

Photon-tagged measurements of jet quenching with ATLAS

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(University of Colorado Boulder)

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Run: 286834
Event: 124877733
2015-11-28 01:15:42 CEST
Pb+Pb $\sqrt{s_{NN}} = 5.02$ TeV
photon + multijet event
 $\sum E_T^{\text{FCal}} = 4.06$ TeV



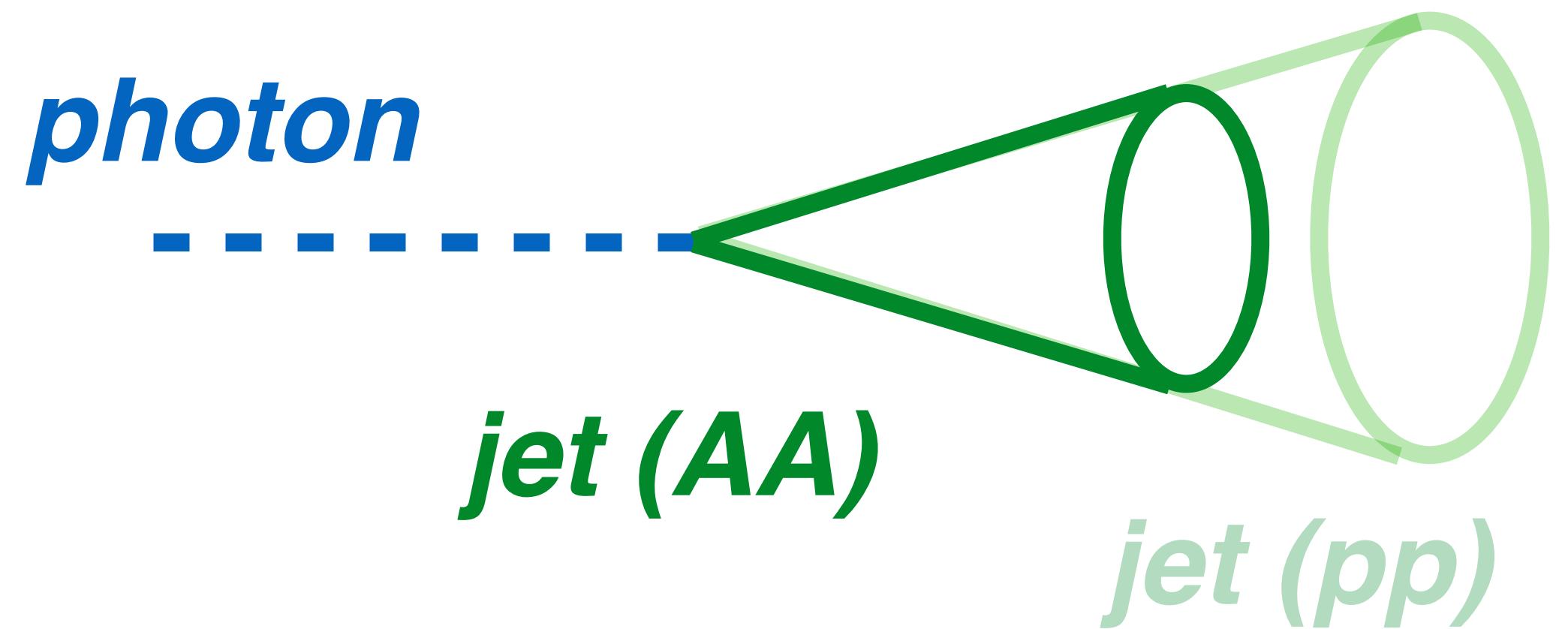
$p_T = 200$ GeV
photon

EMCal

HCal

balancing
jet(s)?

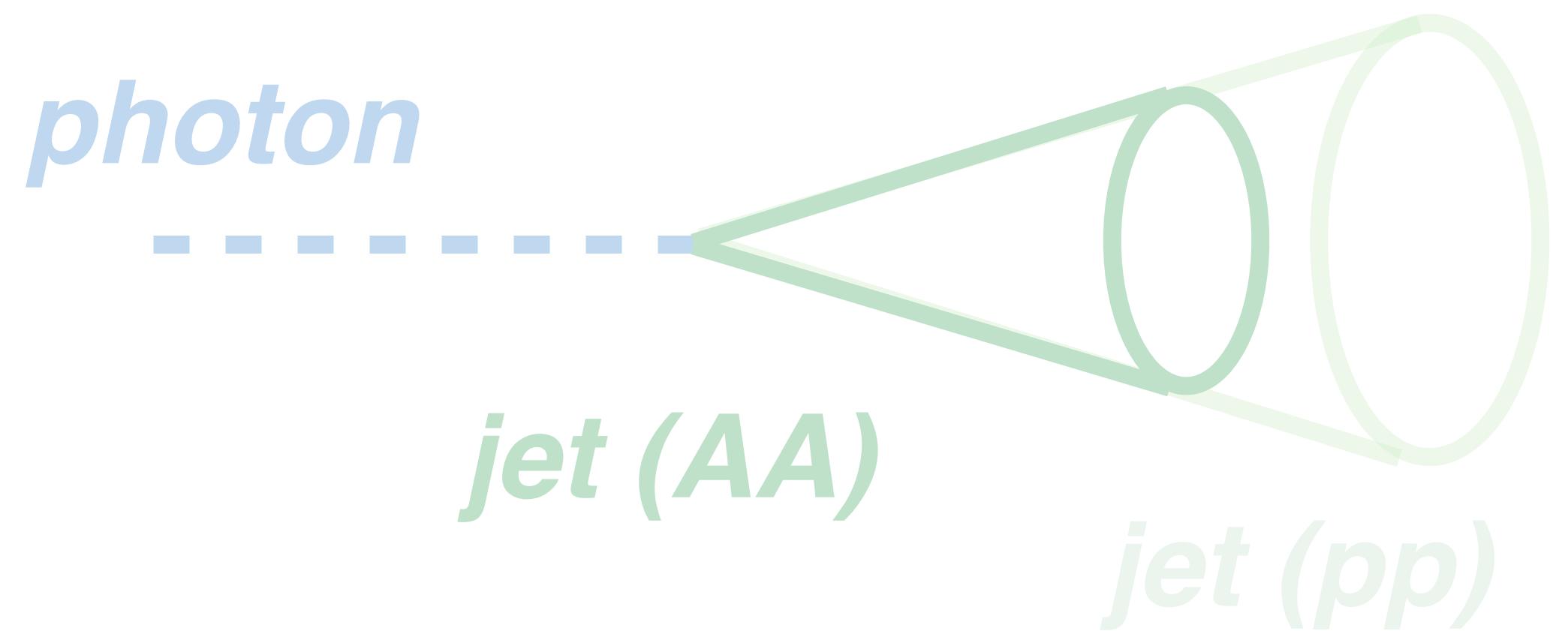
What is the (absolute) amount of energy lost in cone?



Photon+jet p_T -balance

$$\rightarrow x_{J\gamma} = p_T^{jet} / p_T^{\gamma} \text{ (for } \Delta\phi > 7\pi/8\text{)}$$

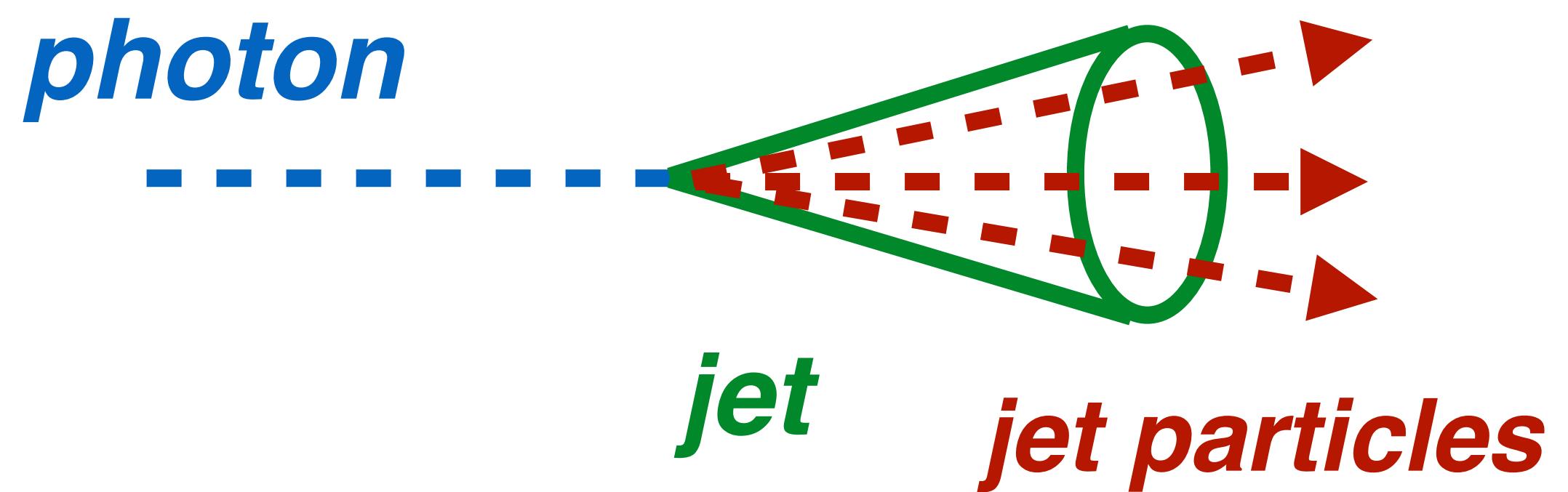
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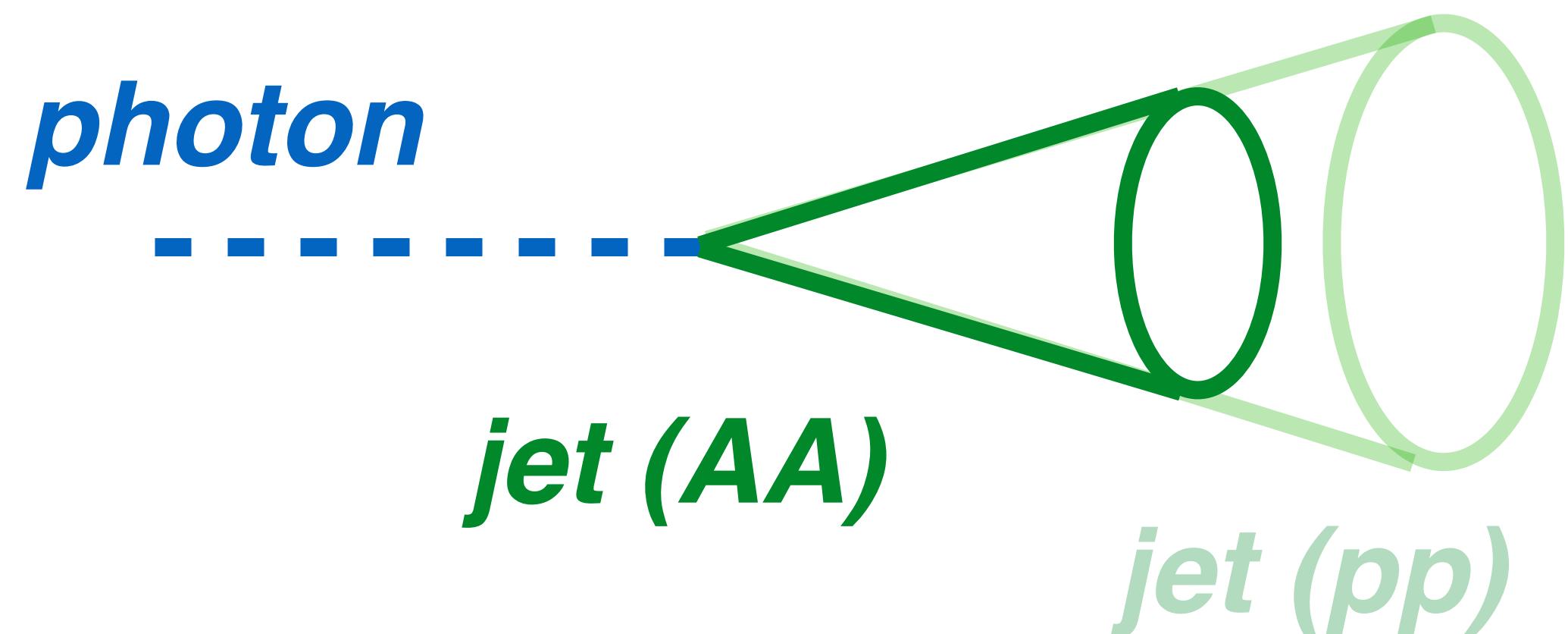
How is the parton shower in cone modified by medium?



Photon-tagged **frag. function**
(with respect to the **jet**)

$$\rightarrow D(p_T^h) \text{ or } D(z = p_T^h / p_T^{jet})$$

What is the (absolute) amount of energy lost in cone?



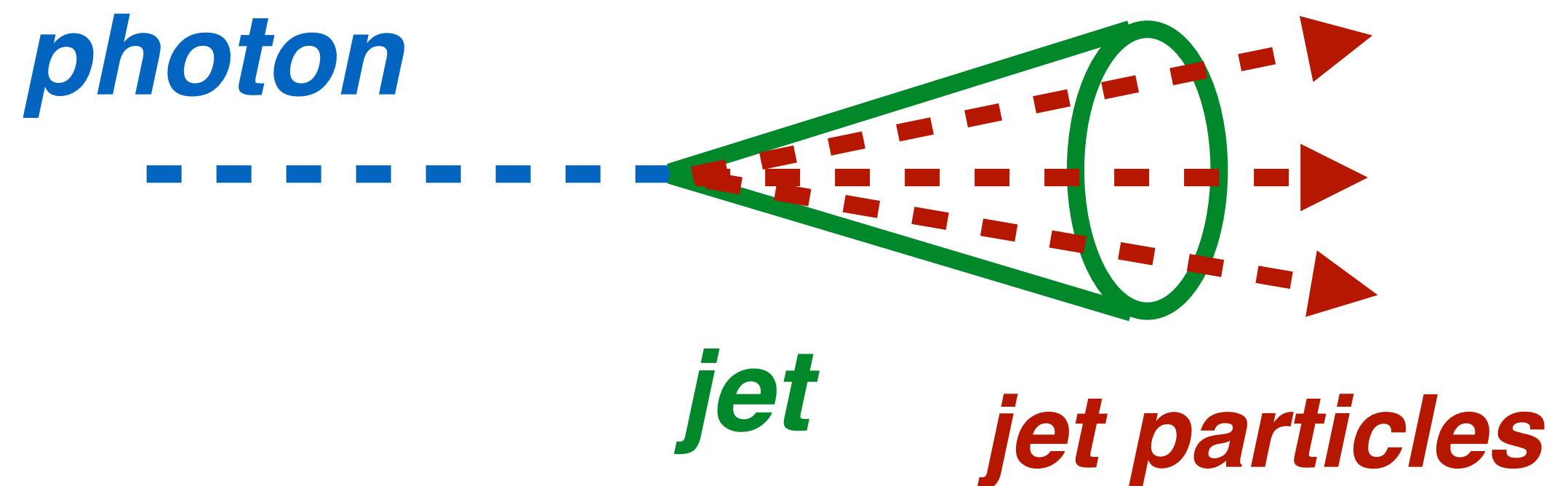
Photon+jet p_T -balance

$$\rightarrow x_{J\gamma} = p_T^{\text{jet}} / p_T^\gamma \text{ (for } \Delta\phi > 7\pi/8\text{)}$$

NEW @  2018

ATLAS-CONF-2018-009

How is the parton shower in cone modified by medium?



Photon-tagged **frag. function**
(with respect to the **jet**)

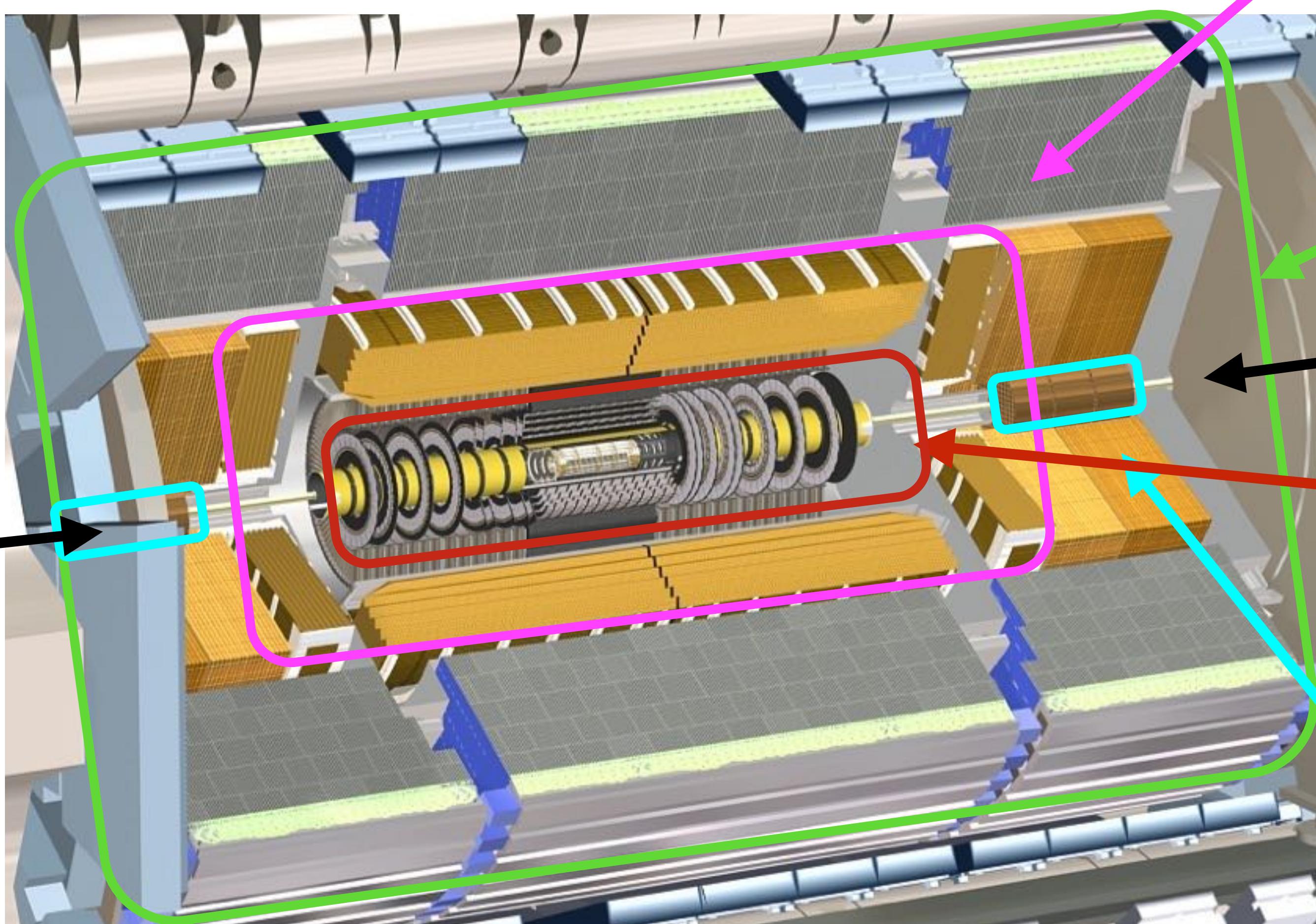
$$\rightarrow D(p_T^h) \text{ or } D(z = p_T^h / p_T^{\text{jet}})$$

NEW @  2018

ATLAS-CONF-2017-074



Photons, jets, hadrons



Photons in EMCal
 $p_T > 63.1 \text{ GeV}$, $|\eta| < 2.37$
(excluding 1.37-1.56)

Z. Citron, 10:00am

Jets in calorimeter
 $|\eta| < 2.8$, $p_T > 31.6 \text{ GeV}$

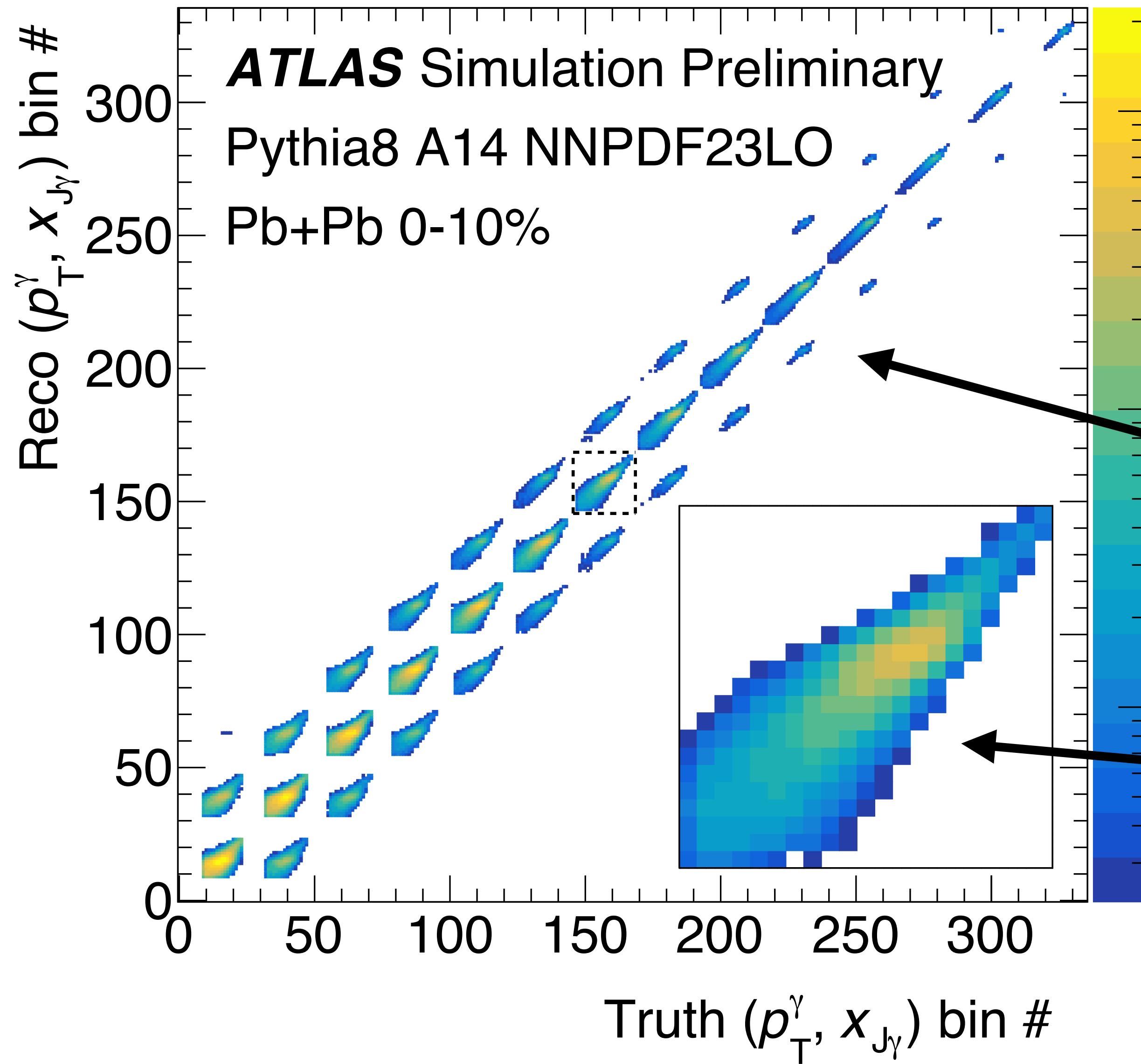
M. Spousta, 11:10am

Tracks in
inner detector ($|\eta| < 2.5$)

M. Rybář, 12:30pm

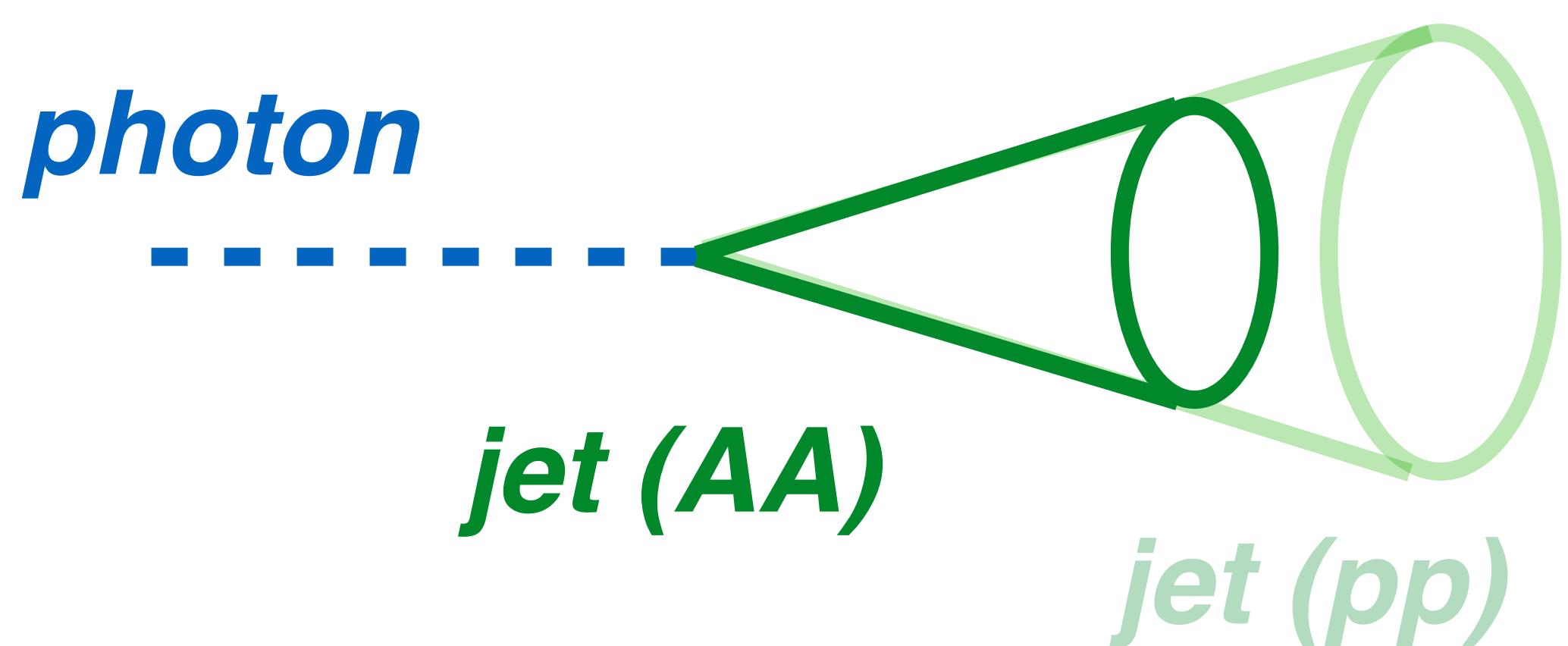
Centrality in
FCal ($3.2 < |\eta| < 4.9$)

Correction for detector effects



- 2-D unfolding in $(p_T^\gamma, x_{J\gamma})$
 - $(p_T^{\text{jet}}, p_T^h)$ or (p_T^{jet}, z) for FF measurement
- big “blocks” show the $(p_{T\gamma}^{\text{truth}}, p_{T\gamma}^{\text{reco}})$ correlation*
- $(x_{J\gamma}^{\text{truth}}, x_{J\gamma}^{\text{reco}})$ correlation at fixed $(p_{T\gamma}^{\text{truth}}, p_{T\gamma}^{\text{reco}})$*
- final results at “*particle level*”

What is the (absolute) amount of energy lost in cone?

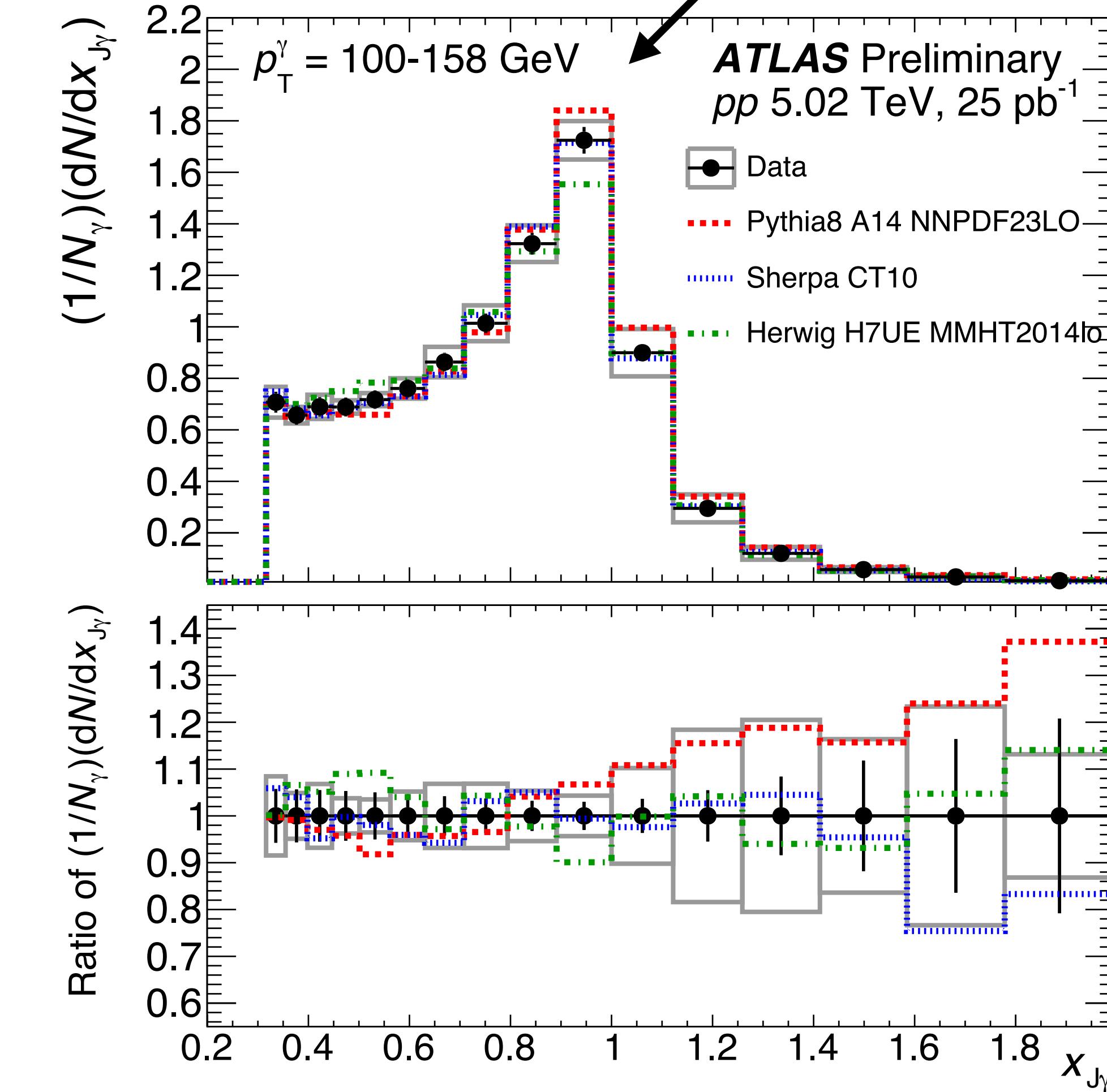
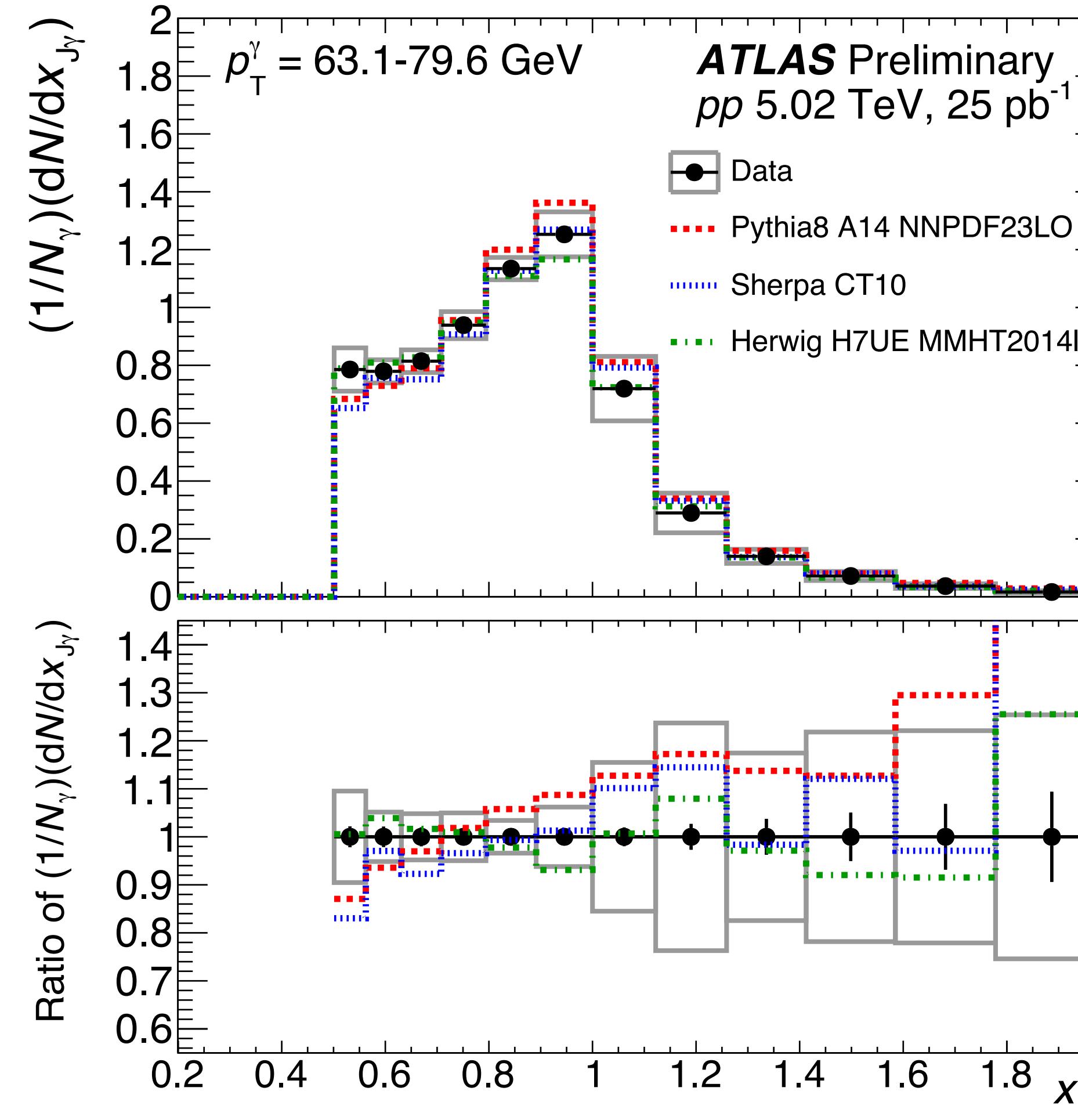


Photon+jet p_{T} -balance

$$\rightarrow x_{J\gamma} = p_{\text{T}}^{\text{jet}} / p_{\text{T}}^{\gamma} \quad (\text{for } \Delta\phi > 7\pi/8)$$

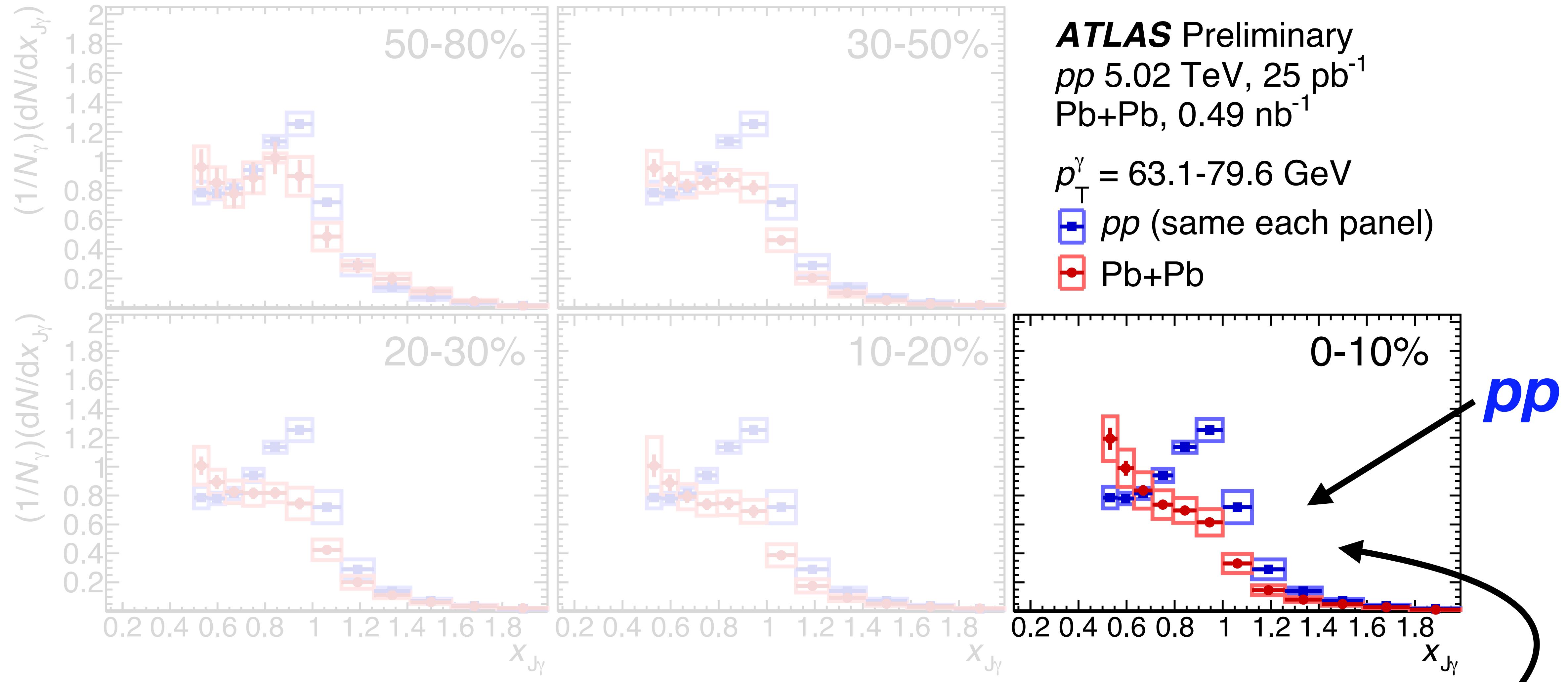
Photon+jet p_T balance in pp

*unfolding recovers
sharp peak...*

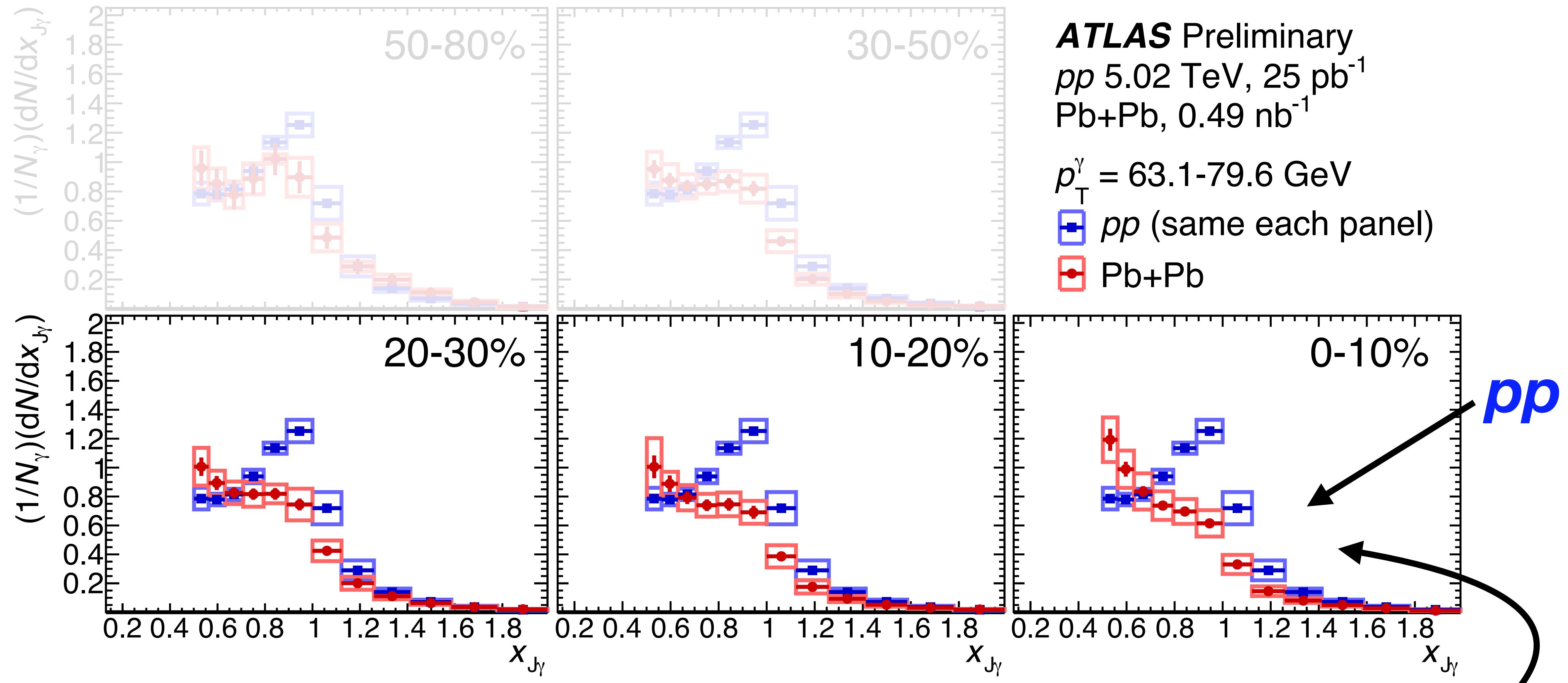


Compare directly to MC generators: **Pythia 8** **Sherpa** **Herwig 7**

Pb+Pb, $p_{\text{T}}\gamma = 63.1\text{-}79.6 \text{ GeV}$



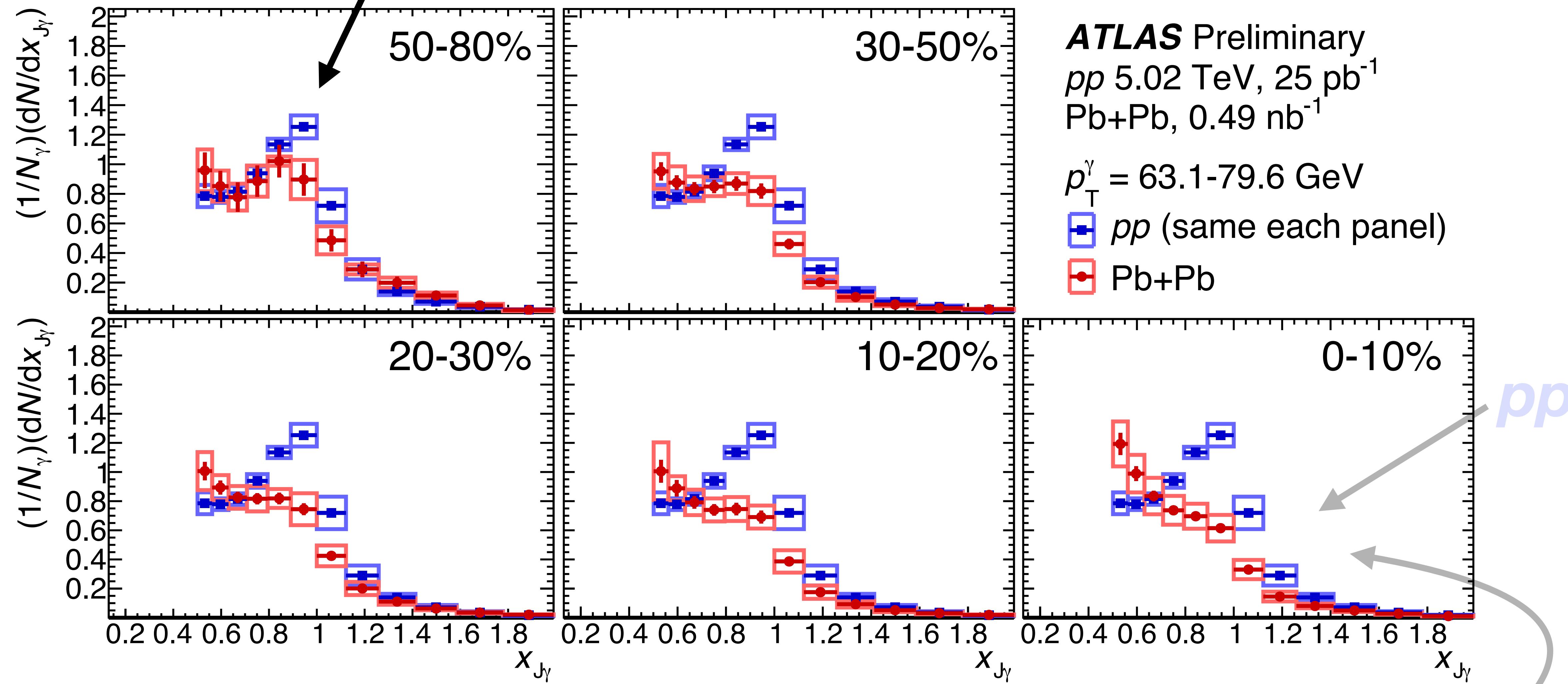
Pb+Pb, $p_{\text{T}}\gamma = 63.1\text{-}79.6 \text{ GeV}$



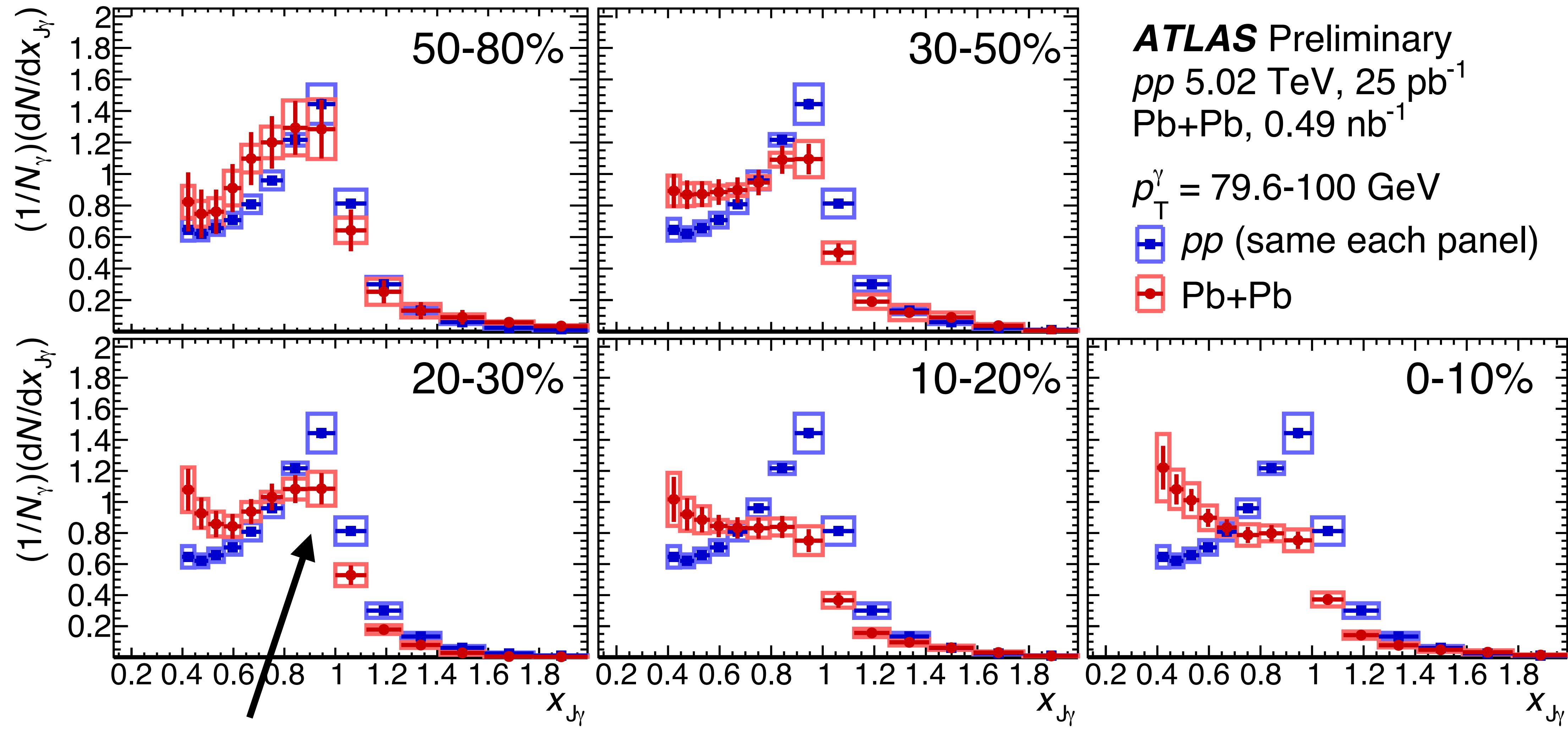
peaked structure destroyed in **0-10% Pb+Pb**

