Recent results from the ATLAS heavy ion program

Laura Havener, Columbia University
on behalf of the ATLAS Collaboration
Bormio 2018
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Heavy ion collisions

- **Collide heavy ions at very high energies to study QCD at high temperatures**
- **Produces the high temperature phase of QCD, quark-gluon plasma (QGP)**

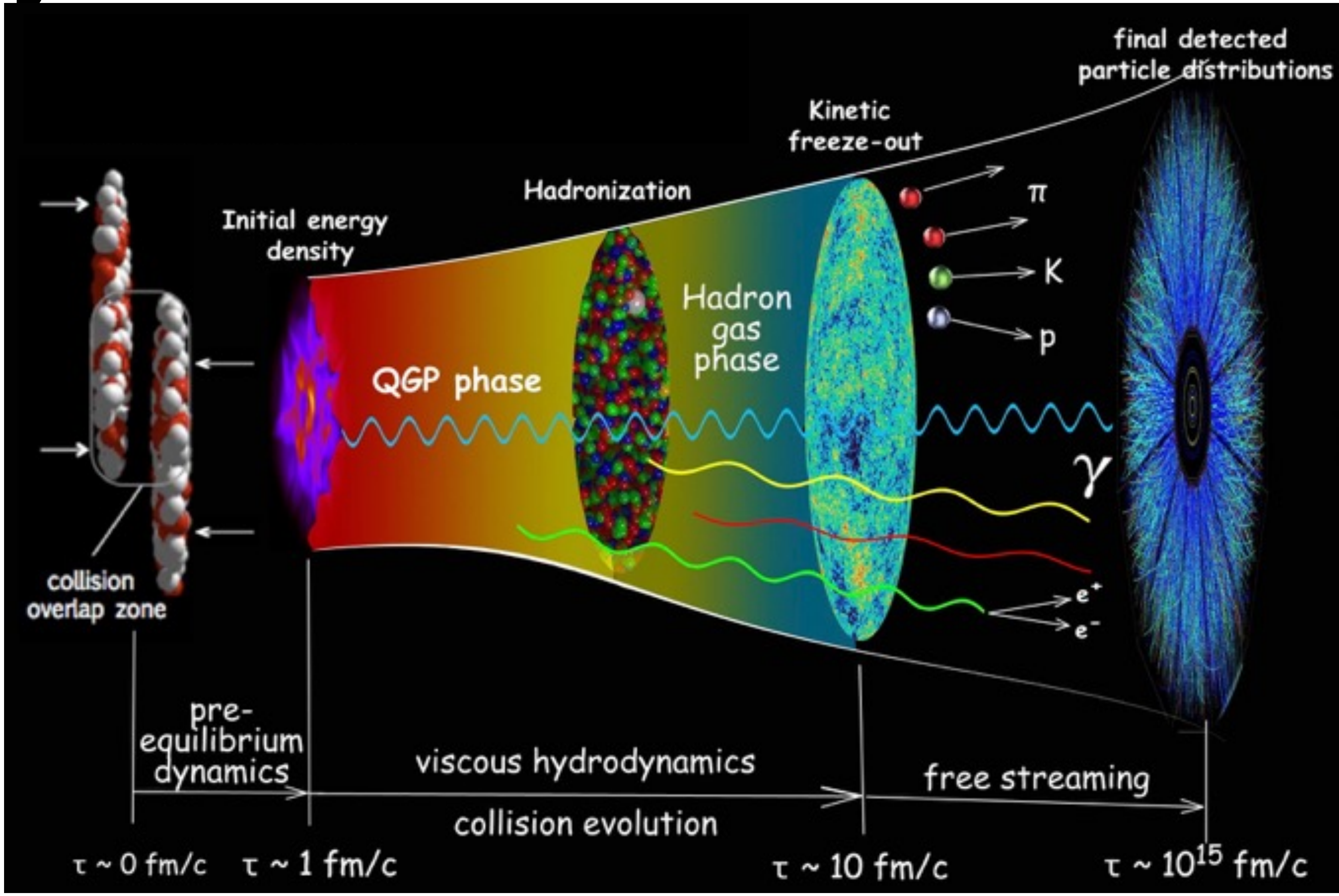


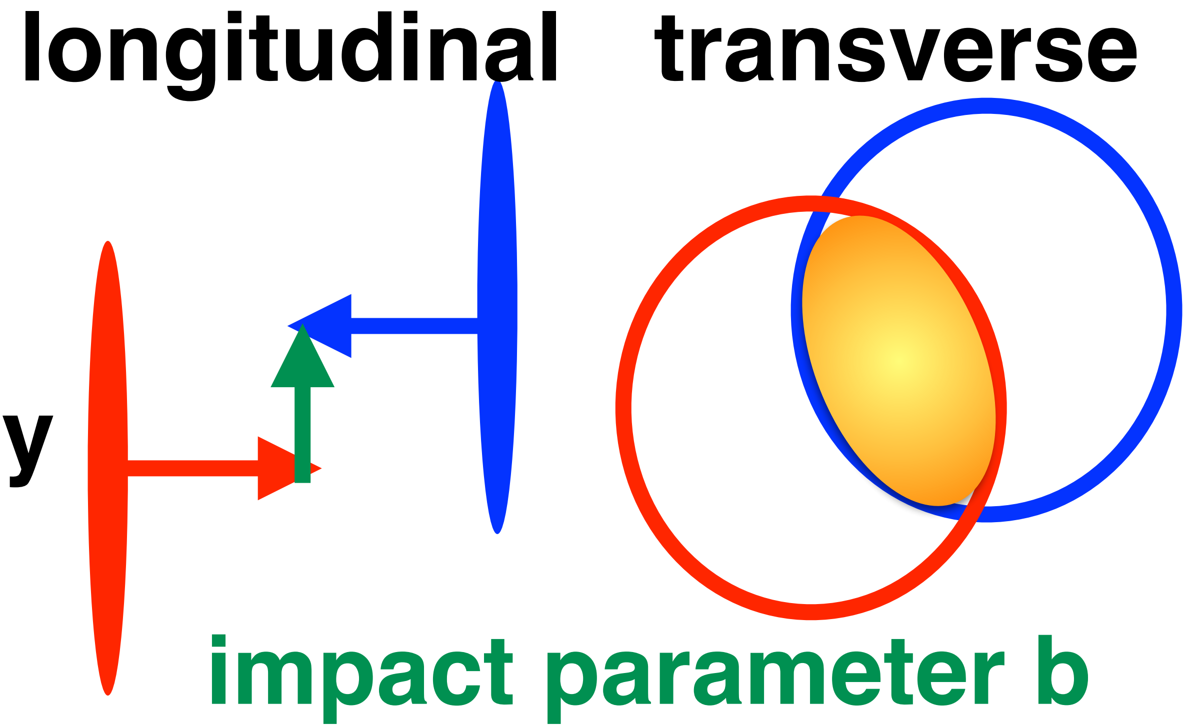
Image by Chun Shen

- **Collective expansion of the system is described by relativistic hydrodynamics**
  - ► **Low shear viscosity makes a nearly perfect fluid that's bulk dynamics are driven by strong coupling**
  - ► **Very opaque allows for large parton energy loss**

Centrality

- **Nucleon flux increases with increasing centrality (or decreasing b)**
- **Properties of AA collisions vary hugely with degree of overlap**

➡ **Define "centrality classes" as events with similar degrees of overlap**



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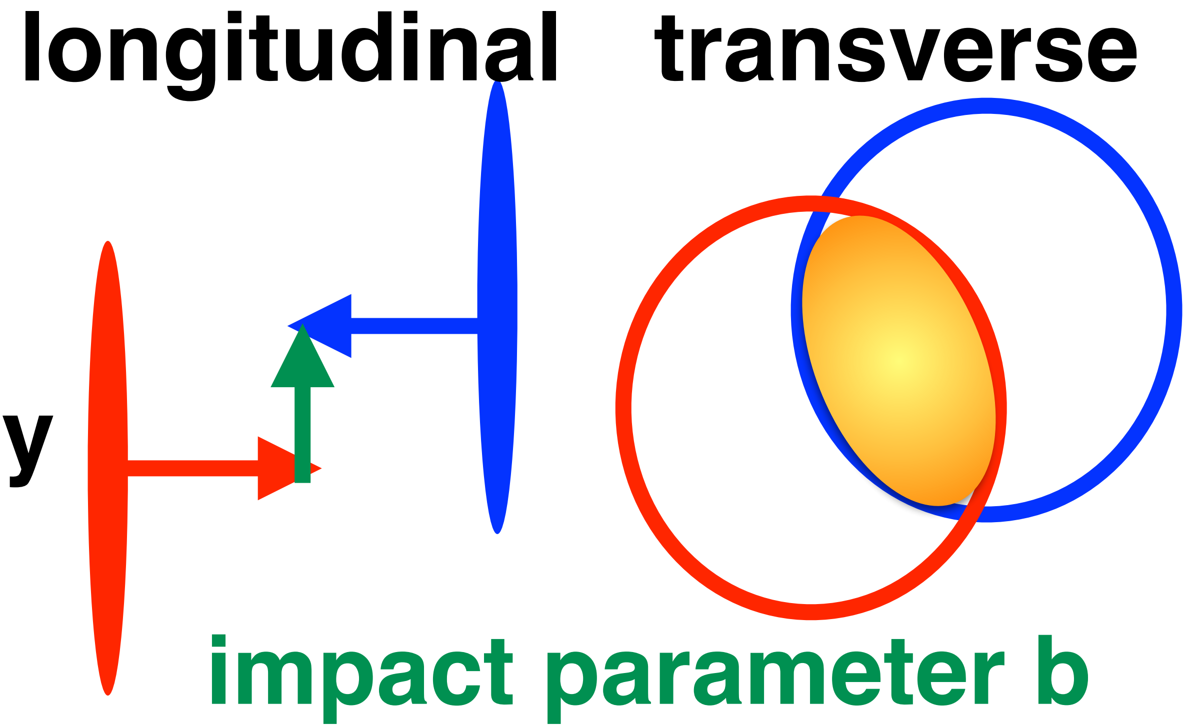
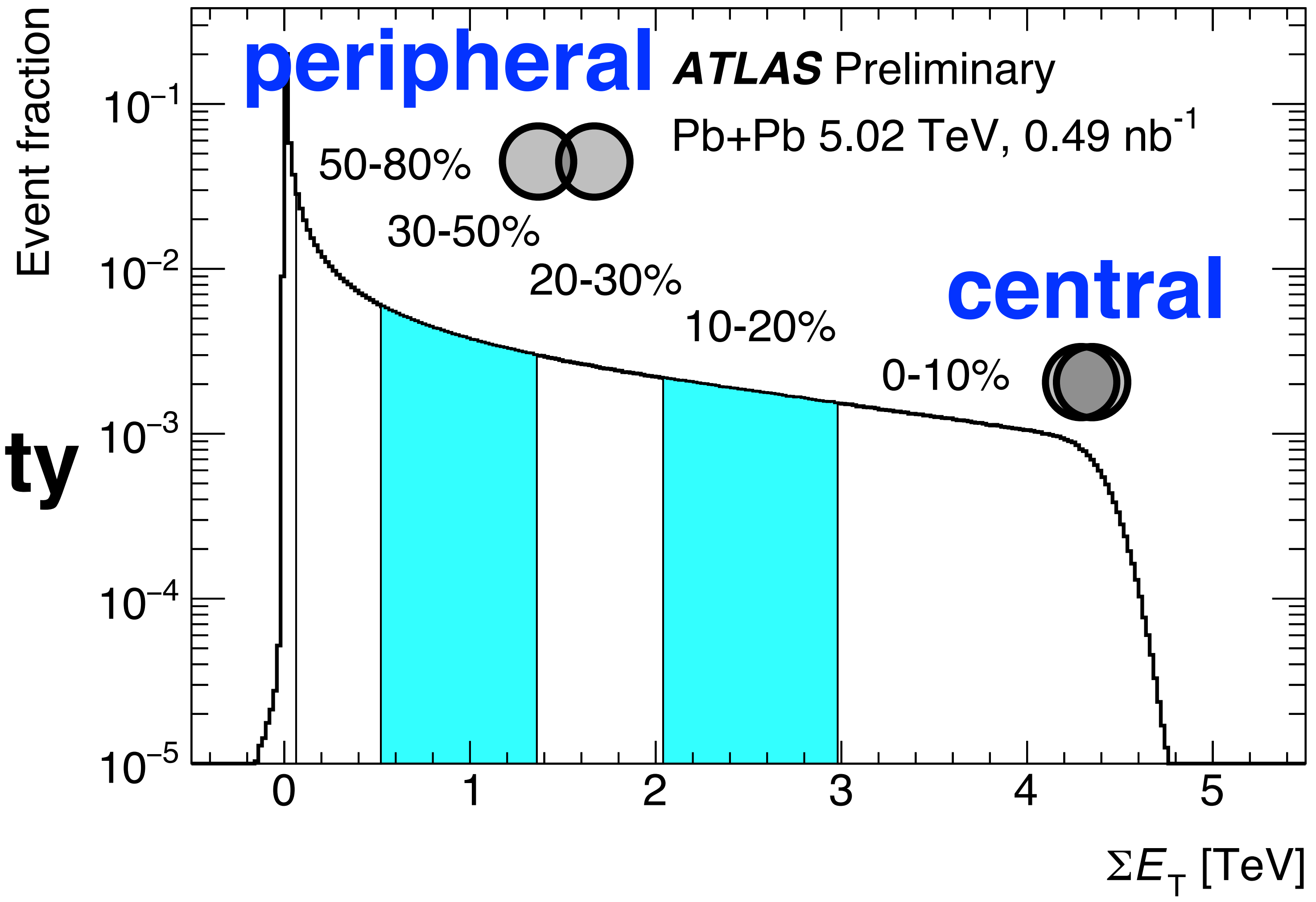


- **In ATLAS FCal E_T is a measure of event activity in Pb+Pb**
  - **Partition distribution into quantiles**



Characterizing the QGP

- **Hard probes:**
  - ➡ **Electro-weak bosons, heavy flavor, jets, hadrons, quarkonia**
- **Global properties:**
  - ➡ **correlations and fluctuations of soft particles**

▶ ***Separate initial and final state by looking at p+Pb and pp collisions***

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Produced early in the collision where the initial state is well understood such that any differences from *pp* in the final state are from interactions with the medium

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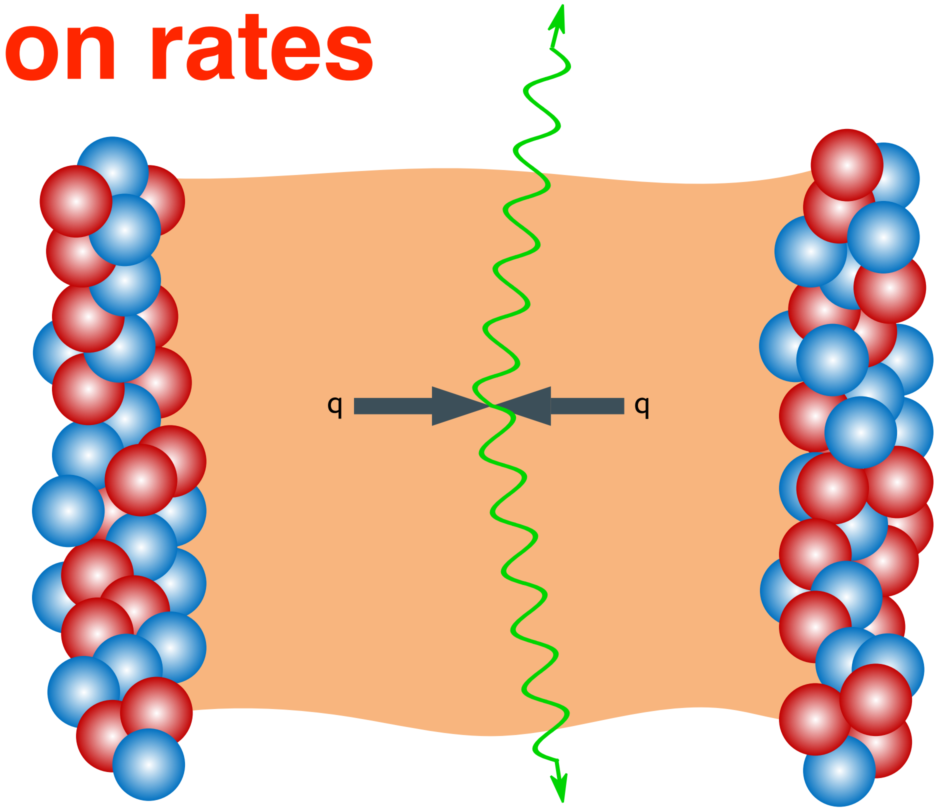
photons, Z, and W bosons don't interact strongly with the medium so expect no modification to their production rates

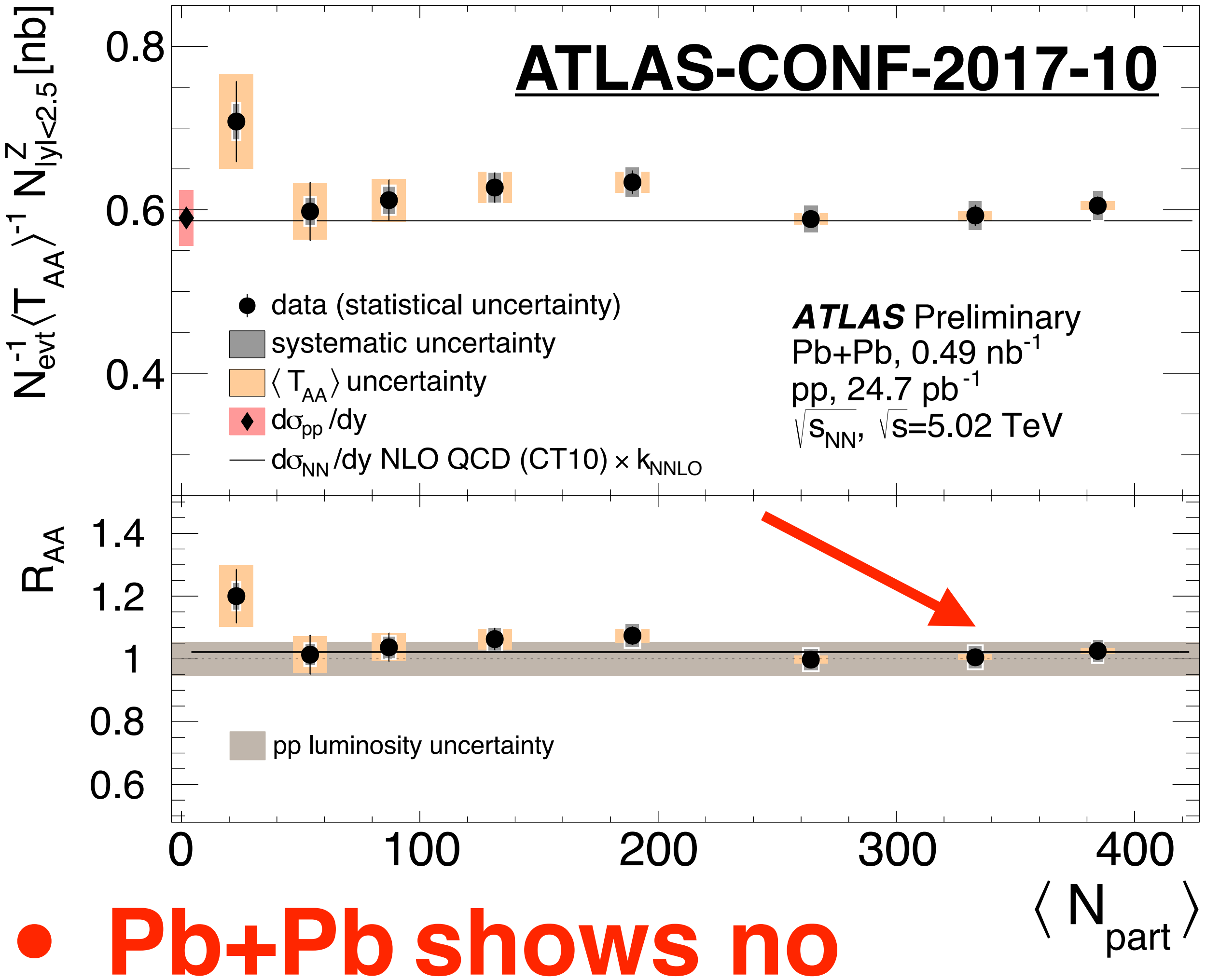
▸ ***Separate initial and final state by looking at p+Pb and pp collisions***



Z boson production

- **The rate of Z boson was measured in 5.02 TeV Pb+Pb and p+Pb data and compare to pp using R_{AA} and R_{pPb}**

$$R_{AA} = \frac{1}{< T_{AA} > N_{evt}} \frac{dN_{Pb+Pb}/dy}{d\sigma_{pp}/dy}$$



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  - ***Indicates control over the geometry***

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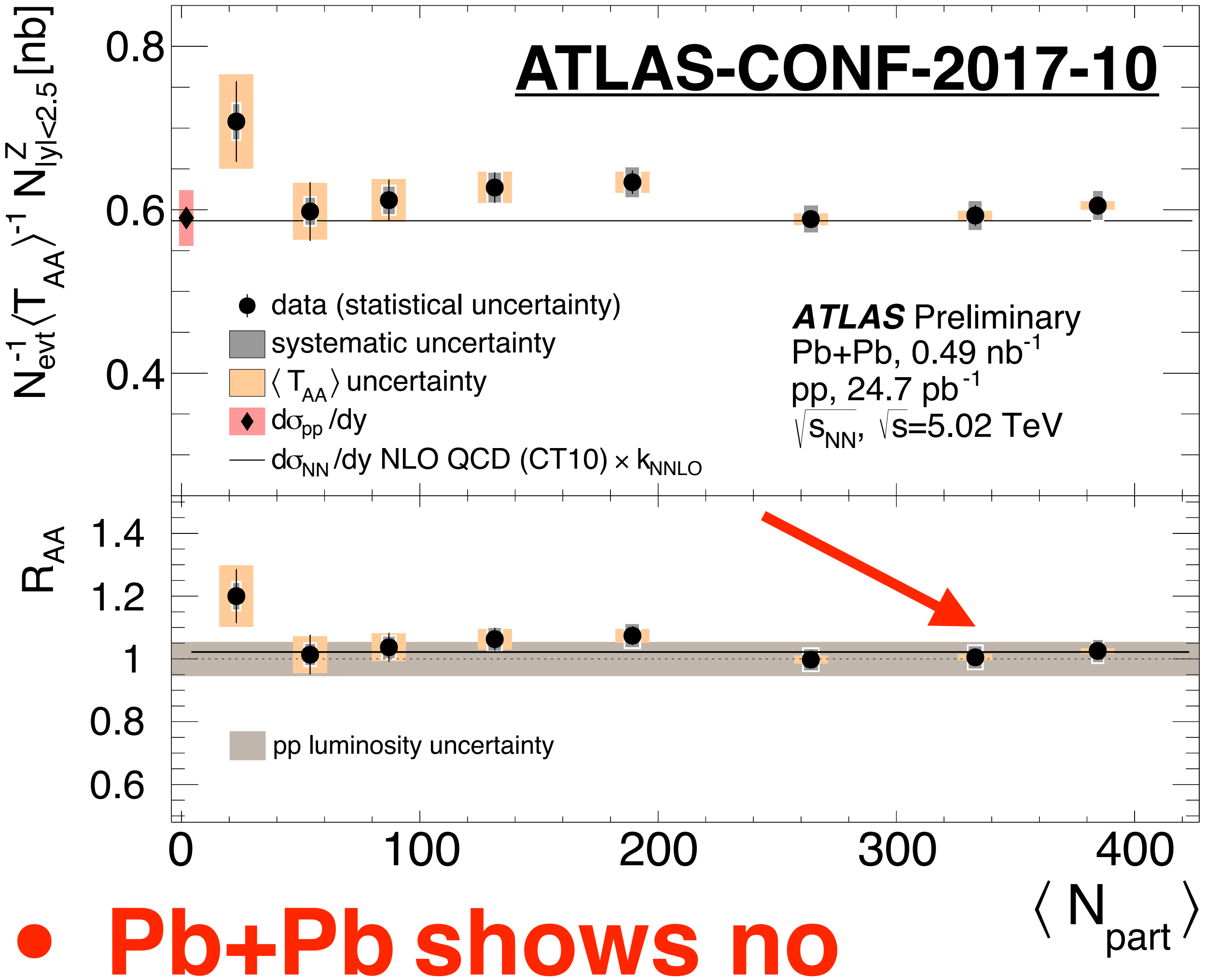
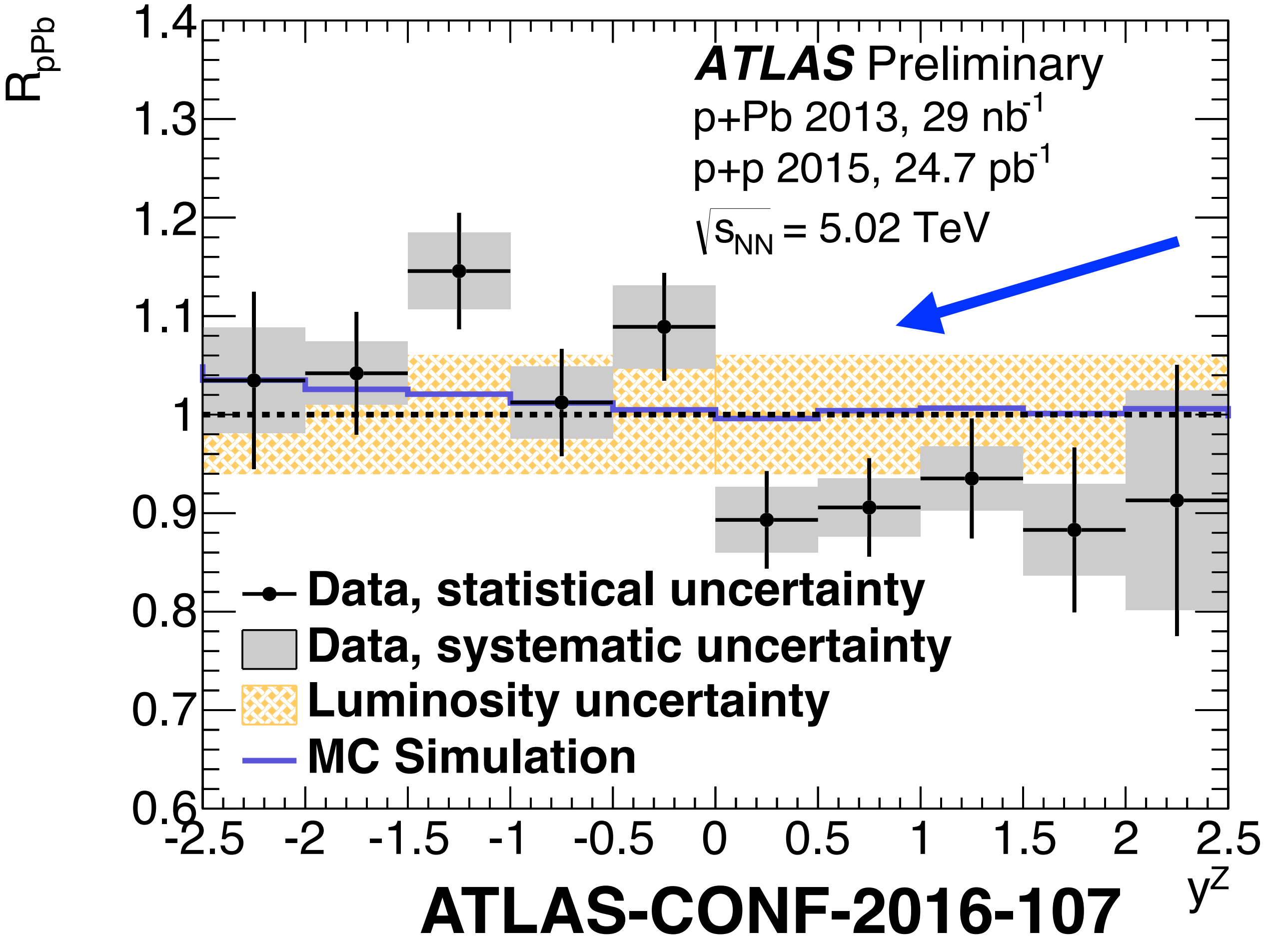


ATLAS-CONF-2017-10



ATLAS-CONF-2016-107

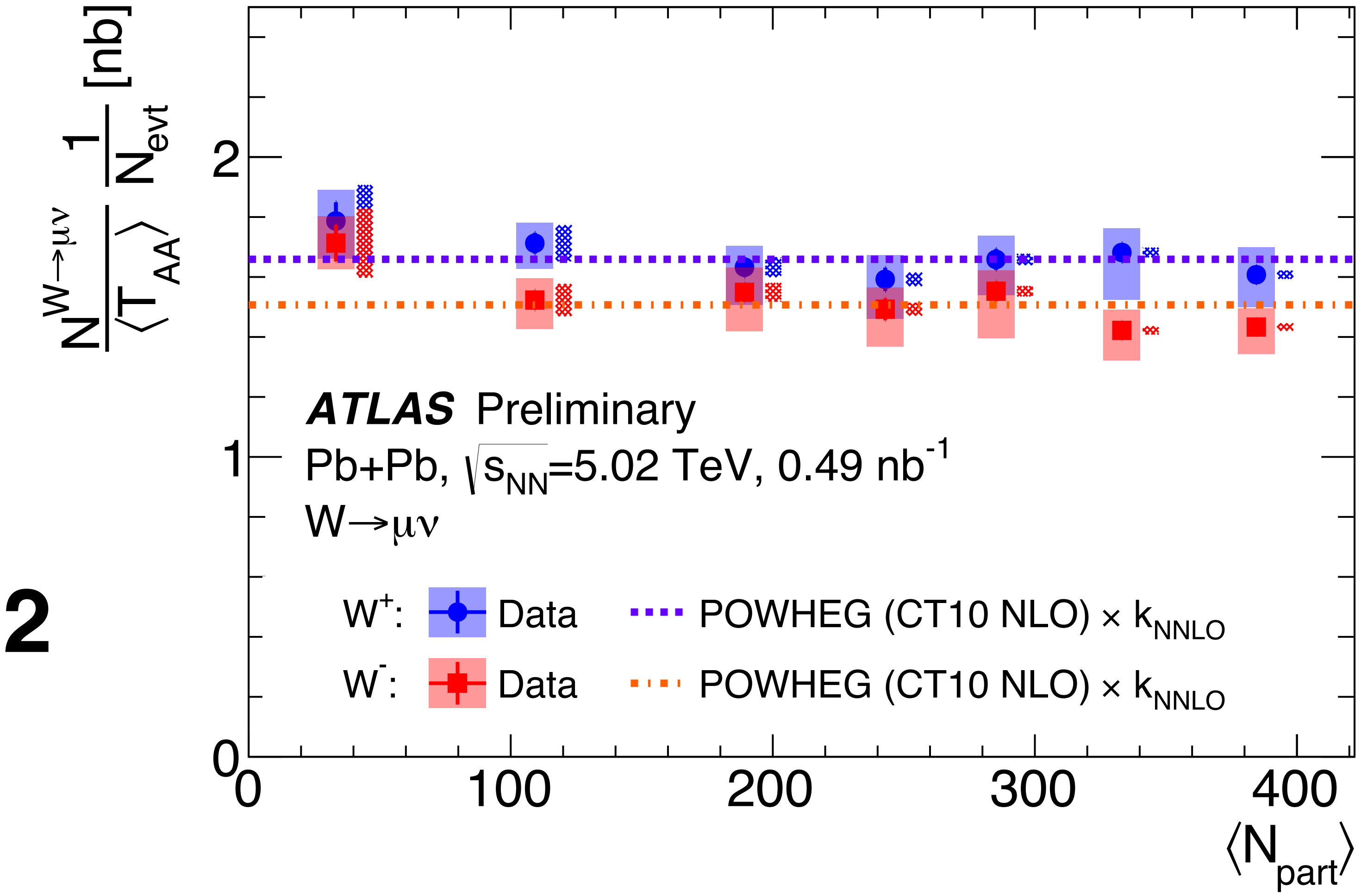
- **p+Pb shows slight forward-backward asymmetry consistent with nPDFs effects**

$$R_{pPb} = \frac{1}{A_{Pb}} \frac{d\sigma_{pPb}/dy}{d\sigma_{pp}/dy}$$

- **Pb+Pb shows no modification with centrality**
  - ***Indicates control over the geometry***

