

# Energy loss and modification of photon-tagged jets with ATLAS

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*Aix-Les-Bains, France*



Run: 286834

Event: 124877733

2015-11-28 01:15:42 CEST

Pb+Pb  $\sqrt{s_{NN}} = 5.02 \text{ TeV}$

photon + multijet event

$\sum E_T^{\text{FCal}} = 4.06 \text{ TeV}$



$p_T = 200 \text{ GeV}$   
photon

EMCal

HCal

balancing  
jet(s)?

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



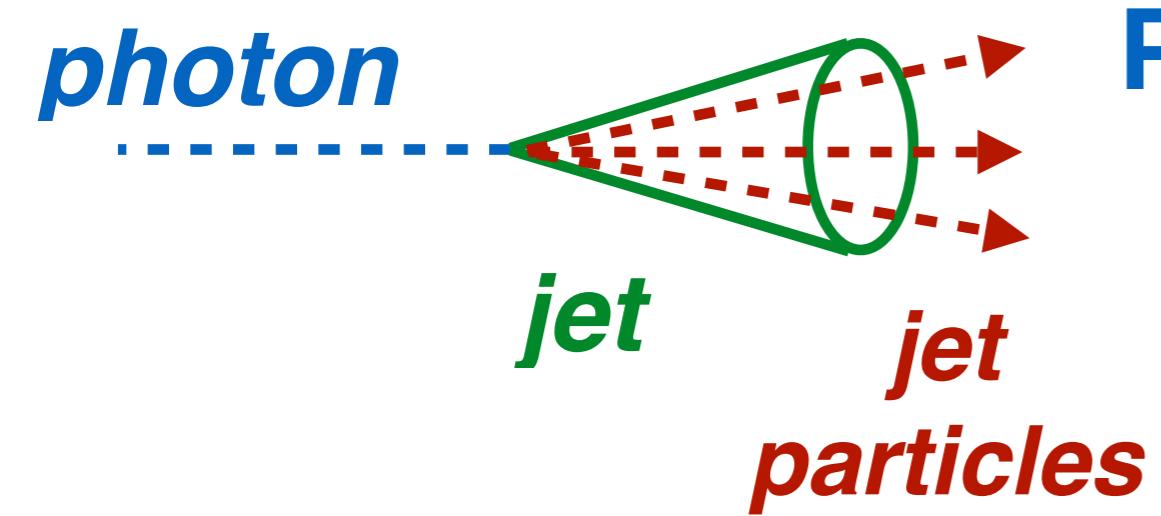
**Photon+jet**  $p_T$ -balance  
→  $x_{J\gamma} = p_T^{jet} / p_T^\gamma$  (for  $\Delta\phi > 7\pi/8$ )

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**Photon+jet  $p_T$ -balance**  
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How is the parton shower in cone modified by medium?



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

→  $D(p_T^h)$  or  $D(z = p_T^h / p_T^{jet})$

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

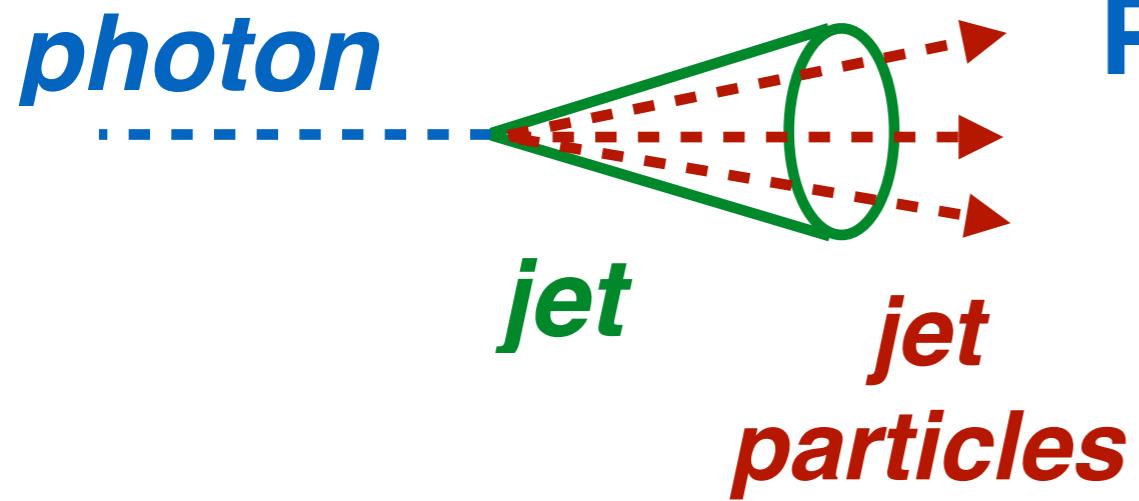


**Photon+jet  $p_T$ -balance**

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

`nucl-ex/1809.07280`

How is the parton shower in cone modified by medium?



**Photon-tagged frag. function**

(with respect to the **jet**)

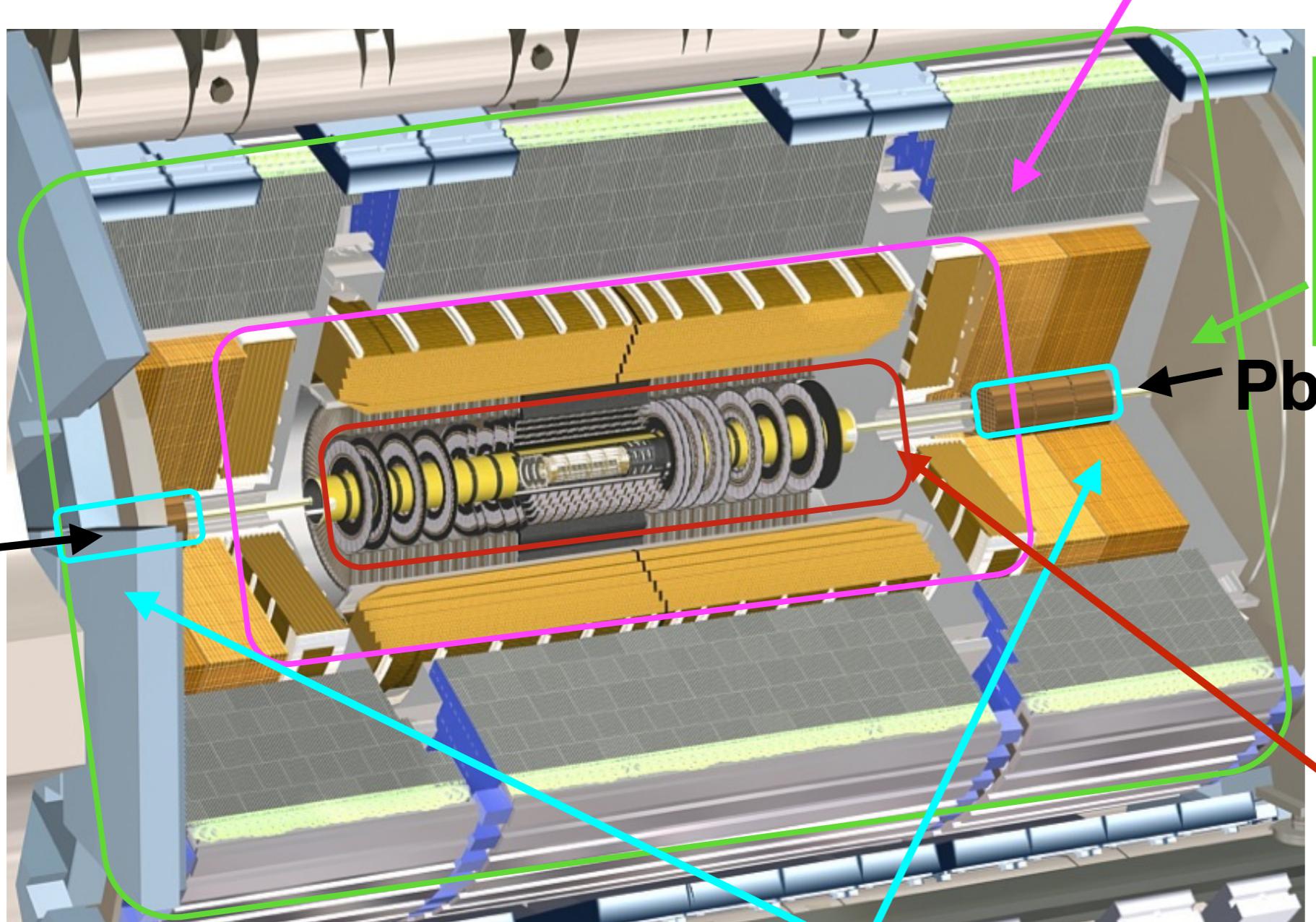
$$\rightarrow D(p_T^h) \text{ or } D(z = p_T^h / p_T^{\text{jet}})$$

`ATLAS-CONF-2017-074`



# Photons, jets, hadrons

**M. Spousta Wed. 11:05**  
Photons in EMCal  
 $p_T > 63.1 \text{ GeV}$ ,  $|\eta| < 2.37$



**R. Slovak Thu. 9:00**  
Jets in EM+HCals  
 $|\eta| < 2.8$   
 $p_T > 31.6 \text{ GeV}$

**A. Puri**  
**Thu. Plenary**  
Tracks in inner  
detector  
 $p_T > 1 \text{ GeV}$   
 $|\eta| < 2.5$

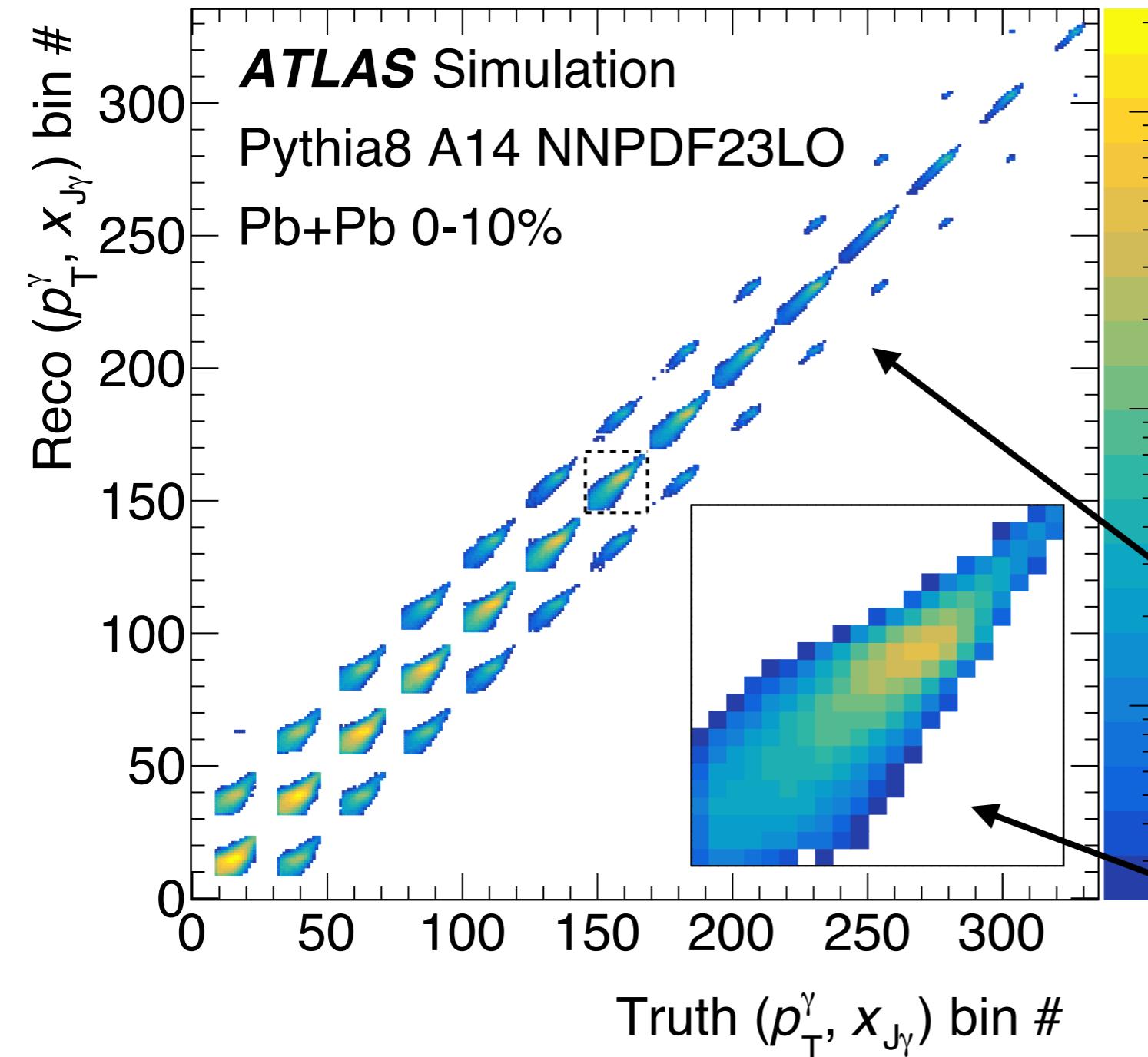
Centrality in  
FCal ( $3.2 < |\eta| < 4.9$ )

# Correction for detector effects

- 2-D unfolding in  $(p_T^\gamma, x_{J\gamma})$ 
  - $(p_T^{\text{jet}}, p_T^h)$  or  $(p_T^{\text{jet}}, z)$  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  $(p_T^{\gamma,\text{truth}}, p_T^{\gamma\text{reco}})$*



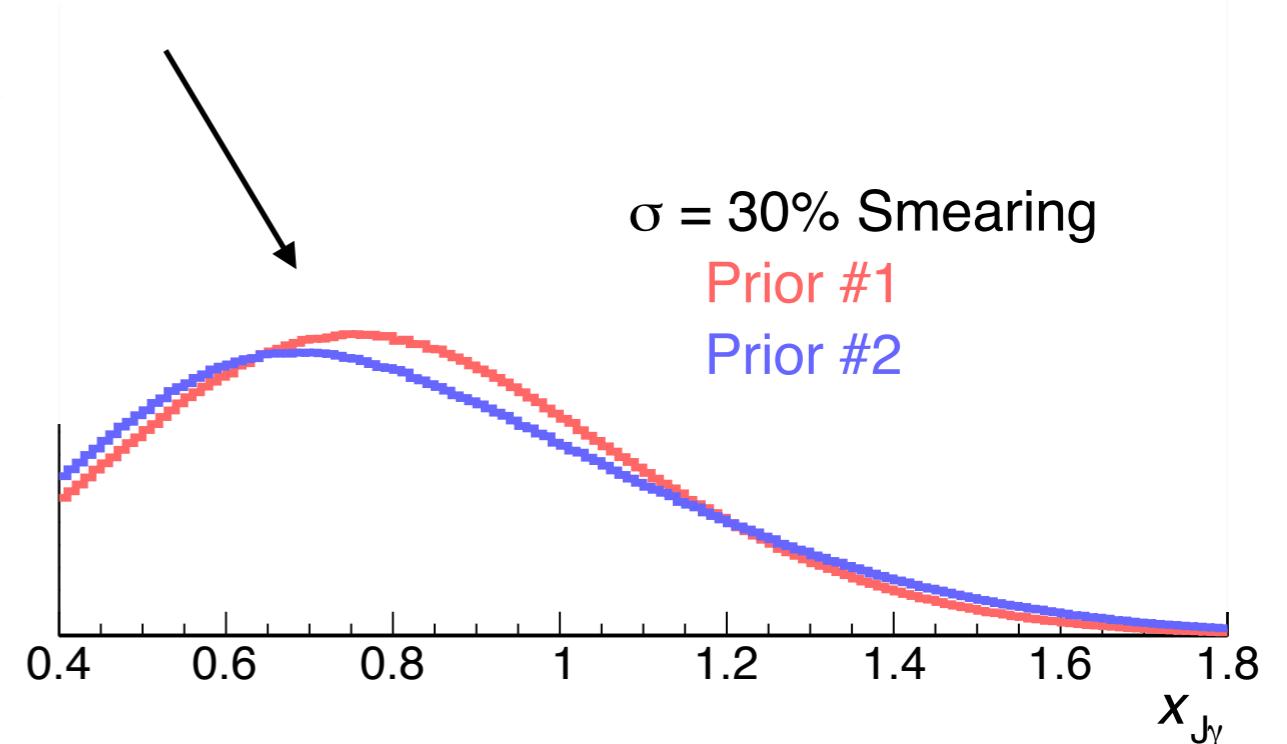
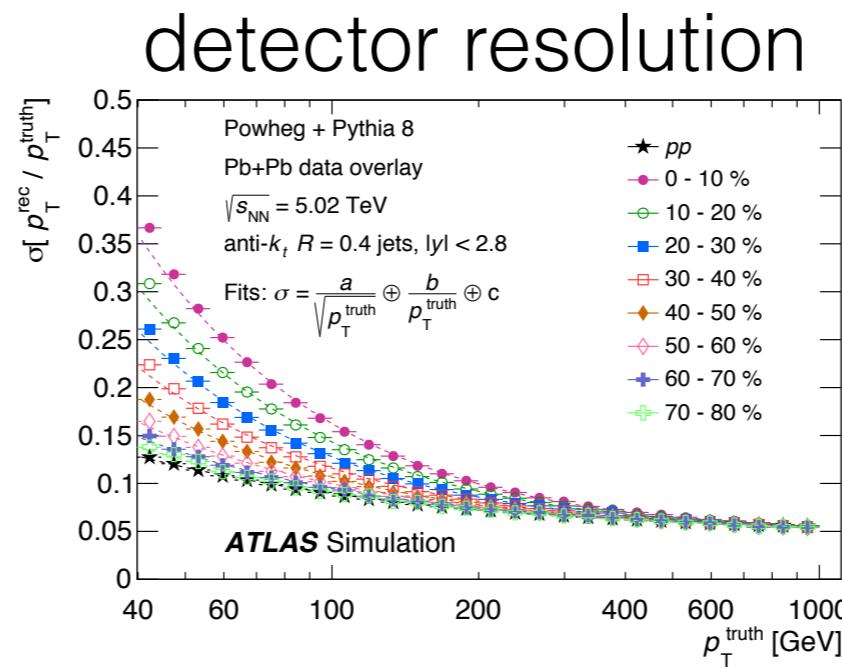
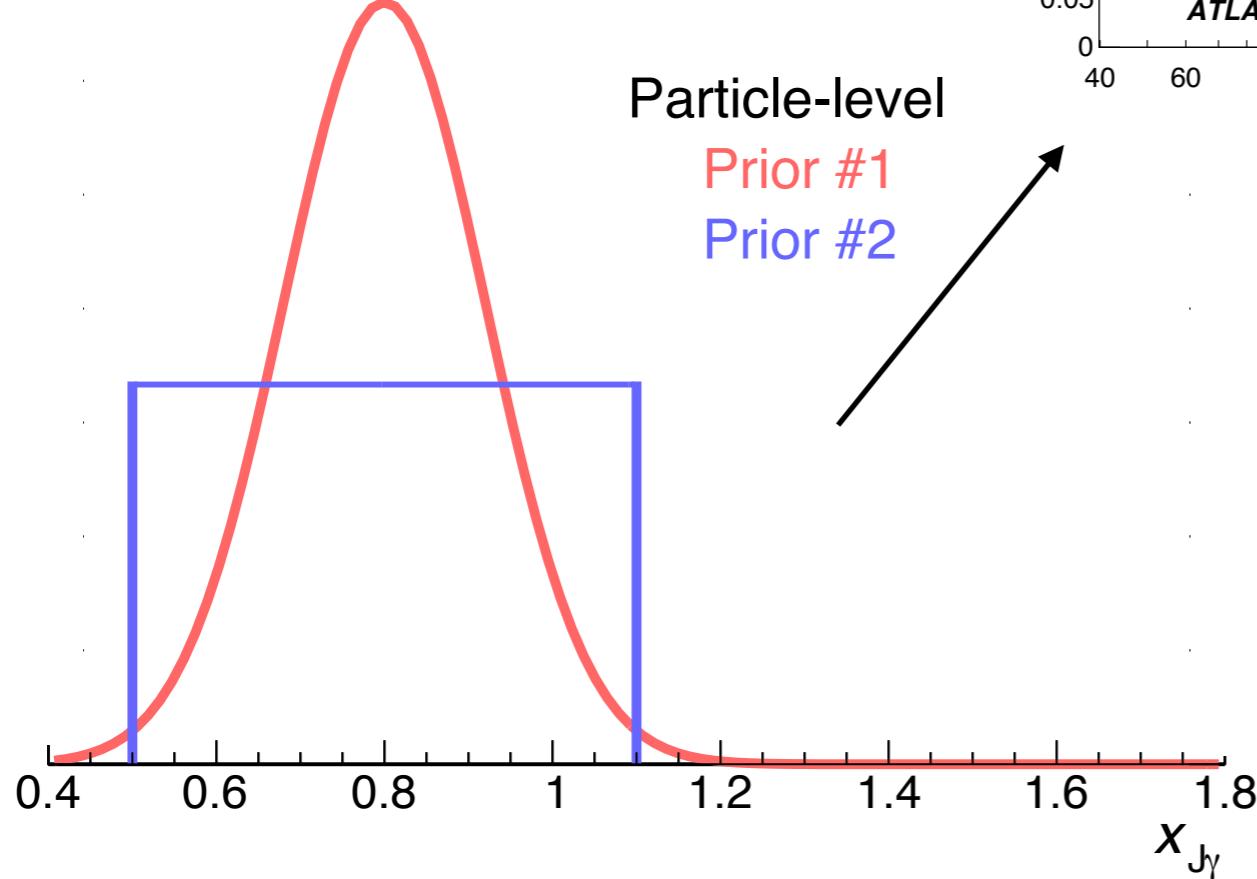
Final results at “detector-free” or “particle” level

- direct data-to-data comparisons, data-to-theory, LHC-to-future RHIC experiments (sPHENIX), etc., *without smearing*

# Crucial for understanding *distributions* of energy loss:

Milhano & Zapp hep-ph/1512.08107, Hu, Peng & Wang nucl-th/1808.05310, etc.

Very different  
particle-level  
distributions...



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

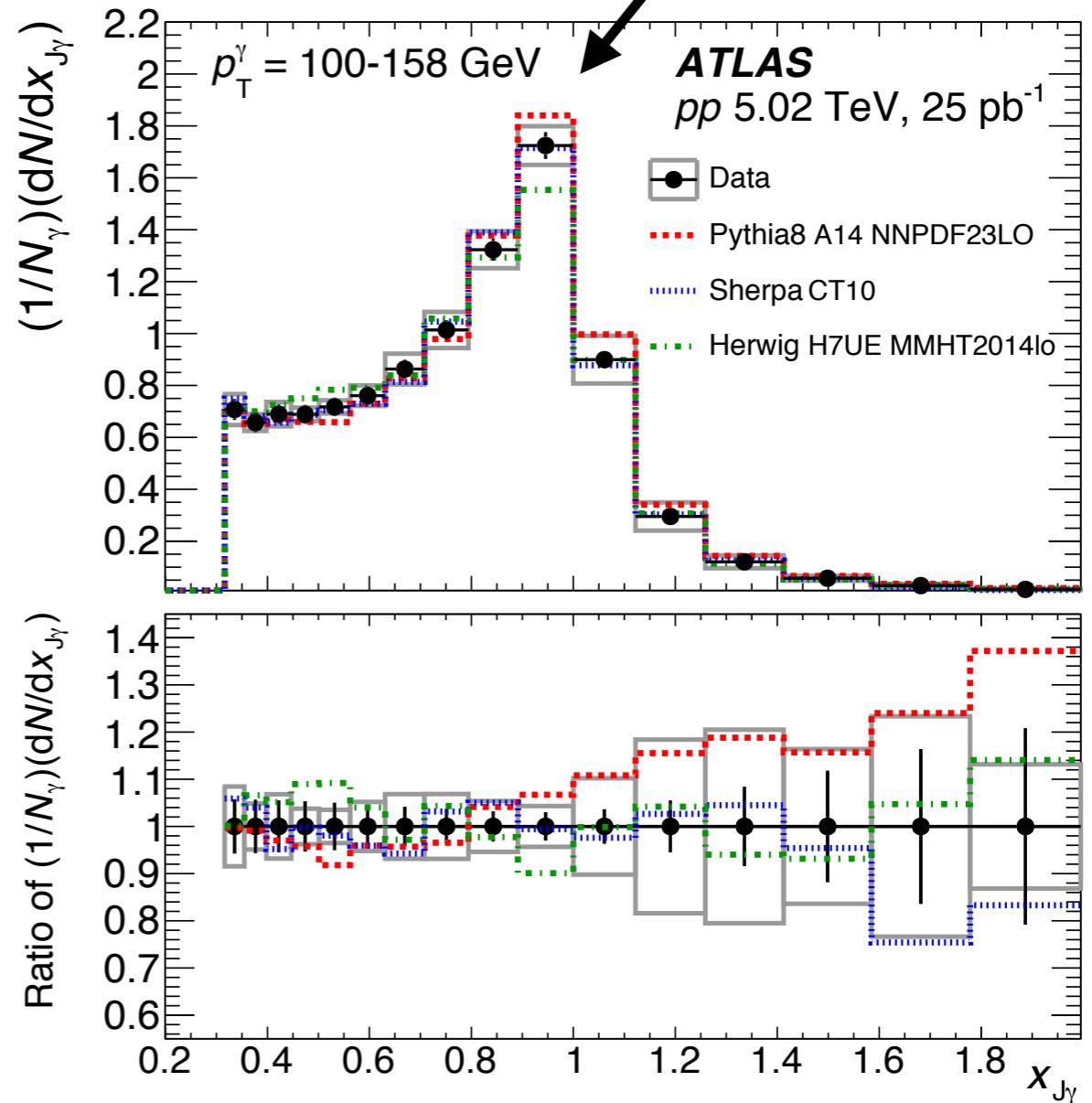
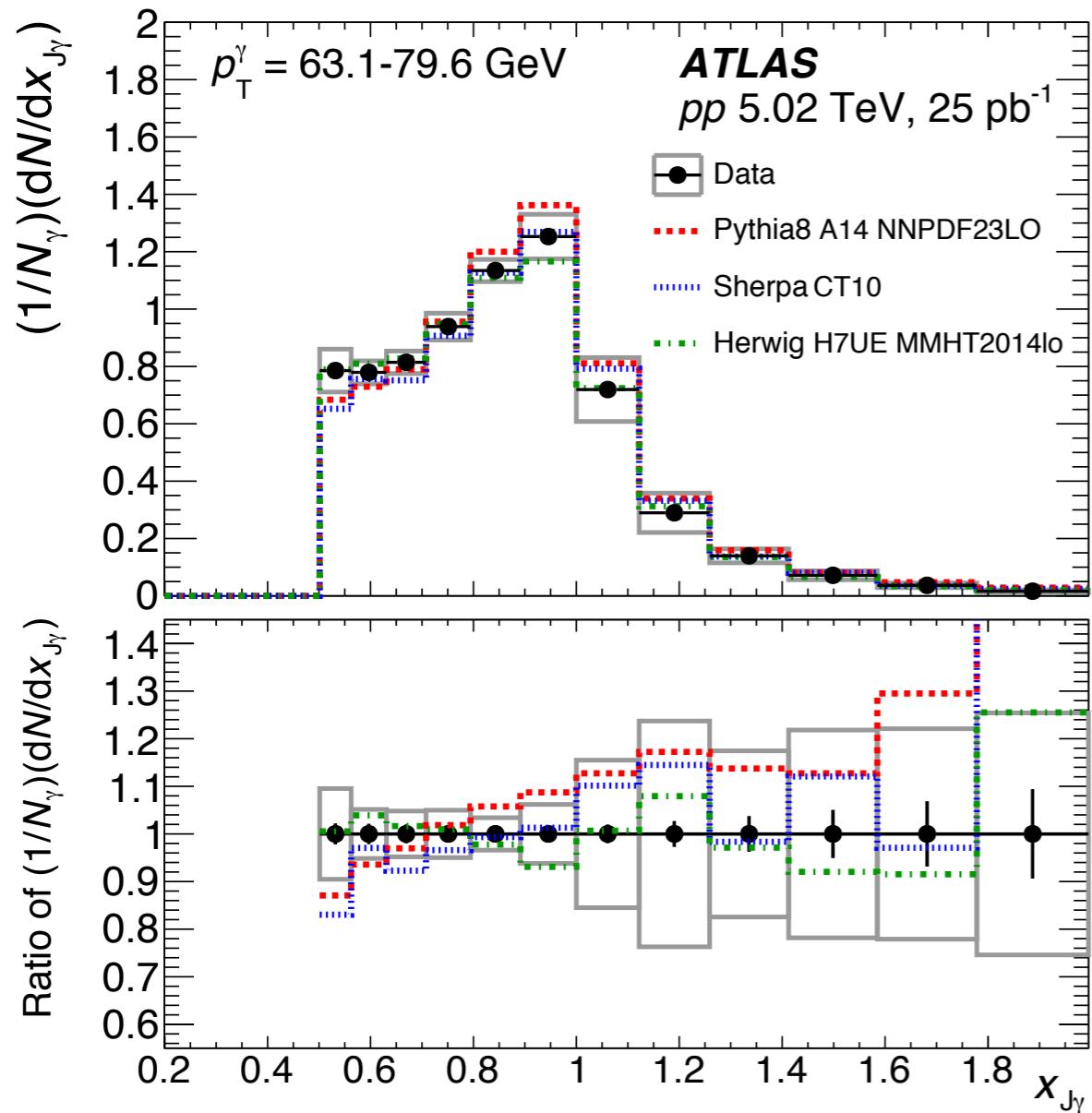


**Photon+jet  $p_T$ -balance**

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

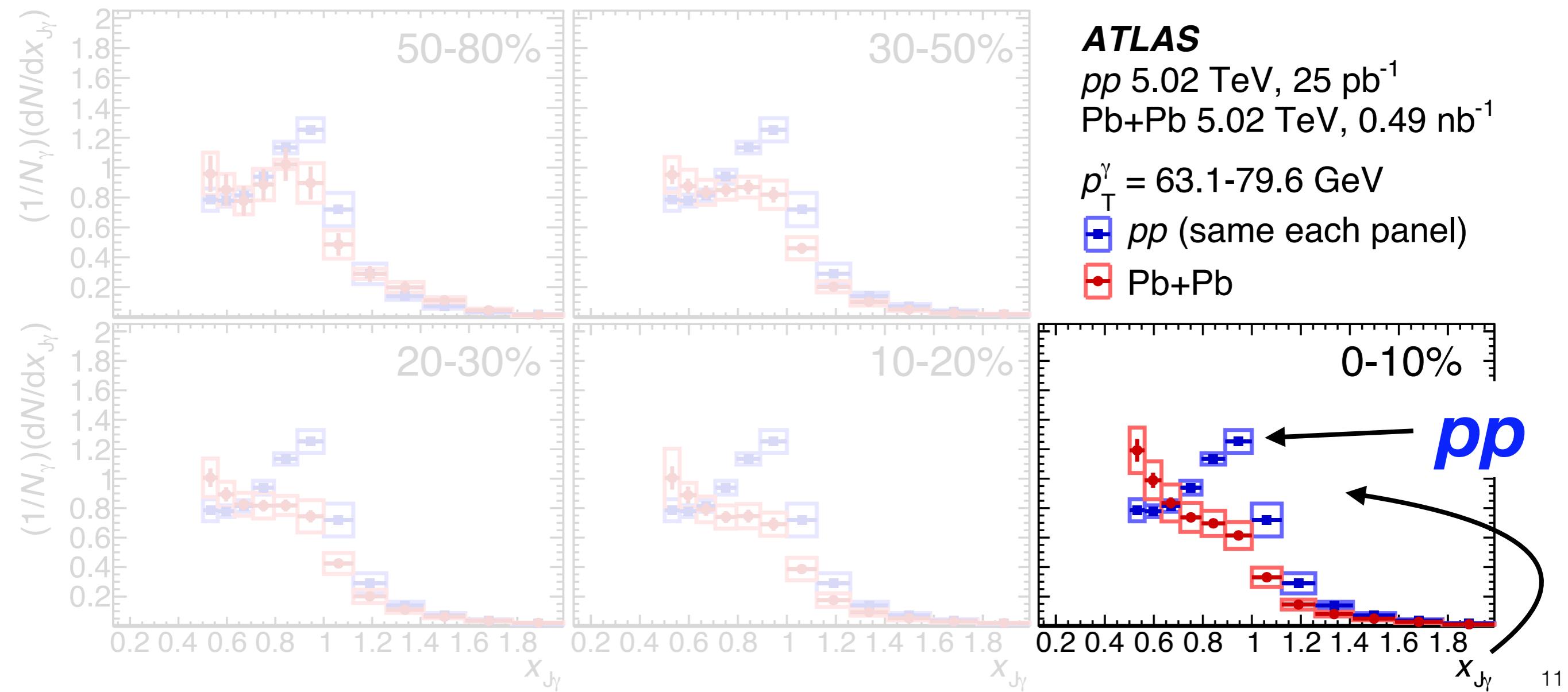
# Photon+jet $p_T$ balance in $pp$

*unfolding recovers  
sharp peak...*



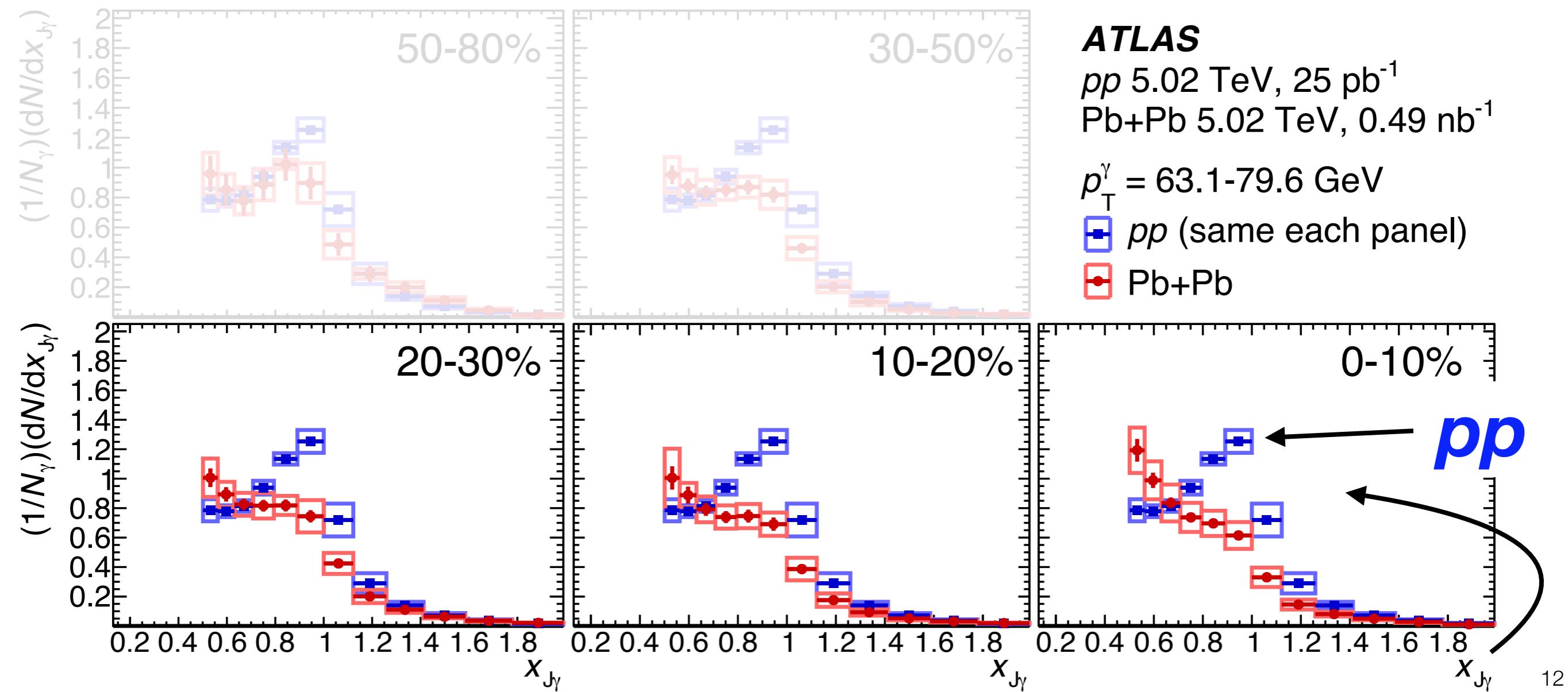
Compare directly to MC generators at particle-level:  
**Pythia 8** **Sherpa** **Herwig 7**

Results:  $p_T\gamma =$   
63.1-79.6 GeV



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

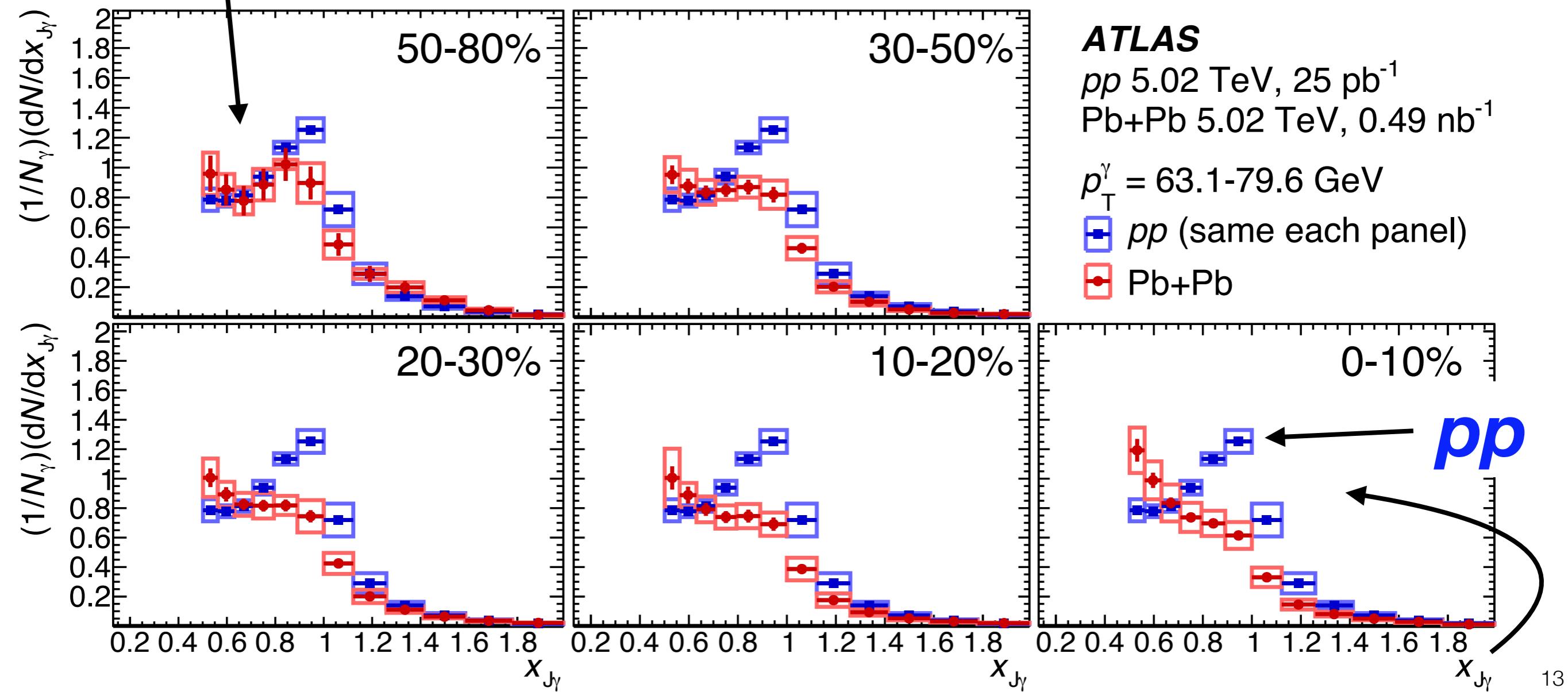
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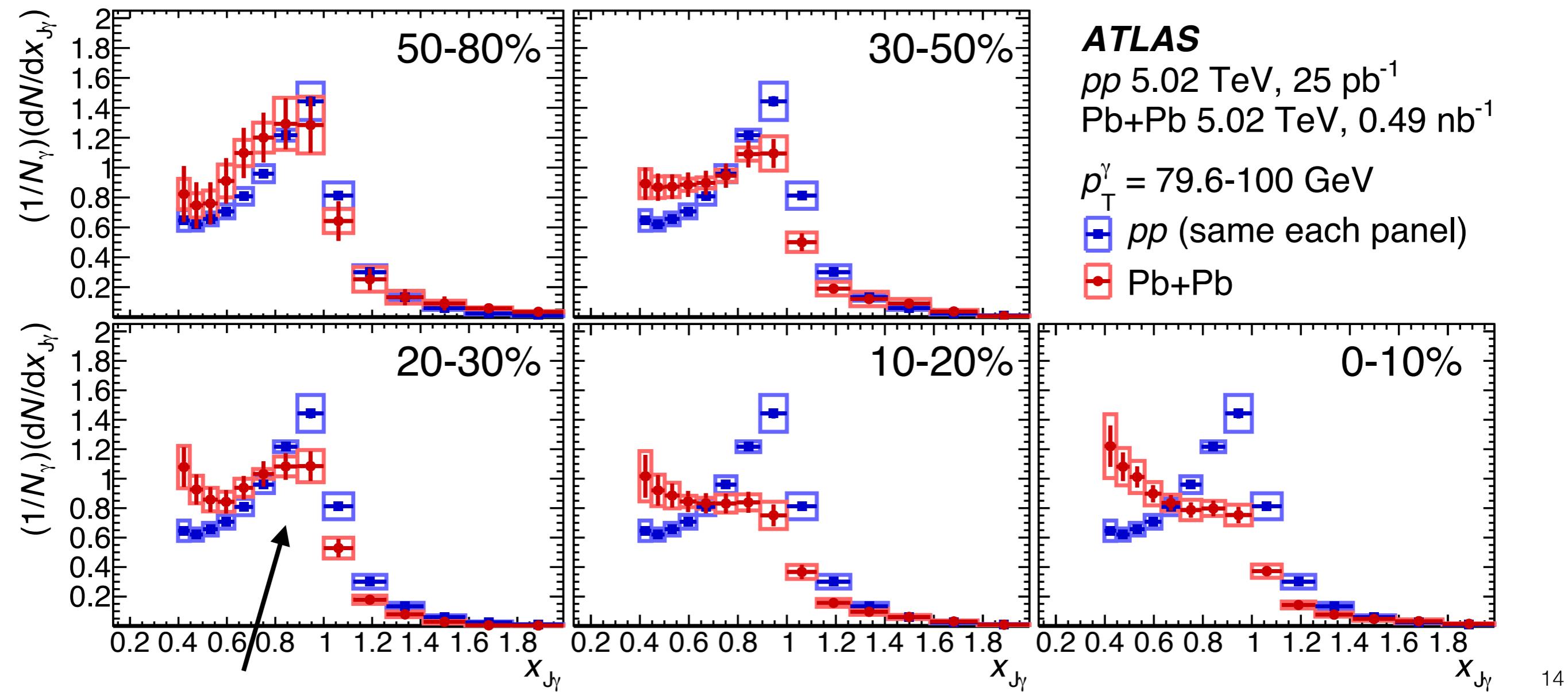
*peak returns in  
**50-80%** Pb+Pb  
events*

