Searching for **jet-induced** **diffusion wakes** of *quark gluon plasma* via **jet-track correlations** in heavy ion collisions with the ATLAS detector

arXiv:2408.08599

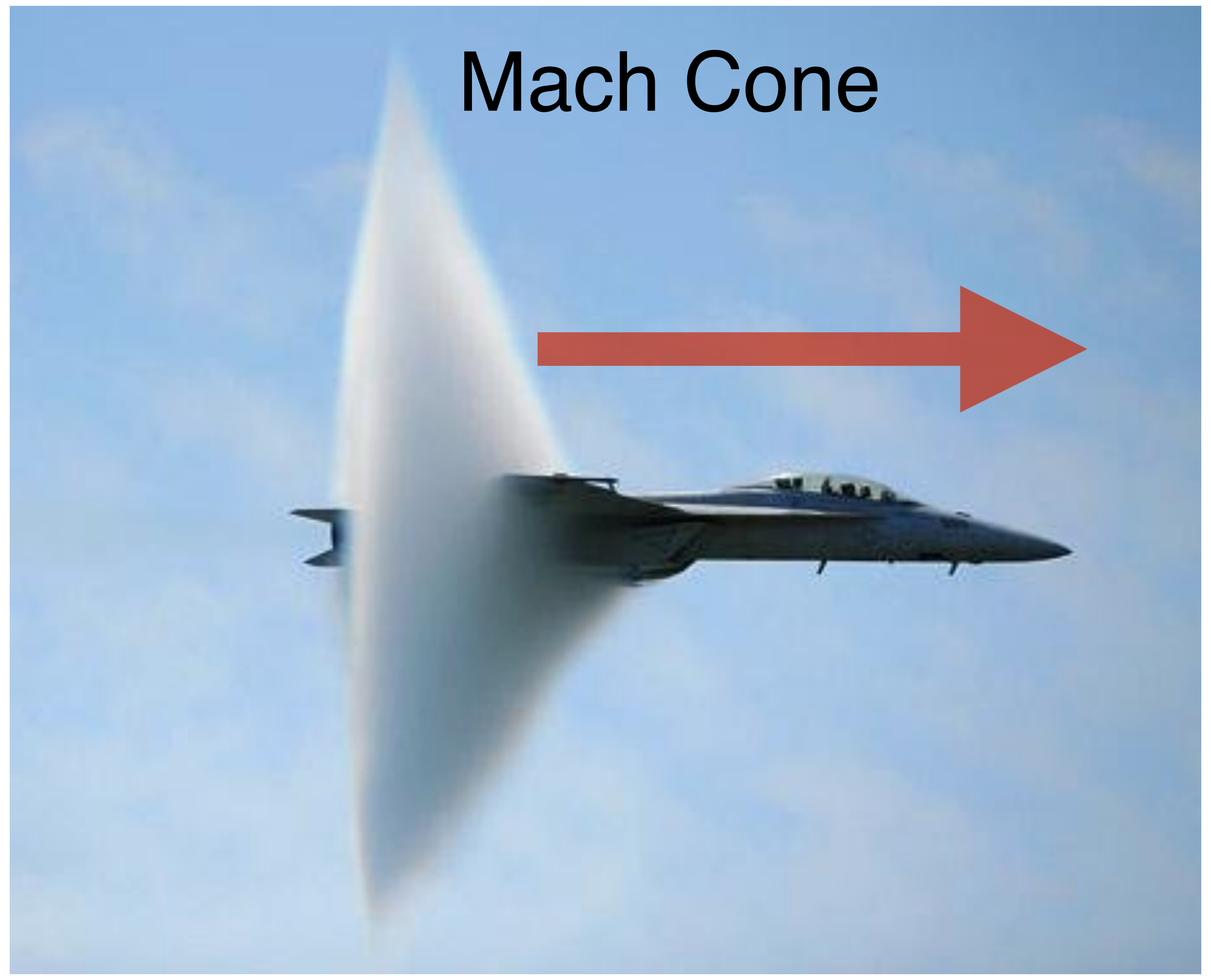
Yeonju Go

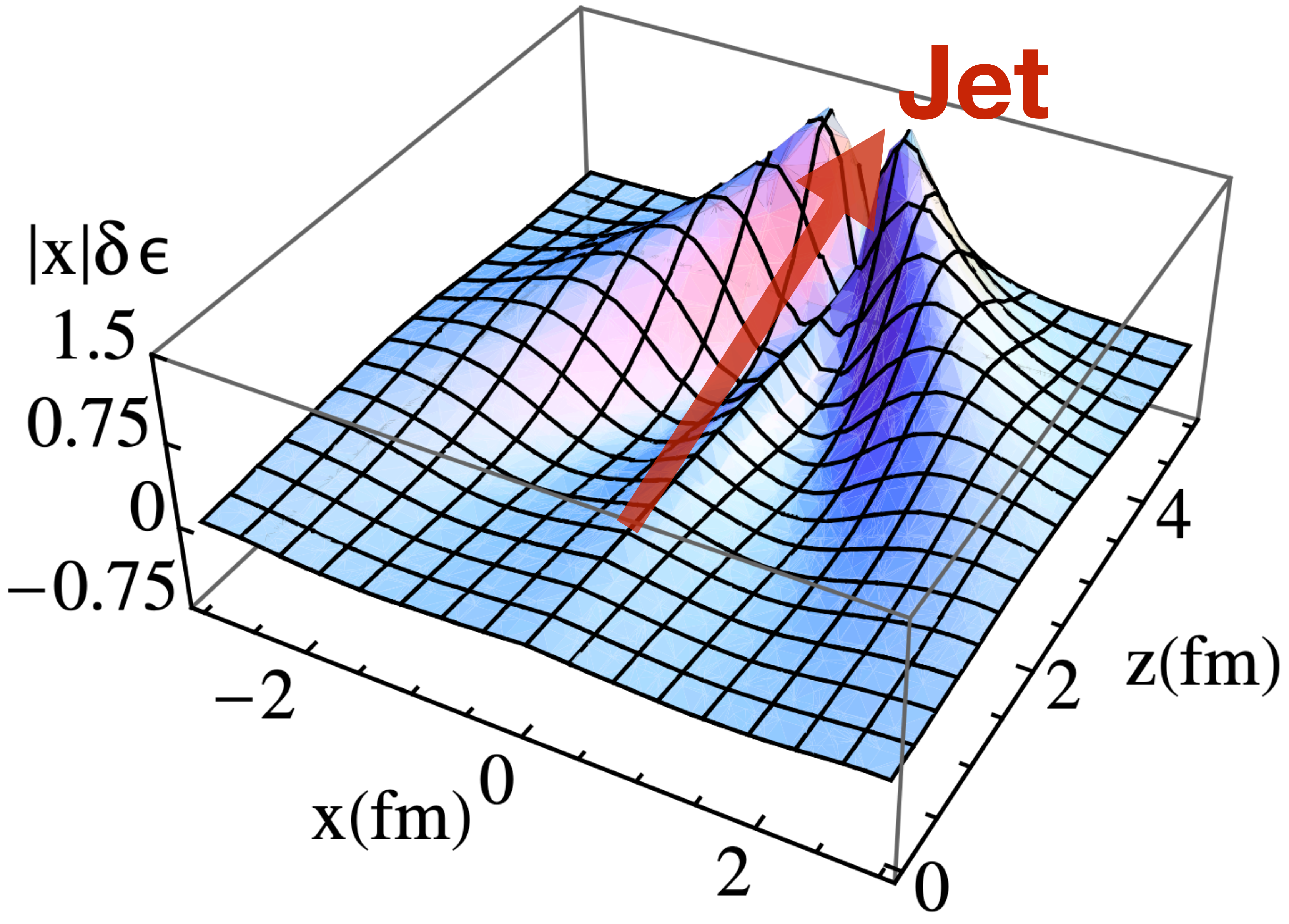
Brookhaven National Laboratory

Hard Probes 2024
Nagasaki, Japan
Sep. 23-27 2024

Medium response induced by jets

PRL 103, 152303 (2009)



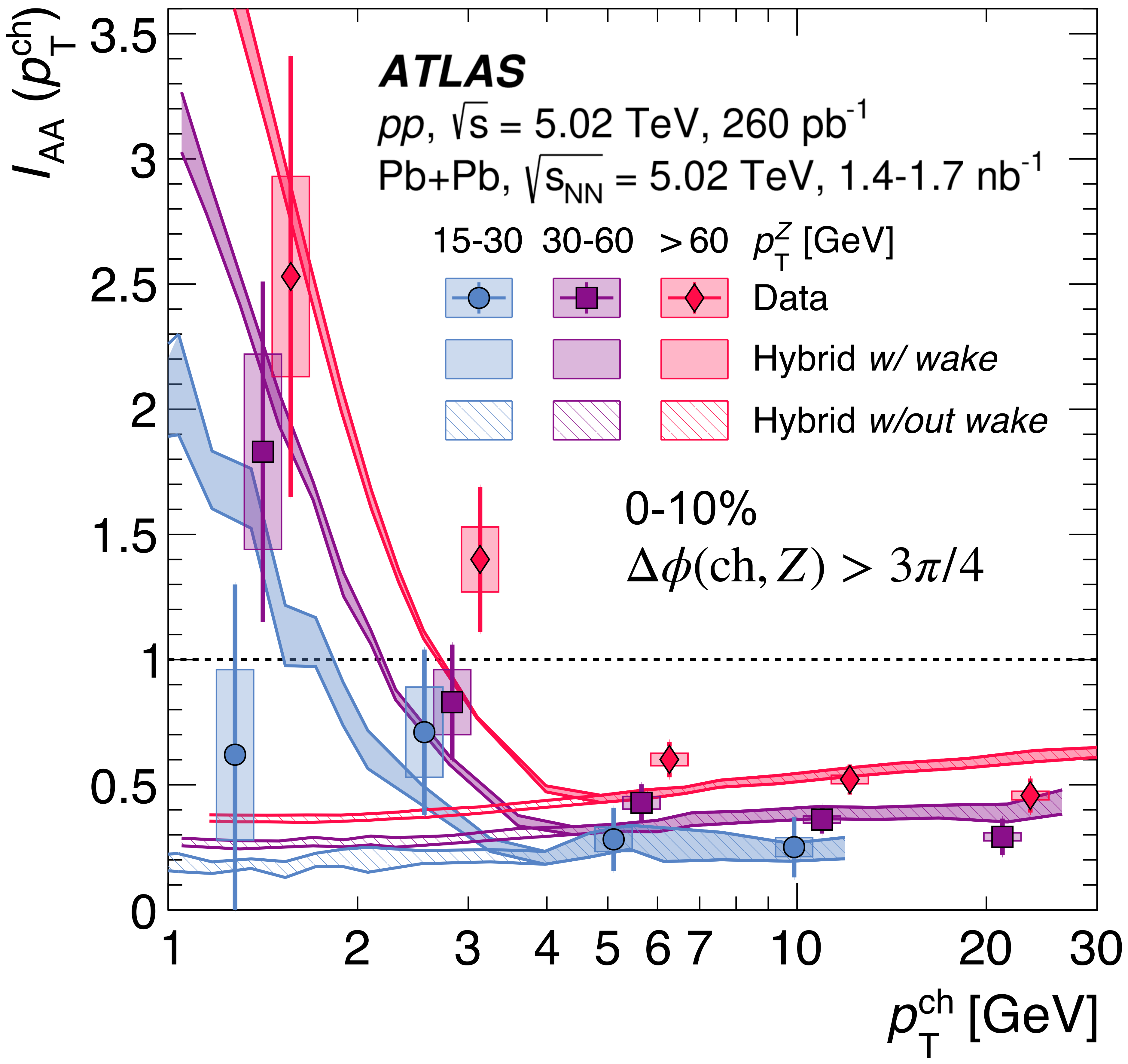


- When a high-p_T parton loses energy in medium, the energy may be transferred to the medium
- Typical structure of *medium response*;
  - ➡ enhancement in the jet direction, called e.g. wake
  - ➡ depletion in the opposite jet direction, called e.g. diffusion wake