*peak returns in 50-80%
Pb+Pb events*

Pb+Pb, $p_T\gamma = 63.1\text{-}79.6 \text{ GeV}$



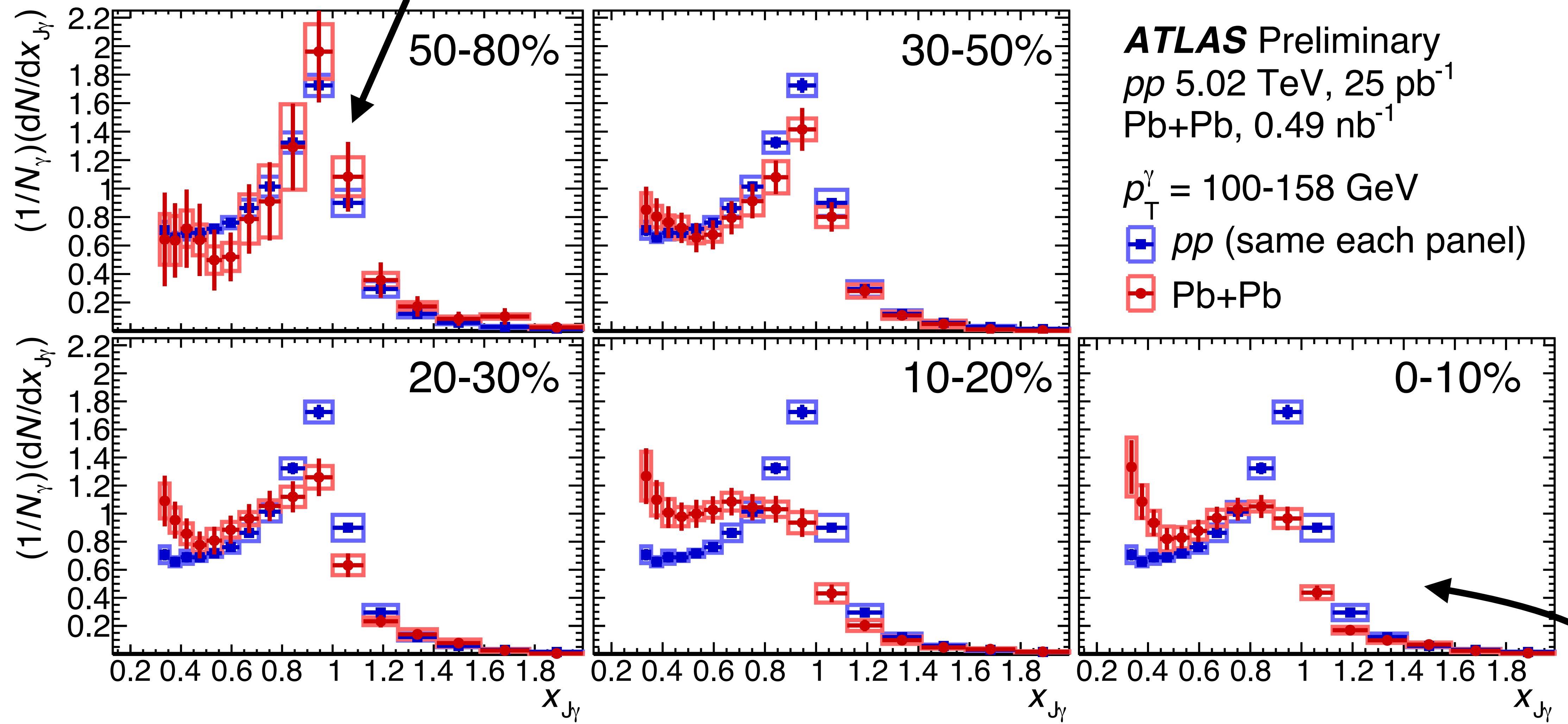
peaked structure destroyed in 0-10% Pb+Pb



peaked structure (jets w/o E -loss?) visible in **20-30%**

**50-80% $Pb+Pb$ events
compatible with pp**

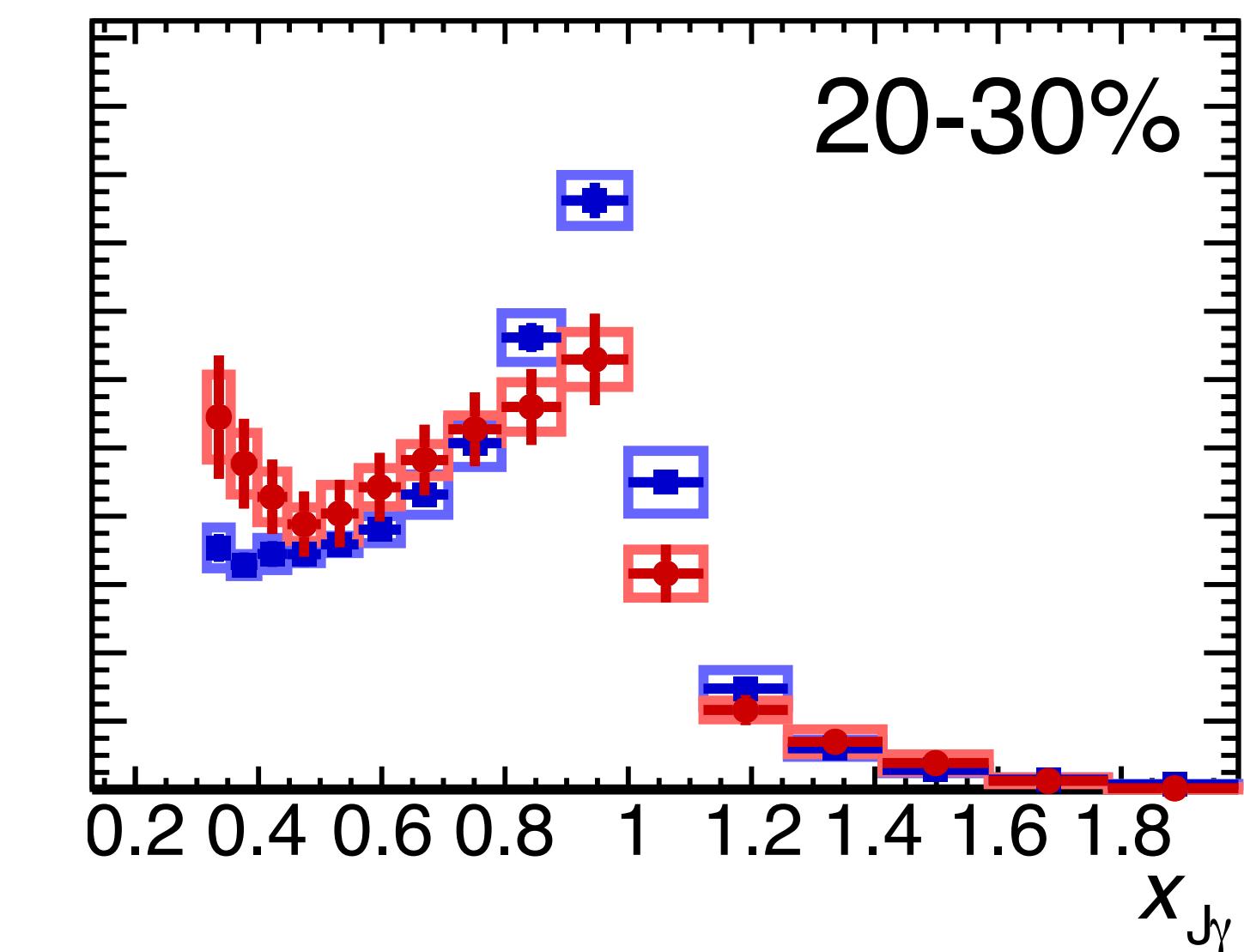
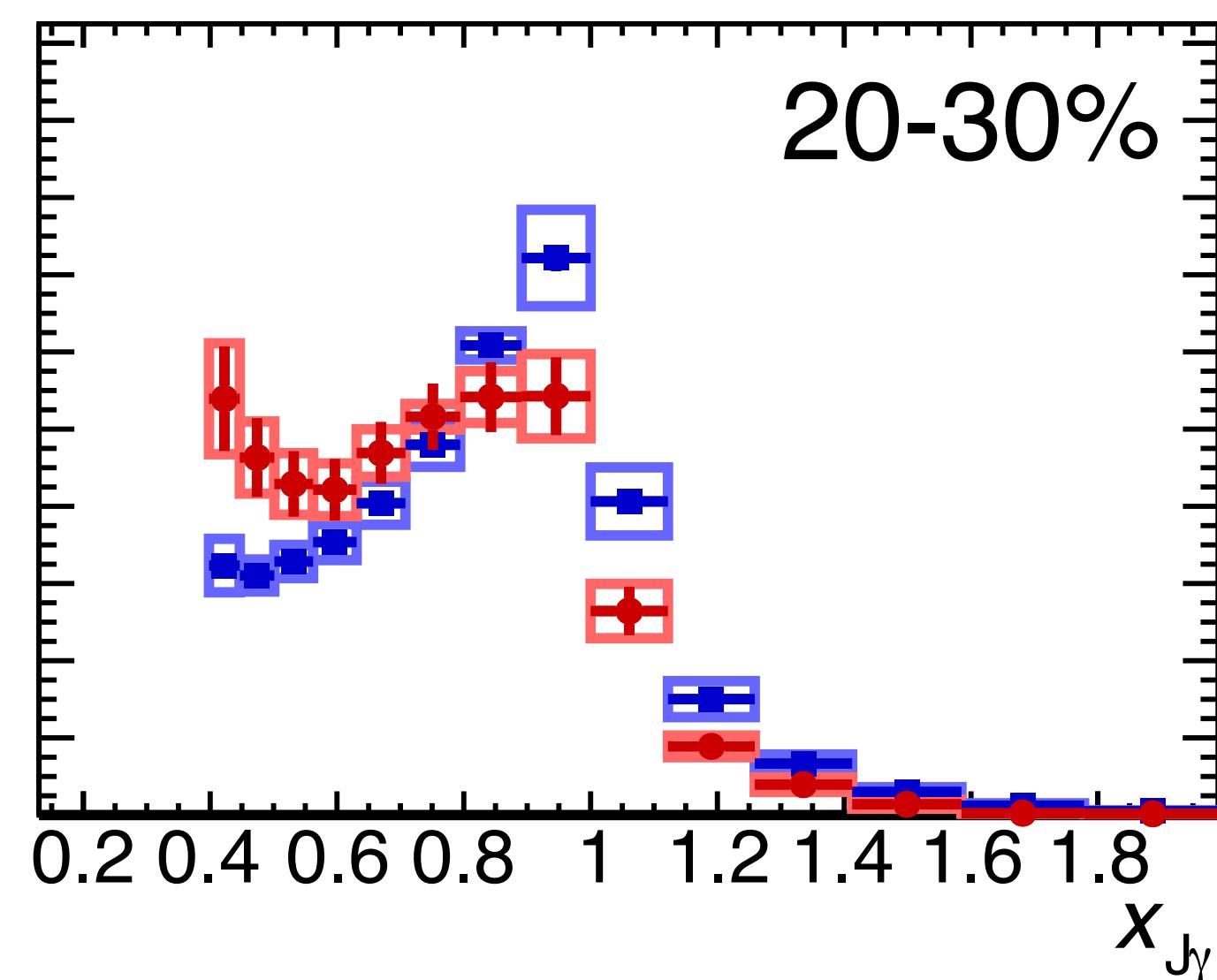
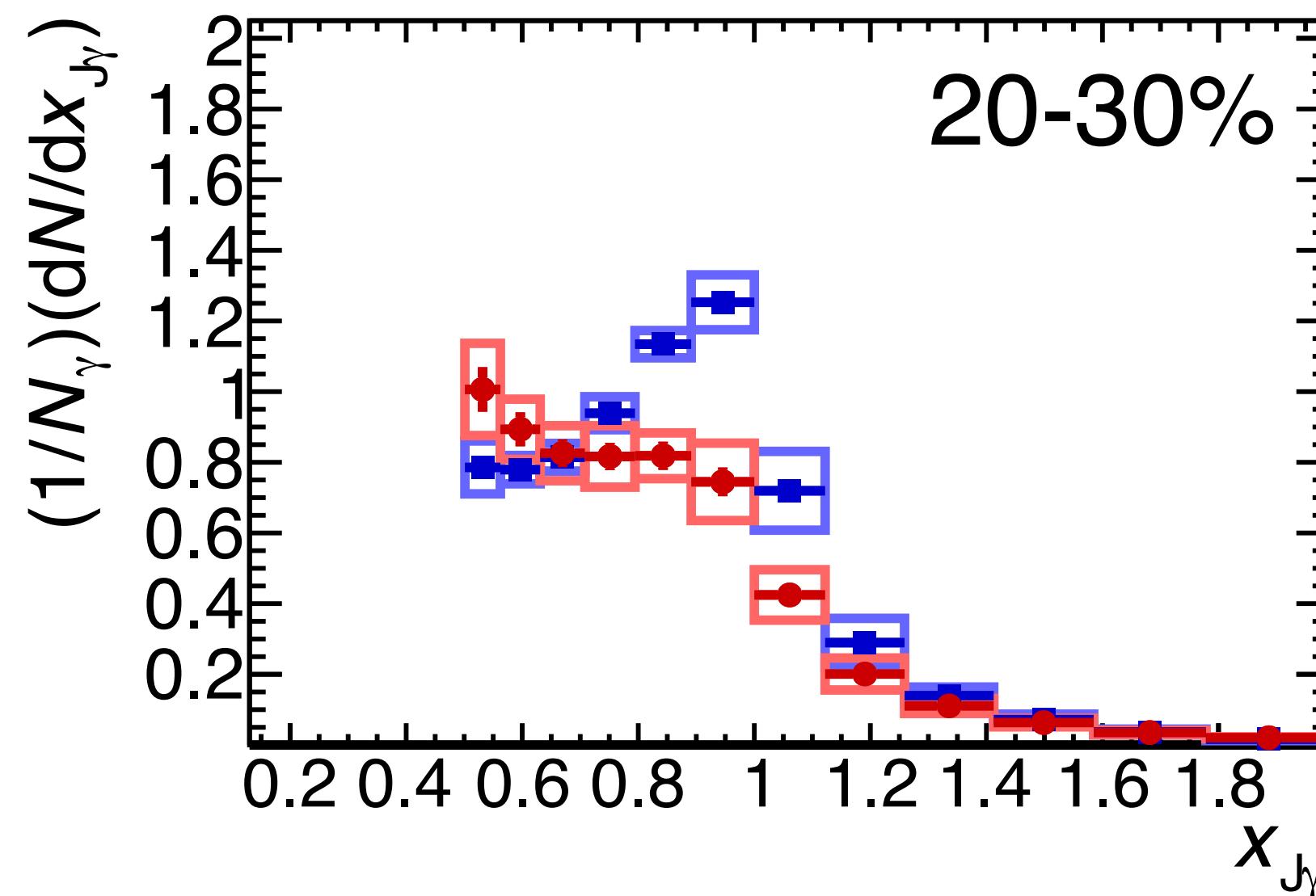
$Pb+Pb, p_T^\gamma = 100-158 \text{ GeV}$



visible peak even in 0-10% $Pb+Pb$

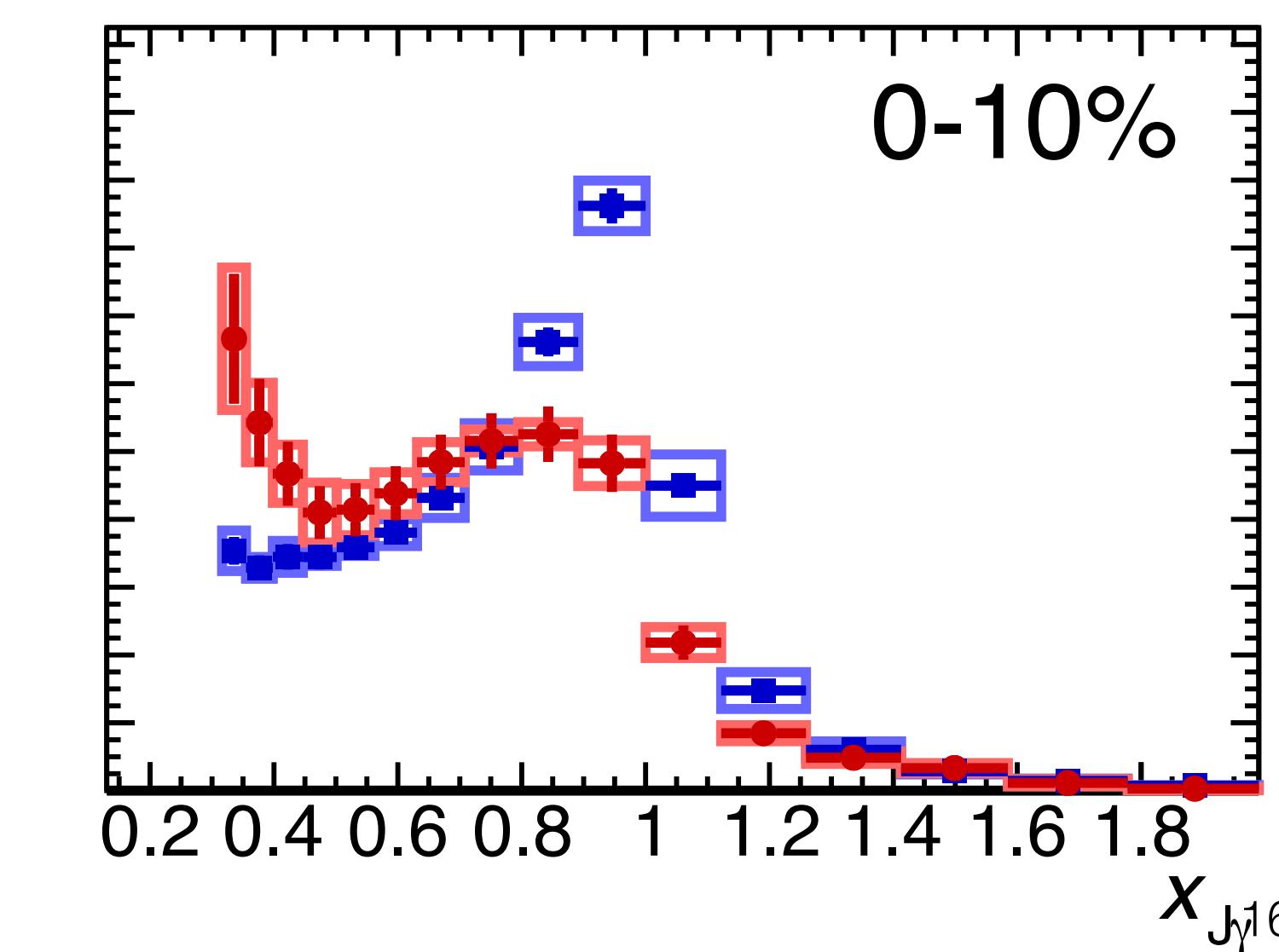
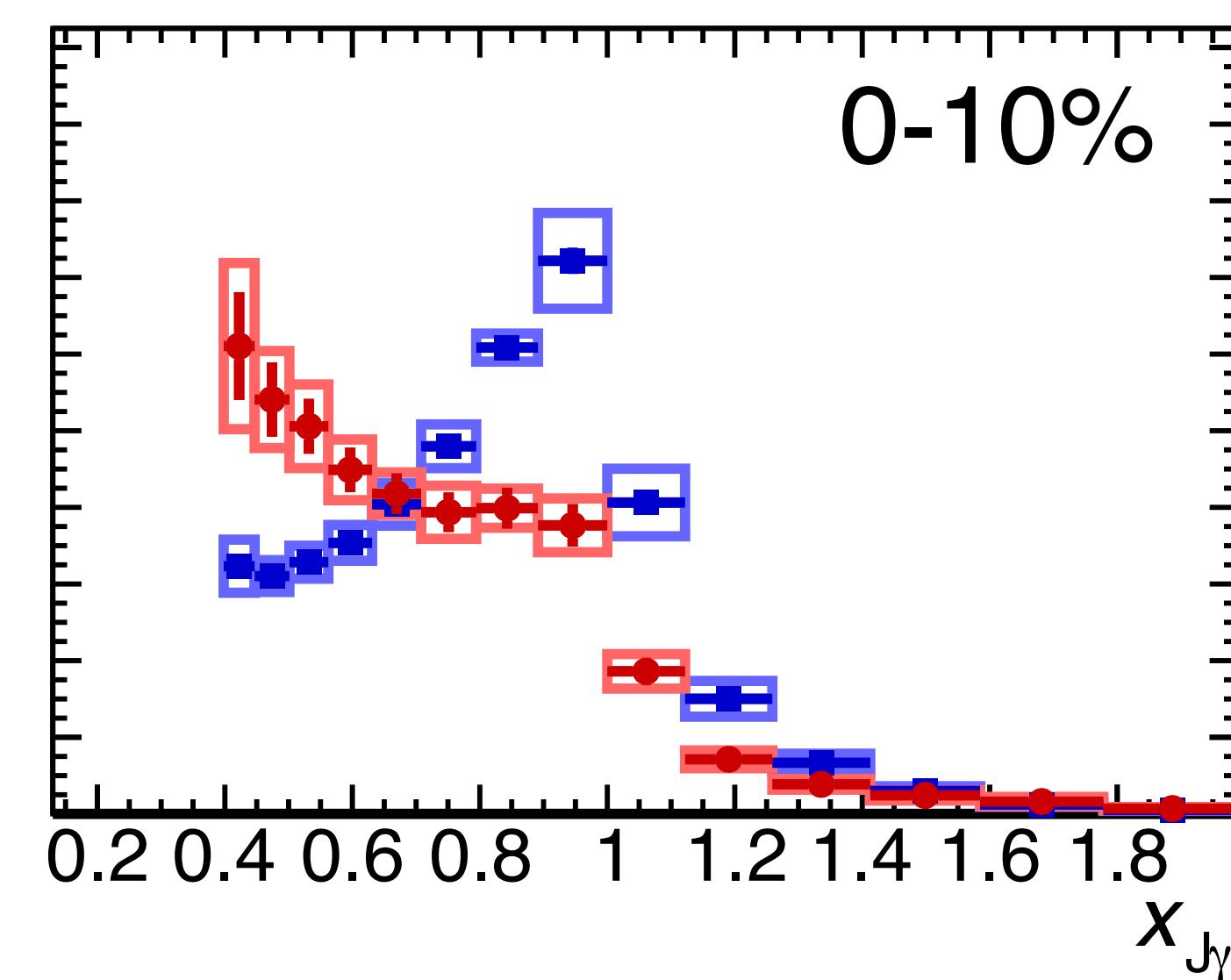
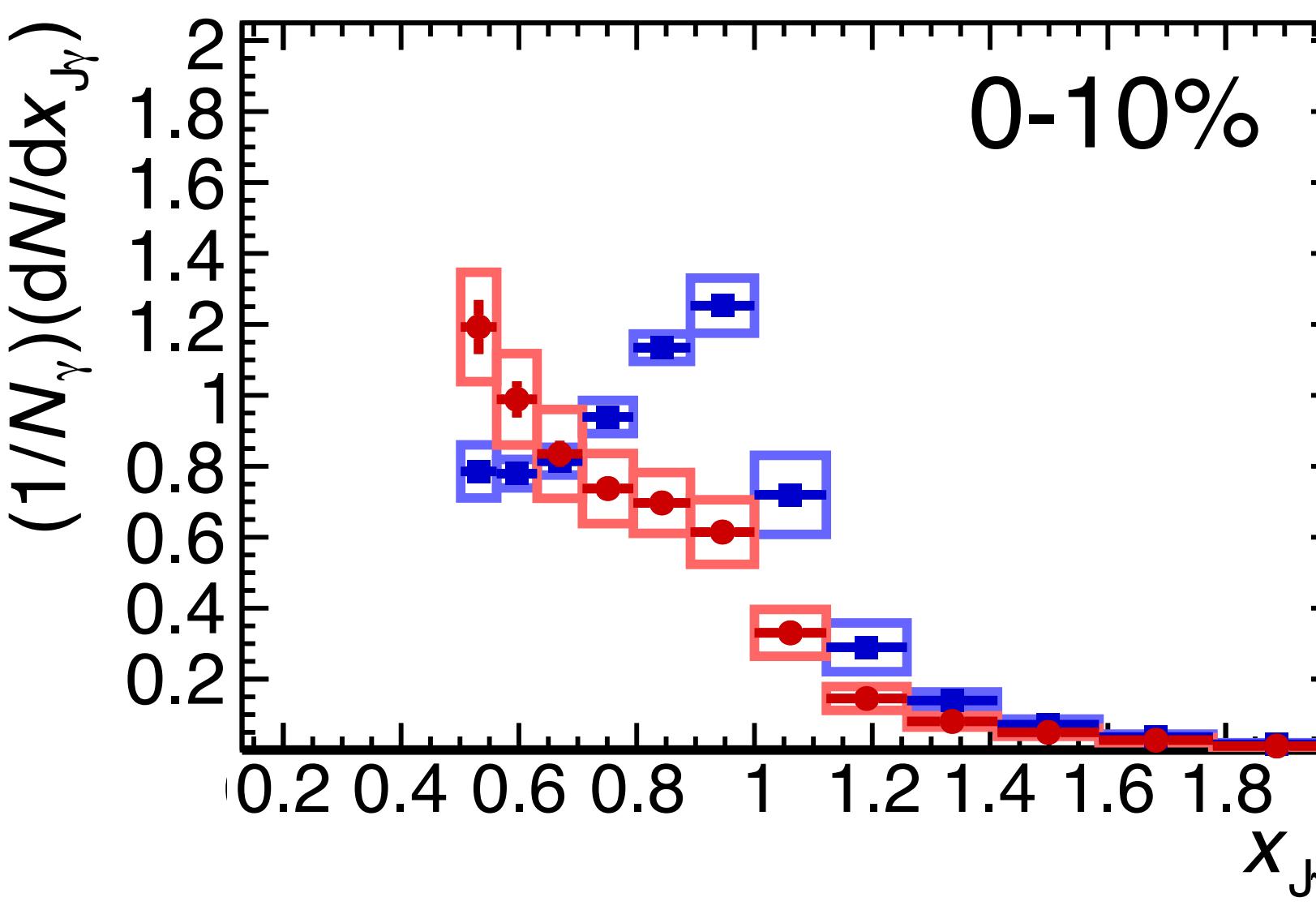
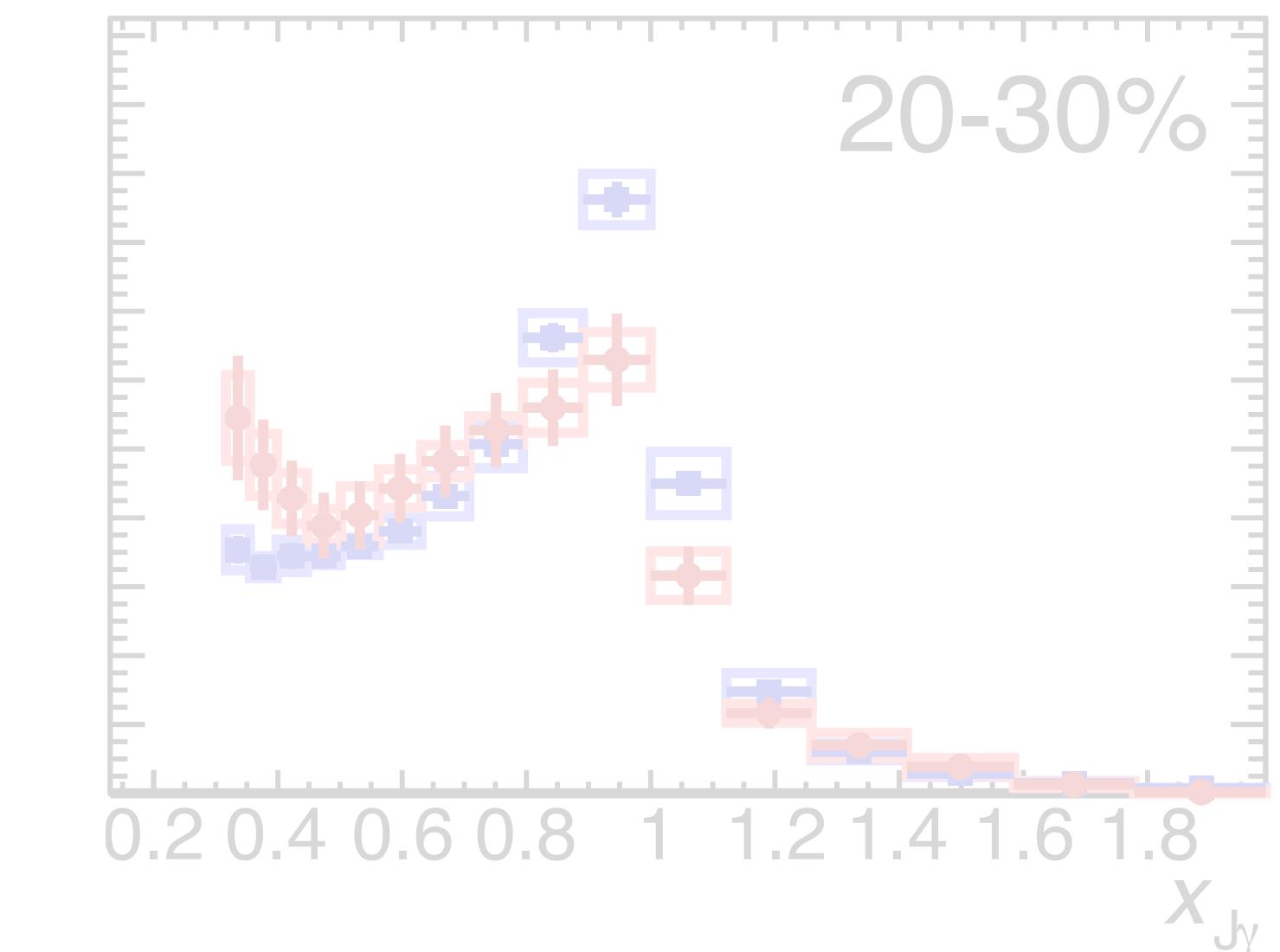
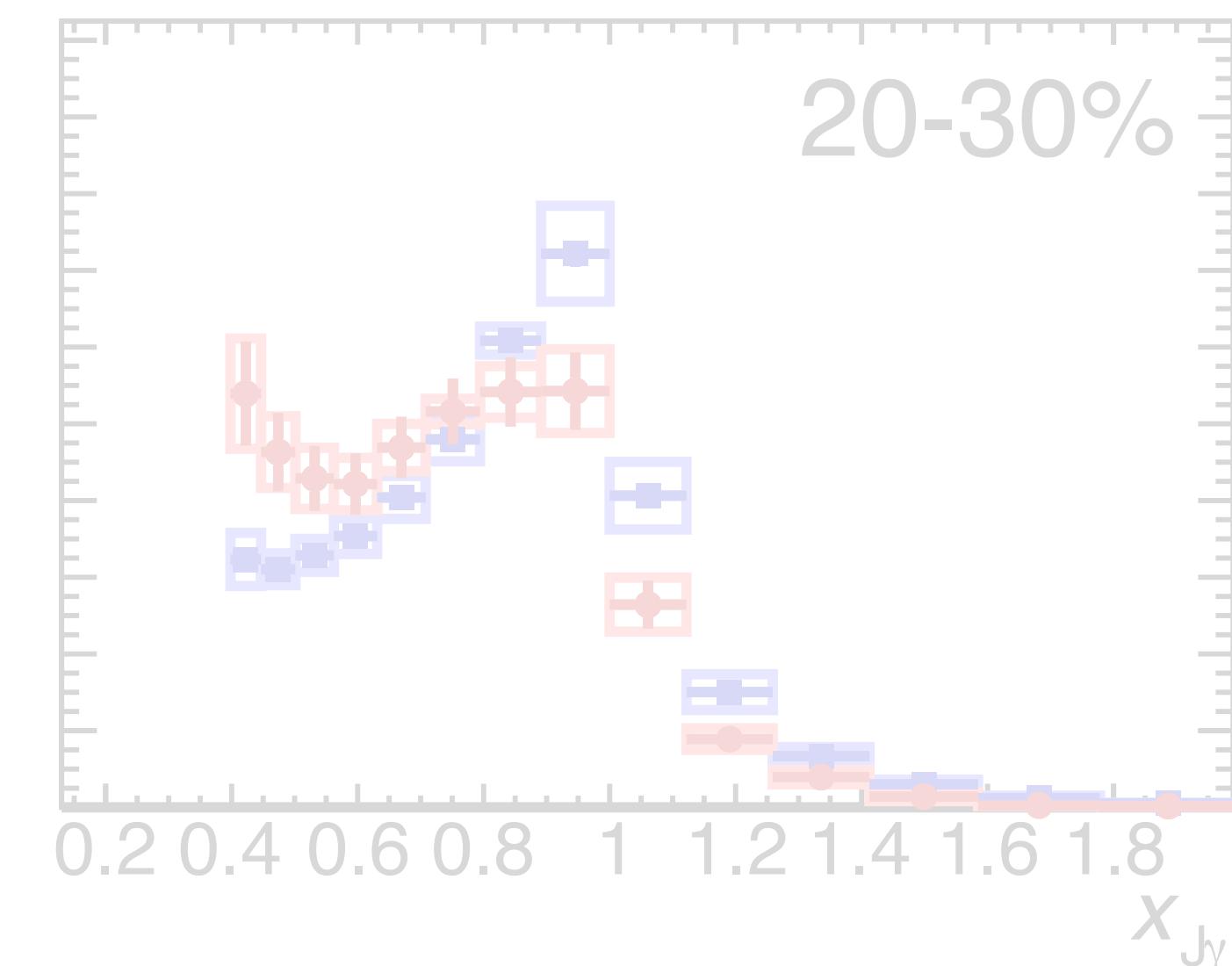
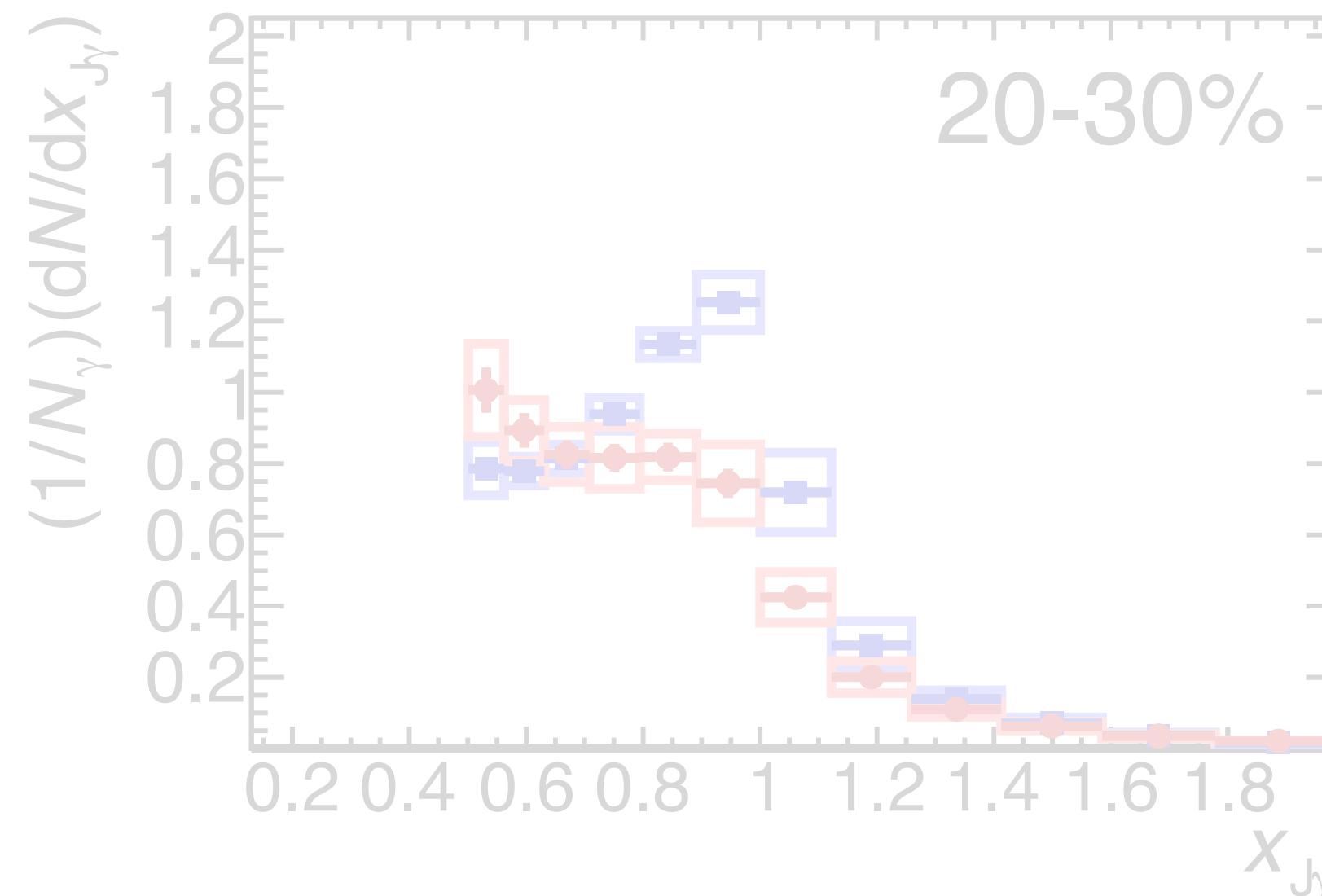
Fix centrality, explore p_T^γ -evolution

→ ***higher p_T^γ***



Fix centrality, explore $p_T\gamma$ -evolution

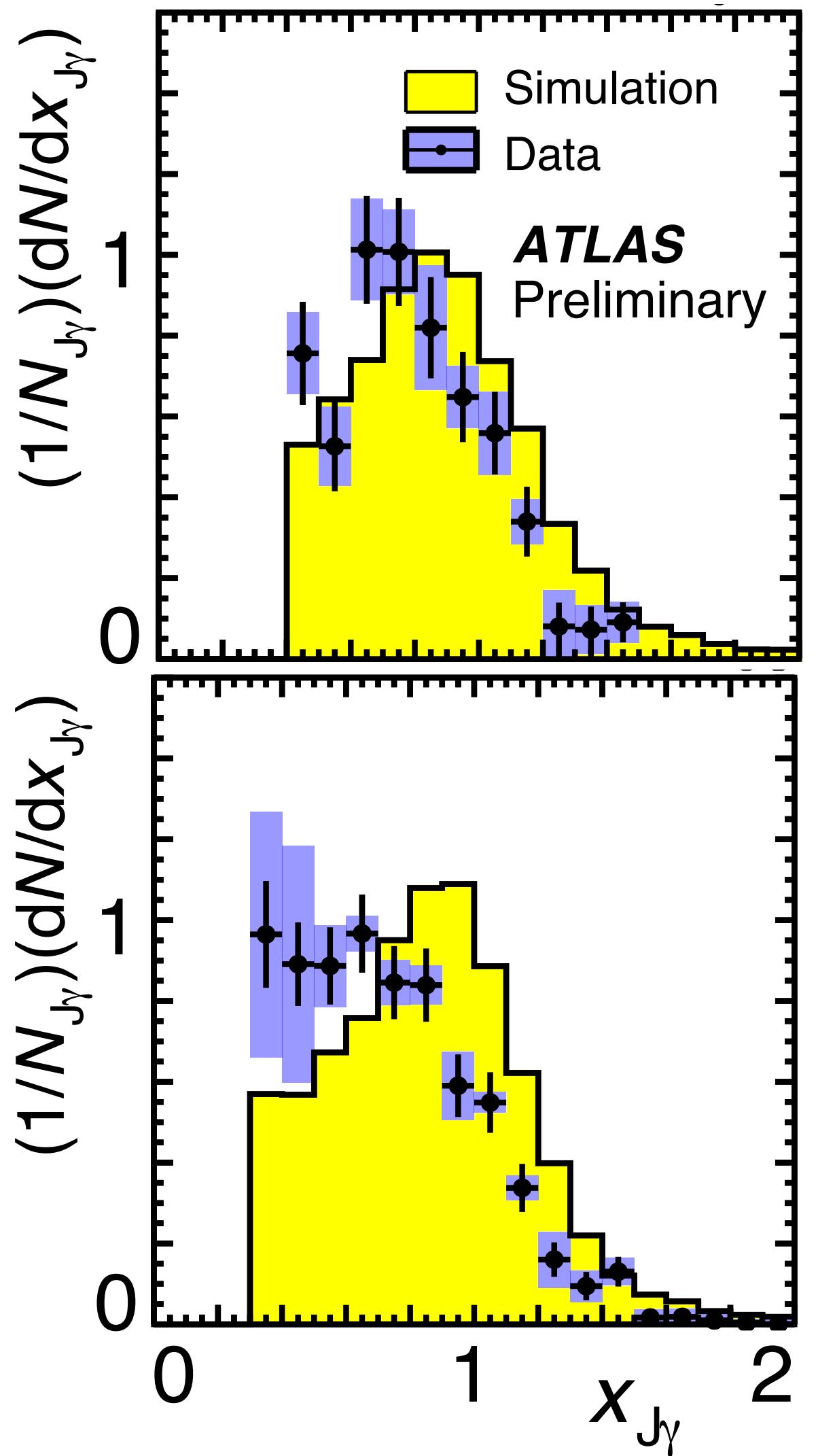
→ ***higher $p_T\gamma$***



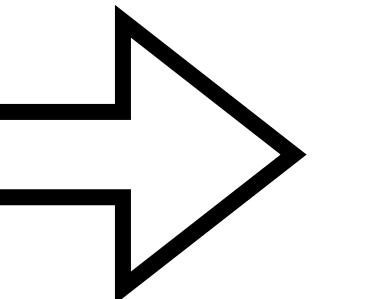
20-30% Pb+Pb
 $p_{T\gamma} = 79.6-100$ GeV

0-10% Pb+Pb
 $p_{T\gamma} = 100-158$ GeV

QM '17



Unfolding



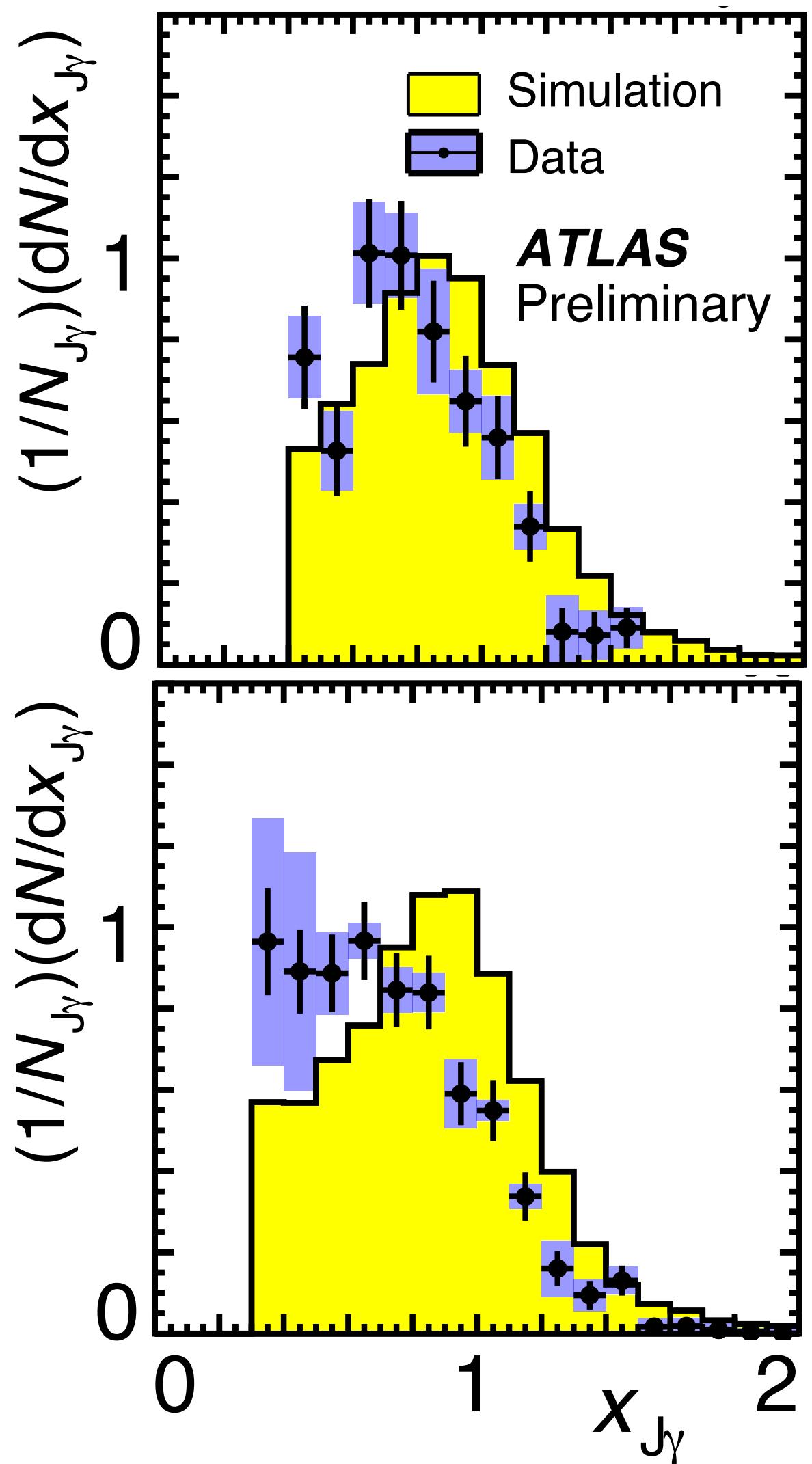
*uncorrected **Pb+Pb data** to
smeared Pythia: bulk shift...*

20-30% Pb+Pb
 $p_{T\gamma} = 79.6-100$ GeV

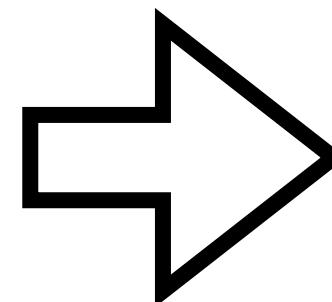
0-10% Pb+Pb
 $p_{T\gamma} = 100-158$ GeV

QM '17

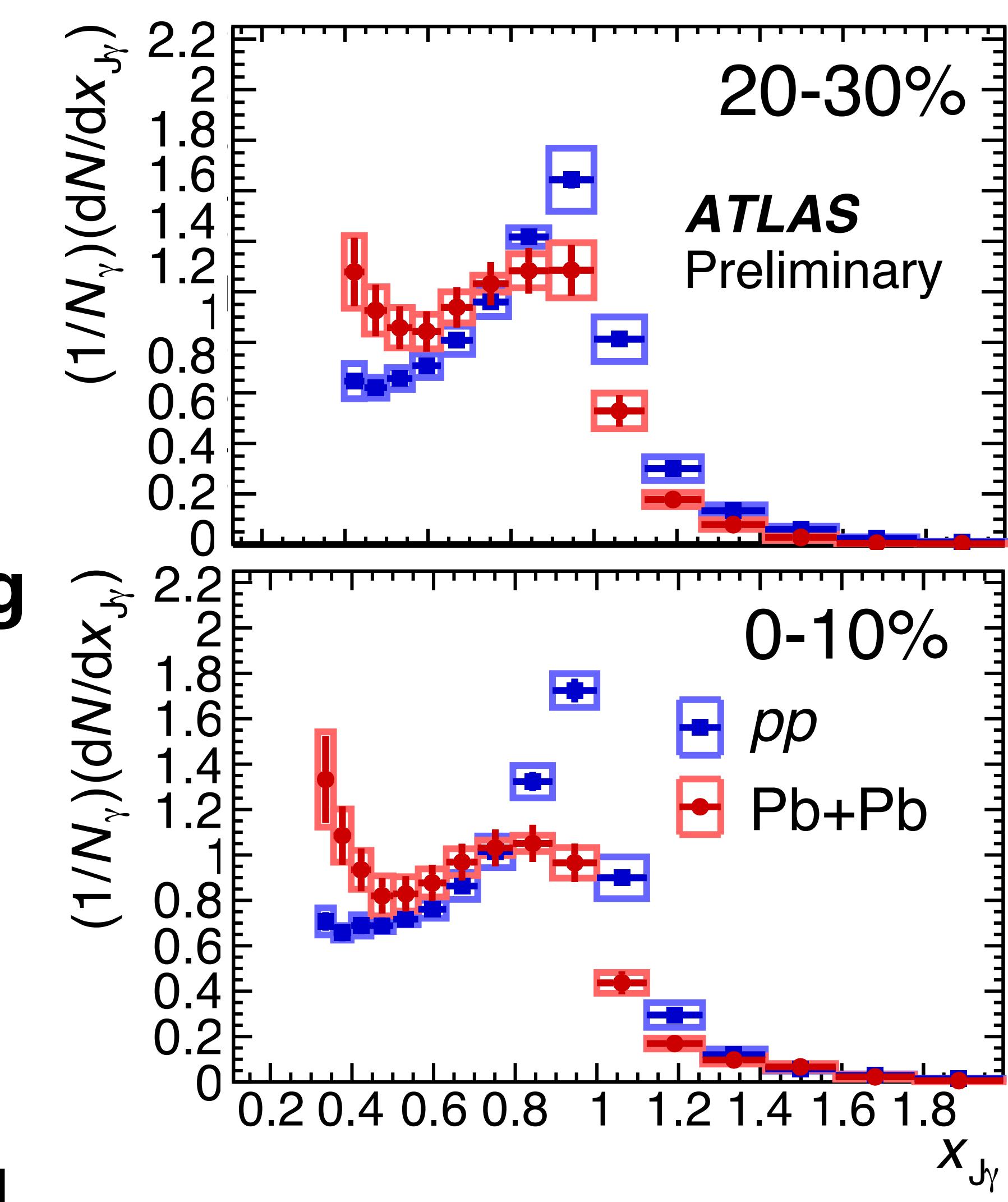
uncorrected **Pb+Pb data** to
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Unfolding

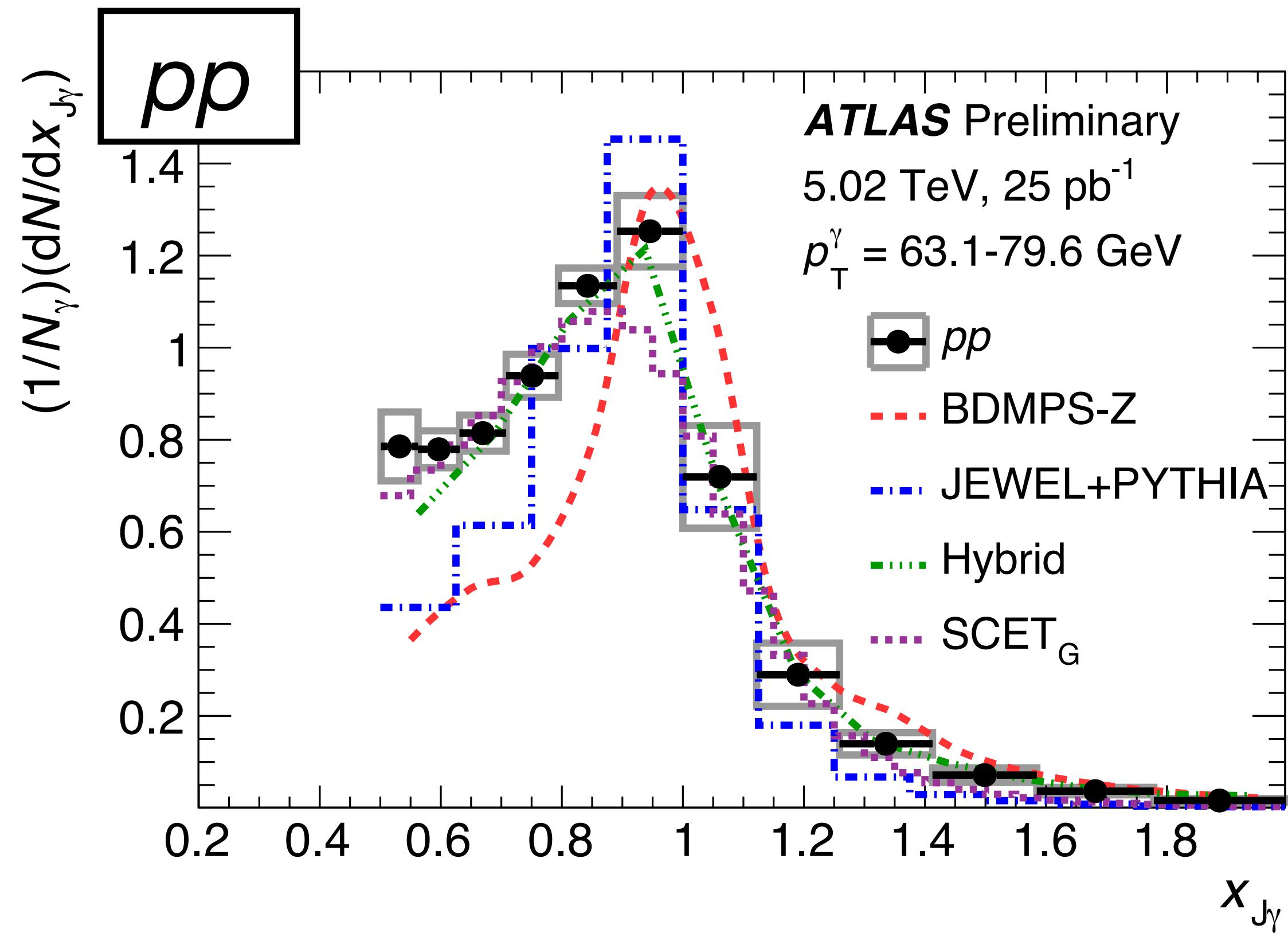


QM '18

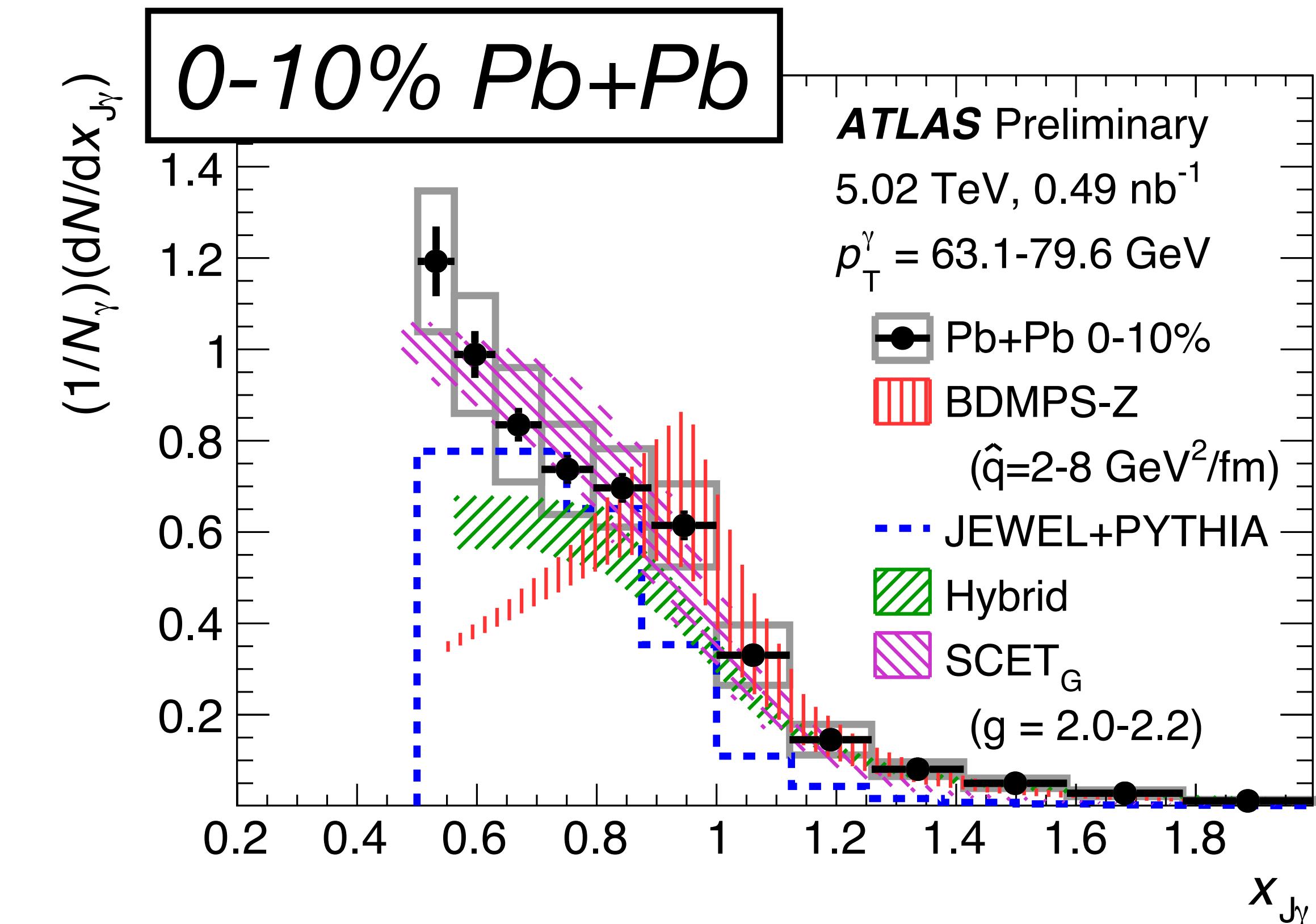


unfolded **Pb+Pb-pp**
comparison: jets lose small/large amounts of energy!

