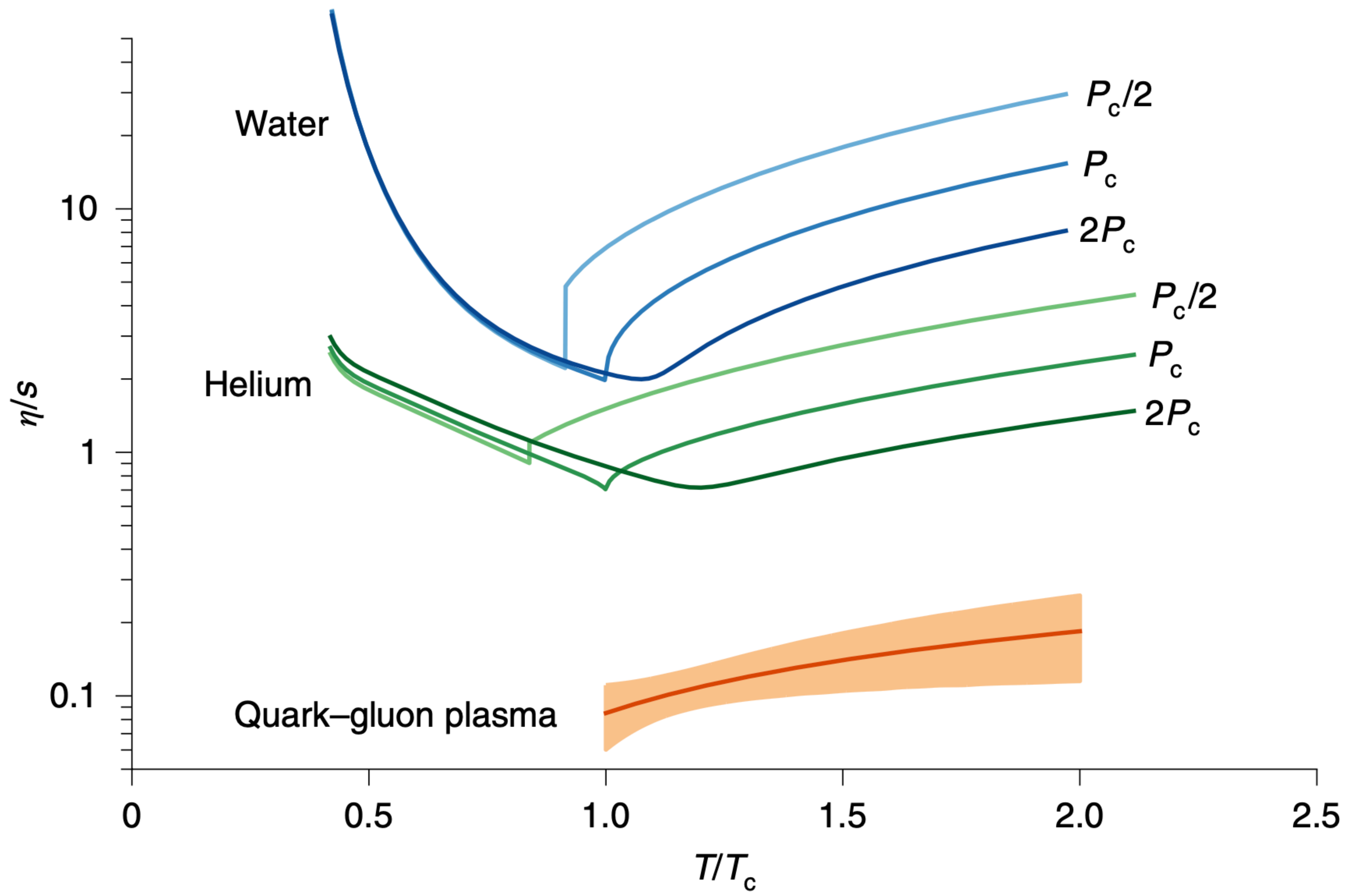
Search for the quark-gluon plasma diffusion wake via measurements of jet-hadron correlations in photon-jet events in Pb+Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV with the ATLAS detector

The ATLAS Collaboration

This note describes the measurement of jet-hadron correlations in photon-jet events, using 1.7 nb^{-1} of Pb+Pb data taken at $\sqrt{s_{NN}} = 5.02$ TeV with the ATLAS detector in 2018. Events are selected with high-p_T photons (90 – 180 GeV) and jets ($p_T > 40$ GeV), where the photon and jet are back-to-back in azimuth, $|\Delta\phi(\gamma,\text{jet})| > 3\pi/4$. Then the angular correlation is reported as a function of relative pseudorapidity $|\Delta\eta(\text{jet,track})|$ between these jets and charged hadrons with $p_T = 0.5$–2.0 GeV in opposite azimuthal hemispheres $|\Delta\phi(\text{jet,track})| > \pi/2$. These correlations in central Pb+Pb collisions are predicted to be sensitive to the diffusion wake in the quark-gluon plasma resulting from the lost energy of high-p_T partons traversing the plasma. No diffusion wake signal is observed within the current sensitivity and limits on the diffusion wake amplitude are quantified.

Quark Gluon Plasma and Heavy-ion Collisions



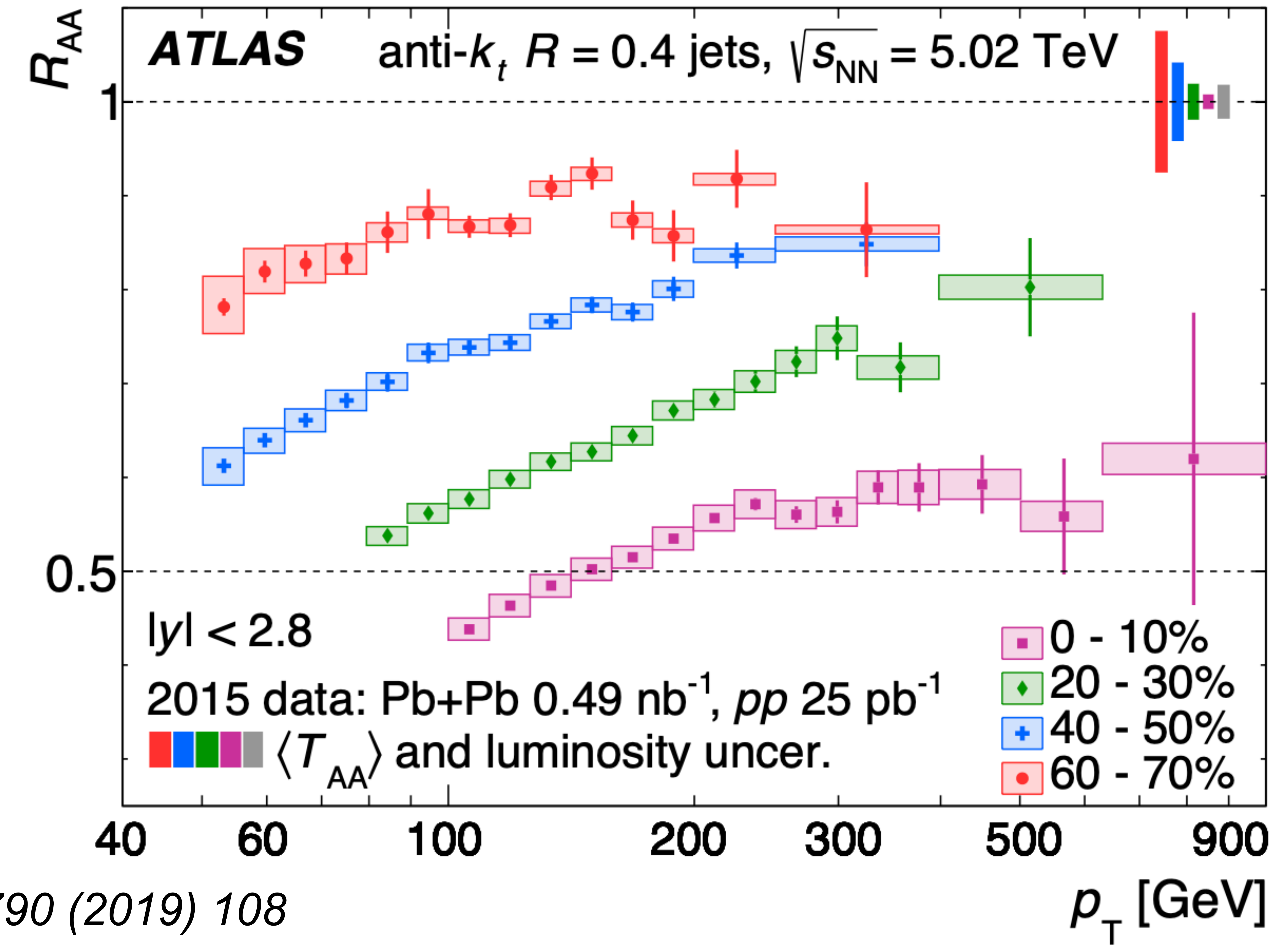


Nature Physics 15 (2019) 1113

- ***Quark Gluon Plasma (QGP)***: extremely hot and dense phase of matter in which quarks and gluons are no more confined into hadrons
  - ➡ properties known as an almost perfect fluid
  - ➡ lowest specific sheer viscosity (η/s) of any known substance

Jet Quenching

- Understand parton-to-medium interaction in QGP using the jet quenching phenomenon
- Various LHC & RHIC results of **nuclear modification factor (R_{AA})** show *significant suppression* of jets in heavy ion collisions compared to that in pp collisions

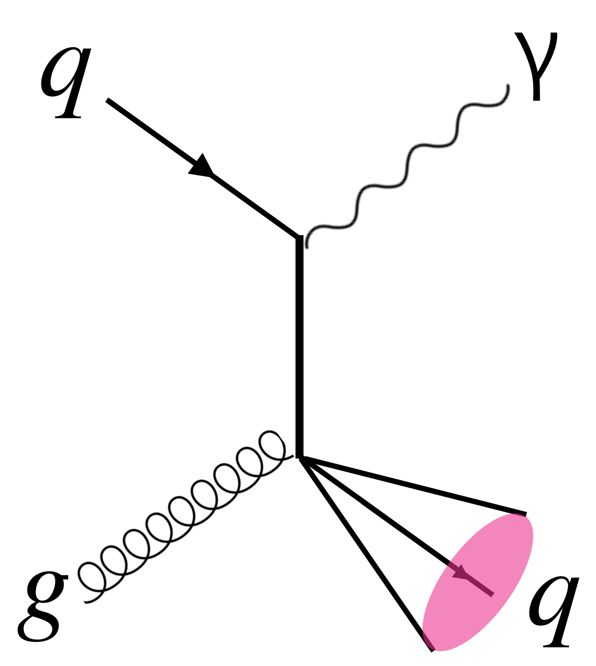


PLB 790 (2019) 108

$$R_{AA} = \frac{1}{N_{evt}} \frac{d^2 N^{Pb+Pb}}{dp_T d\eta} \Big/ \langle T_{AA} \rangle \frac{d^2 \sigma^{pp}}{dp_T d\eta}$$

Color-charge-dependent Jet Quenching

- **Photon-tagged jet vs Inclusive jet**
  - Inclusive jet production in p_T < ~200 GeV is dominated by **gluon-initiated jets**
  - Jets in association with photon (pp→γ+jet+X) are largely produced by Compton scattering → **quark-initiated jets**
  - Comparing photon-tagged jet and inclusive jet, one can examine the ***sensitivity to color charge in jet energy loss in QGP***



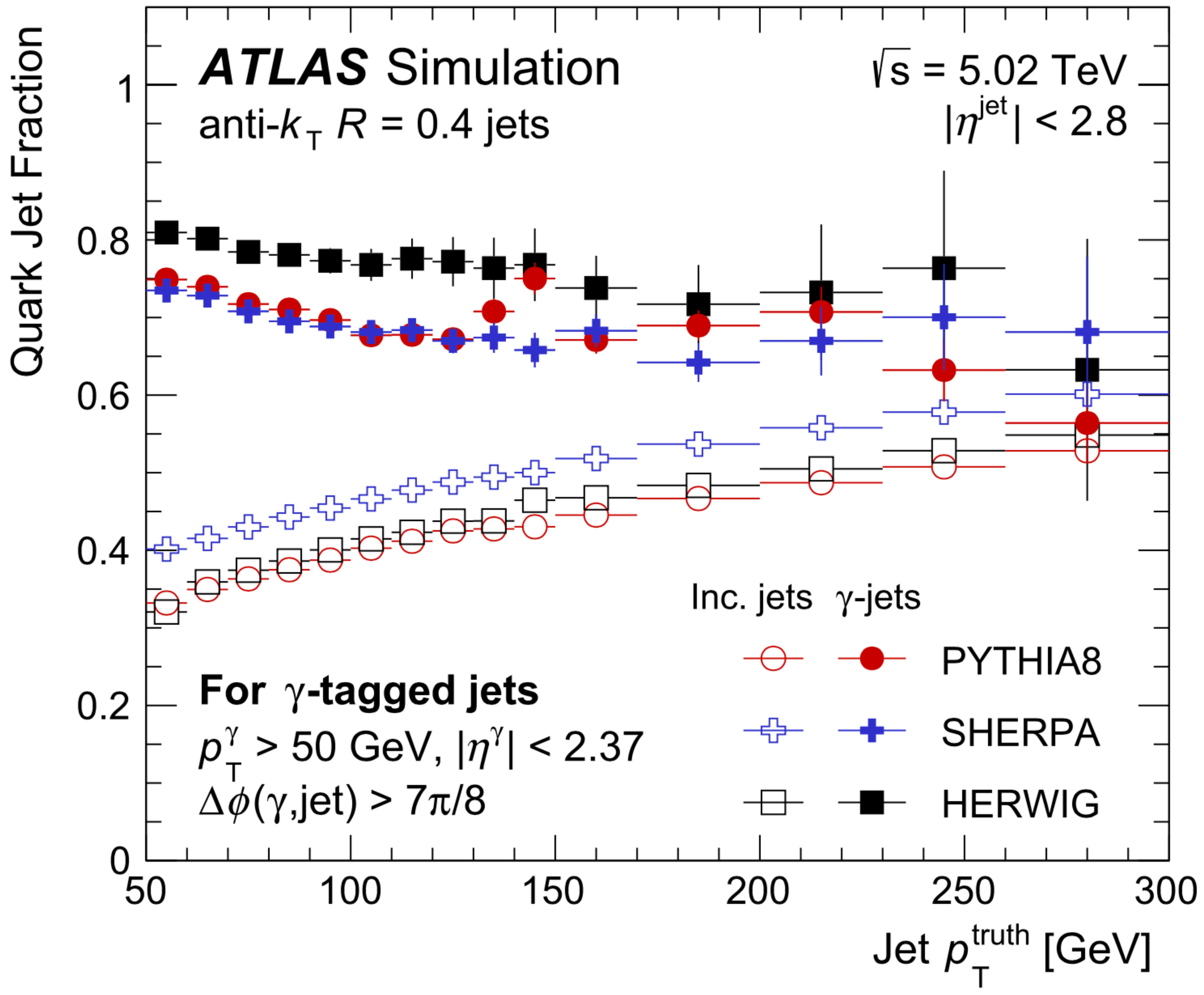
q-g Compton scattering

$$\langle \Delta E_g \rangle \propto \alpha_s C_R \hat{q} L^2$$

Casimir color factor
4/3 for quarks
3 for gluons

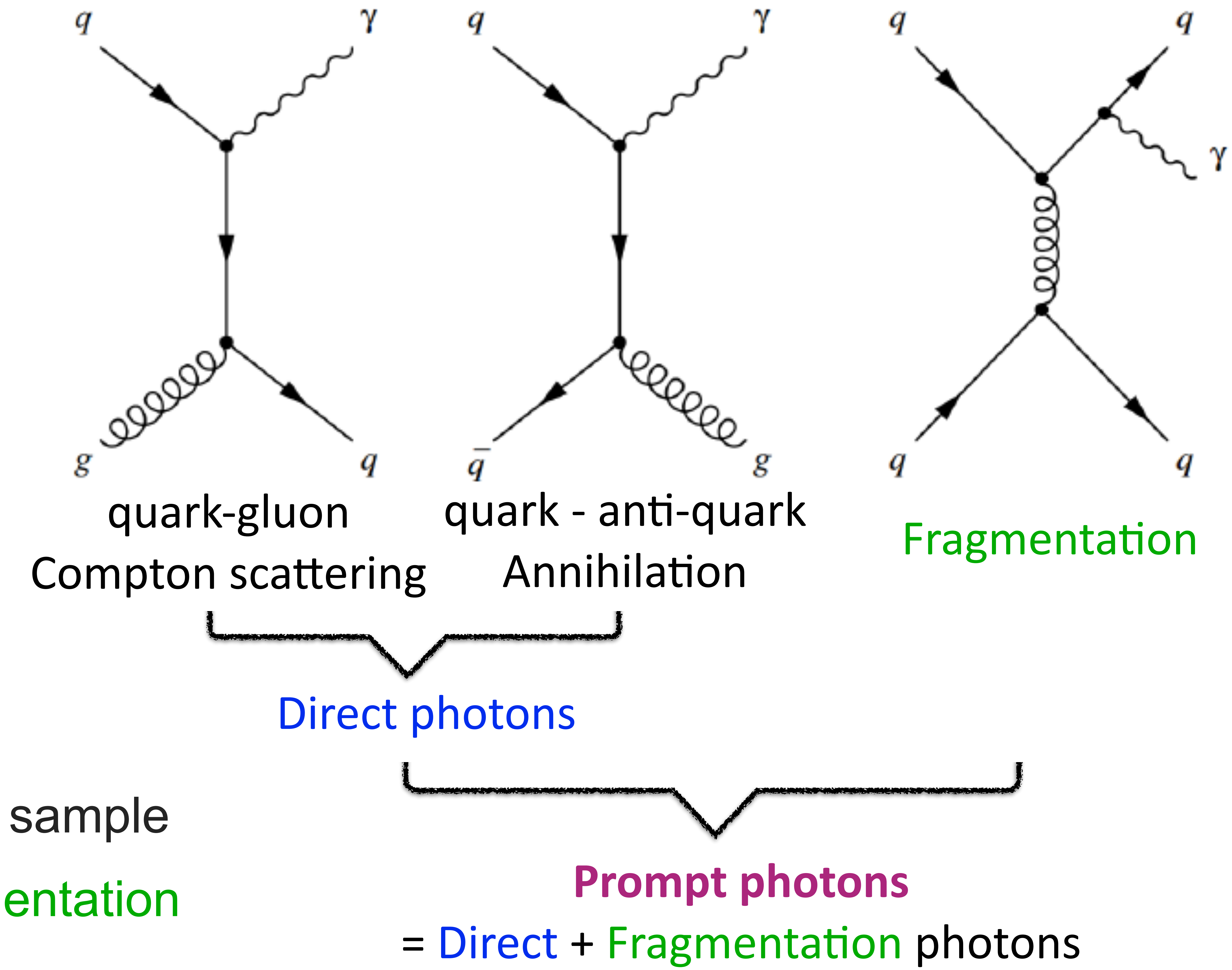
$$\Delta E_{gluon} > \Delta E_{quark}$$

PLB 846 (2023) 138154



Prompt Isolated Photons

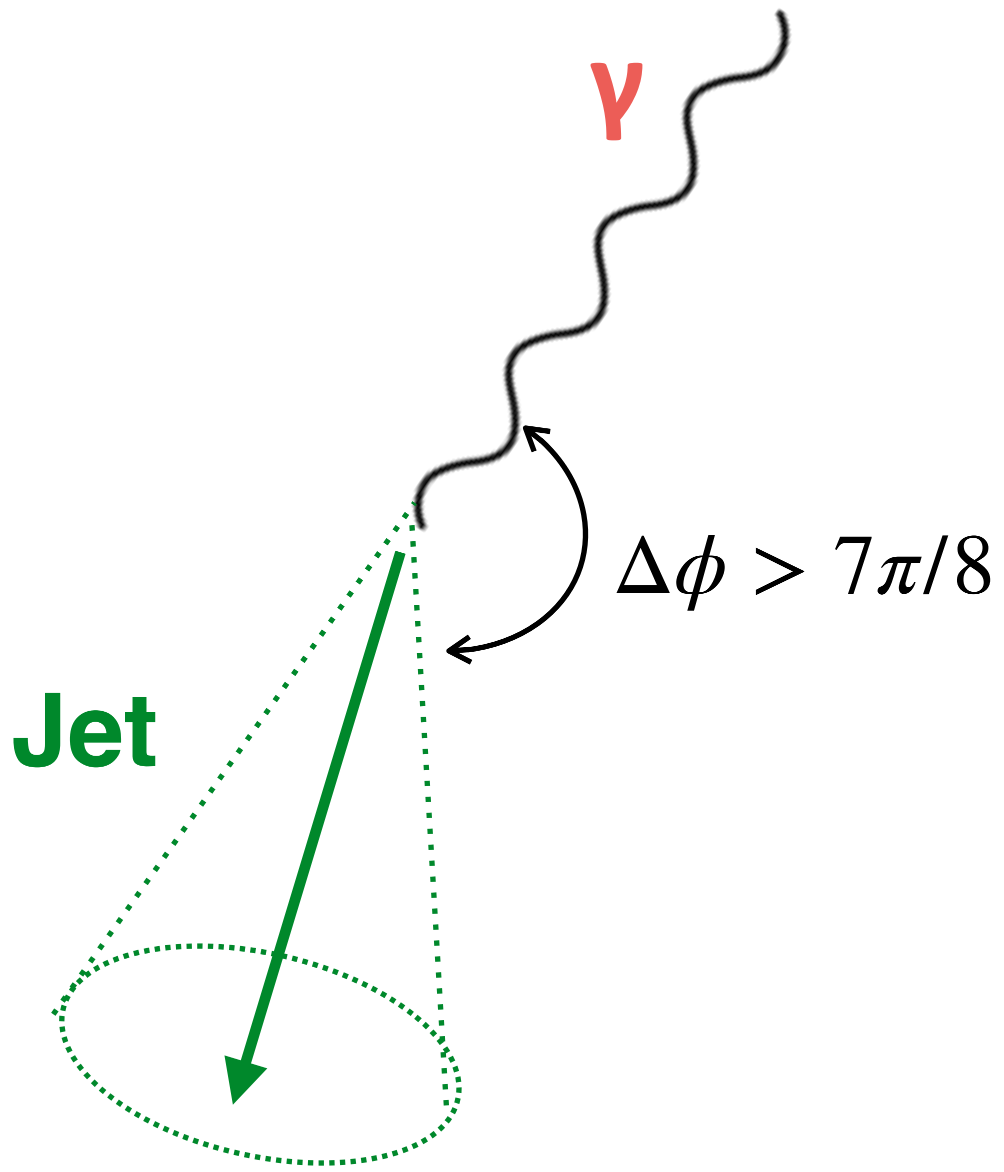
- **Direct photon**
  - produced from **primary vertex**
  - Processes : Compton scattering, Annihilation
- **Fragmentation photon**
  - radiated from partons after the primary hard scattering
- **Decay photon**
  - decayed from hadrons, such as $\pi^0 \rightarrow \gamma\gamma$
  - **major background**