W boson production

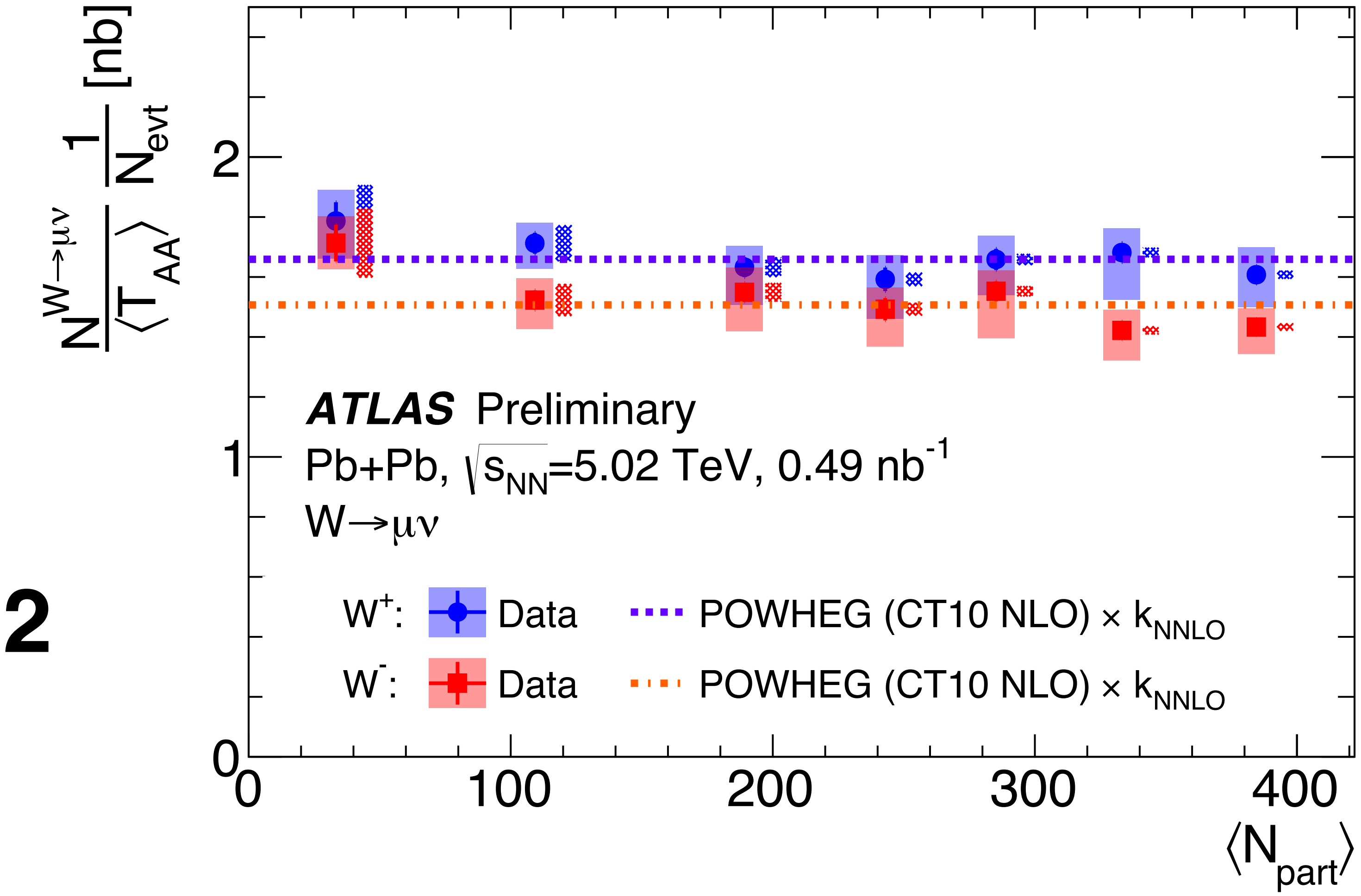
- **W+ and W- in the muon channel for 5.02 TeV Pb+Pb**
- **The yields scaled by T_{AA} have no dependence on N_{part}**
- **W+ yield is 10% higher than W-**

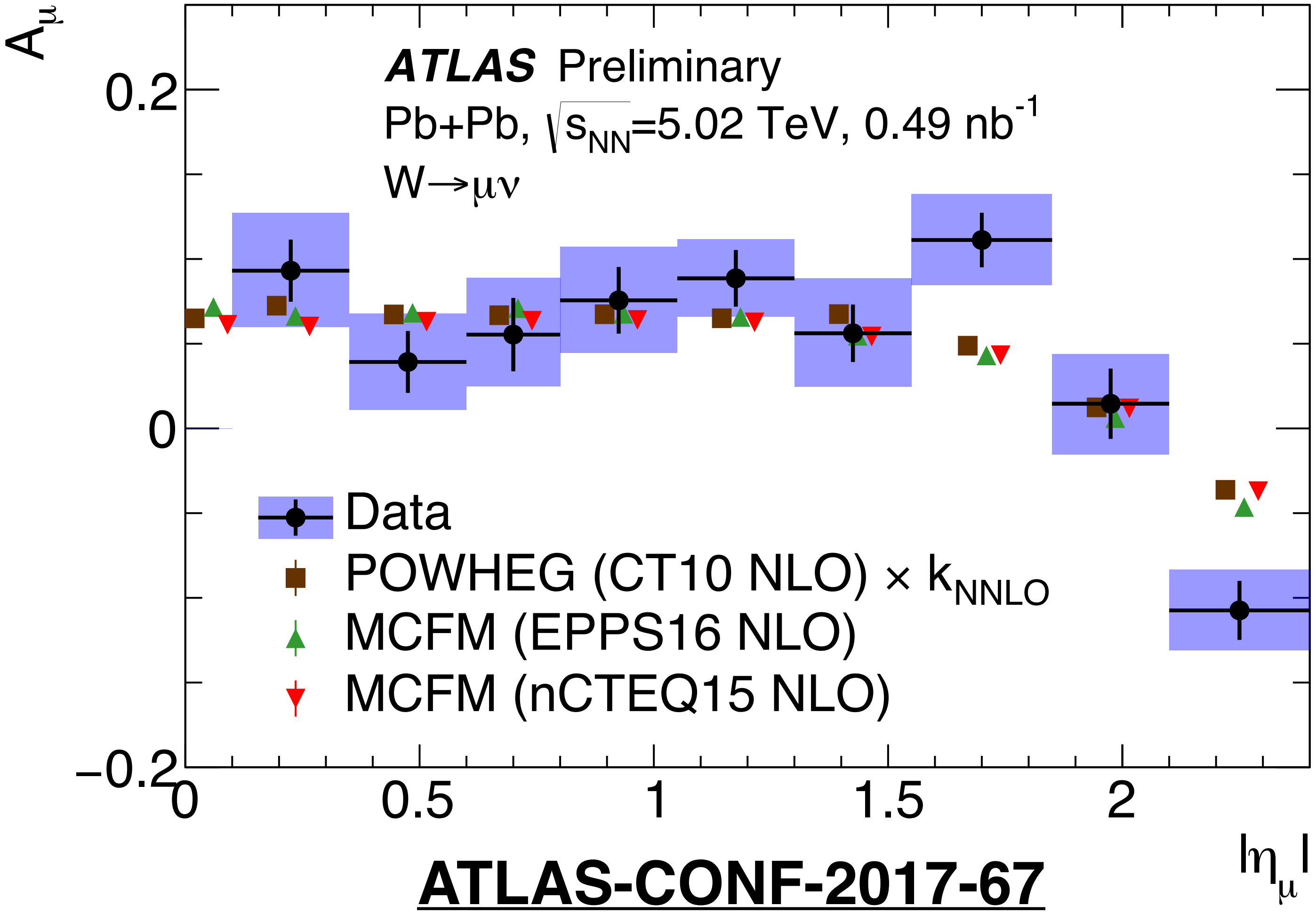


ATLAS-CONF-2017-67

W boson production

- **W+ and W- in the muon channel for 5.02 TeV Pb+Pb**
- **The yields scaled by T_{AA} have no dependence on N_{part}**
- **W+ yield is 10% higher than W-**
- **The asymmetry is consistent with POWHEG scaled to NNLO accuracy**





ATLAS-CONF-2017-67

Characterizing the QGP

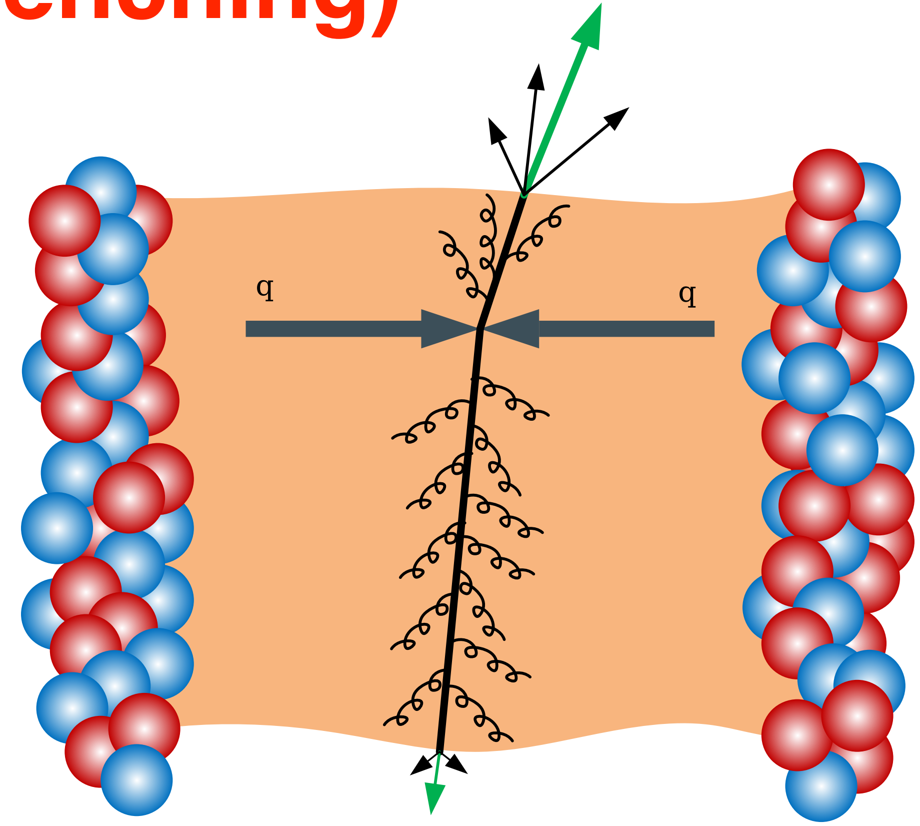
- **Hard probes:**
  - ➡ Electro-weak bosons, heavy flavor, **jets**, hadrons, quarkonia

Produced early in the collision where the initial state is well understood such that any differences from *pp* in the final state are from interactions with the medium

Partons lose energy through interactions with the medium (jet quenching)

- **Global properties:**
  - ➡ **correlations and fluctuations of soft particles**

▸ ***Separate initial and final state by looking at p+Pb and pp collisions***



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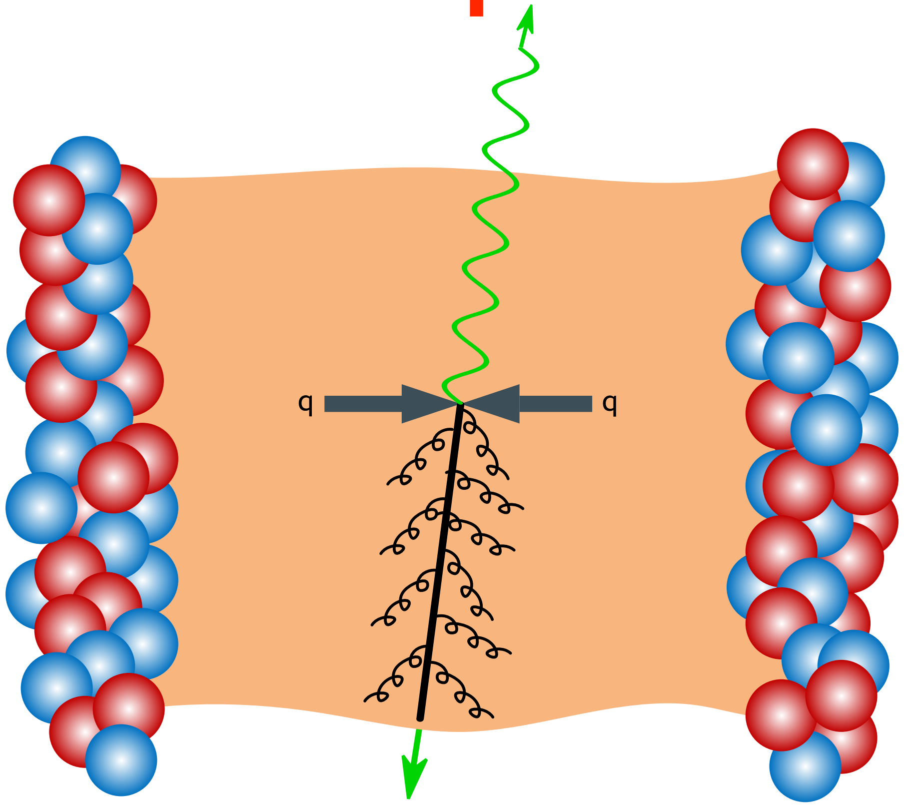
γ+jet used to look at energy loss of the recoiling jet since photons aren't expected to interact strongly with the medium

The initial production distributions are different

More likely to originate from quark jets than inclusive/dijets so it's a probe of the flavor dependence



Jet suppression

- **Jets expected to be suppressed at a fixed p_T compared to *pp* collisions**

  ➡ **Measure with the R_{AA}**

Jet suppression

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➡ **Measure with the R_{AA}**

$$R_{\mathrm{AA}} = \frac{\boxed{\frac{1}{N_{\mathrm{evnt}}}\frac{\mathrm{d}^2 N^{PbPb}_{\mathrm{jet}}}{\mathrm{d}p_{\mathrm{T}}\mathrm{d}y}\Big|_{\mathrm{cent}}}}{\boxed{\langle T_{\mathrm{AA}}\rangle_{\mathrm{cent}}} \times \boxed{\frac{\mathrm{d}^2\sigma^{pp}_{\mathrm{jet}}}{\mathrm{d}p_{\mathrm{T}}\mathrm{d}y}}}$$

Jet yield in heavy ion

Nuclear thickness function

Jet cross-section in *pp* collisions

Jet suppression

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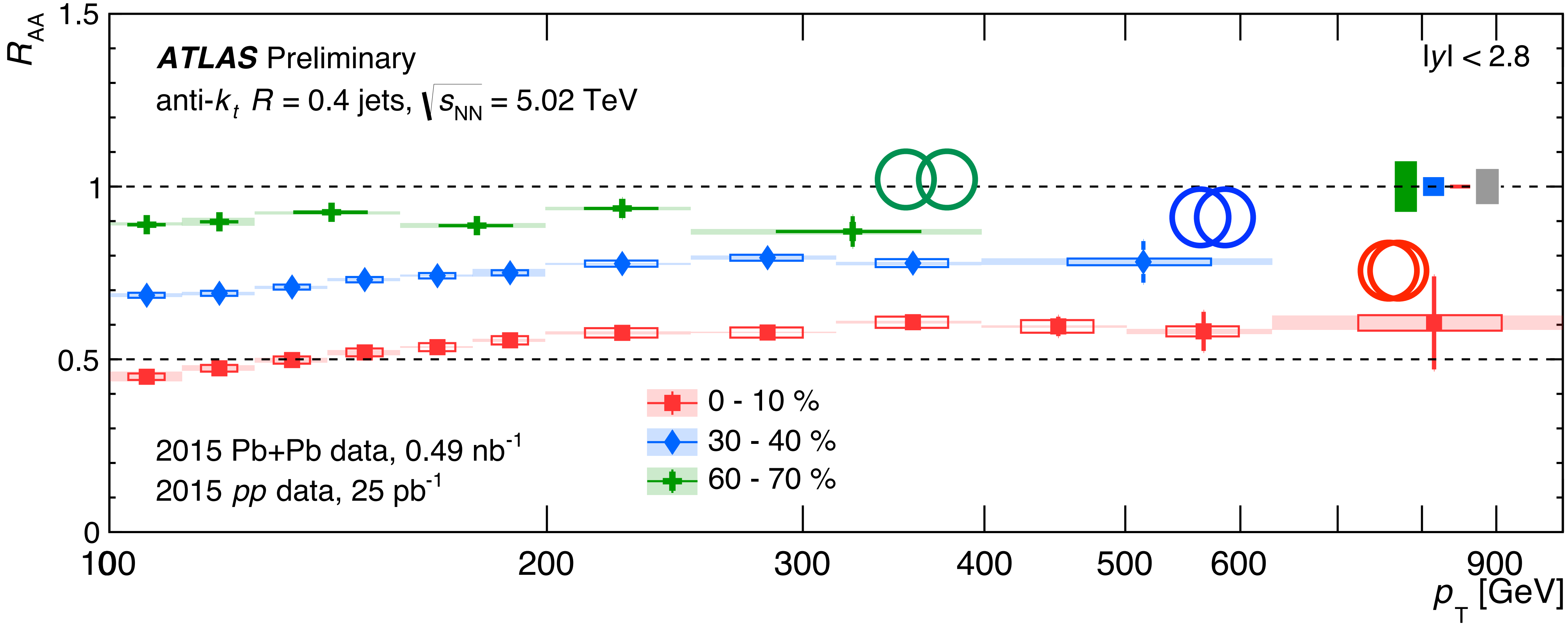
- **R_{AA} below 1 for all centralities**



ATLAS-CONF-2017-009

Jet suppression

- **Jets expected to be suppressed at a fixed p_T compared to *pp* collisions**

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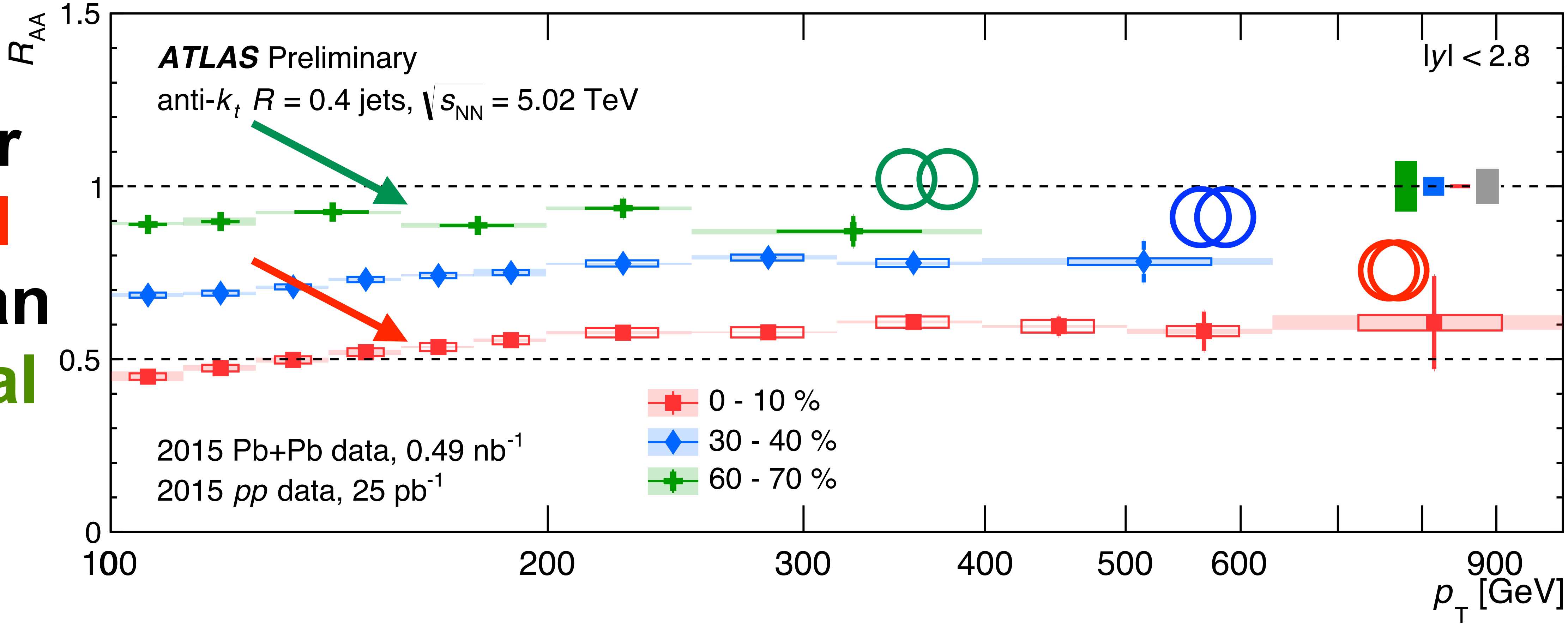
Jet cross-section in *pp* collisions

- **R_{AA} below 1 for all centralities**

R_{AA} lower in central (~0.6) than peripheral (~0.9)



ATLAS-CONF-2017-009

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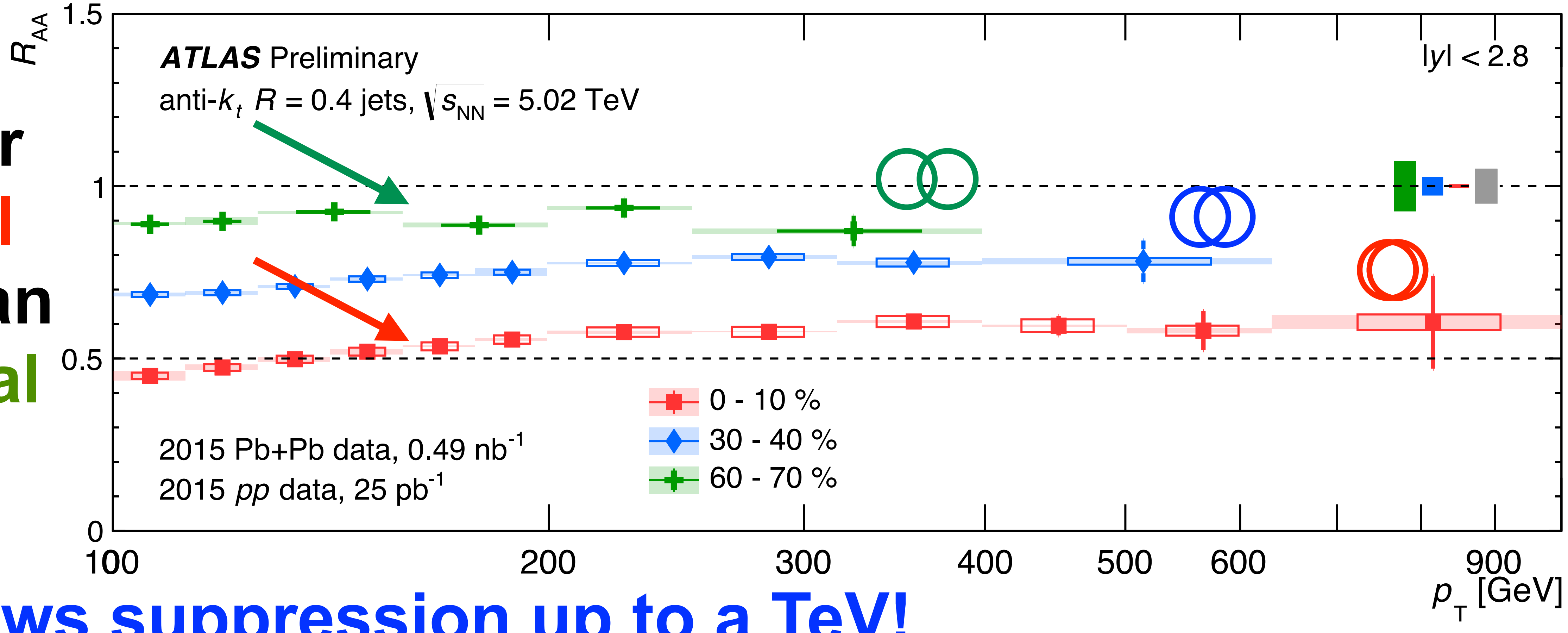
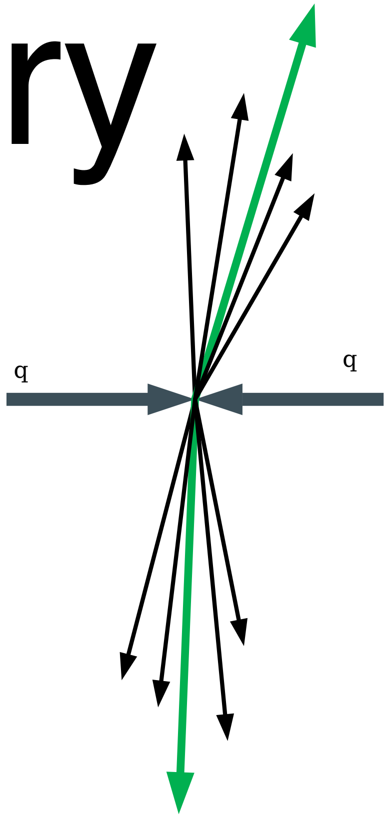


▸ **R_{AA} shows suppression up to a TeV!**

ATLAS-CONF-2017-009

Dijet asymmetry

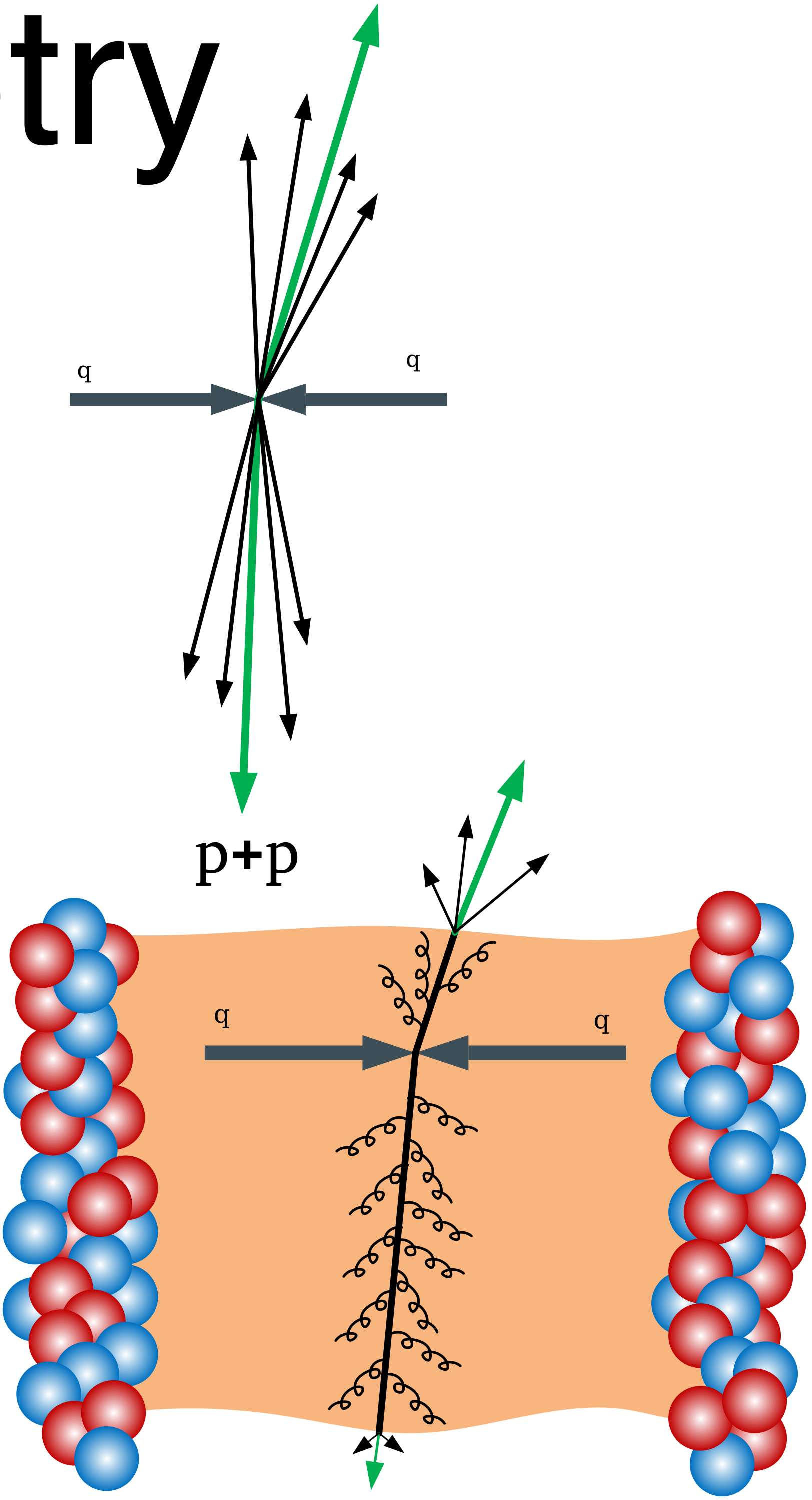
- **Dijets in pp collisions are approximately balanced in energy**



p+p

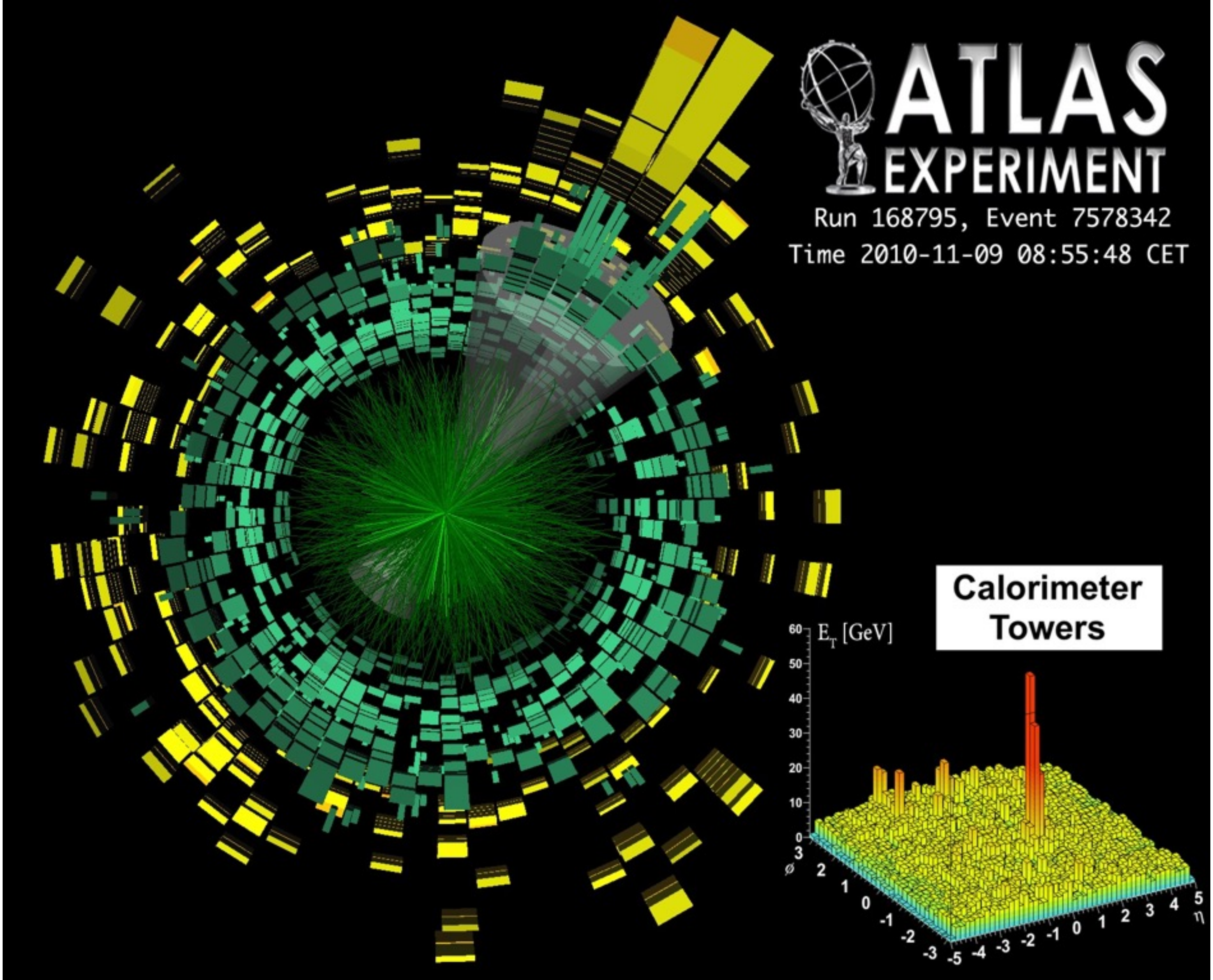
Dijet asymmetry

- **Dijets in pp collisions are approximately balanced in energy**
- **In Pb+Pb the two jets lose different amounts of energy because they travel different paths in the plasma or jet-by-jet fluctuations in the energy loss**
  - **Use ratio of the lower jet p_T (sub-leading jet) to the higher jet p_T (leading jet)**
- **Compare Pb+Pb to pp dijets where we expect the x_J ~1**