Results:  $p_T^\gamma =$   
63.1-79.6 GeV



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

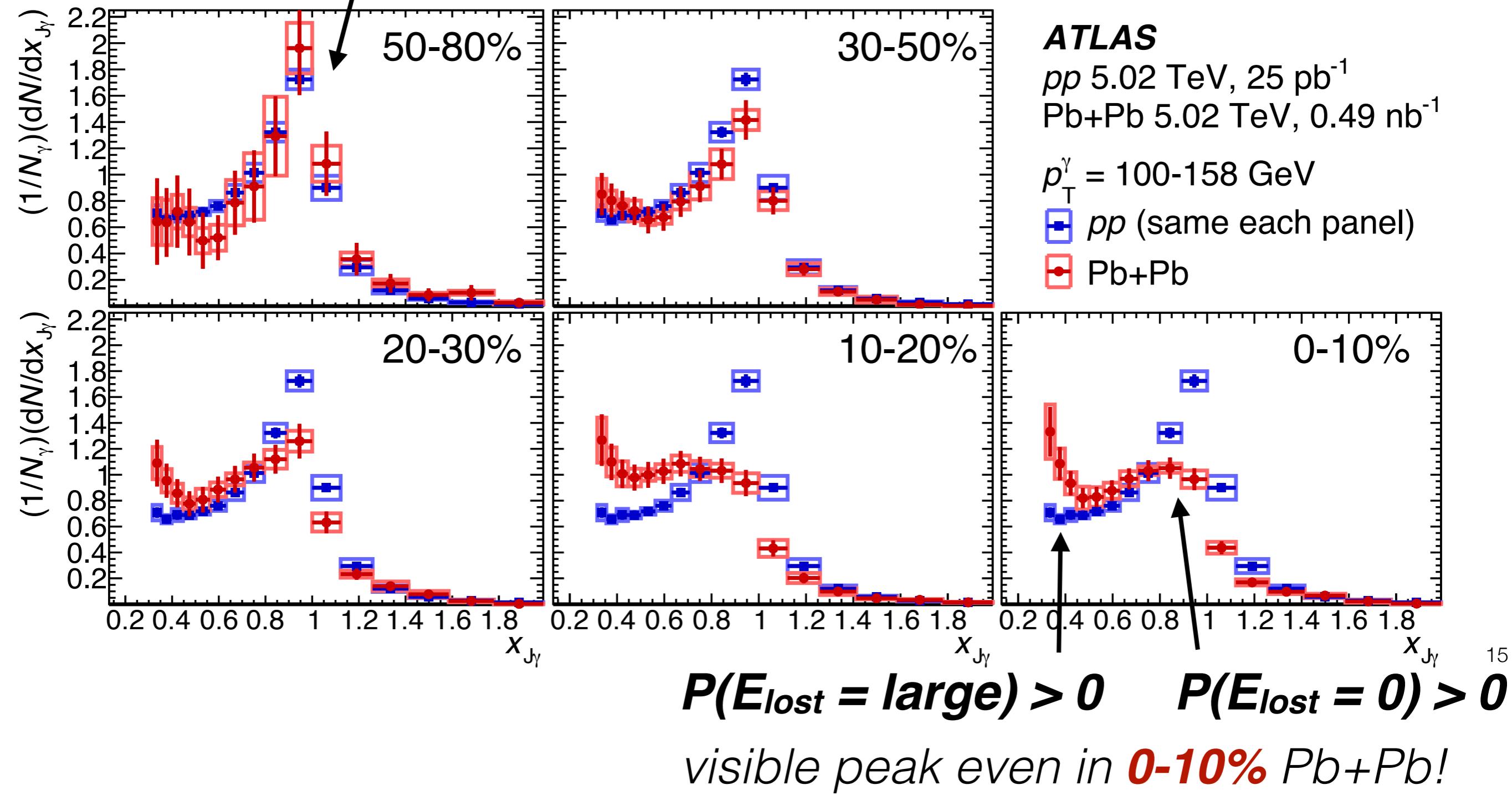
Results:  $p_T\gamma =$   
79.6-100 GeV



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

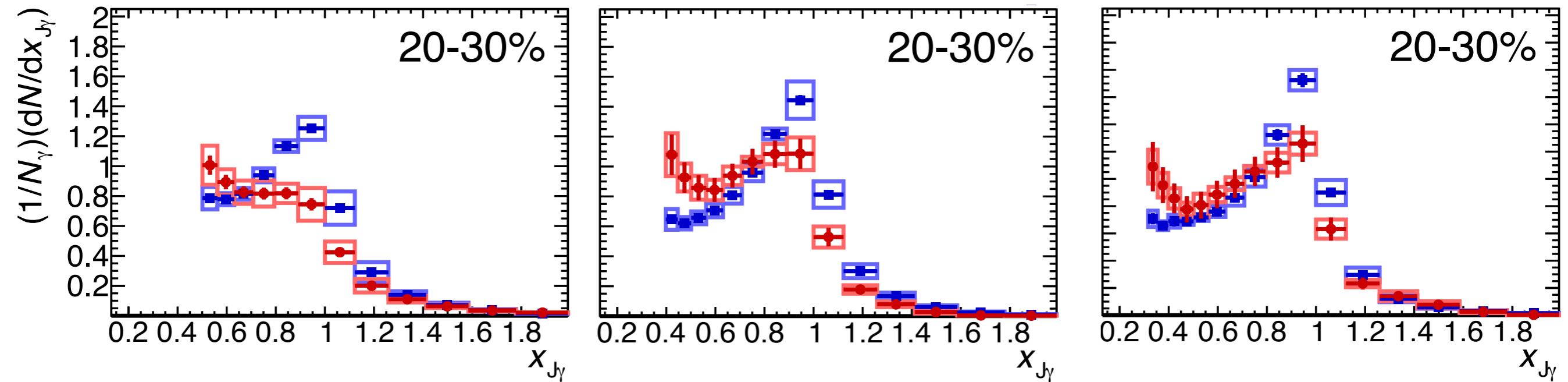
**50-80%  $Pb+Pb$**   
 events compatible  
 with  **$pp$**

Results:  $p_T\gamma =$   
 100-158 GeV



Fix centrality, explore  $p_T\gamma$ -evolution

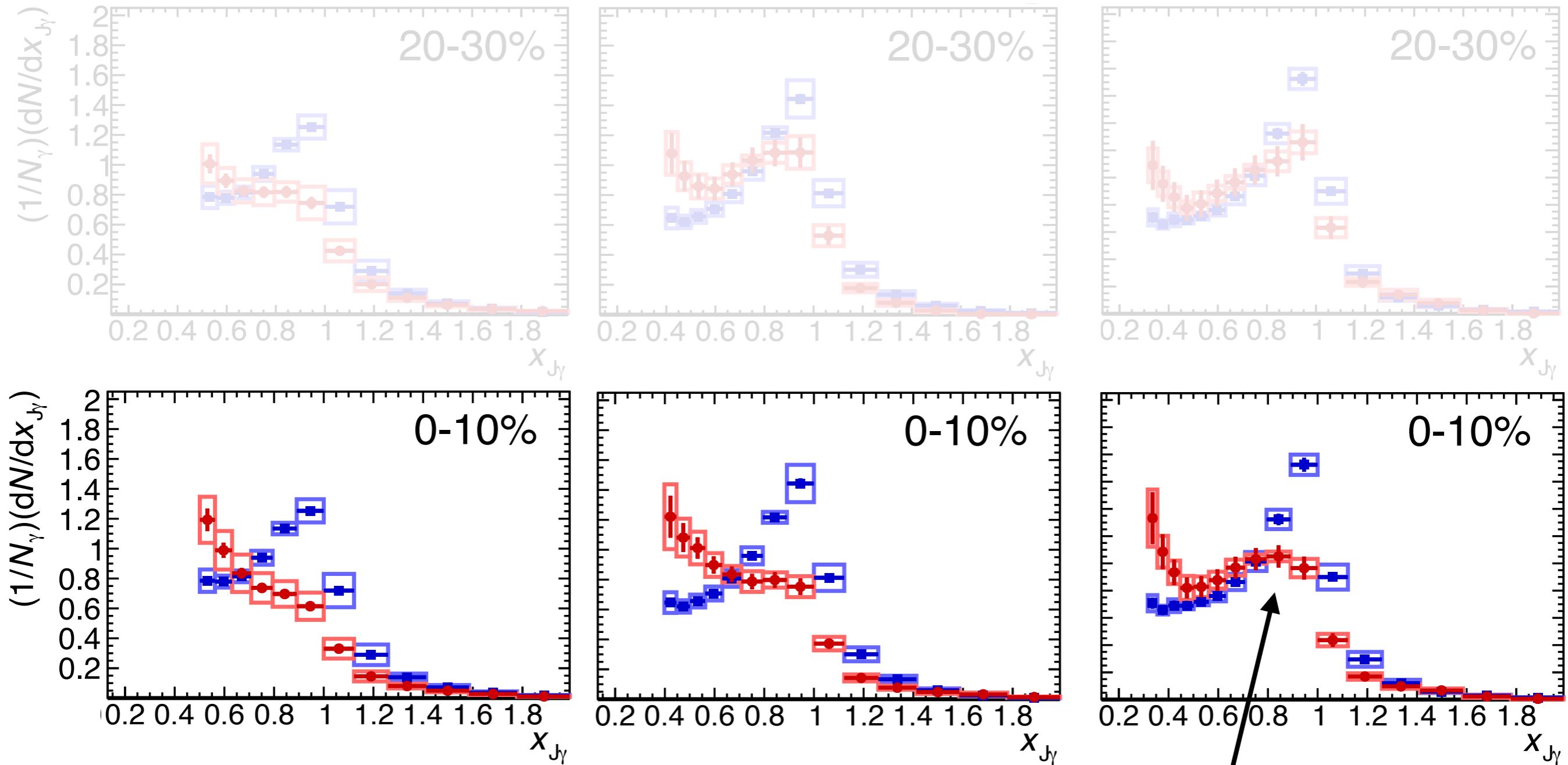
→ ***higher  $p_T\gamma$***



*fractional energy loss decreases with  $p_T\gamma$ ...?*

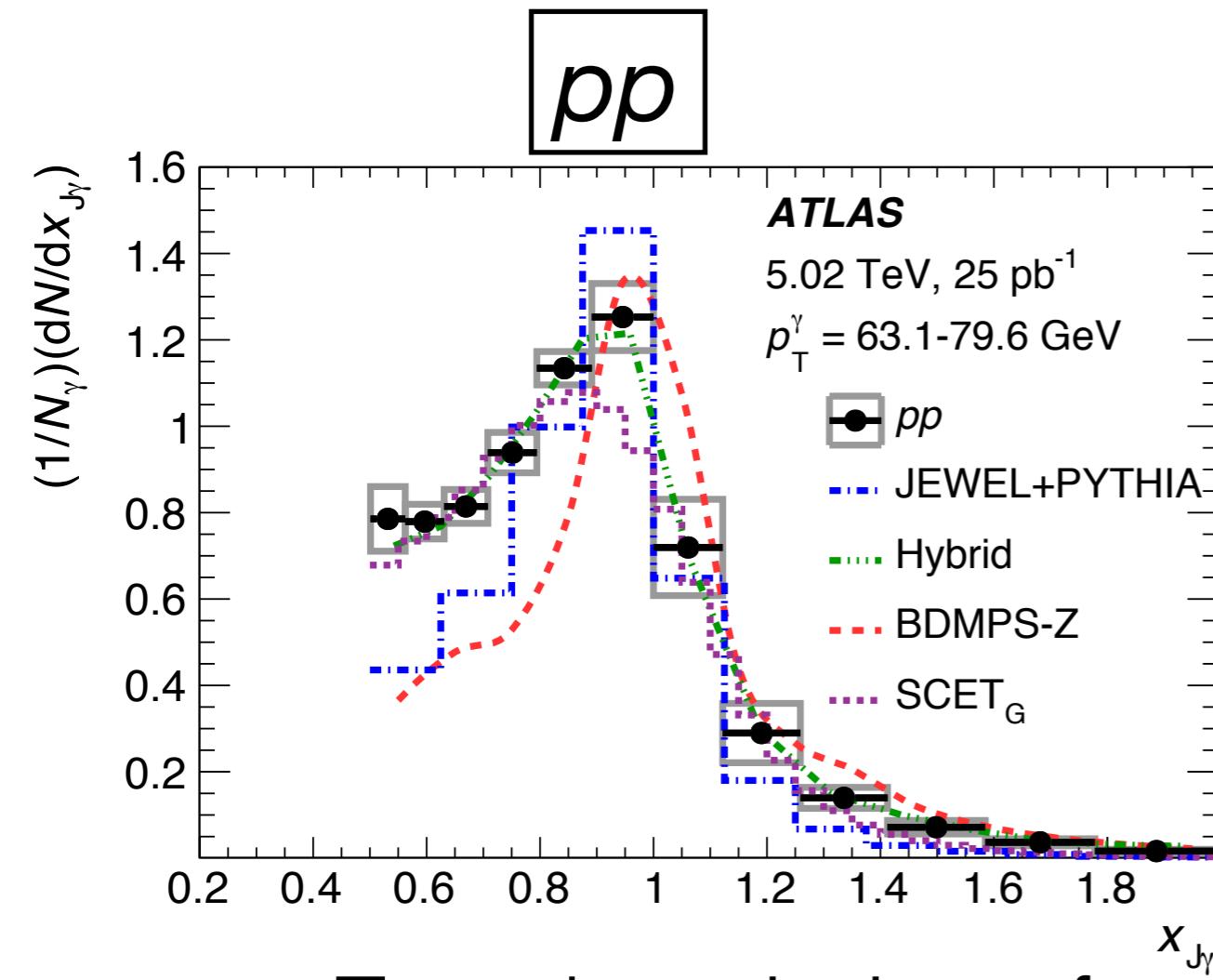
# Fix centrality, explore $p_T\gamma$ -evolution

→ ***higher  $p_T\gamma$***



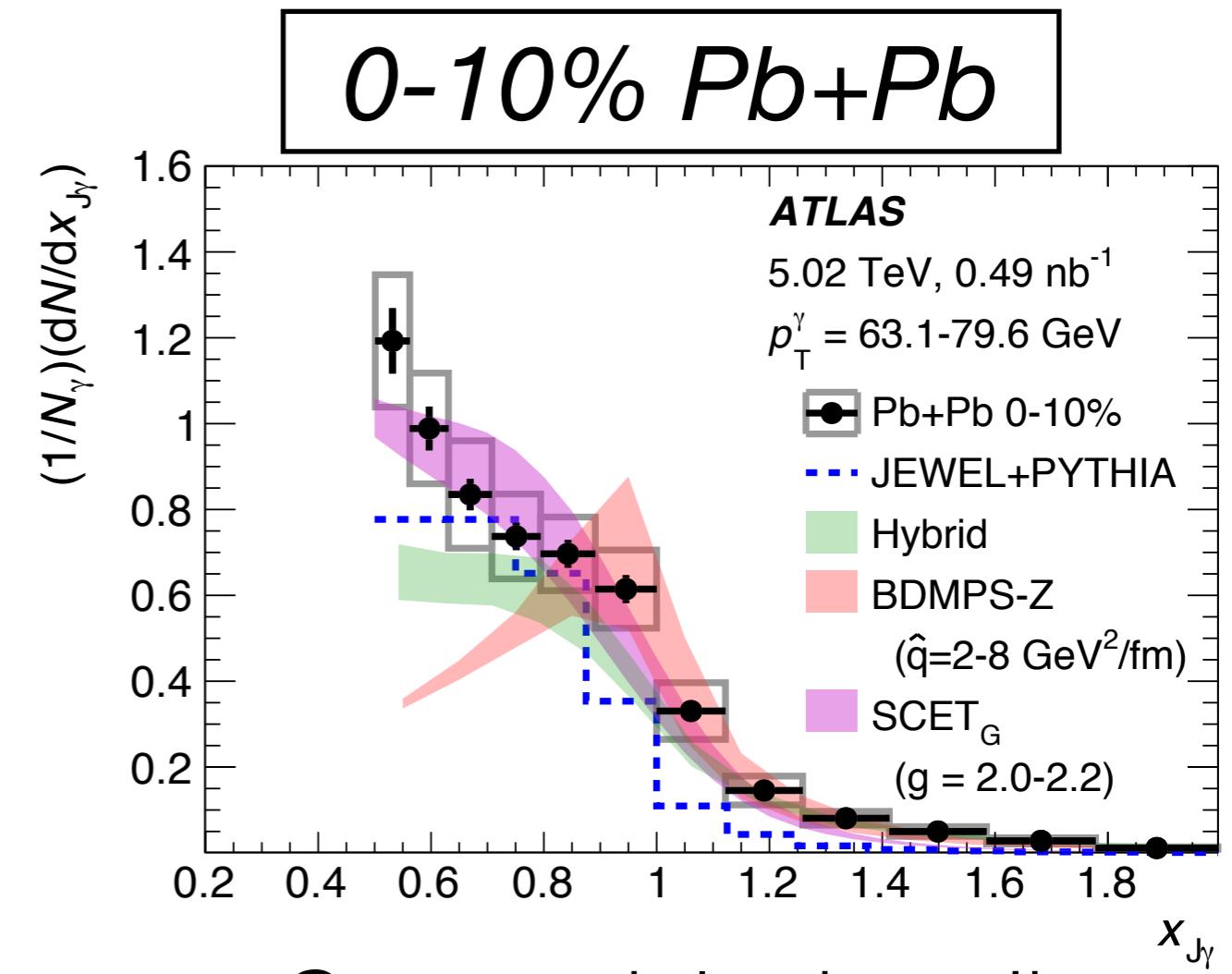
*jets which lose ~no energy, even in 0-10%...*

# Direct comparisons to theory (no smearing)



Test description of vacuum ( $pp$ ) baseline

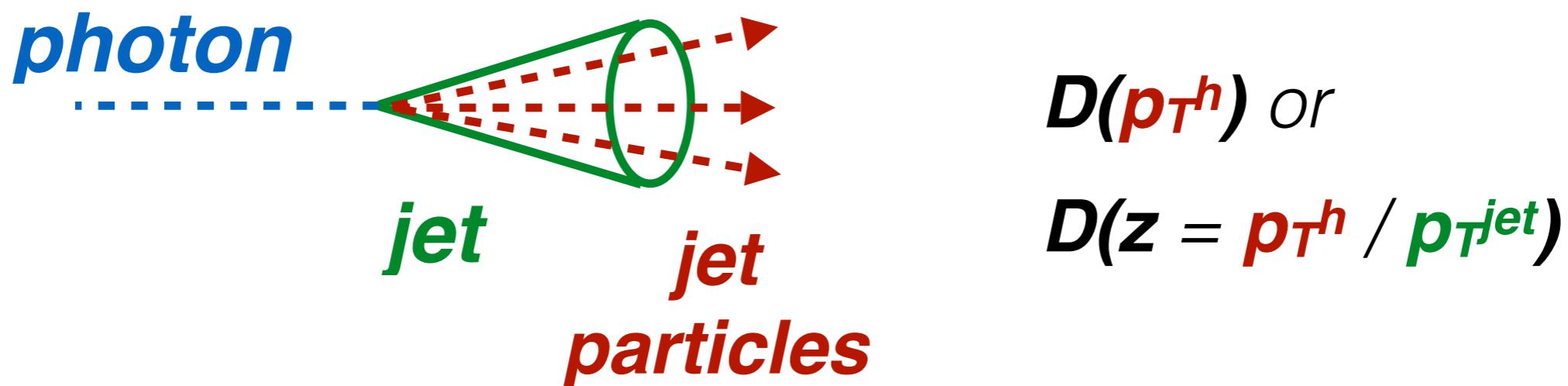
Models with Pythia vacuum distribution (e.g. **Hybrid**) tend to do well...



Can models describe centrality /  $p_T^\gamma$  evolution?

Difficult to describe detailed shape! (**SCET<sub>G</sub>** tends to do well...)

How is the parton shower in cone modified by medium?



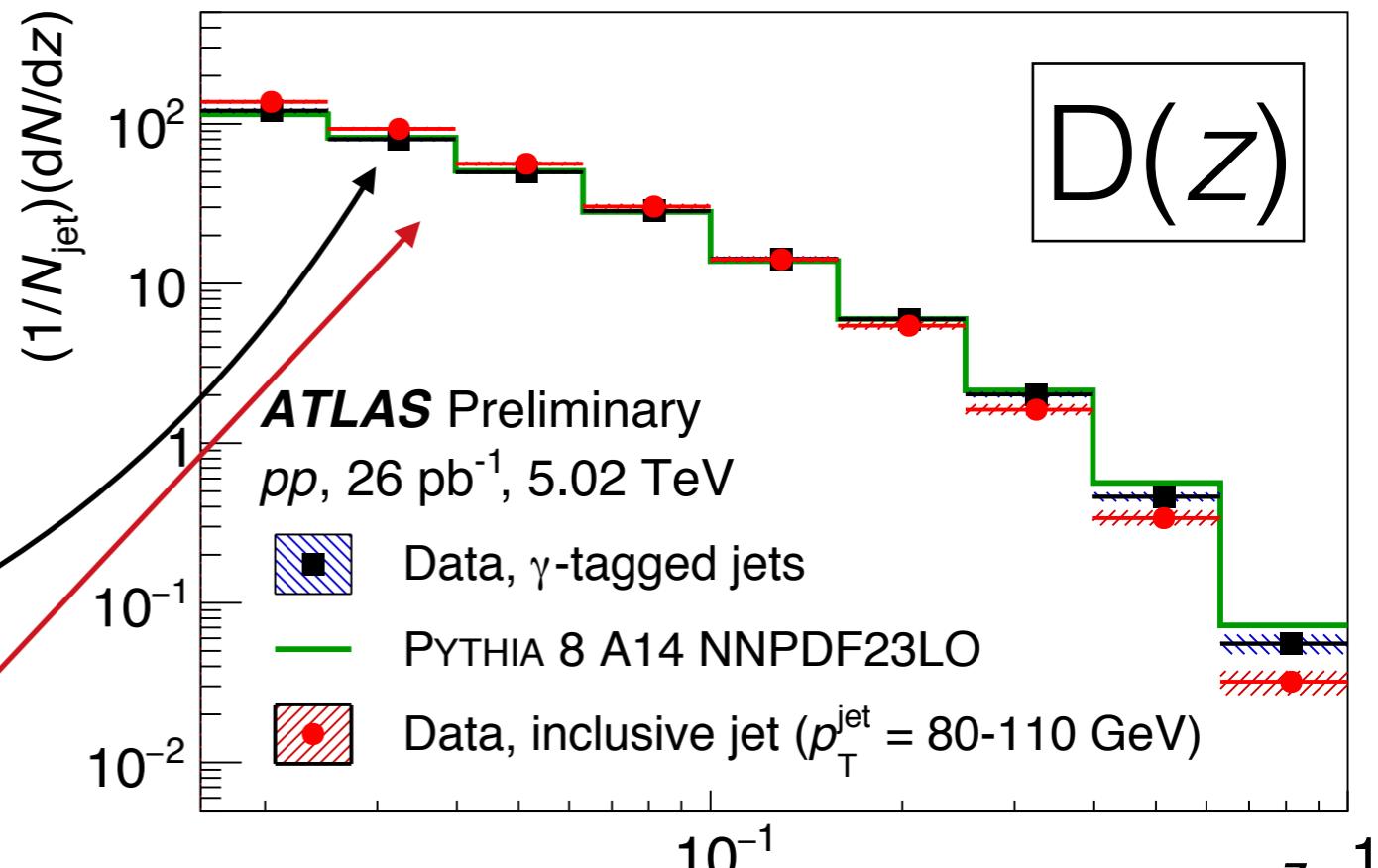
## Photon-tagged frag. function

(with respect to the jet  $p_T$  & selection — match definition used for inclusive jet studies)

# $\gamma$ -tagged jet FF in $pp$

**$\gamma$ -tagged jet**  
(quark jet-dominant)

**Inclusive jet**  
(gluon jet-dominant)



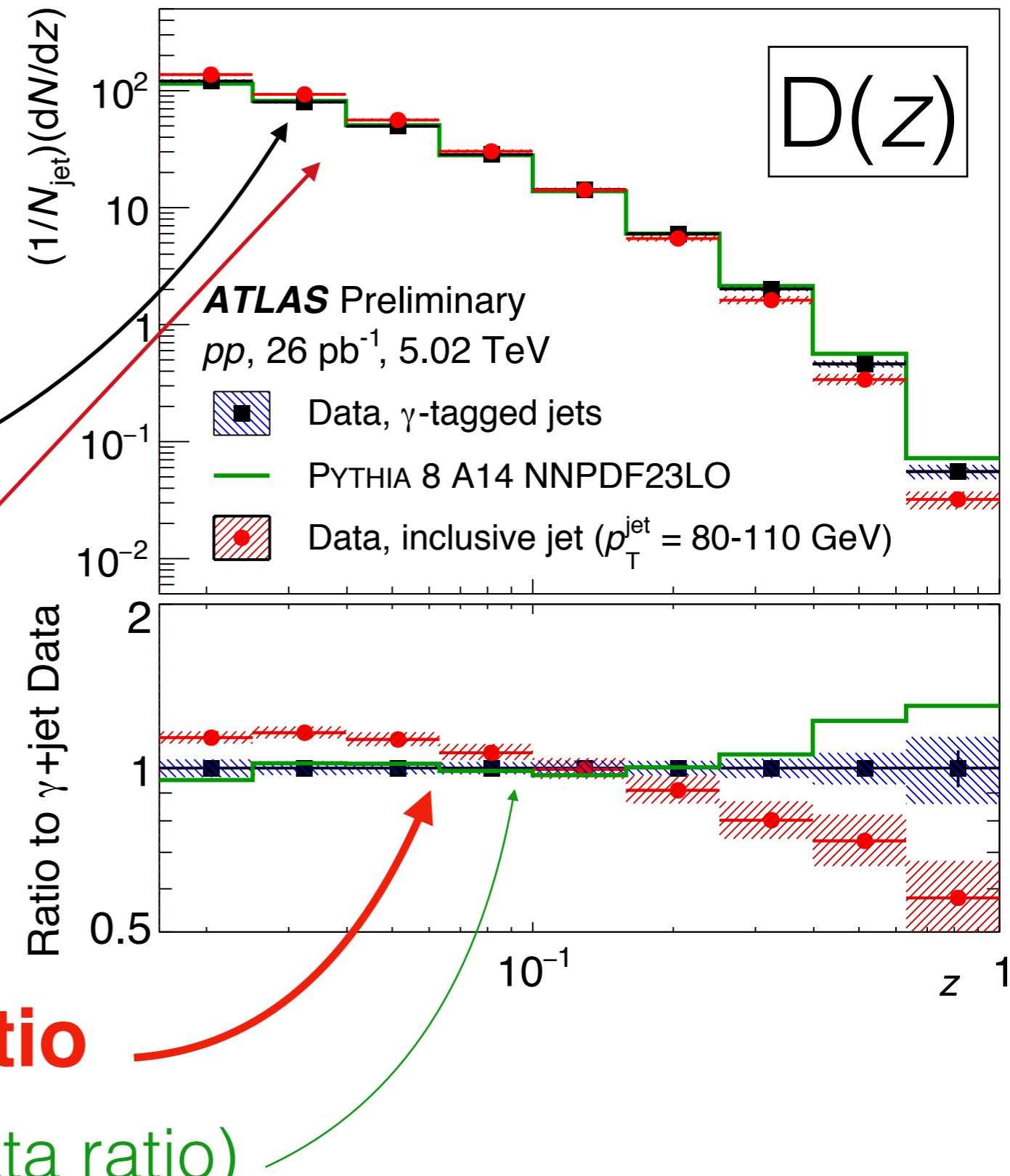
# $\gamma$ -tagged jet FF in $pp$

**$\gamma$ -tagged jet**  
(quark jet-dominant)

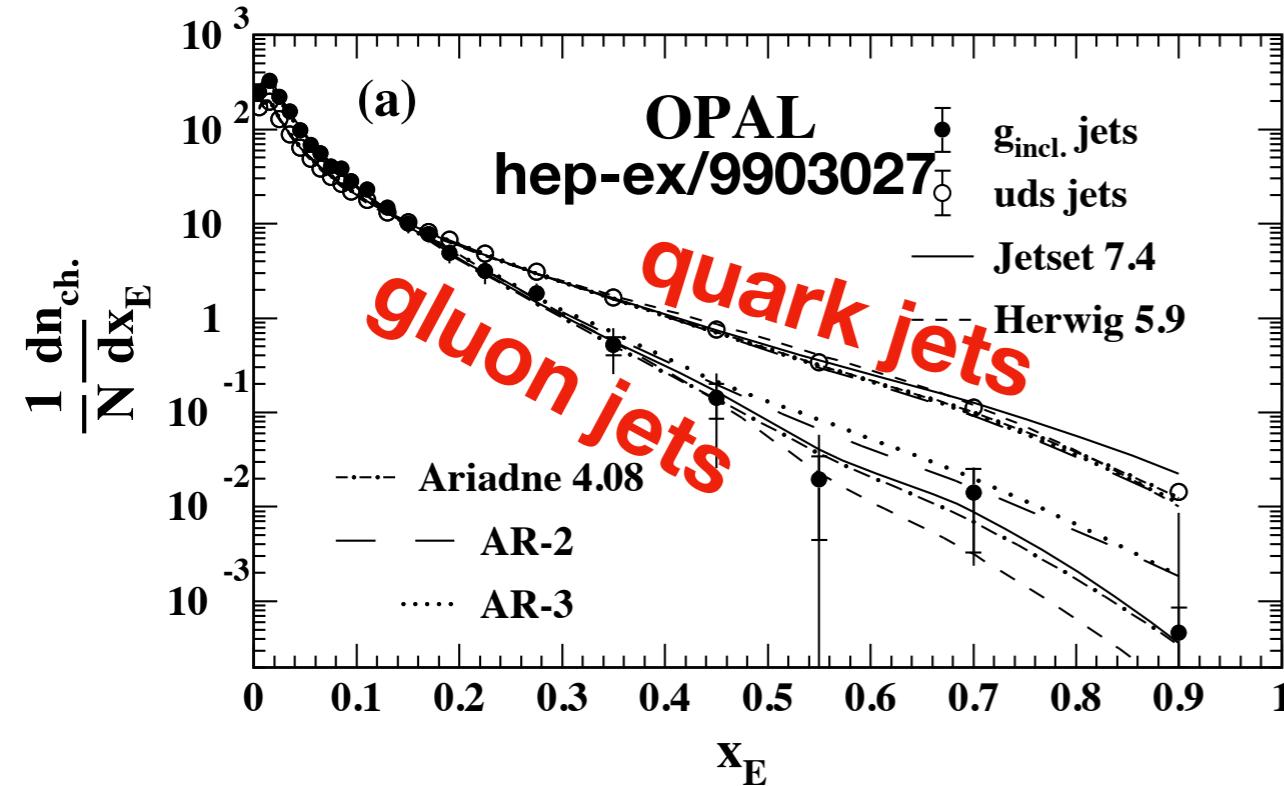
**Inclusive jet**  
(gluon jet-dominant)

**Inclusive /  $\gamma$ -tagged ratio**

(also  $\gamma$ -tagged Pythia/data ratio)



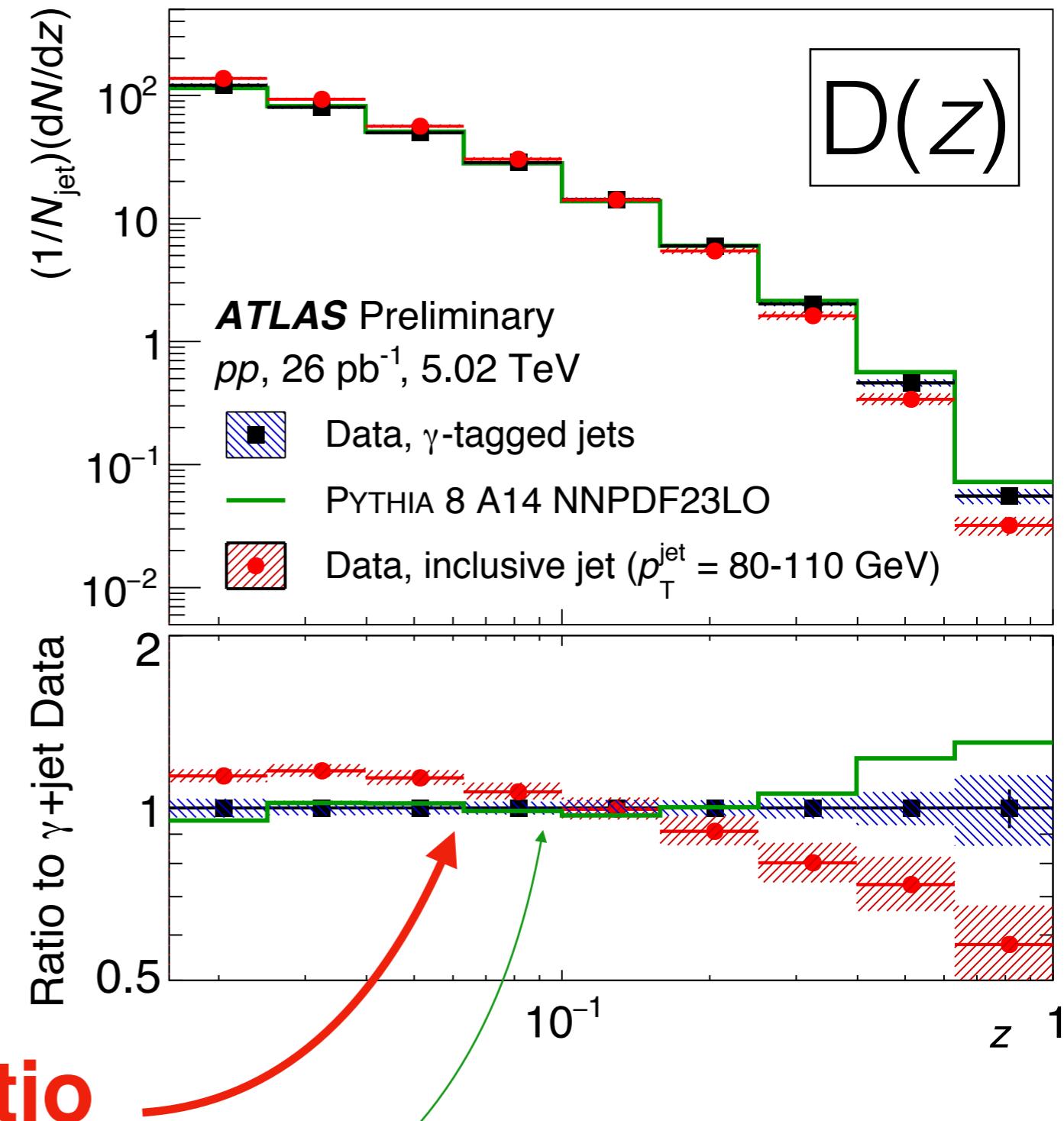
# $\gamma$ -tagged jet FF in $pp$



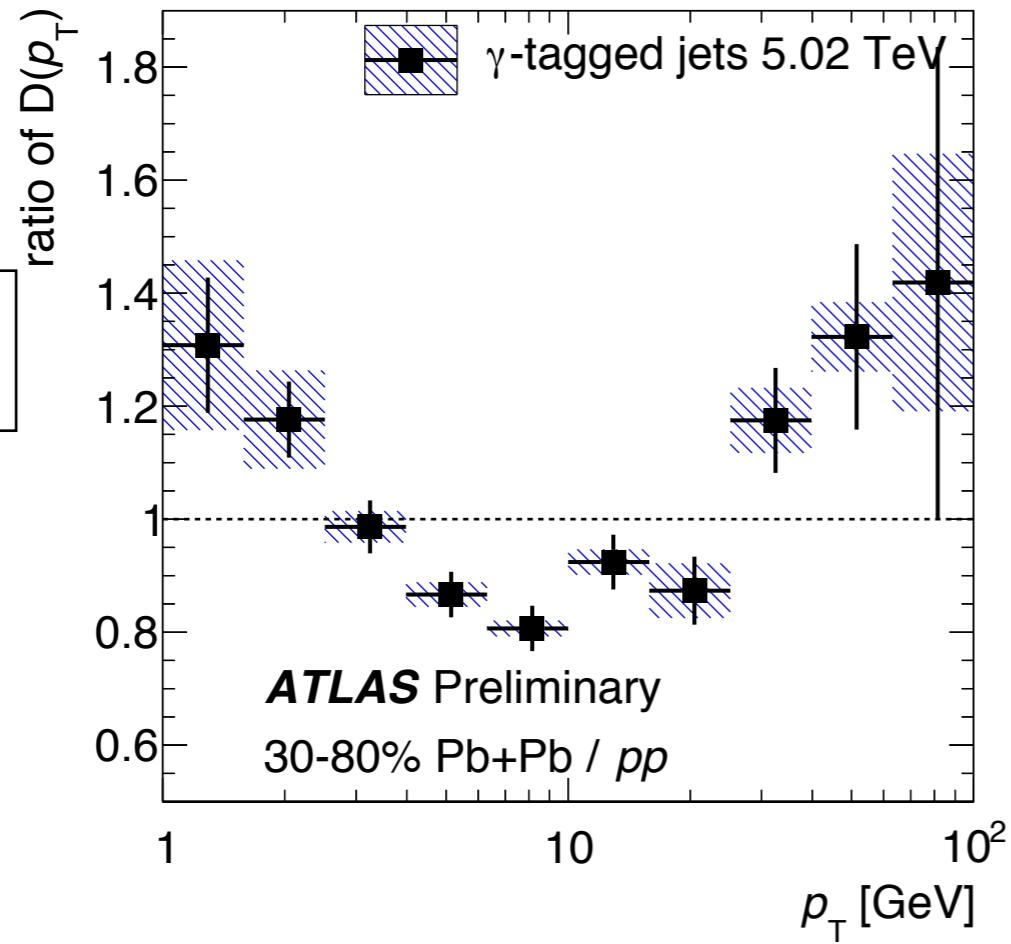
*Fragmentation  
difference as expected  
from, e.g. LEP*

**Inclusive /  $\gamma$ -tagged ratio**

(also  $\gamma$ -tagged Pythia/data ratio)