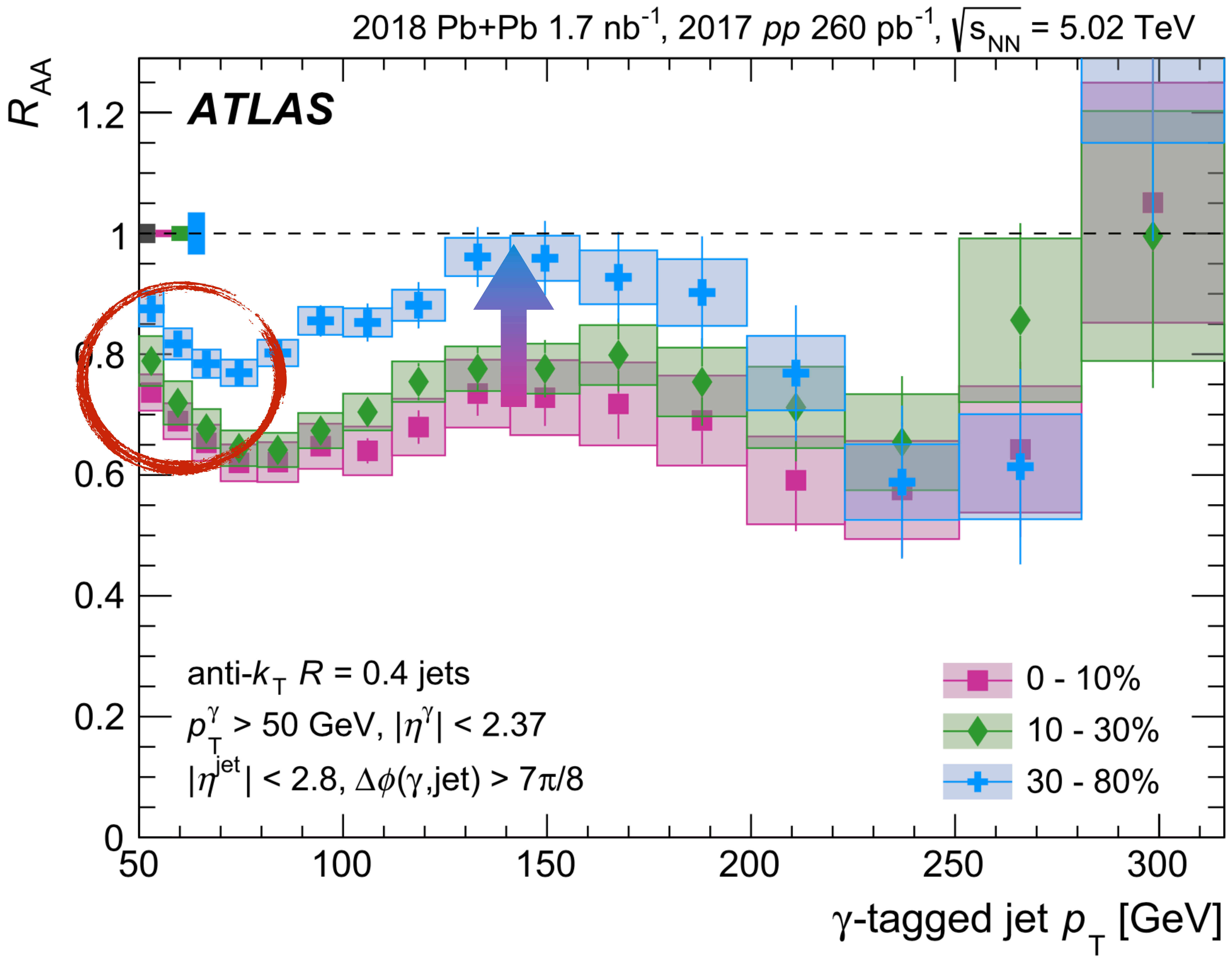
- Photon ***Isolation*** condition significantly reduces decay photons and fragmentation photons in the sample
- Discrimination between isolated direct and fragmentation photons is arbitrary in experiment

Event Selection & Analysis Procedure

- **Photons**
  - ➡ $p_T > 50$ GeV
  - ➡ $|\eta| < 2.37$
  - ➡ Prompt Isolated photons (direct+fragmentation photons)
- **Jets**
  - ➡ anti-k_T R=0.4
  - ➡ $50 < p_T < 316$ GeV/c
  - ➡ $|\eta| < 2.8$
  - ➡ $\Delta\varphi(\gamma,\text{jet}) > 7\pi/8$
  - ➡ all (photon, jet) pairs are considered rather than just leading objects
- **Main analysis procedure**
  - ➡ combinatoric background jet subtraction using event-mixing technique
  - ➡ subtraction of jets associated with background-photons using photon purity
  - ➡ 2D simultaneous unfolding for photon p_T and jet p_T
  - ➡ final observables (e.g. cross section, R_{AA}, S_{loss}, etc) as a function of jet p_T

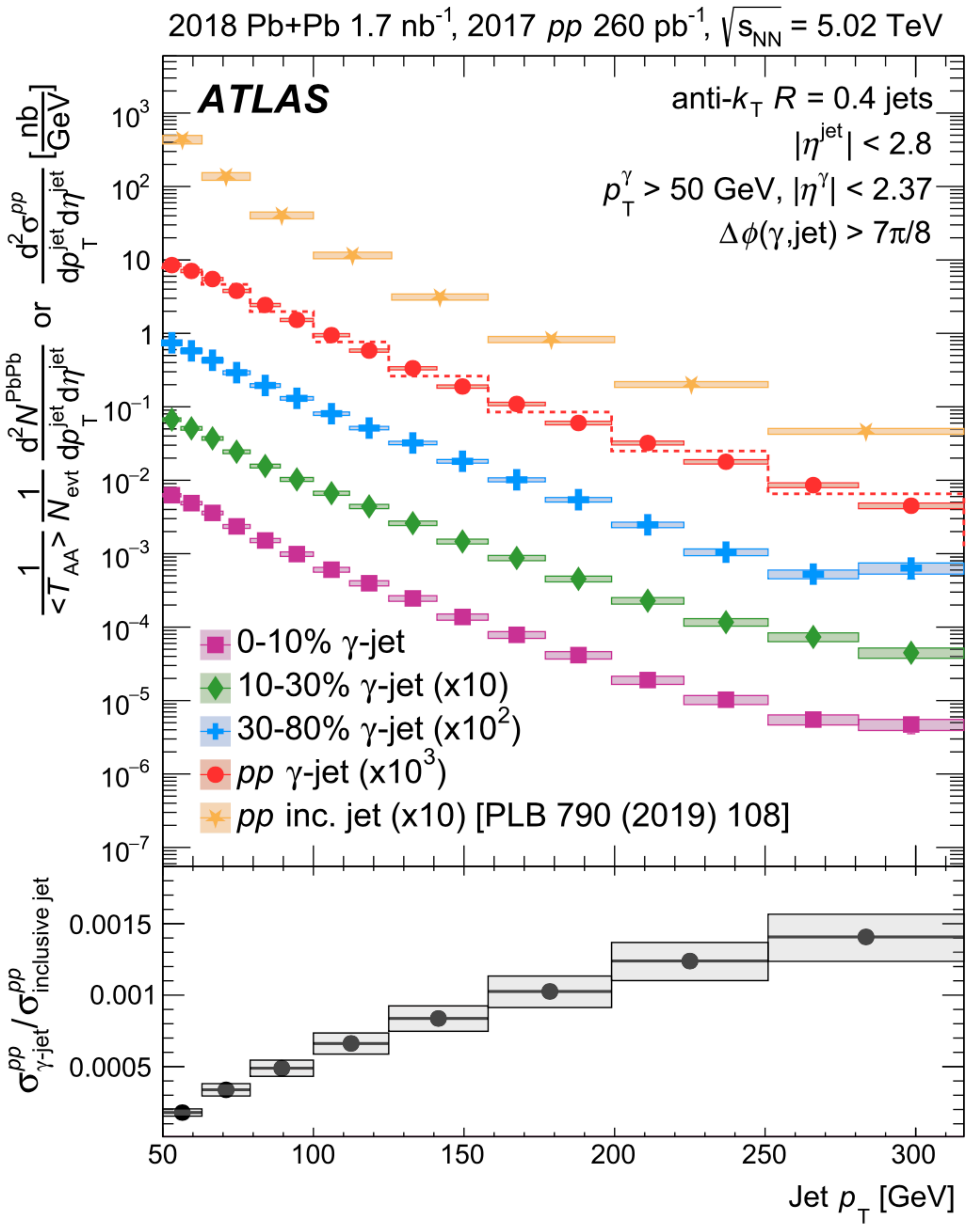


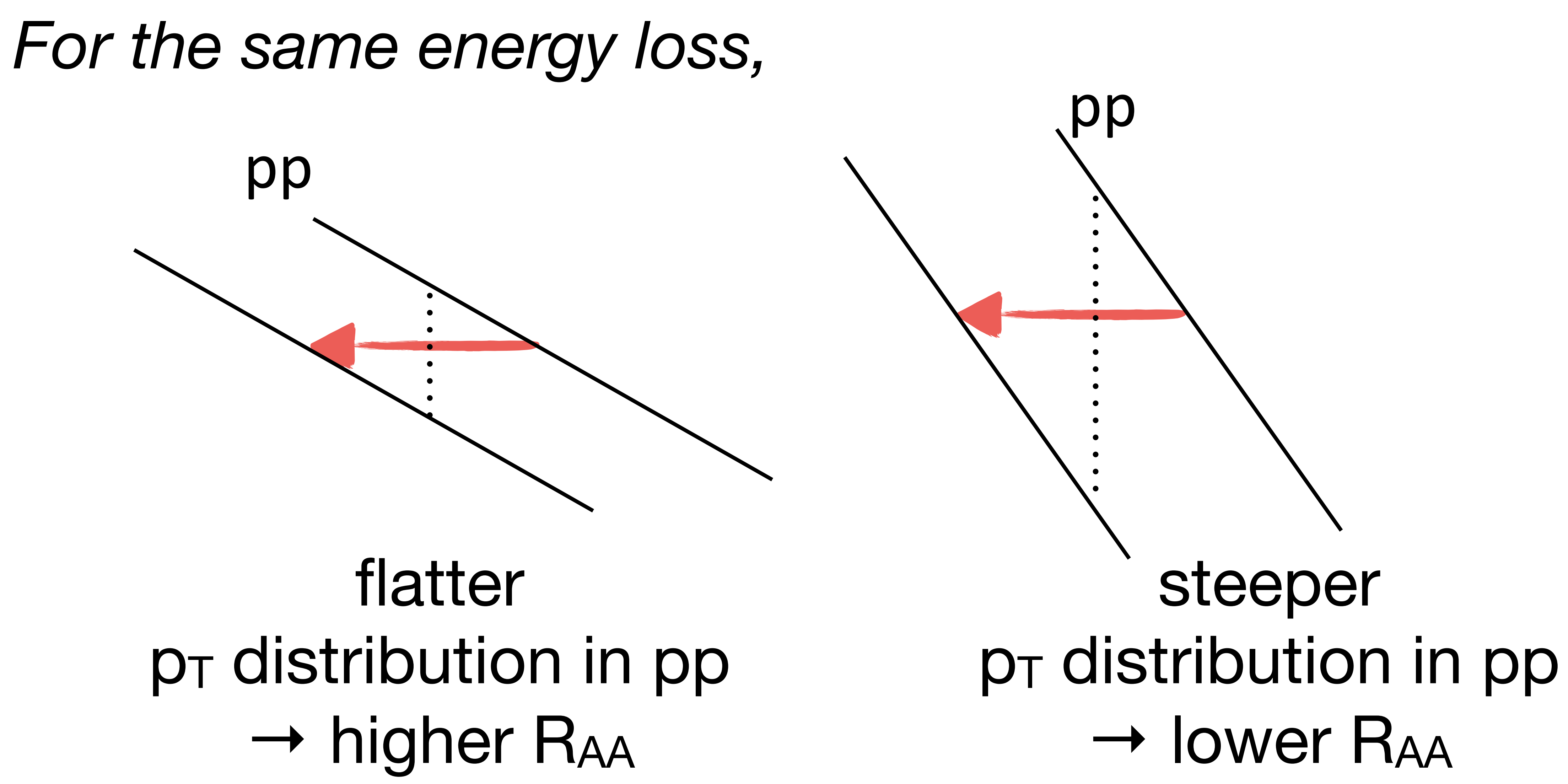
Nuclear Modification Factor (R_{AA})



- Centrality ordering in R_{AA}
- For jet p_T < ~80 GeV, photon p_T > 50 GeV threshold effect

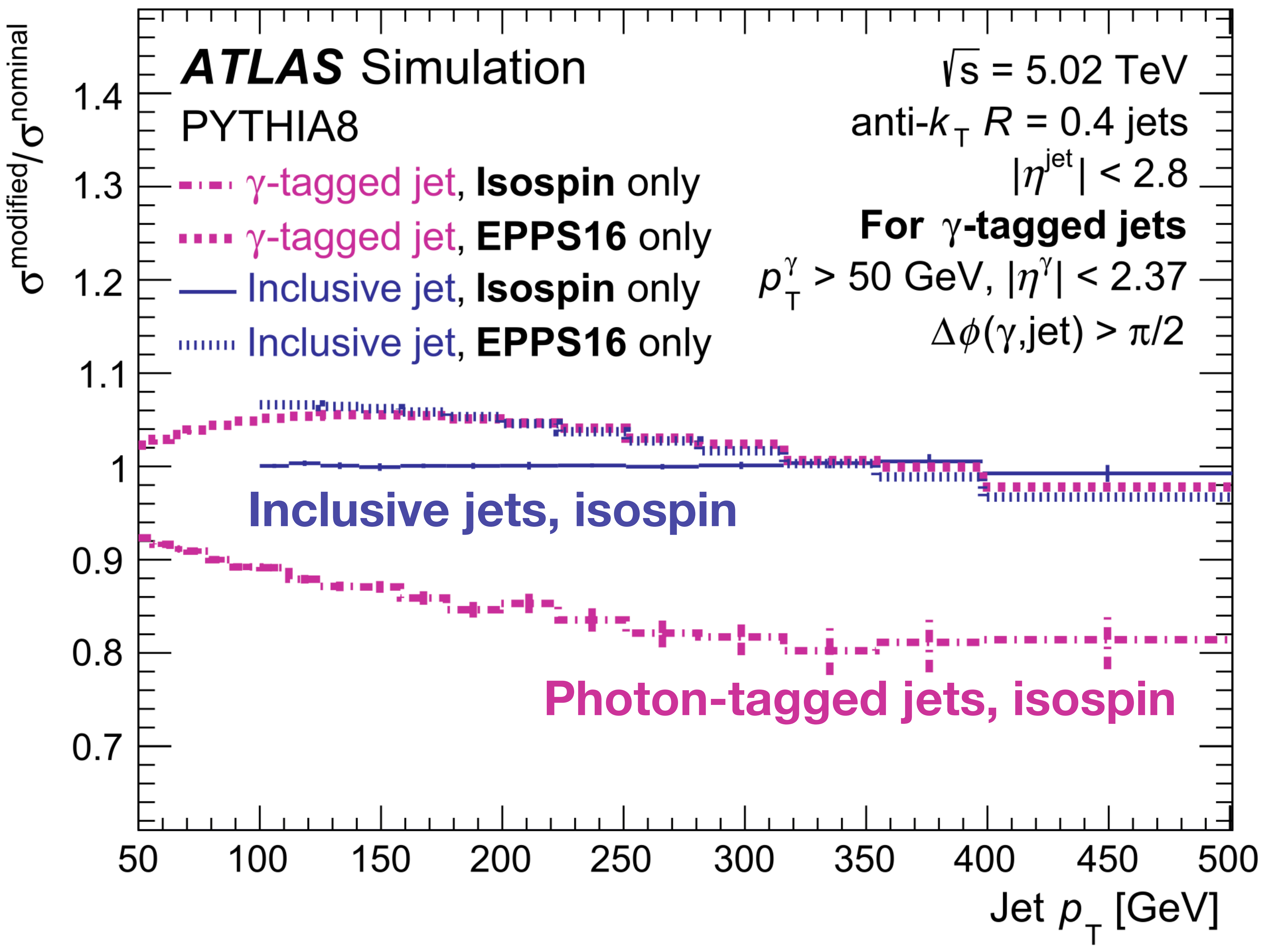
γ-jets vs. inclusive jets: p_T spectra in pp





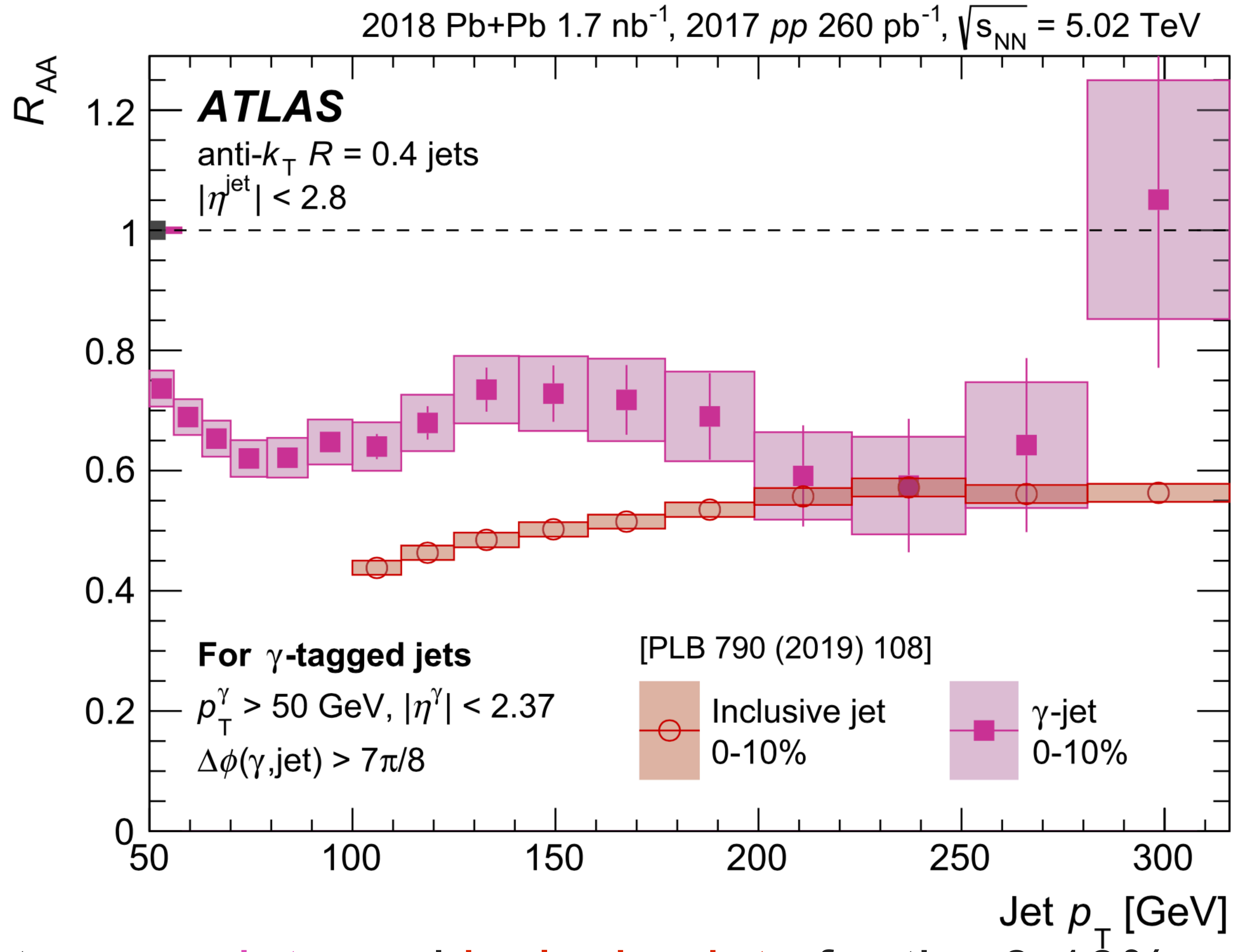
- σ(γ-jet) in pp collisions (without energy loss in QGP) has a less steep spectrum than σ(inclusive jet)
  - This impact must be considered when comparing R_{AA} between two different samples