A+A

$$x_J = \frac{p_{T2}}{p_{T1}}$$



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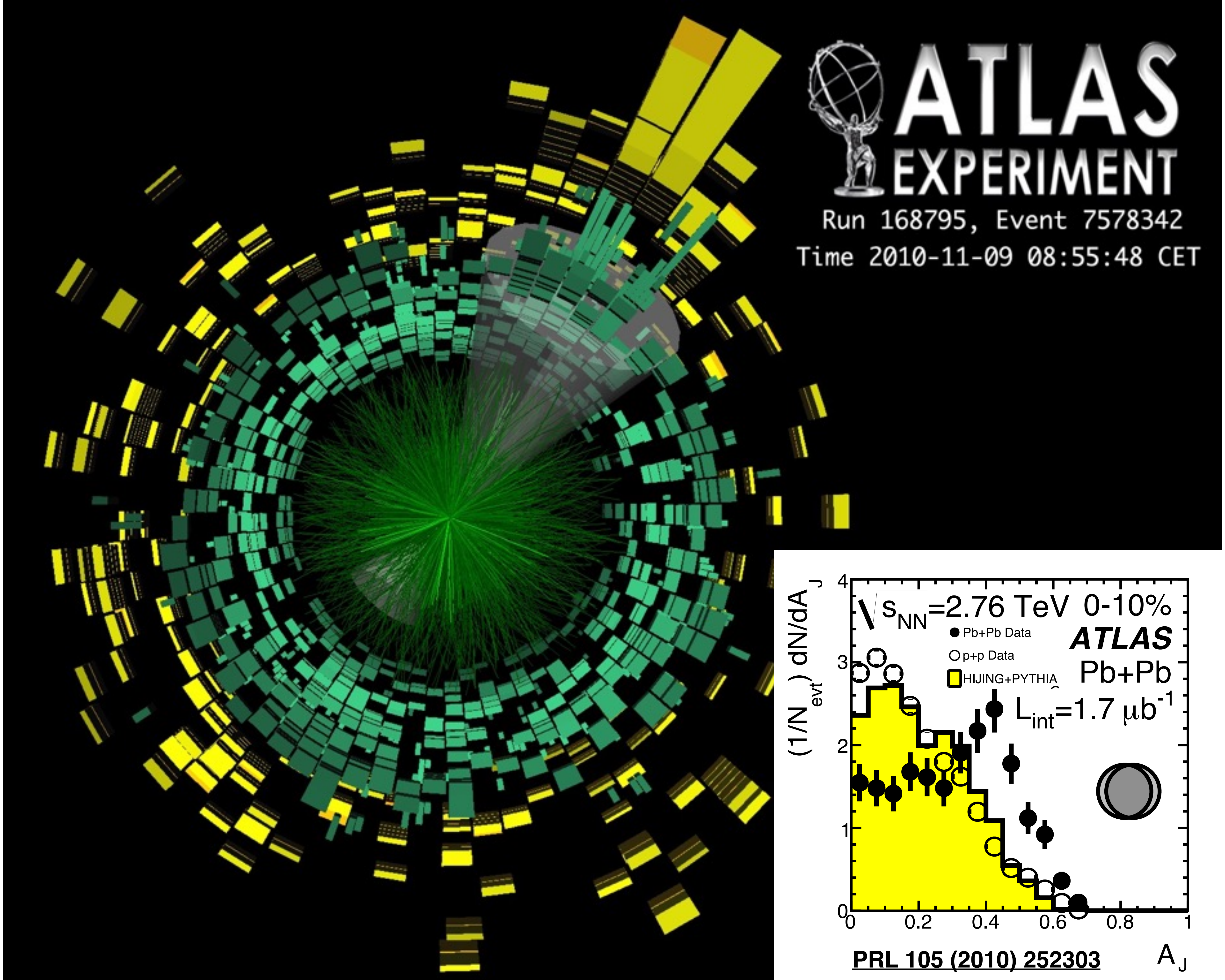
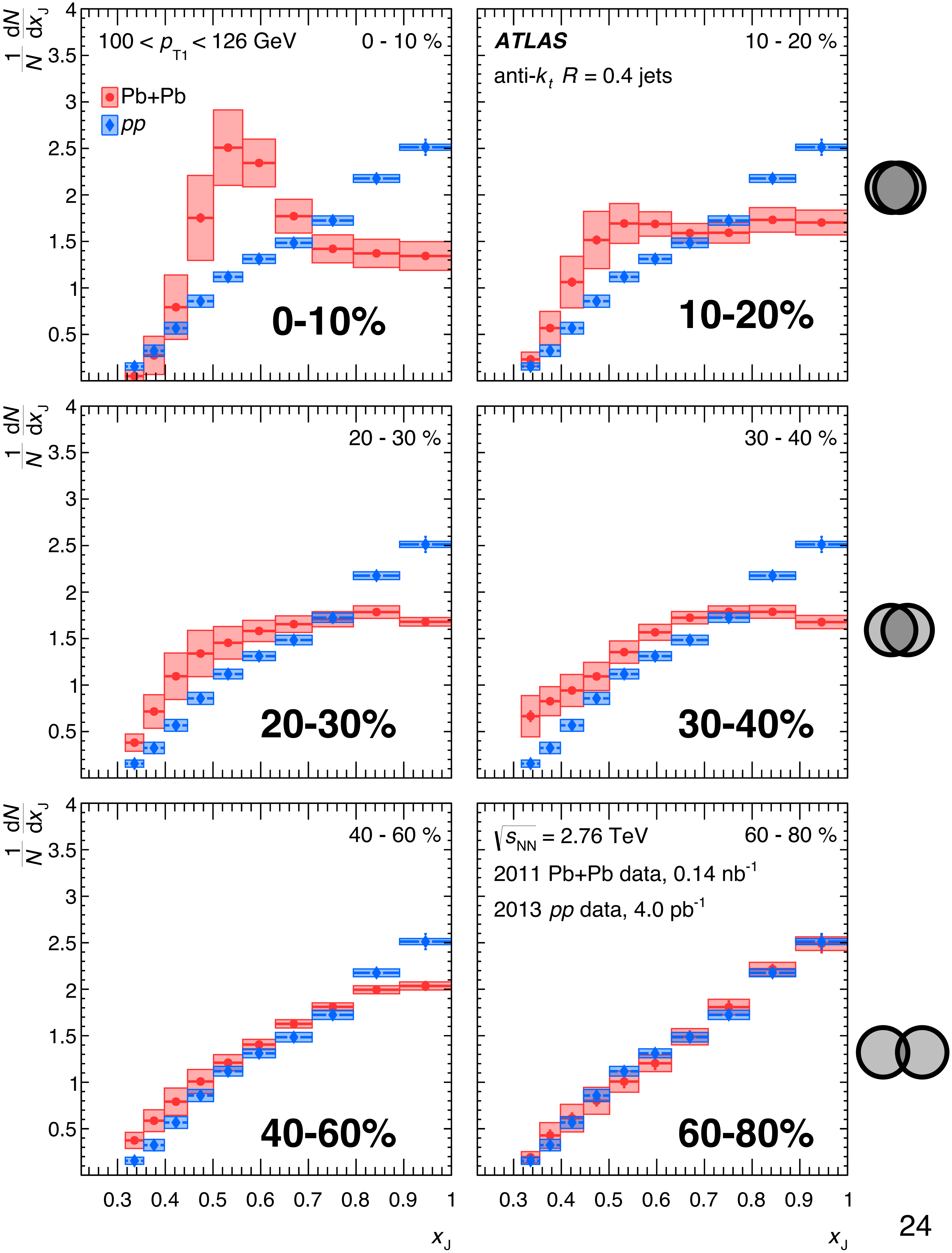


PRL 105 (2010) 252303

x_J distribution

PLB 774 (2017) 379

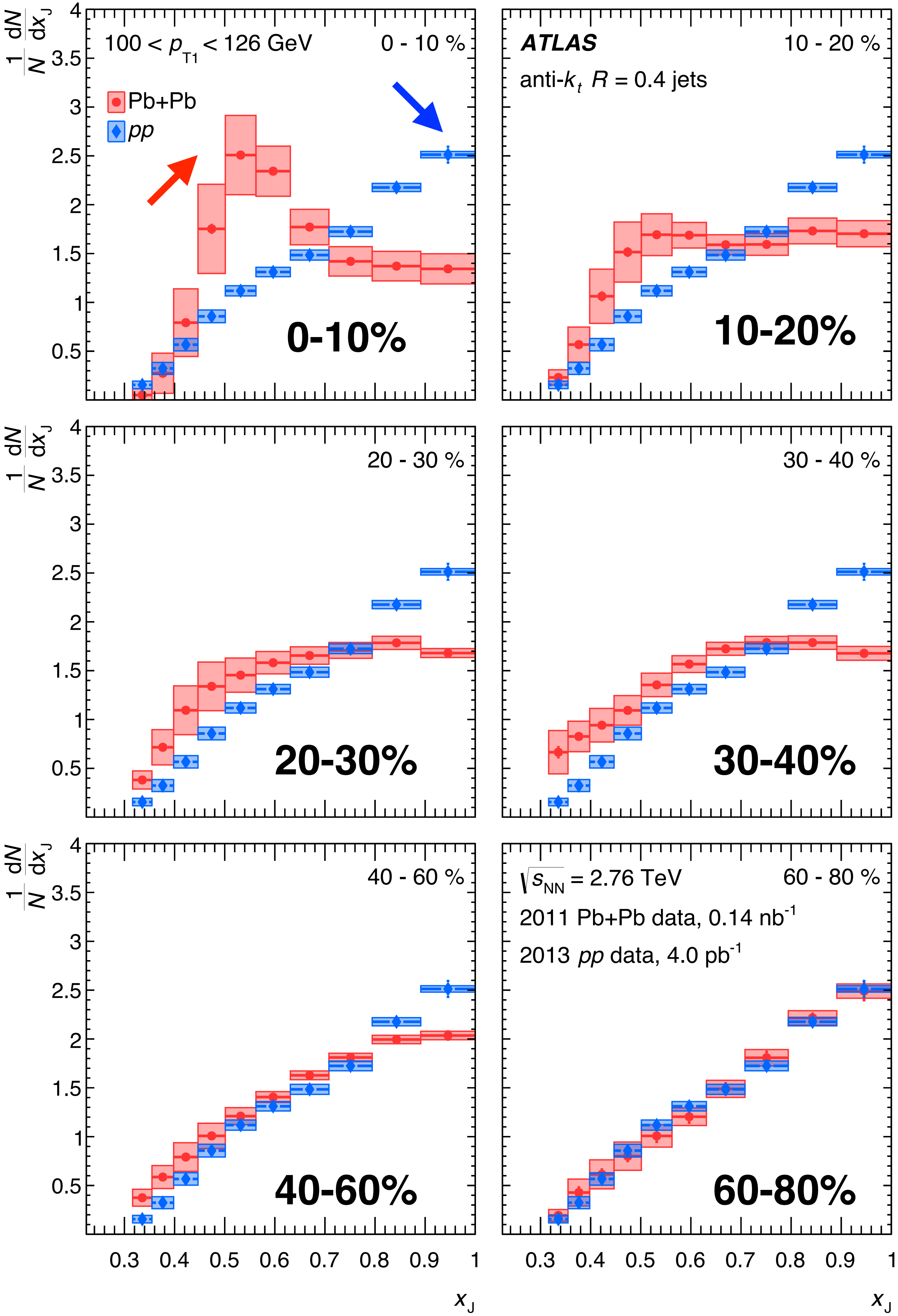
- **Pb+Pb more asymmetric in more central collisions**

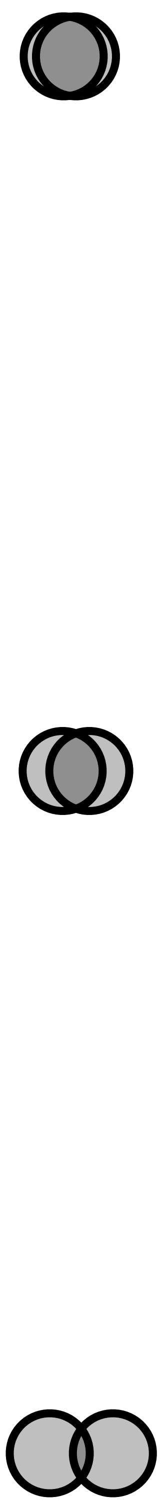


x_J distribution

PLB 774 (2017) 379

- **Pb+Pb more asymmetric in more central collisions**
- **Most probable configuration for *pp* collisions is x_J ~1**
- **For central Pb+Pb collisions it is x_J ~0.5**

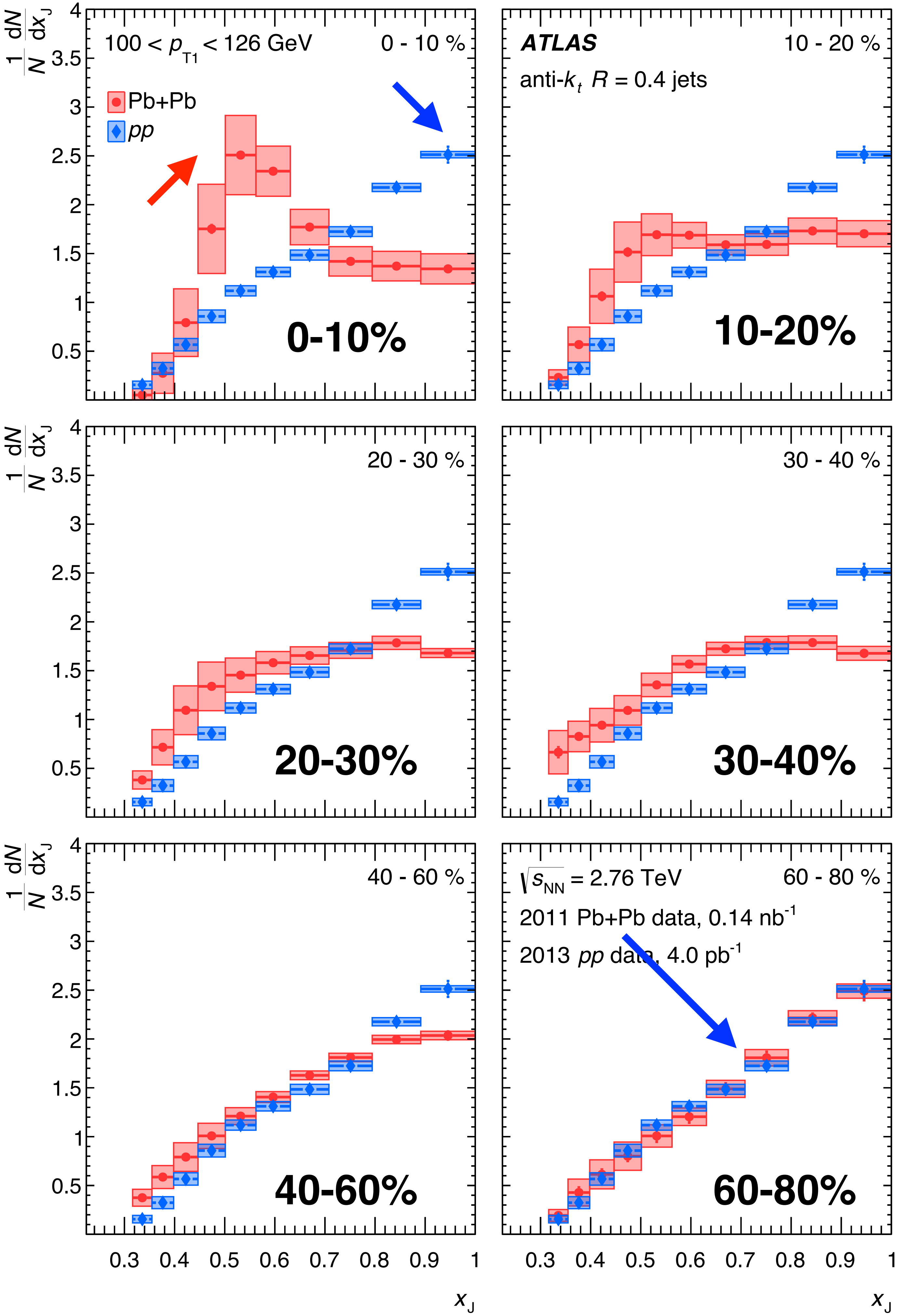


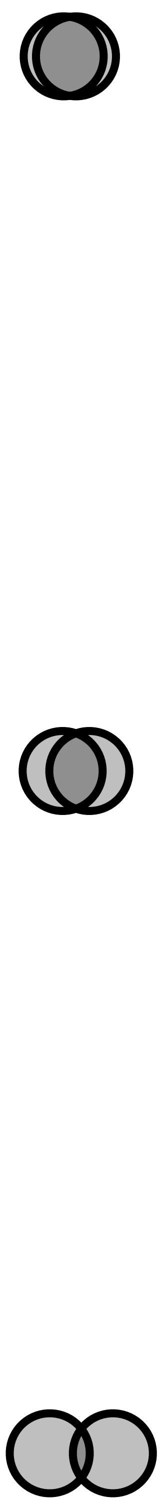


x_J distribution

PLB 774 (2017) 379

- **Pb+Pb more asymmetric in more central collisions**
- **Most probable configuration for *pp* collisions is $x_J \sim 1$**
- **For central Pb+Pb collisions it is $x_J \sim 0.5$**
- **As Pb+Pb becomes more peripheral the distribution is like *pp***





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PLB 774 (2017) 379

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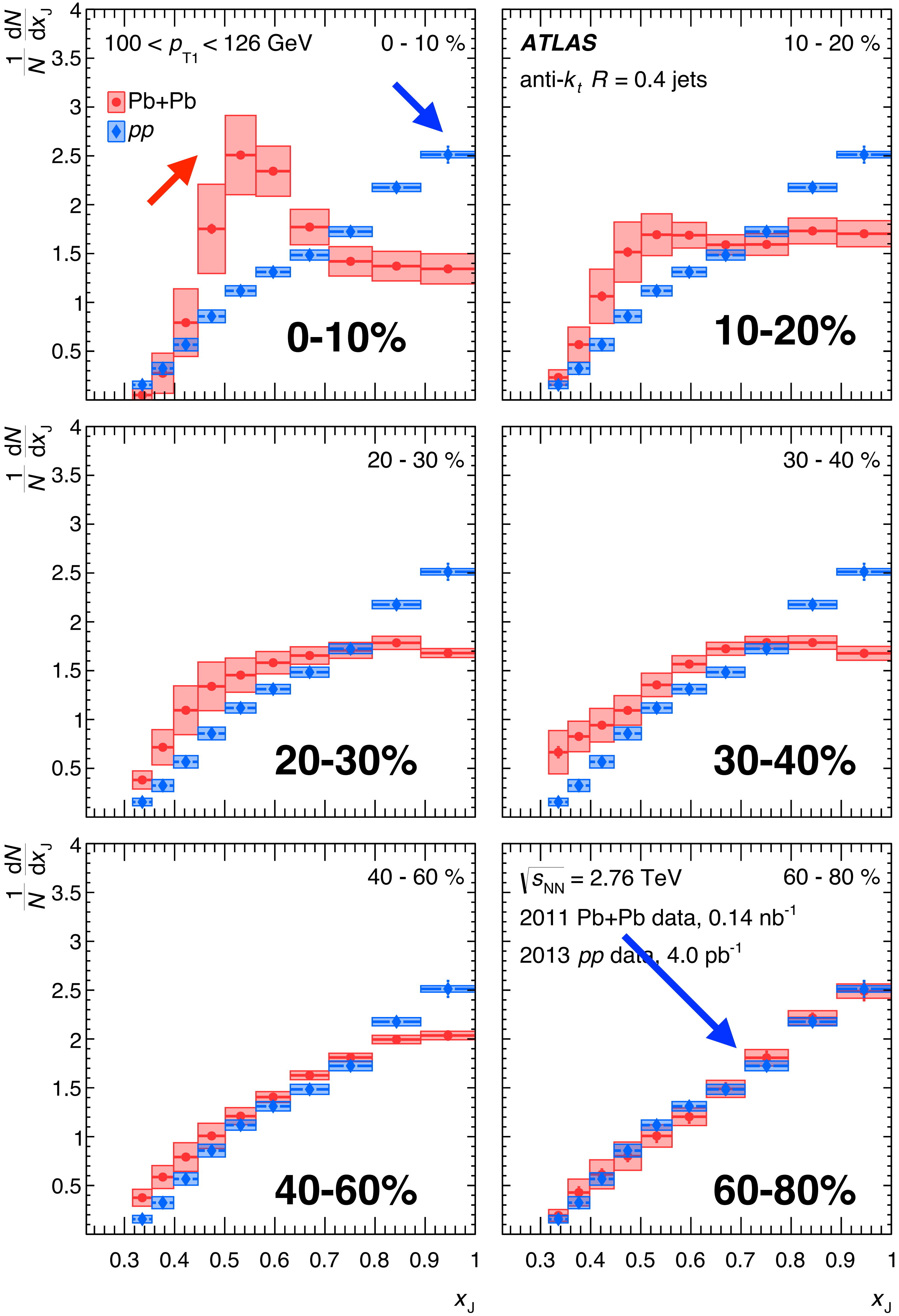
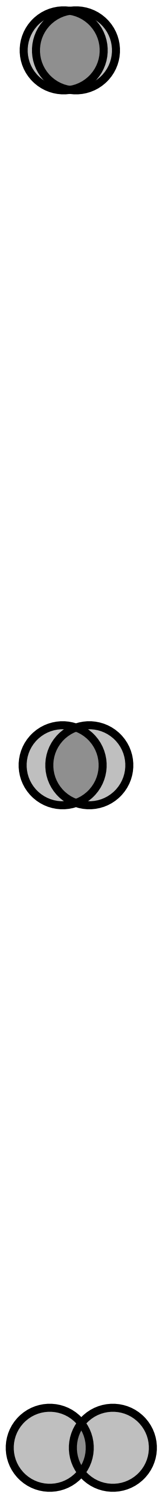
- Most probable configuration for *pp* collisions is $x_J \sim 1$
- For central Pb+Pb collisions it is $x_J \sim 0.5$
- As Pb+Pb becomes more peripheral the distribution is like *pp*
- Unfolded for detector effects





ATLAS-CONF-2016-110

$$x_{J\gamma} = \frac{p_{T,jet}}{p_{T,\gamma}}$$

γ-jet asymmetry

- **The photon is not expected to interact with the plasma so the energy loss of the recoiling jet can be probed**
- **Measured $x_{J\gamma}$ for $p_{T\gamma} > 60$ GeV, $p_{T,jet} > 30$ GeV, $\Delta\phi > 7\pi/8$**

ATLAS-CONF-2016-110

$$x_{J\gamma} = \frac{p_{\mathrm{T,jet}}}{p_{\mathrm{T},\gamma}}$$

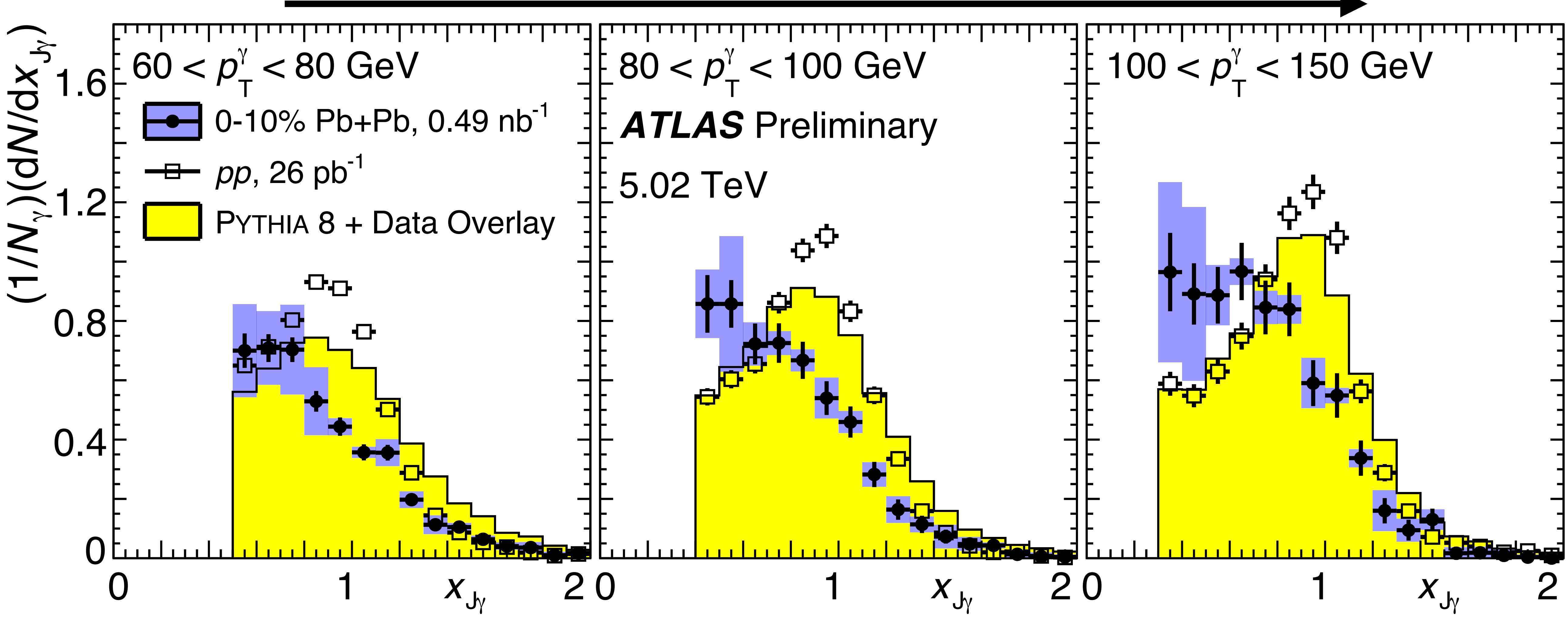
γ-jet asymmetry

0-10%

- **The photon is not expected to interact with the plasma so the energy loss of the recoiling jet can be probed**
- **Measured $x_{J\gamma}$ for $p_{T\gamma} > 60$ GeV, $p_{\mathrm{T,jet}} > 30$ GeV, $\Delta\phi > 7\pi/8$**