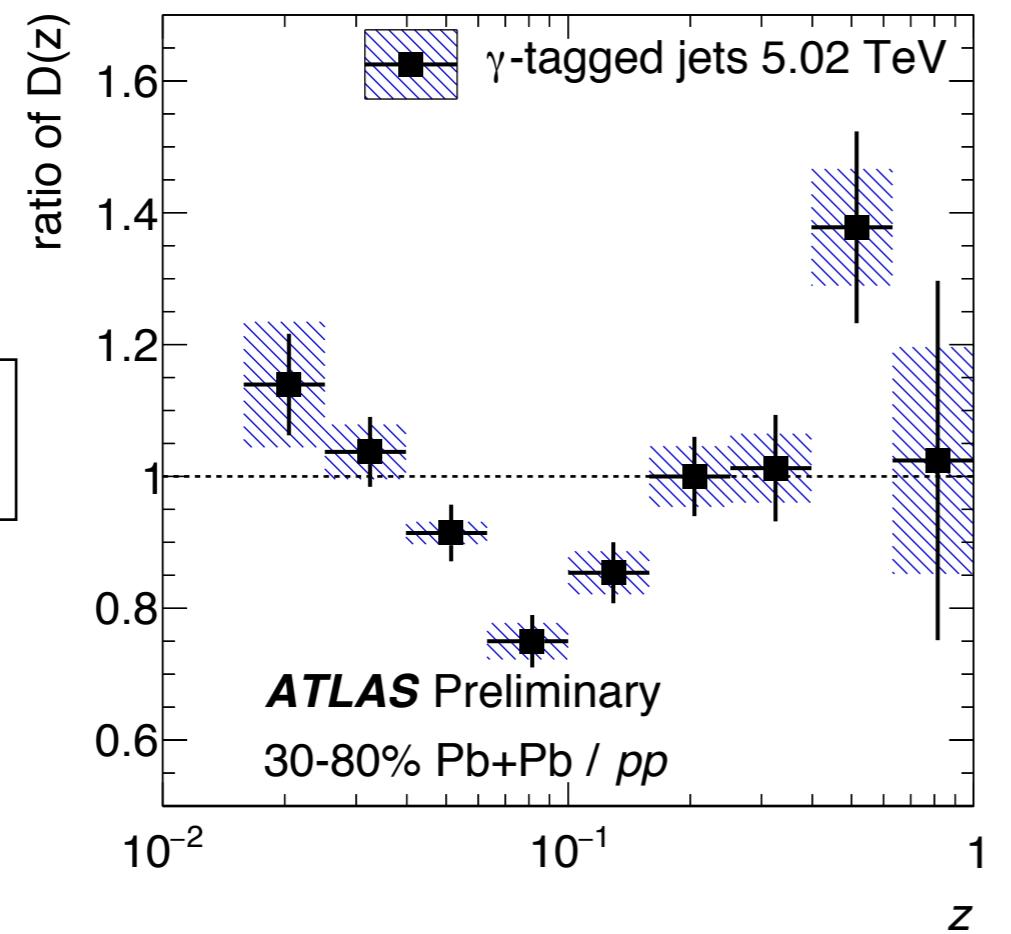


# **30-80% Pb+Pb / pp**



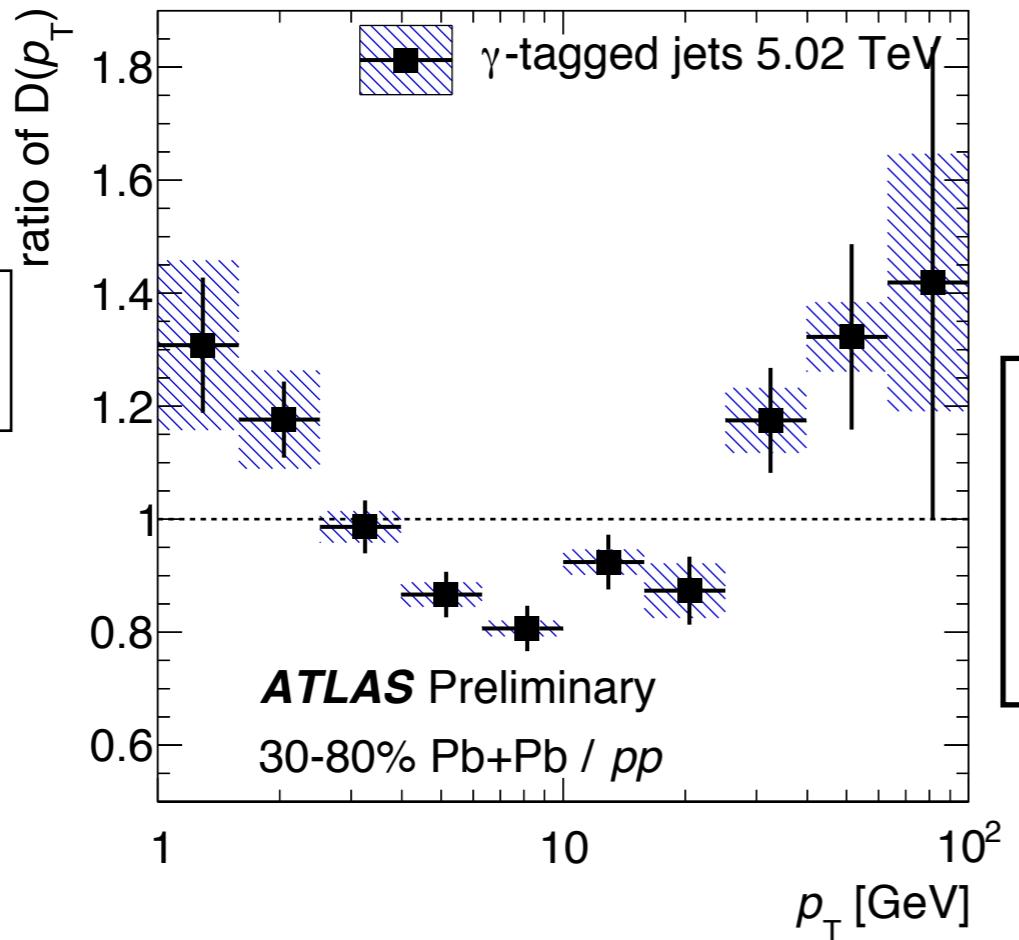
**$\gamma$ -tagged jet FF in  
30-80% Pb+Pb**

*(rise at large- $z$  /  $p_T$ ?)*



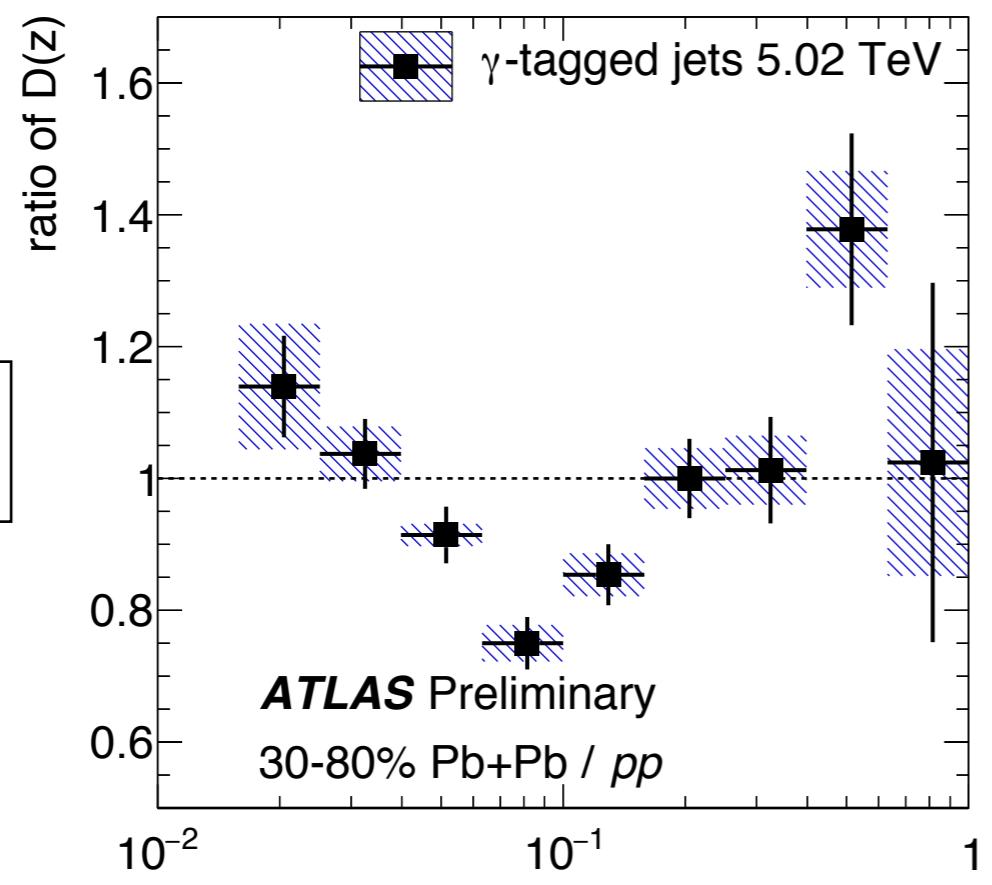
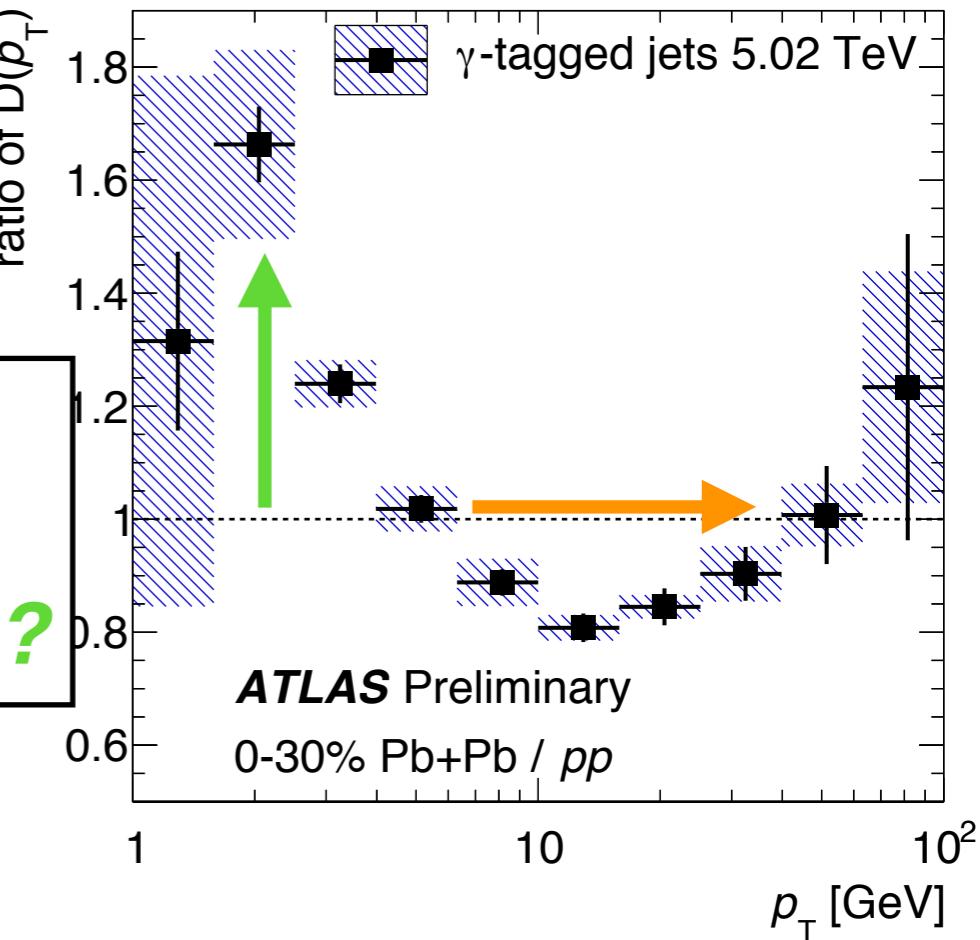
*(less obvious here...)*

# *30-80% Pb+Pb / pp*

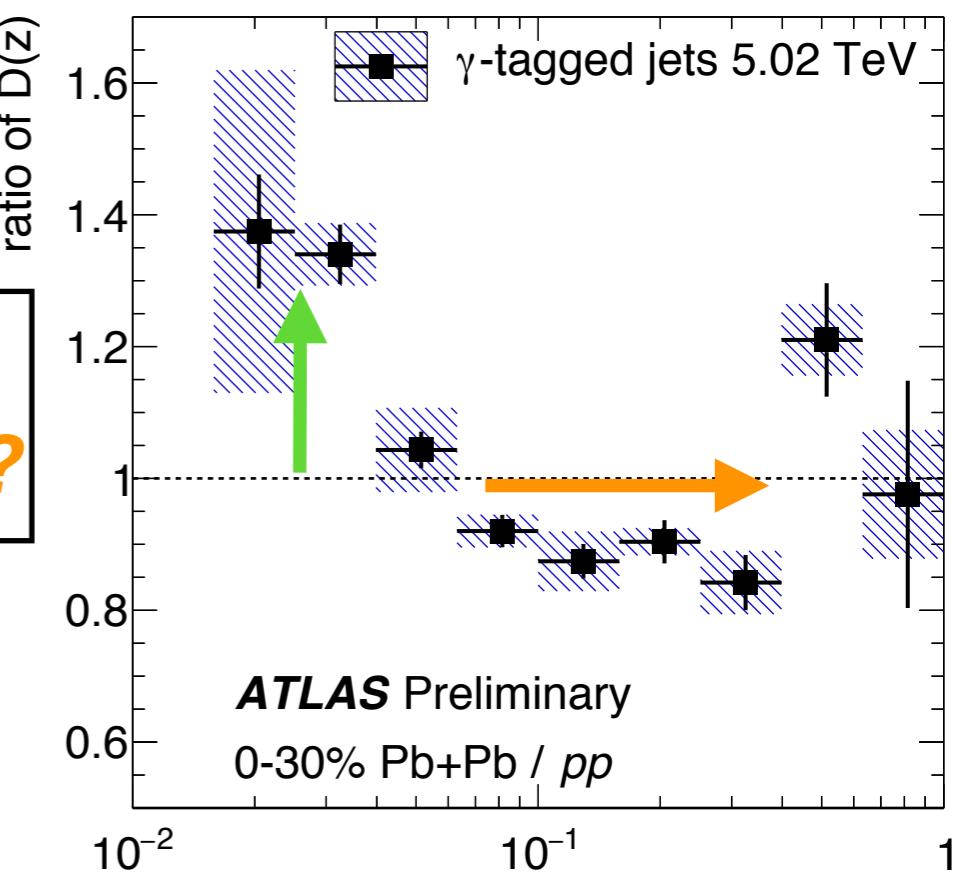


*larger  
medium  
response?*

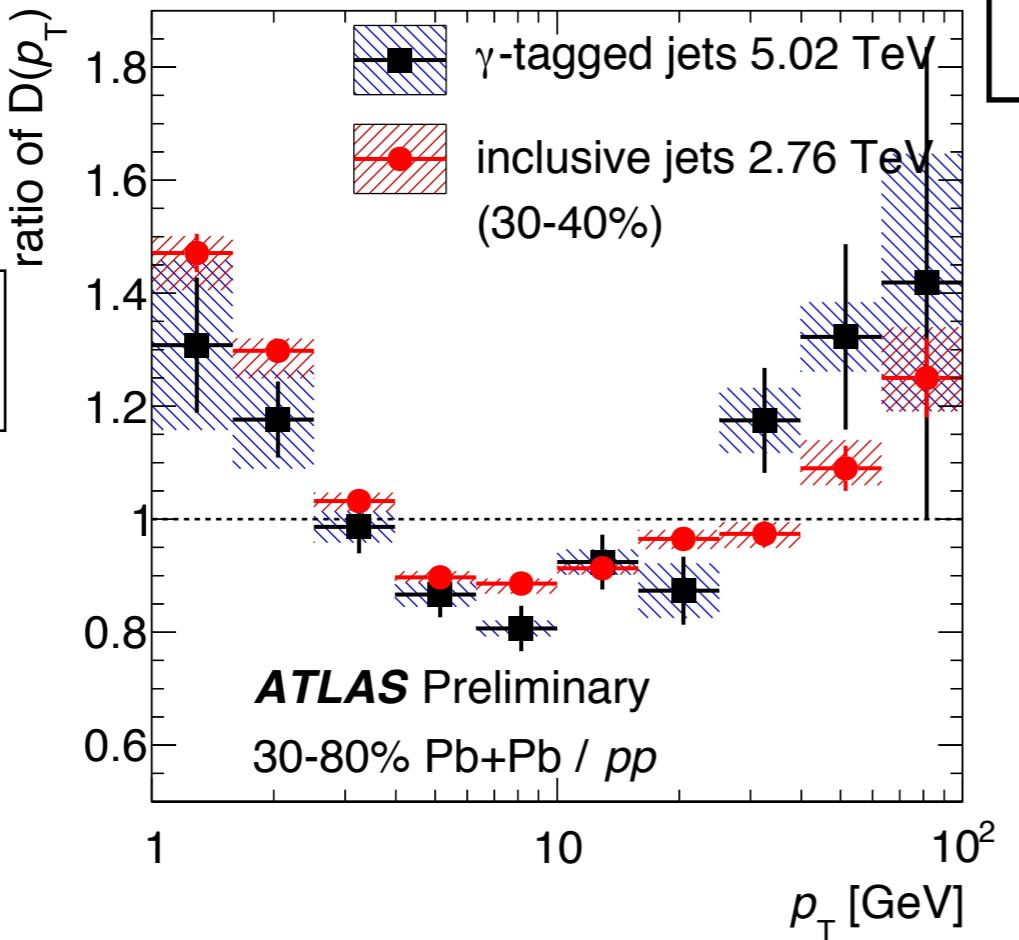
# *0-30% Pb+Pb / pp*



*more  
softening?*

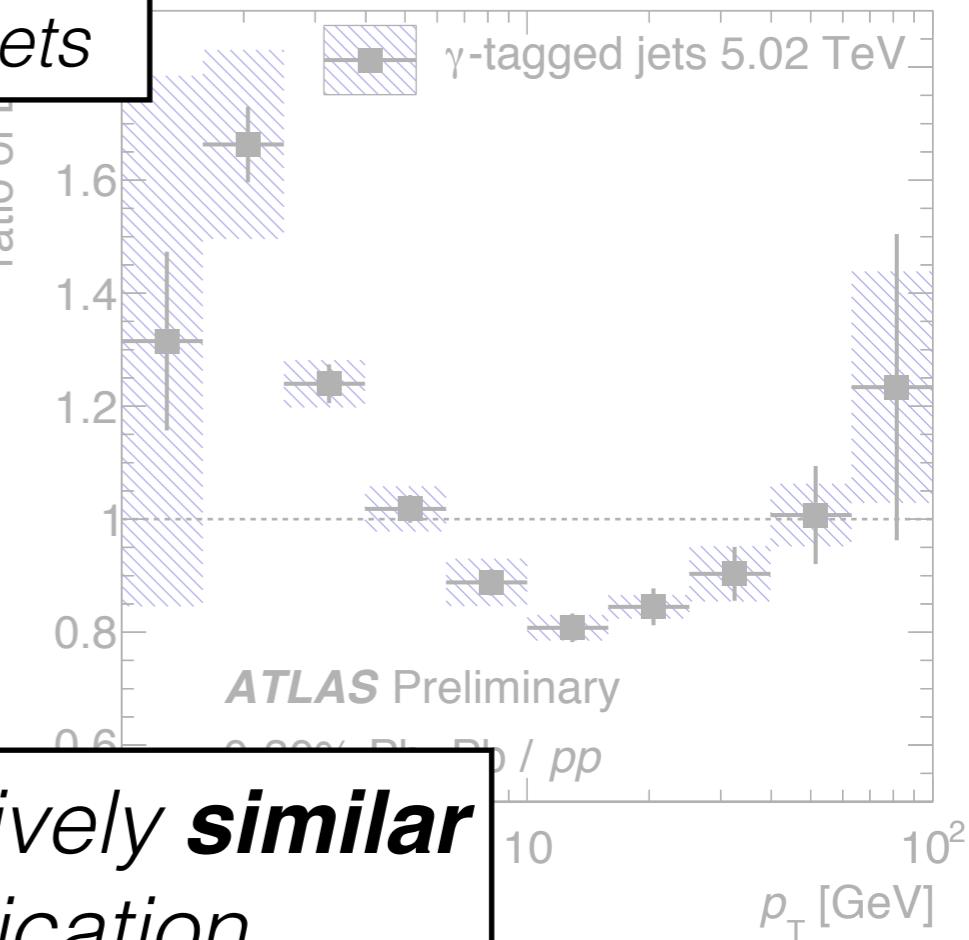


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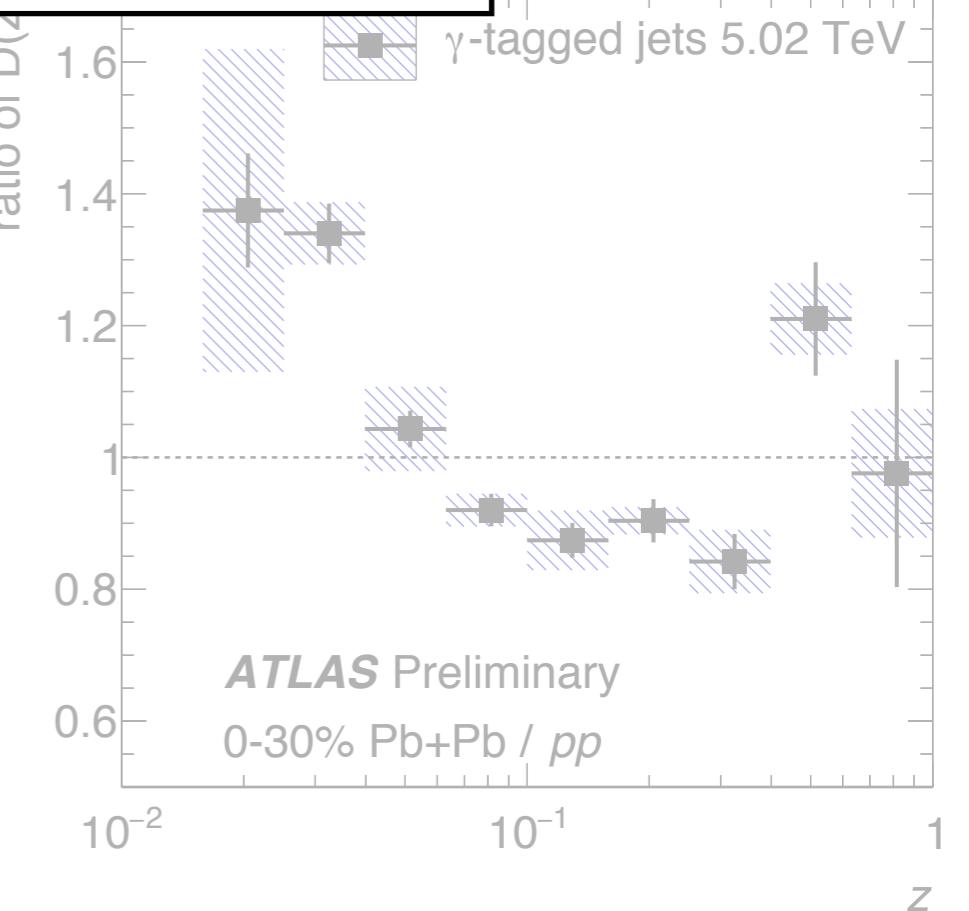
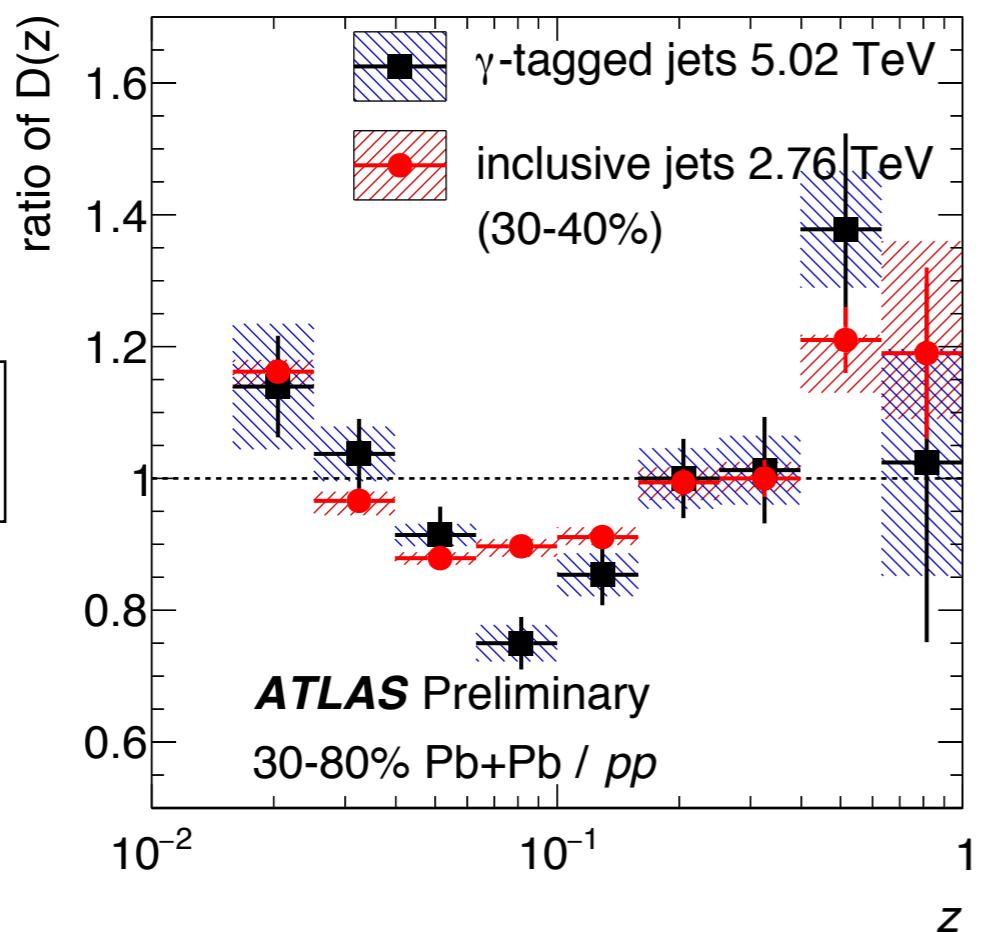


**inclusive (gluon-dominant) jets**

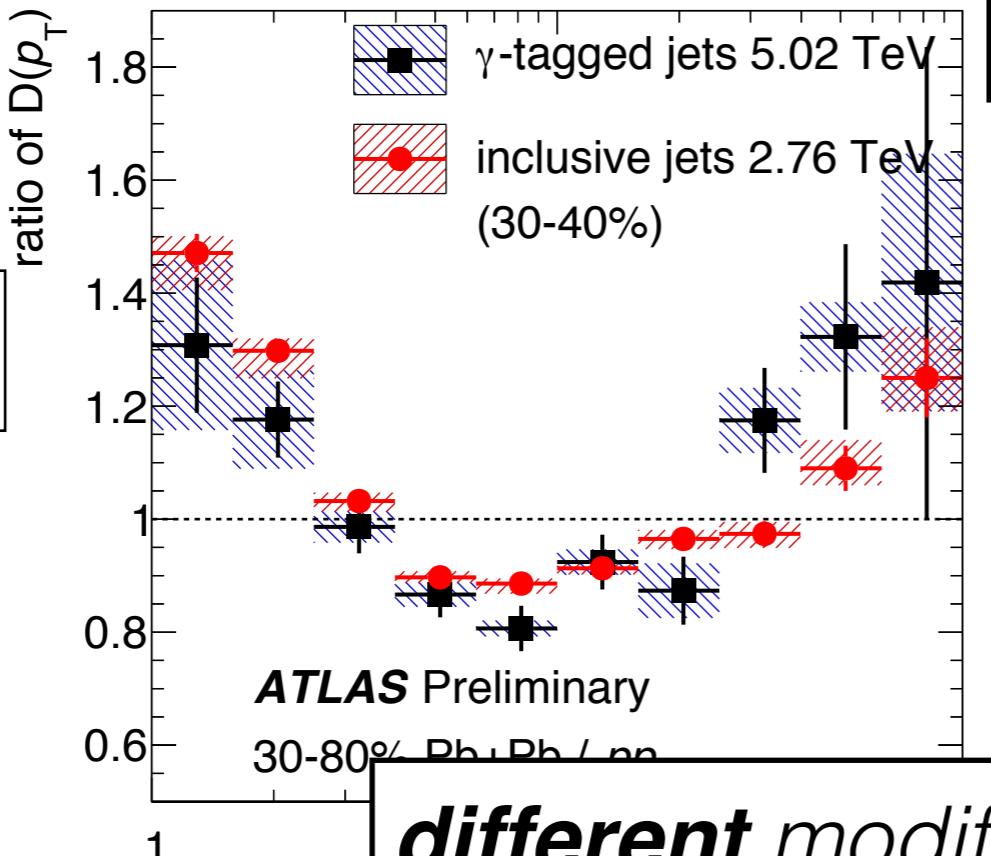
# **0-30% Pb+Pb / pp**



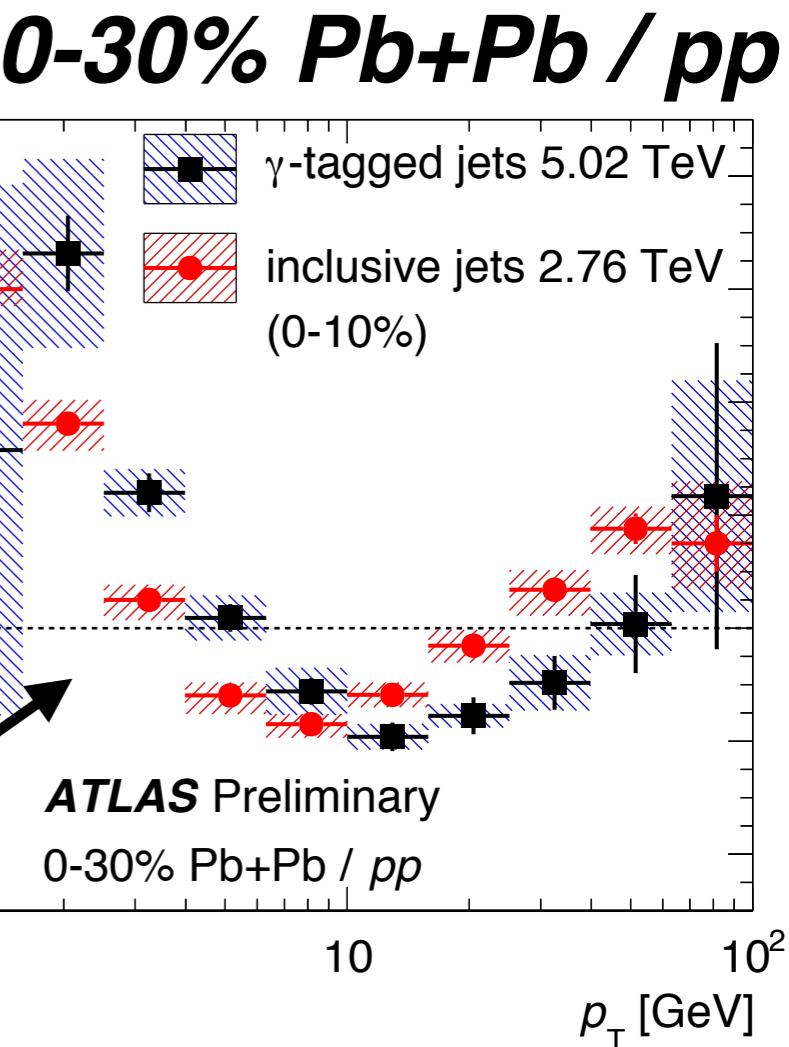
*quantitatively **similar** modification...*



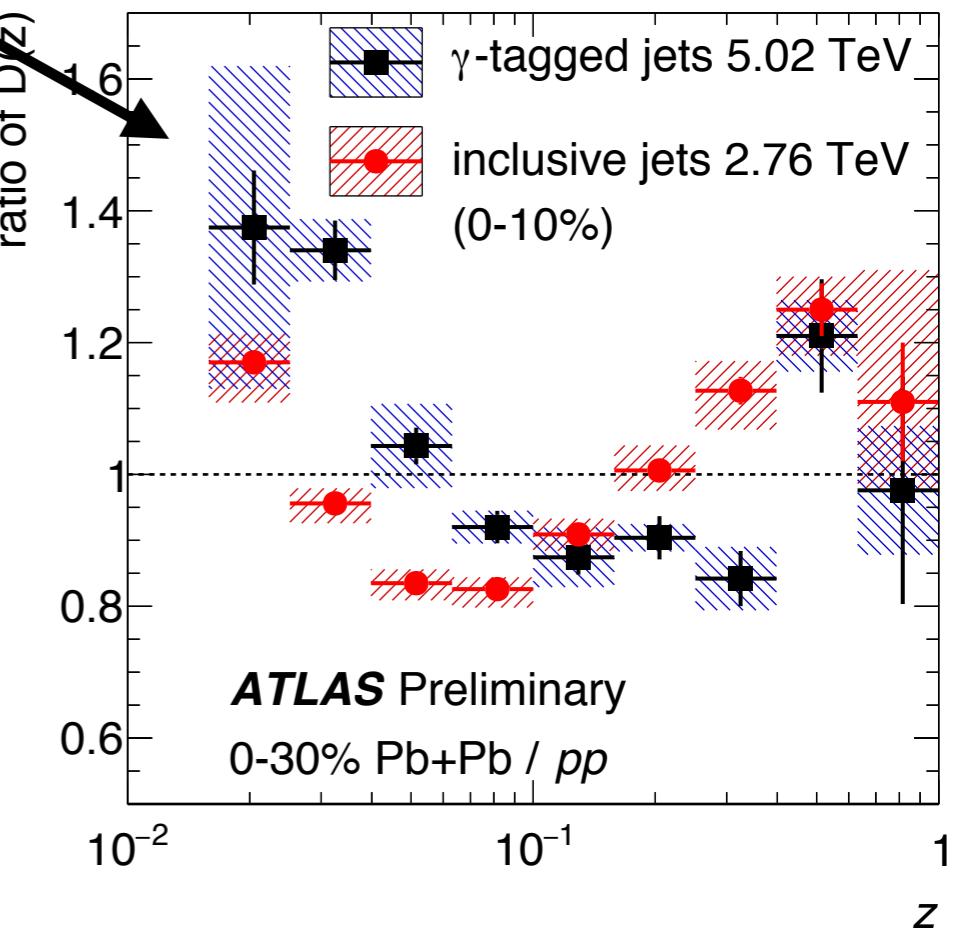
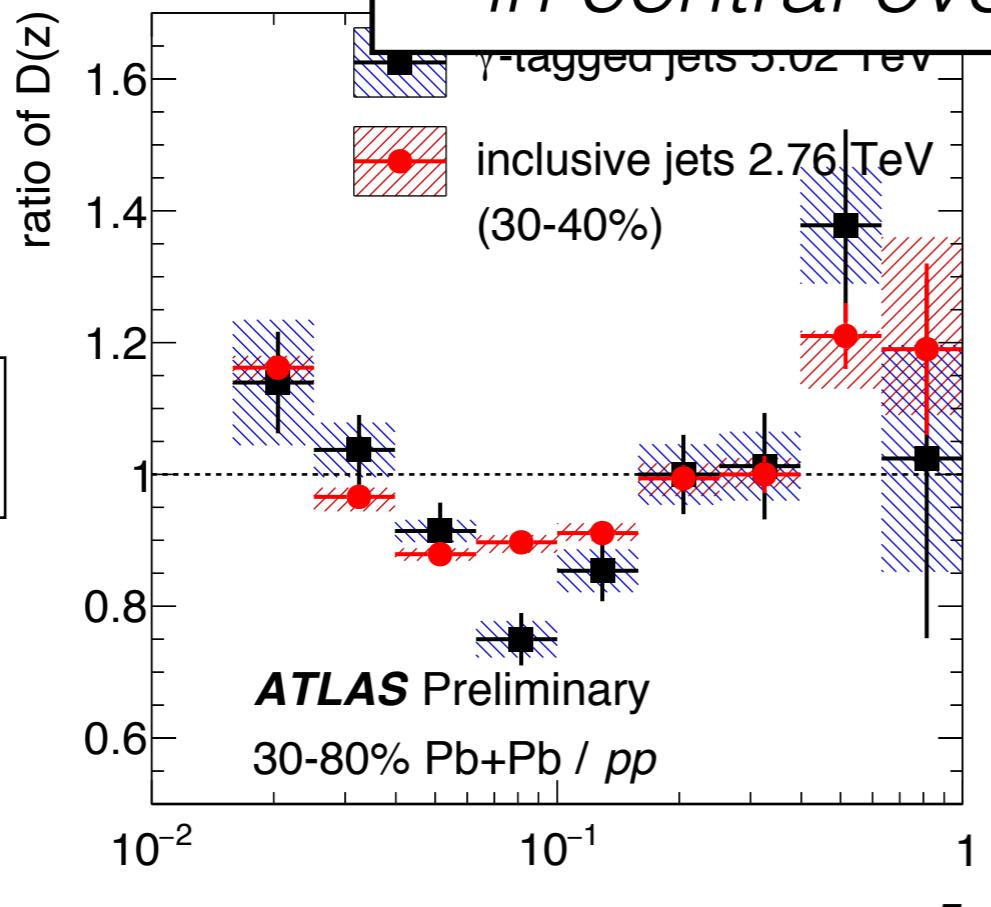
# **30-80% Pb+Pb / pp**



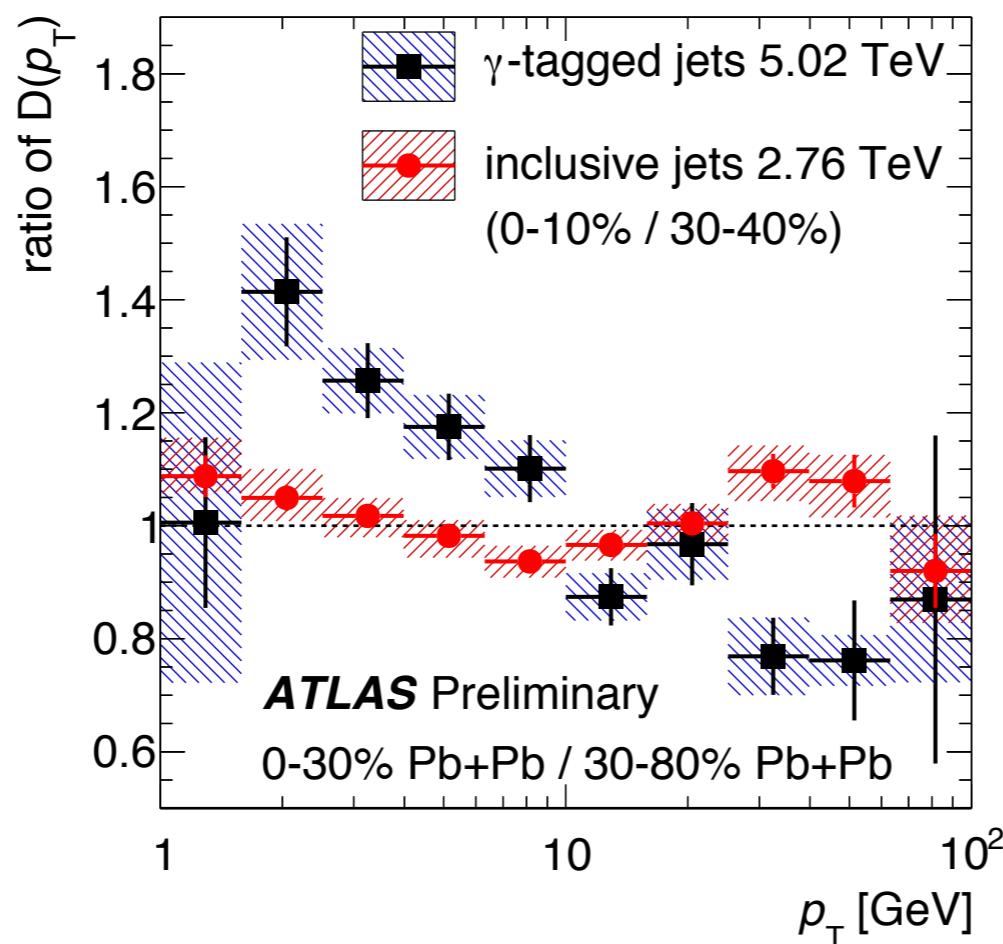
## **inclusive (gluon-dominant) jets**



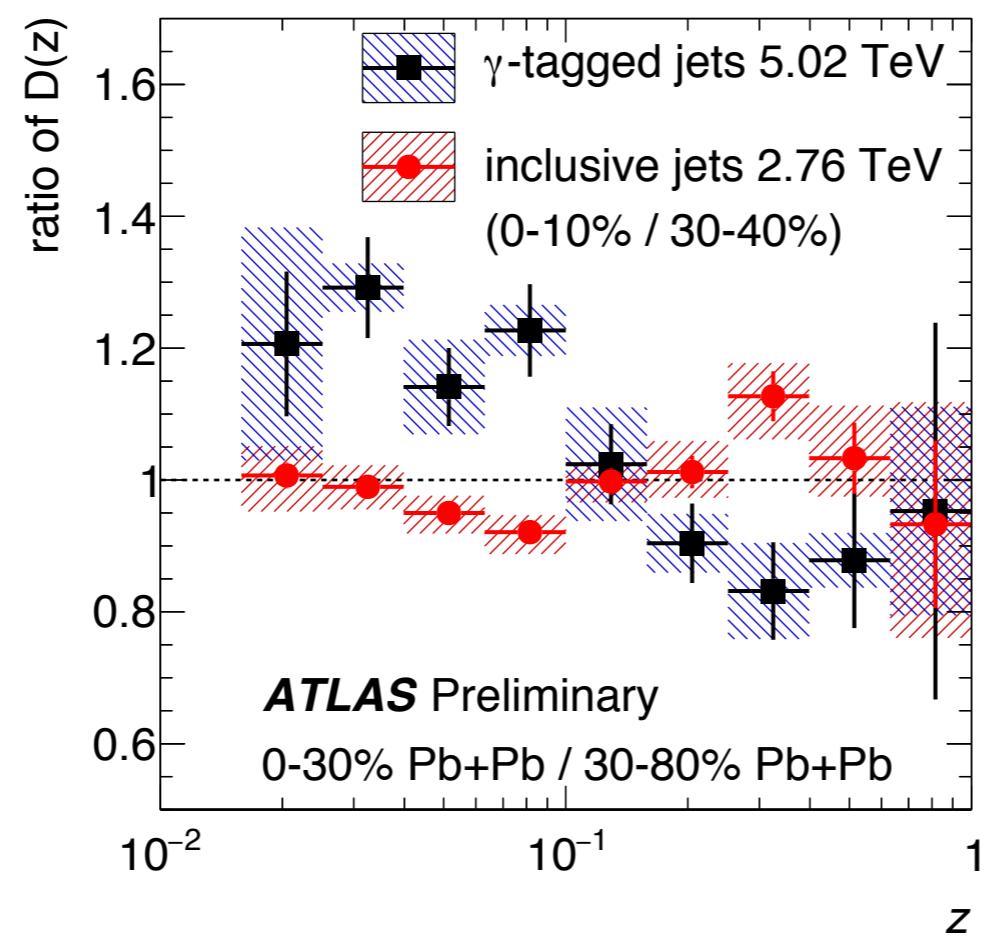
***different modification in central events!***