Direct comparisons to theory (no smearing)

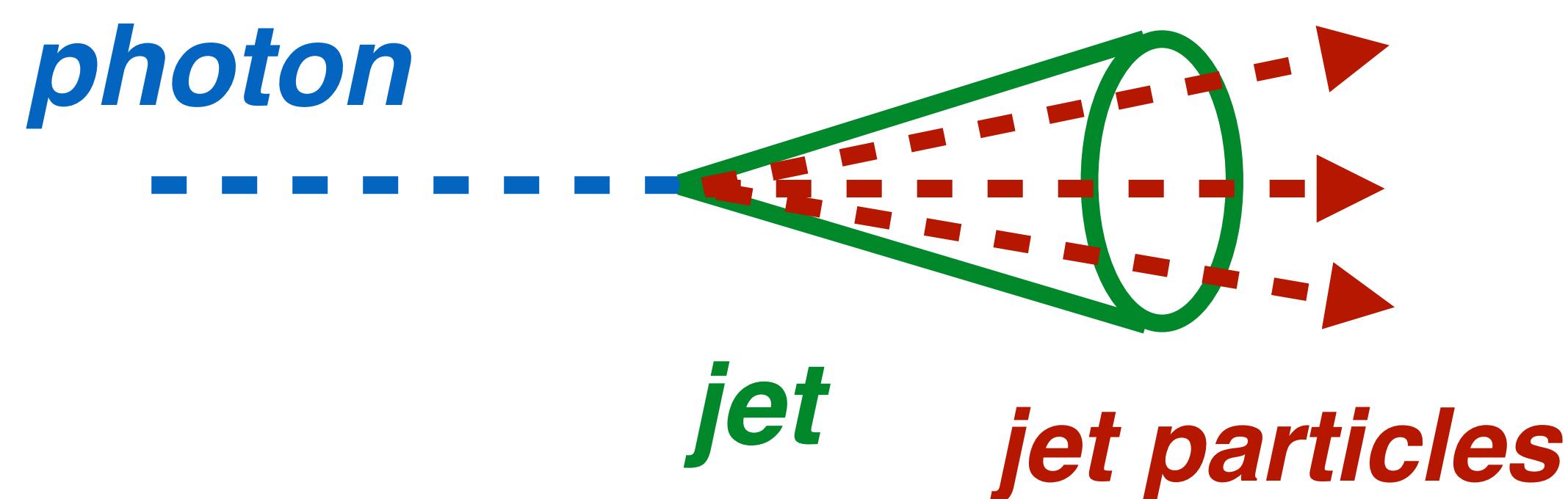


Test description of
vacuum (pp) baseline



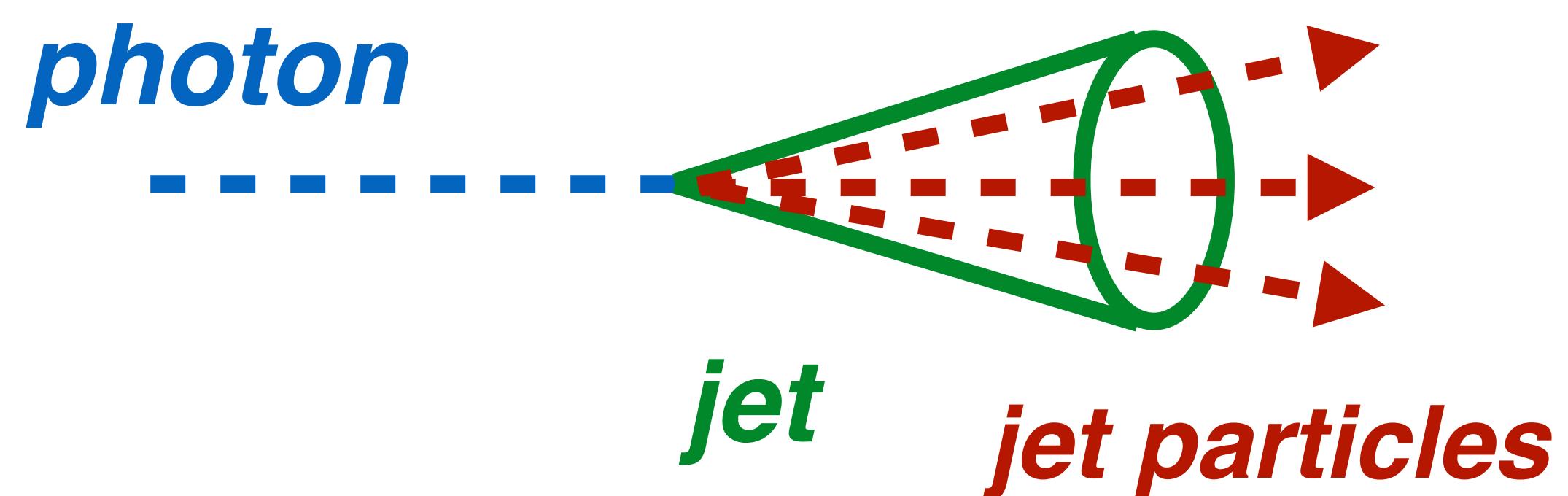
Can models describe
centrality / p_T^γ evolution?

How is the parton shower in cone modified by medium?



Photon-tagged **frag. function**
(with respect to the **jet**)
→ $D(\mathbf{p}_T^h)$ or $D(z = \mathbf{p}_T^h / \mathbf{p}_T^{jet})$

How is the parton shower in cone modified by medium?



Photon-tagged **frag. function**
(with respect to the **jet**)
→ $D(p_T^h)$ or $D(z = p_T^h / p_T^{jet})$

Kinematic selection intended to
pick out only the leading
(dominantly quark) jet :

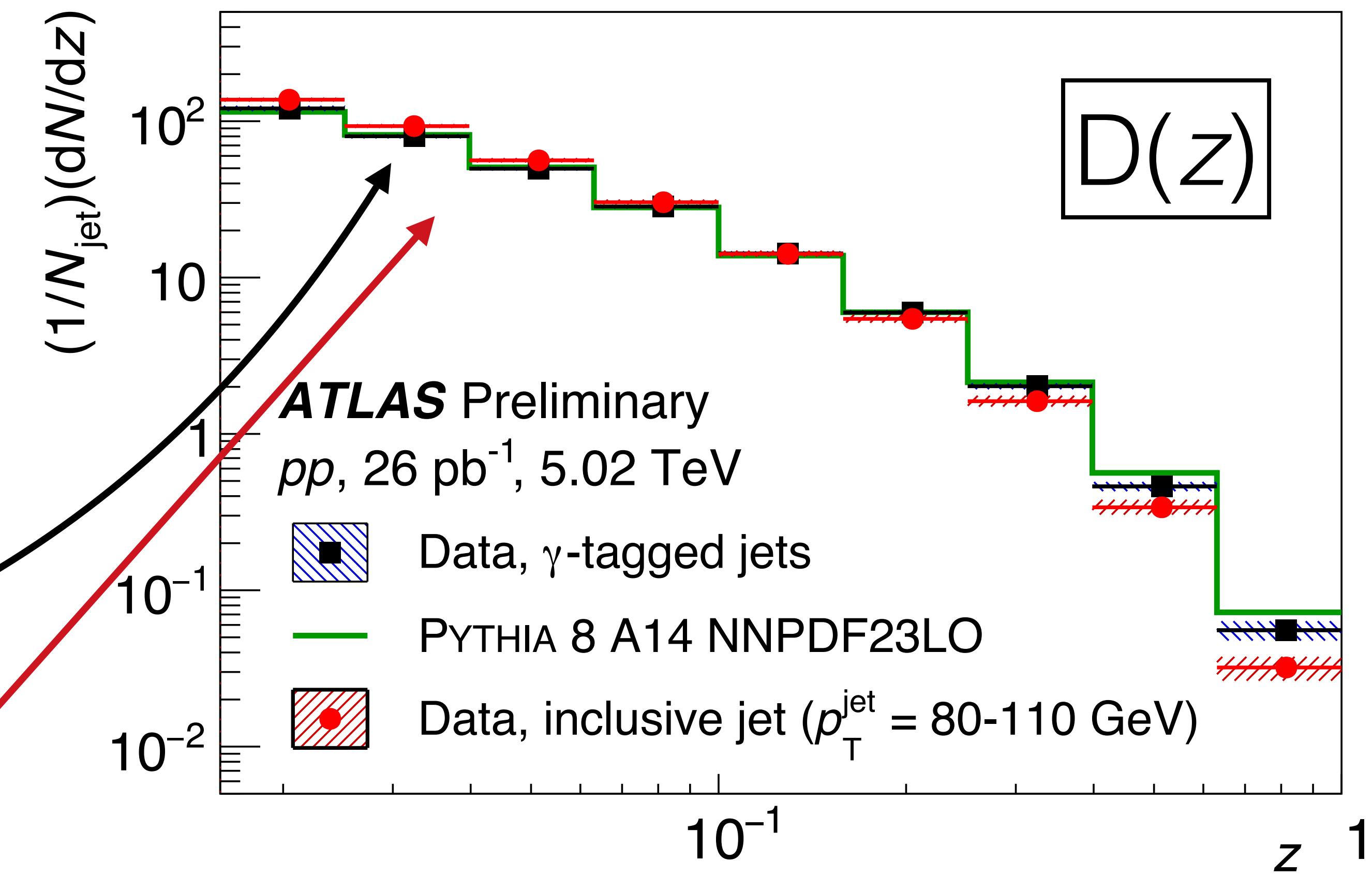
$p_T^g = 79.6\text{-}125 \text{ GeV}$

$p_T^{jet} = 63.1\text{-}144 \text{ GeV}$

γ -tagged jet FF in pp

γ -tagged jet
(quark jet-dominant)

Inclusive jet
(gluon jet-dominant)

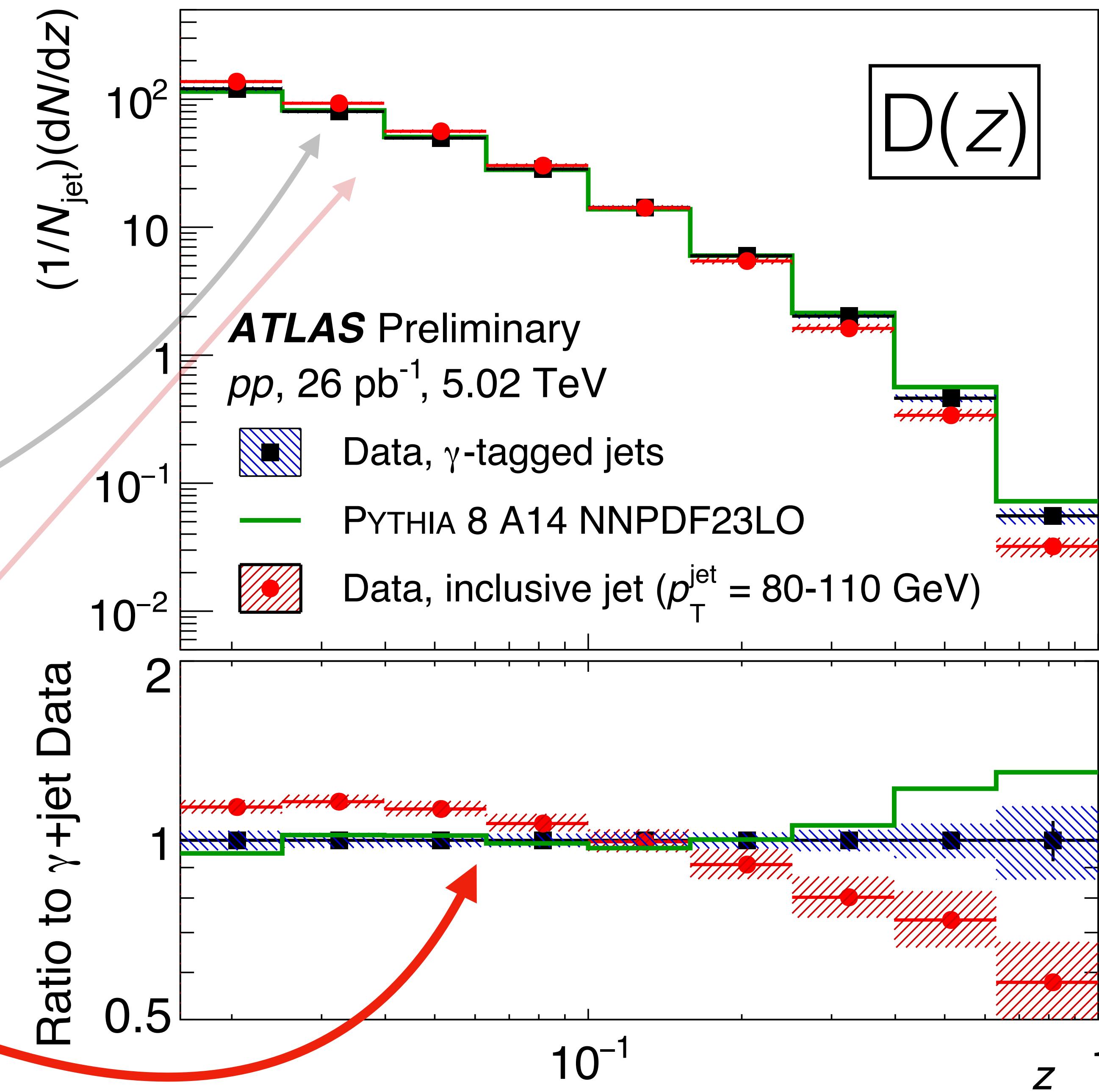


γ -tagged jet FF in pp

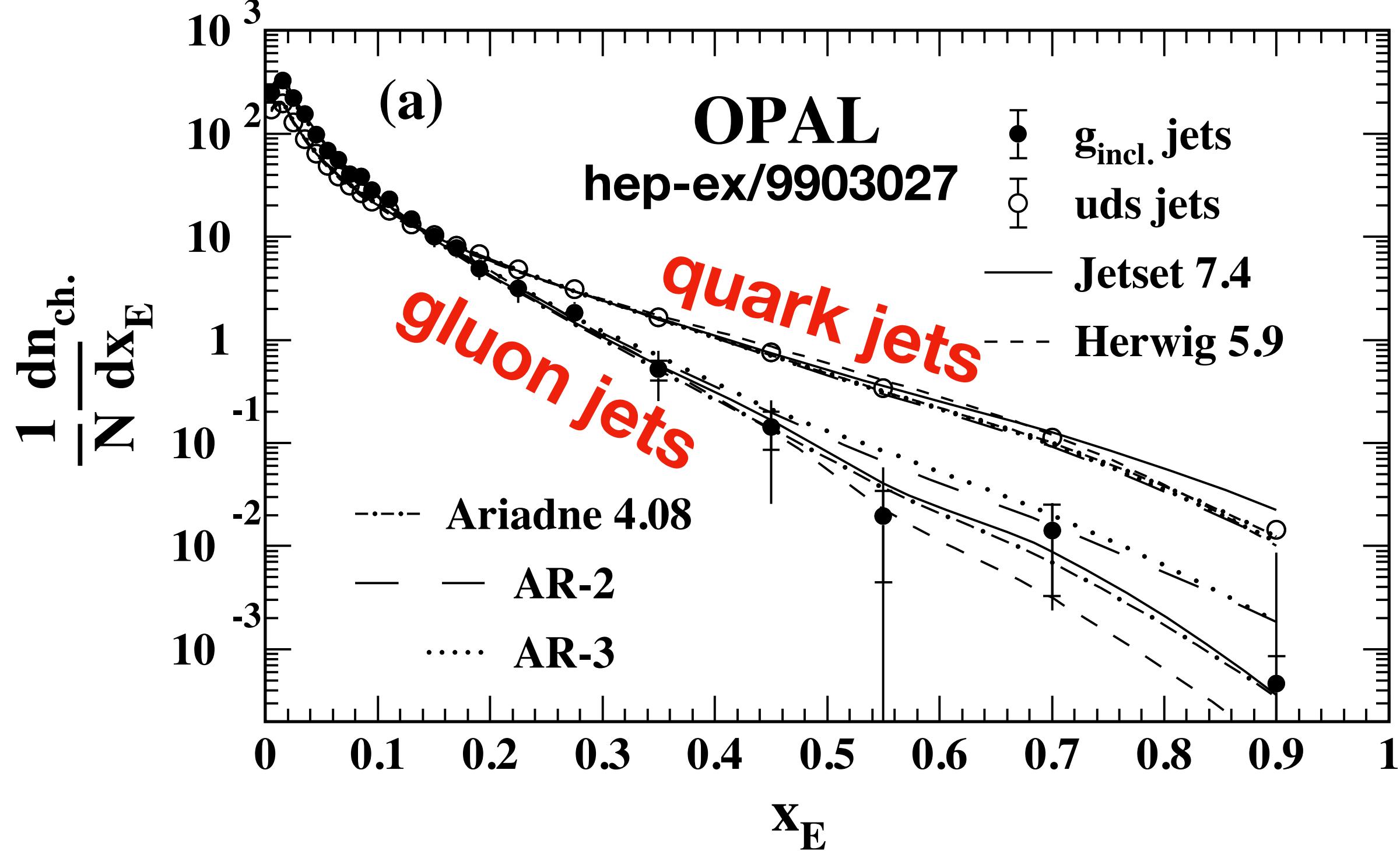
γ -tagged jet
(quark jet-dominant)

Inclusive jet
(gluon jet-dominant)

Inclusive / γ -tagged ratio



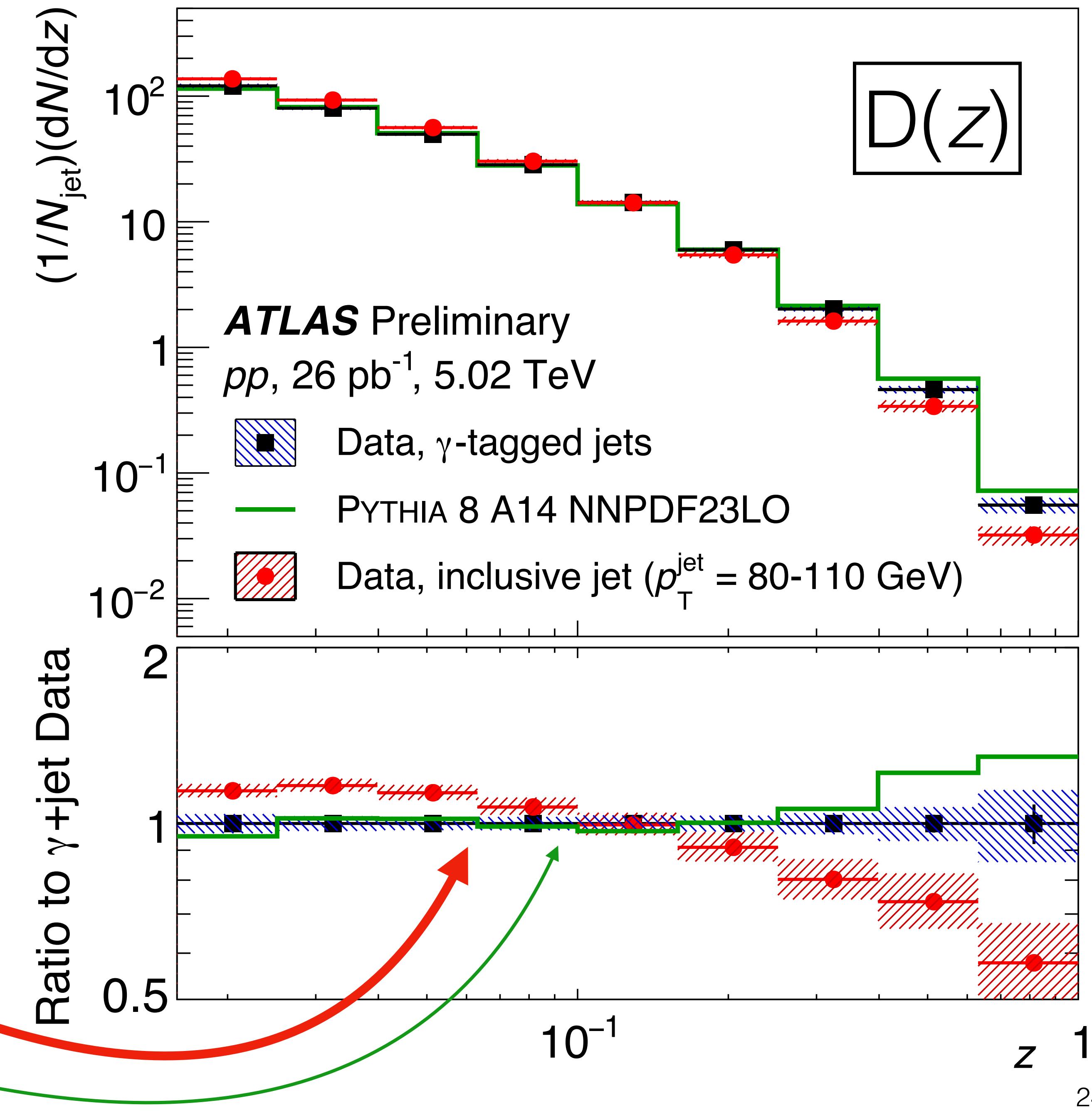
γ -tagged jet FF in pp



Fragmentation difference as expected from, e.g. LEP

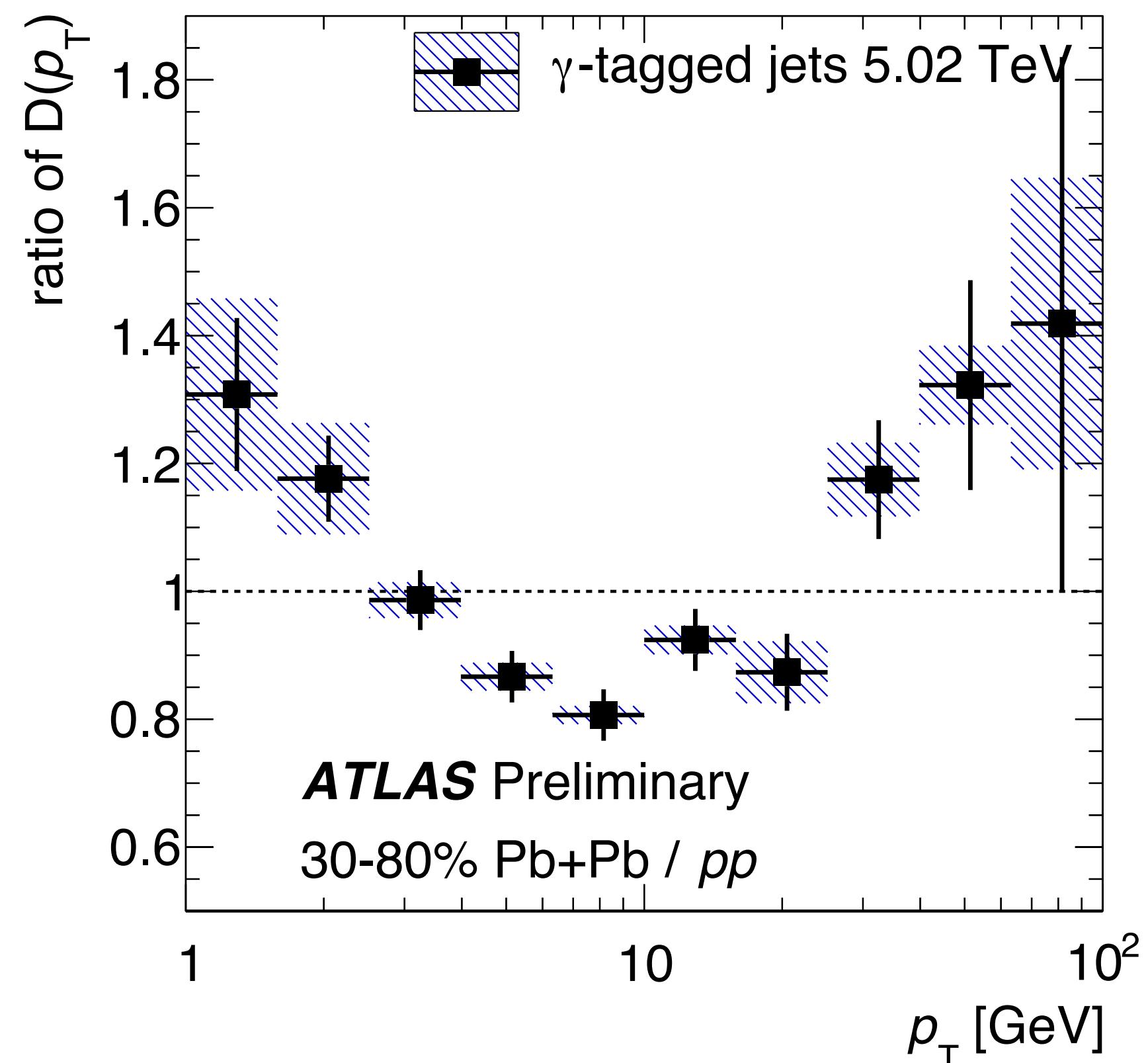
Inclusive / γ -tagged ratio

(also γ -tagged Pythia/data ratio)



γ -tagged jet FF ratios in Pb+Pb

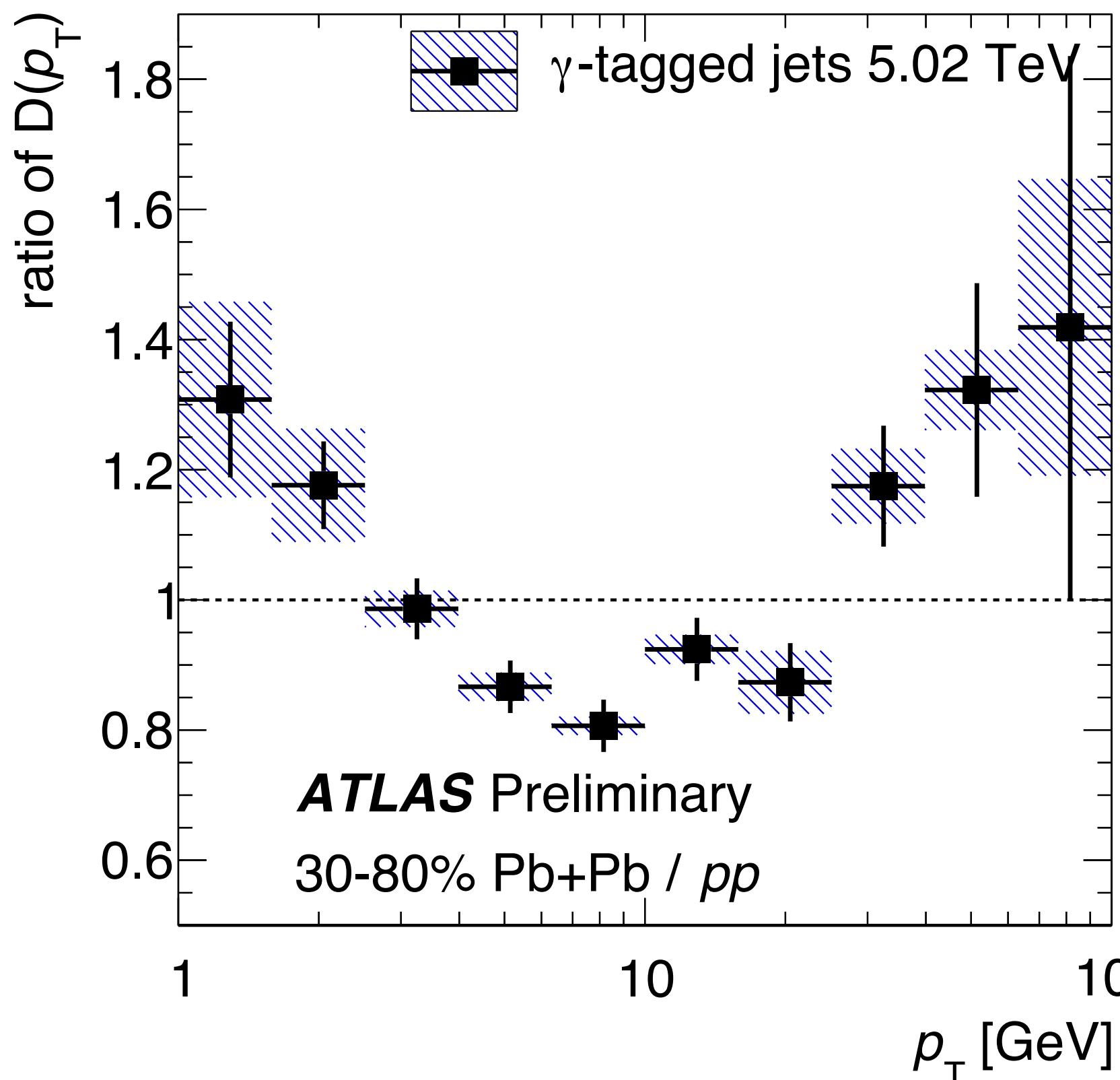
30-80% Pb+Pb / pp



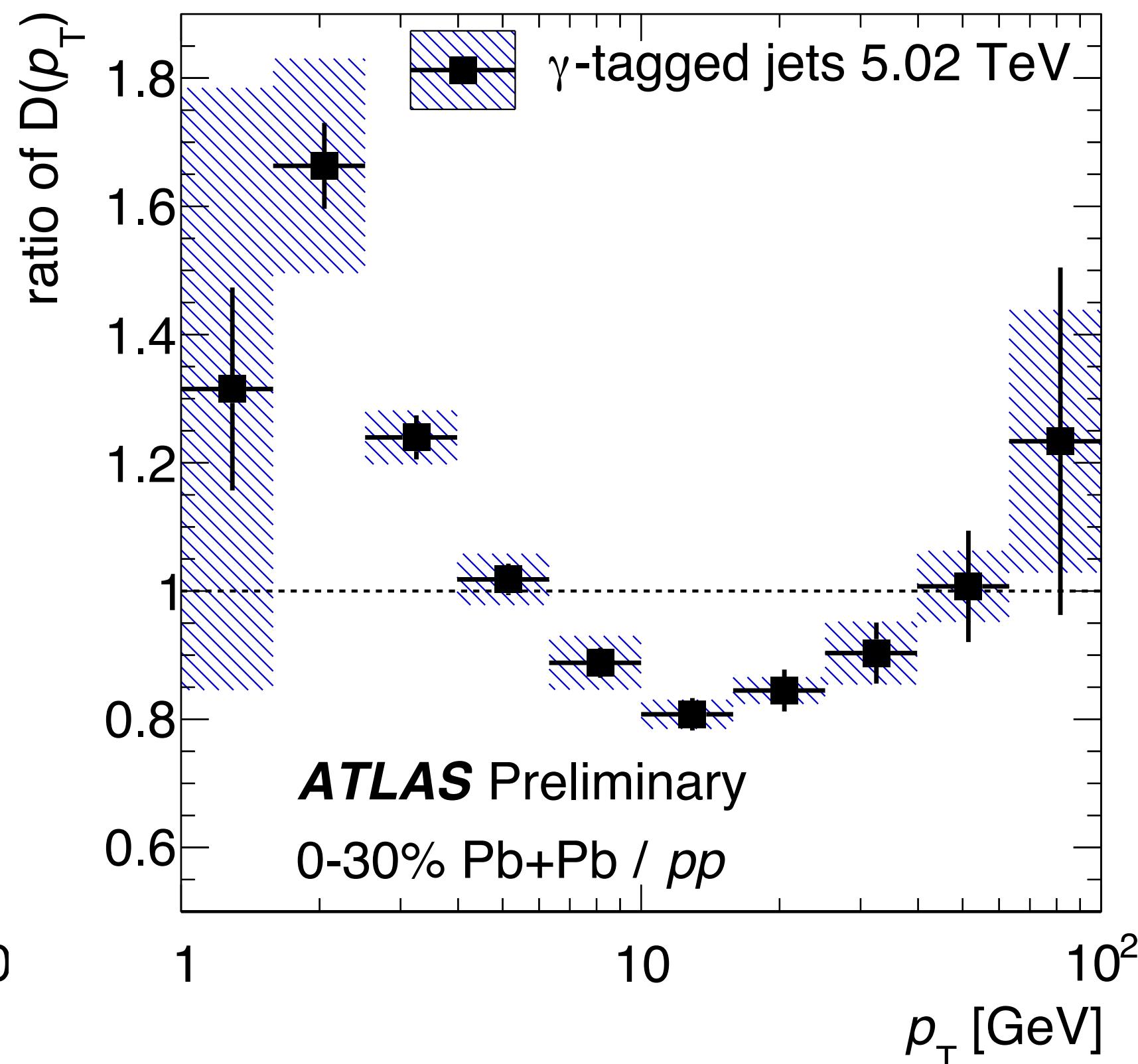
*familiar pattern of
modification here...*

γ -tagged jet FF ratios in Pb+Pb

30-80% Pb+Pb / pp



0-30% Pb+Pb / pp



familiar pattern of modification here...

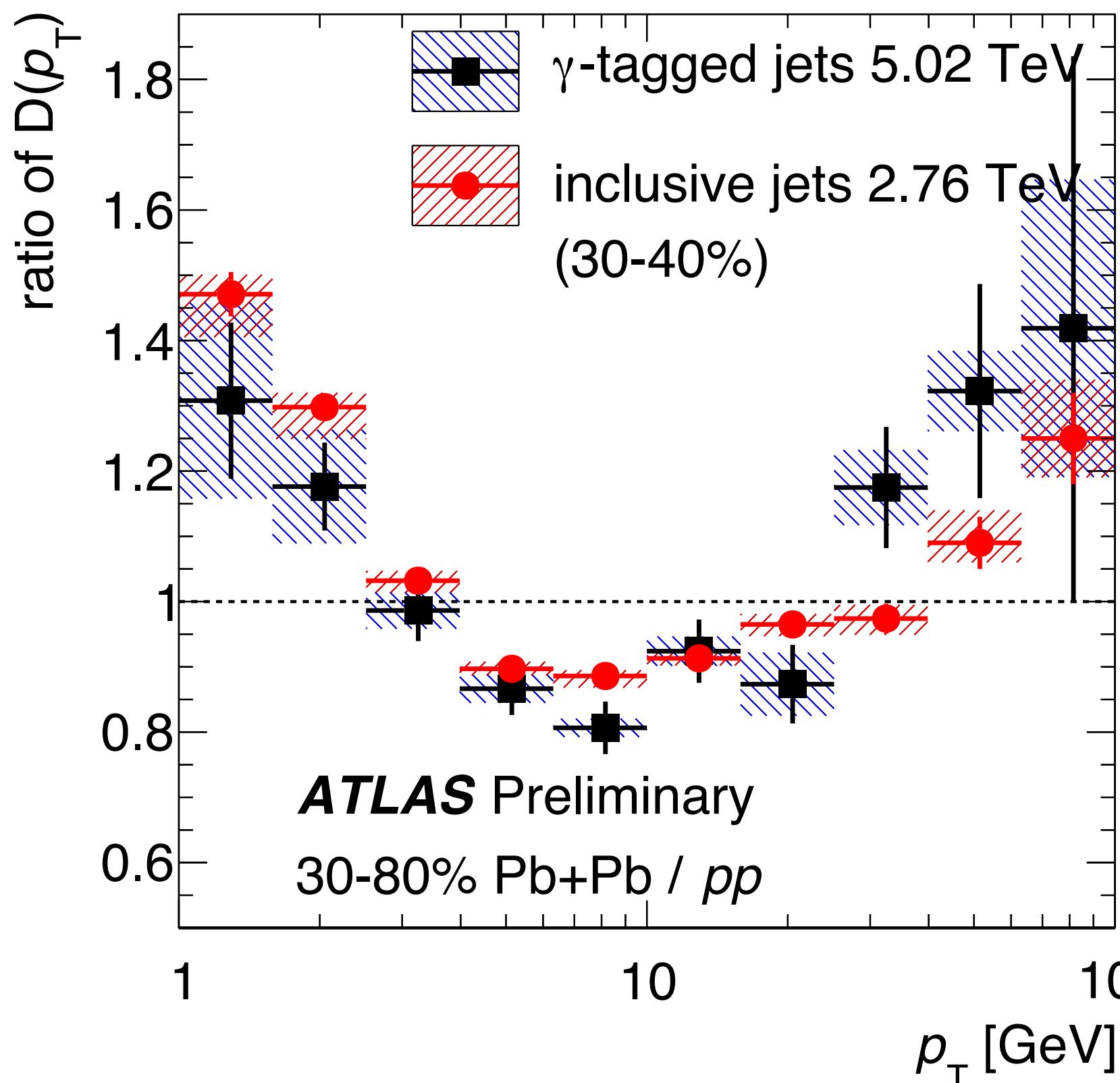
... different pattern here!

Compare to unfolded inclusive jet FF measurement @ 2.76 TeV...

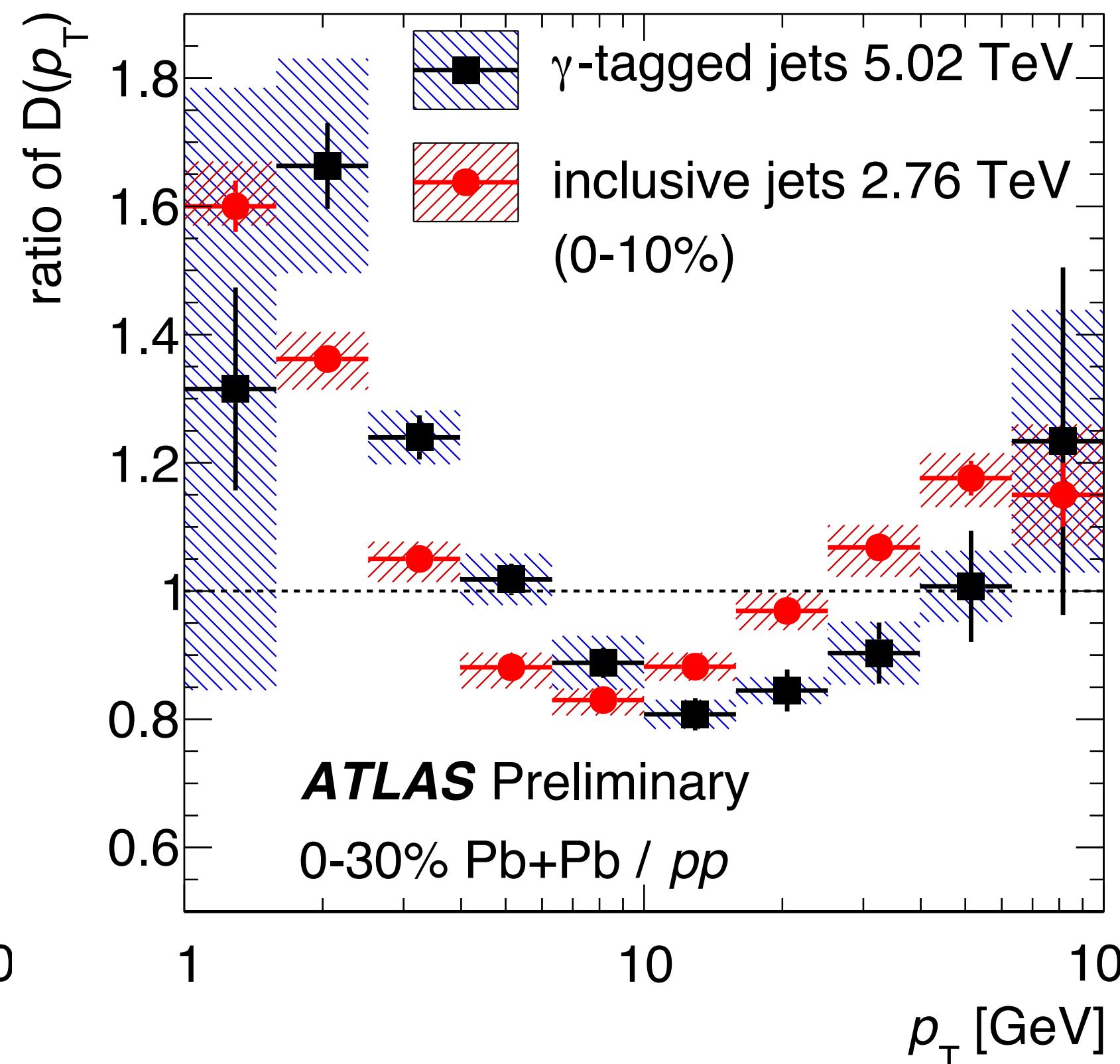
(new 5.02 TeV results: M. Rybář, this room, 12:30pm)

γ -tagged jet FF ratios in Pb+Pb

30-80% Pb+Pb / pp



0-30% Pb+Pb / pp



familiar pattern of
modification here...

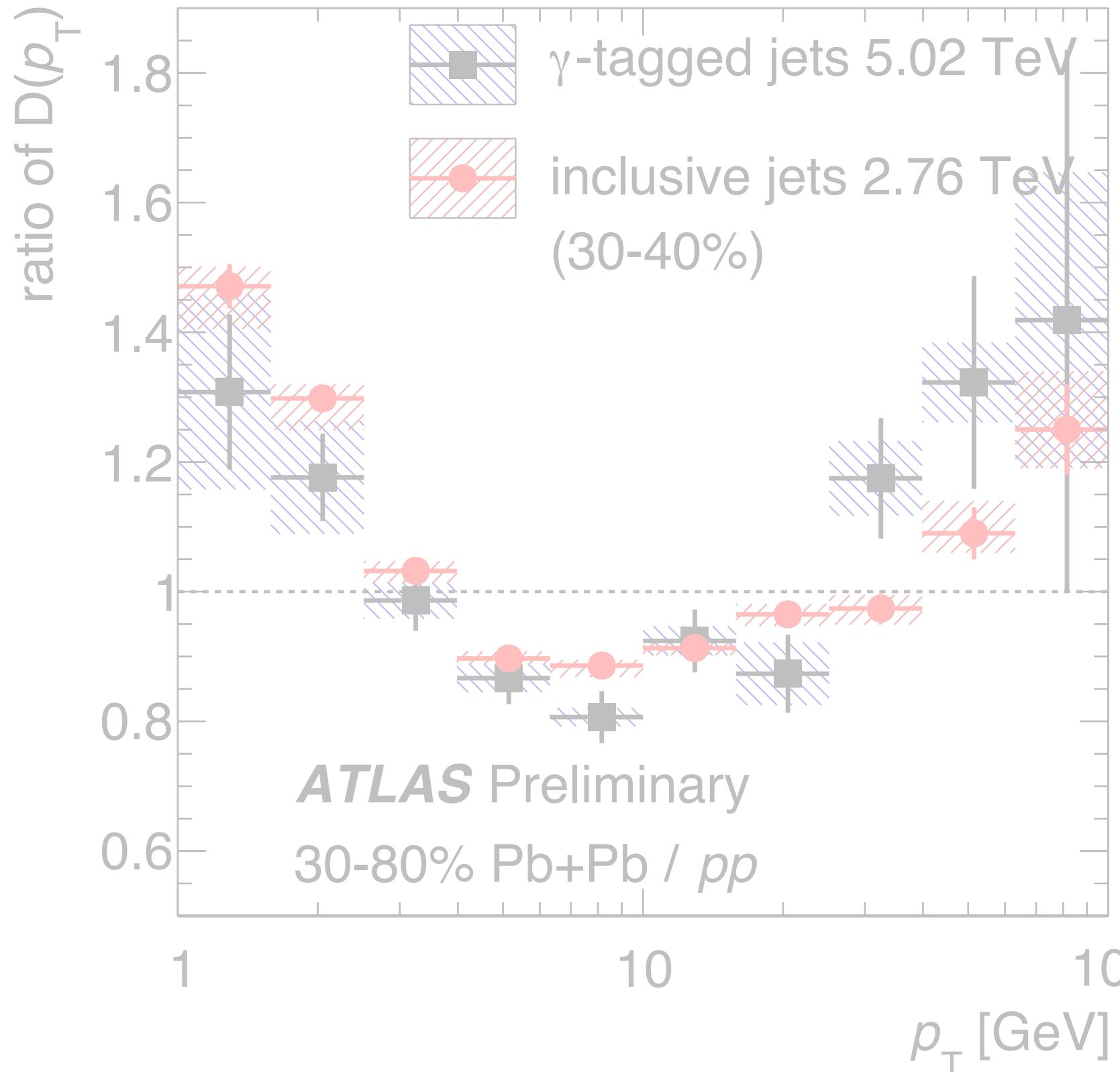
... different pattern
here!

Compare to unfolded
inclusive jet FF
measurement
@ 2.76 TeV...

Inclusive vs.
 γ -tagged FF's
modified differently!

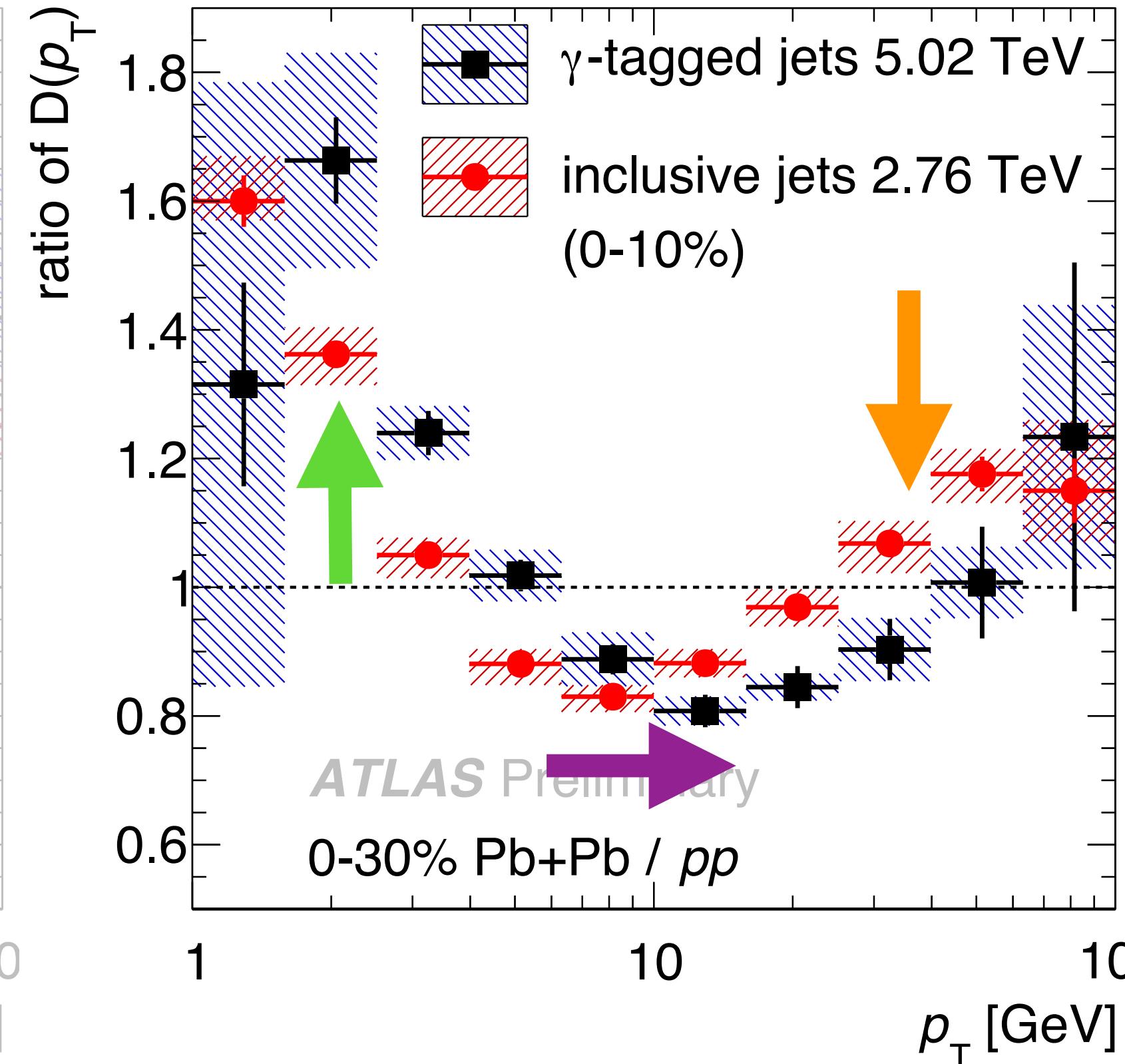
γ -tagged jet FF ratios in Pb+Pb

30-80% Pb+Pb / pp



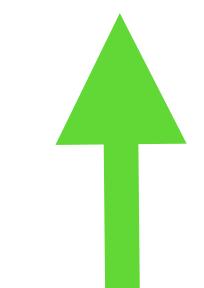
familiar pattern of
modification here...

0-30% Pb+Pb / pp



... different pattern
here!

