Jet quenching and medium response measurements using electroweak bosons

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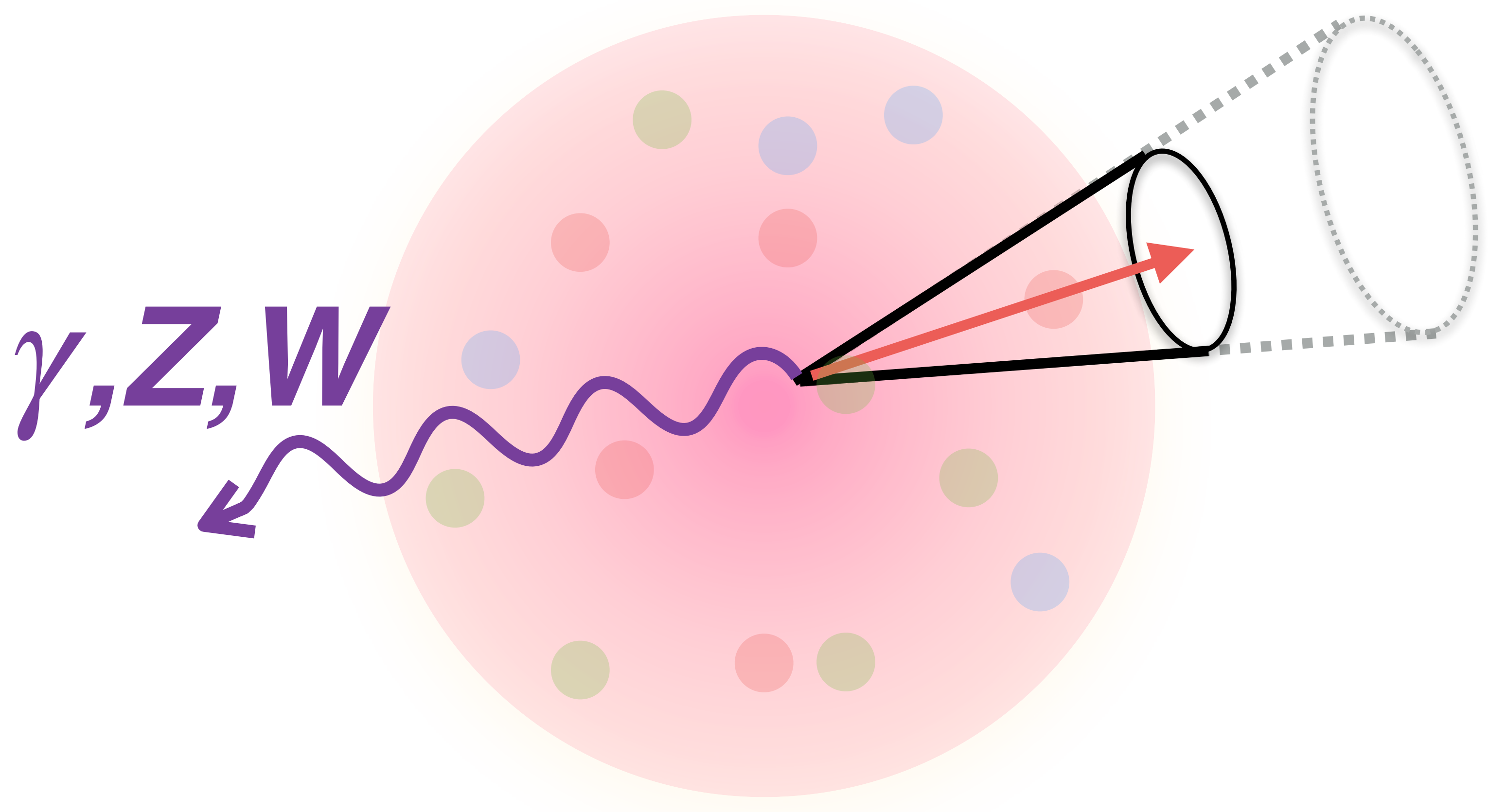
NEW JET QUENCHING TOOLS TO EXPLORE EQUILIBRIUM AND NON-EQUILIBRIUM DYNAMICS IN HEAVY-ION COLLISIONS

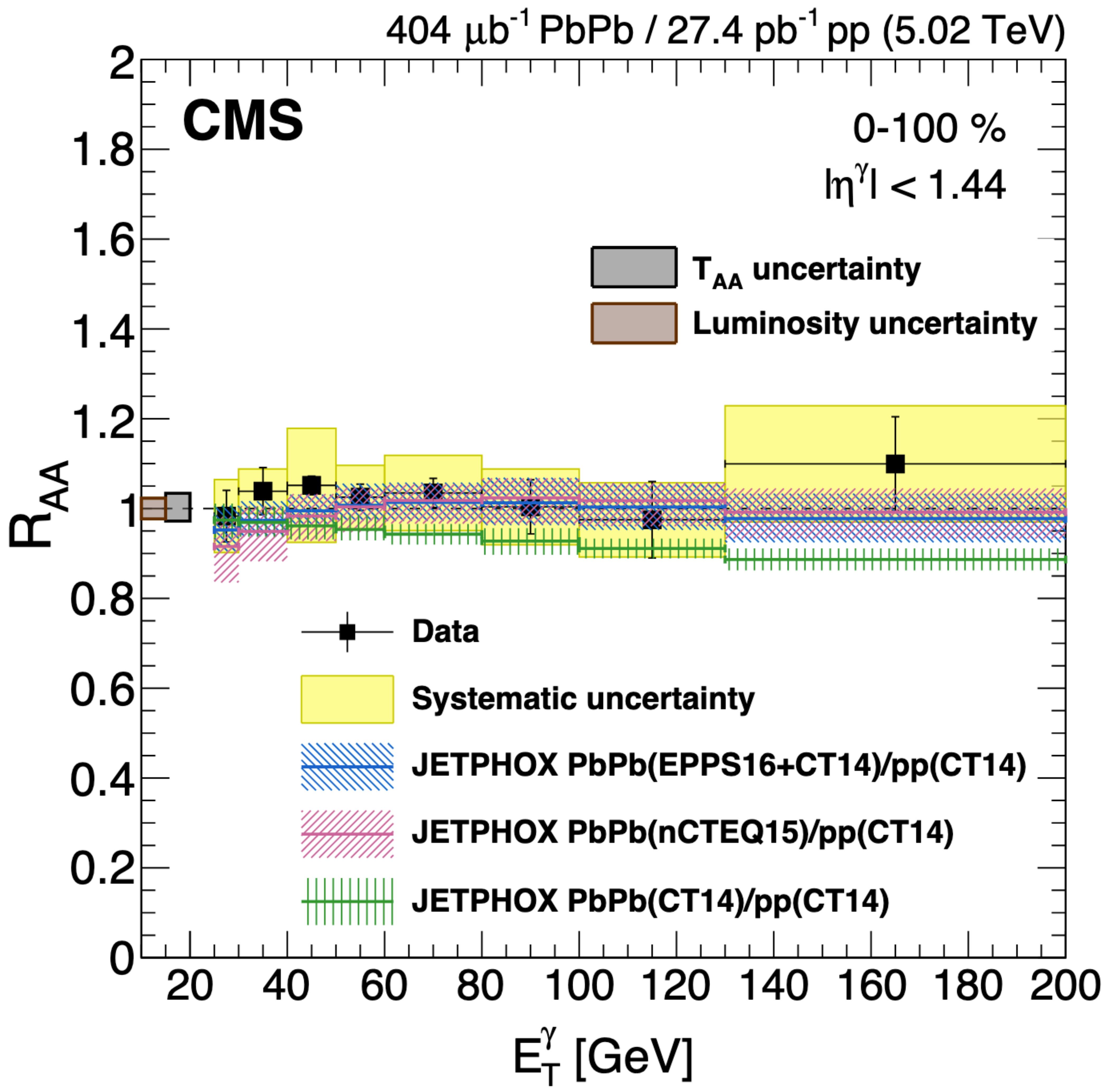
Electroweak bosons in heavy ion collisions

JHEP 07 (2020) 116

- Photons, Z, W bosons carry no color charge
  ➡ do not strongly interact with the QGP



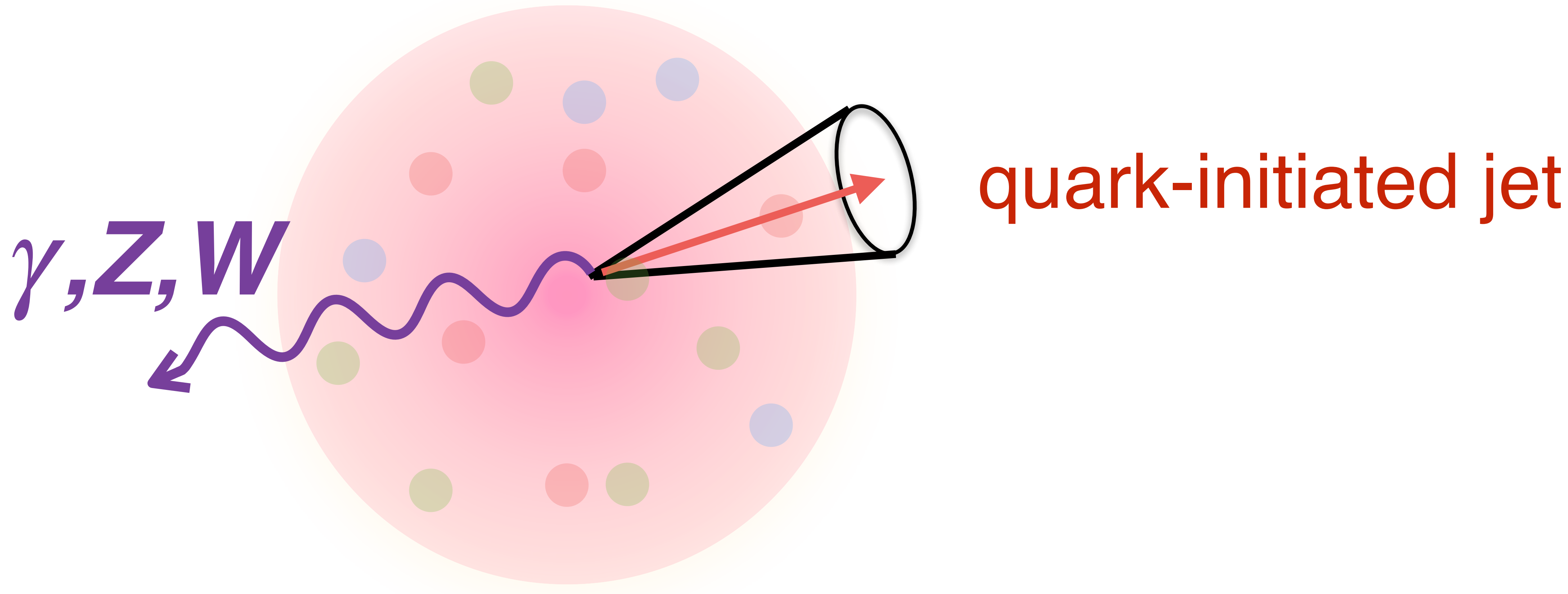
Electroweak bosons provide
initial, unmodified information of hard scattering



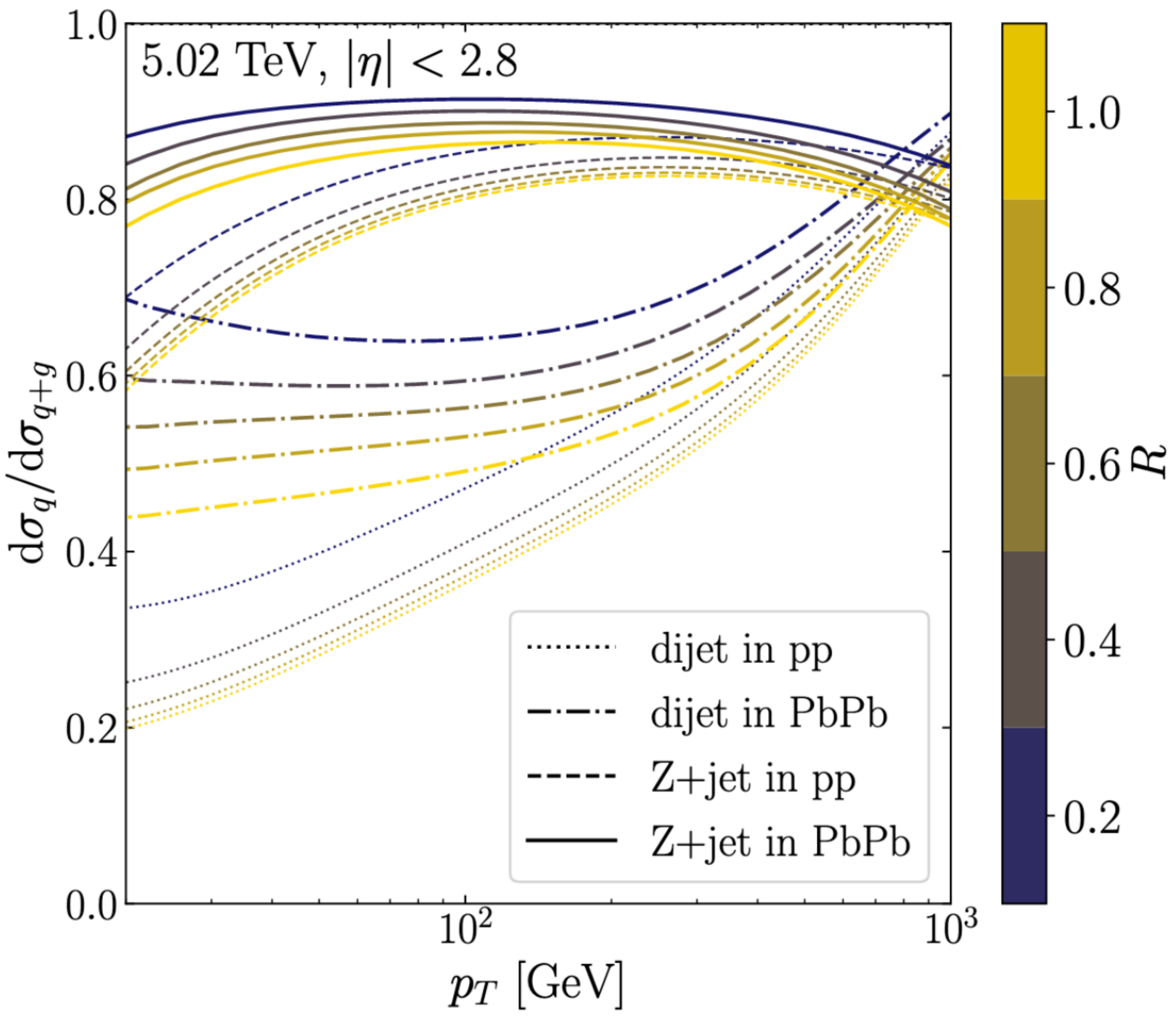
Electroweak bosons in heavy ion collisions

JHEP 10 (2021) 038

- Jets associated with electroweak bosons are primarily quark-initiated



Electroweak bosons allow us to study color-charge dependence of jet quenching



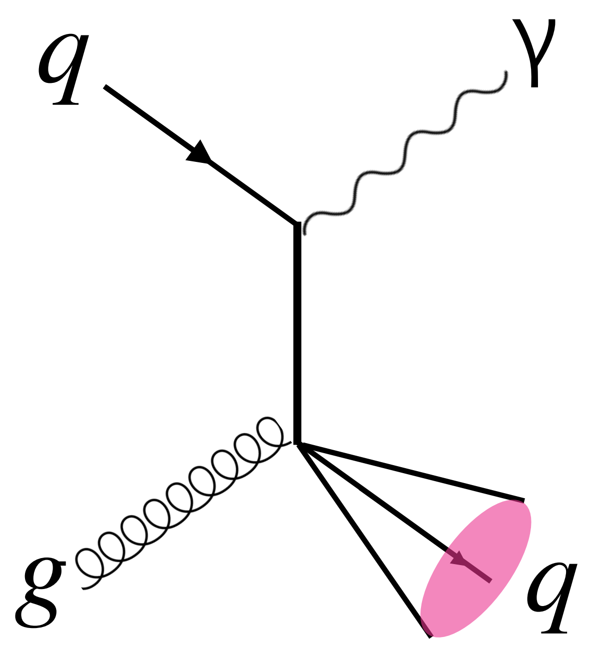
Color-charge-dependent Jet Quenching

- Comparing photon-tagged jet vs. Inclusive jet
  - ➡ quark- vs. gluon-initiated jets

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

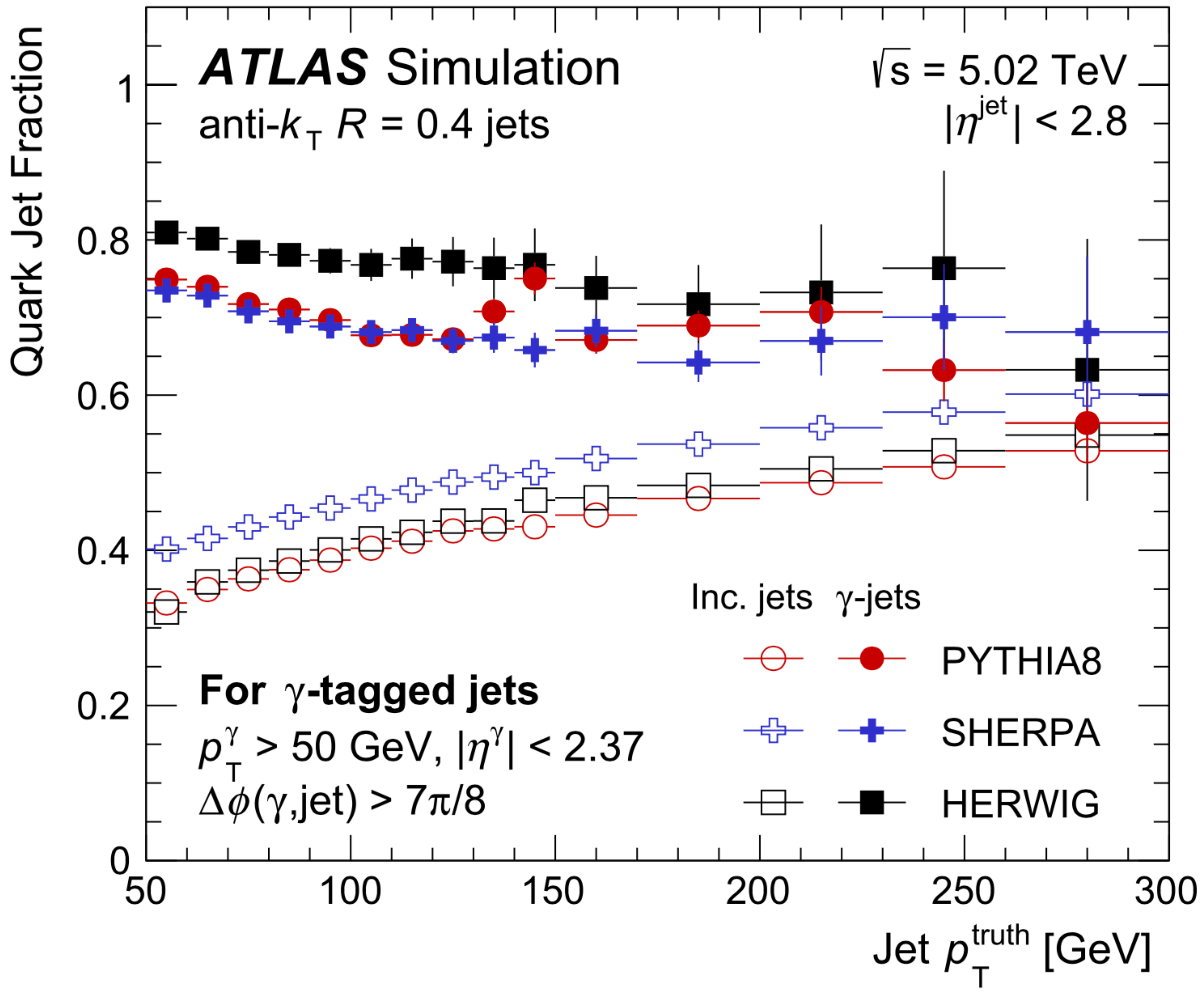
Casimir color factor
4/3 for quarks
3 for gluons

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



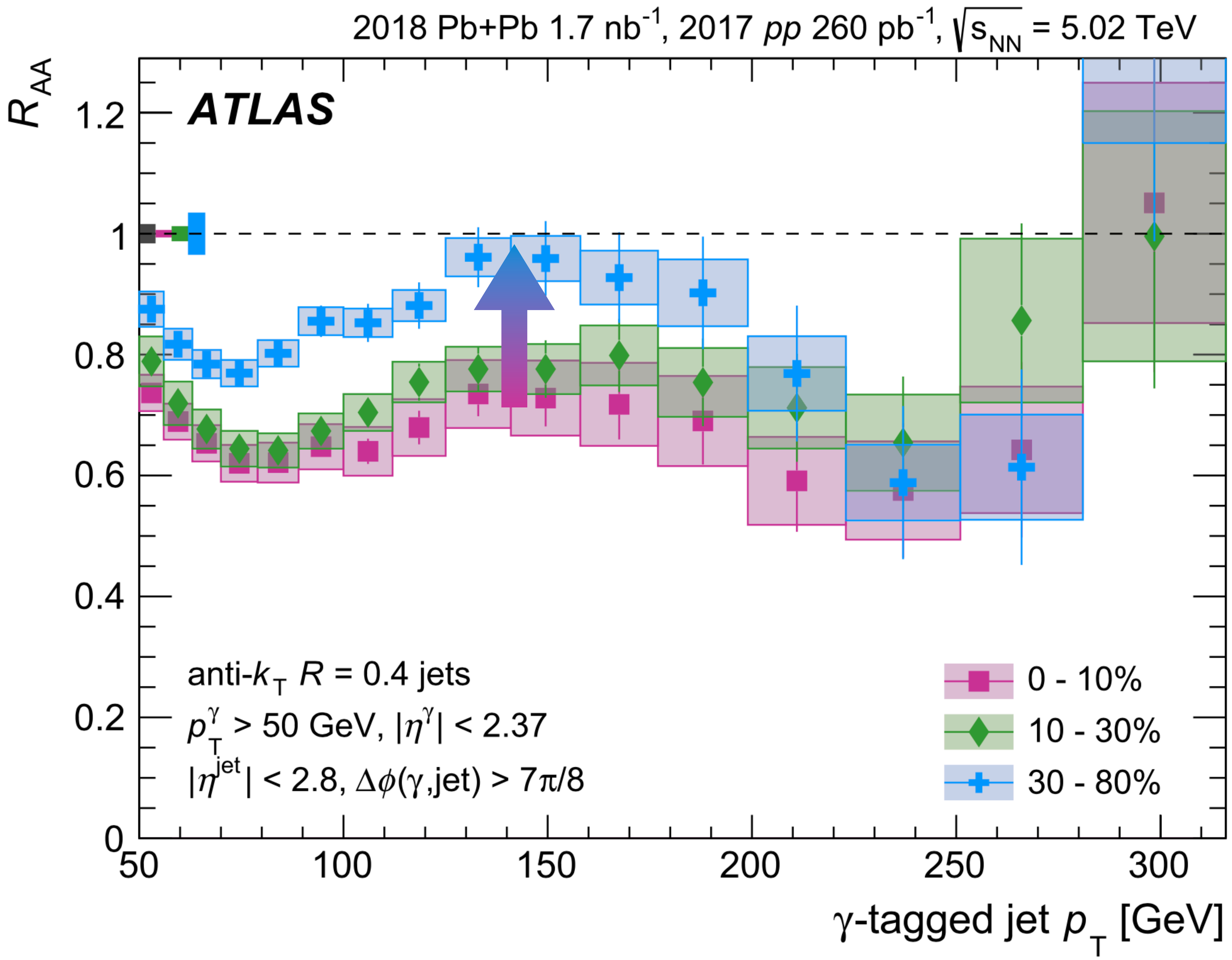
q-g Compton scattering

PLB 846 (2023) 138154



Does quark-initiated jets lose less energy than gluon-initiated jets in the medium?

γ-tagged Jet R_{AA}



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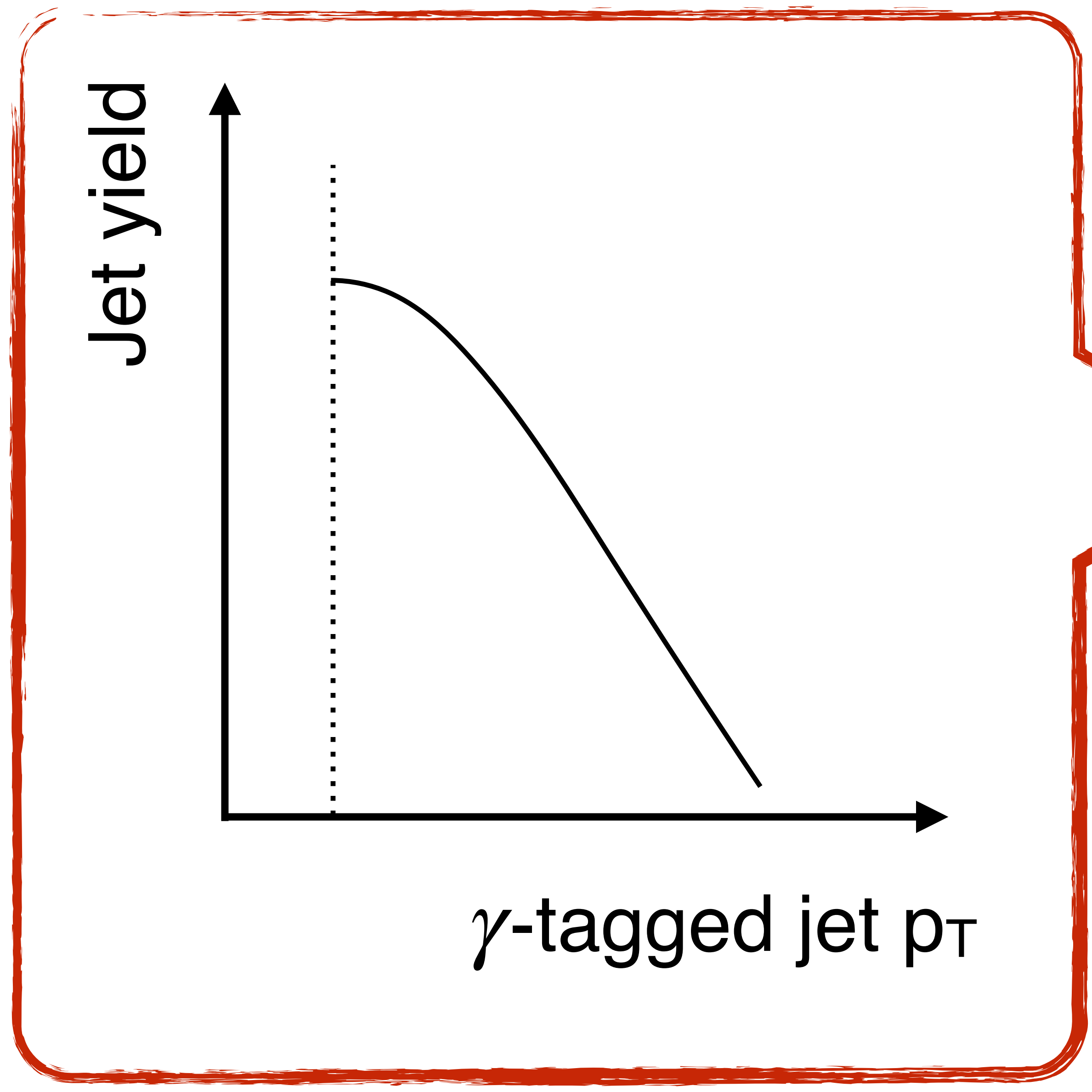
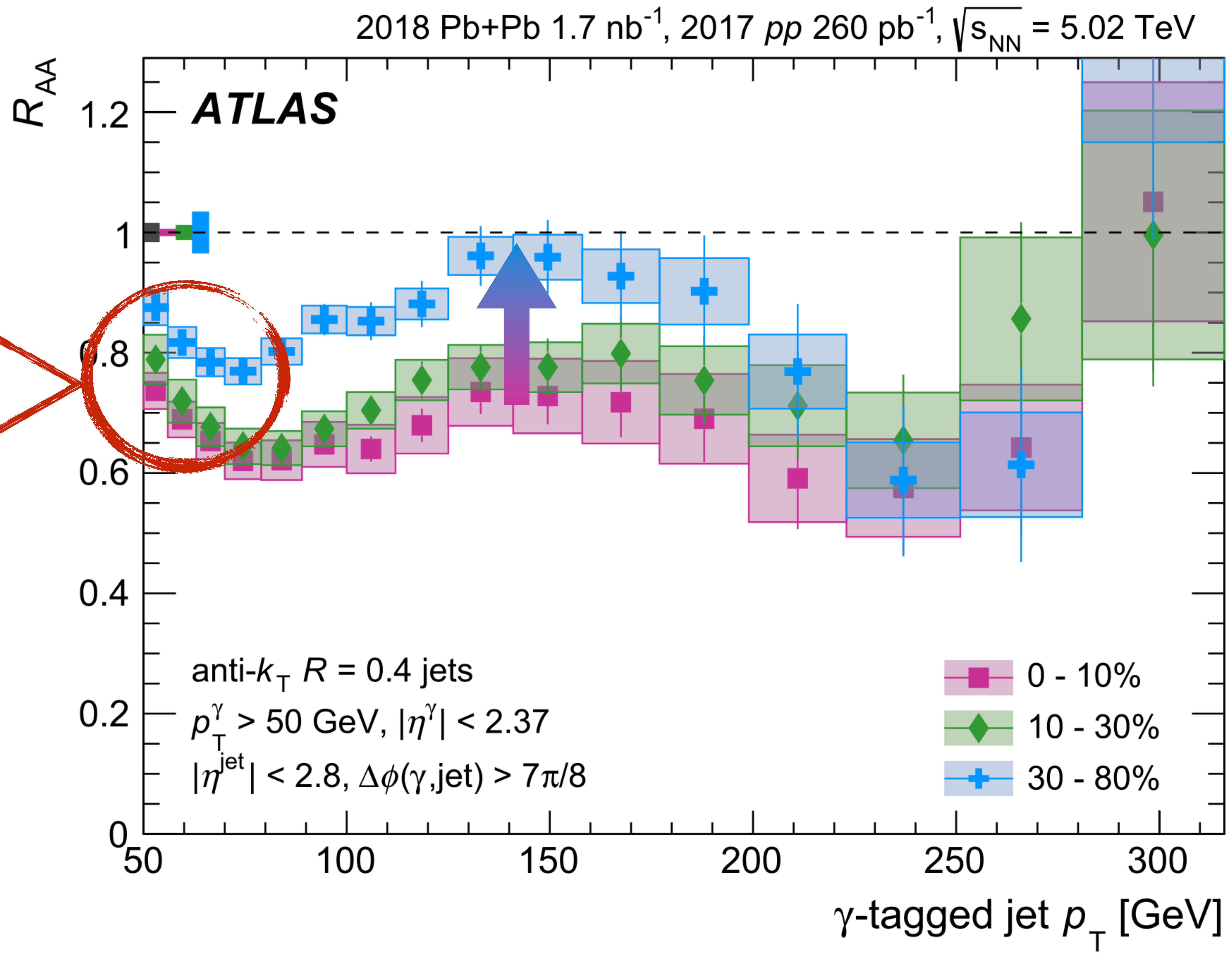
- Centrality ordering in R_{AA}
- For jet p_T < ~80 GeV, photon p_T > 50 GeV threshold effect

γ-tagged Jet R_{AA}





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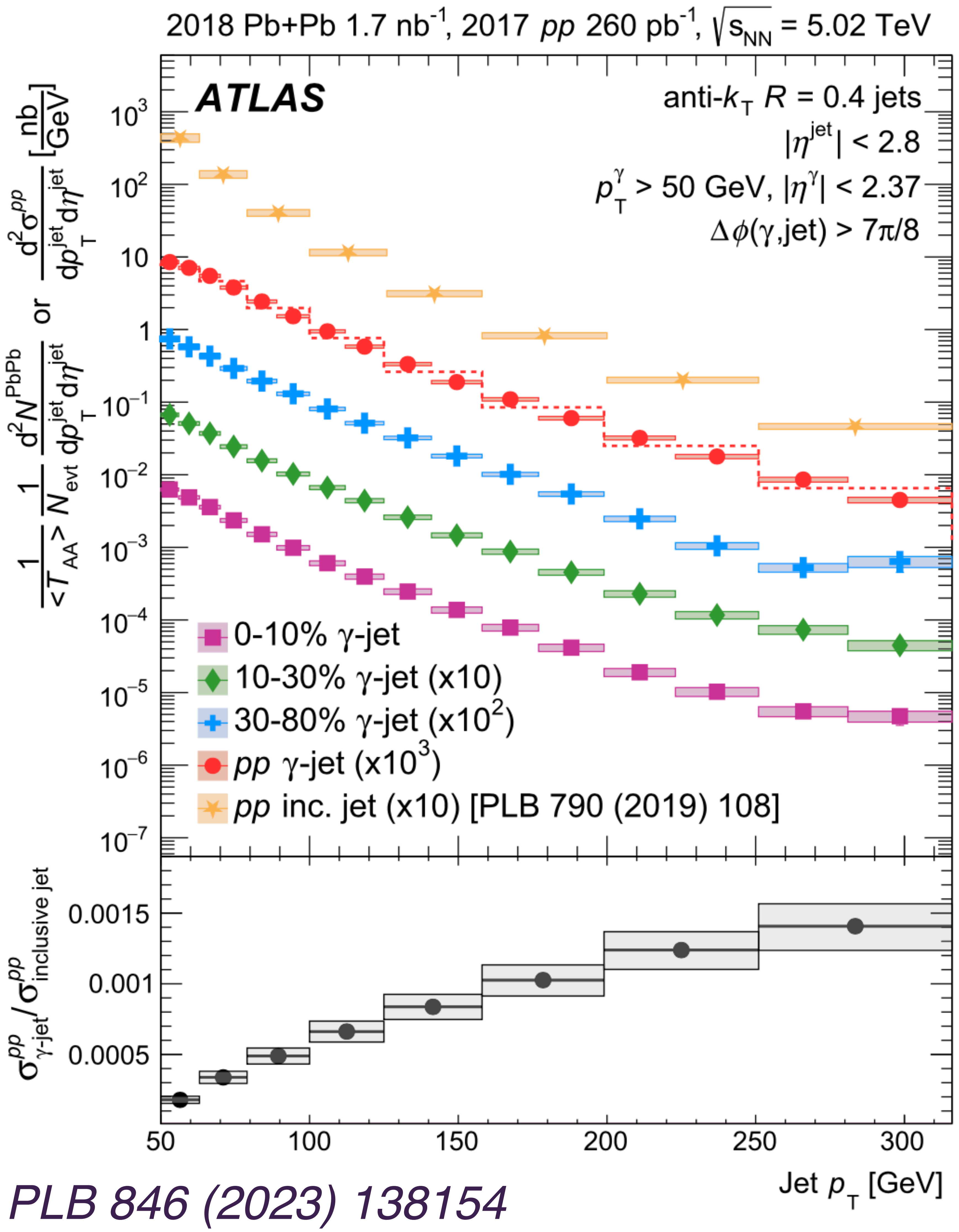
γ-jets vs. inclusive jets: p_T spectra in pp



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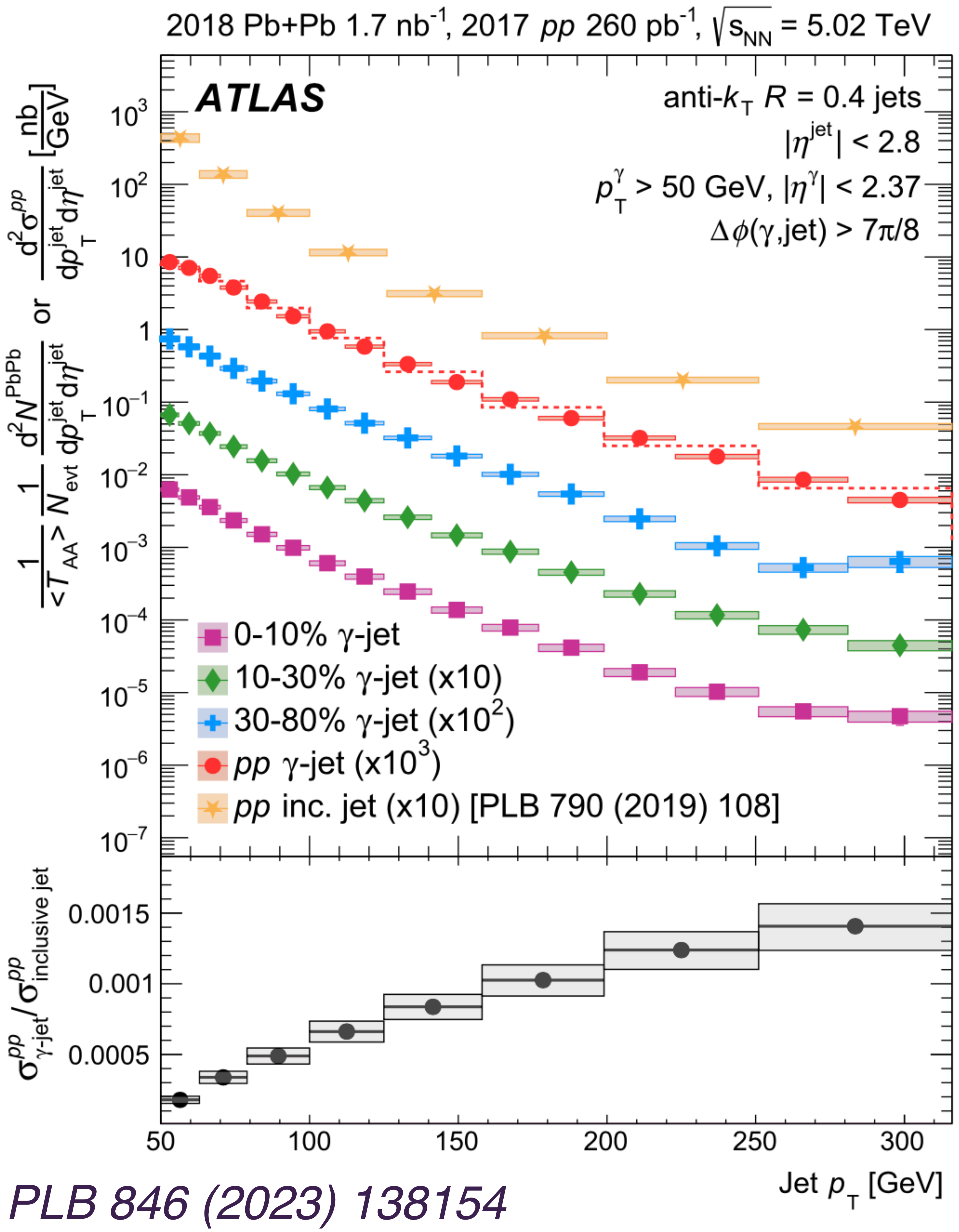
γ-jets vs. inclusive jets: p_T spectra in pp



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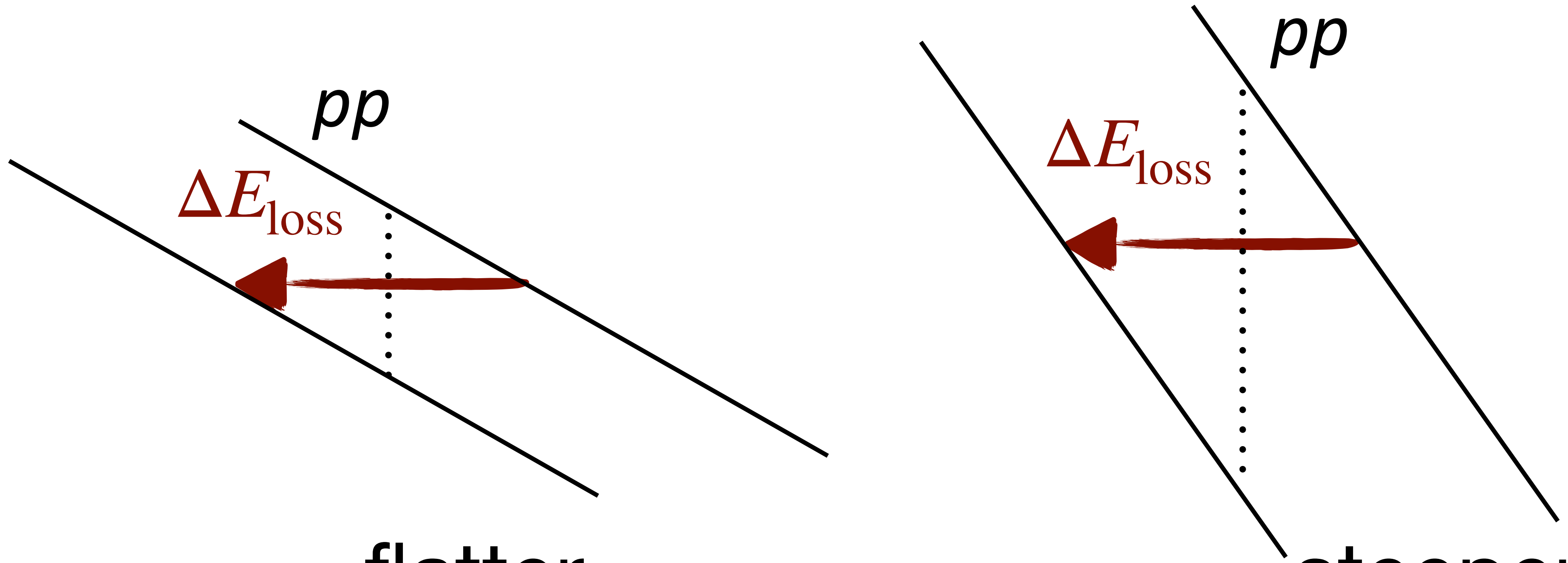
For the same amount of energy loss,