$D(p_T)$



$D(z)$

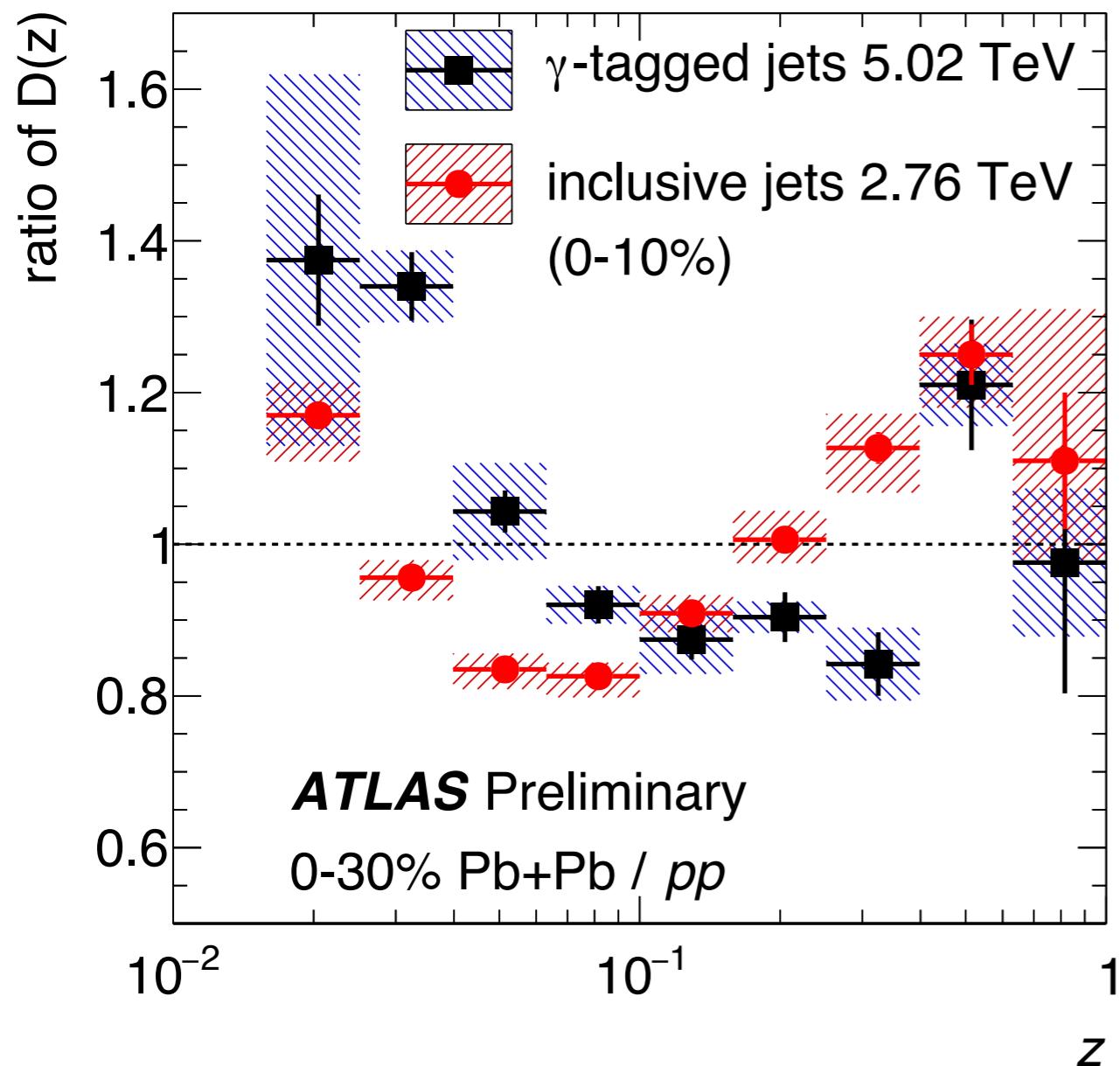


take **0-30% Pb+Pb / 30-80% Pb+Pb** ratio

(like an “ $R_{CP}$ ”)

weak centrality dependence for **inclusive jets**

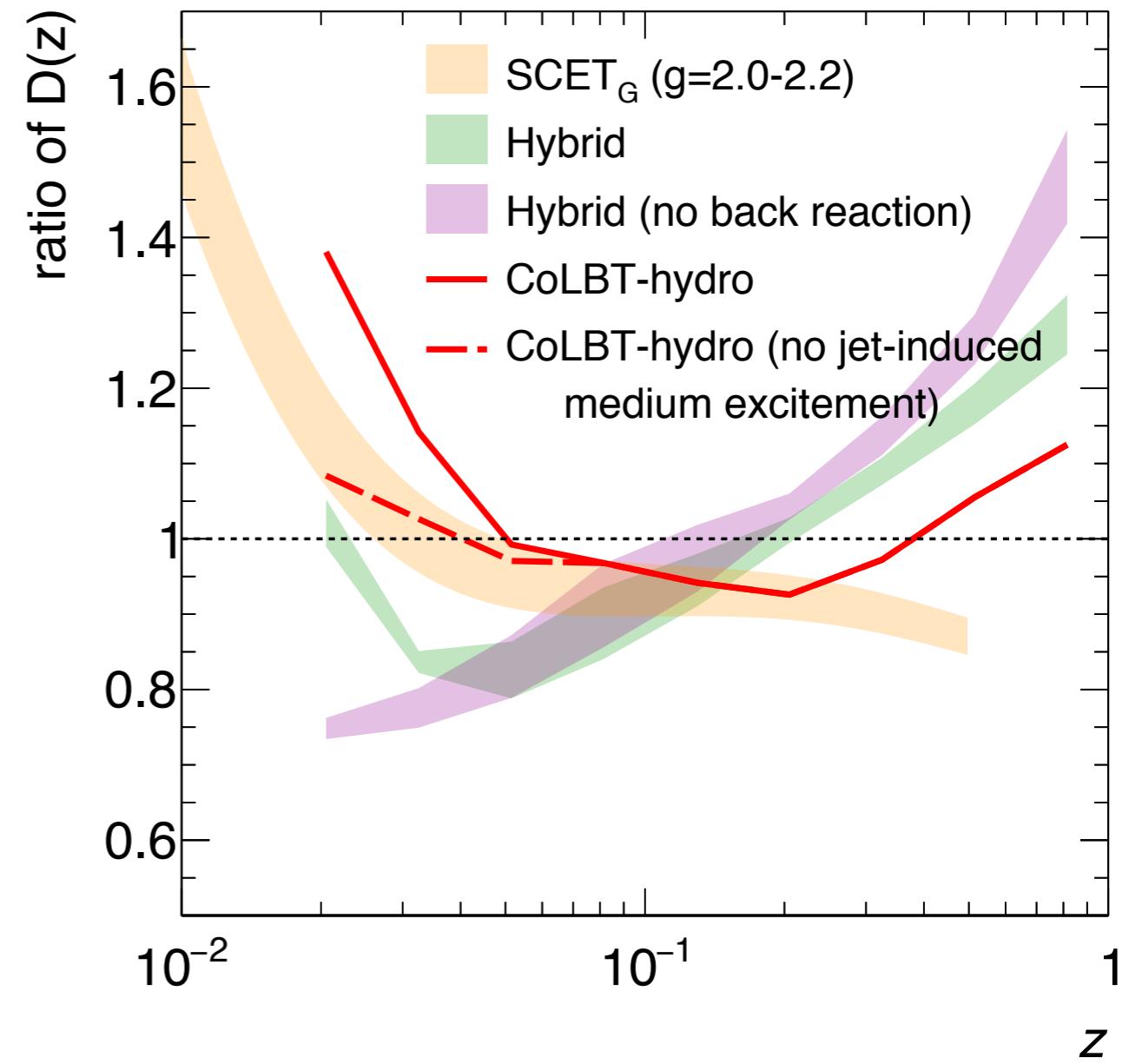
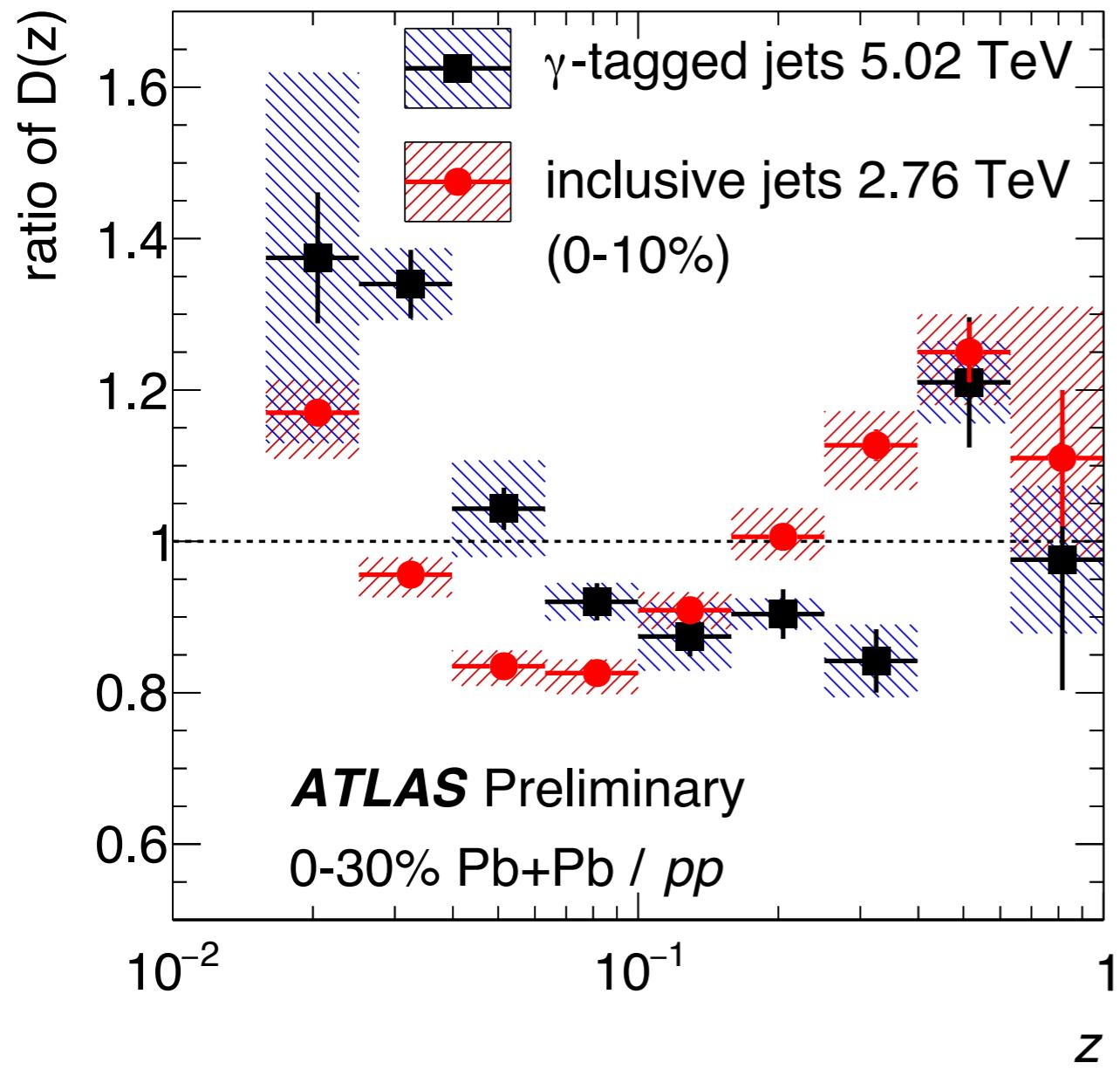
**photon-tagged jets** continue to be modified with centrality...



*how much of this can be attributed just to flavor?*

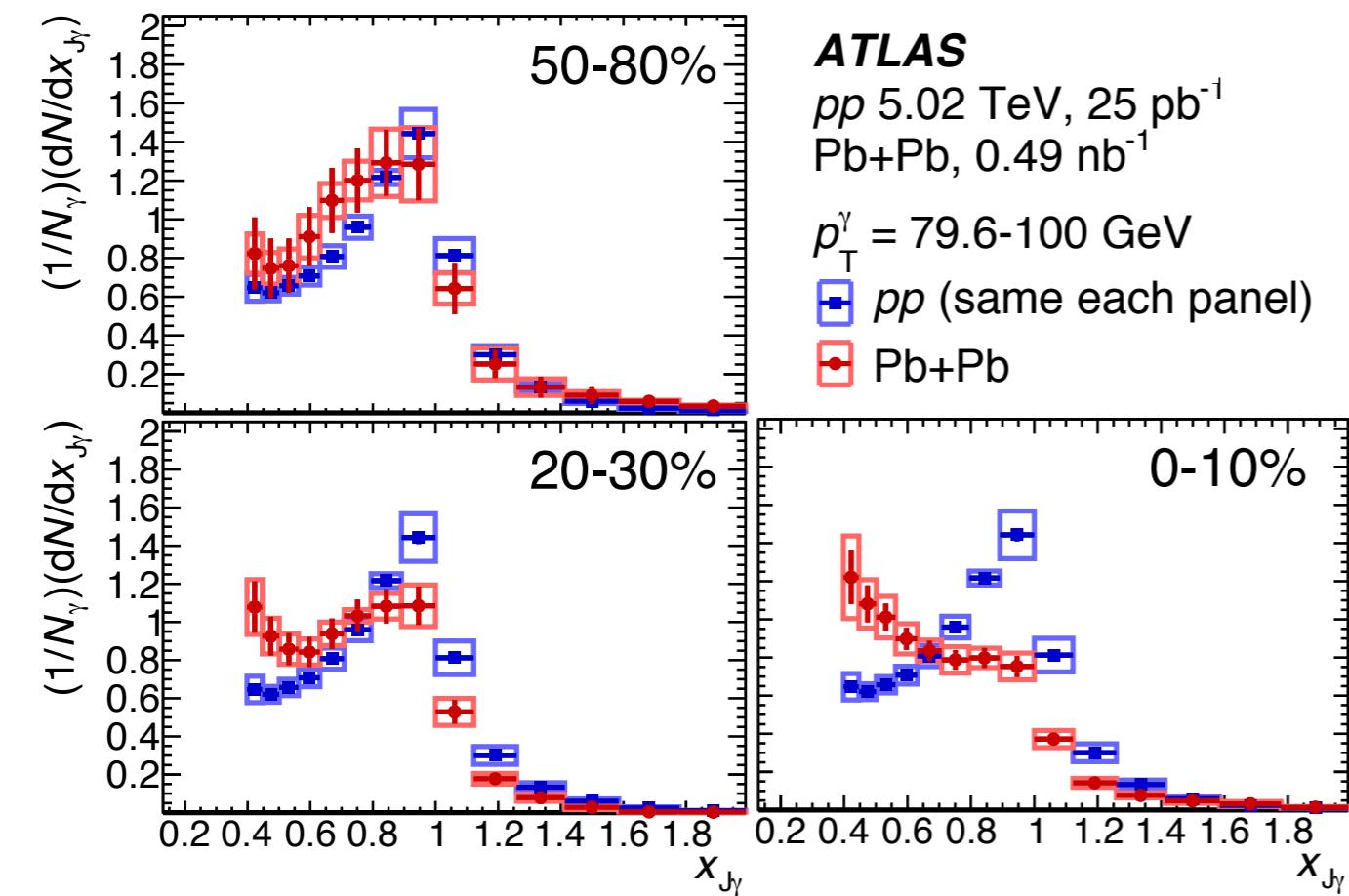
*... and how much to selection effects?*

*(bias against strongly modified jets w/ **inclusive selection**, but not with **photon tag**?)*



Some models do predict a large low- $z$  enhancement (**CoLBT-hydro**)  
 Will be interesting to test full centrality & flavor dependence...

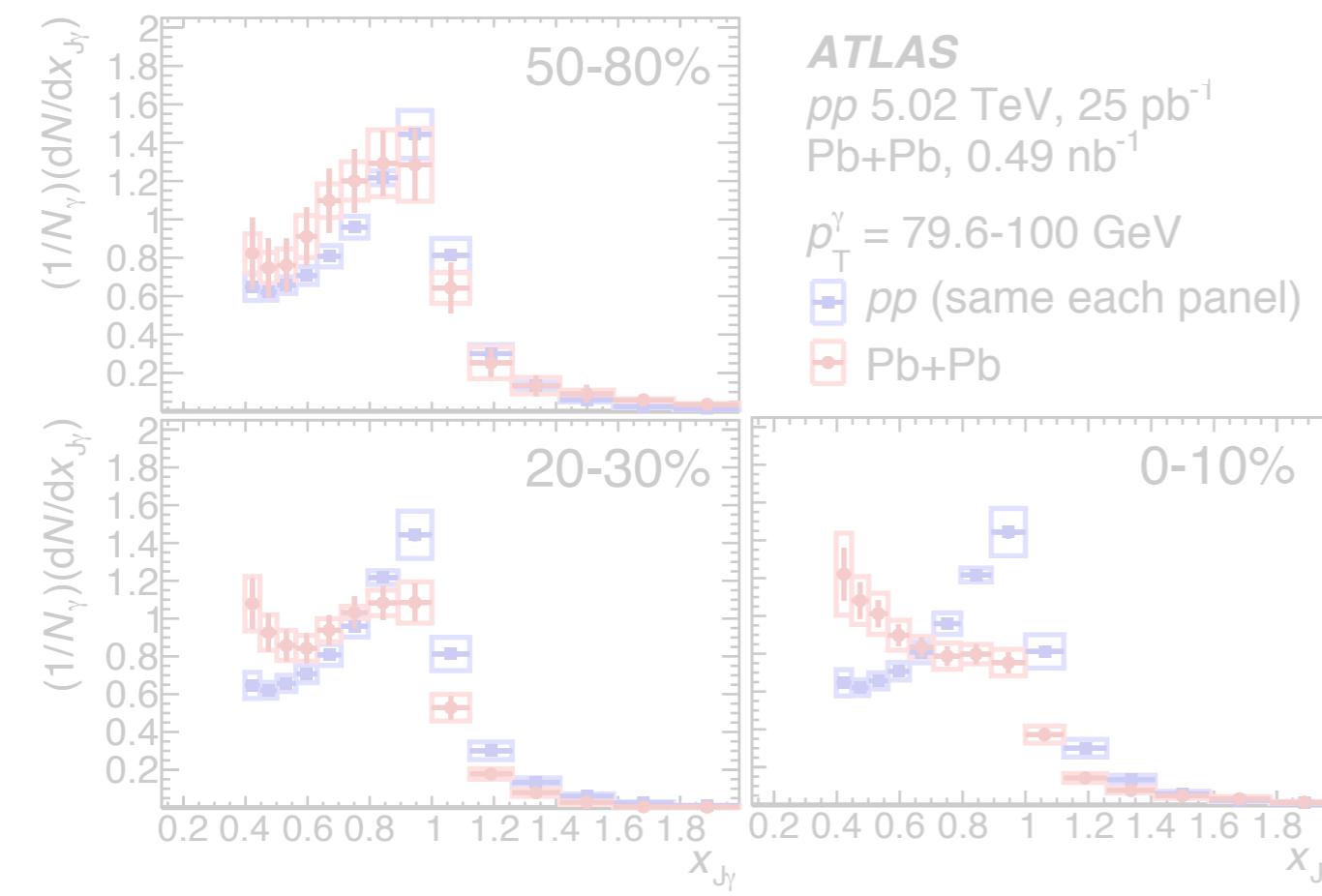
# Conclusions



$\gamma$ +jet  $p_T$ -balance

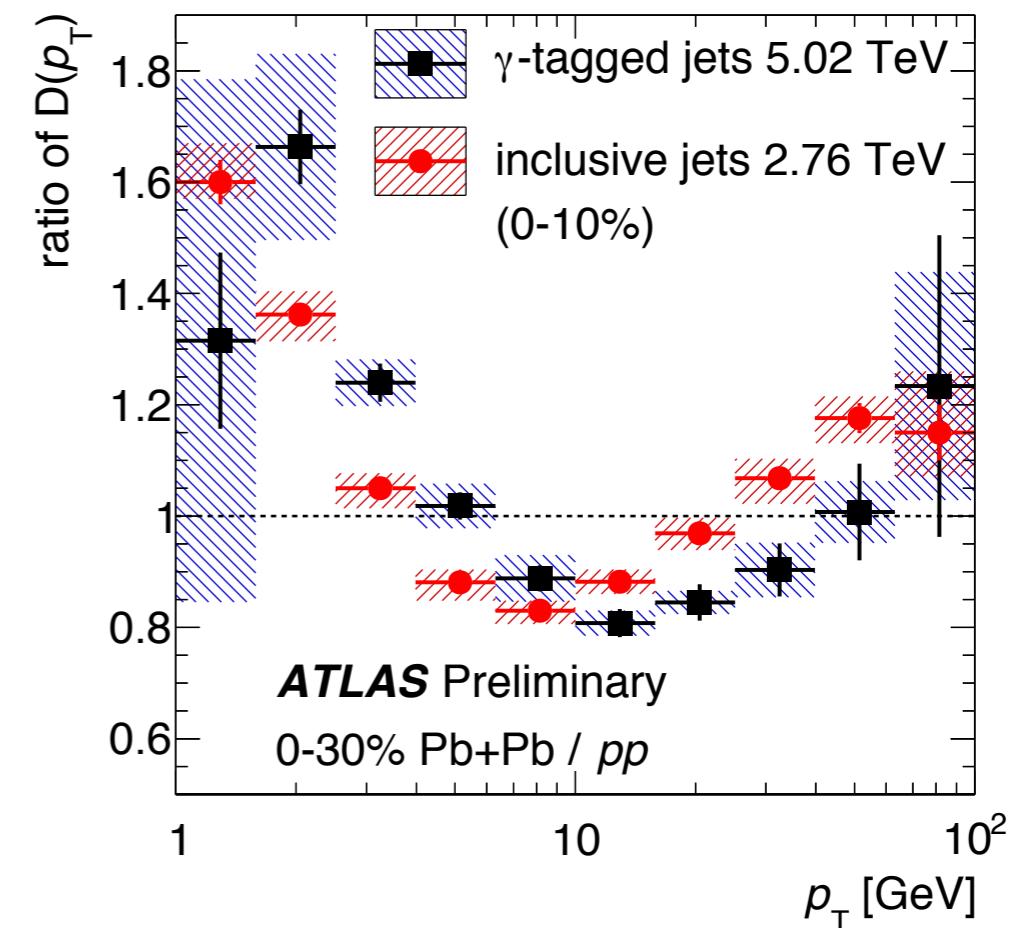
→ **pp-like peaked  $x_{J\gamma}$  in Pb+Pb:**  
variation in jet-by-jet  $E$ -loss

# Conclusions



$\gamma$ +jet  $p_T$ -balance

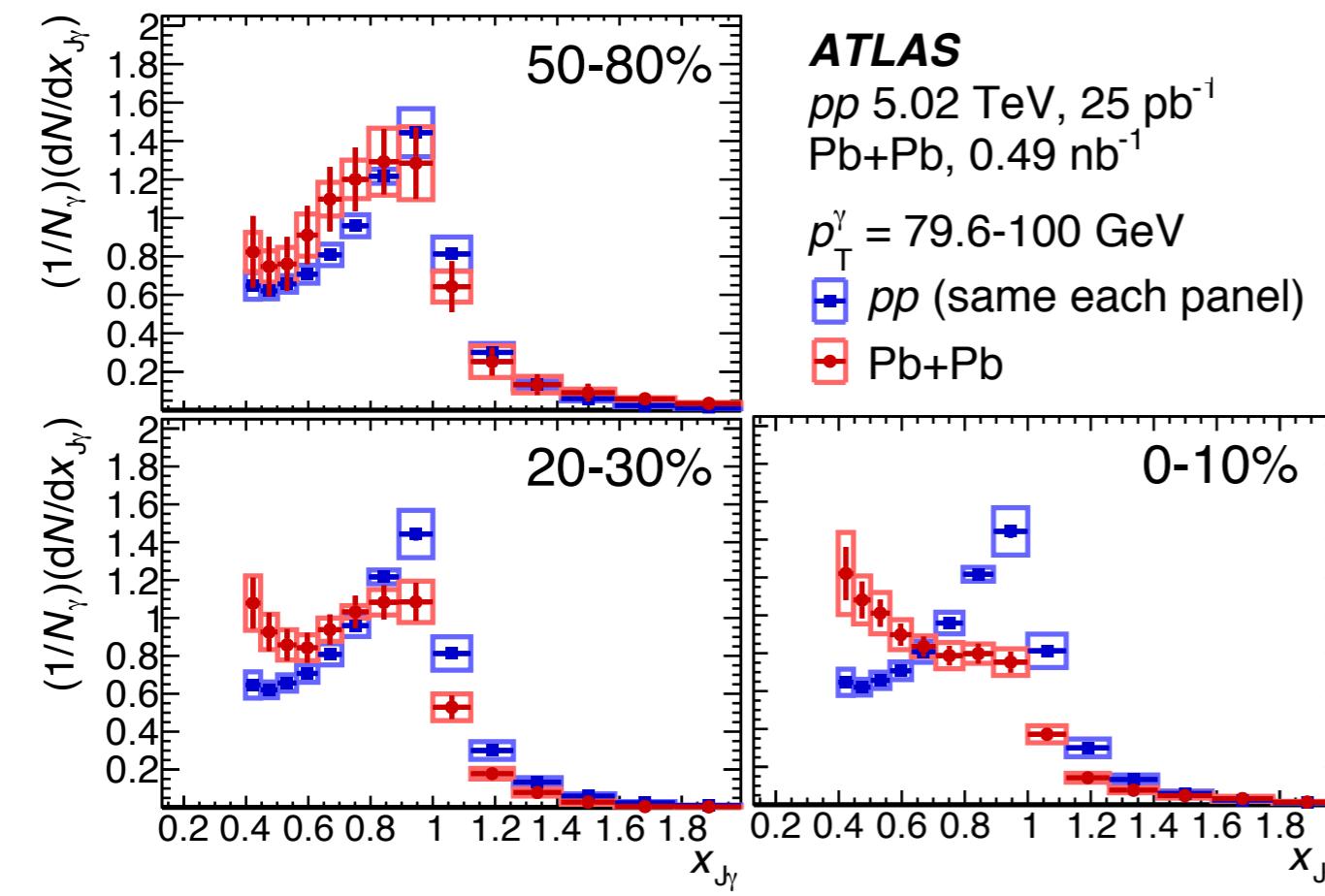
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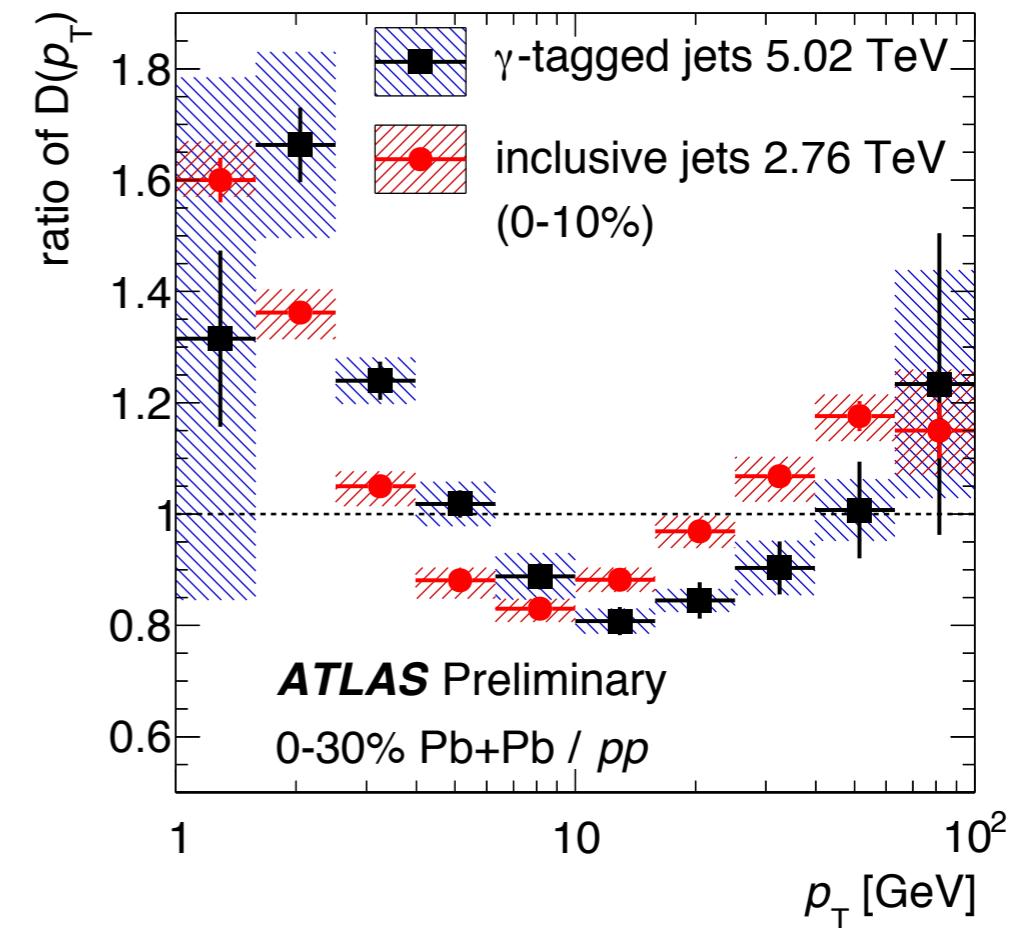
$\gamma$ -tagged jet frag. functions:

→ **different modification** in central  
evts. than **inclusive jets**

# Conclusions



**ATLAS**  
 $pp$  5.02 TeV, 25 pb $^{-1}$   
 $Pb+Pb$ , 0.49 nb $^{-1}$   
 $p_T^\gamma = 79.6$ -100 GeV  
◻  $pp$  (same each panel)  
●  $Pb+Pb$



$\gamma$ +jet  $p_T$ -balance

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

$\gamma$ -tagged jet frag. functions:

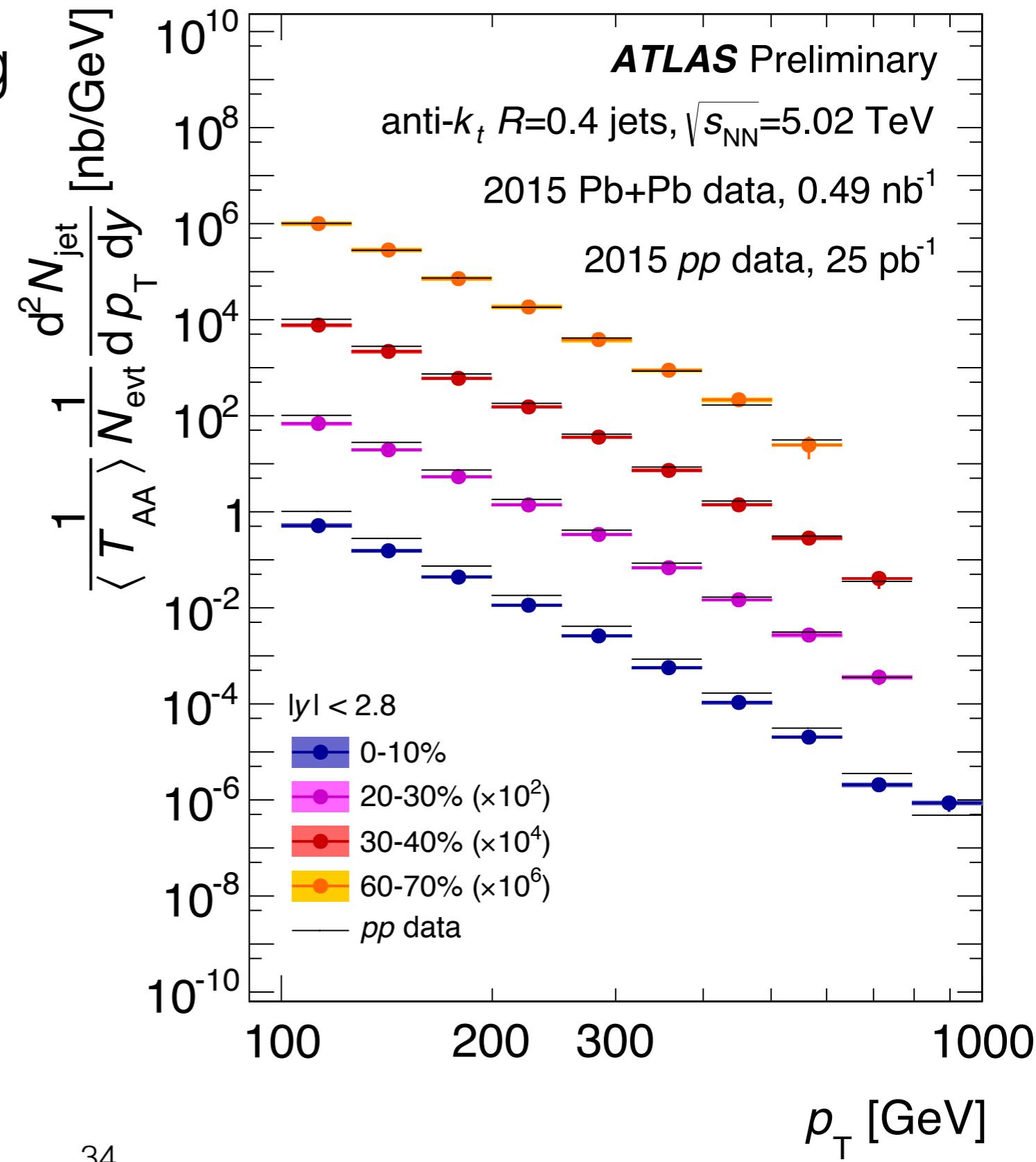
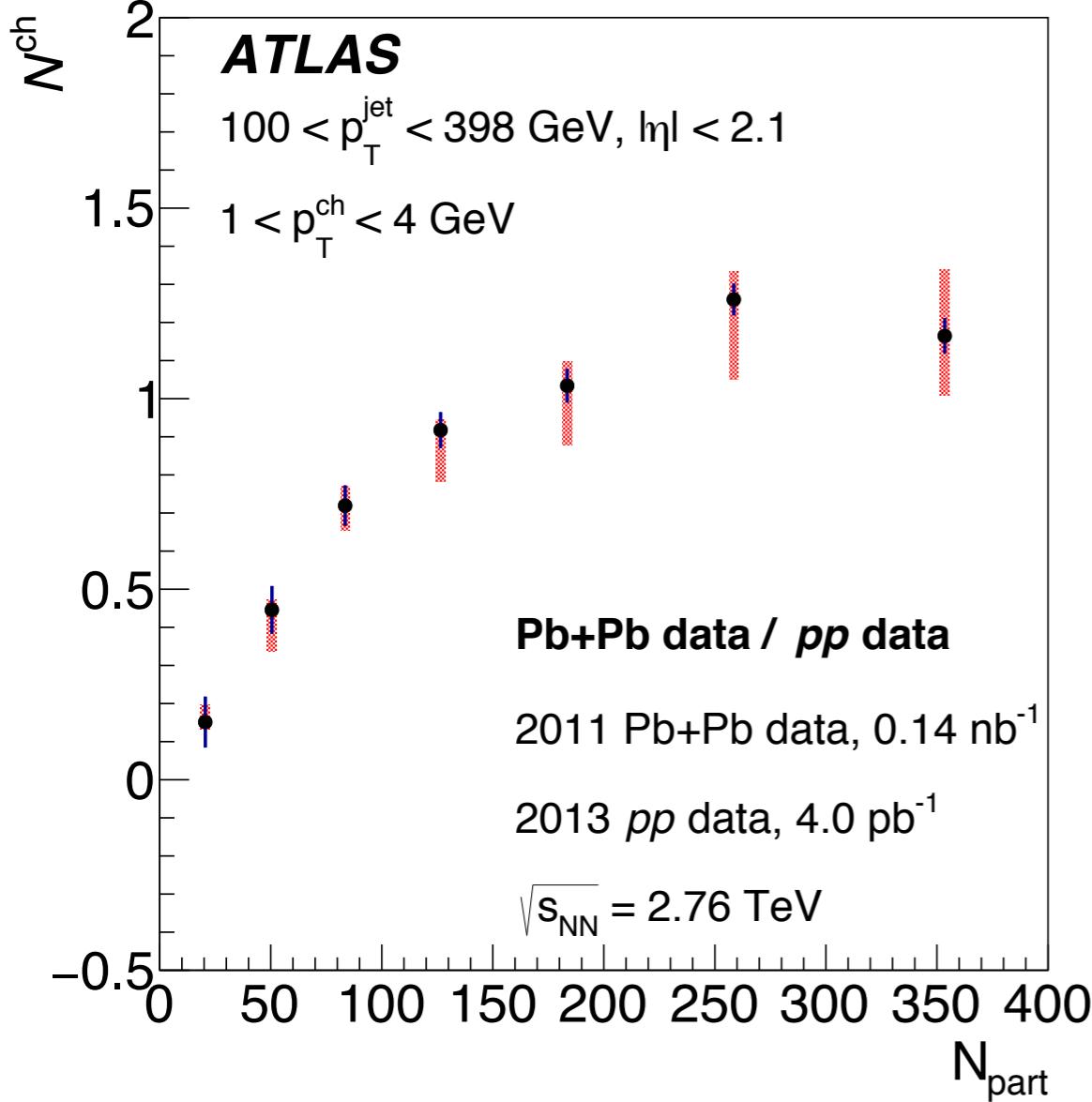
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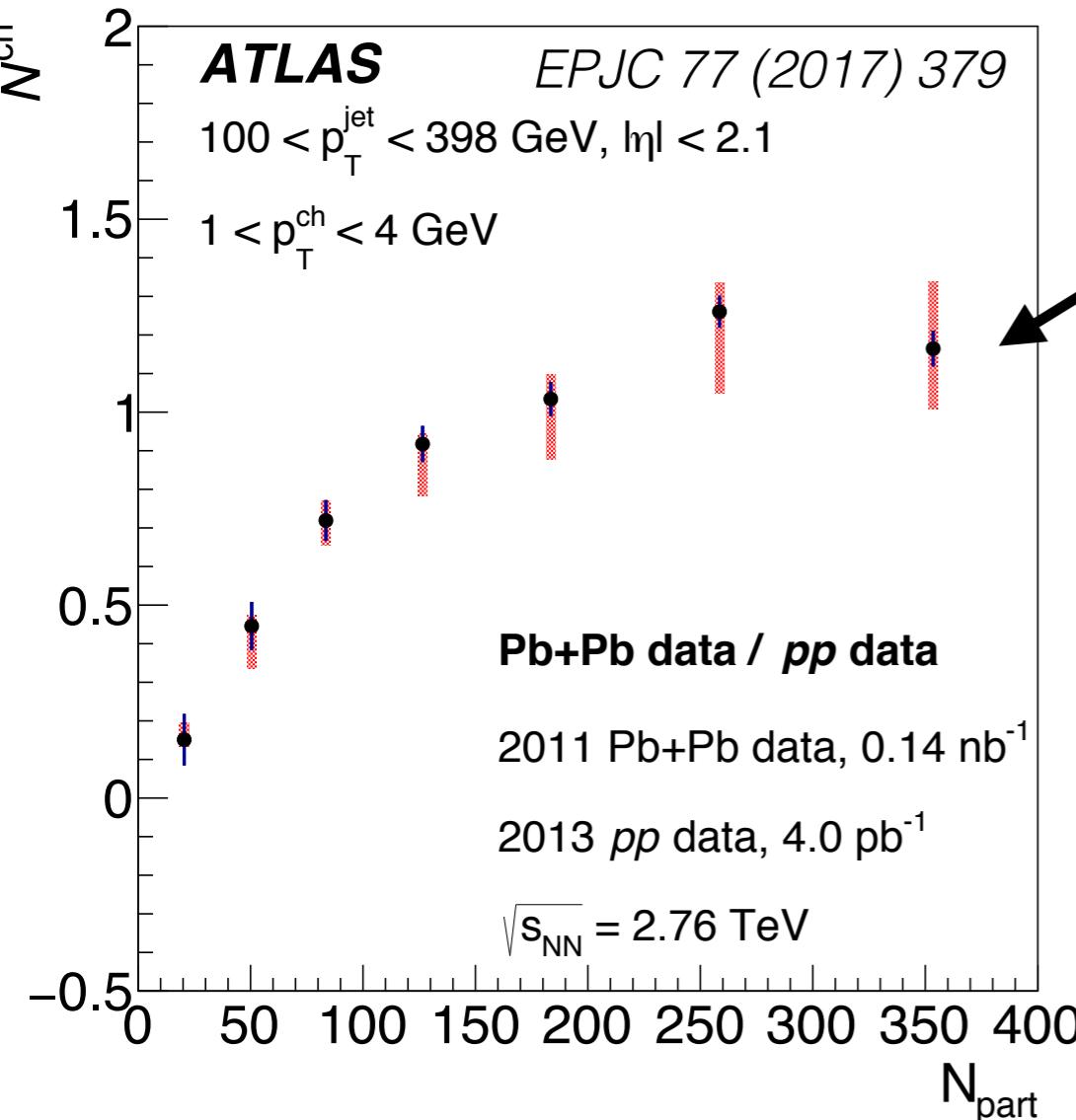