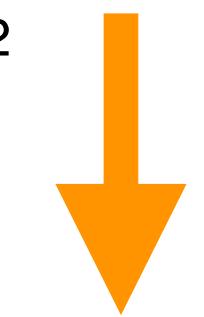
**γ -tagged jet FF vs.
inclusive jet FF:**



more enhancement
at low- p_T^h



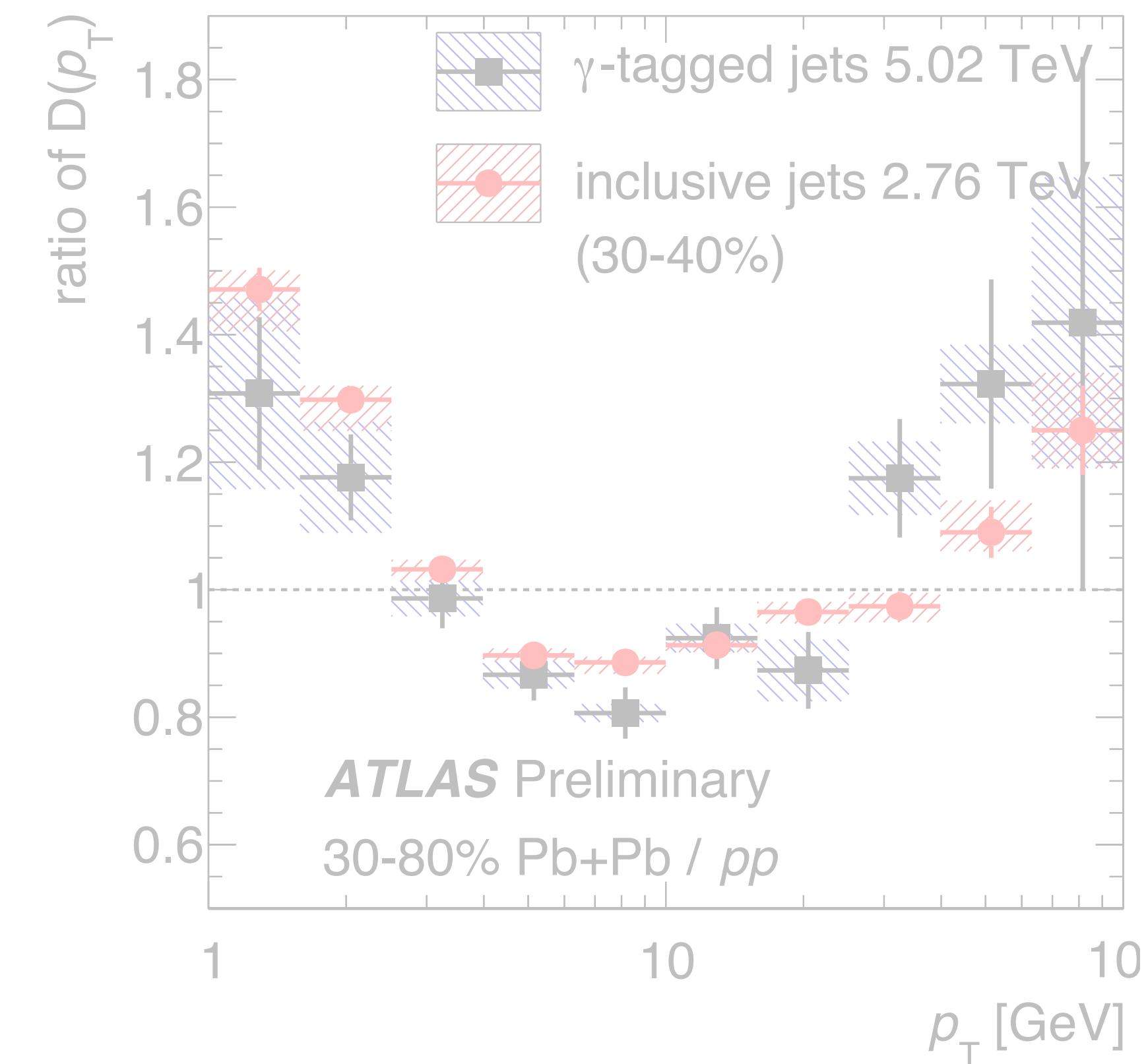
shift of mid- p_T^h
minimum,



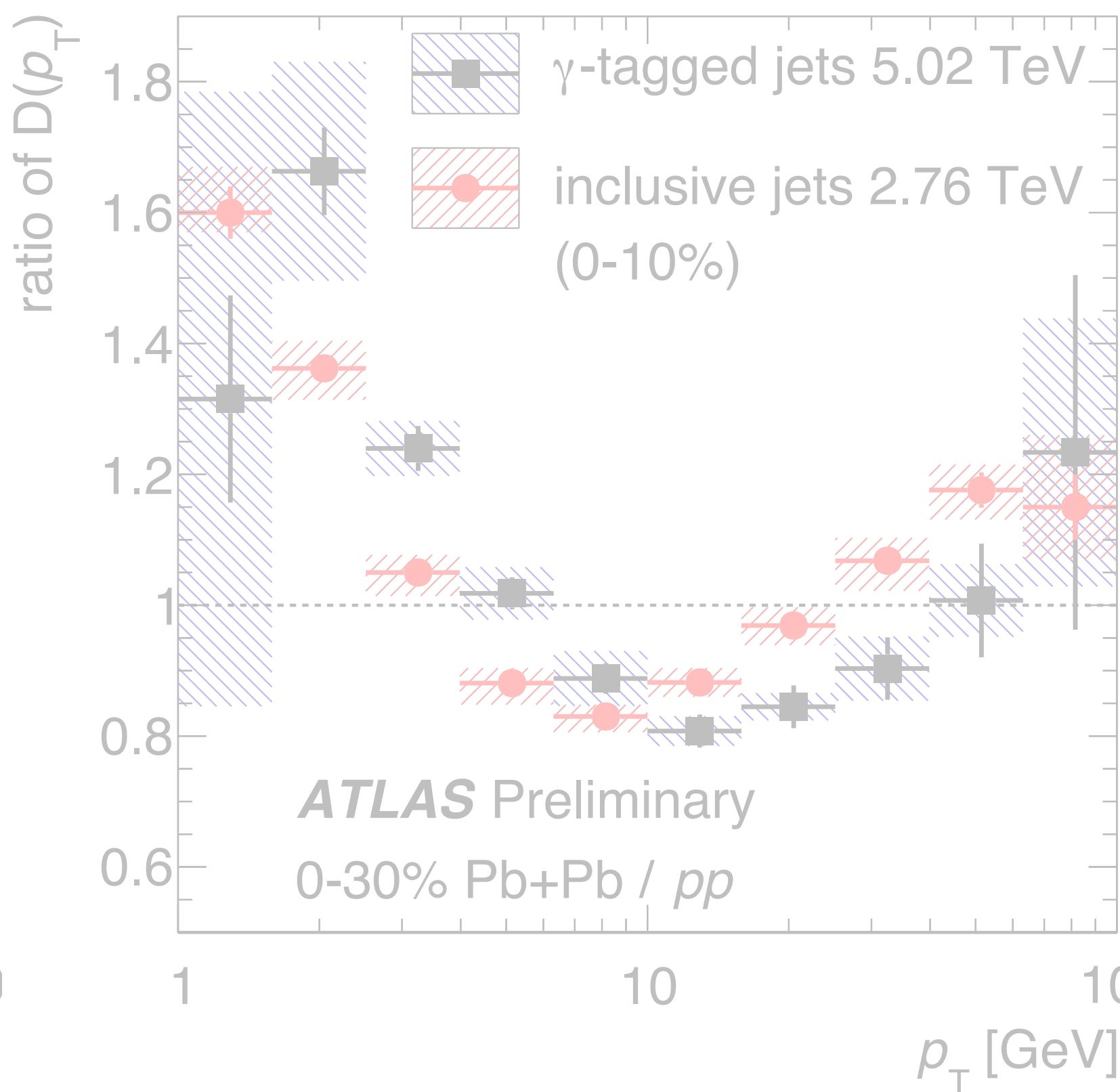
no enhancement at
large- p_T^h !

γ -tagged jet FF vs. inclusive jet FF

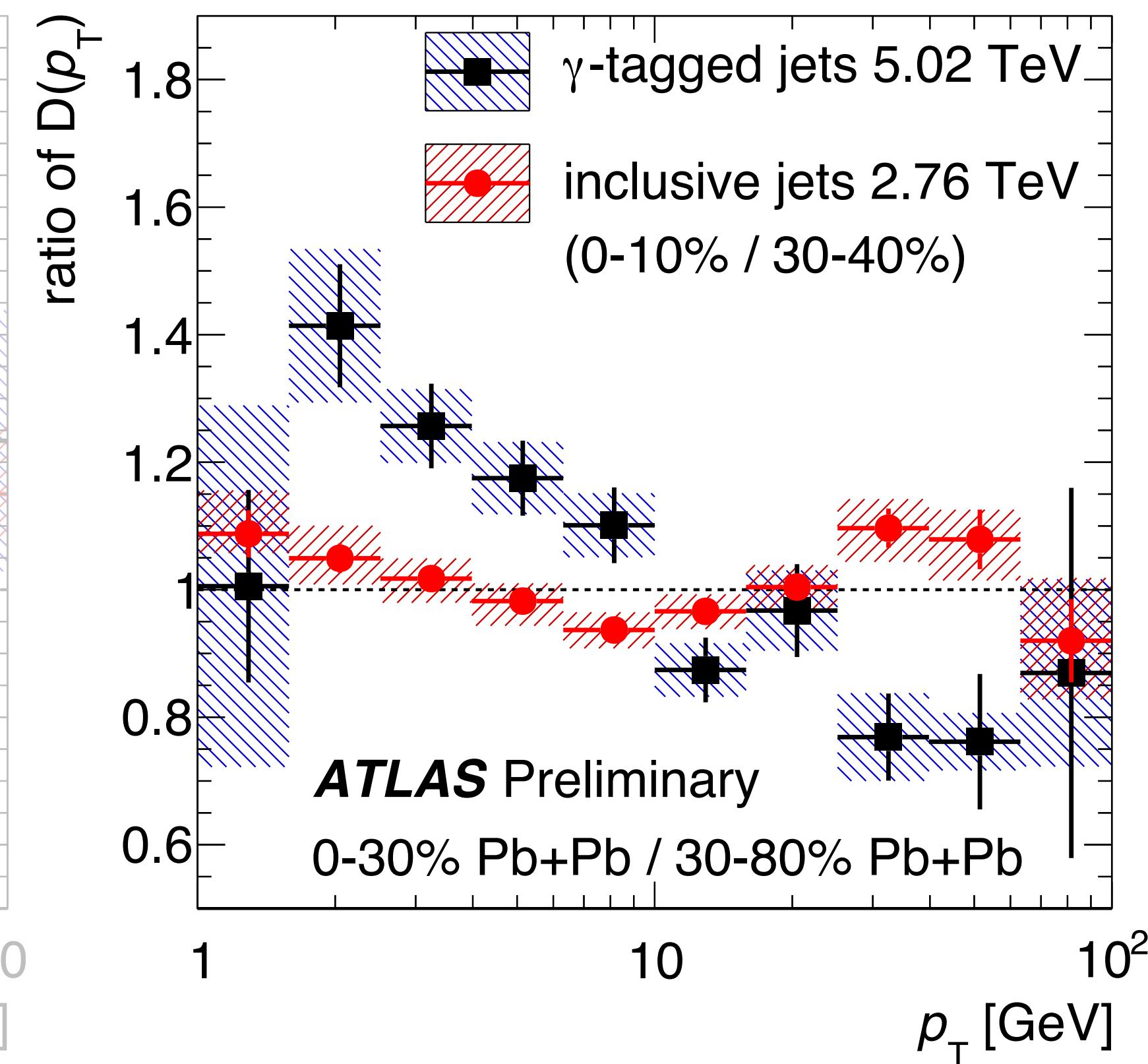
30-80% Pb+Pb / pp



0-30% Pb+Pb / pp

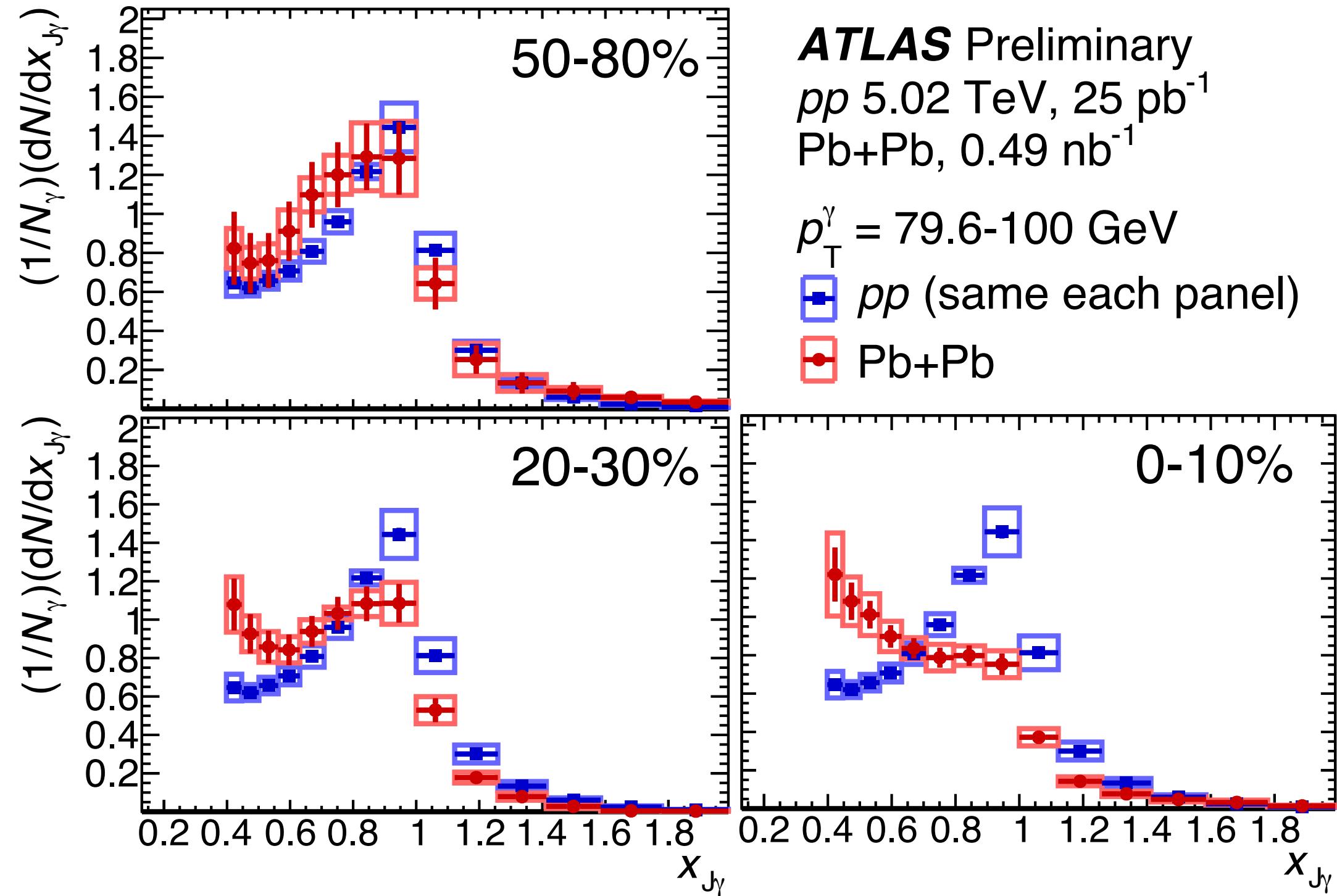


0-30% / 30-80%



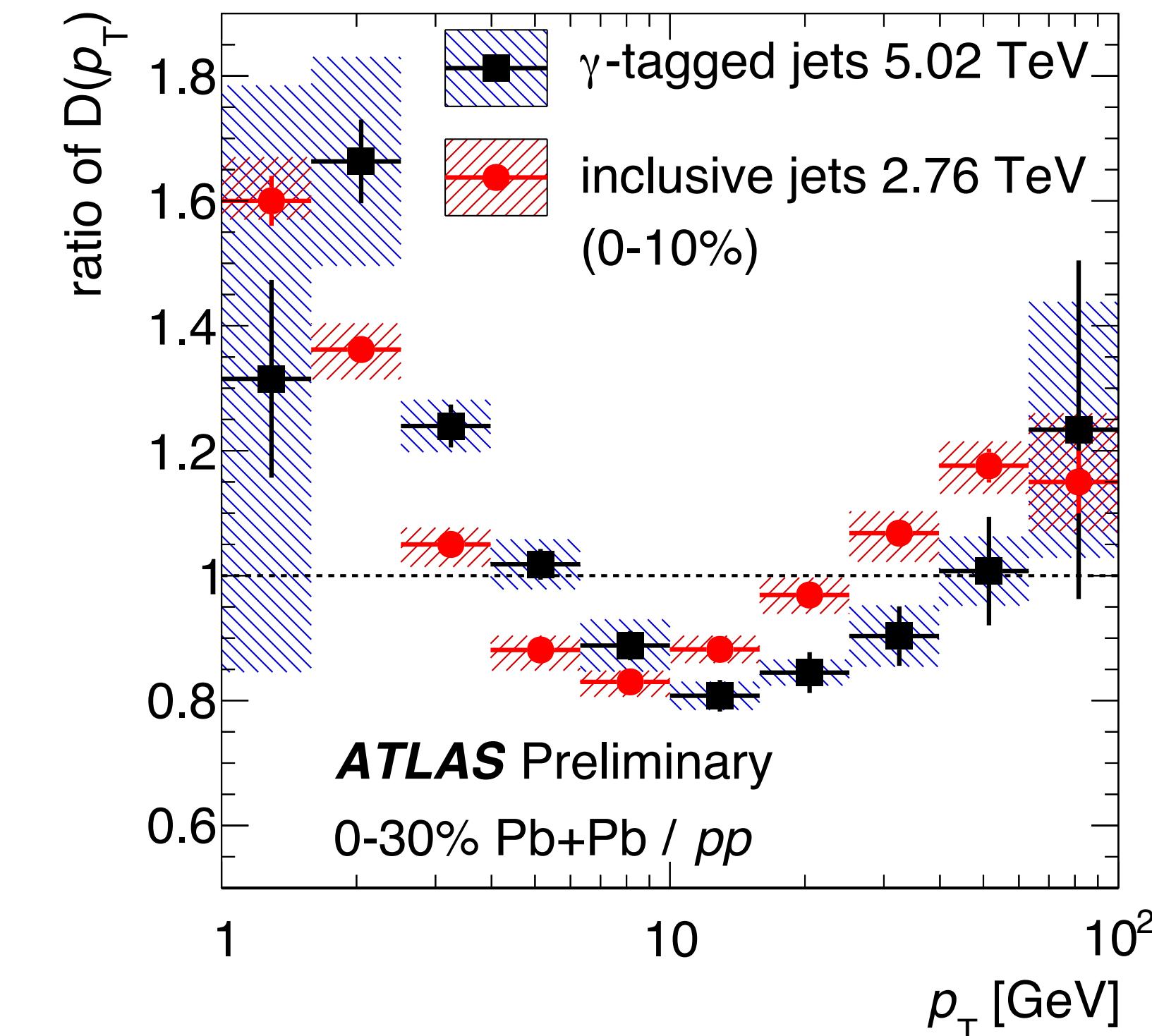
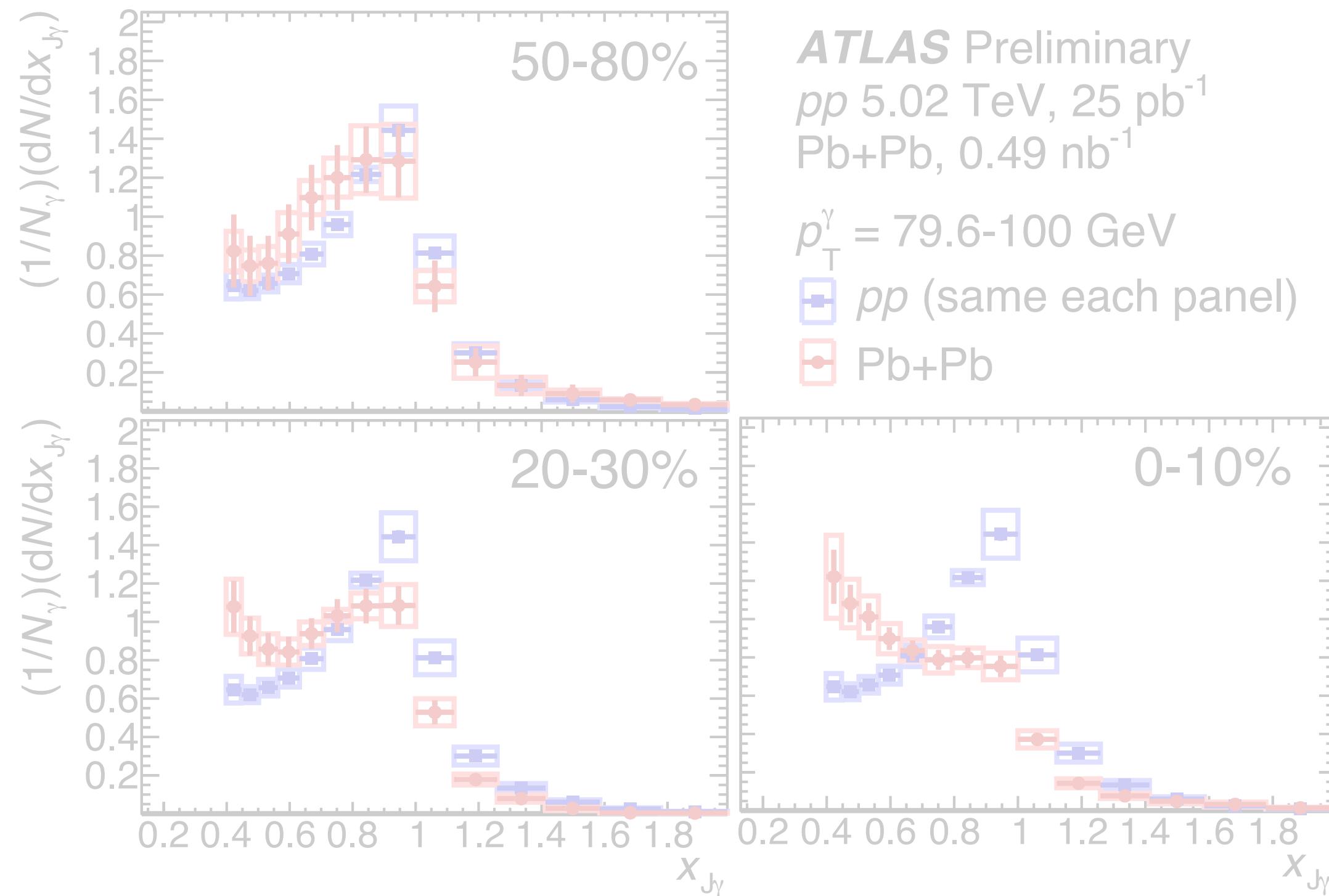
Stronger centrality dependence for
how γ -tagged jets are modified

γ -tagged jet quenching (w/ unfolding for detector effects)



- γ +jet p_T -balance
 - **pp -like peaked $x_{J\gamma}$ in $Pb+Pb$:**
variation in jet-by-jet E -loss

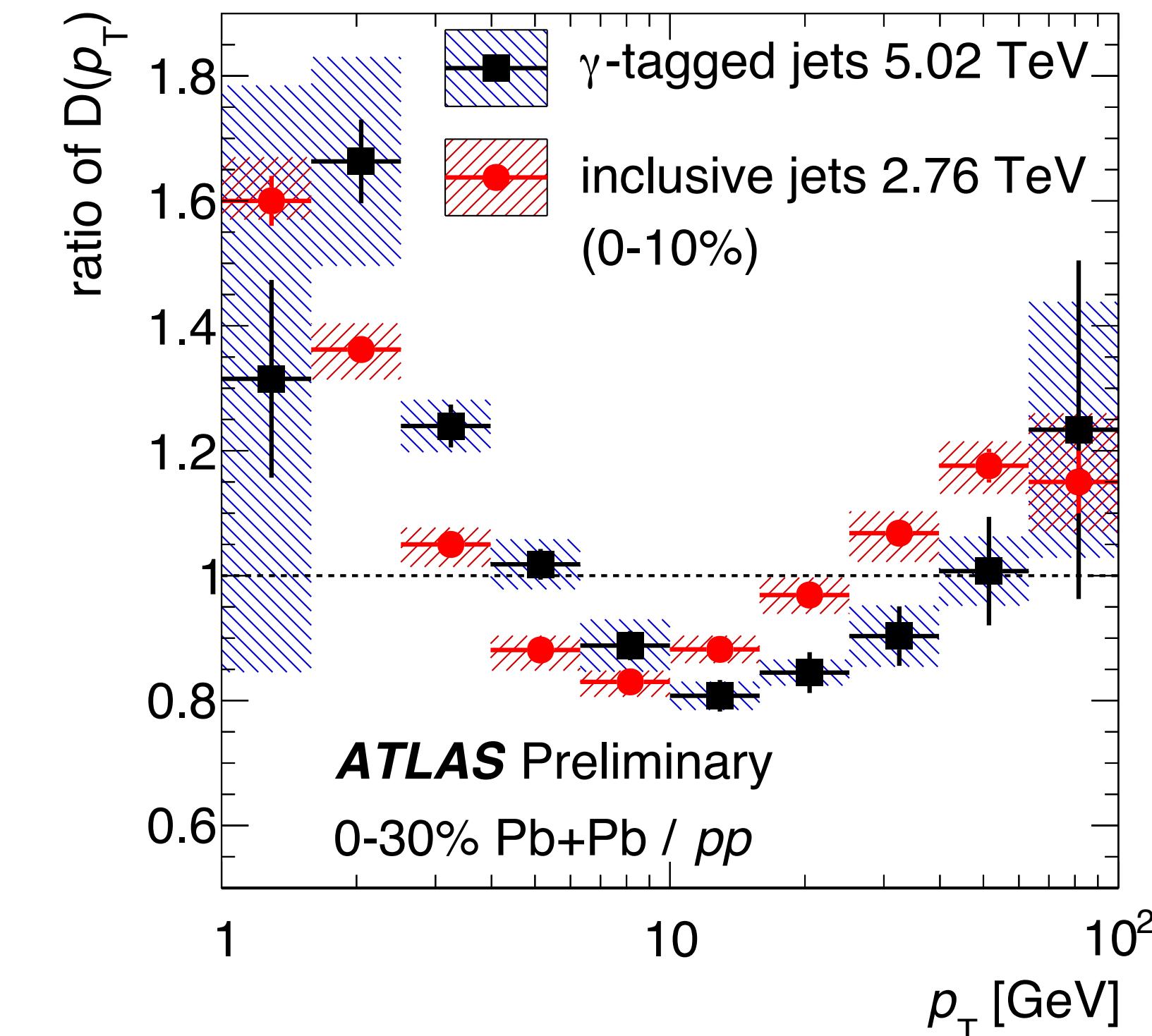
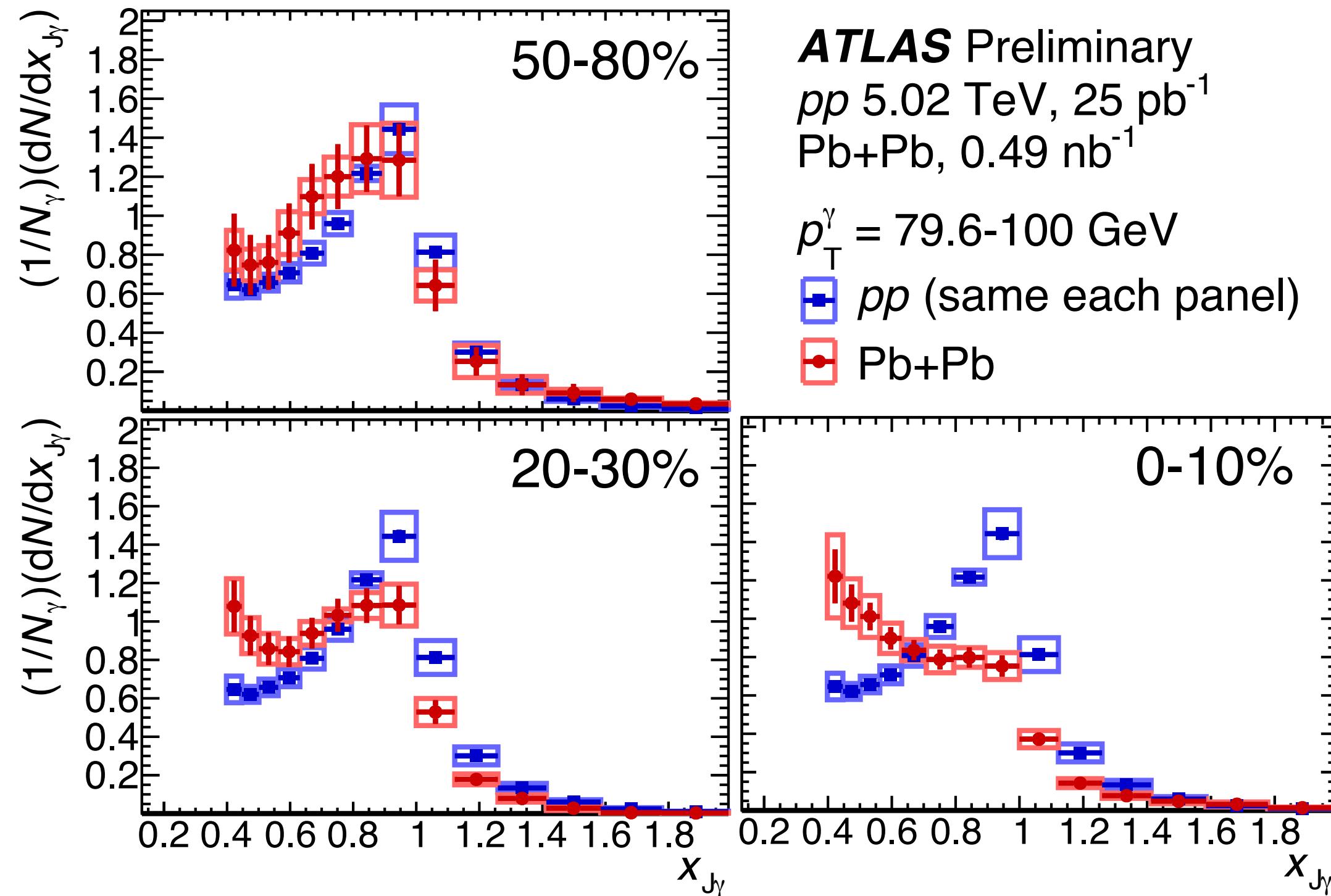
γ -tagged jet quenching (w/ unfolding for detector effects)



- γ +jet p_T -balance
 - **pp-like peaked $x_{J\gamma}$ in $Pb+Pb$:**
variation in jet-by-jet E -loss

- γ -tagged jet frag. functions:
 - **different modification** in central evts. than **inclusive jets**

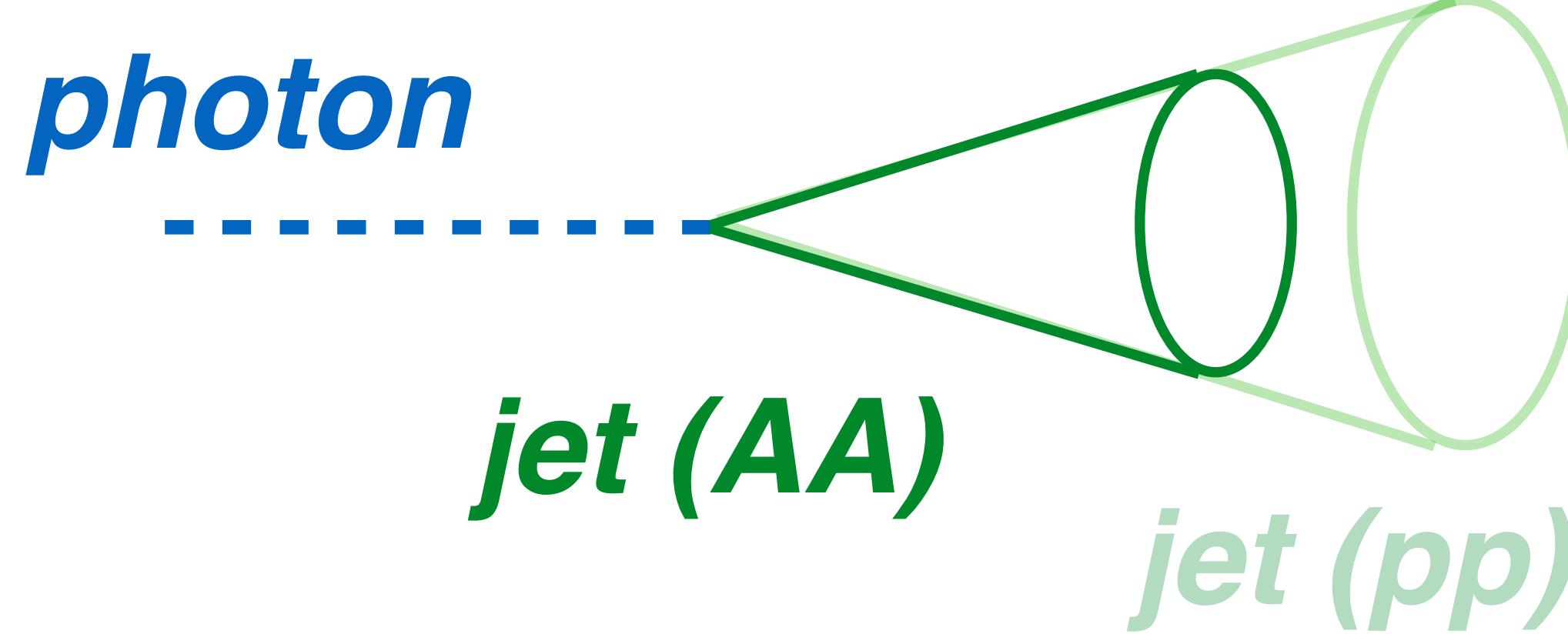
γ -tagged jet quenching (w/ unfolding for detector effects)



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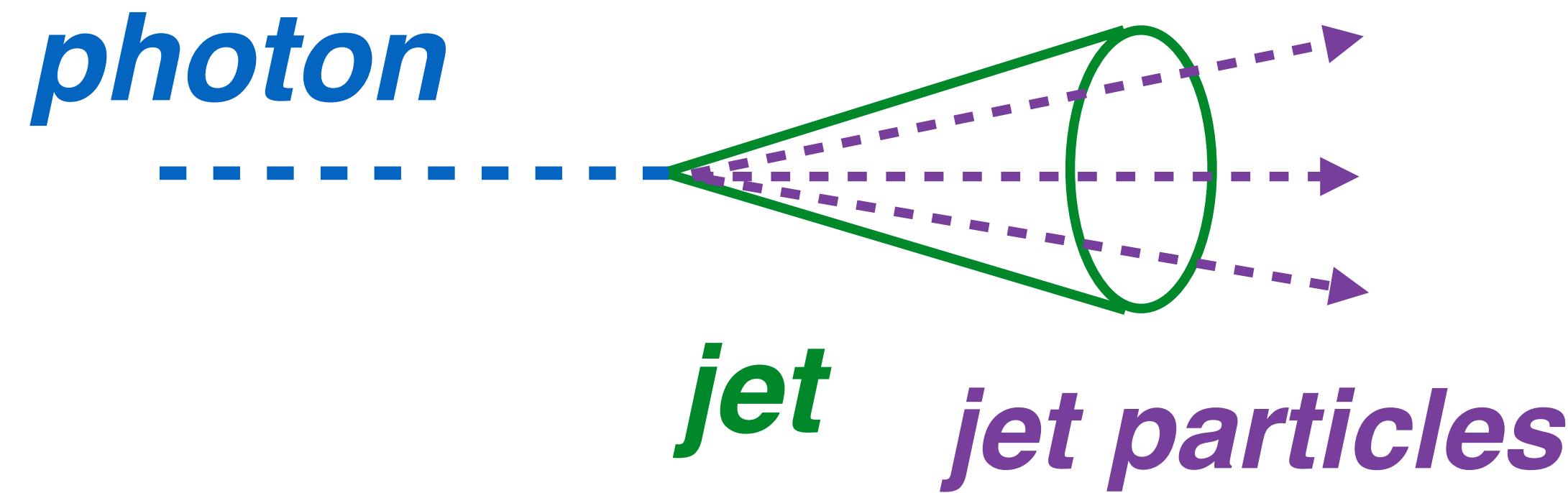
- γ -tagged jet frag. functions:
→ **different modification** in central
evts. than **inclusive jets**

backup



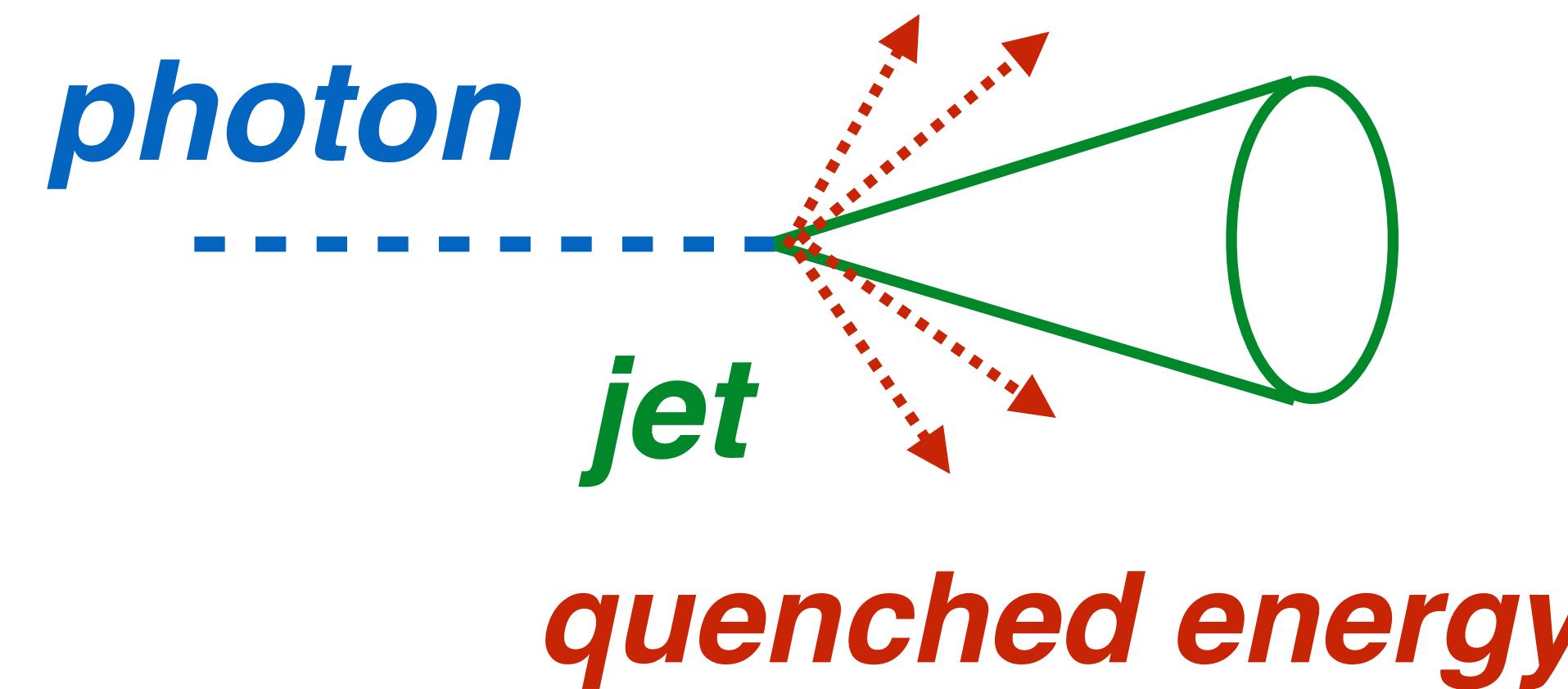
1. What is the (absolute) amount of energy lost in cone?

→ **photon+jet** p_T -balance



2. How is the parton shower in cone modified by medium?

→ **photon**-tagged **frag. function** (with respect to the **jet**)

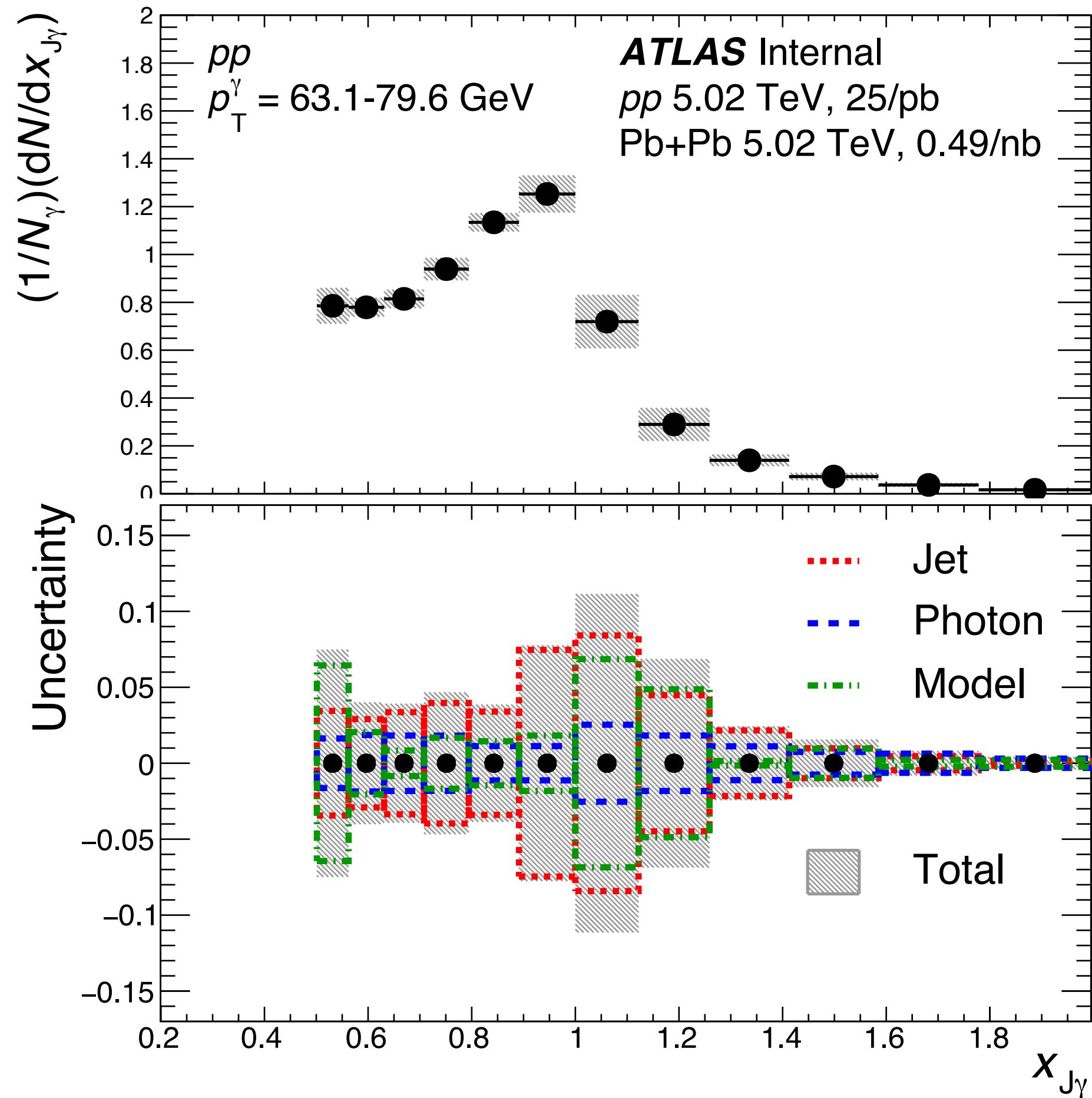


3. Where does the lost energy go?

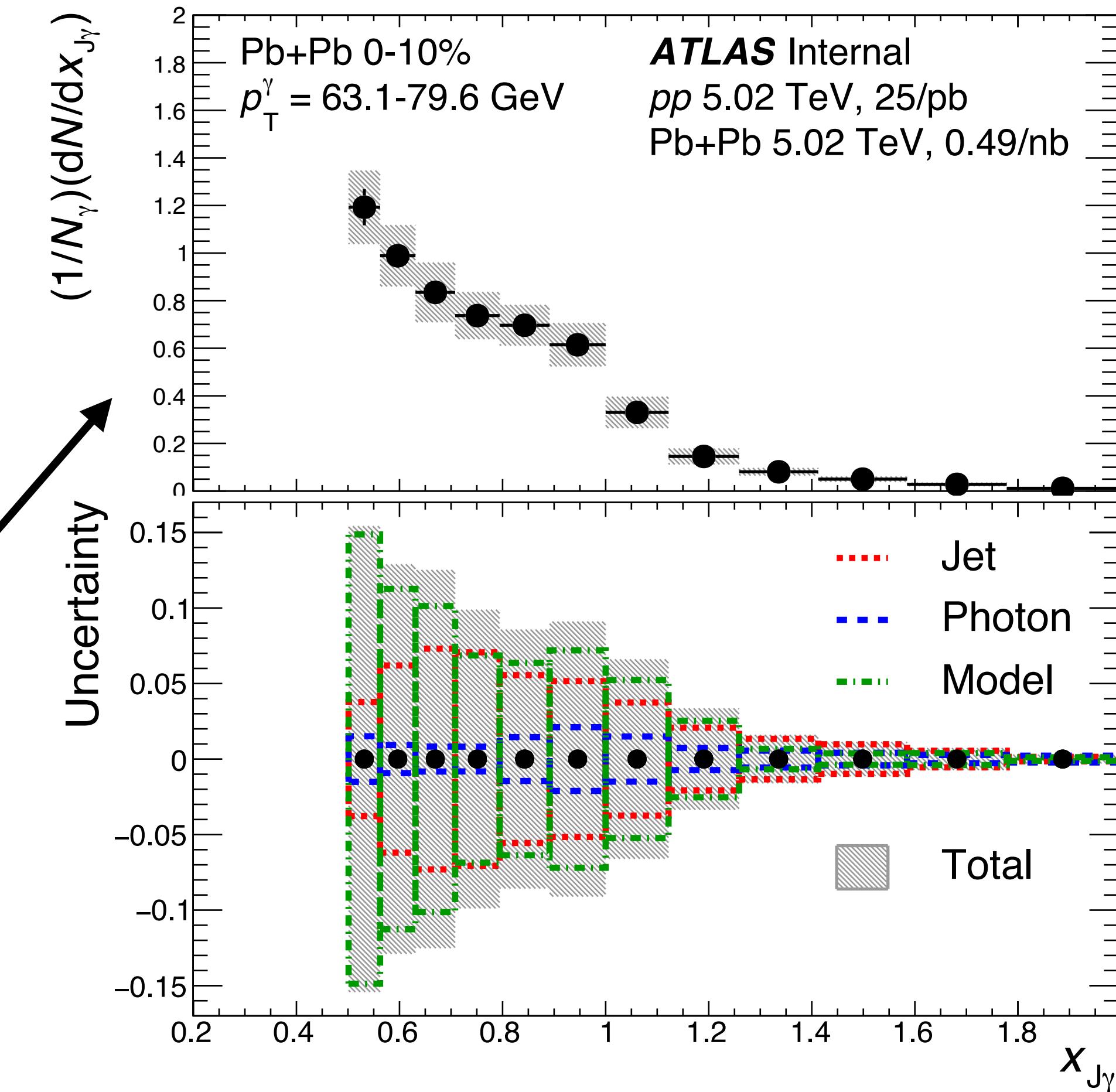
→ **photon-hadron** corr. broadly in angle / momentum

Systematic uncertainties (on $x_{J\gamma}$)

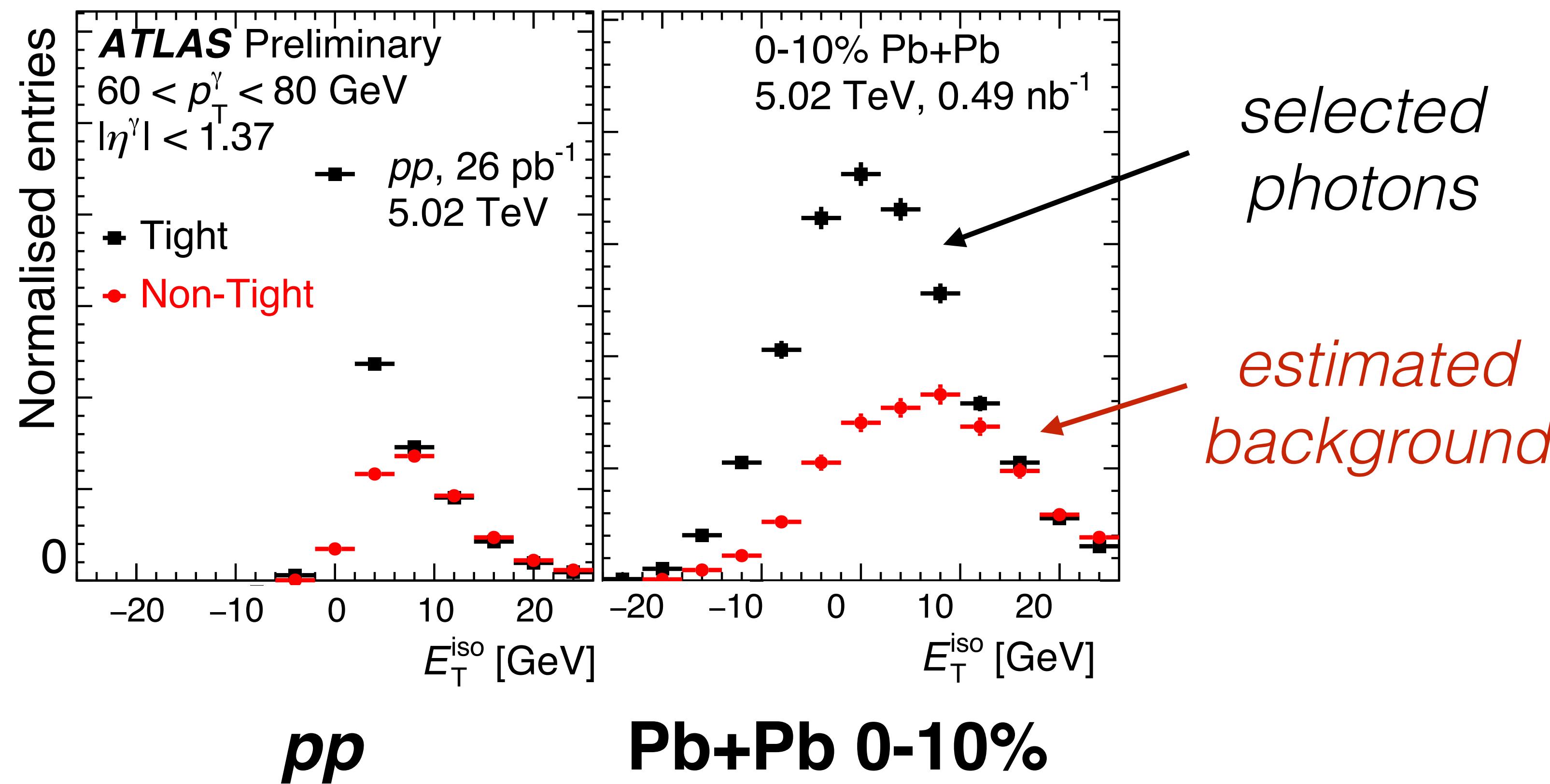
- Dominant: standard HI jet p_T scale, resolution uncertainties
 - *Sub-dominant*: photon ID, isolation, dijet background
 - Co-dominant in central events: prior/MC/combinatorial bkg.
- FF measurement also includes tracking uncertainties