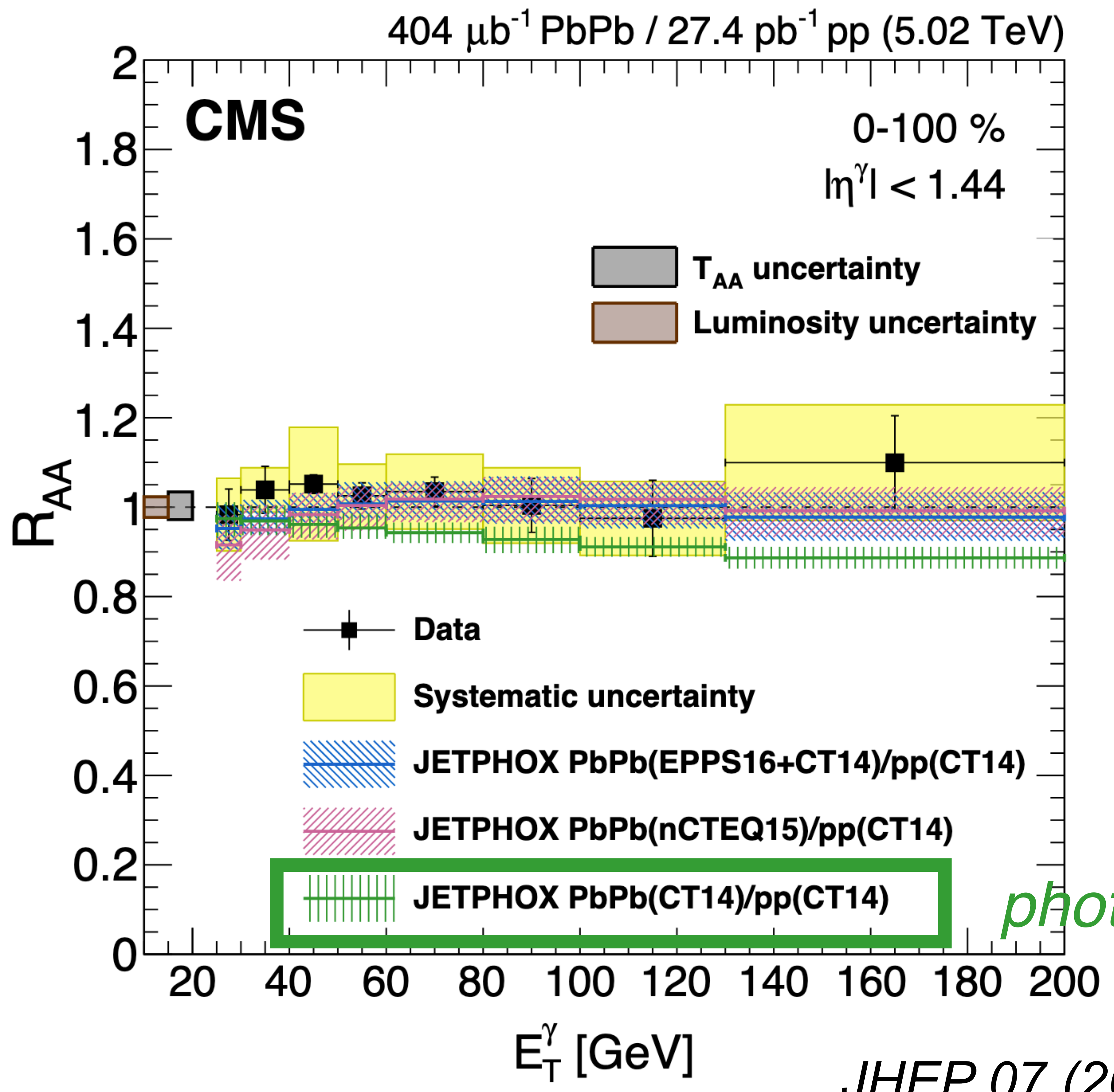
flatter
p_T distribution in *pp*
→ higher R_{AA}

steeper
p_T distribution in *pp*
→ lower R_{AA}

- 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 & nPDF effect

- **Isospin Effect**: effect from the different up- and down-quark composition of the nucleus compared to the proton



photon production rate decreases

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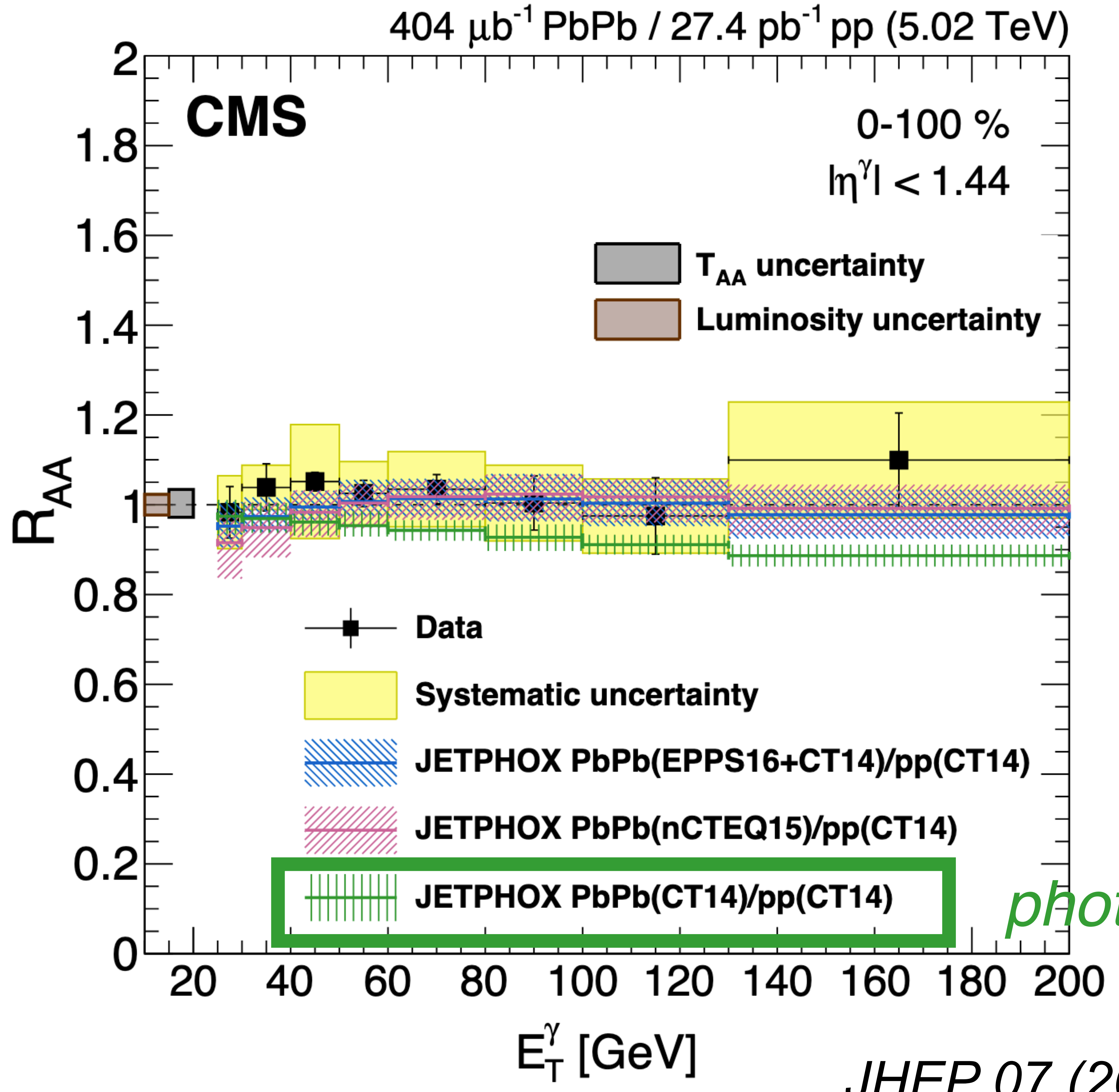
γ-jets vs. inclusive jets: Isospin & nPDF effect

- **Isospin Effect**: effect from the different up- and down-quark composition of the nucleus compared to the proton

- **Nuclear Parton Distribution Functions (nPDFs)**: modification of PDFs of nucleons inside nuclei compared to free proton PDFs



photon production rate decreases

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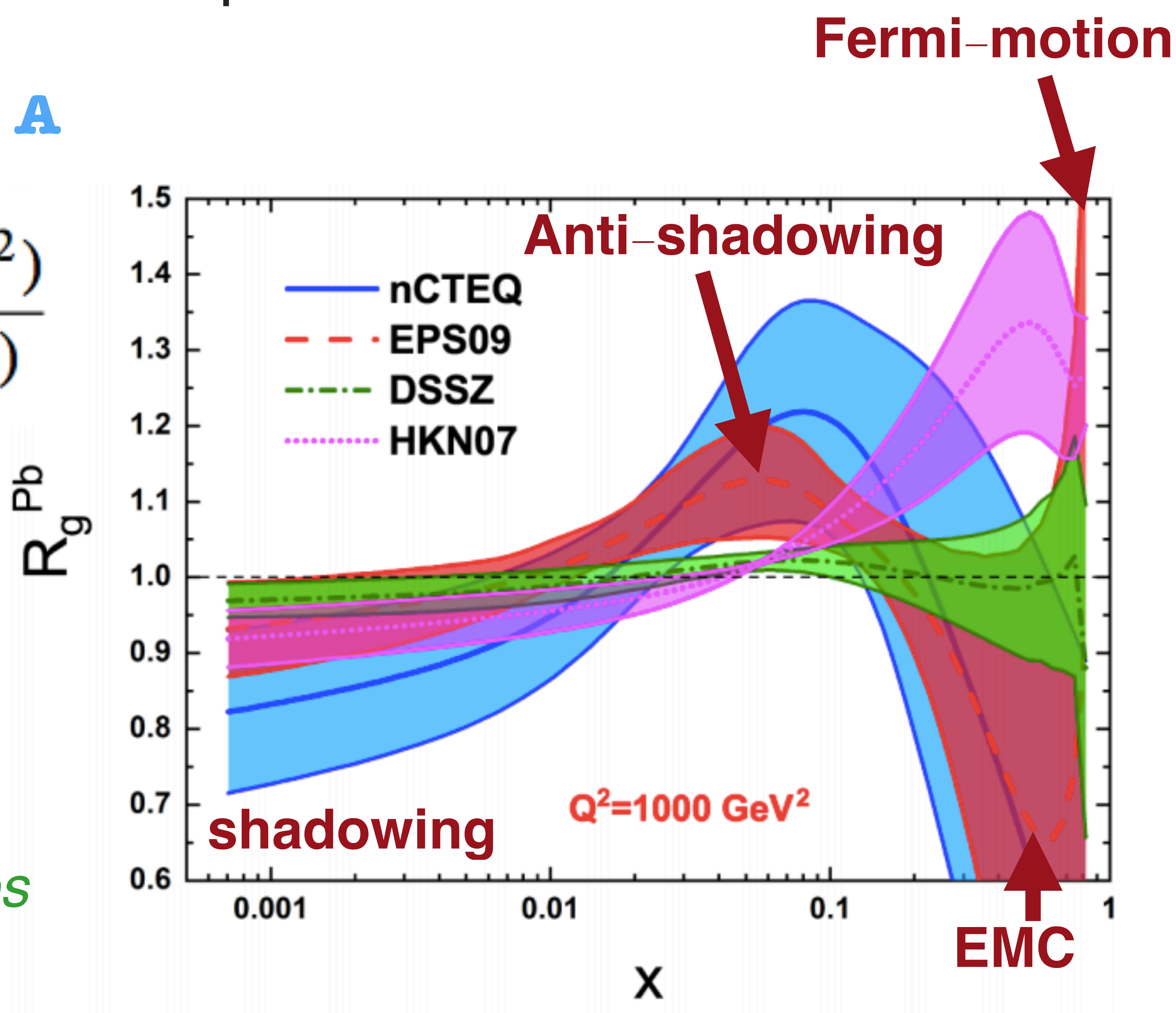
proton PDF in nucleus A

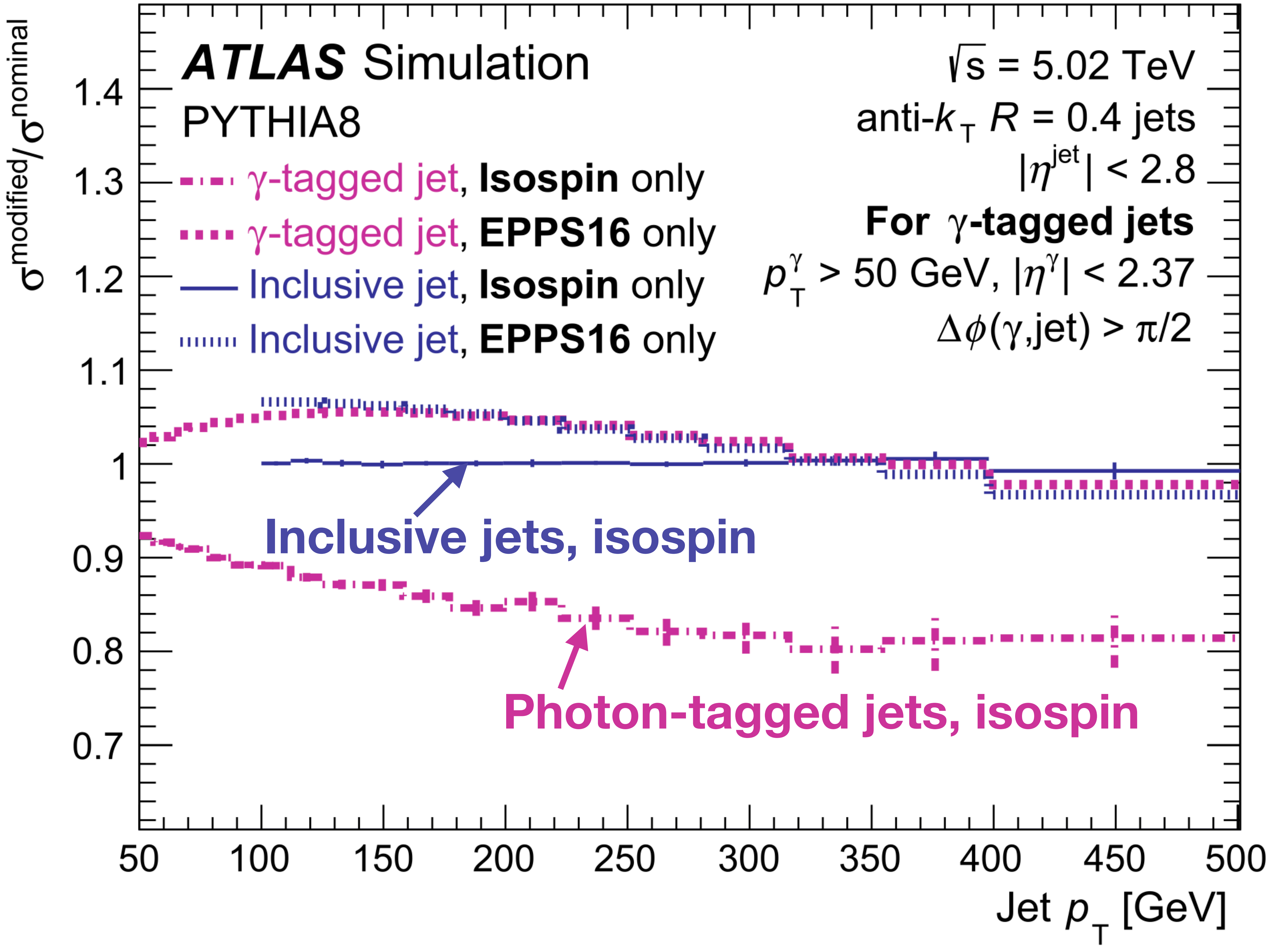
$$R_i^A(x, Q^2) \equiv \frac{f_i^{p/A}(x, Q^2)}{f_i^p(x, Q^2)}$$

free proton PDF



PRC 99 (2019) 055206

γ-jets vs. inclusive jets: Isospin effect



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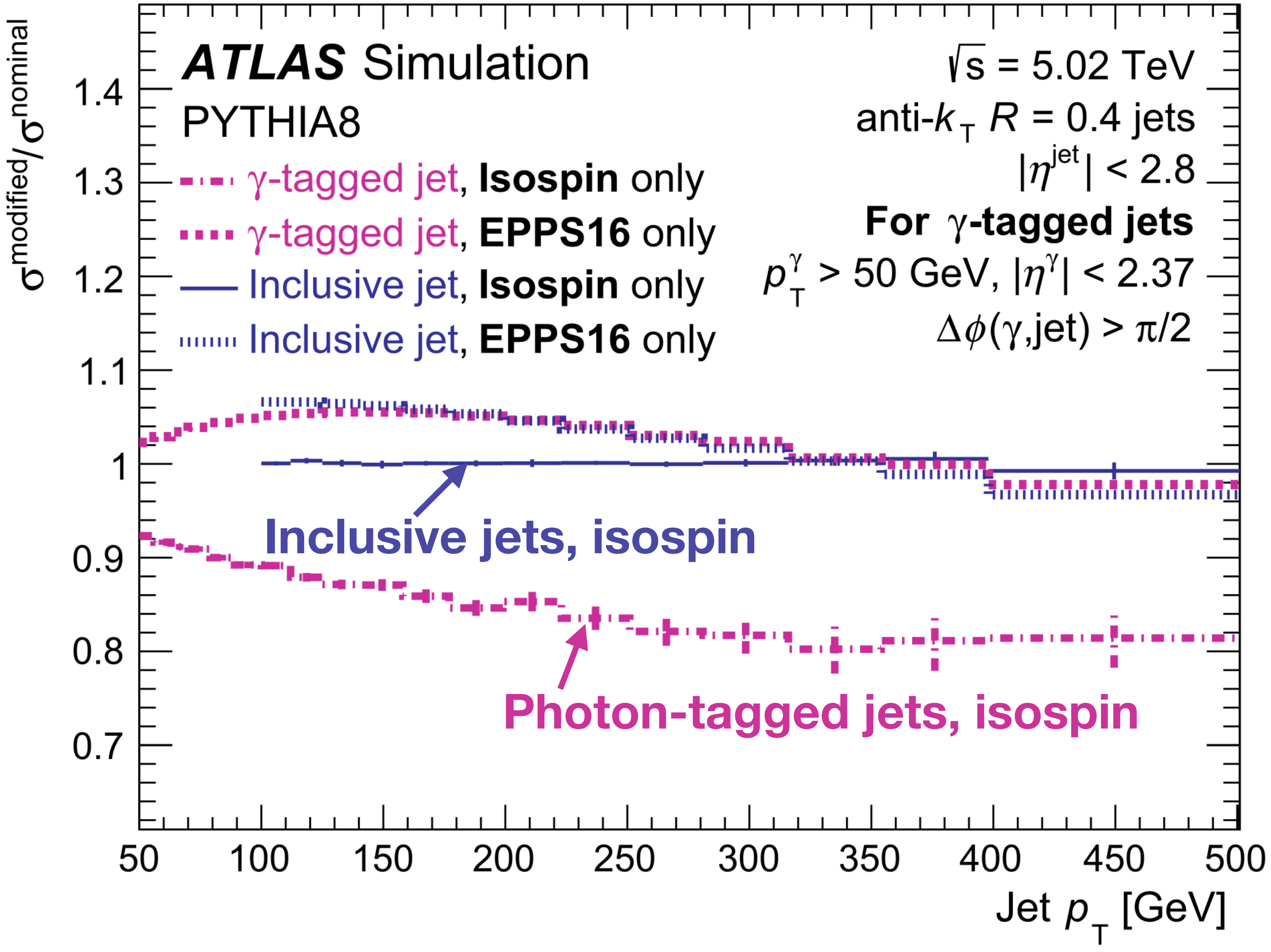
- nPDF only effect; event-by-event weighting

$$\sigma^{\text{modified}}/\sigma^{\text{nominal}} = \left(\sigma_{pp} \times R_A(x_1, f_1, Q^2) \times R_A(x_2, f_2, Q^2)\right)/\sigma_{pp}$$

➡ The nPDF (EPPS16) effect is similar for both photon-tagged jets and inclusive jets

γ-jets vs. inclusive jets: Isospin effect



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- Isospin only effect; *Z protons and (A-Z) neutrons*

$$\sigma^{\text{modified}}/\sigma^{\text{nominal}} = \left(Z^2\sigma_{pp} + 2Z(A-Z)\sigma_{pn} + (A-Z)^2\sigma_{nn}\right)/A^2\sigma_{pp}$$

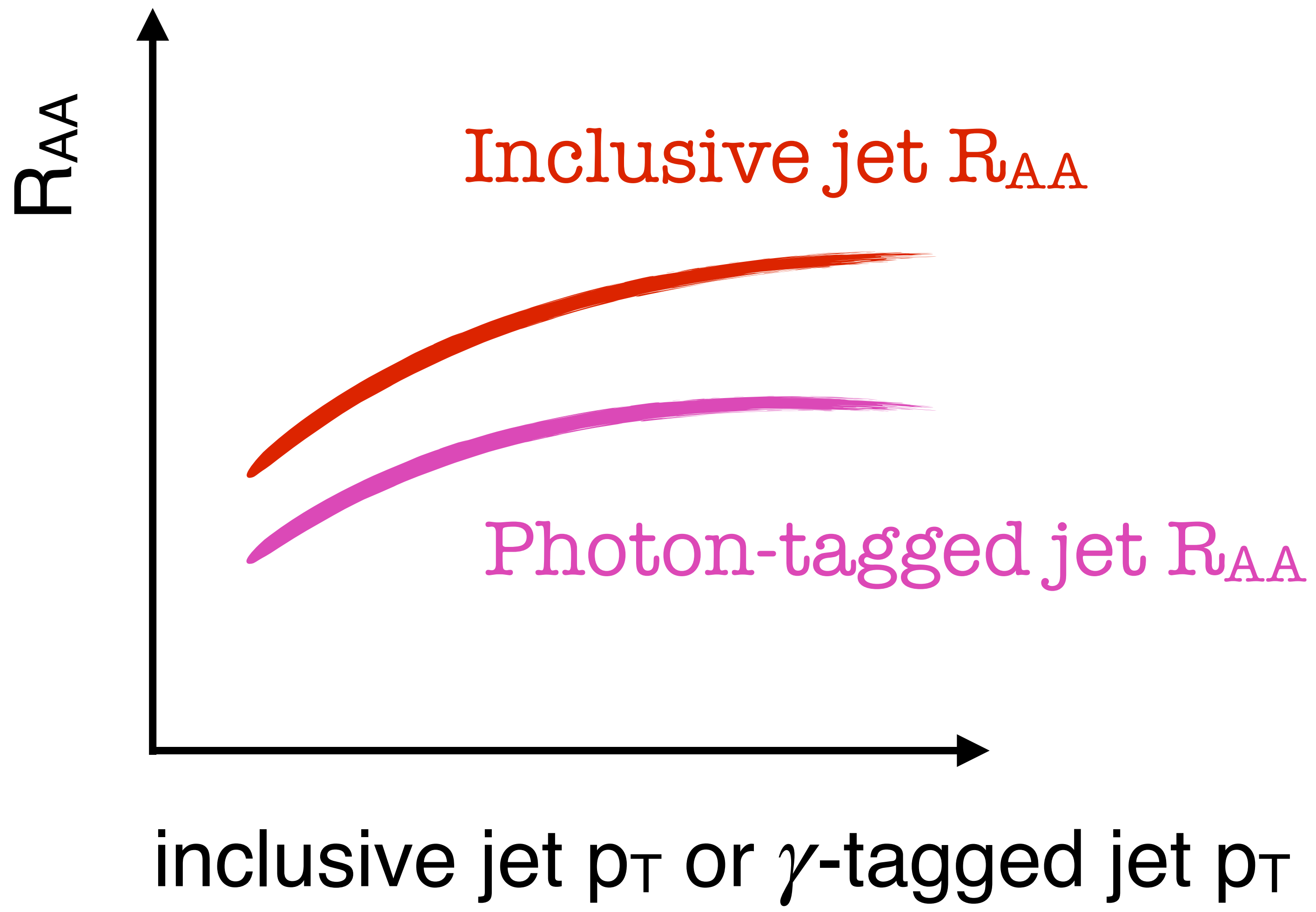
➡ The isospin effect reduces the production rate of photon-tagged jets in Pb+Pb collisions, while the production rate of inclusive jets remains unaffected.

γ-jets vs. inclusive jets: Other Effects

- In summary, the other effects besides the difference in energy loss:
  - ➡ the p_T spectrum in pp effect increases photon-tagged jets R_{AA} by ~5-10% ⬆
  - ➡ the isospin effect decreases photon-tagged jets R_{AA} by ~10-20% ⬇

*Assuming the **same amount of energy loss** (but w/ different isospin + p_T spectrum effects) btw the inclusive jets vs γ-tagged jets*

*The combined effects (excluding the energy loss) **decrease** photon-tagged jet R_{AA} (by ~5-10%)*



γ-jets vs. inclusive jets R_{AA}: q/g Energy Loss

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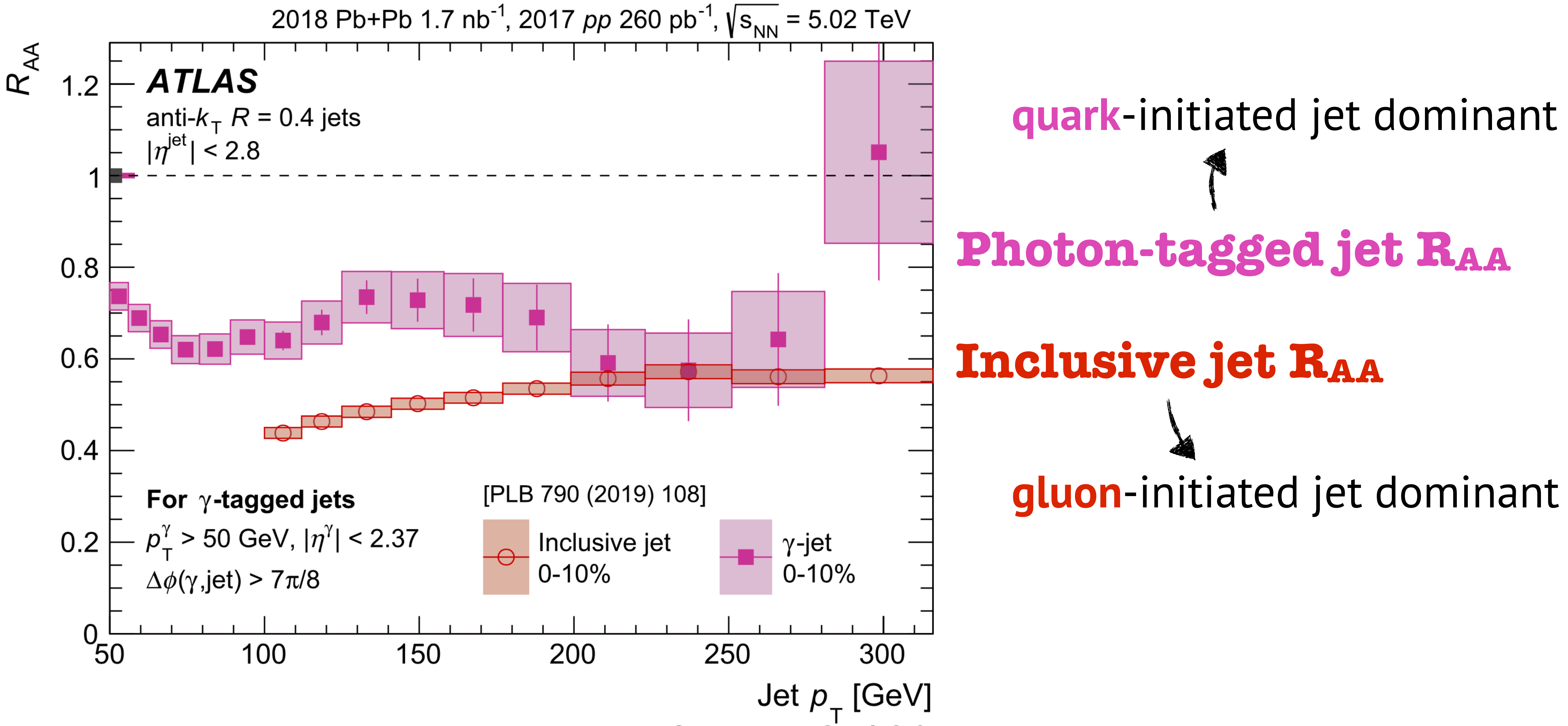
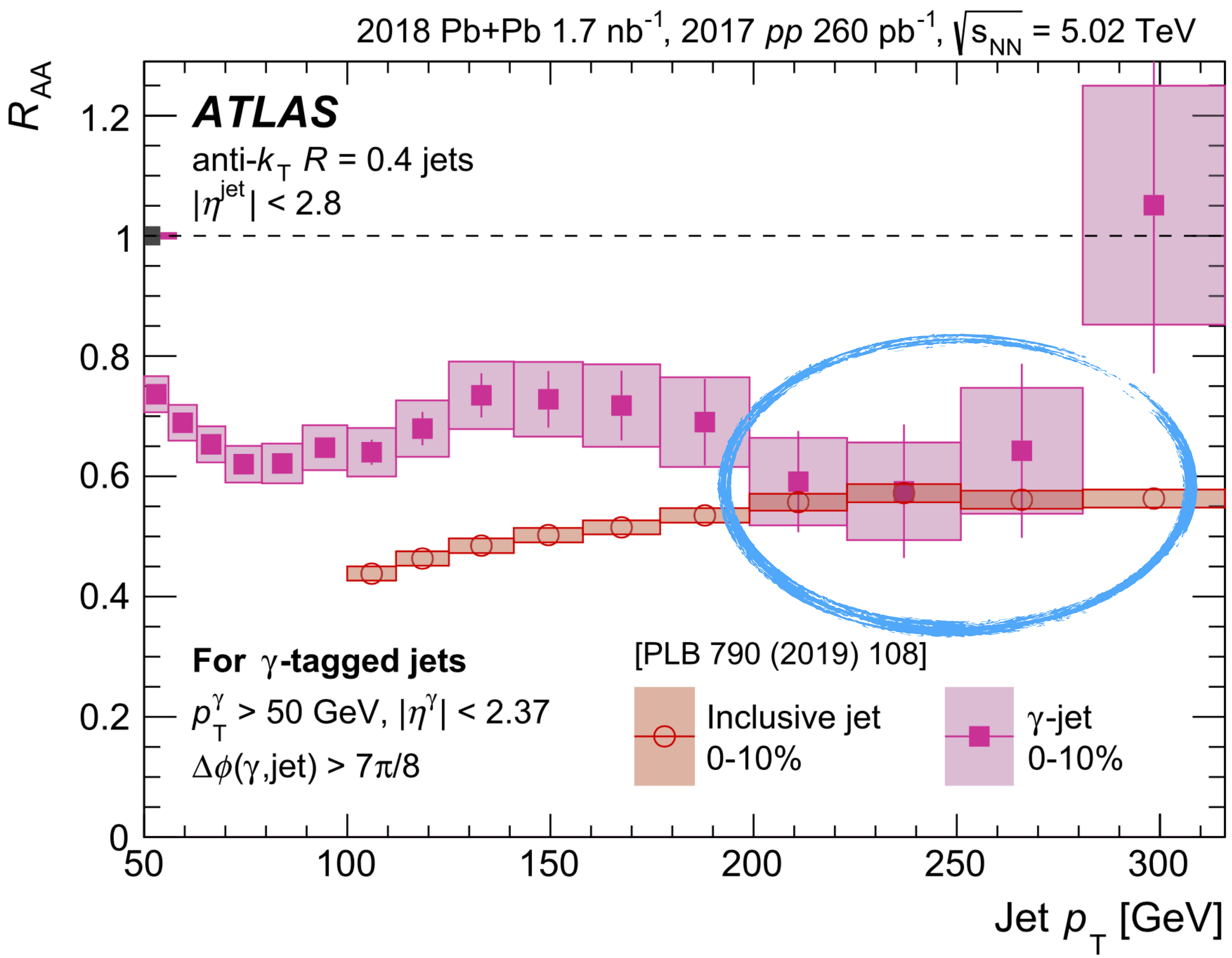


- Comparison in R_{AA} between γ-jets and inclusive jets for the 0-10% centrality bin
- For p_T < ~200 GeV, R_{AA} (γ-jets) > R_{AA} (inclusive jets)
  ➡ indicates that quark-initiated jets lose less energy than gluon-initiated jets

γ-jets vs. inclusive jets R_{AA}: q/g Energy Loss



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

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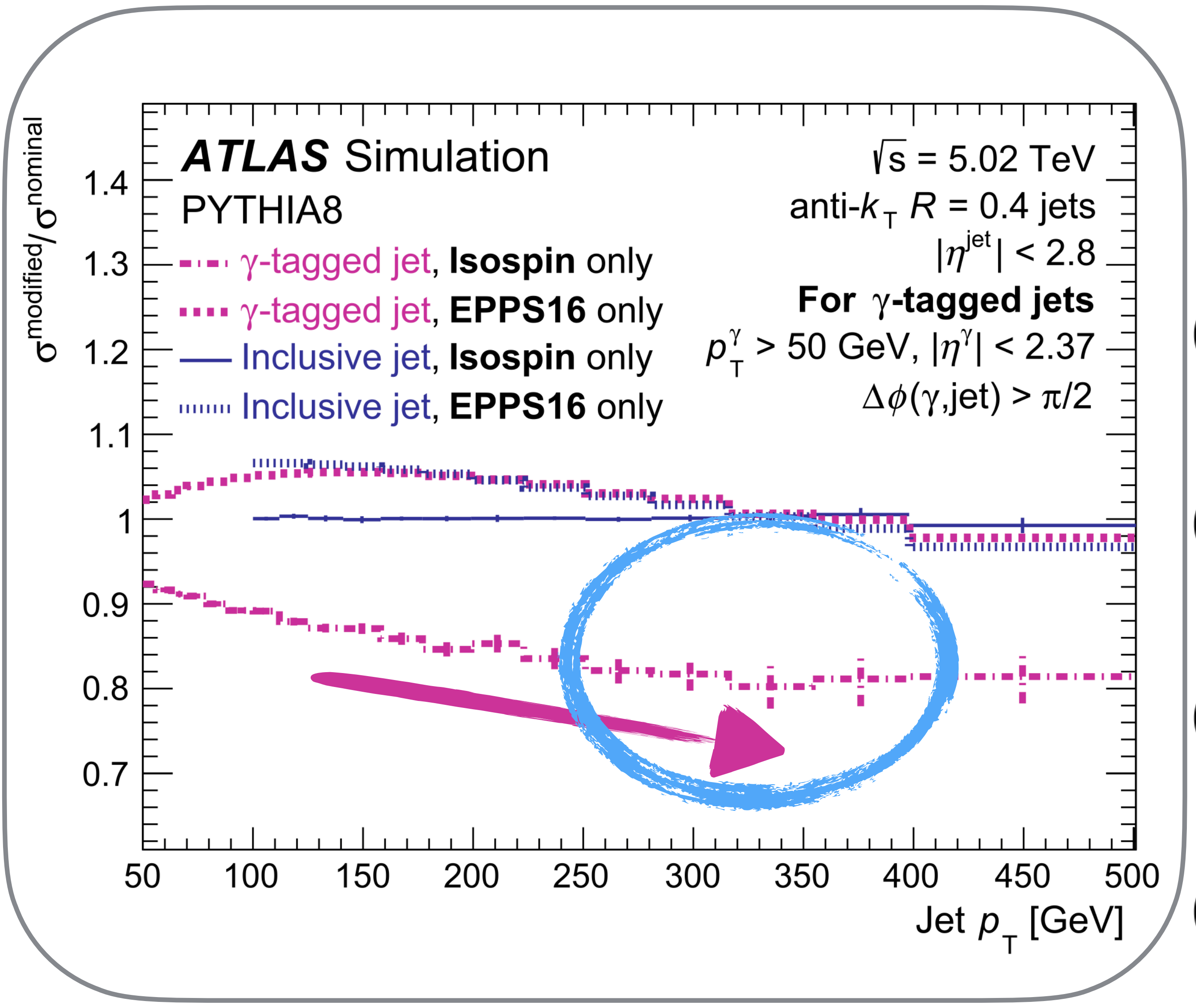
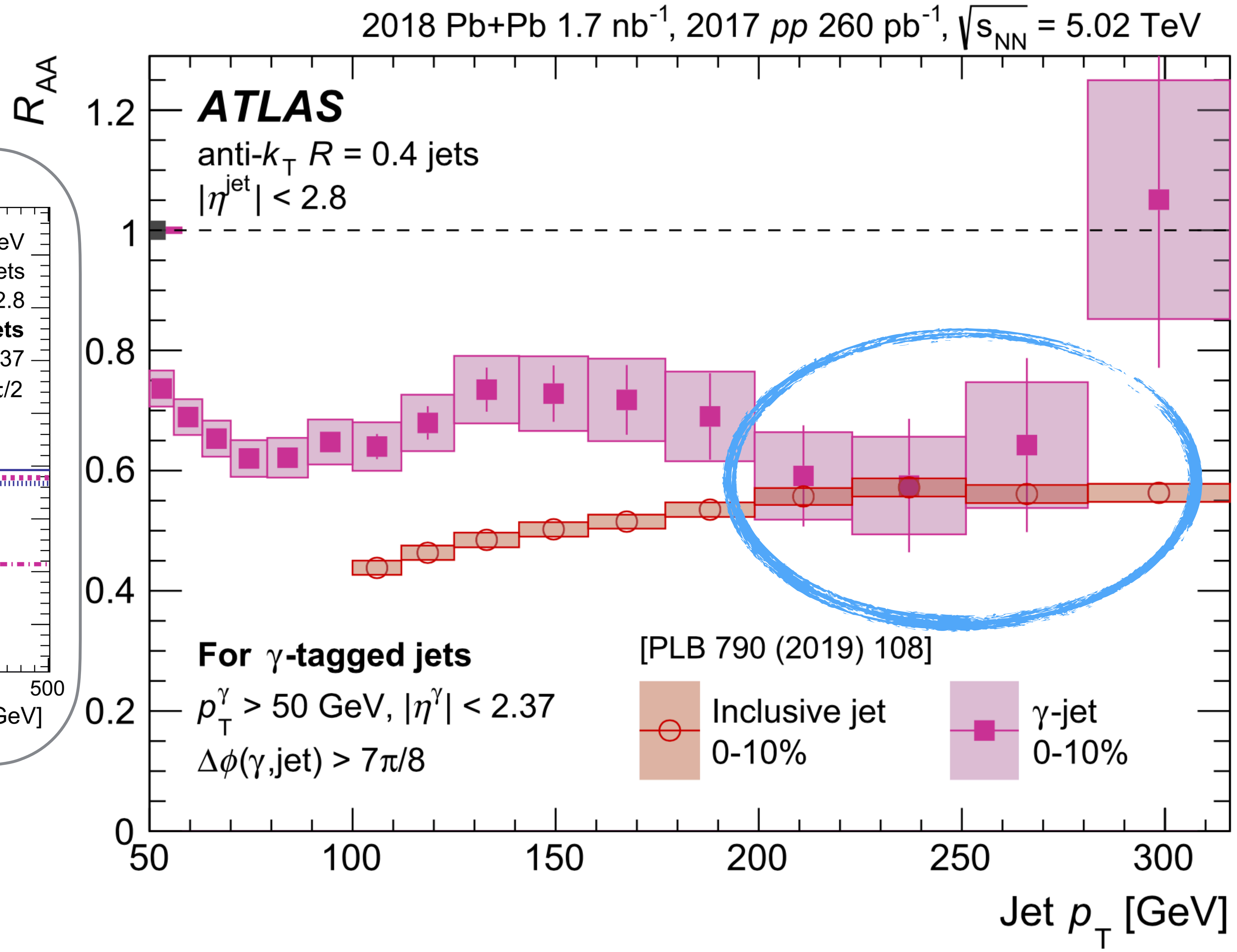
γ-jets vs. inclusive jets R_{AA}: q/g Energy Loss