Medium response (wake) in jet direction

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

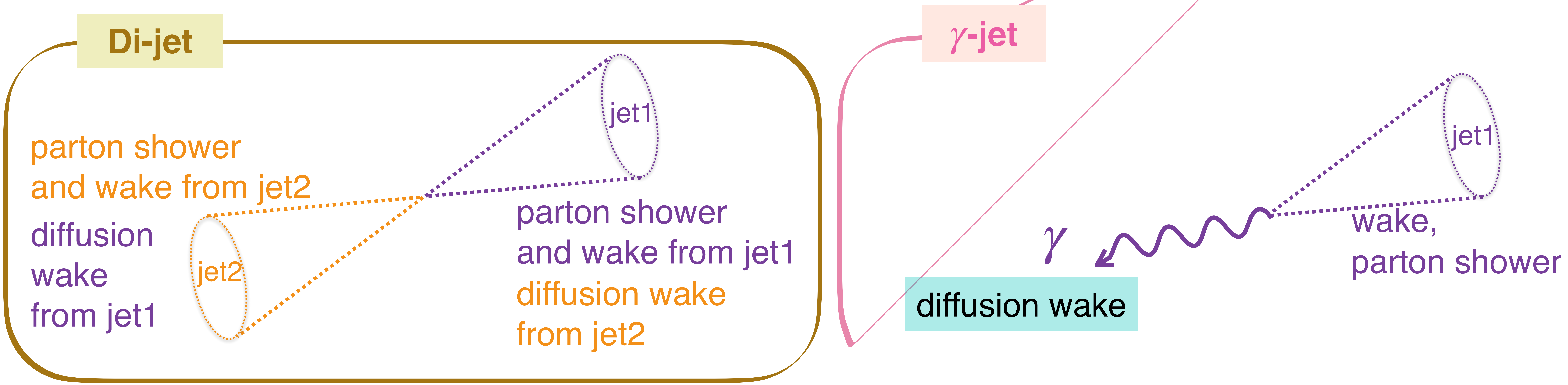
PRL 126 (2021) 072301



- Numerous observations of **enhancement of low-p_T particles** and particles **at larger angles** relative to the jet
  - ➡ but, hard to disentangle between in-medium parton shower modification and medium response

Diffusion wake using γ-jets

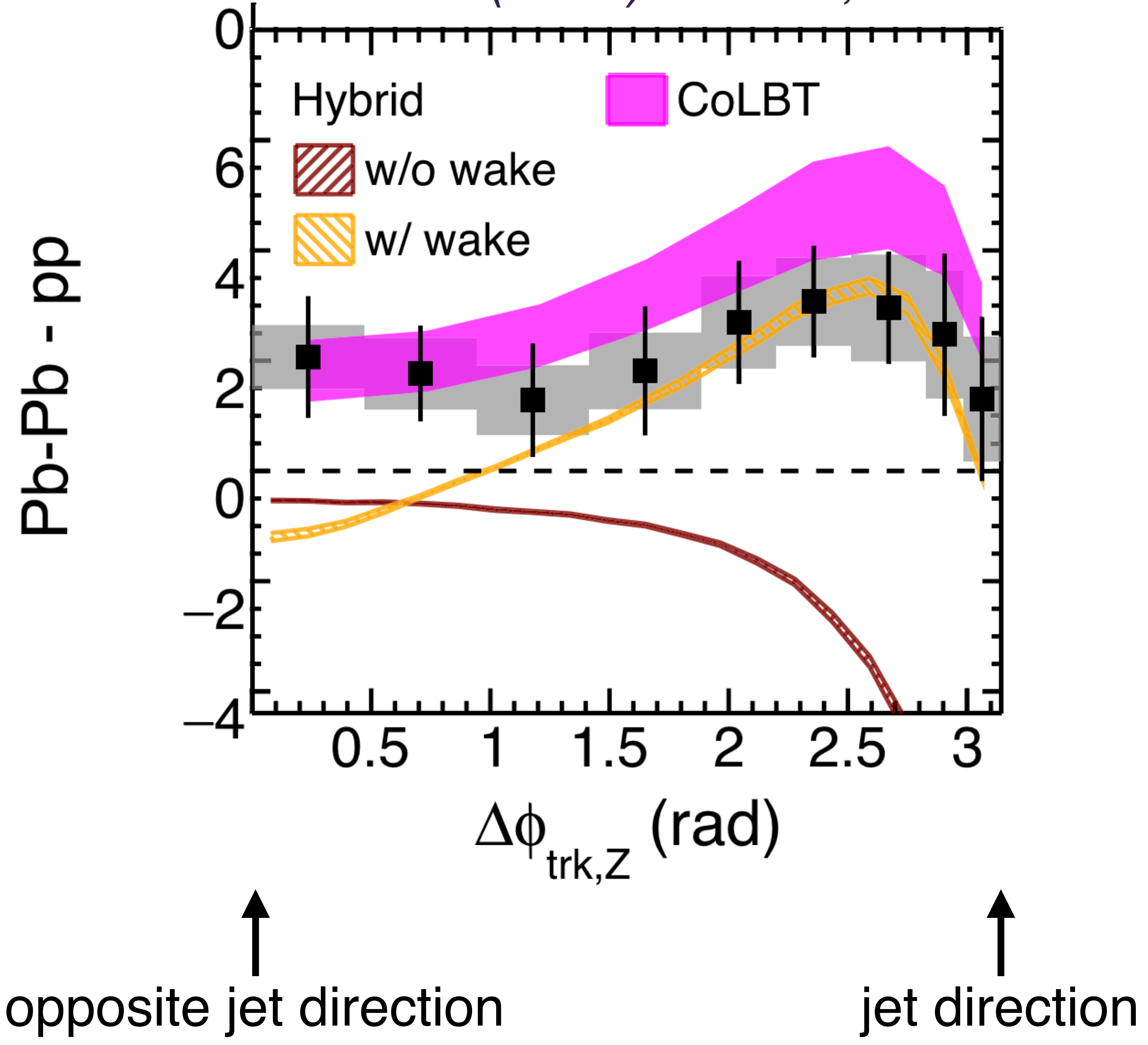
- **Diffusion wake** (depletion) in boson-jet events;
  - ➡ unlike **di-jet** events, a jet associated with a boson e.g. photon is **NOT** contaminated by in-medium parton shower modification or wake caused by the other jet in the opposite direction



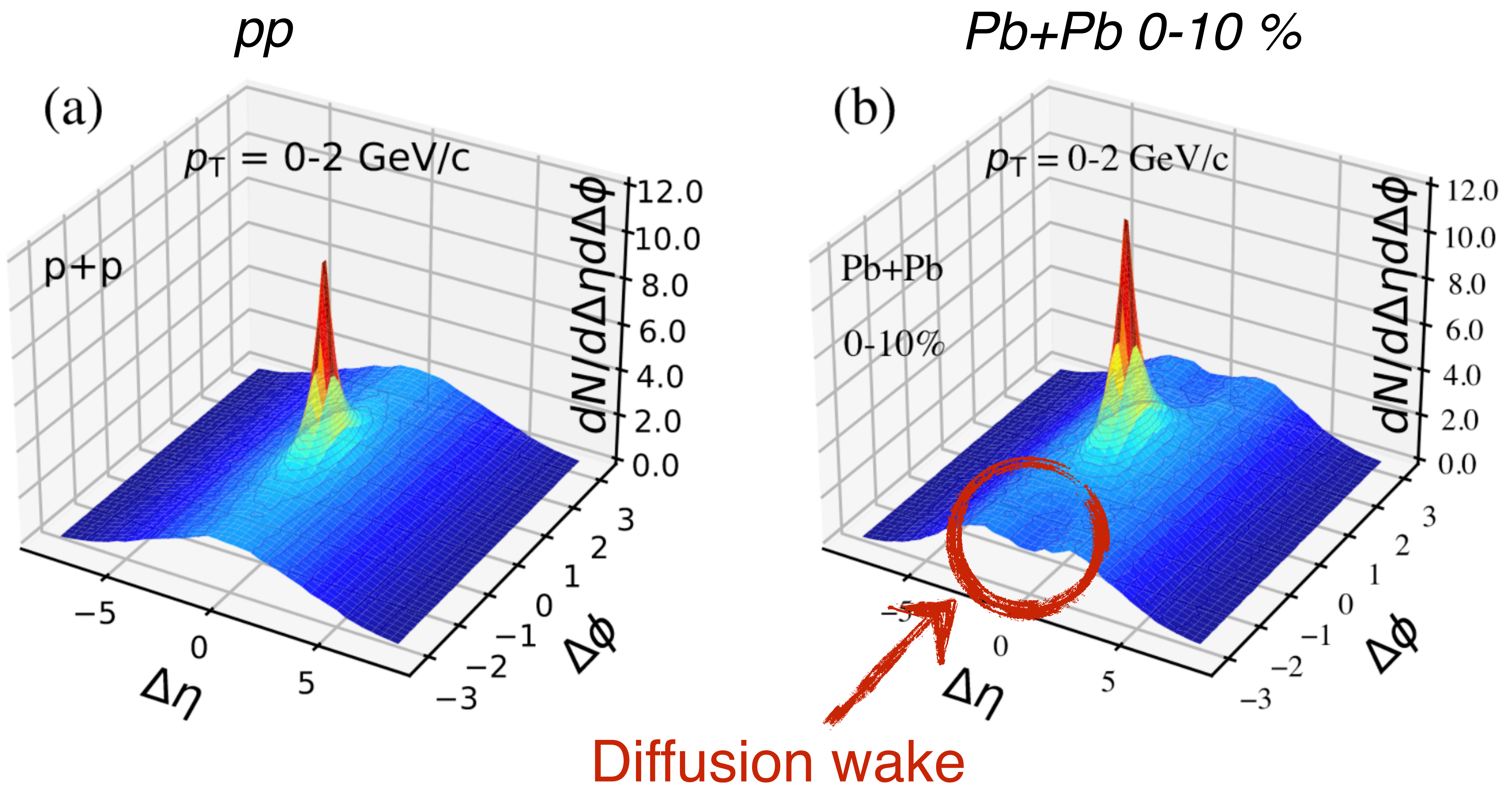
3D jet-hadron angular correlations

- CoLBT model predicts overall enhancement from **multi-parton interaction (MPI)**
  - ➡ Jet-hadron angular correlations **not only in ϕ but also in η**