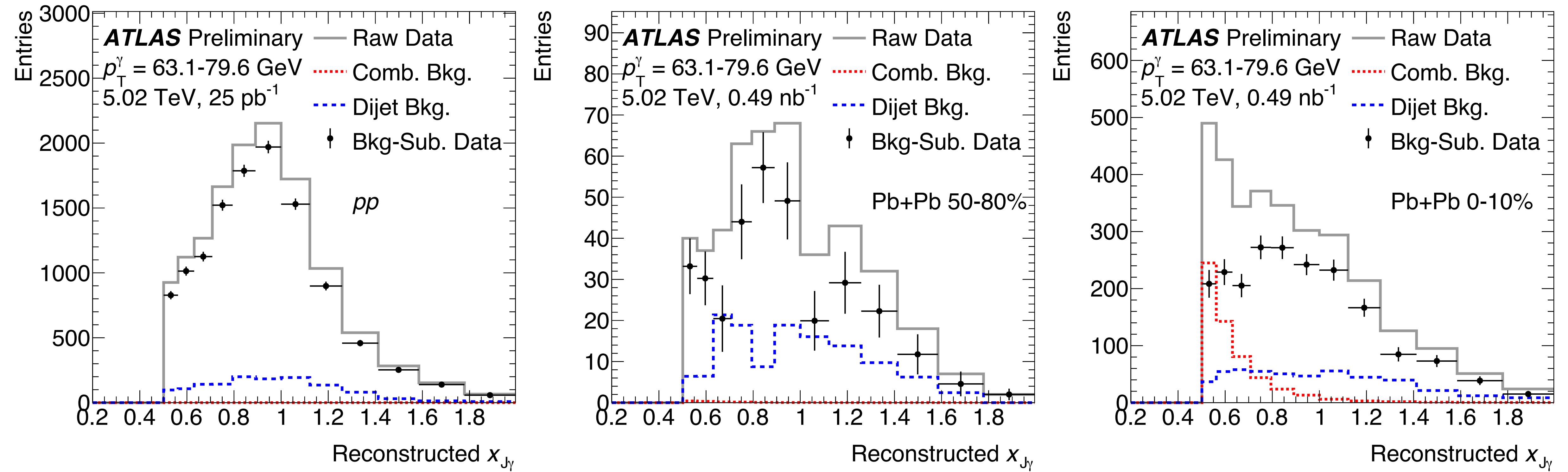
pp
0-10%
Pb+Pb



Photon selection

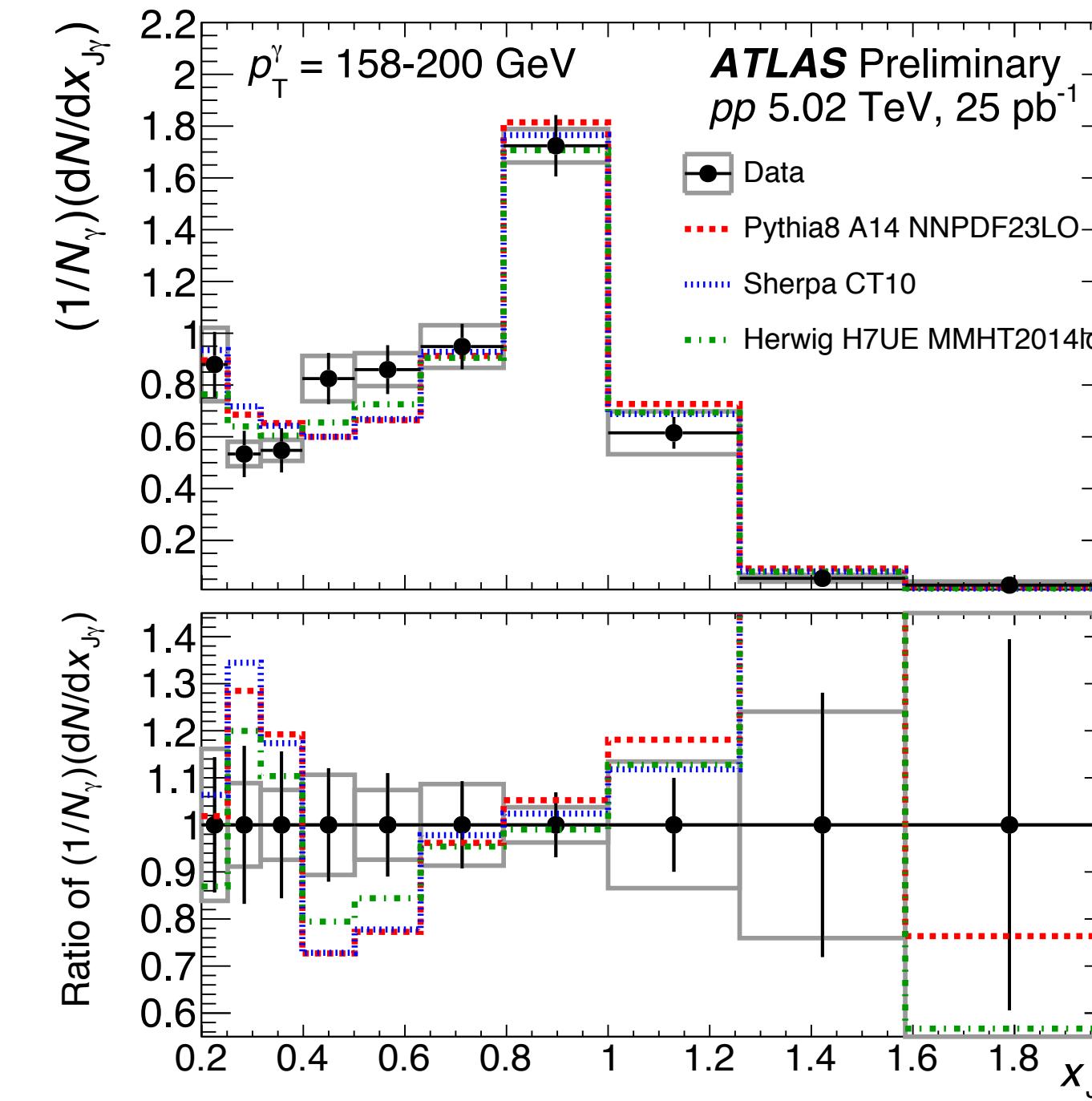
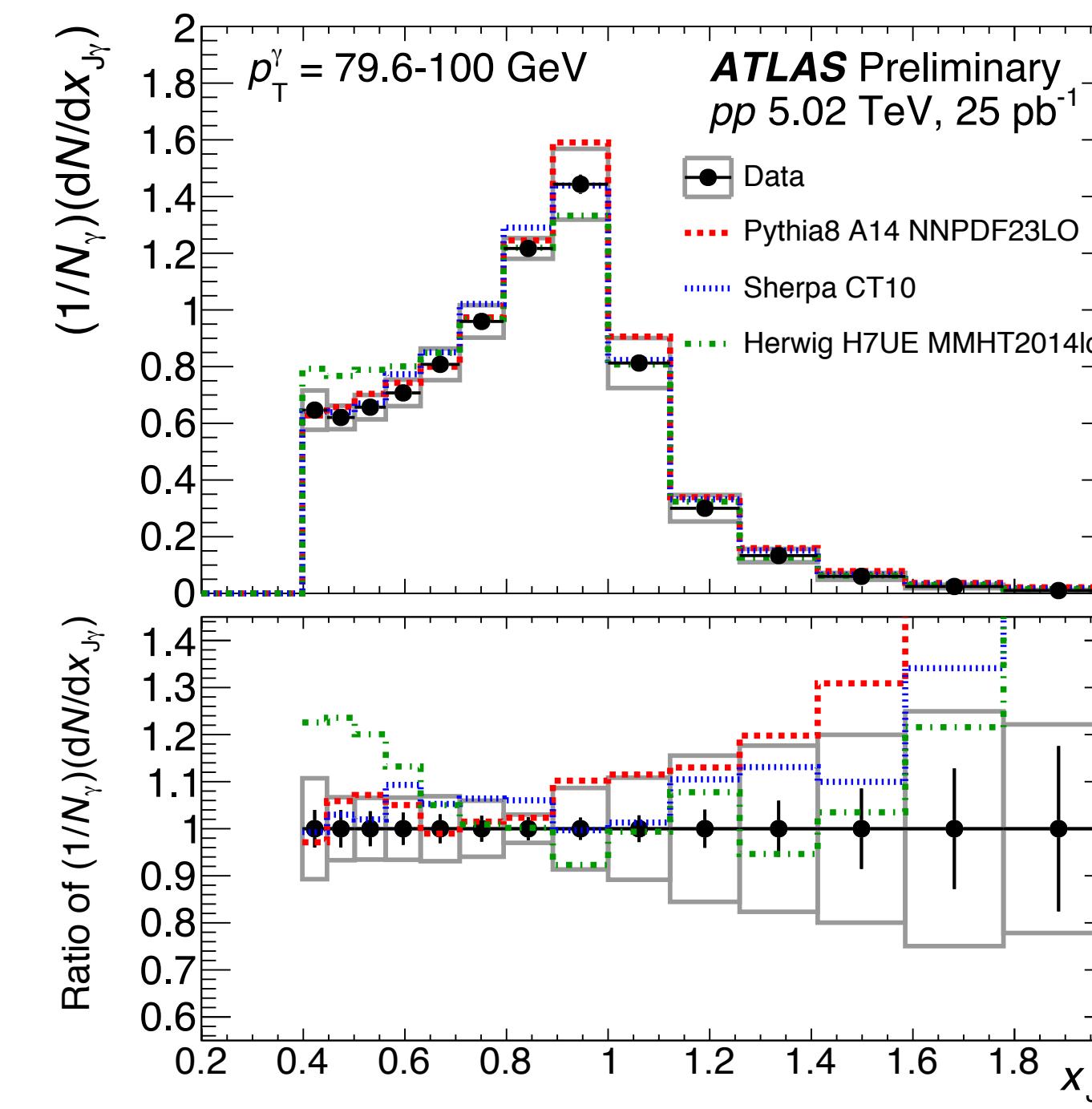
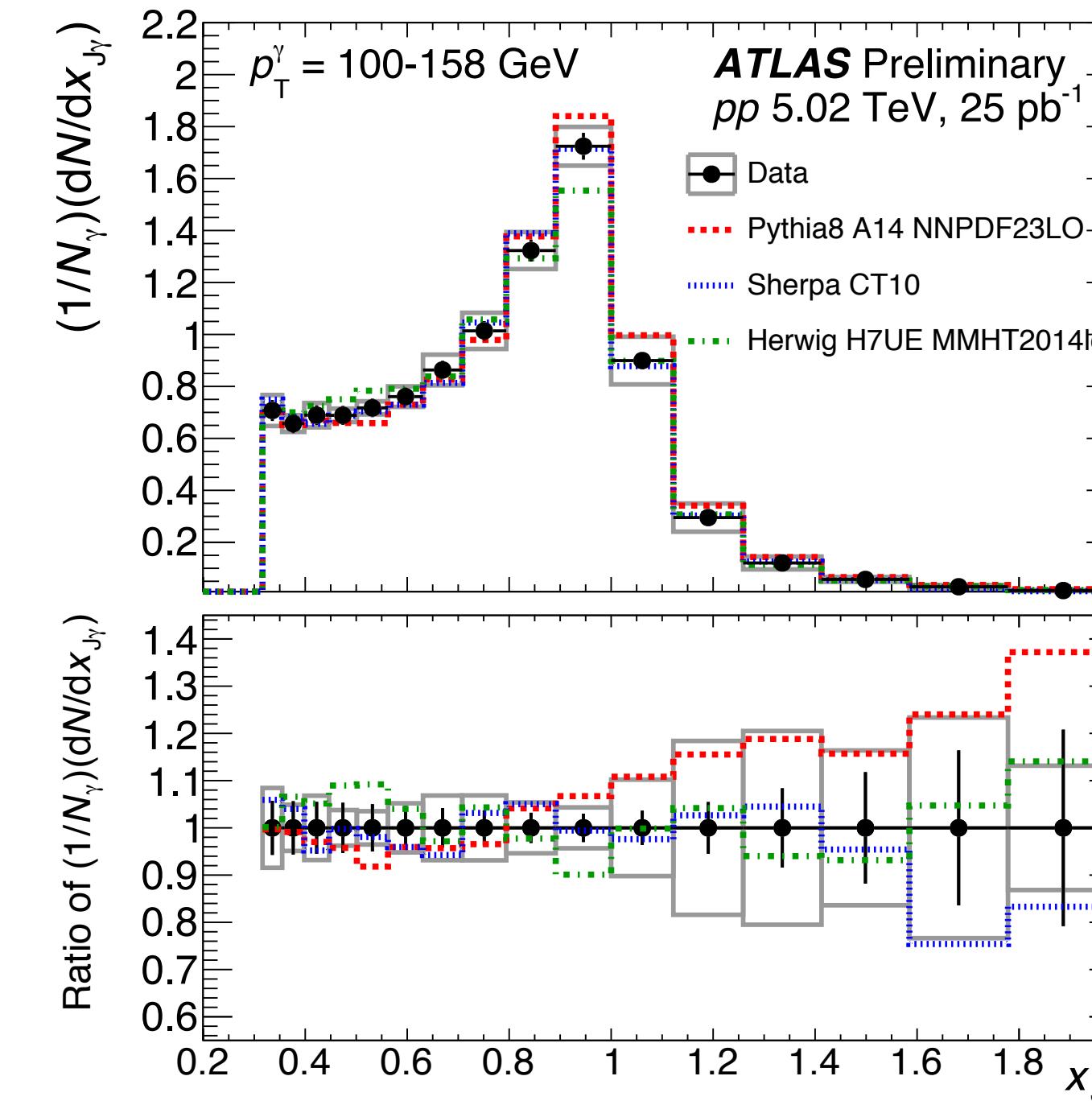
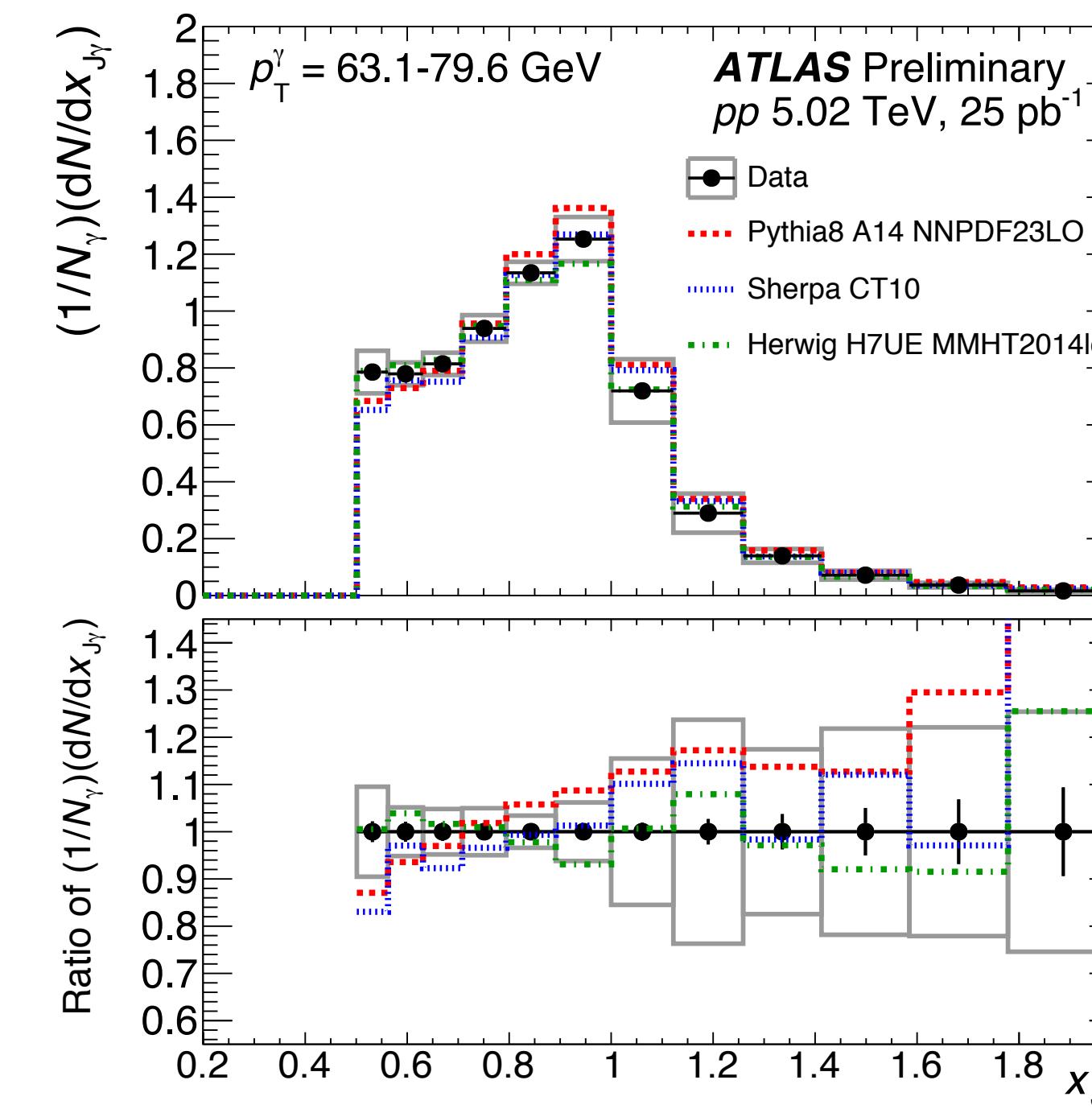


- Photons are required to pass ID cuts & be experimentally isolated
 - purity estimated with standard “double sideband” approach, >95% (>80%) in pp (central Pb+Pb)



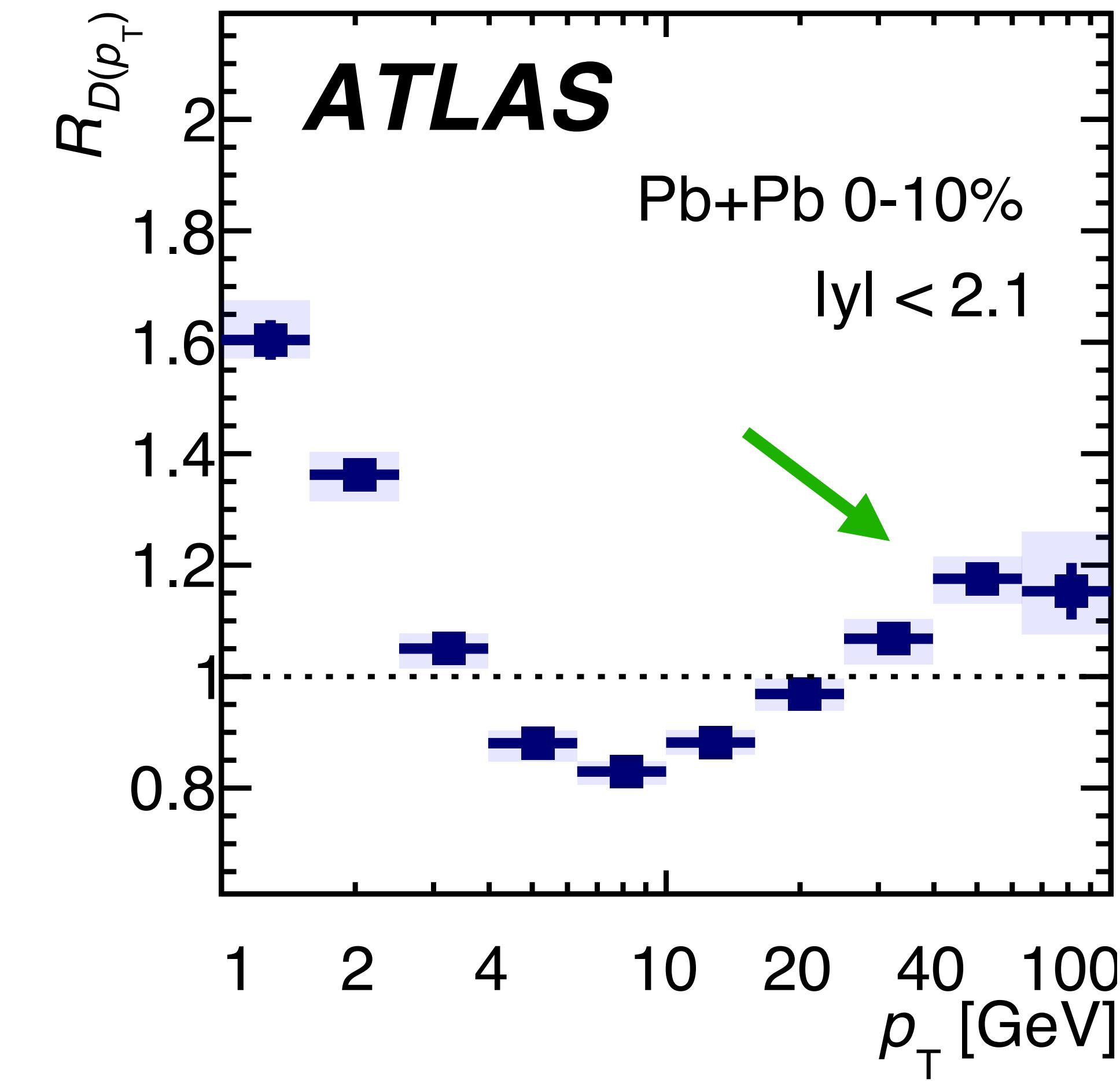
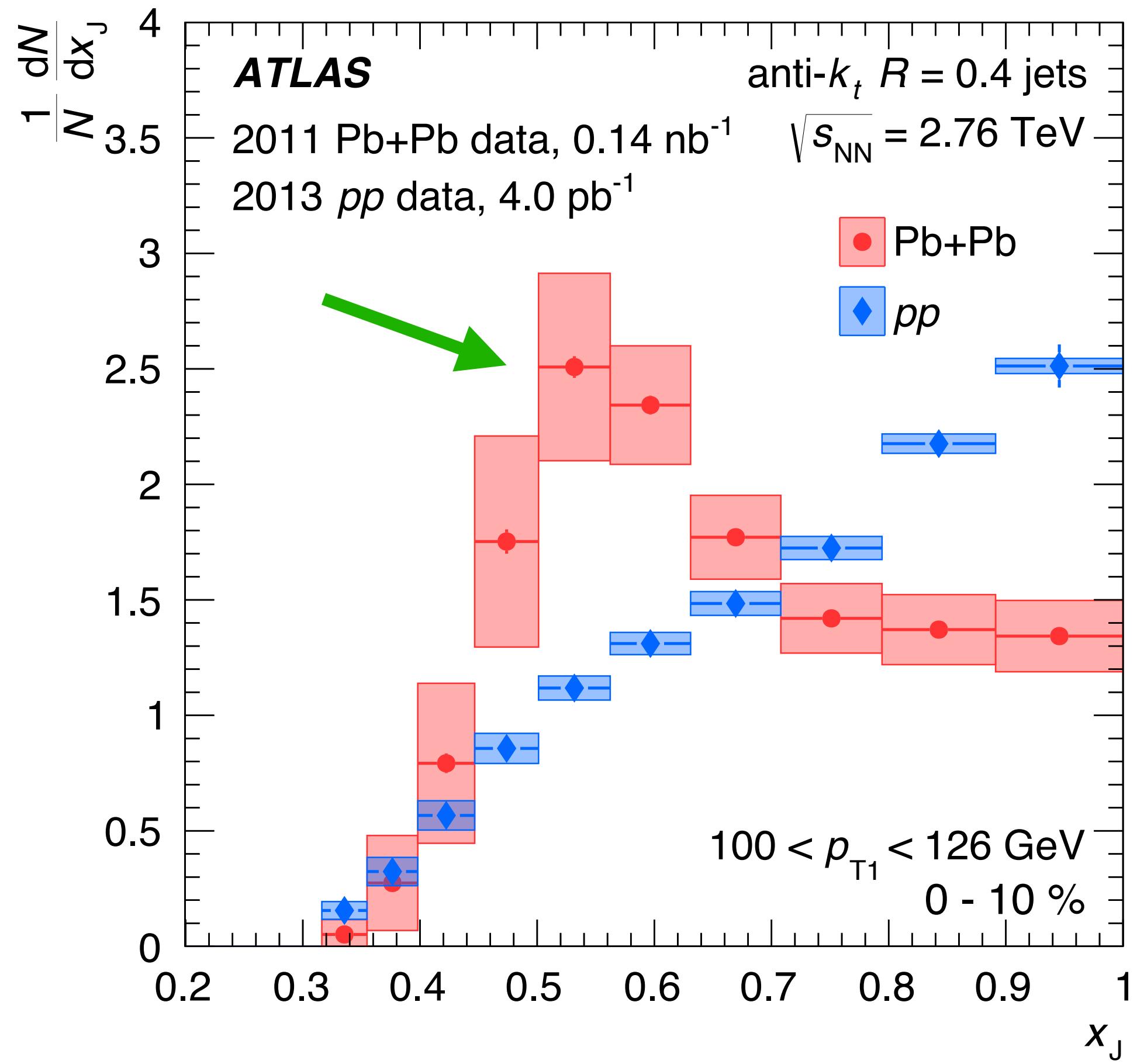
- Data-driven background corrections
 - **combinatoric** photon+jet pairs
 - **dijets** (π^0 +jet) from impure photon selection
 - FF measurement also includes UE particles in jet cone

Photon-jet p_T balance in pp : additional $p_T\gamma$ bins



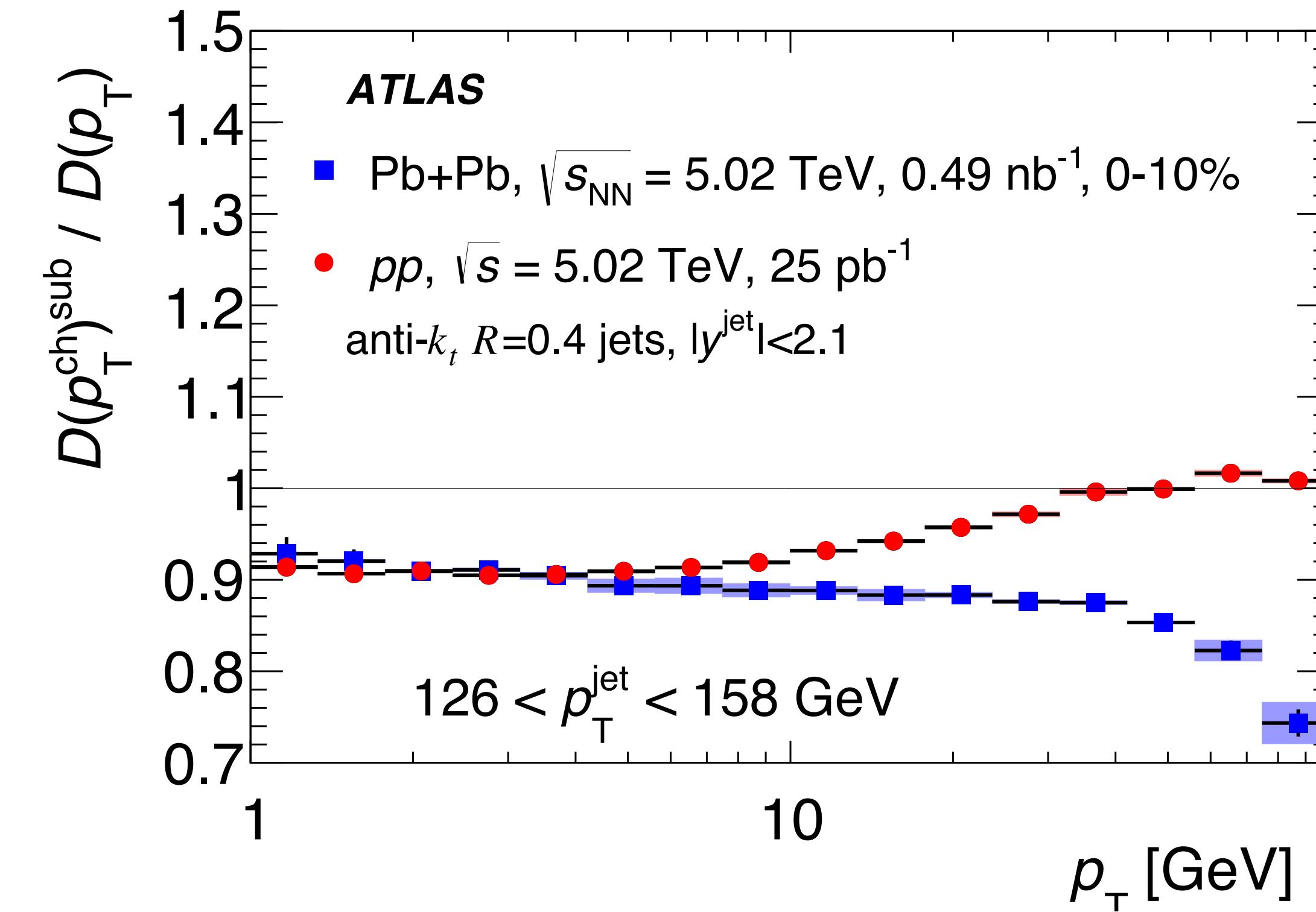
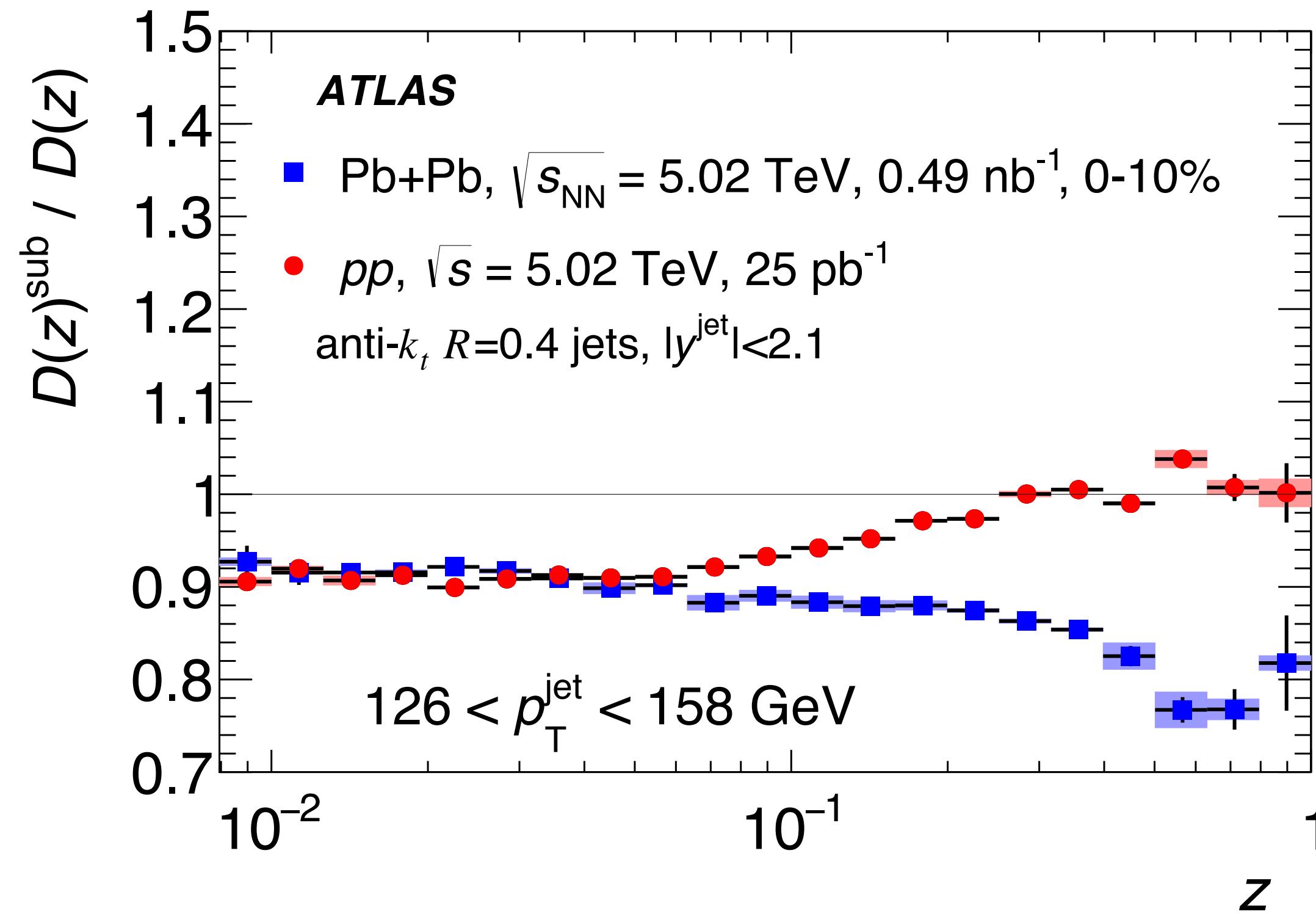
ATLAS measurements with 2-D unfolding

→ needed to reveal otherwise hidden physical features of distributions

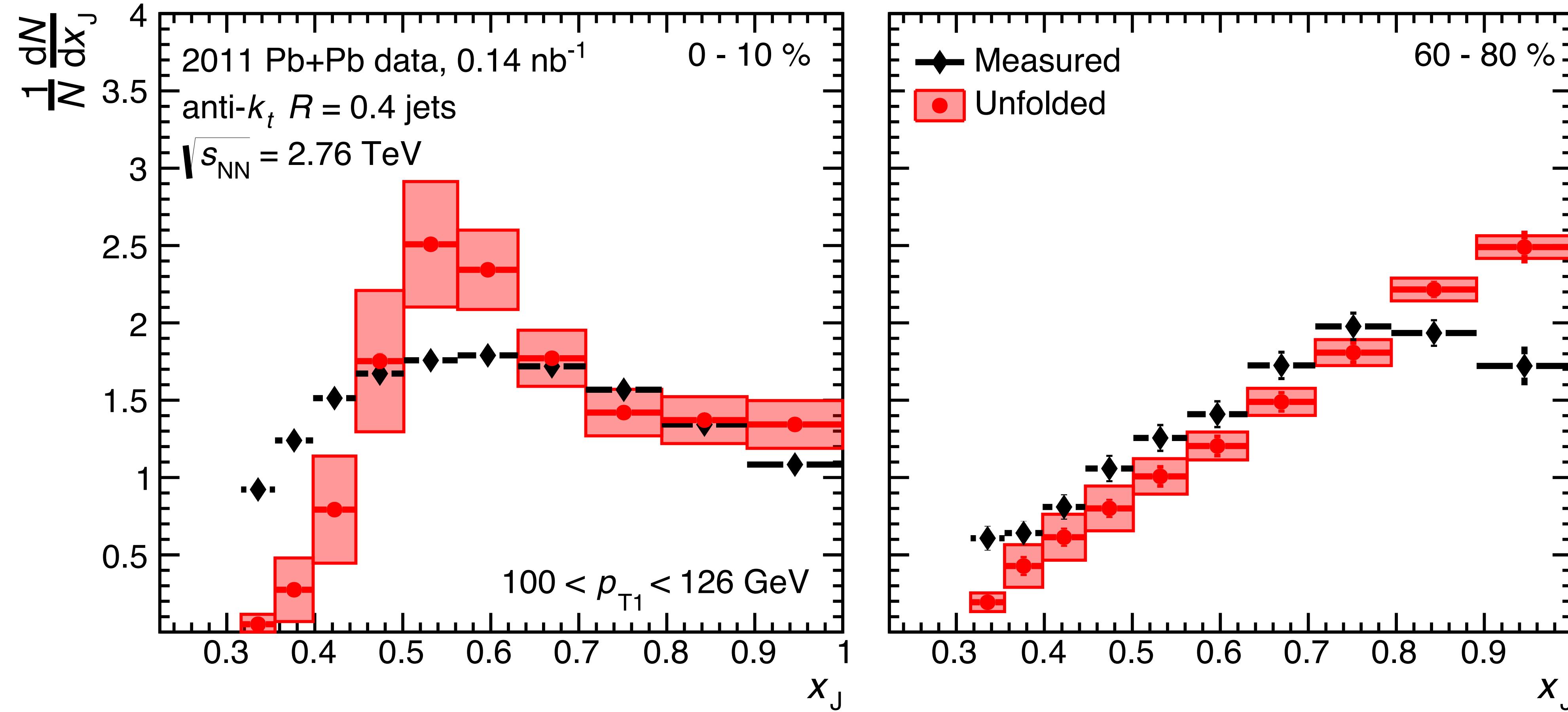


dijet pT-asymmetry in 0-10% Pb+Pb

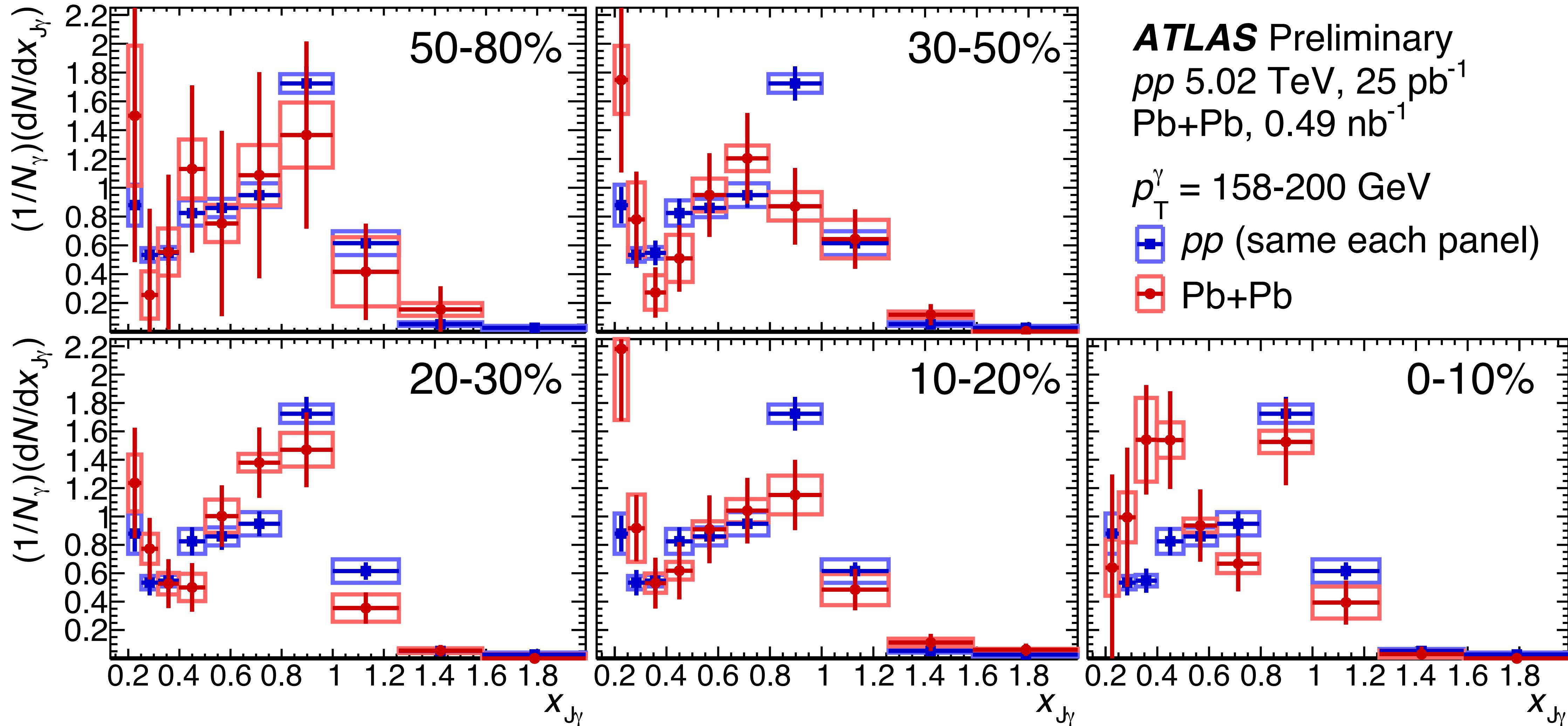
Effect of unfolding on ... inclusive jet fragmentation functions

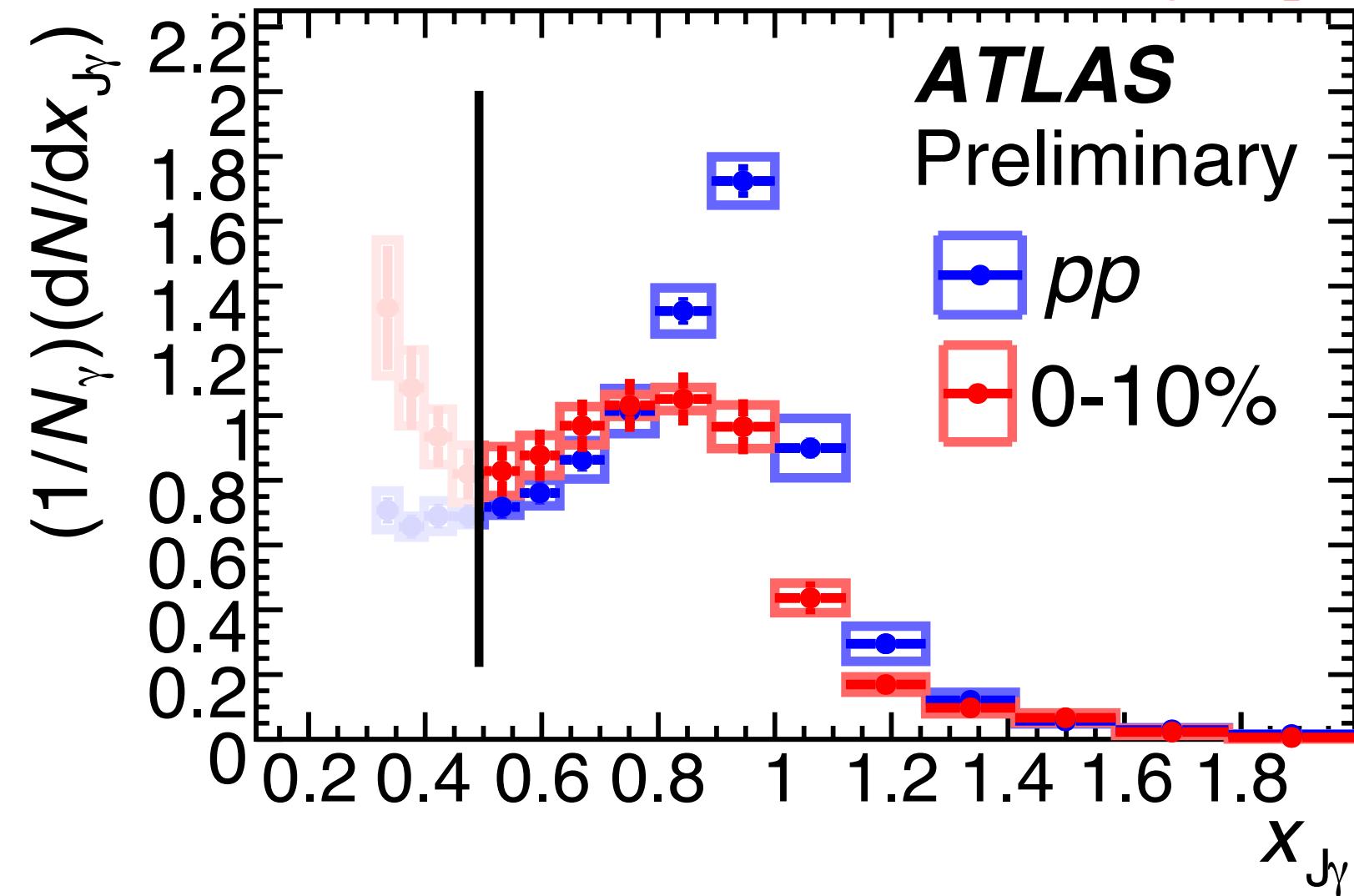


Effect of unfolding on ... dijet p_T -asymmetry



Pb+Pb, $p_{\text{T}}\gamma = 158\text{-}200 \text{ GeV}$

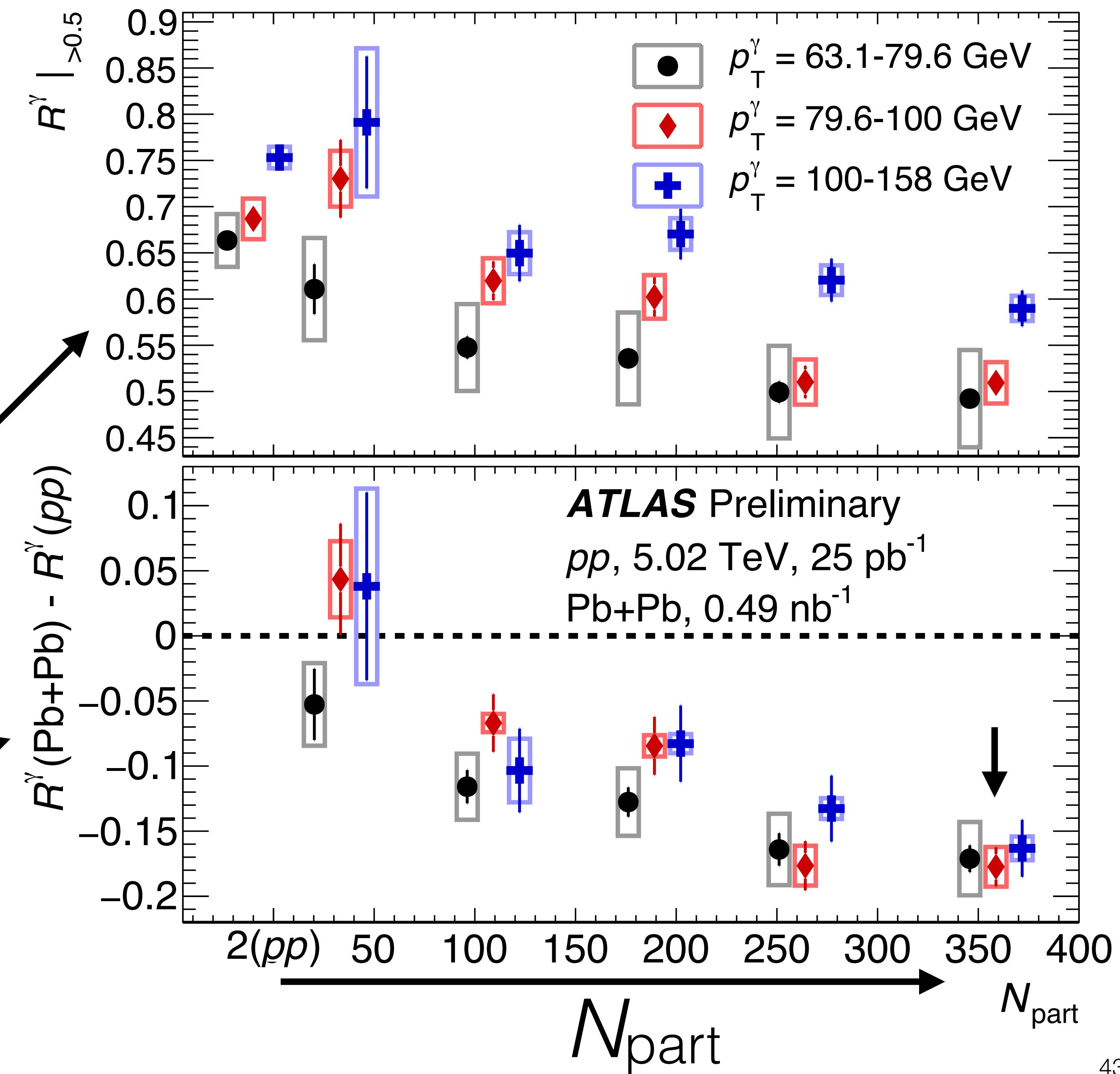


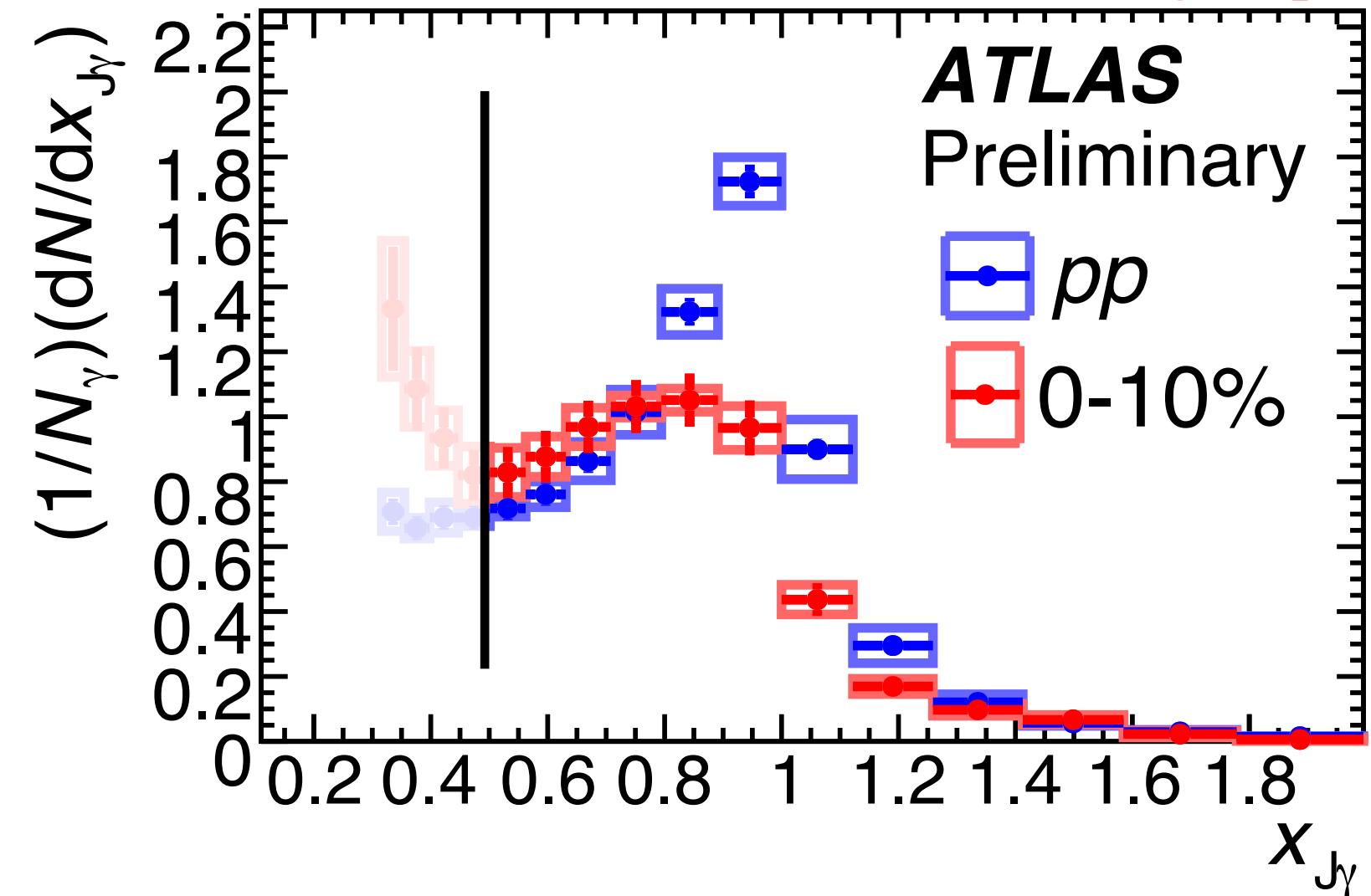


$R\gamma$ = fraction of photons
with leading jet $x_{J\gamma} > 0.5$

$R\gamma(Pb+Pb) - R\gamma(pp)$
(with common
systematics cancelled)

$\Delta R\gamma = -0.15$ to -0.20 in
0-10% events

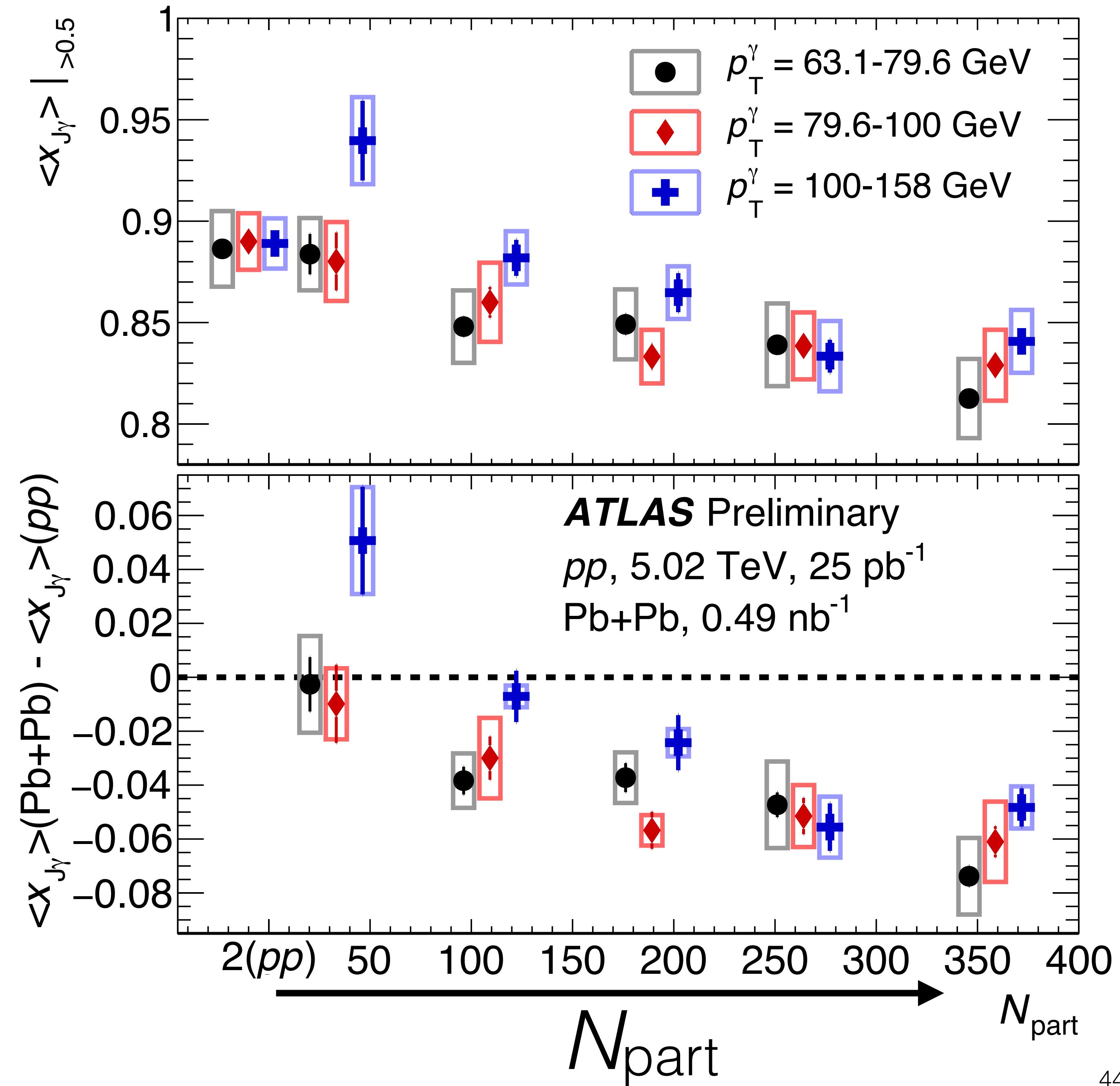


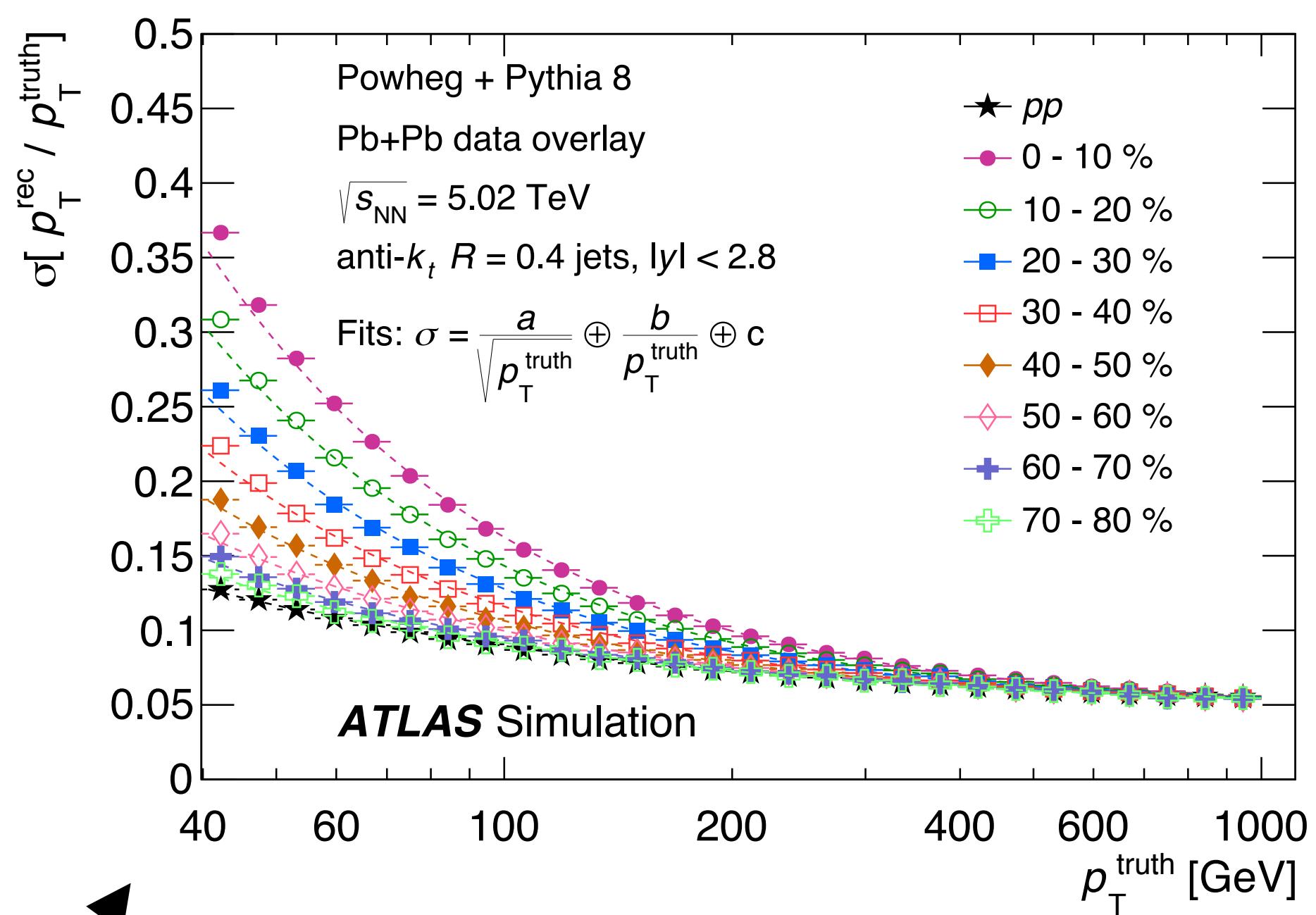
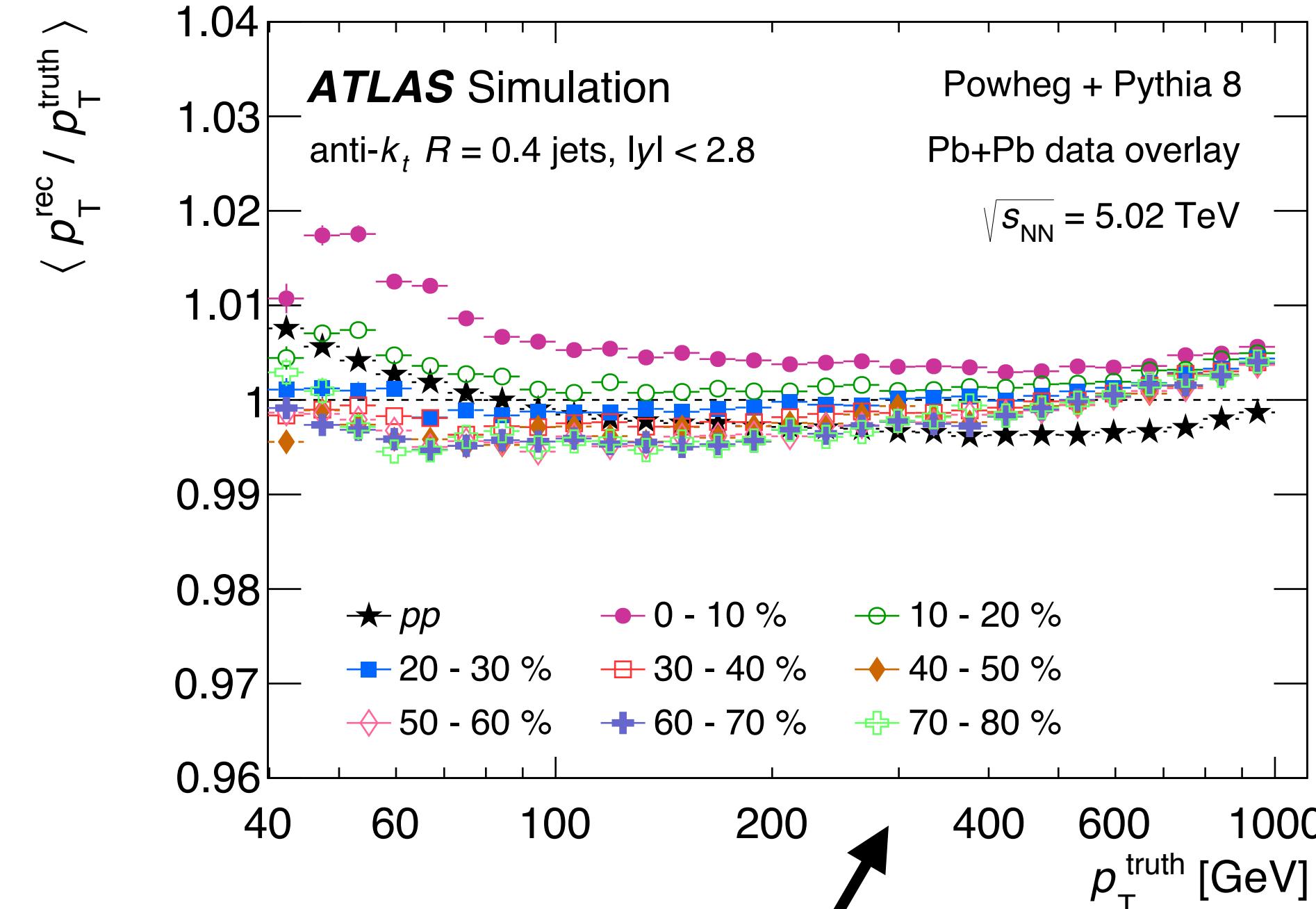