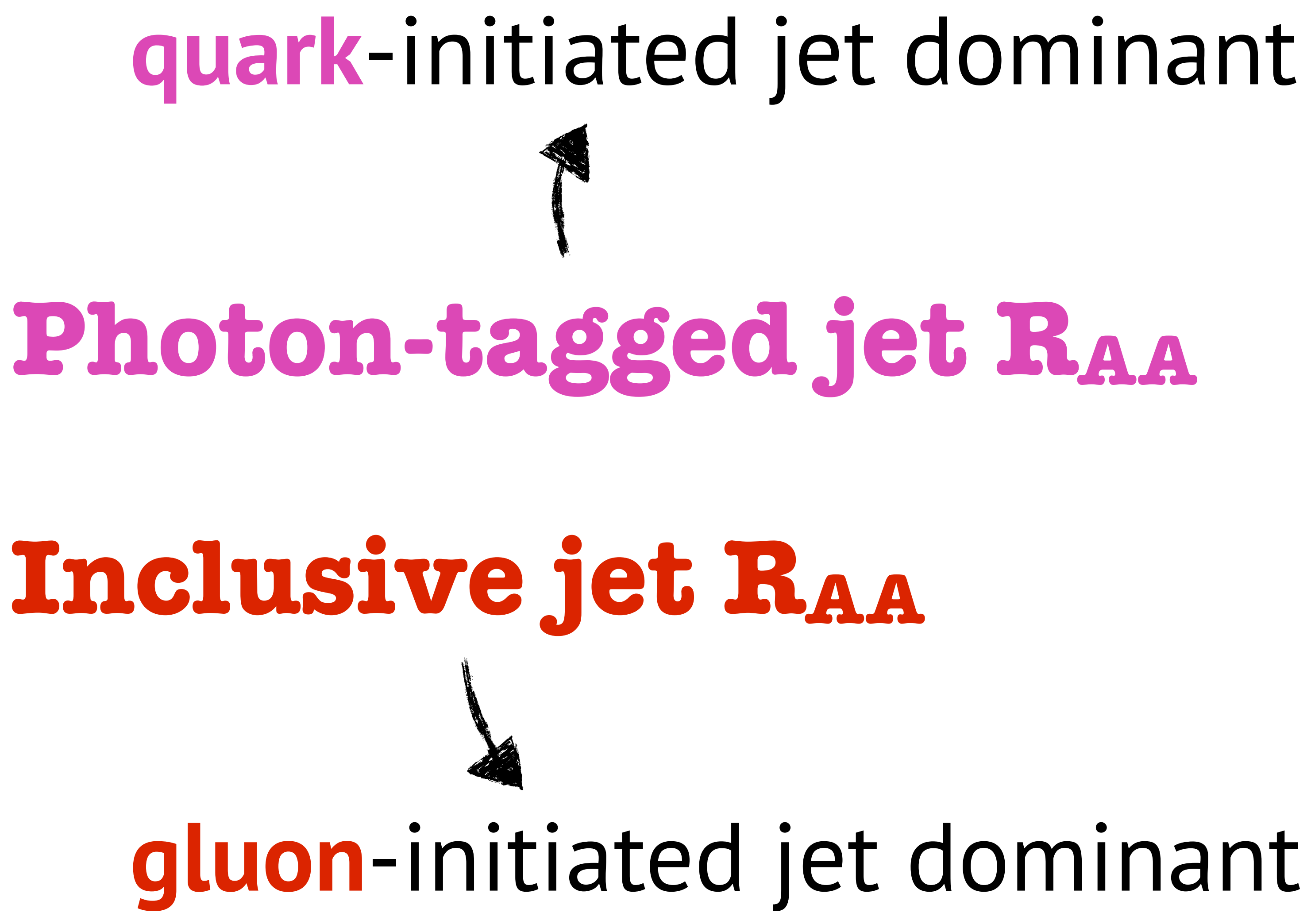
γ-jets vs. inclusive jets: Isospin effect



- nPDF effects (dashed lines) are similar for both photon-tagged jets and inclusive jets
- The photon-tagged jet production rate **decreases** in Pb+Pb collisions because of the **isospin effect** (solid lines), while the inclusive jet production rate in Pb+Pb collisions is not affected by the isospin effect
- In summary for *other effects* besides the different q/g fraction,
  - ➡ the **p_T spectrum** effect ***increases*** photon-tagged jets R_{AA} by ~5-10%
  - ➡ the **isospin** effect ***decreases*** photon-tagged jets R_{AA} by ~10-20%
  - ➡ combined effect makes photon-tagged jet R_{AA} lower

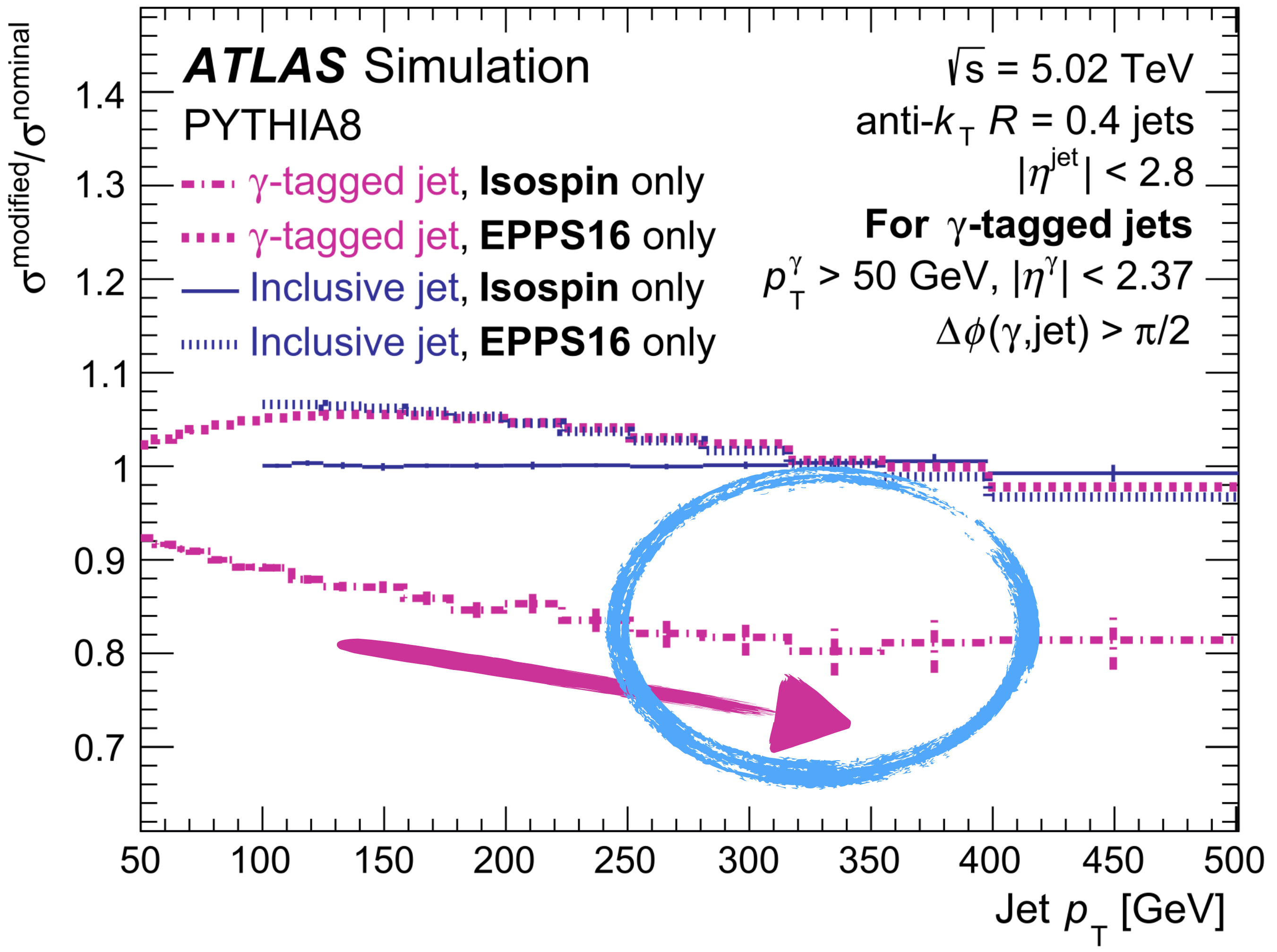
Nuclear Modification Factor (R_{AA})

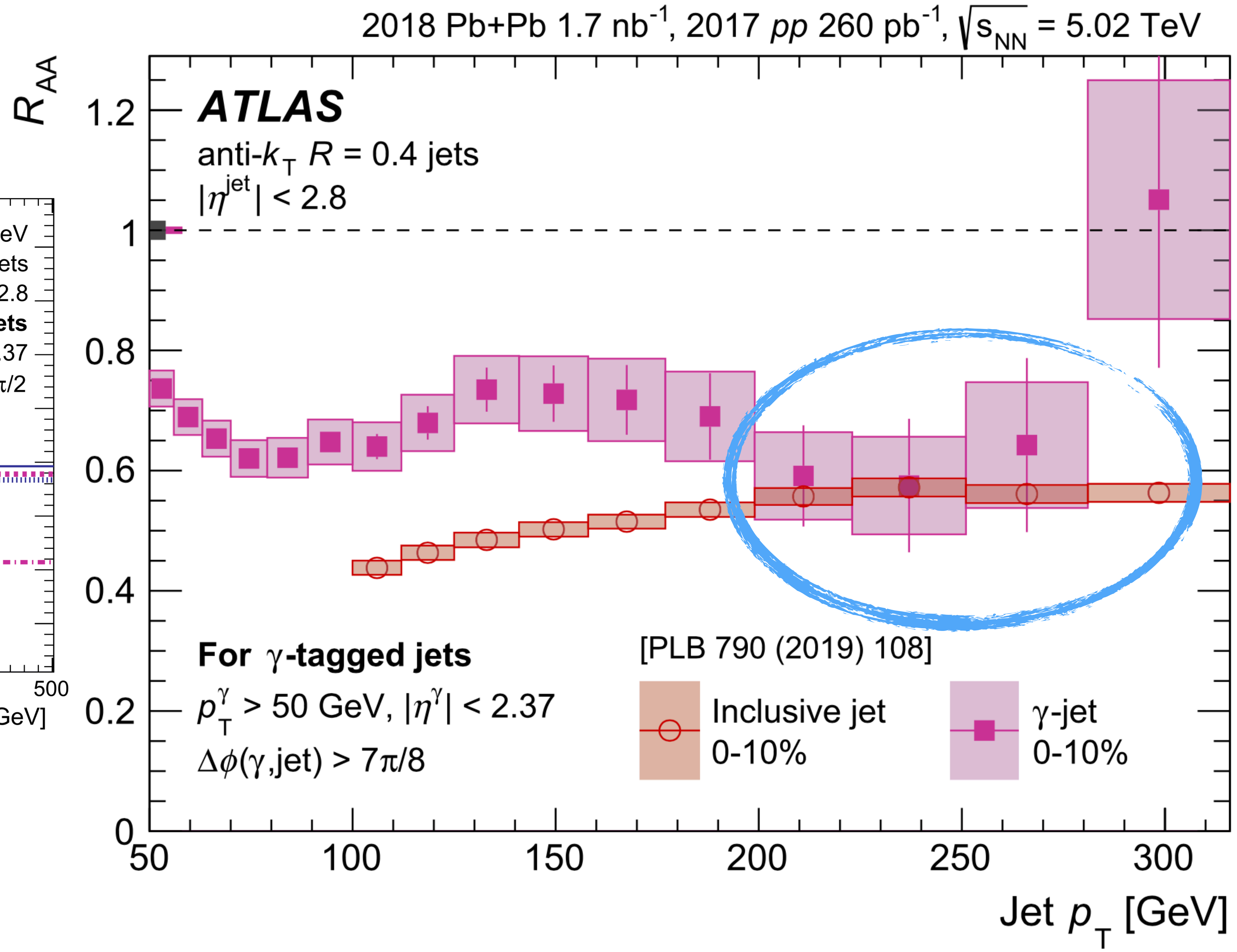


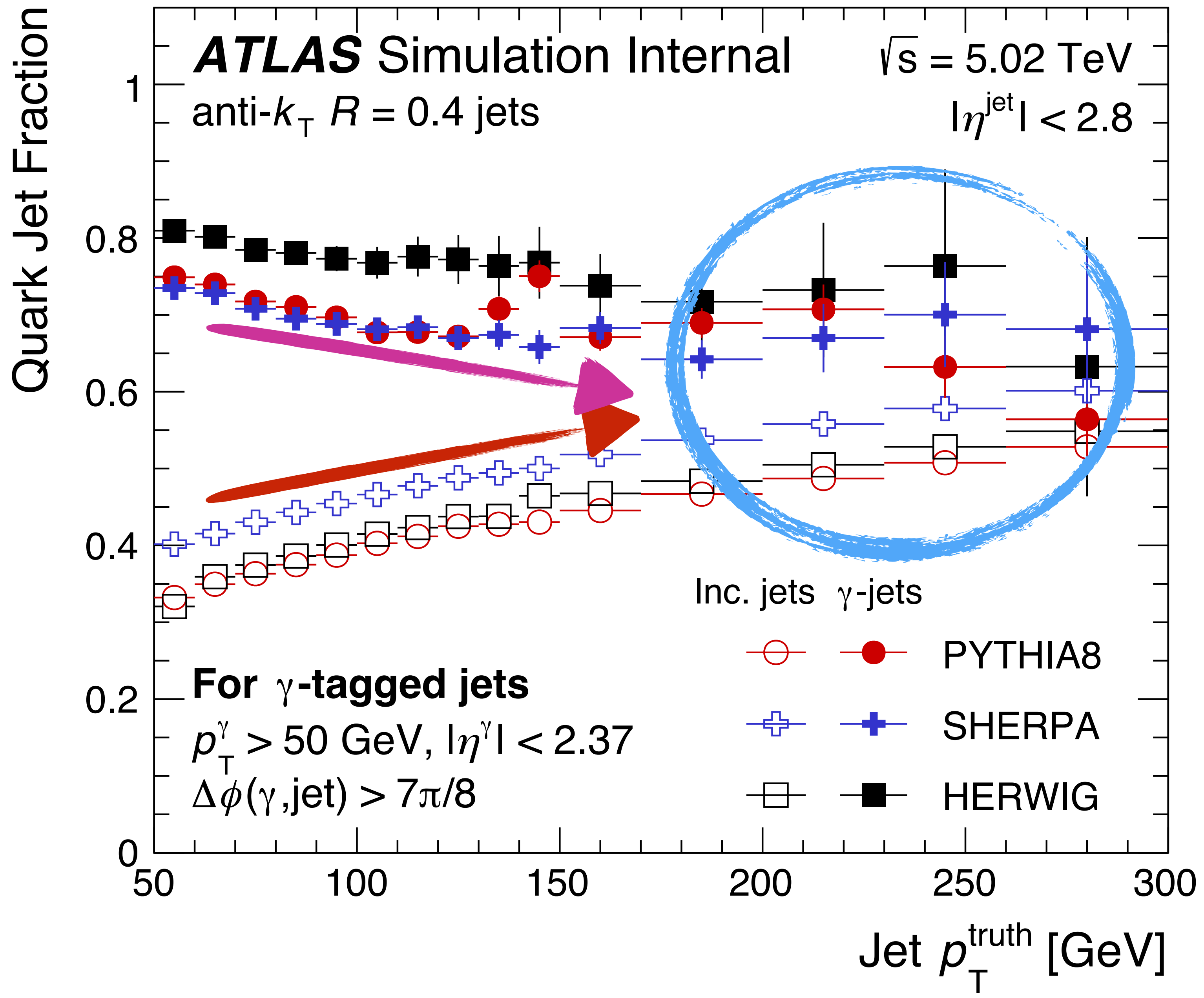


- Comparison in R_{AA} between γ-jets and inclusive jets for the 0-10% centrality bin
- For p_T < ~200 GeV, R_{AA} (γ-jets) > R_{AA} (inclusive jets)
- This indicates that **quark-initiated jets lose less energy** than gluon-initiated jets

Nuclear Modification Factor (R_{AA})







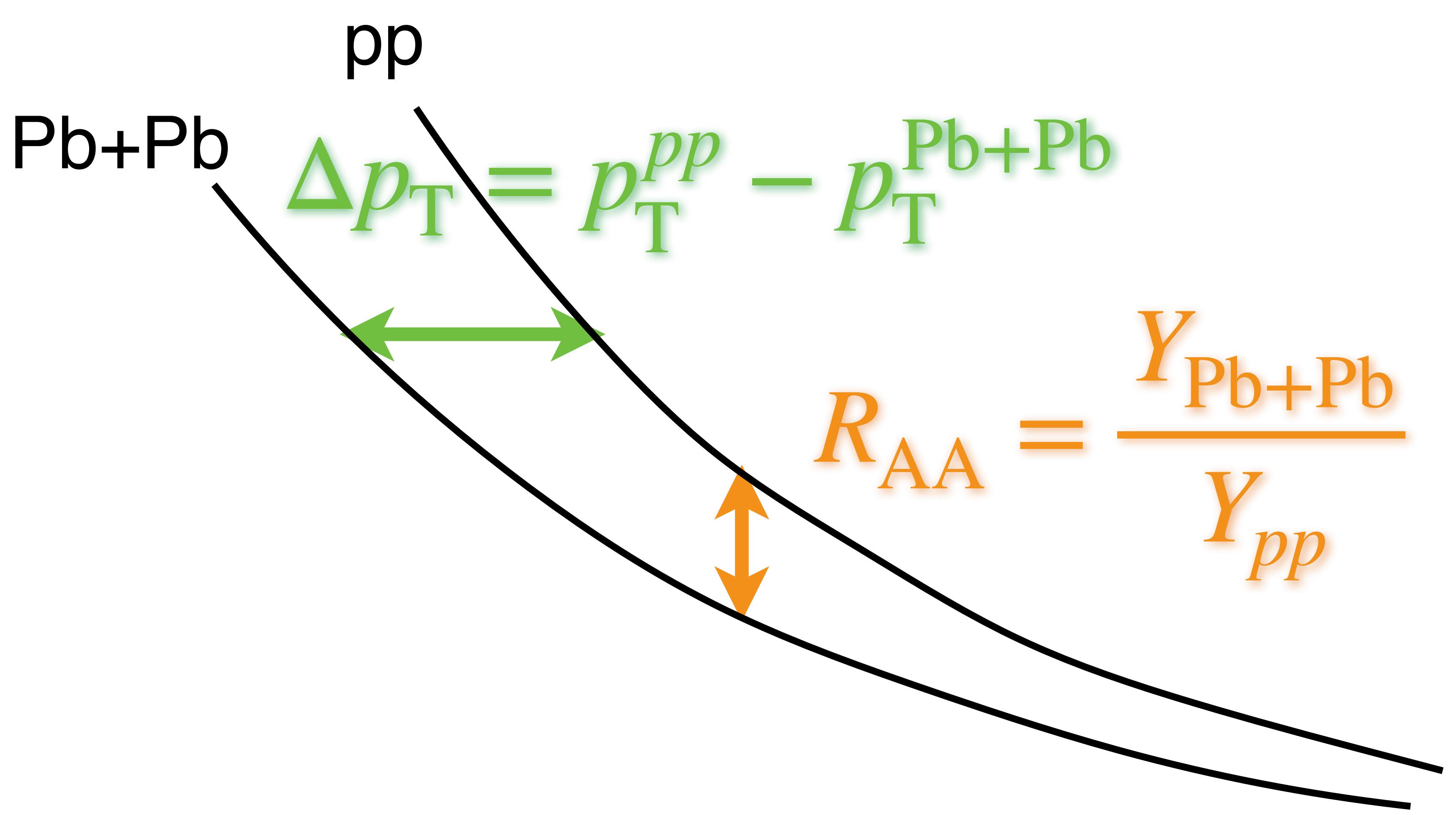
- For p_T > ~200 GeV, R_{AA} (γ-jets) ~ R_{AA} (inclusive jets), why?
  - ➡ Isospin effect becomes larger
  - ➡ Quark-initiated jet fraction becomes similar btw γ-jets and inclusive jets

