arXiv:2408.08599

Search for the **diffusion wake** via measurements of **jet-track correlations** with the ATLAS collaboration

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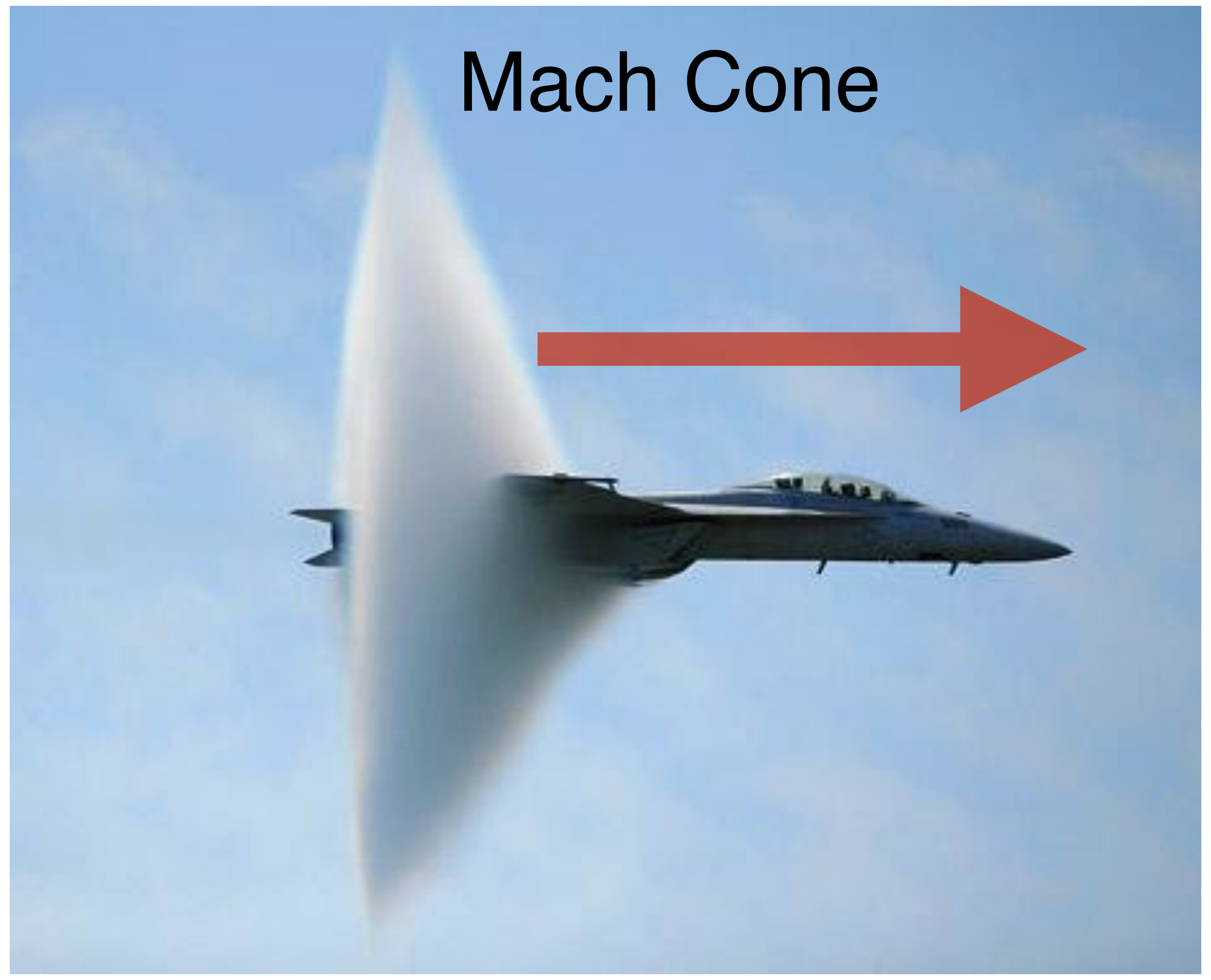
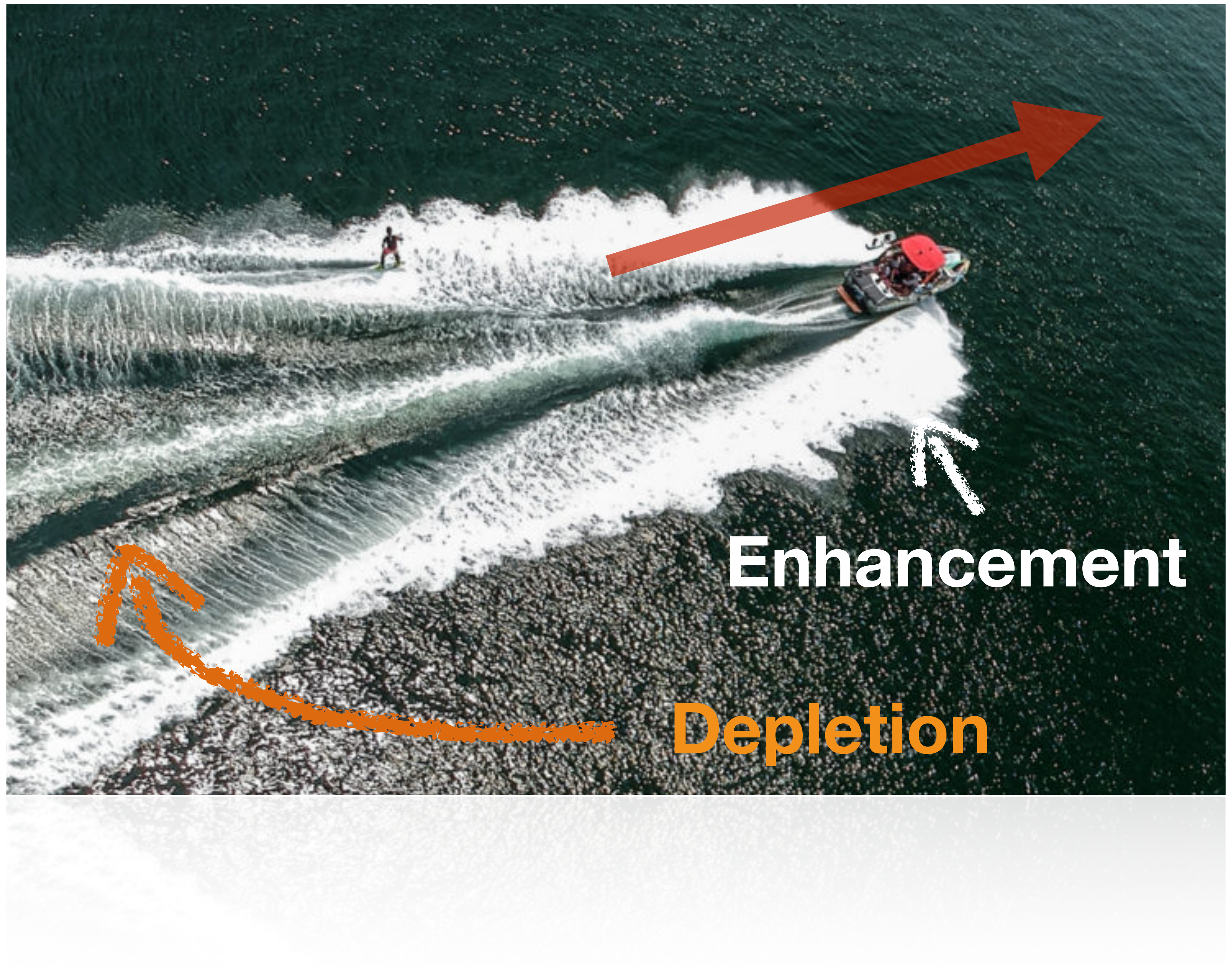
SoftJet 2024
Tokyo, Japan
Sep. 28-29 2024

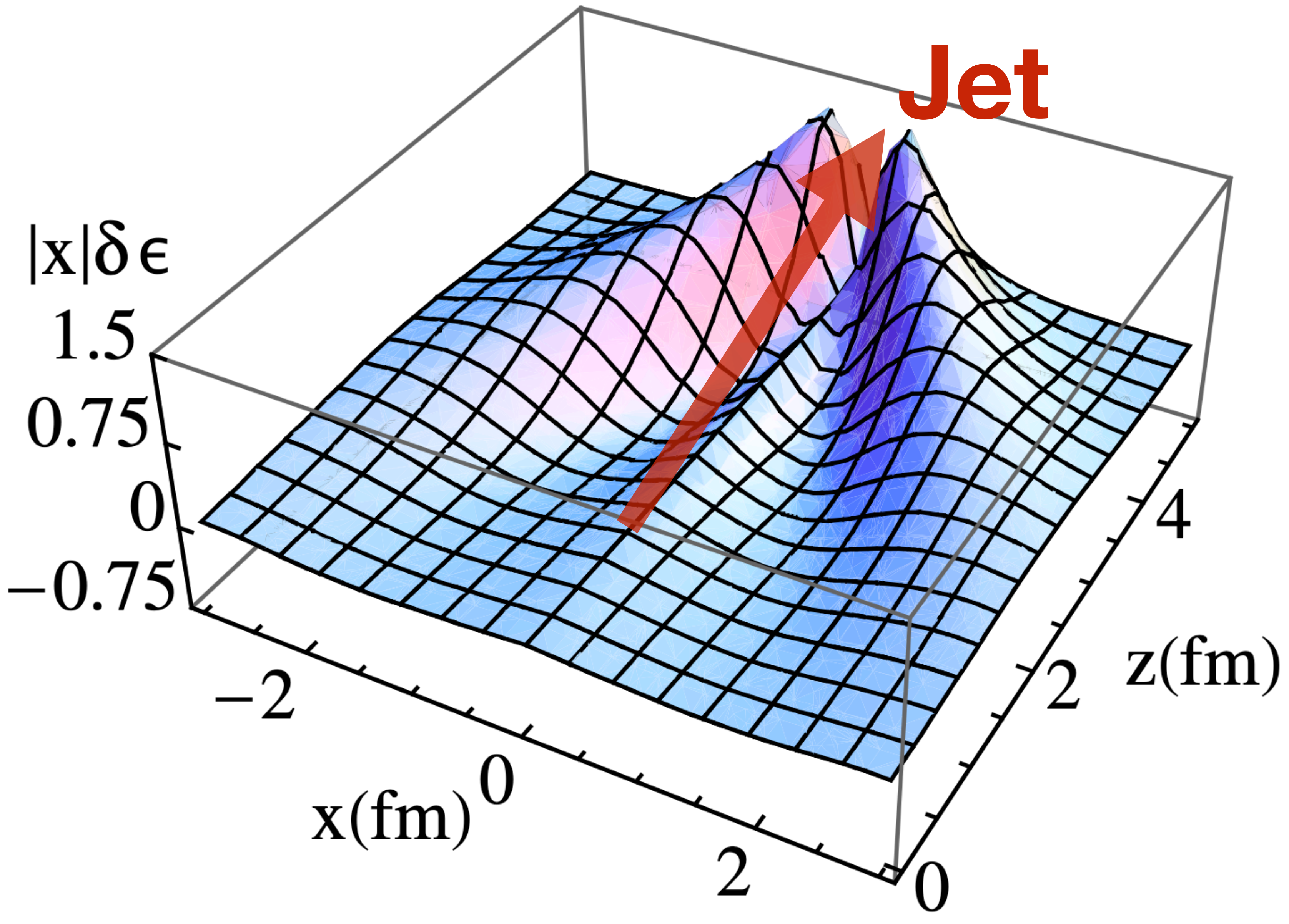
Brookhaven
National Laboratory

Medium response induced by jets





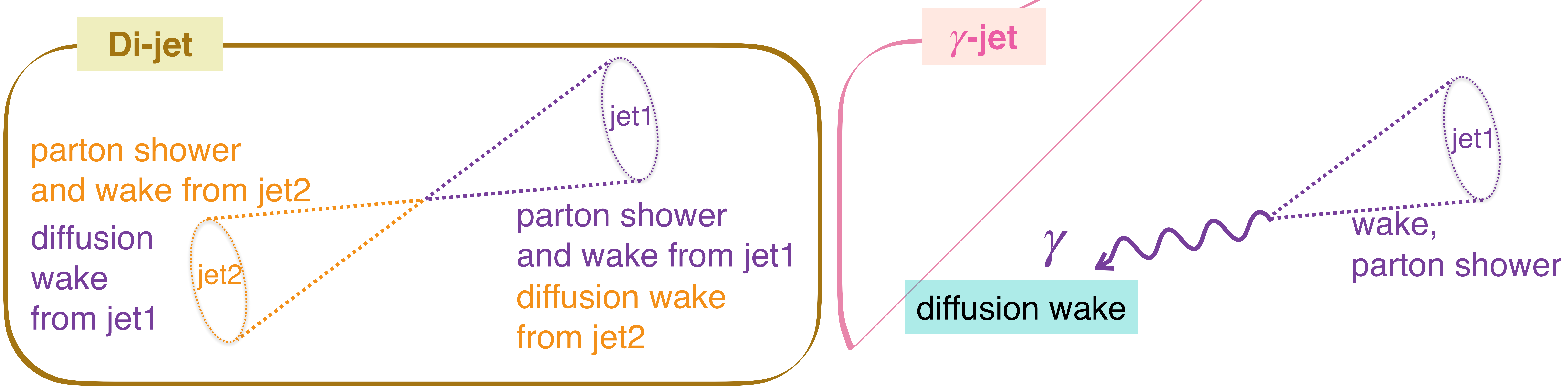
PRL 103, 152303 (2009)