1





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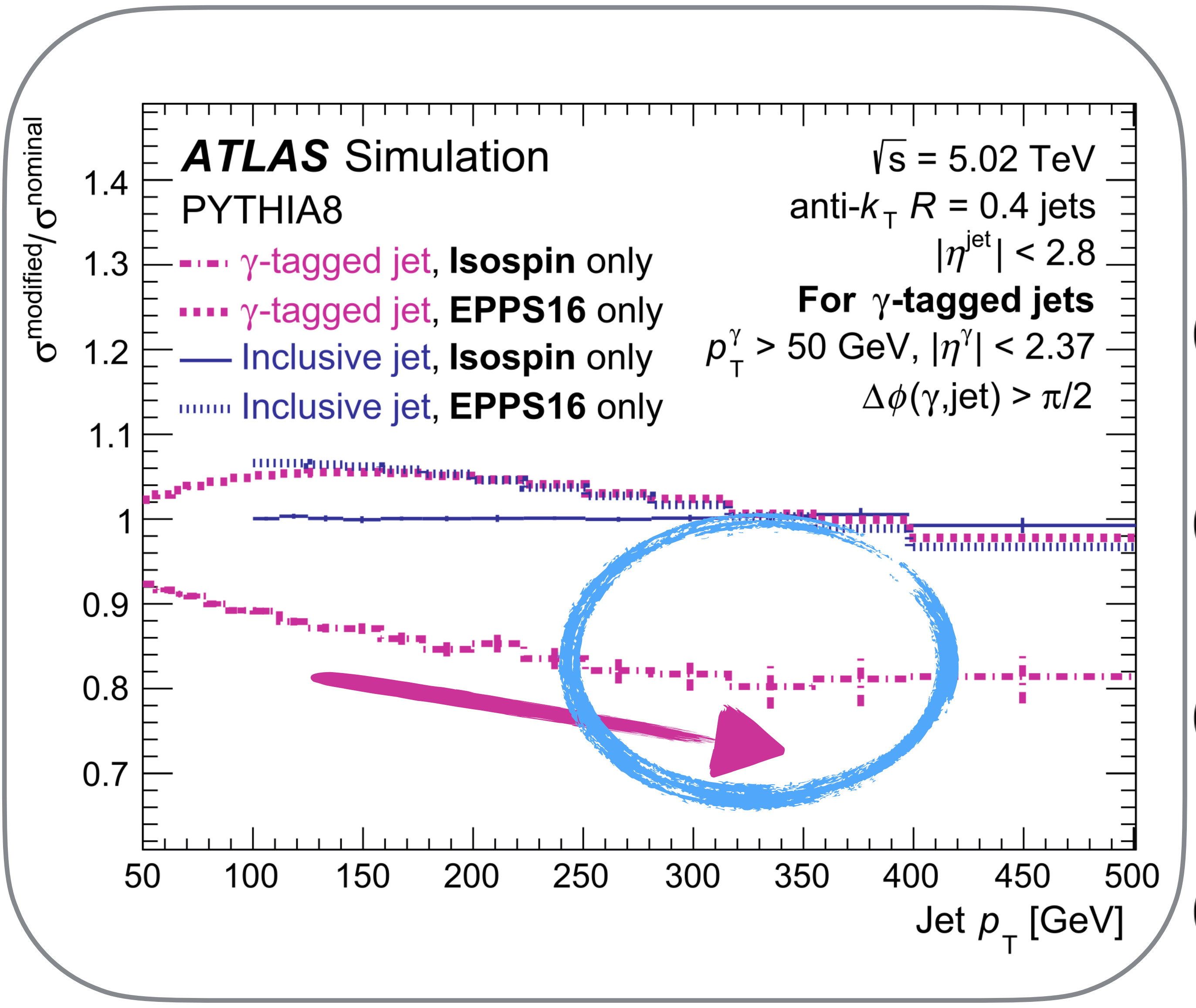

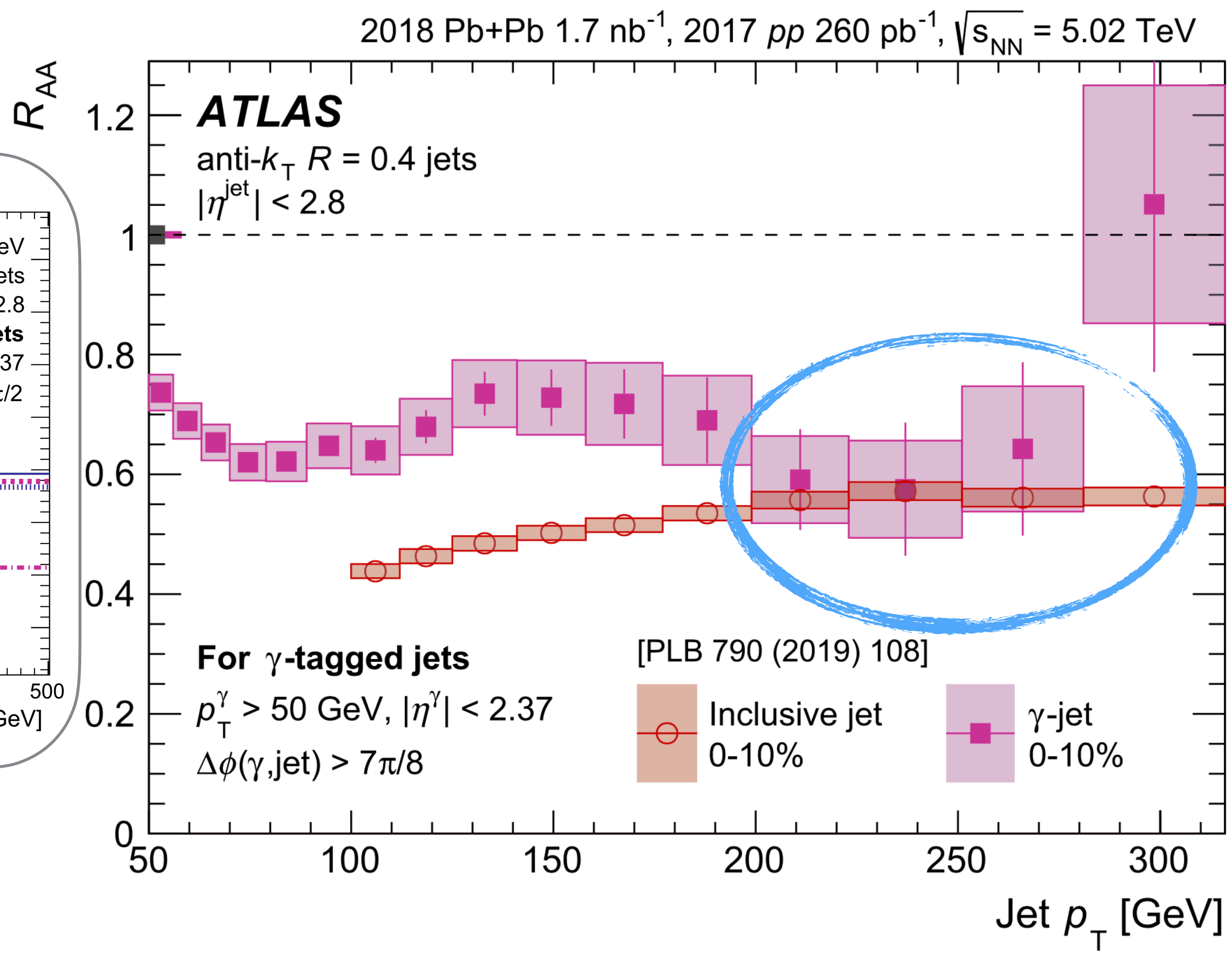

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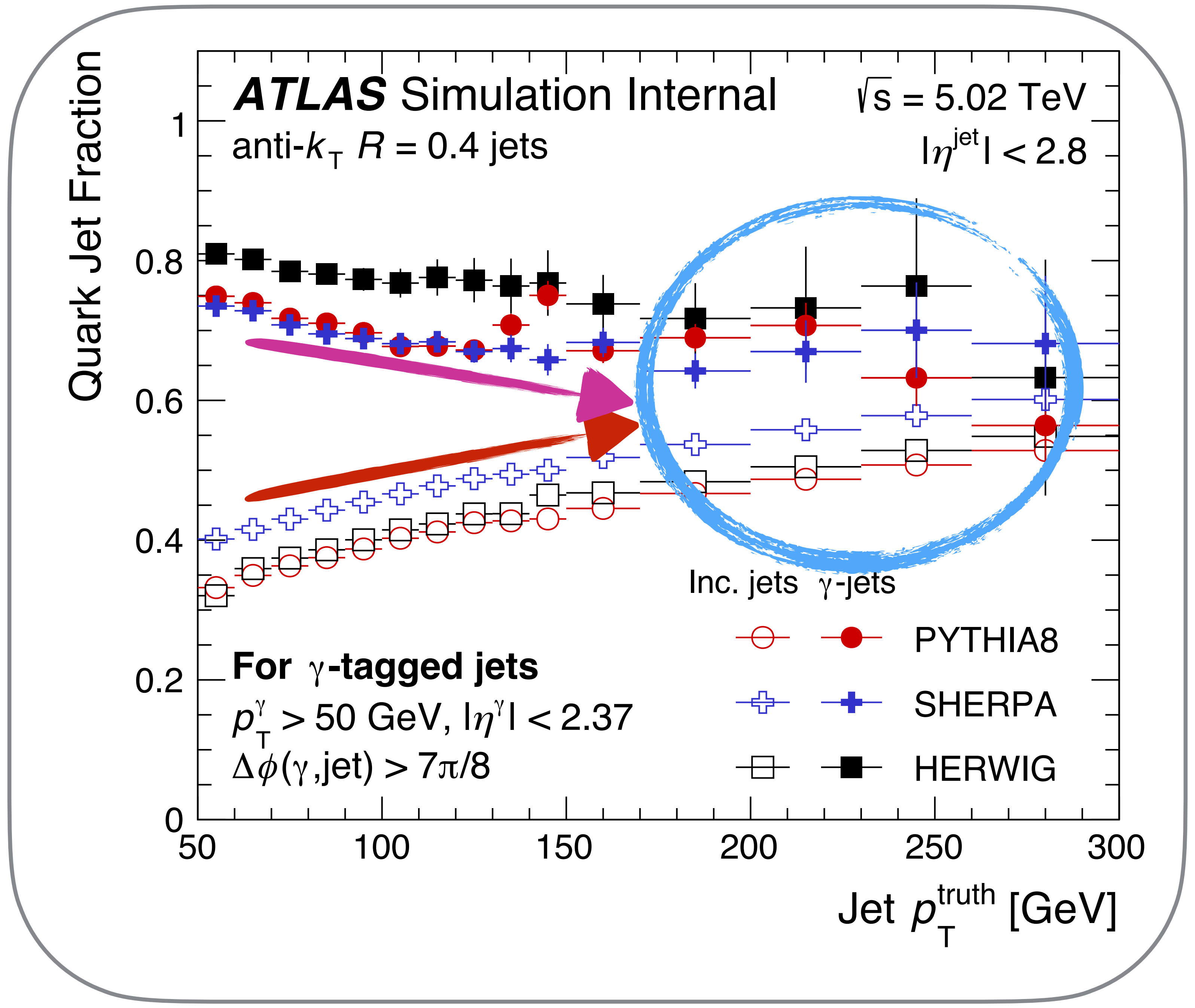

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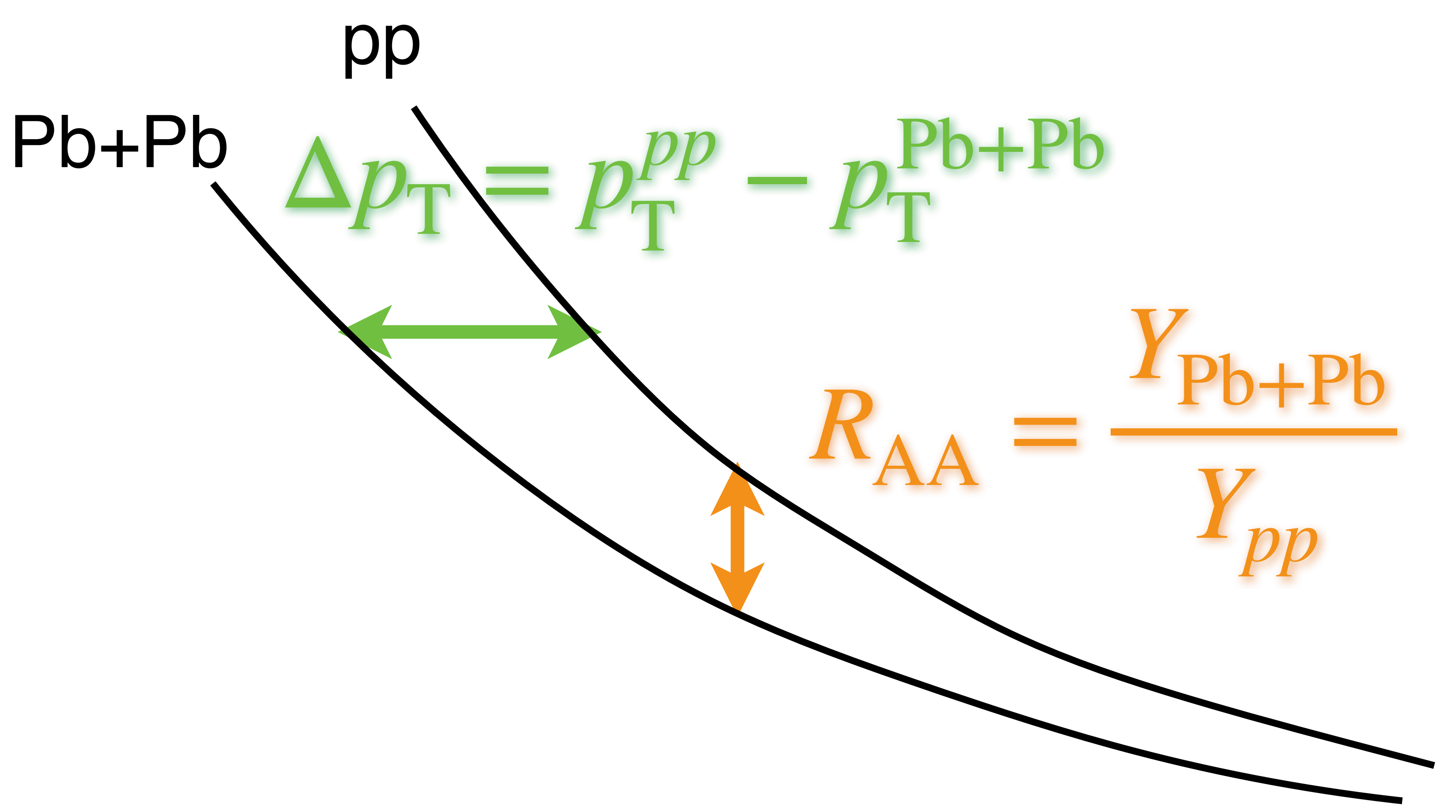
Fractional Energy Loss, S_{loss}

- limitation of R_{AA}: a steeper p_T distribution in pp (before jet quenching) will result in lower R_{AA}
- The S_{loss} (and Δp_T) was originally defined and further detailed by the PHENIX Collaboration
  - ➡ S_{loss} and Δp_T are less affected by the p_T spectrum in pp collisions

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}

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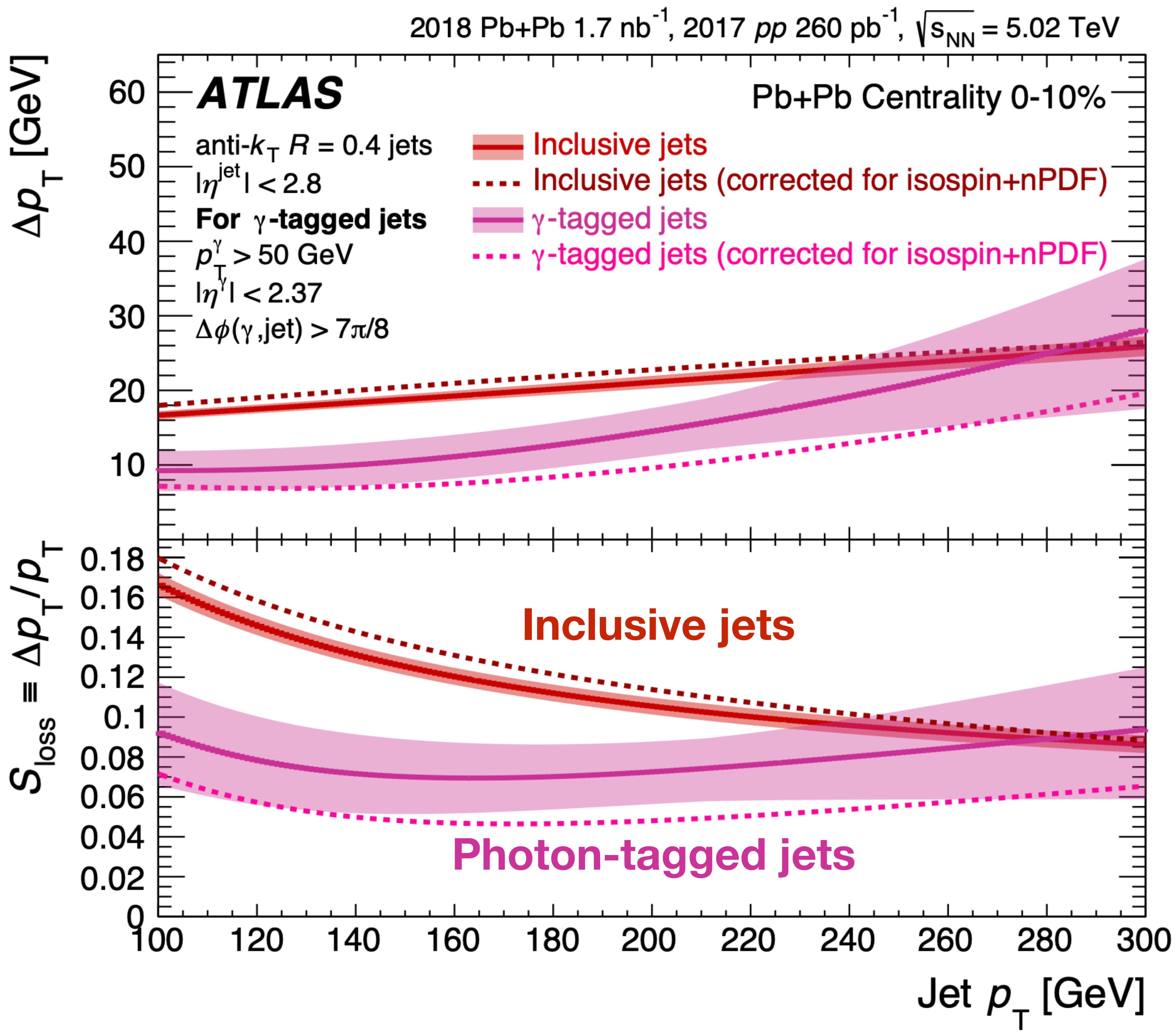
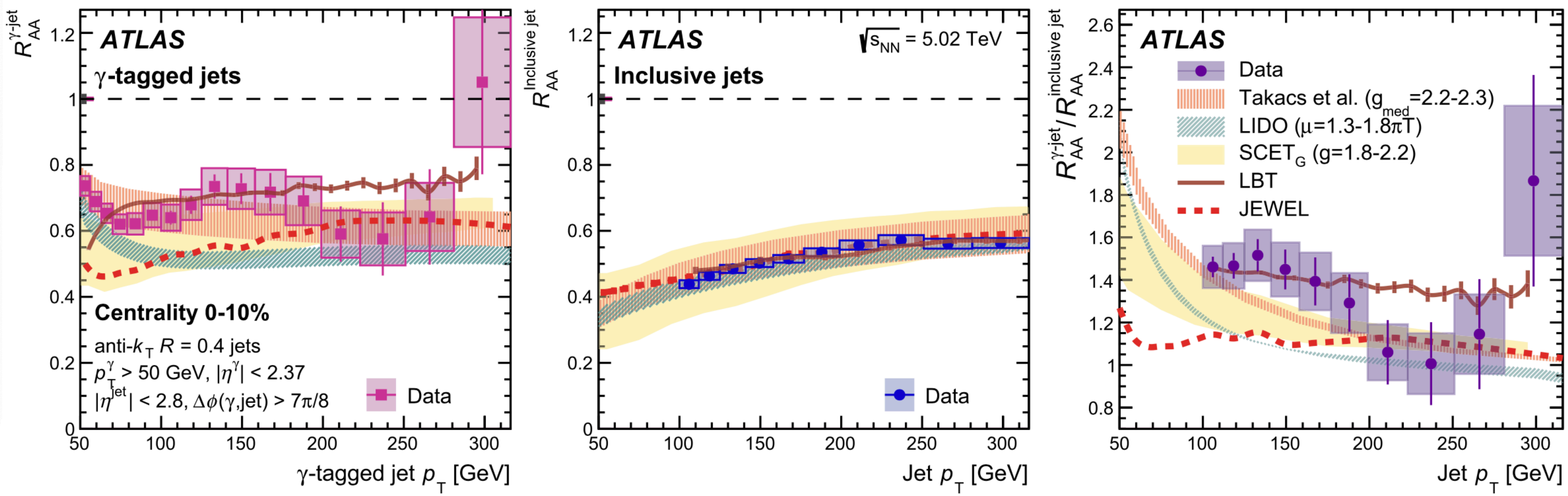


- For < ~200 GeV, S_{loss} and Δp_T of γ-jets are significantly smaller than inclusive jets
- The *isospin(+nPDF)-corrected* S_{loss} and Δp_T even strengthen the evidence that

quark-initiated jets ***lose less energy*** than gluon-initiated jets

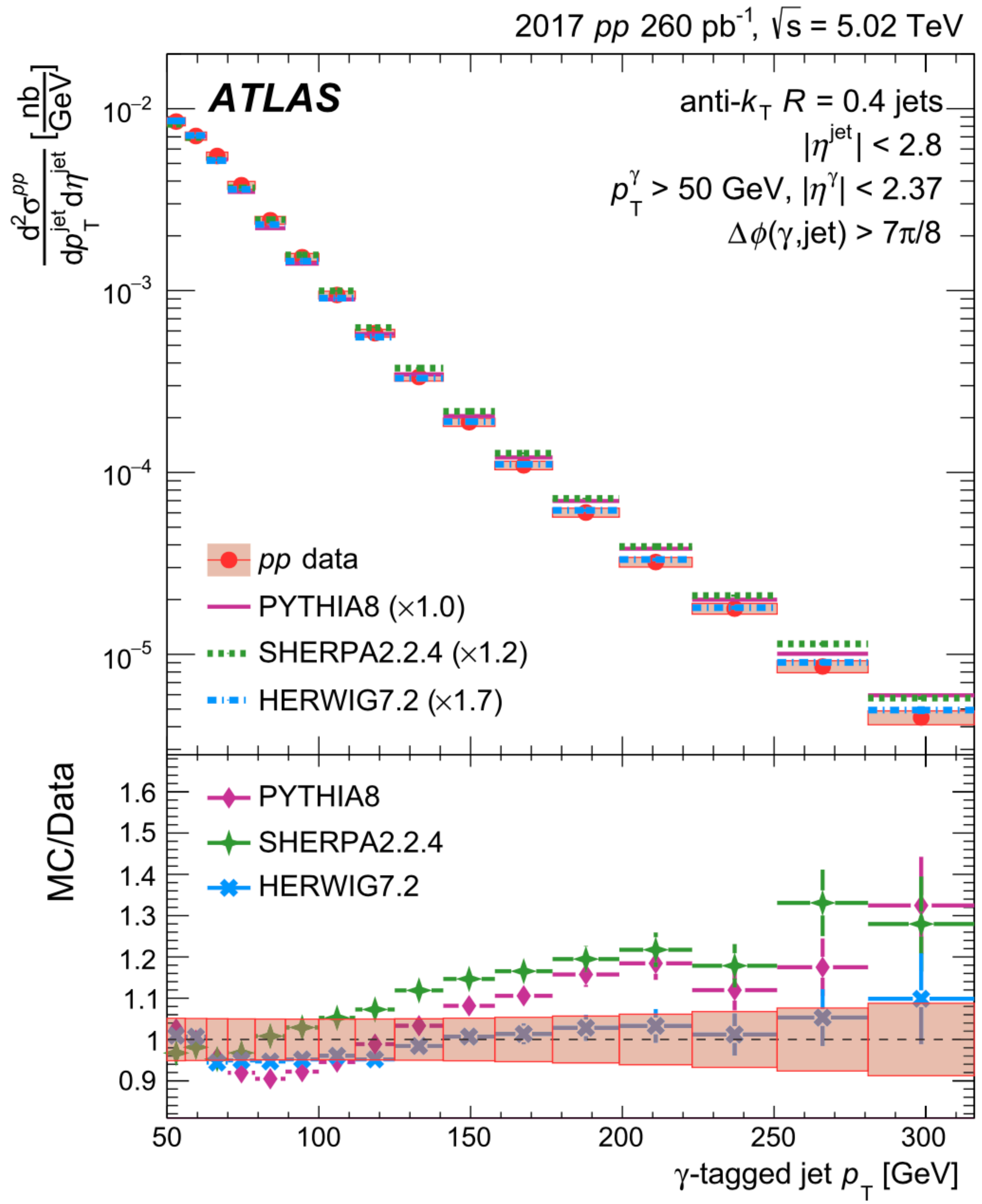
Theory Comparison: R_{AA}



PLB 846 (2023) 138154

- 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

γ-jet 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, the differences in cross section in pp between the data and predictions needs to be considered

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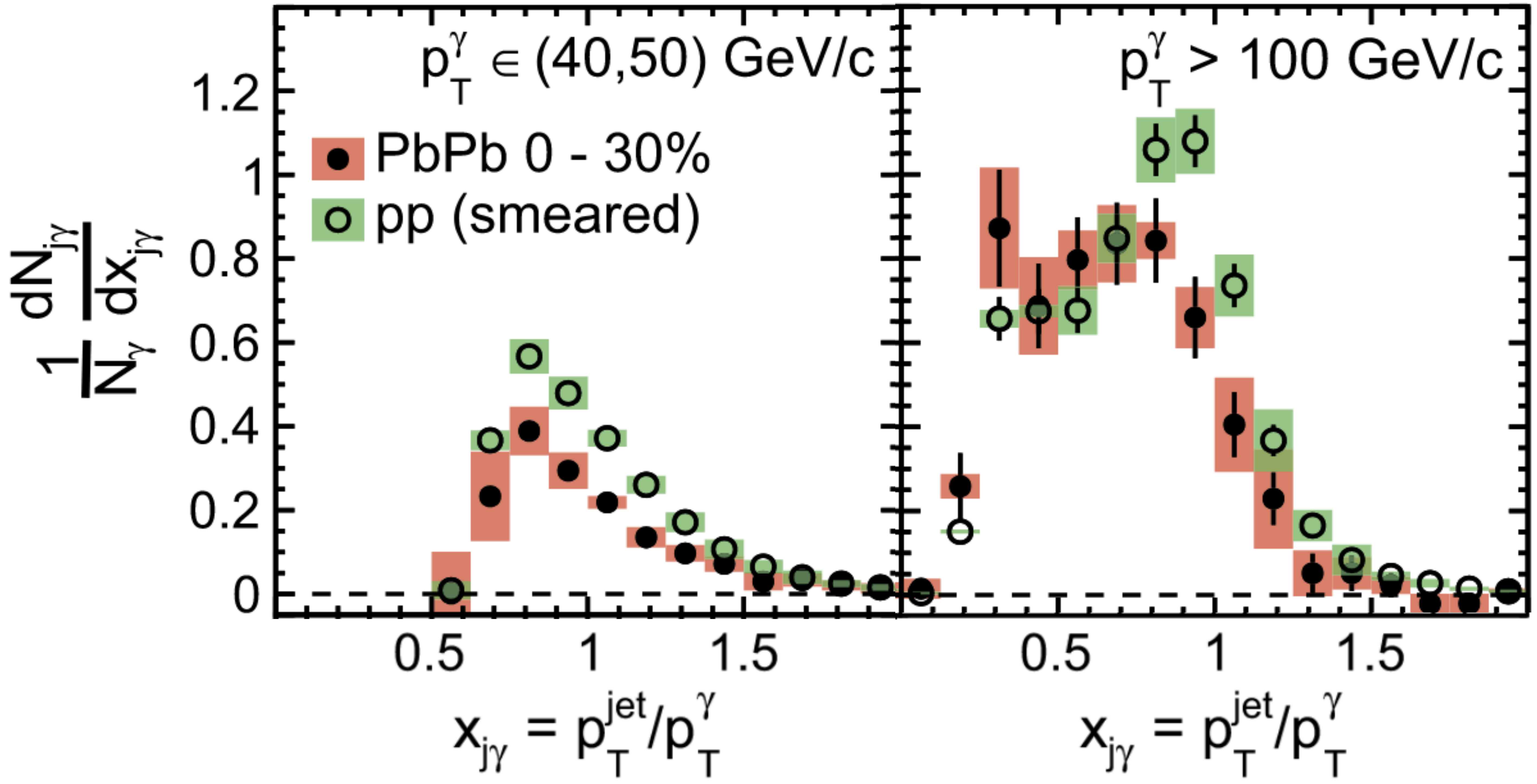
$x_{J\gamma}$; Jet Energy Loss



CMS

anti-k_T jet R = 0.3, $p_T^{jet} > 30$ GeV/c

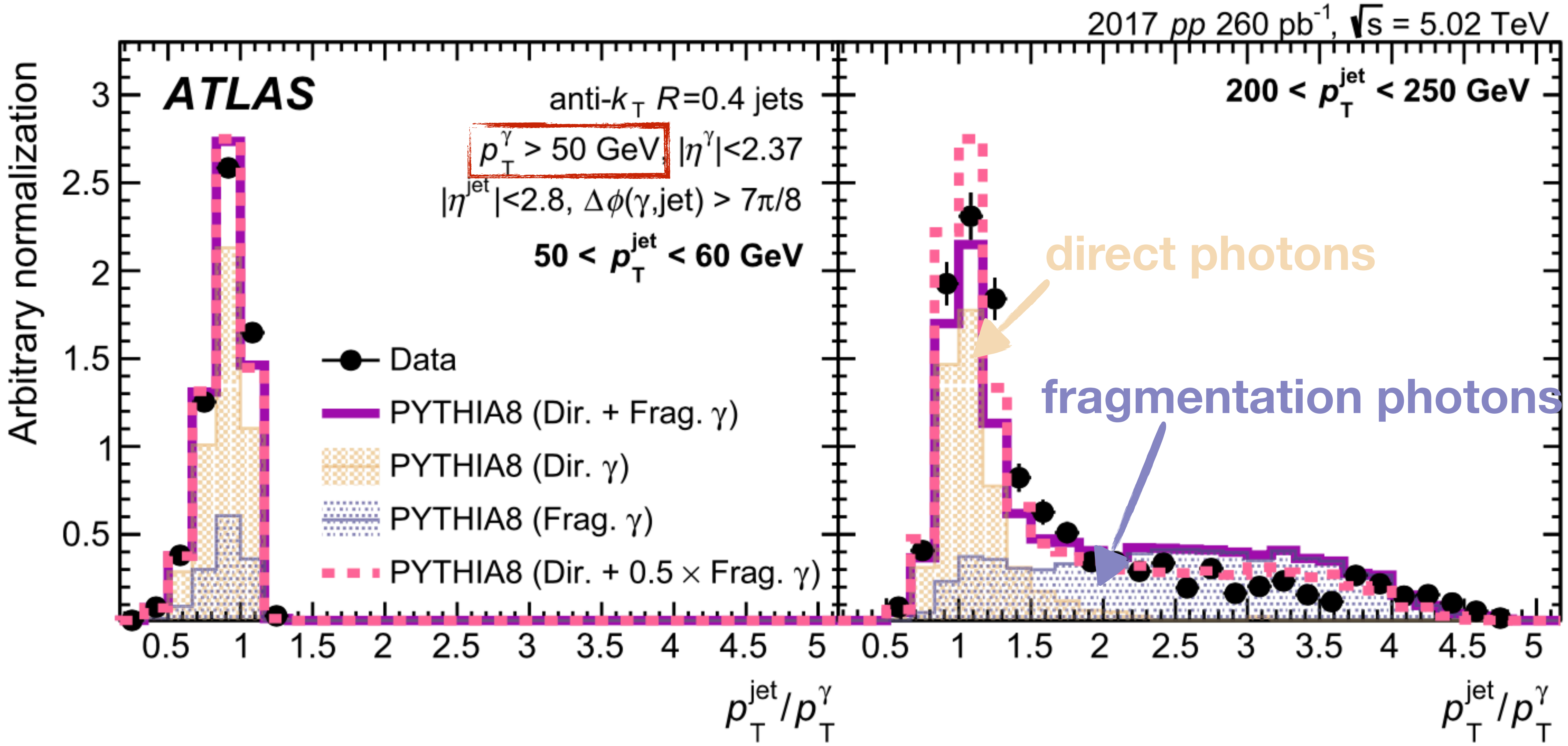
$|\eta^{jet}| < 1.6$, $|\eta^\gamma| < 1.44$, $\Delta\phi_{j\gamma} > \frac{7\pi}{8}$

PLB 785 (2018) 14

- Lower $x_{J\gamma}$ in Pb+Pb; jet energy loss
- $x_{J\gamma}$ in photon p_T bins → dominated by the leading order contribution of photon production

Fragmentation Photons: Data vs. MC

50 < jet p_T < 60 GeV   200 < jet p_T < 250 GeV



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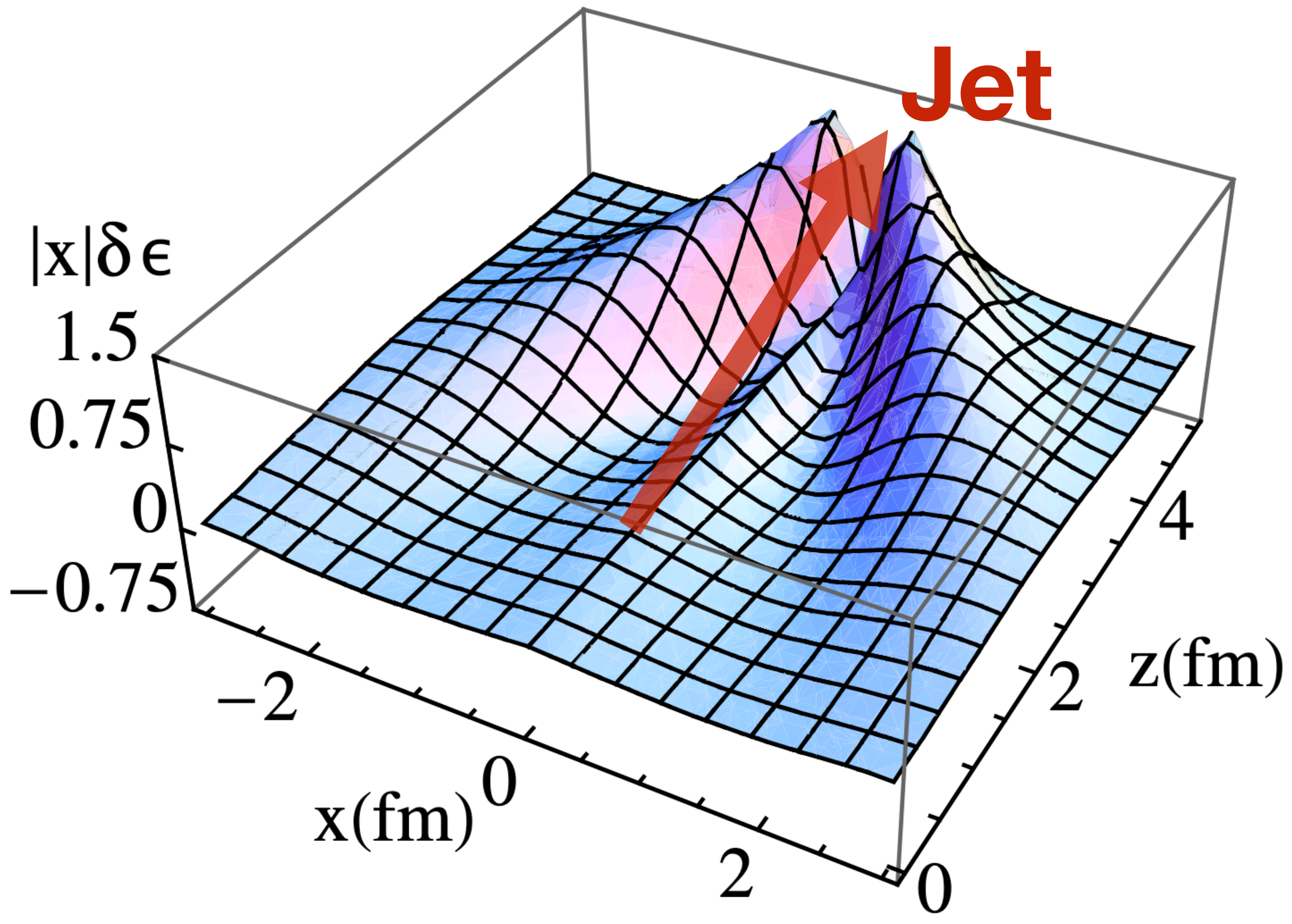
- $x_{J\gamma}$ in photon p_T bins → dominated by the leading order contribution
- $x_{J\gamma}$ in jet p_T bins → at higher jet p_T bin, the larger fragmentation photon (higher order) contribution
- Potential mis-modeling of the fraction of direct and fragmentation photons in MC

Medium Response Incurred by Jets

Mutual Interaction: Medium ⇄ Jets

- As jets are modified by medium, the medium is also affected by jets!
- By energy and momentum conservation, lost jet energy ➡ into medium

PRL 103, 152303 (2009)



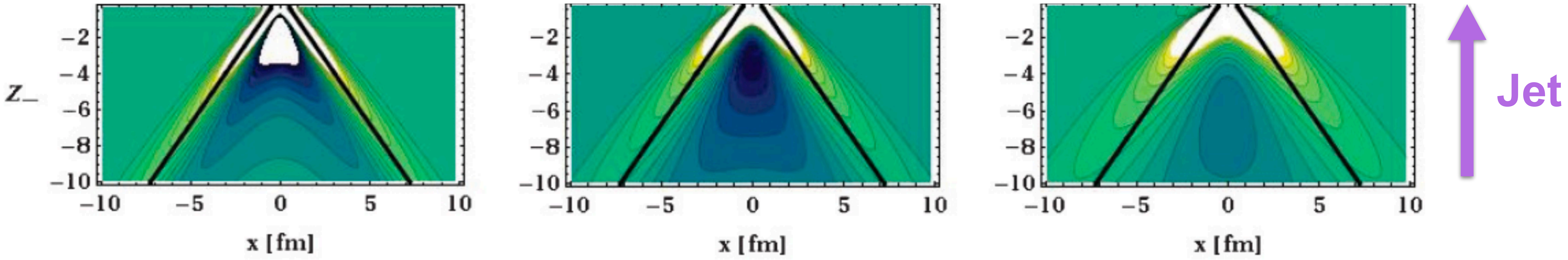
- Typical structures formed; *Mach cone, sonic boom, shock wave, wake, diffusion wake, …*
  - ➡ enhancement in jet direction
  - ➡ depletion opposite jet direction

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

$\eta/s = 1/4\pi$ $\eta/s = 3/4\pi$ $\eta/s = 6/4\pi$

PRC 79 (2009) 054909



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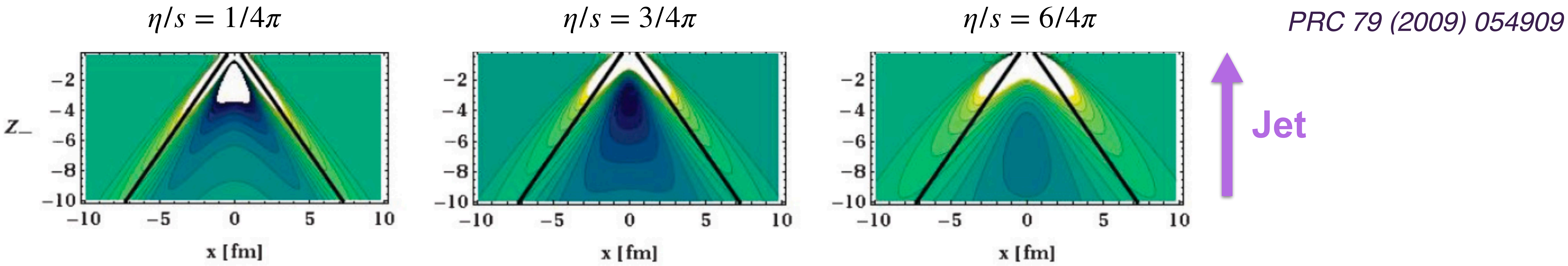