# Inclusive jet FF

$\downarrow \cdots \cdot$  after quenching

$$\frac{D(z; p_T^{\text{jet}}) \text{ in } \mathbf{A+A}}{D(z; p_T^{\text{jet}}) \text{ in } \mathbf{p+p}}$$

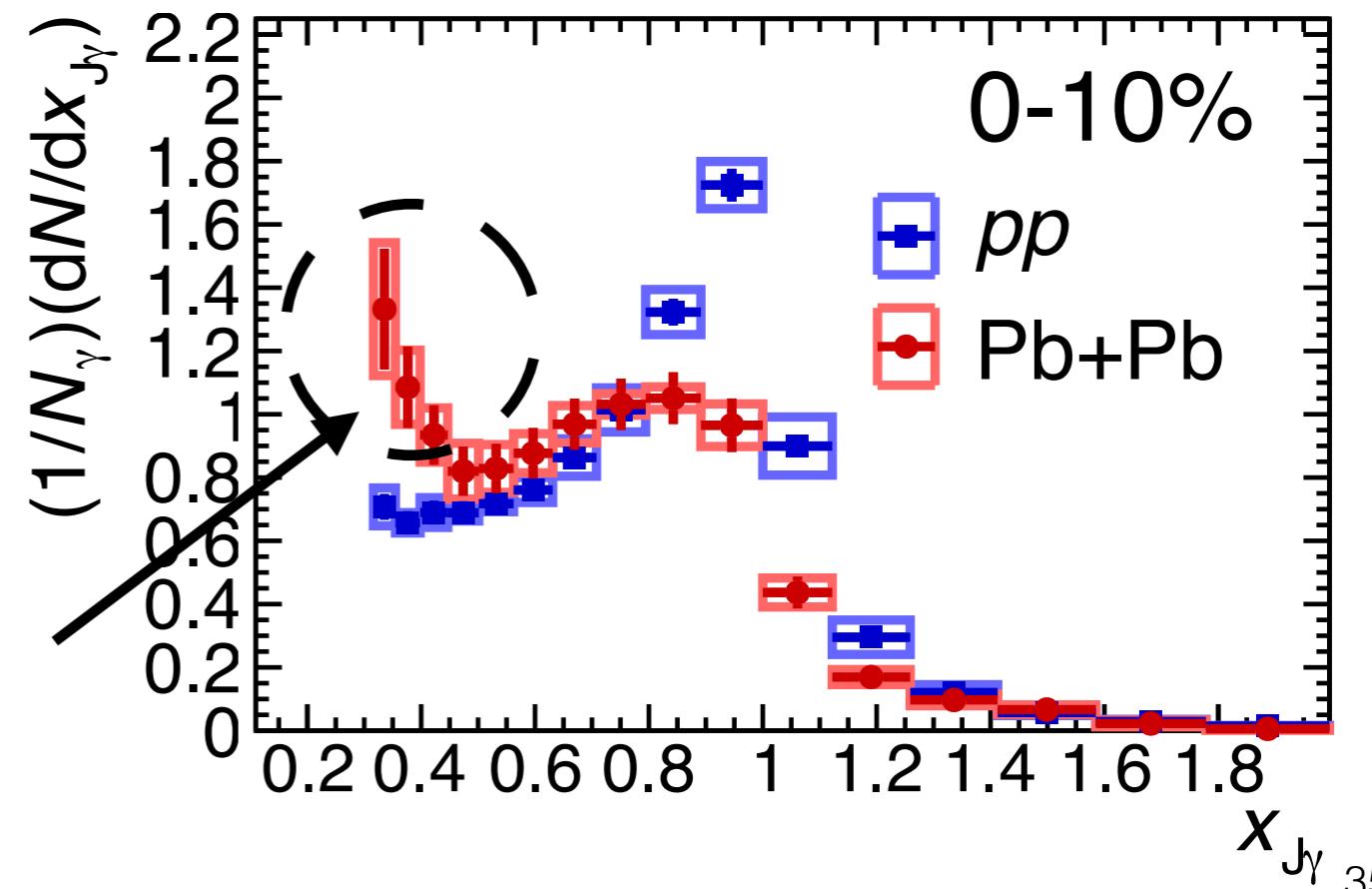




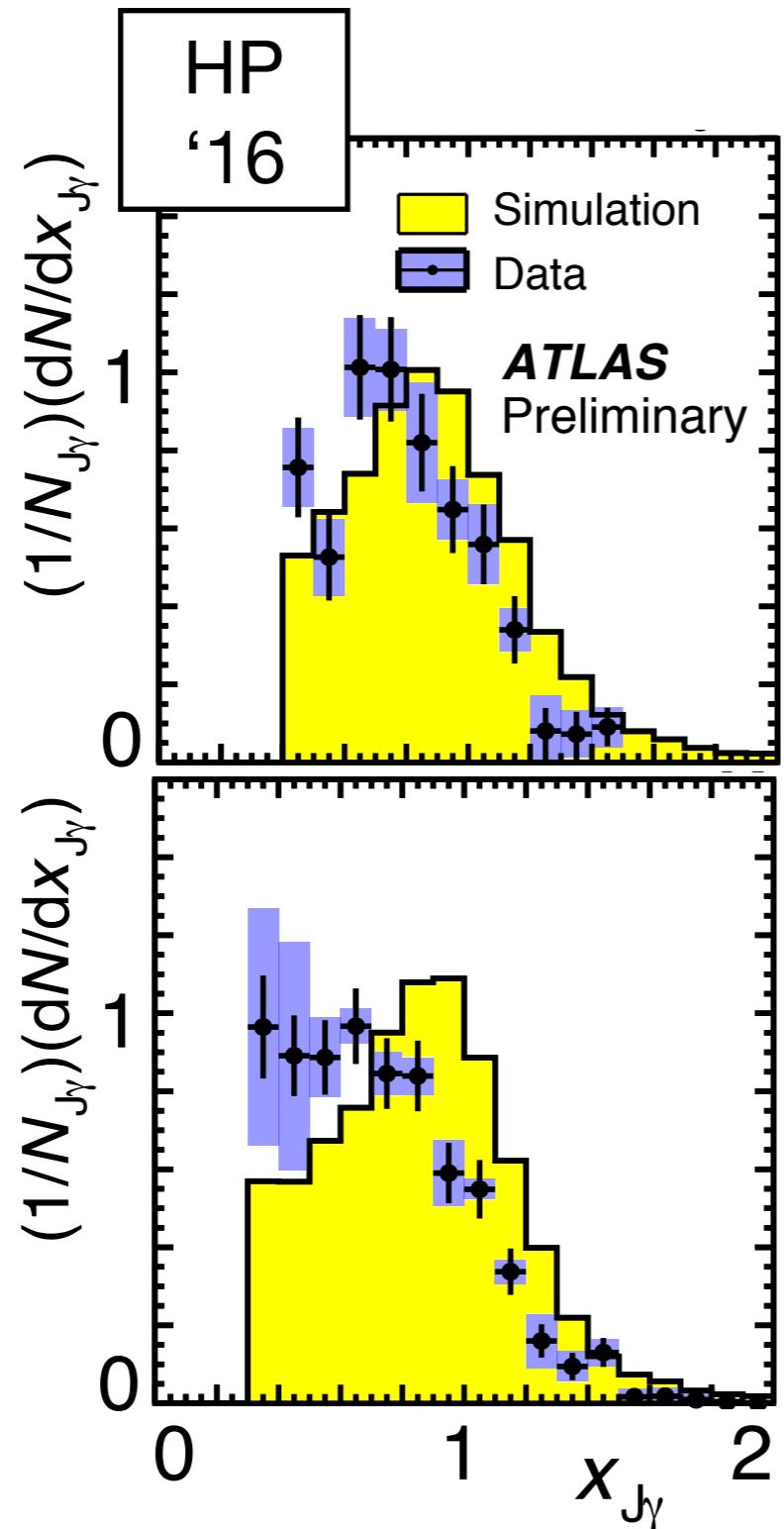
*but a photon tag allows access to extremely modified jets...*

*why FF modification not continue with  $N_{\text{part}}$ ?*

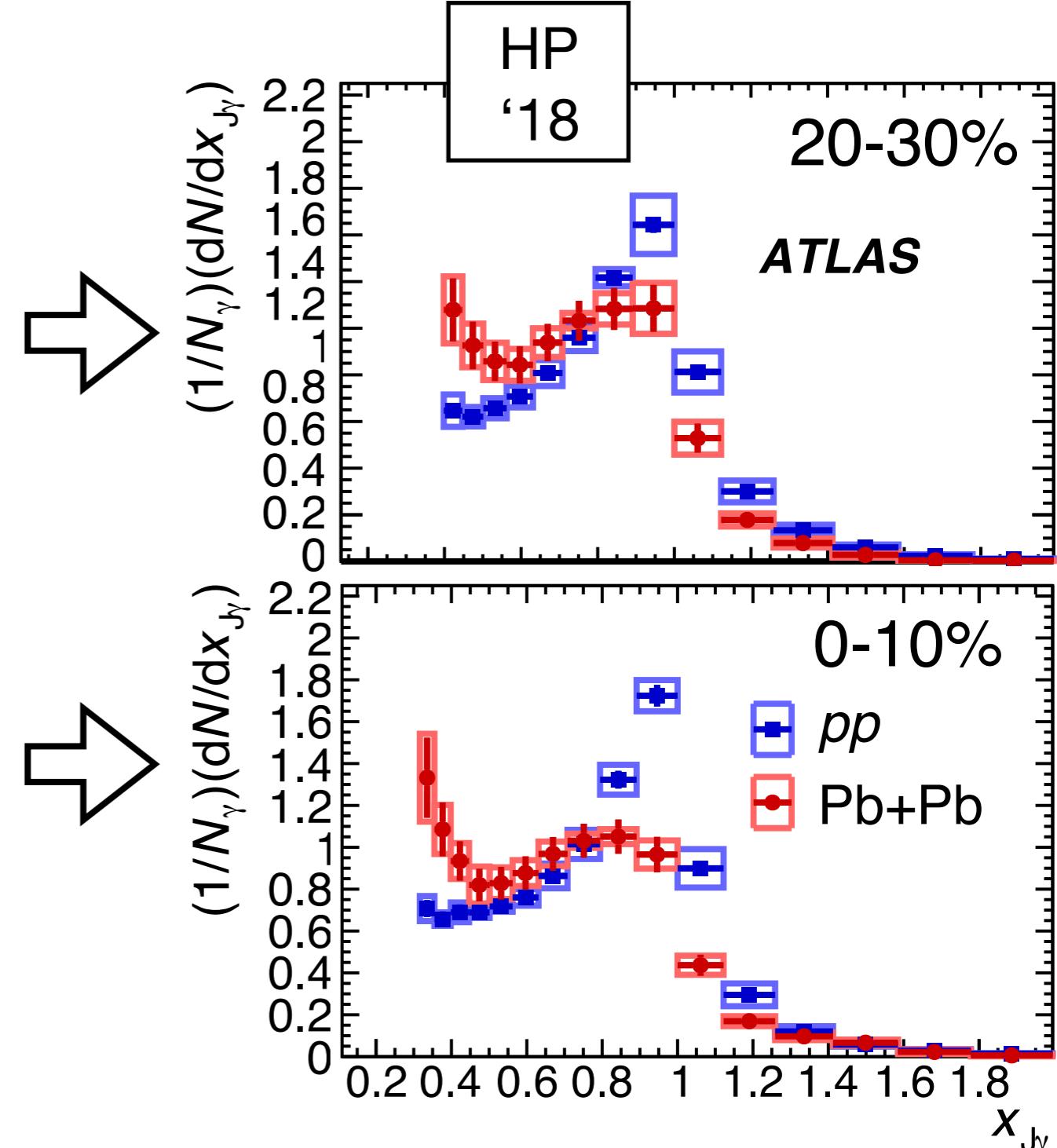
*selection bias against most strongly modified (inclusive) jets?*



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



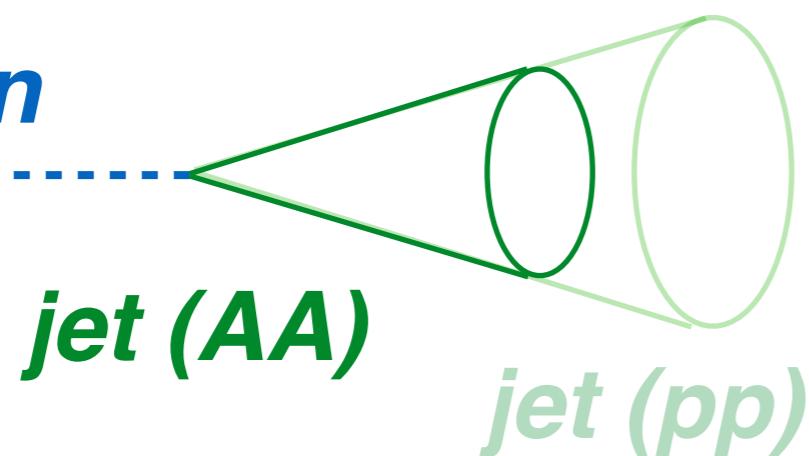
0-10% Pb+Pb  
 $p_{T\gamma} =$   
100-158 GeV



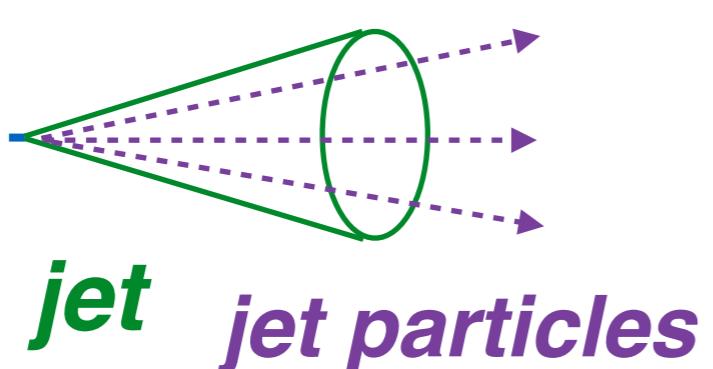
uncorrected **Pb+Pb data** to  
**smeared Pythia** : bulk shift...

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

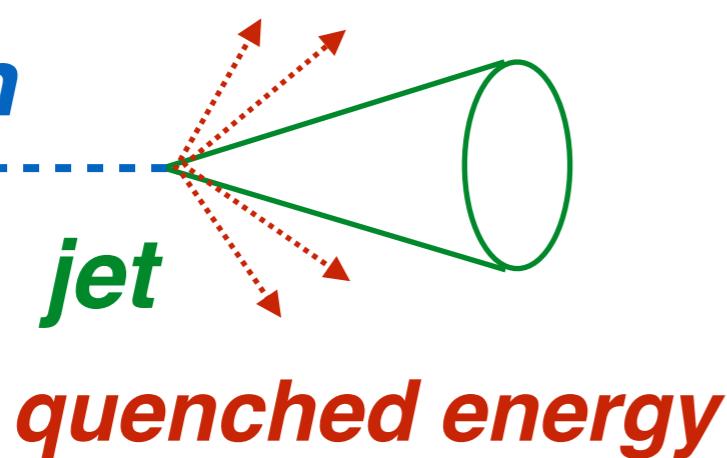
**photon**



**photon**



**photon**



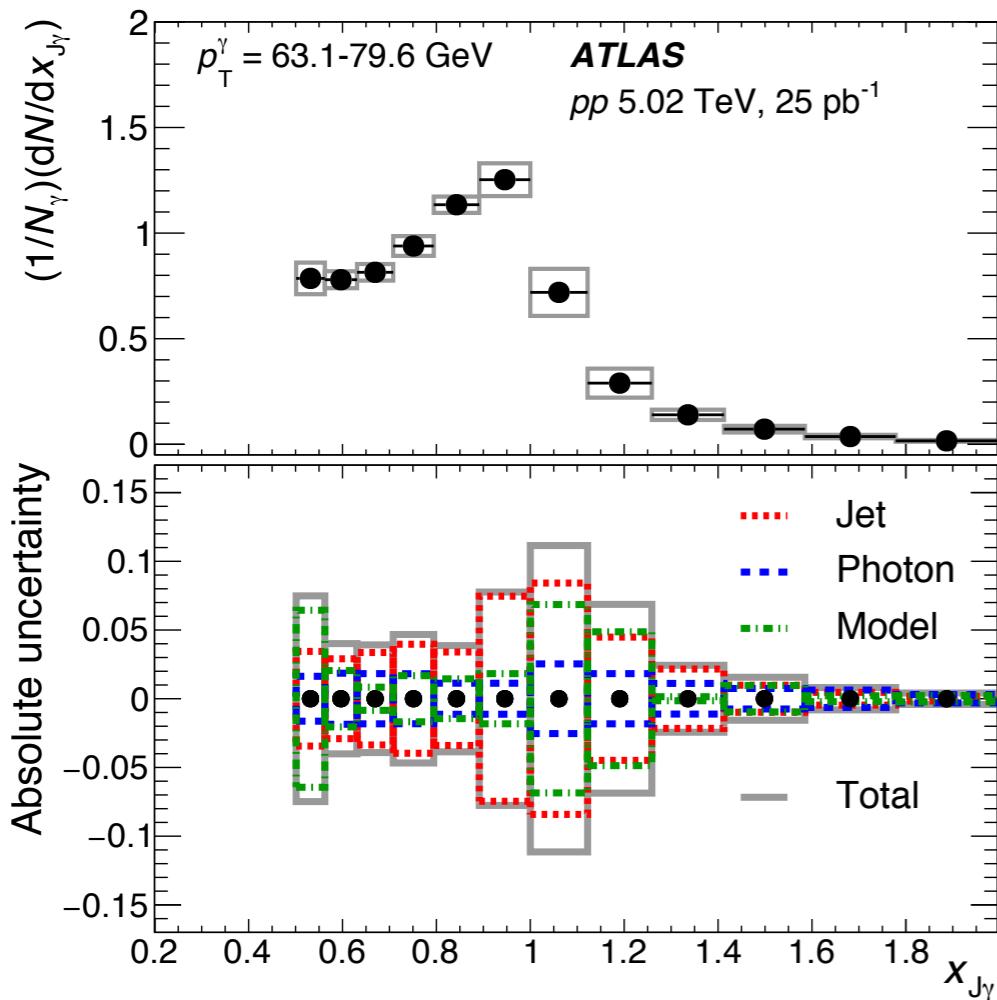
1. What is the (absolute) amount of energy lost in cone?  
→ **photon+jet**  $p_T$ -balance

2. How is the parton shower in cone modified by medium?  
→ **photon**-tagged **frag. function**  
(with respect to the **jet**)

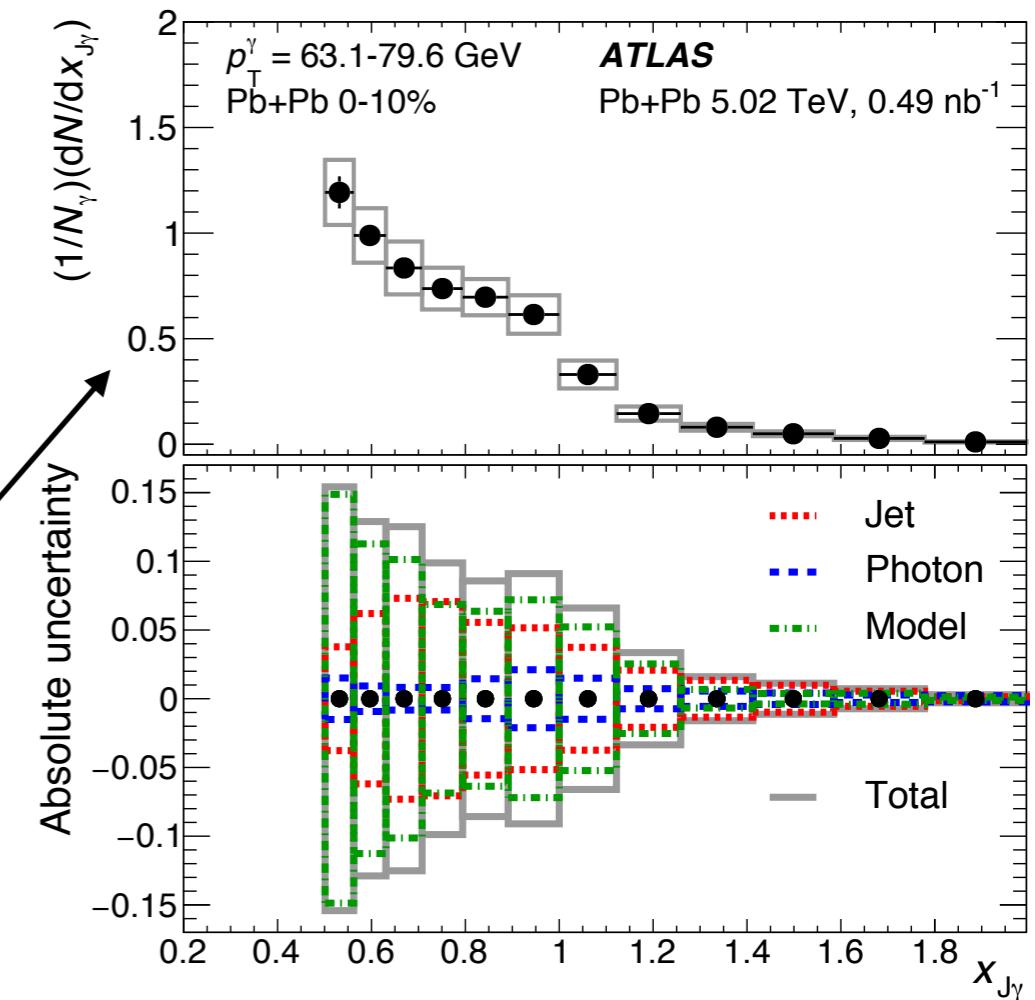
3. Where does the lost energy go?  
→ **photon-hadron** corr. broadly in angle / momentum

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

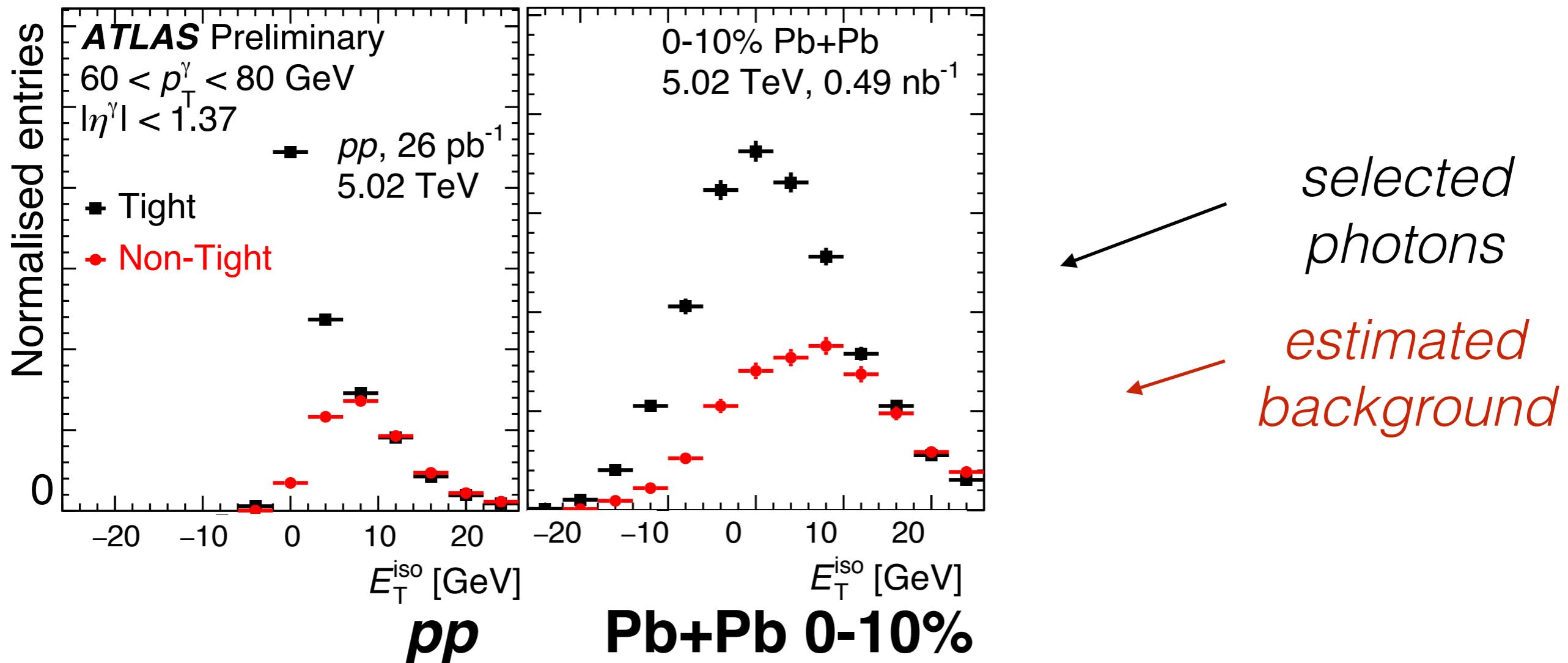
- Dominant: standard HI jet  $p_T$  scale, resolution uncertainties
  - *Sub-dominant*: photon ID, isolation, dijet background
  - Co-dominant in central events: prior/MC/combinatorial bkg.
- FF measurement also includes tracking uncertainties



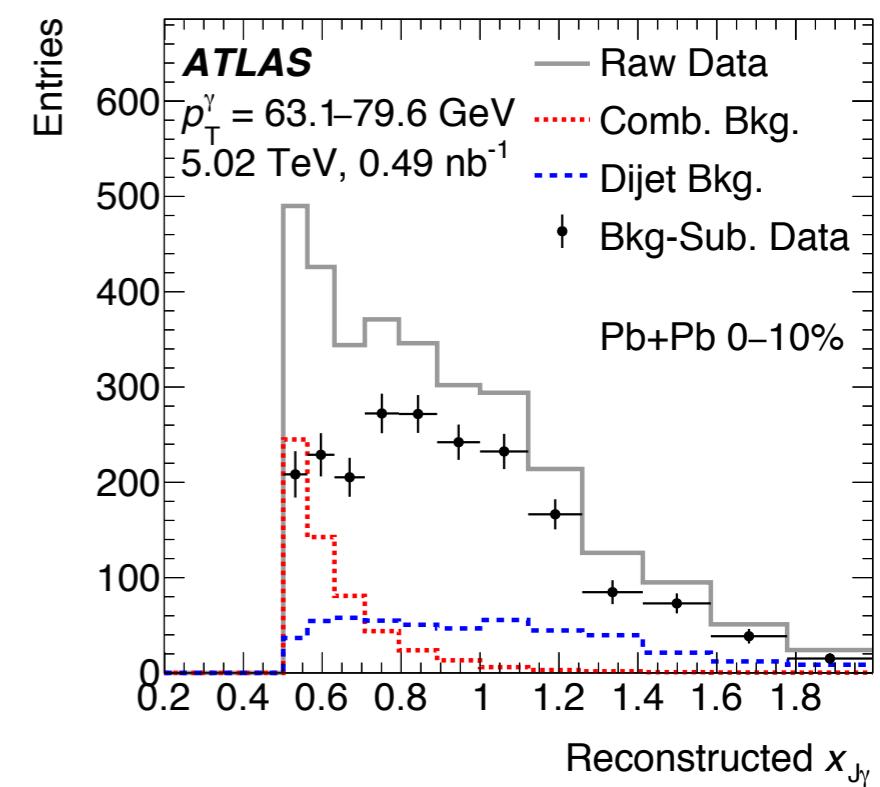
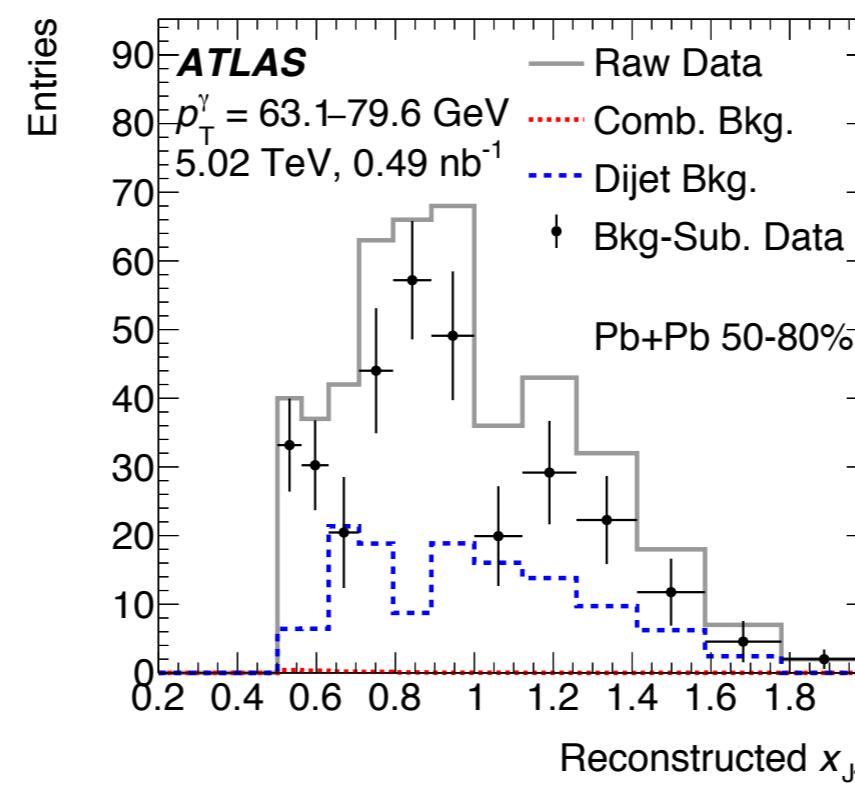
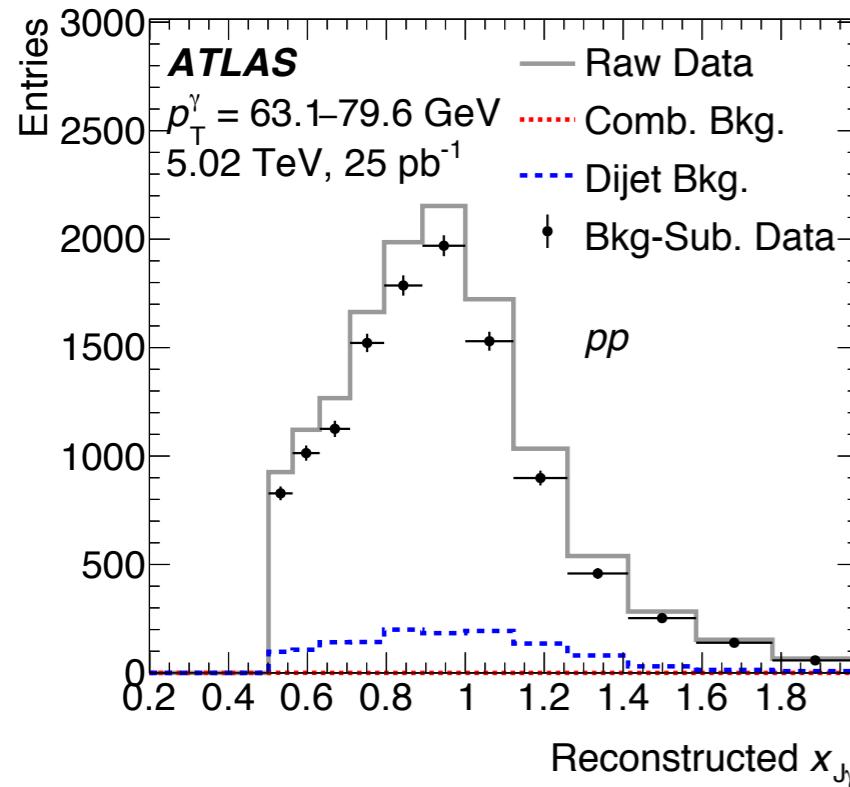
**pp**  
**0-10%**  
**Pb+Pb**



# Photon selection

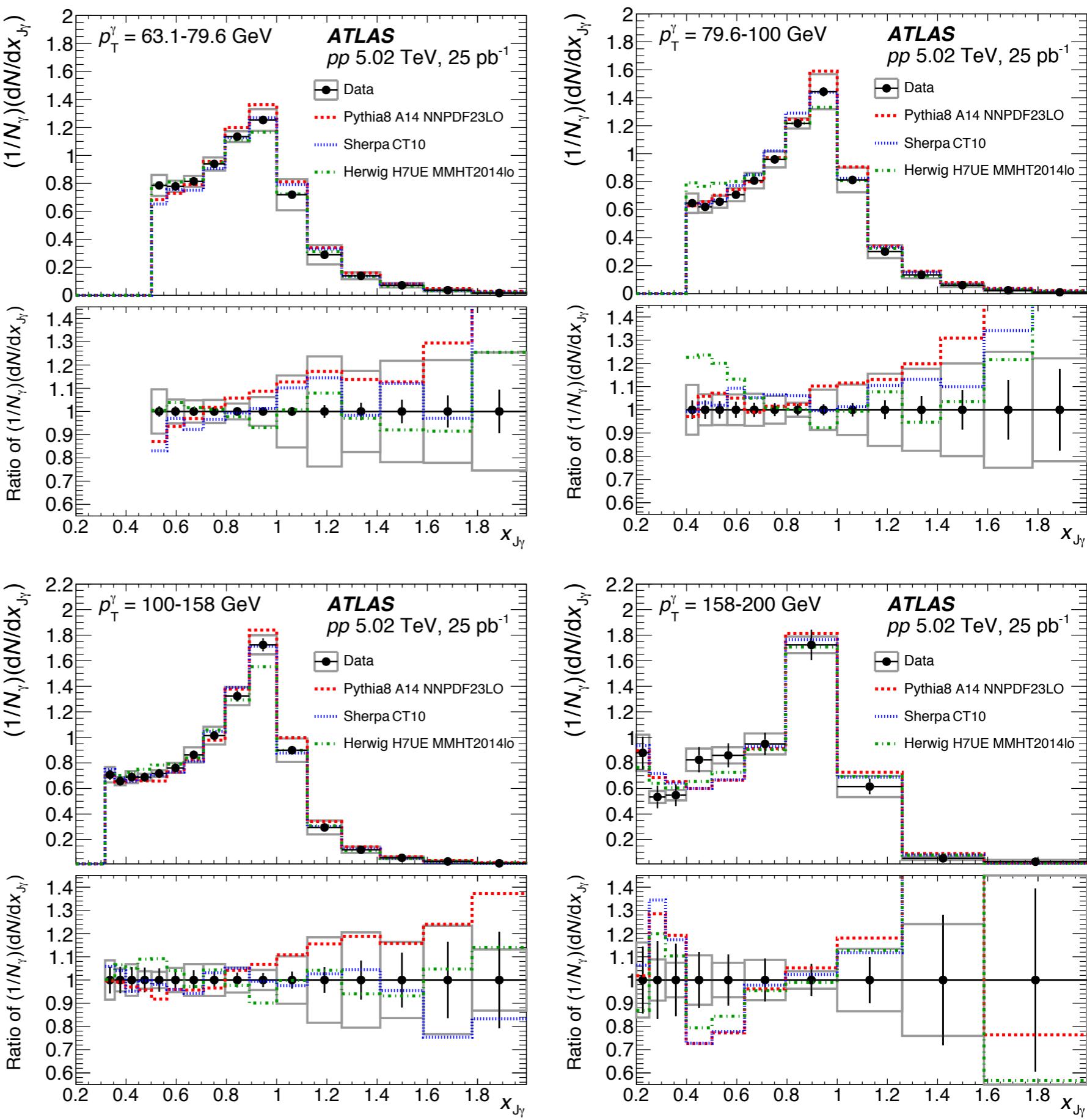


- Photons are required to pass ID cuts & be experimentally isolated
  - purity estimated with standard “double sideband” approach, >95% (>80%) in  $pp$  (central Pb+Pb)



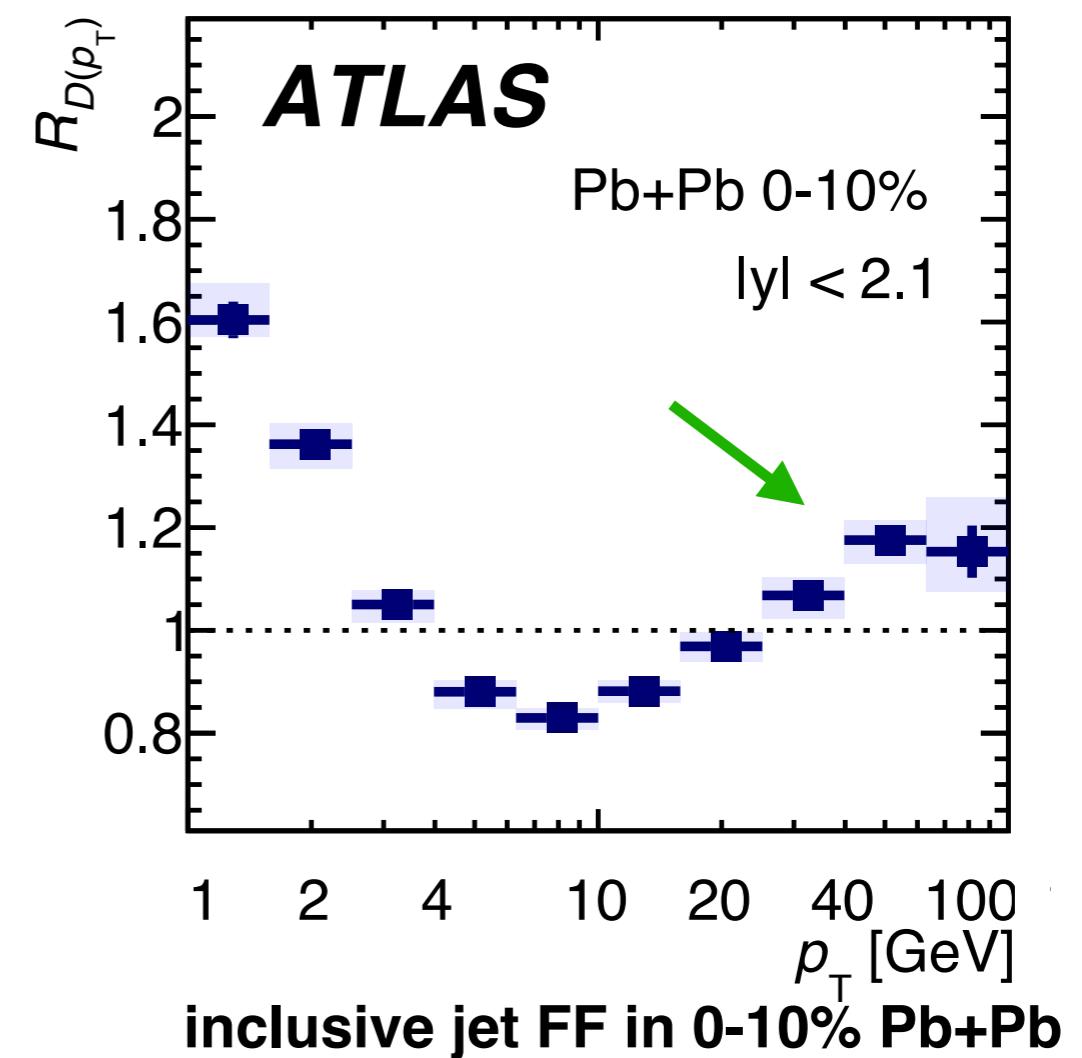
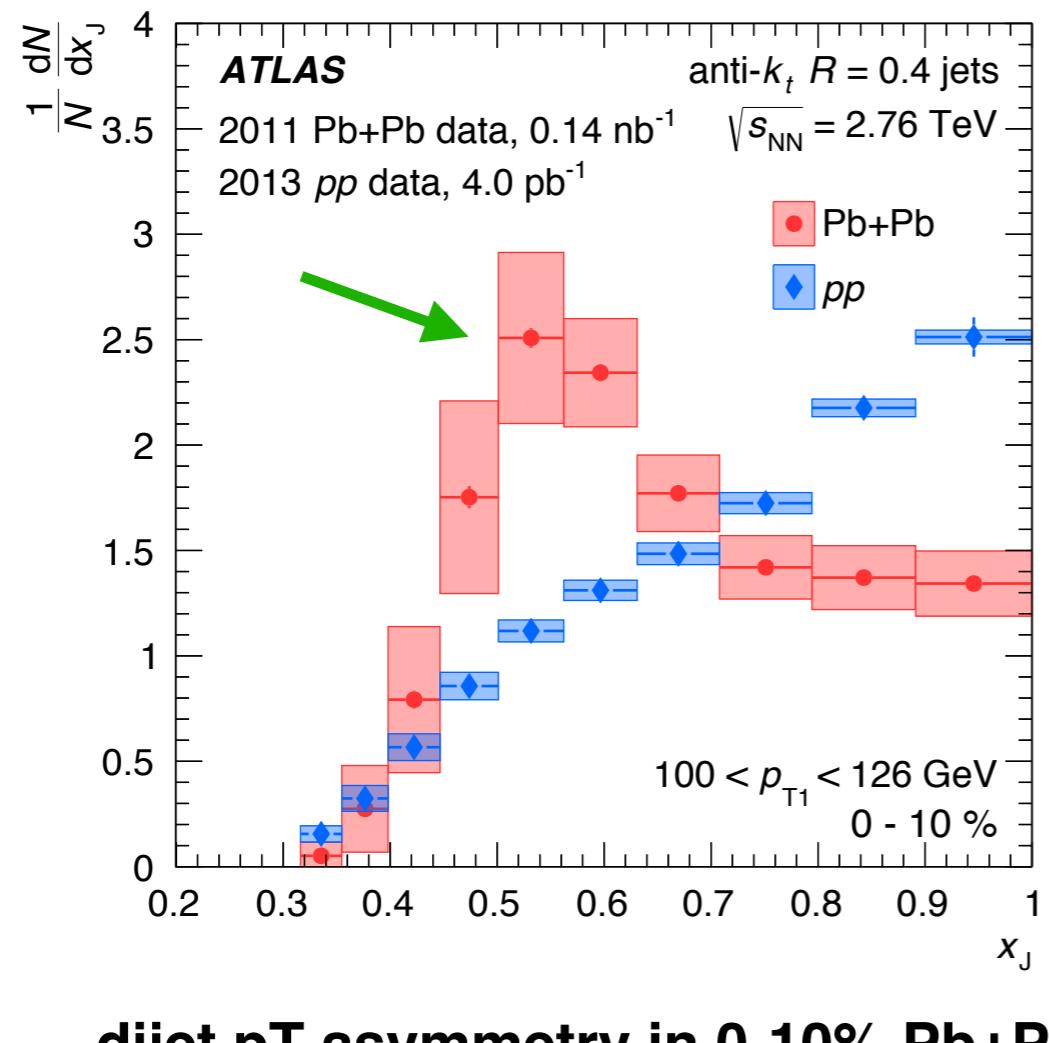
- Data-driven background corrections
  - **combinatoric** photon+jet pairs
  - **dijets** ( $\pi^0$ +jet) from impure photon selection
  - FF measurement also includes UE particles in jet cone