$\langle x_{J\gamma} \rangle$ = truncated mean $x_{J\gamma}$
of leading jets with $x_{J\gamma} > 0.5$

$\langle x_{J\gamma} \rangle(PbPb) - \langle x_{J\gamma} \rangle(pp)$ →
(can be interpreted as per-
jet fractional energy loss)

$\Delta \langle x_{J\gamma} \rangle = -0.07$ to -0.06
in $0-10\%$ events

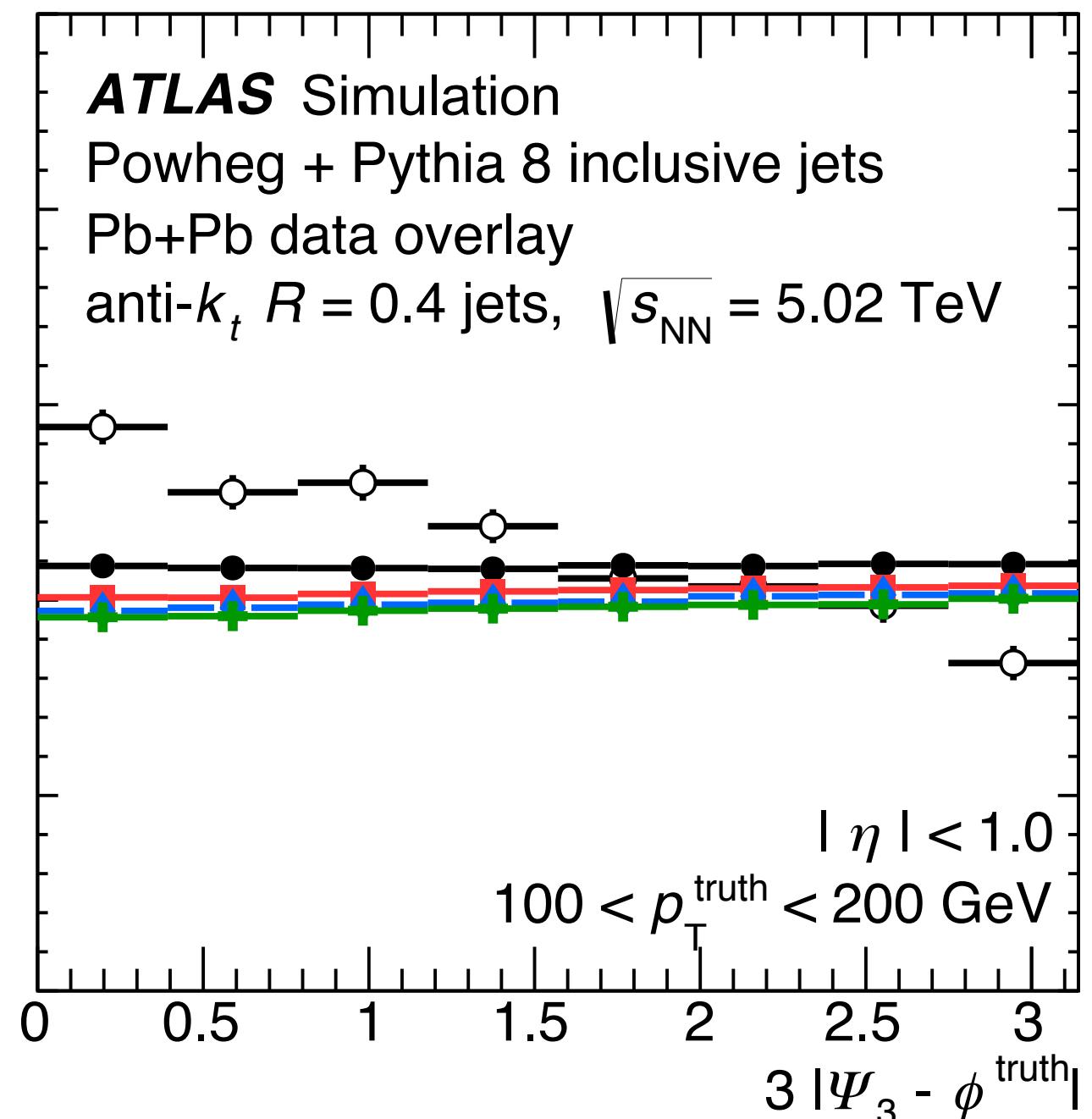
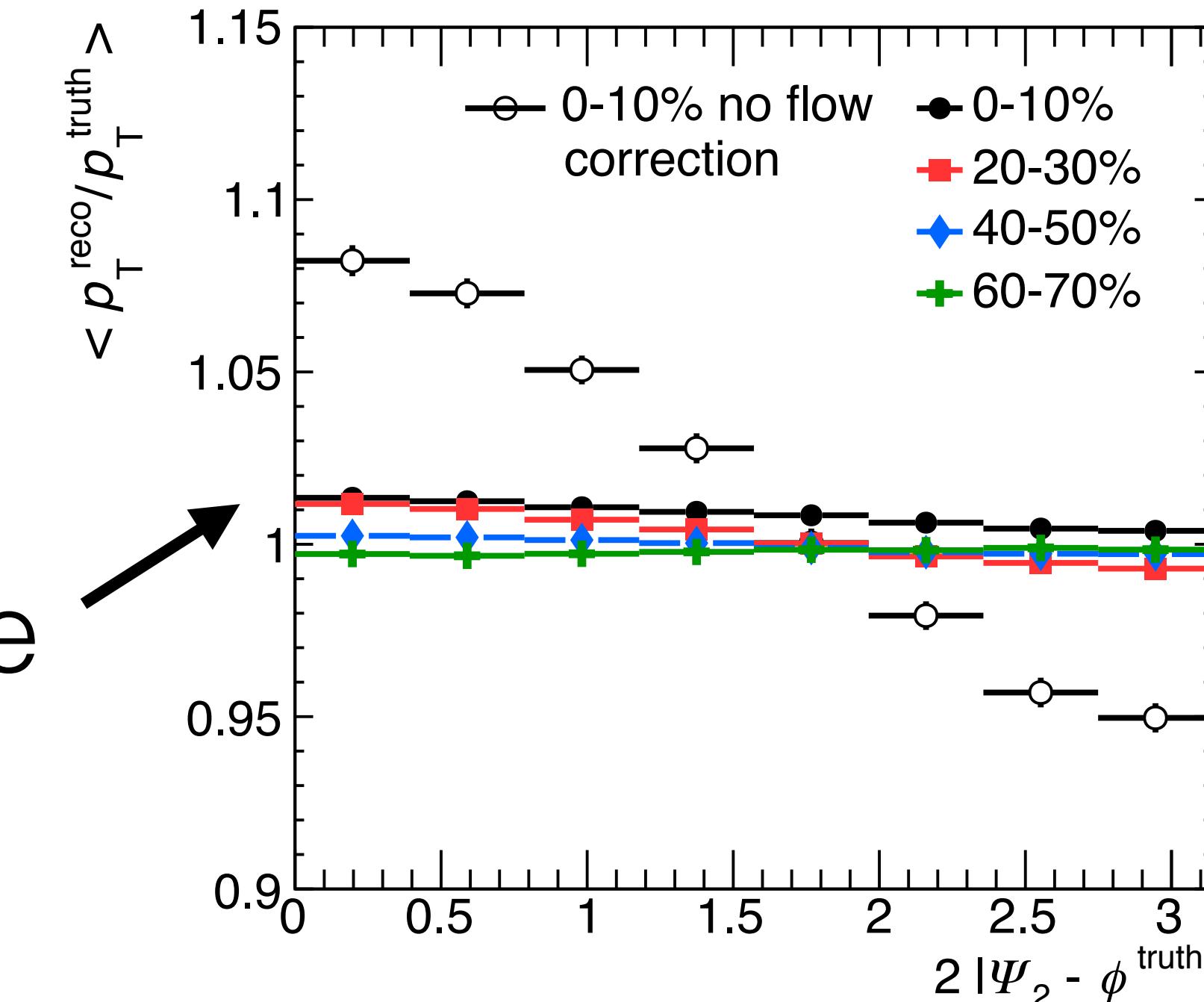




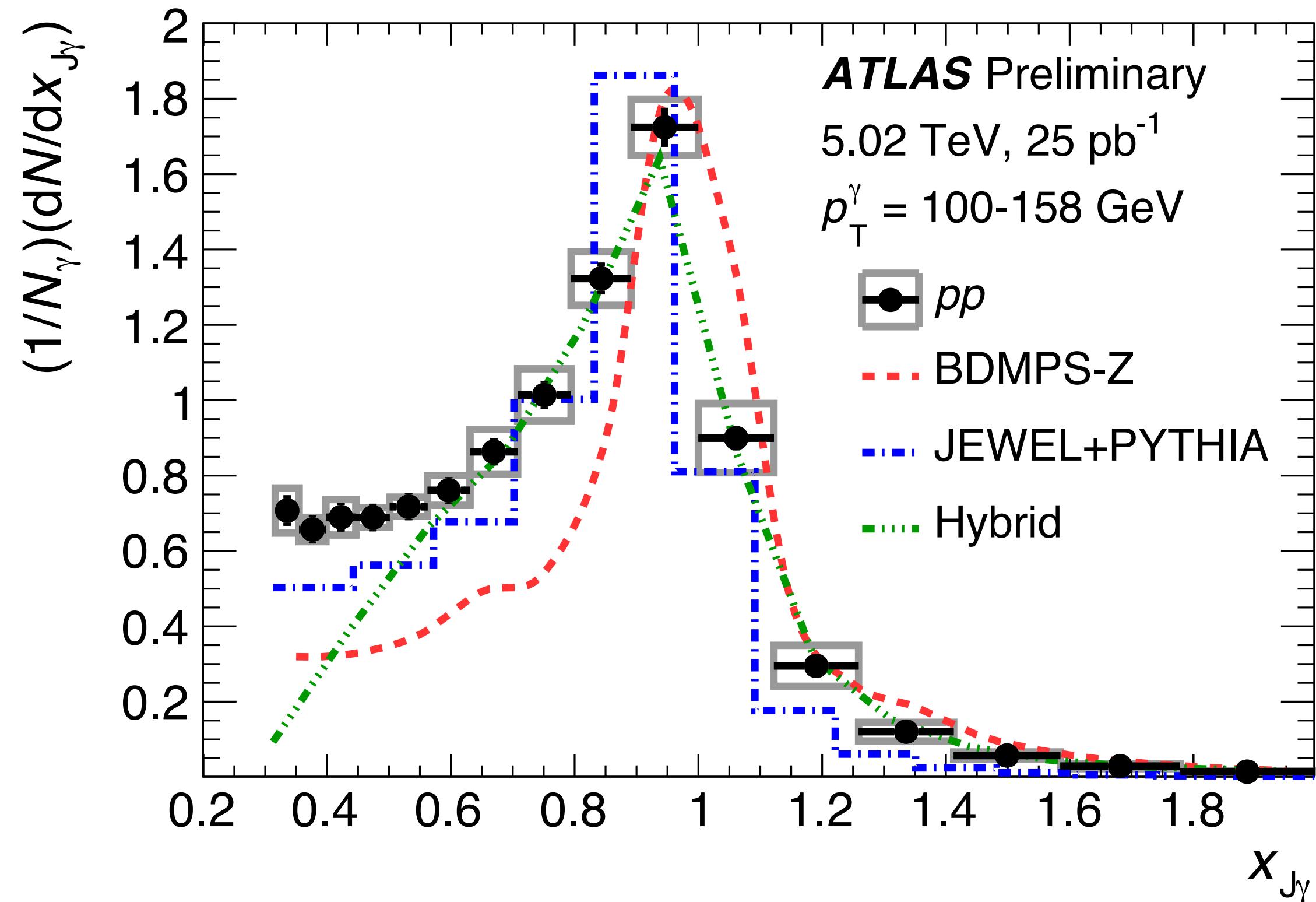
Mean p_T response vs. p_T

Mean p_T resolution vs. p_T

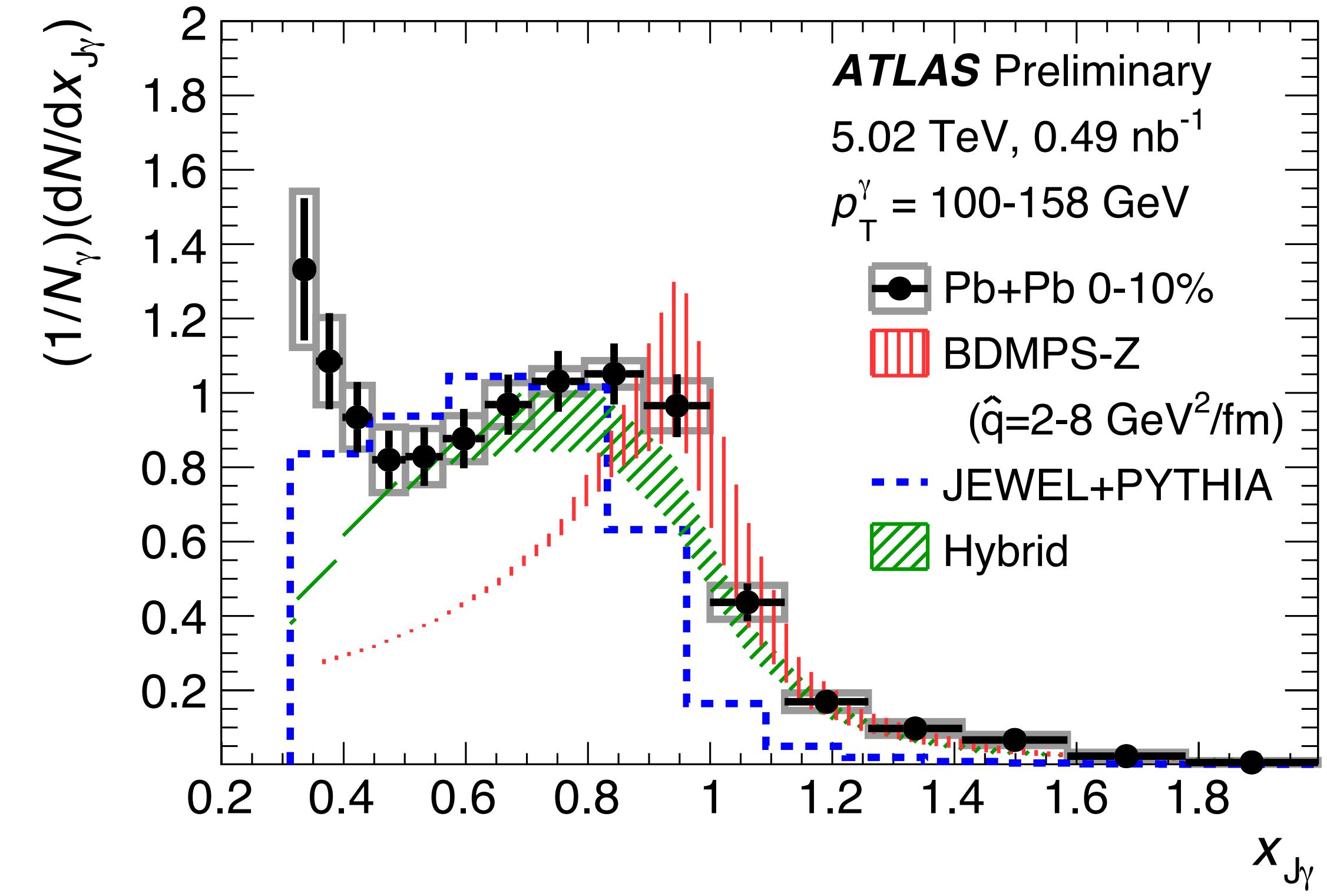
response vs. reaction plane



Comparisons to theory (higher- $p_T\gamma$)

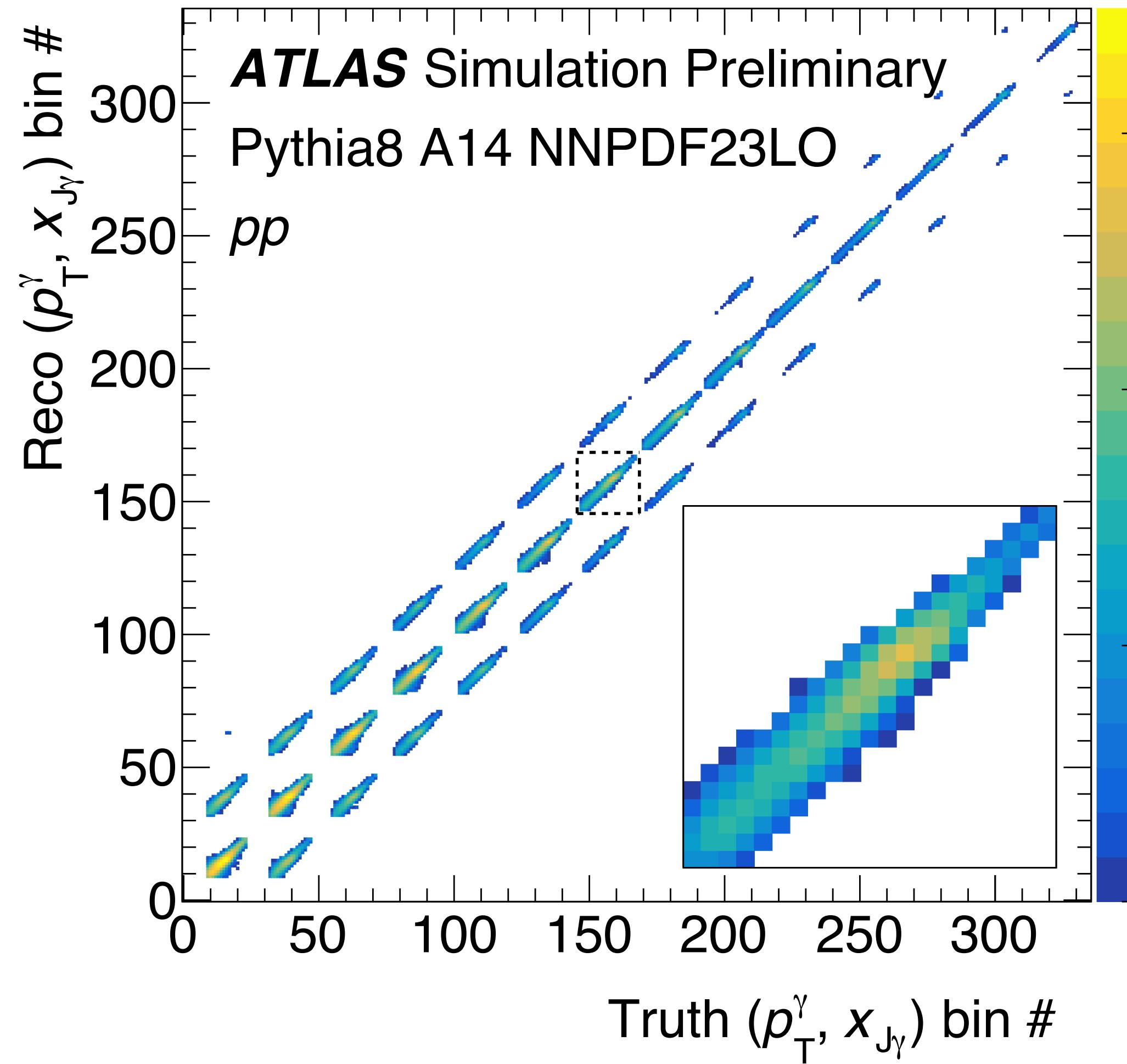


pp

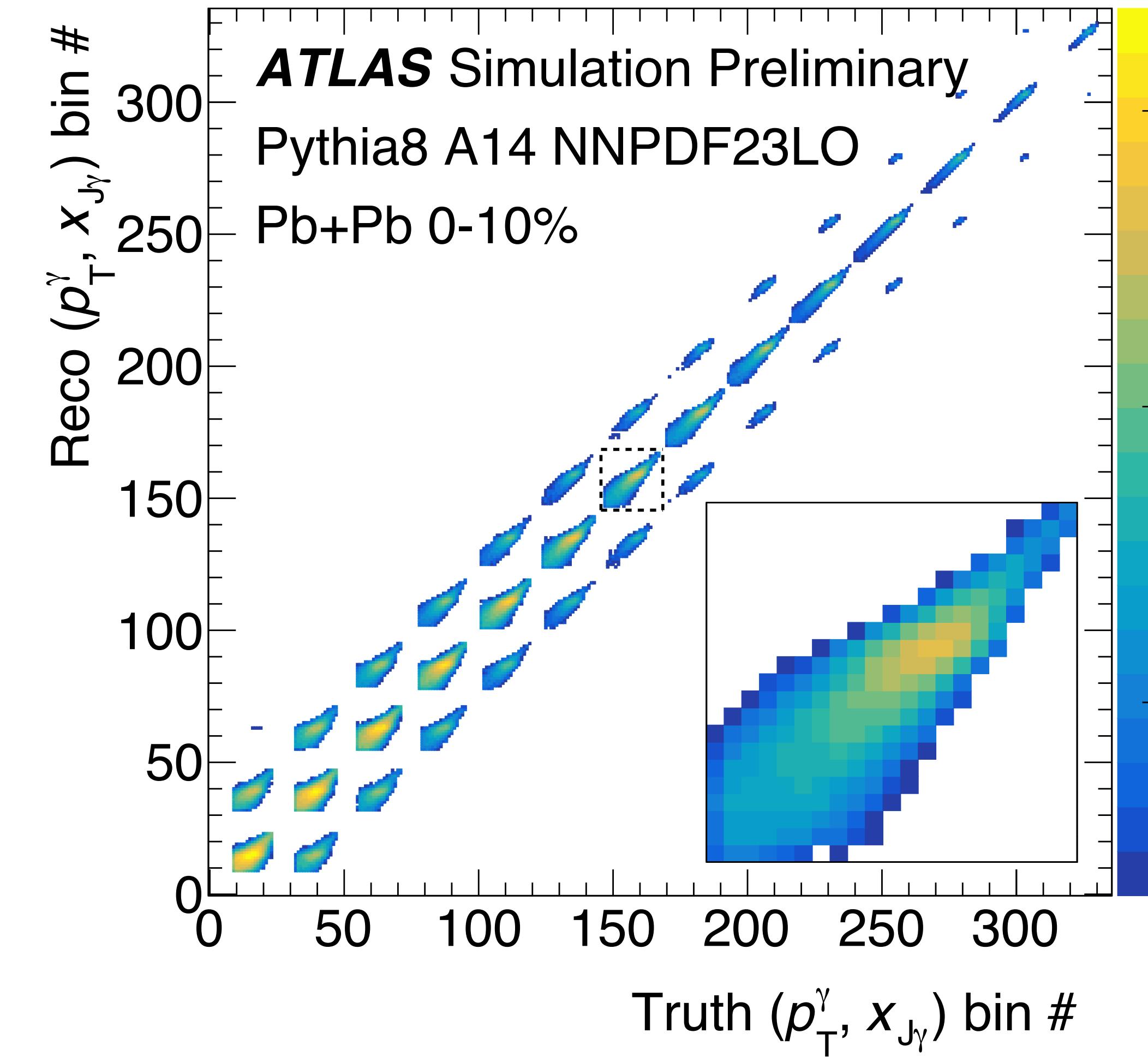


$0-10\% Pb+Pb$

Correction for detector effects

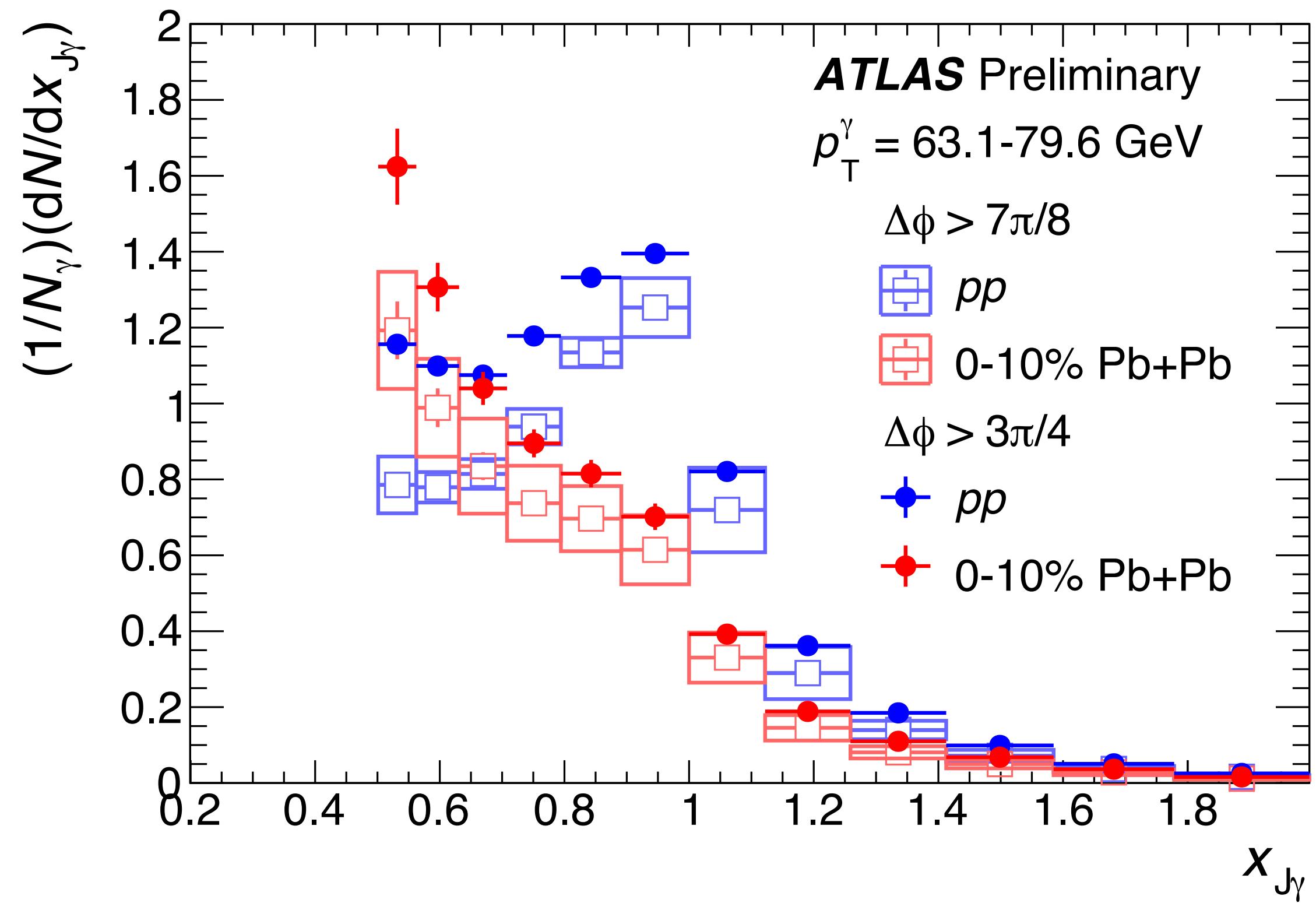


pp

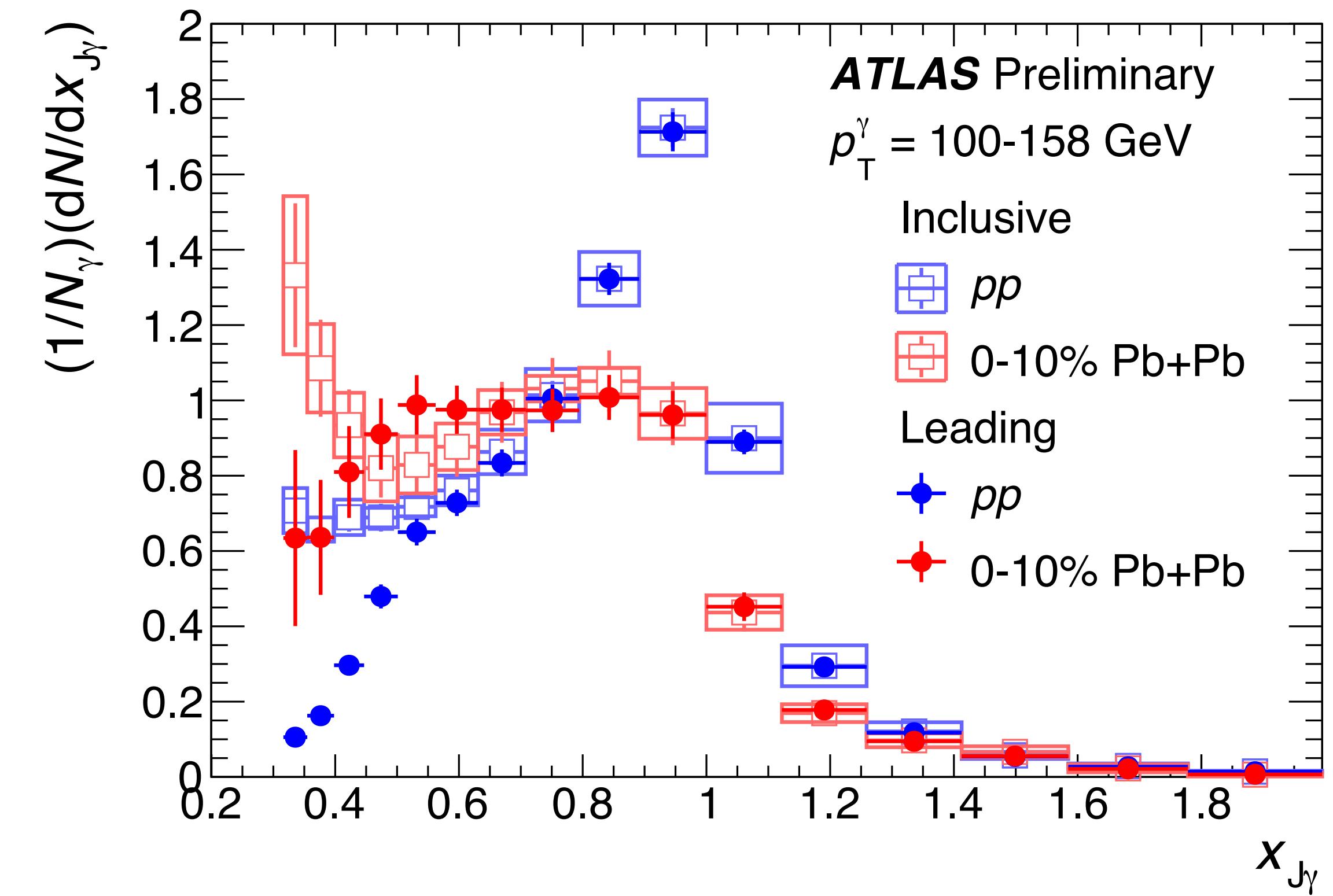


0-10% Pb+Pb

Cross-check with alternate fiducial definitions



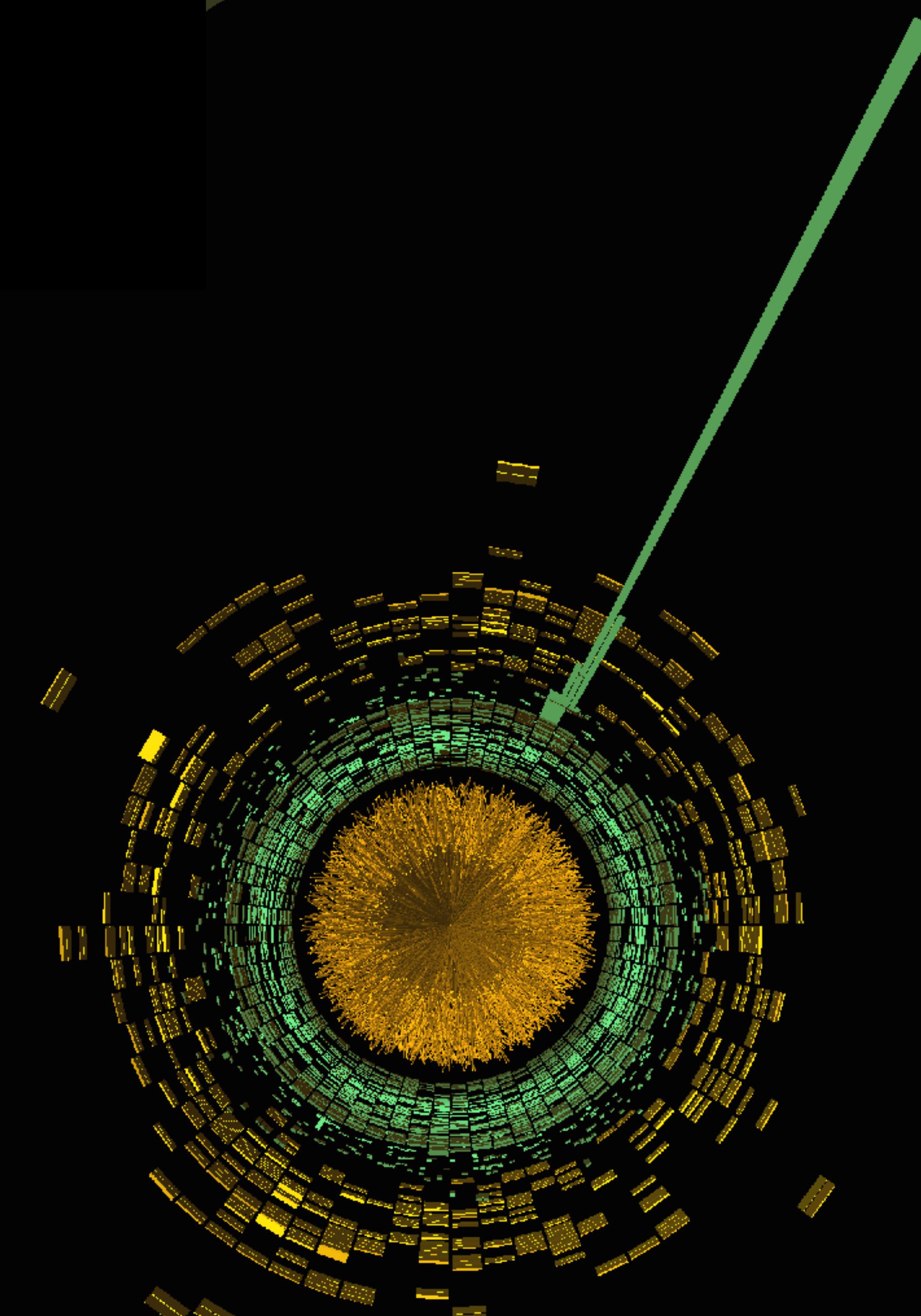
Open $\Delta\phi$ window from
 $>7\pi/8$ to $>3\pi/8$

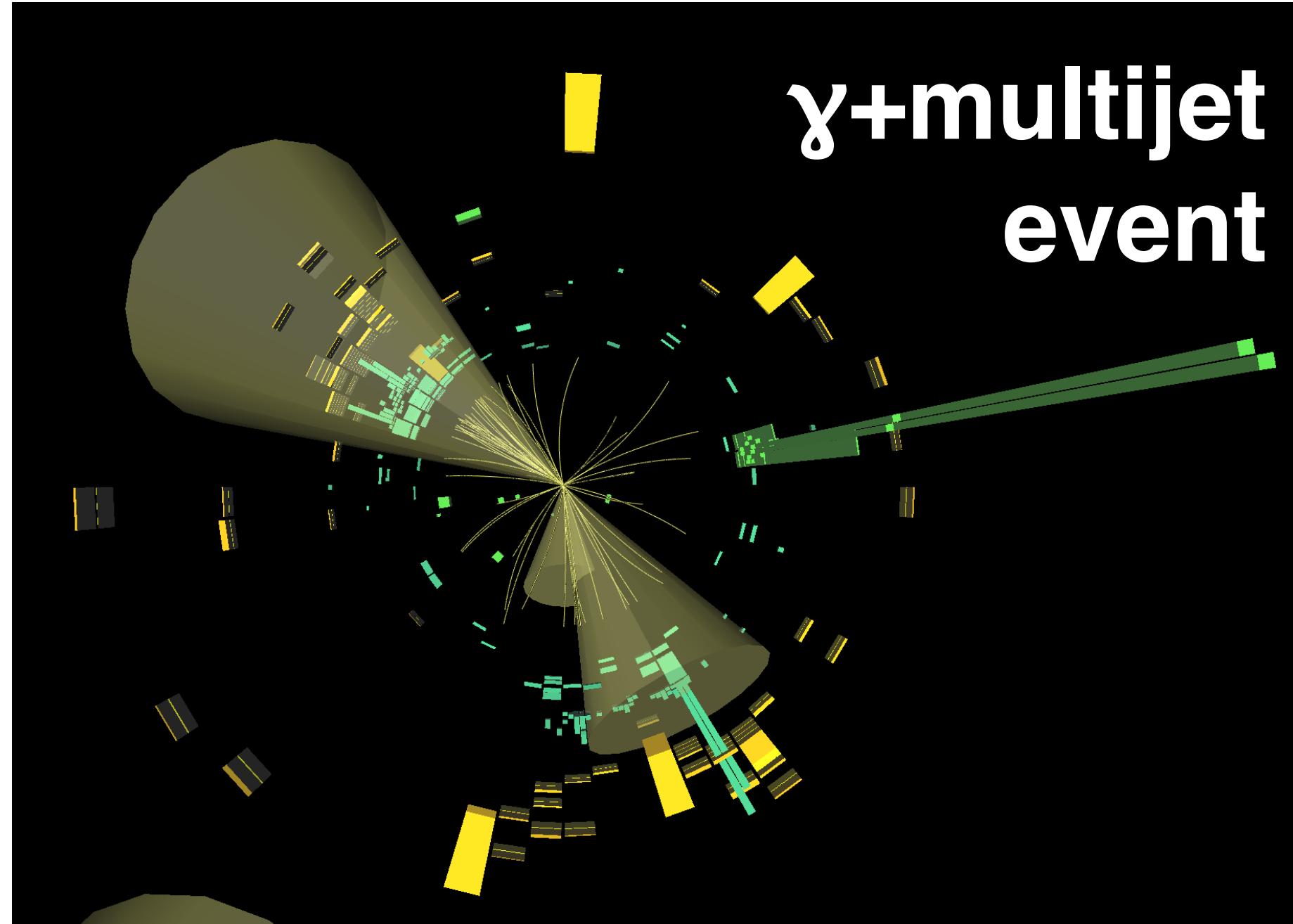


Select leading jet only instead of
all jets with $\Delta\phi > 7\pi/8$

Photon-tagged measurements possible in Run 2:

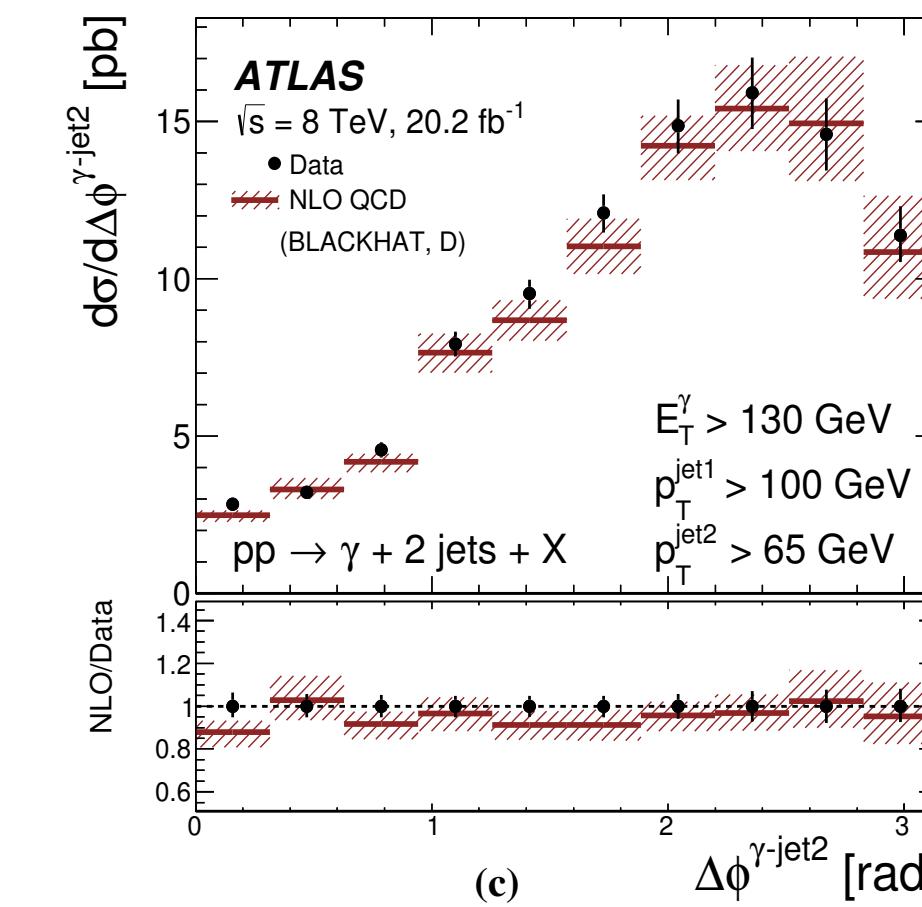
1. γ +jet: absolute E -loss
2. $D(z)$ for γ -tagged jets in
 $Pb+Pb$ & $p+p$
3. γ -tagged R_{AA}
4. γ +jet vs. reaction plane
5. missing- p_T flow w/ external
scale



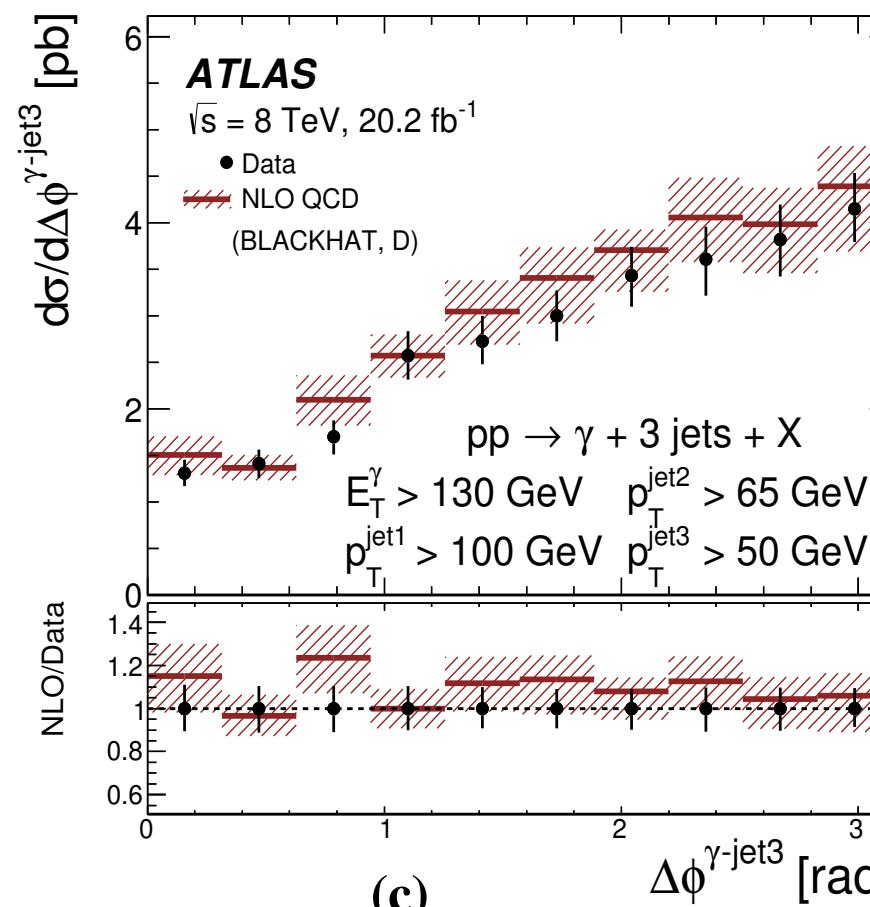


*Large differences
for inclusive vs.
leading at low- $x_{J\gamma}$...*

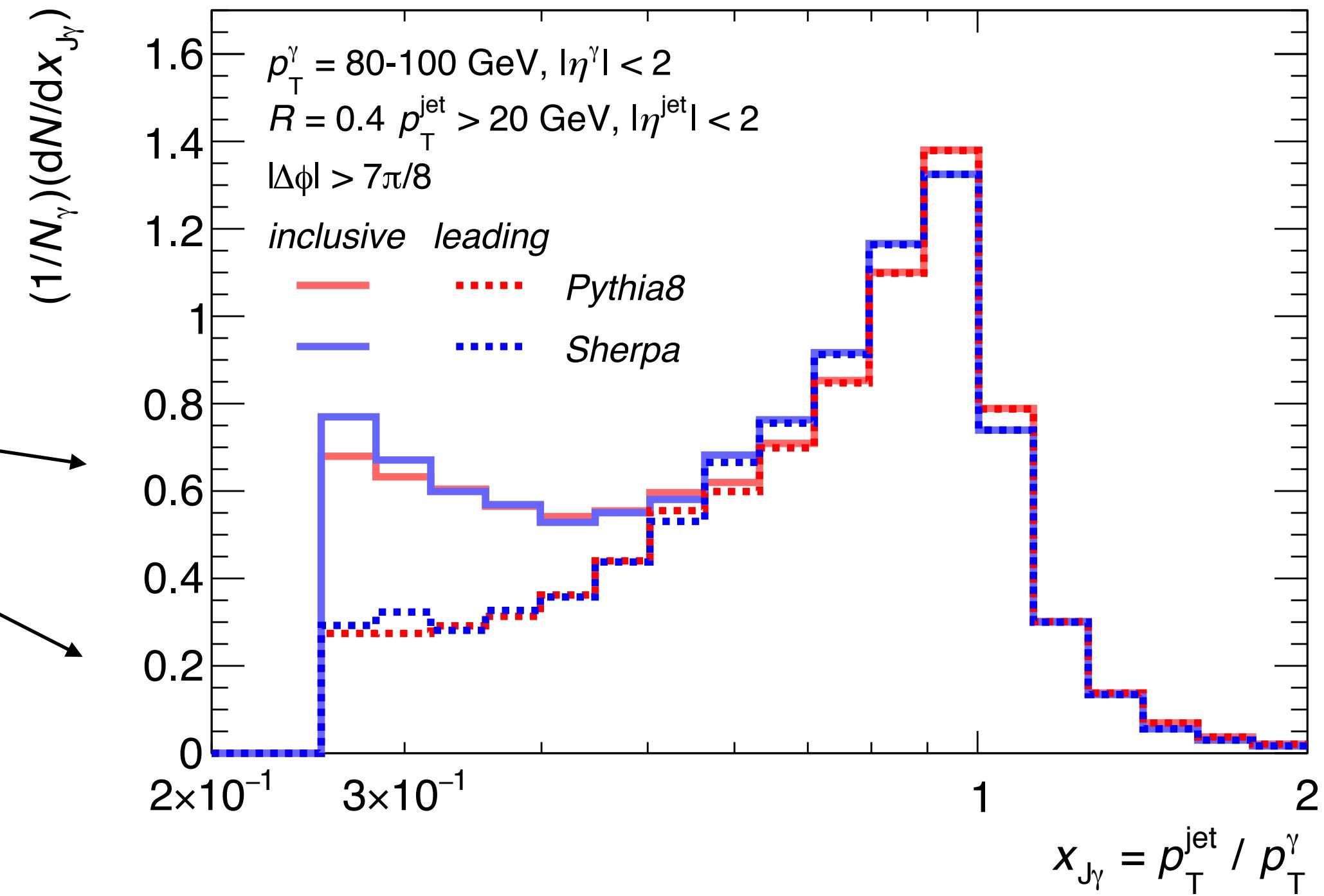
*Measured in detail by
HEP community, e.g.*



$d\sigma/d\phi(\gamma+\text{jet}2)$



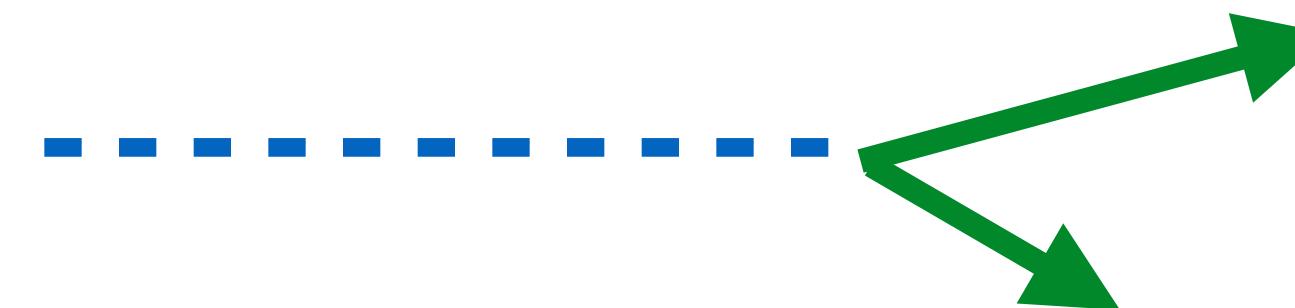
$d\sigma/d\phi(\gamma+\text{jet}3)$



Sensitivity to analysis choices...