➡ **Pb+Pb has more asymmetric pairs than *pp* and MC**

increasing $p_{T\gamma}$



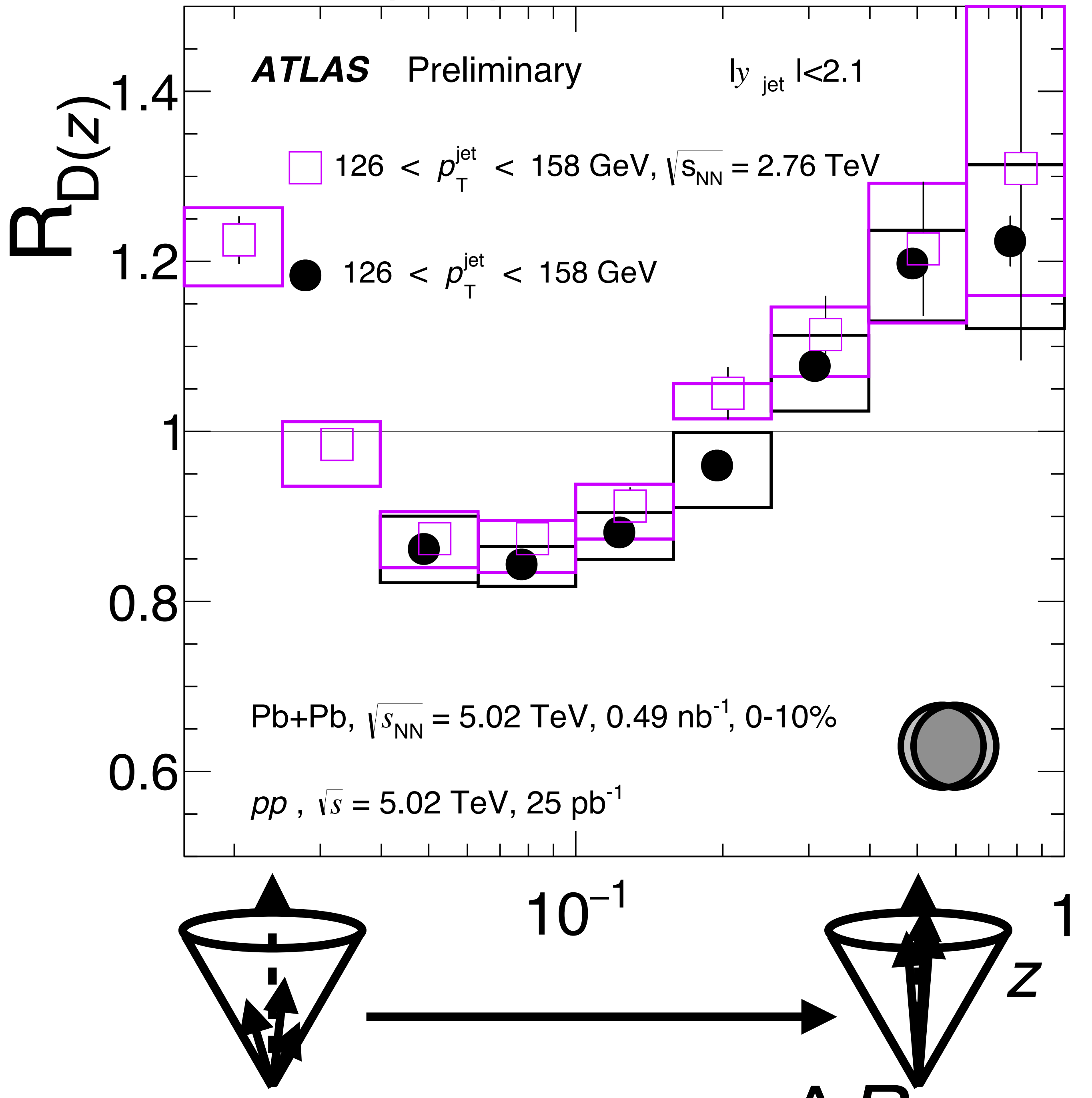
- **Corrected for background and JES but not unfolded.**

Internal structure: Pb+Pb

- **Ratio of fragmentation functions used to see modification of jet structure**

$$R_{D(z)} = \frac{D(z)_{\mathrm{PbPb}}}{D(z)_{\mathrm{pp}}}$$

EPJC 77 (2017) 379 **ATLAS-CONF-2017-005**



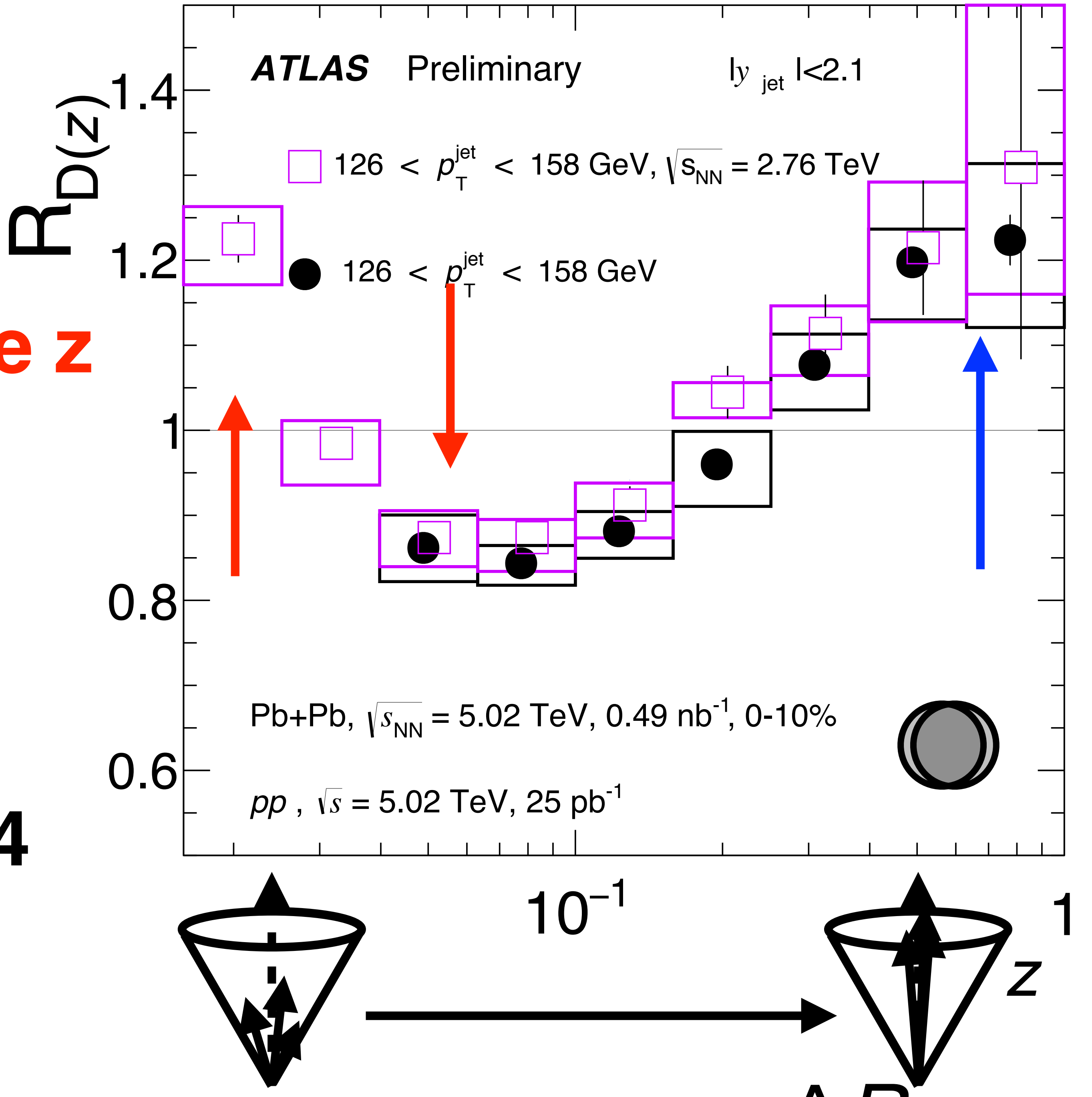
$$D(z) = \frac{1}{N_{\mathrm{jet}}} \frac{\mathrm{d}N_{ch}}{\mathrm{d}z} \qquad z = \frac{p_{\mathrm{T}} \cos \Delta R}{p_{\mathrm{T}}^{\mathrm{jet}}}$$

Internal structure: Pb+Pb

- Ratio of fragmentation functions used to see modification of jet structure

$$R_{\mathrm{D(z)}} = \frac{D(z)_{\mathrm{PbPb}}}{D(z)_{\mathrm{pp}}}$$

EPJC 77 (2017) 379   ATLAS-CONF-2017-005



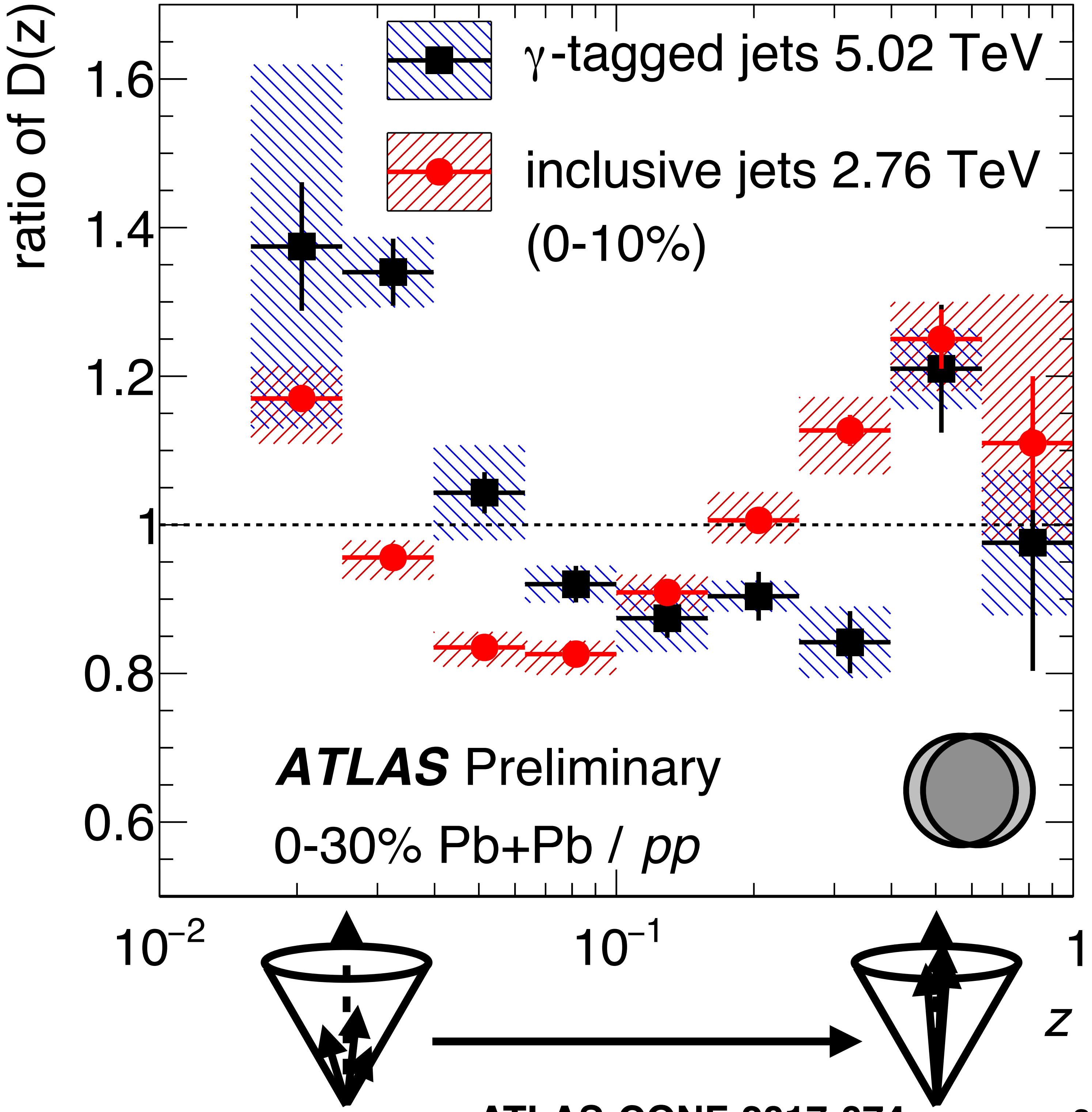
- Enhancement at low z and suppression at intermediate z
  - ➡ Energy is transferred to soft particles in and around the jet
  - ➡ Low z missing from 5.02 TeV because $p_{\mathrm{T}}^{\mathrm{trk}}$ cut at 4 GeV
- Enhancement at high z
  - ➡ More quark jets at high z

$$D(z) = \frac{1}{N_{\mathrm{jet}}}\frac{\mathrm{d}N_{ch}}{\mathrm{d}z}$$

$$z = \frac{p_{\mathrm{T}}\cos\Delta R}{p_{\mathrm{T}}^{\mathrm{jet}}}$$

Internal structure: γ-tagged

- **FF in γ-tagged jets compared to inclusive jets**



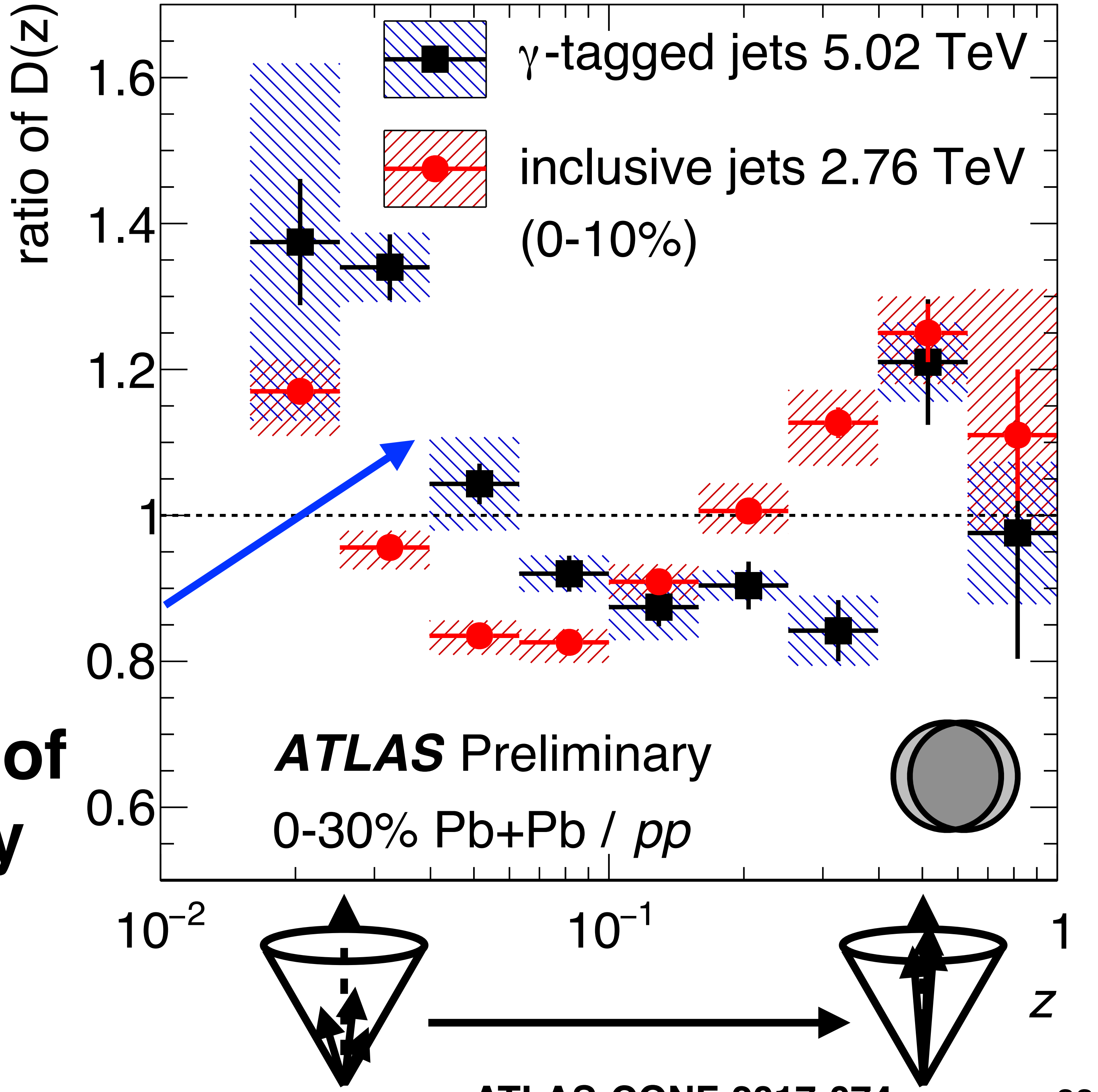
ATLAS-CONF-2017-074

Internal structure: γ-tagged

- **FF in γ-tagged jets compared to inclusive jets**

➡ **γ-tagged jets have stronger modification in central**

- **This could be do to the effect of different jet p_T selections?**
- **Preferential selection of jets losing less energy in the inclusive case?**



ATLAS-CONF-2017-074

Characterizing the QGP

- **Hard probes:**
  - ➡ Electro-weak bosons, heavy flavor, jets, hadrons, **quarkonia**

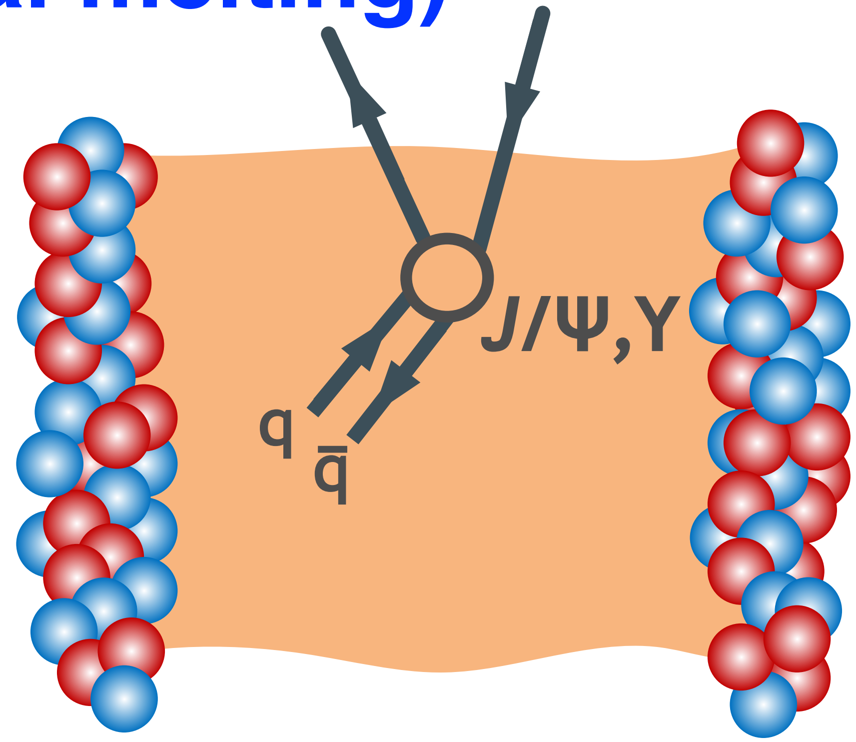
Information on the temperature of medium

Medium allows for color charge screening which results in a suppression in the production of the bound states

Suppression is stronger the more loosely bound the quarkonia state is (sequential melting)

- **Global properties:**
  - ➡ **correlations and fluctuations of soft particles**

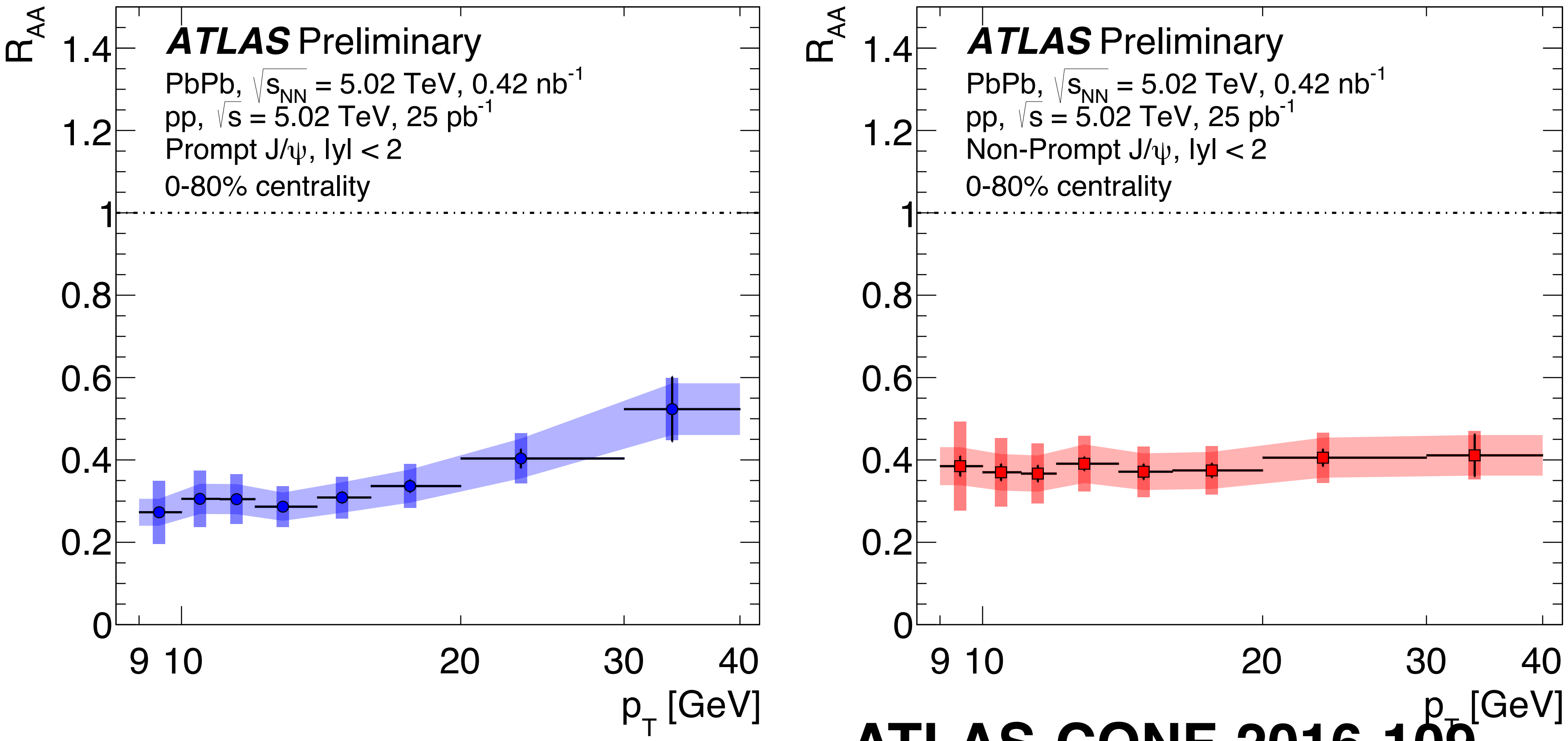
- ▸ ***Separate initial and final state by looking at p+Pb and pp collisions***



J/ψ and ψ(2s) production

- **Quarkonia in p+Pb and Pb+Pb compared to pp**

R_{AA} similar for prompt and non-prompt J/ψ

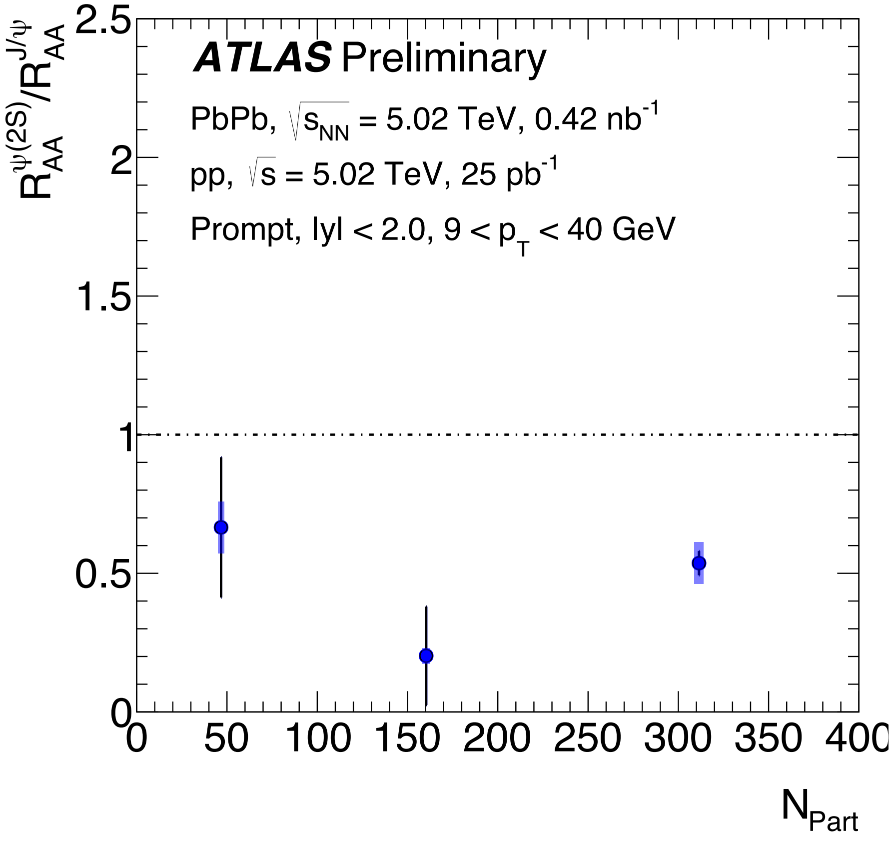


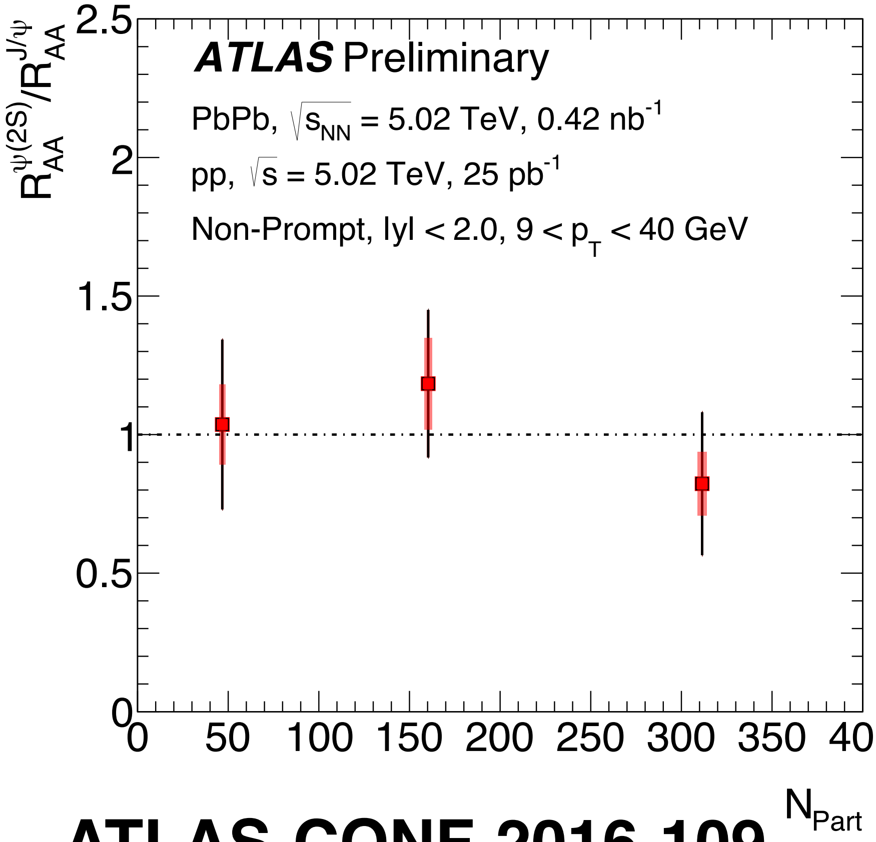
ATLAS-CONF-2016-109

J/ψ and ψ(2s) production

- **Quarkonia in p+Pb and Pb+Pb compared to pp**

Compare R_{AA} or R_{pPb} in ψ(2s) to J/ψ since sequential melting suggests that $R_{AA}(\psi(2s)) < R_{AA}(J/\psi)$





ATLAS-CONF-2016-109

- **Pb+Pb: ψ(2s) to J/ψ double ratio below unity for prompt and ~unity for non-prompt**