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

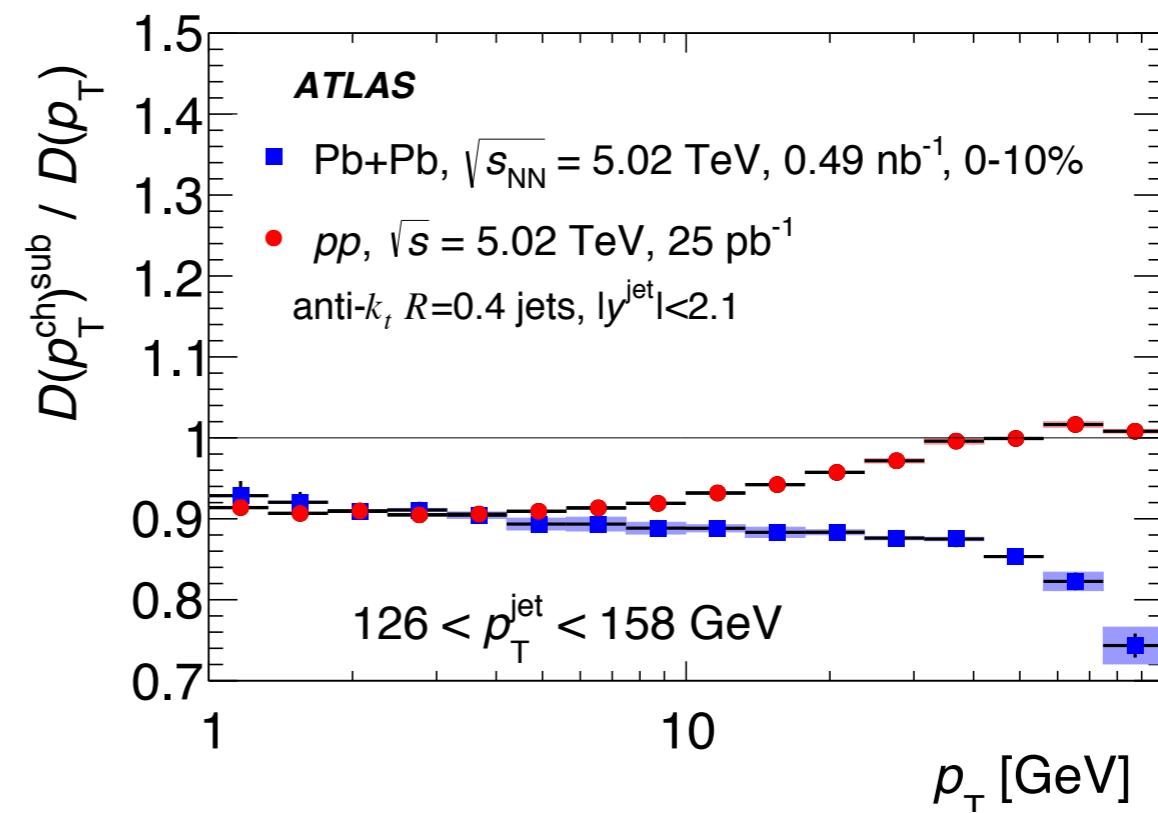
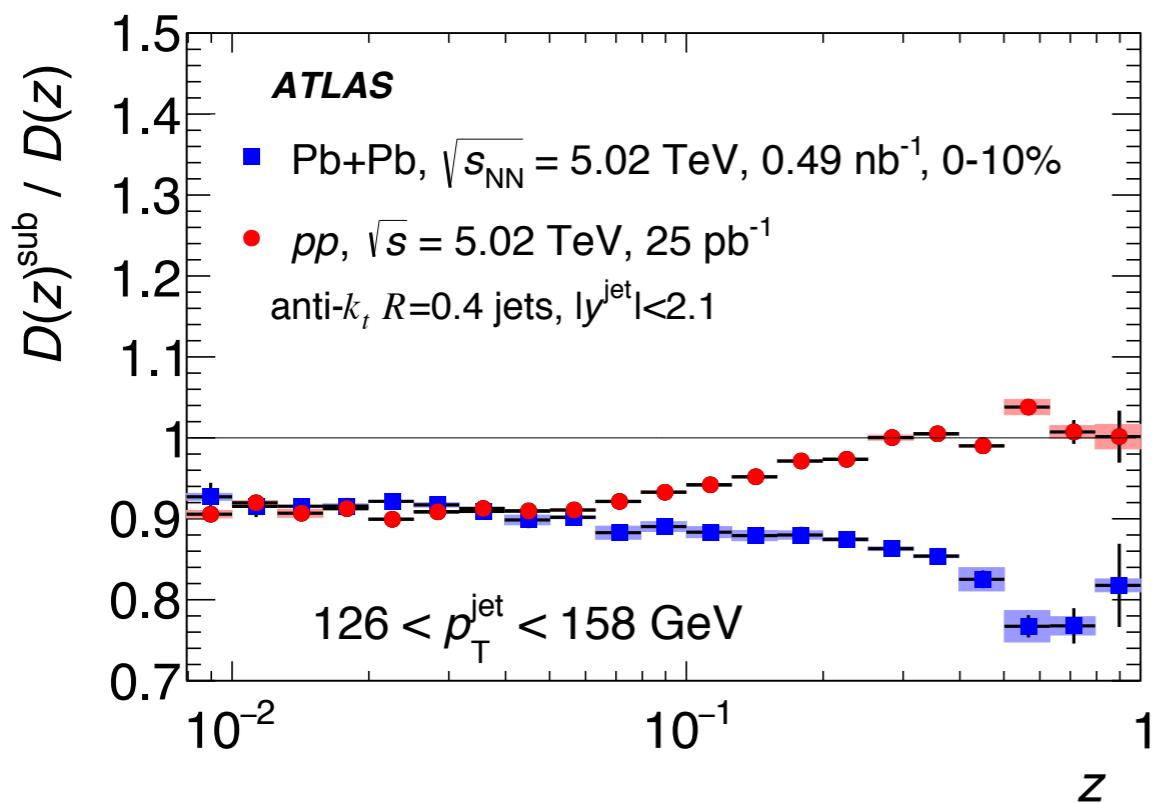


# ATLAS measurements with 2-D unfolding

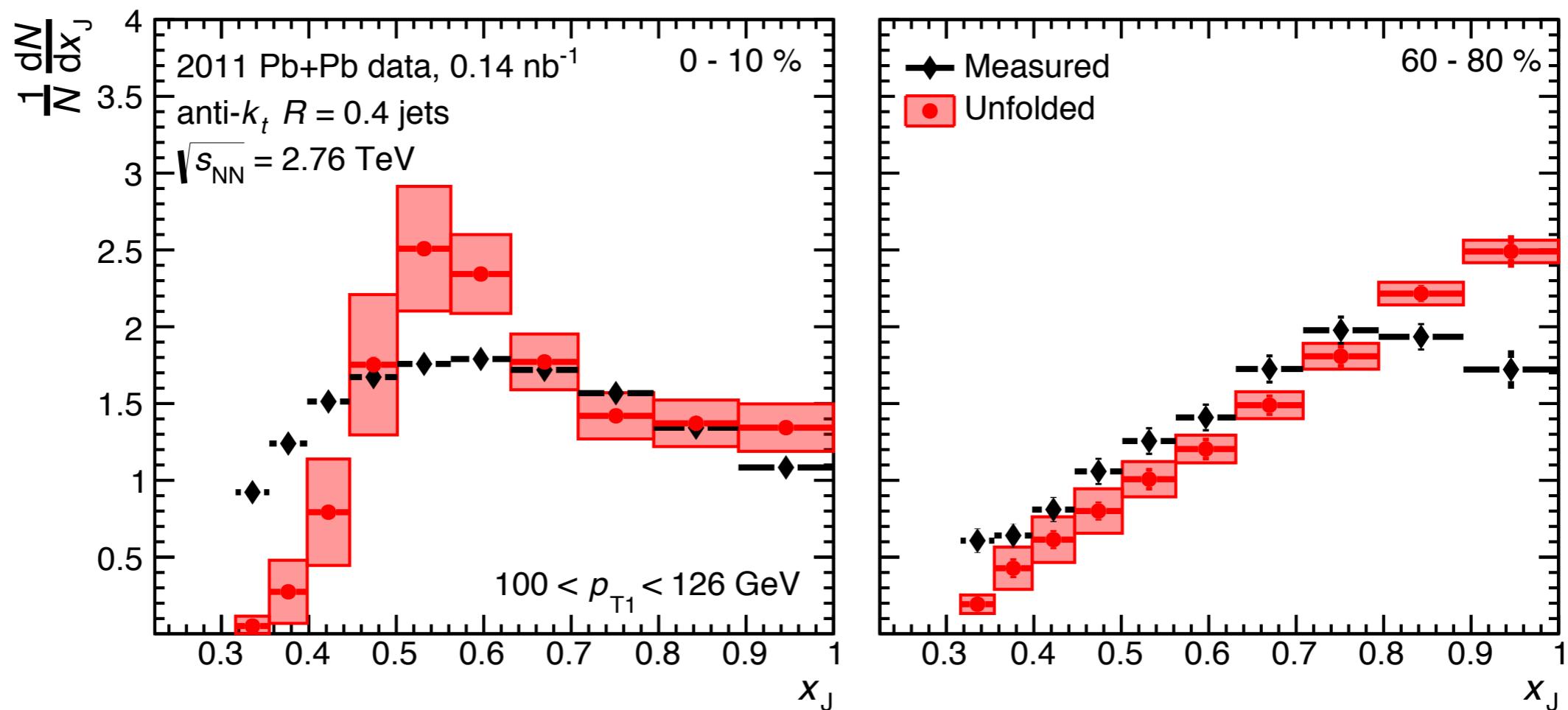
→ needed to reveal otherwise hidden physical features of distributions



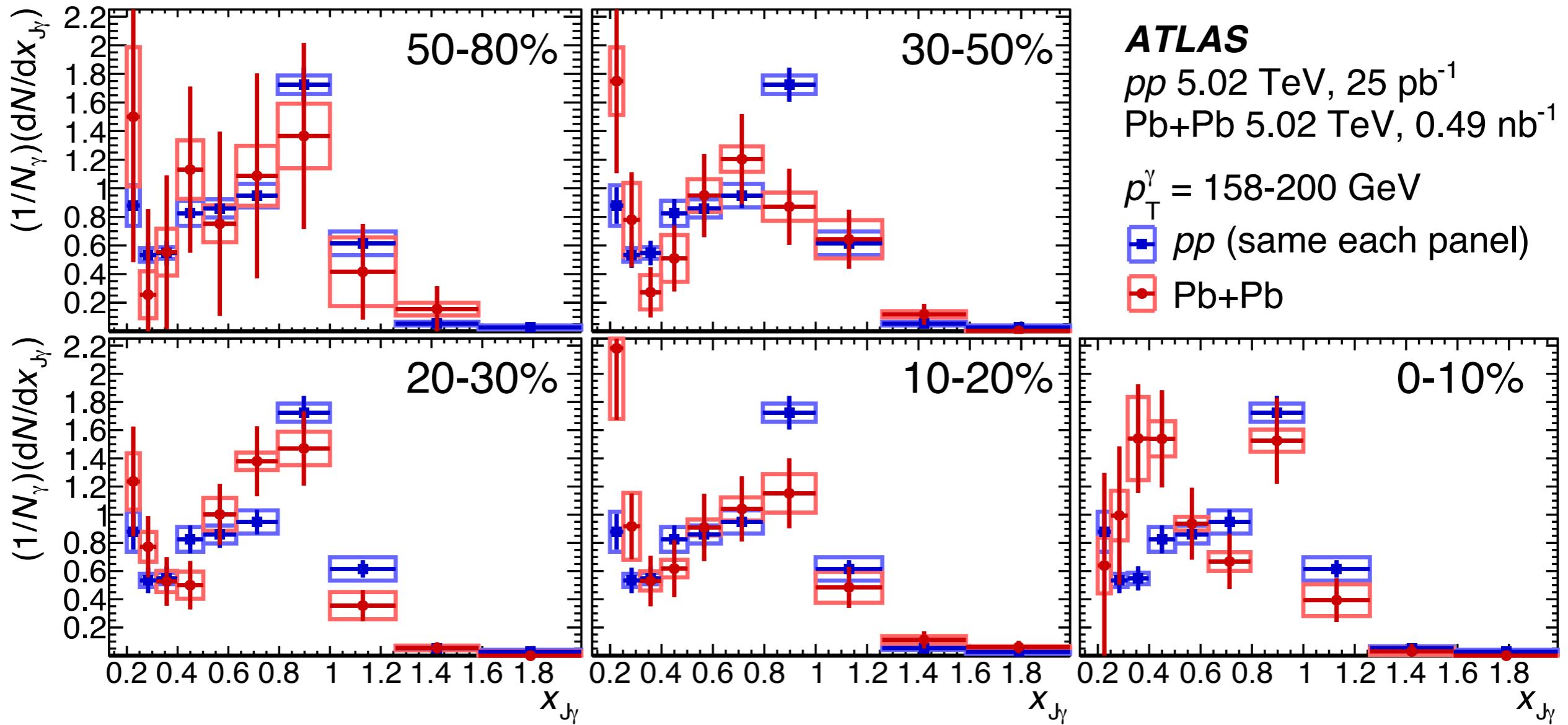
# Effect of unfolding on ... inclusive jet fragmentation functions

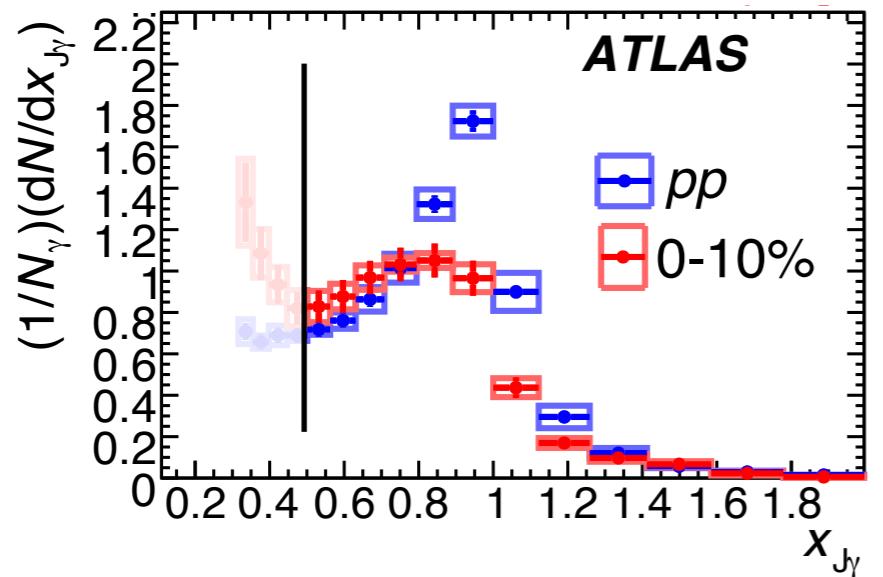


# Effect of unfolding on ... dijet $p_T$ -asymmetry



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

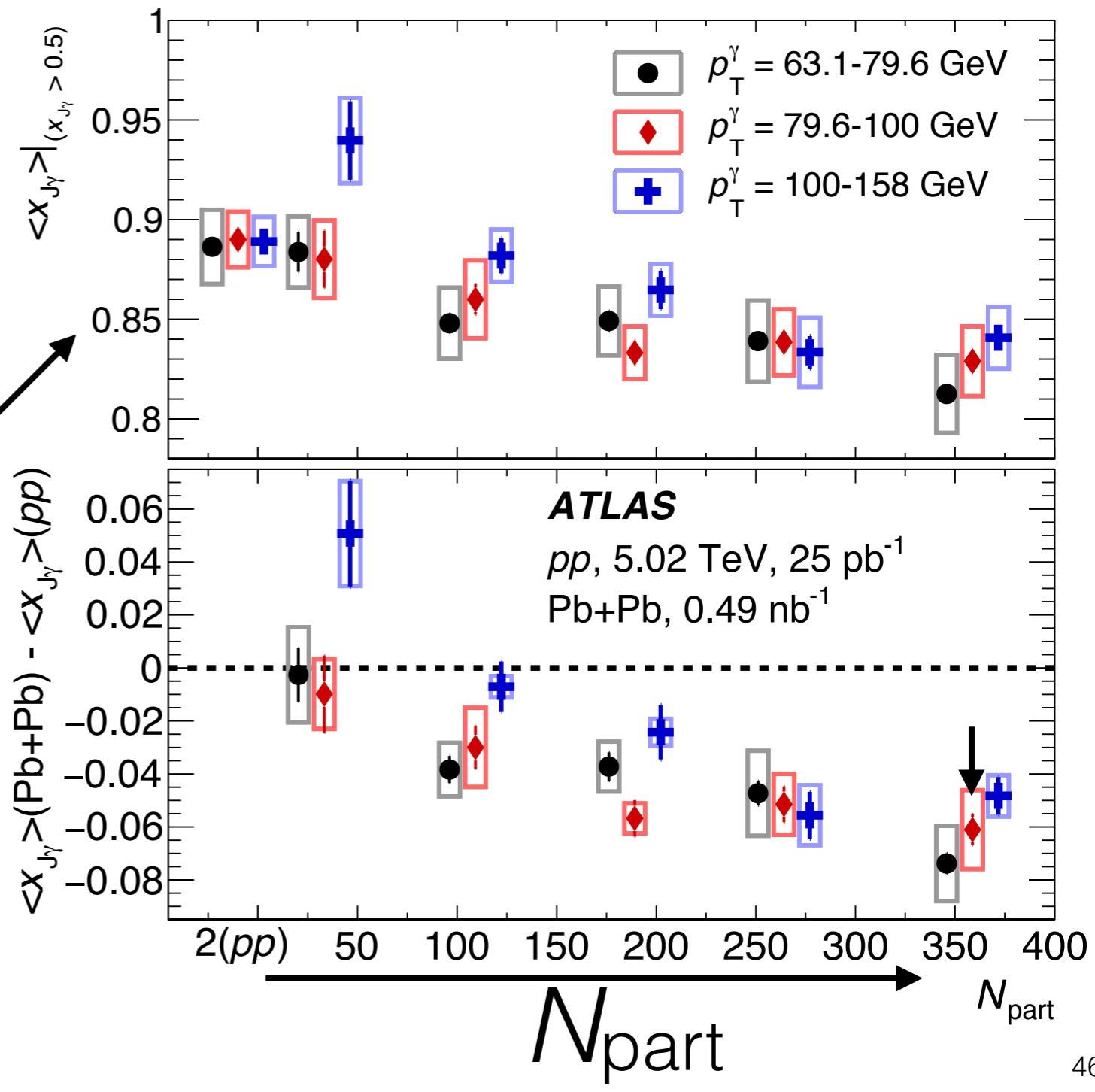


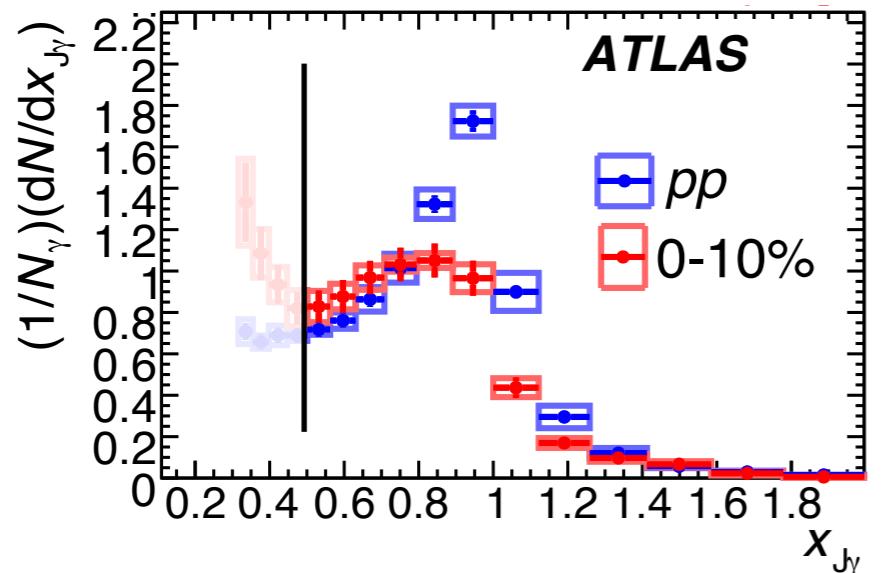


$R\gamma$  = fraction of photons with leading jet  $x_{J\gamma} > 0.5$

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

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

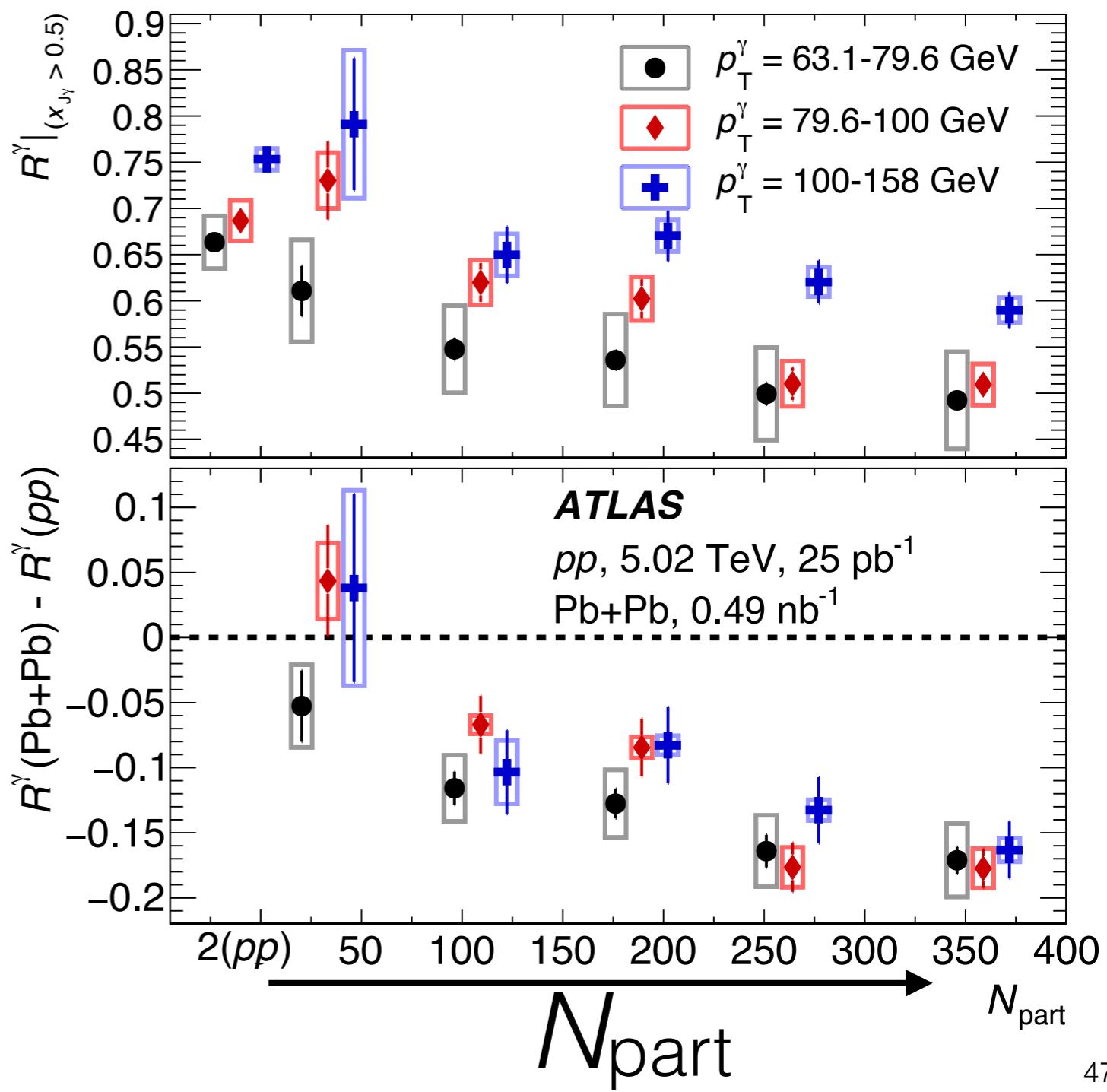


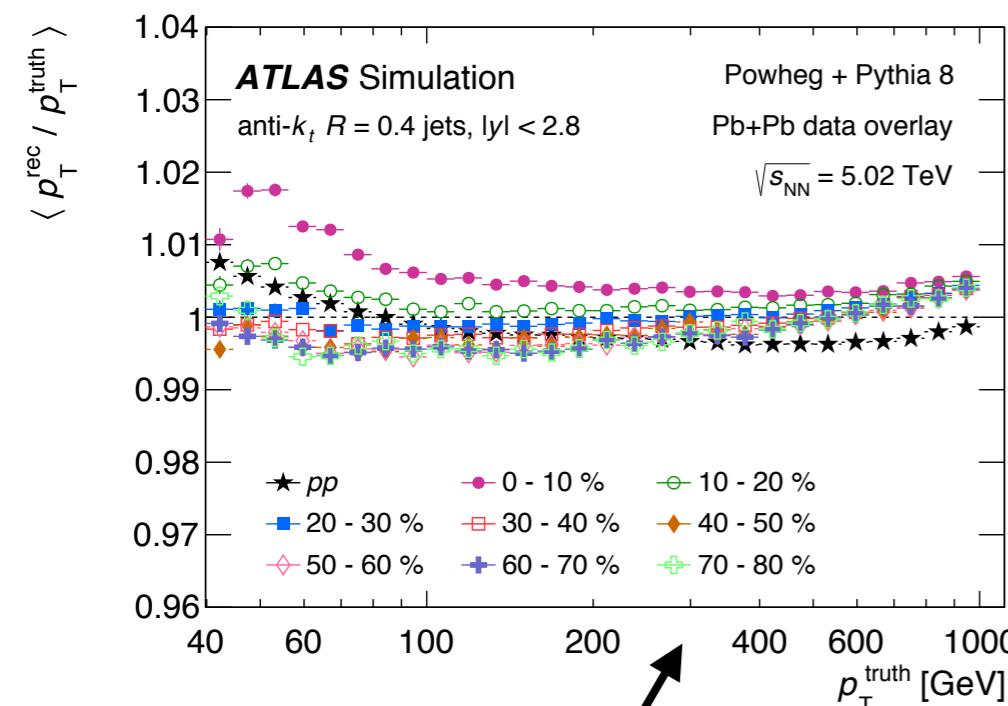


$\langle x_{J\gamma} \rangle$  = truncated mean  $x_{J\gamma}$   
of leading jets with  $x_{J\gamma} > 0.5$

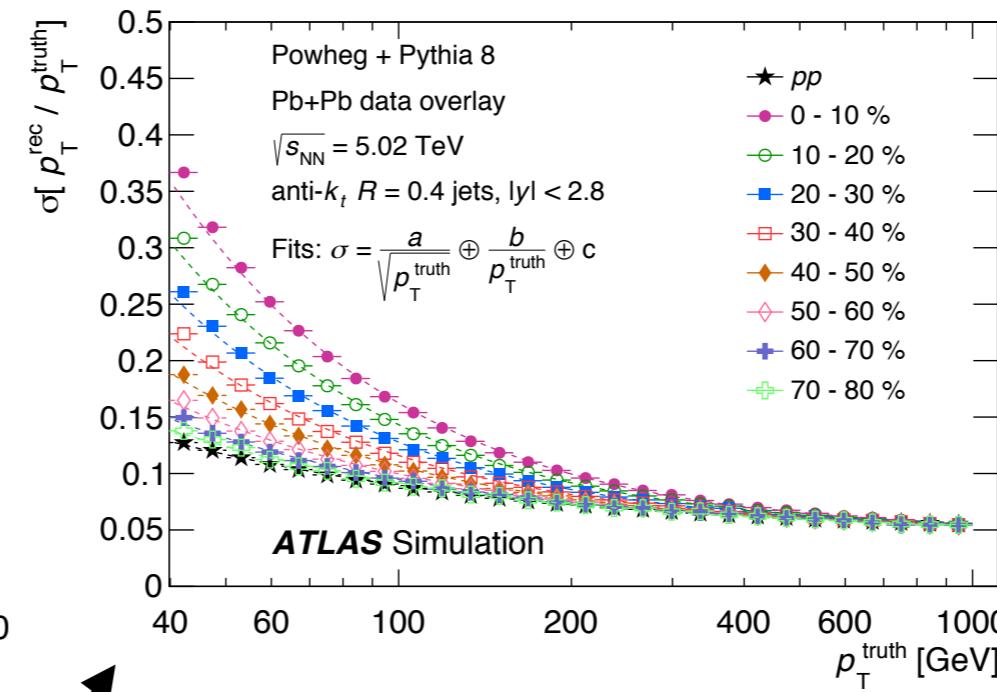
$\langle x_{J\gamma} \rangle(\text{PbPb}) - \langle x_{J\gamma} \rangle(pp)$  →  
(can be interpreted as  
per-jet fractional energy  
loss)

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

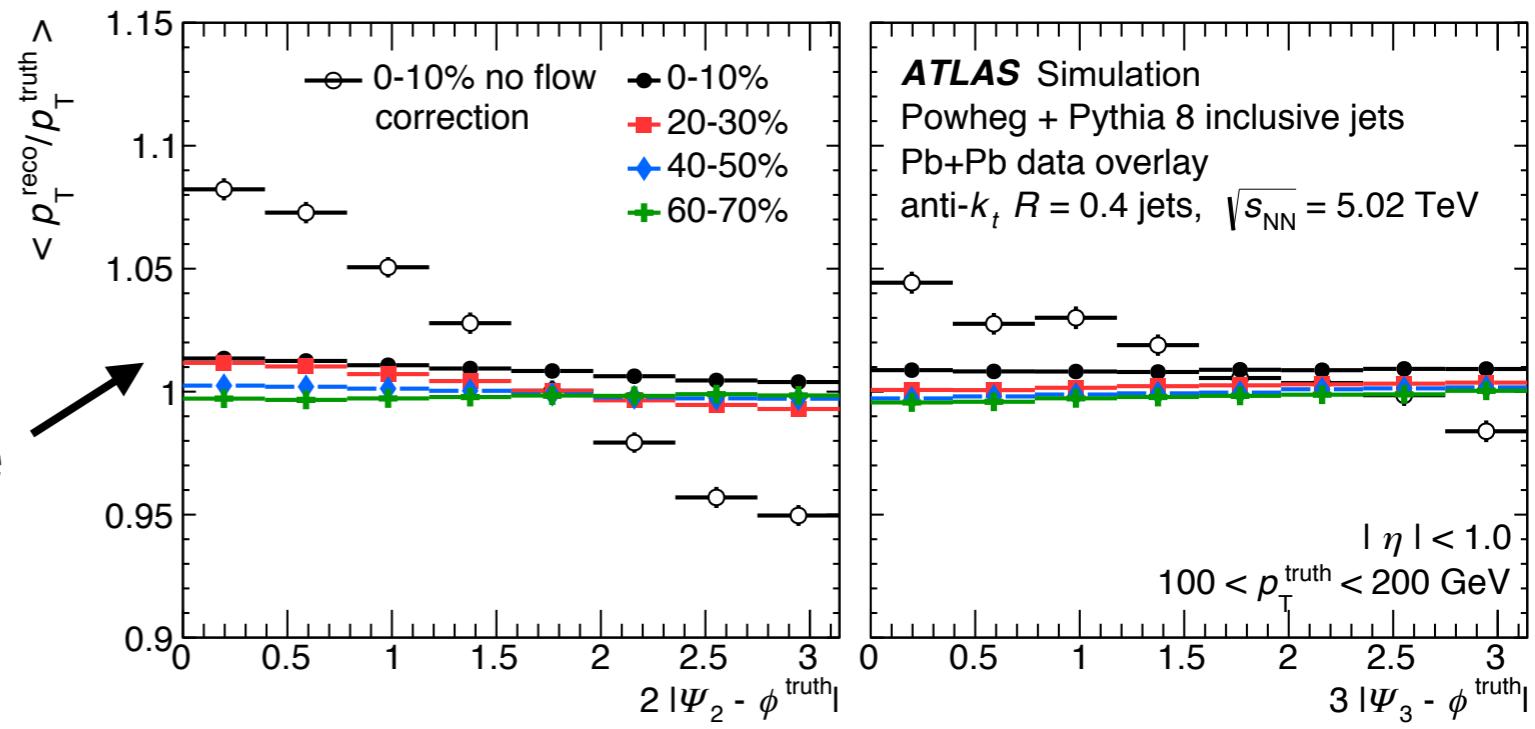




Mean  $p_T$  response vs.  $p_T$

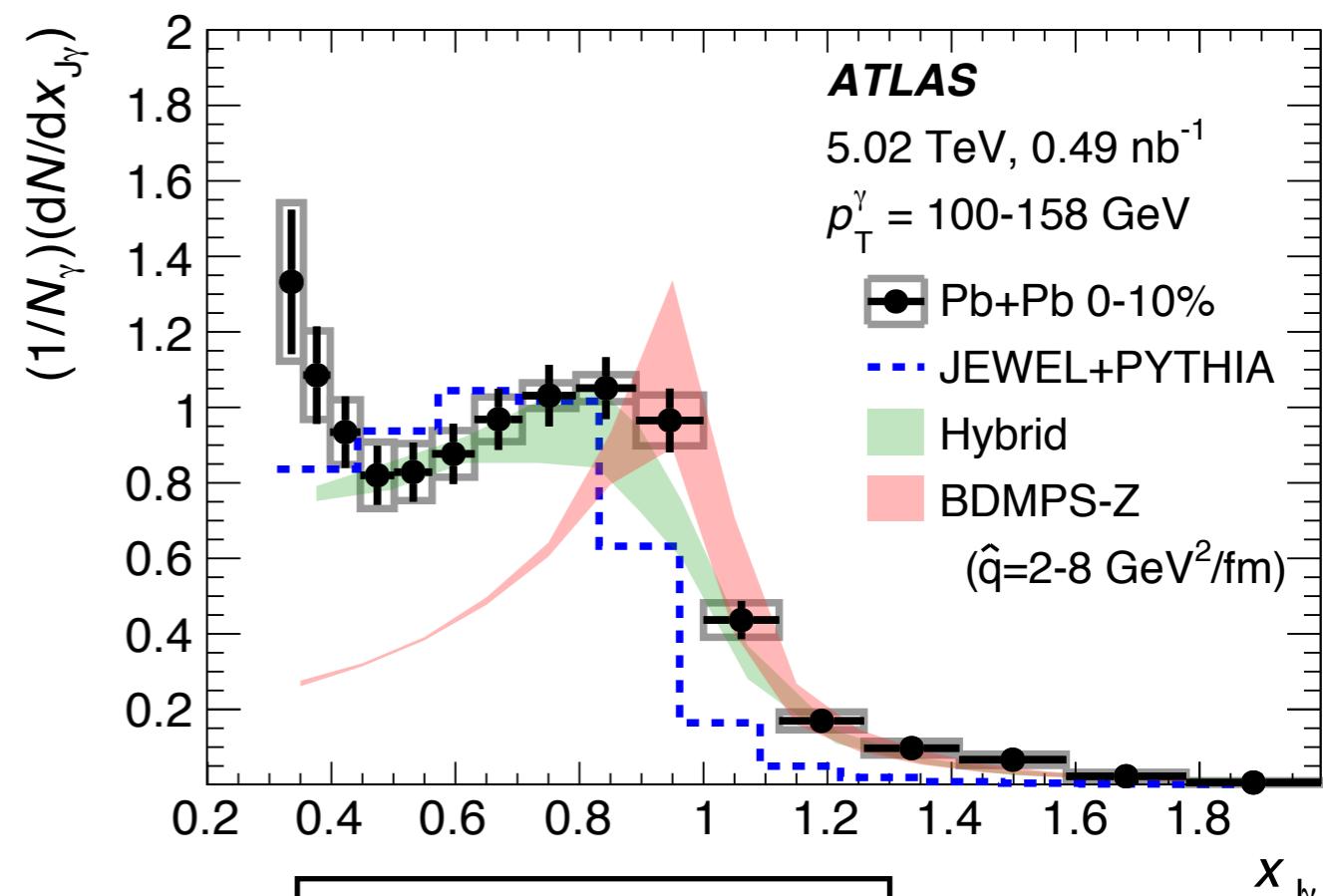
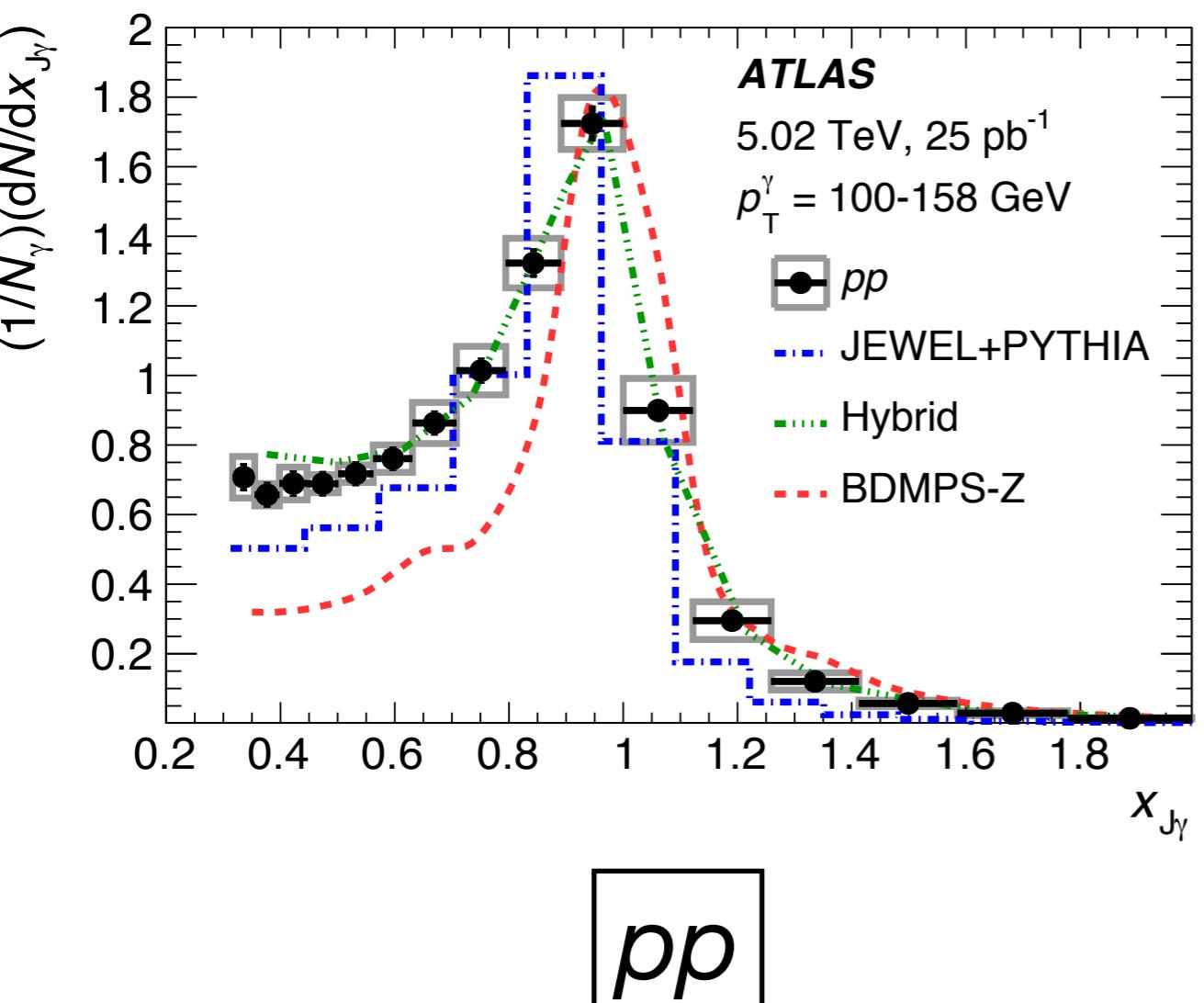