Fractional Energy Loss, S_{loss}

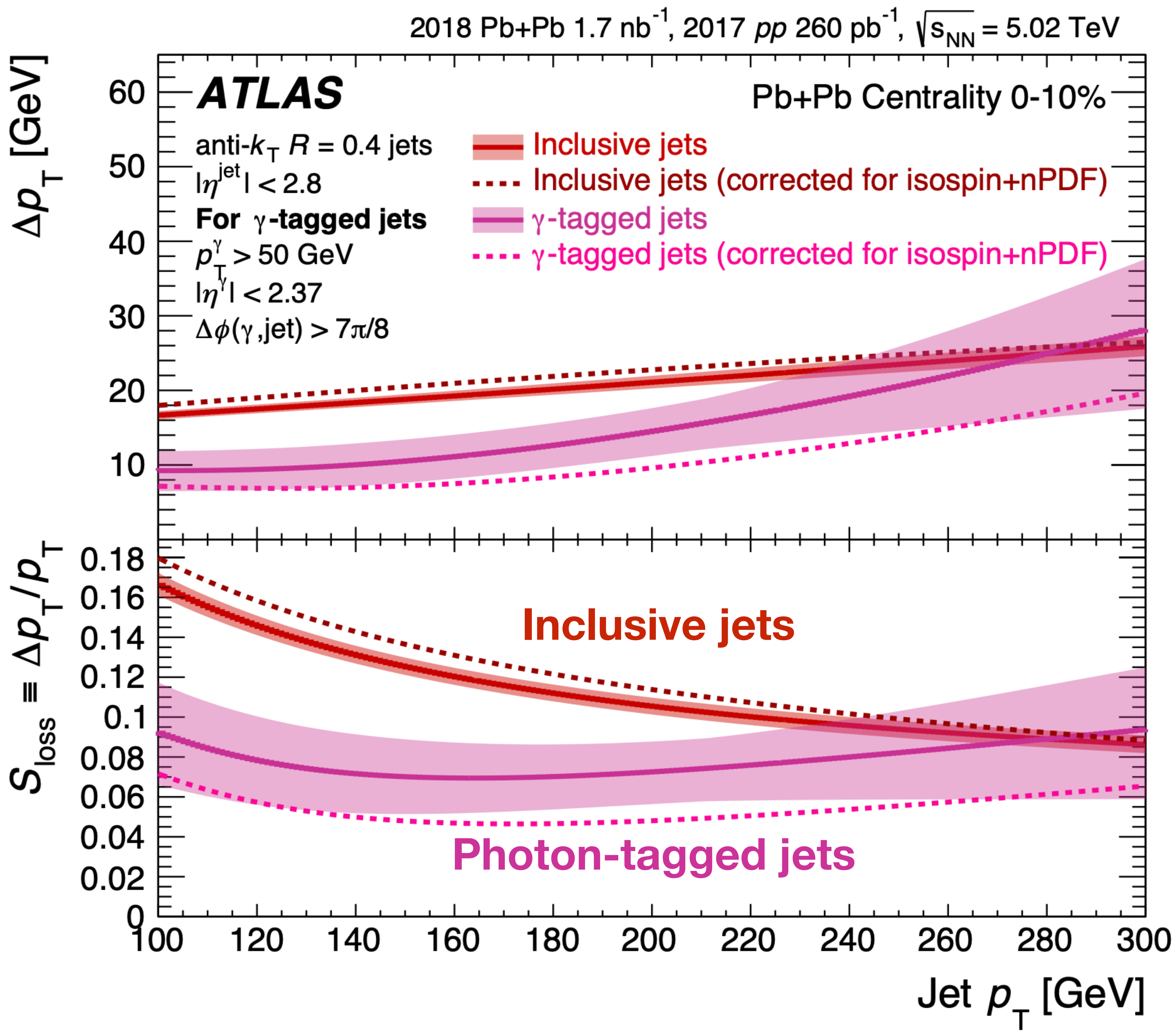
- limitation of **R_{AA}**: a steeper p_T distribution in *pp* (before jet quenching) will result in lower R_{AA}
- but, **S_{loss}** and **Δp_T** are less affected by the p_T spectrum in *pp* collisions
- The **S_{loss}** was originally defined and further detailed by the PHENIX Collaboration: *Nucl. Phys. A 757 (2005) 184, Phys. Rev. C 76 (2007) 034904, JHEP 09 (2001) 033*

$$\Delta p_T = p_T^{pp} - p_T^{\mathrm{Pb+Pb}} \quad \text{when} \quad \frac{1}{\langle T_{AA}\rangle}\frac{1}{N_{evt}}\frac{d^2N^{\mathrm{Pb+Pb}}\,(p_T^{\mathrm{Pb+Pb}} = p_T^{pp} - \Delta p_T)}{dp_T^{\mathrm{Pb+Pb}}d\eta} = \frac{d^2\sigma^{pp}\,(p_T^{pp})}{dp_T^{pp}\,d\eta} \times \left[1 + \frac{d\Delta p_T}{dp_T^{pp}}\right]$$

$$S_{loss}(p_T^{pp}) \equiv \frac{\Delta p_T}{p_T^{pp}}$$

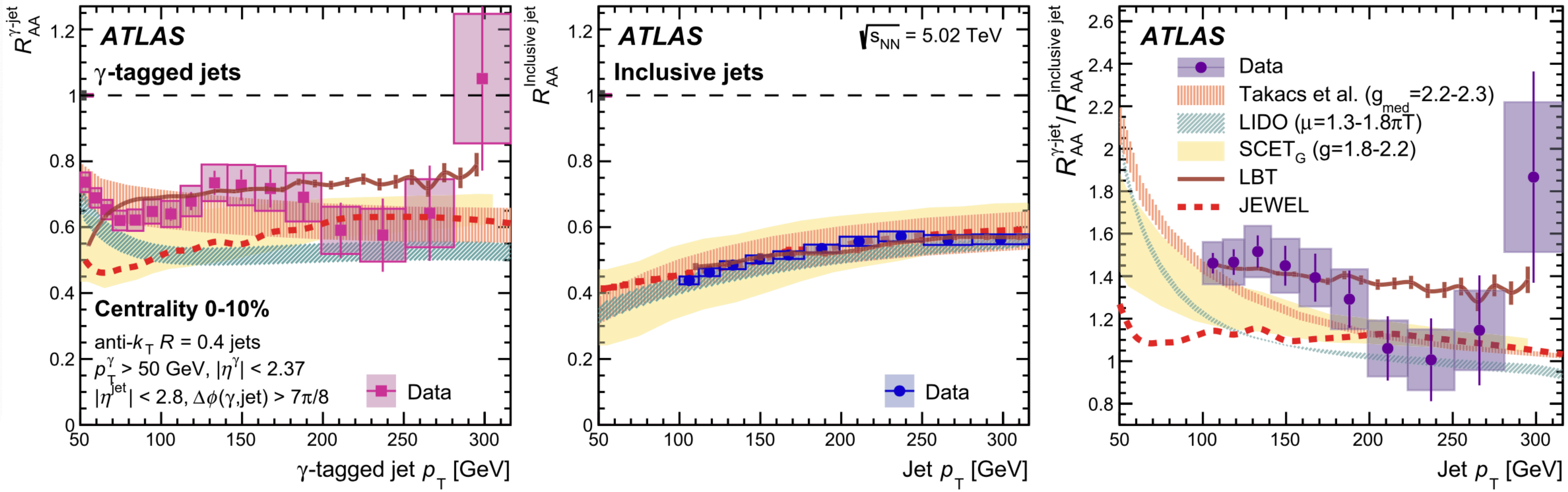


Fractional Energy Loss, S_{loss}



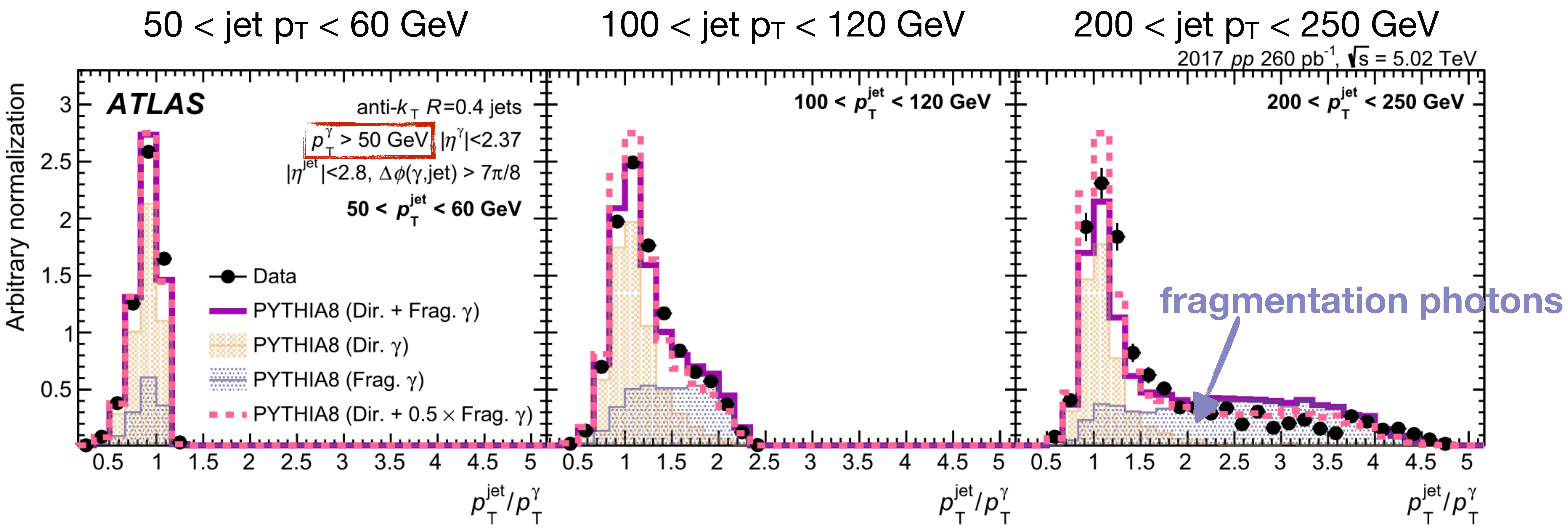
- For < ~200 GeV, S_{loss} and Δp_T values for γ-jets are significantly smaller than those for inclusive jets
  - ➡ significant color-charge dependence to jet energy loss
- The isospin-corrected S_{loss} and Δp_T (dashed lines) even strengthen the evidence that **quark-initiated jets lose less energy than gluon-initiated ones**

Theory Comparison: R_{AA}



- Inclusive jet: data is well described by all calculations
- Photon-tagged jet: data is generally higher than many of the calculations
- Theory predictions include *color-charge dependence of the parton-QGP interaction*
- For both data and calculations, generally, $R_{AA}^{\gamma-\text{jet}}/R_{AA}^{\text{inclusive jet}}$ > 1 at R_{AA} < ~ 200 GeV

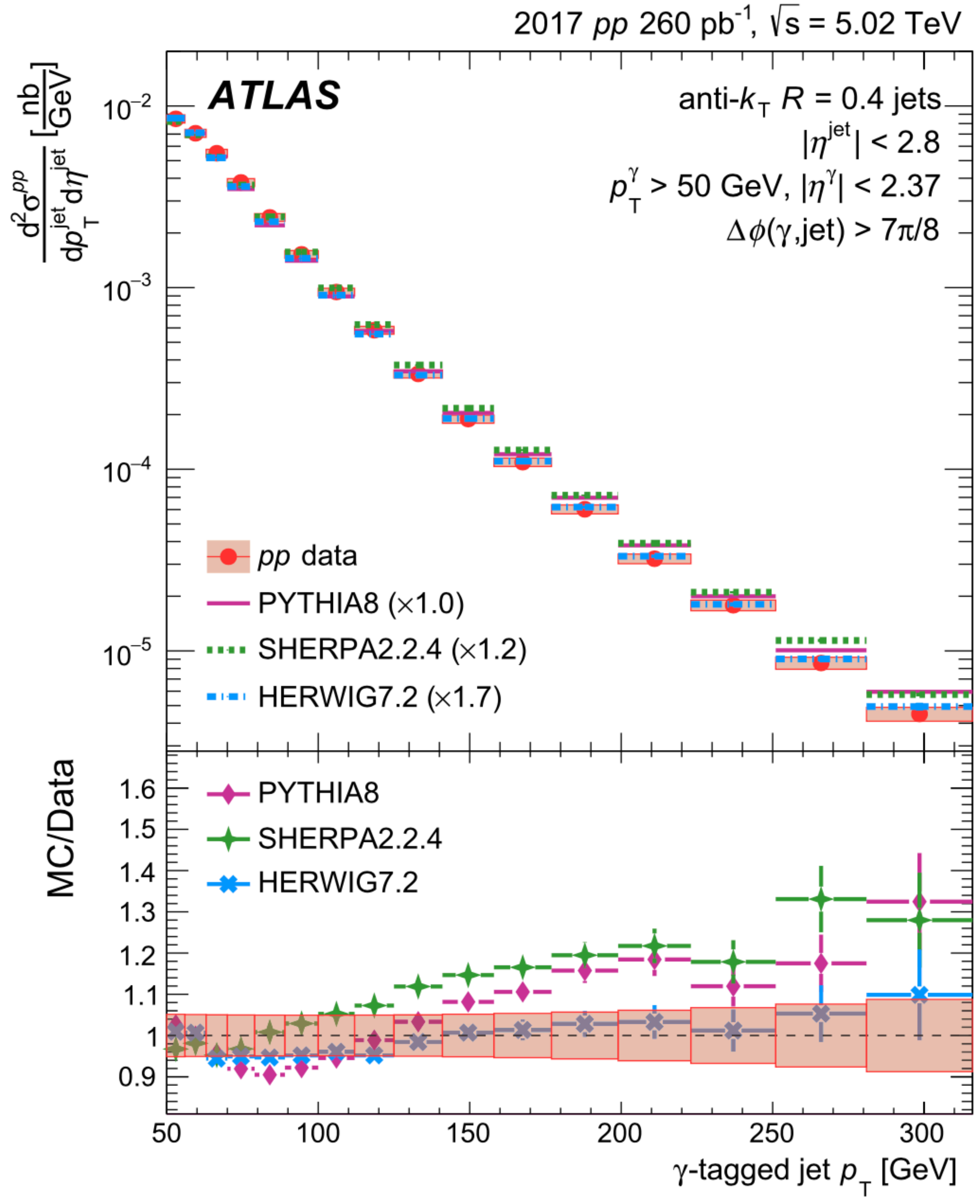
Discussion) Jet p_T dependent $X_{J\gamma}$: Data vs. MC



- $X_{J\gamma}$ is measured in each jet p_T bin
  → he higher jet p_T, the larger fragmentation photon contribution
- This demonstrates the direct-fragmentation photon fraction in each jet p_T bin in our sample
- ***Potential mis-modeling*** of the fraction of direct-fragmentation photons in MC

Note that these are reconstructed-level jets and photons
for both data and MC, without any corrections
(i.e. photon purity, efficiency, unfolding)

Discussion) Cross section in pp: Data vs. MC

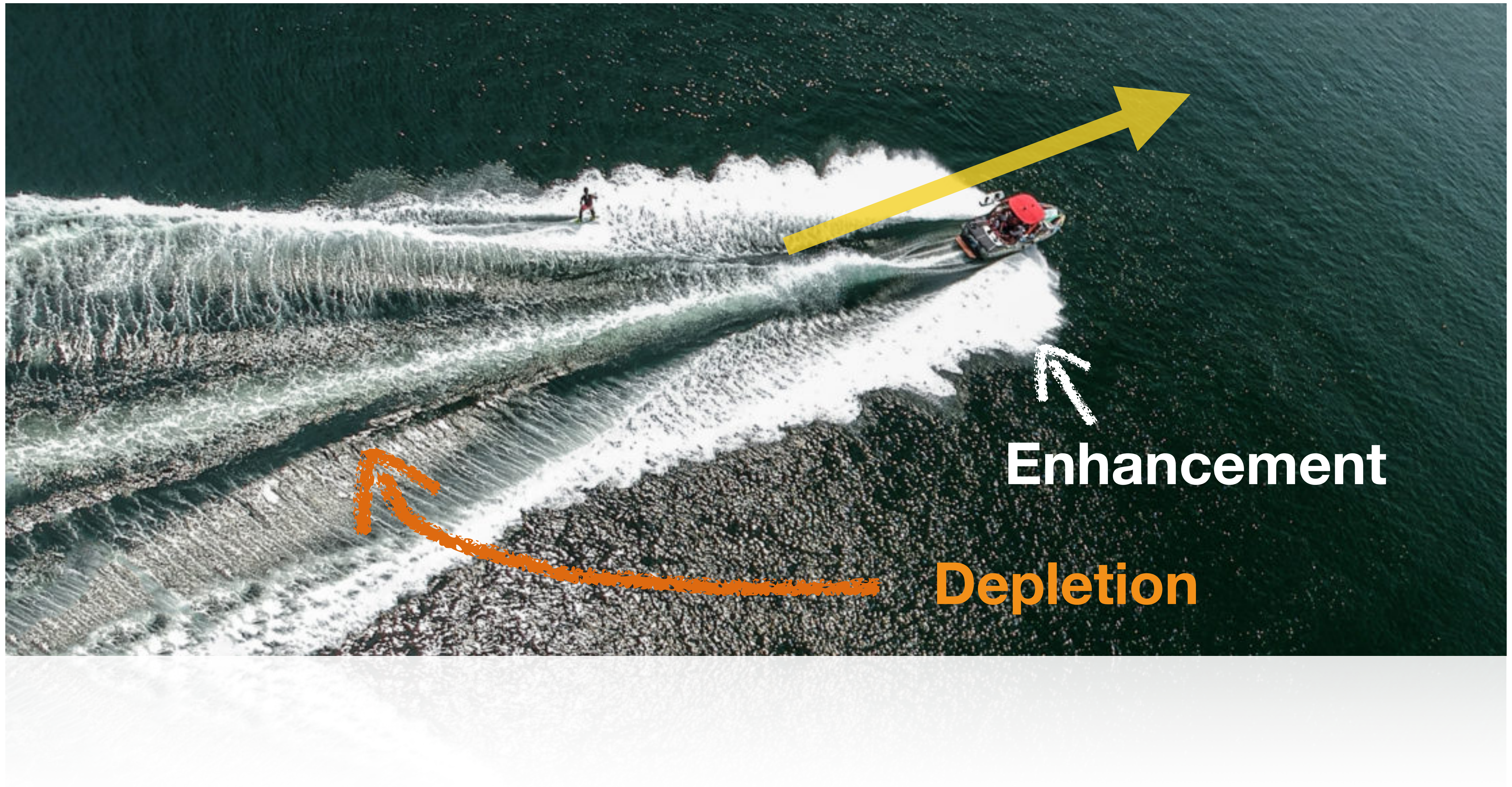


- MC generators (Pythia, Sherpa, Herwig) do not describe the data well for either p_T spectrum or the total cross section
  - ➡ If theory predictions use one of these MC generators, one needs to consider the differences between the data and predictions

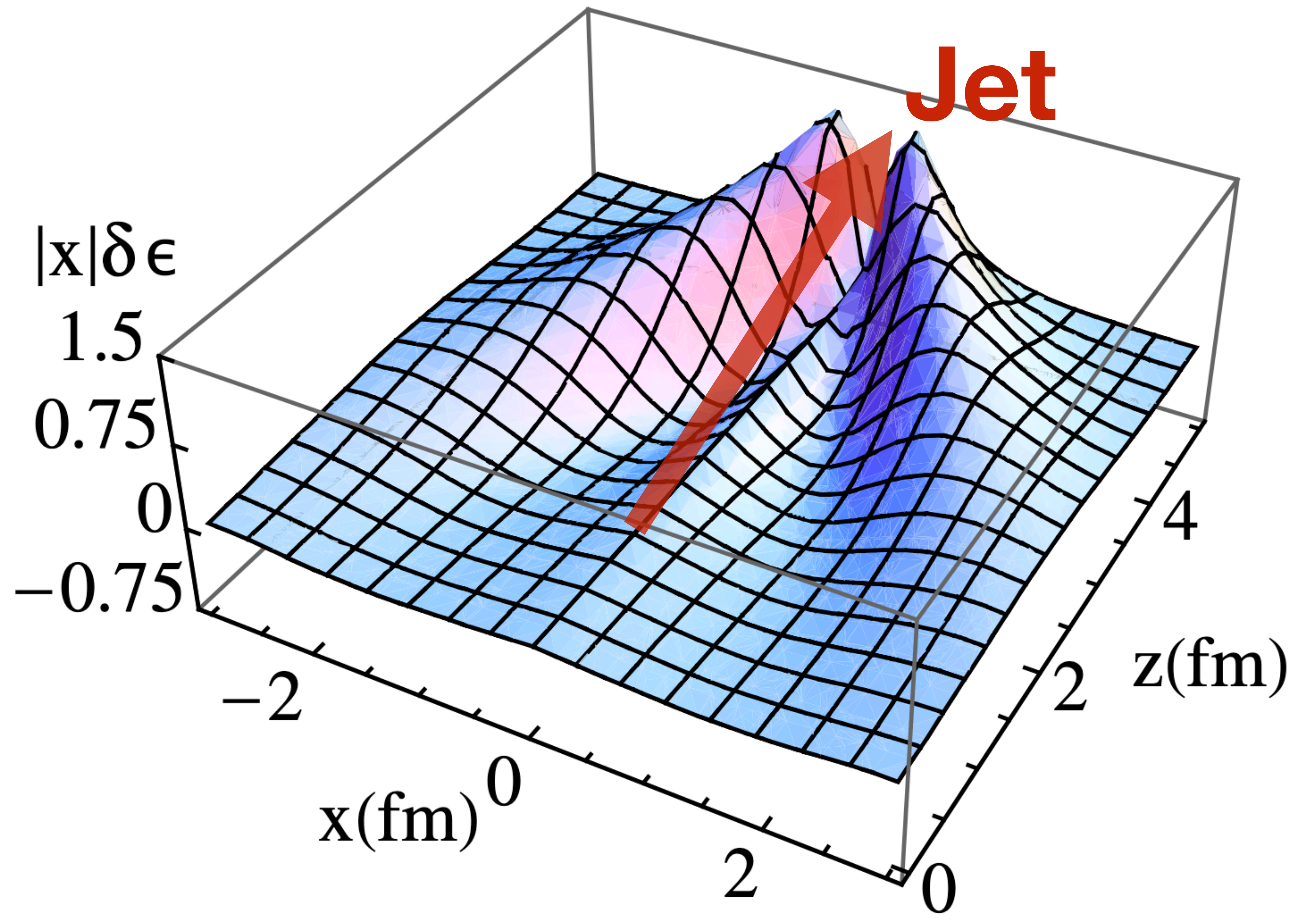
Medium Modification Incurred by Jets

Mutual Interaction : Medium ⇄ Jets

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



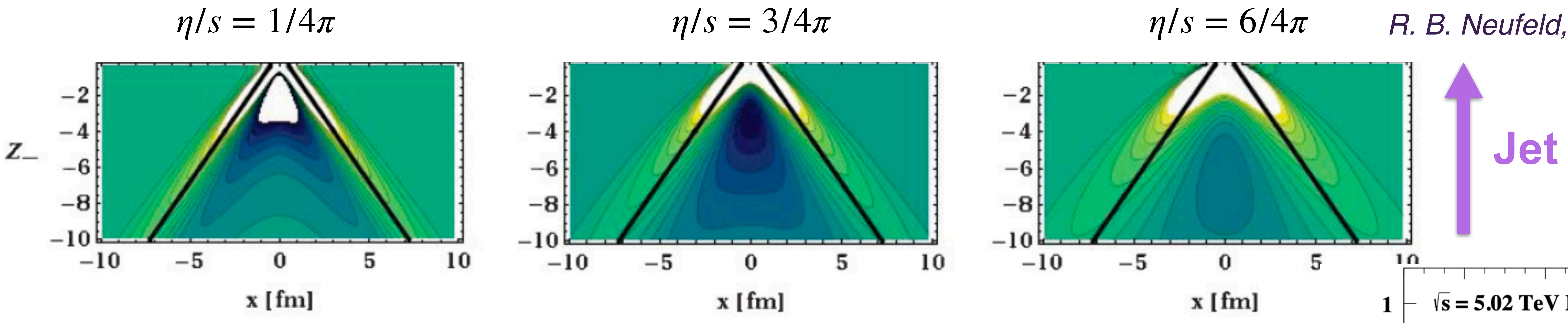
G.-Y. Qin et al, PRL 103, 152303 (2009)



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

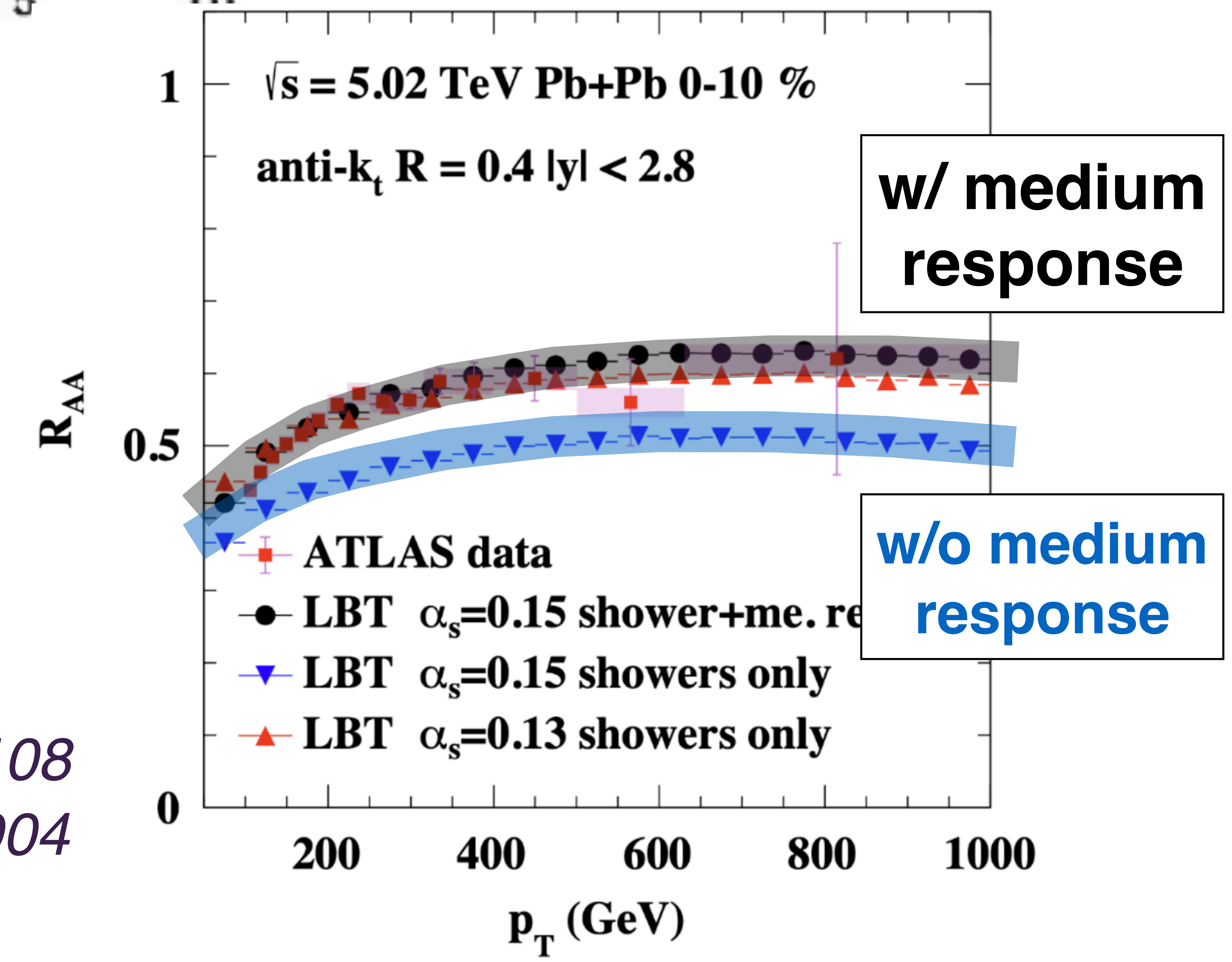
Why is medium response important to understand?