- 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

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



Di-jet

parton shower
and wake from jet2

diffusion
wake
from jet1

jet2

jet1

parton shower
and wake from jet1

diffusion wake
from jet2

γ-jet

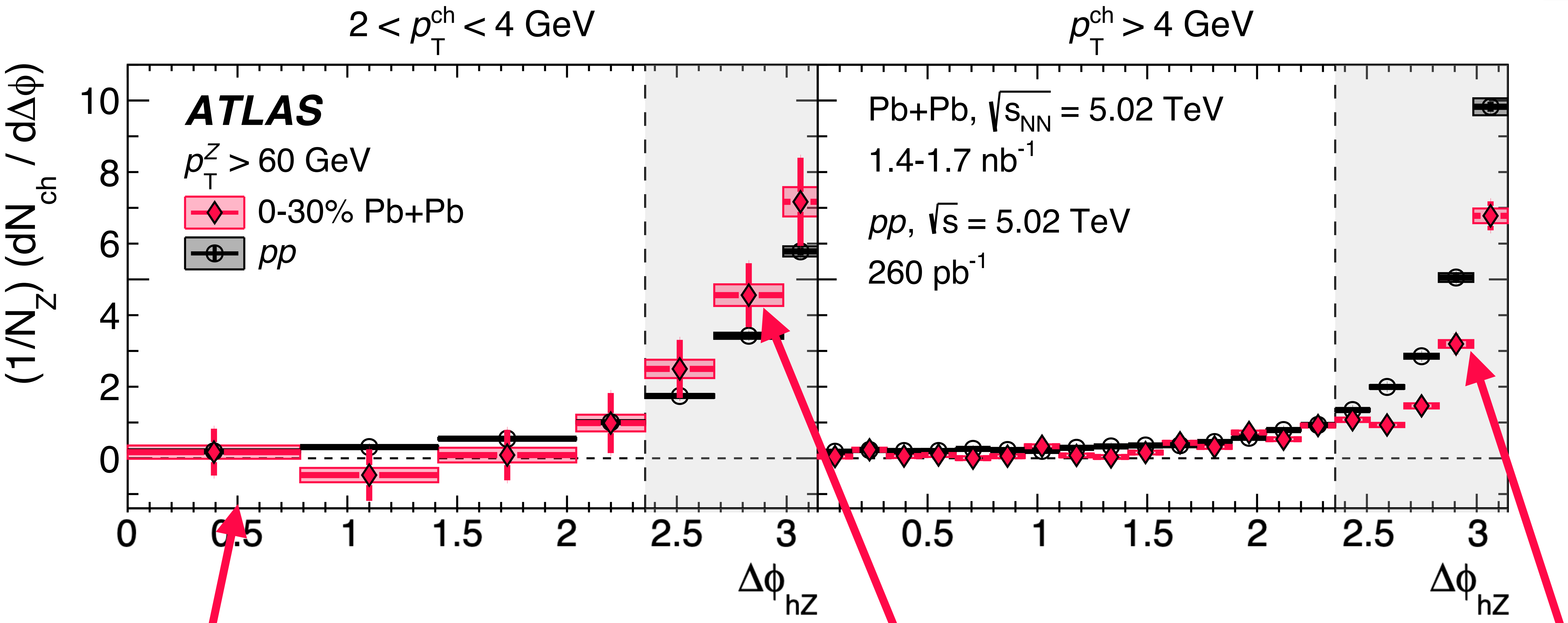
γ

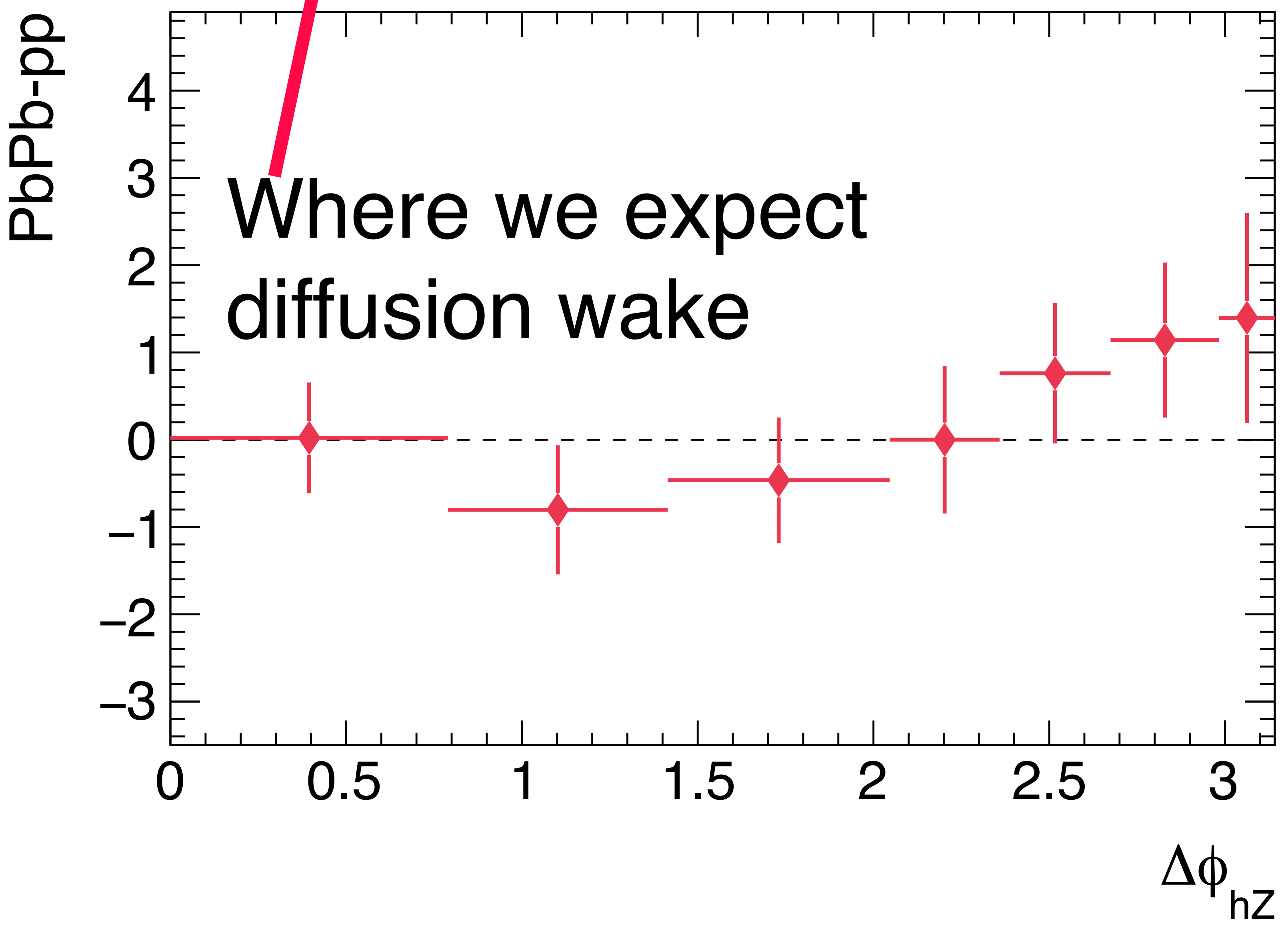
diffusion wake

jet1

wake,
parton shower

Previous measurements of Z-hadron correlations





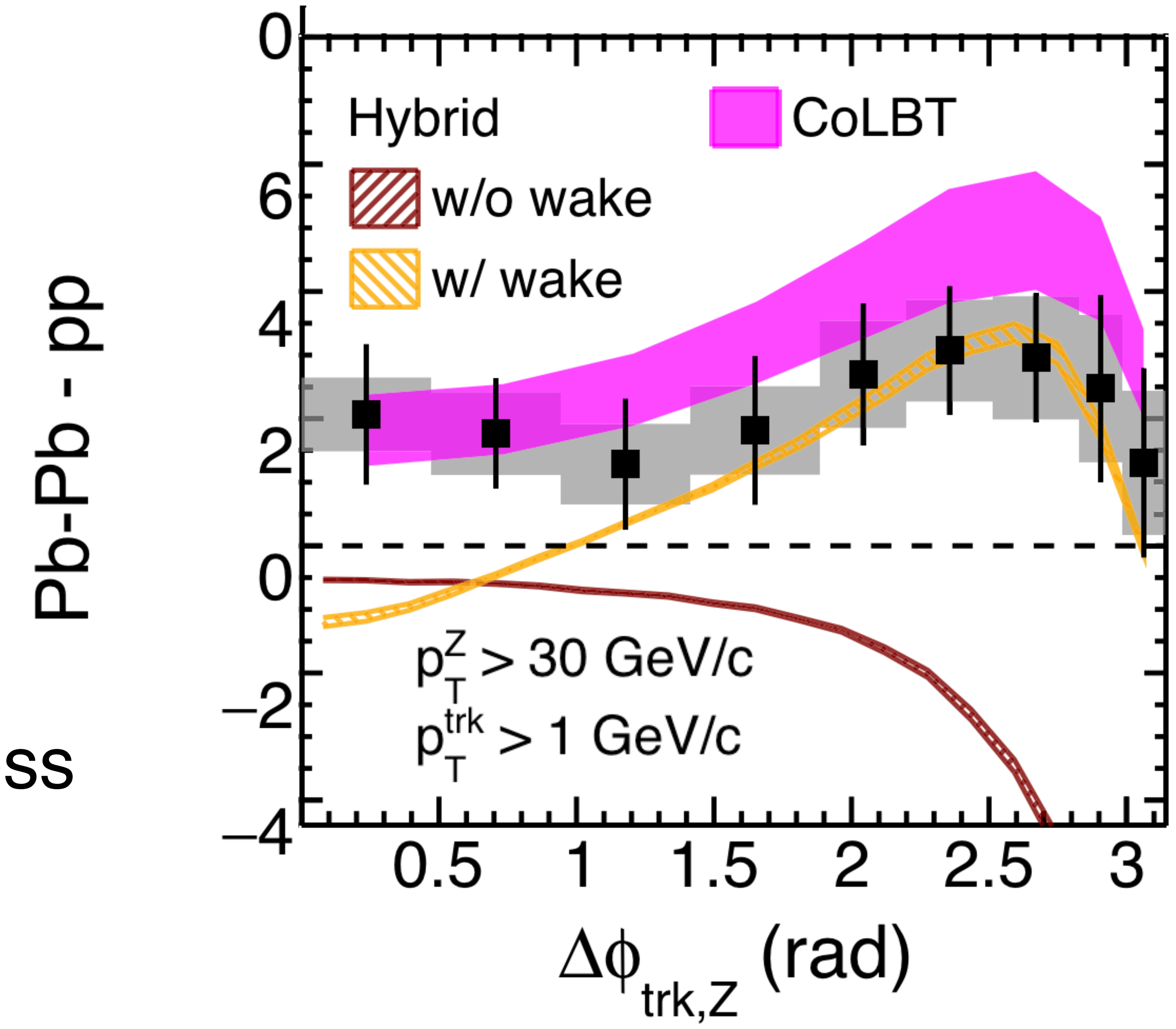
Where we expect diffusion wake

Hint of wake

Jet energy loss

ATLAS, PRL 126 (2021) 072301

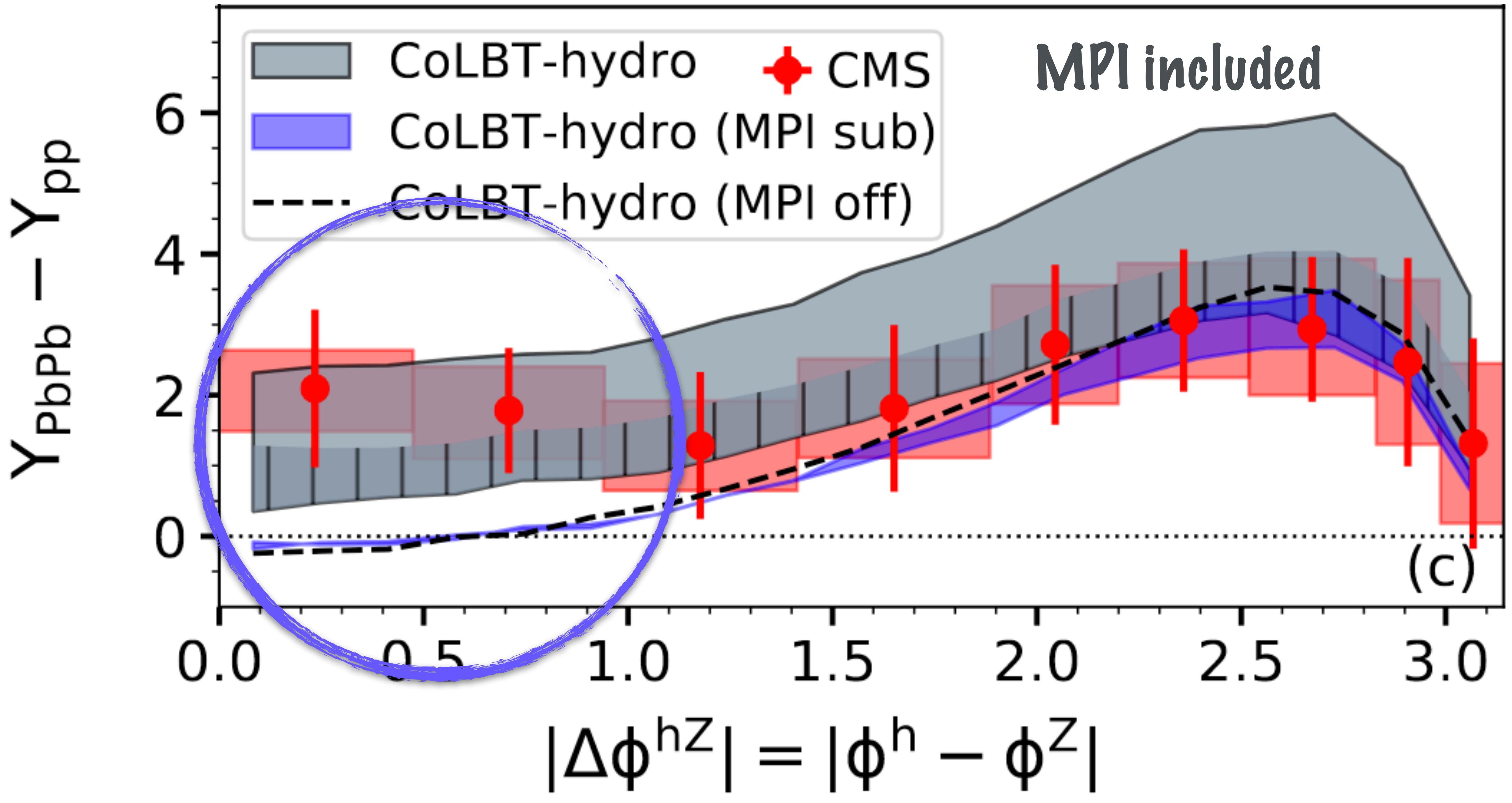
CMS, PRL 128 (2022) 122301



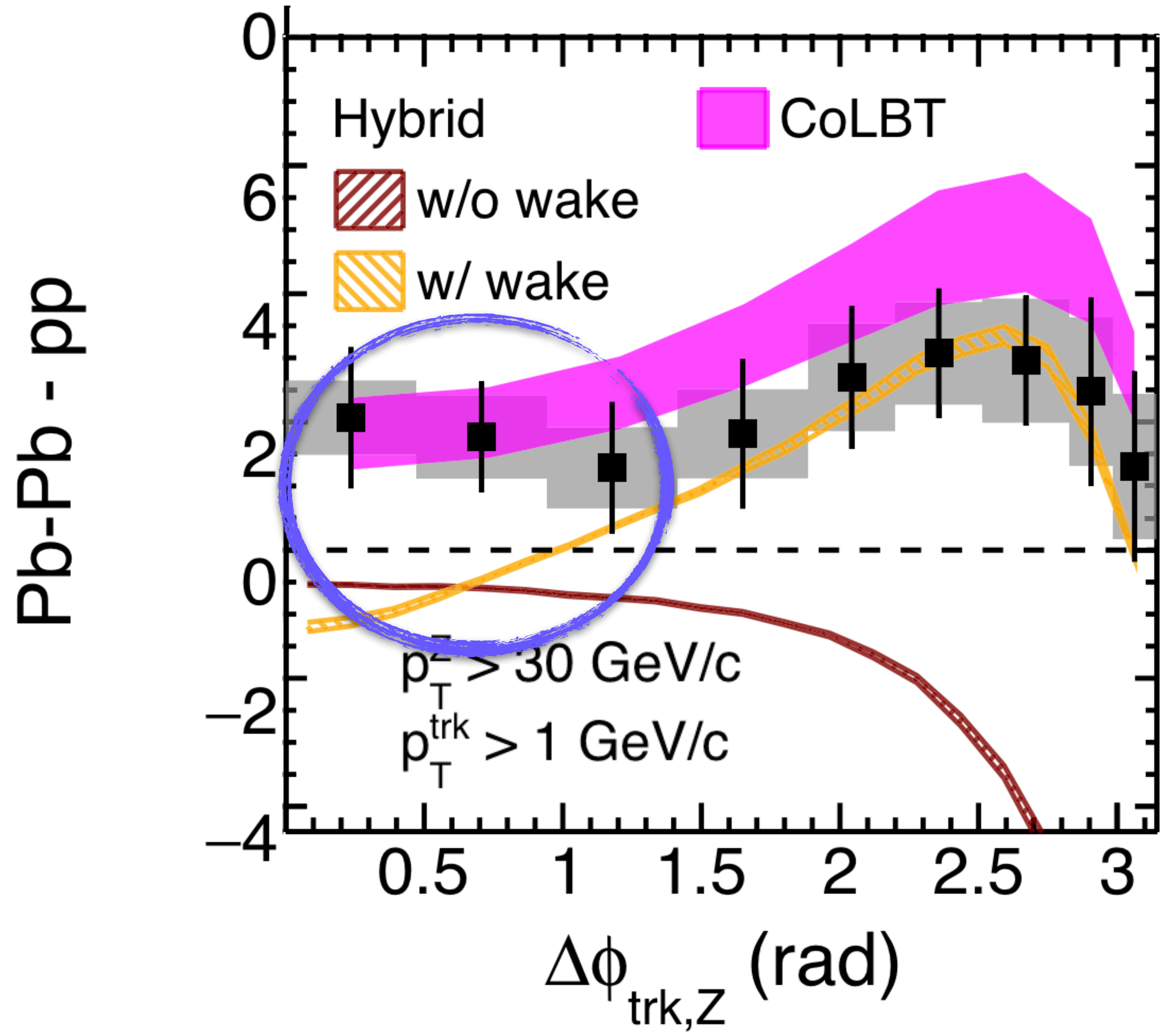
- Note differences in analysis between ATALS and CMS
  - ➡ track p_T ranges
  - ➡ different background subtraction methods

Previous measurements of Z-hadron correlations

CoLBT-hydro *PRL 127 (2021) 082301*



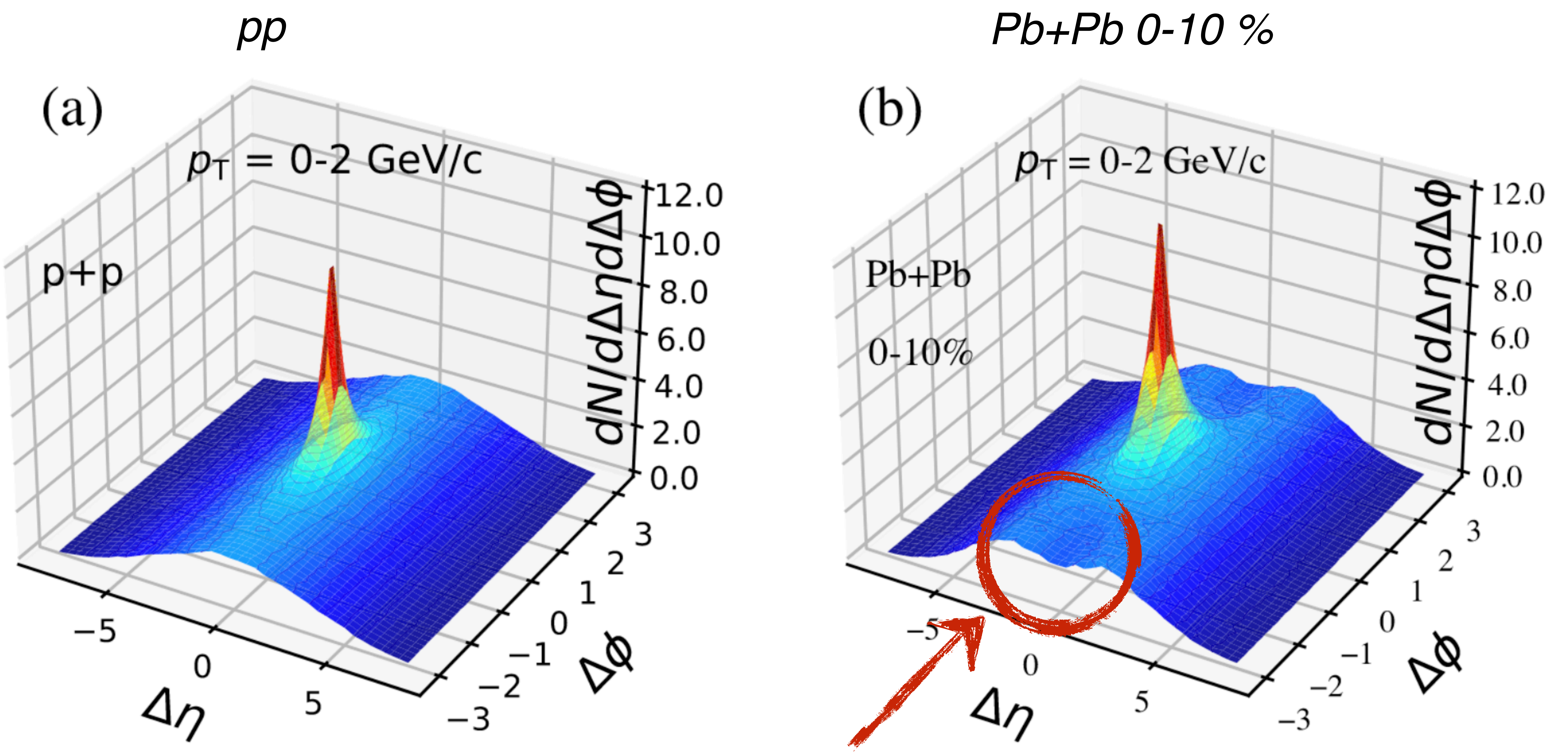
CMS, PRL 128 (2022) 122301



- Particle enhancement at $\Delta\phi(\mathrm{trk}, \mathrm{Z}) \sim 0$ in the previous CMS Z-hadron correlation measurement is explained by MPI effect by CoLBT

3D jet-hadron angular correlations

- Jet-hadron angular correlations **not only in ϕ but also in η** to distinguish the **diffusion wake** from MPI