PRL 128 (2022) 122301, CMS



PRL 130, 052301 (2023), CoLBT

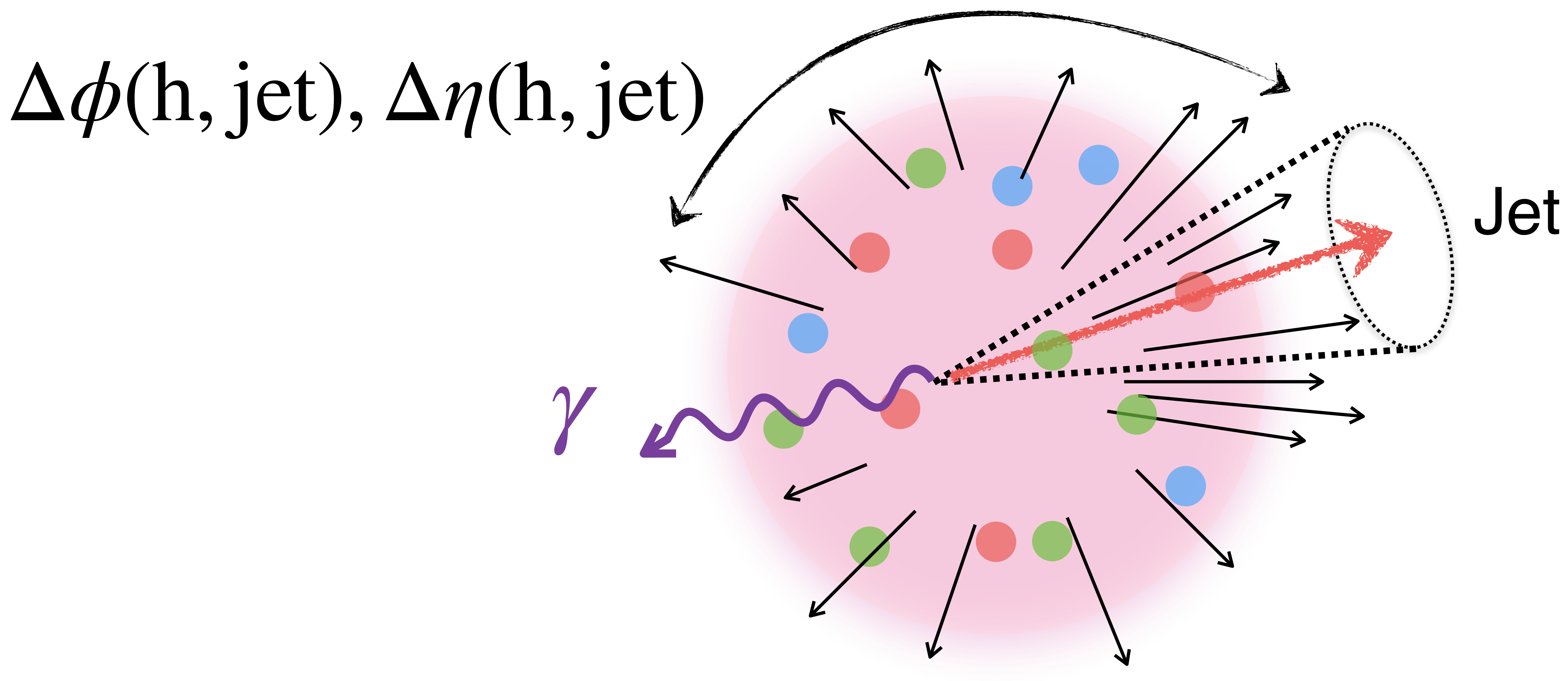


Analysis selections

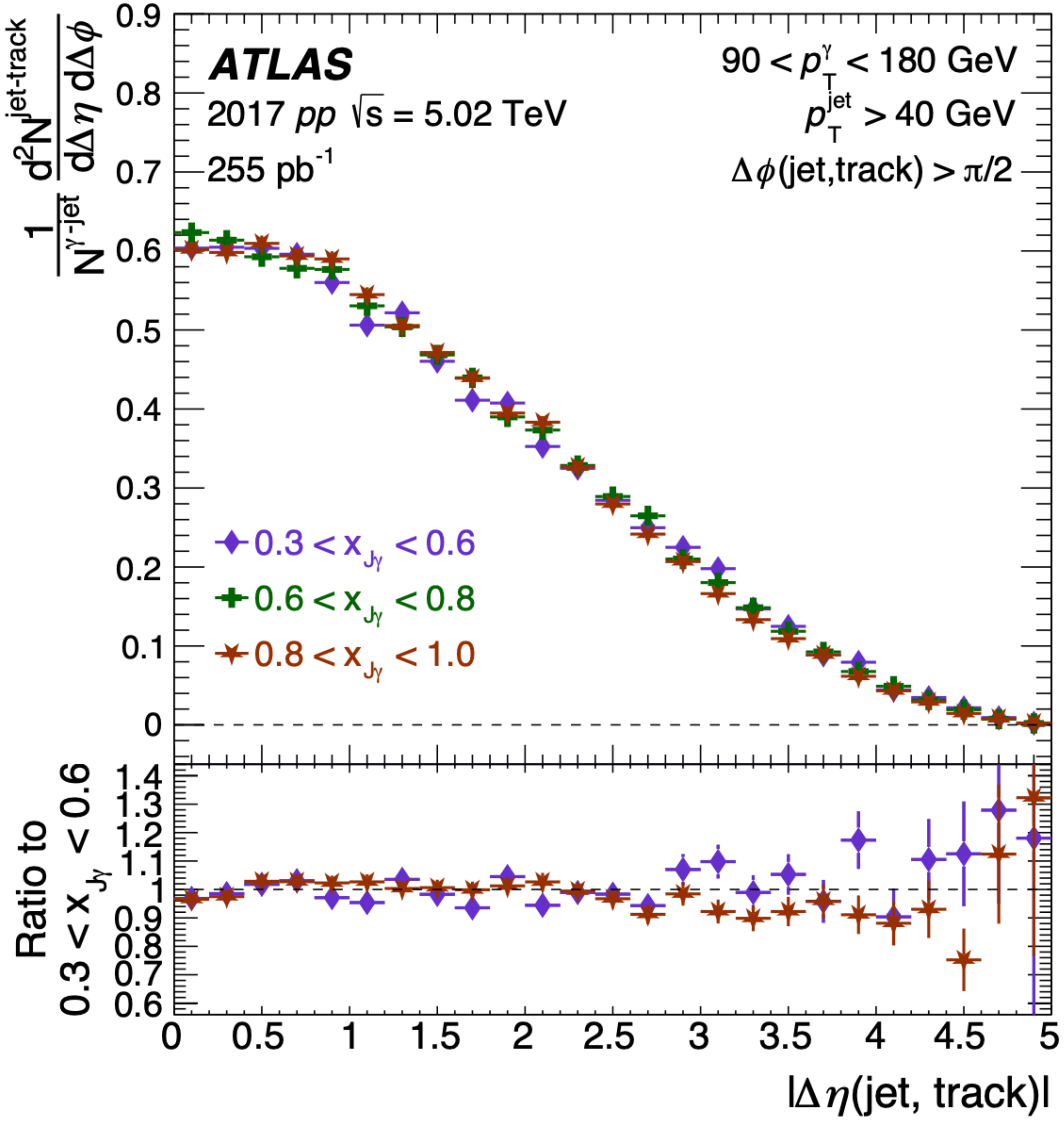
arXiv:2408.08599

- Centrality 0-10%
- *Photons*
  - ➡ 90-180 GeV and $|\eta|$<2.37
  - ➡ only leading prompt Isolated photons (direct+fragmentation photons)
- *Jets*
  - ➡ p_{T} > 40 GeV and $|\eta|$<2.5
  - ➡ only leading jets in $\Delta\phi(\gamma,\mathrm{jet}) > 3\pi/4$
- *Tracks*
  - ➡ 0.5-2 GeV and $|\eta|$<2.5 → low-p_{T} tracks; sensitive to the medium response
  - ➡ $\Delta\phi$(jet, track) > $\pi/2$ → in the opposite hemisphere
- Three $x_{\mathrm{J}\gamma}$ regions: $0.3 < x_{\mathrm{J}\gamma} < 0.6$, $0.6 < x_{\mathrm{J}\gamma} < 0.8$ and $0.8 < x_{\mathrm{J}\gamma} < 1.0$

larger jet energy loss (↑ $0.3 < x_{\mathrm{J}\gamma} < 0.6$) … less jet energy loss (↑ $0.8 < x_{\mathrm{J}\gamma} < 1.0$)



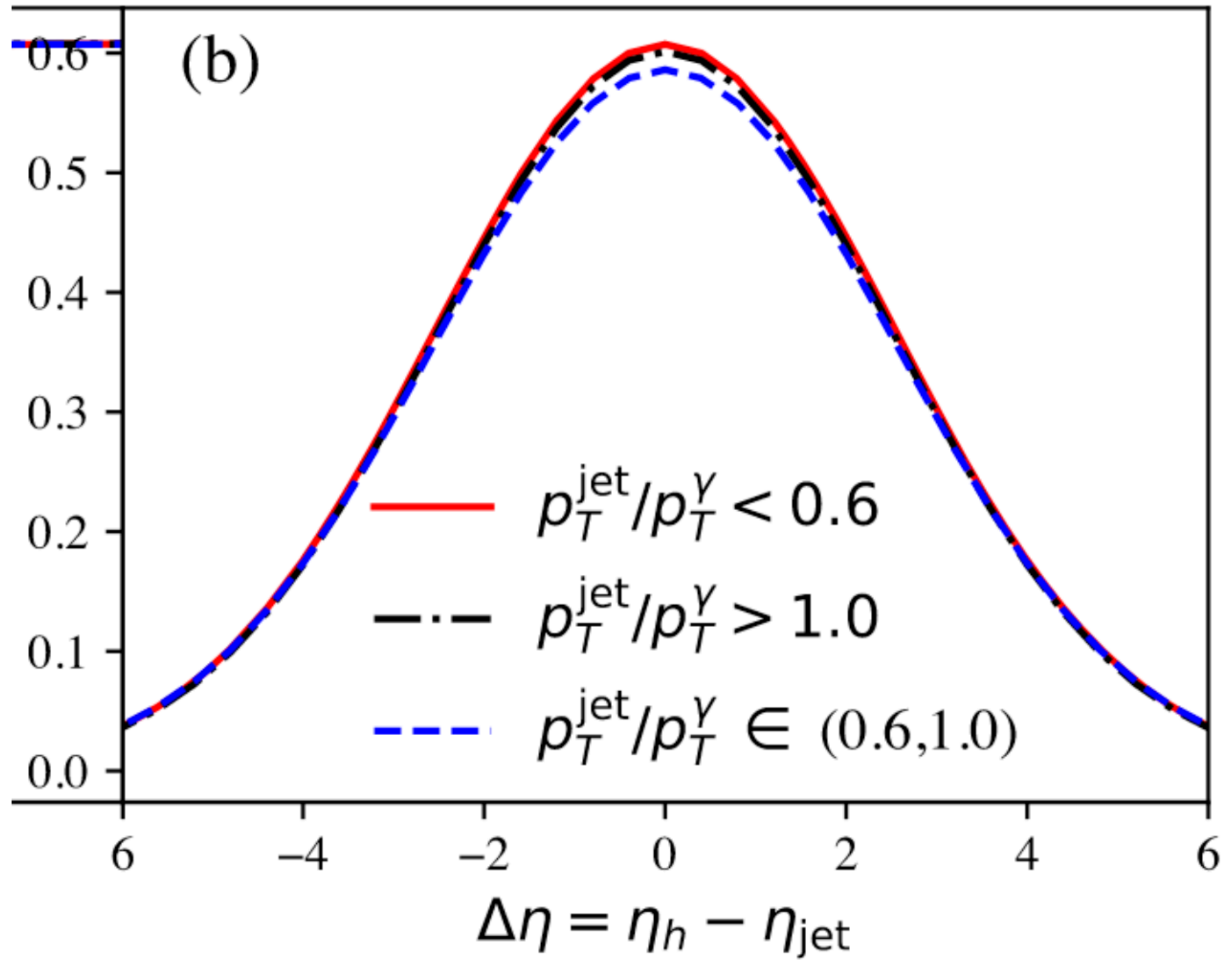
$|\Delta\eta(\text{jet, track})|$ in pp collisions



arXiv:2408.08599

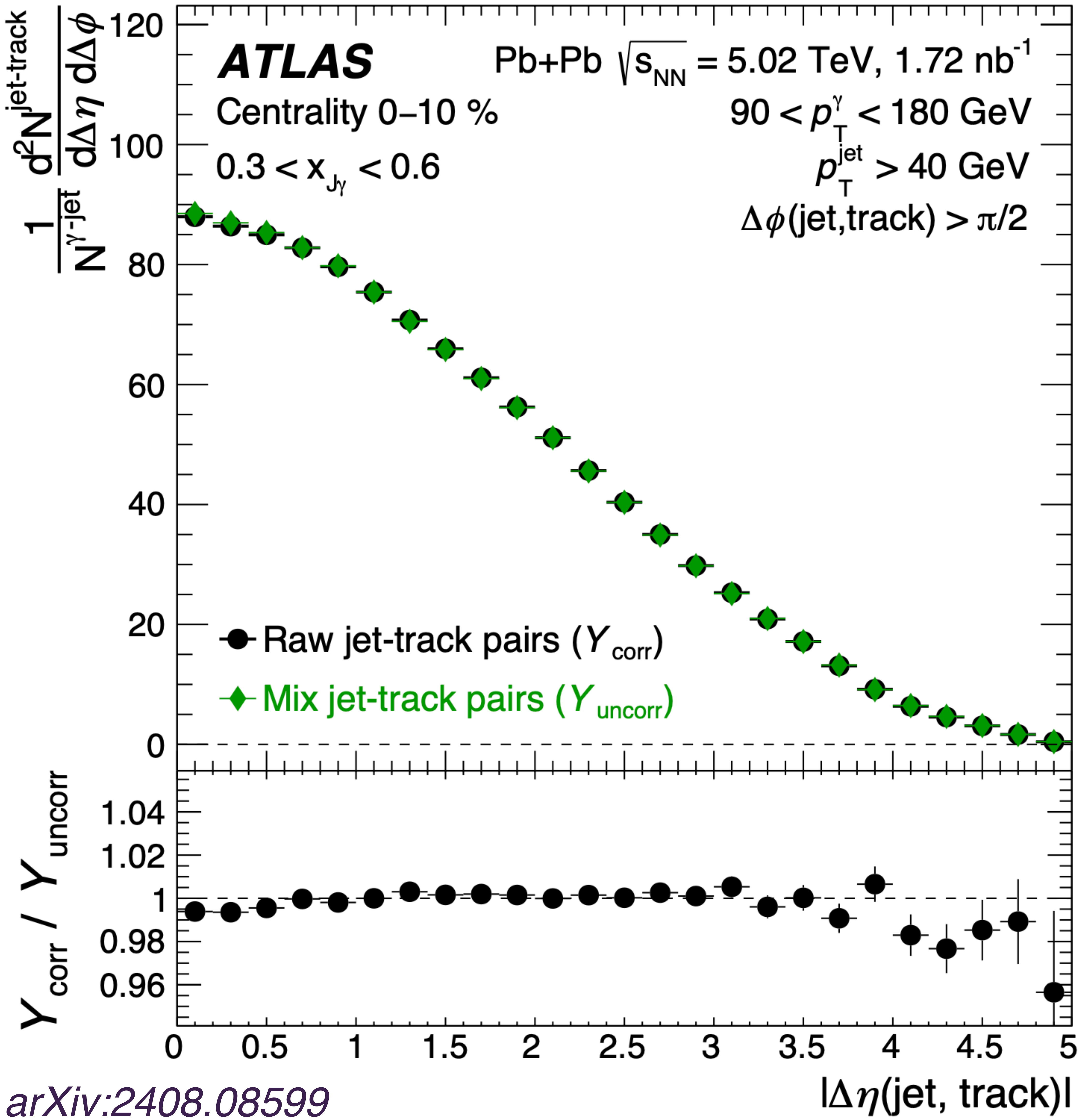
- The yield distributions as a function of $|\Delta\eta(\text{jet, track})|$ in the three $x_{J\gamma}$ regions are **consistent with each other** within uncertainties
  ➡ in agreement with the theory expectation

Multi-parton interaction (MPI)