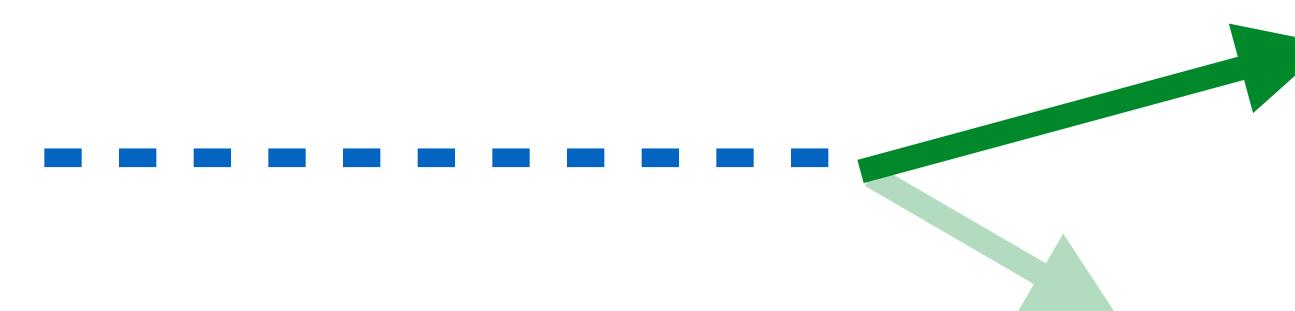
1. Photon + *inclusive* jets

- experimentally easy, but can't extract per-jet $\langle E_{\text{loss}} \rangle$



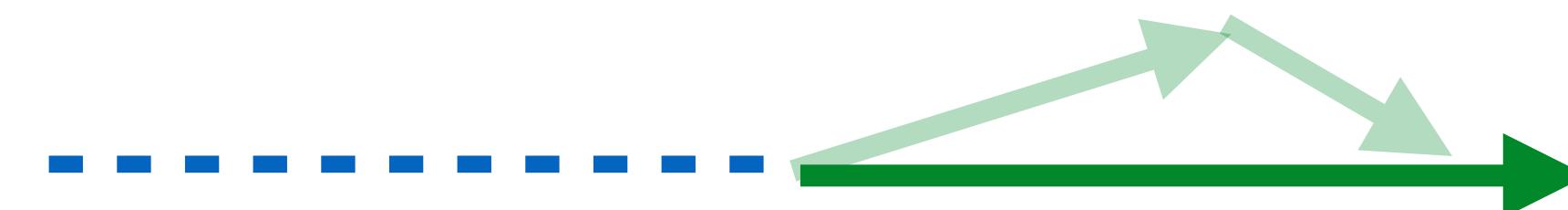
2. Photon + *leading* jet

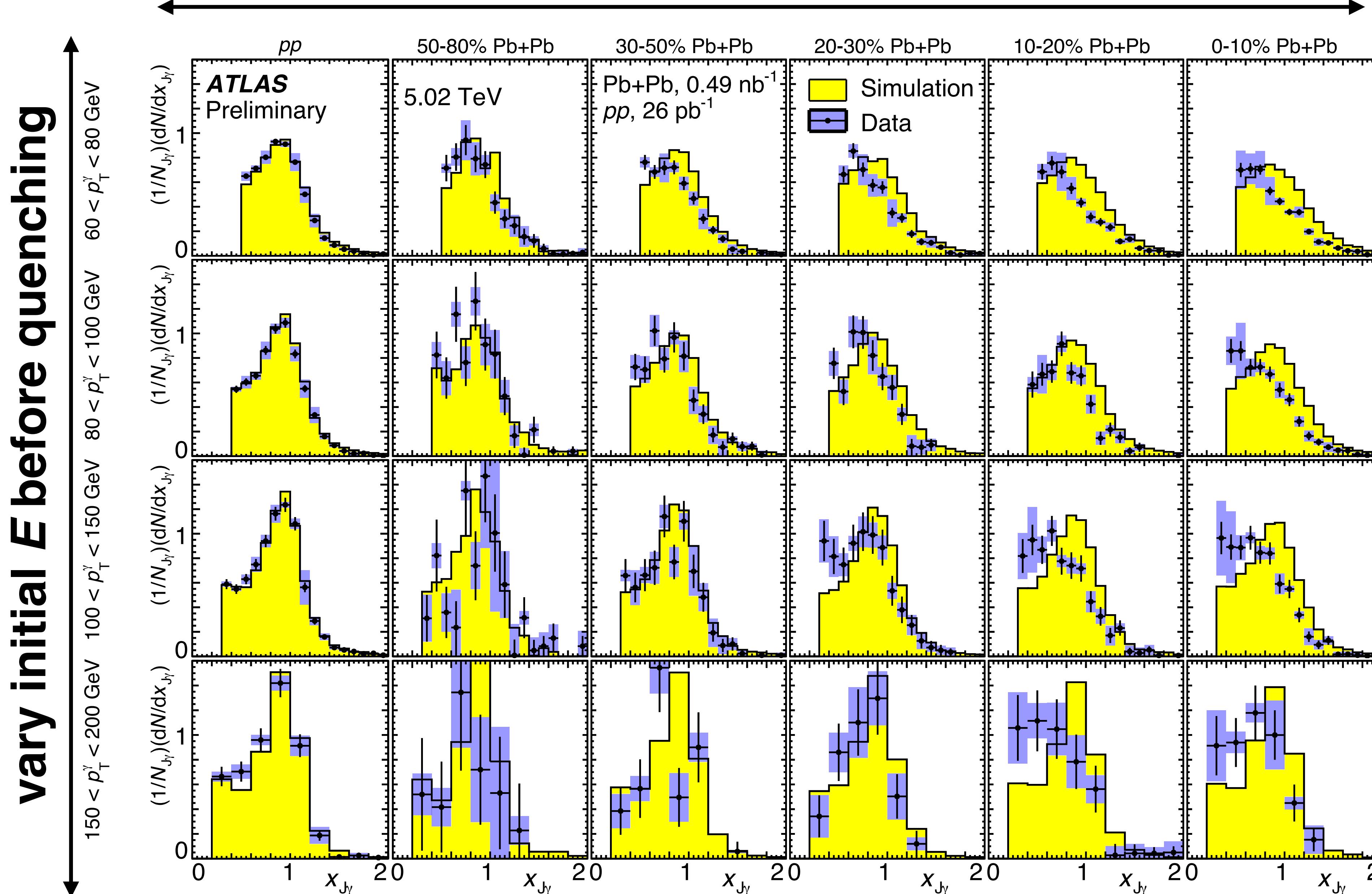
- better-defined “leading quark” probe



3. Photon + $\sum p_T$ of high- p_T jets

- E -loss of entire recoiling hadronic system



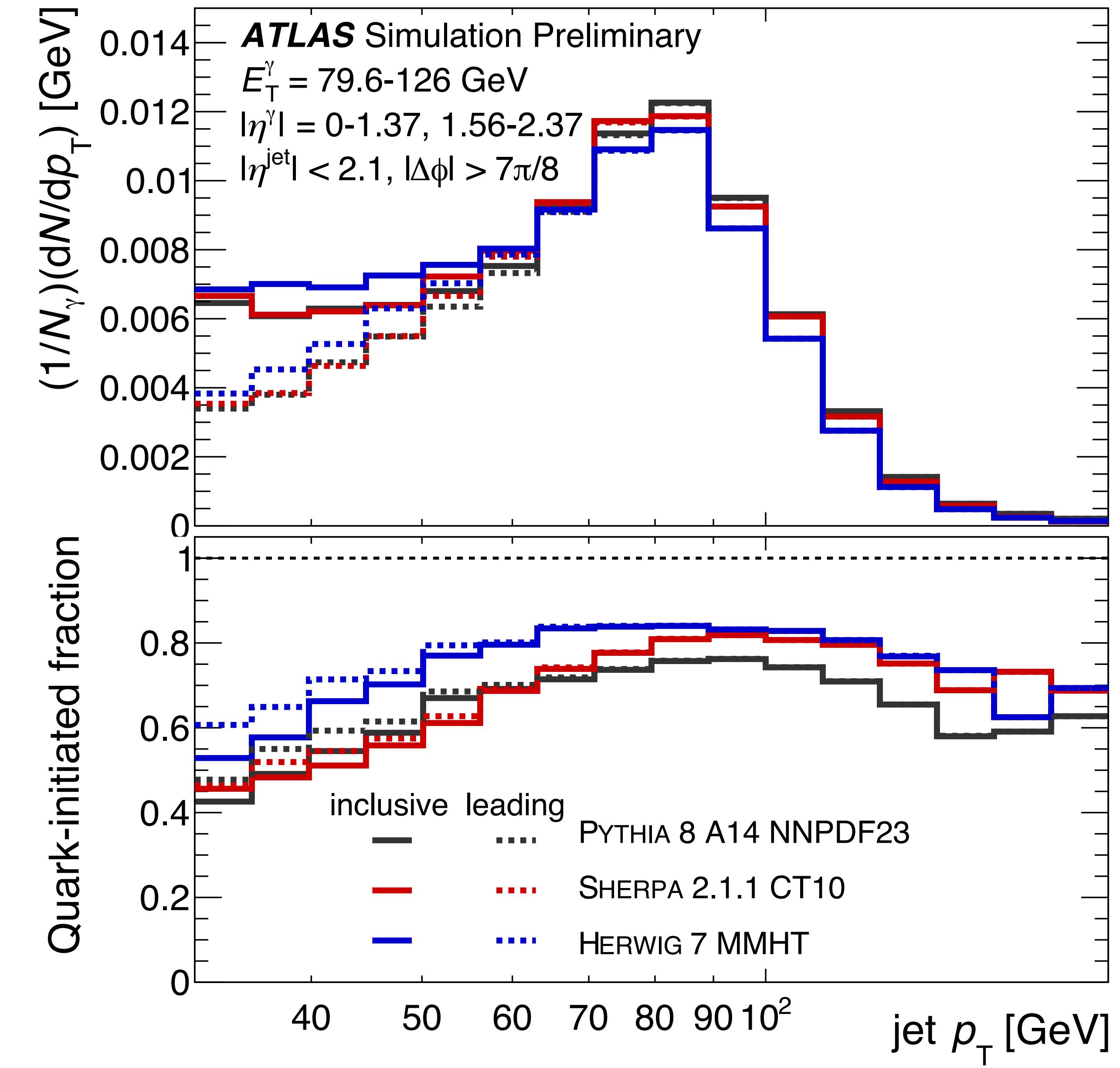
vary system size

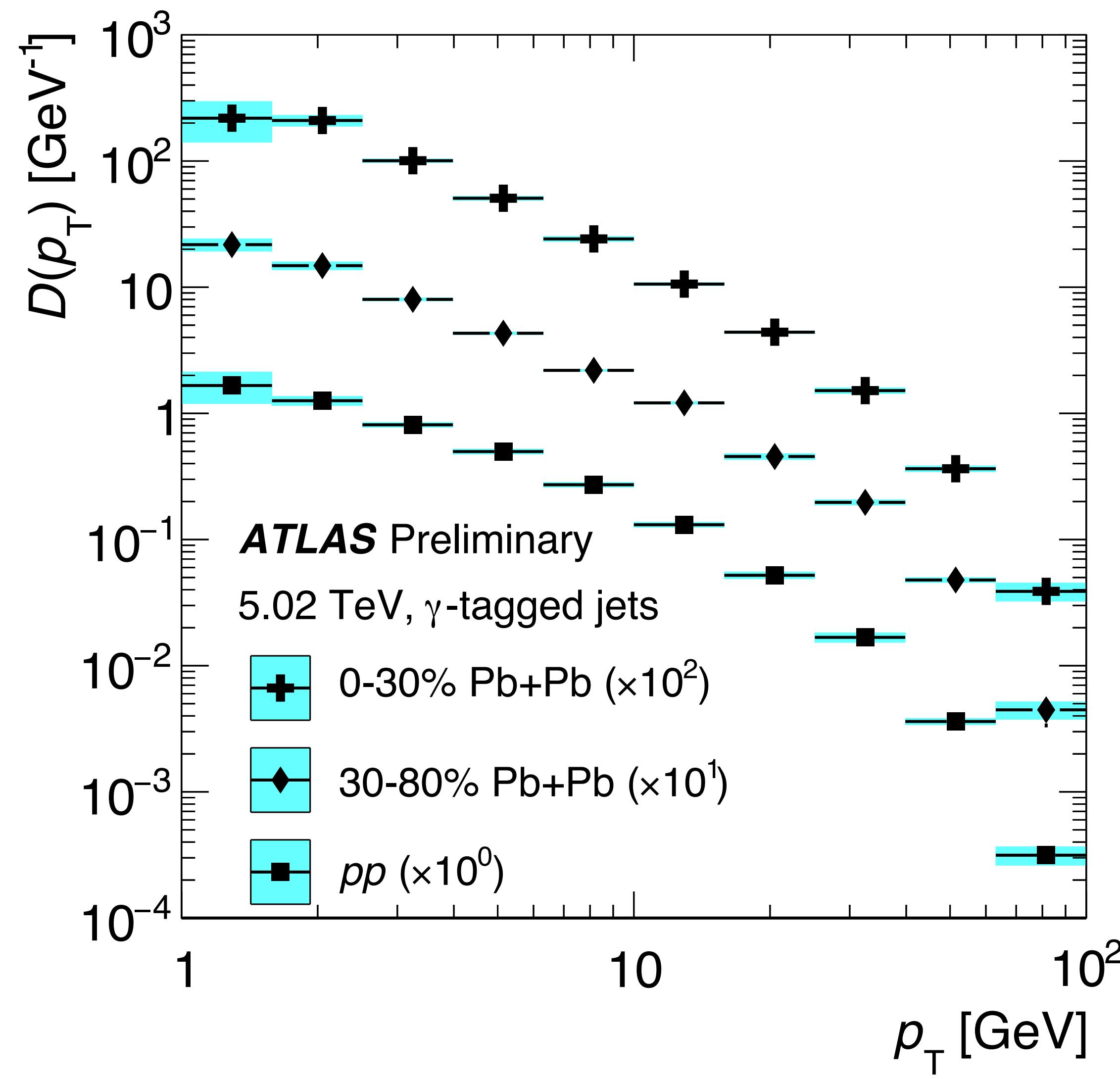
$p_T^\gamma = 79.6\text{-}125 \text{ GeV}$

 p_T →

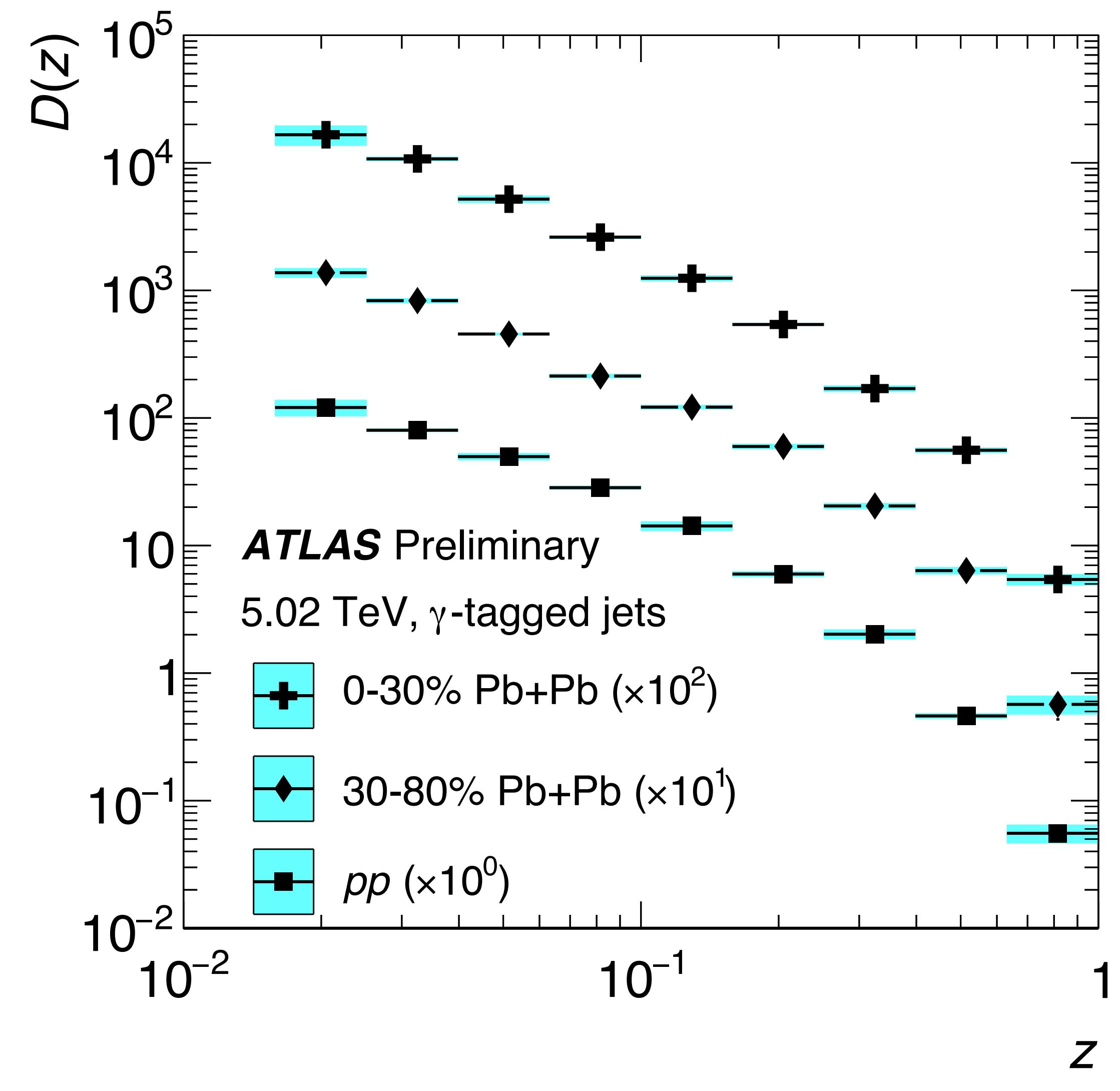
 $p_T^{jet} = 63.1\text{-}144 \text{ GeV}$


- no jets with $x_{J\gamma} < 0.5$ accepted (only leading jets)
- 73-83% quark-initiated jets

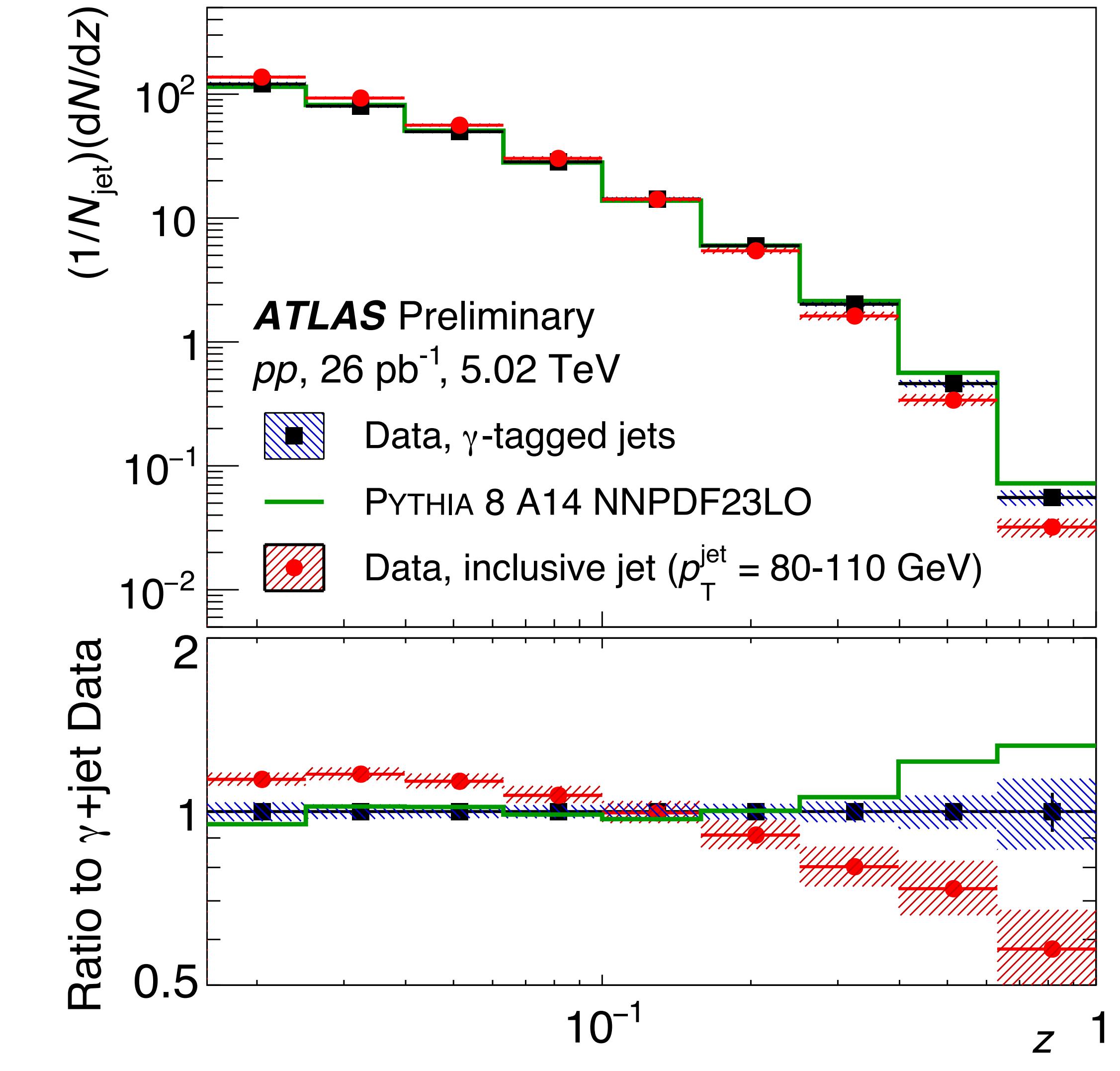
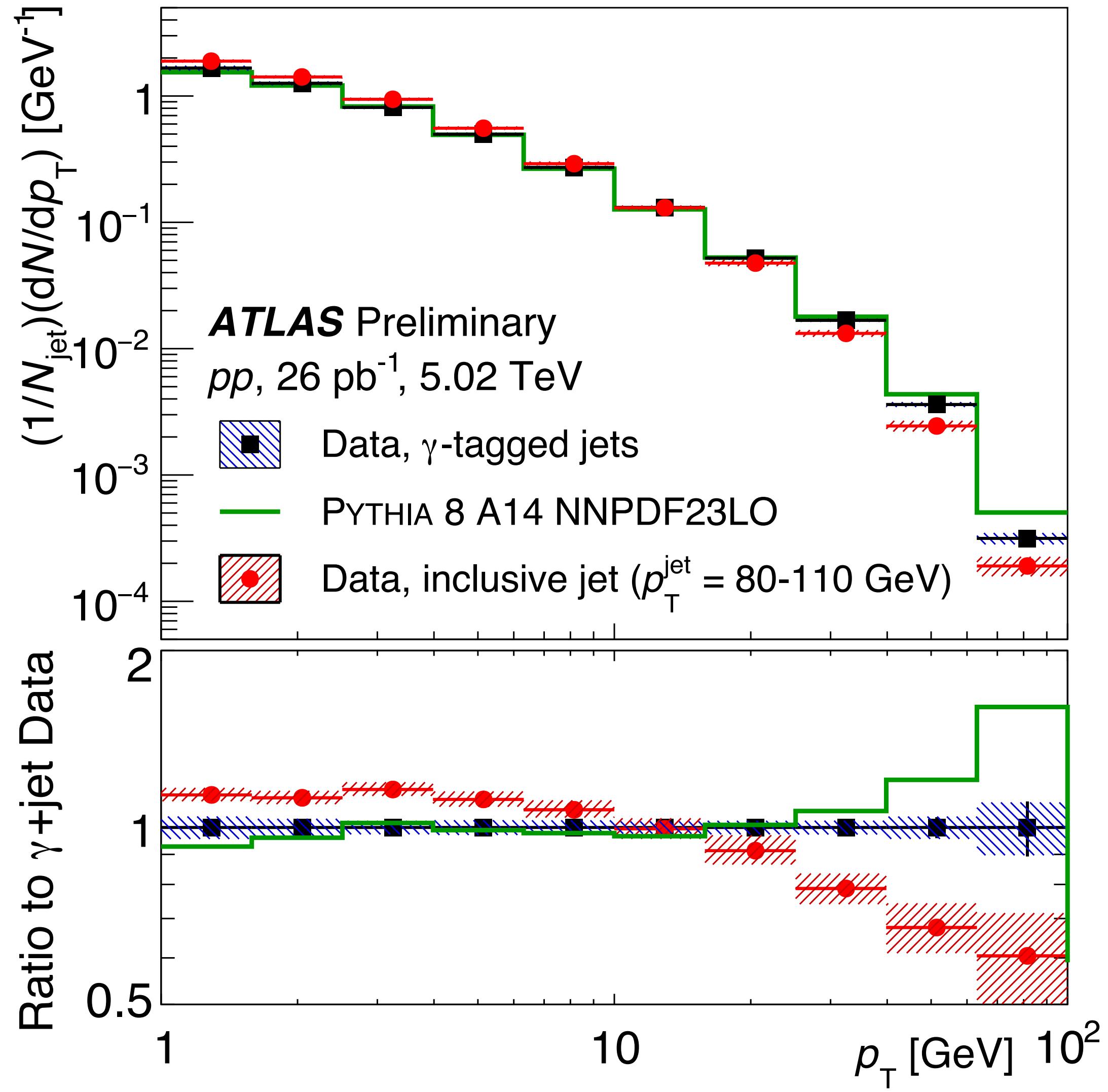




$D(p_T)$

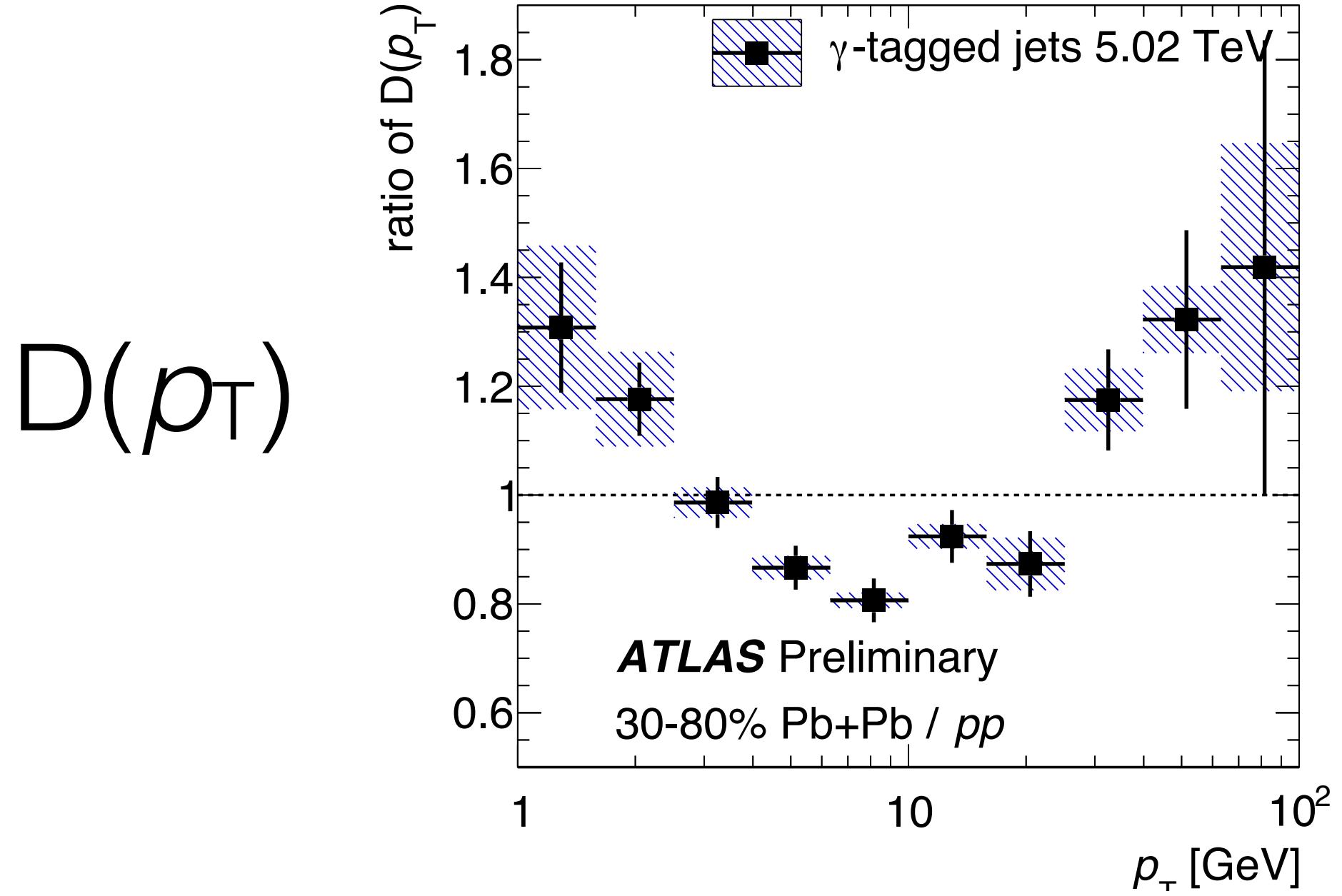


$D(z)$

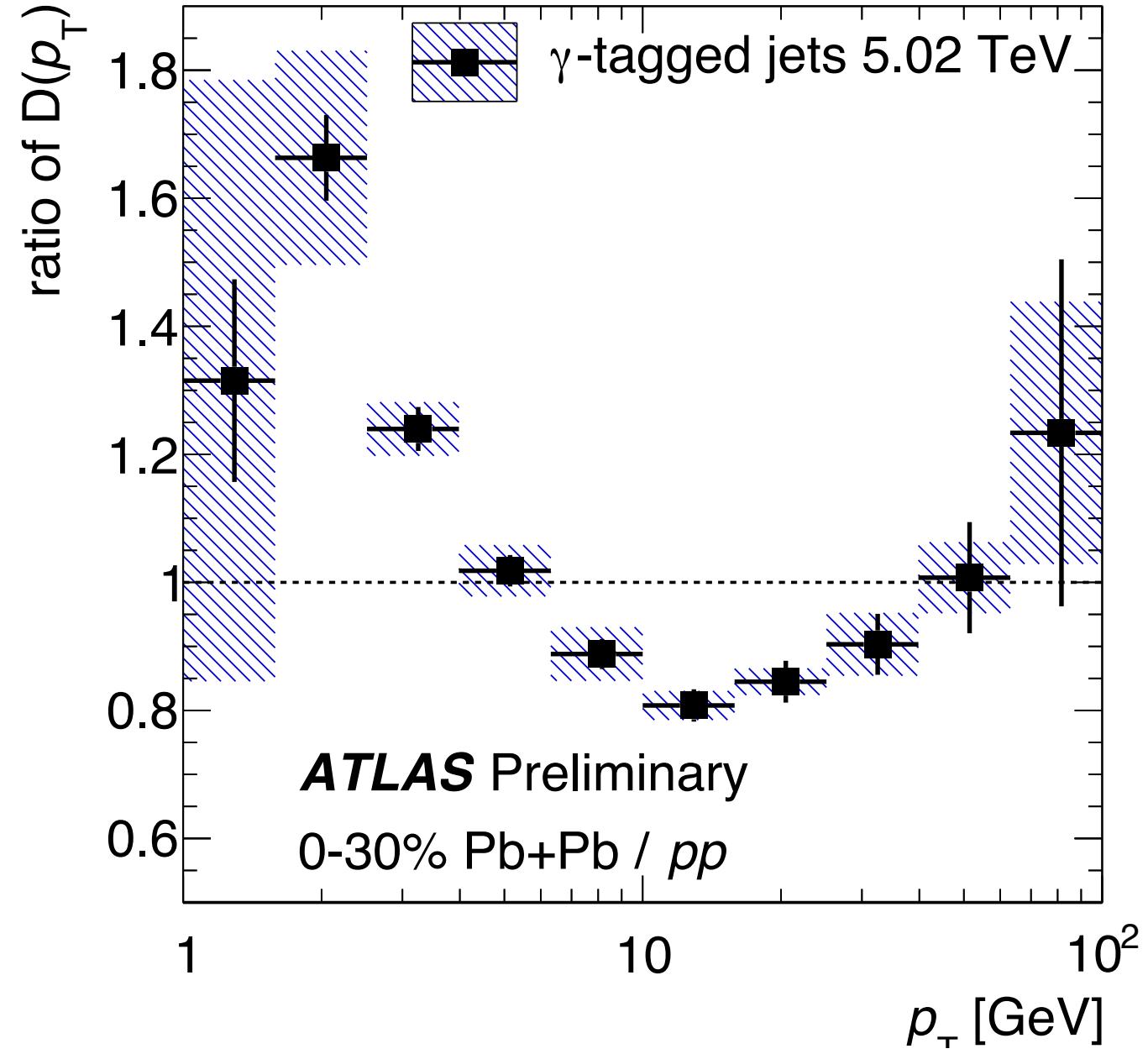


γ -tagged

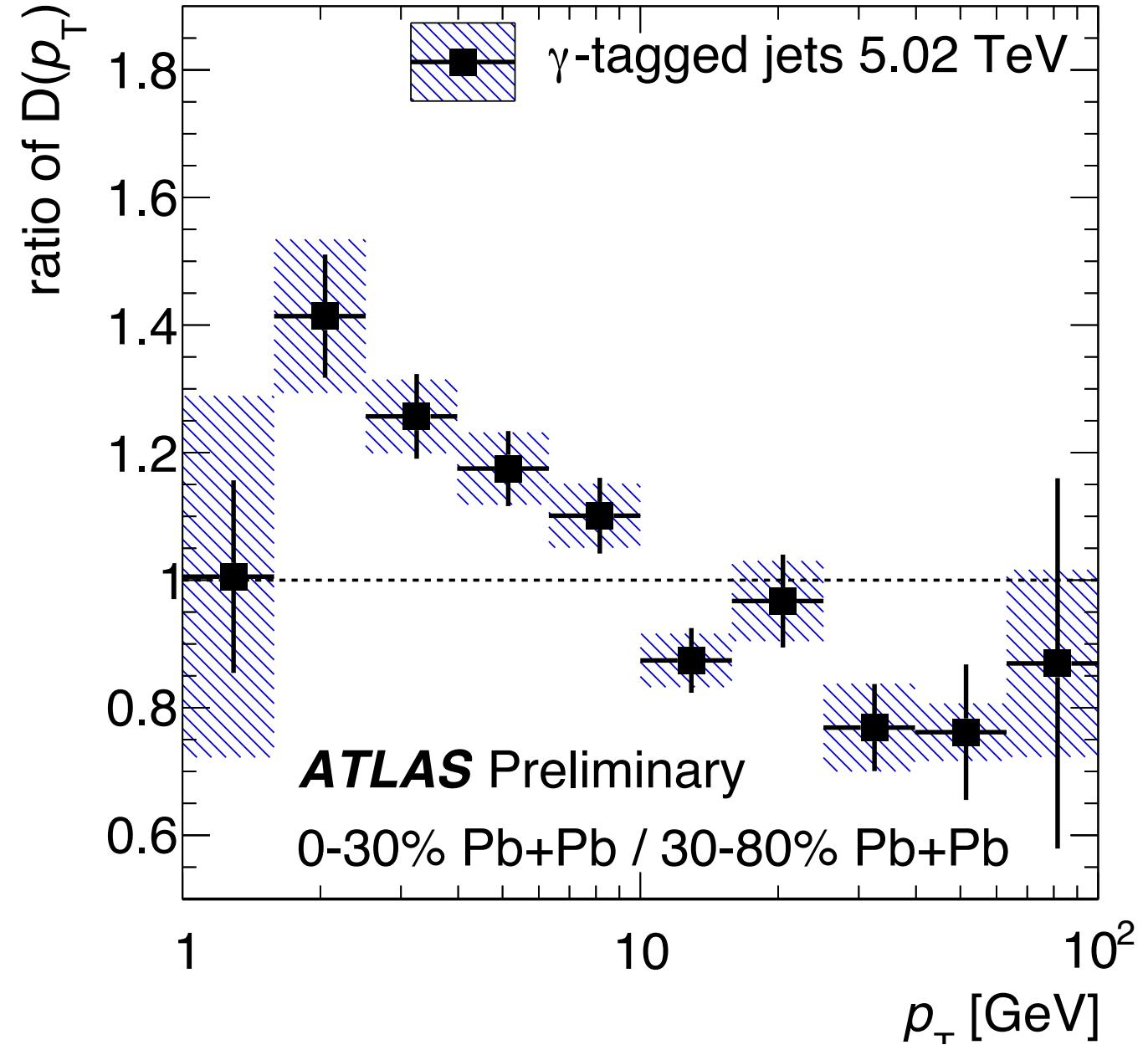
30-80% / pp



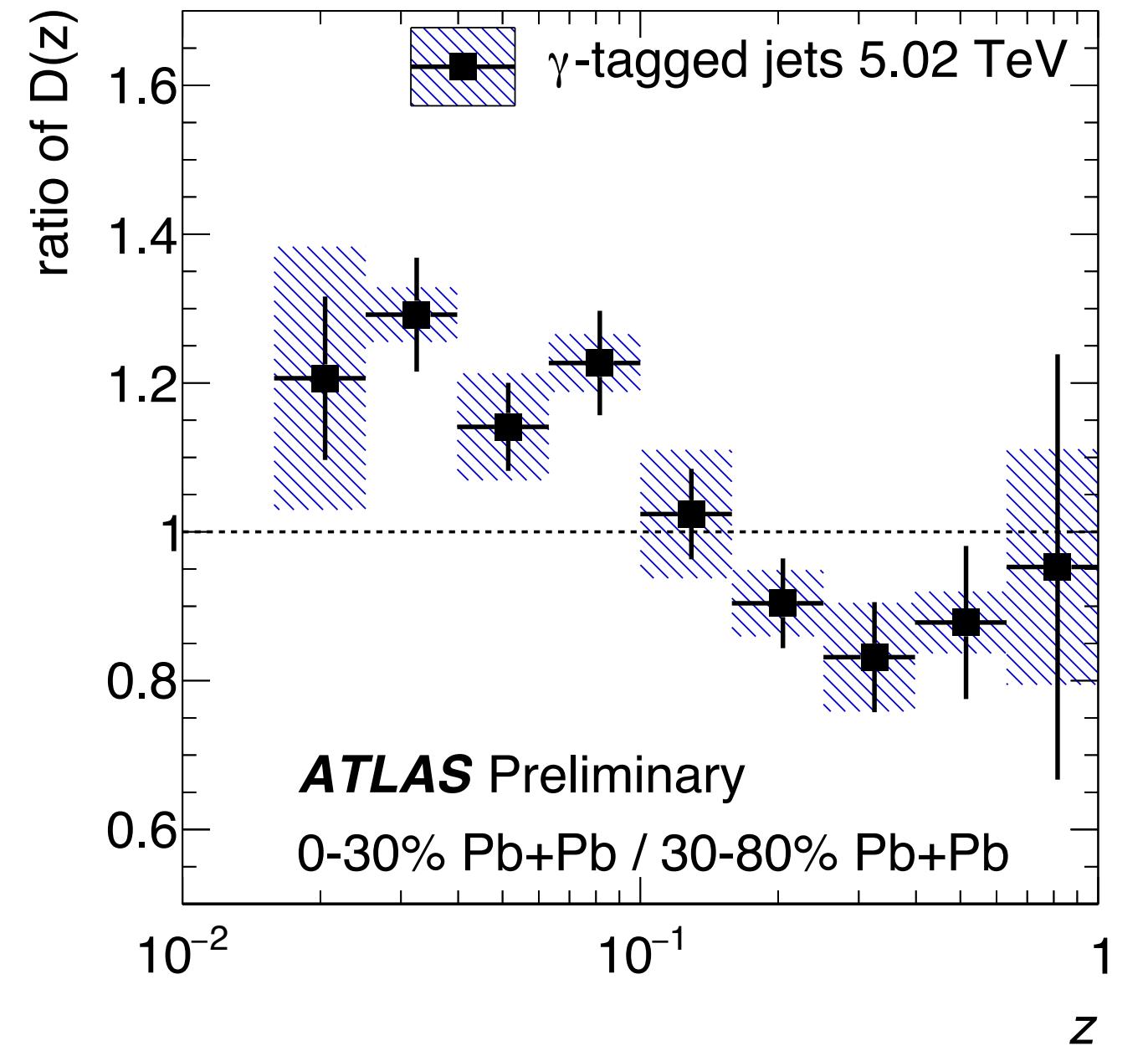
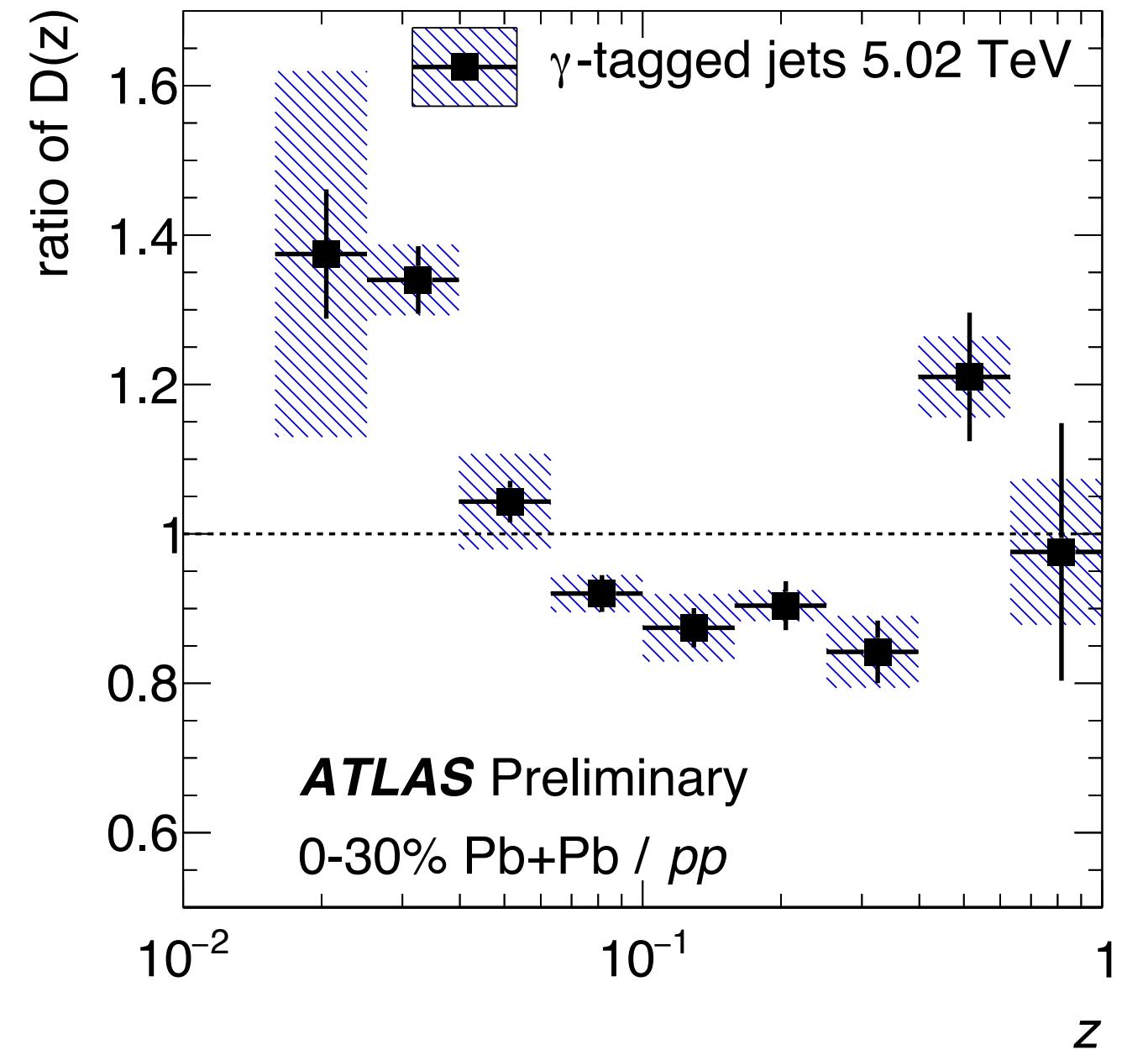
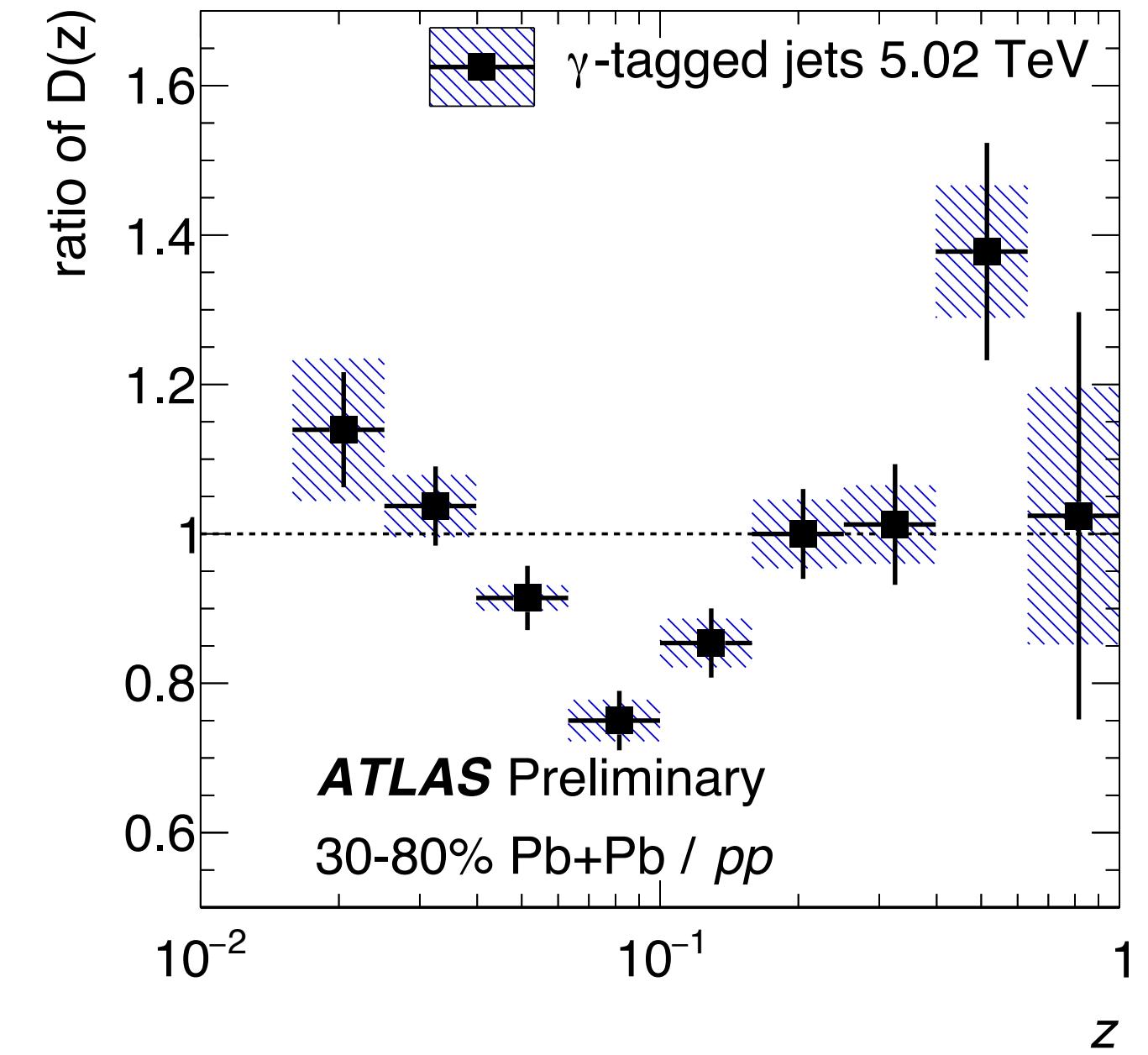
0-30% / pp



0-30% / 30-80%



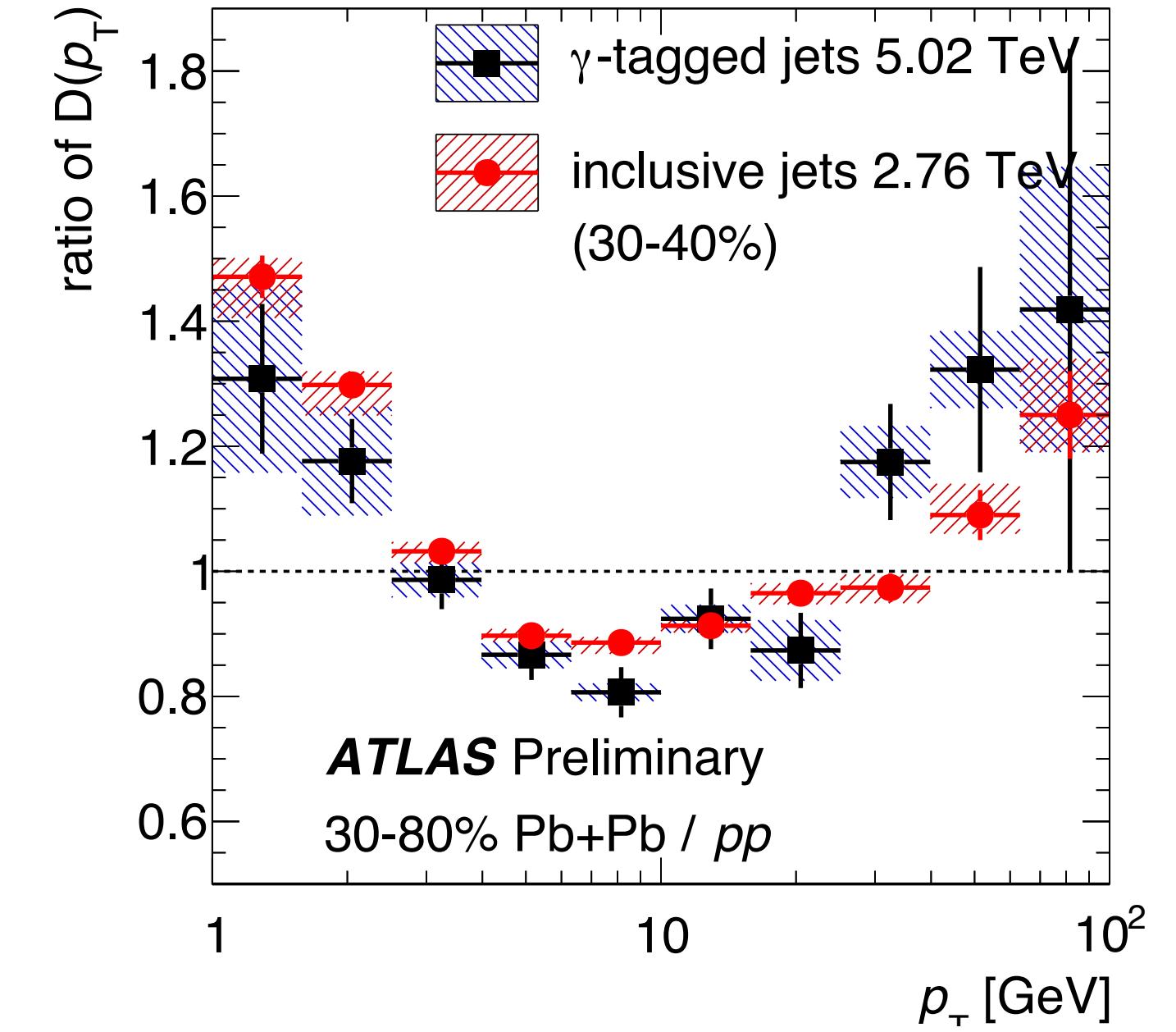
D(z)