J/ψ and ψ(2s) production

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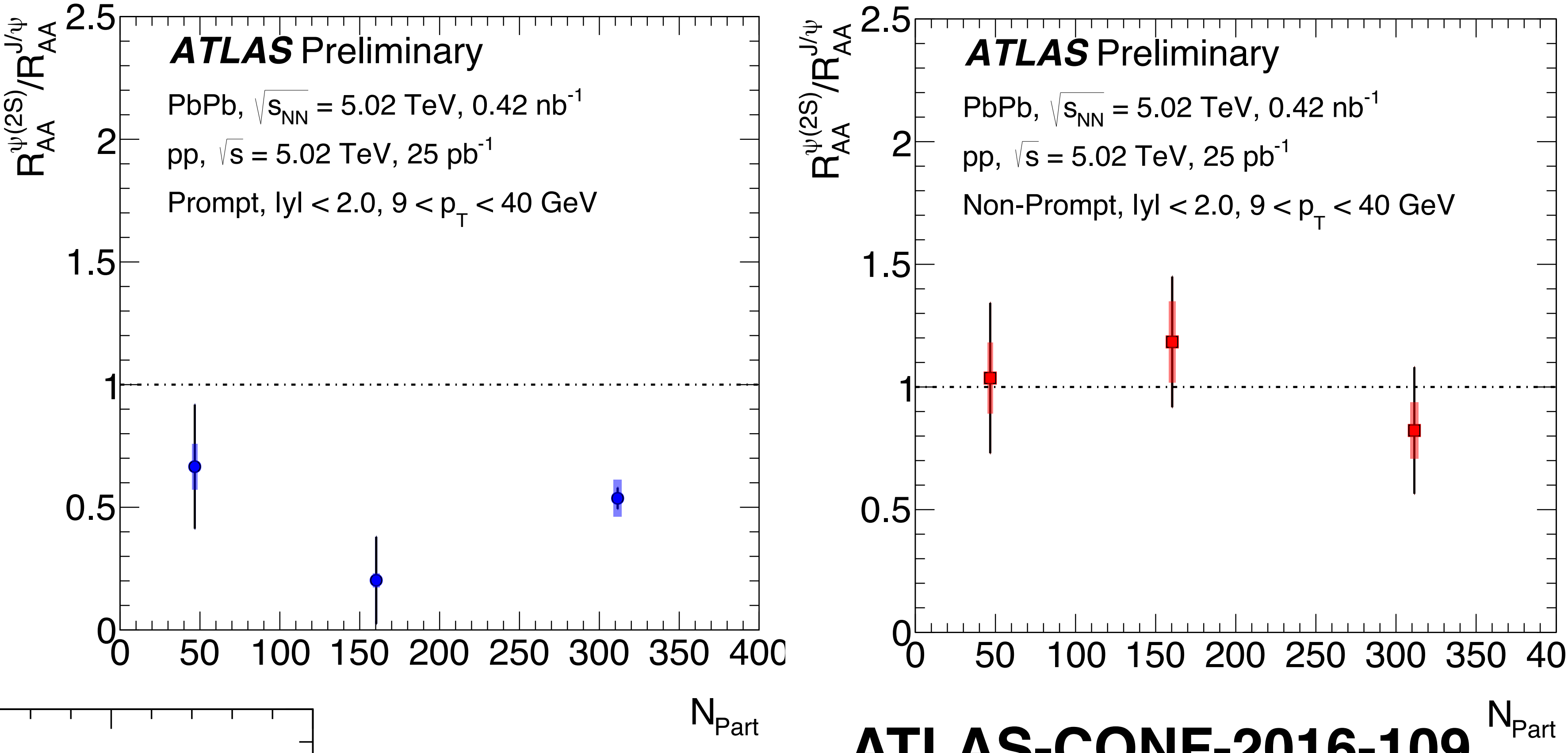
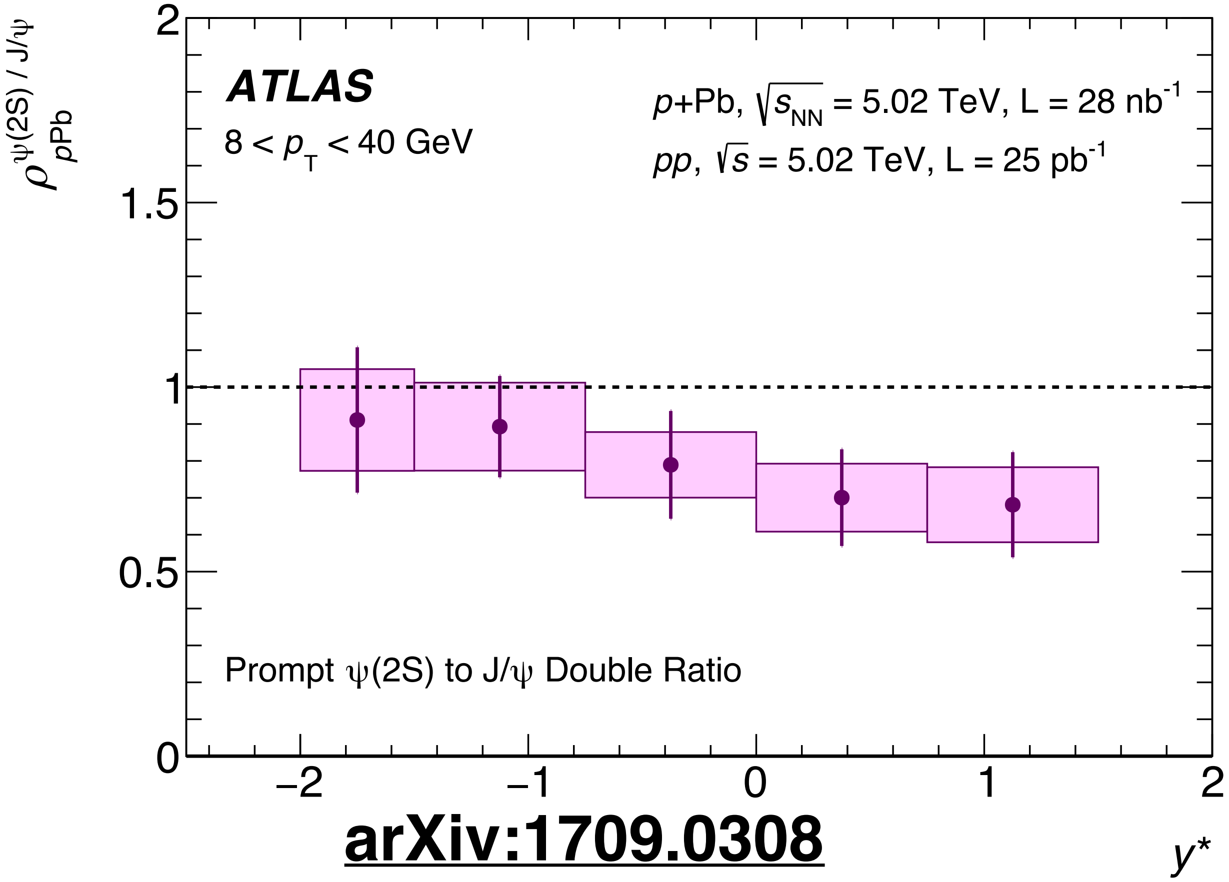
Compare R_{AA} or R_{pPb} in ψ(2s) to J/ψ since sequential melting suggests that $R_{AA}(\psi(2s)) < R_{AA}(J/\psi)$



<u>ATLAS-CONF-2016-109</u>



<u>arXiv:1709.0308</u>

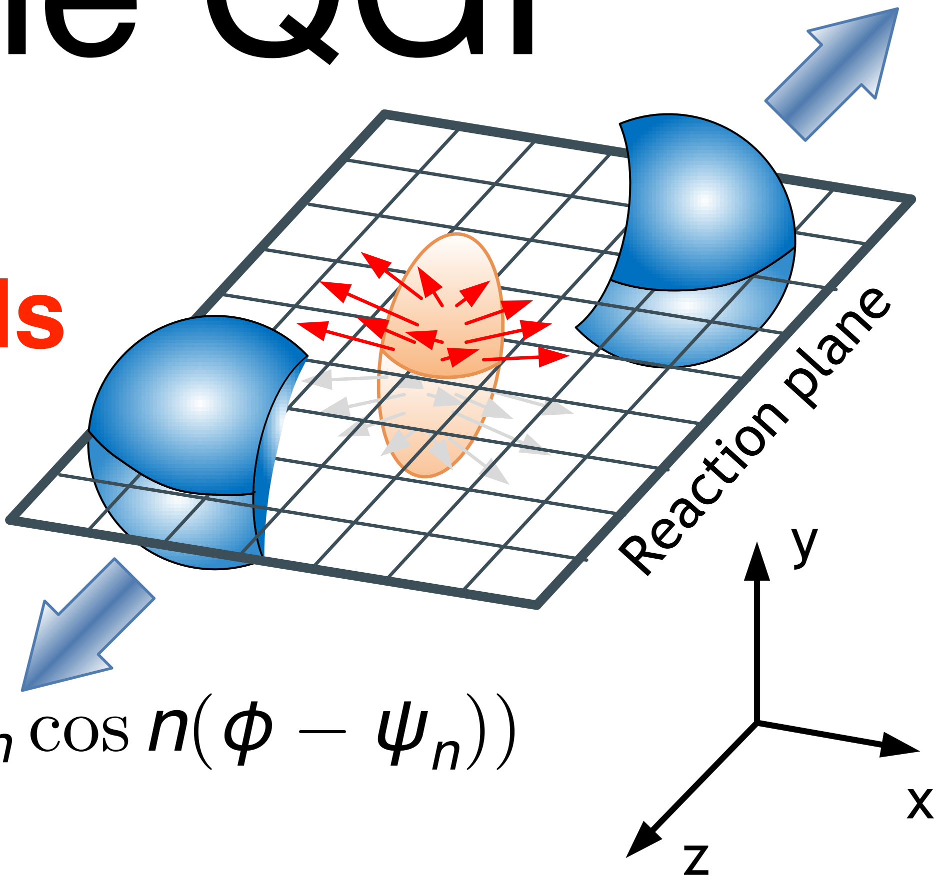
- **Pb+Pb: ψ(2s) to J/ψ double ratio below unity for prompt and ~unity for non-prompt**
- **p+Pb: ψ(2s) to J/ψ double ratio decreases with rapidity**

Characterizing the QGP

- Hard probes:
  - ➡ Electro-weak bosons, heavy flavor, jets, hadrons, quarkonia

Initial spatial anisotropy leads to flow in the final state

$$\frac{dN}{d\phi} = N_0(1 + 2\sum_{i=1} v_n \cos n(\phi - \psi_n))$$



- **Global properties:**
  - ➡ **correlations and fluctuations of soft particles**

▸ ***Separate initial and final state by looking at p+Pb and pp collisions***

Characterizing the QGP

- Hard probes:
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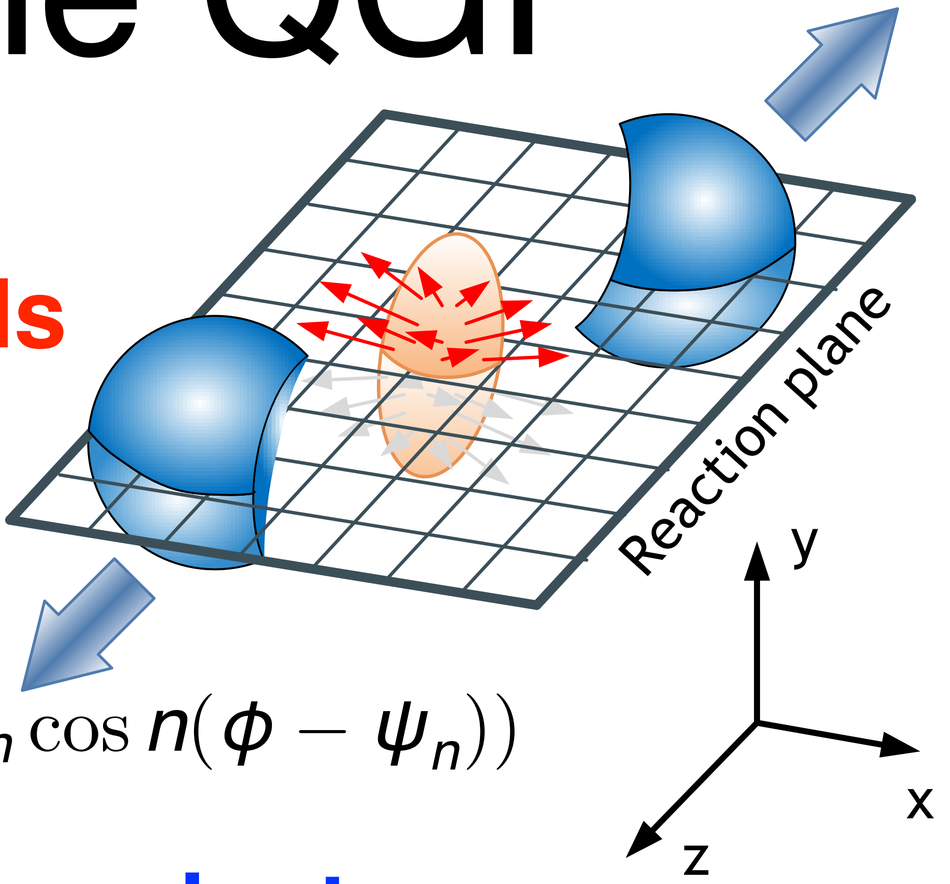


$$\frac{dN}{d\phi} = N_0(1 + 2\sum_{i=1} v_n \cos n(\phi - \psi_n))$$

- **Global properties:**
  - ➡ correlations and fluctuations of soft particles

Multi-particle cumulants measure correlations between large number of particles and are used to suppress non-flow contributions

- ▸ *Separate initial and final state by looking at p+Pb and pp collisions*

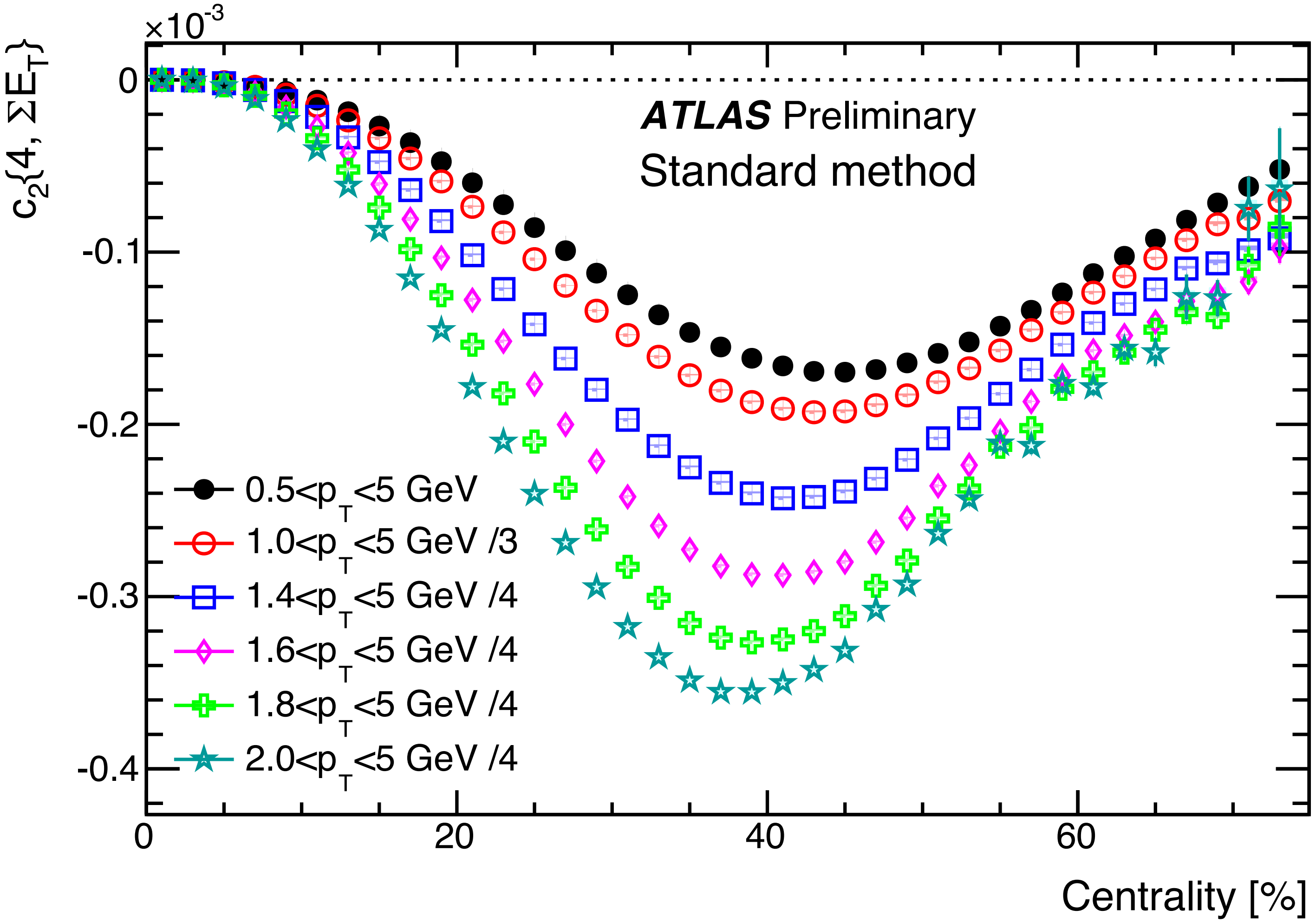
$$c_n\{4\} \equiv \langle\langle 4\rangle\rangle - 2\langle\langle 2\rangle\rangle^2$$

$$v_n\{4\} \equiv \sqrt{-c_n\{4\}}$$

Multi-particle cumulants

Multi-particle cumulants measured in 5.02 TeV Pb+Pb

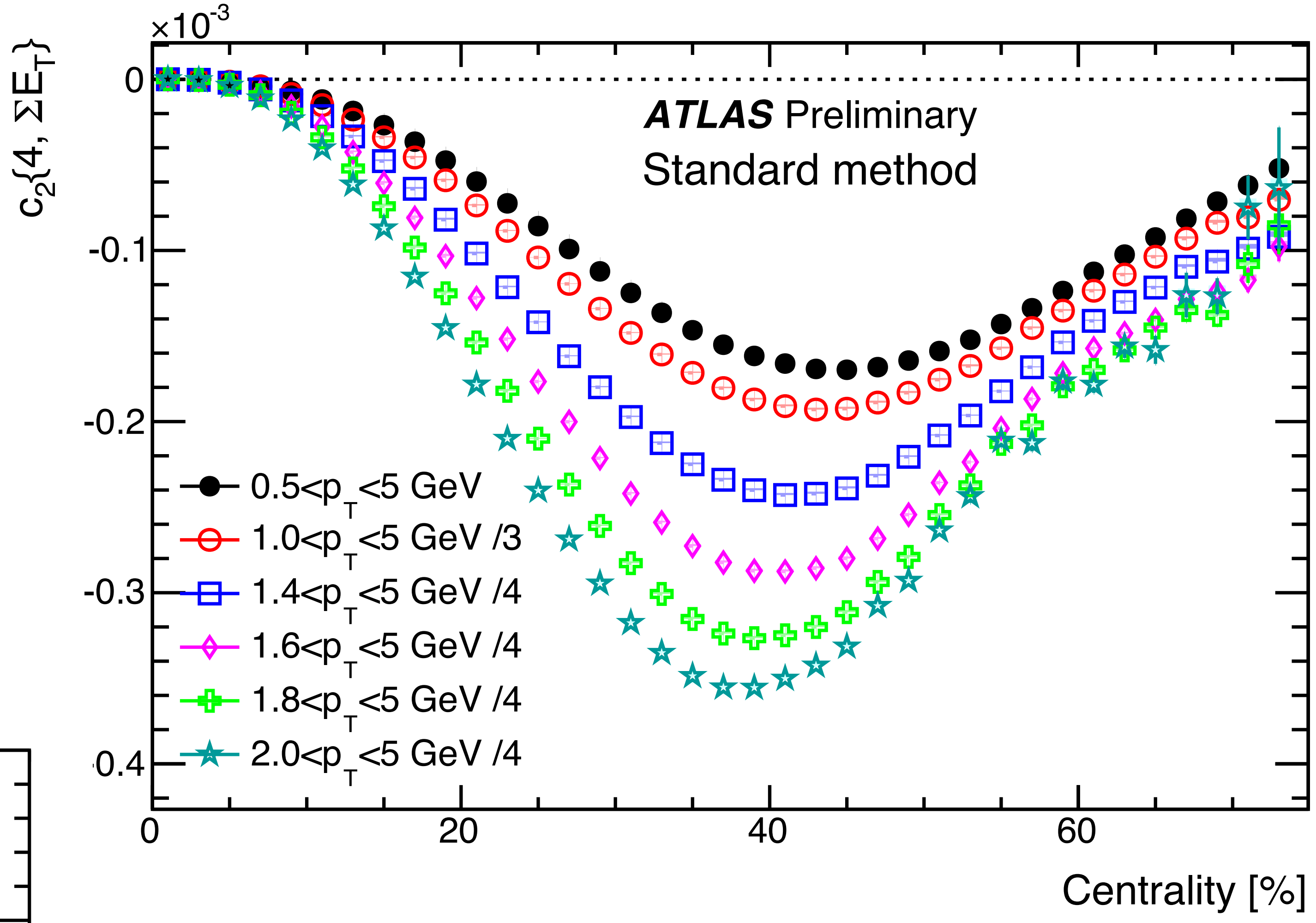
Measuring $c_n\{4\}$ gives insight into the nature of flow fluctuations



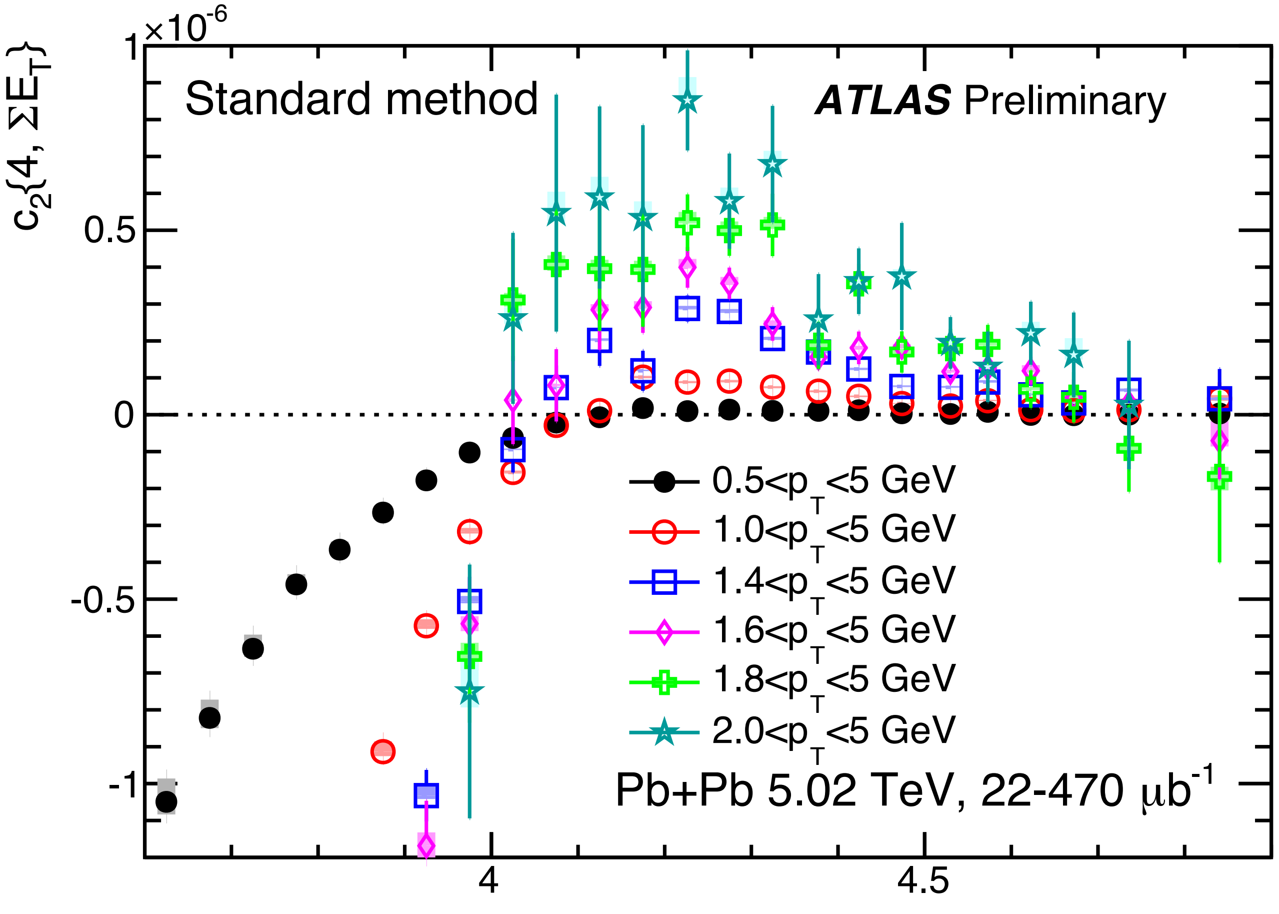
ATLAS-CONF-2017-066

Multi-particle cumulants

Multi-particle cumulants measured in 5.02 TeV Pb+Pb



Measuring $c_n\{4\}$ gives insight into the nature of flow fluctuations



$c_2\{4\} > 0$ in ultra central

strong indication of non-gaussian flow fluctuations?

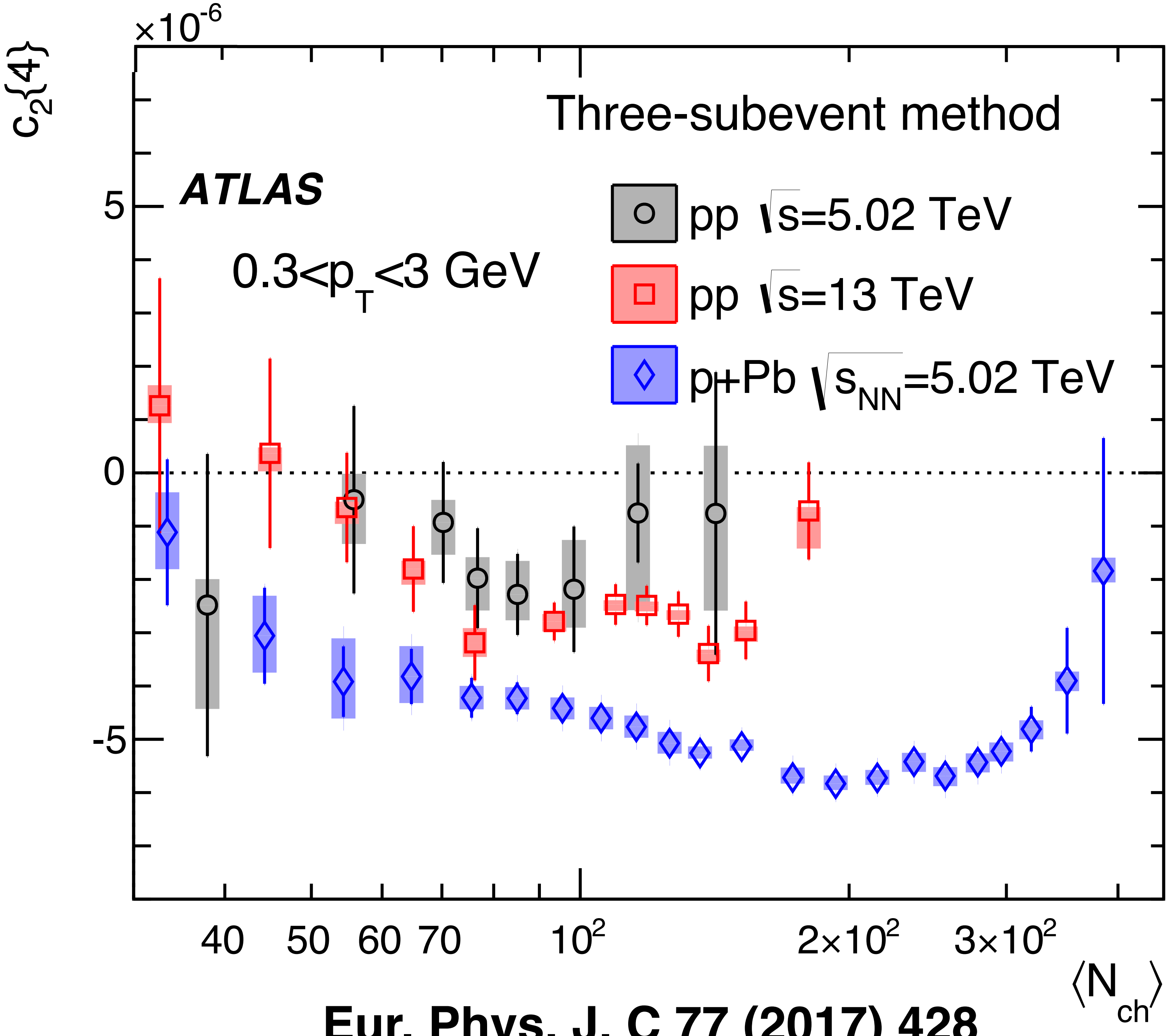
ATLAS-CONF-2017-066

Multi-particle cumulants

- **Sub-event method suppresses non-flow by using particles from different sub-events separated in η**

- **Negative $c_2\{4\}$ in pp and p+Pb is direct evidence of collective flow**

- **$c_2\{4\}$ in *pp* nearly independent of N_{ch}**



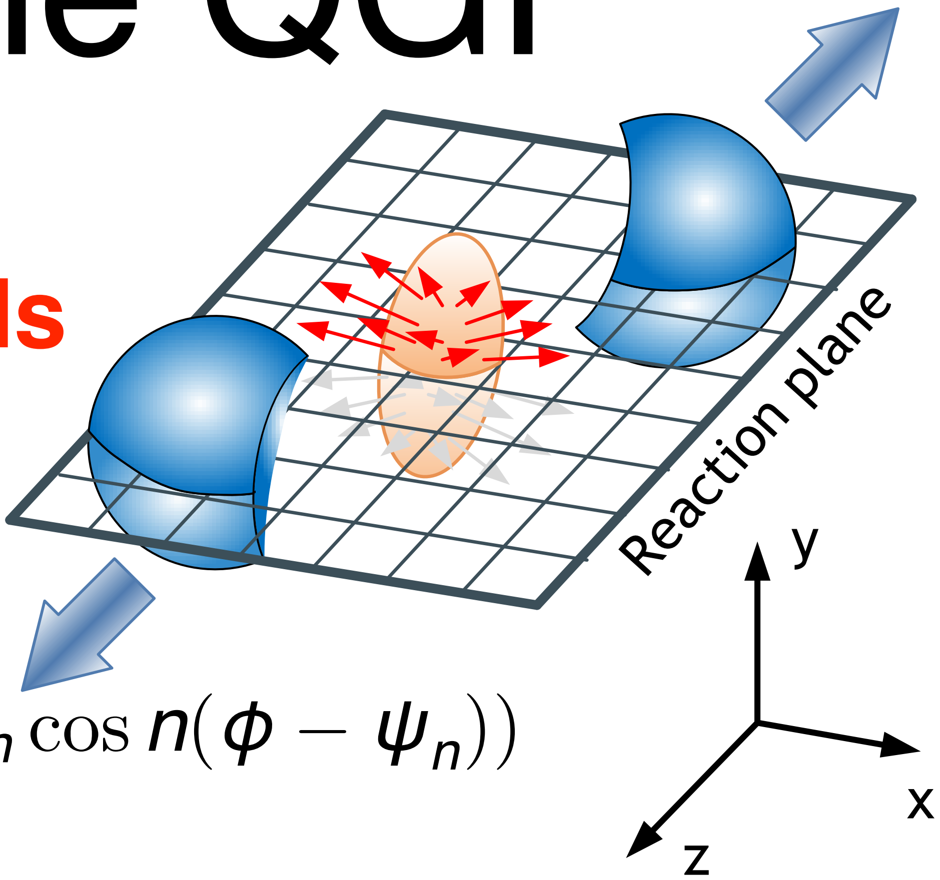
Eur. Phys. J. C 77 (2017) 428

arXiv:1708.03559

Characterizing the QGP

- Hard probes:
  - ➡ Electro-weak bosons, heavy flavor, jets, hadrons, quarkonia

Initial spatial anisotropy leads to flow in the final state



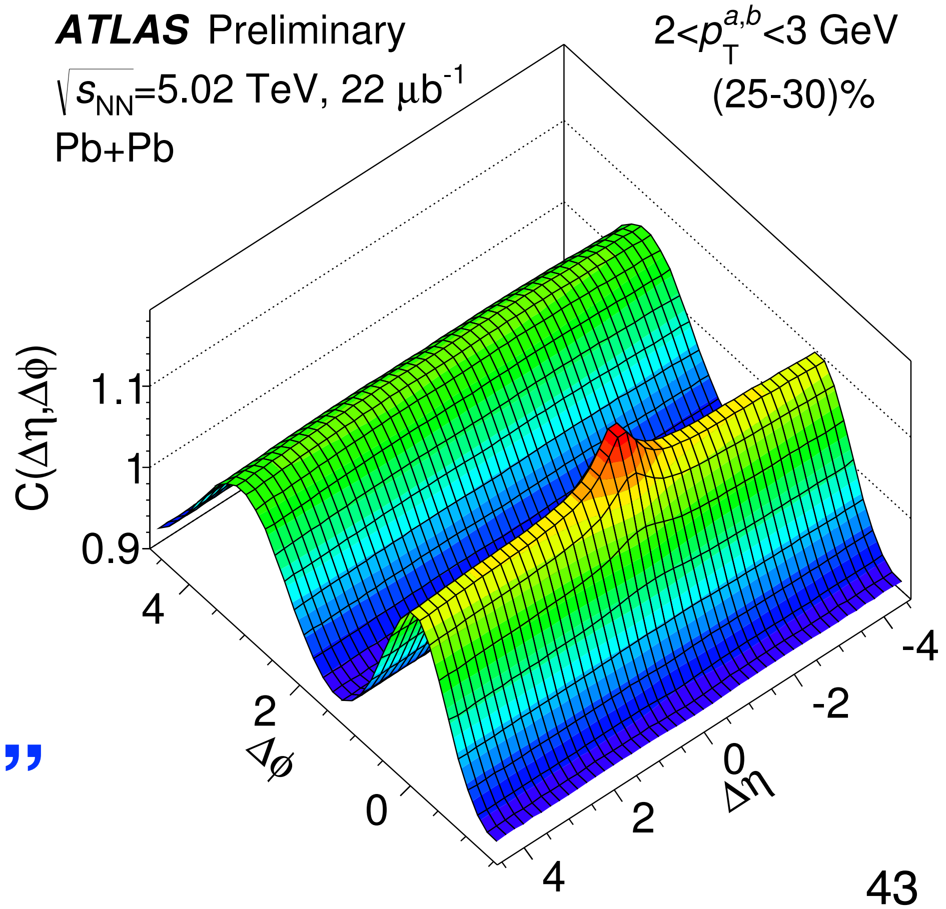
$$\frac{dN}{d\phi} = N_0(1 + 2\sum_{i=1} v_n \cos n(\phi - \psi_n))$$