- 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

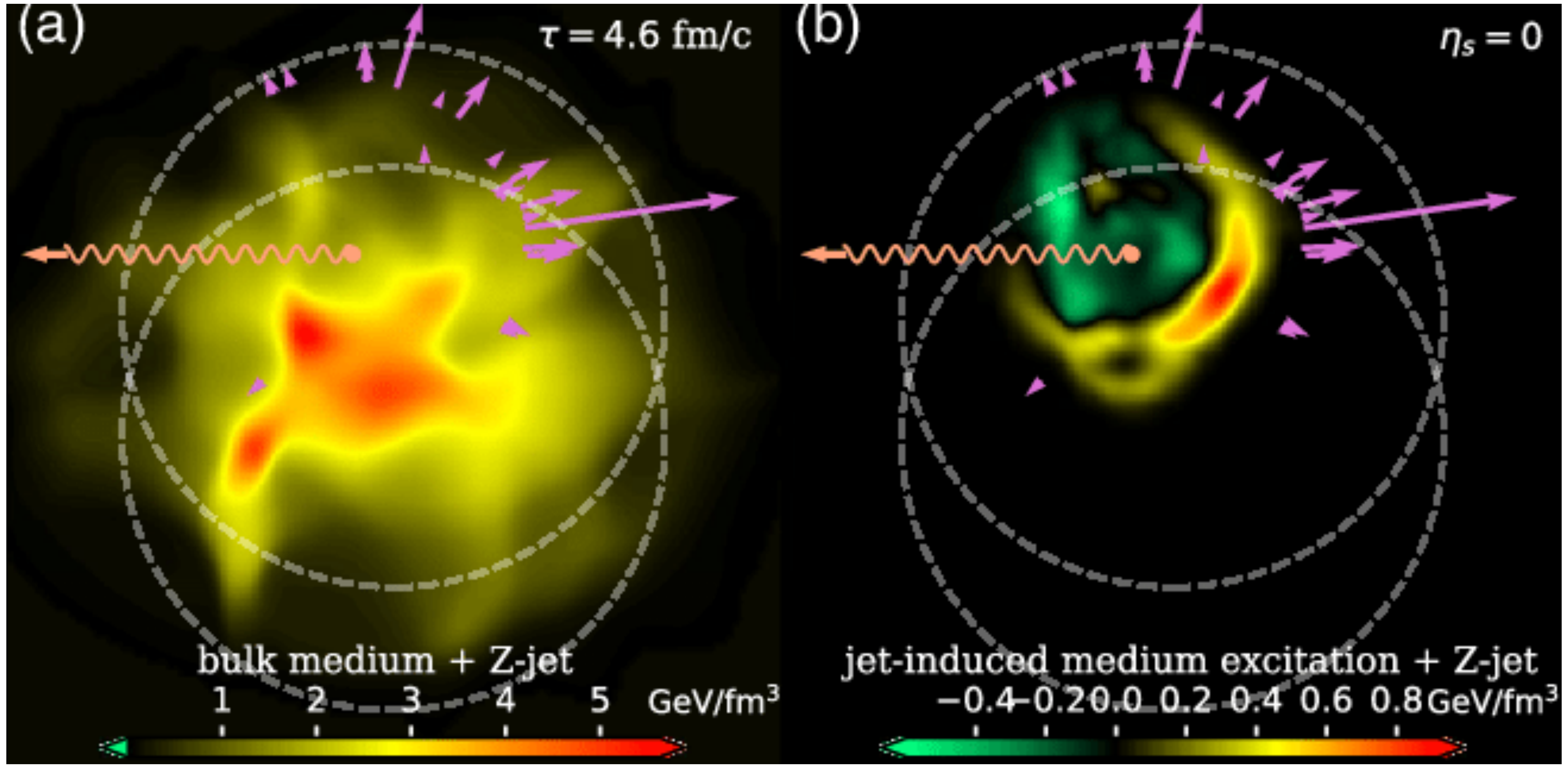
- In-medium thermalization information e.g. E_{med}, D_{diff}, τ_{th}
- Medium response affects the extraction of jet transport coefficient
  ➡ can be related to local gluon density distribution of the medium



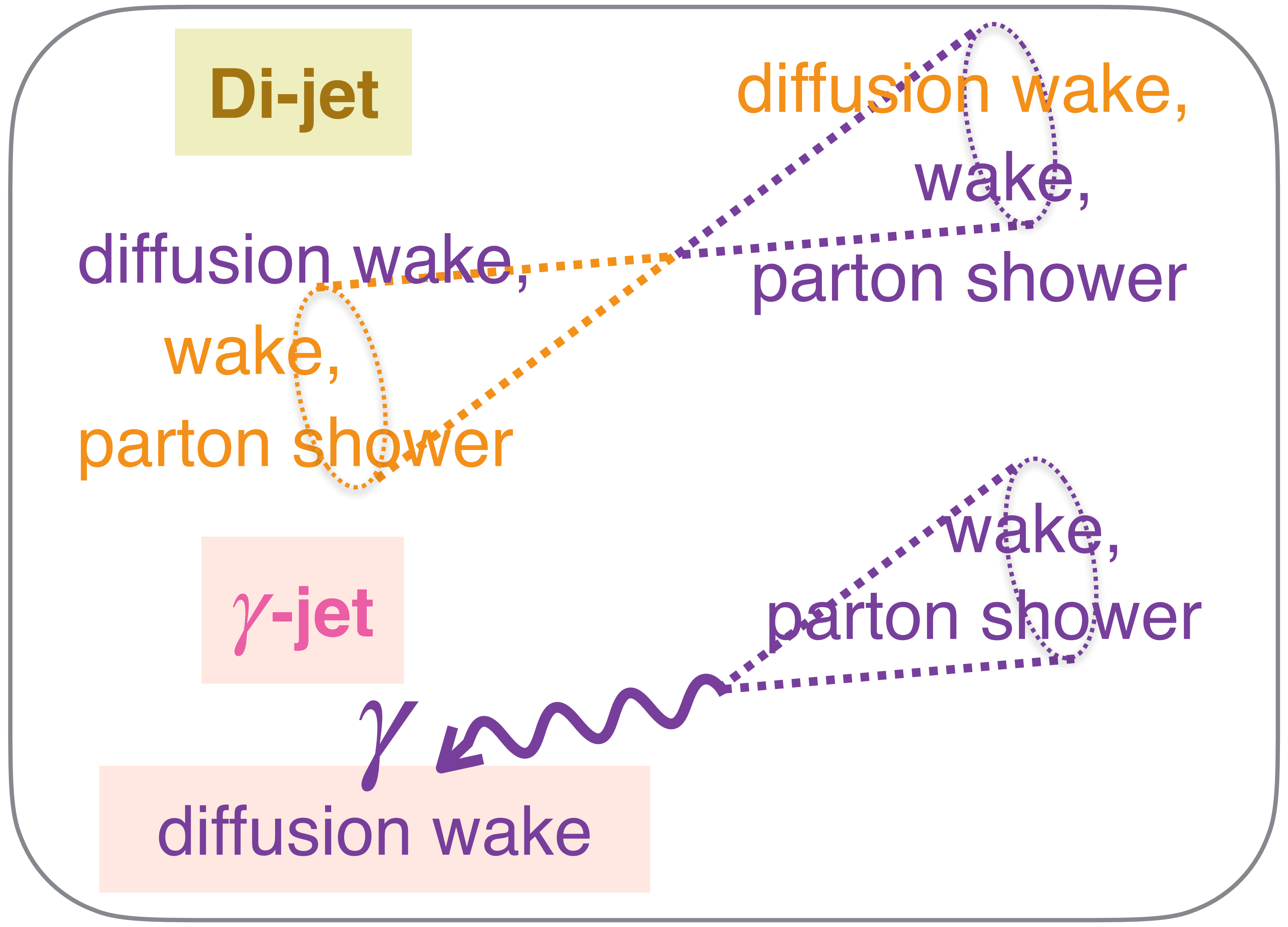
ATLAS, PLB 790 (2019) 108
Yayun He et al, PRC 106 (2022) 044904

Looking for Diffusion Wake in Photon-Jet events (1)

- **Jet-hadron correlation** to study medium modification incurred by jets
  - ➡ Modification in **jet** direction, so-called **wake effect**, **Mach cone**, are convoluted with **in-medium parton shower modification** and **medium response** → hard to disentangle …
  - ➡ Diffusion wake in photon-jet events; unlike **di-jet** events, a jet associated a photon is **NOT** contaminated by wake or in-medium parton shower modification by another jets



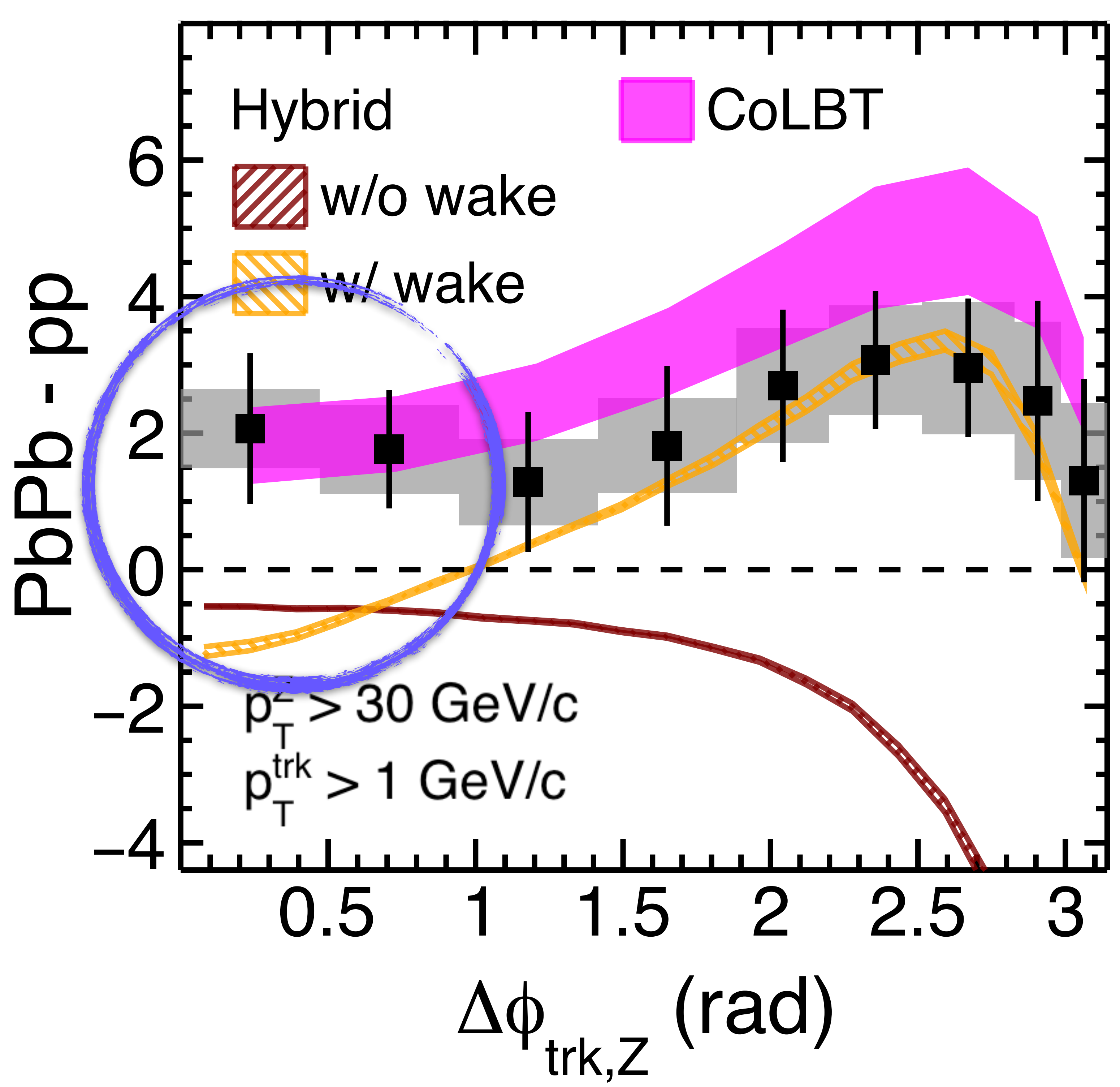
CoLBT, Xin-Nian et al, PRL127, 082301 (2021)



Looking for Diffusion Wake in Photon-Jet events (2)

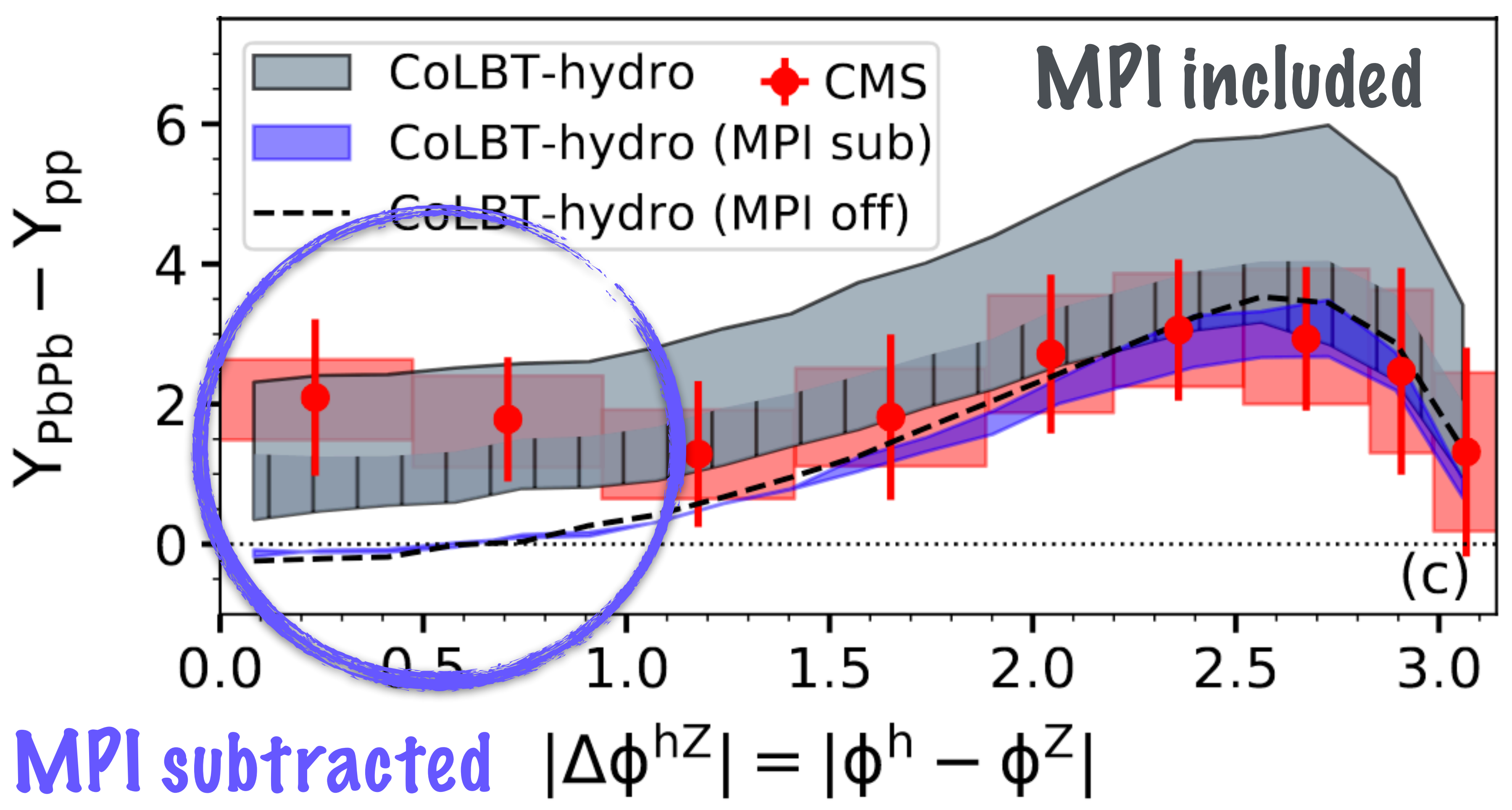
- CoLBT model predicts
  - ➡ Yield as a function of $\Delta\phi$: overall enhancement from multi-parton interaction (MPI) at $\Delta\phi \sim \pi$