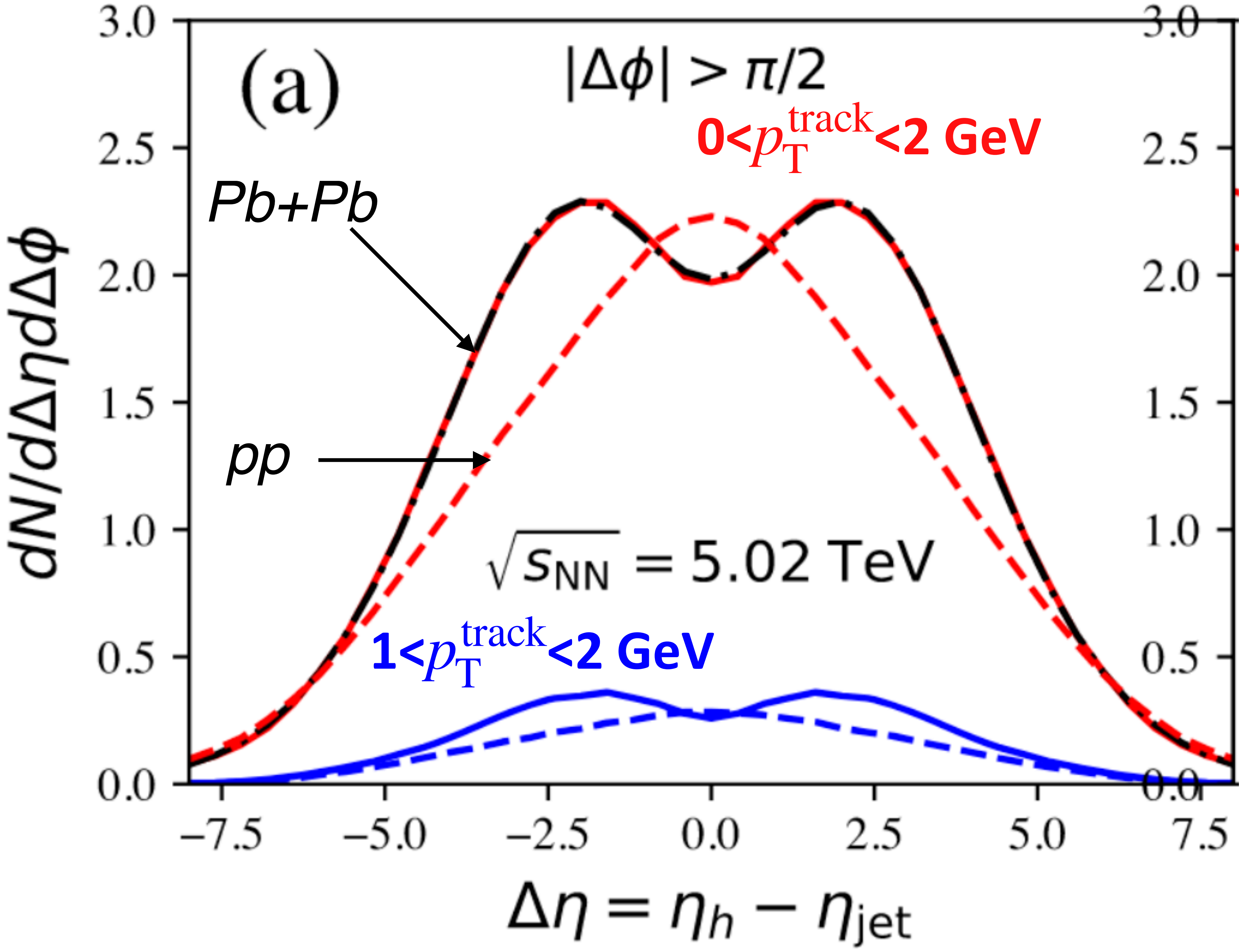


Diffusion wake

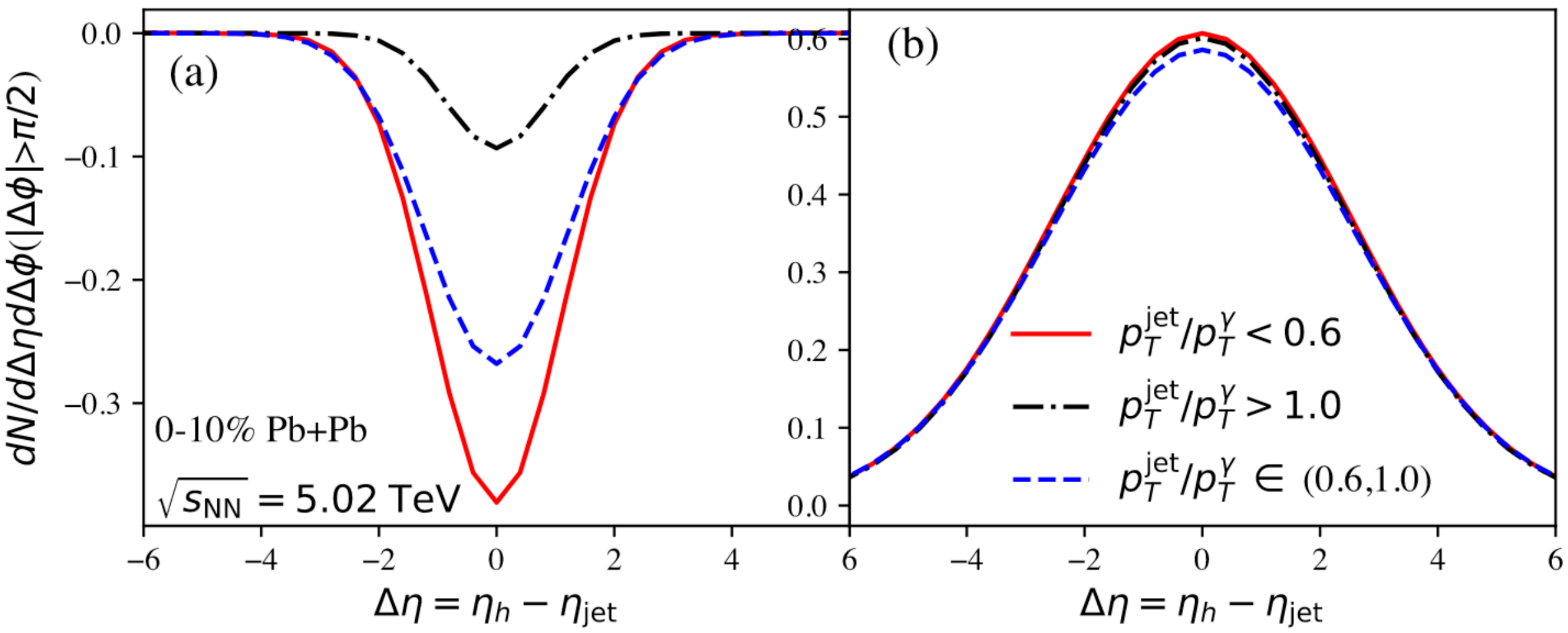
PRL 130, 052301 (2023), CoLBT

Diffusion wake: dependence on jet energy loss

PRL 130, 052301 (2023), CoLBT



Diffusion Wake **Multi-parton interaction (MPI)**



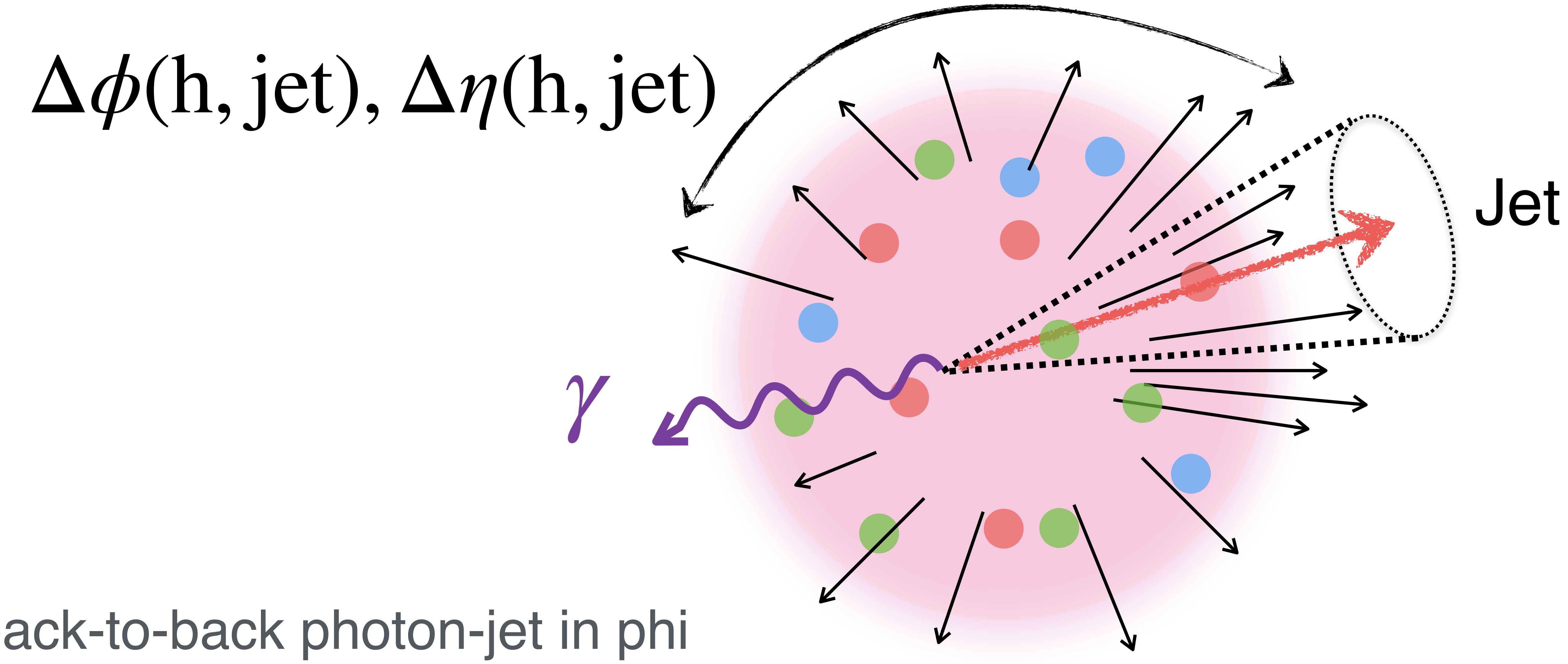
- Smaller $x_{J\gamma} = p_T^{jet}/p_T^{\gamma}$ indicates **larger jet energy loss** and **longer path** through the medium and hence larger medium response i.e., diffusion wake
- However, the MPI signal has no significant dependence on the $x_{J\gamma}$, while the diffusion wake does

Analysis selections

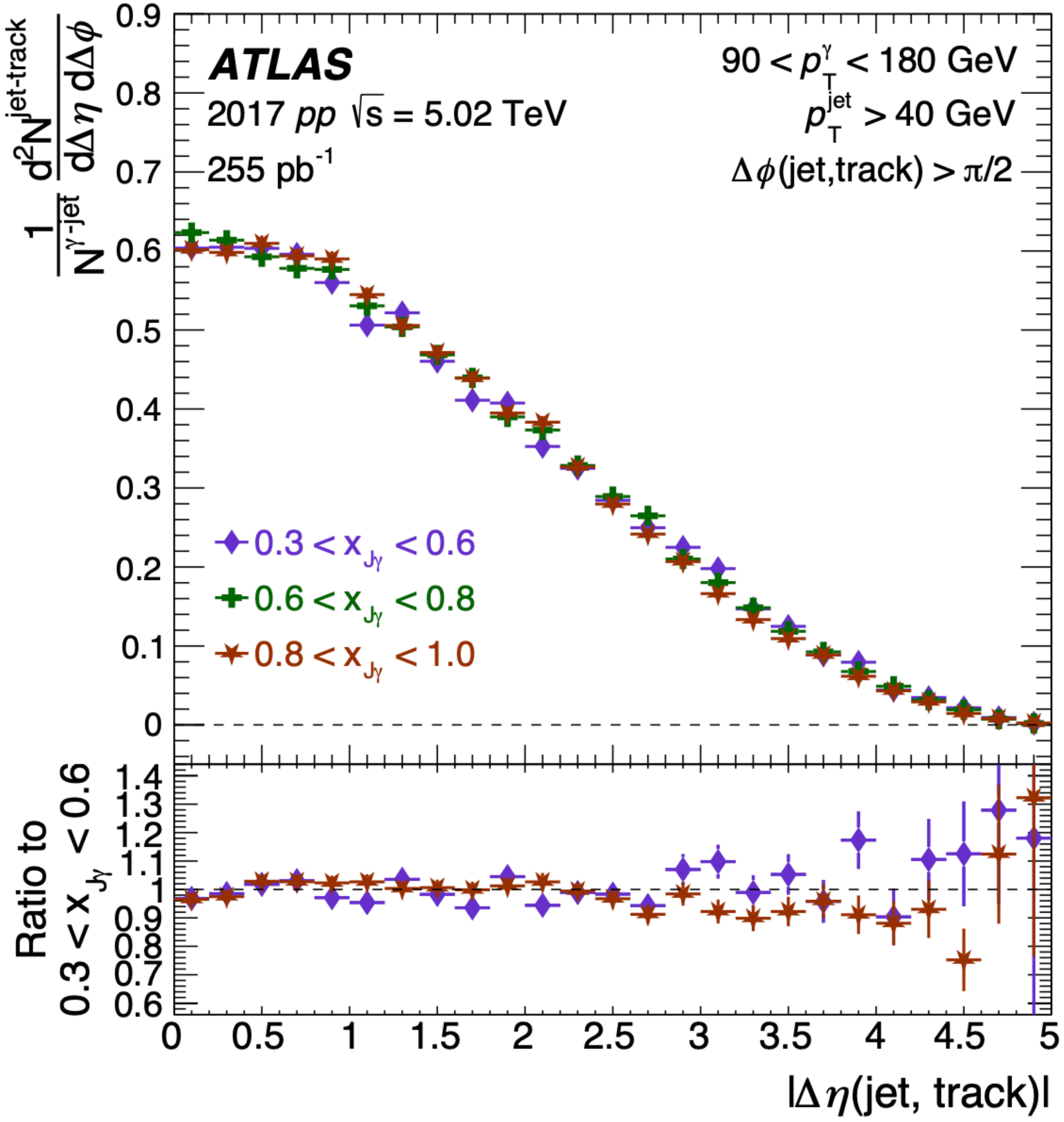
- Centrality 0-10%
- *Photons*
  - ➡ 90-180 GeV and $|\eta|<2.37$
  - ➡ only leading prompt Isolated photons (direct+fragmentation photons)
- *Jets*
  - ➡ p_{T} > 40 GeV and $|\eta|<2.5$
  - ➡ only leading jets in $\Delta\phi(\gamma,\mathrm{jet}) > 3\pi/4$ → back-to-back photon-jet in phi
- *Tracks*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

$\uparrow$ larger jet energy loss

$\uparrow$ less jet energy loss



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



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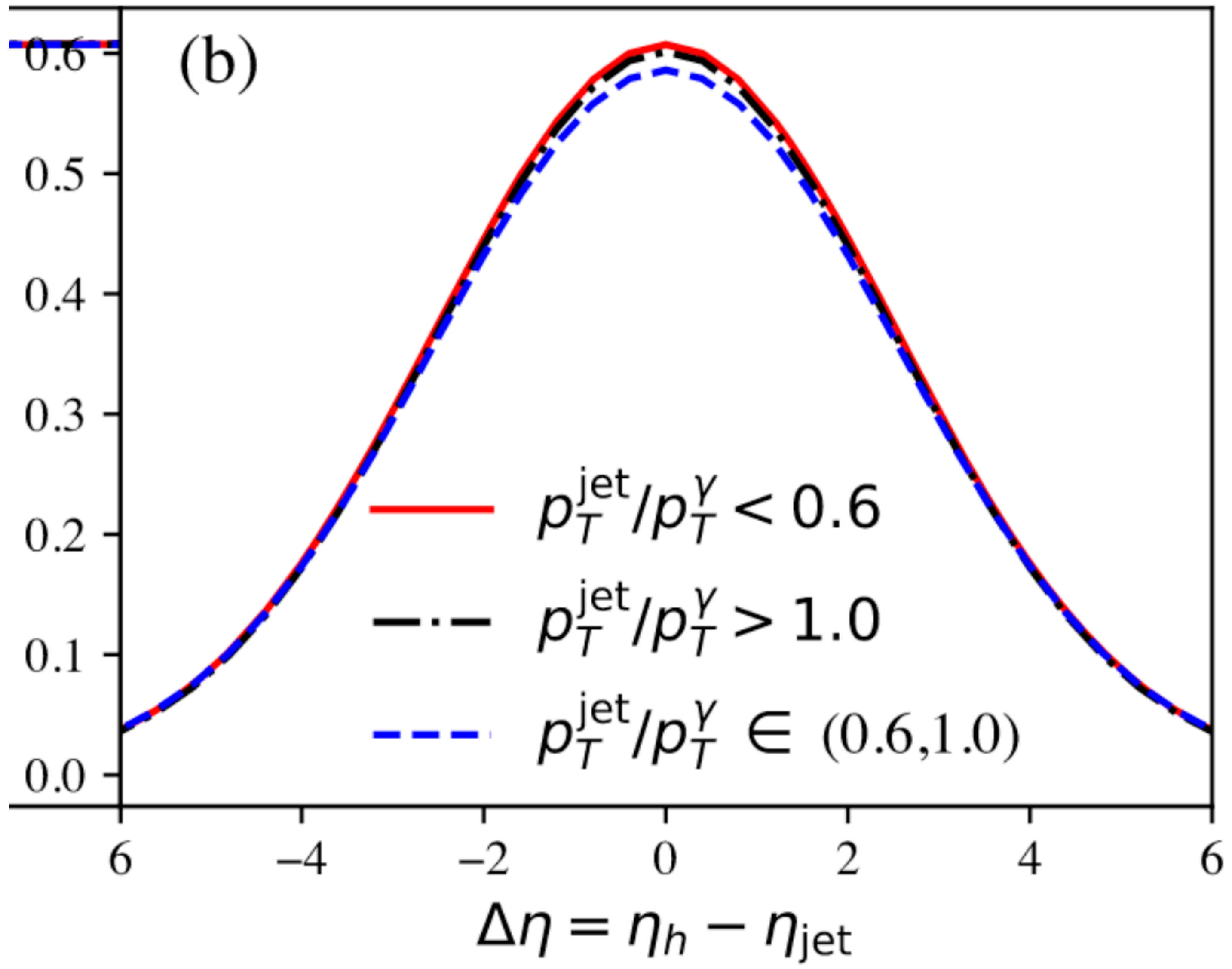
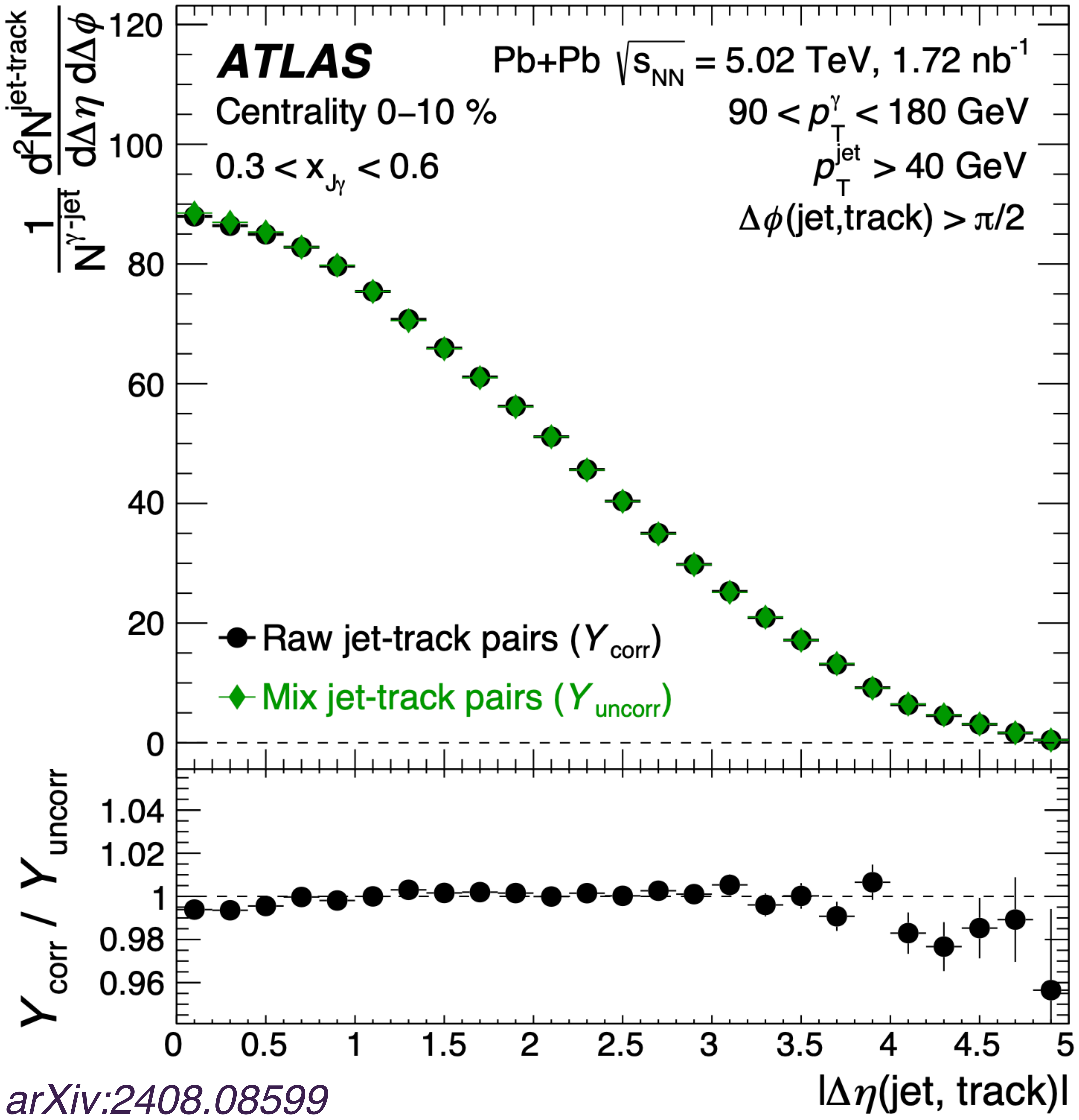
- The yield distributions as a function of $|\Delta\eta$(jet, track)| in the **three $x_{J\gamma}$ regions are consistent with each other** within uncertainties
  ➡ in agreement with the theory expectation