PRL 130, 052301 (2023), CoLBT

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



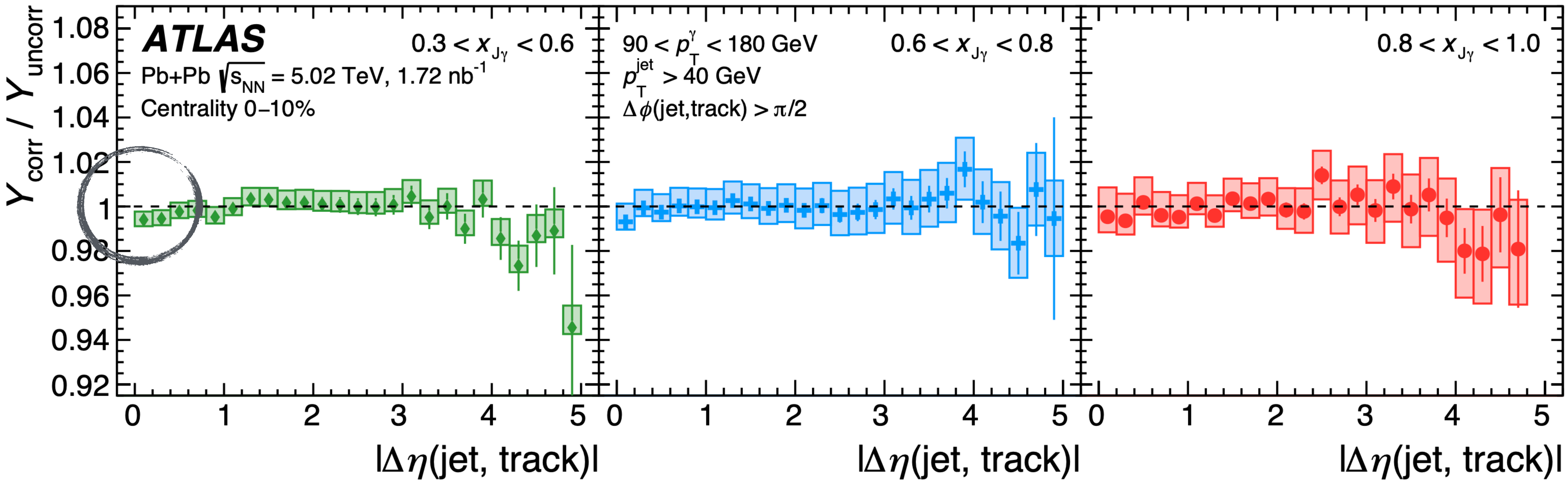
arXiv:2408.08599

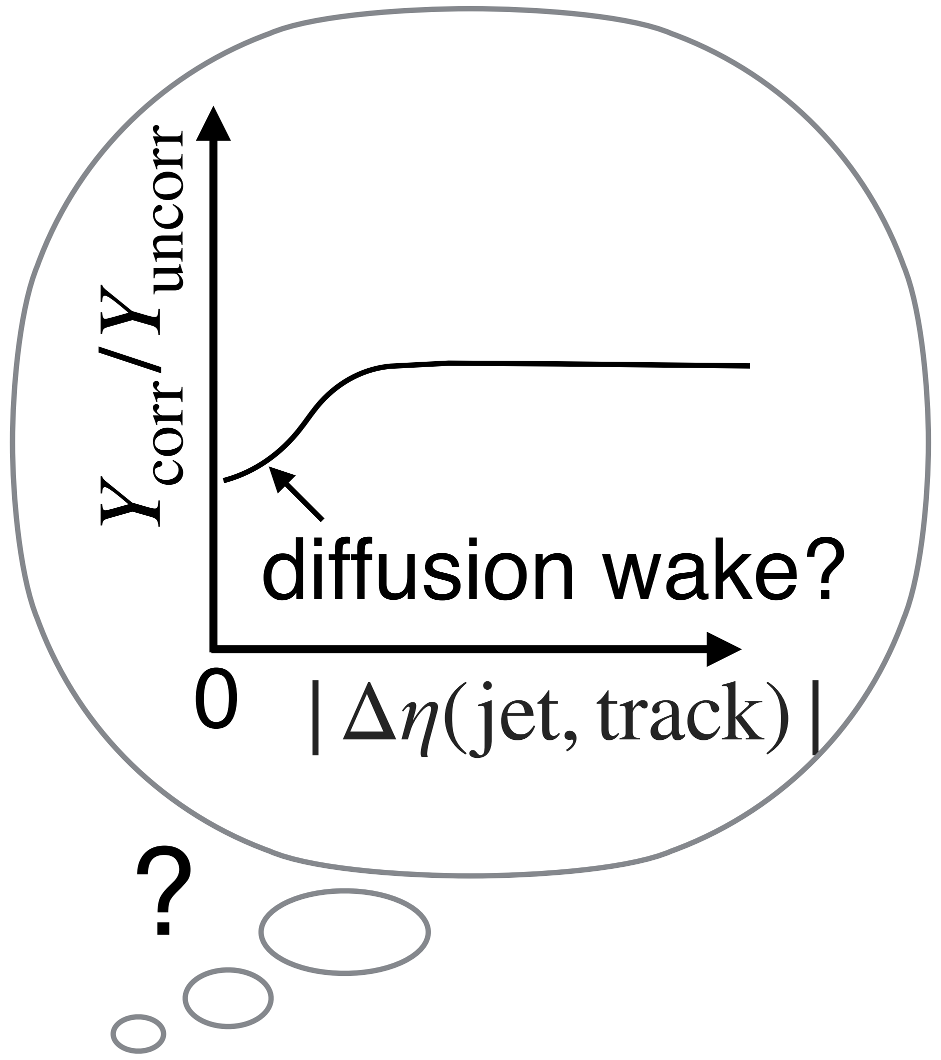
- Tracks produced from the bulk medium constitute a background
  - ➡ estimated using an *event mixing technique*
  - ➡ this “uncorrelated tracks” (Y_{uncorr}) is used as a reference for the track-jet correlation in photon-jet events.
- Event mixing technique
  - ➡ A photon-jet pair in a given event is matched with tracks in a different minimum-bias (MB) Pb+Pb event
  - ➡ When mixing the two events, an MB Pb+Pb event is chosen to have similar properties as the signal event
    - i.e. ΣE_T^{FCal}, event plane angle, vertex z position

Relative yield ratio: Y_{corr}/Y_{uncorr}

arXiv:2408.08599

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





- Y_{corr}/Y_{uncorr} indicates the ***relative modification of bulk medium***
- *No clear diffusion wake signal* found within uncertainties for the higher $x_{J\gamma}$ regions
- Small diffusion wake signal in the lowest $x_{J\gamma}$ region

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

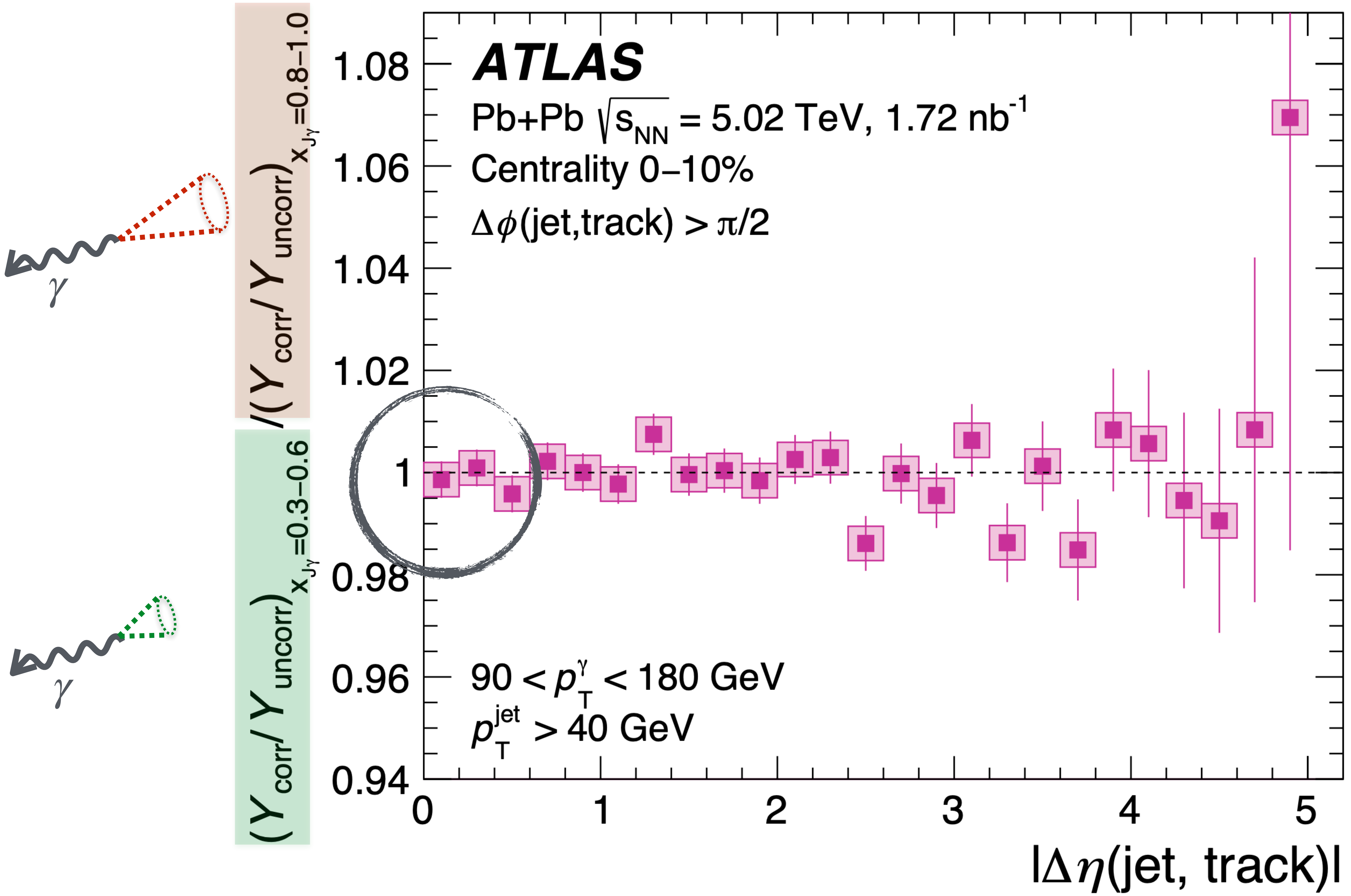
Relative yield ratio: Y_{corr}/Y_{uncorr}

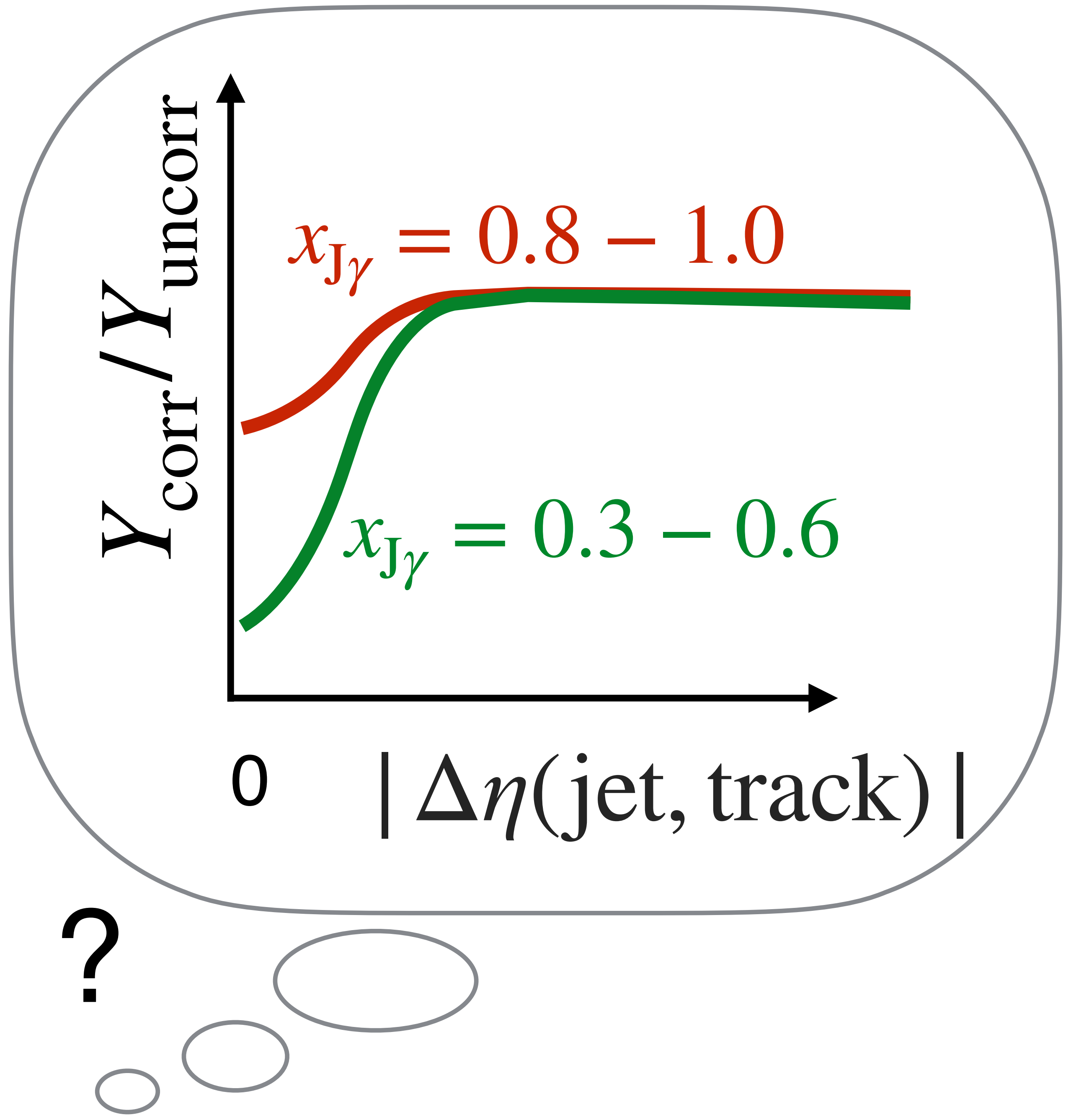
arXiv:2408.08599

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

- Y_{corr}/Y_{uncorr} indicates the ***relative modification of bulk medium***
- *No clear diffusion wake signal* found within uncertainties for the higher $x_{J\gamma}$ regions
- Small diffusion wake signal in the lowest $x_{J\gamma}$ region