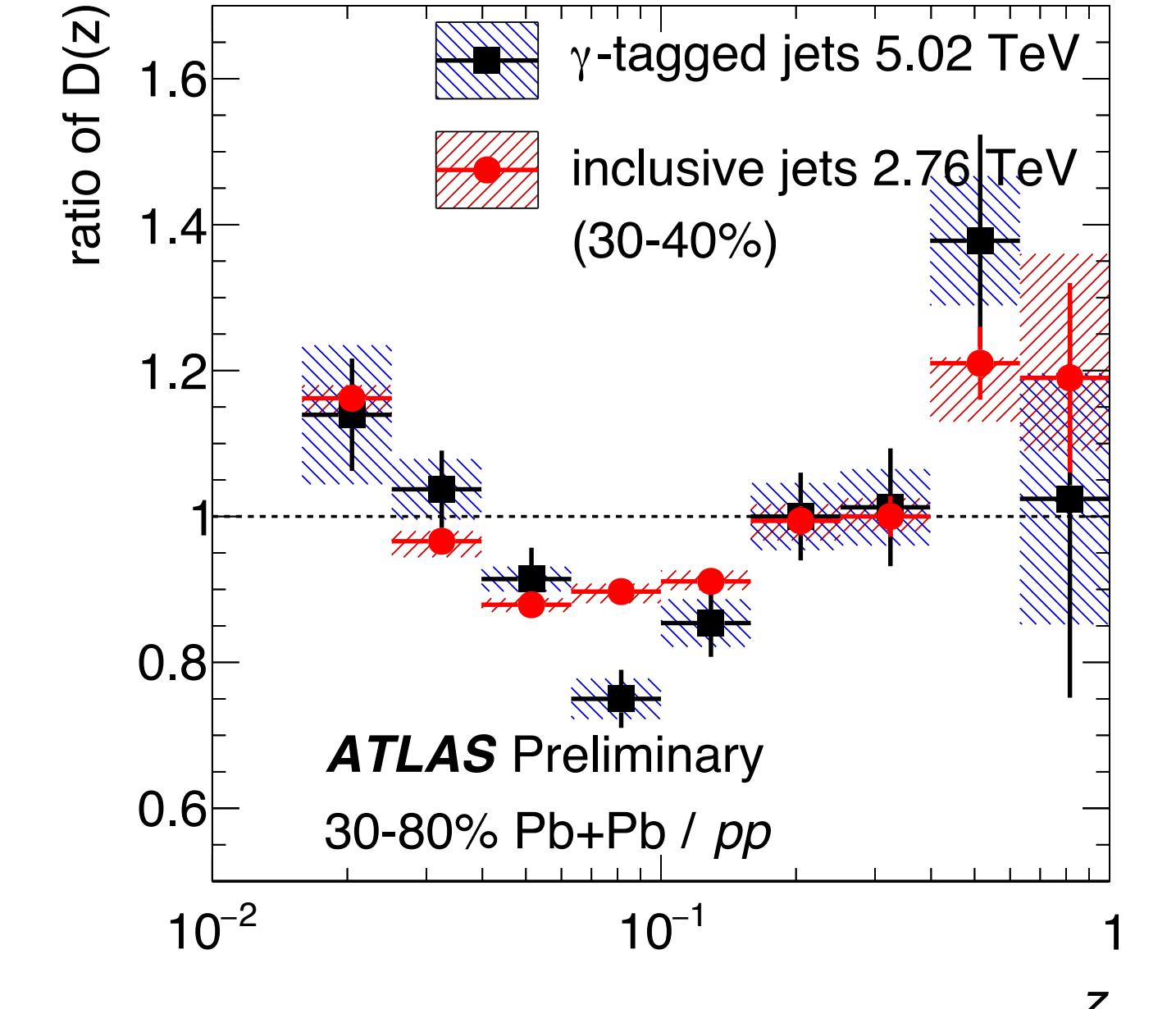
**γ -tagged
inclusive**

30-80% / pp

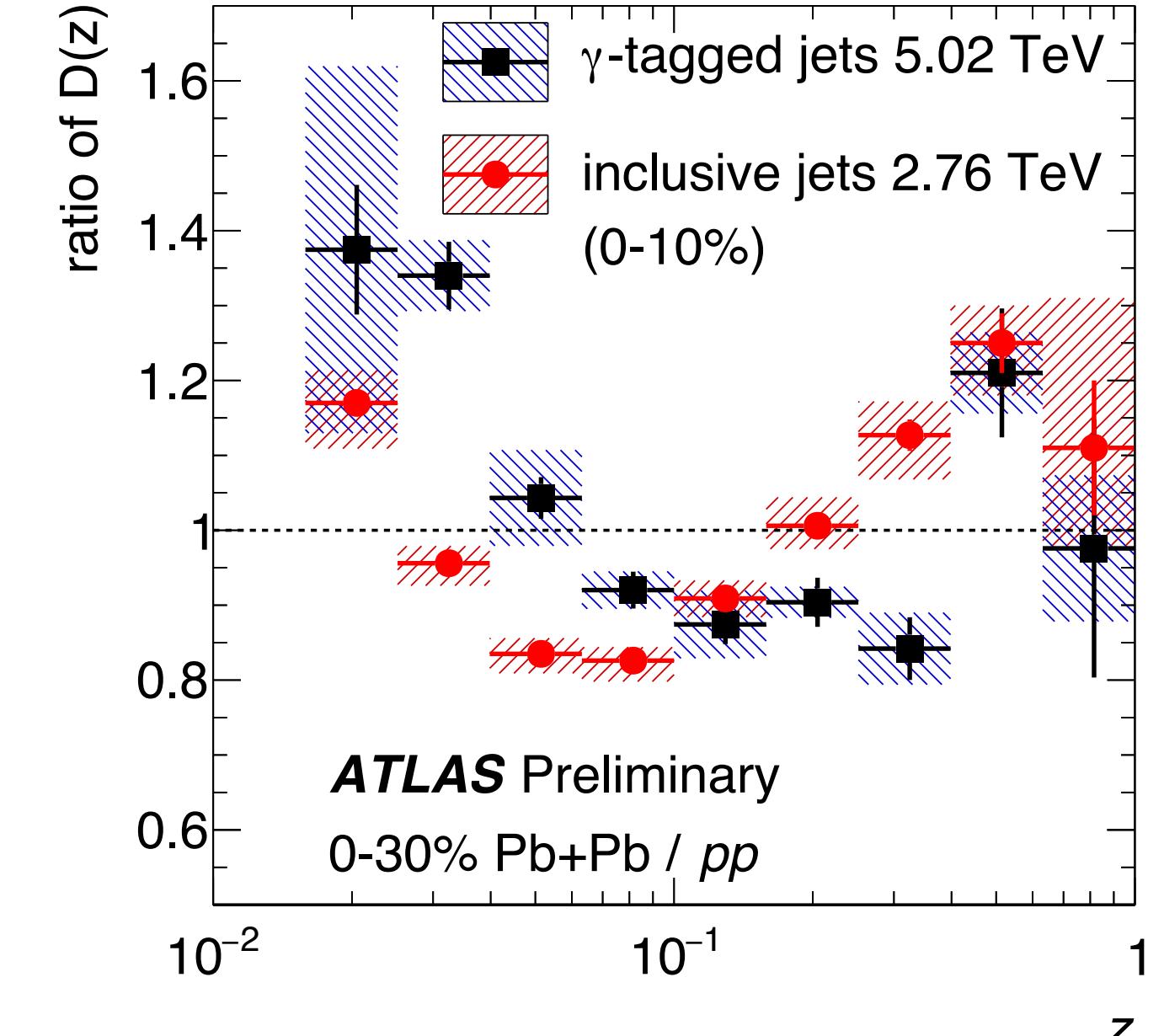
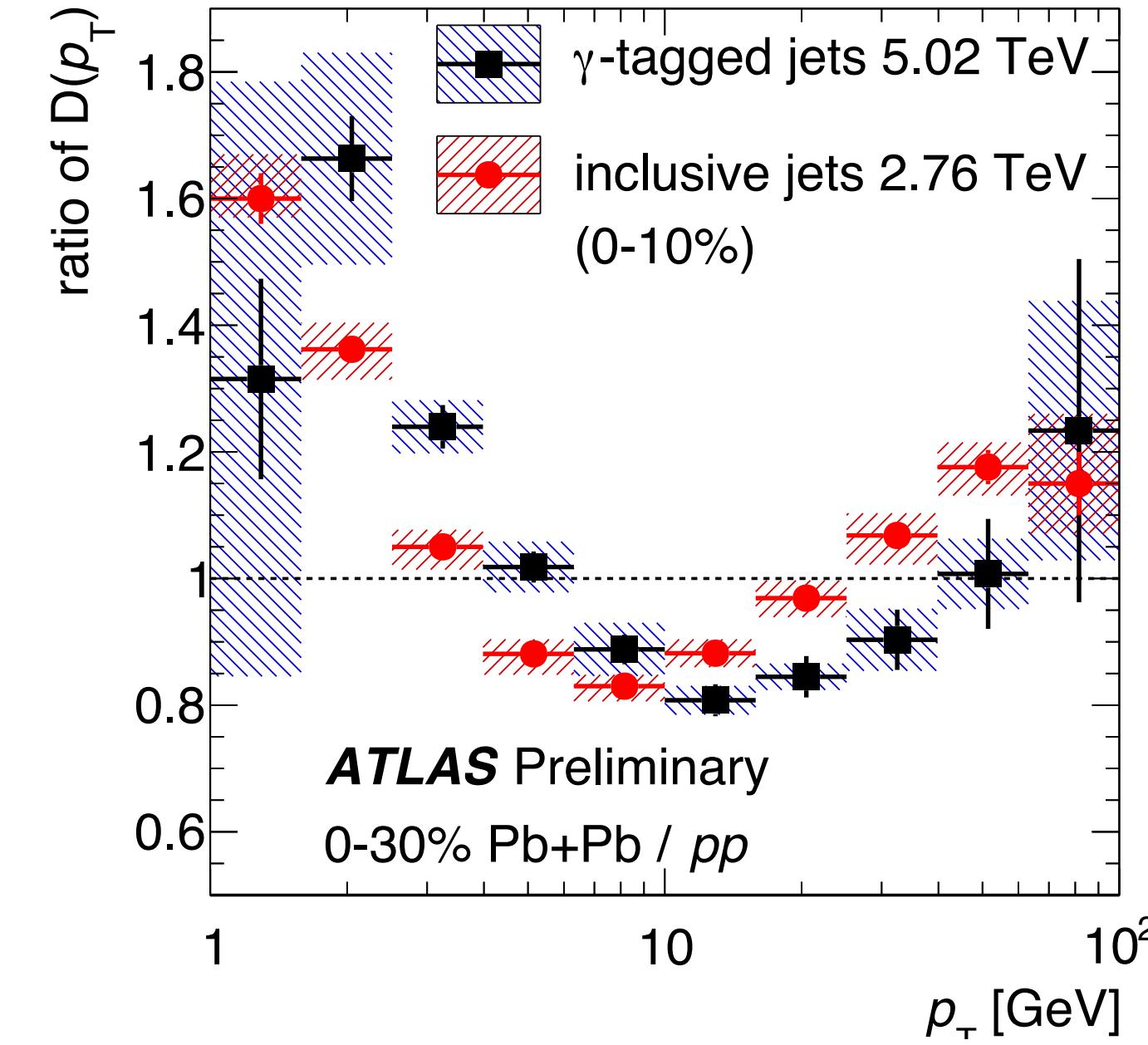
$D(p_T)$



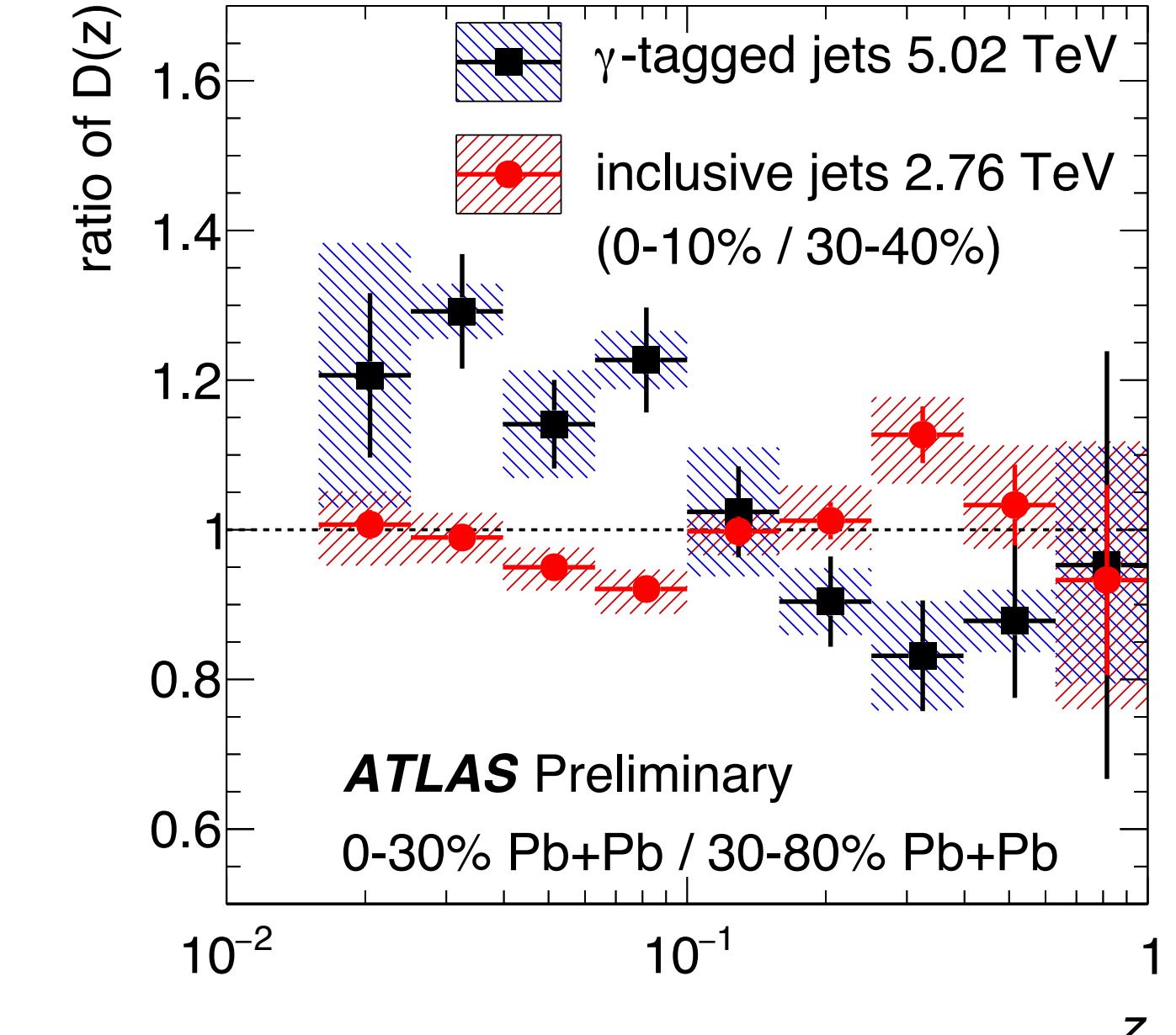
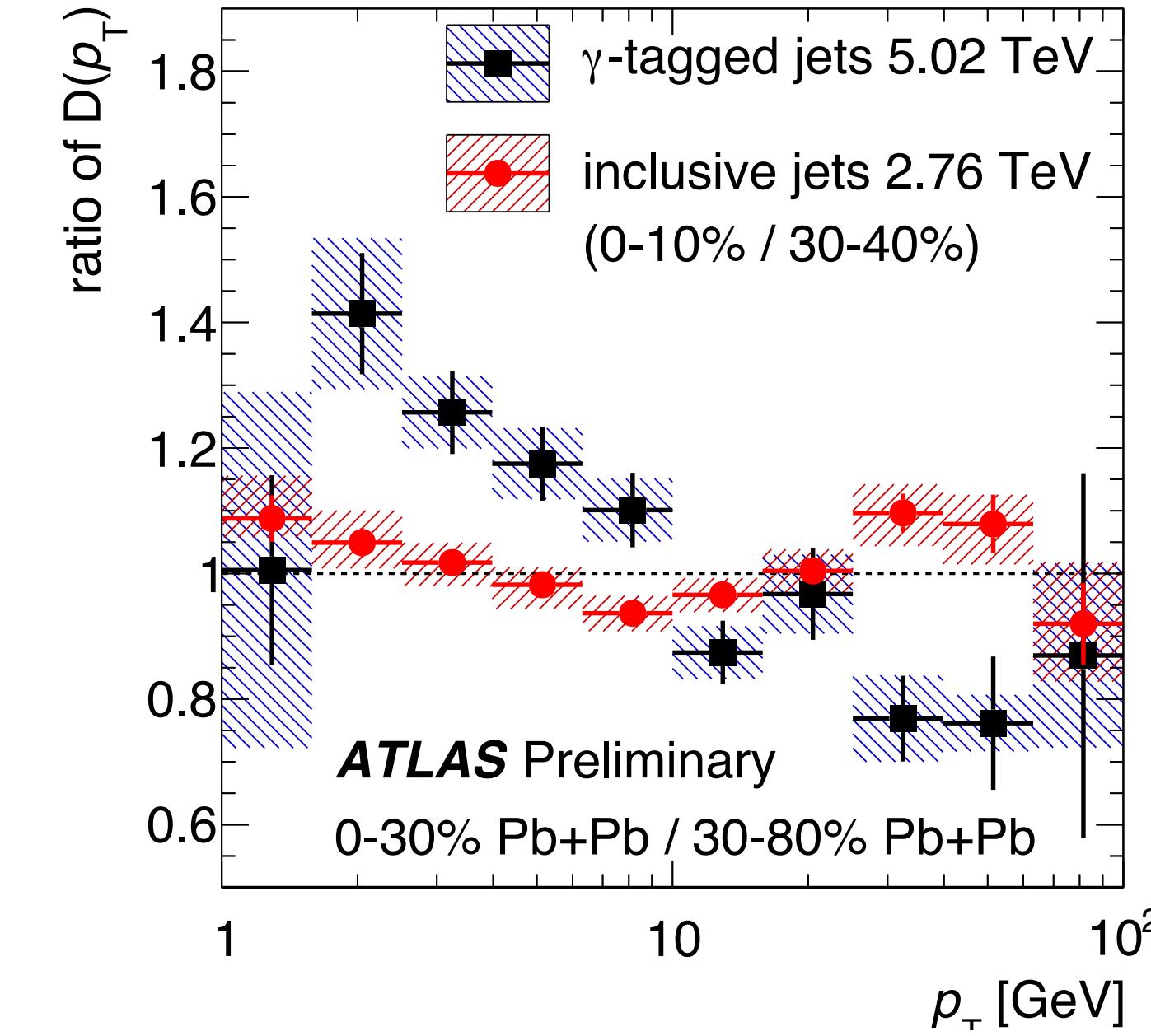
$D(z)$

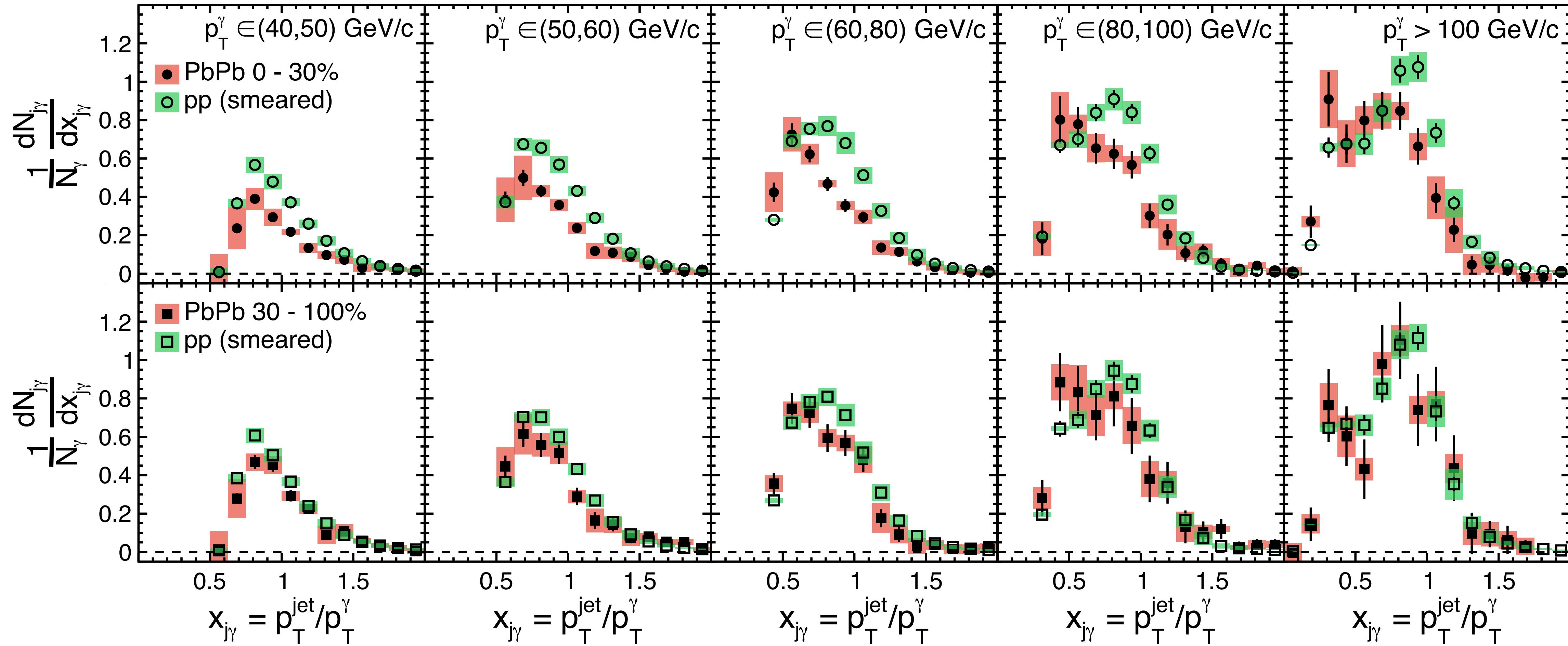


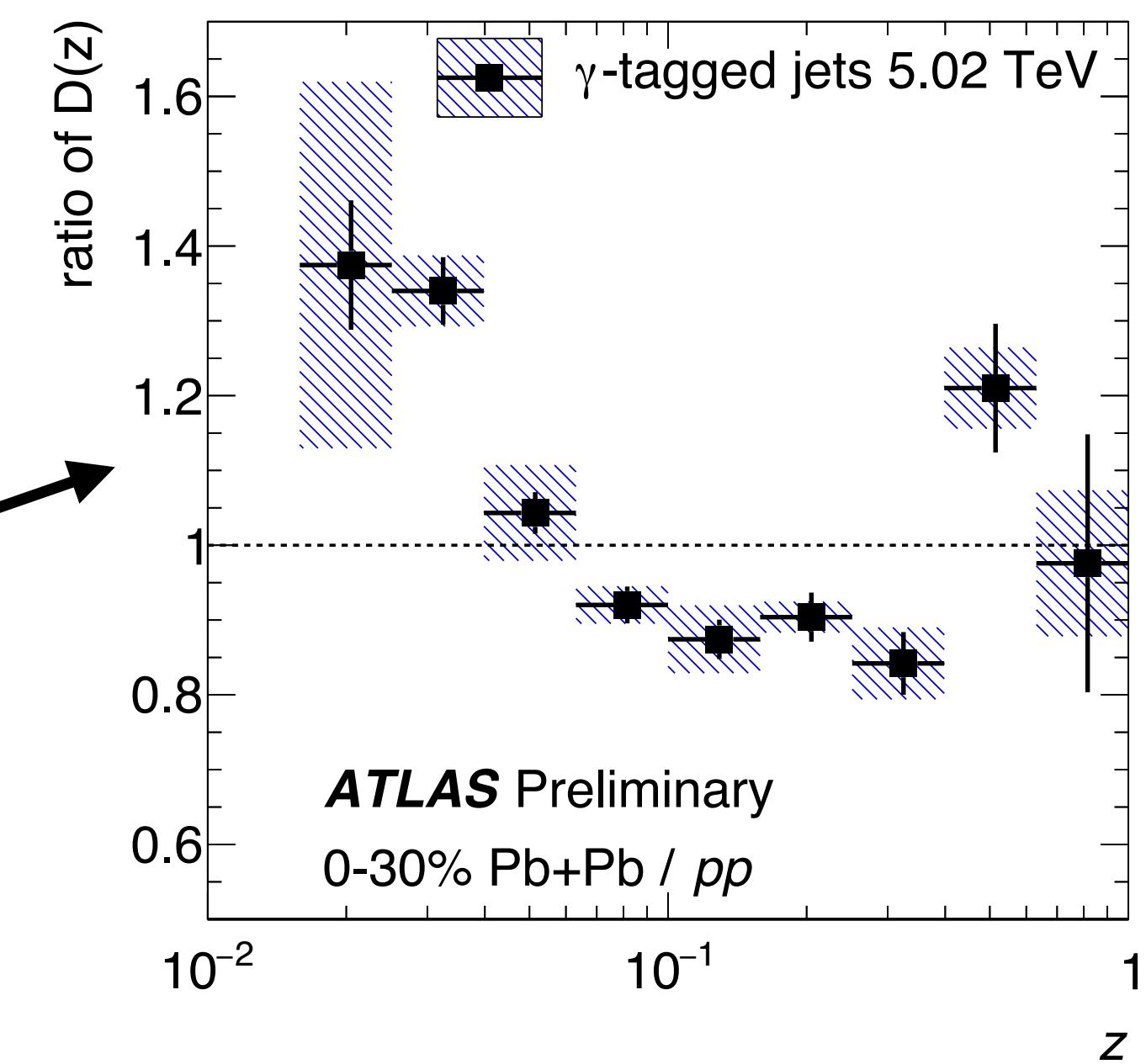
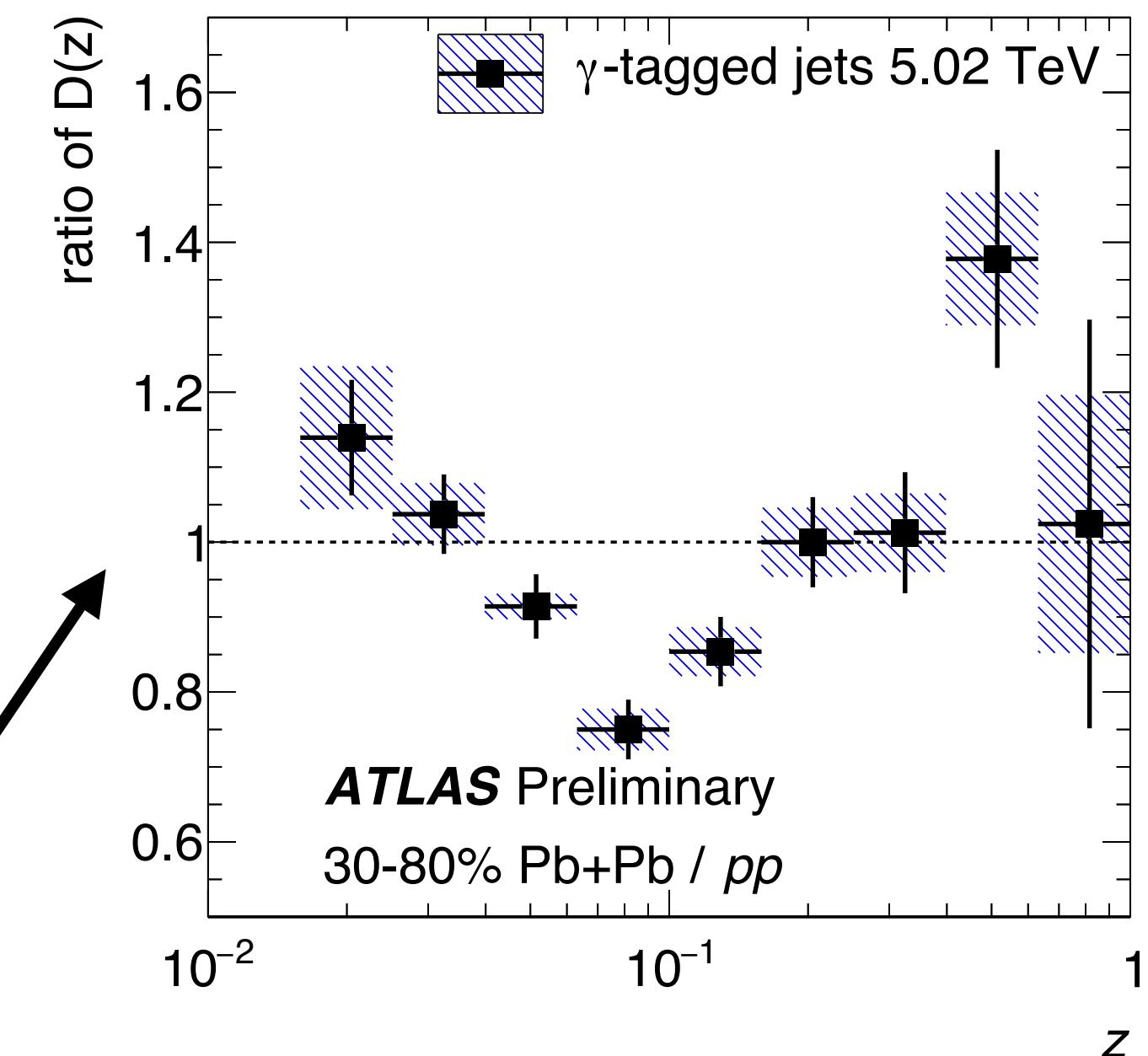
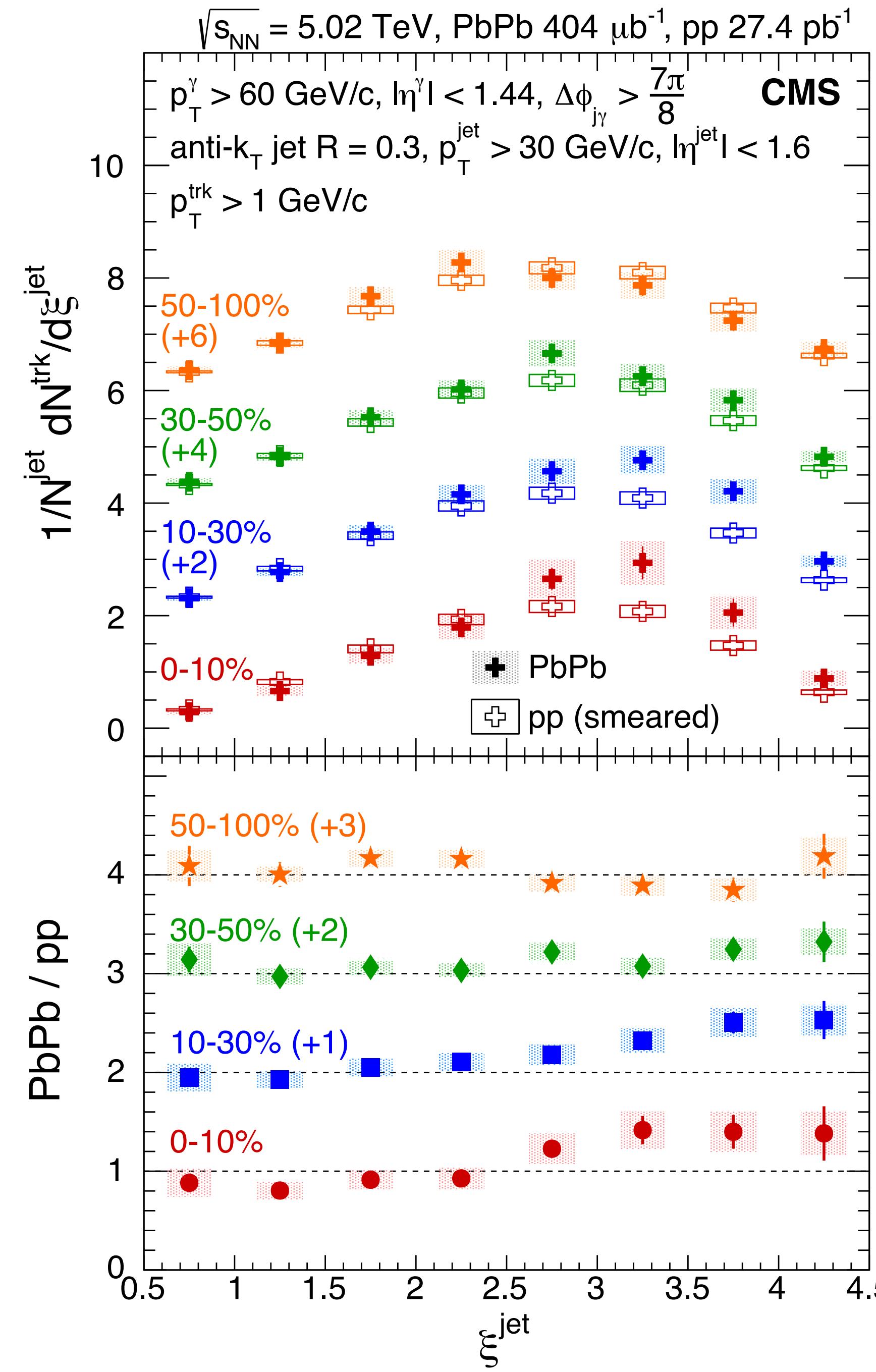
0-30% / pp

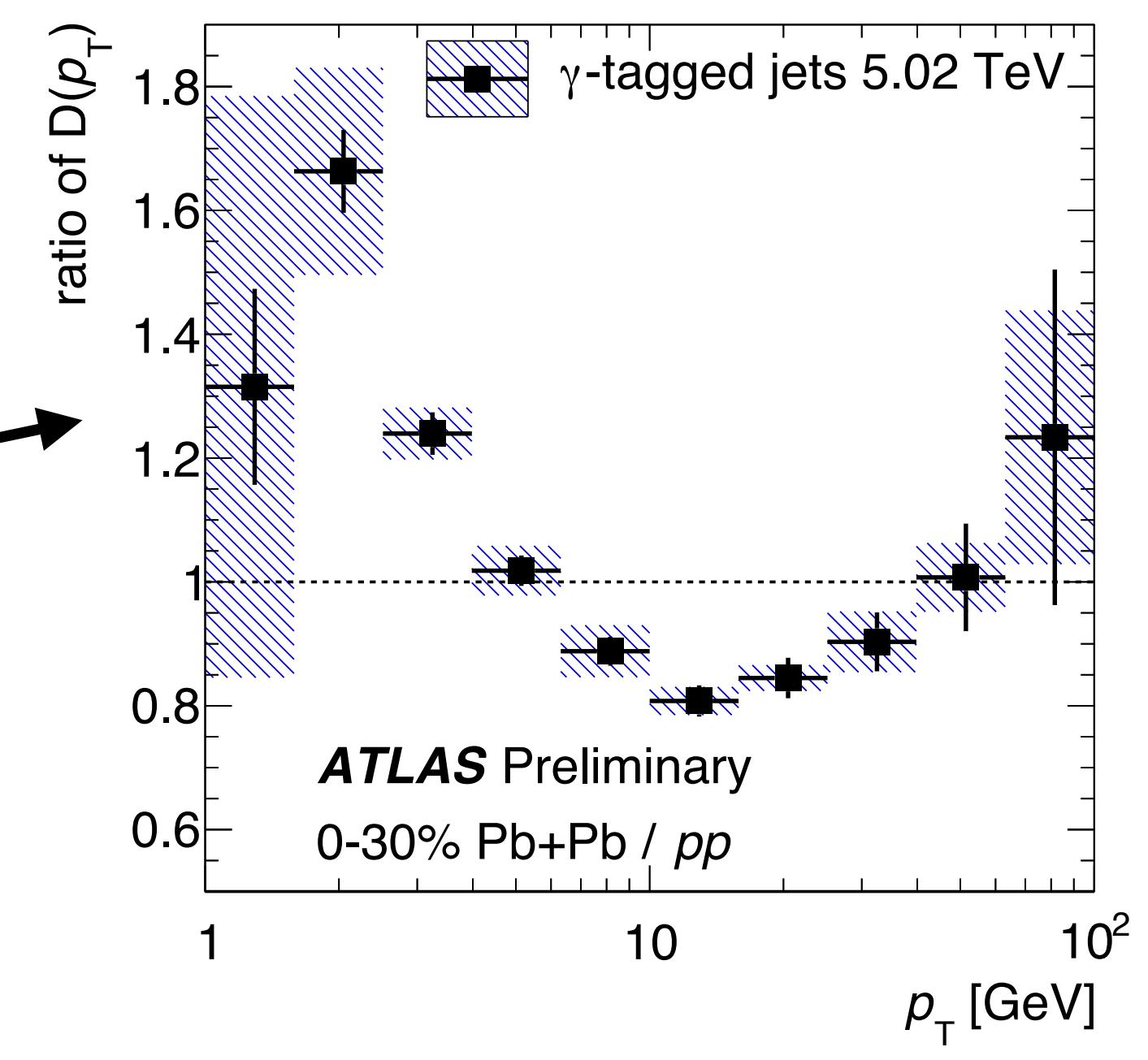
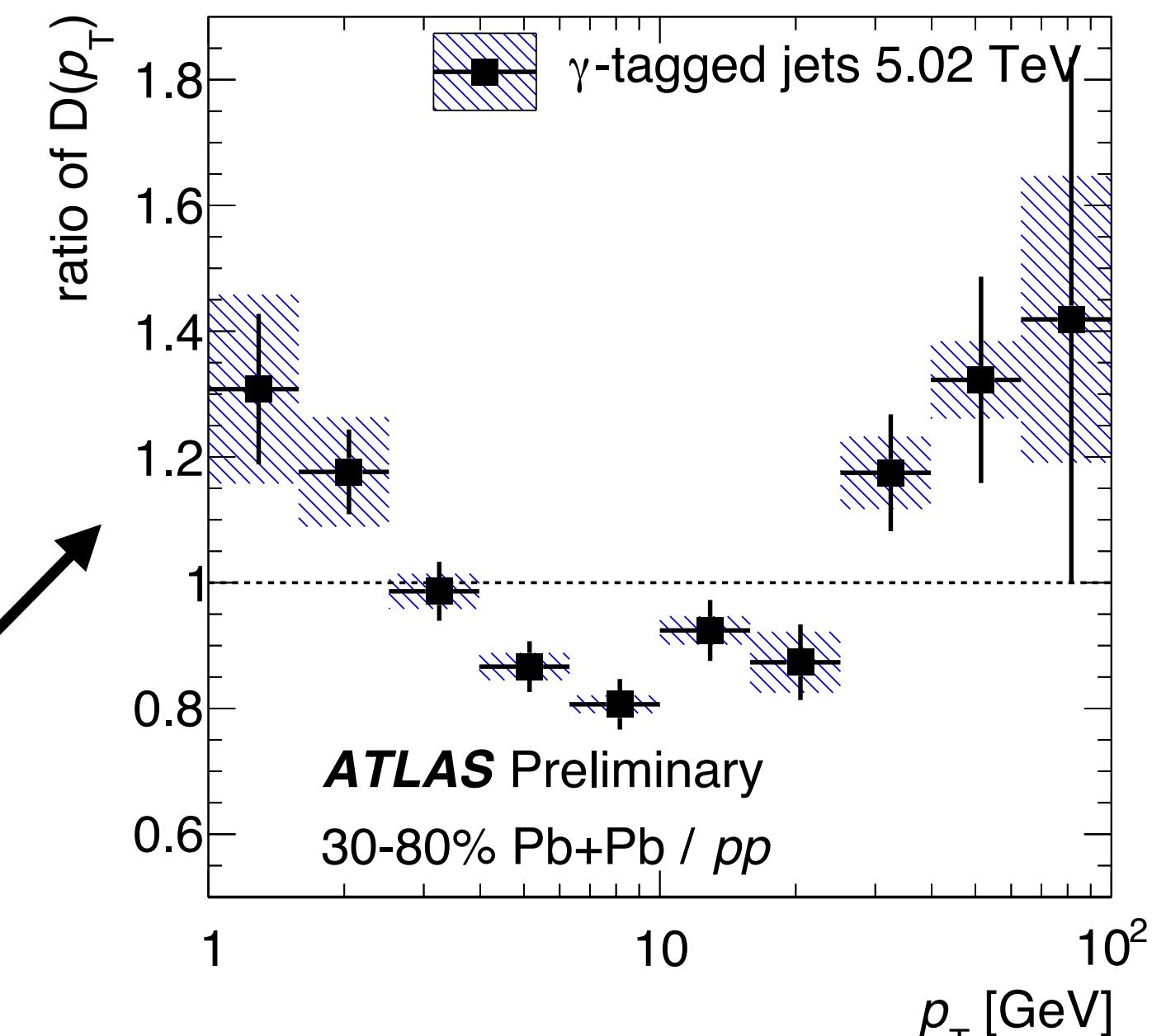
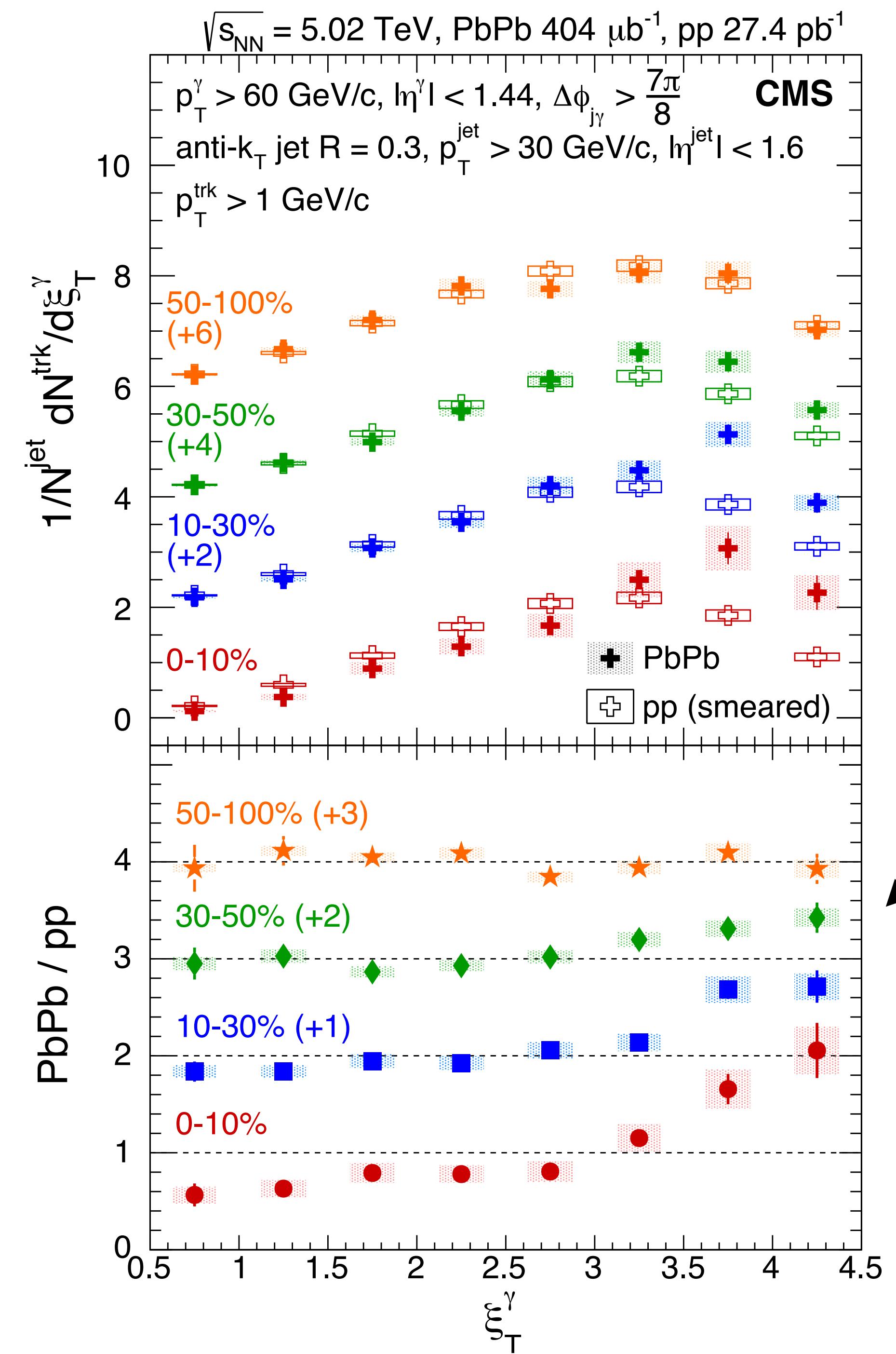


0-30% / 30-80%

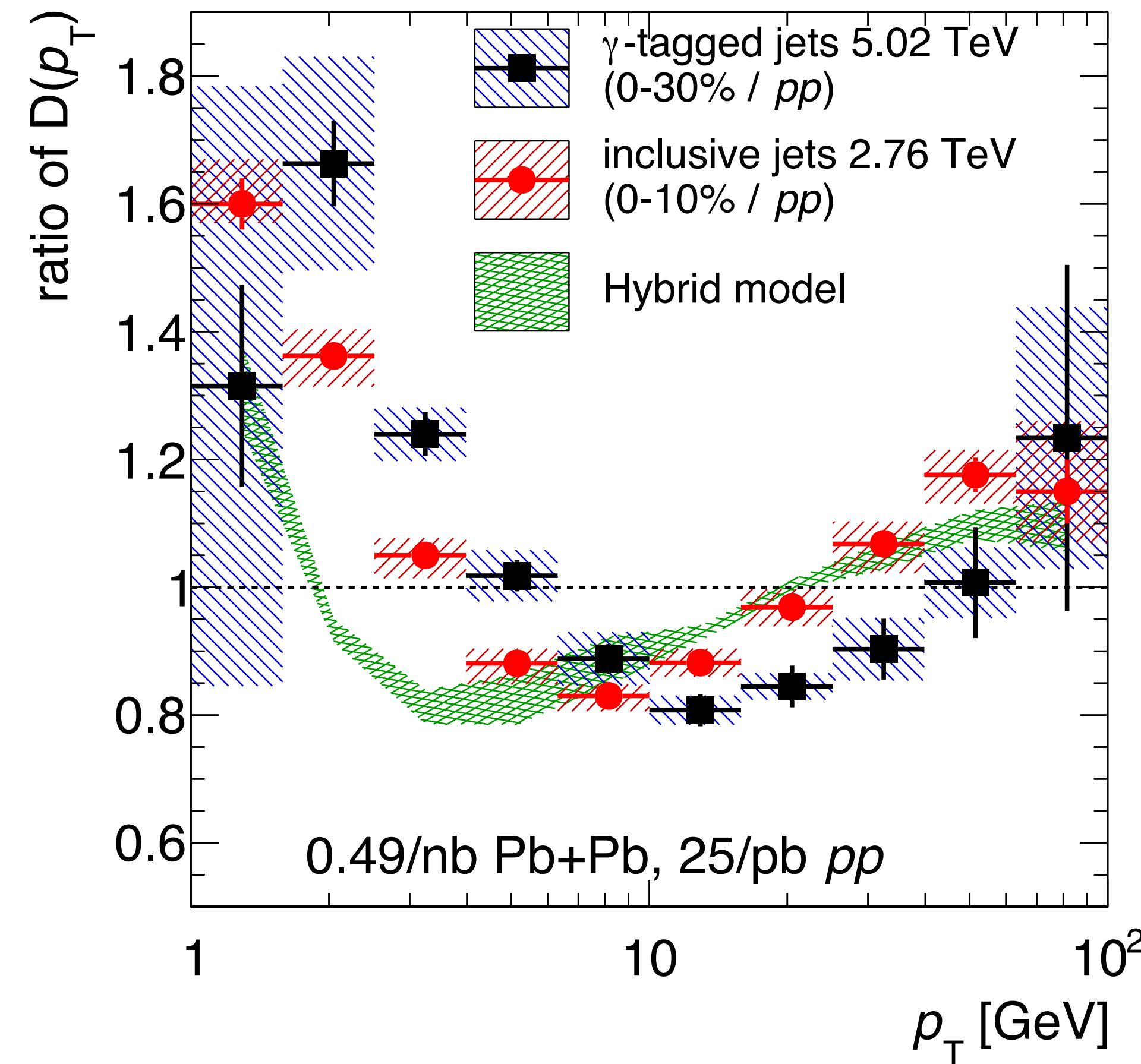


CMSanti- k_T jet $R = 0.3$, $p_T^{\text{jet}} > 30 \text{ GeV}/c$, $|\eta^{\text{jet}}| < 1.6$, $|\eta^\gamma| < 1.44$, $\Delta\phi_{j\gamma} > \frac{7\pi}{8}$, $\sqrt{s_{\text{NN}}} = 5.02 \text{ TeV}$, PbPb $404 \mu\text{b}^{-1}$, pp 27.4 pb^{-1} 

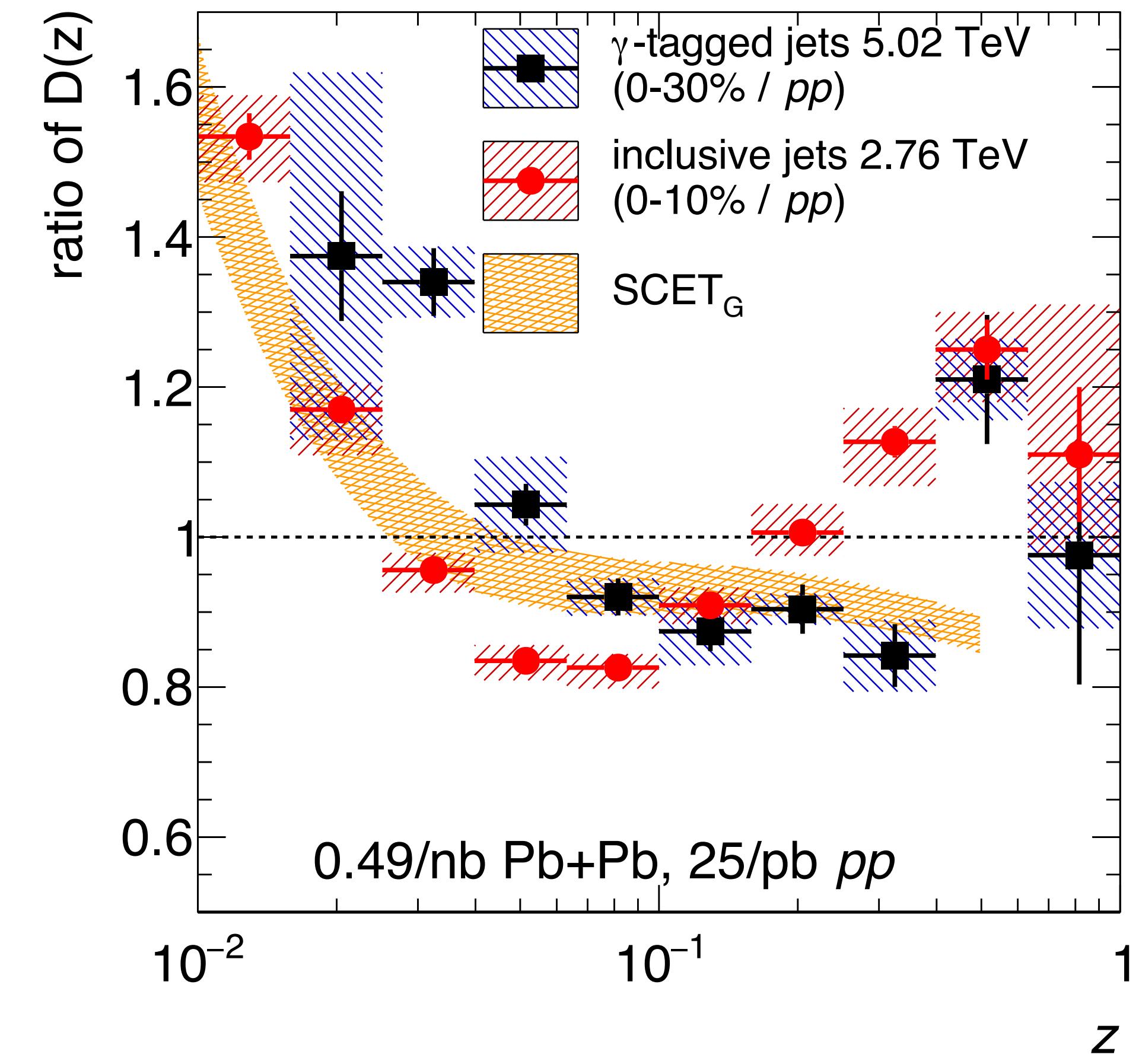




Teaser comparisons to theory...



Hybrid model (0-30%, vs. p_T)
with back-reaction



SCET_G calculation (0-30%, vs. z)