Multi-parton interaction (MPI)



PRL 130, 052301 (2023), CoLBT

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



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- 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. $\Sigma E_{\mathrm{T}}^{\mathrm{FCal}}$, event plane angle, vertex z position

Event Mixing Matching Condition

$\Sigma E_{\mathrm{T}}^{\mathrm{FCal}}$ in events with the photon–jet production (“signal” event)

= $\Sigma E_{\mathrm{T}}^{\mathrm{FCal}}$ from the photon–jet production *correlated*

+ $\Sigma E_{\mathrm{T}}^{\mathrm{FCal}}$ from bulk medium without the photon–jet production *uncorrelated*

$\Sigma E_{\mathrm{T}}^{\mathrm{FCal}}$ from the photon–jet production is estimated in pp data (cross-checked with MC), and has a mean value $\Sigma E_{\mathrm{T}}^{\mathrm{FCal},pp}$ = 17 GeV

➡ When mixing signal and MB events,

$\Sigma E_{\mathrm{T}}^{\mathrm{FCal}}$ in MB event = $\Sigma E_{\mathrm{T}}^{\mathrm{FCal}}$ in a given signal event - $\Sigma E_{\mathrm{T}}^{\mathrm{FCal},pp}$

- ±50% variation on $\Sigma E_{\mathrm{T}}^{\mathrm{FCal},pp}$ is considered as systematic uncertainties
  - ➡ this approximately 1σ of the $\Sigma E_{\mathrm{T}}^{\mathrm{FCal},pp}$ distributions

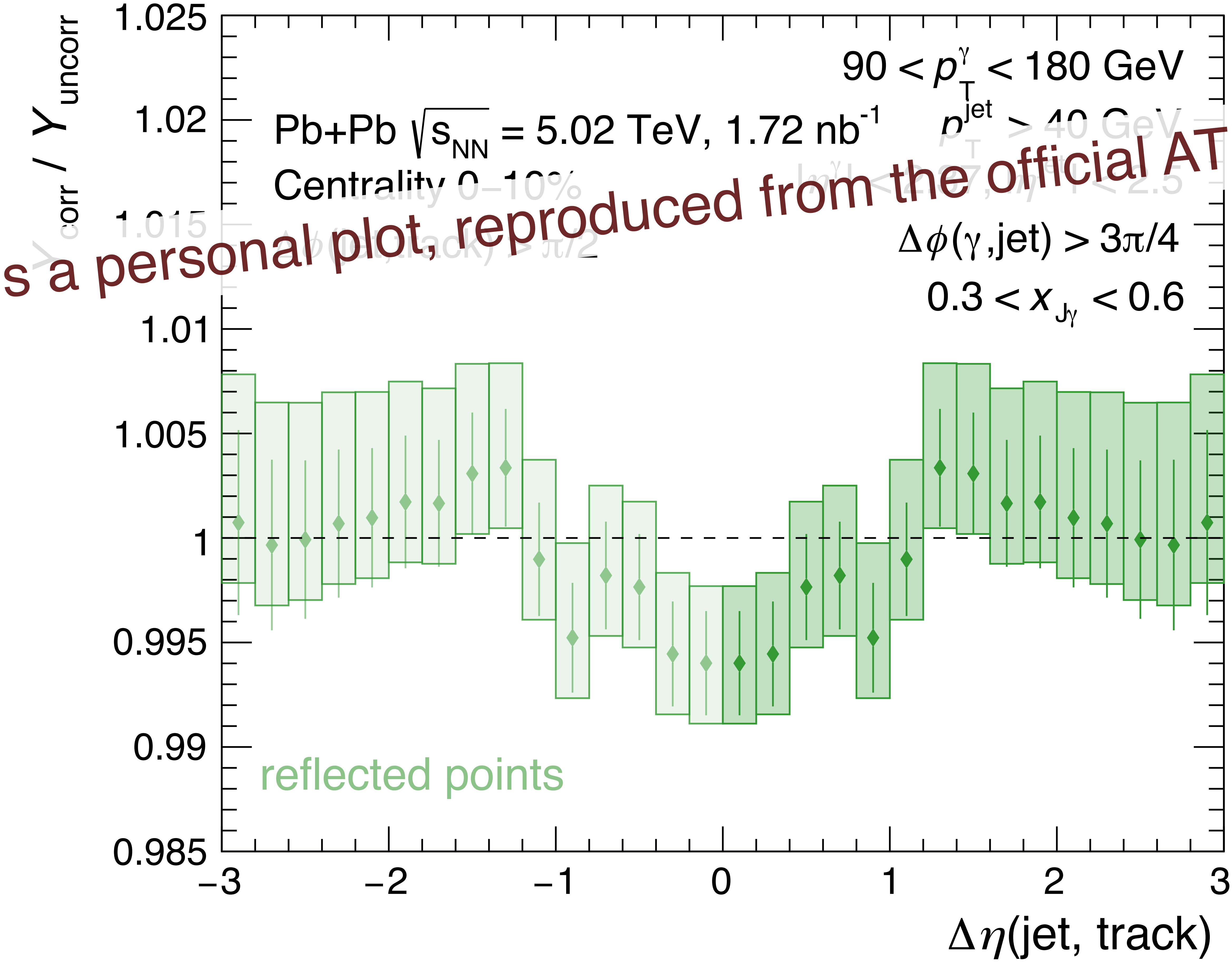
Relative yield ratio: $Y_{\mathrm{corr}}/Y_{\mathrm{uncorr}}$

arXiv:2408.08599

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

- $Y_{\mathrm{corr}}/Y_{\mathrm{uncorr}}$ 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 shown in the lowest $x_{J\gamma}$ region

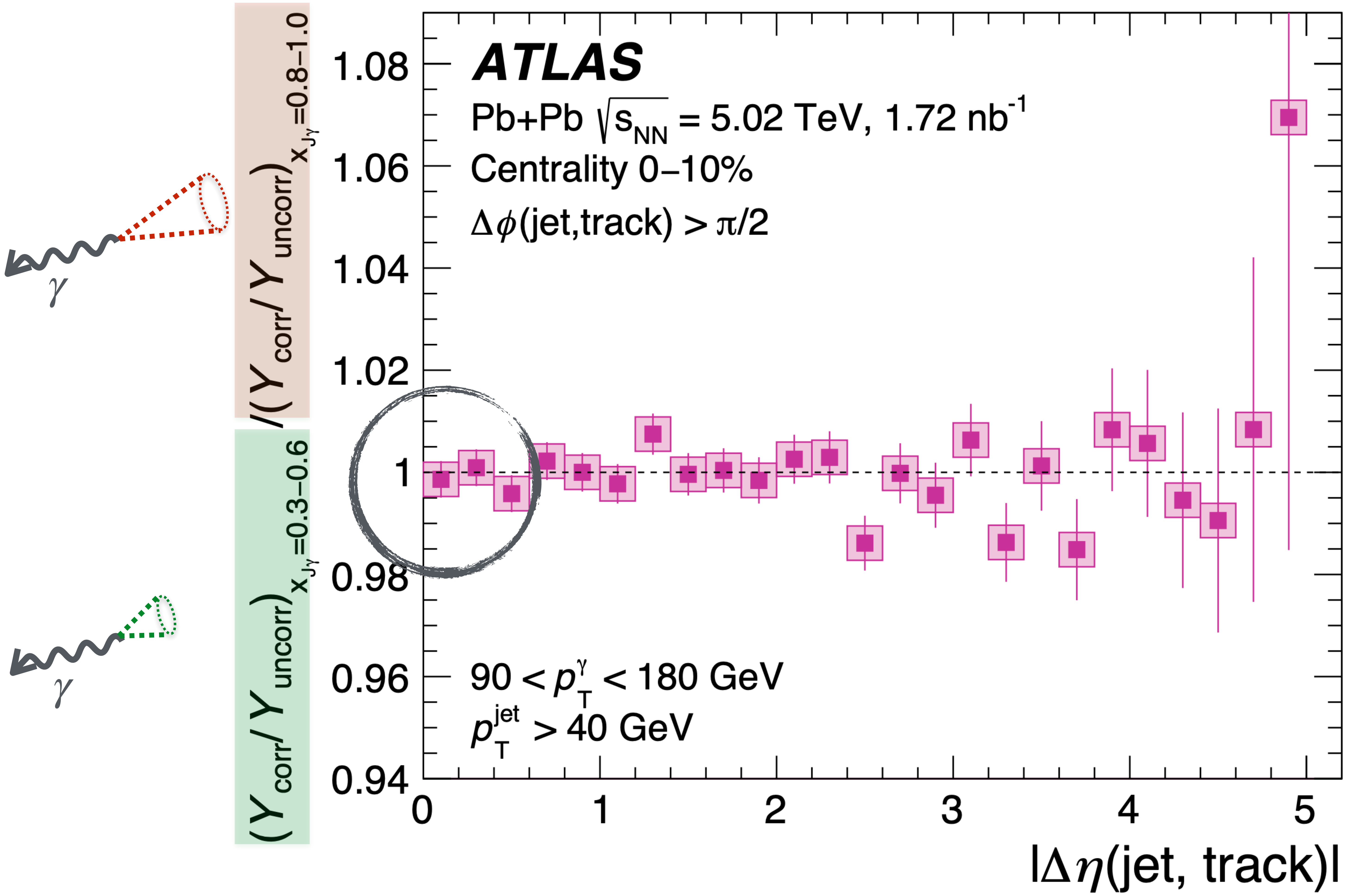
Diffusion wake signal



This is a personal plot, reproduced from the official ATLAS figure

- There is a clear but small diffusion wake dip at the lowest $x_{J\gamma}$

Double ratio



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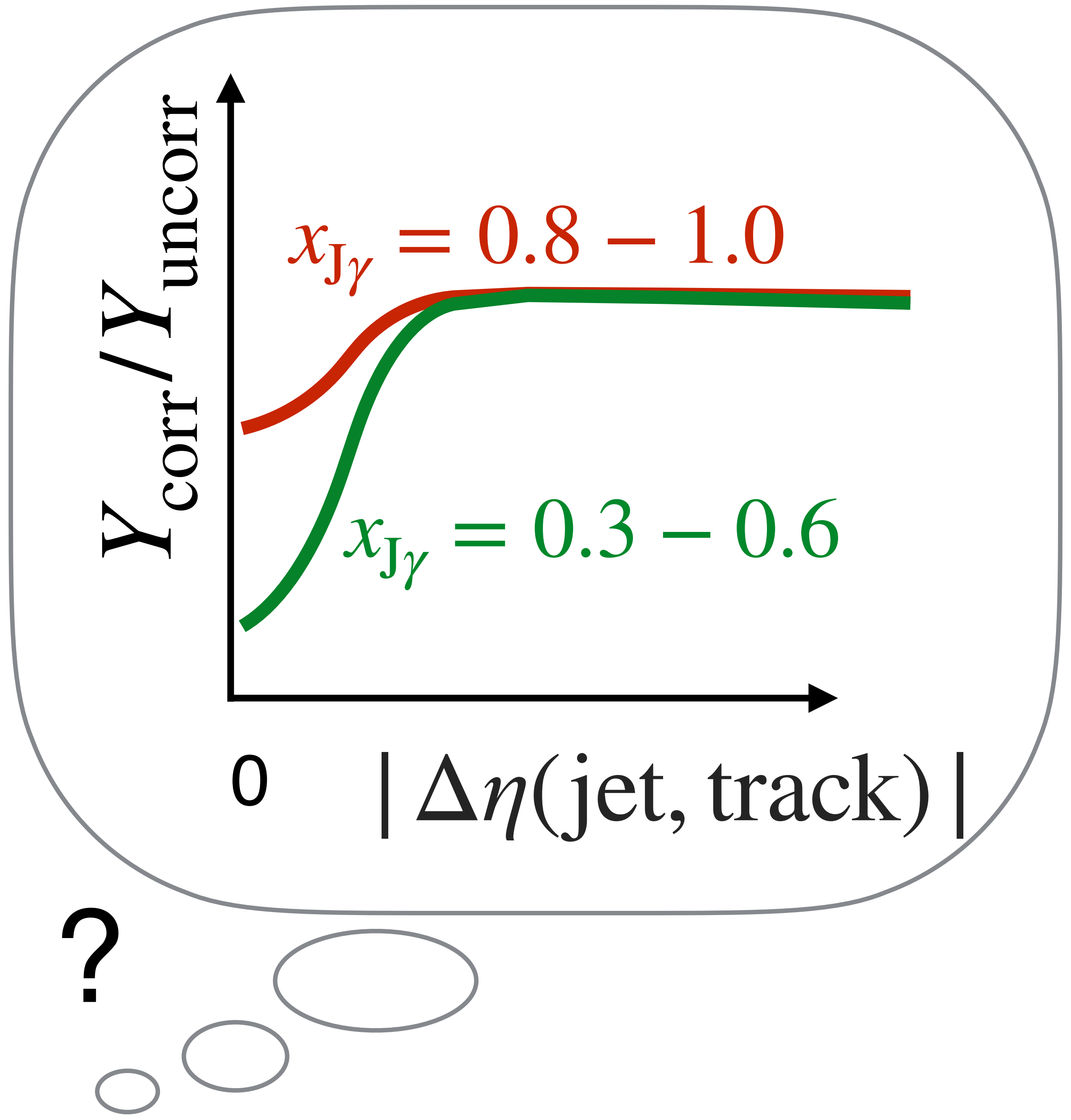
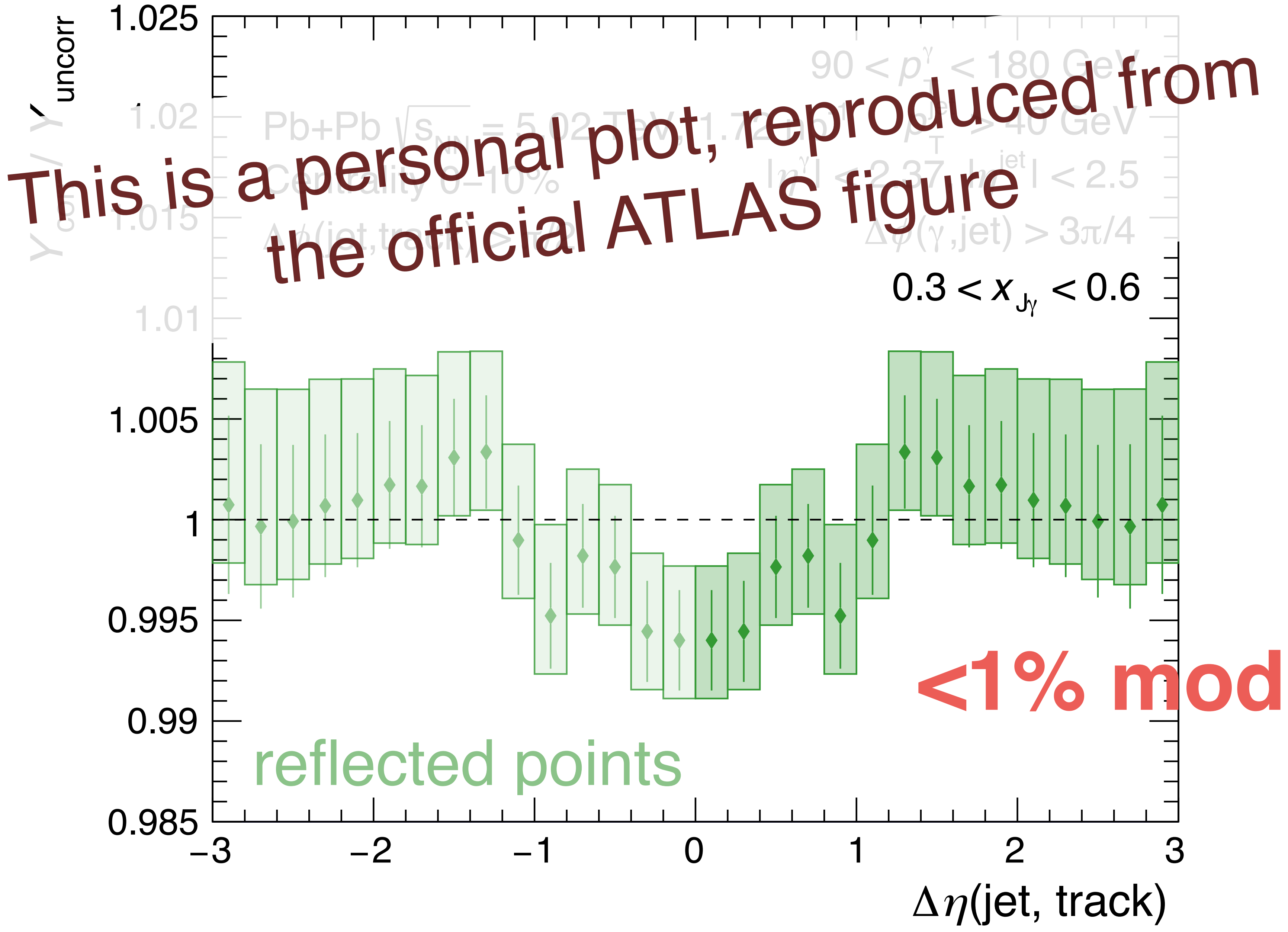


- The results are consistent with unity within uncertainties
  - ➡ no significant $x_{J\gamma}$-dependence of the diffusion wake is found

Diffusion wake amplitude



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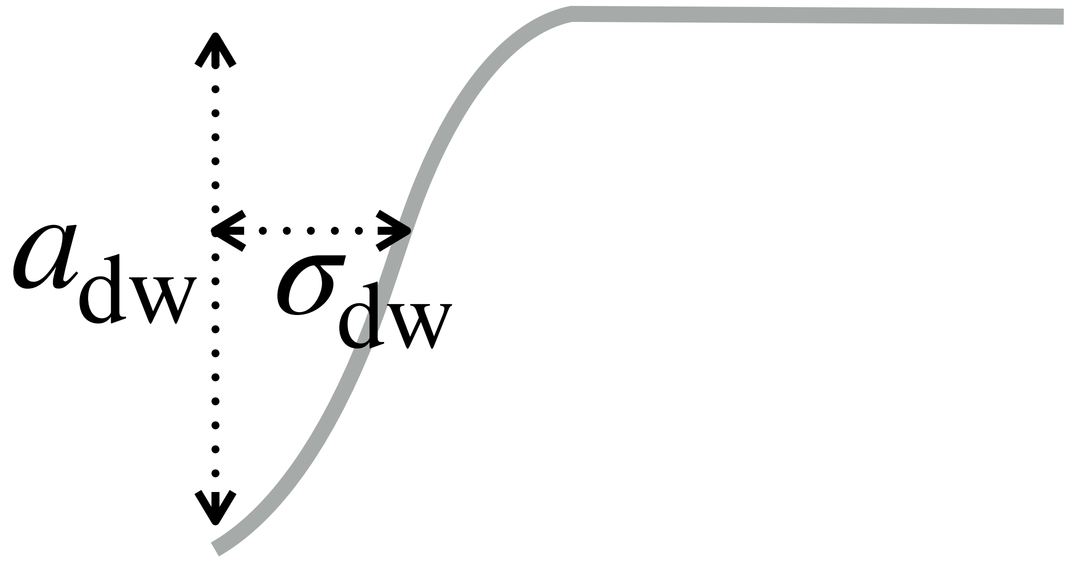
<1% modulation?