Double ratio

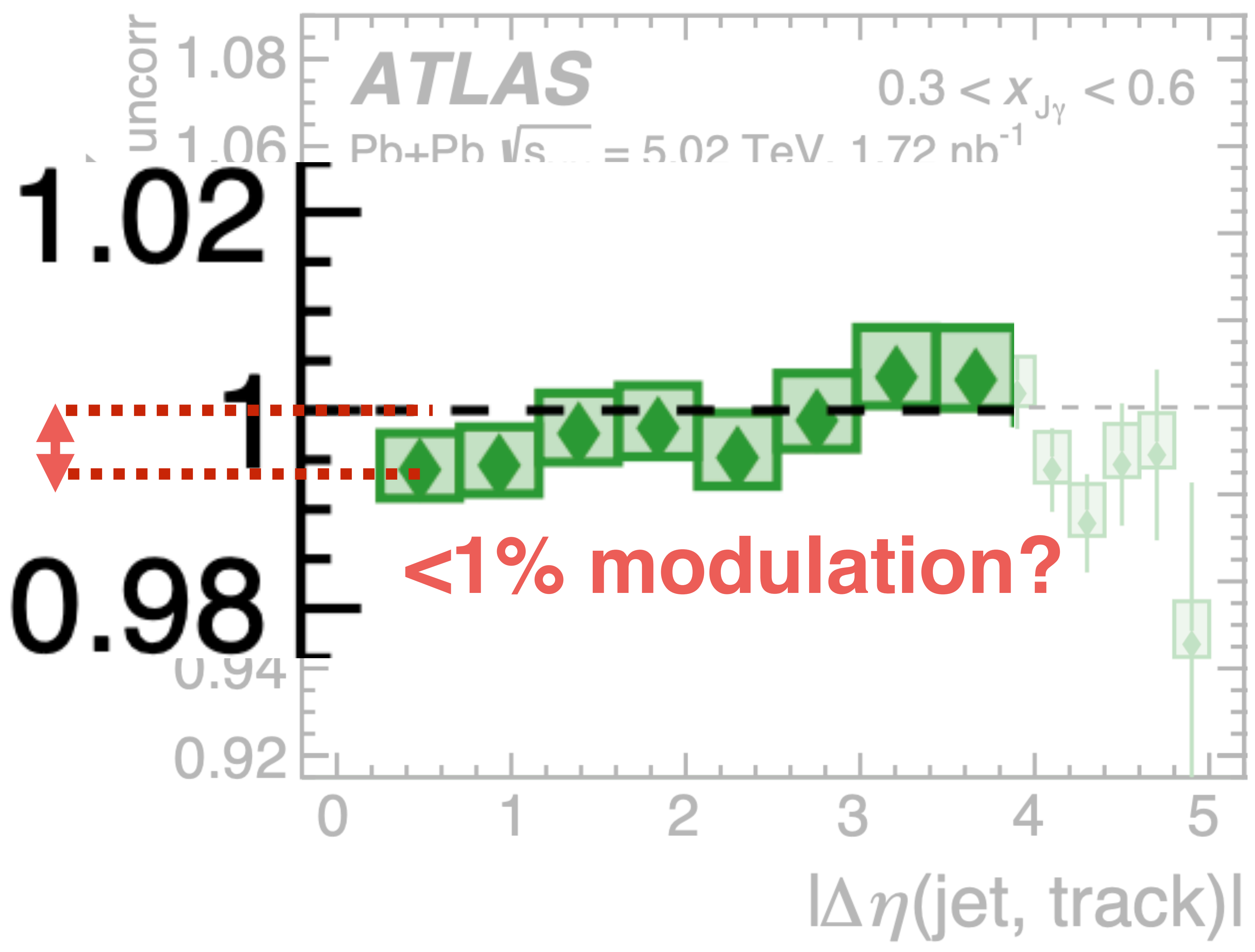




- The results are consistent with unity within uncertainties
  - ➡ no significant $x_{J\gamma}$-dependence of the diffusion wake is found

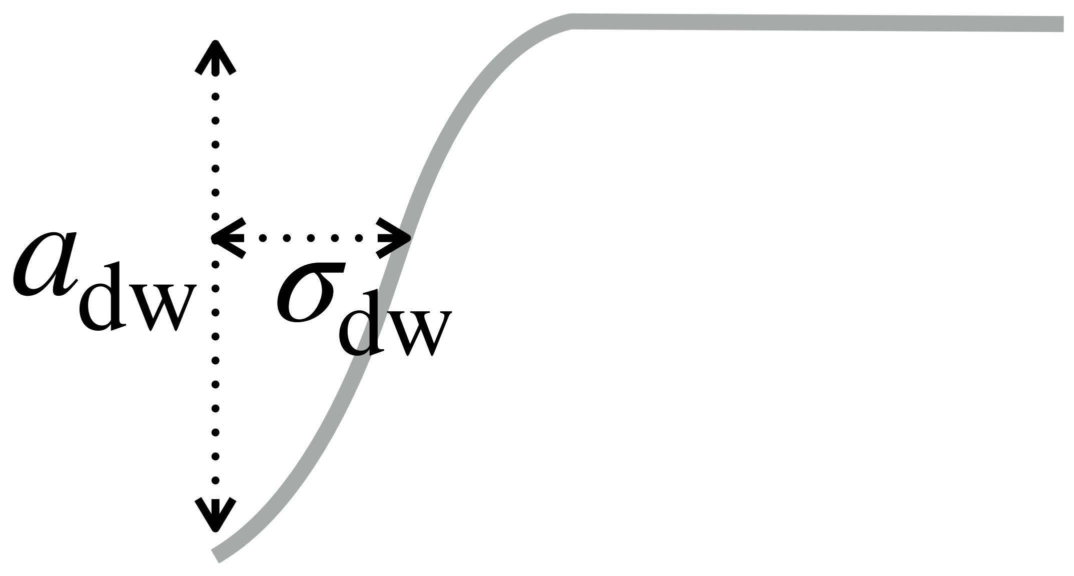
arXiv:2408.08599

Diffusion wake amplitude



Diffusion Wake Amplitude   Diffusion Wake Width

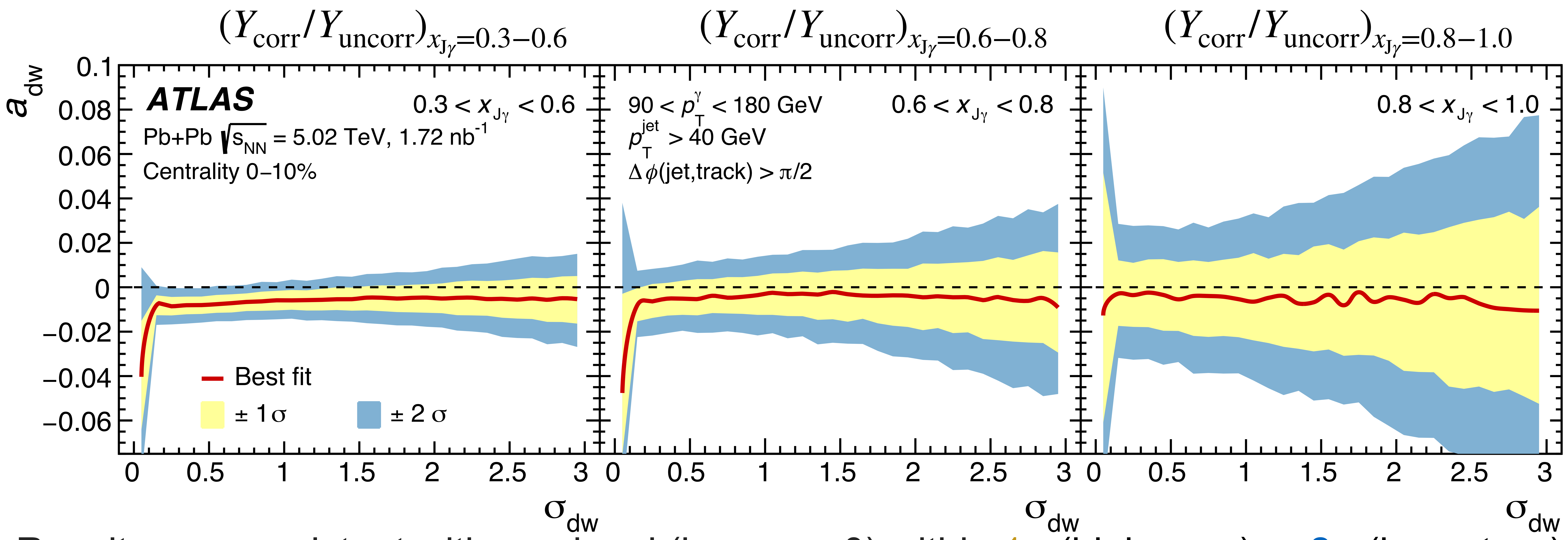
$$a_0 + a_{\mathrm{dw}} \cdot e^{-|\Delta\eta(\mathrm{jet,track})|^2/(2\sigma_{\mathrm{dw}}^2)}$$



- To quantify the diffusion wake, *Gaussian fits* are performed
  - ➡ diffusion wake would have a ***negative amplitude*** ($a_{\mathrm{dw}} < 0$)
- For probability distributions, **Monte Carlo sampling method** is used
  - ➡ ***statistical*** *and* ***systematic uncertainties*** *and* ***their correlations*** *are considered*
  - ➡ the fit is repeated with the σ_{dw} fixed, representing a different hypothesis each time, while a_{dw} and a_0 are treated as free parameters