***CMS** PRL 128 (2022) 122301*



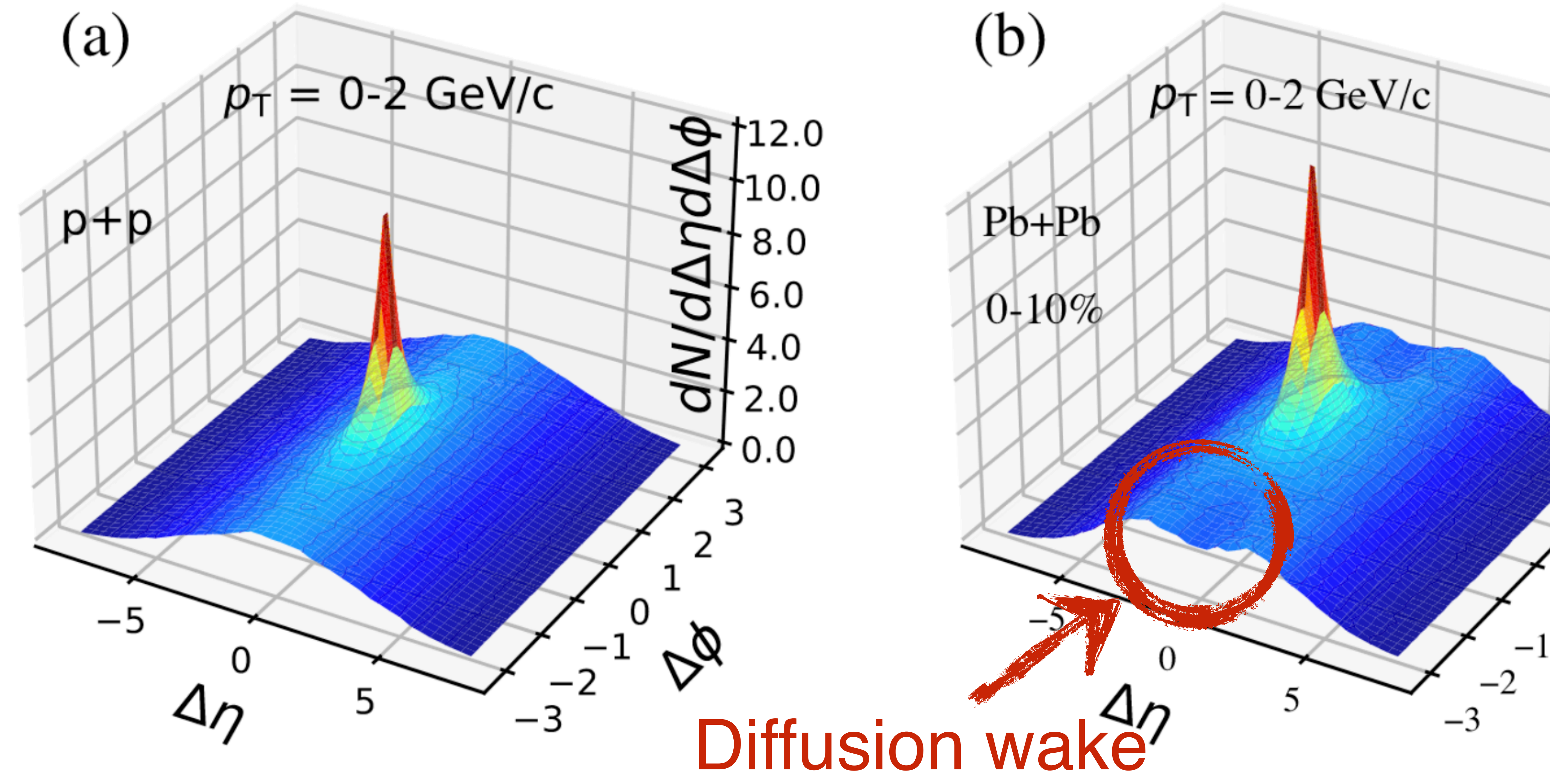
Wei Chen, PRL 127 (2021) 082301

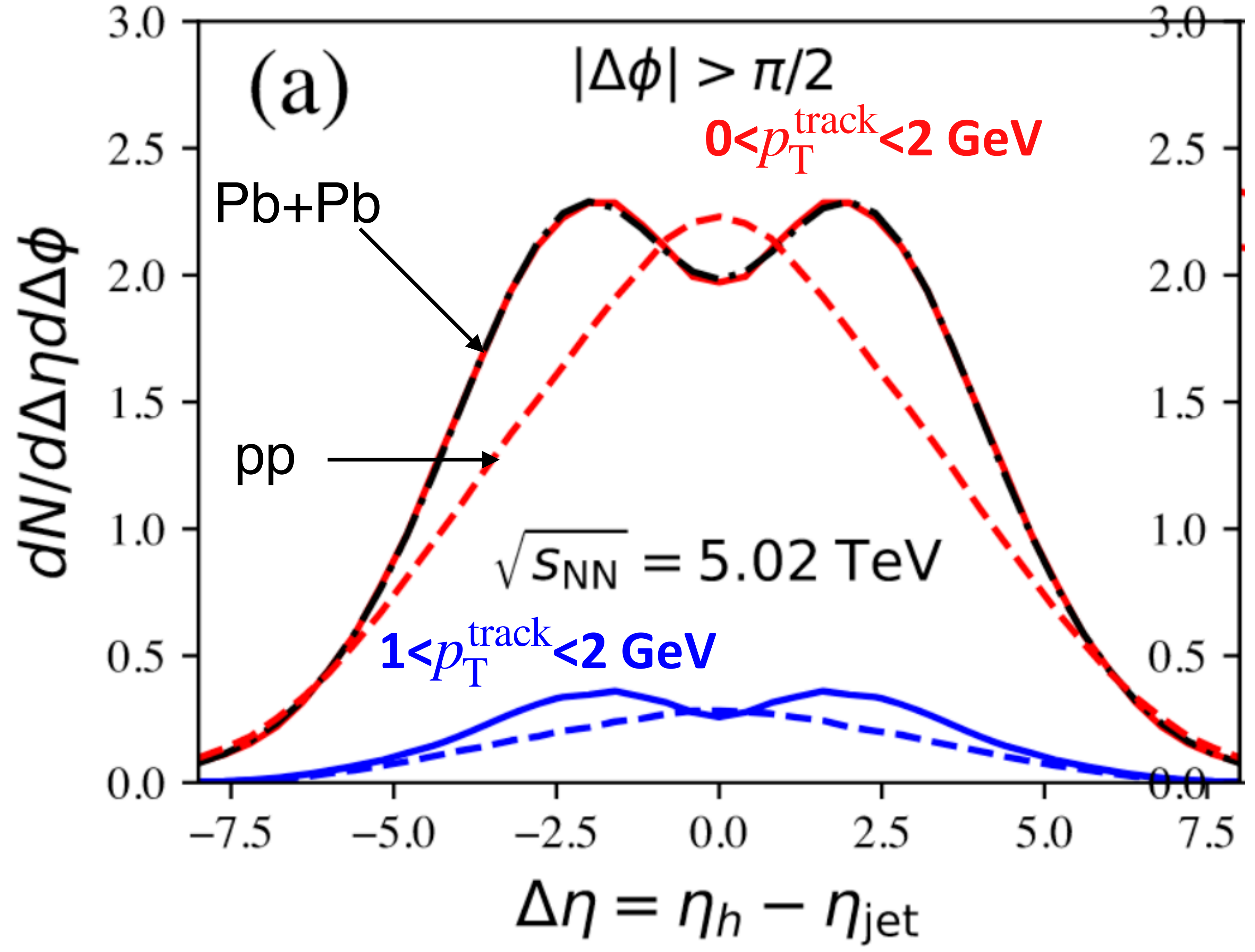
CoLBT-hydro



Looking for Diffusion Wake in Photon-Jet events (2)

- CoLBT model predicts
  - ➡ Yield as a function of $\Delta\phi$: overall enhancement from multi-carton interaction (MPI) at $\Delta\phi \sim \pi$
  - ➡ Jet-hadron $(\Delta\phi, \Delta\eta) \sim (\pi,0)$ in γ-jet events
  - ➡ Unambiguous diffusion wake signal



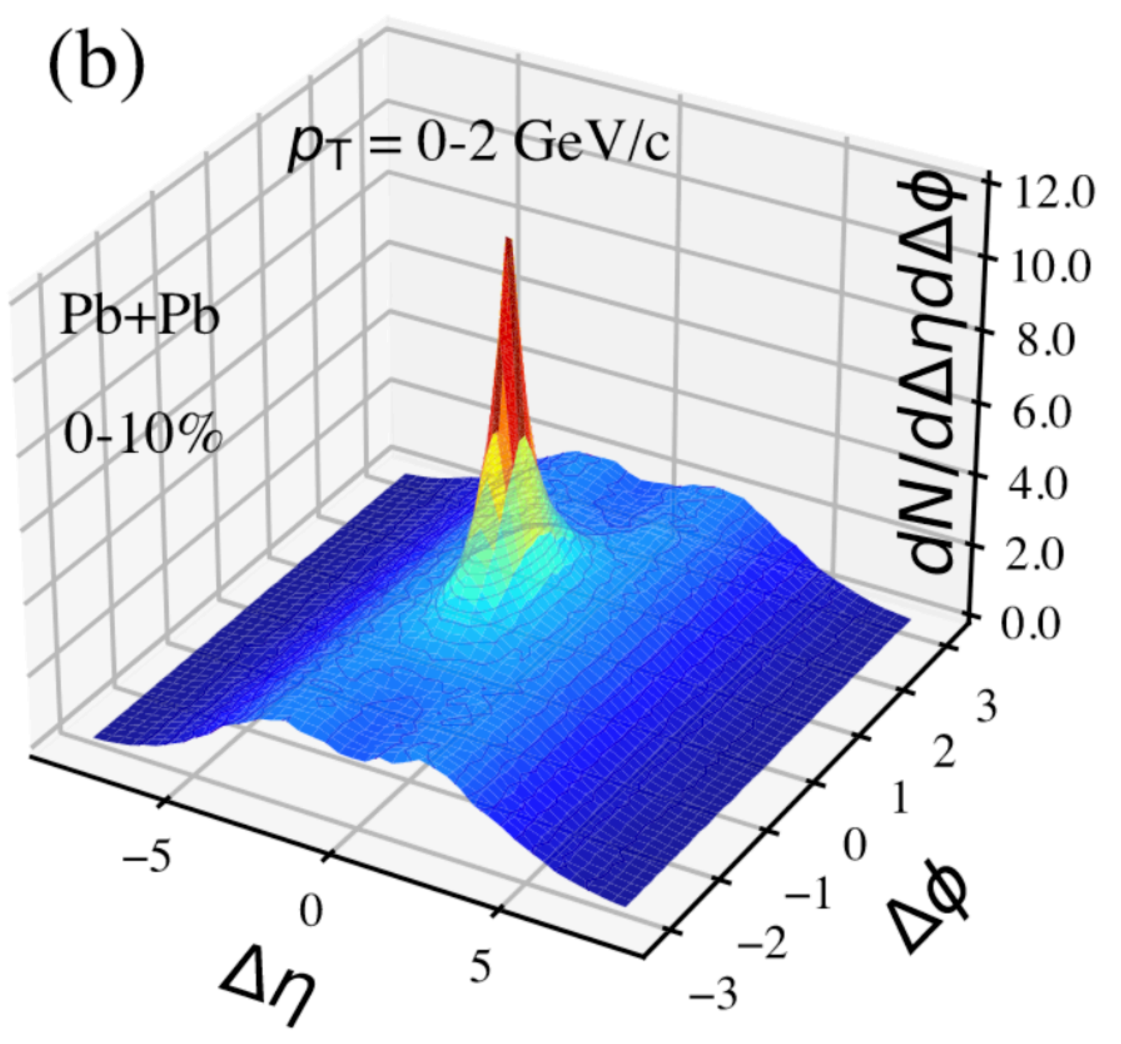


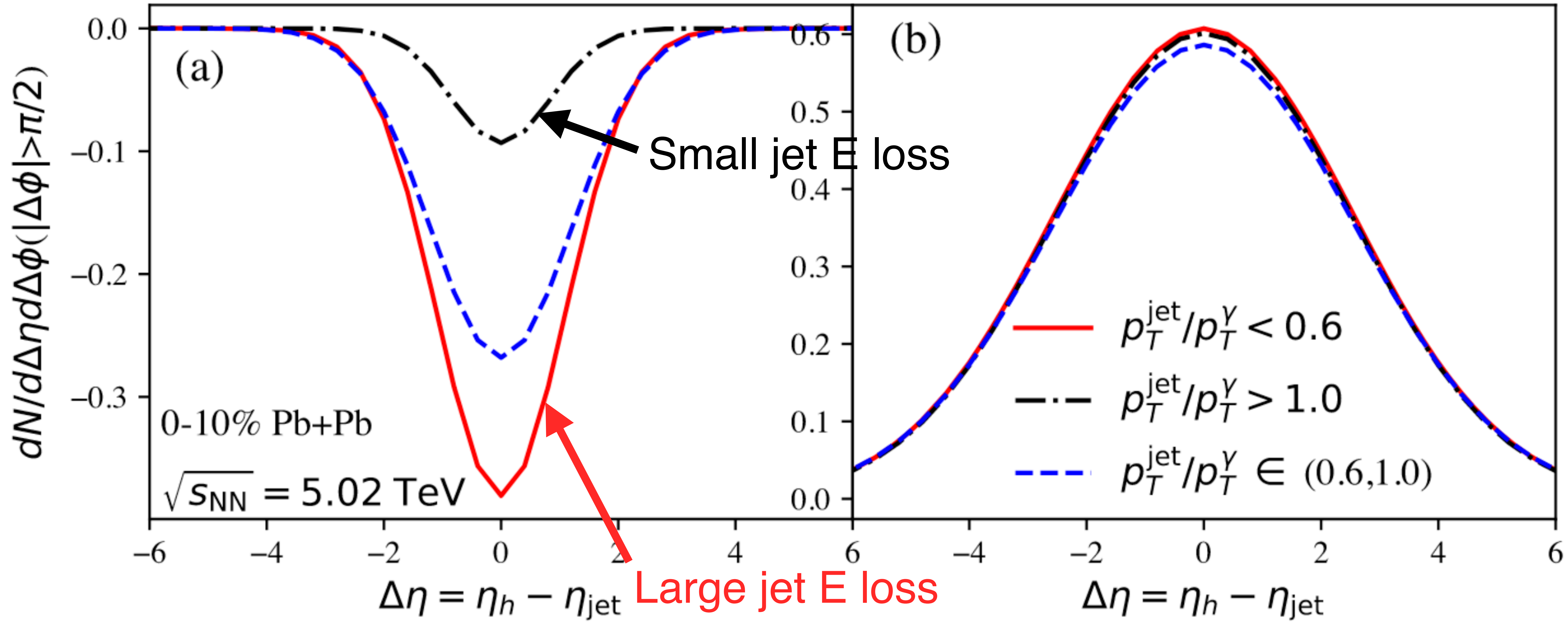
Note) the "bulk only" yield is subtracted from the "bulk + photon+jet" yield

CoLBT, Xin-Nian et al, PRL 130, 052301 (2023)

Diffusion Wake: Dependence on Jet Energy Loss

CoLBT, Xin-Nian et al, PRL 130, 052301 (2023)

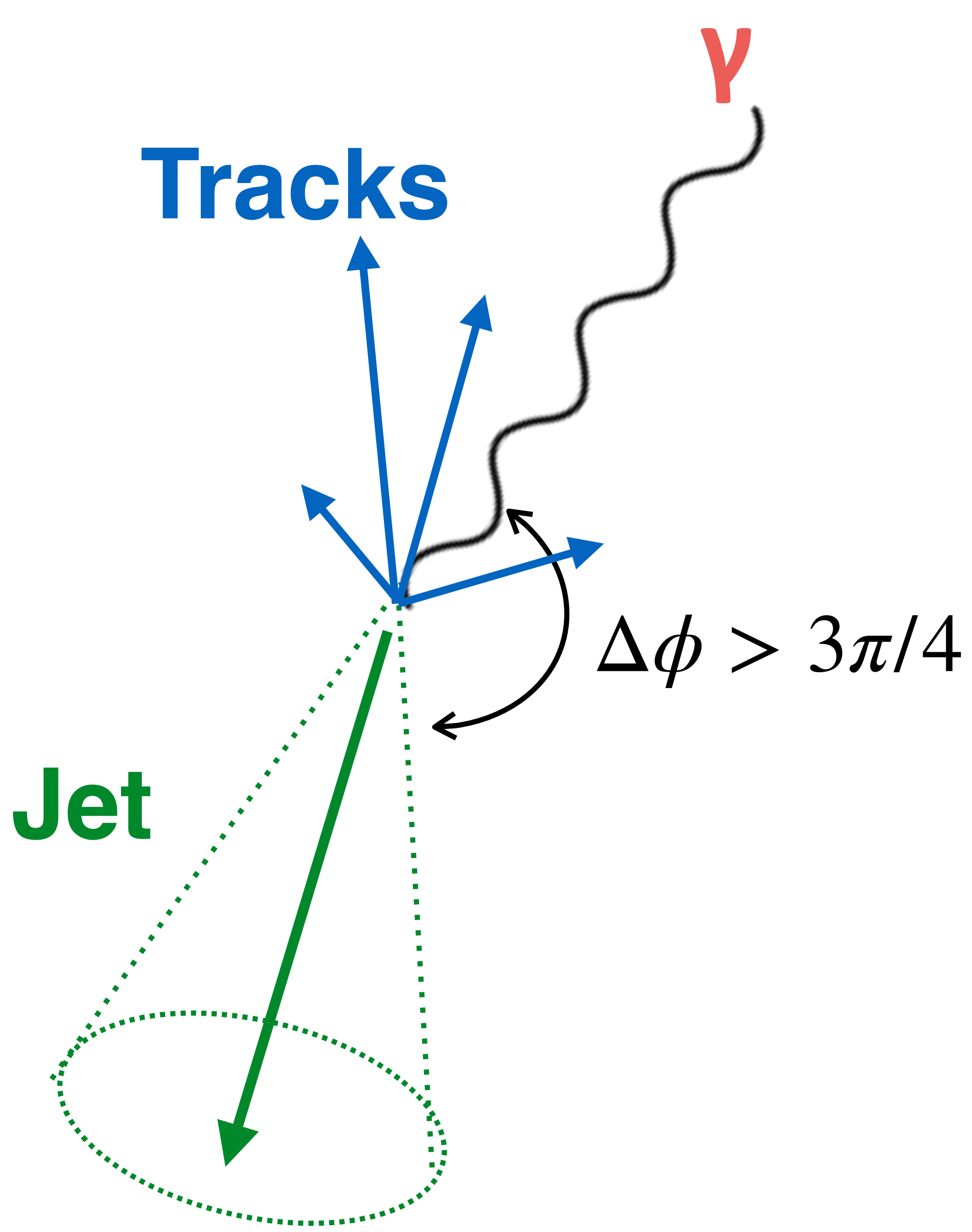




- Smaller $x_{J\gamma} = p_T^{jet}/p_T^\gamma$ means **larger jet energy loss** and **longer path** through the medium and hence larger medium response i.e., diffusion wake
- However, the MPI signal has no significant dependence on the $x_{J\gamma}$, while the diffusion wake does

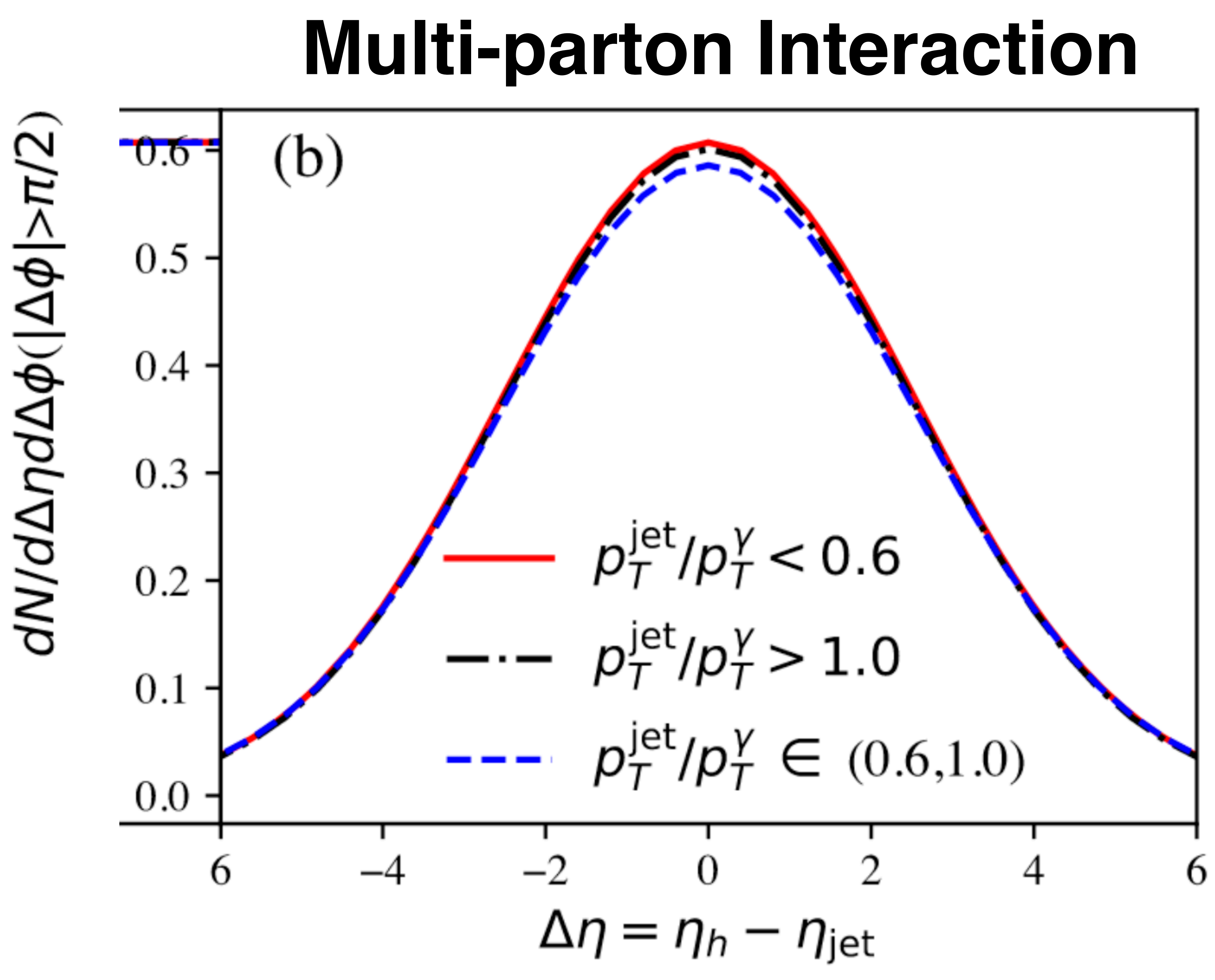
Event Selection

- **Photons**
  - ➡ p_T > 50 GeV
  - ➡ |η| < 2.37
  - ➡ Prompt Isolated photons (direct+fragmentation photons)
- **Jets**
  - ➡ anti-k_T R=0.4
  - ➡ 50 < p_T < 316 GeV/c
  - ➡ |η| < 2.5
  - ➡ Δφ(γ,jet) > 3π/4
  - ➡ only leading photons and leading jets are considered
- **Tracks**
  - ➡ 0.5 < p_T < 2 GeV
  - ➡ |η| < 2.5
  - ➡ Δφ(jet, track) > π/2