- **In-medium thermalization** information e.g. E_{med}, D_{diff}, τ_{th}
- Medium response affects the extraction of **jet transport coefficient**
  ➡ can be related to local gluon density distribution of the medium

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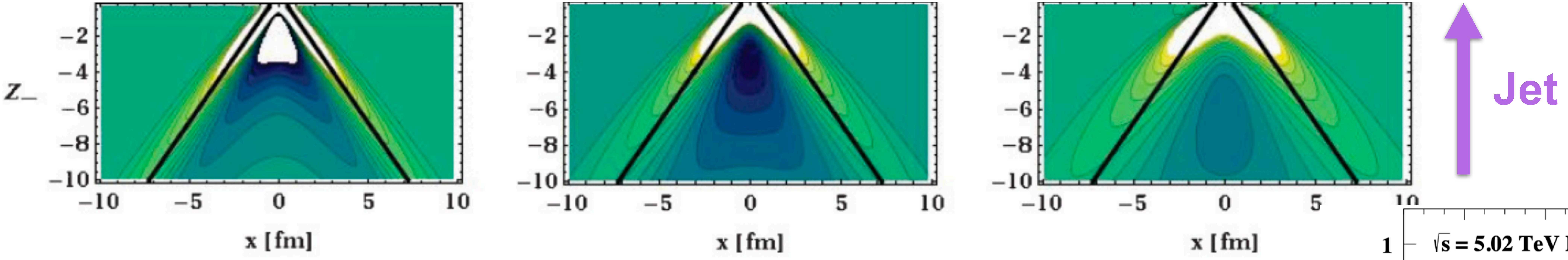
PRC 79 (2009) 054909



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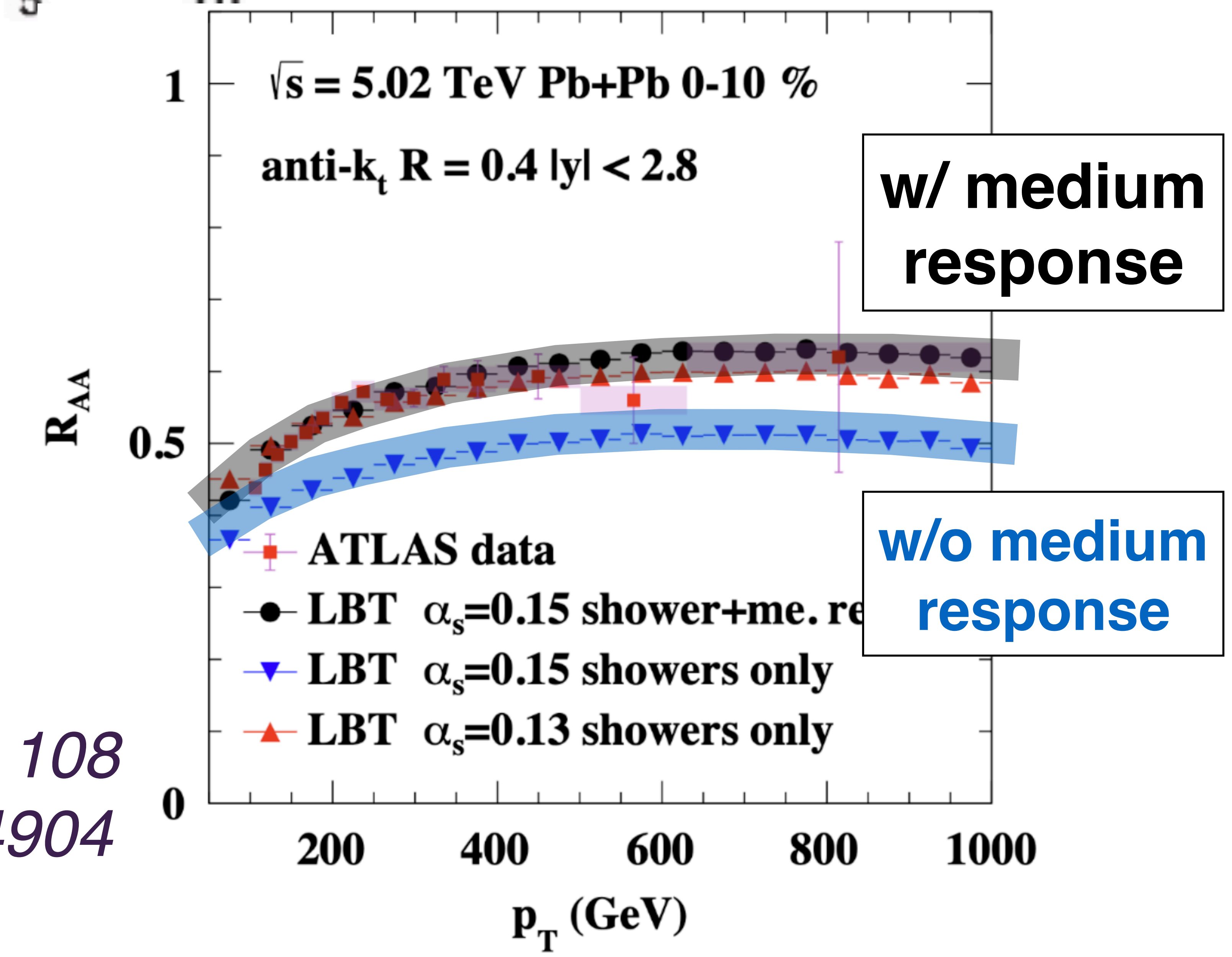
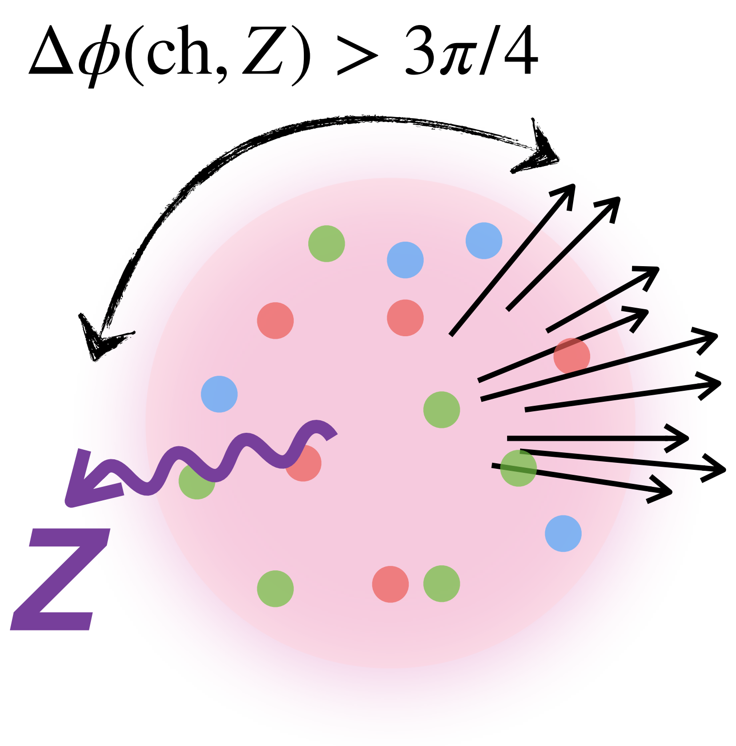


PLB 790 (2019) 108
PRC 106 (2022) 044904

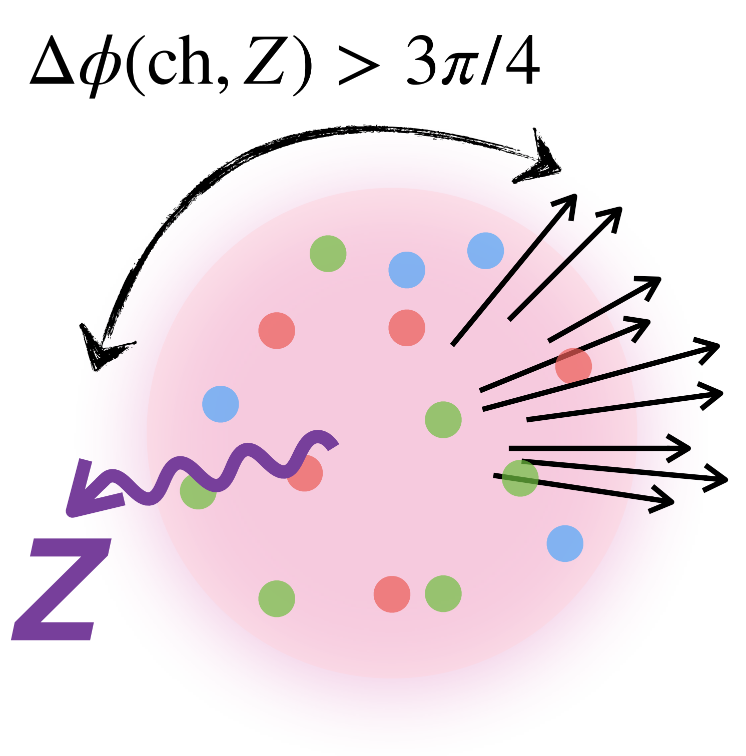
Redistribution of Particles Around Jets

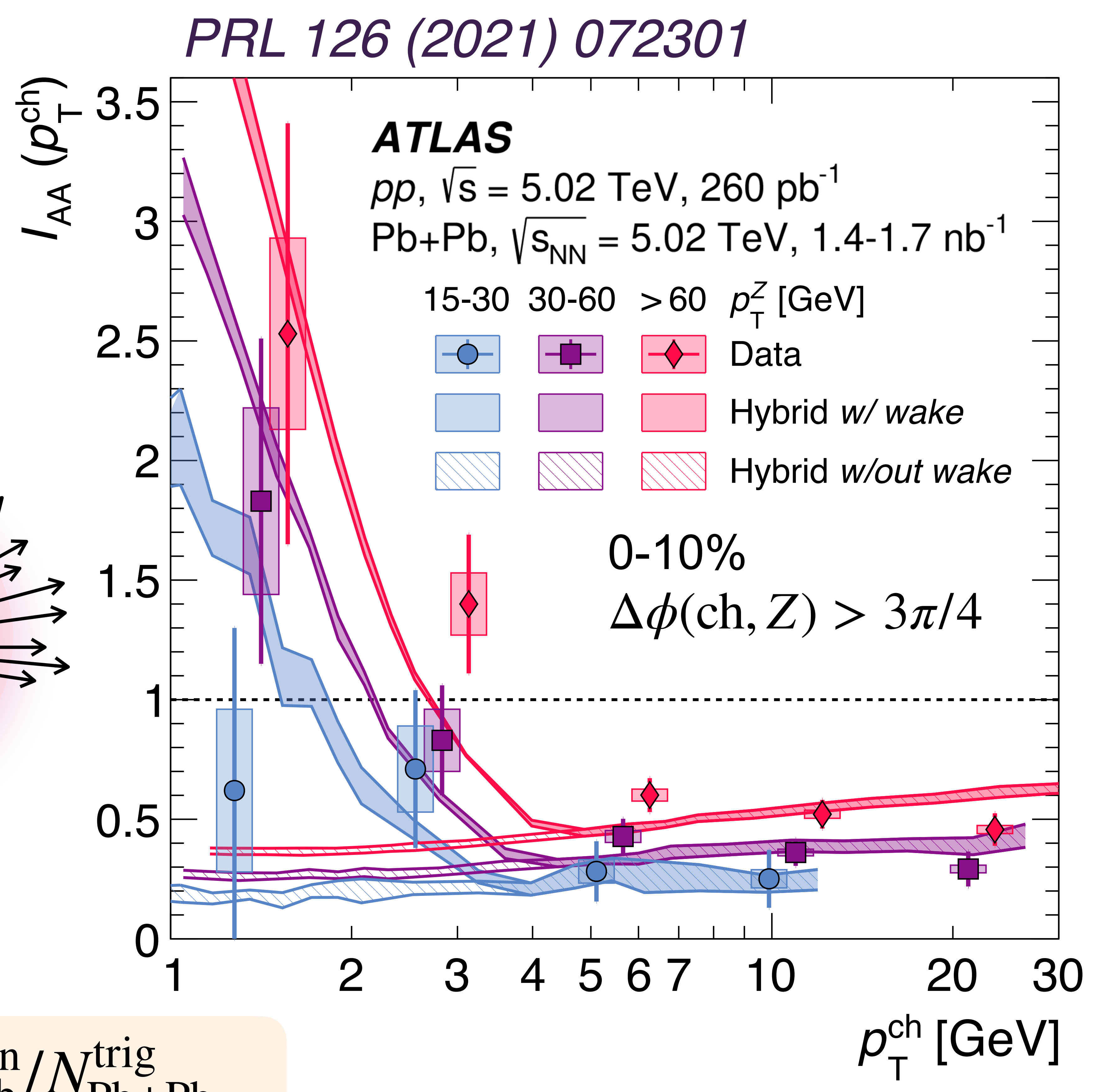


$$I_{\mathrm{AA}} = \frac{Y^{\mathrm{hadron}}_{\mathrm{Pb+Pb}} / N^{\mathrm{trig}}_{\mathrm{Pb+Pb}}}{Y^{\mathrm{hadron}}_{pp} / N^{\mathrm{trig}}_{pp}}$$

- Enhancement of low p_T particles at large angles w.r.t jet axis

Redistribution of Particles Around Jets





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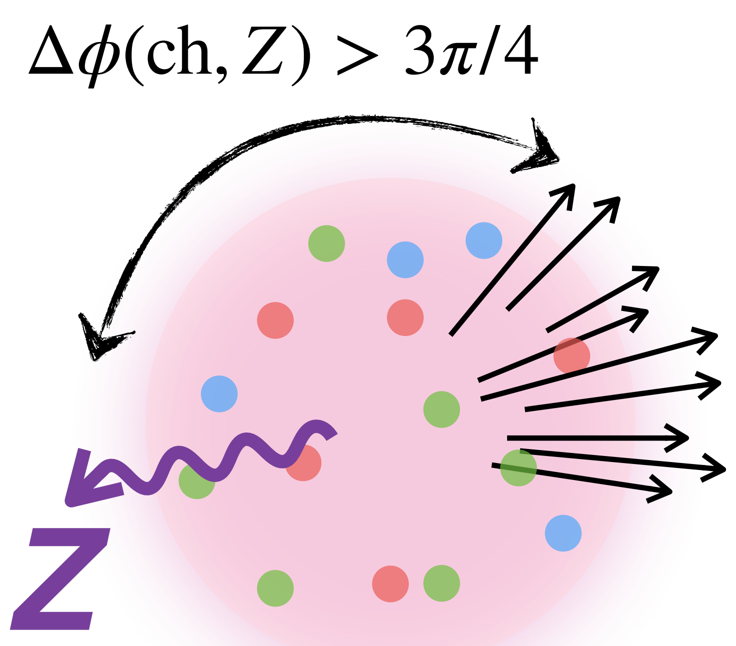
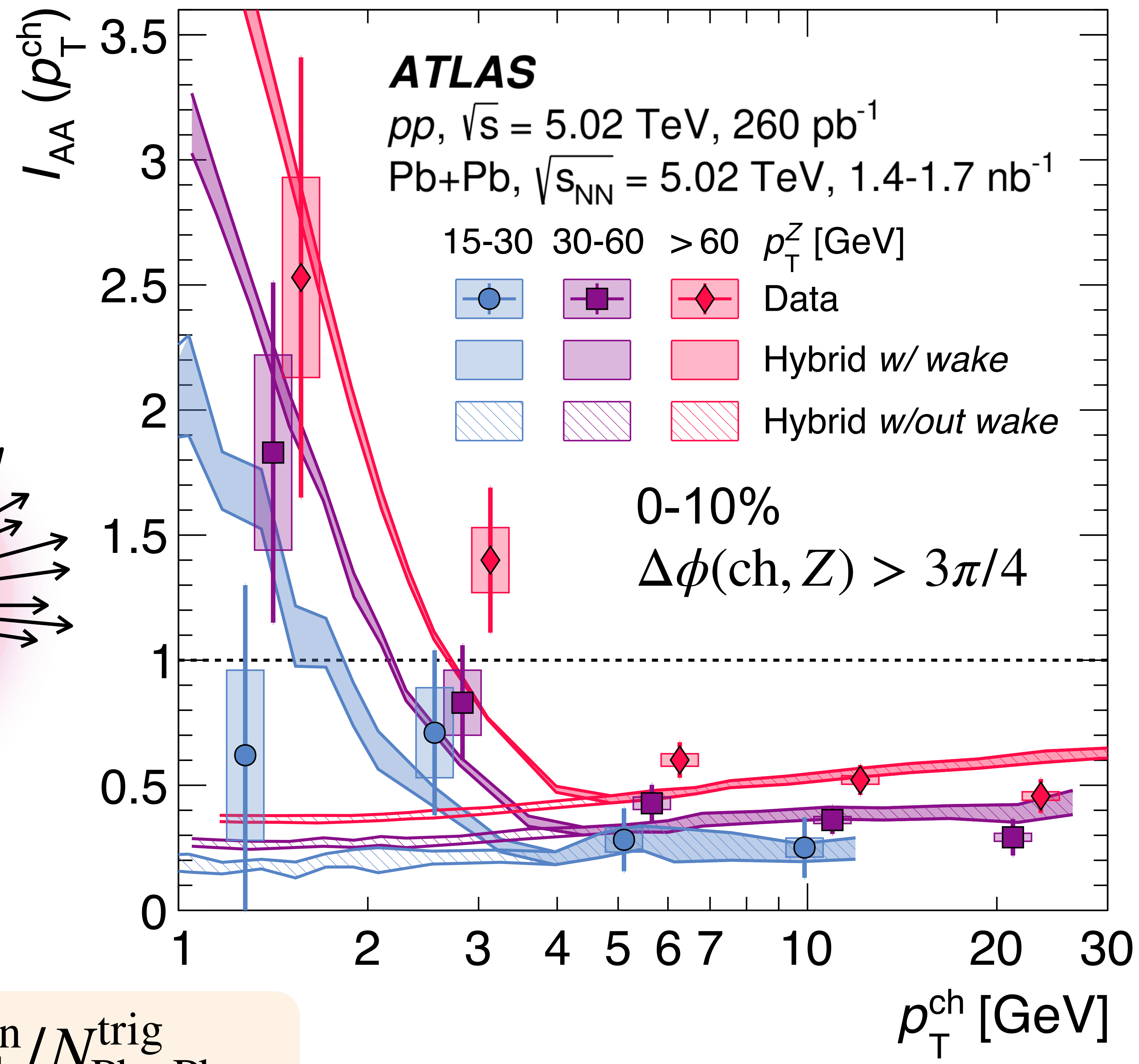
Redistribution of Particles Around Jets

PRL 126 (2021) 072301





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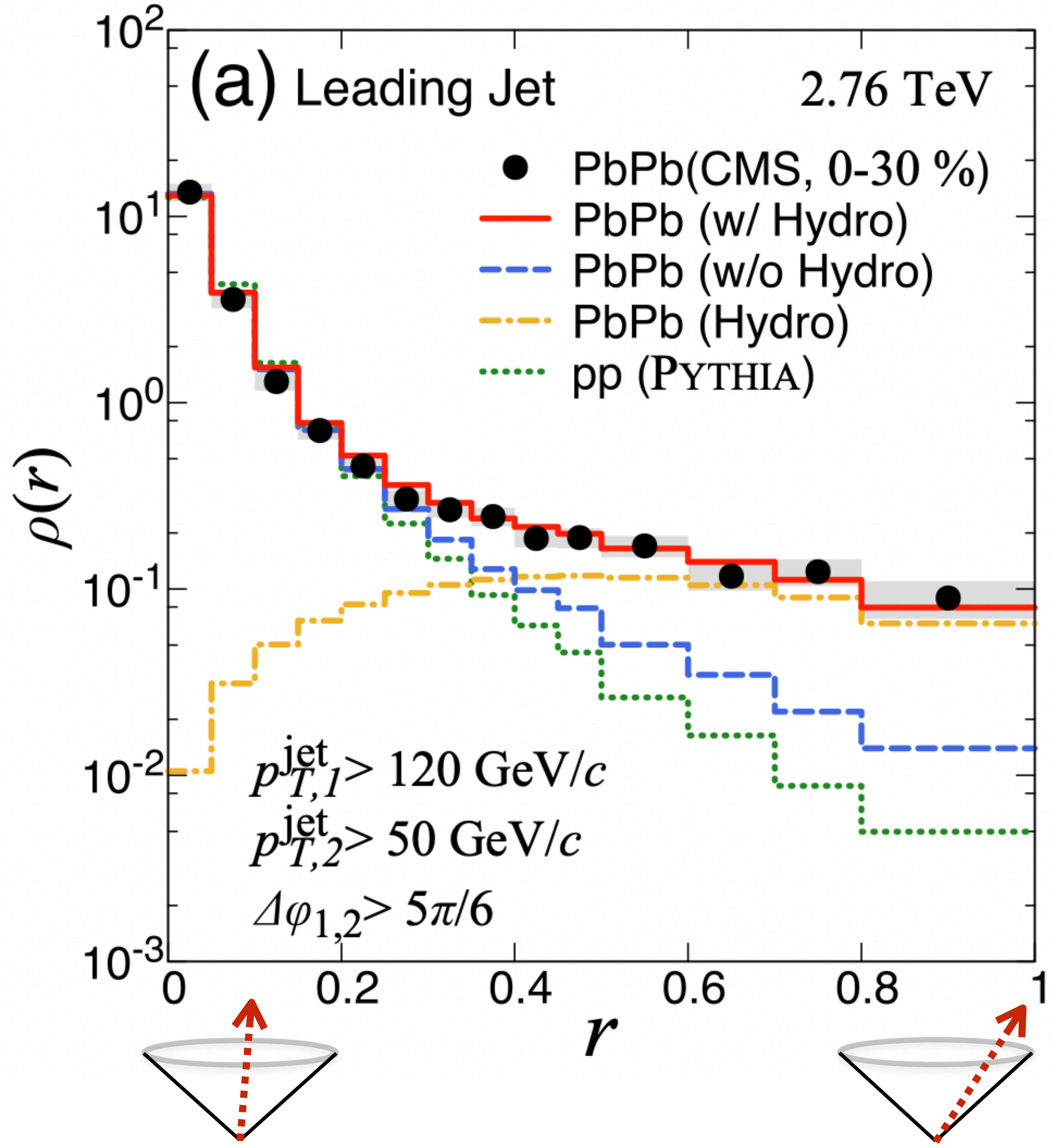
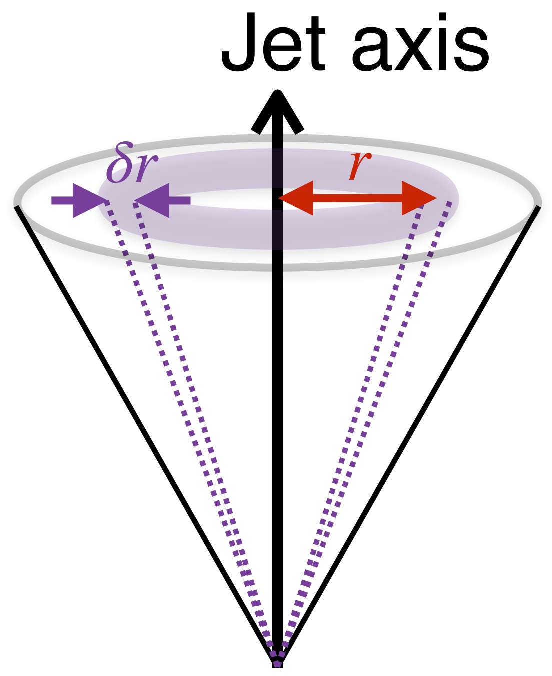


JHEP 11 (2016) 055
PRC 95, 044909 (2017)



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

- Enhancement of low p_T particles at large angles w.r.t jet axis

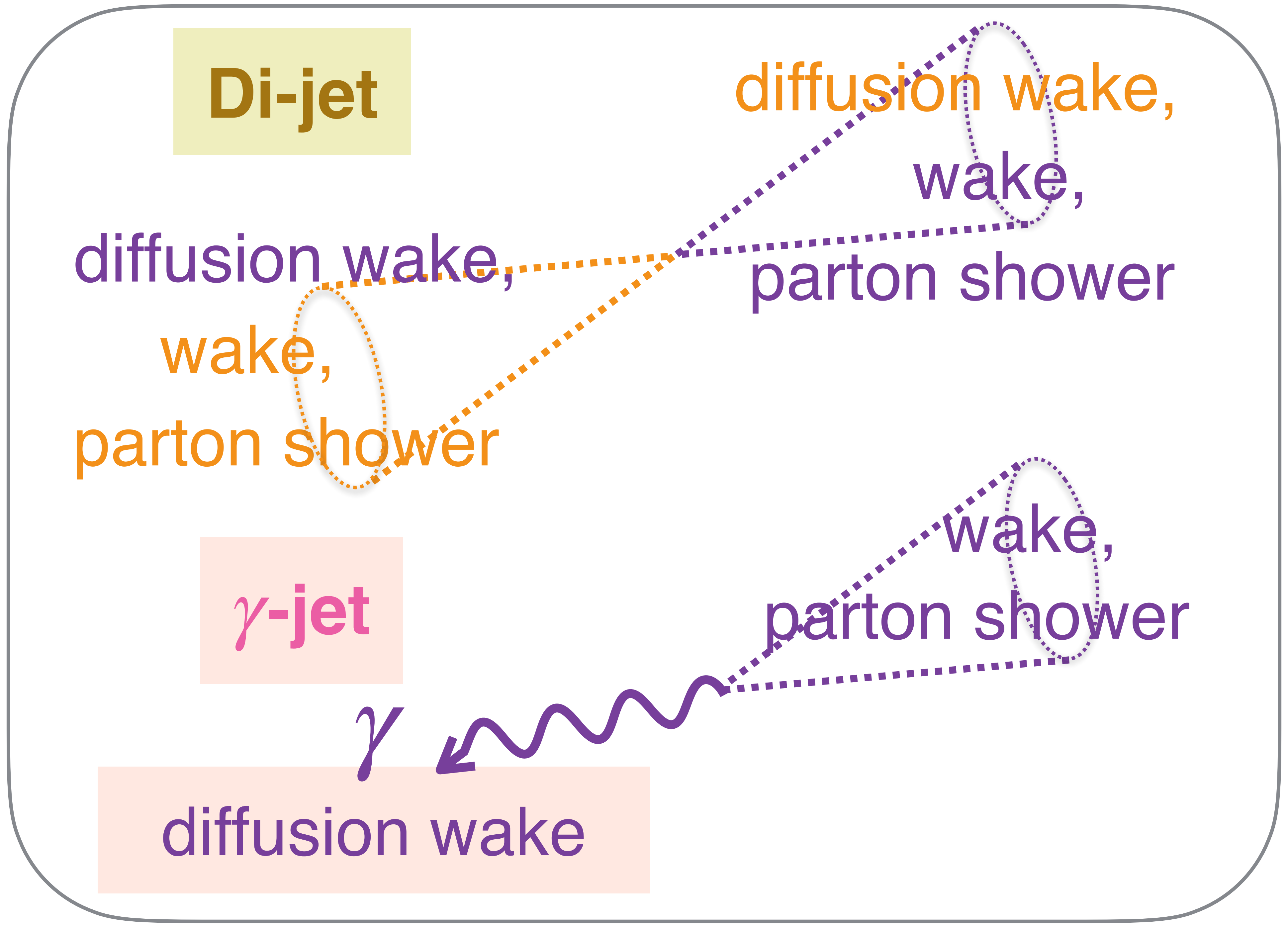
Diffusion Wake Using Boson-jets

- Modification in jet direction are convoluted with ***in-medium parton shower modification*** and ***medium response*** → hard to disentangle …

Diffusion Wake Using Boson-jets

- Modification in jet direction are convoluted with ***in-medium parton shower modification*** and ***medium response*** → hard to disentangle …

- **Diffusion wake** (depletion) effect using jet-hadron correlations in boson-jet events;
  ➡ unlike **di-jet** events, a jet associated a boson e.g. photon is **NOT** contaminated by in-medium parton shower modification or wake caused by the other jet in the opposite direction



Diffusion Wake Using Boson-jets

- Modification in jet direction are convoluted with ***in-medium parton shower modification*** and ***medium response*** → hard to disentangle …

- **Diffusion wake** (depletion) effect using jet-hadron correlations in boson-jet events;
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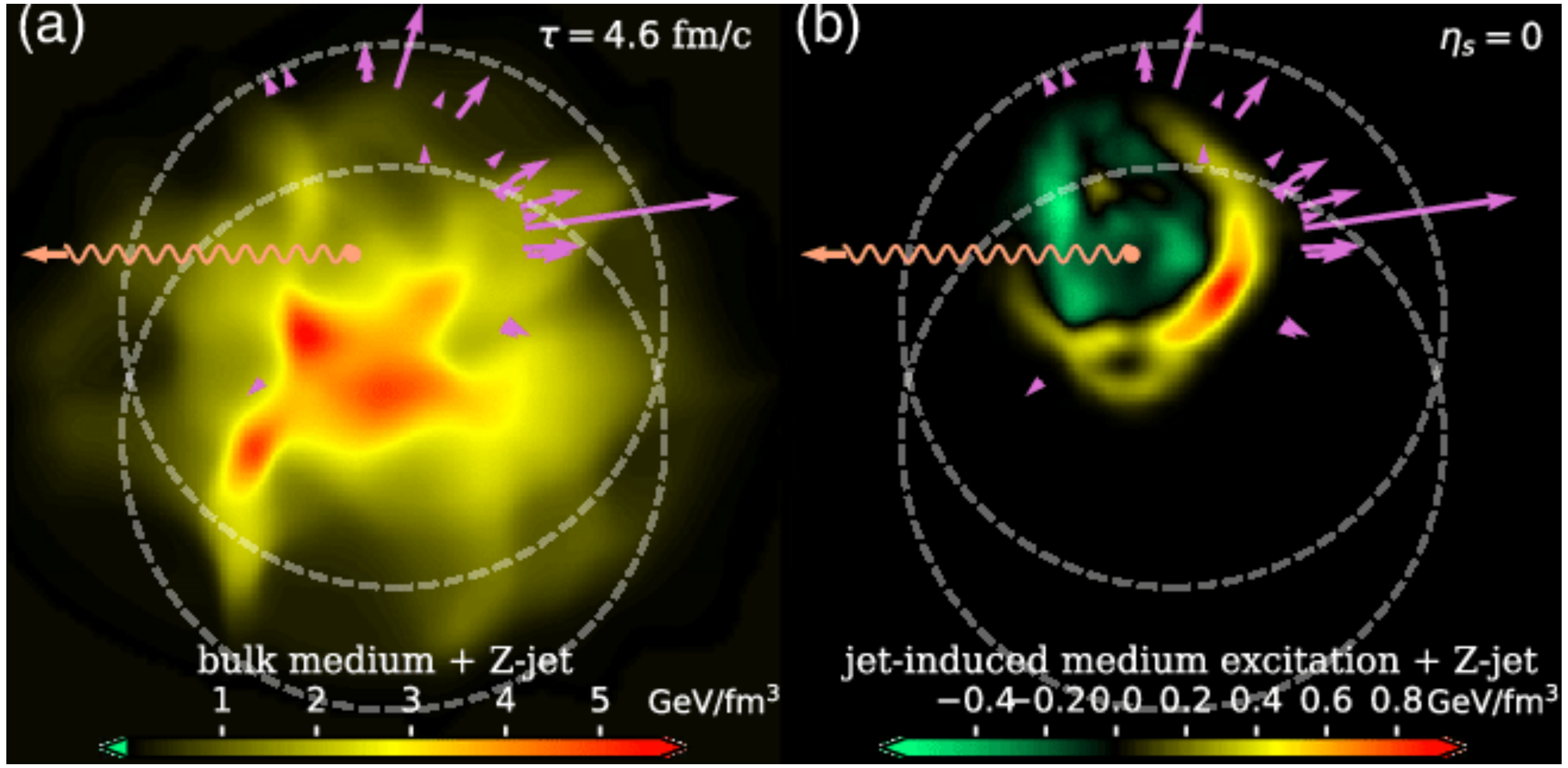
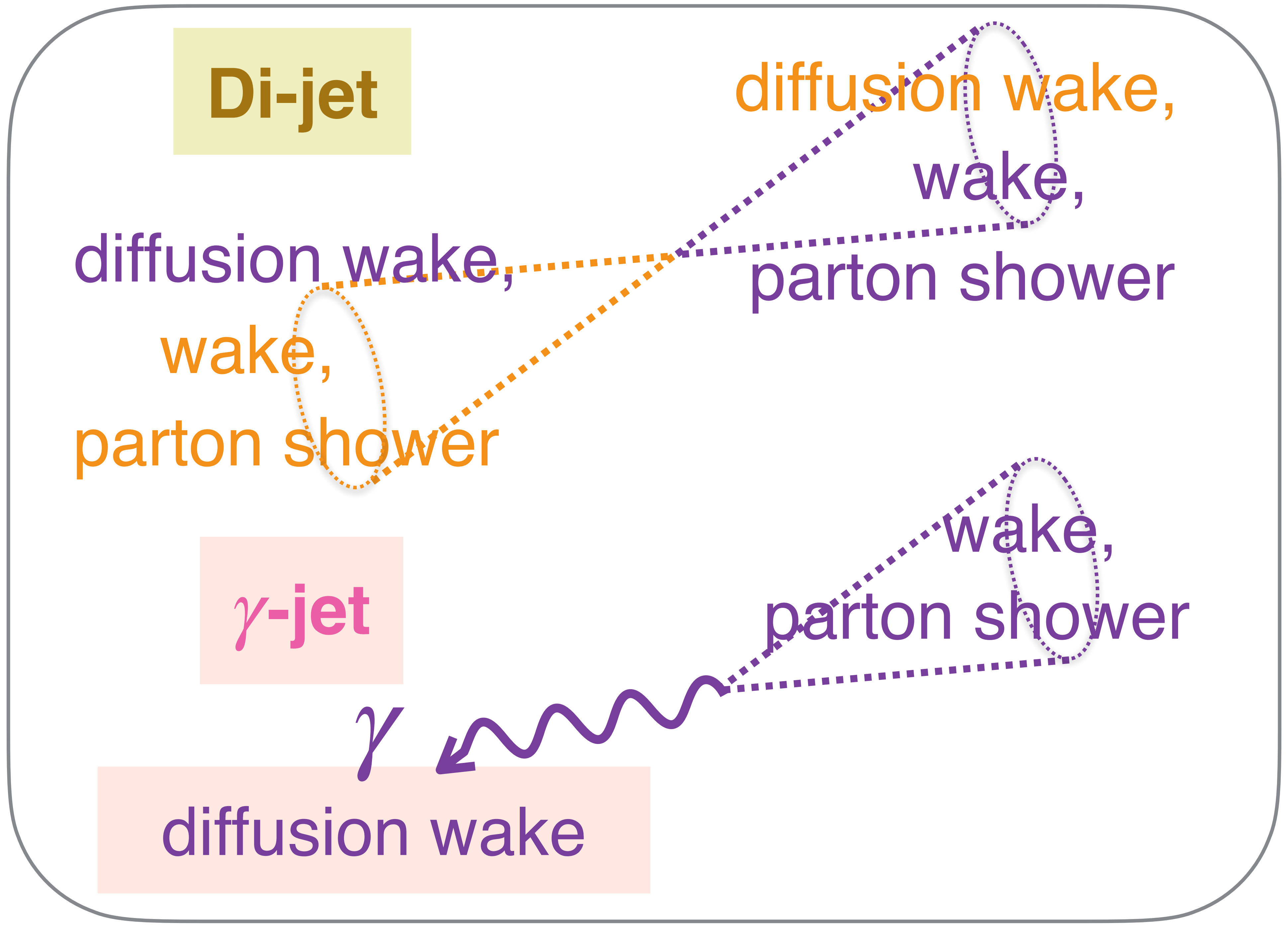
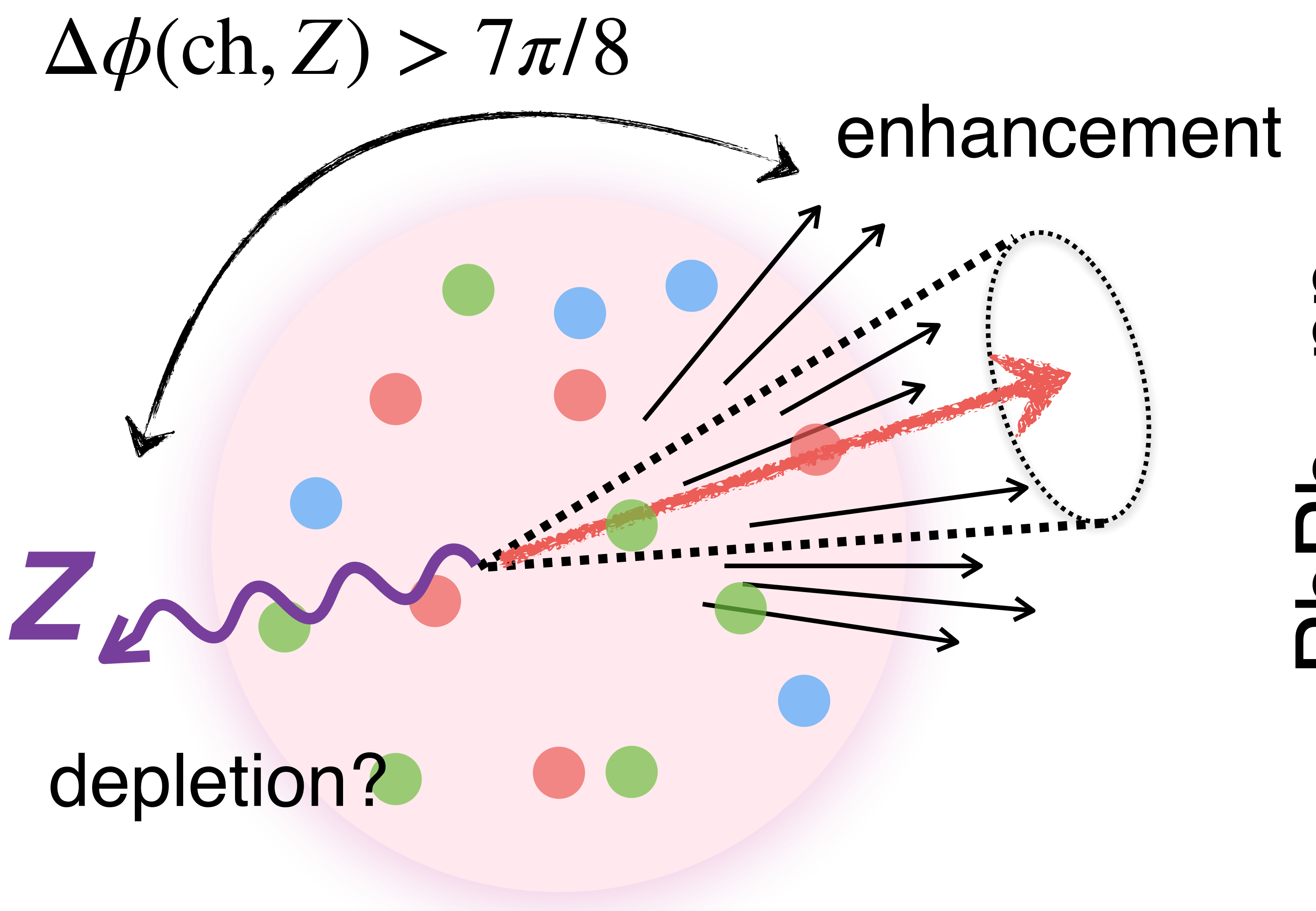


PRL127, 082301 (2021)