- **Global properties:**
  - ➡ **correlations and fluctuations of soft particles**

Collective behavior through 2P correlations in Δη-ΔΦ

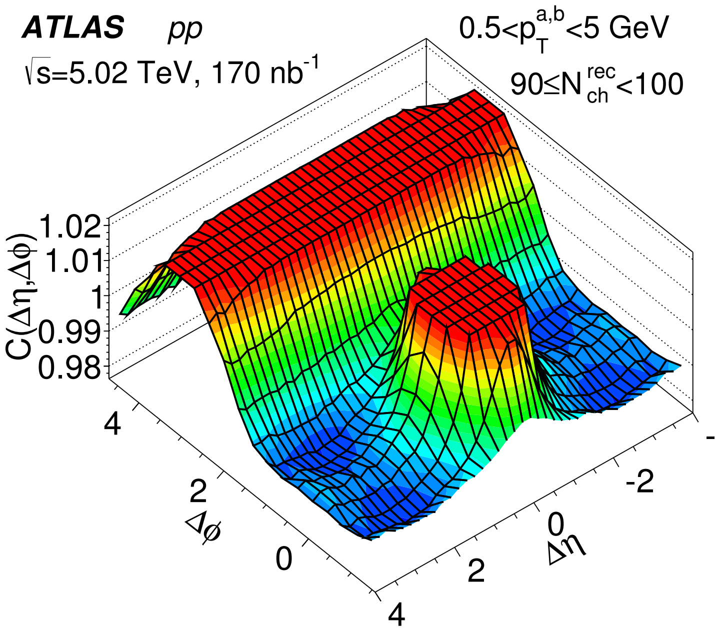
- ▸ *Separate initial and final state by looking at p+Pb and pp collisions*

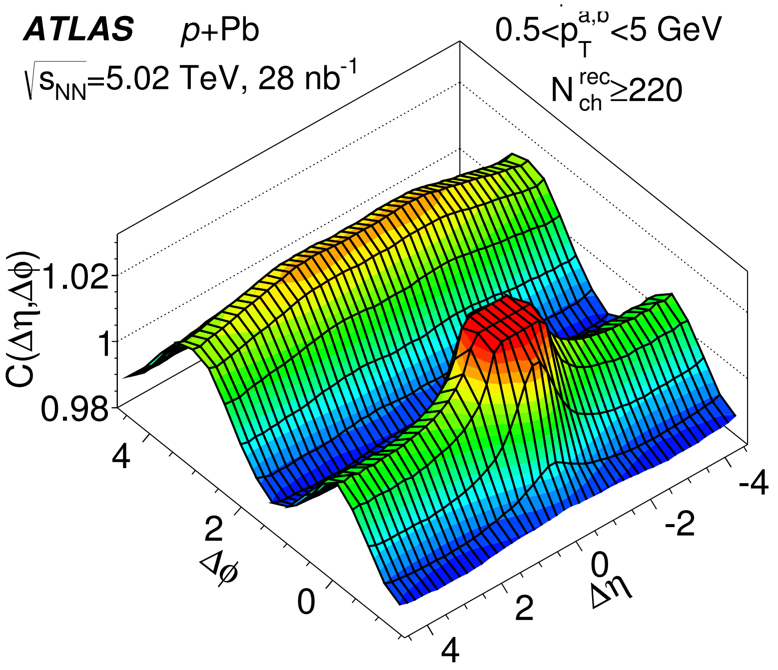
“ridge”



Collectivity in small systems

- **Collectivity seen in small systems in both p+Pb and pp**

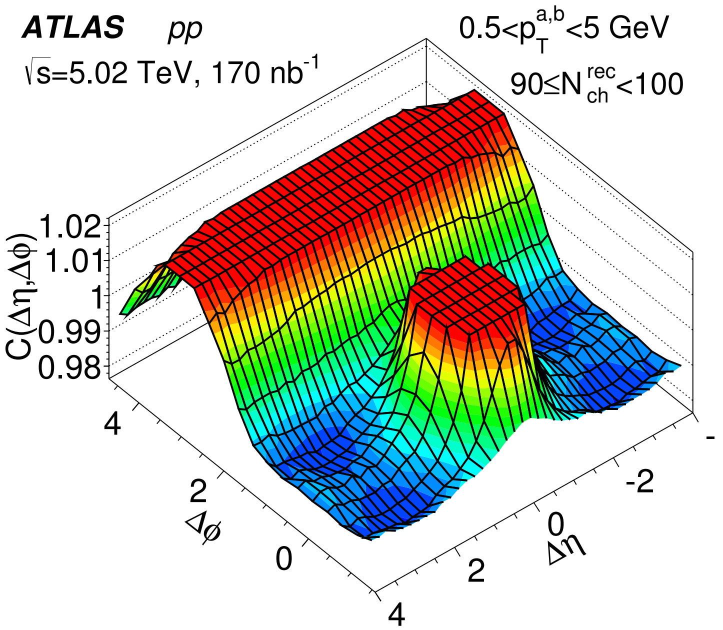


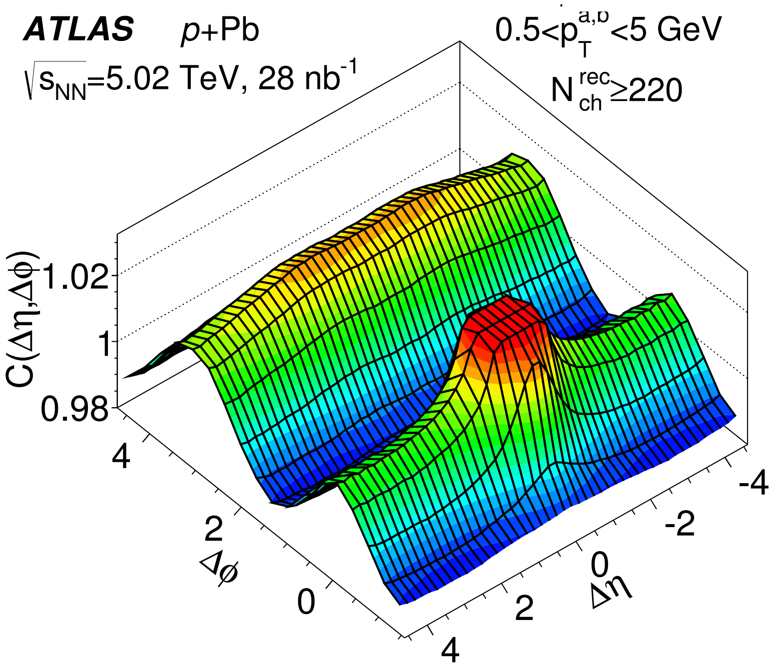


arXiv:1609.06213

Collectivity in small systems

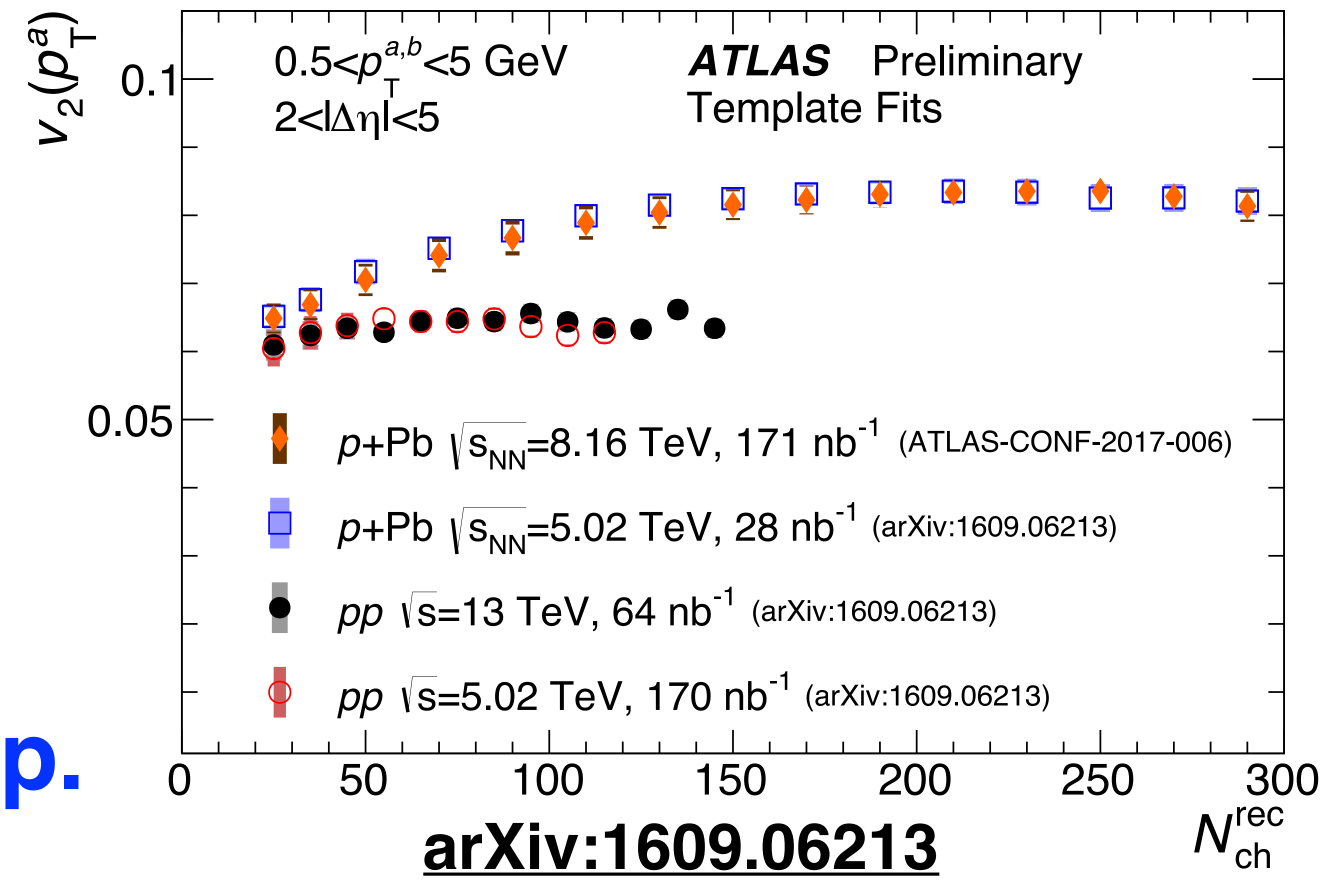
- **Collectivity seen in small systems in both p+Pb and pp**





v_2 flat with N_{ch} in *pp*

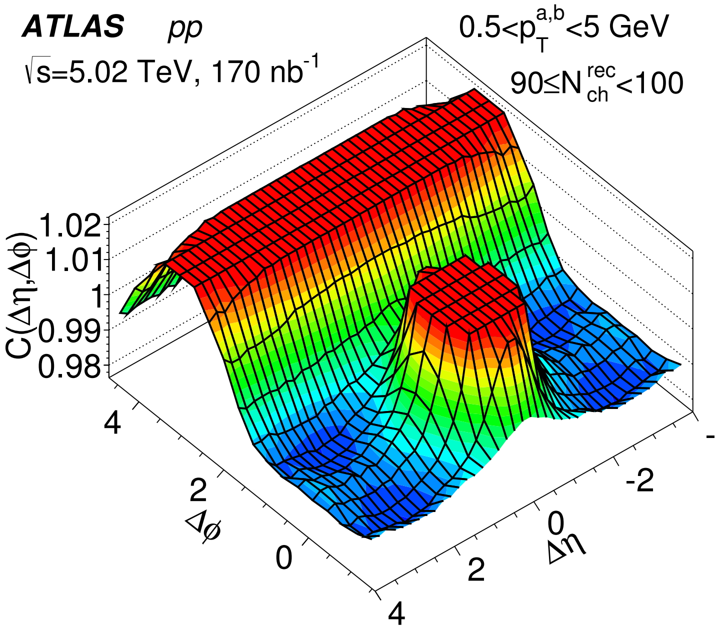
no $\sqrt{s_{NN}}$ dep. but a coll. system dependence is seen

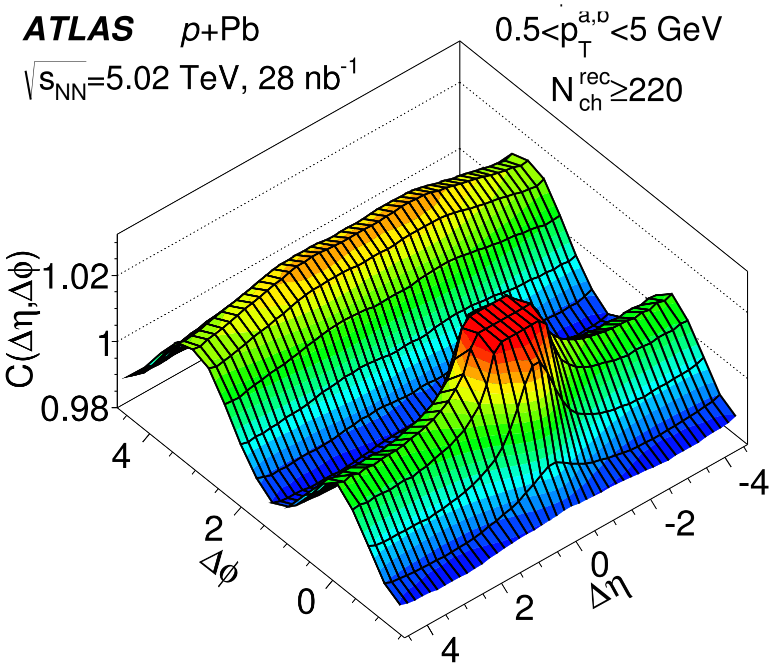


arXiv:1609.06213

Collectivity in small systems

- **Collectivity seen in small systems in both p+Pb and Pb+Pb**

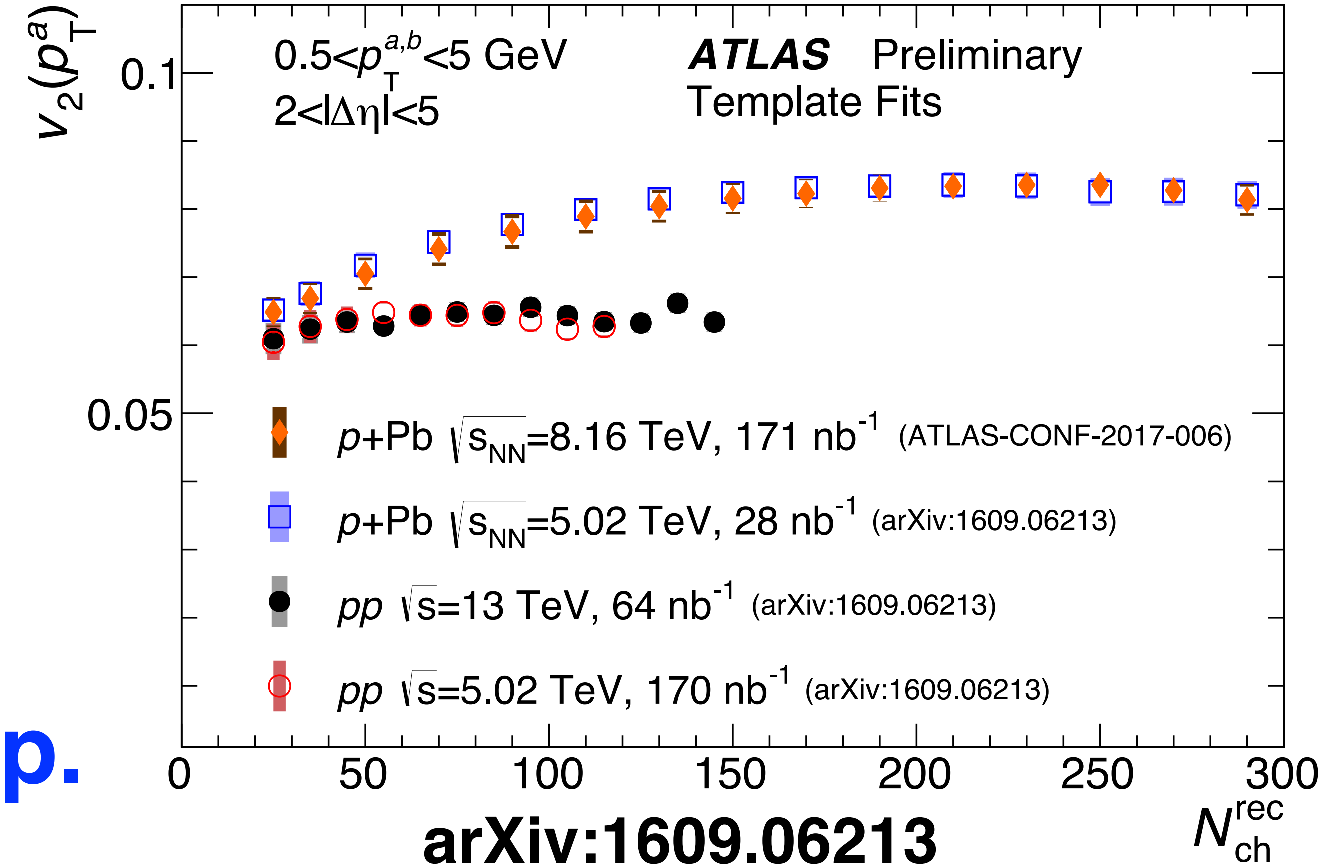




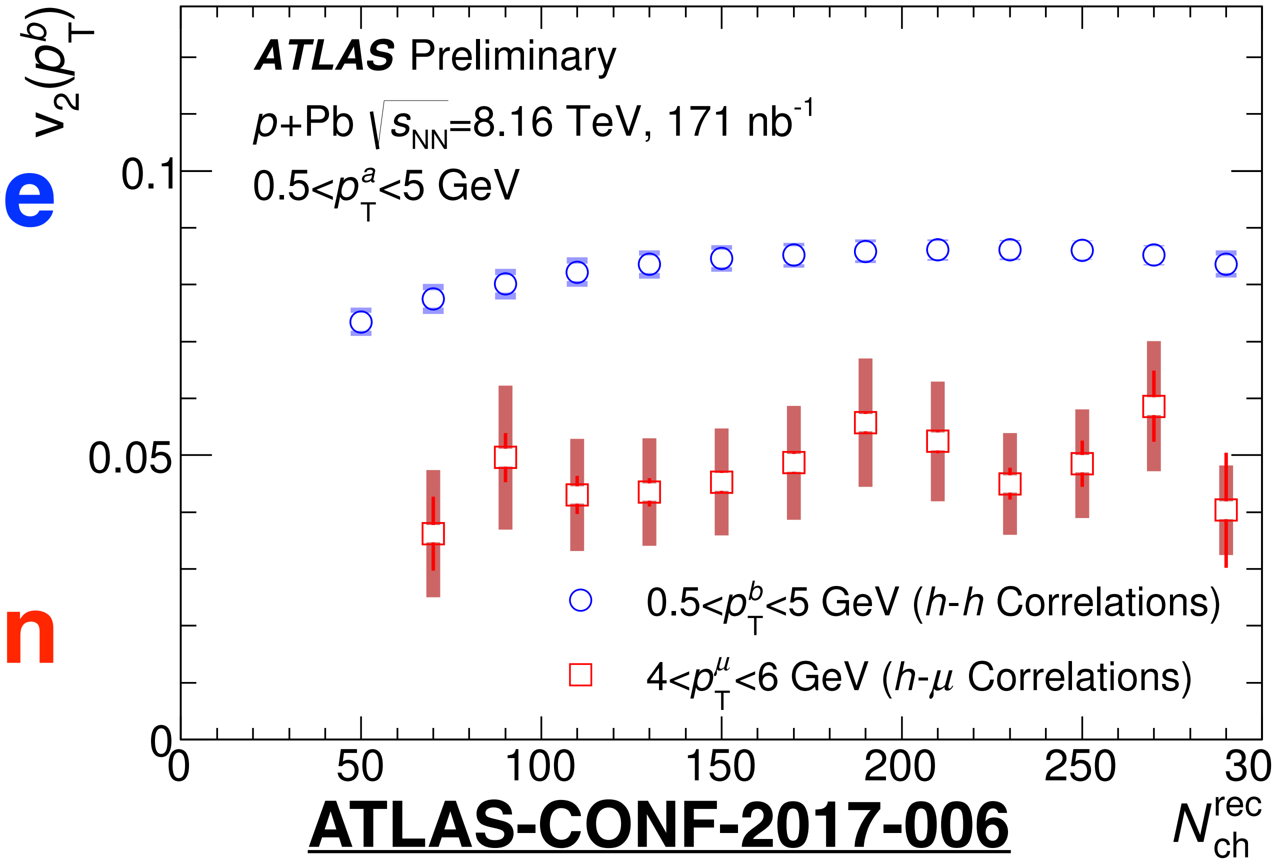
v_2 flat with N_{ch} in *pp*

no $\sqrt{s_{NN}}$ dep. but a coll. system dependence is seen

muon v_2 is smaller than hadron v_2



arXiv:1609.06213



ATLAS-CONF-2017-006

Ultra-peripheral collisions

➡ **photo-nuclear dijets, light-by-light scattering**

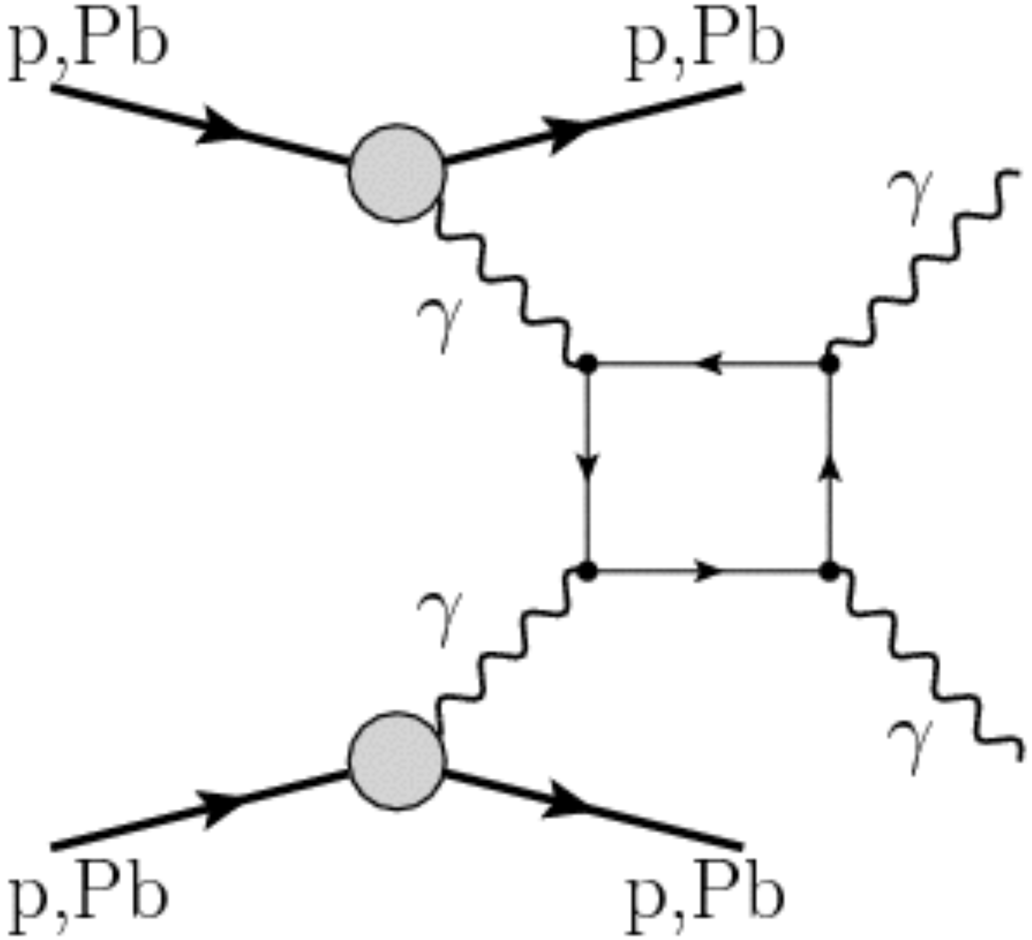
Heavy ions are an intense source of photons in ultra-peripheral collisions

Ultra-peripheral collisions

➡ photo-nuclear dijets, **light-by-light scattering**

Heavy ions are an intense source of photons in ultra-peripheral collisions

Investigate elastic scattering of two photons

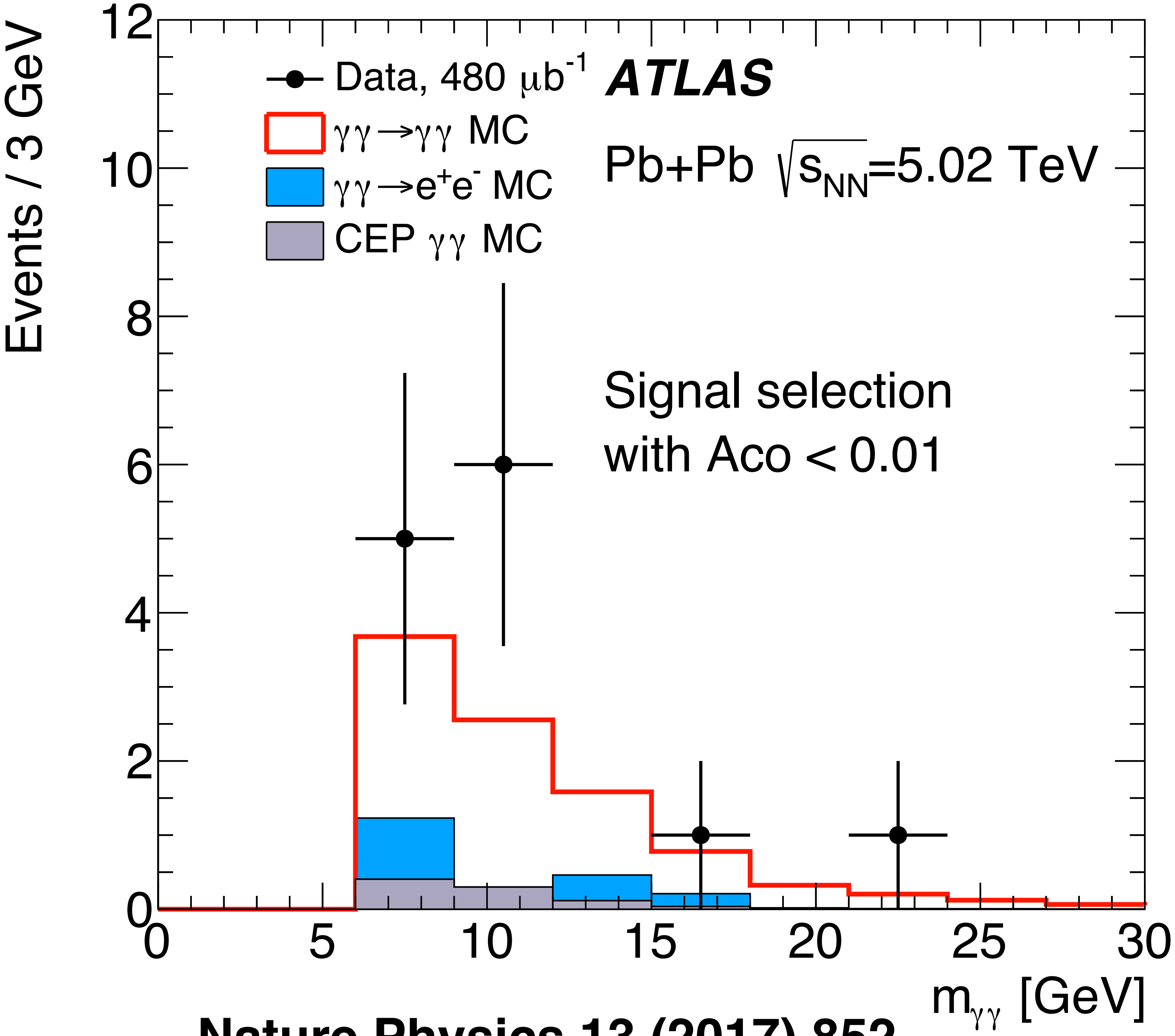


Light-by-light scattering

- **Use Pb+Pb UPC events at 5.02 TeV to be the first direct measurement of elastic scattering of two photons**

- **Excess in data consistent with light-by light scattering**

- **Measured cross section of 70 +/- 20 (stat) +/- 17 (syst) nb agrees with predictions**