Diffusion Wake Amplitude   Diffusion Wake Width

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



- To quantify the diffusion wake, *Gaussian fits* are performed
  - ➡ diffusion wake would have a ***negative amplitude*** (a_{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

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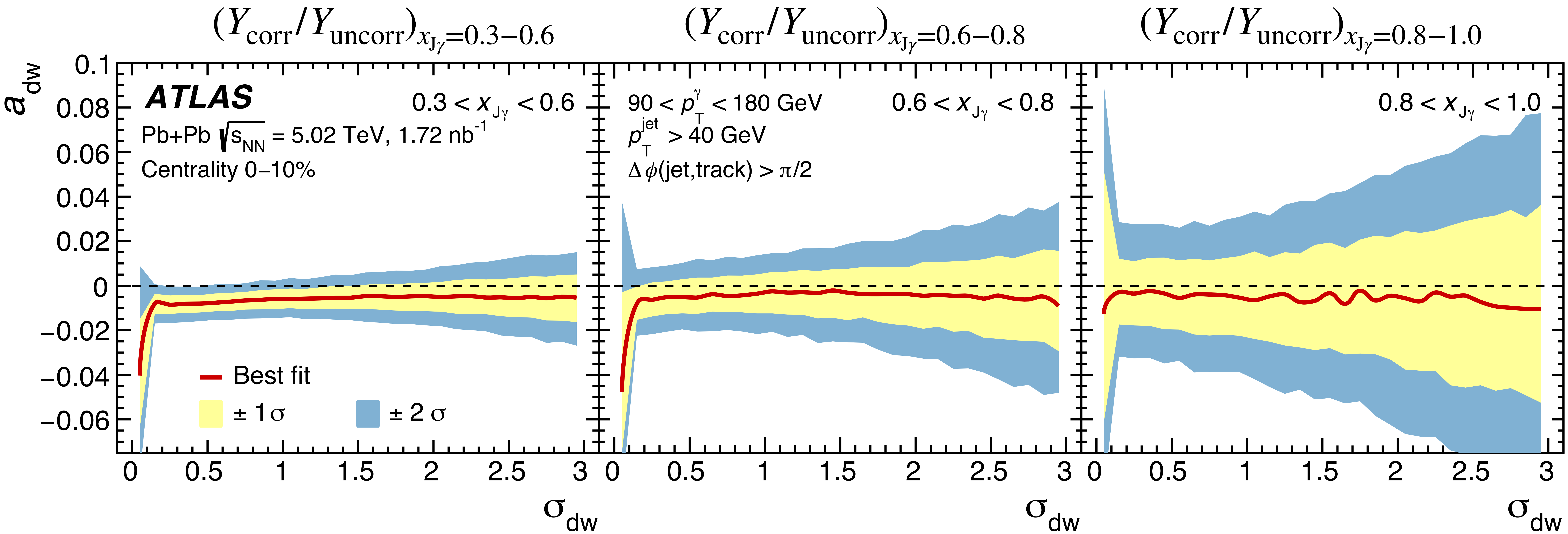


- Results are consistent with no signal (i.e., a_{dw}=0) within 1σ (higher $x_{J\gamma}$) or 2σ (lowest $x_{J\gamma}$)
- Best fits of the diffusion wake amplitude is negative for all $x_{J\gamma}$
- **Diffusion wake amplitude of best fit for the lowest $x_{J\gamma}$ is 0.5-0.8% for the diffusion wake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

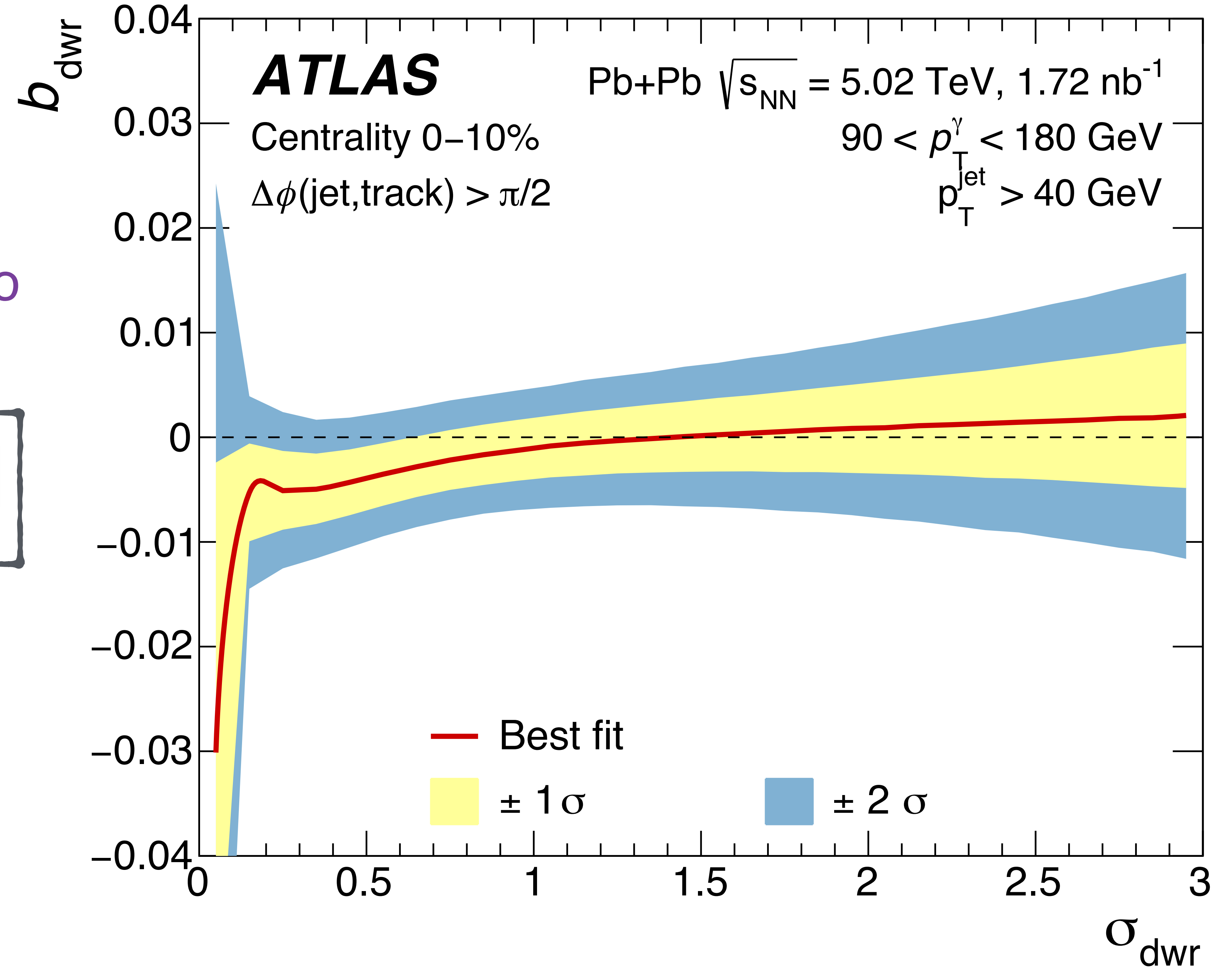
Double ratio amplitude

arXiv:2408.08599

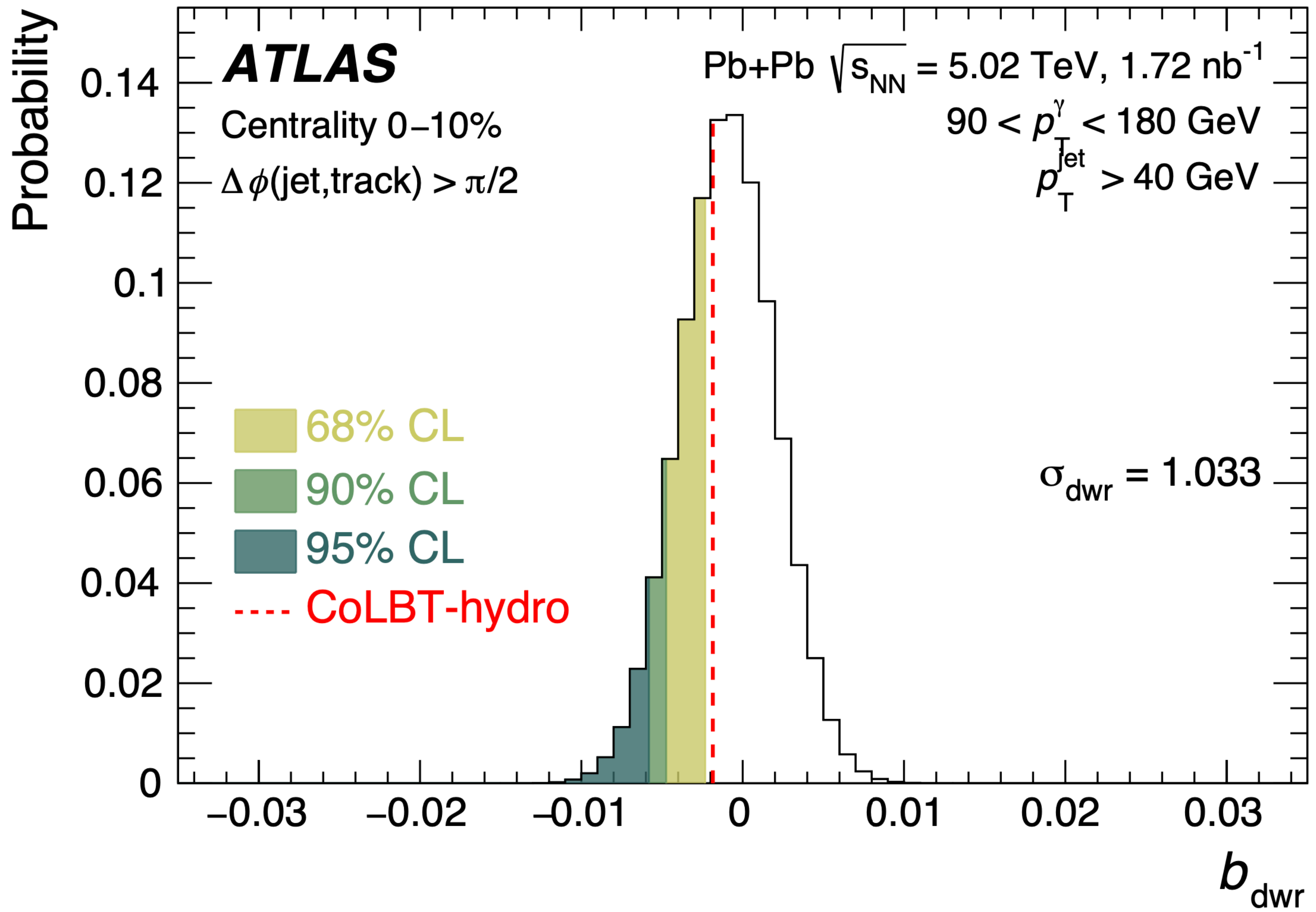
Double Ratio Amplitude

Double Ratio Width

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

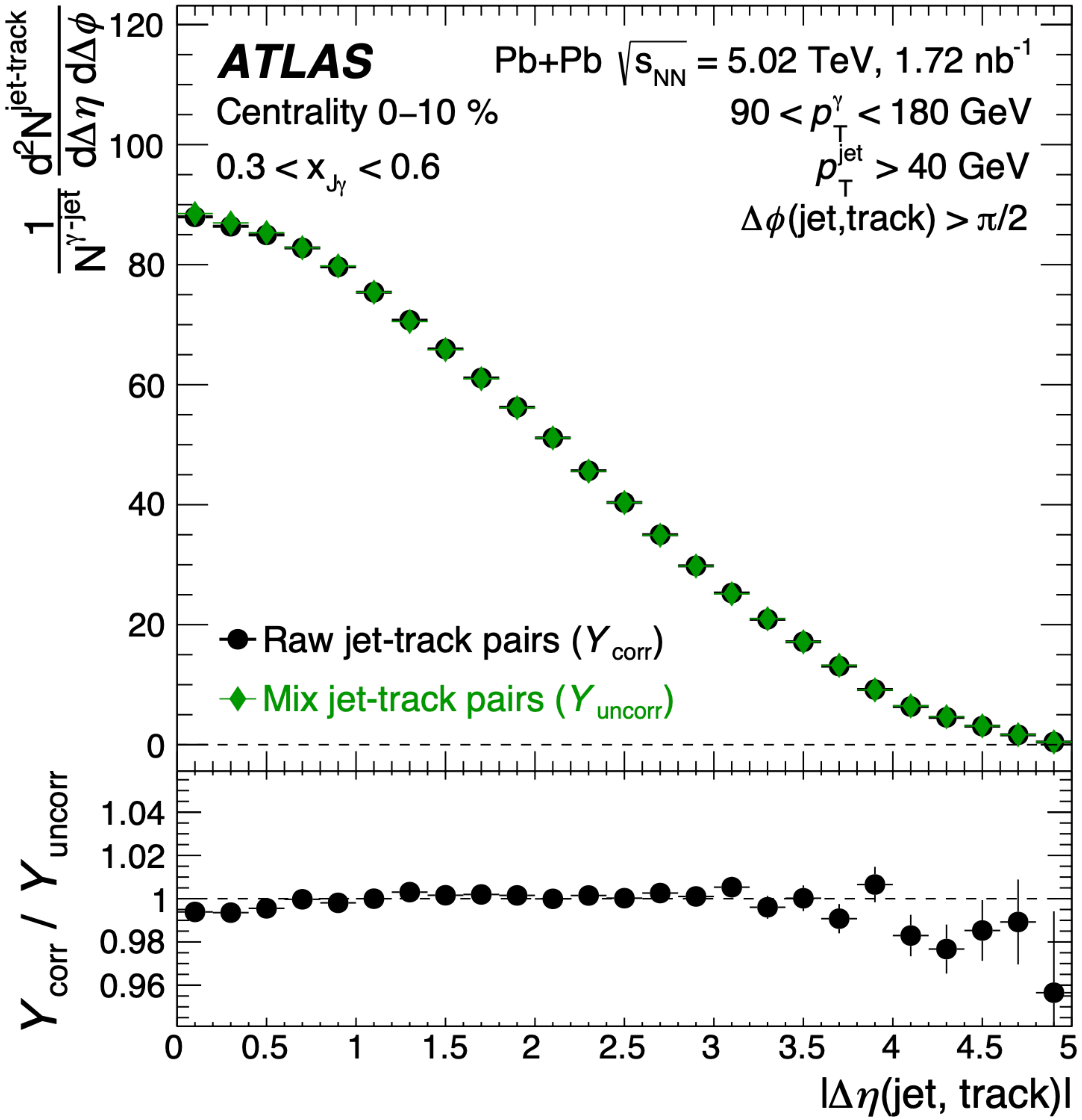


b_{dwr} distributions for width σ_{dwr} = 1.033



- 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

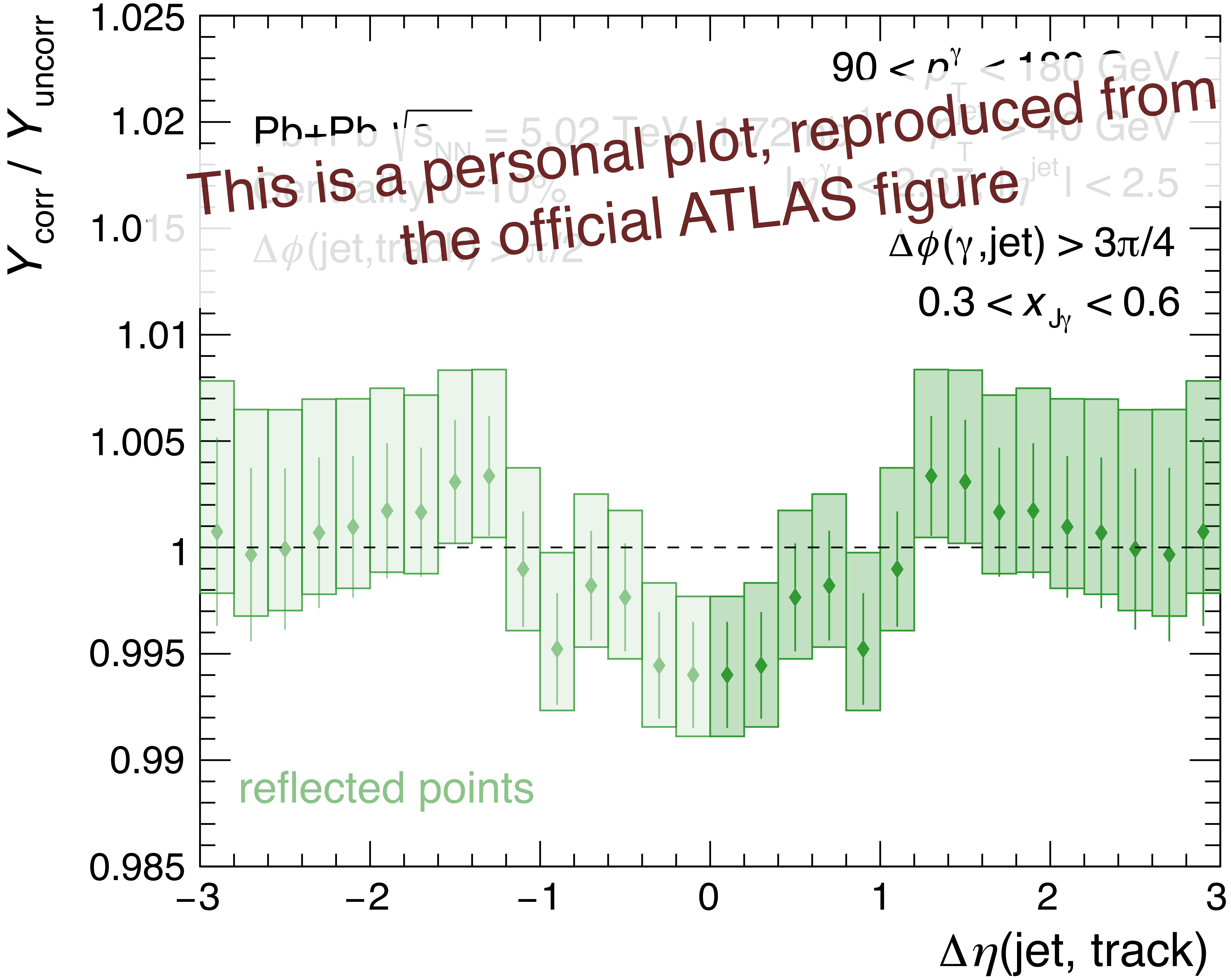
Discussion: how many particles are we missing?



- $\frac{1}{N^{\gamma-\text{jet}}}\frac{d^2N^{\text{jet}-\text{track}}}{d\Delta\eta d\Delta\phi}$ ~ 90 at $|\Delta\eta(\text{jet}, \text{track})| = 0$
- $Y_{\text{corr}}/Y_{\text{uncorr}}$ is about 0.5-0.8%

0.45-0.75 particles
(less than 1 particle in unit η, ϕ)
are reduced by diffusion wake!