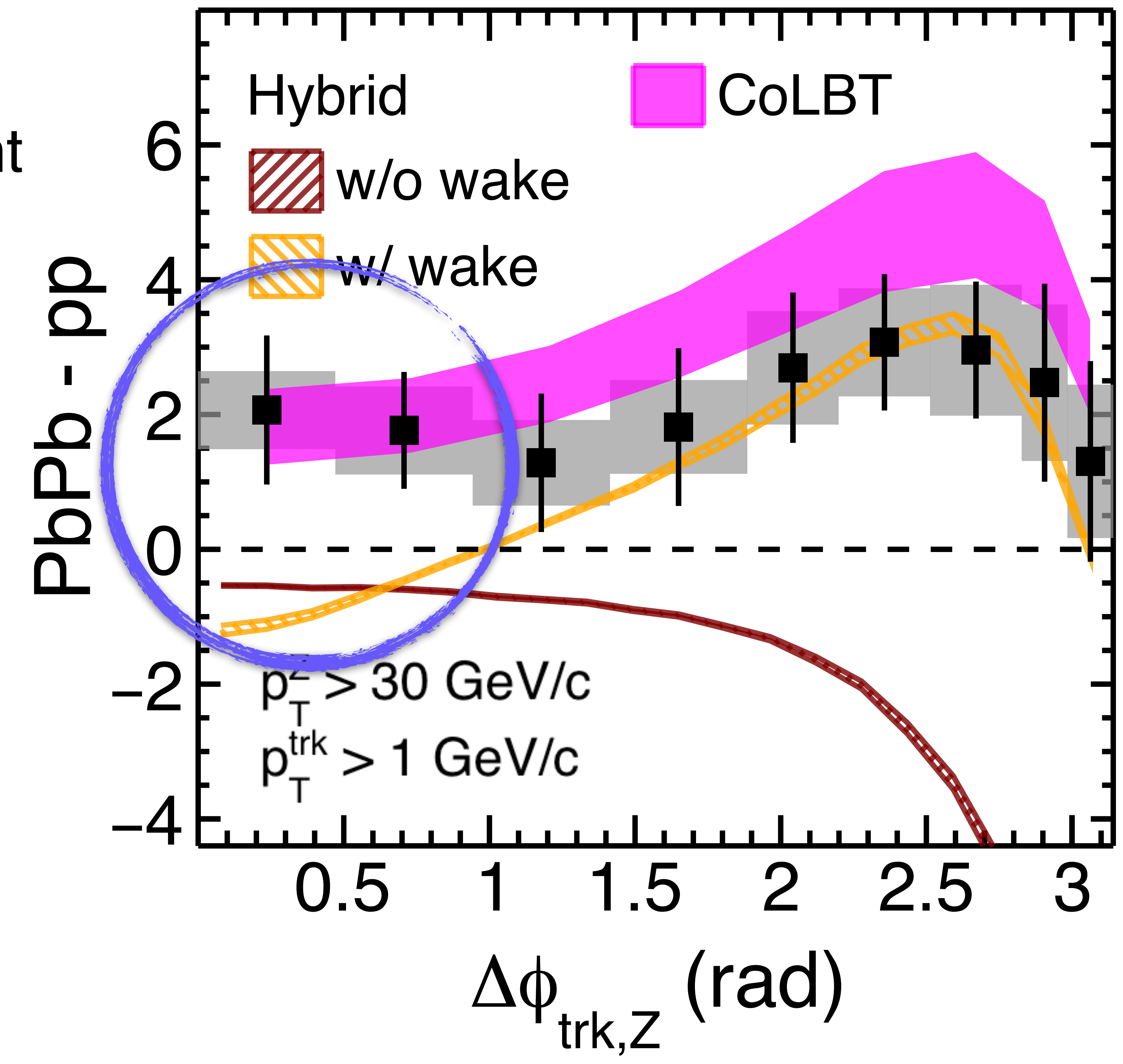


Looking for Diffusion Wake in Photon-Jet events

- CoLBT model predicts overall enhancement from multi-parton interaction (MPI)



PRL 128 (2022) 122301



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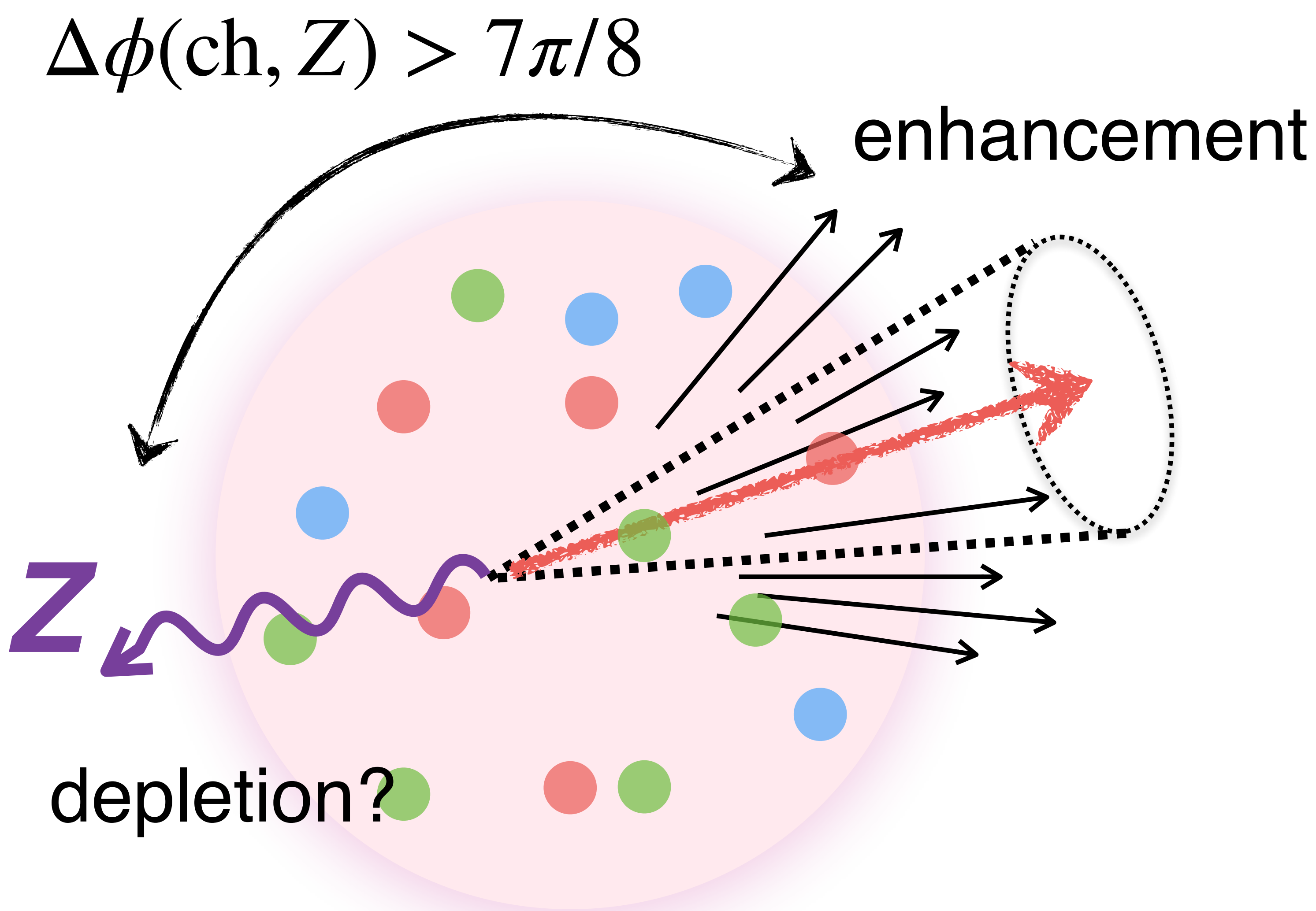
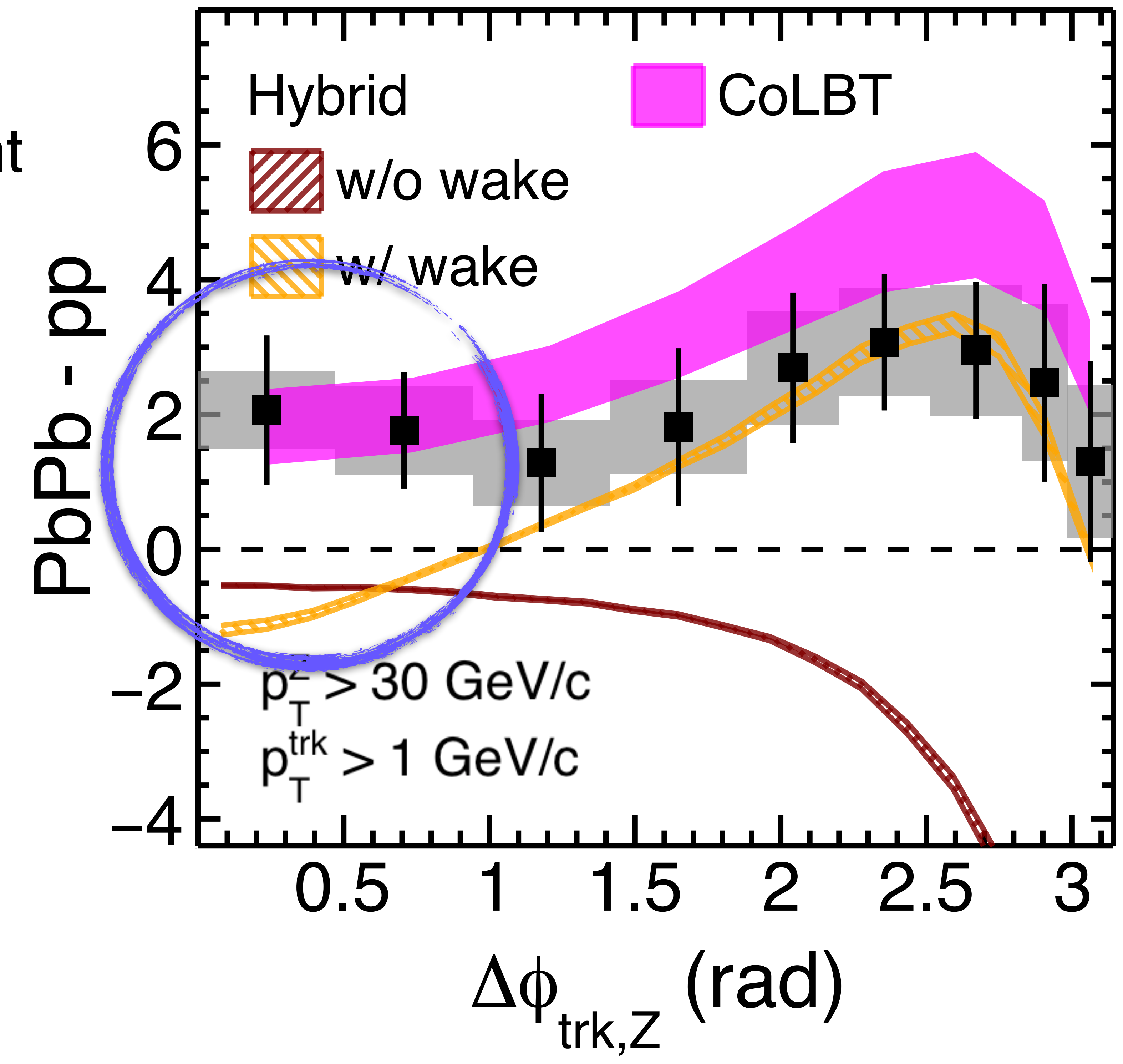
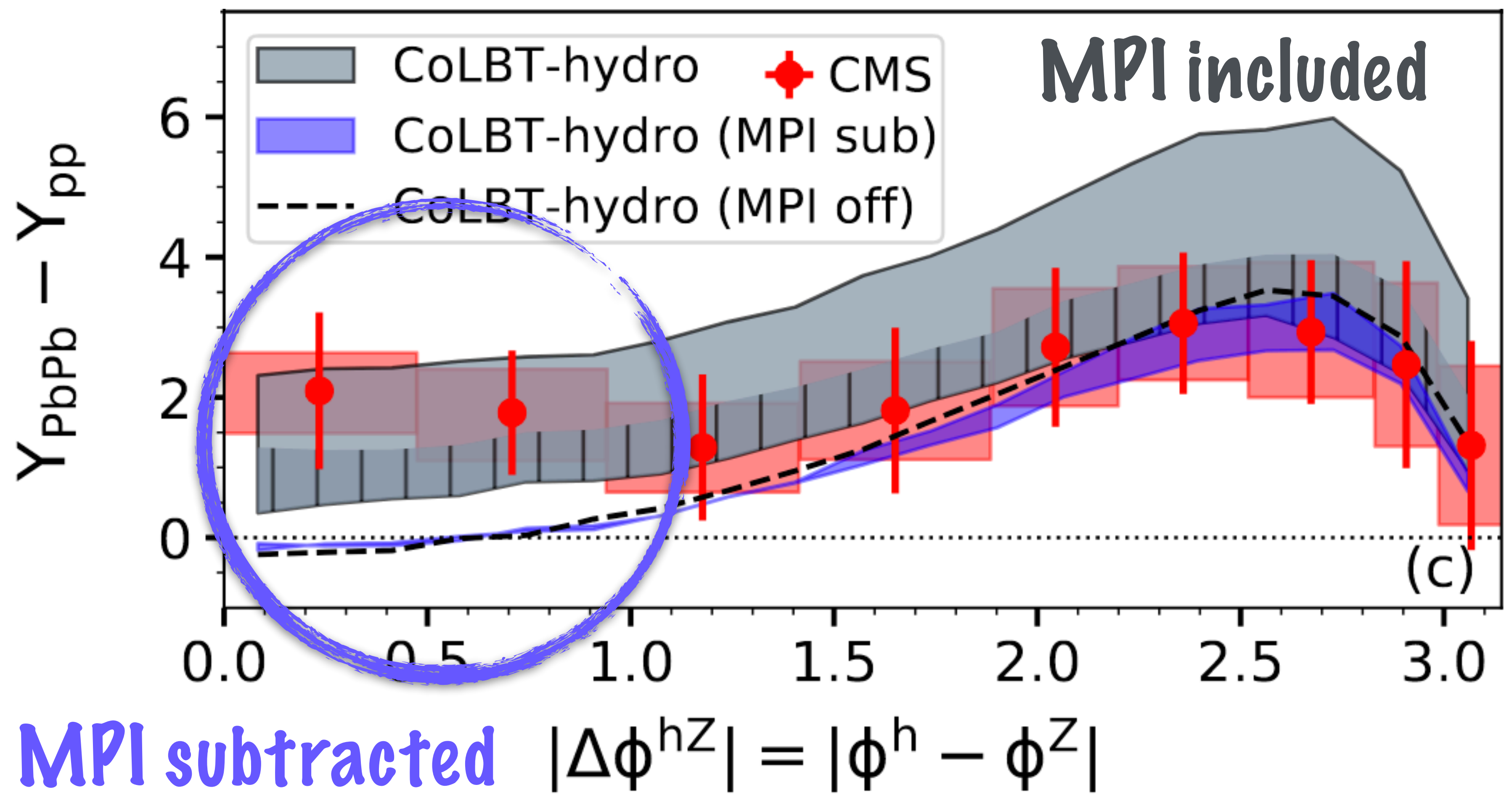


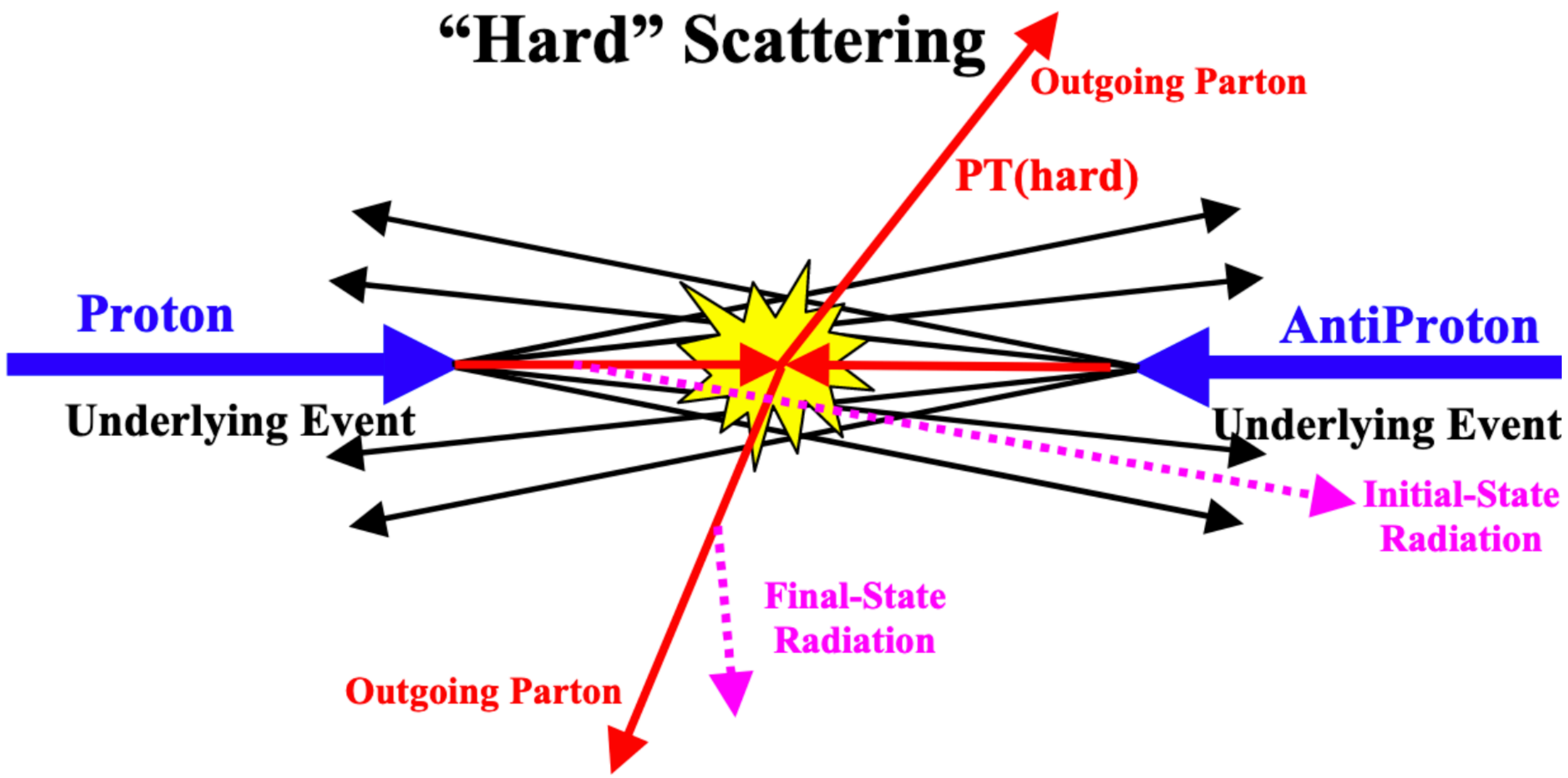
PRL 128 (2022) 122301

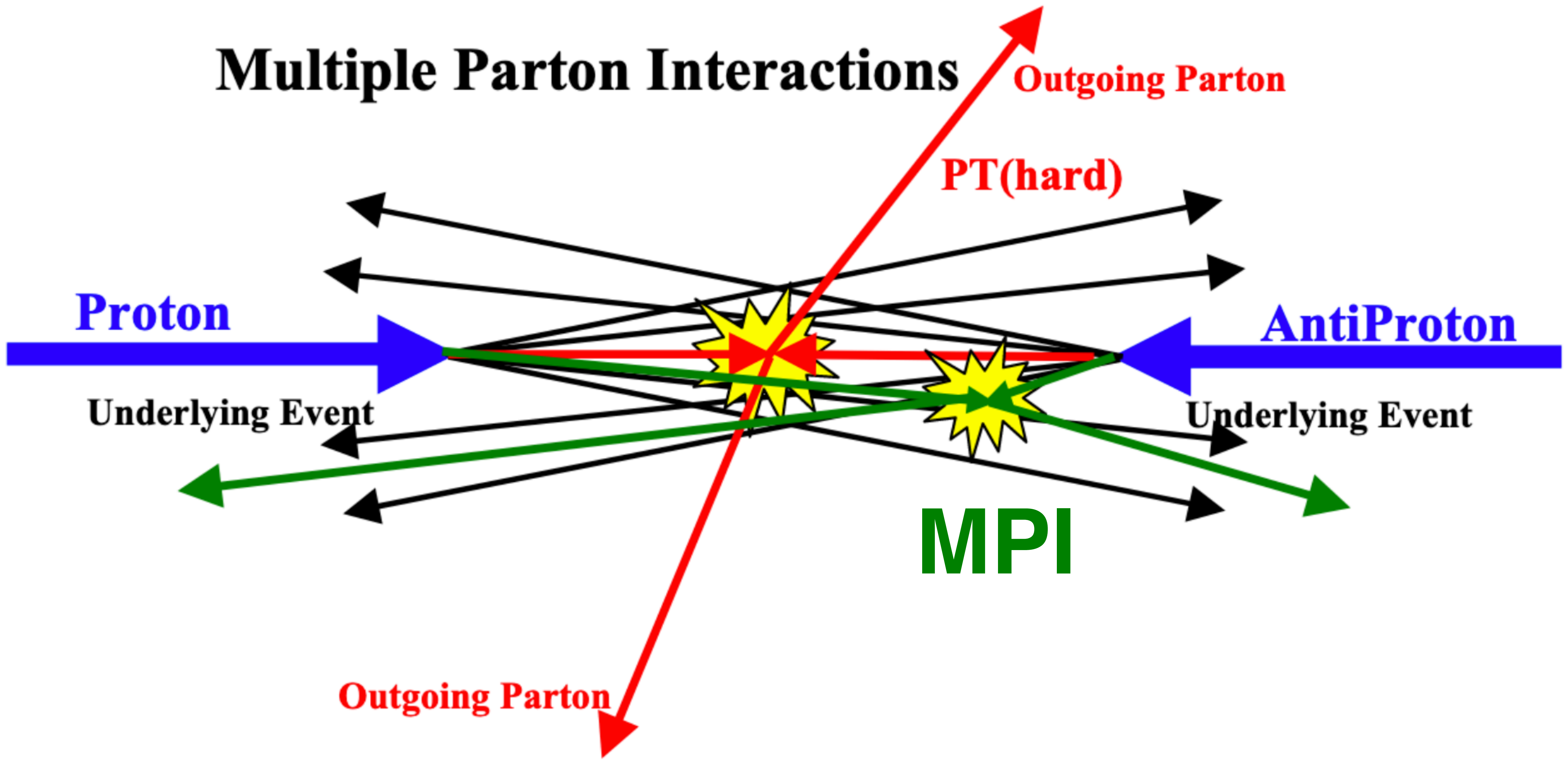


PRL 127 (2021) 082301



Multi Parton Interaction (MPI)

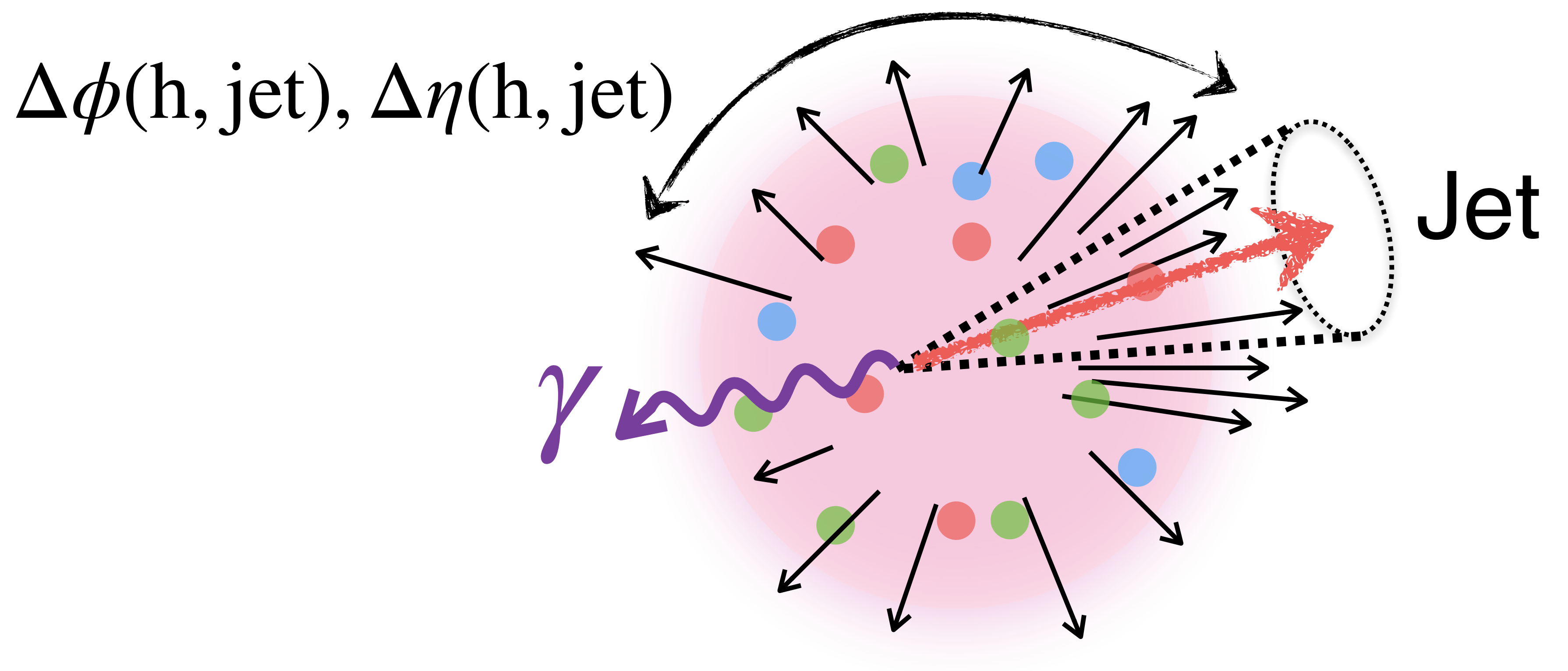


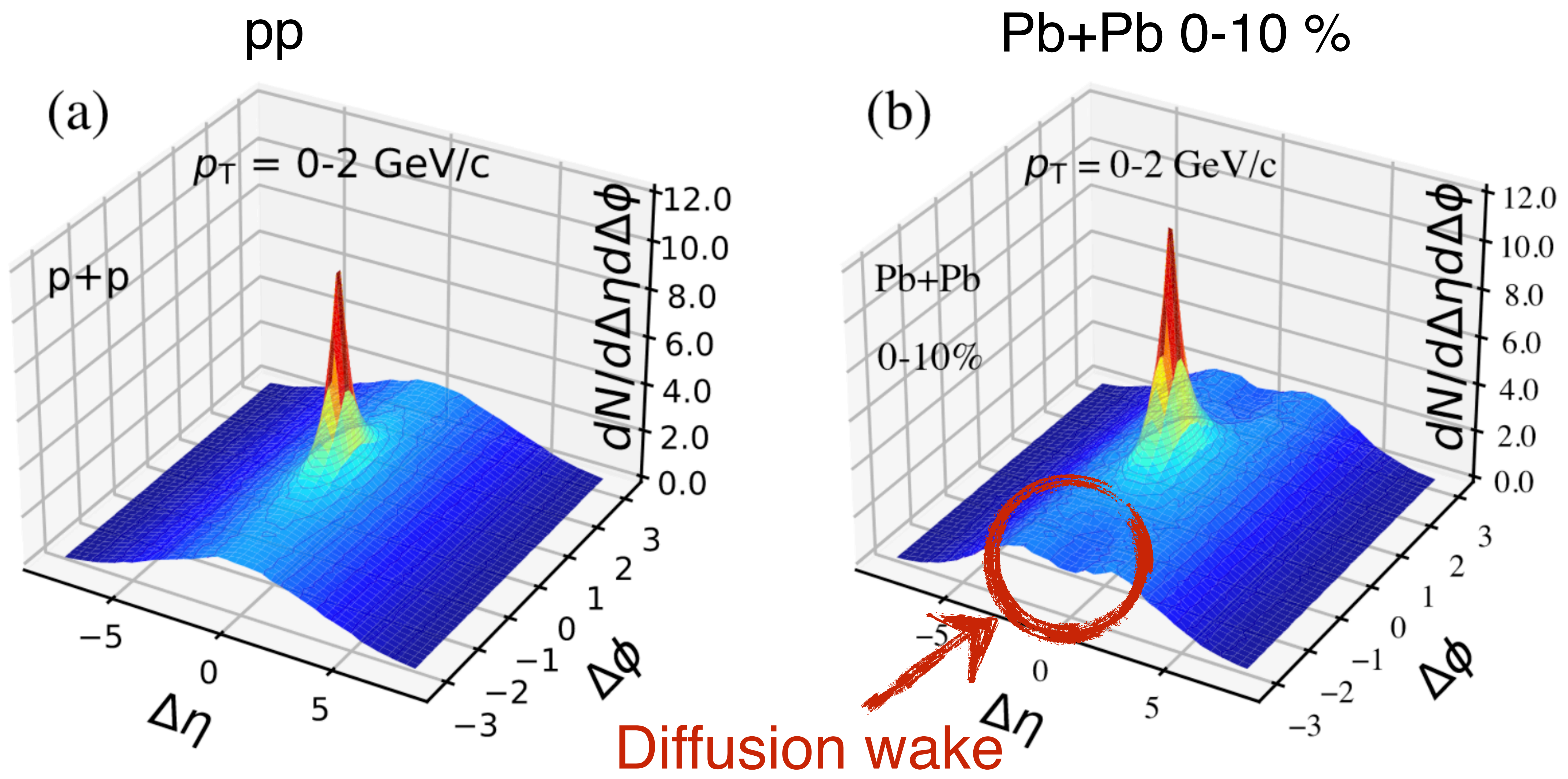


- **Multi Parton Interaction**
  - ➡ additional "semi-hard" parton-parton scattering from the incoming nucleons;
  - ➡ underlying events in pp collisions

3D Jet-Hadron Correlation in Photon-Jet Events

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





PRL 130, 052301 (2023)

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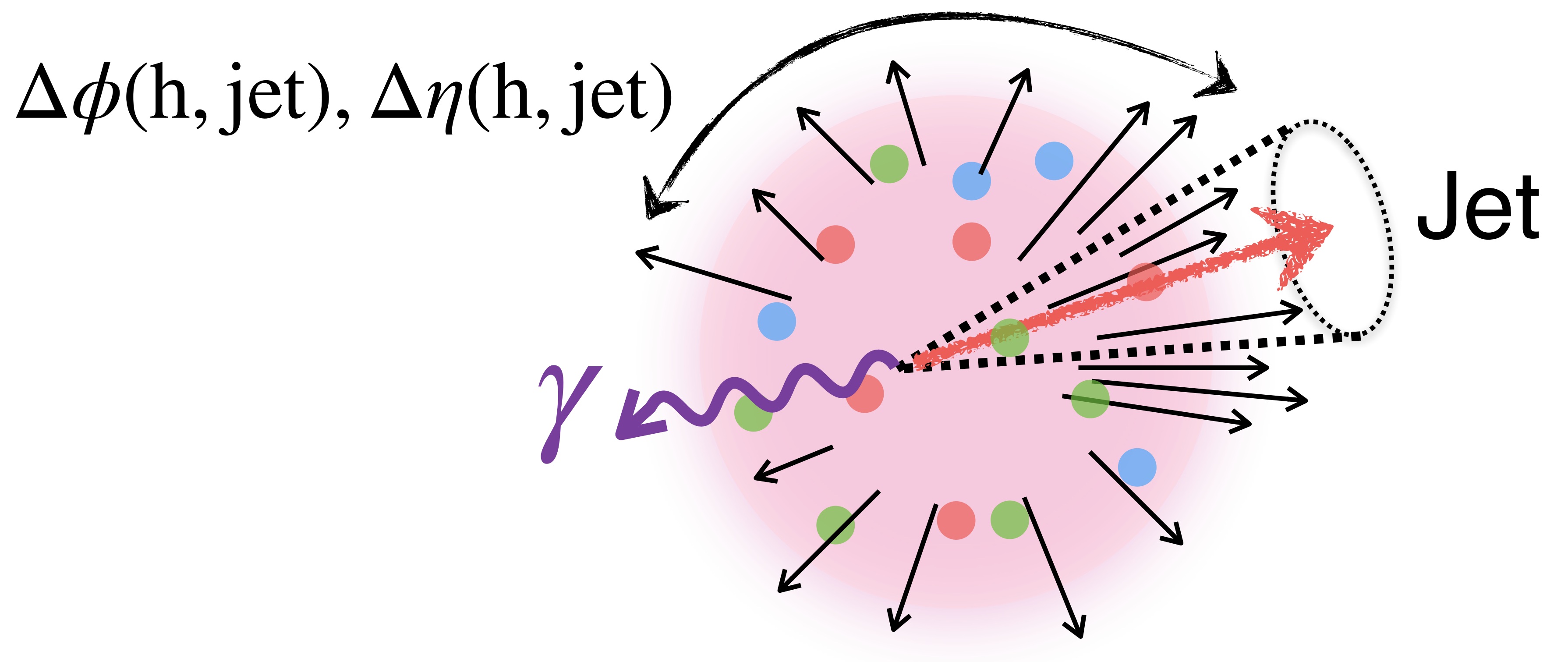
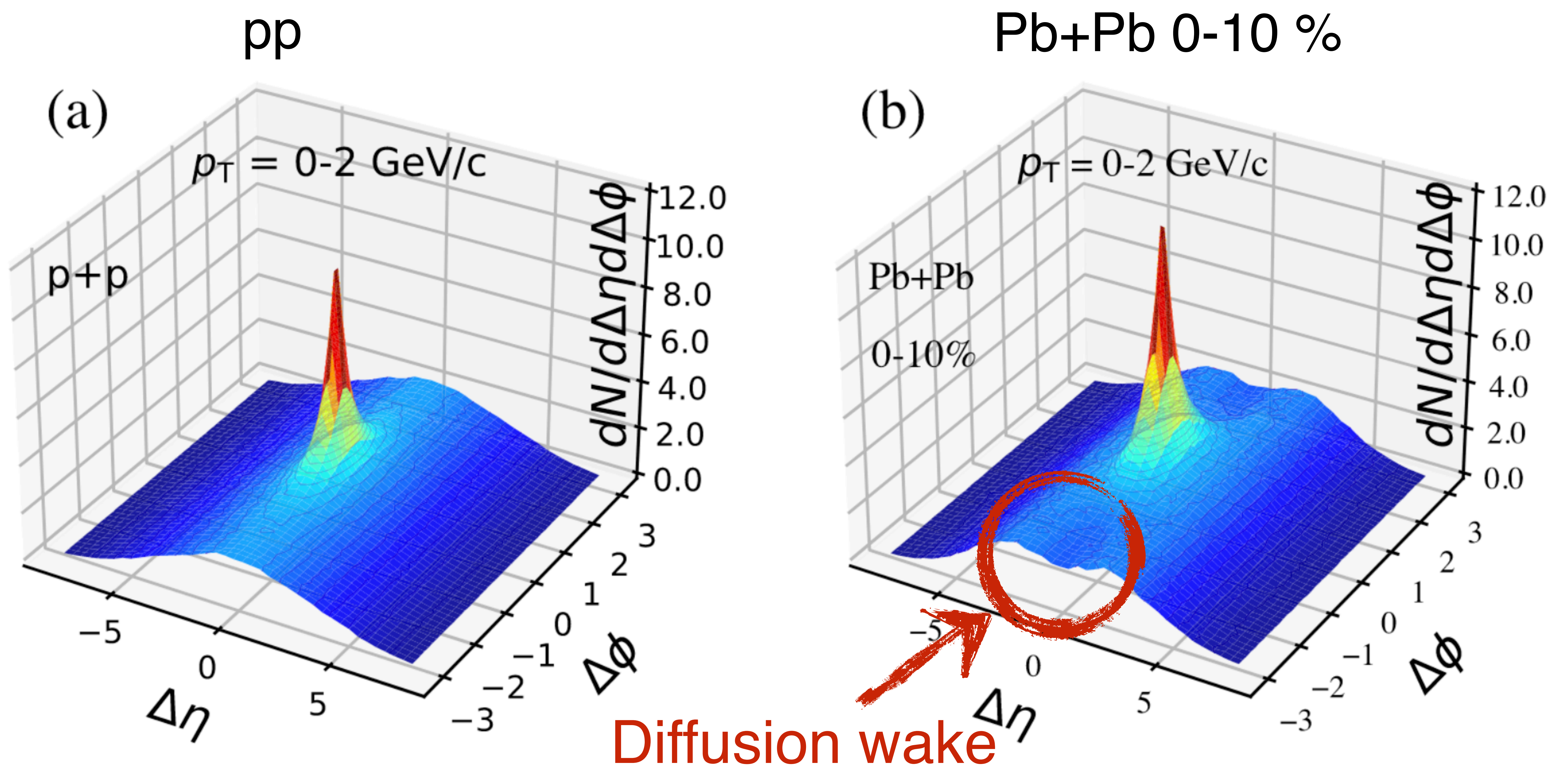
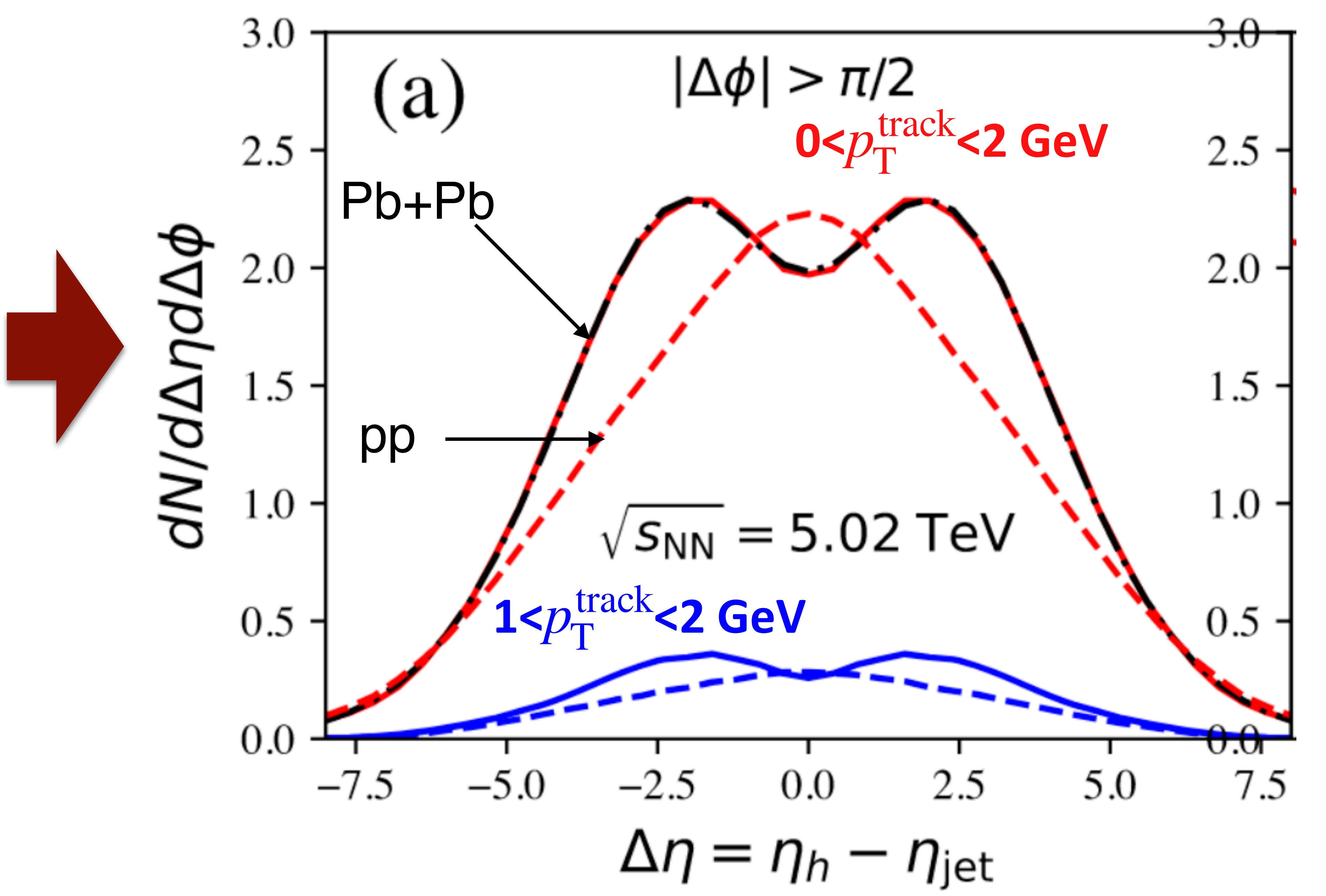