Probability distributions

arXiv:2408.08599



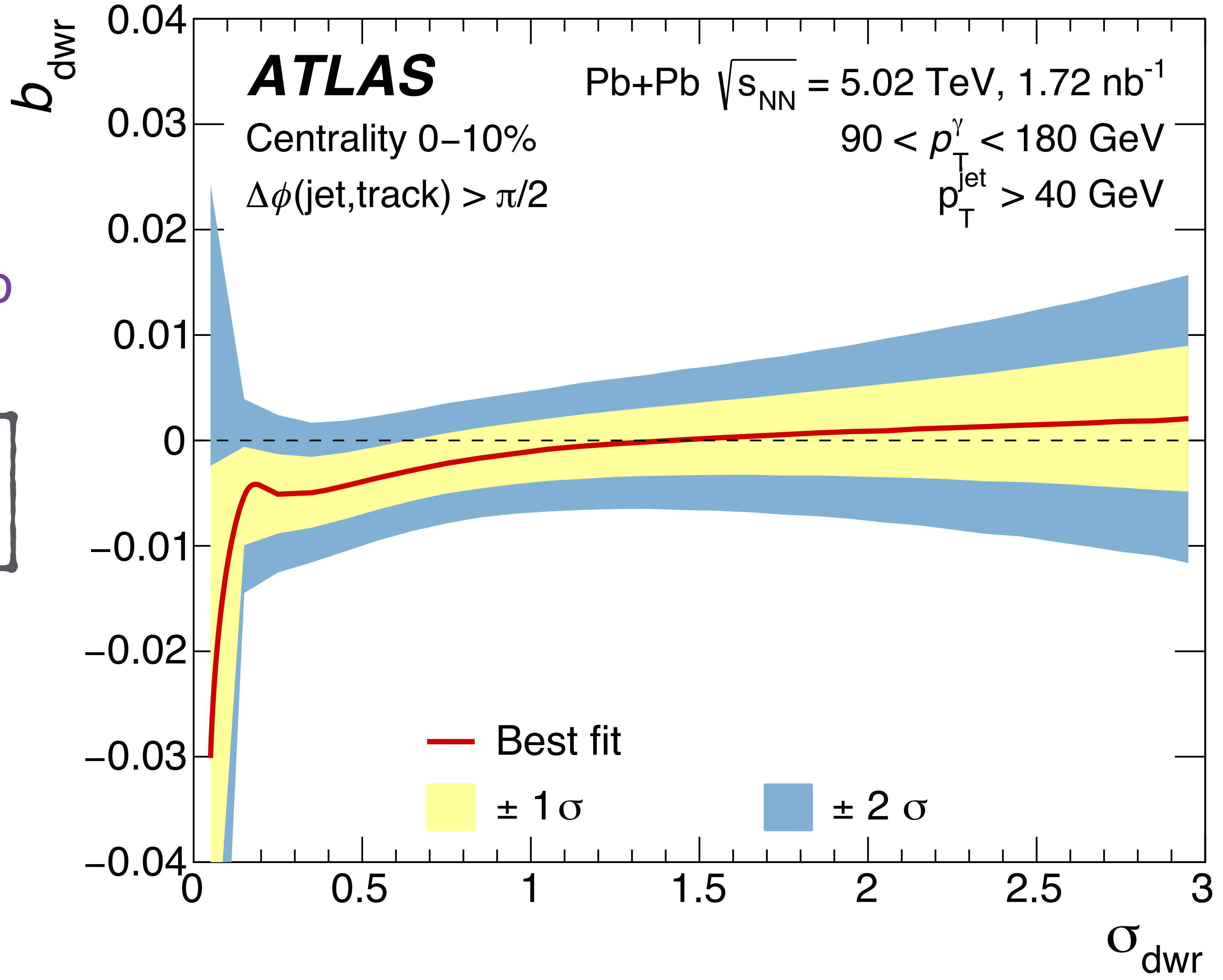
- Results are consistent with no signal (i.e., a_{dw}=0) within 1σ (higher $x_{J\gamma}$) or 2σ (lowest $x_{J\gamma}$)
- Best fits of the diffusion wake amplitude is negative for all $x_{J\gamma}$
- **Diffusion wake amplitude of best fit for the lowest $x_{J\gamma}$ is 0.5-0.8% for the diffusion wake width range of 0.5-1.0**
- *Statistical uncertainty dominates in the probability distributions as systematic uncertainties are highly correlated bin-by-bin*

Double ratio amplitude

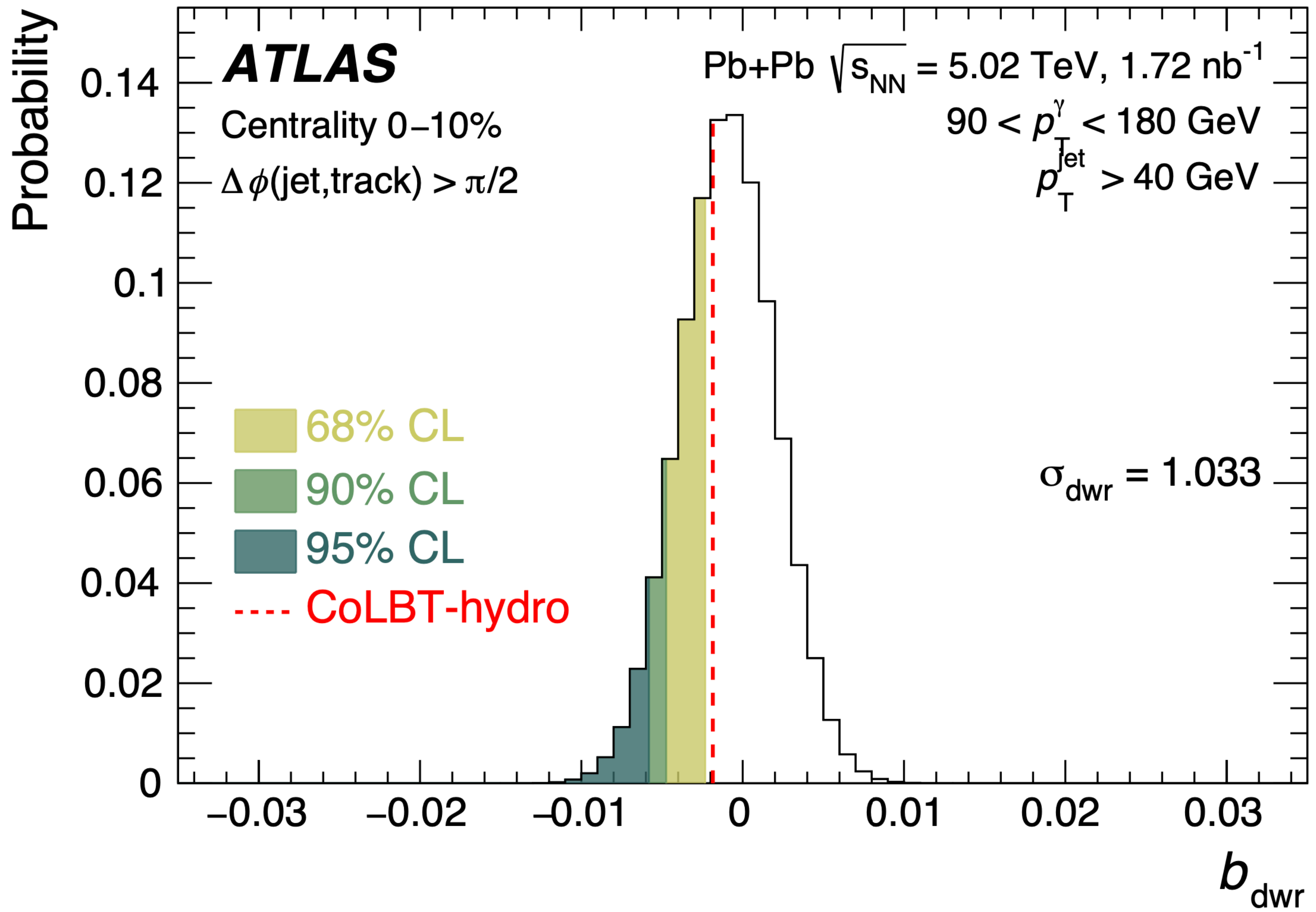
arXiv:2408.08599

Double Ratio Amplitude — Double Ratio Width

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

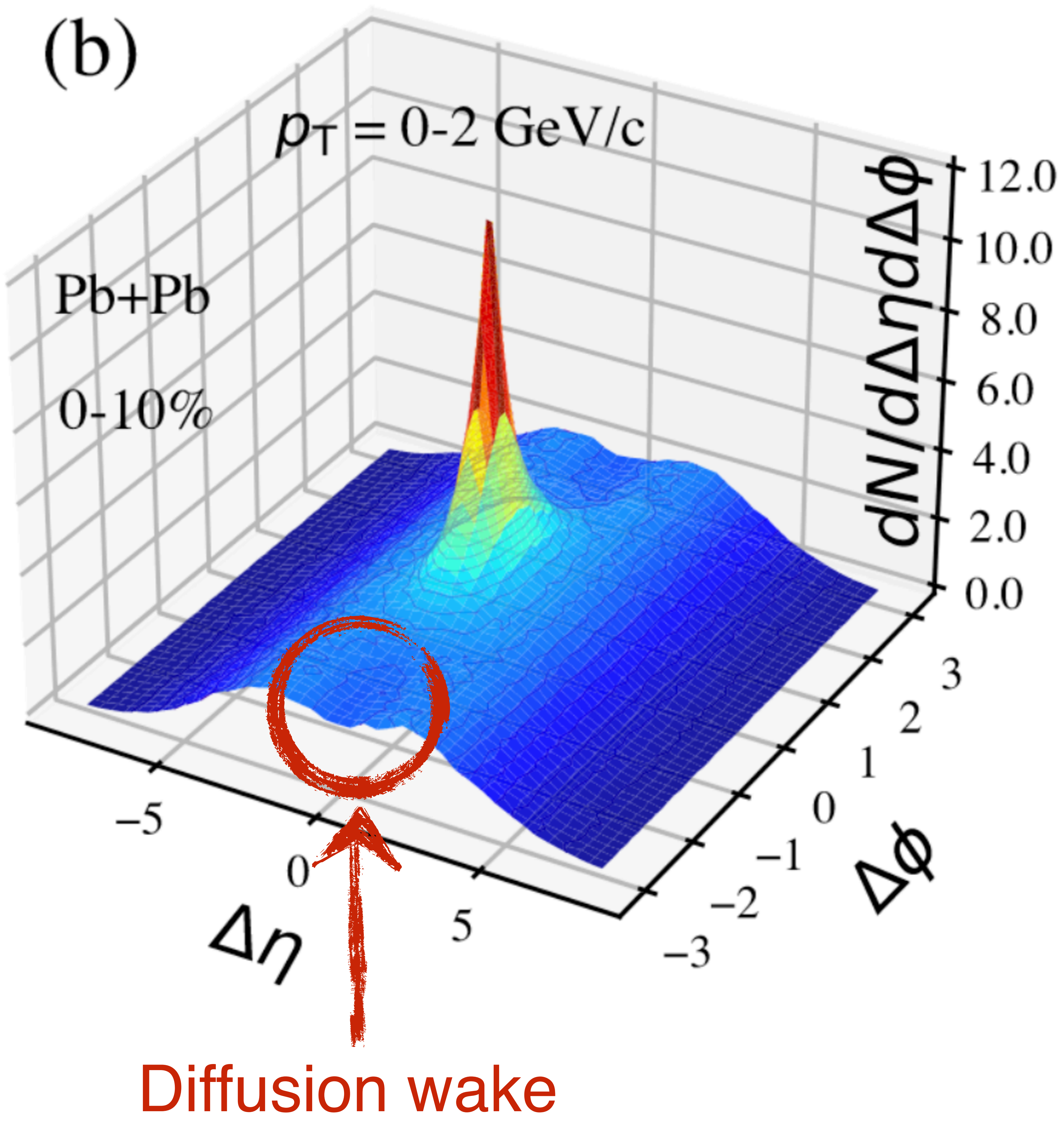


b_{dwr} distributions for width σ_{dwr} = 1.033



- Data indicates no significant, but small, diffusion wake signal that increases with larger parton energy loss
- CoLBT prediction of -0.00185 is consistent with the data *within the 68% confidence level upper limit*
- A diffusion wake double amplitude b_{dwr} value smaller than -0.0058 can be ruled out at 95% confidence level
- **Stat. uncert.** dominates in probability distribution; more statistics will be valuable

Diffusion wake in dijet



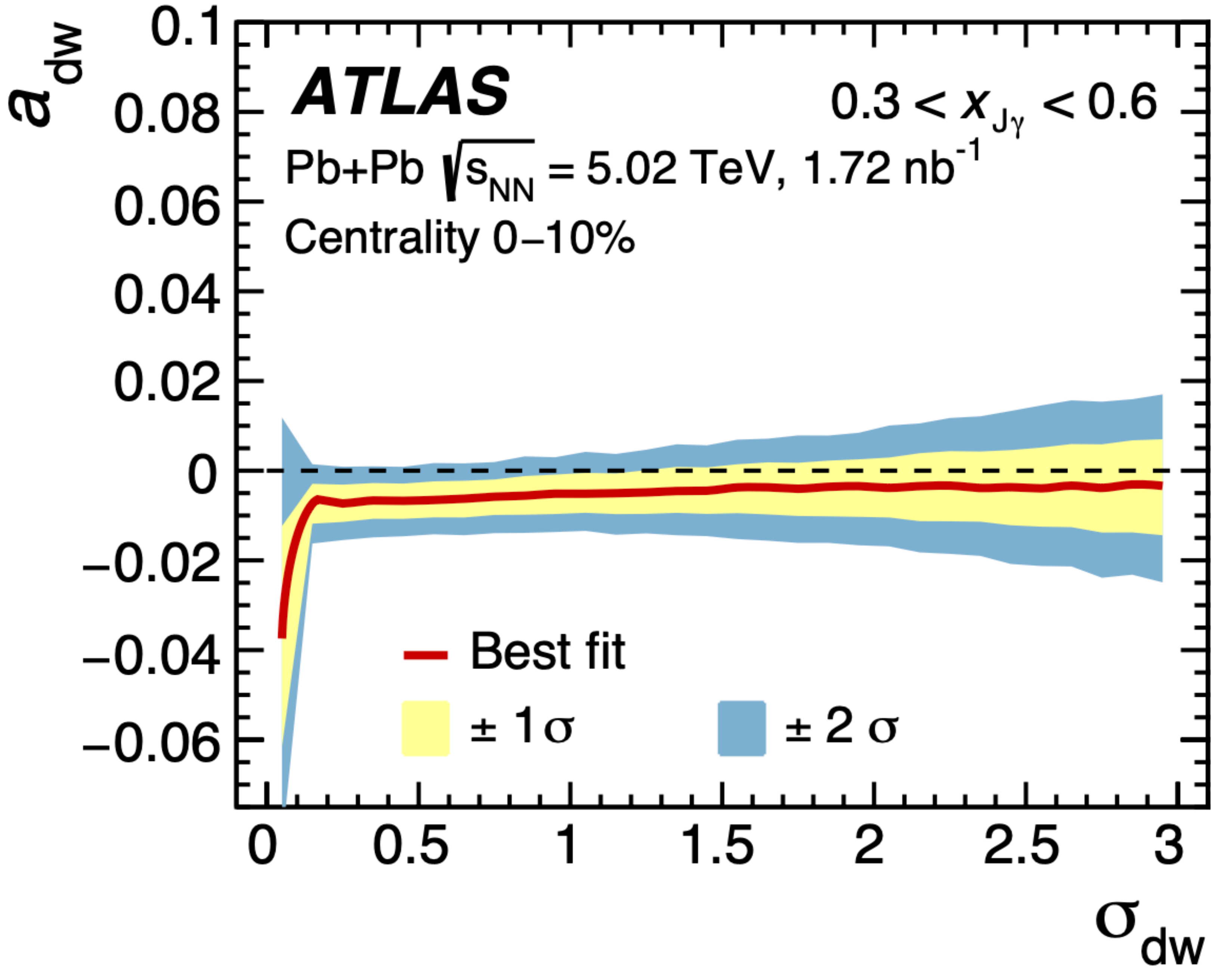
- Diffusion wake is localized in $(\Delta\eta, \Delta\phi) = (0, \pi/2)$
  - ➡ idea) use **dijets** samples of which two jets are separated enough in η to remove contaminations from each other
    - statistically abundant!