Comparison between ATLAS vs CMS



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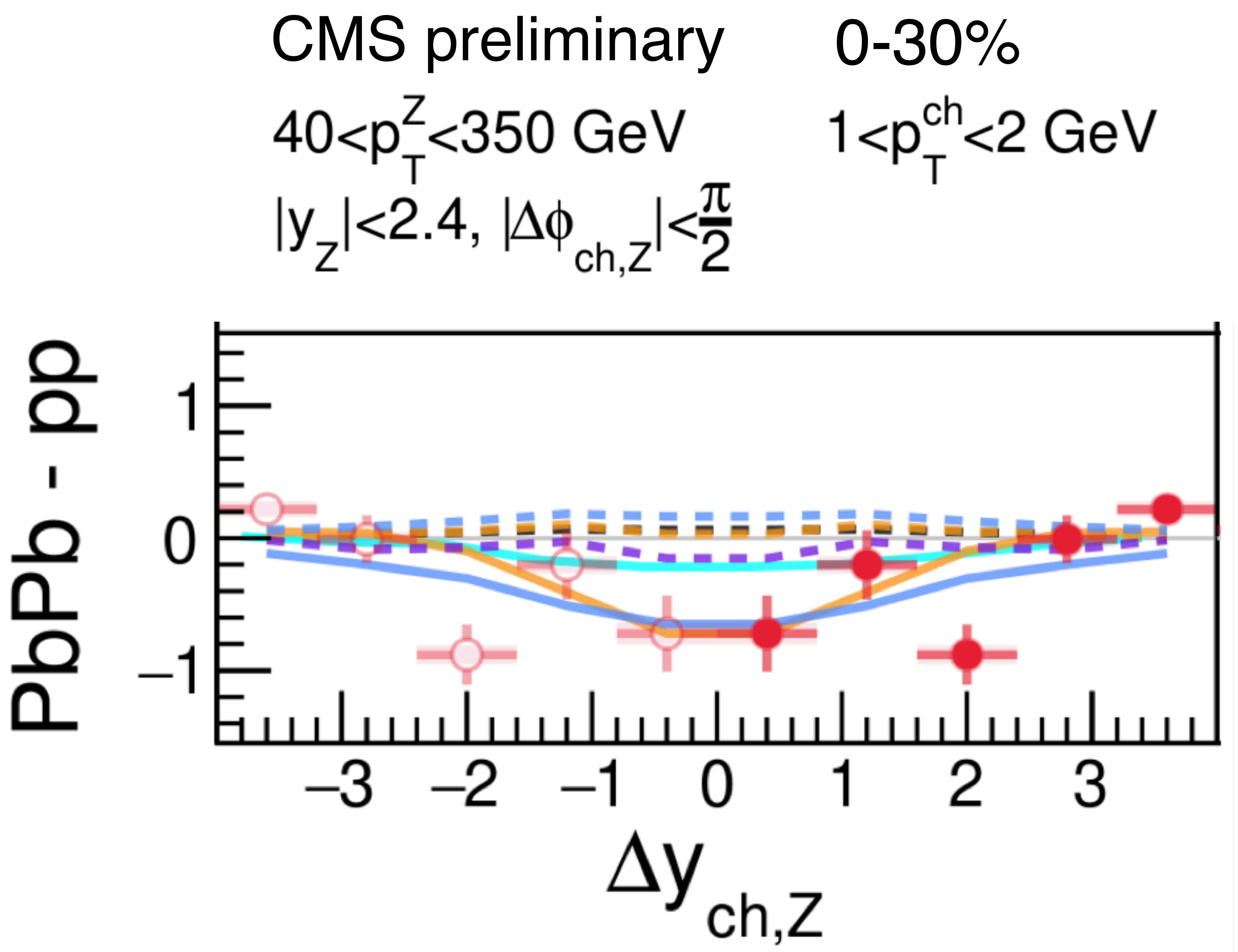


See also Yen-jie and Yi's talks

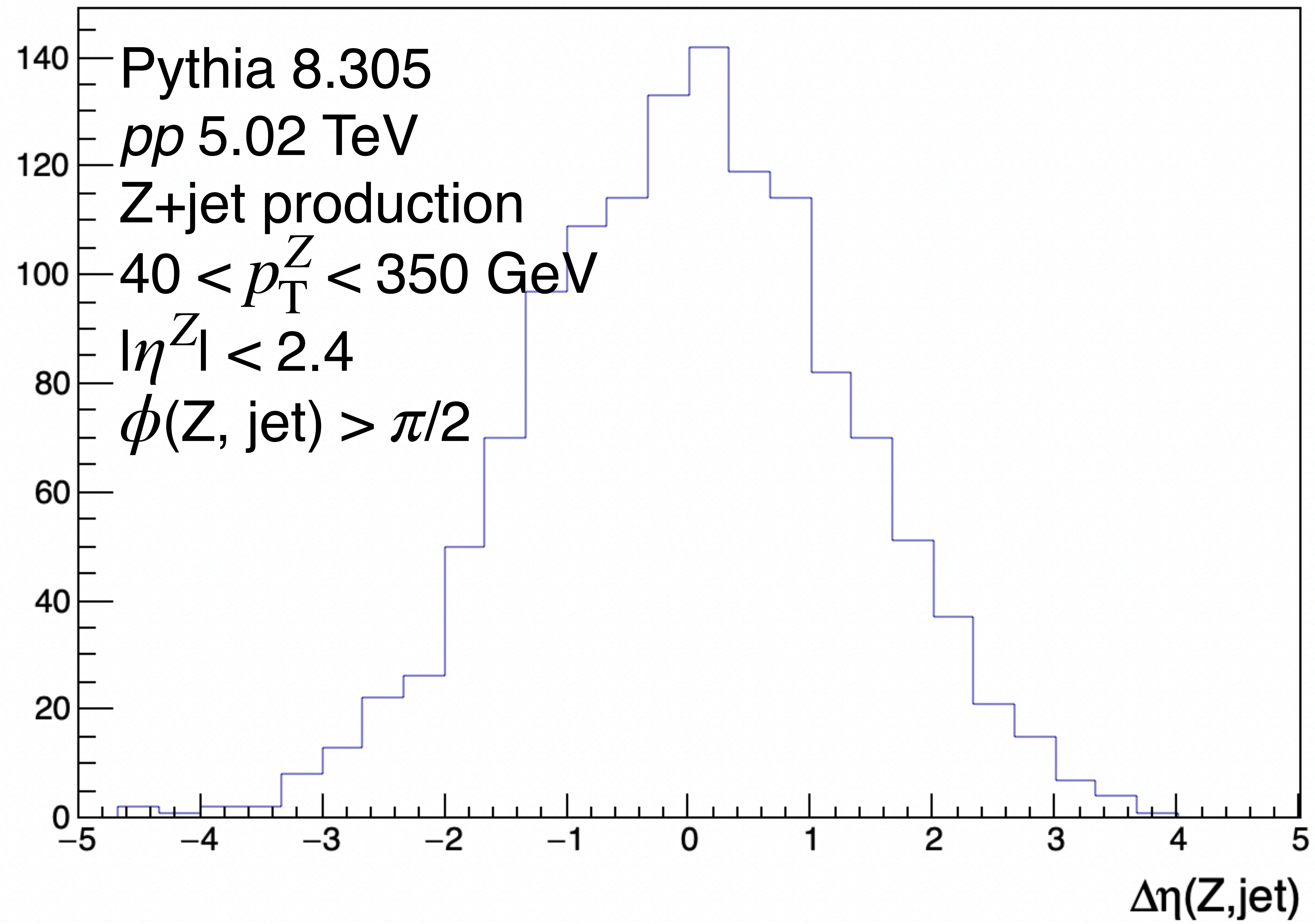
- Both results shows diffusion wake dip, qualitatively consistent with each other

Comparison between ATLAS vs CMS - (1)

CMS

Z+hadron correlations

- Pros
  - ➡ Z: clean probe
  - ➡ centrality control
  - ➡ no jet reconstruction → potentially reach highly quenched jets which usually can’t be experimentally reconstructed
- Cons
  - ➡ no jet reconstruction → no control of jet energy loss, and smearing of angular correlation (especially in eta)



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- Cons
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ATLAS Jet+hadron

correlations in γ+jet events

- Pros
  - ➡ jet reconstruction
    - ➡ direct angular correlation between jet and hadrons
    - ➡ jet-p_T/energy loss control → differential $x_{J\gamma}$ measurement
- Cons
  - ➡ background photons (decay from e.g. π^0) → potentially measure smaller diffusion wake from dijet contamination
  - ➡ can't access extremely quenched jets below $x_{J\gamma}$<0.3

Comparison between ATLAS vs CMS - (2)

CMS
Z+hadron correlations

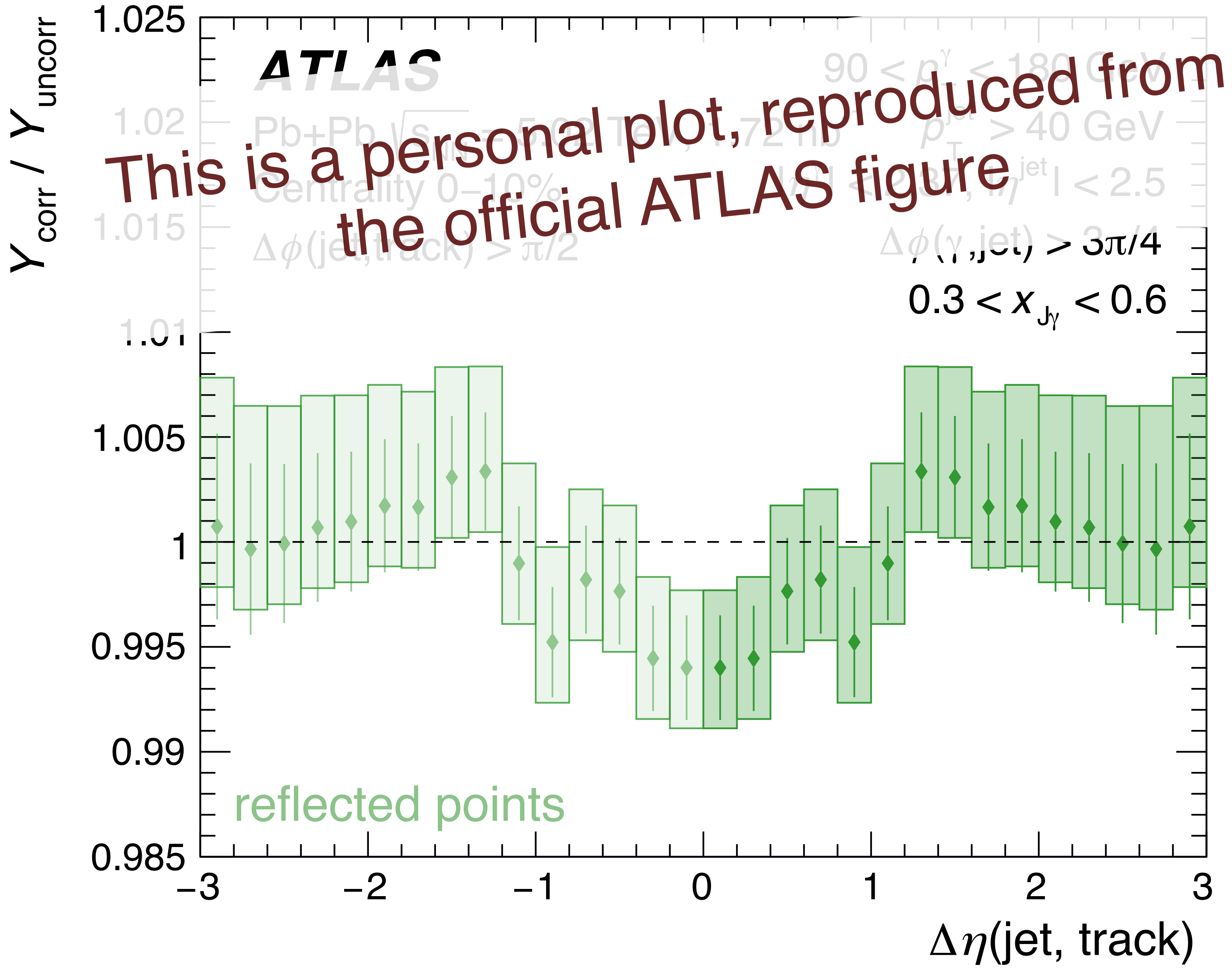
- Other differences
  - ➡ Event mixing: mixing two Z events → potentially remove MPI better
  - ➡ Observable: correlation function ΔN
  - ➡ …

ATLAS Jet+hadron correlations in γ+jet events

- Other differences
  - ➡ Event mixing: mixing (γ+jet signal) and (minimum-bias) events ; with $\Sigma E_{\mathrm{T}}^{\mathrm{Fcal}}$ difference to account for contribution from γ+jet production (including MPI)
  - ➡ Observable: Yield ratio
  - ➡ …

Summary

- **Jet-track η and ϕ angular correlations in photon-jet events** have been firstly 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 show the diffusion wake dip for the lowest* $x_{J\gamma}$ and further *provides* ***probability limits***;
  - ➡ the best fit of the diffusion wake amplitude for the lowest $x_{J\gamma}$ is about 0.5%



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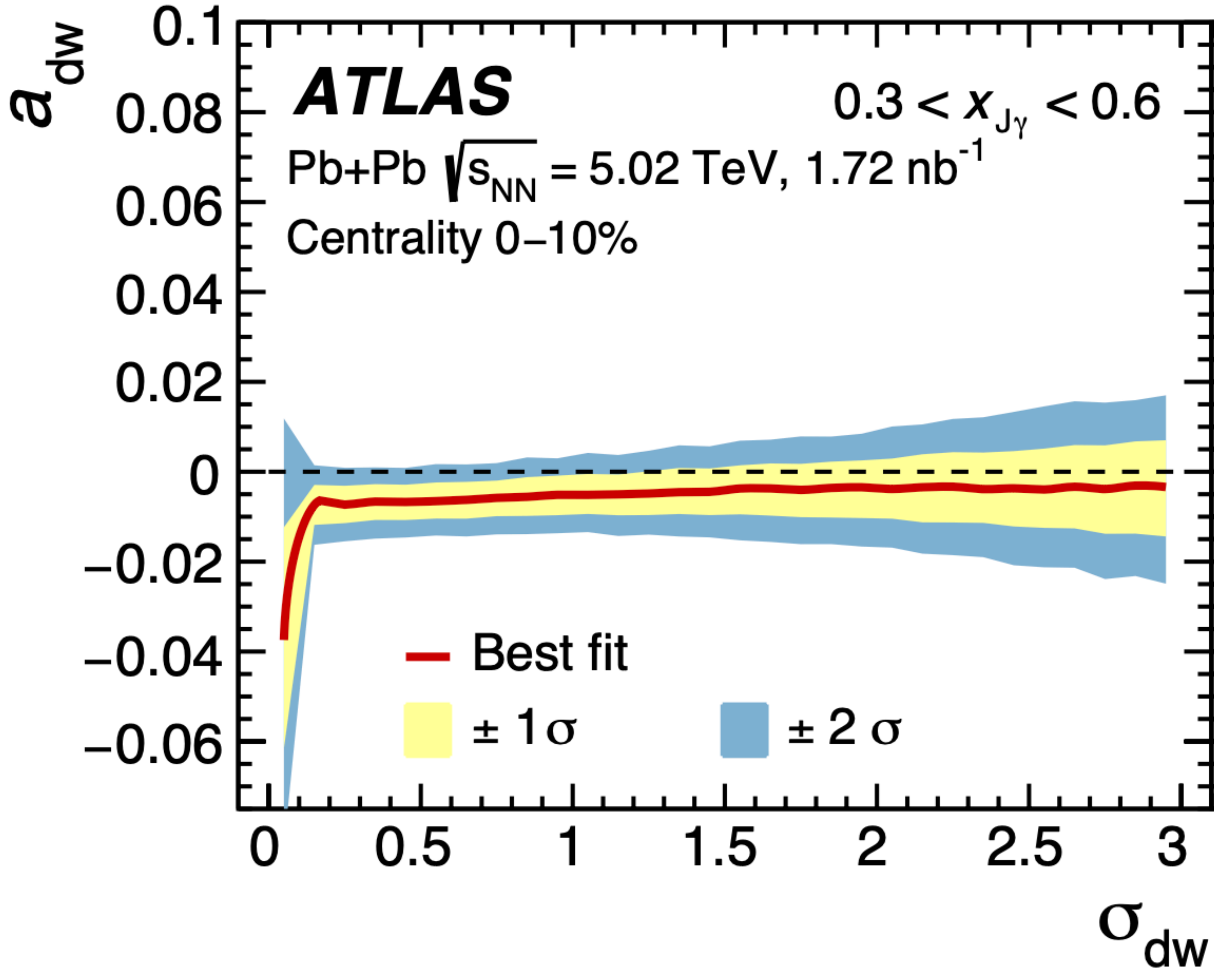
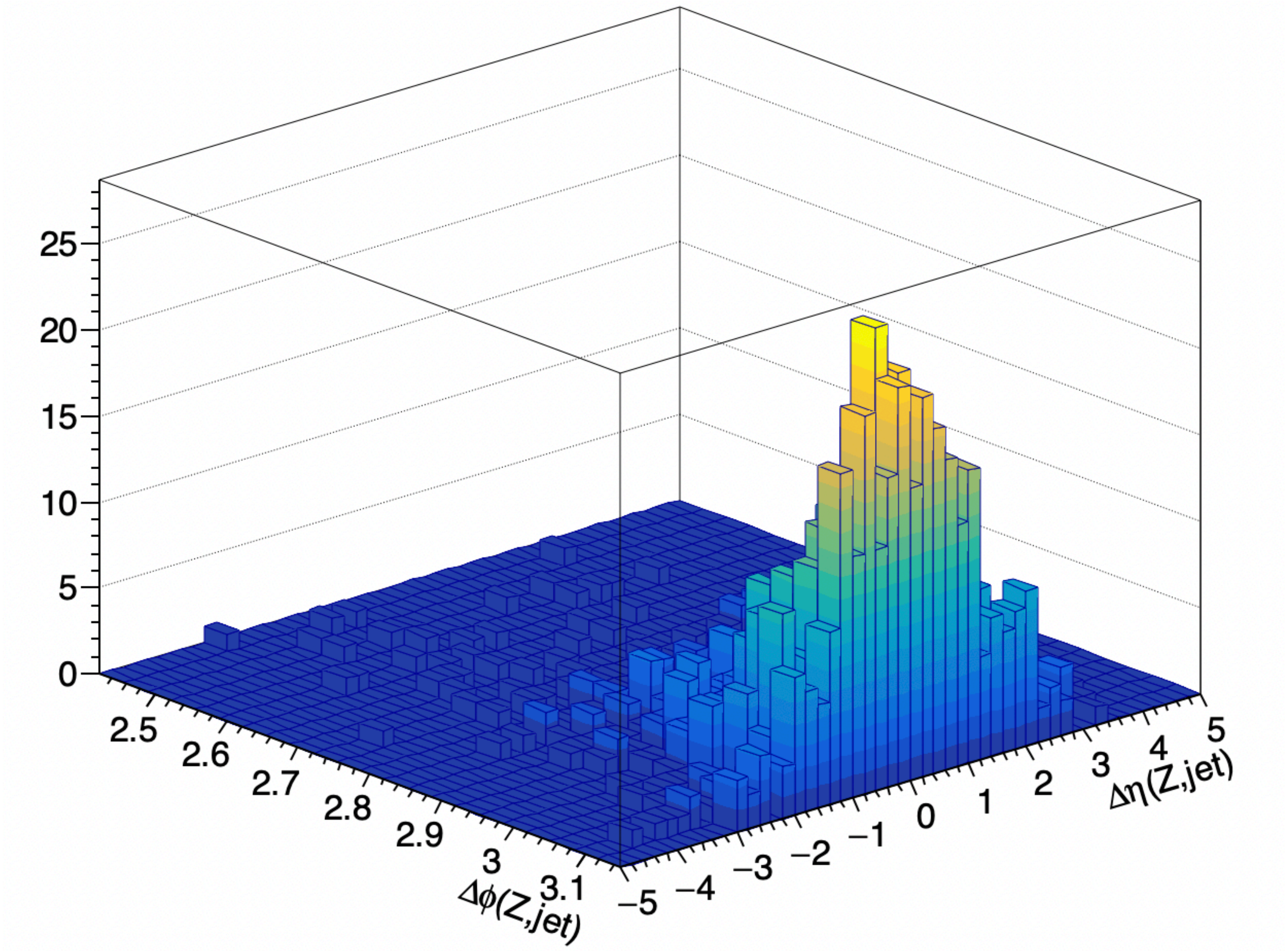
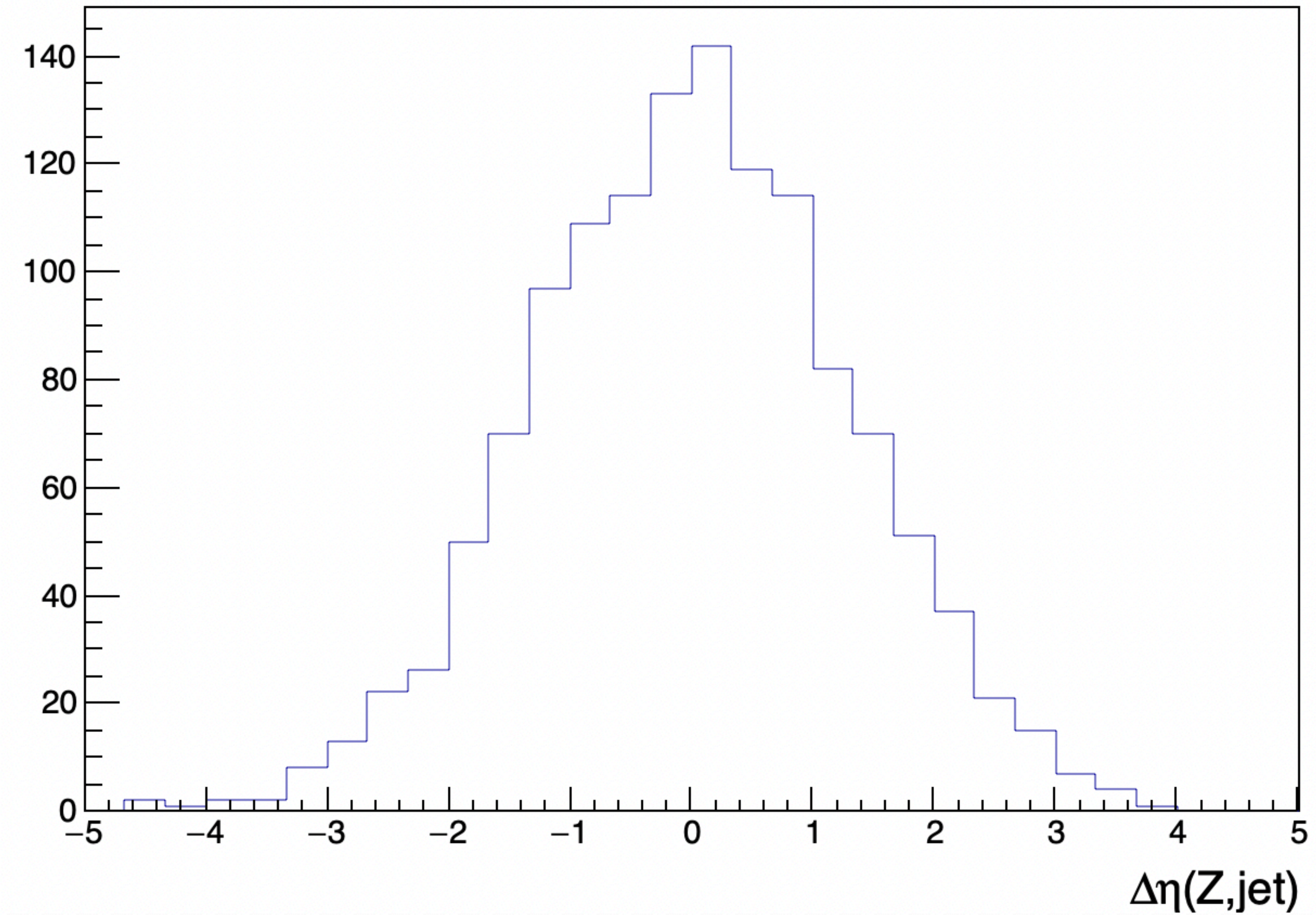