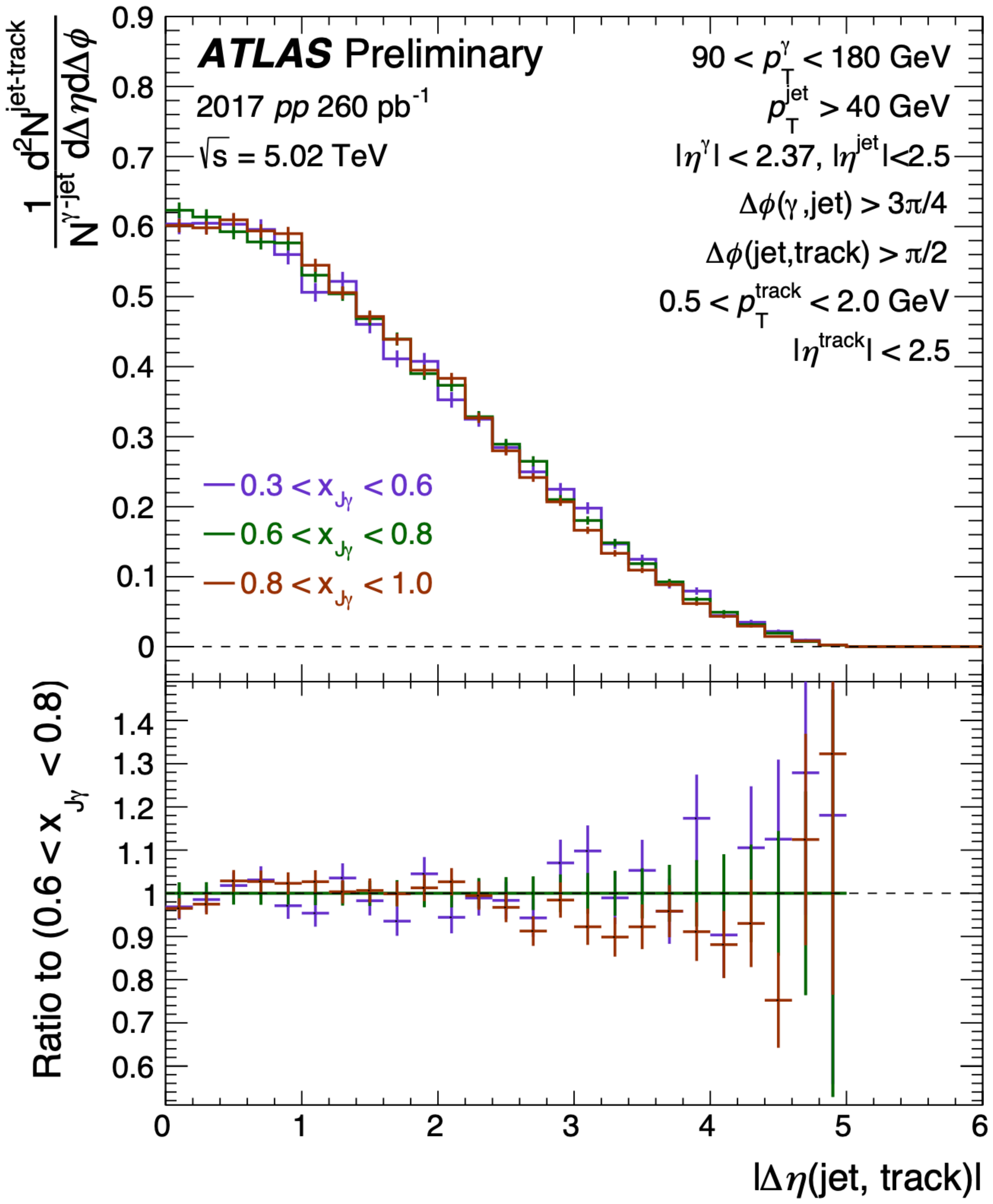


$|\Delta\eta$(jet, track)$|$ distributions in pp collisions

- No $x_{J\gamma}$ dependence found within uncertainties
- The data is in agreement with the theory expectation
- This validates that any $x_{J\gamma}$-dependent change in Pb+Pb should be from different amounts of energy loss

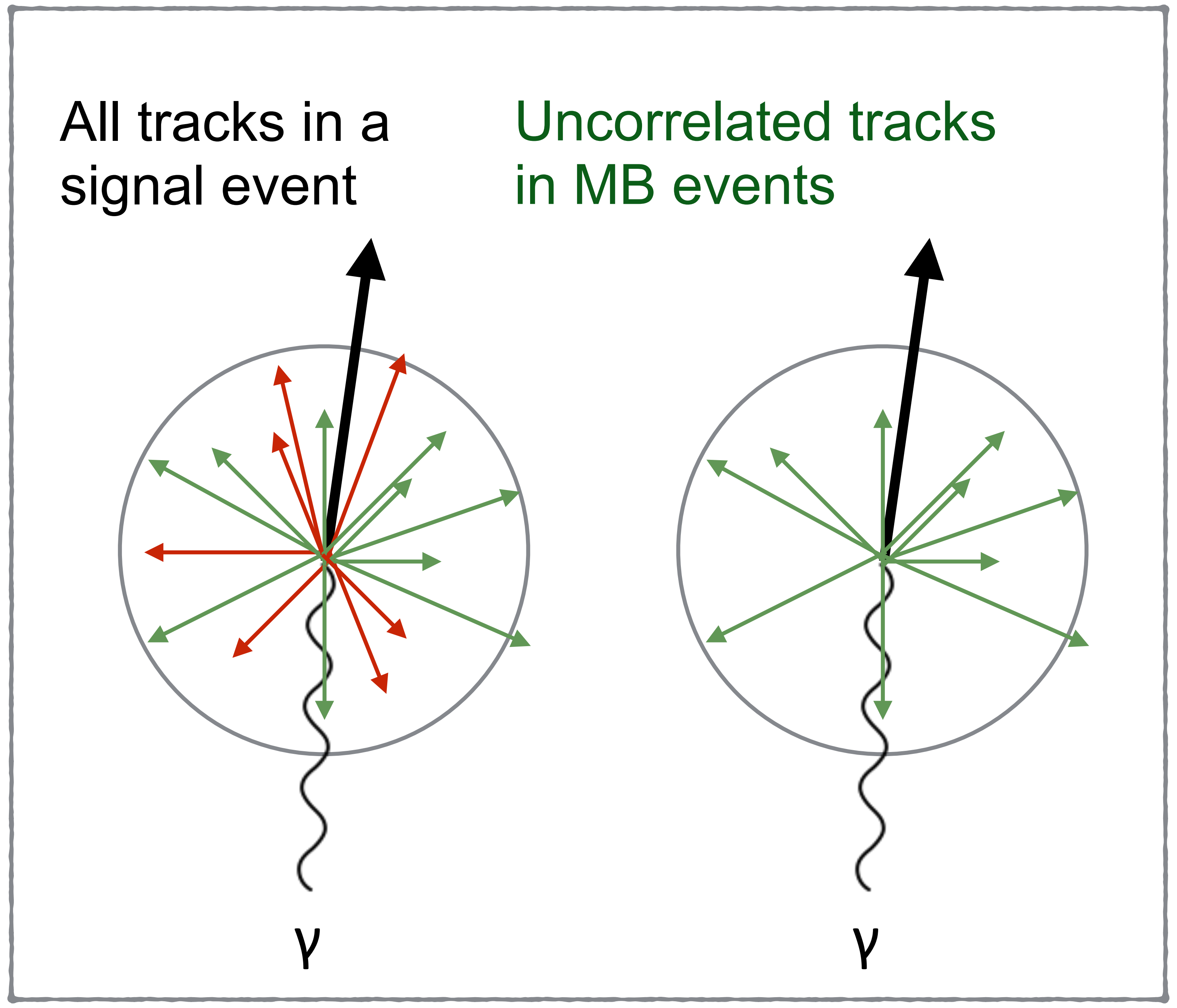


CoLBT, Xin-Nian et al, PRL 130, 052301 (2023)



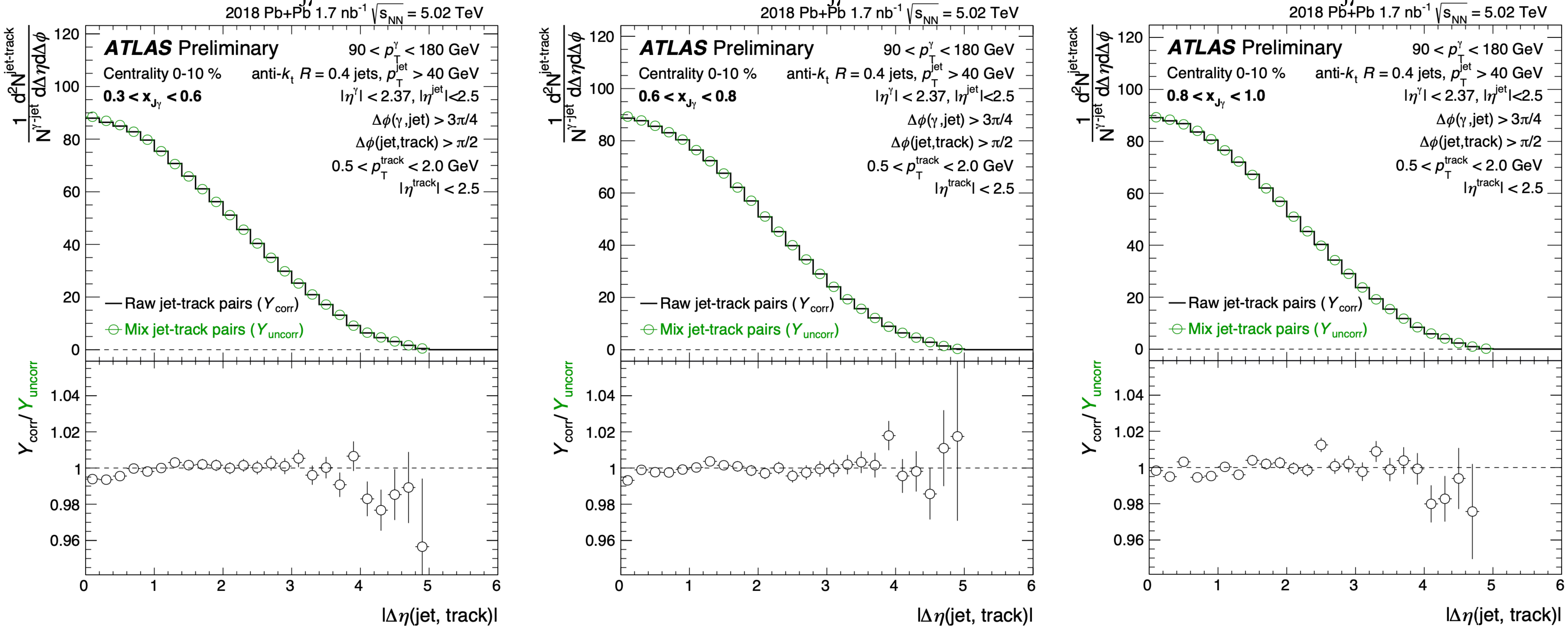
Event Mixing in Pb+Pb collisions

- Bulk medium property w/o jet can be obtained from event mixing
  - ➡ by correlating the photon-jet pair in a signal event with tracks in different minimum-bias (MB) events
    - photon and jet kinematics are exactly the same between signal events and mixed events
  - ➡ matching signal and MB events in bins of
    - $\Sigma E_{\mathrm{T}}^{\mathrm{FCal}}$: 200 bins in [0,5000] GeV; much finer than a 1%-width centrality bin in central collisions
    - Ψ_2: 16 bins in [-π/2,π/2]
    - z vertex: 20 bins in [-10,10] cm; bin width of 1cm



$|\Delta\eta(\text{jet, track})|$ distributions in Pb+Pb collisions

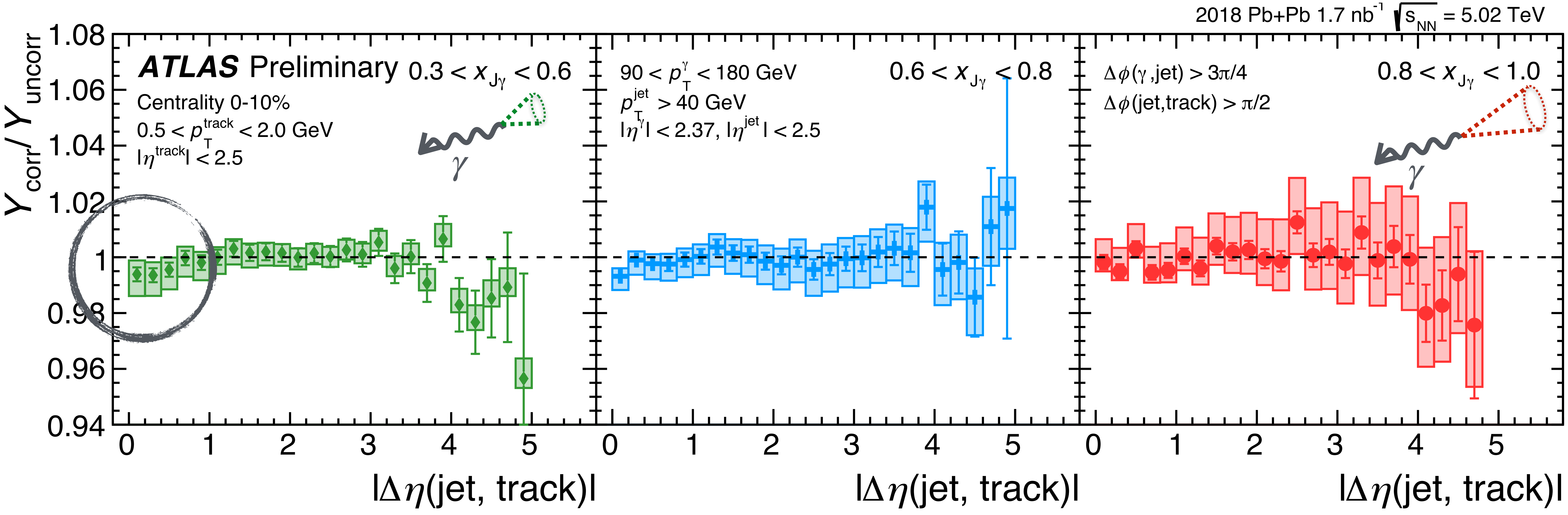
$0.3 < x_{j\gamma} < 0.6$ | $0.6 < x_{j\gamma} < 0.8$ | $0.8 < x_{j\gamma} < 1.0$



- per-(photon, jet) yield ($\frac{1}{N^{\gamma-\text{jet}}}\frac{d^2N^{\text{jet}-\text{track}}}{d\Delta\eta d\Delta\phi} = Y_{\text{corr}}$) as a function of $|\Delta\eta(\text{jet}, \text{track})|$ in three different $x_{J\gamma}$ regions
  - Y_{corr}: jet-track pairs from the signal (photon-jet) events
  - Y_{uncorr}: pairs from mixed events; jets from signal events and tracks from MB events

Relative Yield Ratio Y_{corr}/Y_{uncorr}

$(Y_{corr}/Y_{uncorr})_{x_{J\gamma}=0.3-0.6}$ $(Y_{corr}/Y_{uncorr})_{x_{J\gamma}=0.6-0.8}$ $(Y_{corr}/Y_{uncorr})_{x_{J\gamma}=0.8-1.0}$

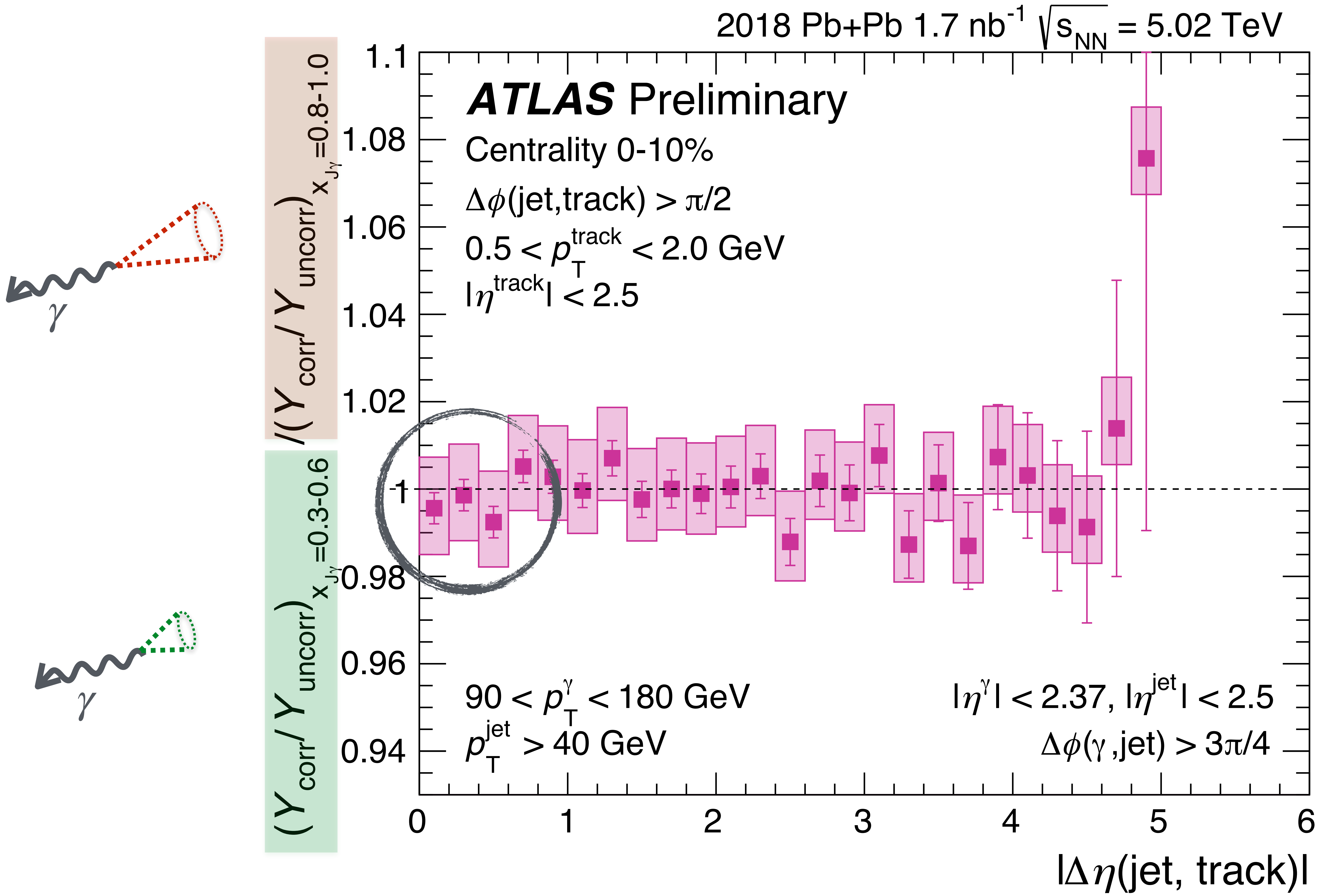


- No clear diffusion wake signal is found within uncertainties for all three $x_{J\gamma}$ regions

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

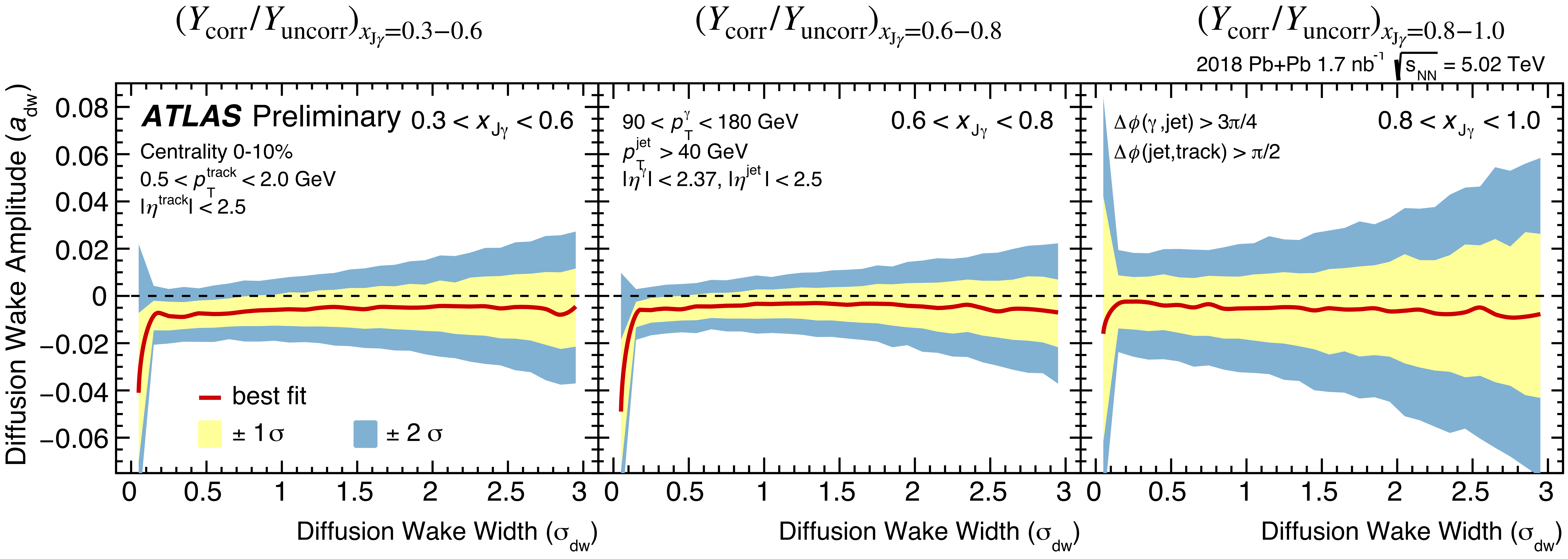
- Y_{corr}/Y_{uncorr}
  ➡ Relative yield ratio btw **signal** and **mixed** events

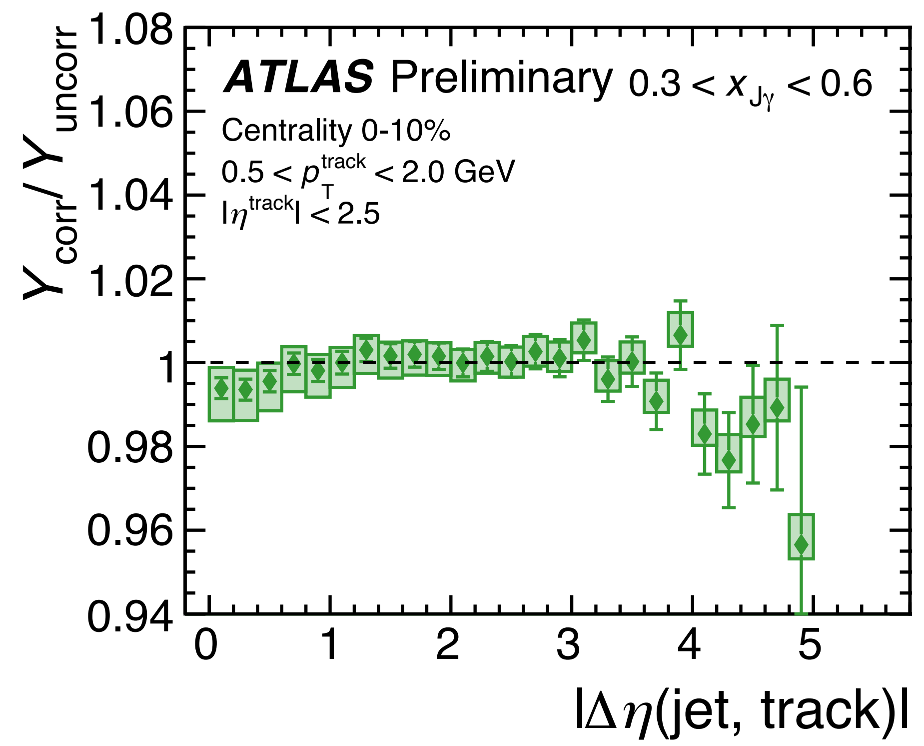
Double Ratio $(Y_{corr}/Y_{uncorr})_{x_{J\gamma}=0.3-0.6}/(Y_{corr}/Y_{uncorr})_{x_{J\gamma}=0.8-1.0}$