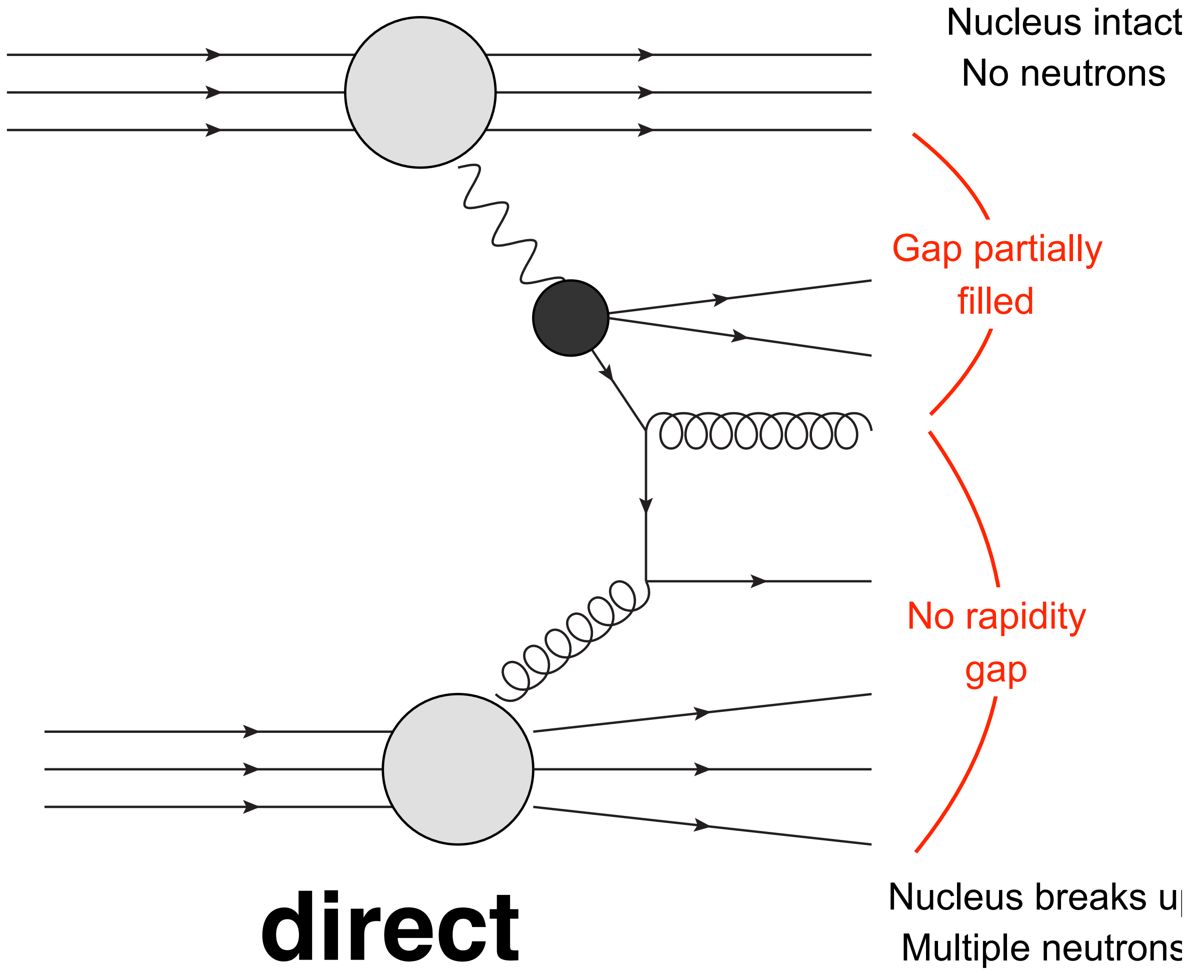
Nature Physics 13 (2017) 852

Ultra-peripheral collisions

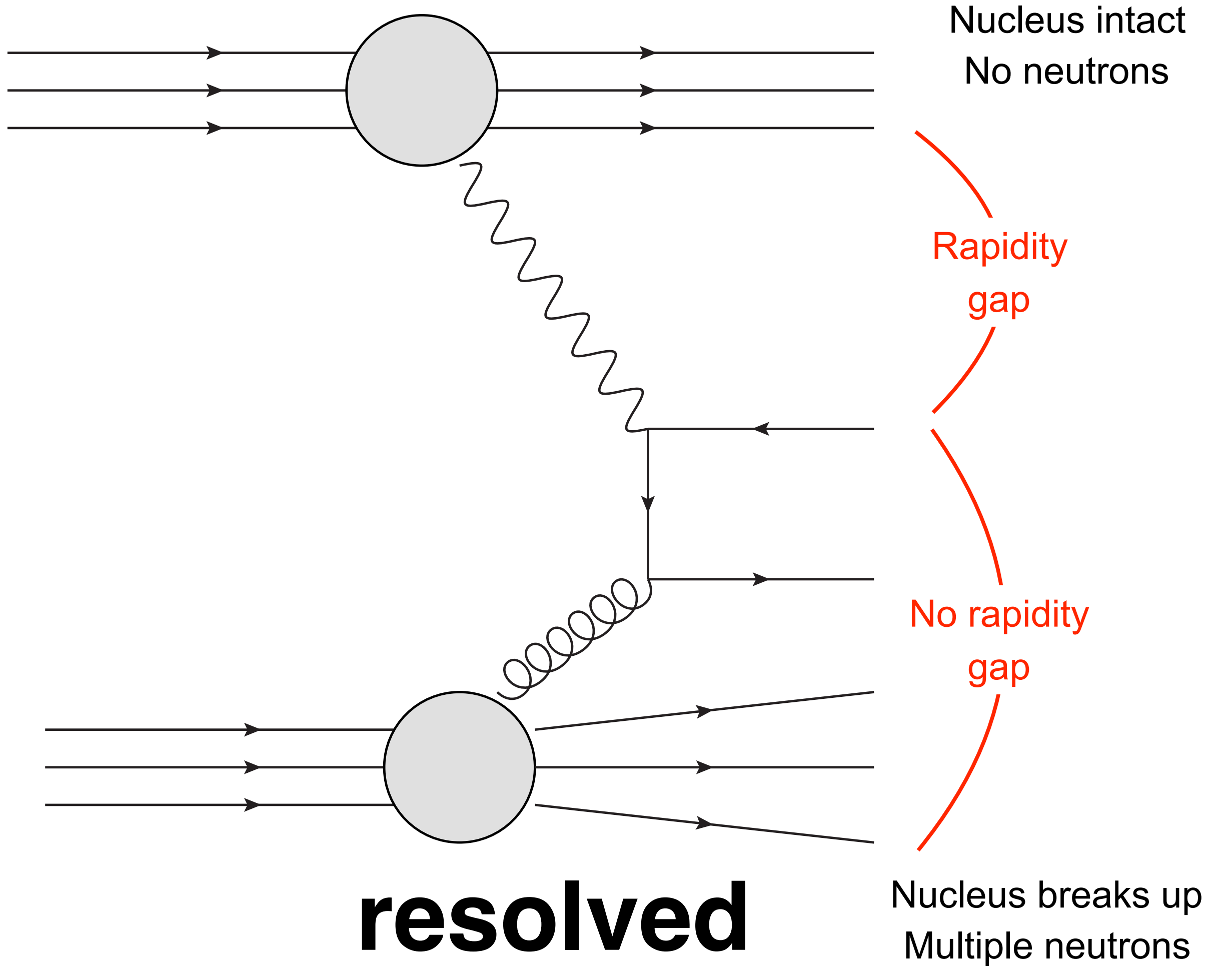
➡ **photo-nuclear dijets,** light-by-light scattering

Heavy ions are an intense source of photons in ultra-peripheral collisions

Study nPDFs with photo-nuclear dijets



direct



resolved

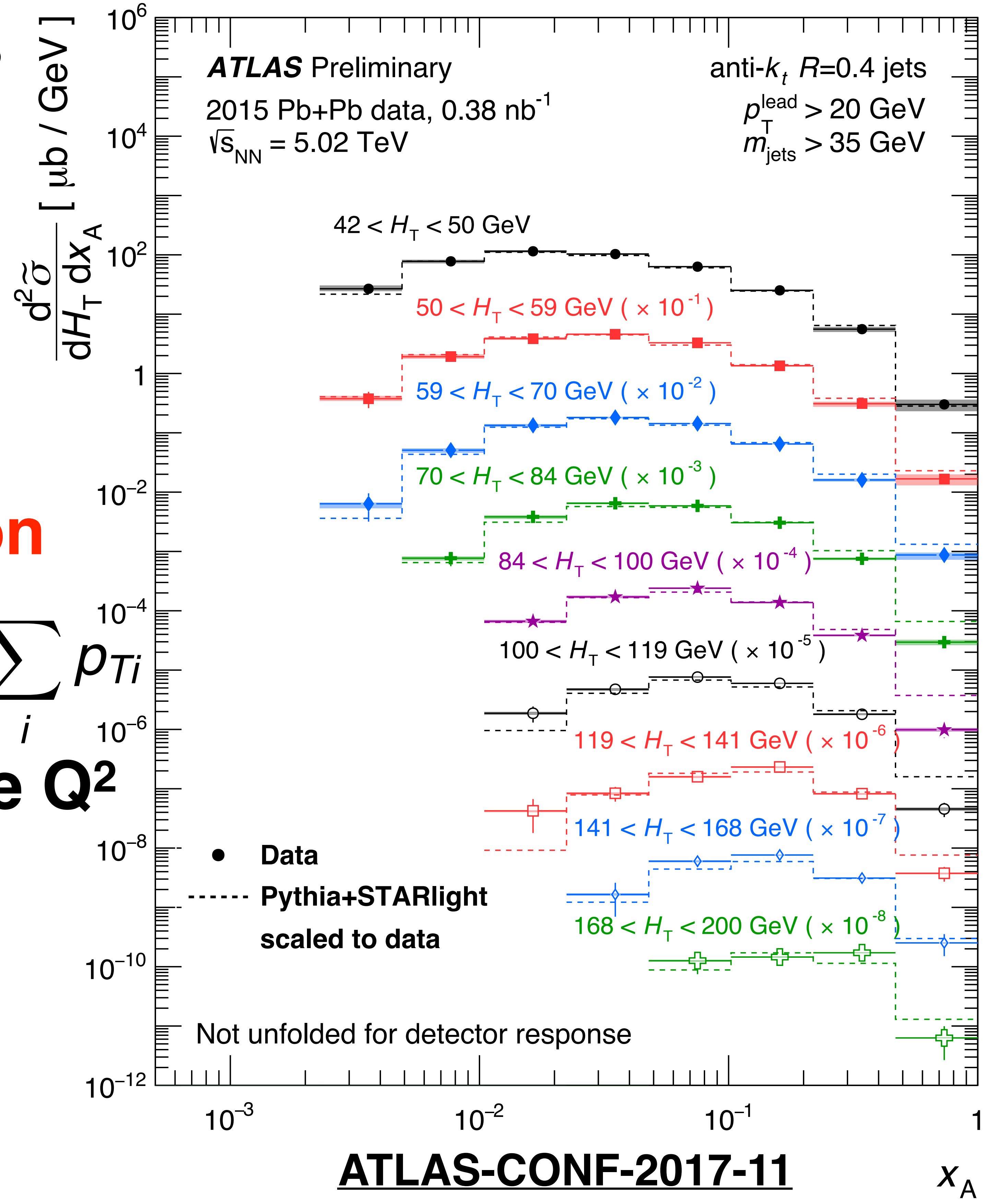
Photo-nuclear dijets

- **Use Pb+Pb UPC events at 5.02 TeV with no neutrons on one side and > 0 on the other side ("Xn0n")**
- **Measure the double differential cross section**

bjorken x in Pb: $x_A = \frac{m_{jets}}{\sqrt{s}} e^{-y_{jets}}$ $H_T = \sum_i p_{Ti}$

E_γ/E_{beam} $z_A = \frac{m_{jets}}{\sqrt{s}} e^{+y_{jets}}$ **like Q^2**

- **Data is compared with Pythia+STARLIGHT model over a large kinematic range**



ATLAS-CONF-2017-11

Conclusion

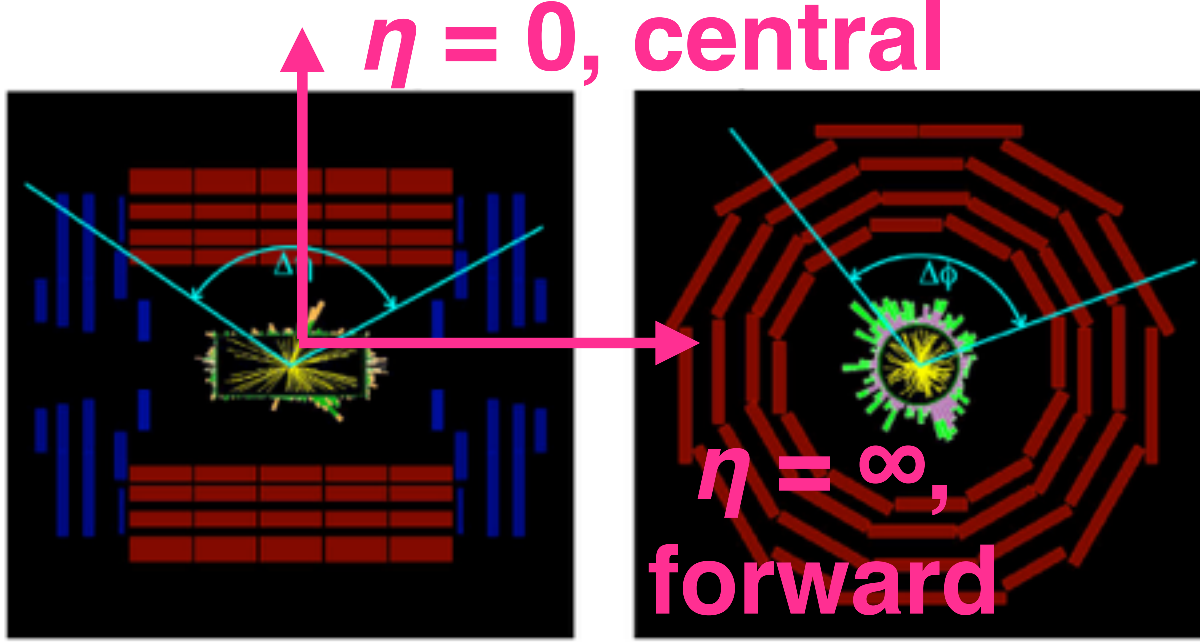
- **Wide variety of new results from ATLAS with new datasets at 5.02 and 8.16 TeV**
  - ➡ **Precision results on jet quenching see suppression up to a TeV, dijet and γ+jet asymmetry, and modification of jet structure in jet and γ+jet systems**
  - ➡ **EW boson measurements indicate an understanding of the geometry**
  - ➡ **Quarkonia exhibits evidence of sequential melting in Pb+Pb**
  - ➡ **Collectivity seen in small systems?**
  - ➡ **UPC events allow for direct photon and photo-nuclear production measurements**

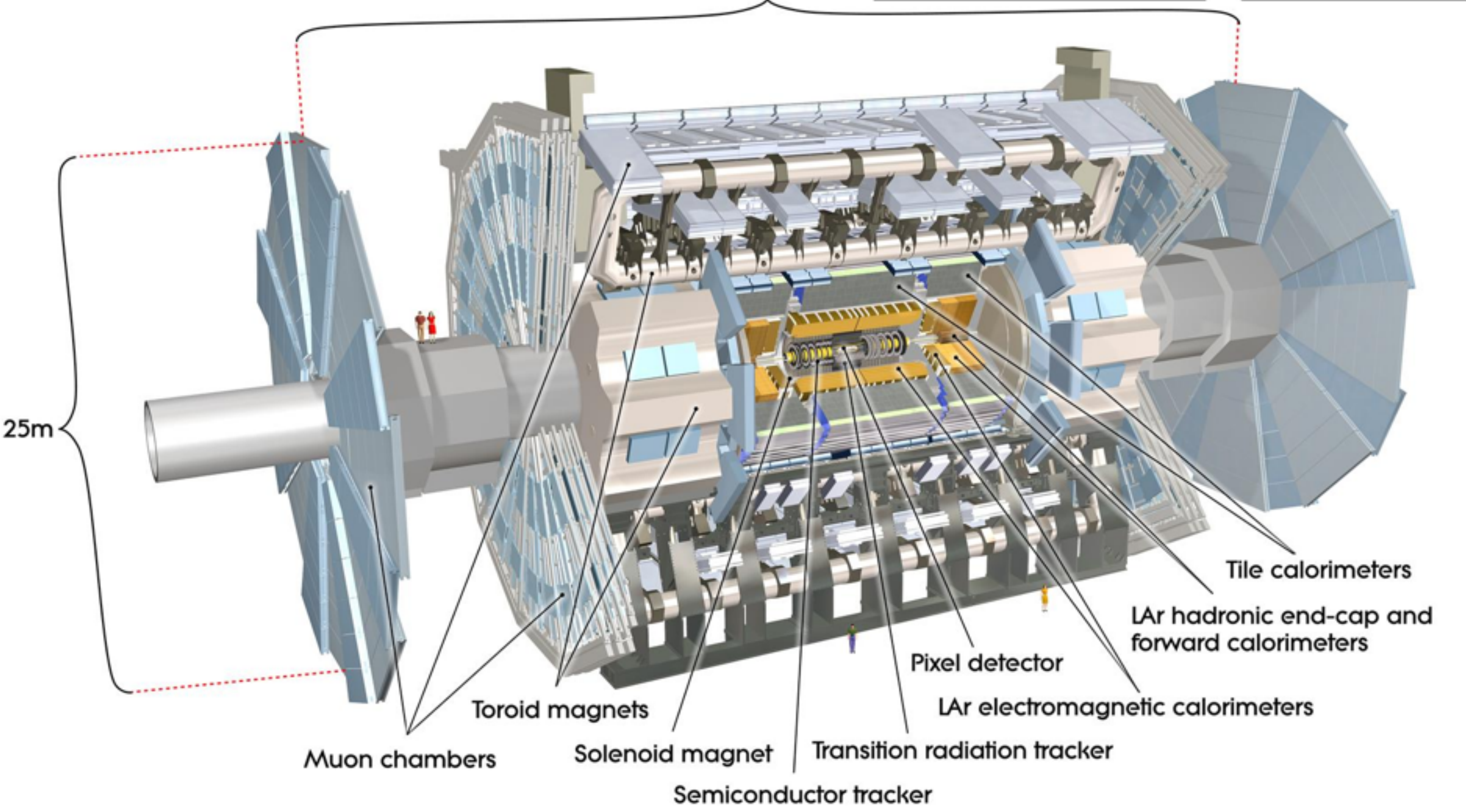
► **Looking forward to more Pb+Pb collisions at 5.02 TeV in 2018!**

Thank you!

Back-up

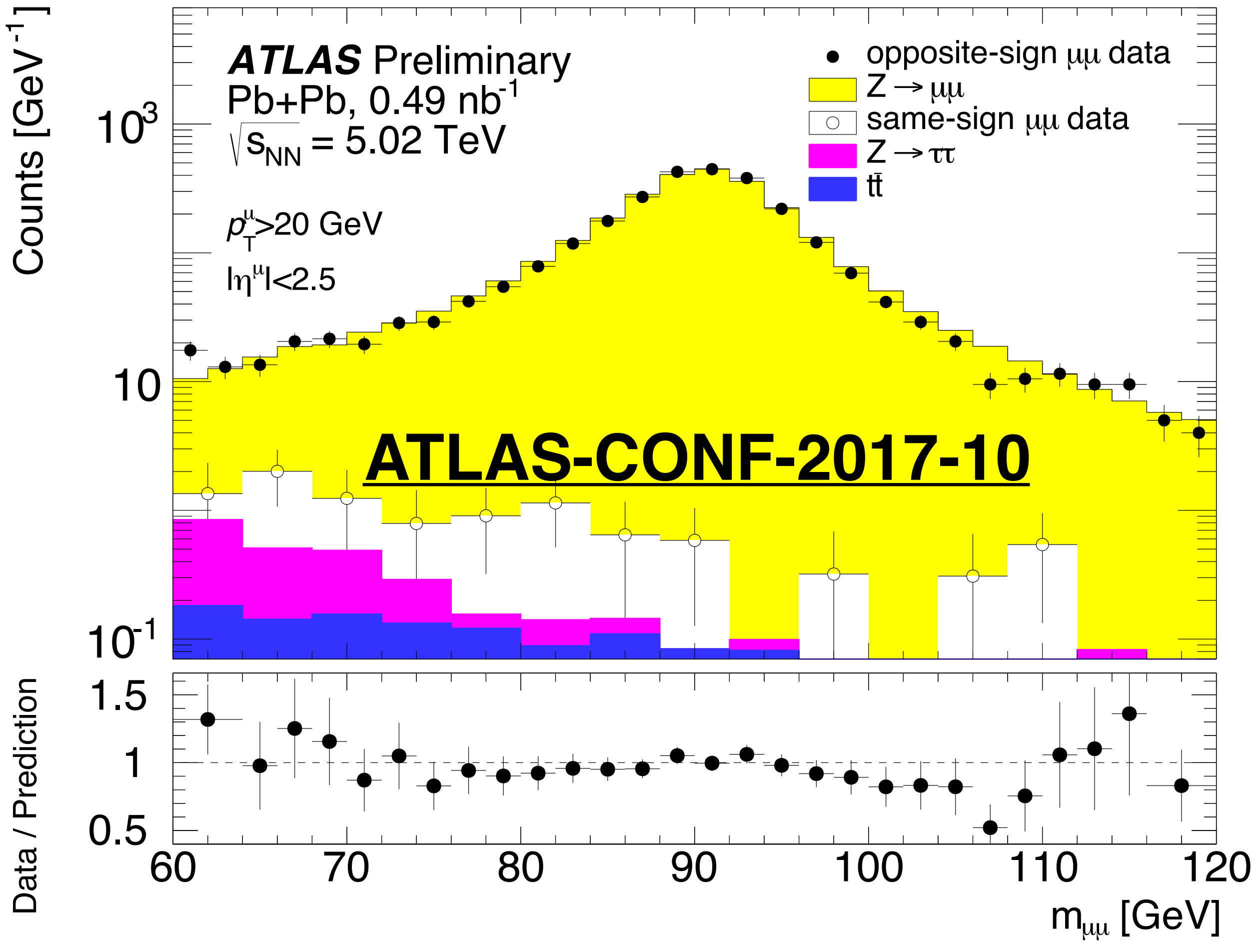
ATLAS Detector



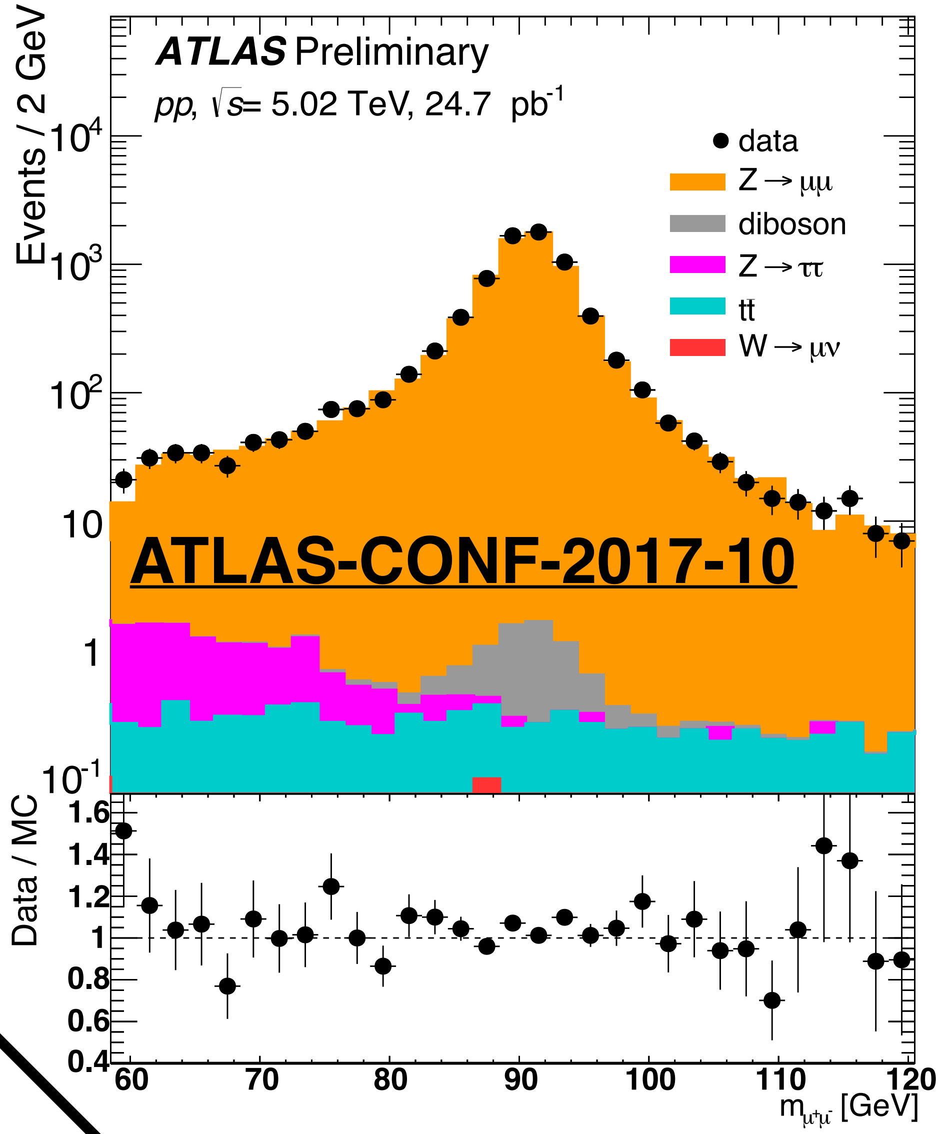


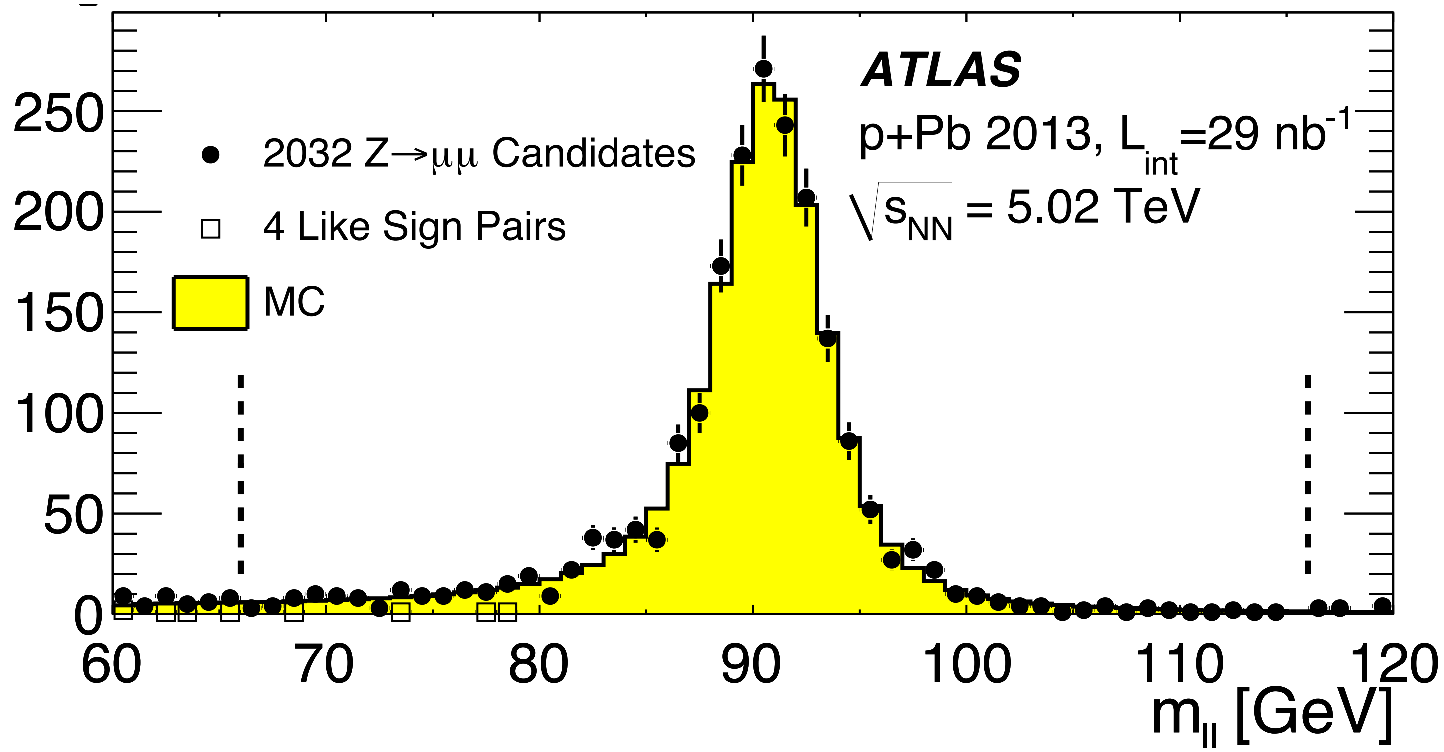
Z boson

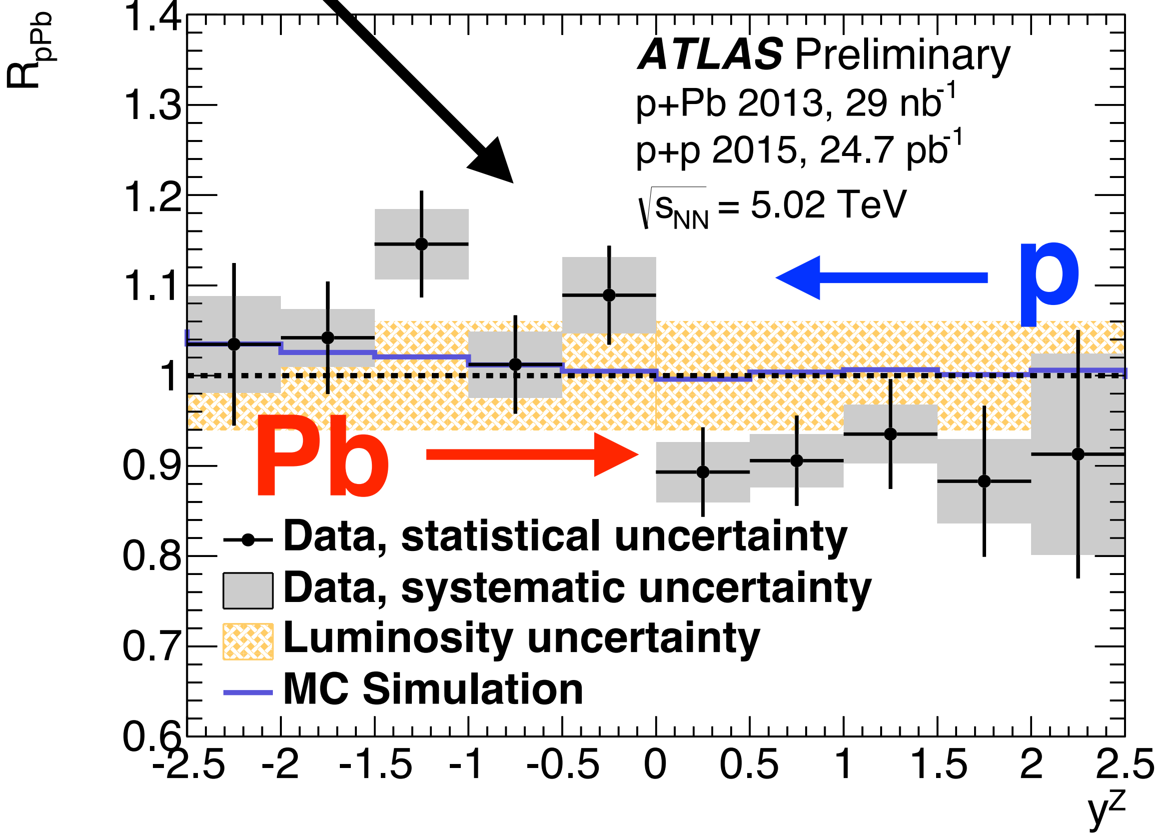
largest sys.: muon reconstruction and id efficiency