Summary

arXiv:2408.08599

- **Jet-track η and ϕ angular correlations in photon-jet events** have been measured and finalized to search for *diffusion wake*
- The measurement is performed with **three different ranges of $x_{J\gamma}$** to select events with **different amounts of parton energy loss**
- *The data provides **probability limits*** on diffusion wake;
  - ➡ The *CoLBT theory prediction* of **-0.0018** for the double ratio **is consistent with the data** within the 68% confidence level upper limit
  - ➡ the best fit of the diffusion wake amplitude for the lowest $x_{J\gamma}$ is about 0.5-0.8% for the diffusion wake width range of 0.5-1.0

See also talk by Dominik at 9:00AM (Wed.) for more photon-jet analyses

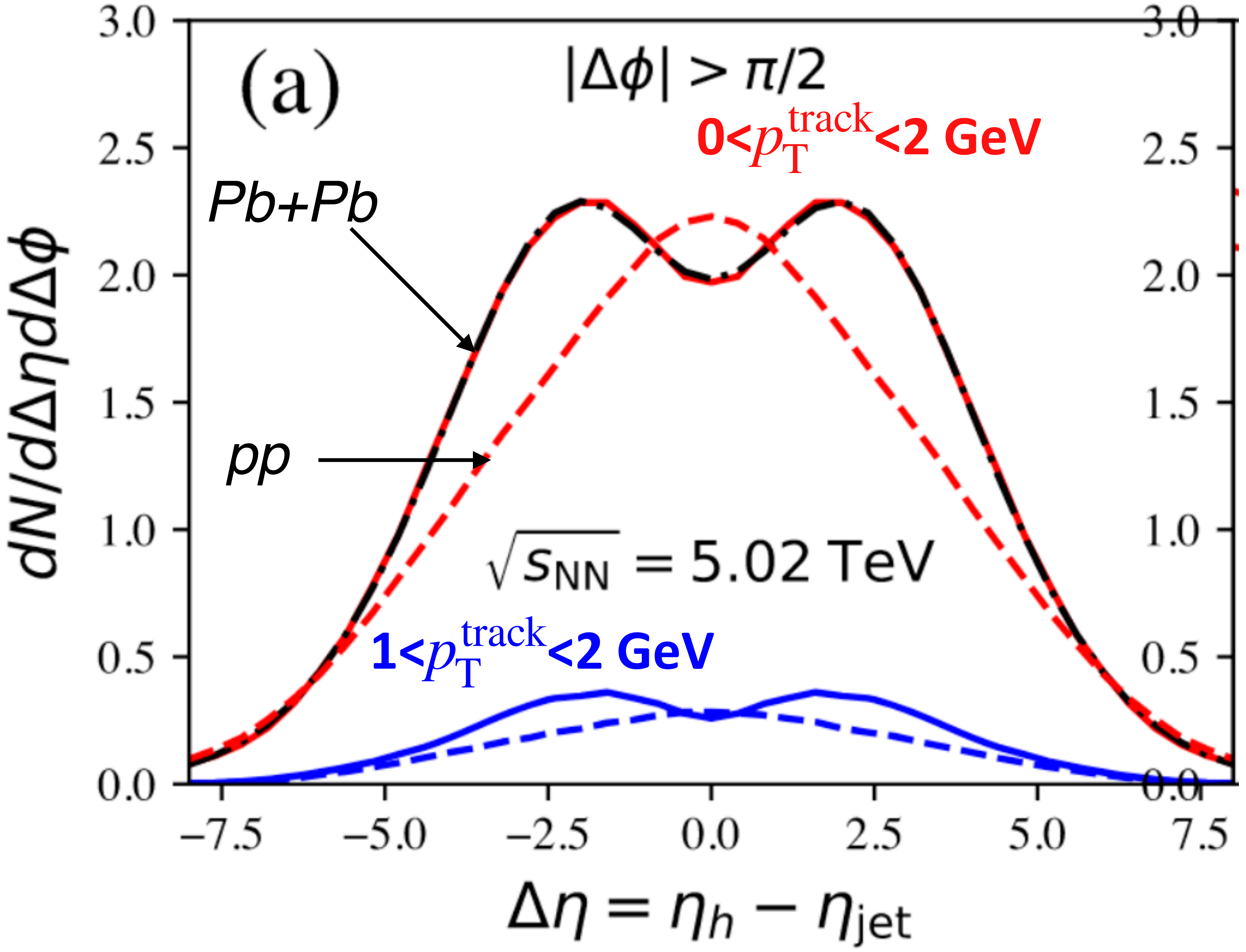


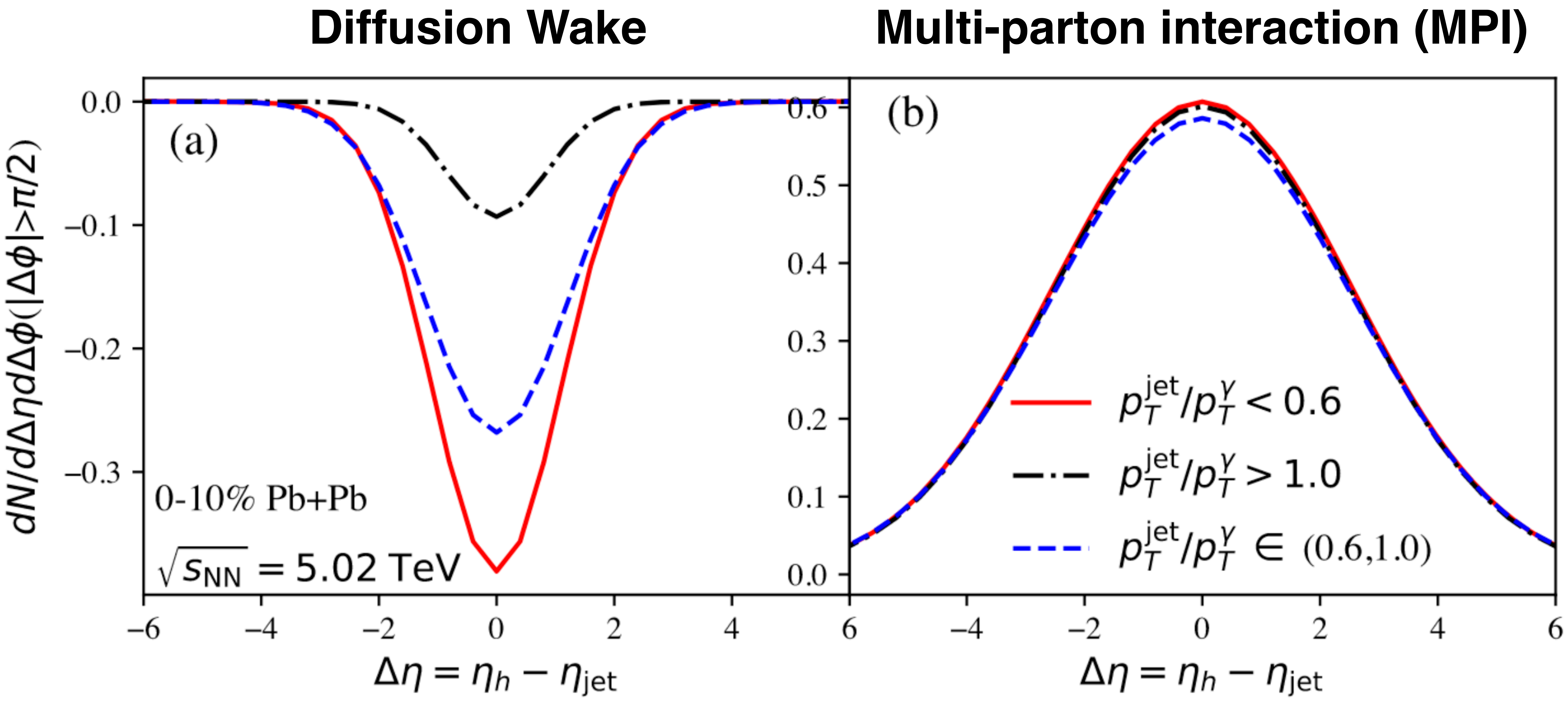
Find other *ATLAS heavy ion* results!

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HeavyIonsPublicResults

BACK UP

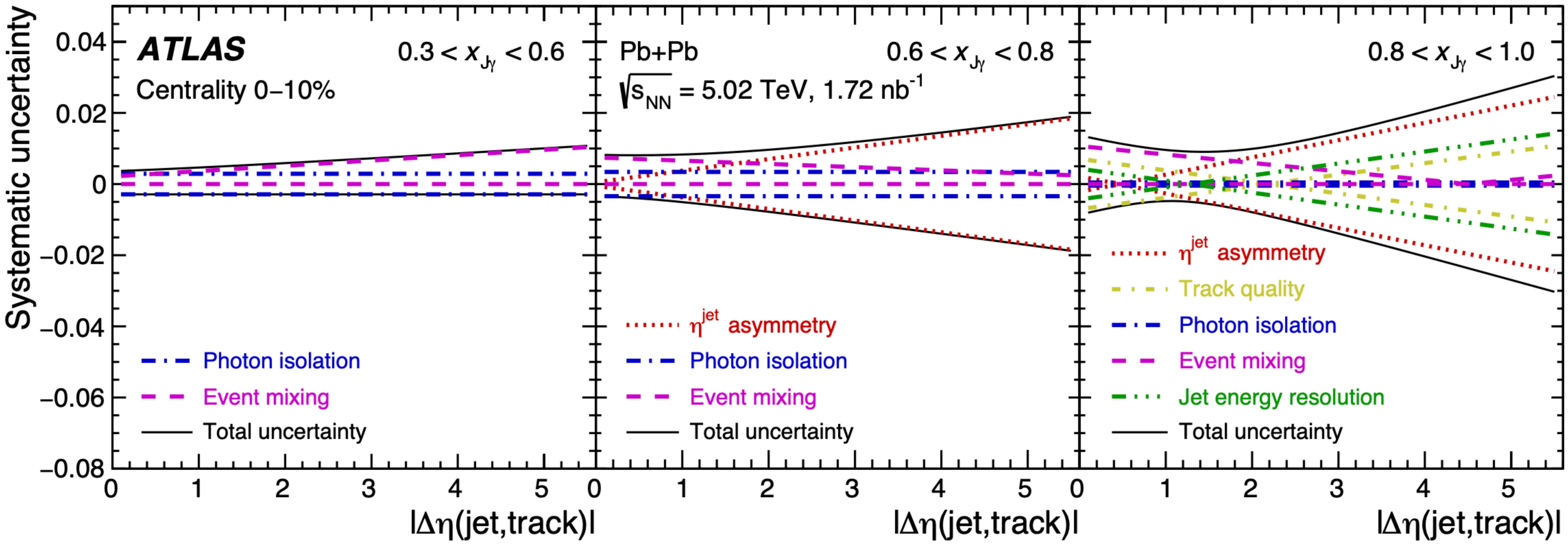
Diffusion wake: dependence on jet energy loss





- Smaller $x_{J\gamma} = p_T^{jet}/p_T^{\gamma}$ indicates **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