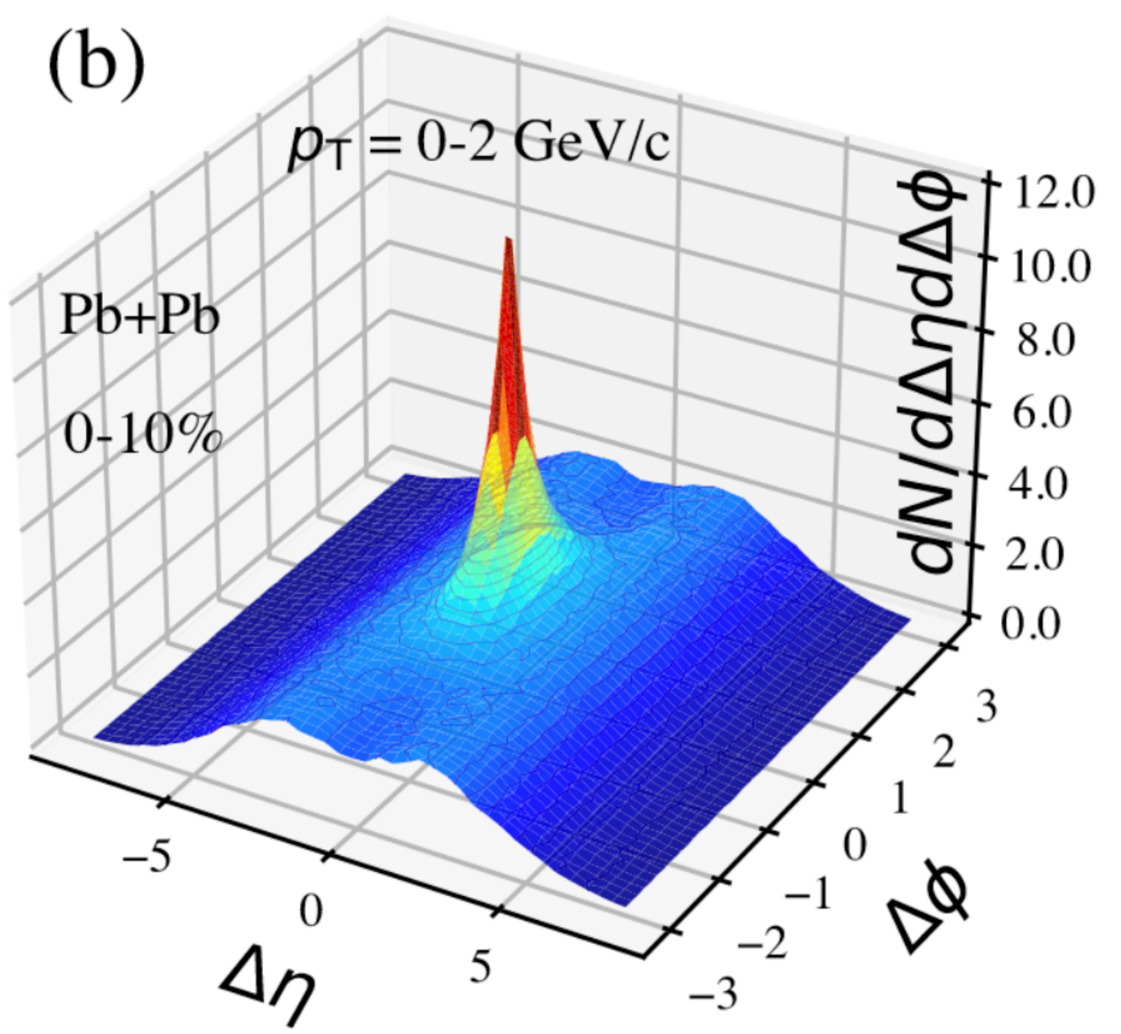


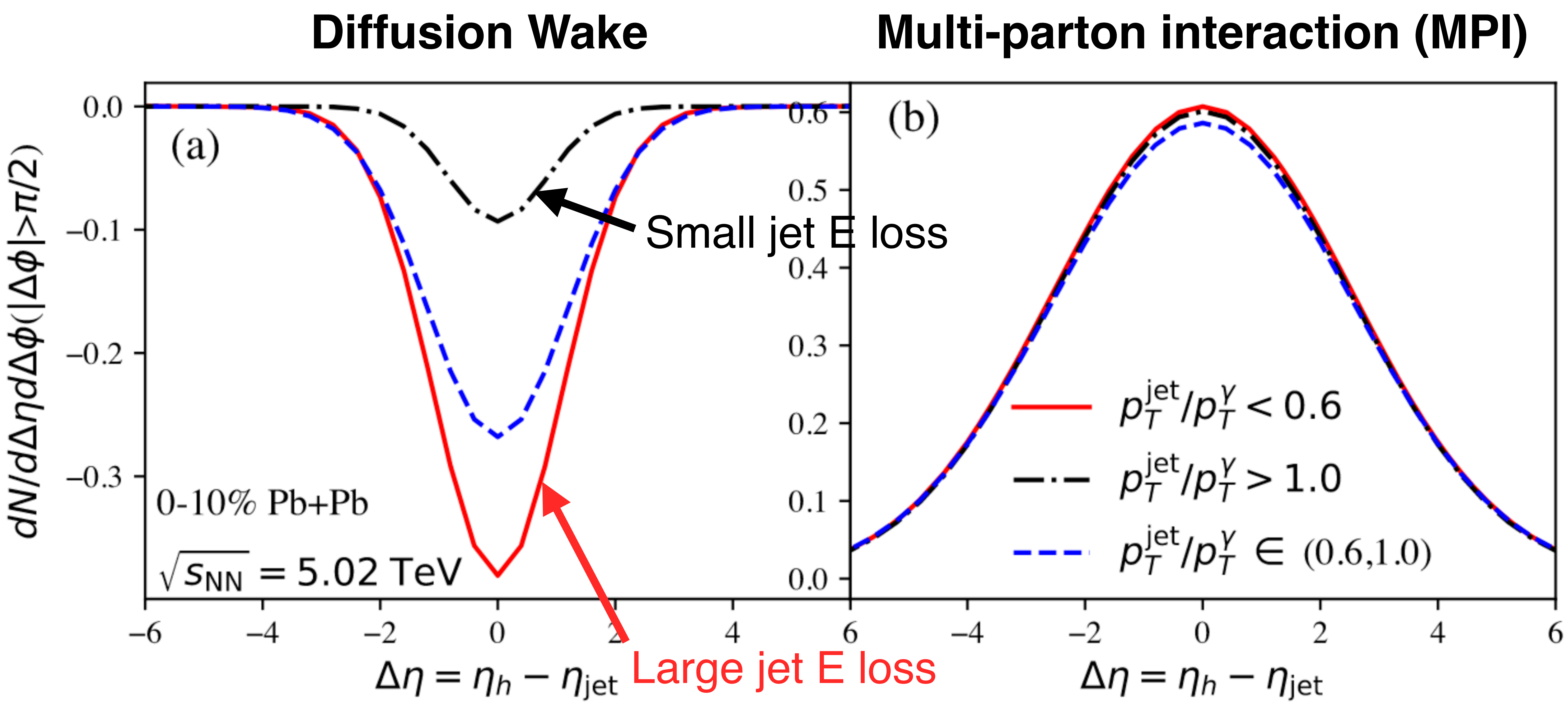


PRL 130, 052301 (2023)

Diffusion Wake: Dependence on Jet Energy Loss

PRL 130, 052301 (2023)

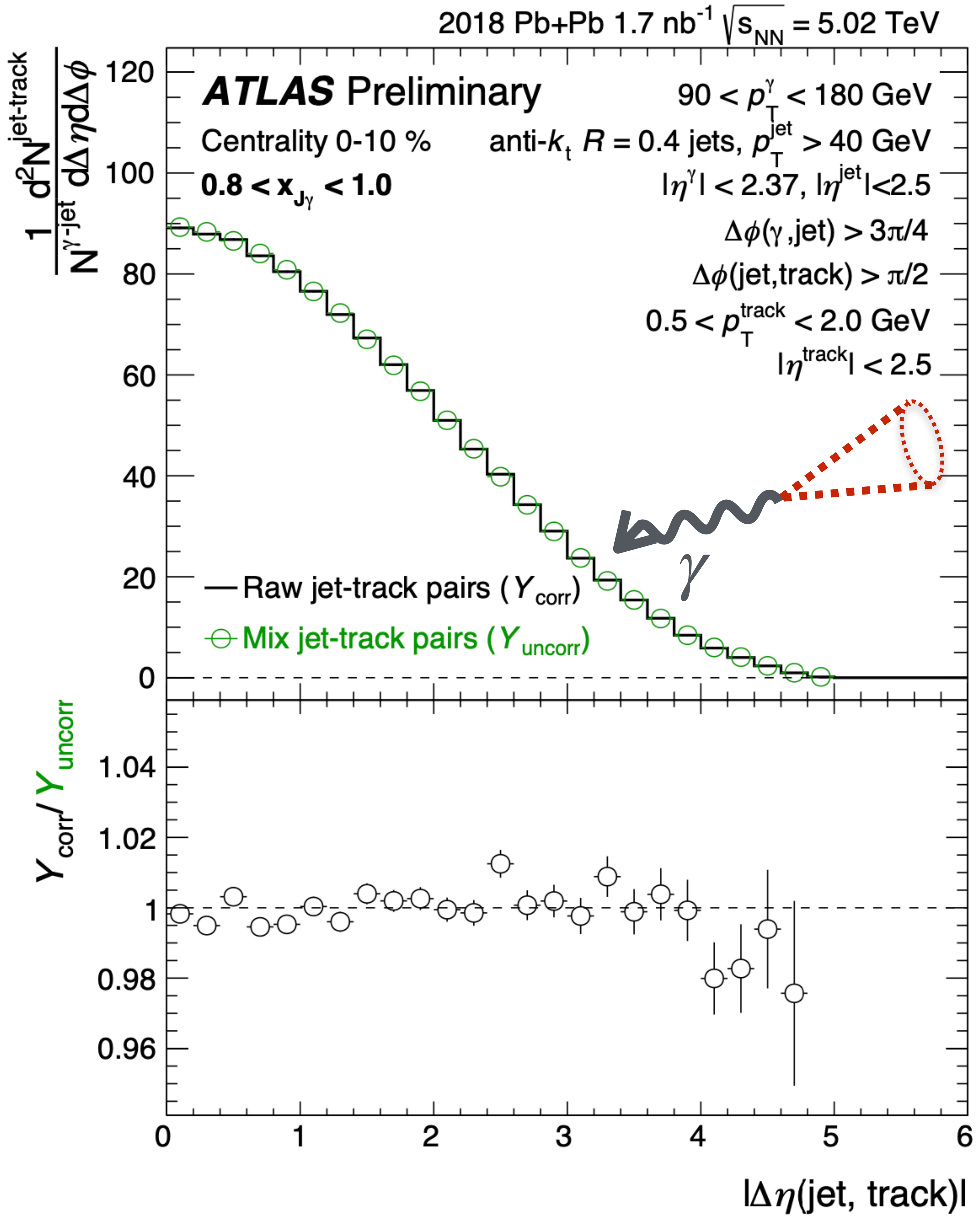




- Smaller $x_{J\gamma} = p_T^{jet}/p_T^{\gamma}$ means larger jet energy loss and longer path through the medium and hence larger medium response i.e., diffusion wake
- However, the MPI signal has no significant dependence on the $x_{J\gamma}$, while the diffusion wake does

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

$0.8 < x_{J\gamma} < 1.0$

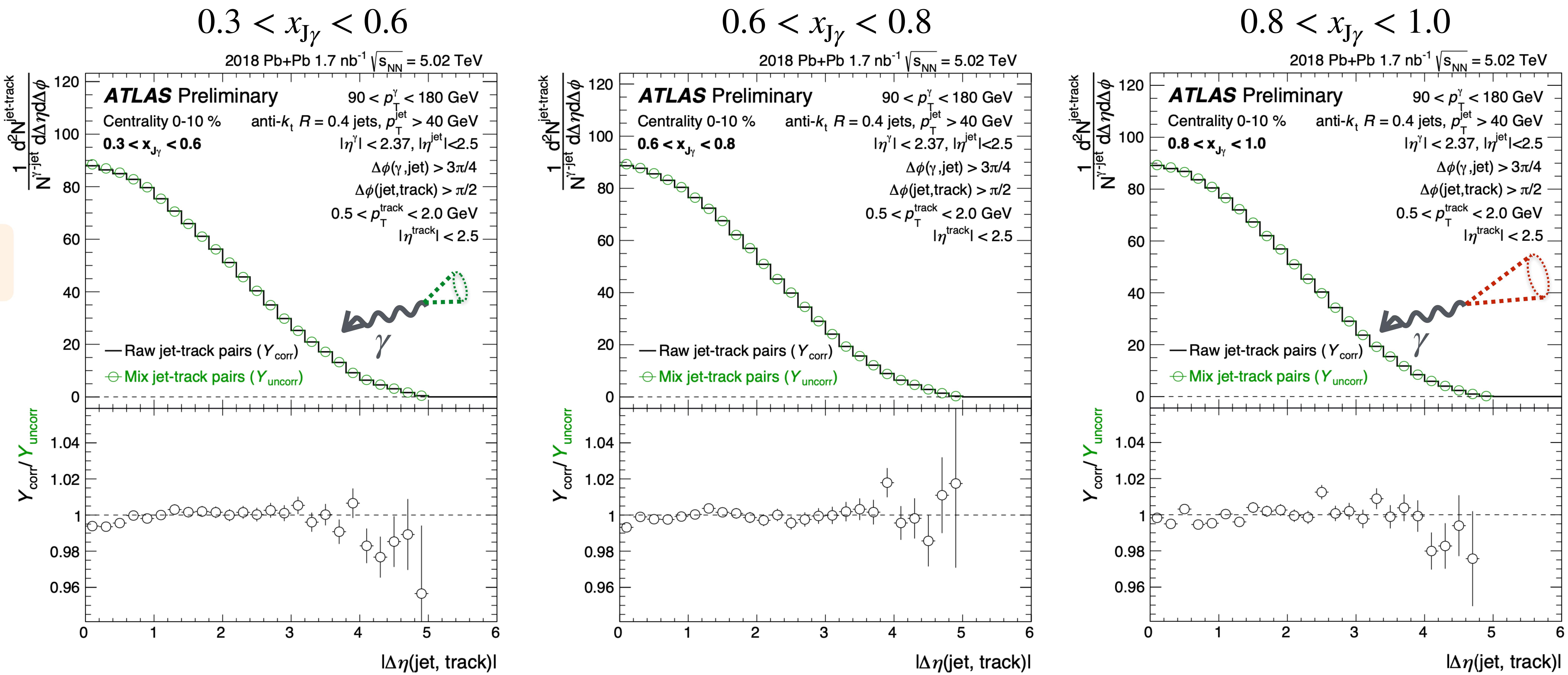


$x_{J\gamma} = p_T^{jet}/p_T^{\gamma}$

- 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 $|\Delta\eta(\text{jet, track})|$ 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

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

$x_{J\gamma} = p_T^{jet}/p_T^{\gamma}$



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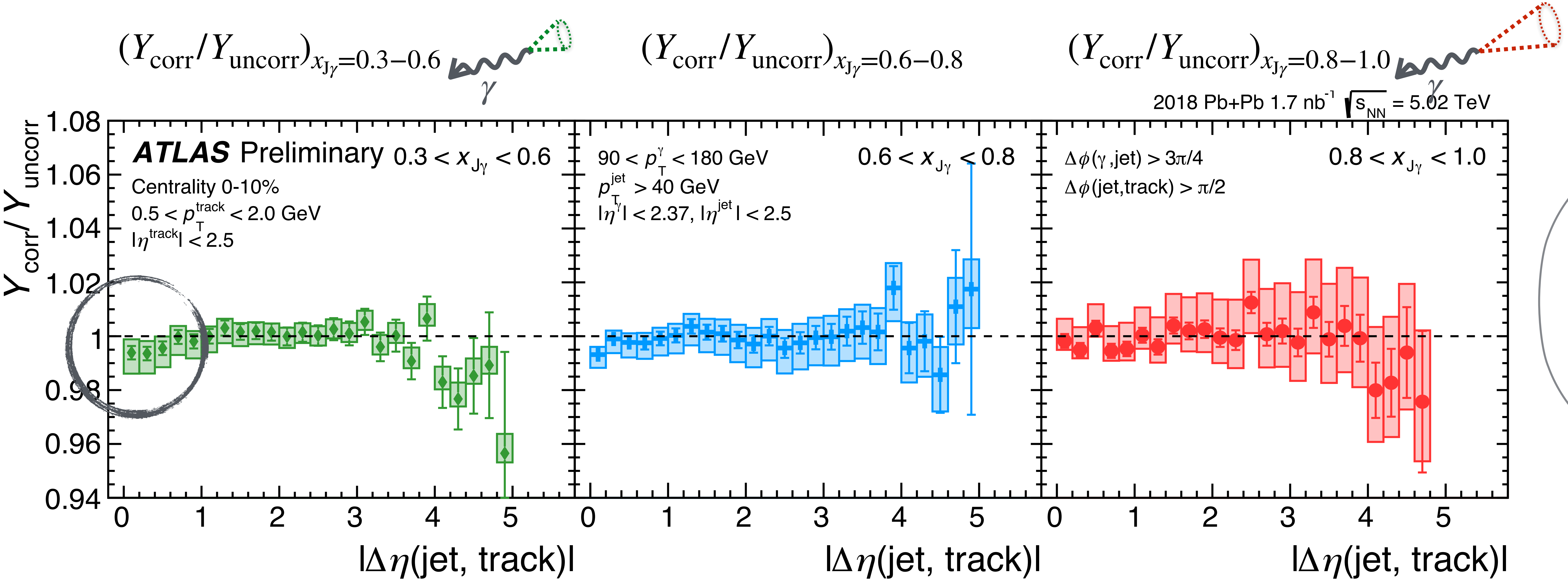
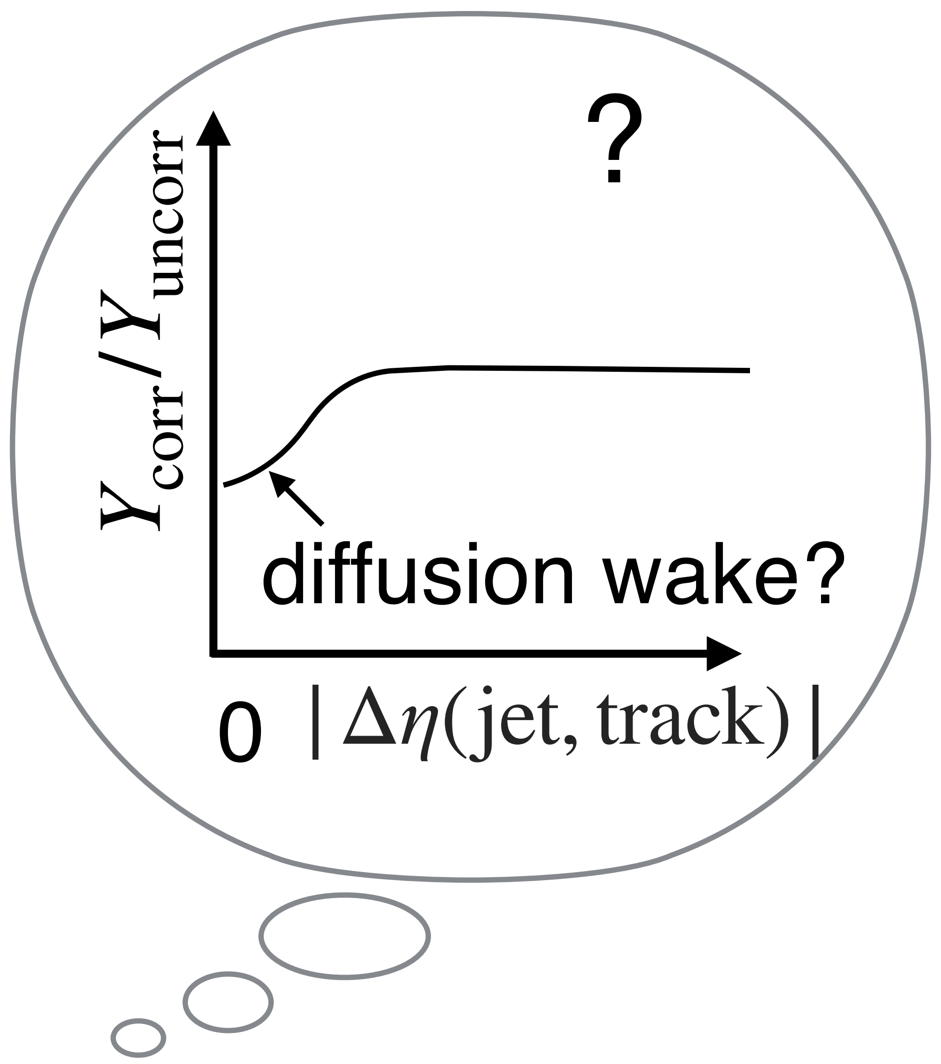
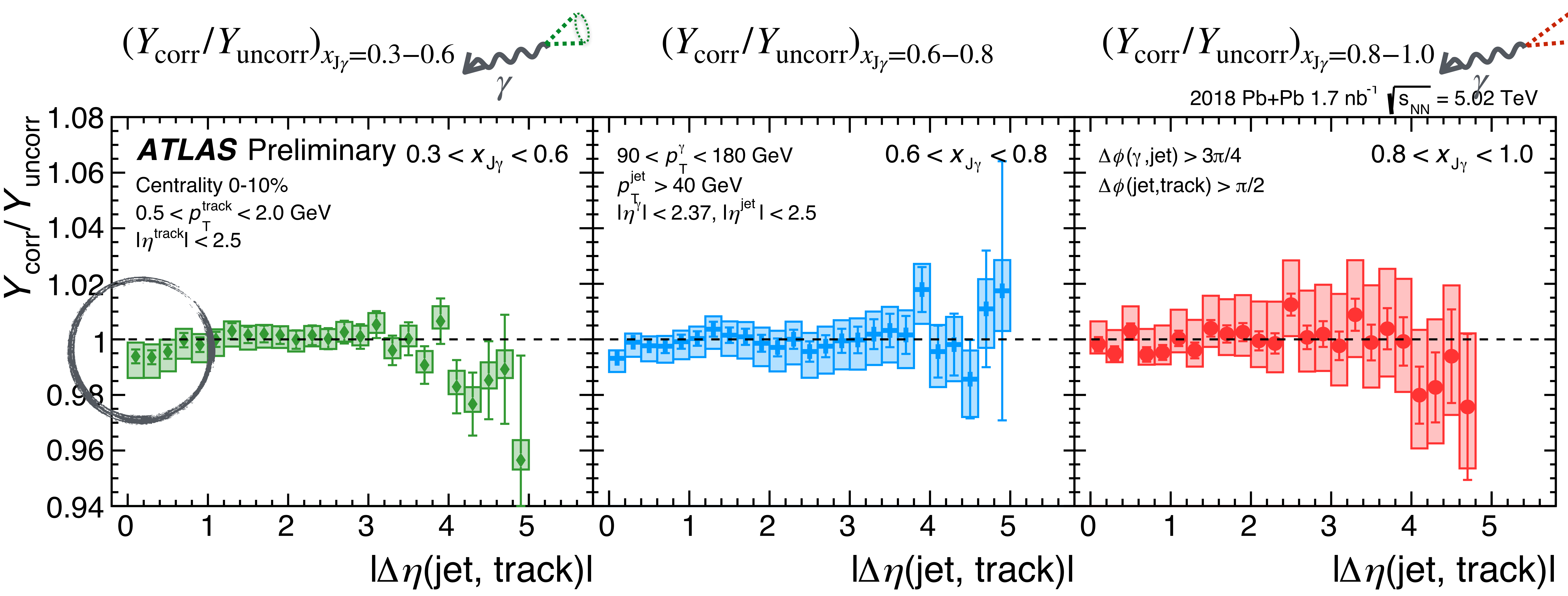
Relative Yield Ratio Y_{corr}/Y_{uncorr}

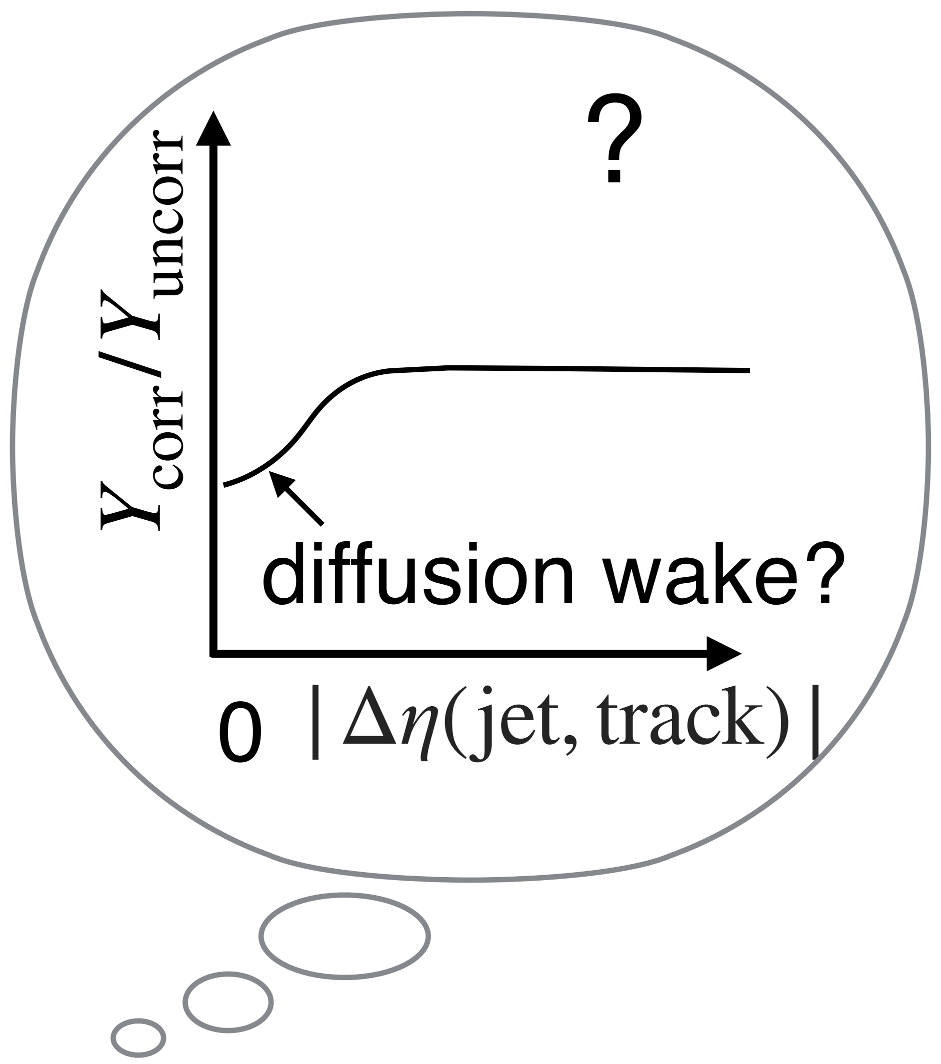




- No clear diffusion wake signal found within uncertainties for all three $x_{J\gamma}$ regions

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



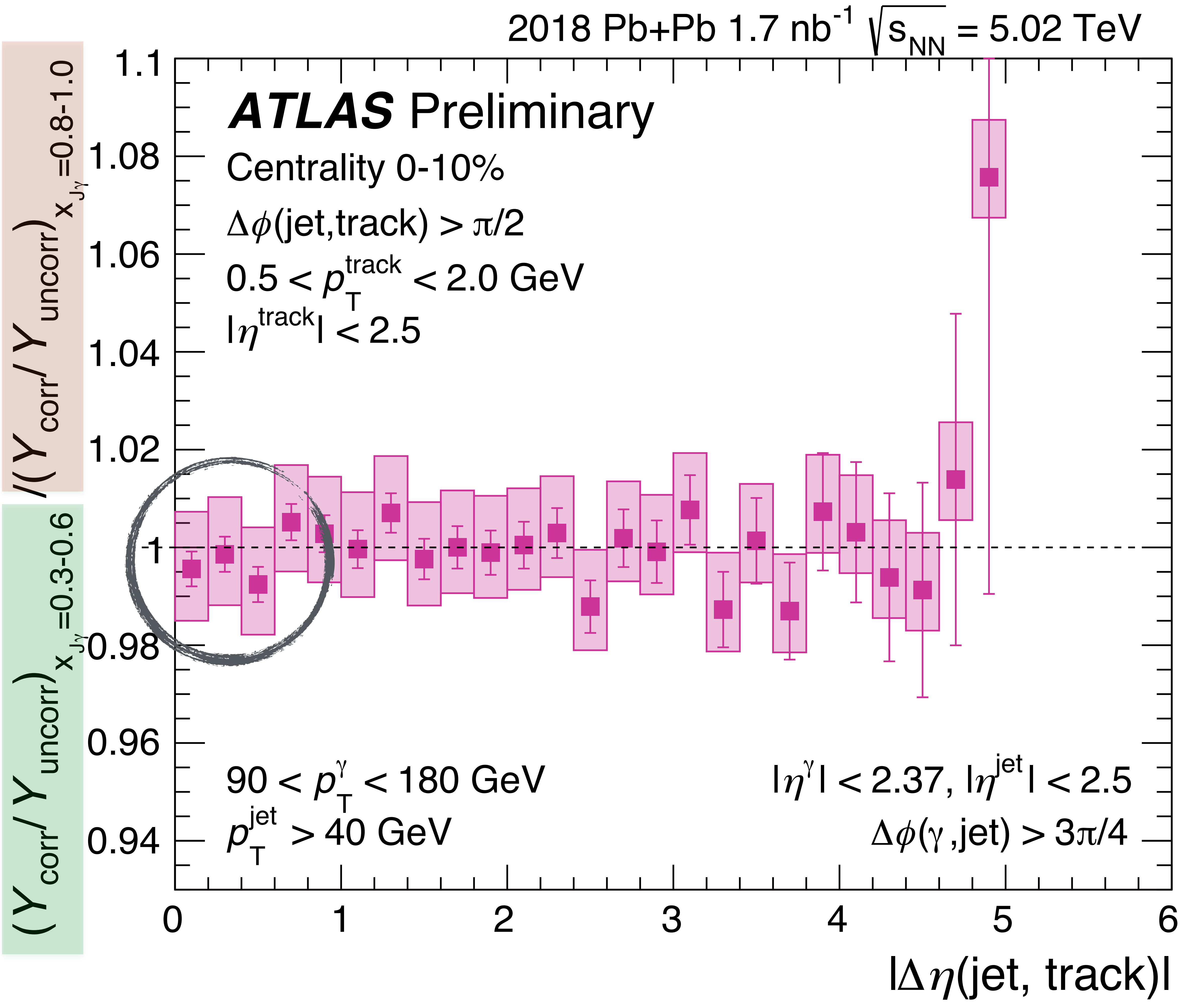


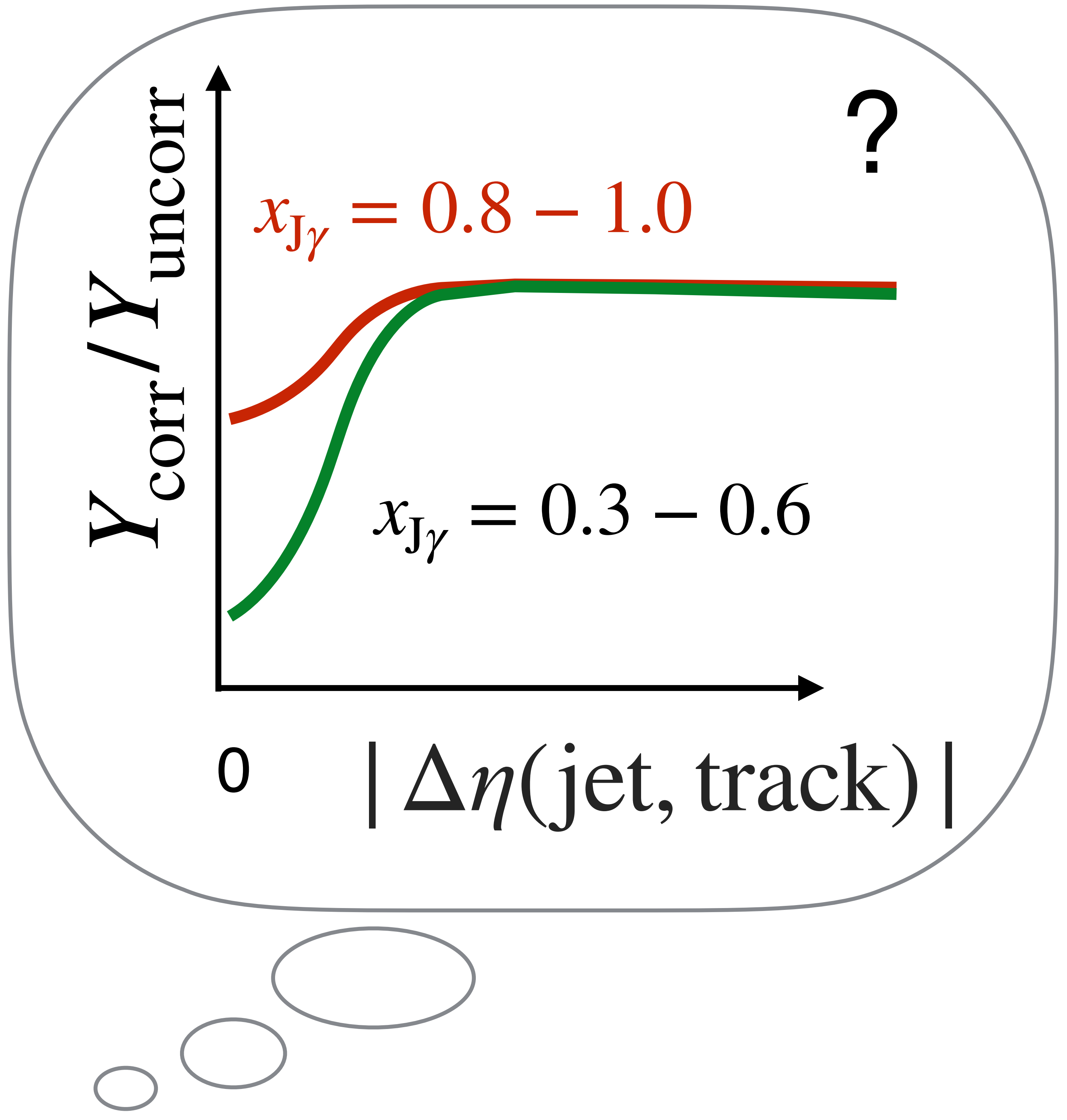
$$Y_{corr} = \frac{1}{N^{\gamma-\text{jet}}} \frac{d^2N^{\text{jet-track}}}{d\Delta\eta d\Delta\phi}$$

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

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

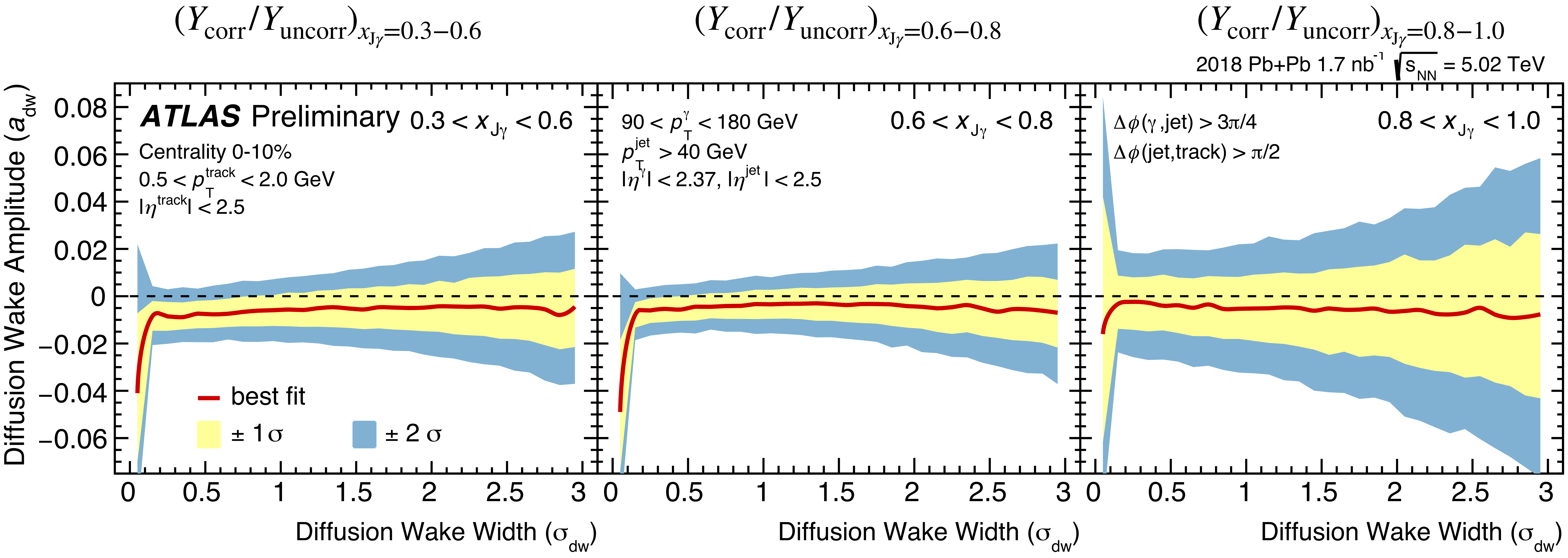
Double Ratio $(Y_{corr}/Y_{uncorr})_{x_{J\gamma}=0.3-0.6}/(Y_{corr}/Y_{uncorr})_{x_{J\gamma}=0.8-1.0}$

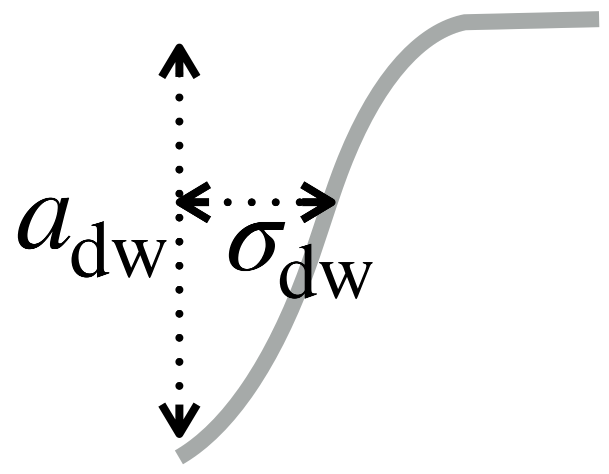


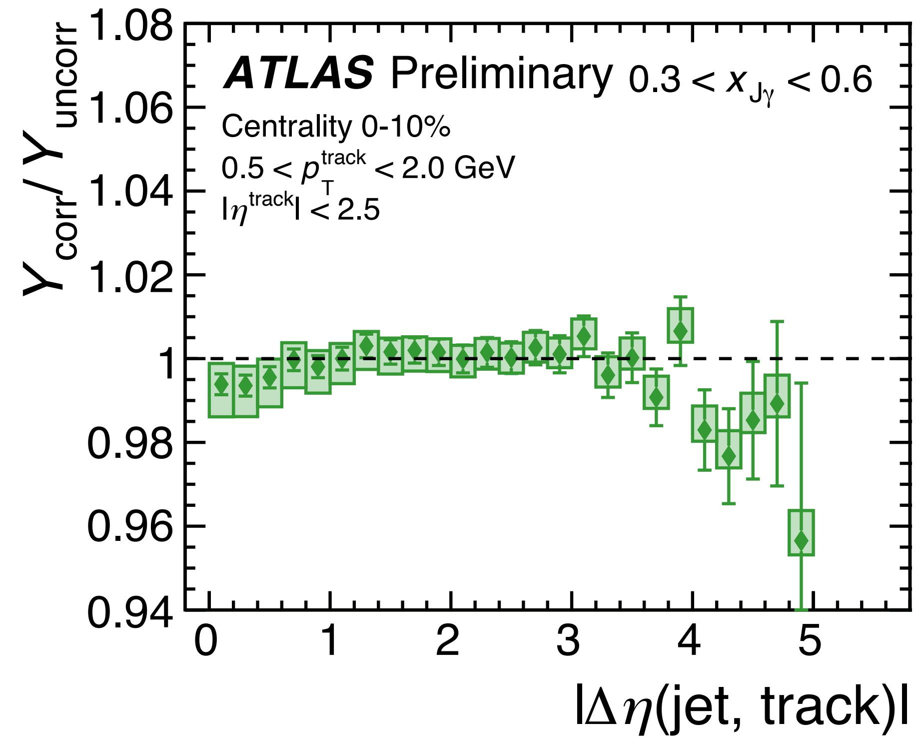


- No clear $x_{J\gamma}$ dependence found in the diffusion wake signal within uncertainties

Probability Distribution of Diffusion Wake







- Monte Carlo sampling method
  ➡ Statistical and systematic uncertainties and their correlations are considered
- 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