- No clear $x_{J\gamma}$ dependence found in the diffusion wake signal within uncertainties

Diffusion Wake Amplitude





- **Monte Carlo sampling method** is used to obtain probability distribution of diffusion wake amplitude, considering all statistical and systematic uncertainties and their correlations.
- *Statistical uncertainty dominates as systematic uncertainties are highly correlated bin-by-bin*
- All results are consistent with no signal, i.e., a_{dw}=0, within approximately 1σ

Diffusion Wake Amplitude Diffusion Wake Width

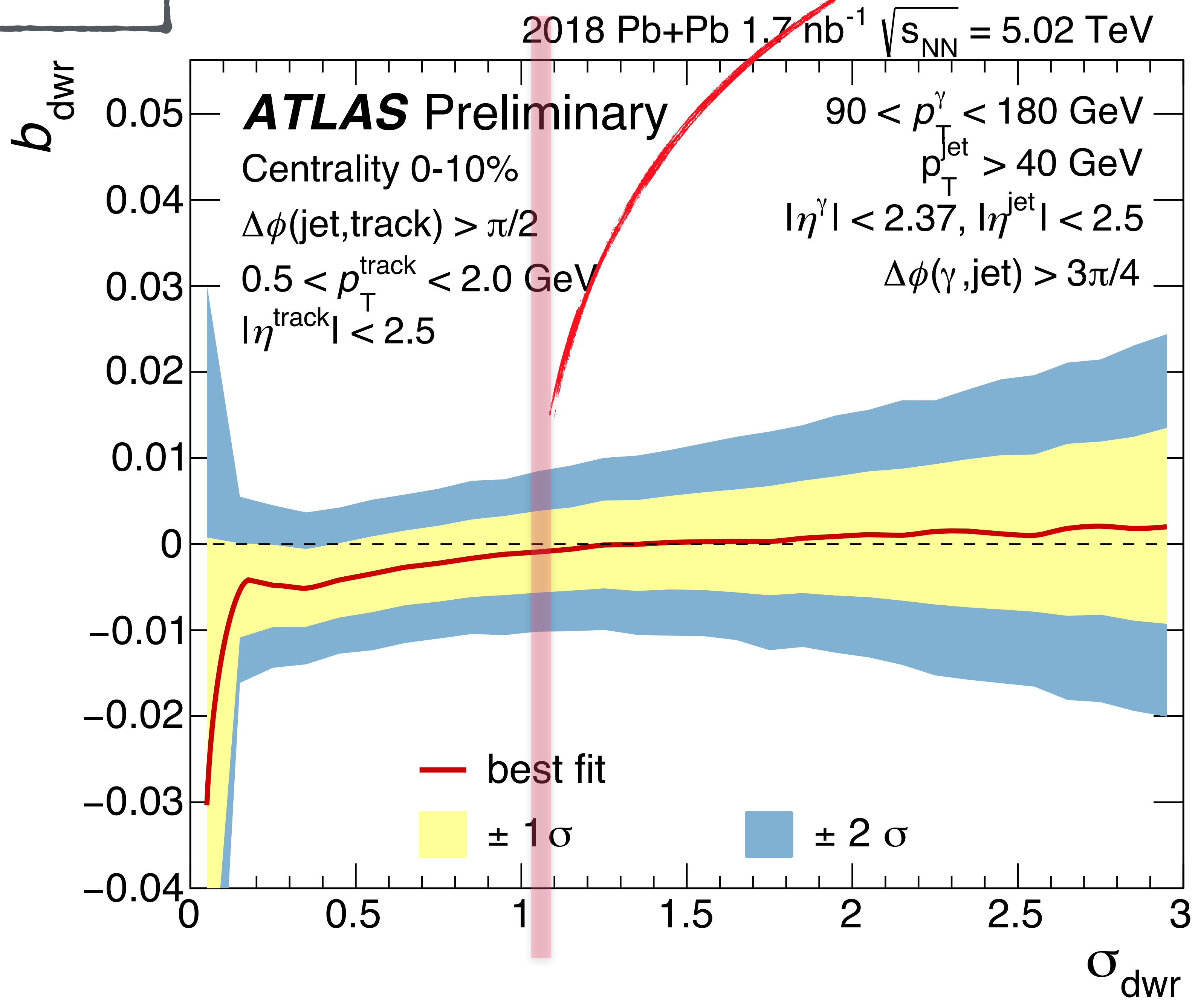
$$a_0 + a_{dw} \cdot e^{-|\Delta\eta(\text{jet,track})|^2/(2\sigma_{dw}^2)}$$

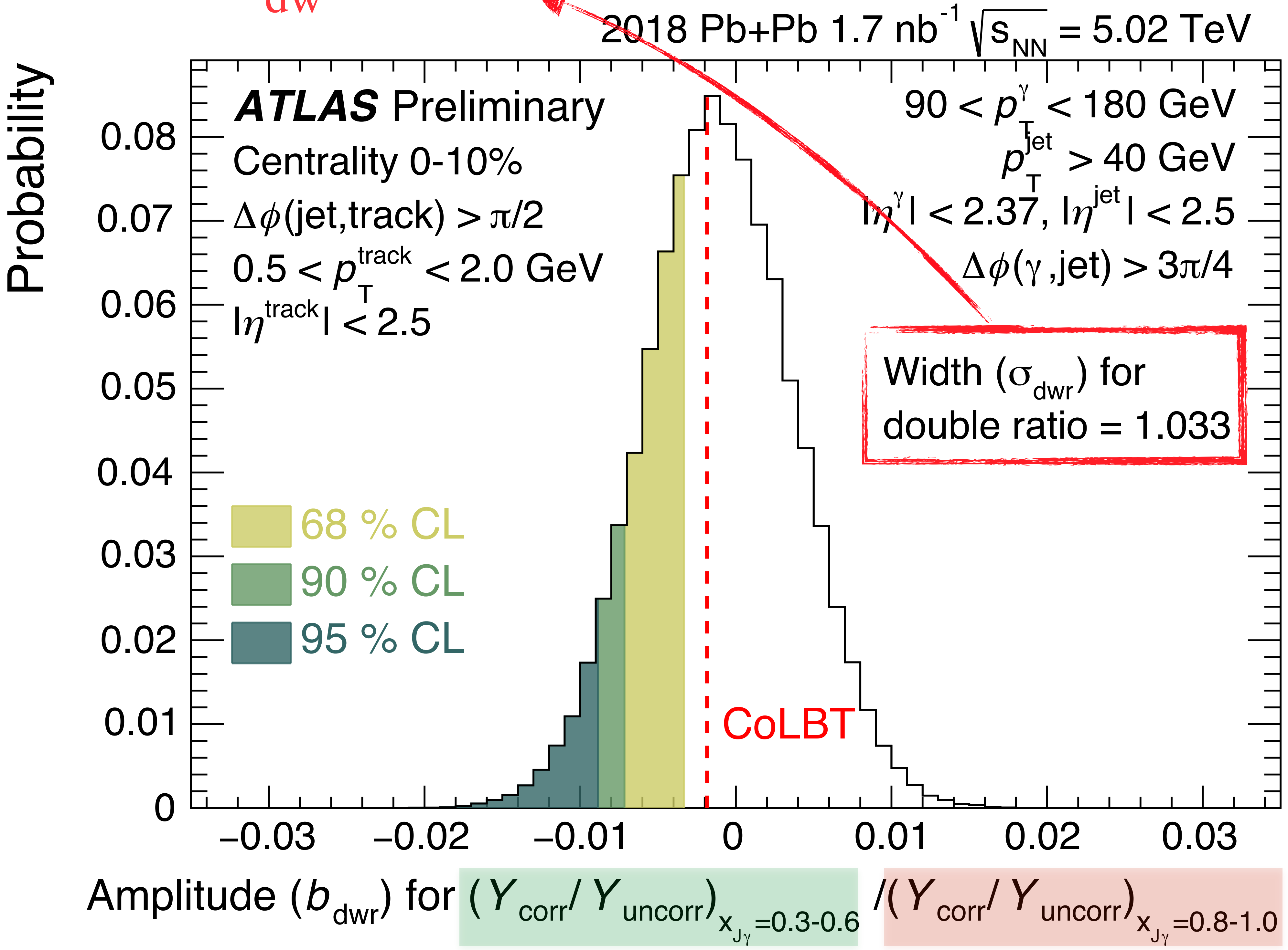
Diffusion Wake Double Ratio Amplitude

Double Ratio Amplitude   Double Ratio Width

$$b_0 + b_{\mathrm{dwr}} \cdot e^{-|\Delta\eta(\mathrm{jet,track})|^2/(2\sigma_{\mathrm{dwr}}^2)}$$

Prob. Dist. for width σ_{dw} = 1.033



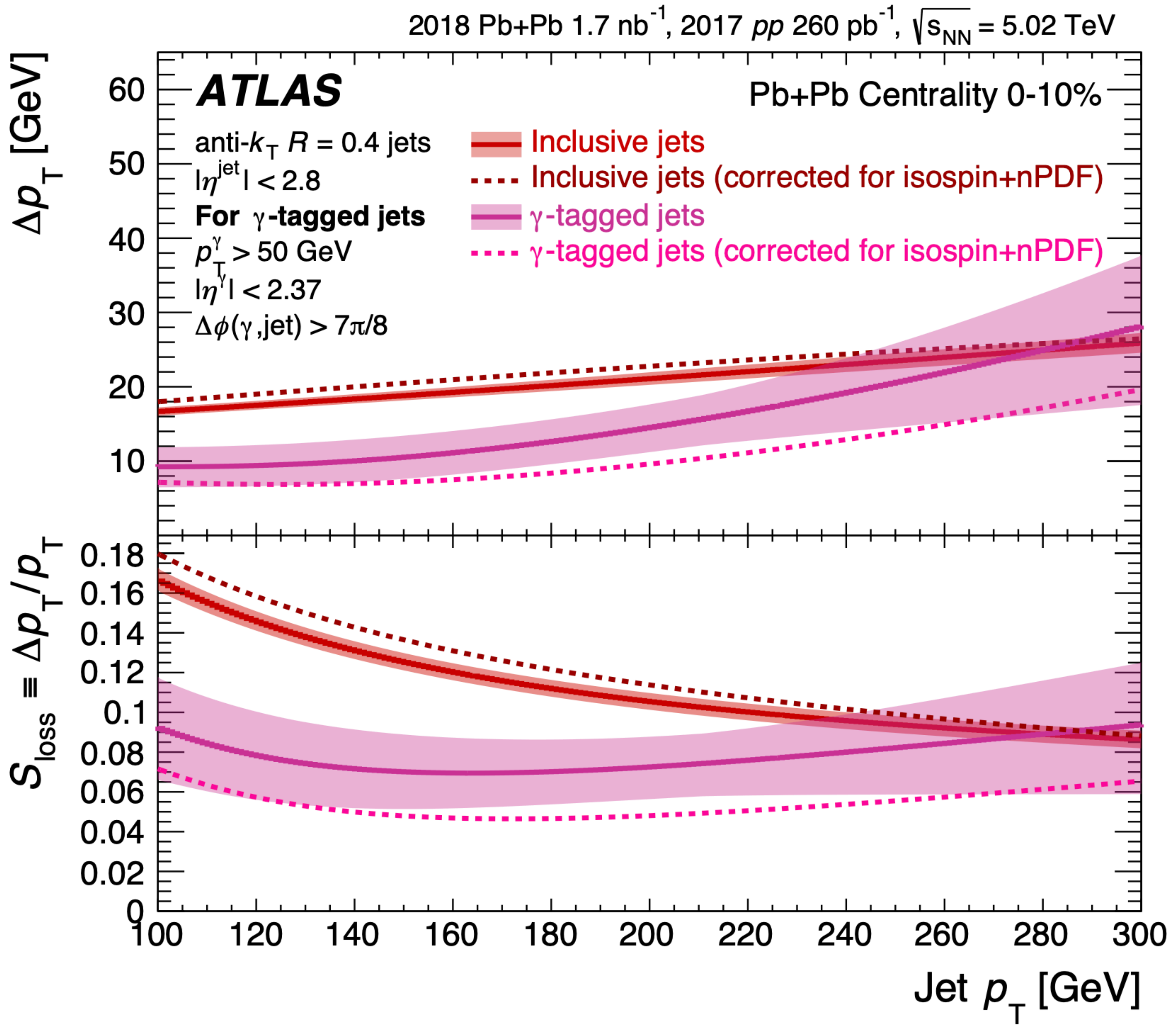


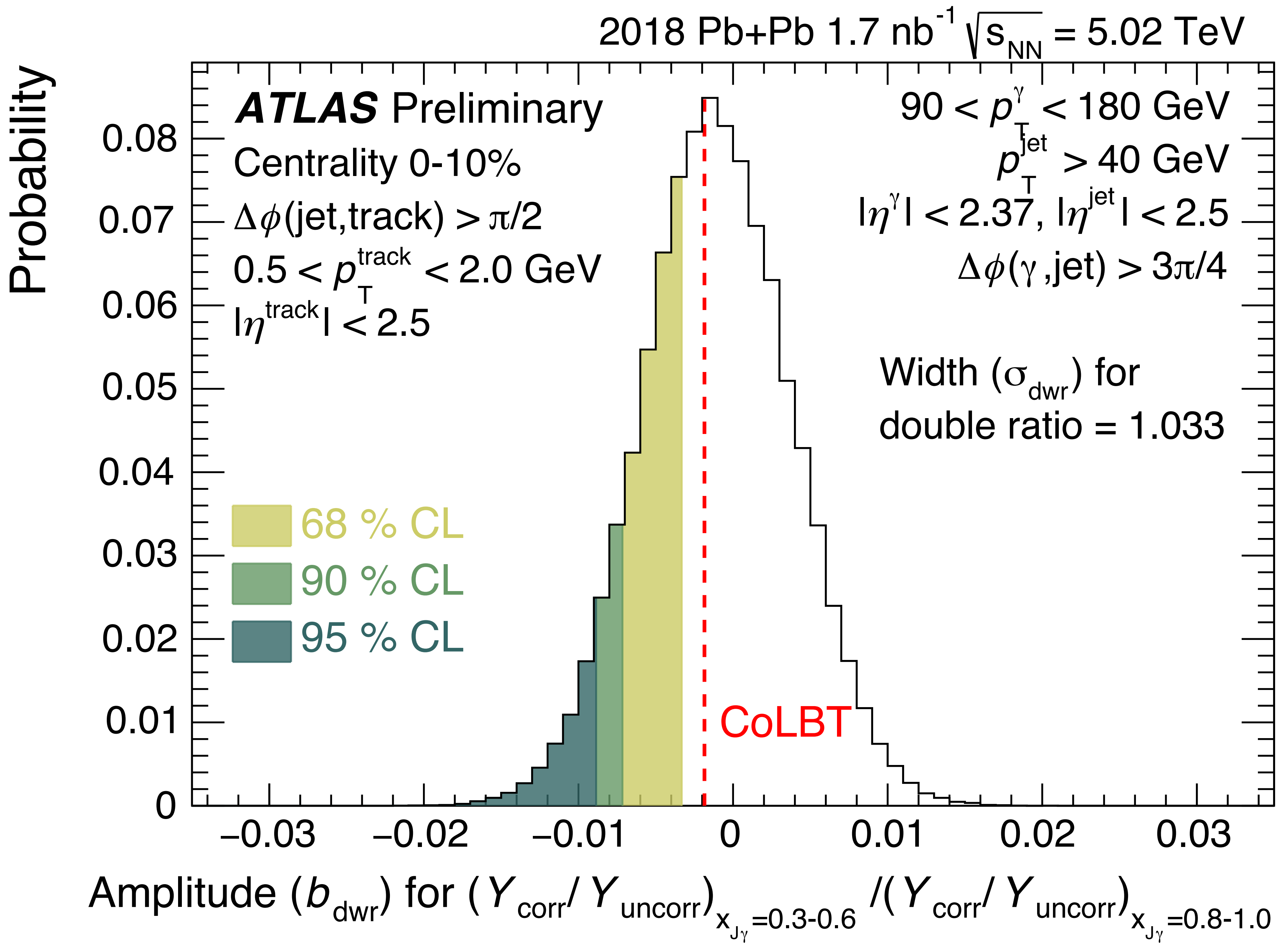
- Data indicates no significant diffusion wake signal that increases with larger parton energy loss

- Data provides limits on double ratio amplitude ($|b_{\mathrm{dwr}}|$)
  - ➡ **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

Summary

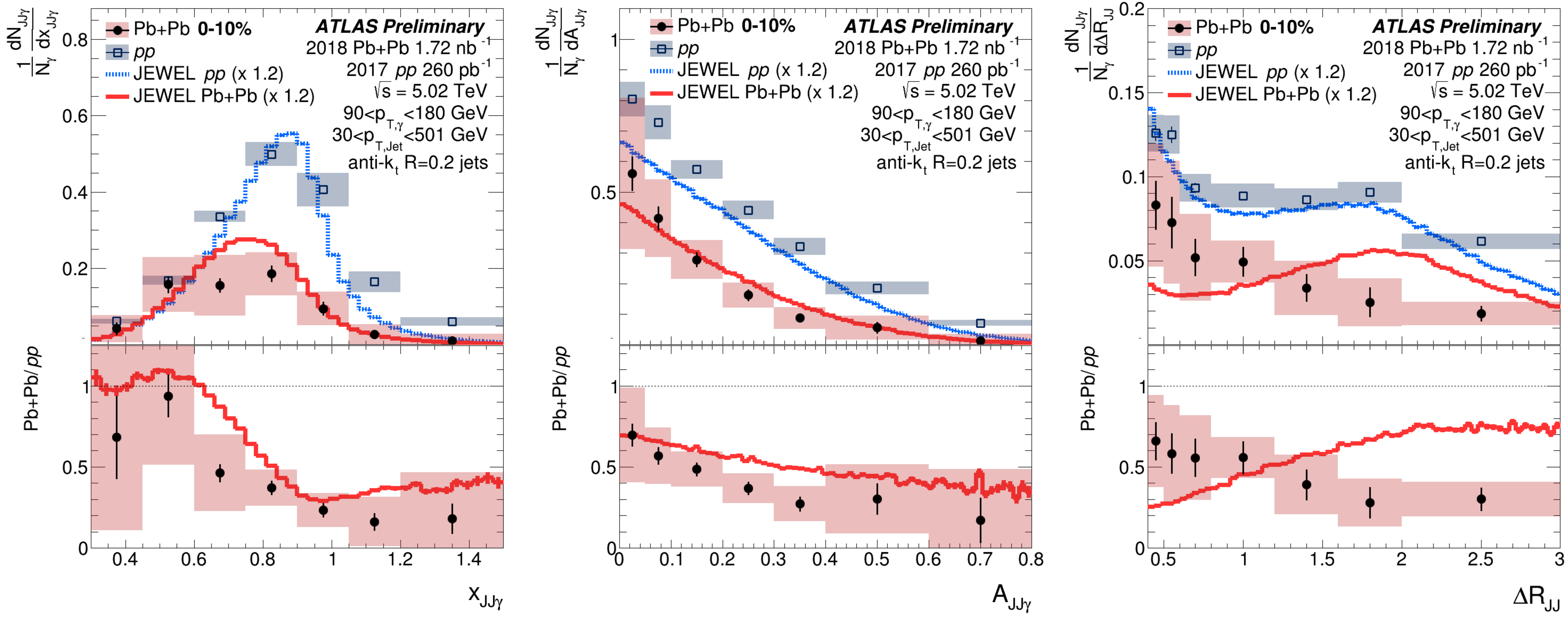
- The photon-tagged jet R_{AA} results provide the strongest confirmation to date of larger jet quenching for gluon-initiated jets compared with quark-initiated jets
- Jet-hadron correlations in photon-jet events provides unambiguous signal of medium response
  - ➡ no significant diffusion wake signal found within current data sensitivity; need for future larger datasets
  - ➡ data provides limits on diffusion wake amplitude





BACK UP

Photon+Multijets



ATLAS-CONF-2023-008

Isospin and nPDF effects

- To calculate this, one should use an updated formula:

$$R_{AA} = \left(Z^2\sigma_{pp}^{\mathrm{nPDF}} + 2Z(A-Z)\sigma_{pn}^{\mathrm{nPDF}} + (A-Z)^2\sigma_{nn}^{\mathrm{nPDF}}\right) \Big/ A^2\sigma_{pp}$$

- Where the nPDF denotes an event-by-event weighting $R_A(x_1, f_1, Q^2) \times R_A(x_2, f_2, Q^2)$
- Since the uncertainties are strongly correlated between $\sigma_{pp}^{\mathrm{nPDF}}$ and σ_{pp}, I instead evaluate this as:

$$R_{AA} = \left(\frac{Z}{A}\right)^2 \frac{\sigma_{pp}^{\mathrm{nPDF}}}{\sigma_{pp}} + \left(2Z(A-Z)\sigma_{pn}^{\mathrm{nPDF}} + (A-Z)^2\sigma_{nn}^{\mathrm{nPDF}}\right) \Big/ A^2\sigma_{pp}$$

- Where I assign zero statistical uncertainty to the first term, but treat the uncertainties in the terms in the second block as fully uncorrelated.