Mean  $p_T$  resolution vs.  $p_T$



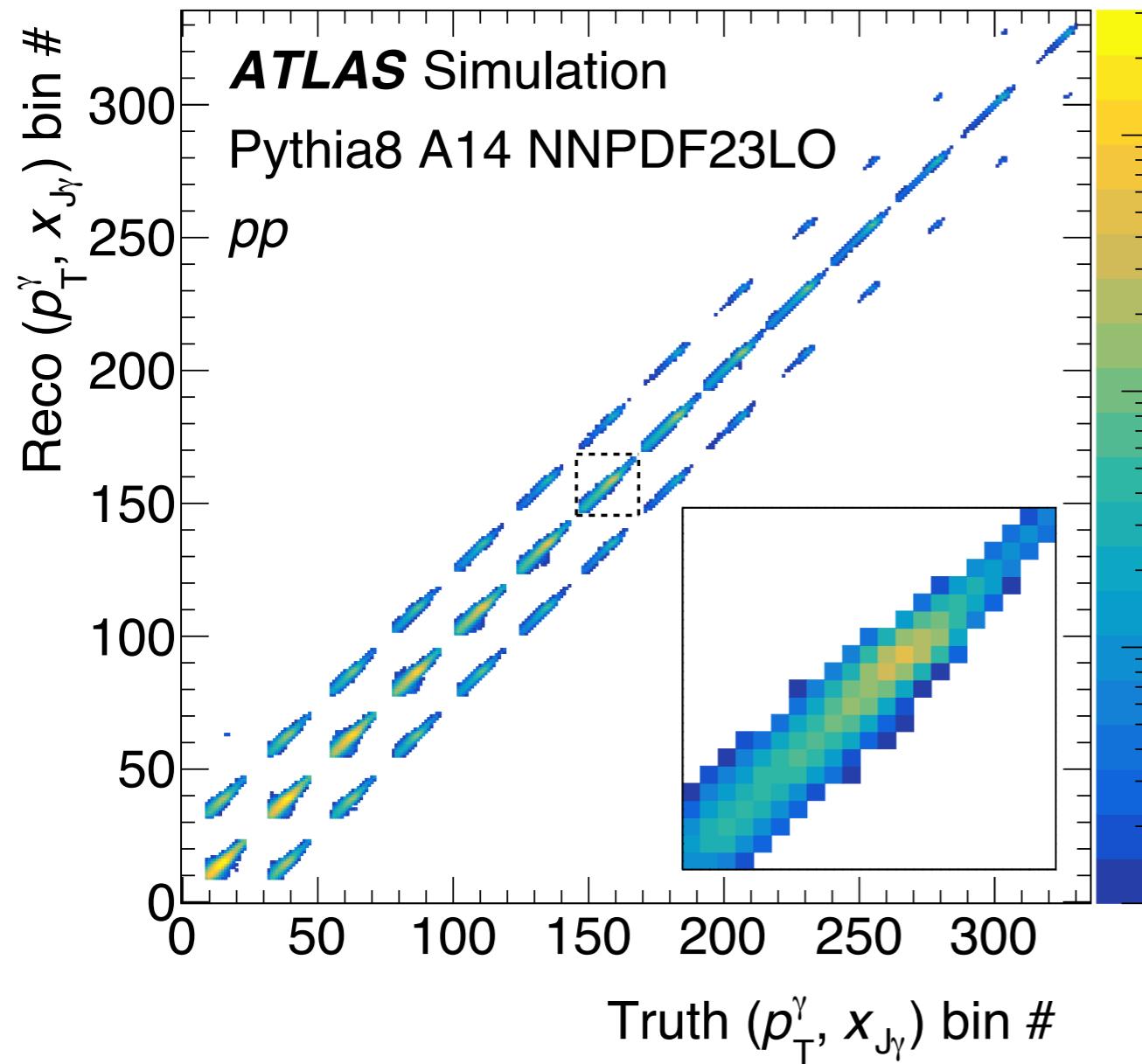
<https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/HION-2017-10/>

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

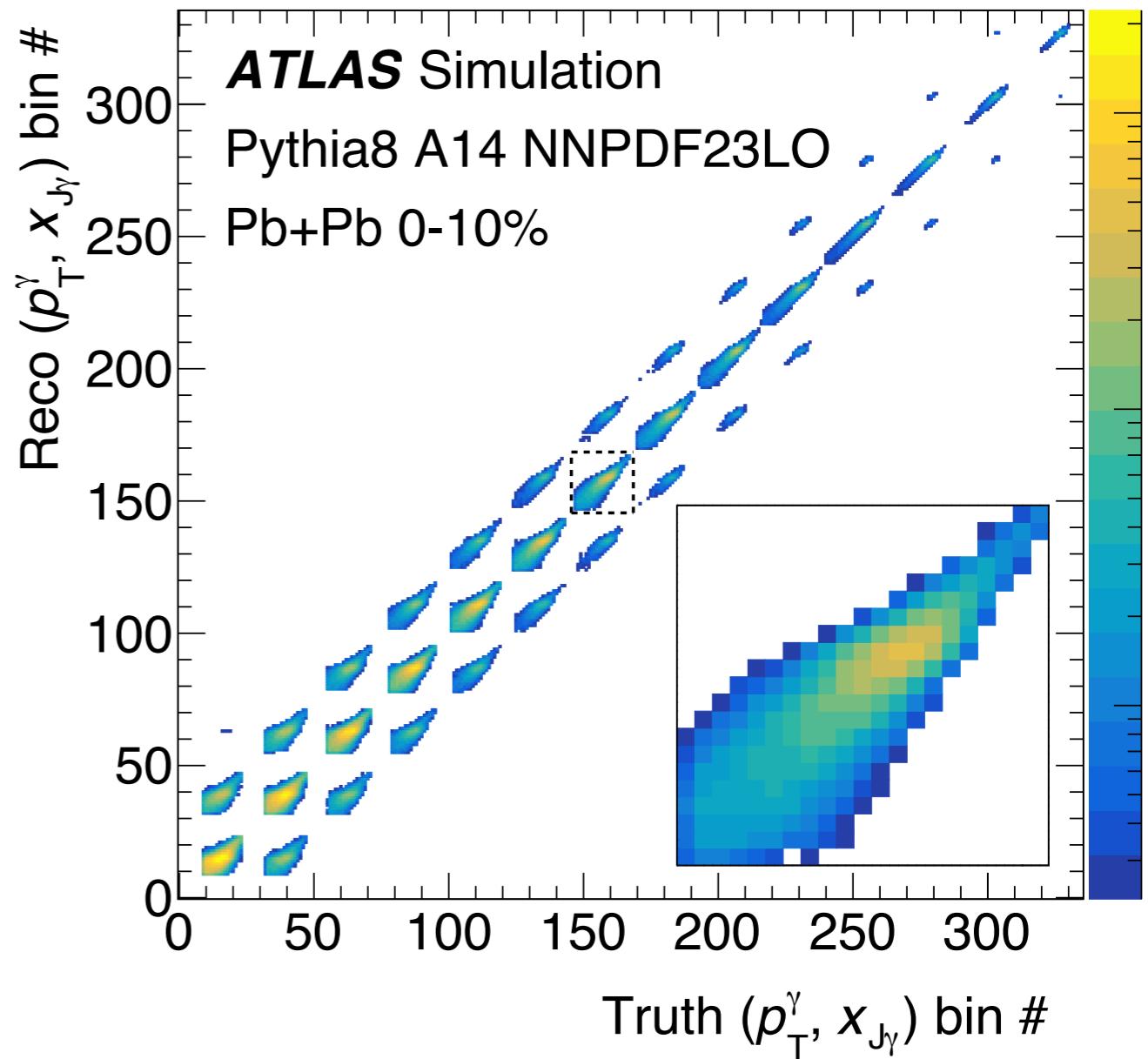


0-10%  
Pb+Pb

# Correction for detector effects

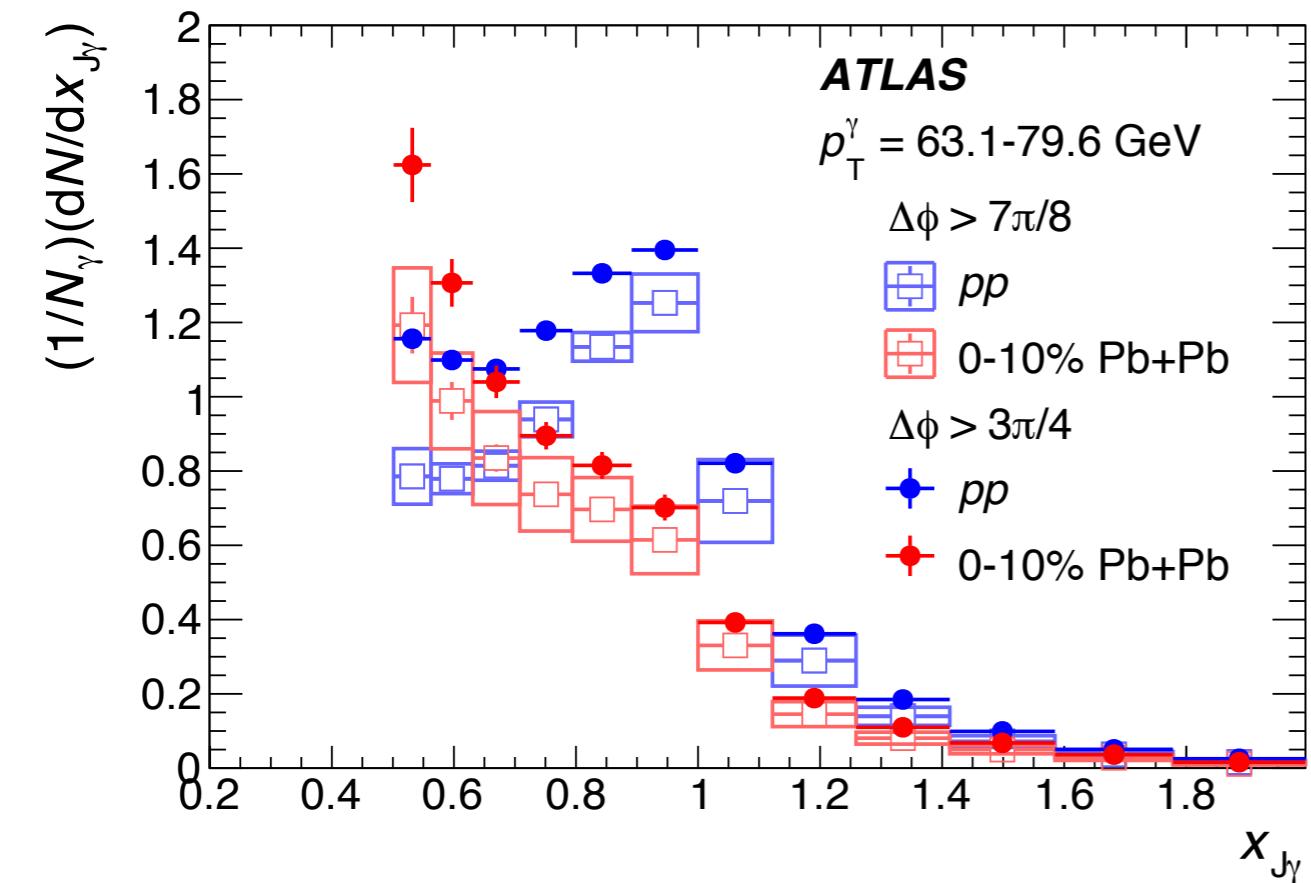


*pp*

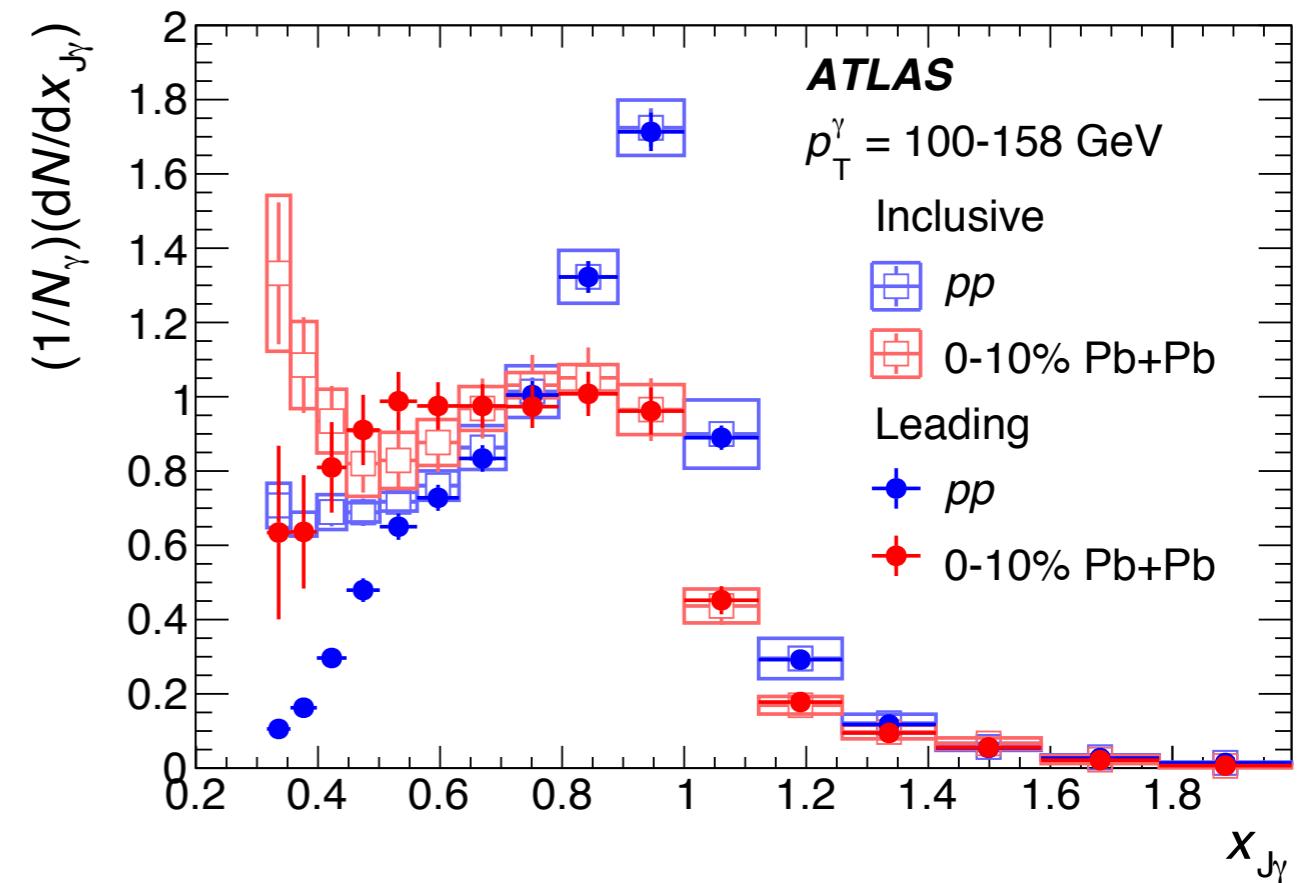


0-10%  
*Pb+Pb*

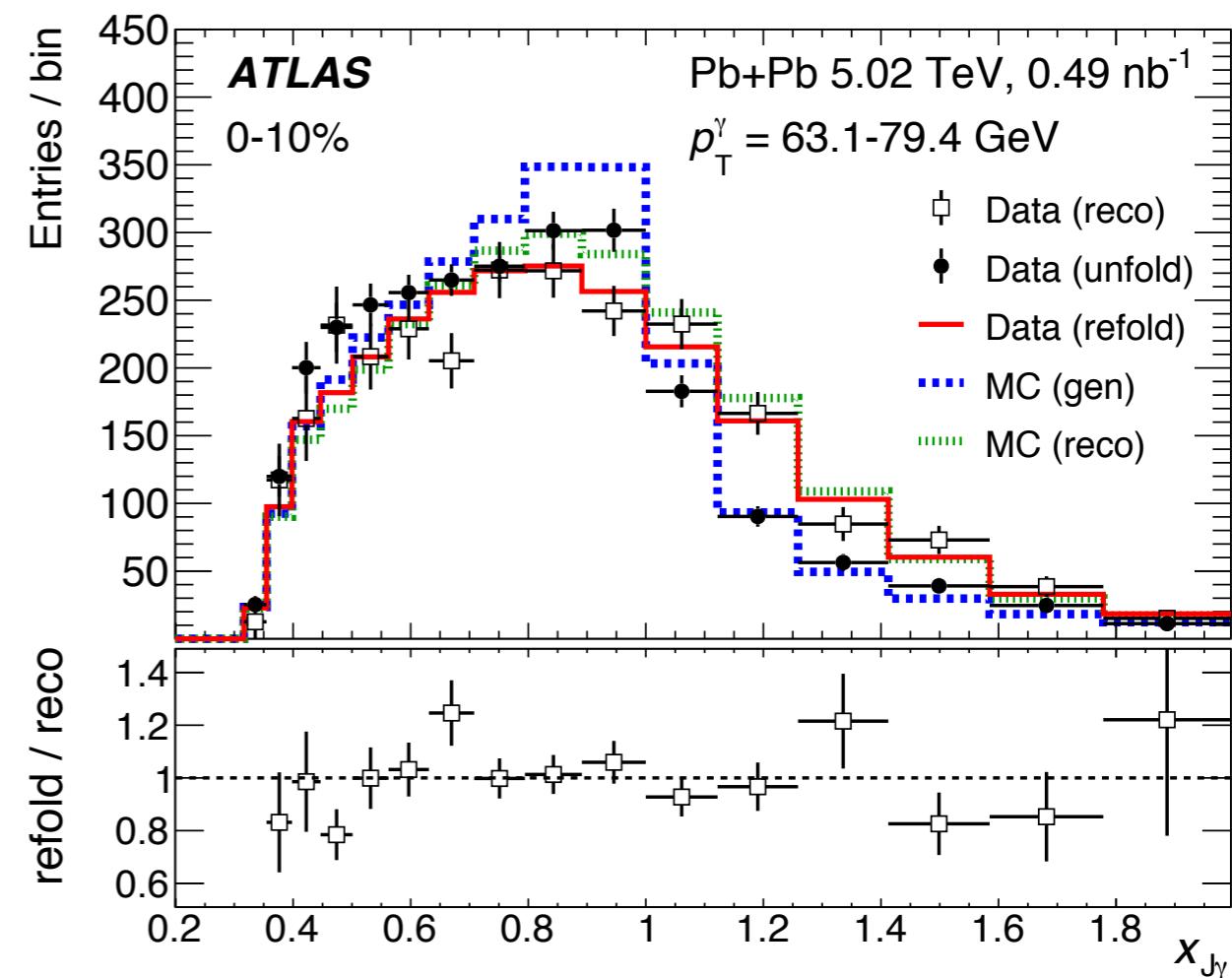
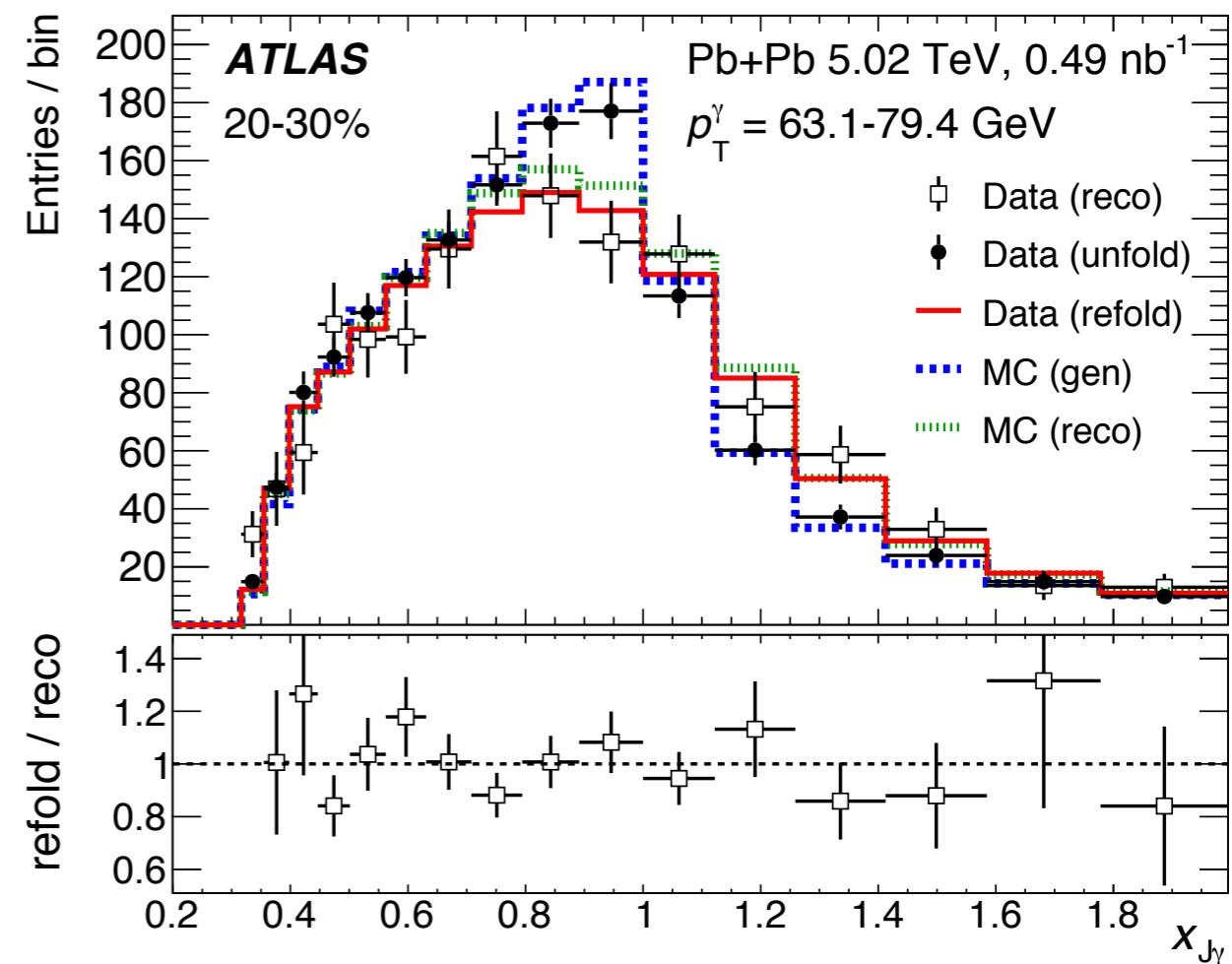
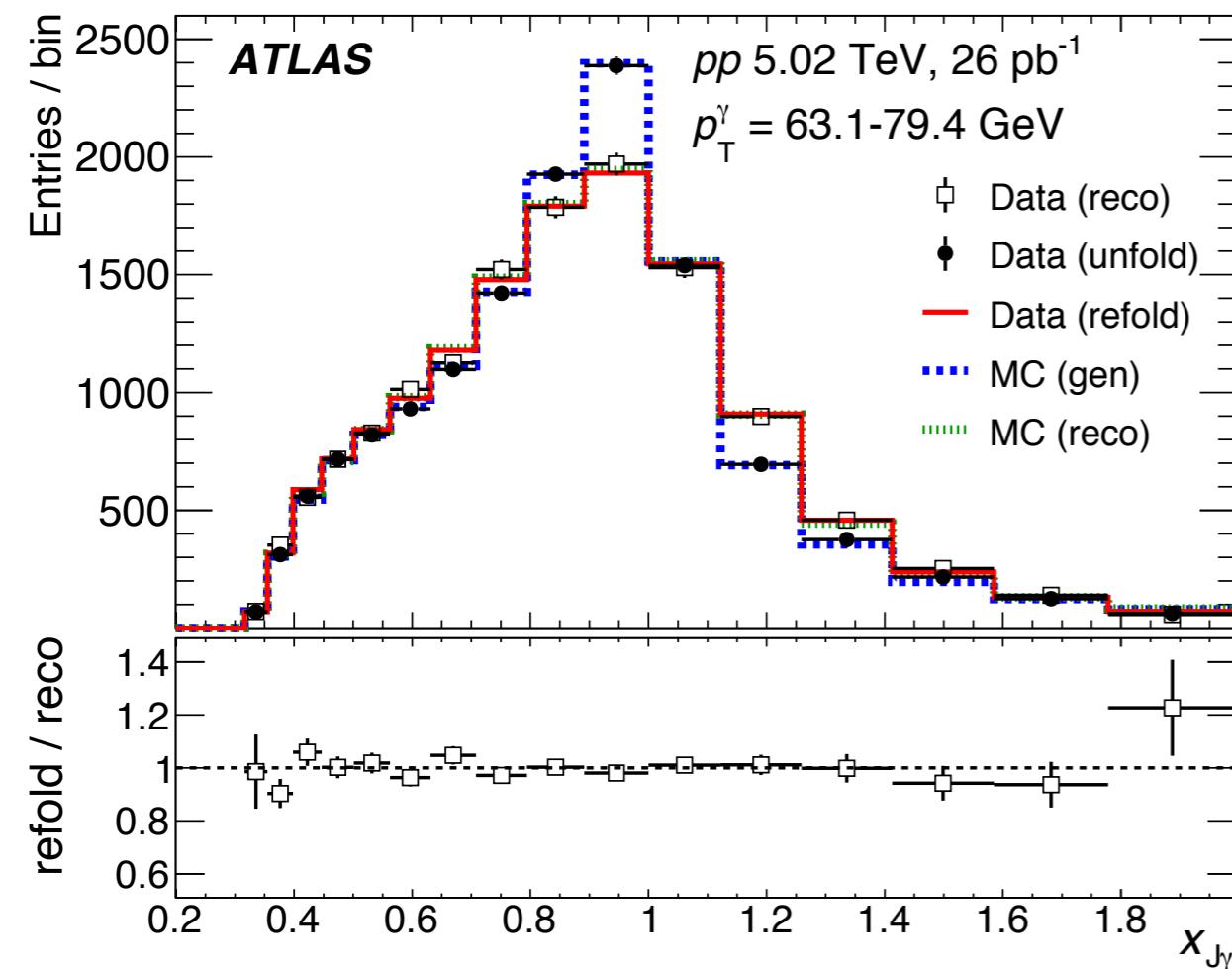
# Cross-check with alternate fiducial definitions



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



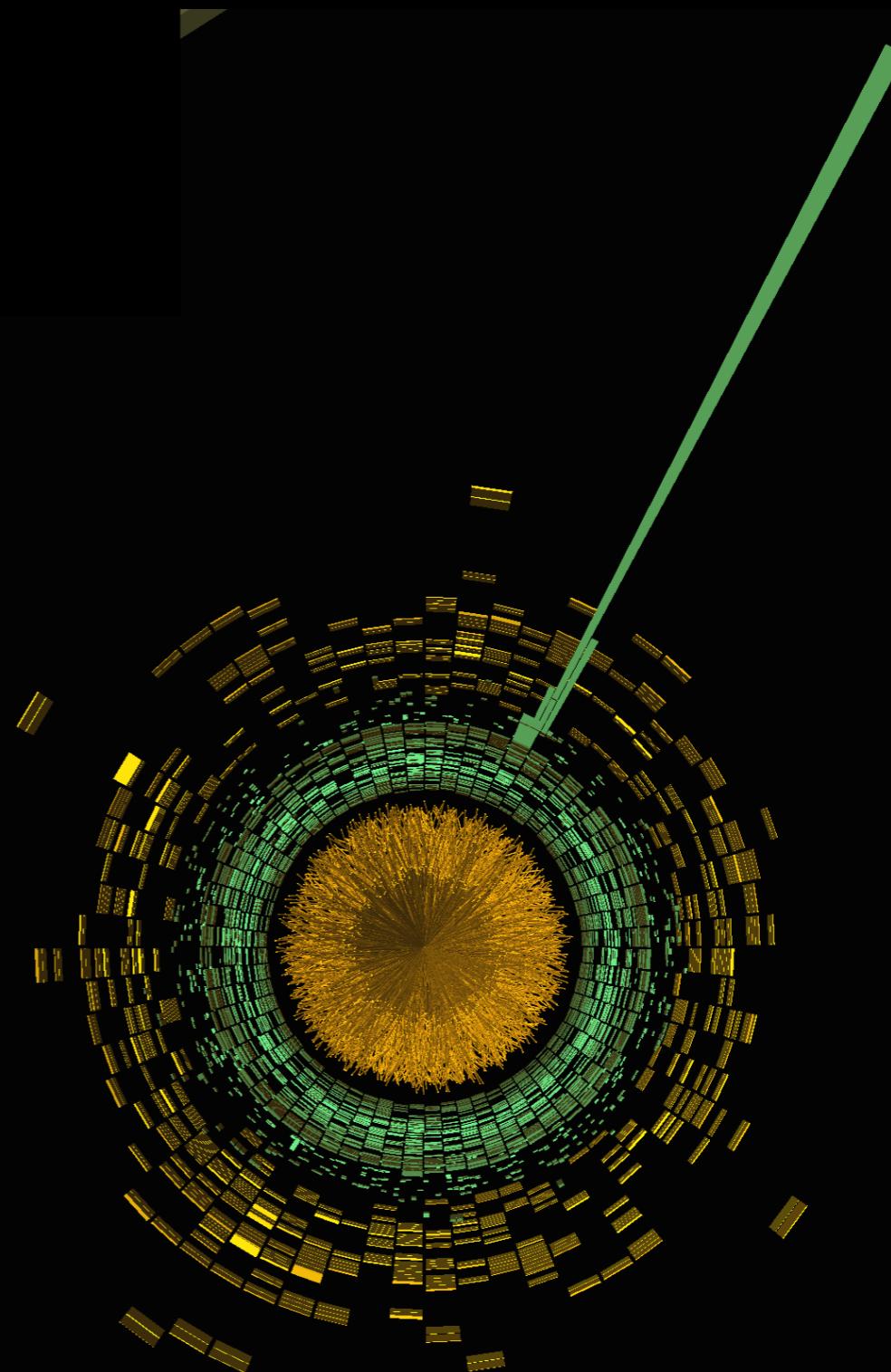
Select leading jet only instead  
of all jets with  $\Delta\phi > 7\pi/8$



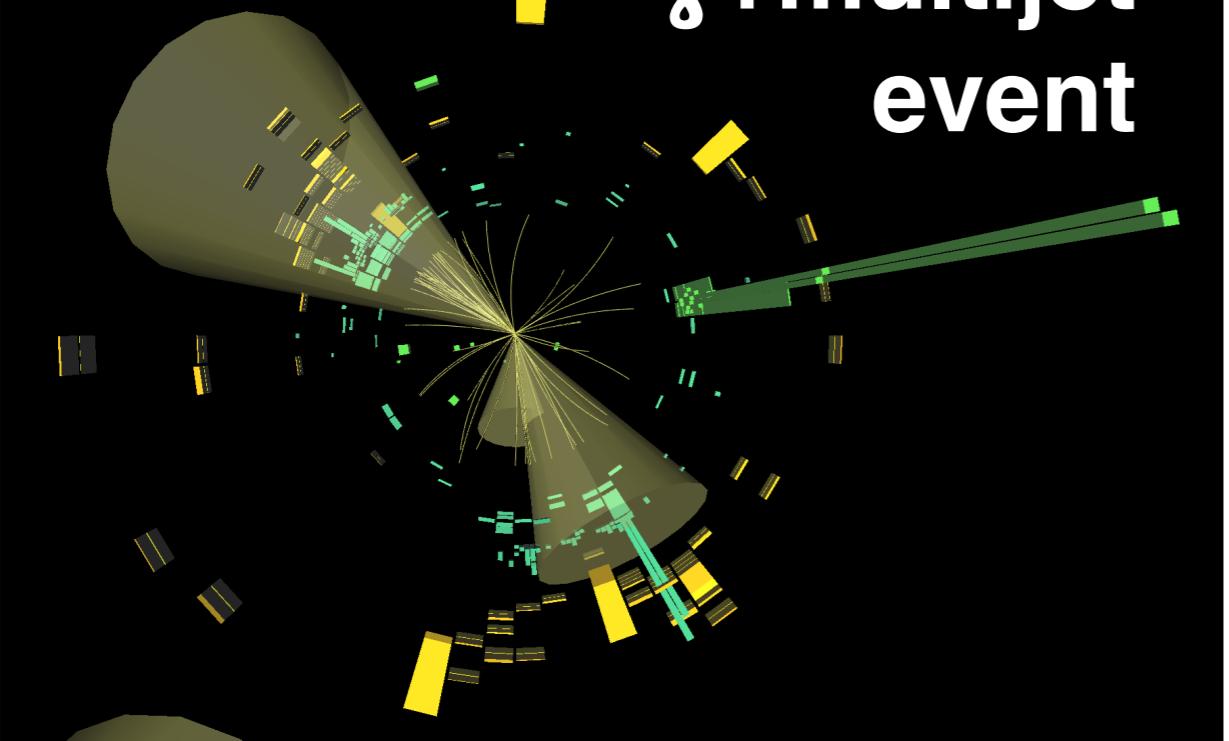


## Photon-tagged measurements possible in Run 2:

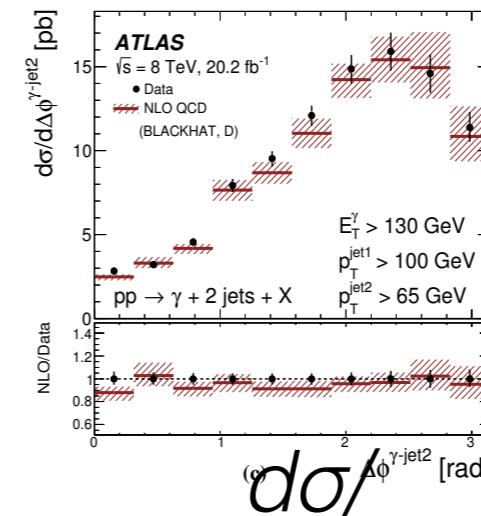
1.  $\gamma$ +jet: absolute  $E$ -loss
2.  $D(z)$  for  $\gamma$ -tagged jets in  $Pb+Pb$  &  $p+p$
3.  $\gamma$ -tagged  $R_{AA}$
4.  $\gamma$ +jet vs. reaction plane
5. missing- $p_T$  flow w/ external scale



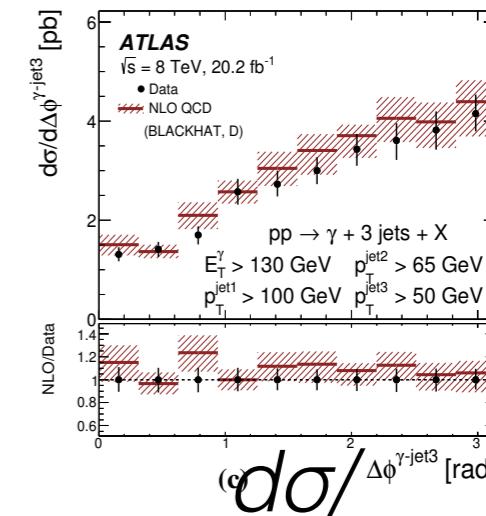
# γ+multijet event



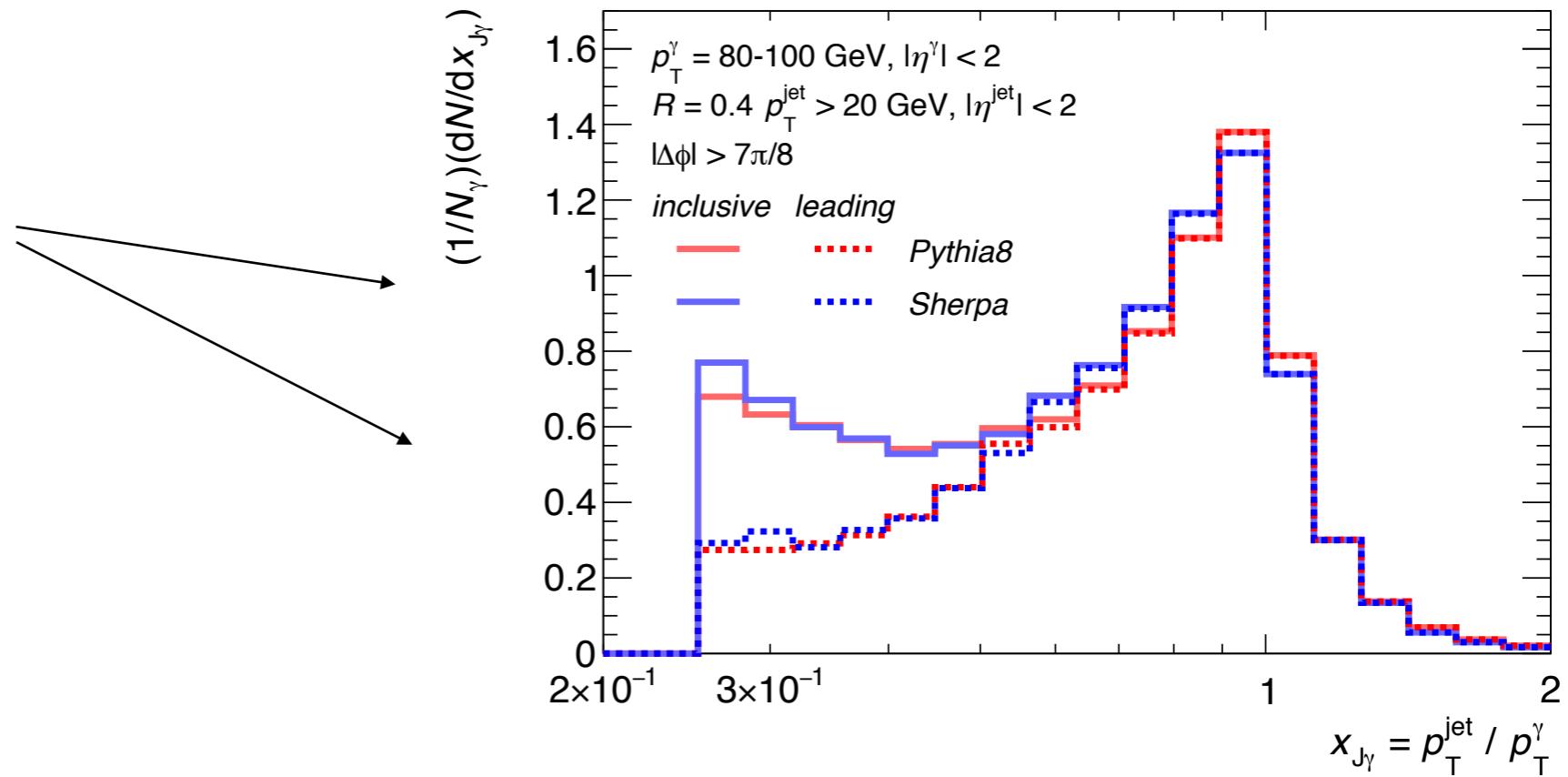
*Measured in detail  
by HEP  
community, e.g.*