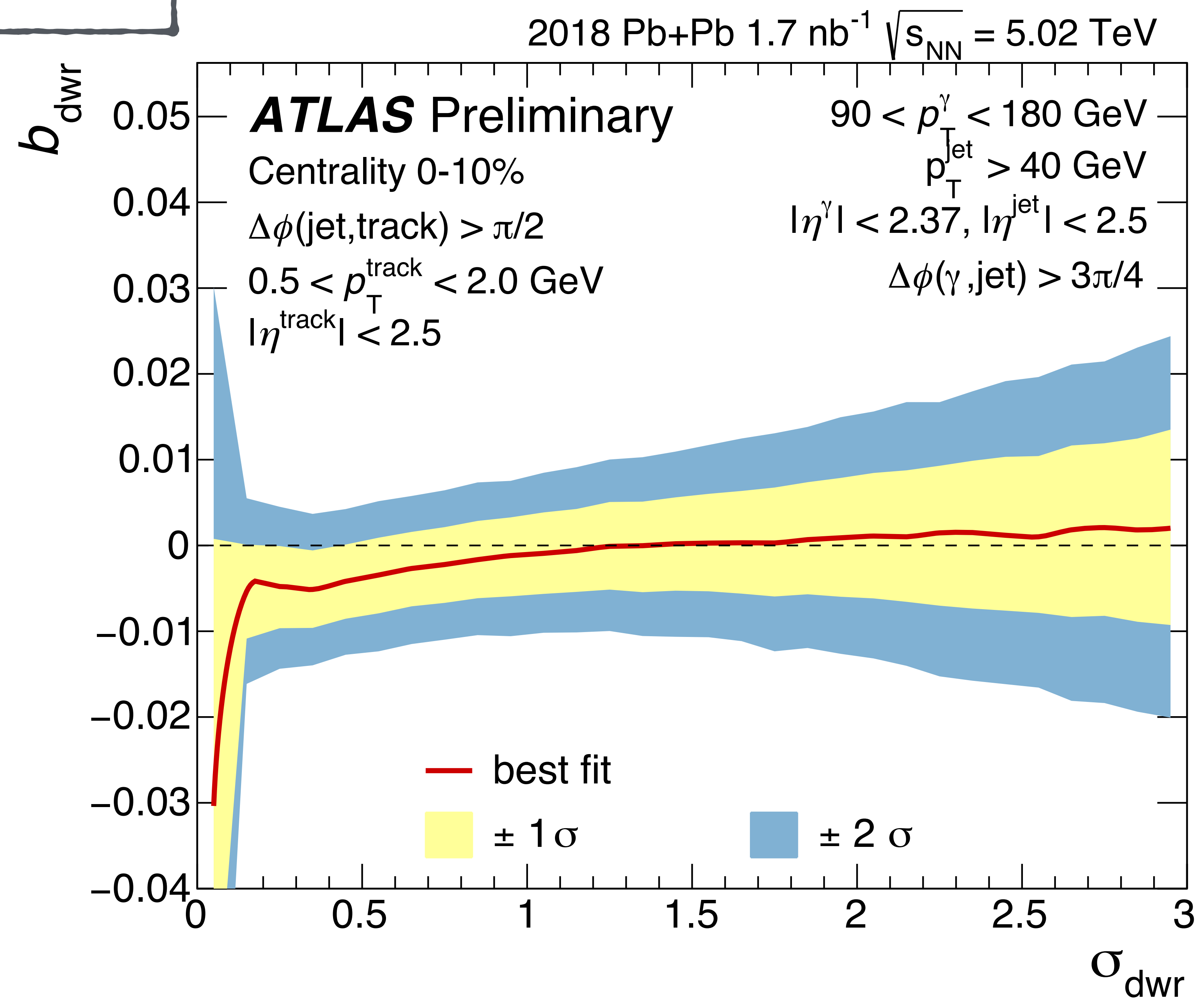
$$a_0 + a_{dw} \cdot e^{-|\Delta\eta(\text{jet,track})|^2/(2\sigma_{dw}^2)}$$

Diffusion Wake Double Ratio Amplitude

Double Ratio Amplitude Double Ratio Width

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

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

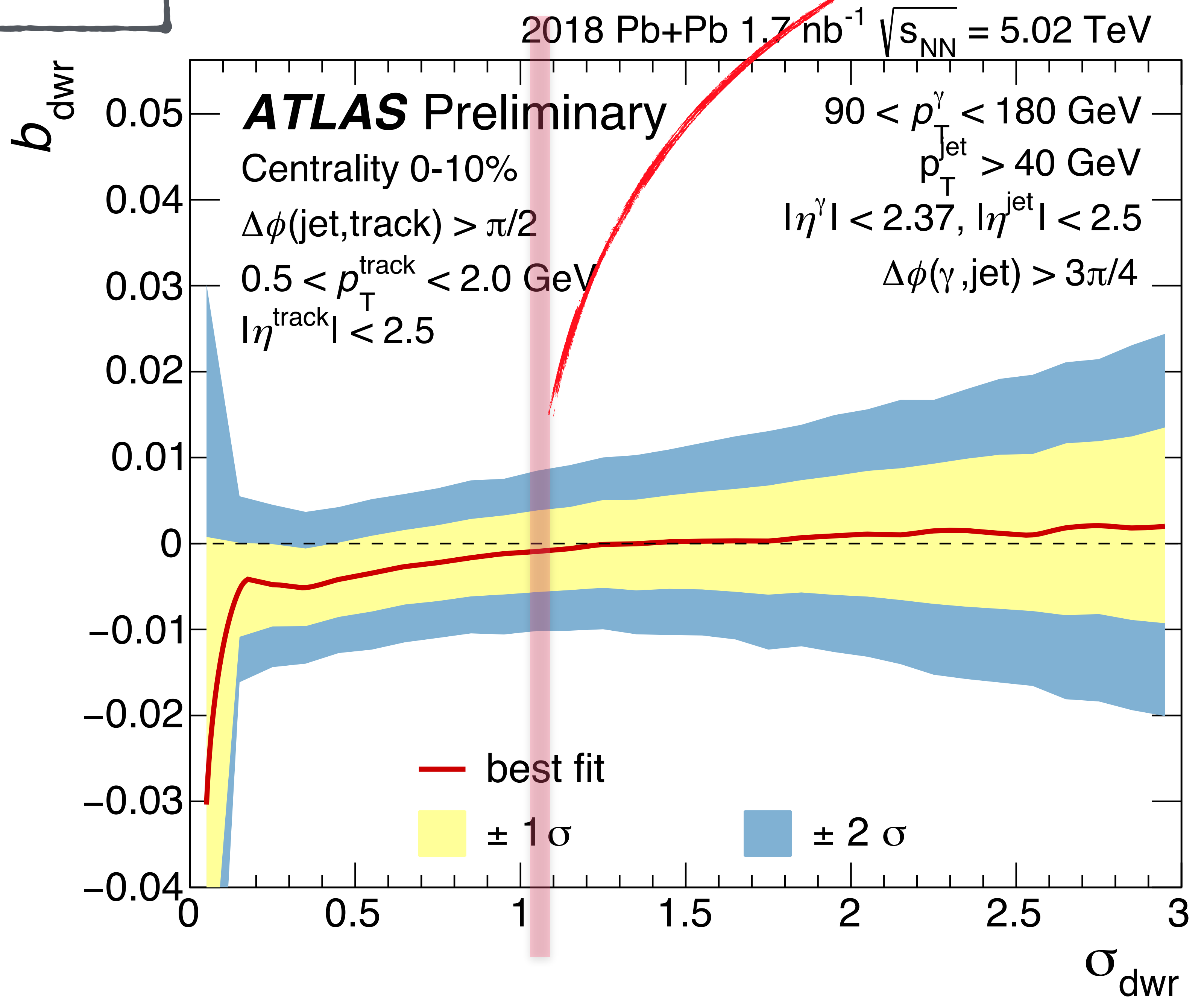


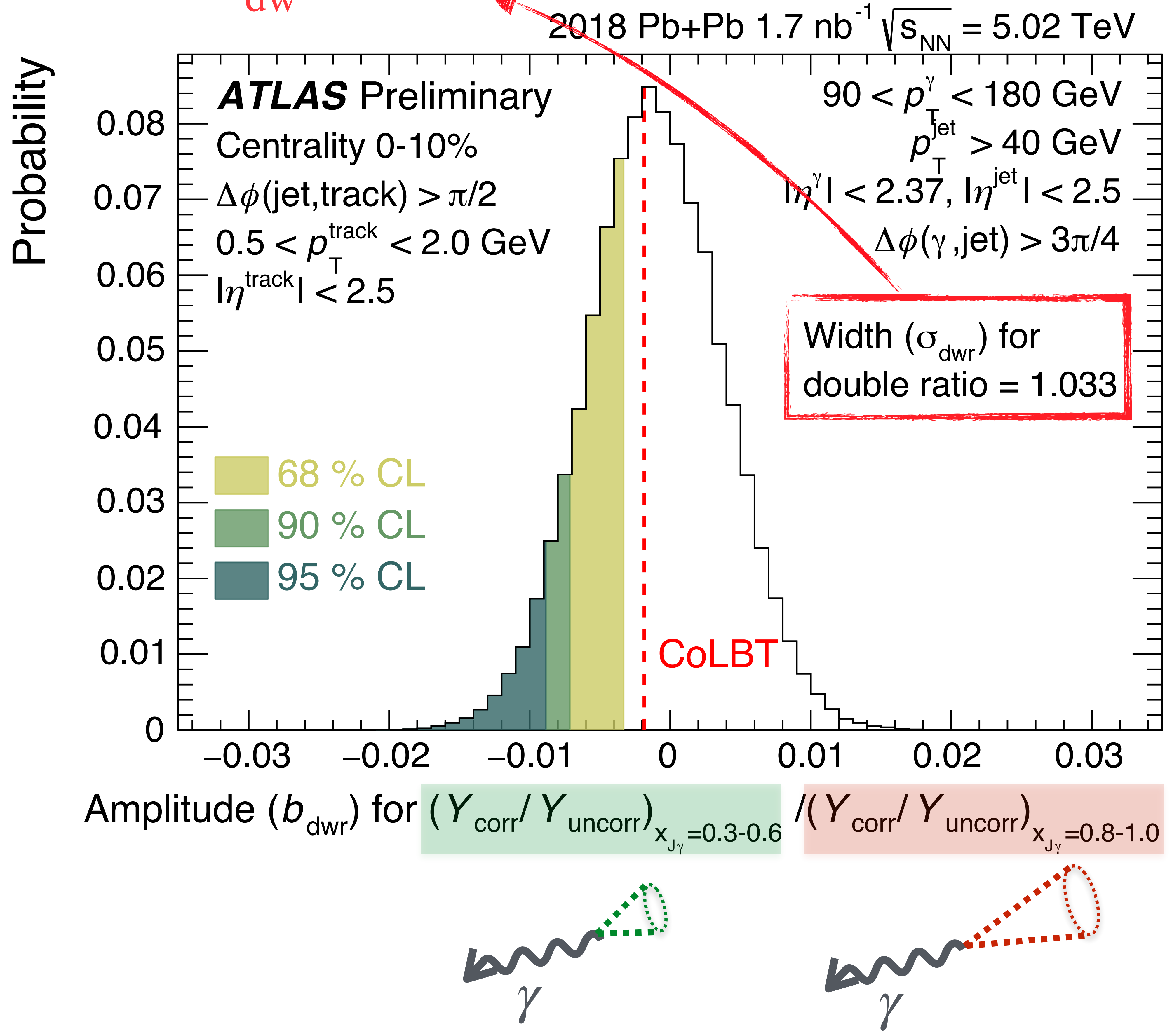
Diffusion Wake Double Ratio Amplitude

Double Ratio Amplitude   Double Ratio Width

$$b_0 + b_{\rm dwr} \cdot e^{-|\Delta\eta(\text{jet,track})|^2/(2\sigma^2_{\rm dwr})}$$

Prob. Dist. for width $\sigma_{\rm dw}$ = 1.033





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

- Data provides limits on double ratio amplitude ($|b_{\rm dwr}|$)
  - ➡ **95% CL upper limit** of **0.0095** does not rule out CoLBT prediction of 0.0018
  - ➡ Stat. uncert. dominates in probability distribution; more statistics will be valuable

“Unambiguous” Medium Response Measurement

- Medium excitation → change the chemical composition of particles via parton coalescence

"Unambiguous" Medium Response Measurement

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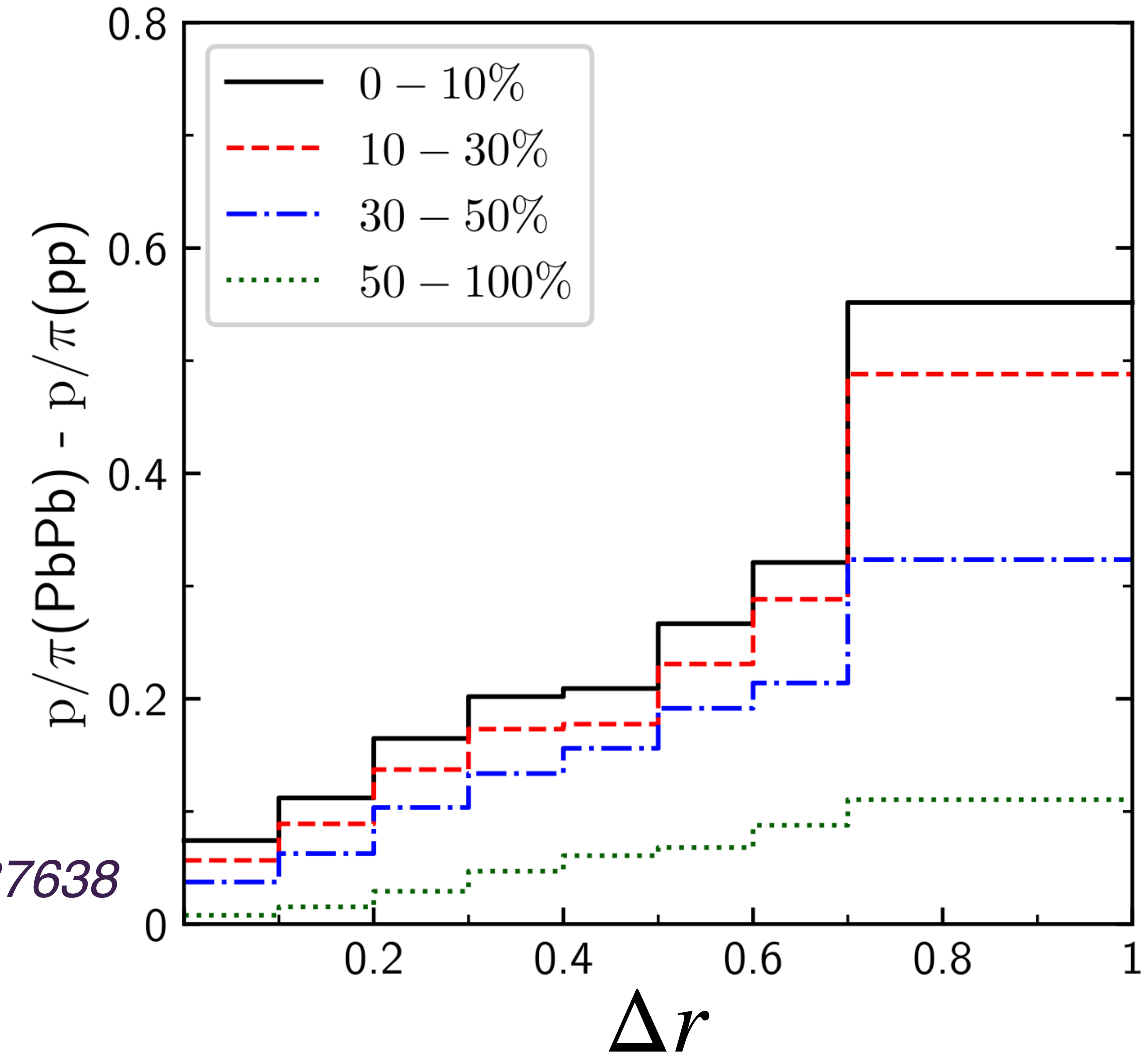
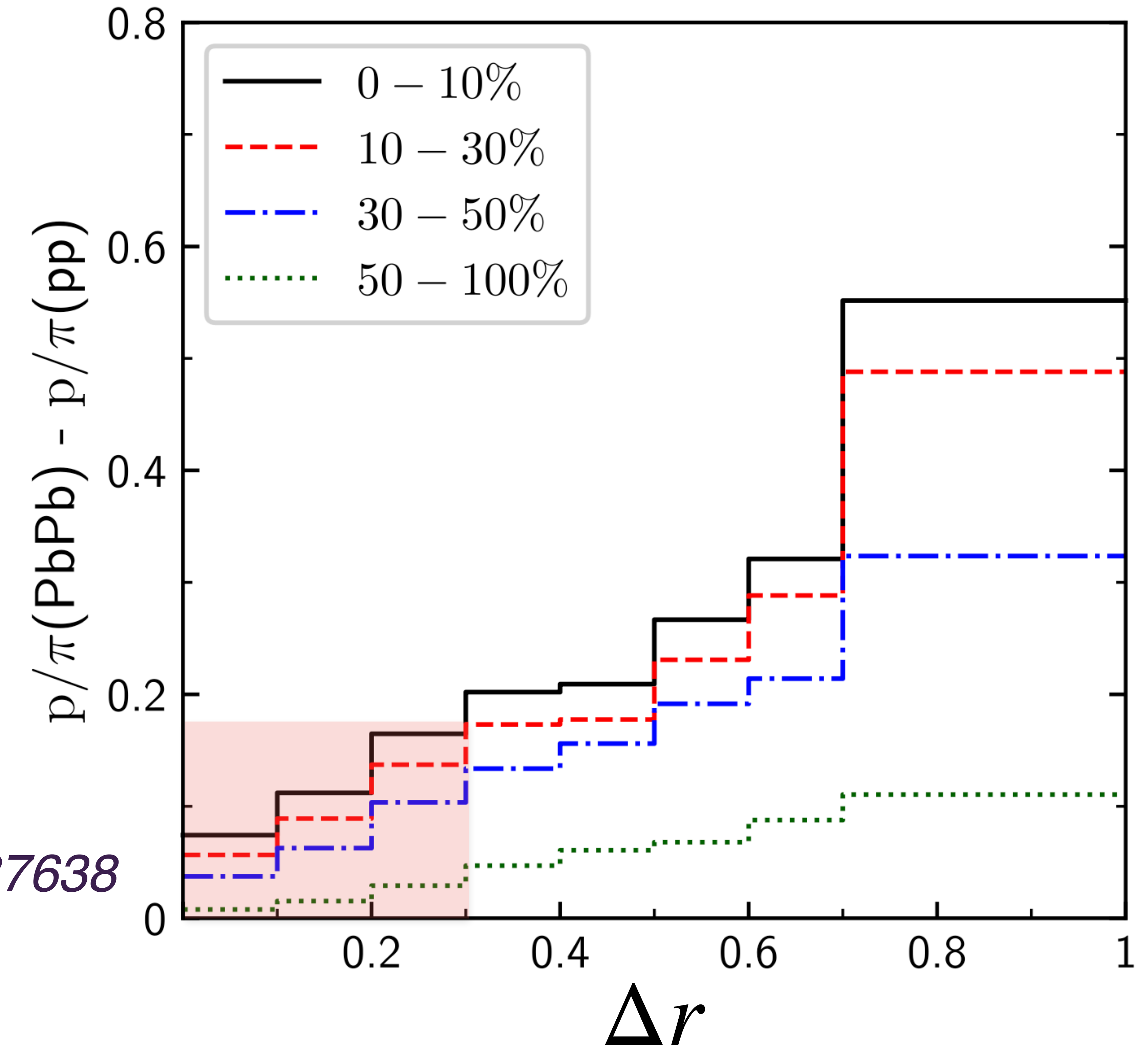


PLB 837 (2023) 137638

"Unambiguous" Medium Response Measurement

- Medium excitation → change the chemical composition of particles via parton coalescence



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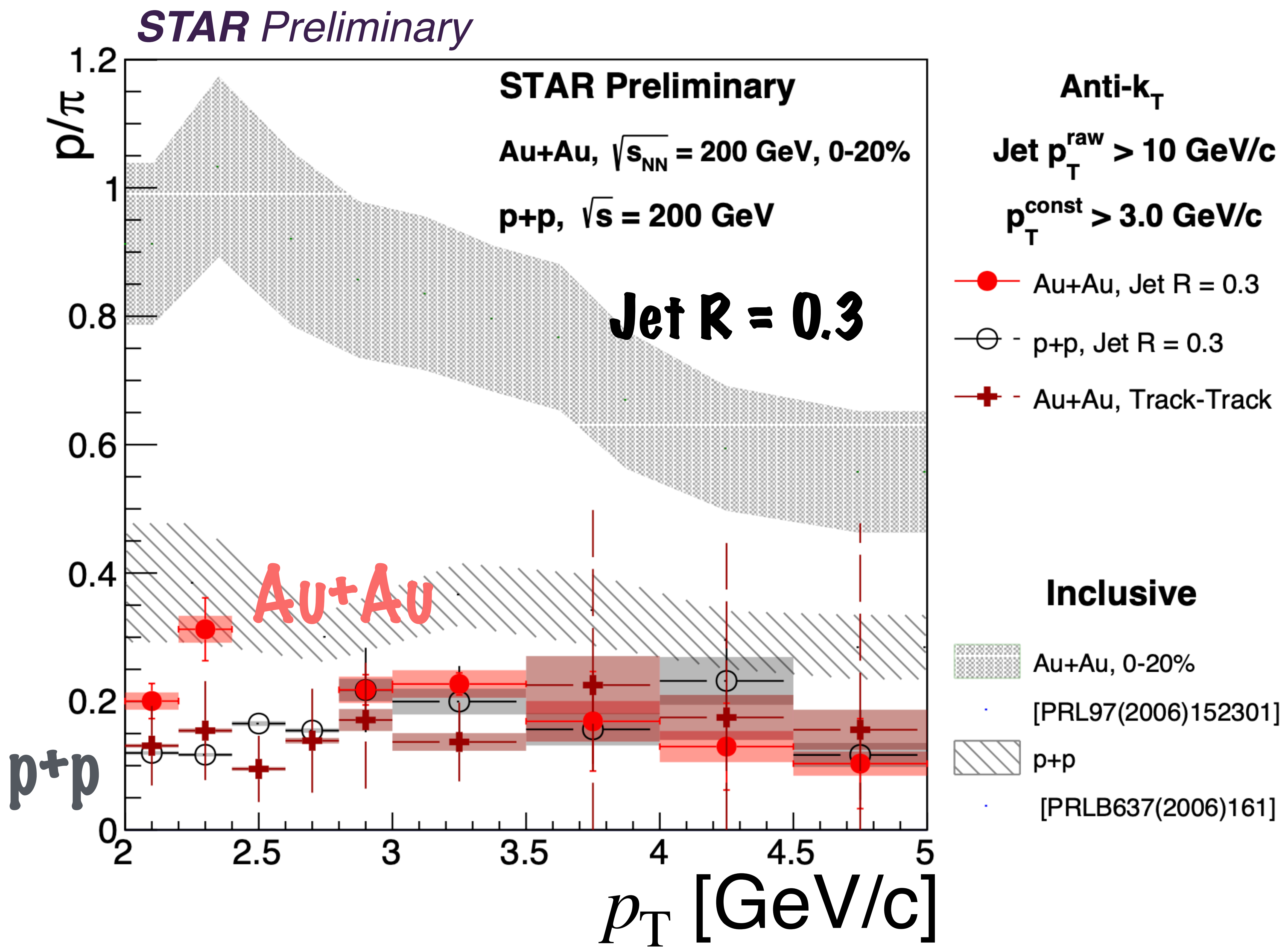

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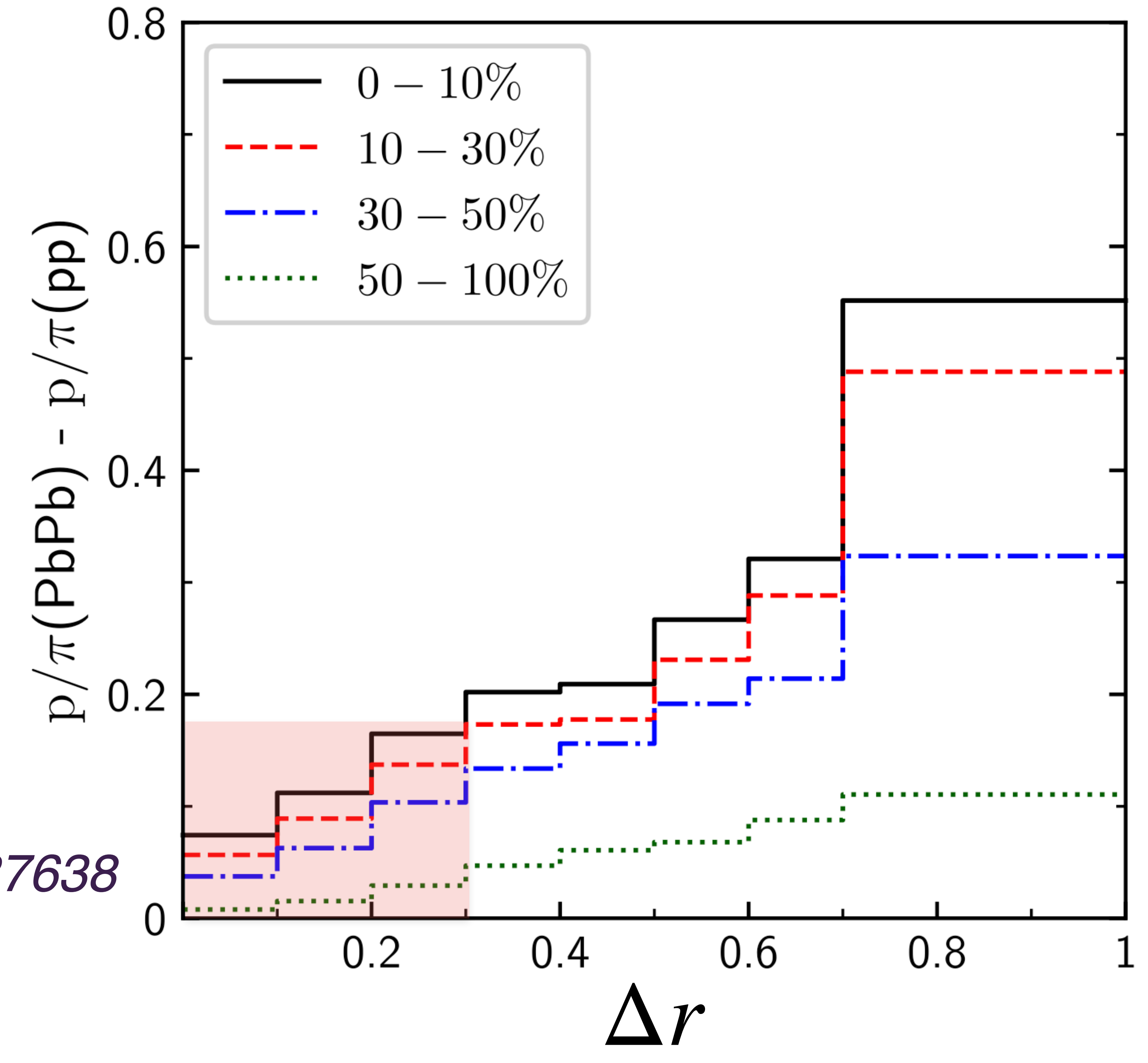

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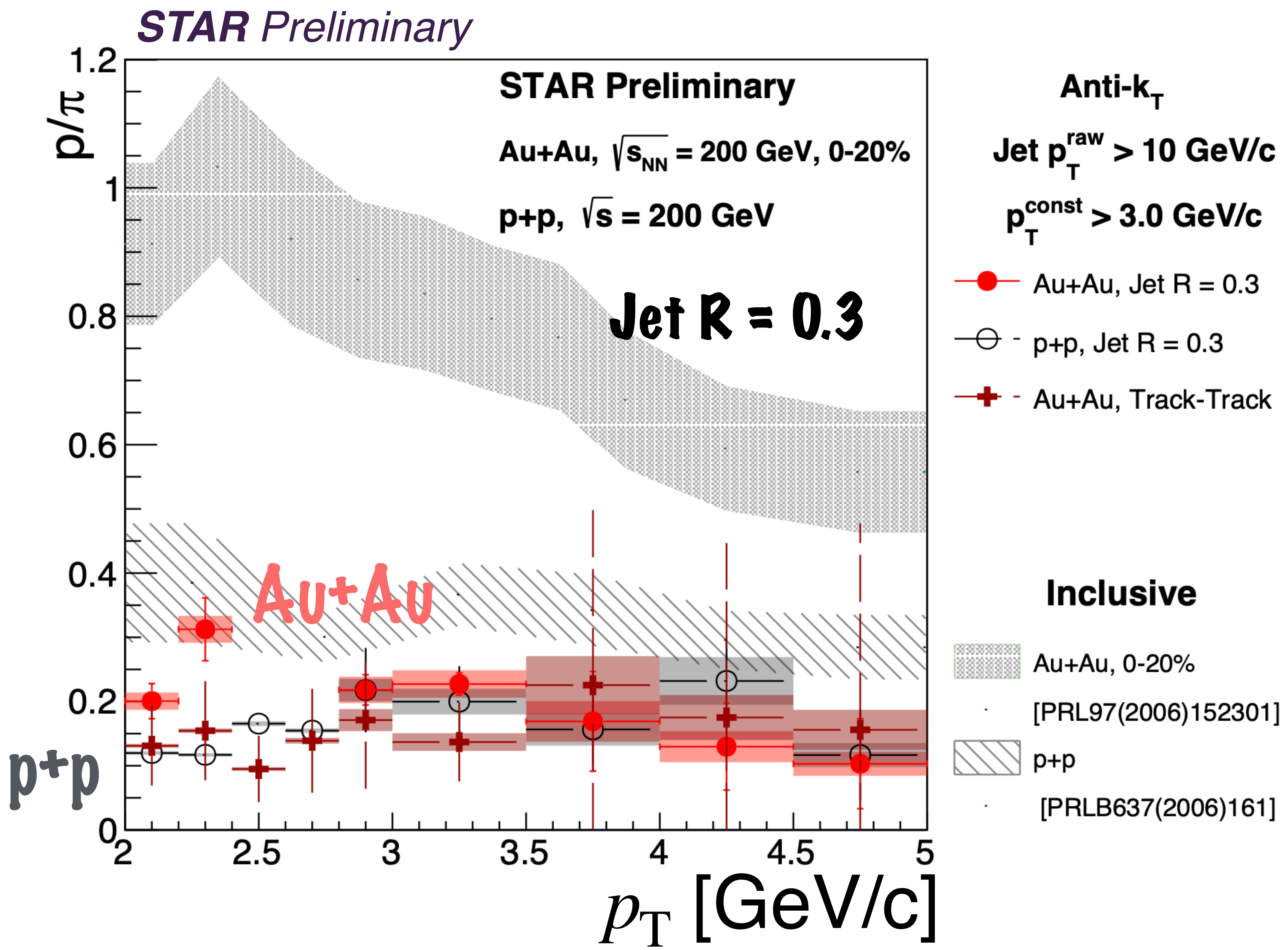

- No significant modification of in Au+Au within uncertainties in data
  - ➡ larger datasets + larger radius would be valuable

Summary & Discussion

- Jet-medium interaction is inherently complex
  ➡ utilizing observables with varying sensitivities to distinct physics effects is crucial for disentangling phenomena e.g.
  - in-medium parton shower vs. medium response   *See talk by Krishna, Hannah*
  - quark vs. gluon jet quenching

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- Jets produced with electroweak (EW) bosons have advantages of
  - ➡ access to initial hard scattering
  - ➡ *quark* tagging

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  - quark vs. gluon jet quenching

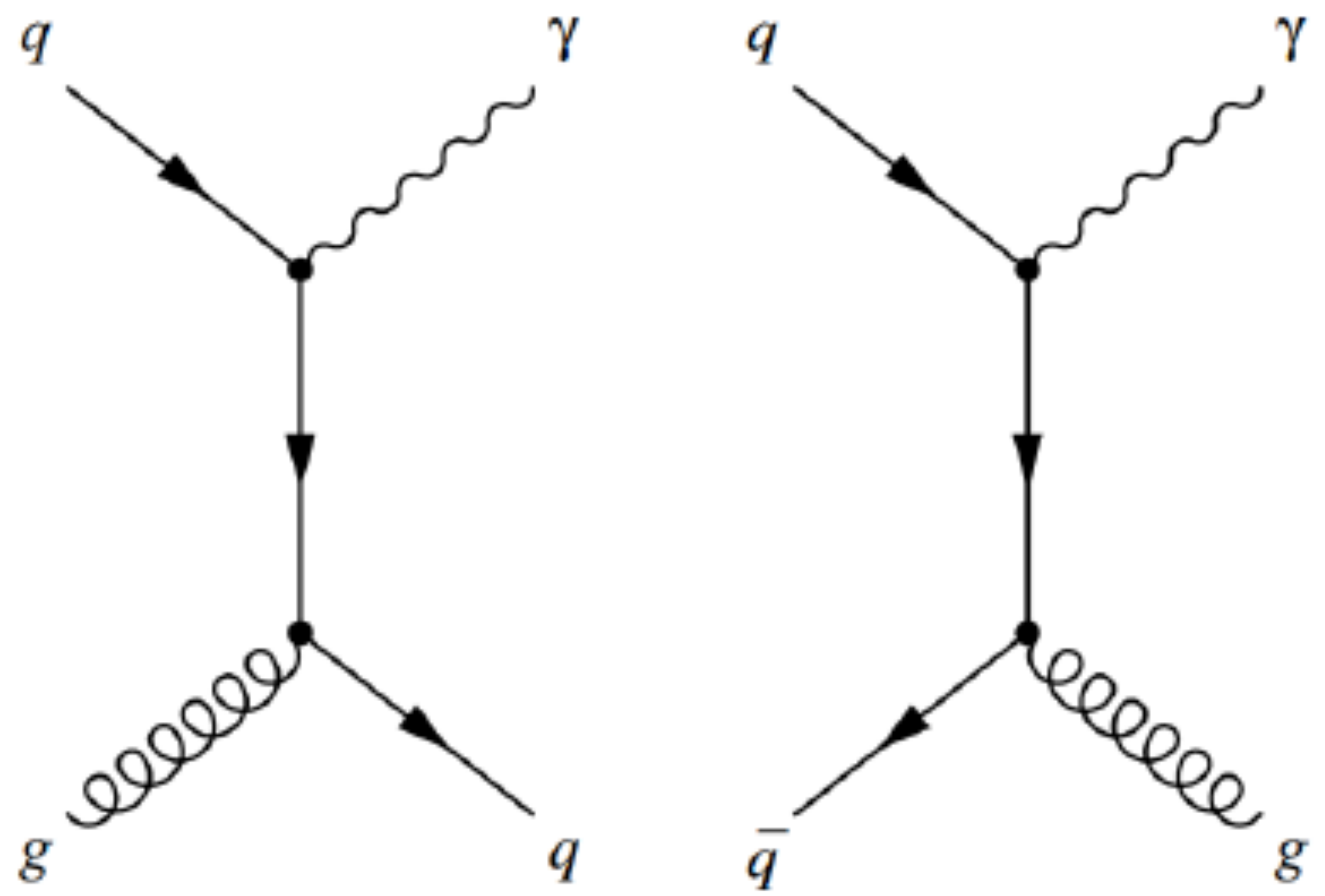
- Jets produced with electroweak (EW) bosons have advantages of
  ➡ access to initial hard scattering
  ➡ *quark* tagging

- Jet+EW boson: “**golden channel**” but rare production rate..
  ➡ will greatly benefit from larger statistics in the future high-luminosity data allowing precise and more differential, multidimensional measurements

BACK UP

Prompt Photons

- Direct photon
  - ➡ produced from primary vertex
  - ➡ Processes : Compton scattering, Annihilation



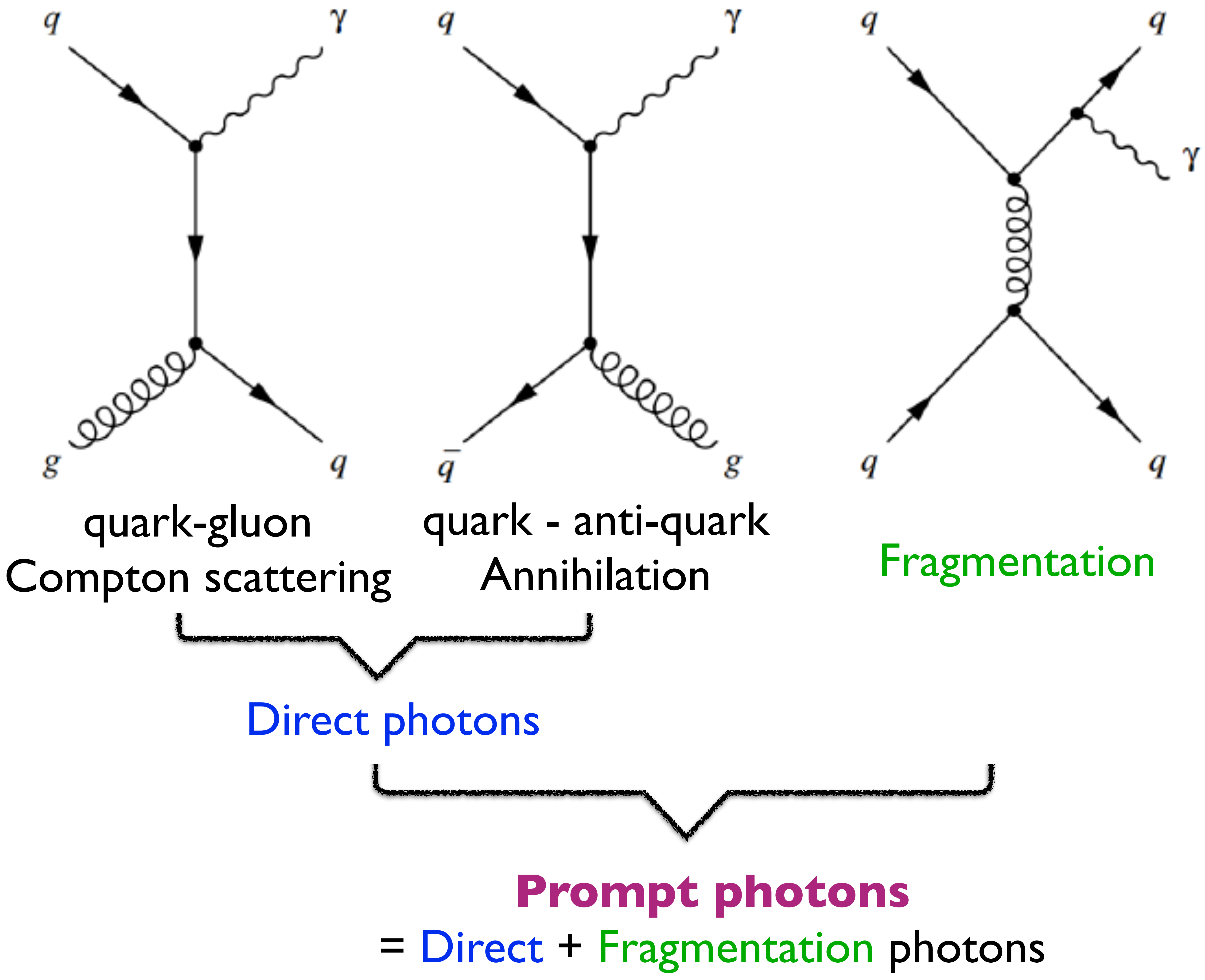
quark-gluon
Compton scattering

quark - anti-quark
Annihilation

Direct photons

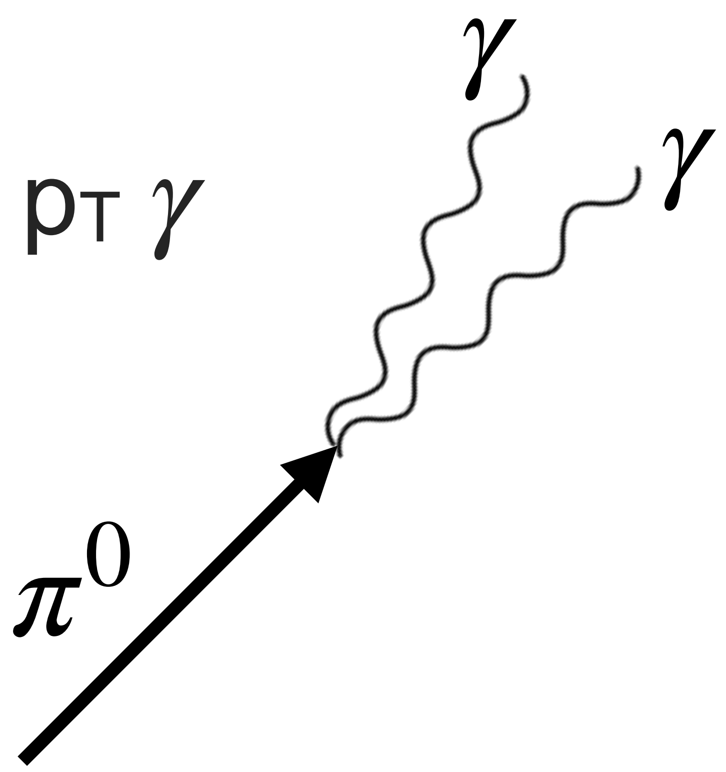
Prompt Photons

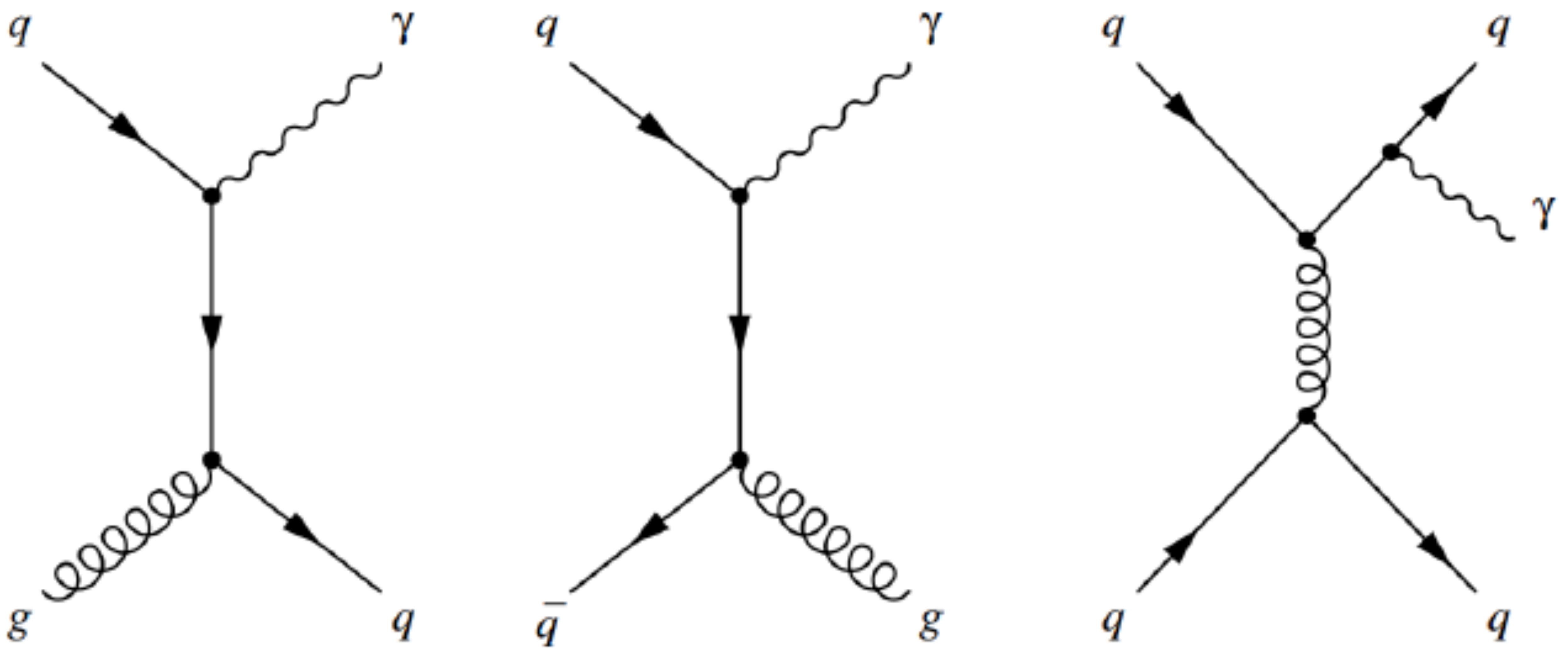
- Direct photon
  - ➡ produced from primary vertex
  - ➡ Processes : Compton scattering, Annihilation
- **Fragmentation photon**
  - ➡ radiated from partons after the primary hard scattering