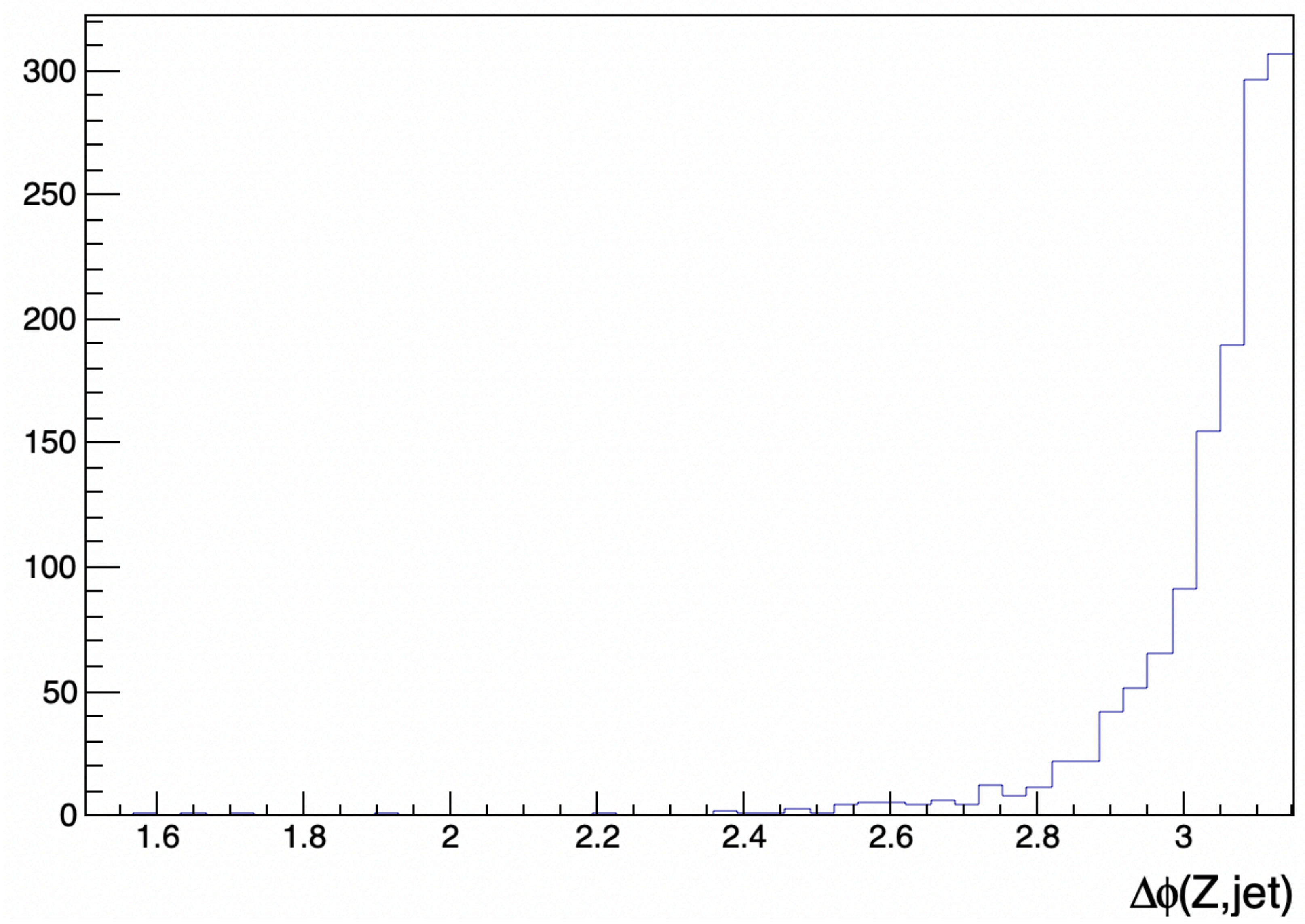
BACK UP

Z-jet angular correlations

Pythia 8.305
pp 5.02 TeV
Z+jet production
$40 < p_{\mathrm{T}}^{Z} < 350$ GeV
$|\eta^{Z}| < 2.4$
ϕ(Z, jet) > π/2

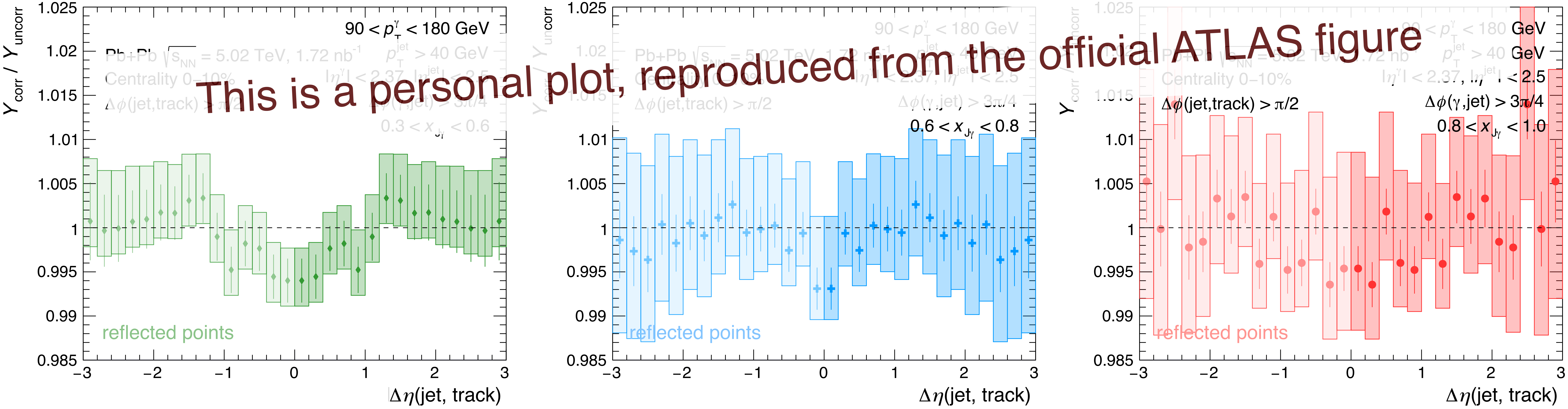






- σ of $\Delta\eta$(Z, jet) ~ 1.3
- σ of $\Delta\phi$(Z, jet) ~0.15

Zoom-in $Y_{\text{corr}}/Y_{\text{uncorr}}$



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

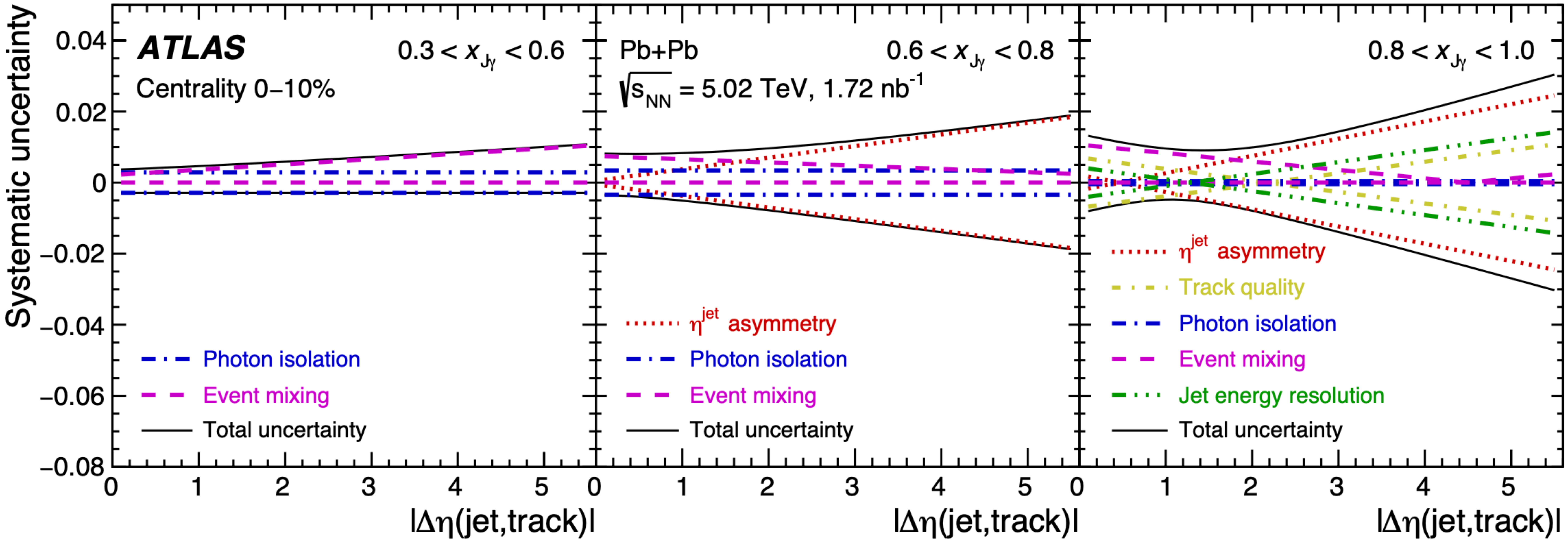
This is a personal plot, reproduced from the official ATLAS figure

- diffusion wake dip shown for the lowest $x_{J\gamma}$

Systematic Uncertainty Determination

- To **avoid double-counting the statistical uncertainties**, a χ^2 test is performed for each source of systematic uncertainty
- The 68% probability level obtained by splitting the datasets 200 times under the same nominal condition, which reflects purely statistical fluctuations $\rightarrow \chi^2_{\mathrm{cut}}$
- Systematic sources which pass the χ^2_{cut} are deemed systematically significant, whether due to a real systematic difference or as the result of a residual statistical fluctuation.

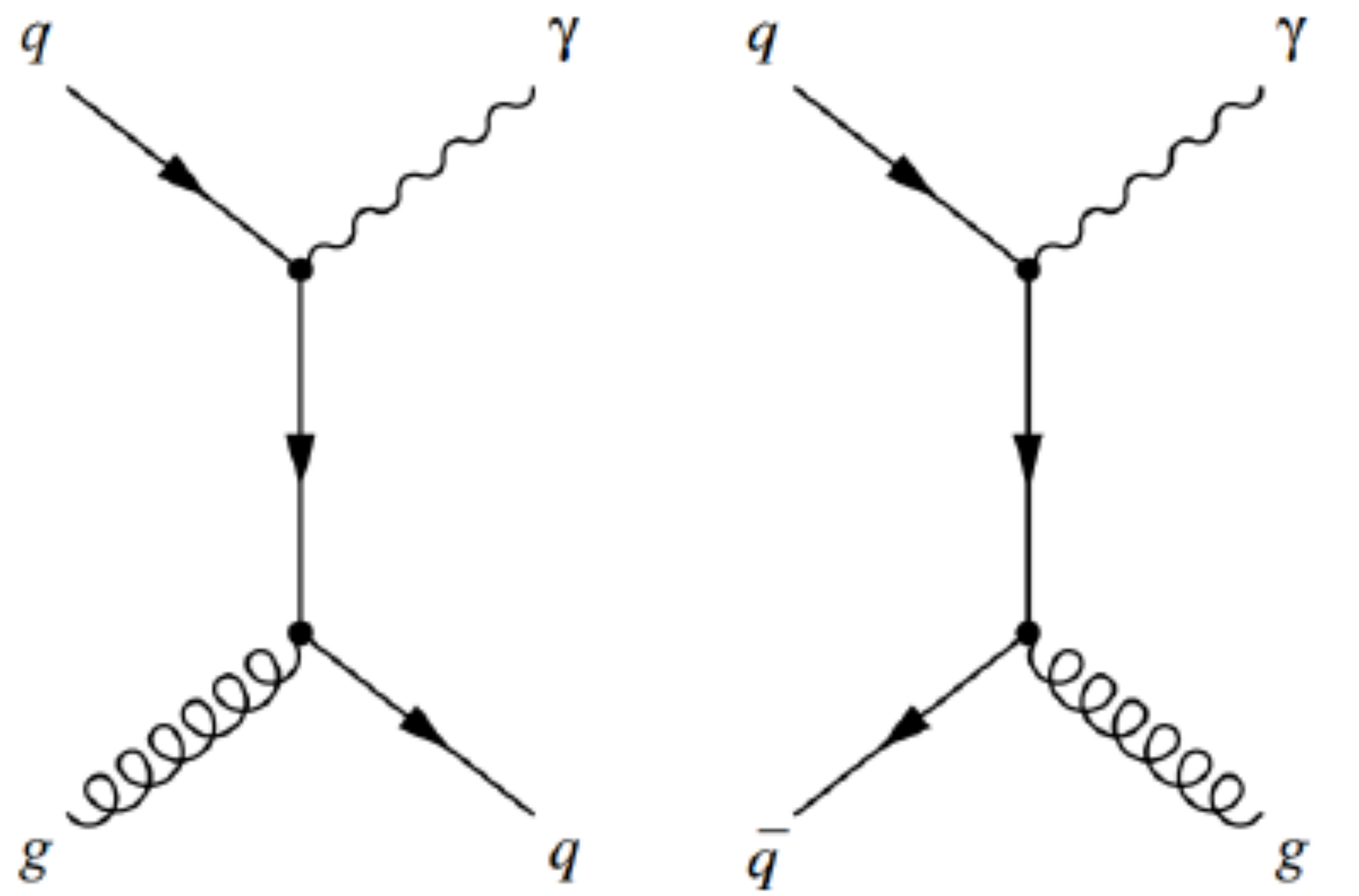
Systematic Uncertainty Summary



- For the double ratio, the different uncertainty contributions are evaluated according to the χ^2 test specifically for this quantity by varying the numerator and denominator together.