$d\phi(\gamma+\text{jet}2) \quad d\phi(\gamma+\text{jet}3)$



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



# Sensitivity to analysis choices...

## 1. Photon + *inclusive* jets

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



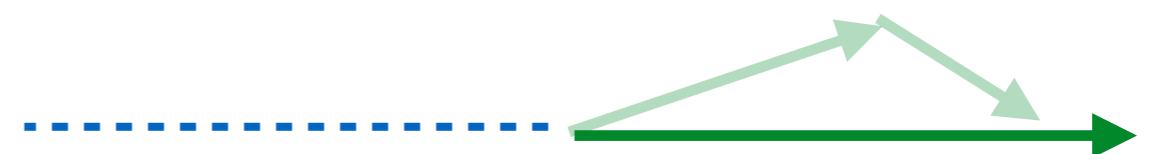
## 2. Photon + *leading* jet

- better-defined “leading quark” probe

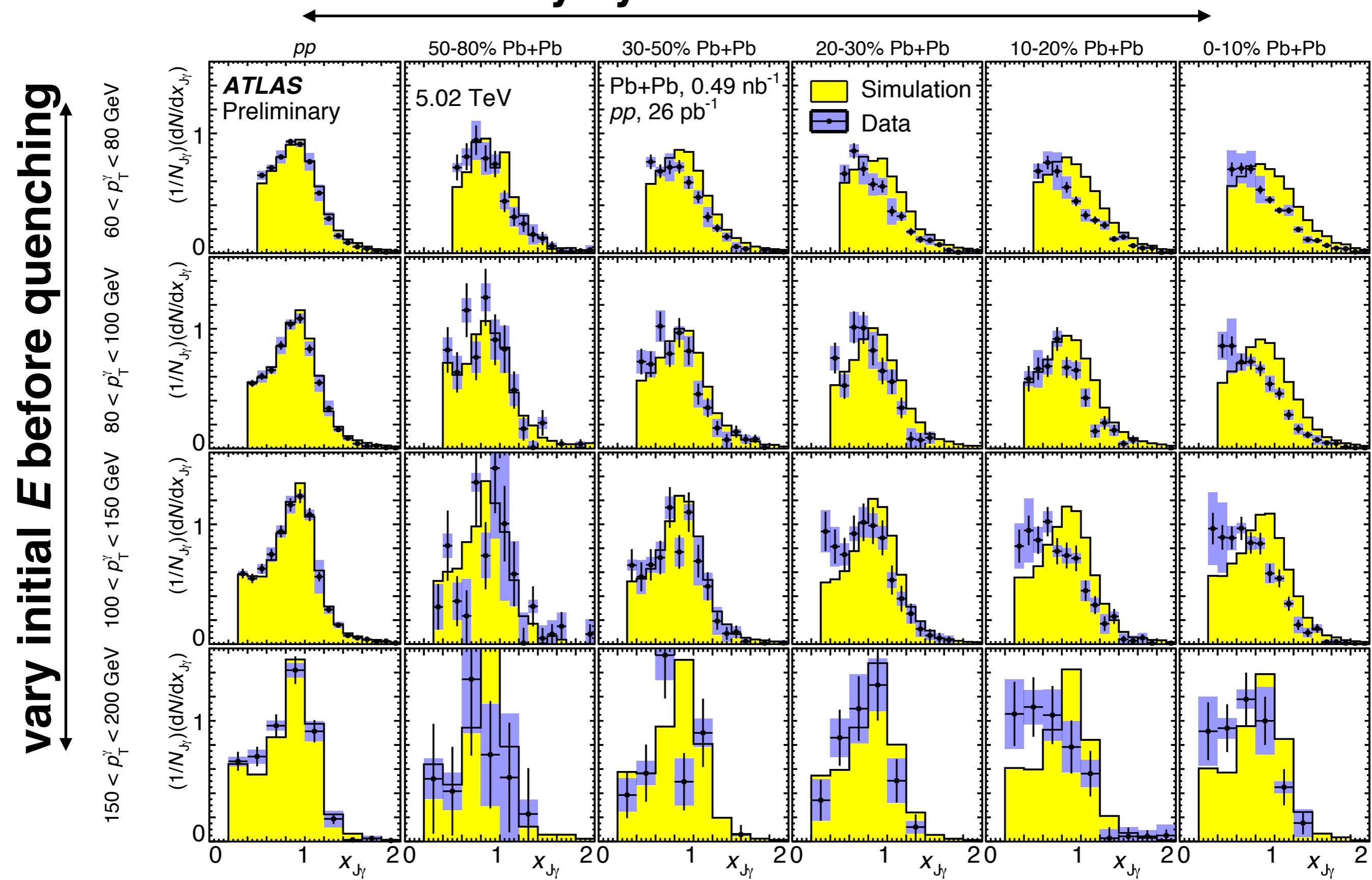


## 3. Photon + $\sum \vec{p}_{\text{T}}$ of high- $p_{\text{T}}$ jets

- $E$ -loss of entire recoiling hadronic system

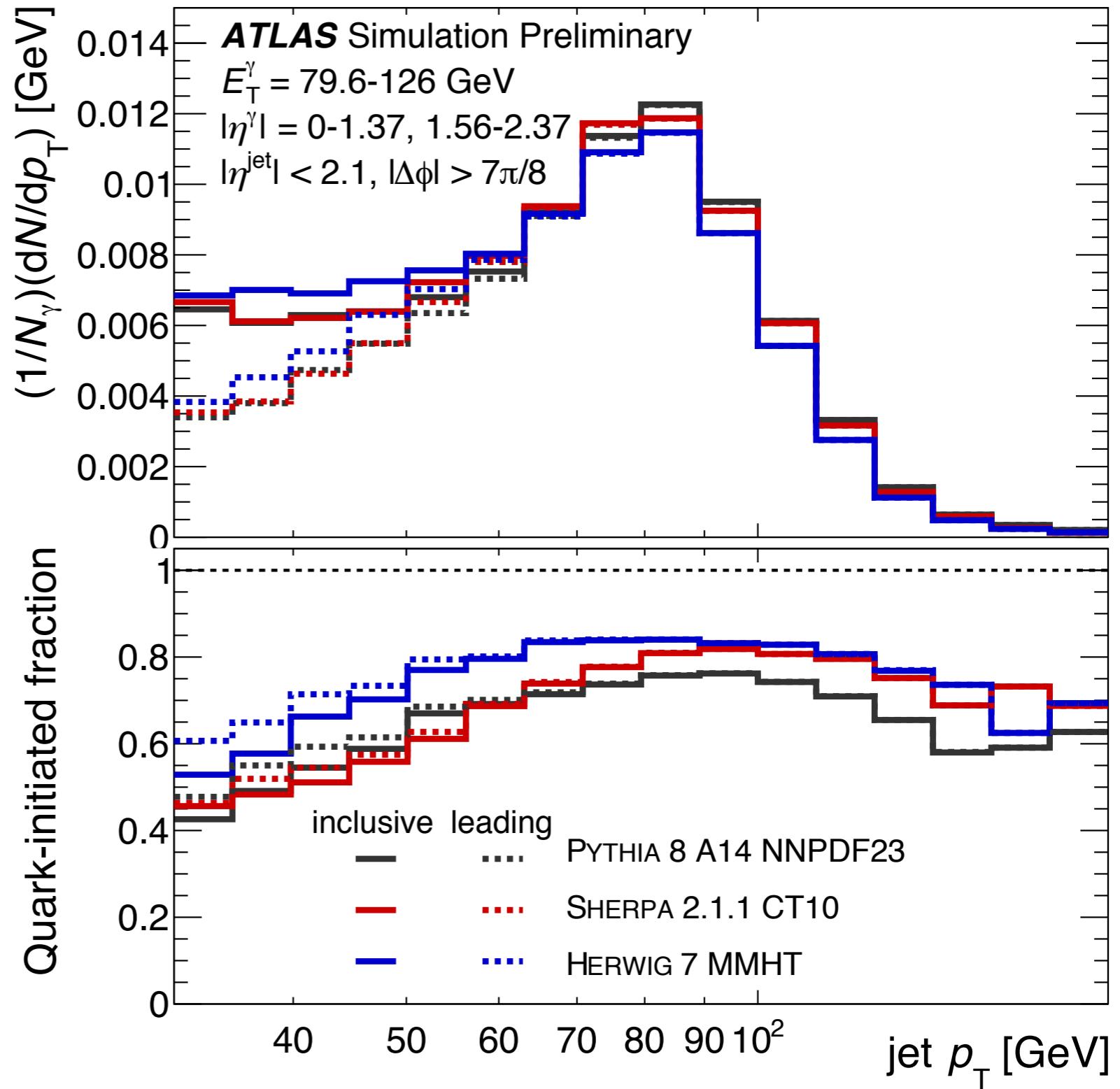


# vary system size

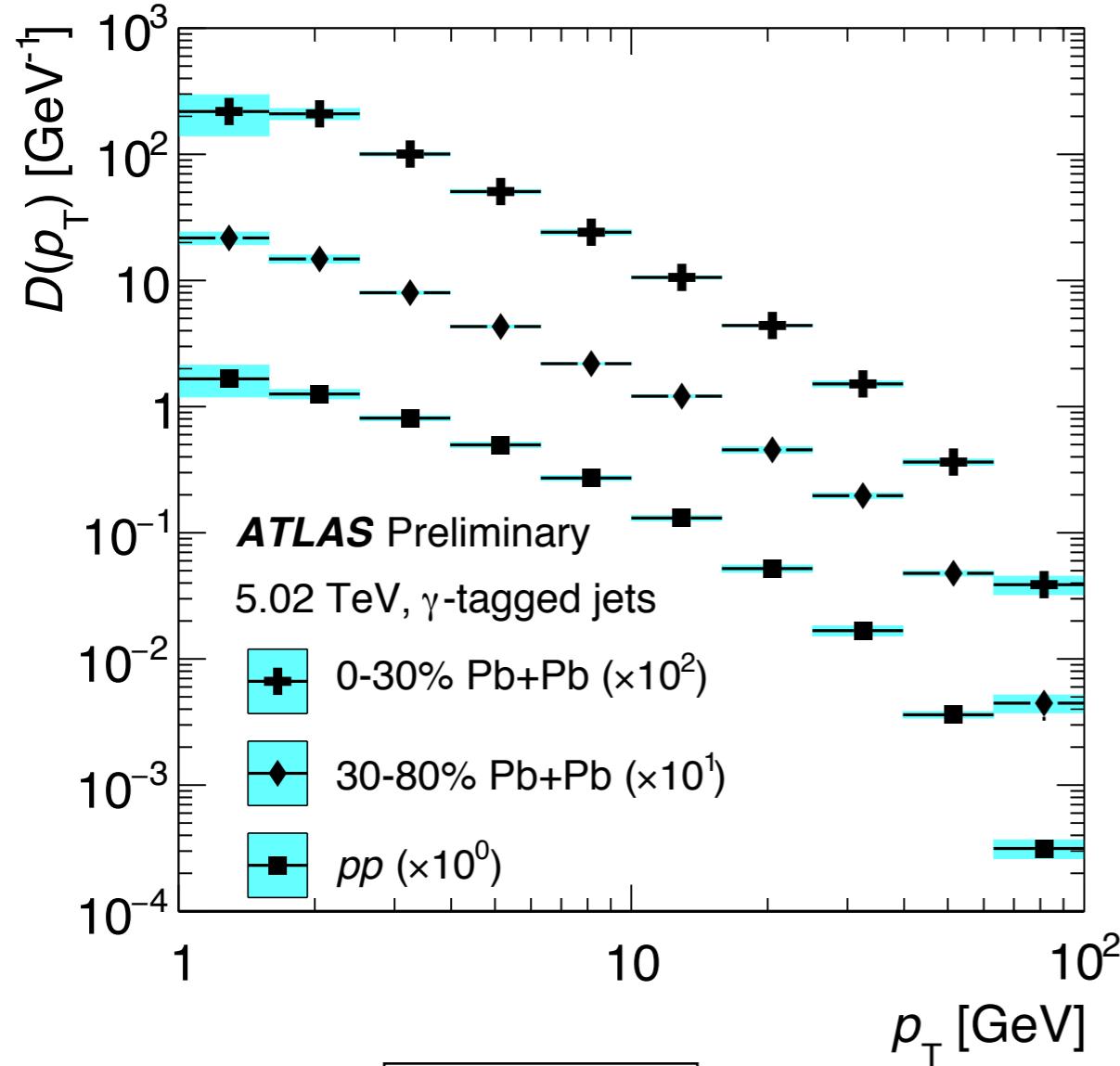


$p_T^\gamma = 79.6\text{-}125 \text{ GeV}$

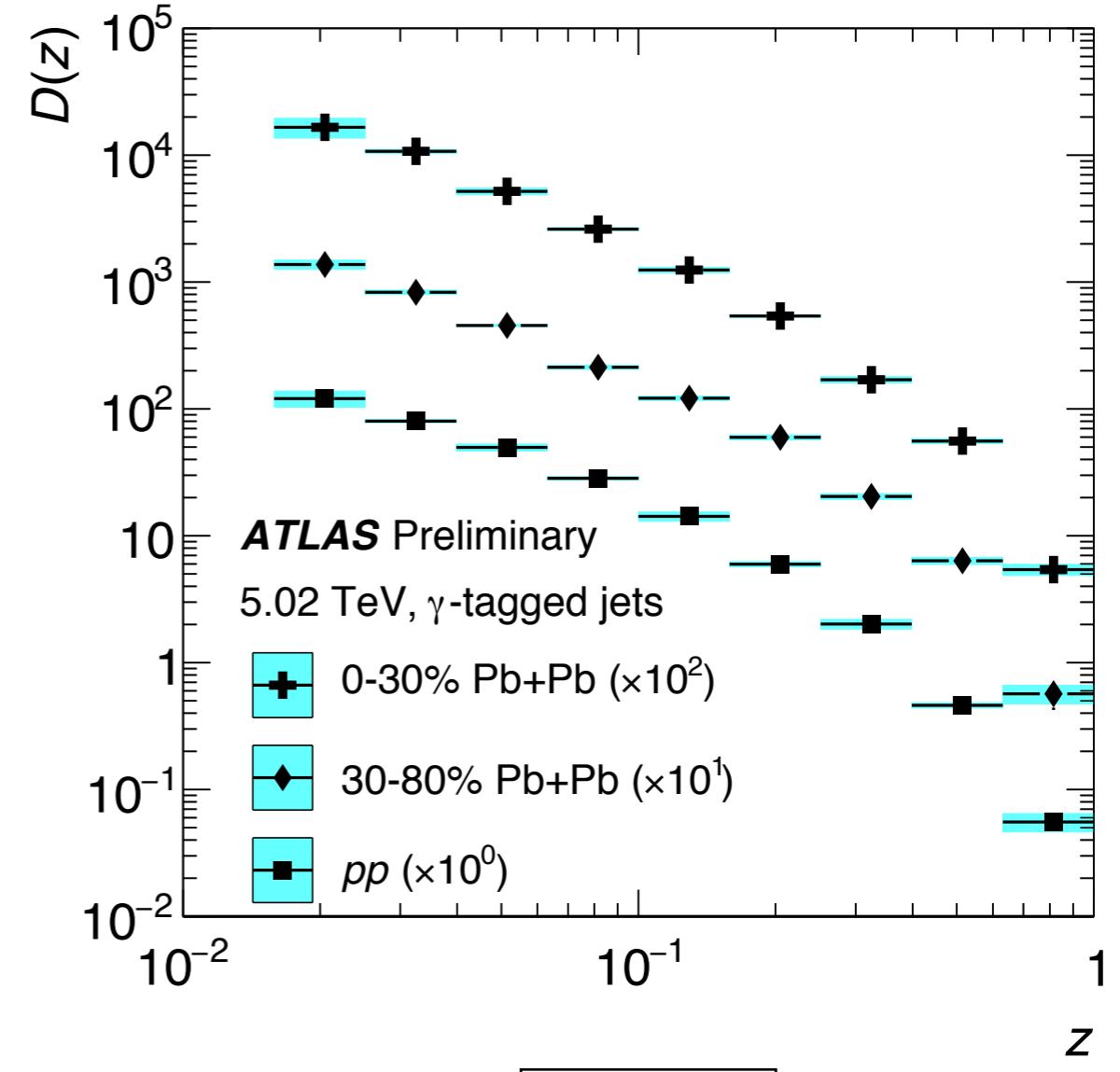
$p_T^{jet} = 63.1\text{-}144 \text{ GeV}$



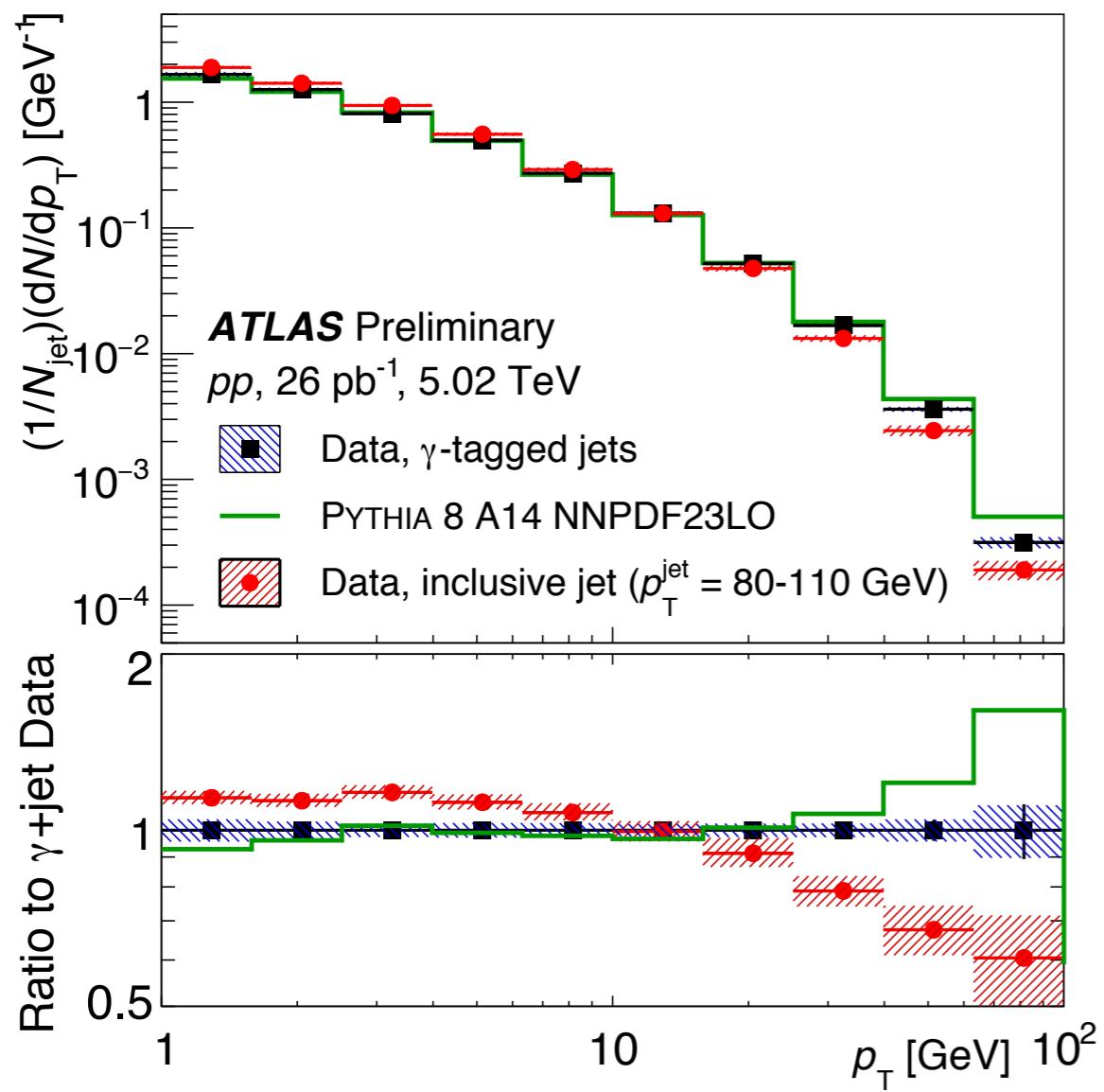
- no jets with  $x_{J\gamma} < 0.5$  accepted (only leading jets)
- 73-83% quark-initiated jets



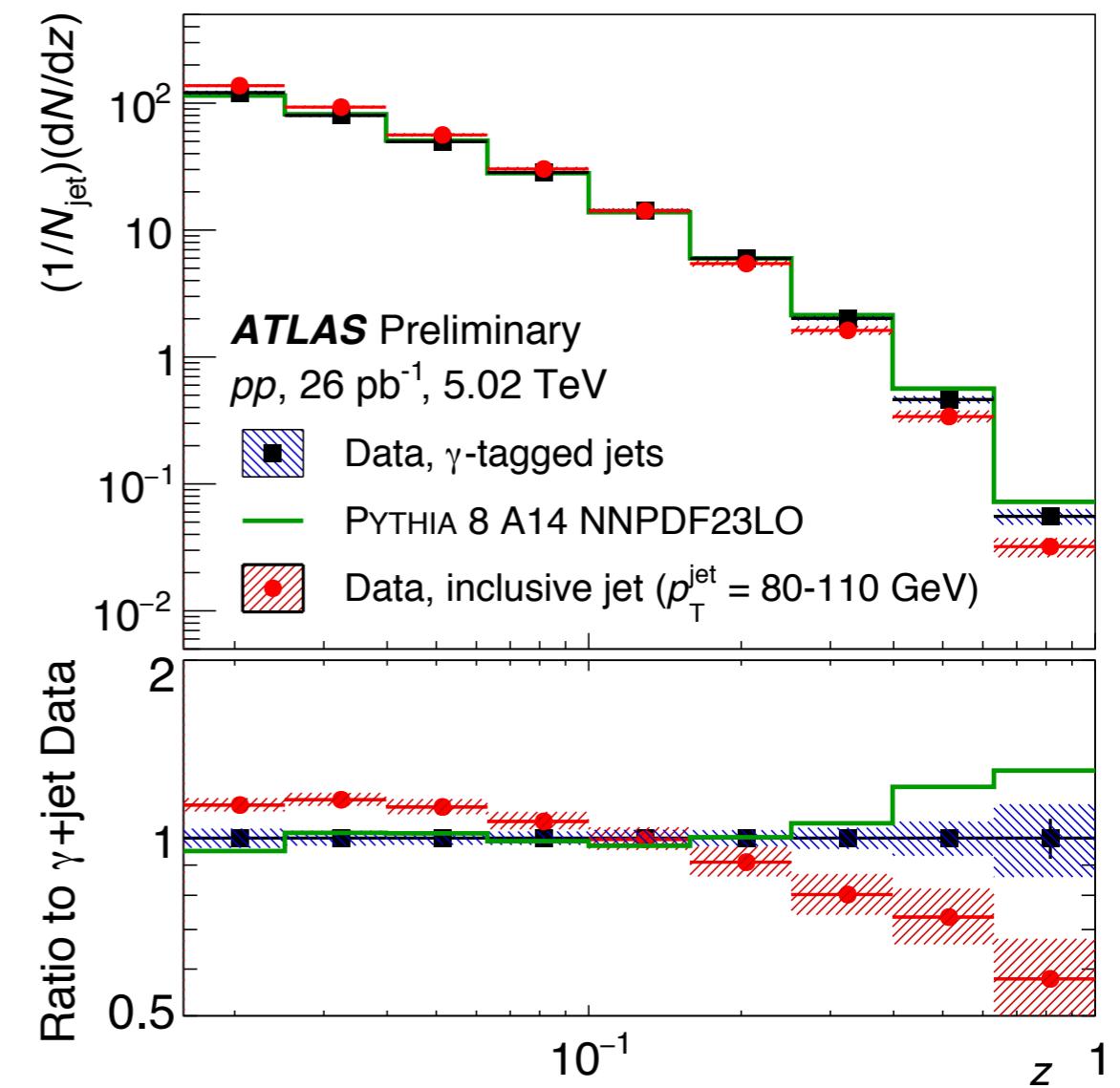
$D(p_T)$



$D(z)$



$D(p_T)$

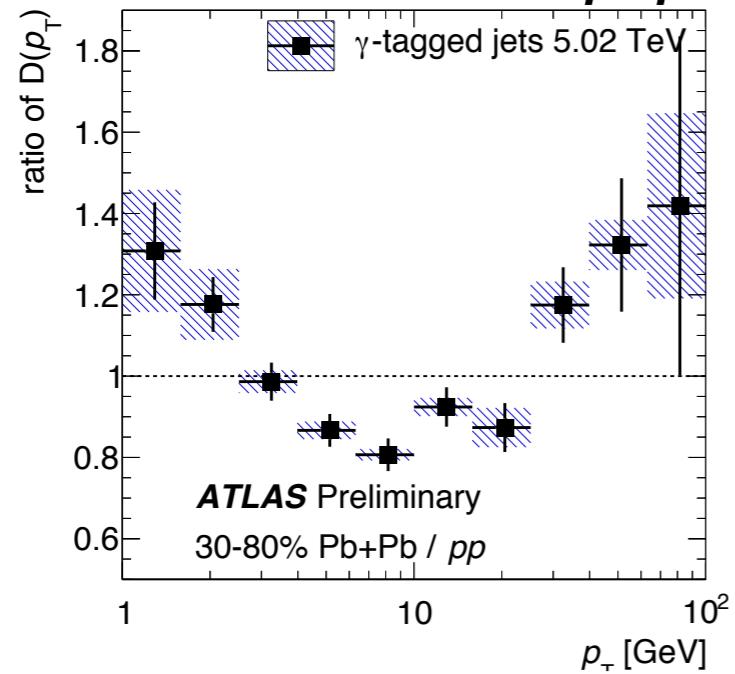


$D(z)$

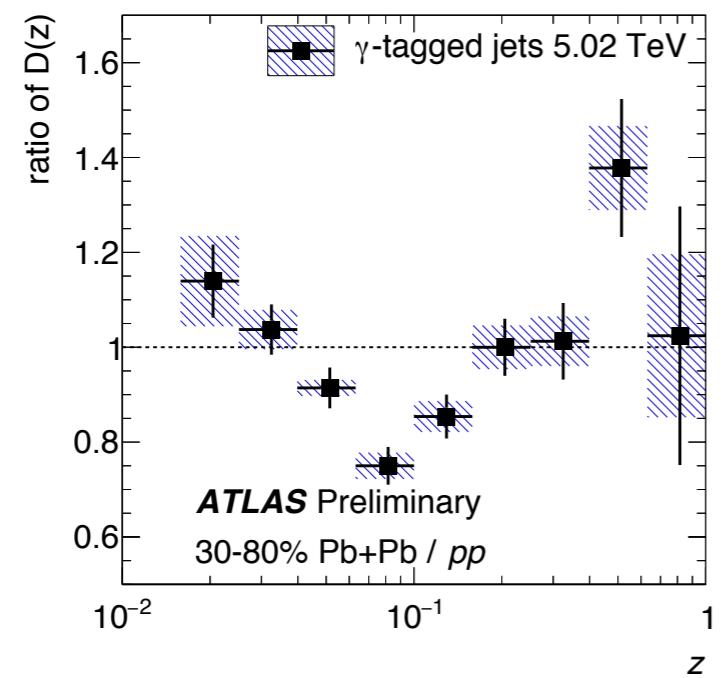
$\gamma$ -tagged

30-80% /  $pp$

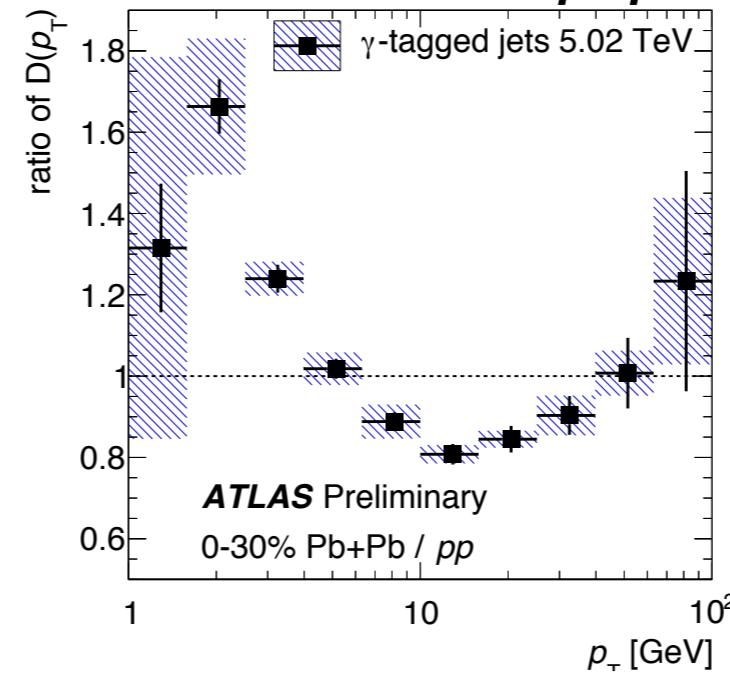
$D(p_T)$



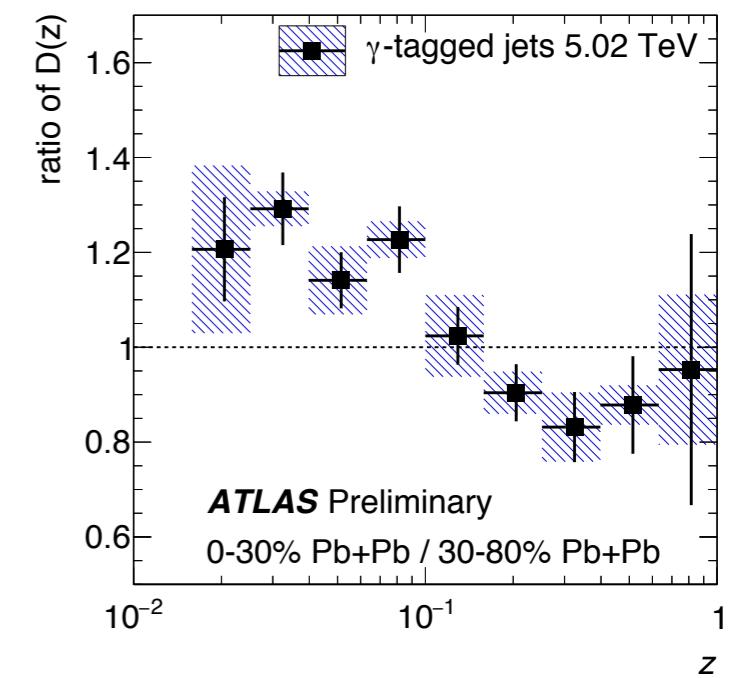
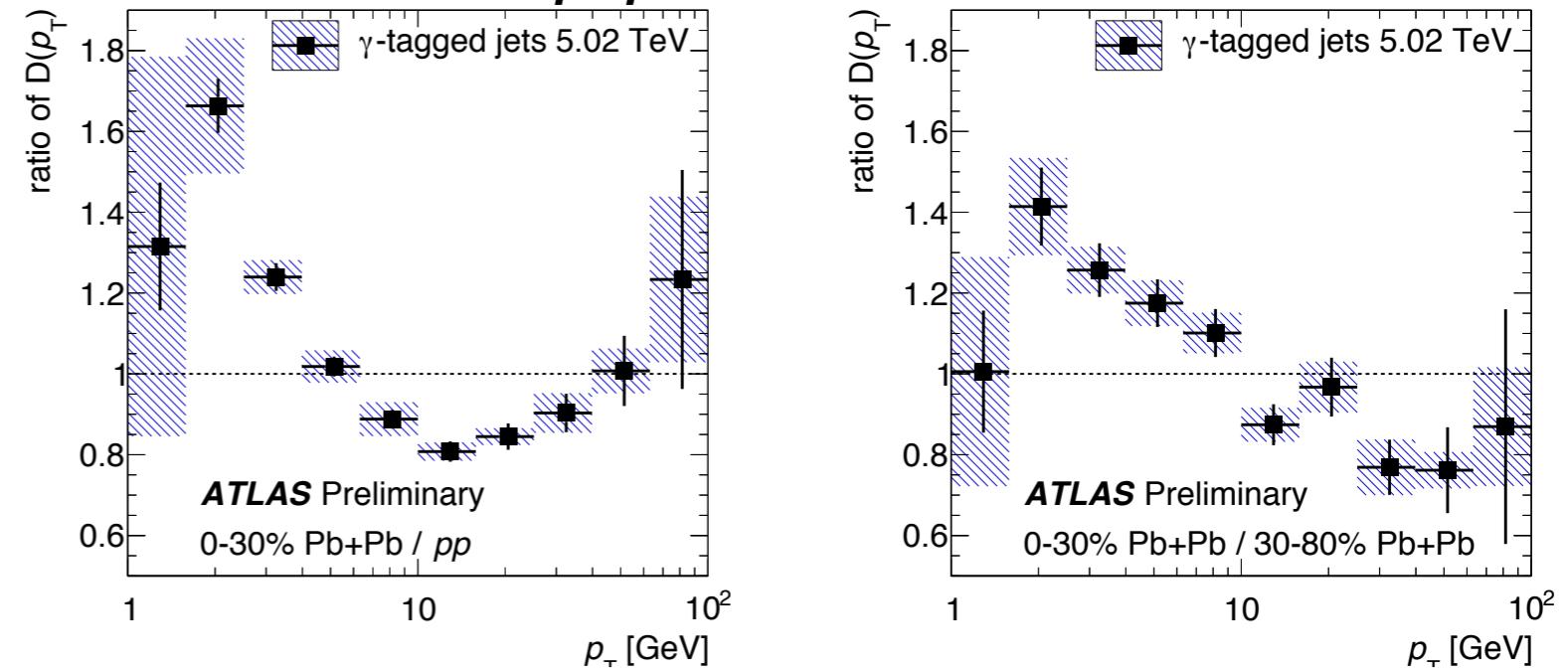
$D(z)$



0-30% /  $pp$

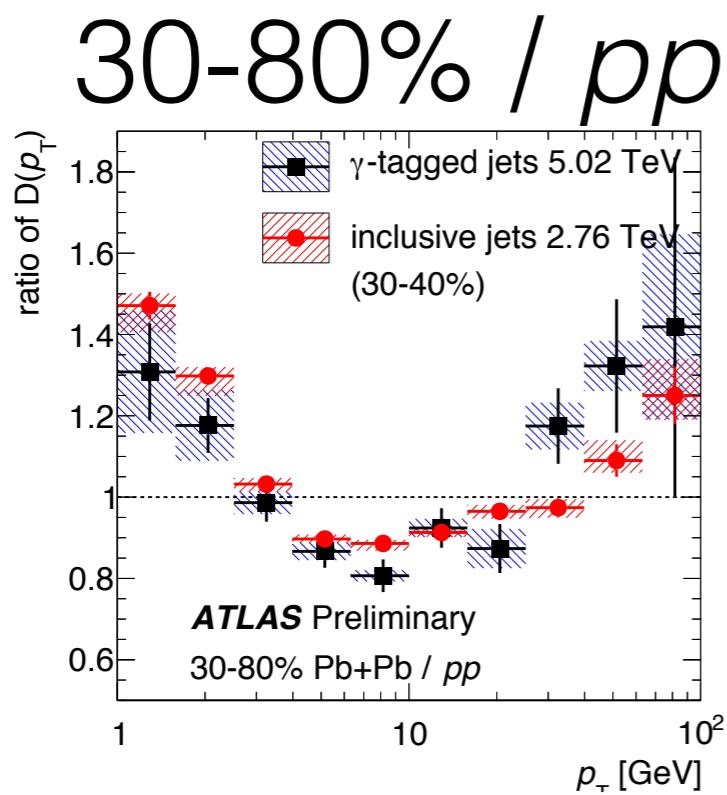


0-30% / 30-80%

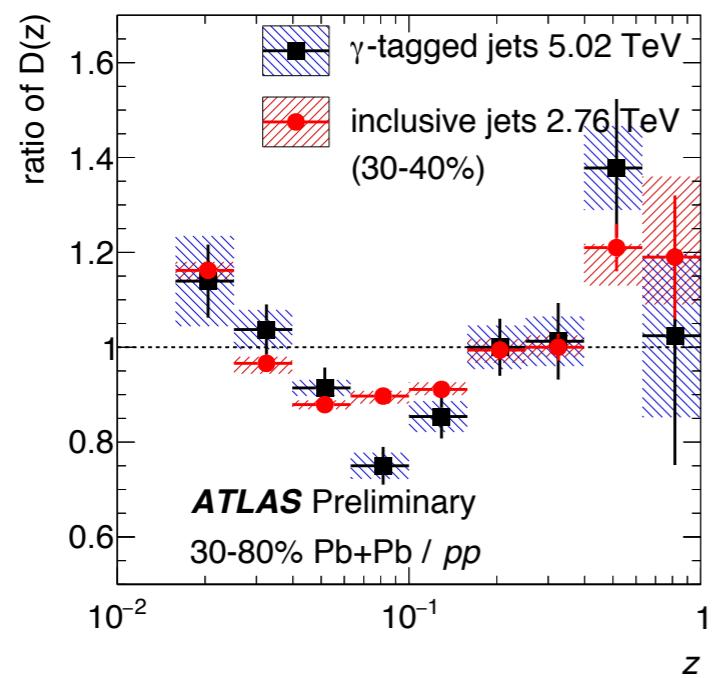


# $\gamma$ -tagged inclusive

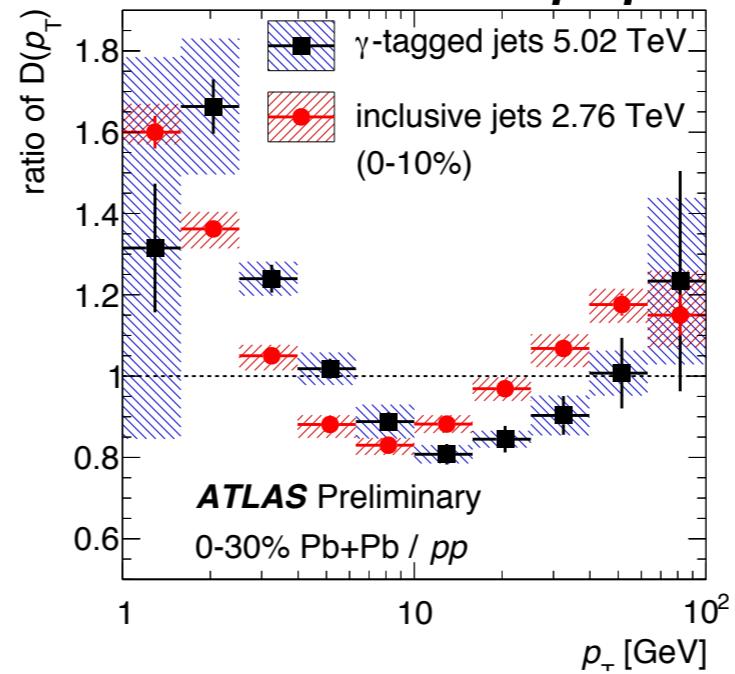
$D(p_T)$



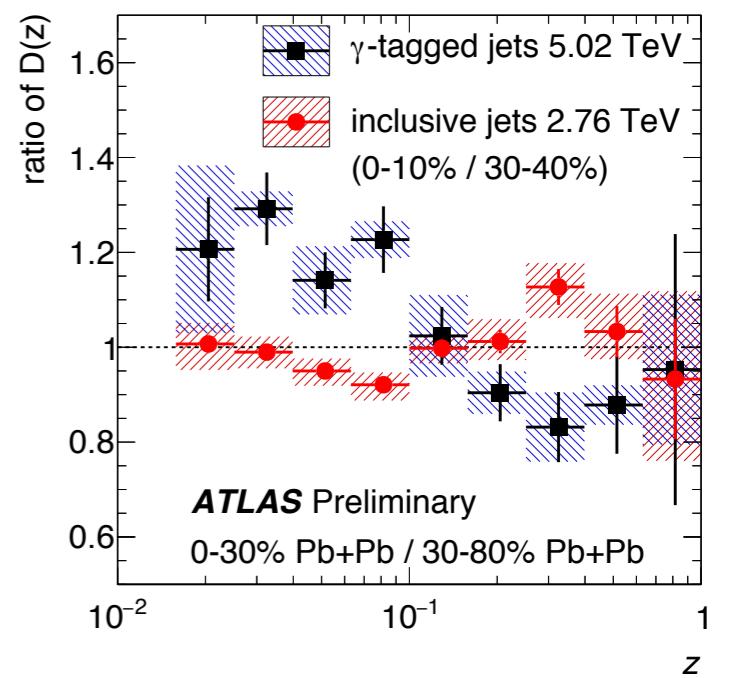
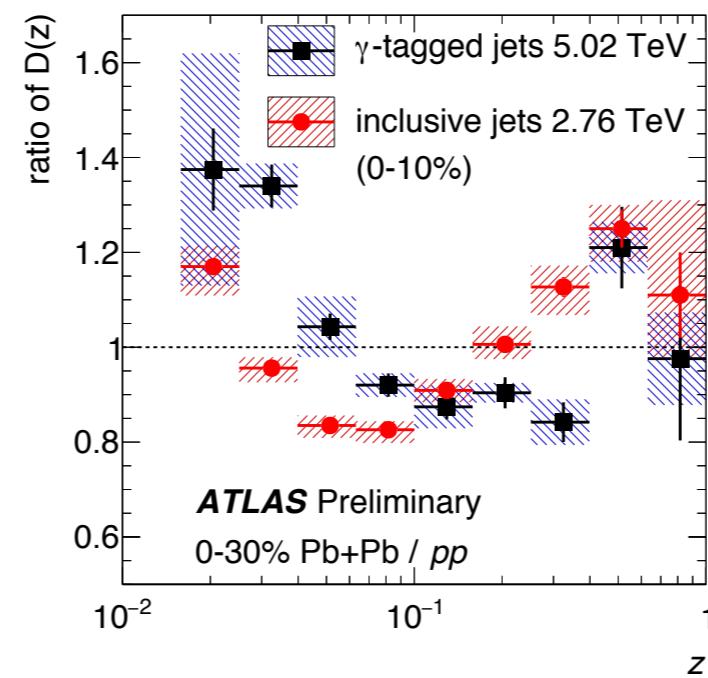
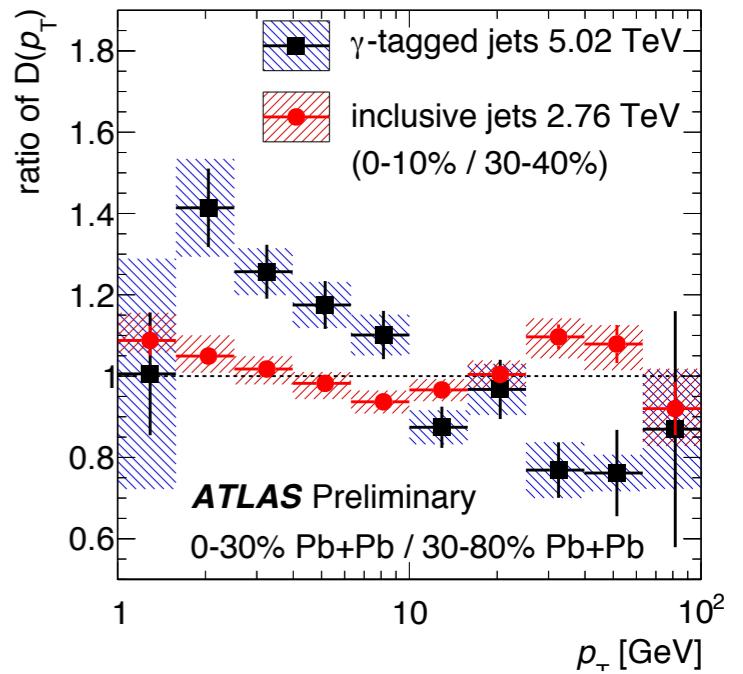
$D(z)$



0-30% /  $pp$



0-30% / 30-80%



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