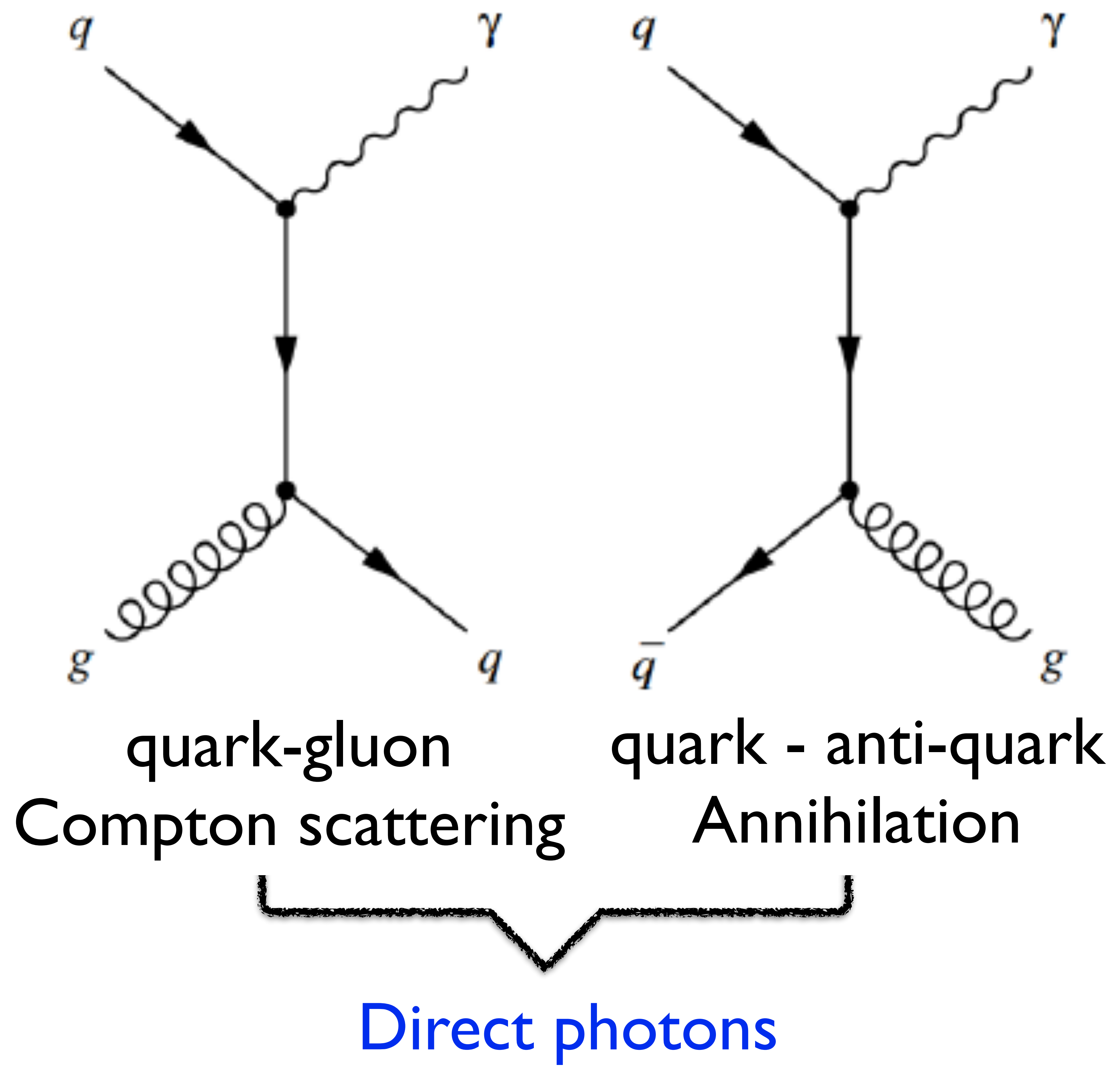
Systematic uncertainty



- Not to double-count statistical uncertainty in systematic uncertainty, a χ^2 method is used to test the significance of the systematic uncertainty of each source of each observable
  - ➡ Systematic sources which pass the χ^2 are deemed systematically significant and considered as systematic uncertainty

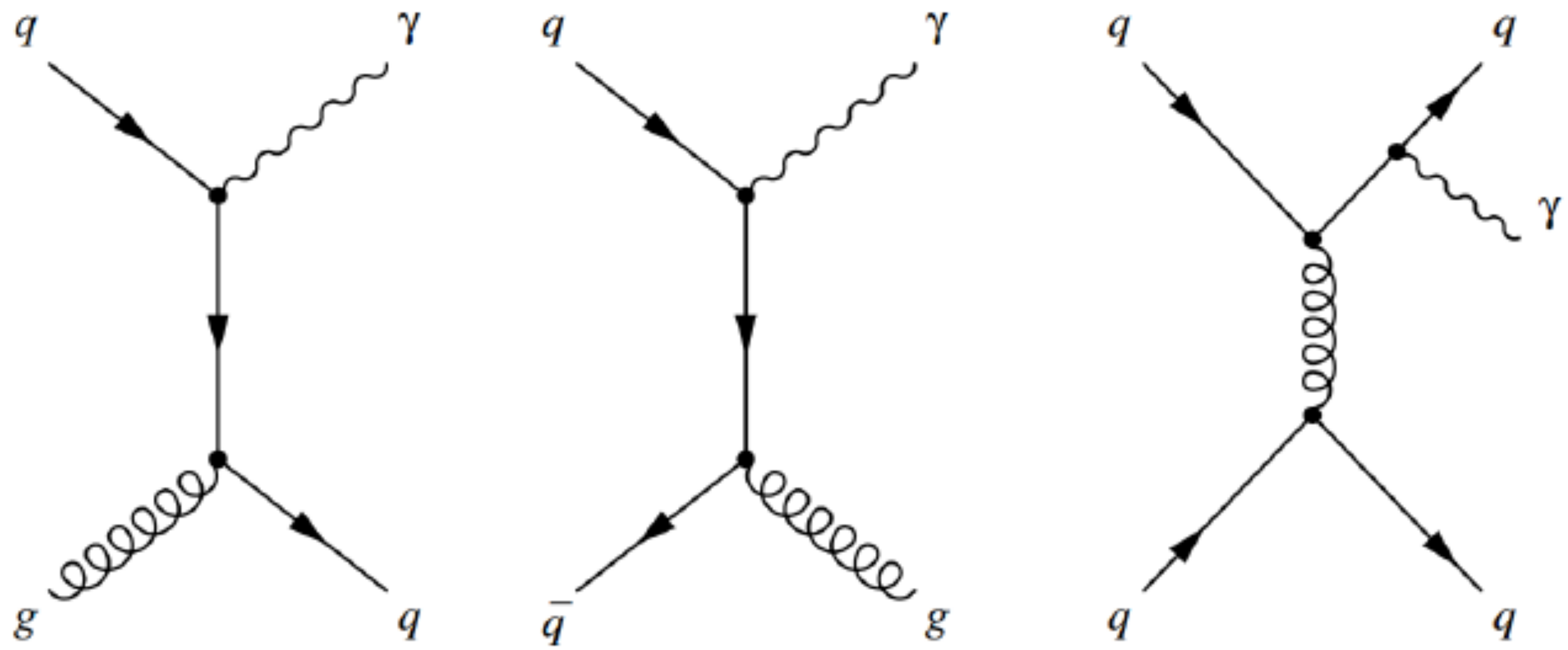
Prompt Photons

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



Prompt Photons

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



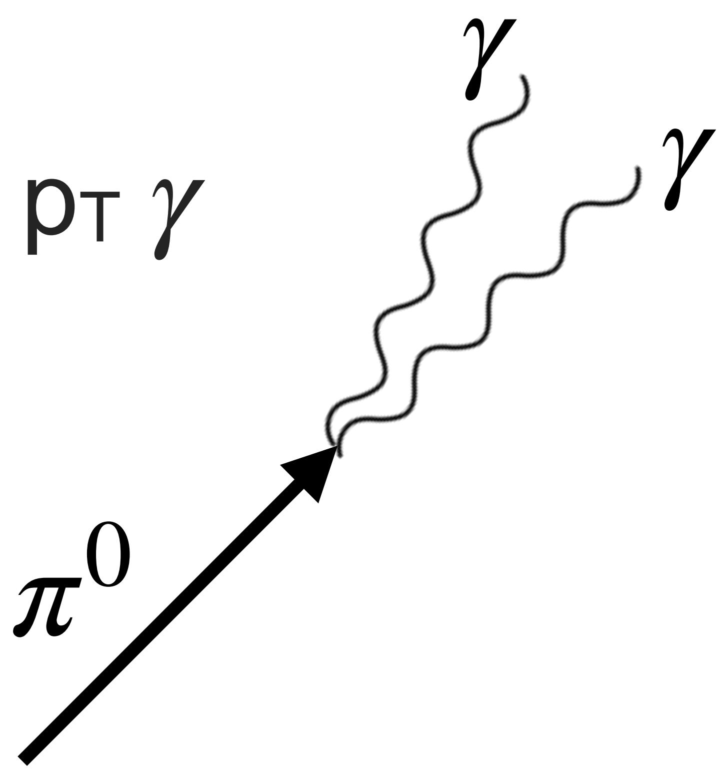
quark-gluon Compton scattering | quark - anti-quark Annihilation | Fragmentation

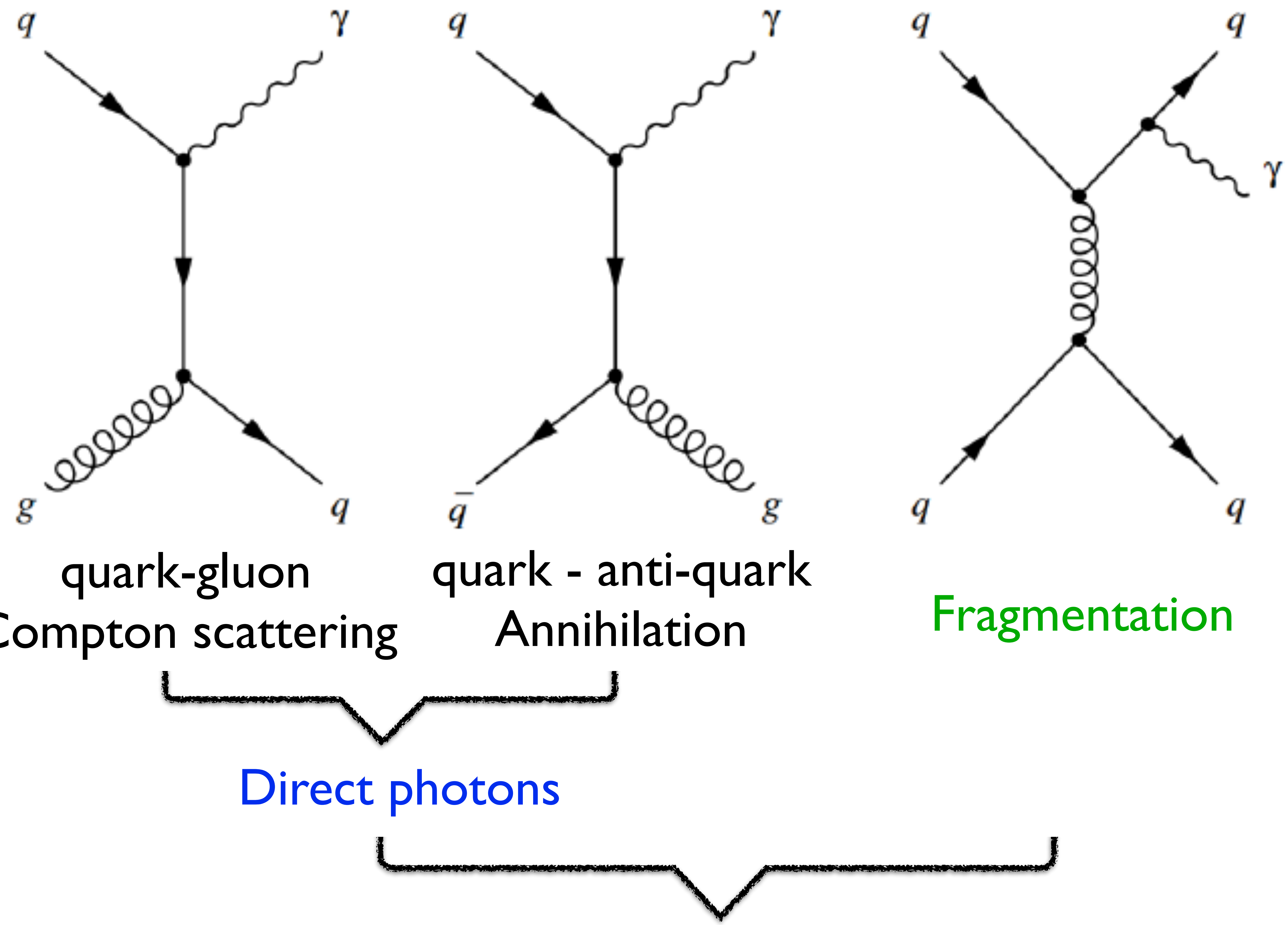
Direct photons

Prompt photons
= Direct + Fragmentation photons

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





Prompt photons
= Direct + Fragmentation photons