Prompt Photons

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



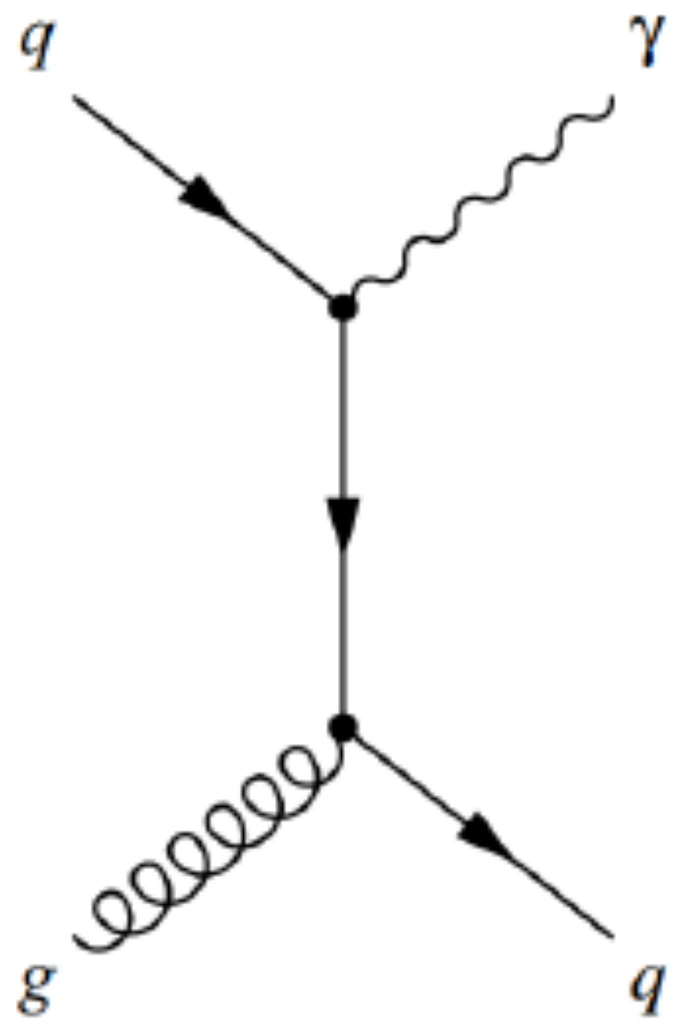
quark-gluon
Compton scattering

quark - anti-quark
Annihilation

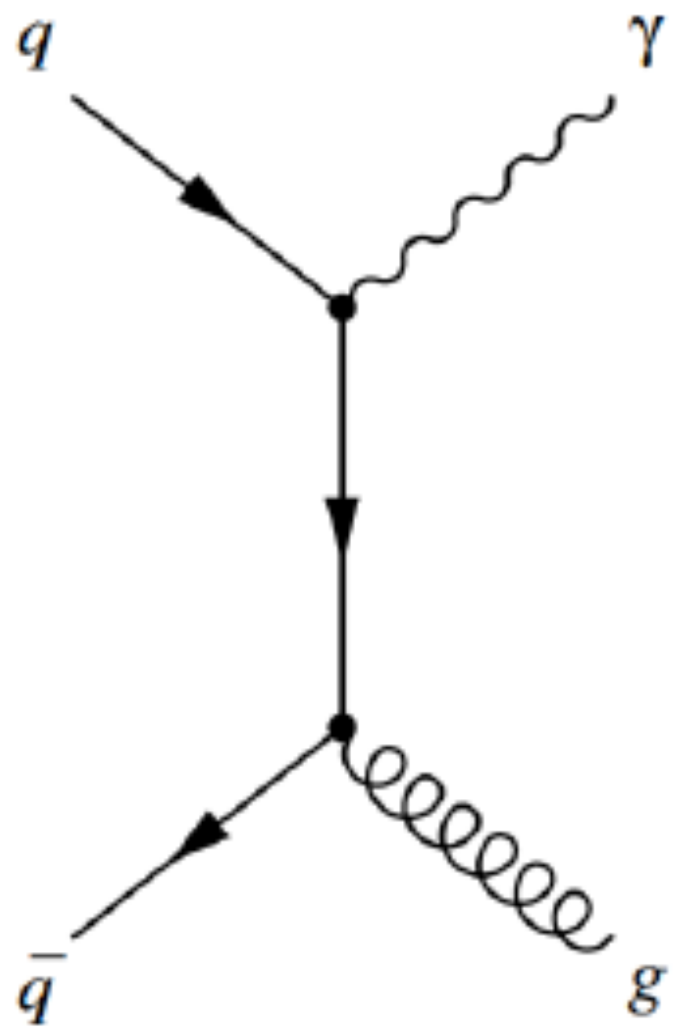
Direct photons

Prompt Photons

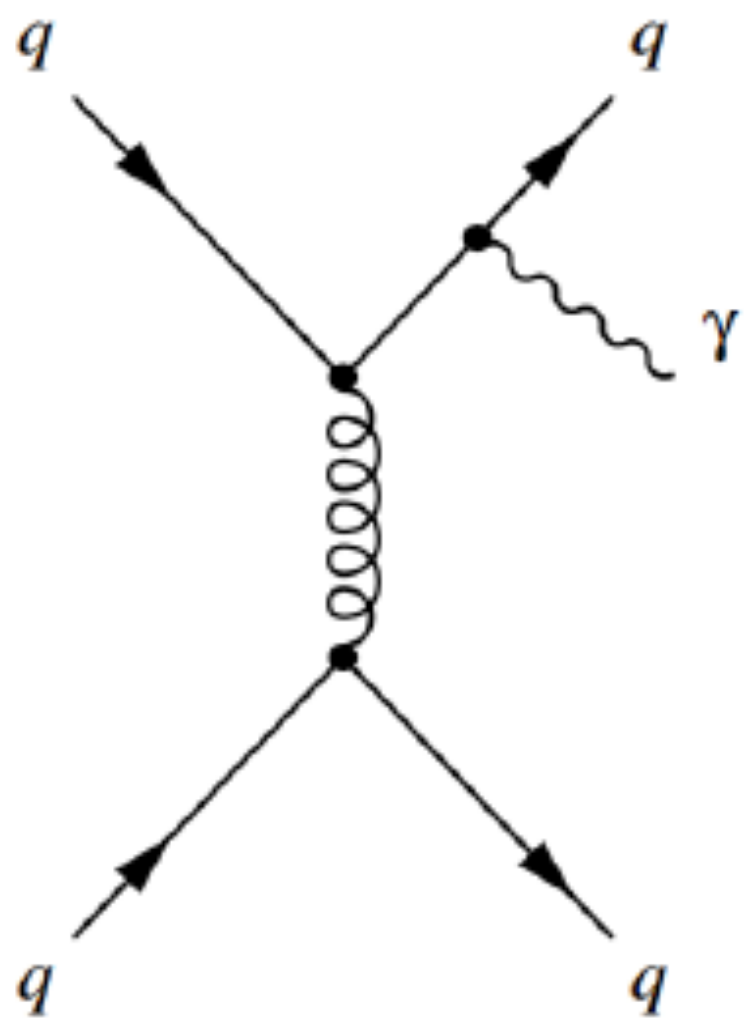
- **Direct photon**
  - ➡ produced from primary vertex
  - ➡ Processes : Compton scattering, Annihilation
- **Fragmentation photon**
  - ➡ radiated from partons after the primary hard scattering



quark-gluon
Compton scattering



quark - anti-quark
Annihilation



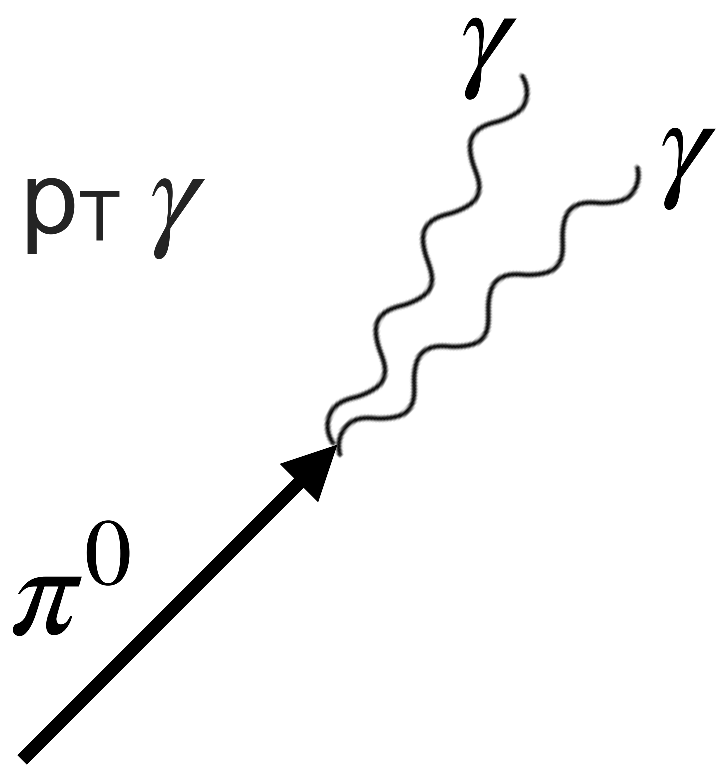
Fragmentation

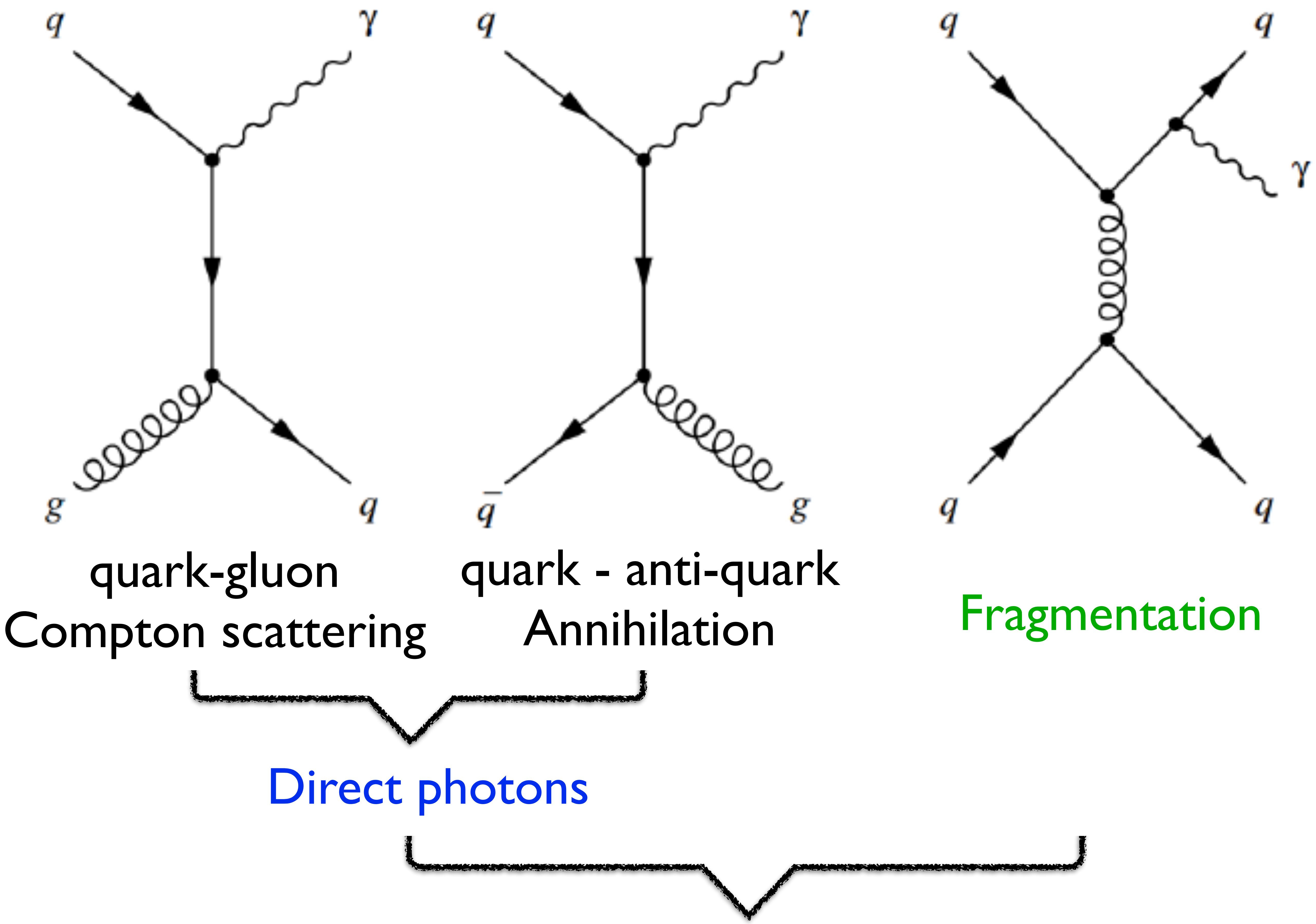
Direct photons

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





quark-gluon
Compton scattering

quark - anti-quark
Annihilation

Fragmentation

Direct photons

Prompt photons
= Direct + Fragmentation photons

Medium response (wake) in jet direction

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

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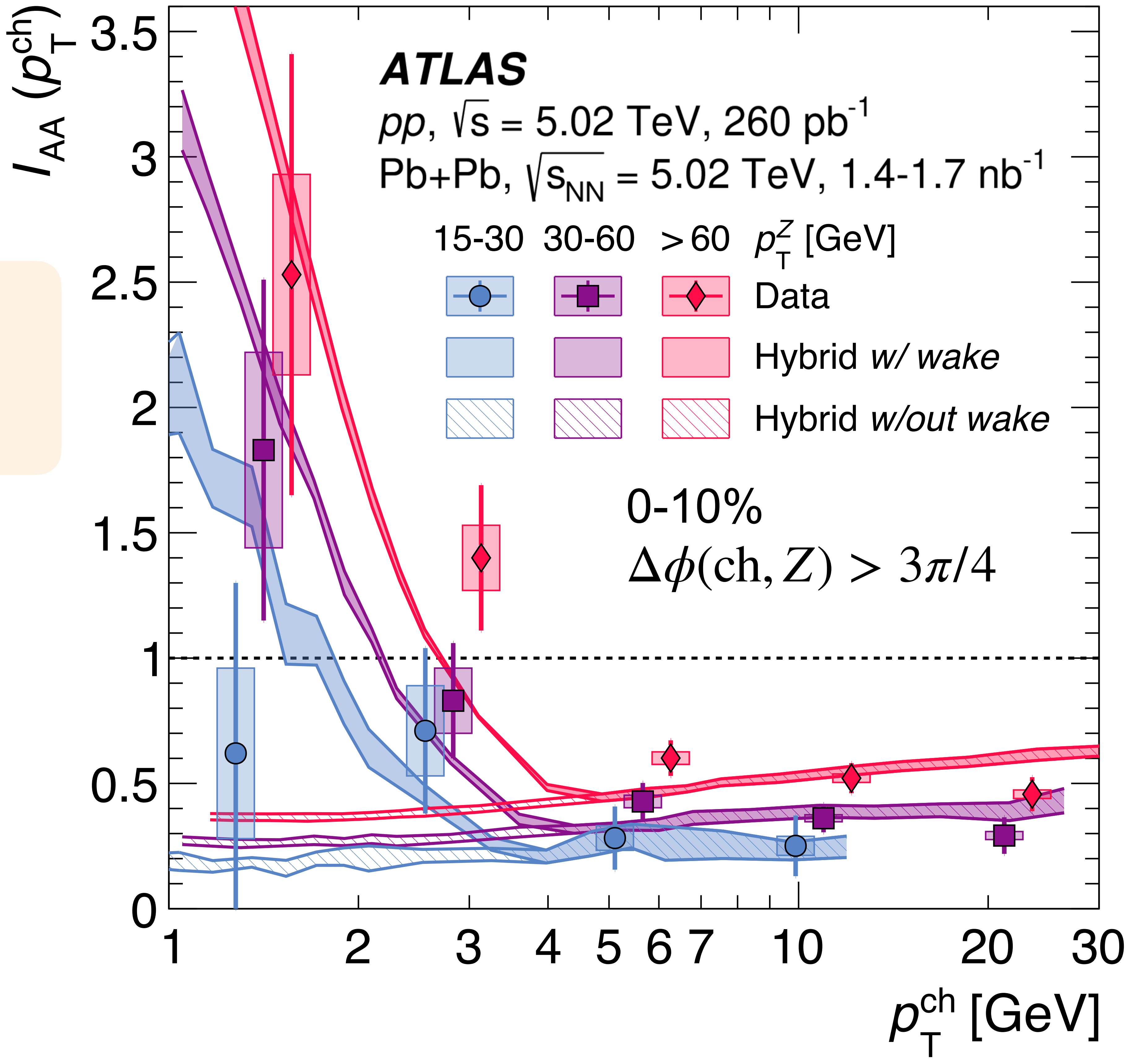

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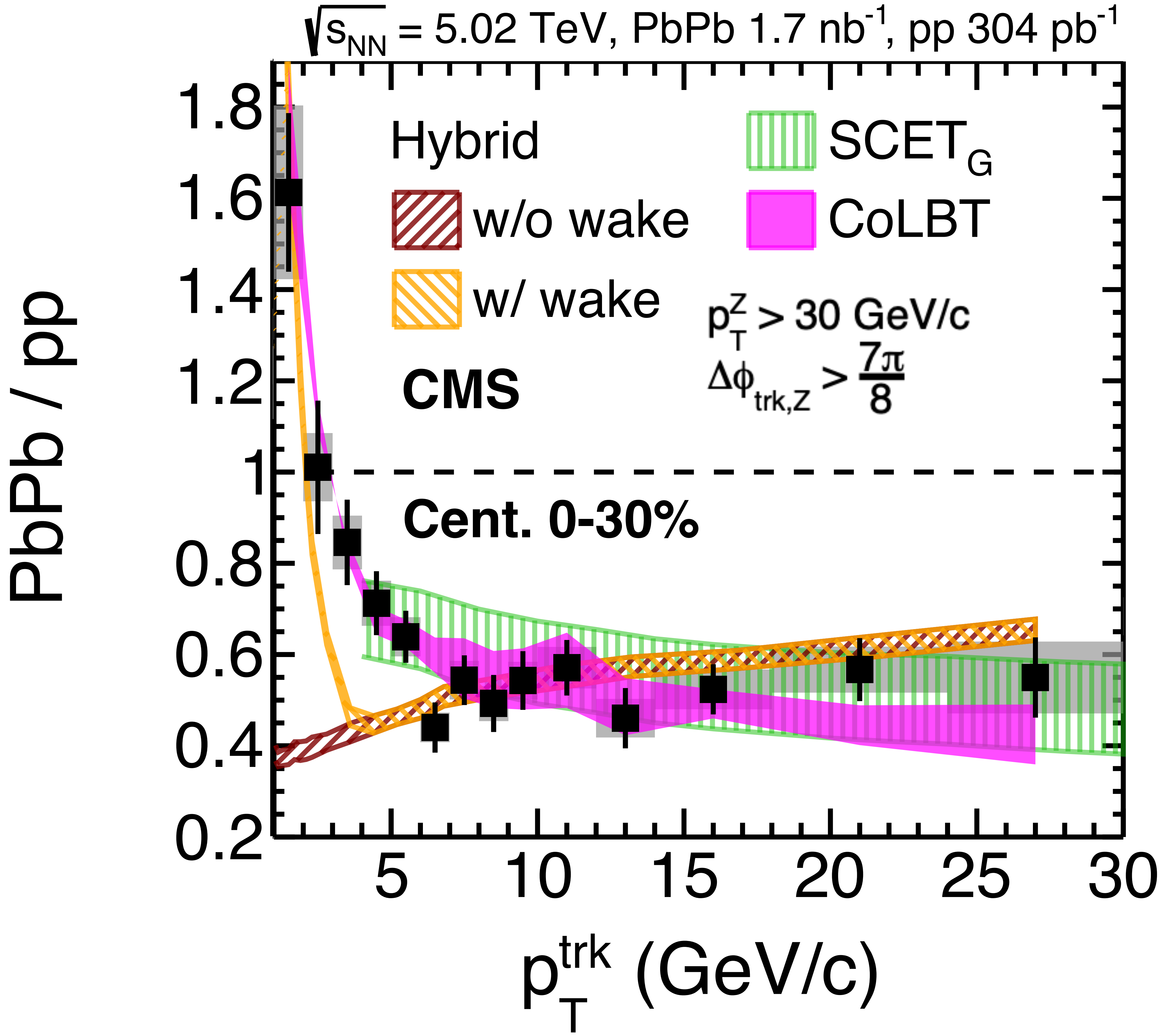

- Numerous observations of **enhancement of low-p_T particles** and particles at larger angles relative to the jet
  - ➡ but, hard to disentangle between in-medium parton shower modification and medium response