Prompt 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 $\pi^0 \rightarrow \gamma\gamma$
  - ➡ the two decay photons often have small opening angles
    $\rightarrow$ reconstructed as a single high p_T γ
  - ➡ major background





quark-gluon Compton scattering

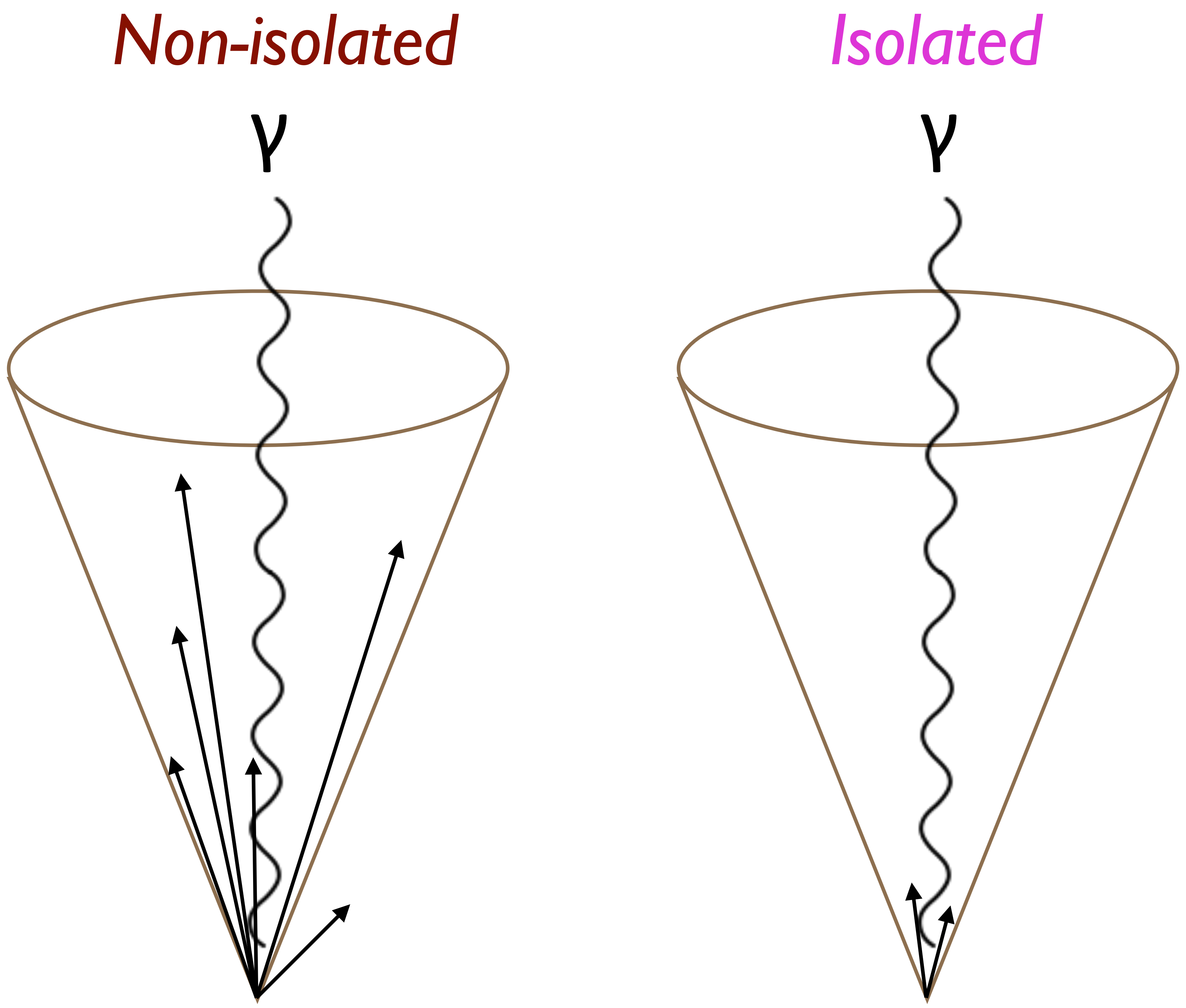
quark - anti-quark Annihilation

Fragmentation

Direct photons

Prompt photons
= Direct + Fragmentation photons

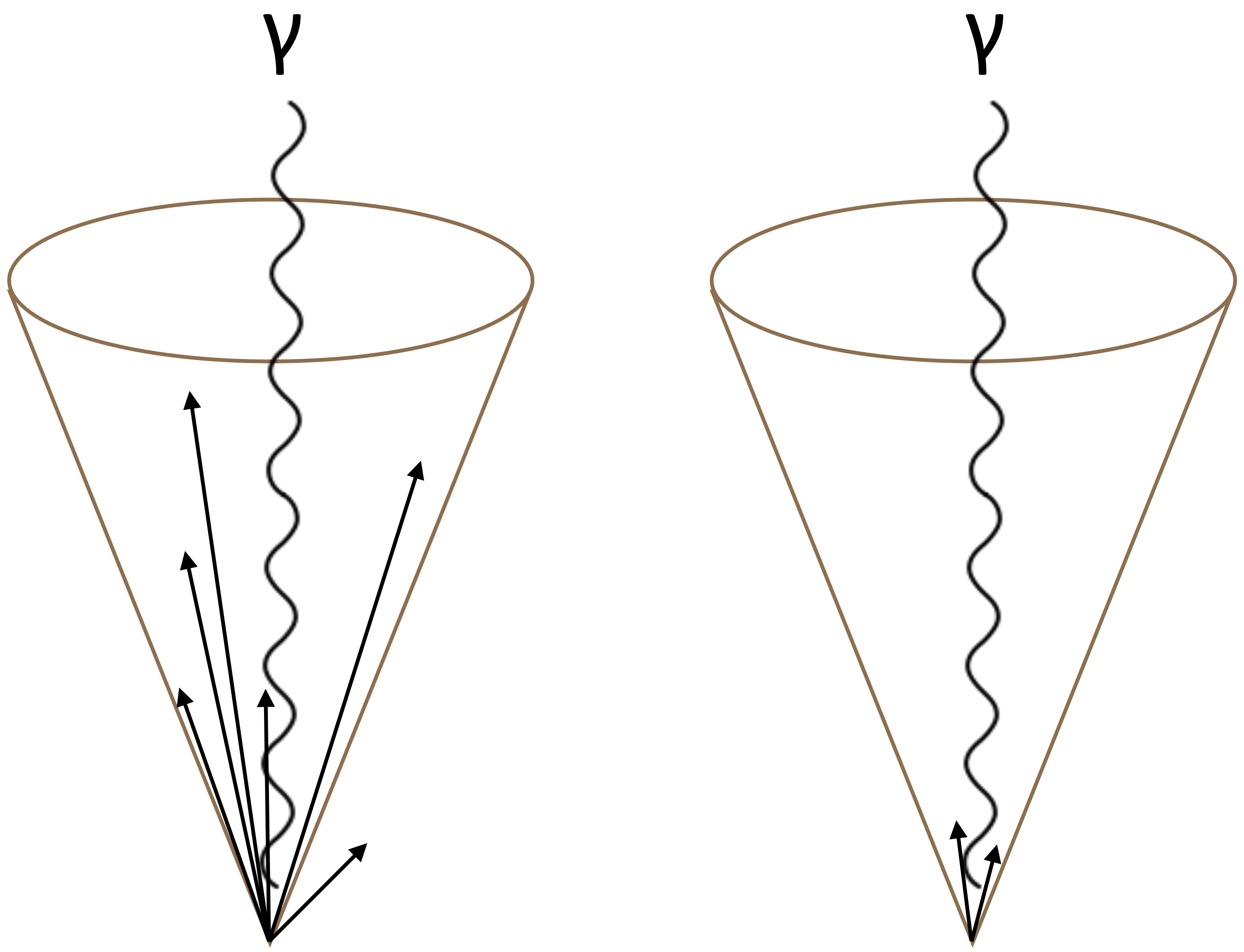
Isolated Photons



Isolated Photons

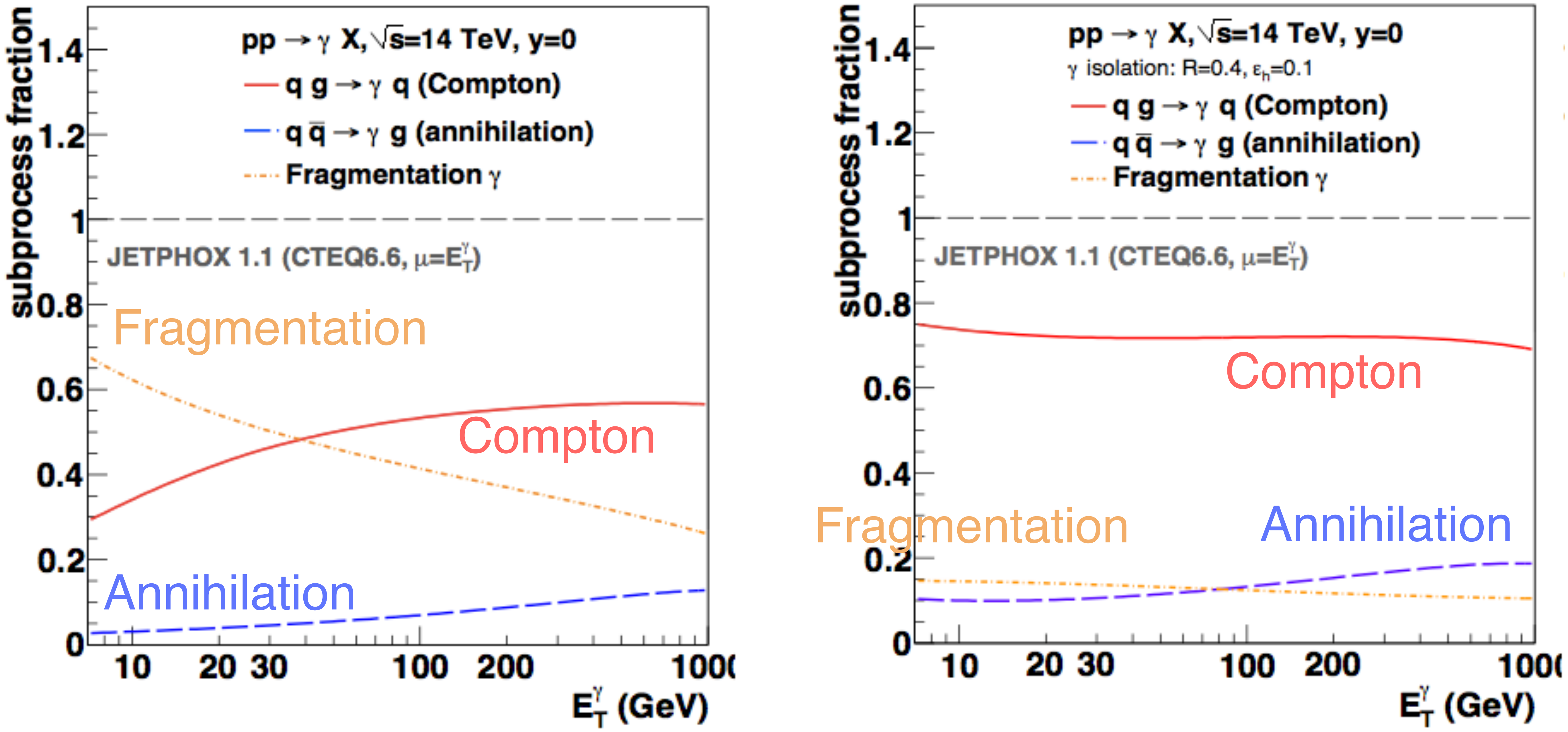
- Photon Isolation condition
  - ➡ suppress significant background photons from neutral meson decay
  - ➡ suppress the fragmentation photon contribution and retain the majority of direct photons
- Discrimination between isolated direct and fragmentation photons is arbitrary in experiment

Non-isolated *Isolated*



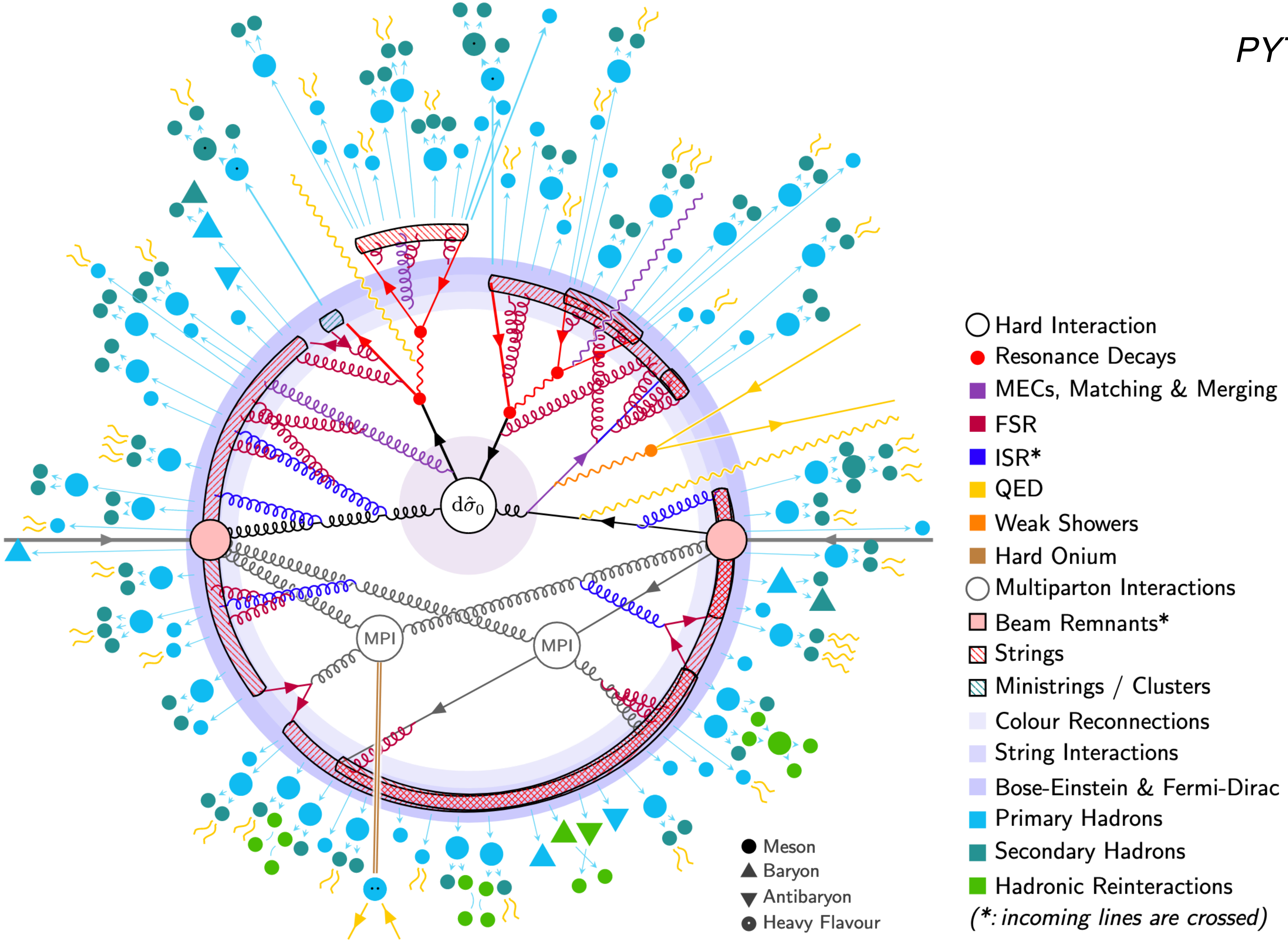
PRC D82 (2010) 014015

Non-isolated *Isolated*



High Energy Hadron Collisions

PYTHIA $pp \to t\bar{t}$ event

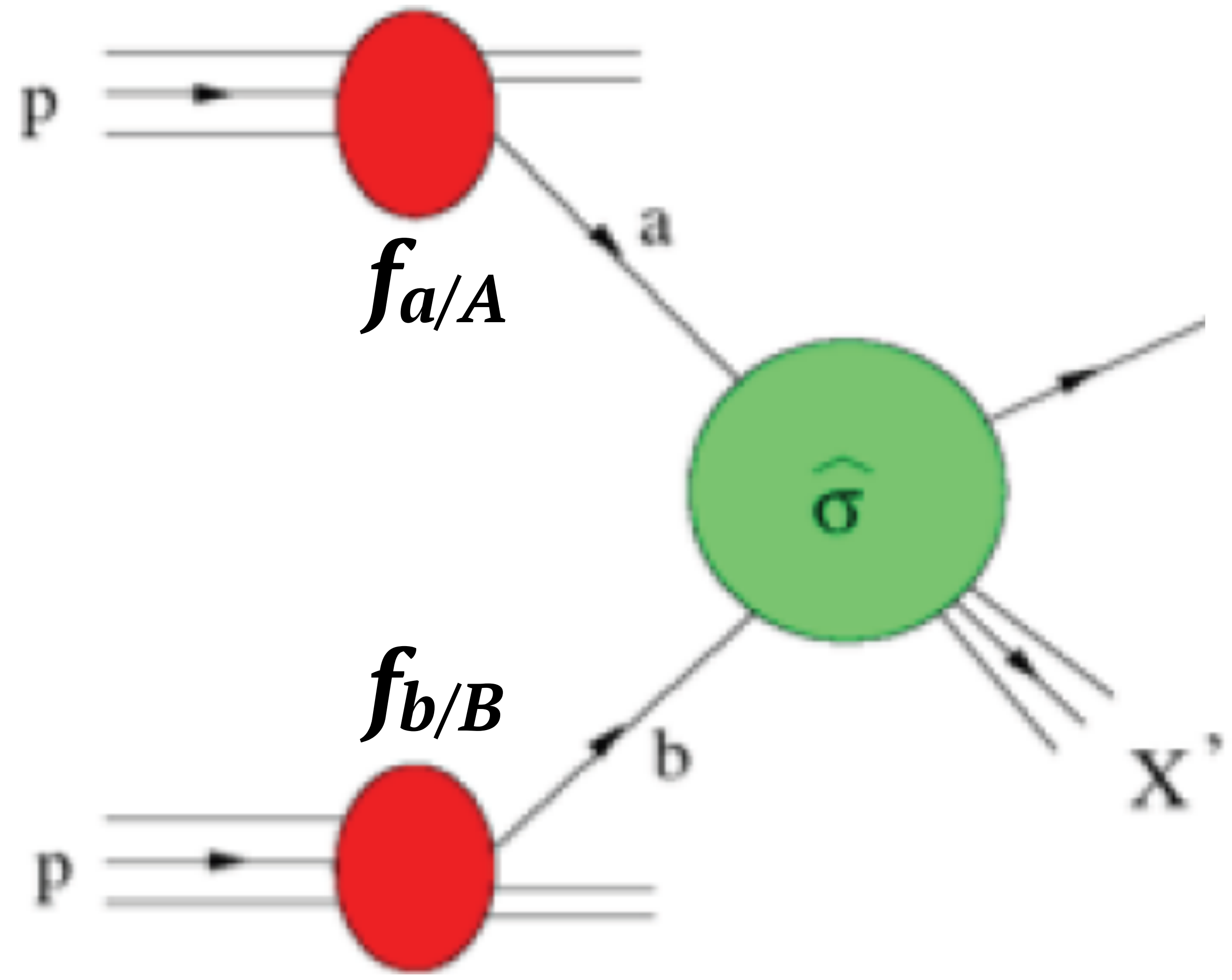


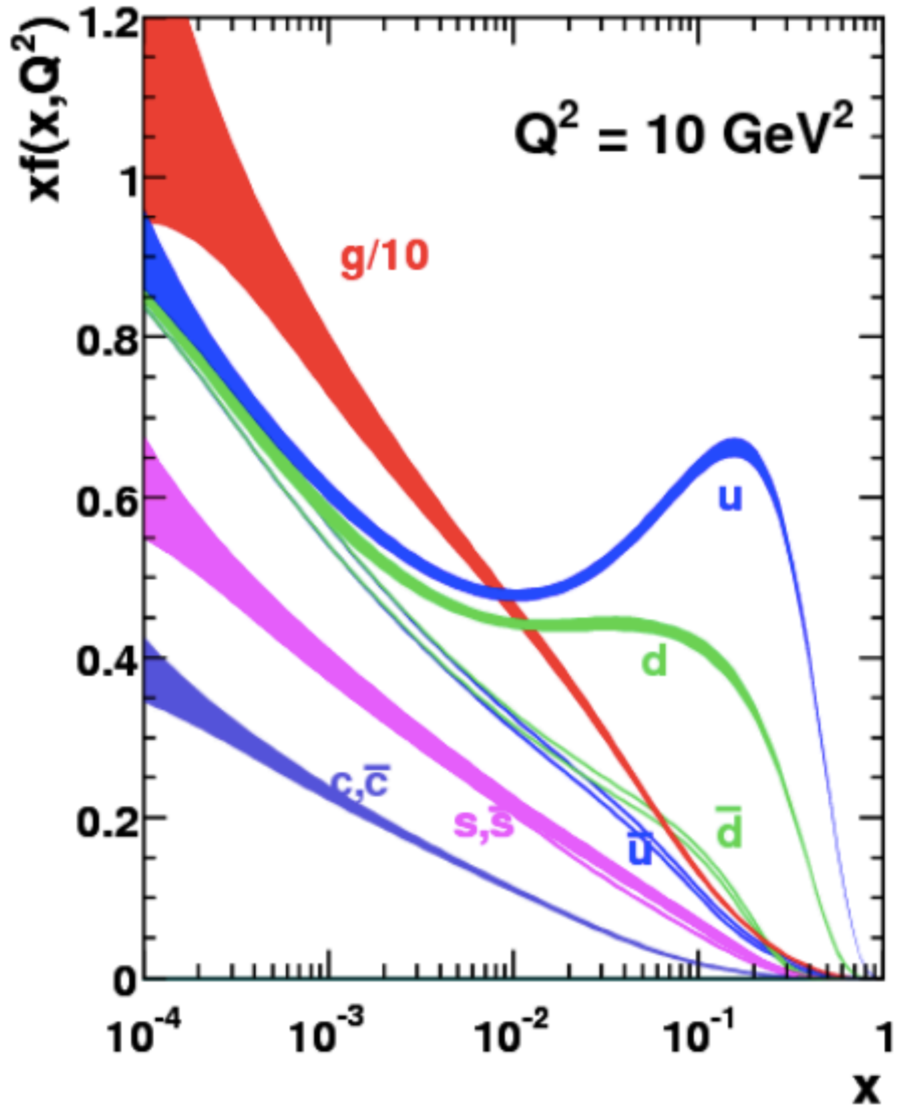
Parton Distribution Functions (PDF)

- QCD Factorization theorem: hadronic cross section is factorized into PDFs of incoming particles and perturbative partonic cross section

$$\sigma_{AB} = \sum_{a,b=q,g} \hat{\sigma}_{ab} \otimes f_{a/A}(x_1, Q^2) \otimes f_{b/B}(x_2, Q^2)$$

- Hadronic cross section
- Partonic cross section
- perturbative QCD
- Parton distribution
- non-perturbative





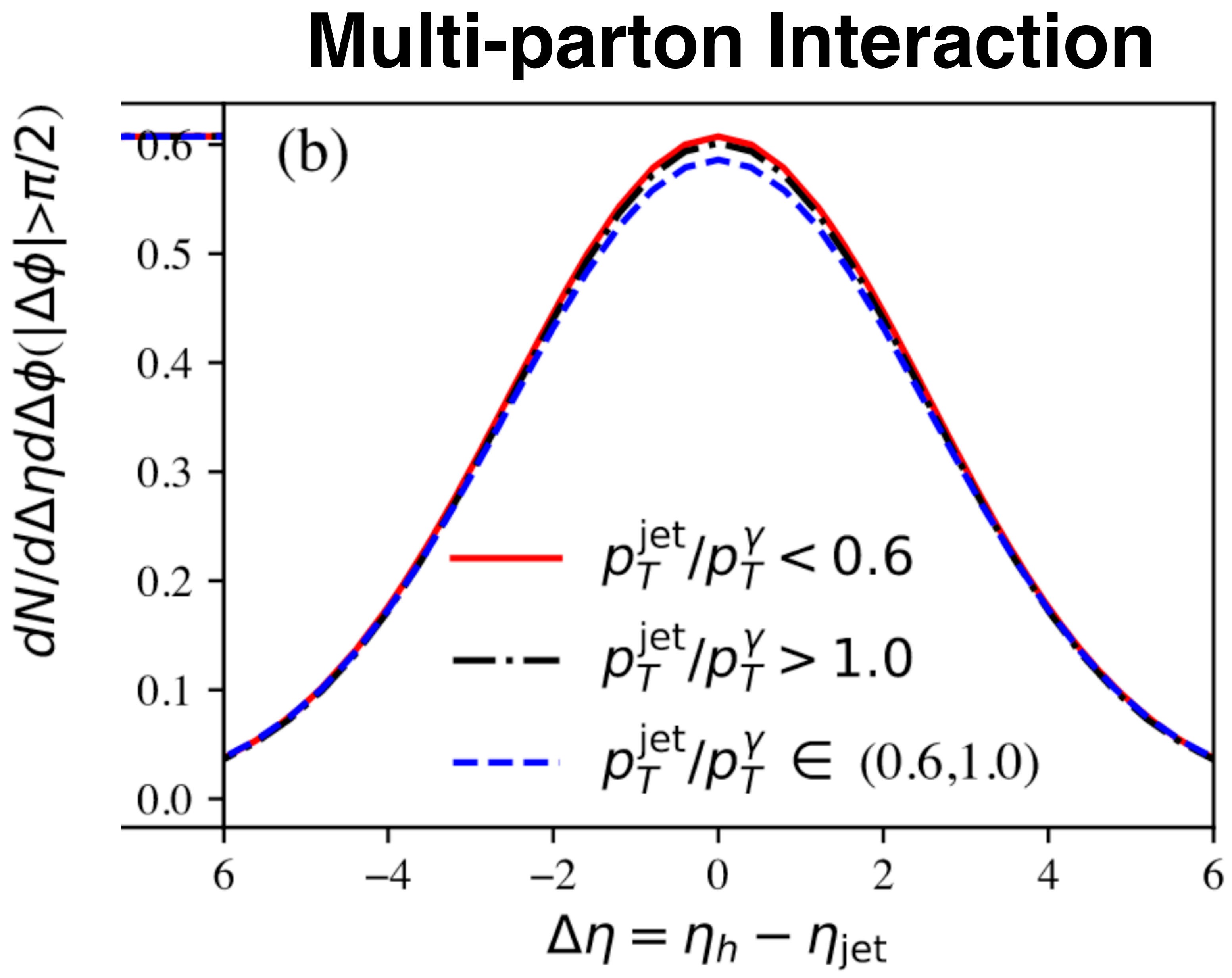
EPJC 63 (2009) 189

MSTW 2008 NLO

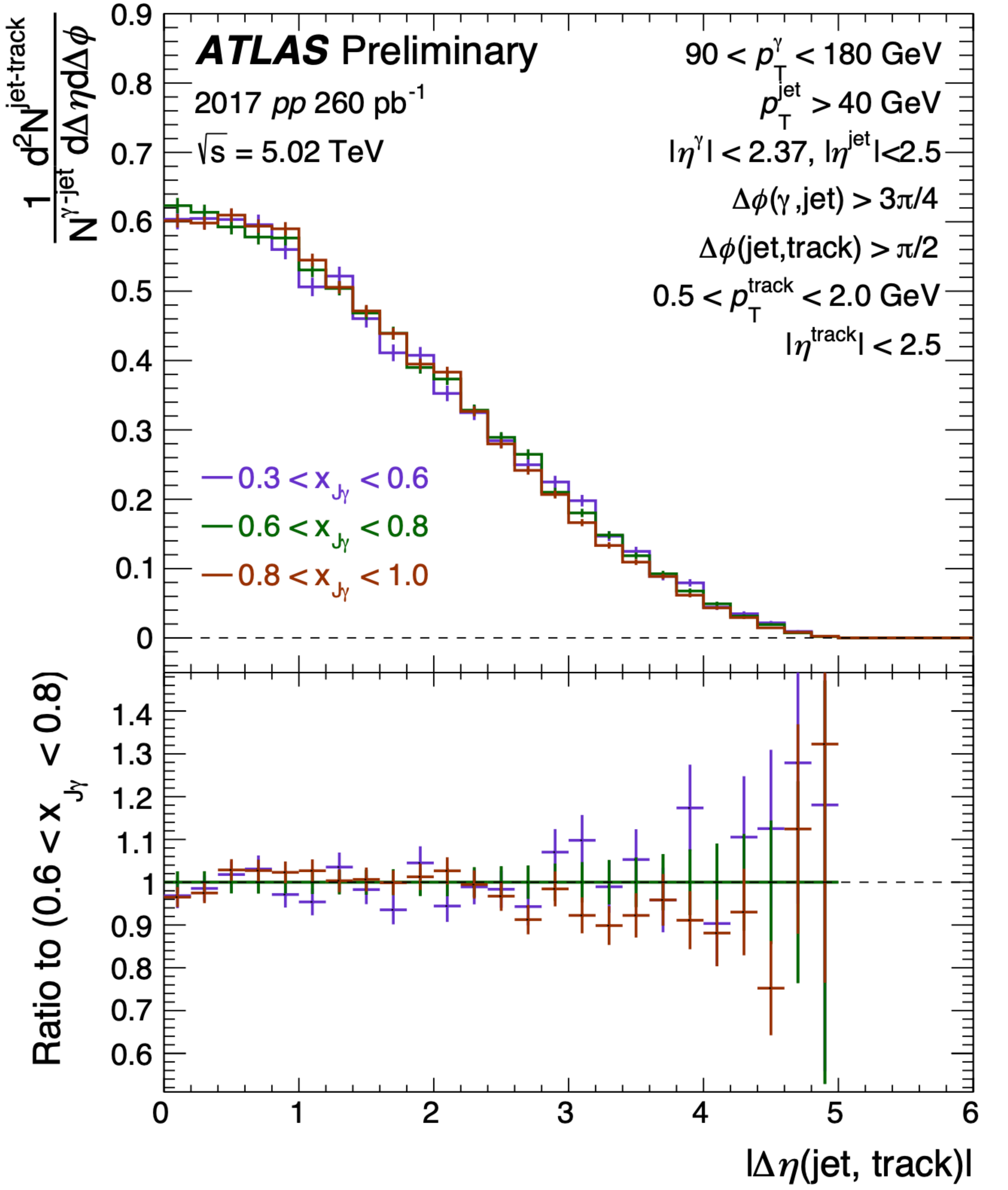
$|\Delta\eta$(jet, track)$|$ distributions in pp collisions

ATLAS CONF-2023-054

- 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

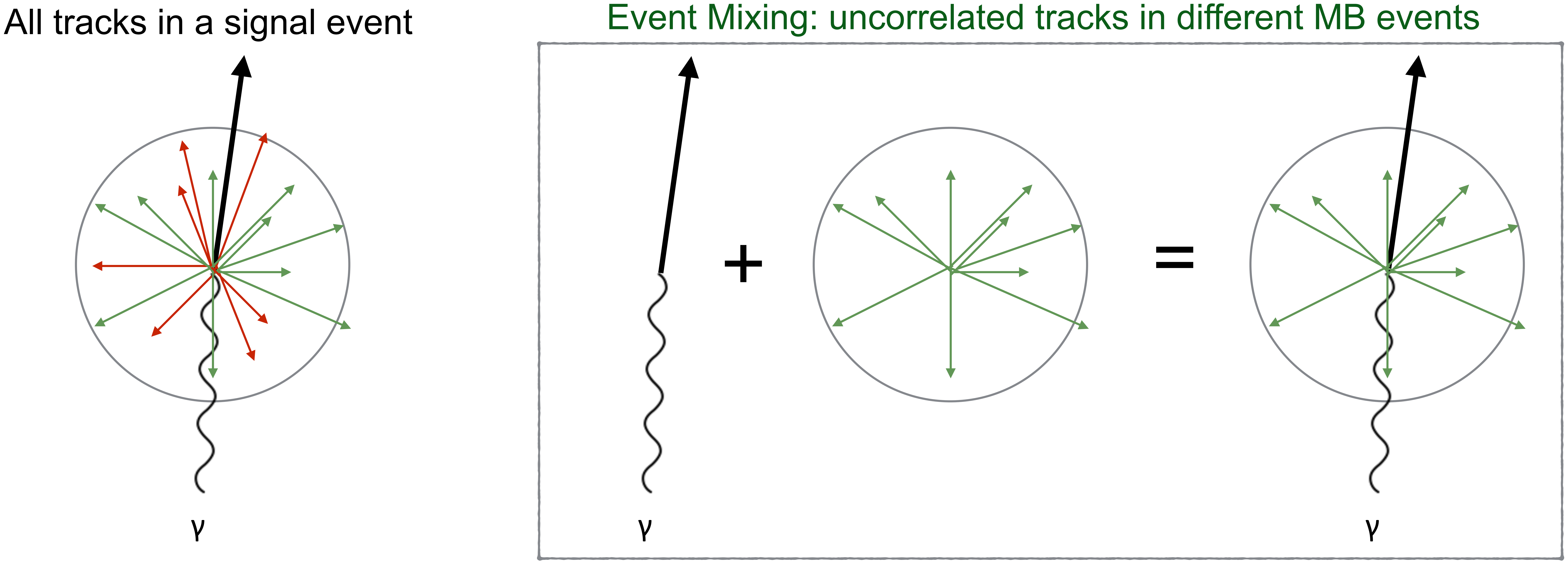


PRL 130, 052301 (2023)



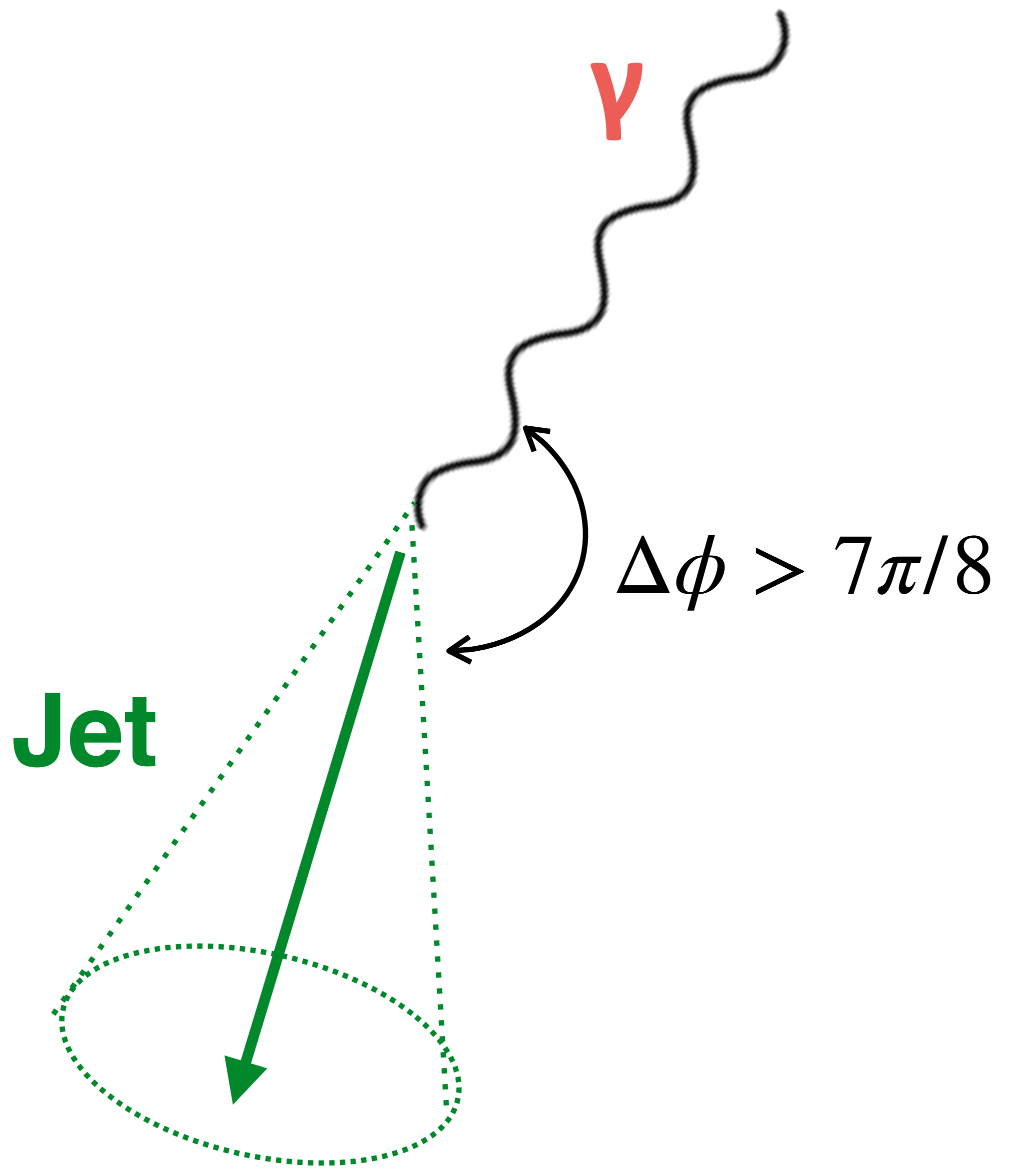
Event Mixing in Pb+Pb collisions

- 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 the signal event and the mixed event
  - ➡ matching signal and MB events in bins of ($\Sigma E_{\mathrm{T}}^{\mathrm{FCal}}$, Ψ_2, z vertex)



Event Selection & Analysis Procedure of γ-Jet R_{AA}

- 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
  - ➡ $\Delta\phi(\gamma,jet) > 7\pi/8$
  - ➡ 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



Event Selection of Jet Hadron Correlation Analysis

- 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
  - ➡ $|\eta| < 2.5$
  - ➡ $\Delta\varphi(\gamma,\text{jet}) > 3\pi/4$
  - ➡ only leading photons and leading jets are considered
- Tracks
  - ➡ $0.5 < p_T < 2$ GeV
  - ➡ $|\eta| < 2.5$
  - ➡ $\Delta\varphi(\text{jet, track}) > \pi/2$