σ for np->Z is slightly different than pp->Z



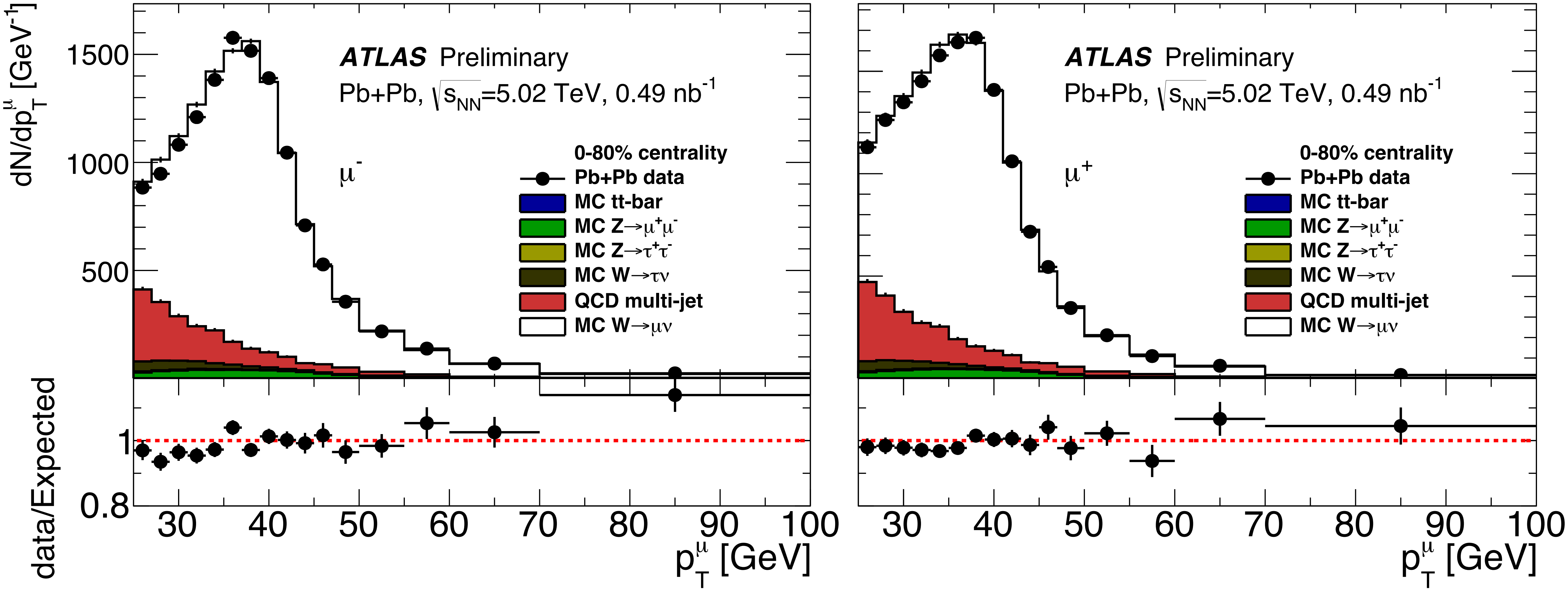




W boson

W+ > W-: isospin effect

Asymmetry decreases at large rapidity because more W- produced at large rapidity

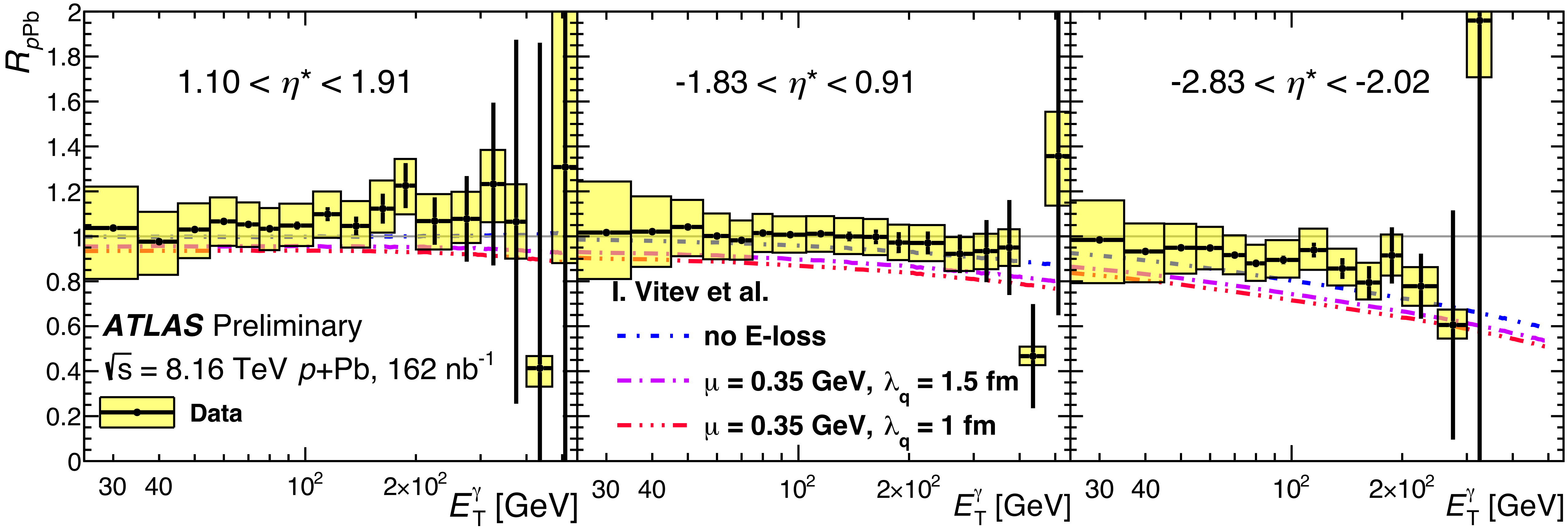


Largest systematic is the muon trigger and QCD multi-jet background

ATLAS-CONF-2017-67

Inclusive Photons

- **Measurement of isolated prompt photons at 8.16 TeV in p+Pb collisions**



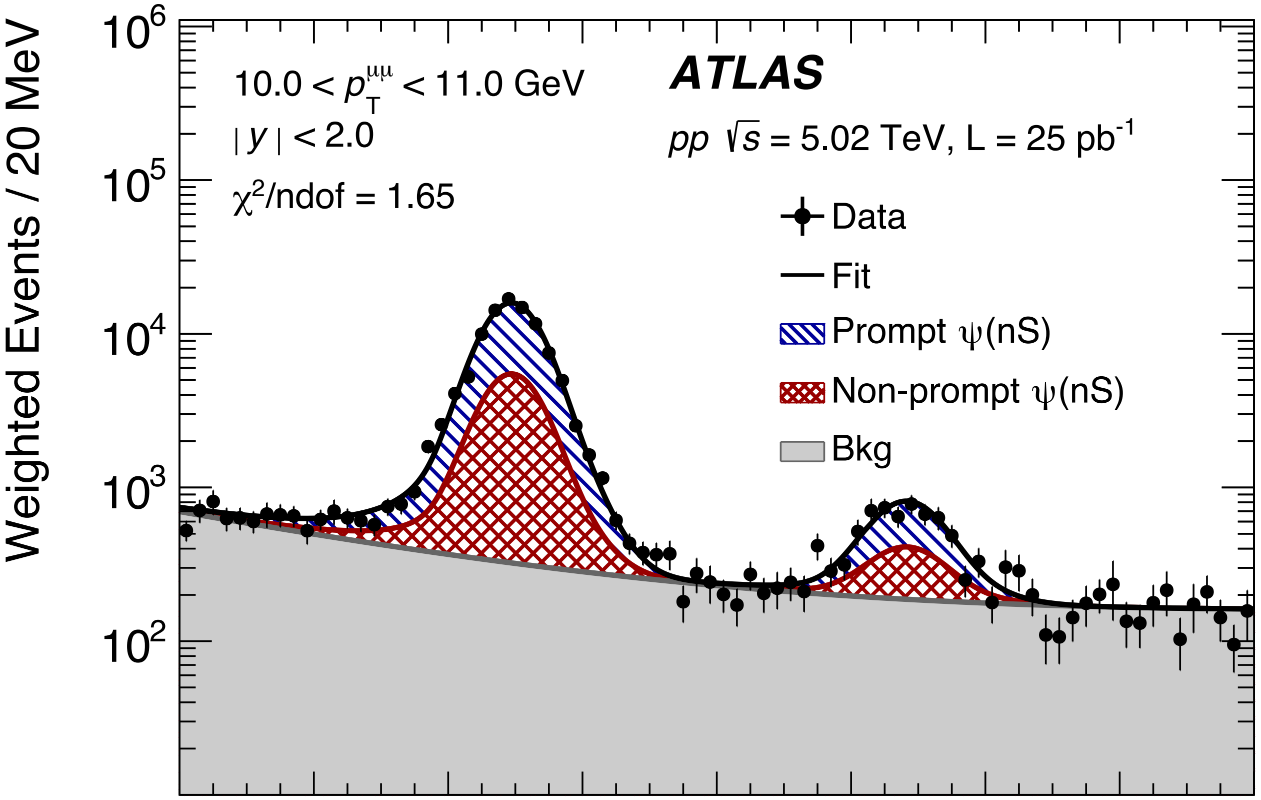
- **R_{pPb} at low rapidity and for low/intermediate E_T consistent with unity**
- **At high photon E_T in backward rapidity it is below unity due to change in u/d quark mixture compared to pp reference**

ATLAS-CONF-2017-72

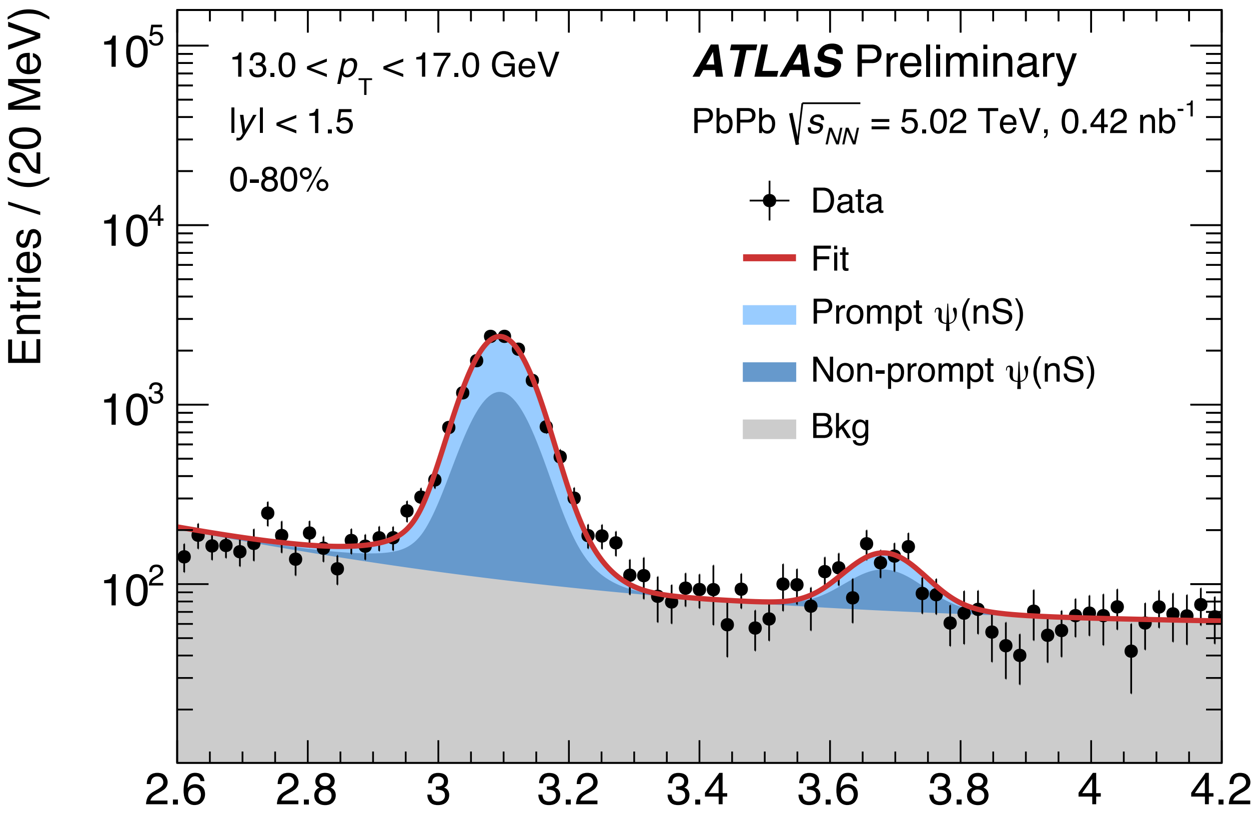
J/ψ and ψ(2s) production

Prompt: c-cbar bound states that experience screening in the medium

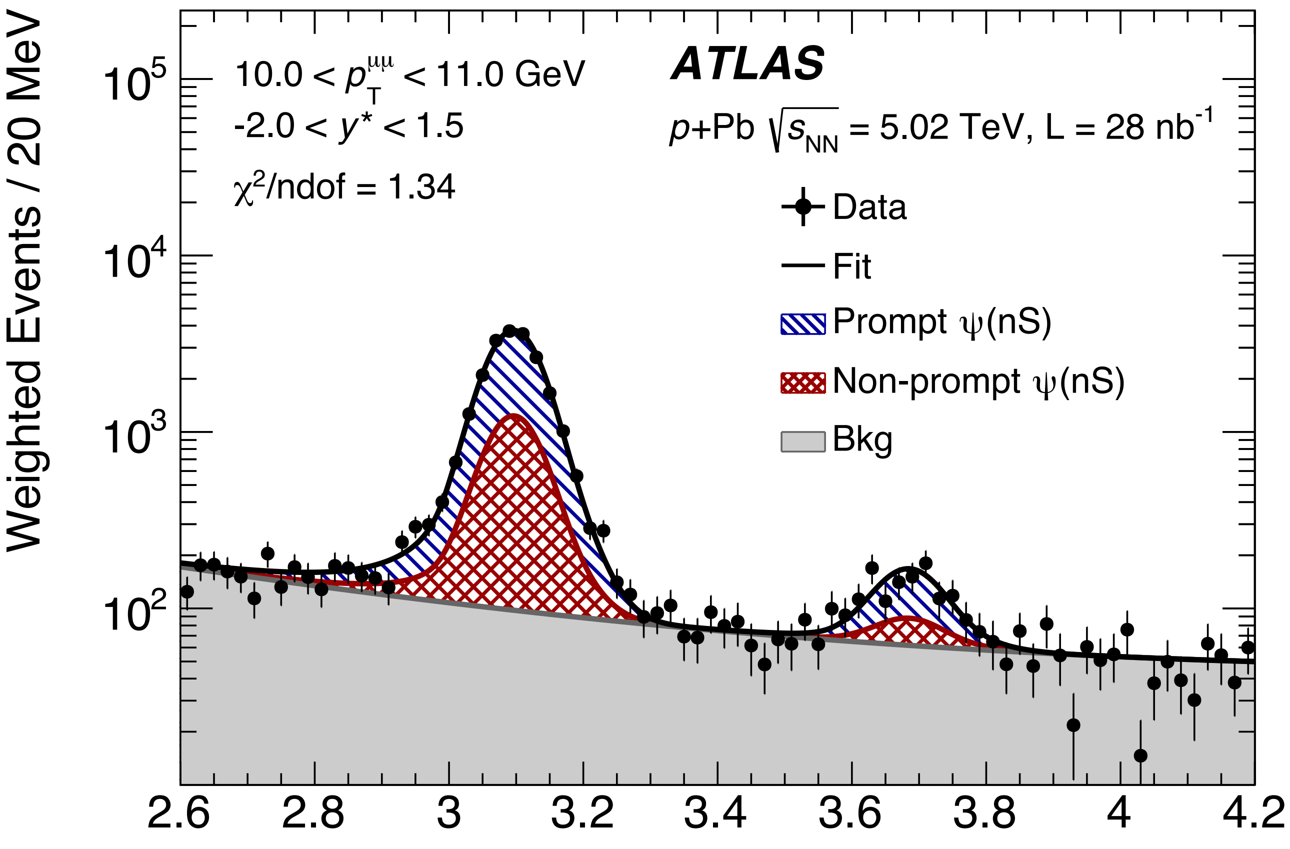
Non-prompt: decay of b quarks that result in a decay vertex separated from the collision vertex by macroscopic distances; quenching by b quark propagation through the medium



Highest sys. is muon reconstruction or the fits for pp and p+Pb

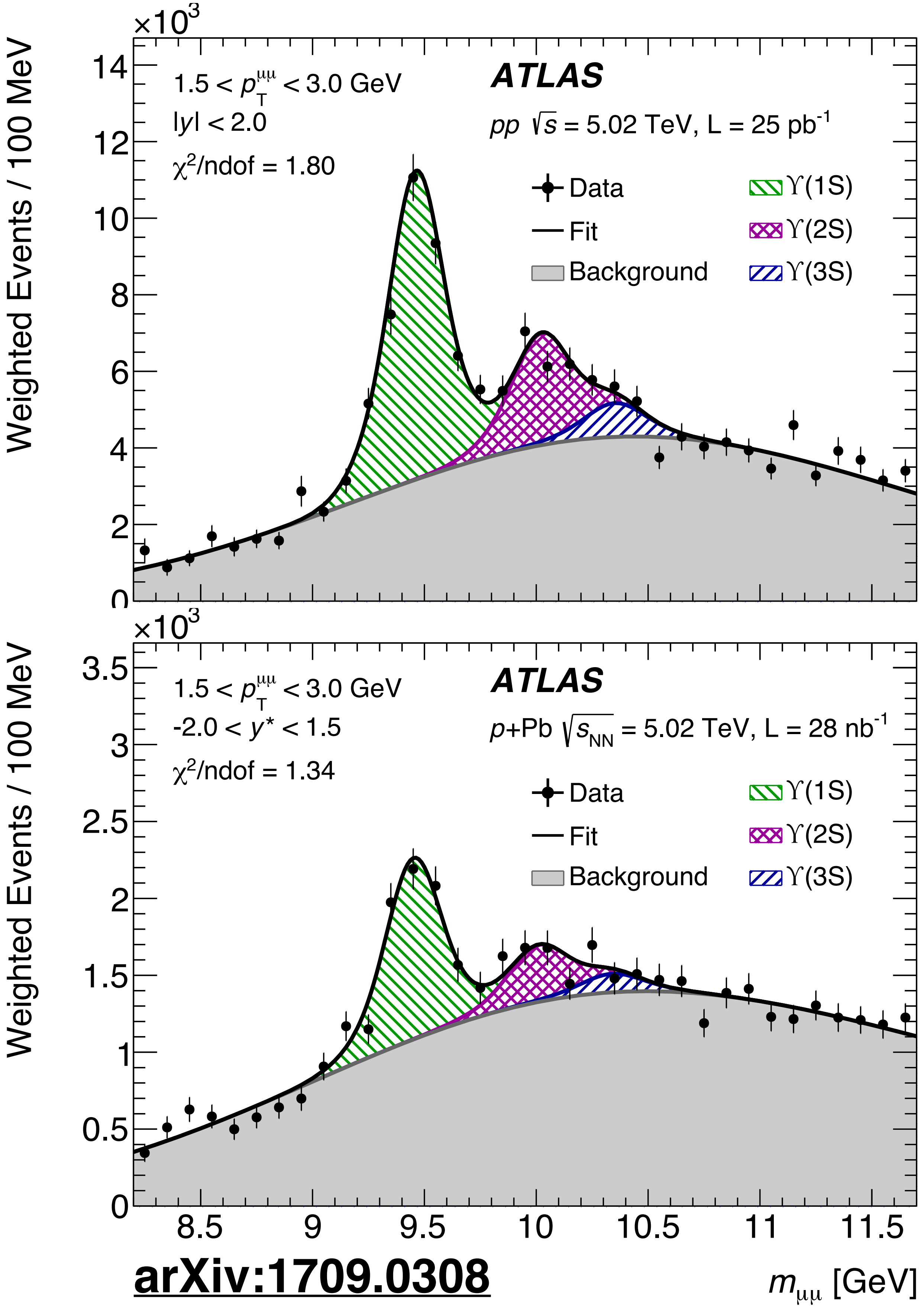


ATLAS-CONF-2016-109

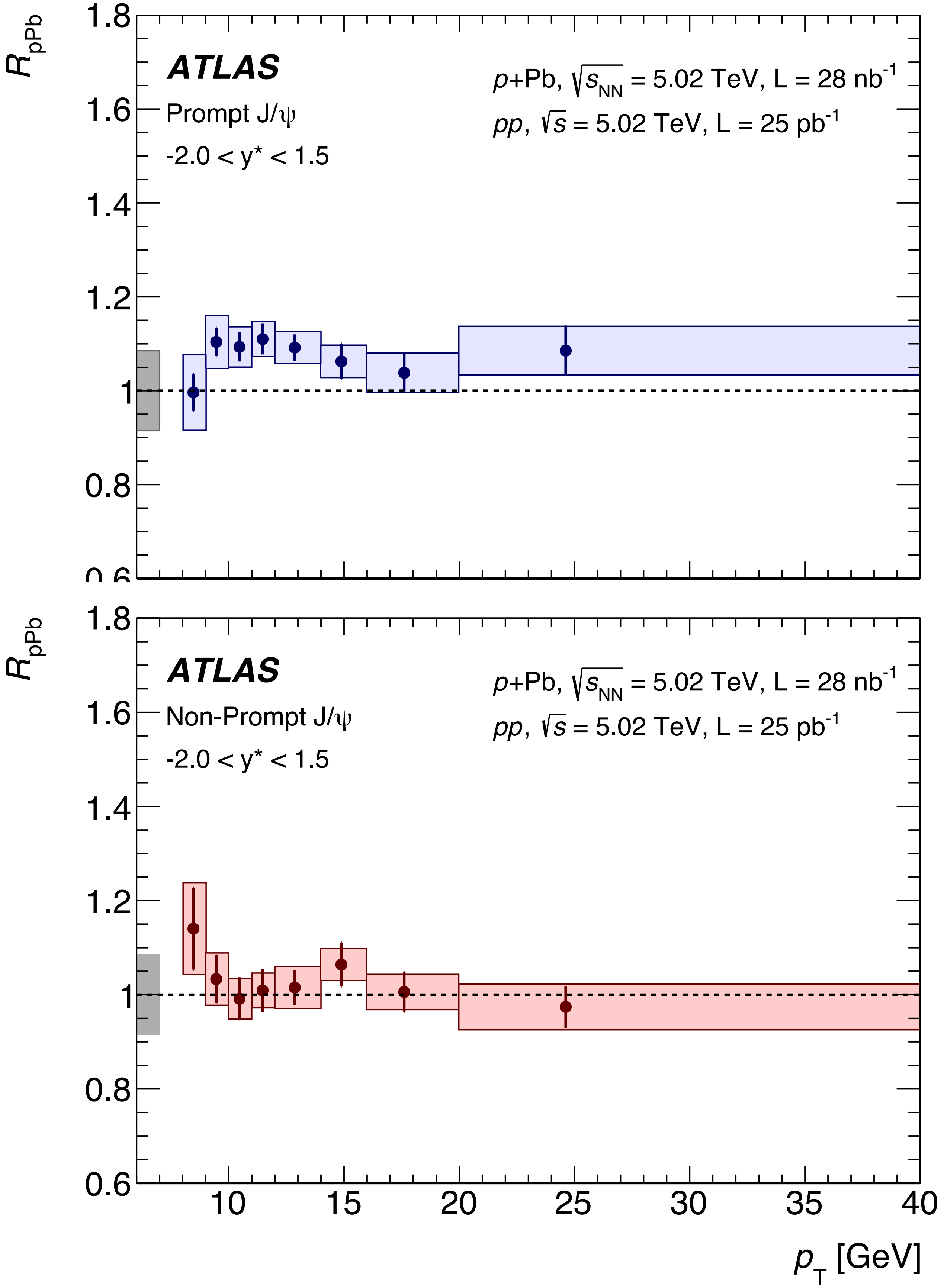


arXiv:1709.0308

J/ψ and ψ(2s) production



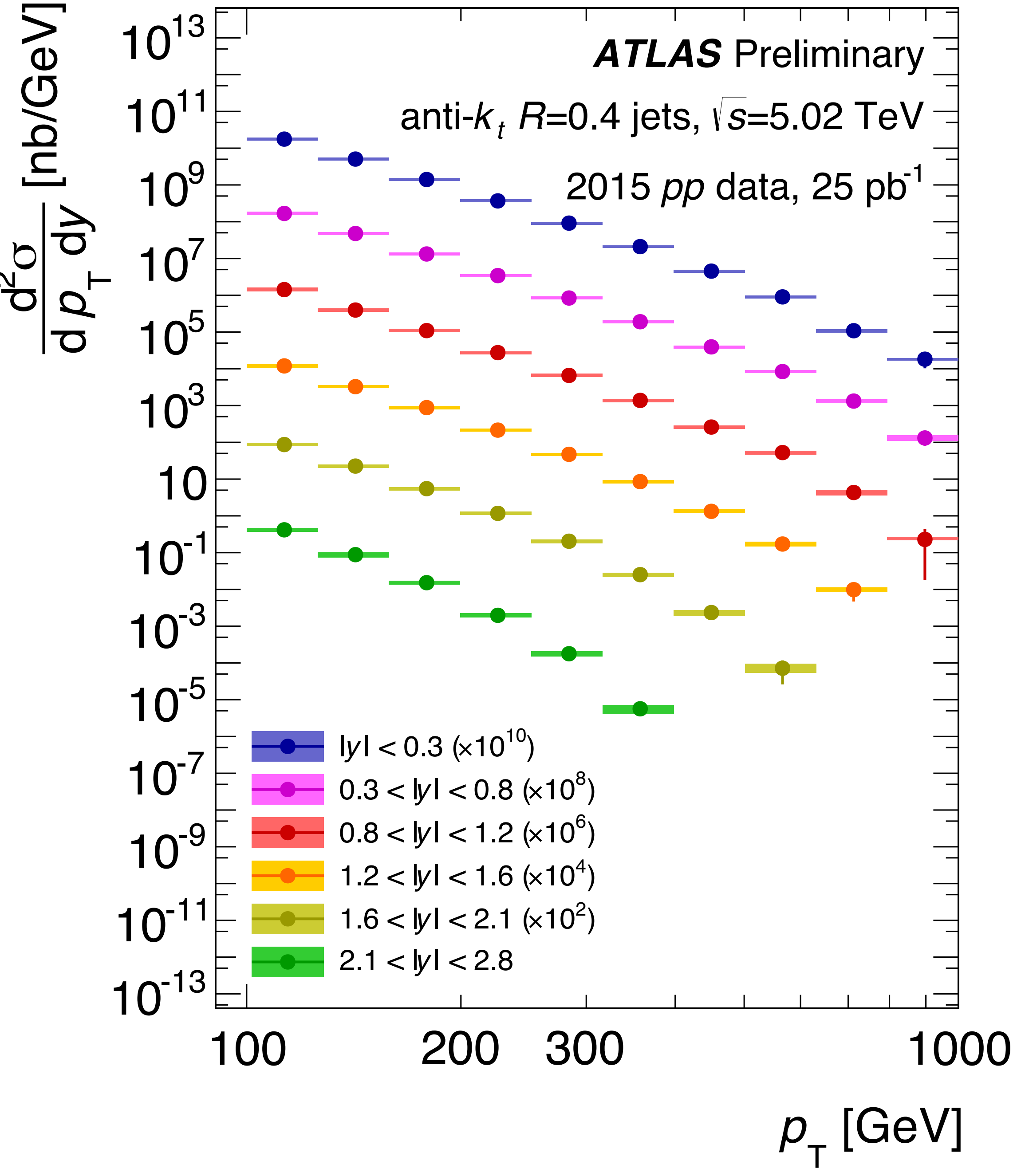
arXiv:1709.0308

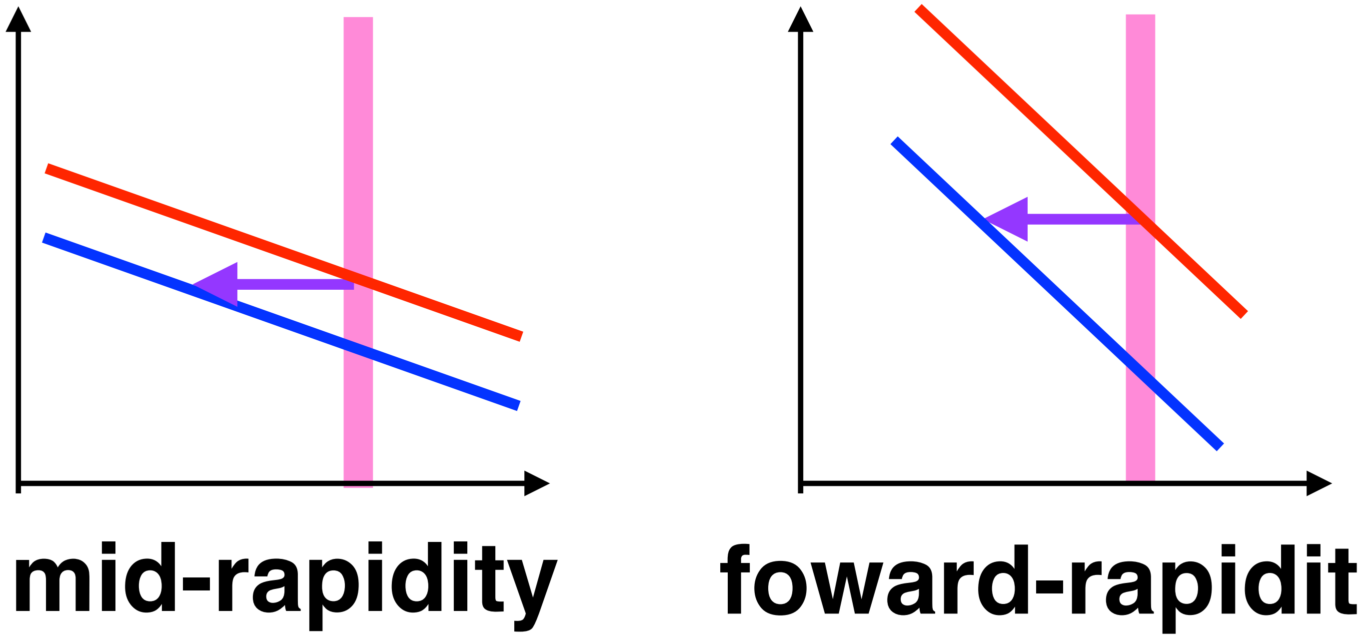


ATLAS-CONF-2017-009

R_{AA} vs. rapidity

Spectra is steeper with increasing rapidity at fixed p_T for the same amount of energy loss and since R_{AA} ~ red/blue.





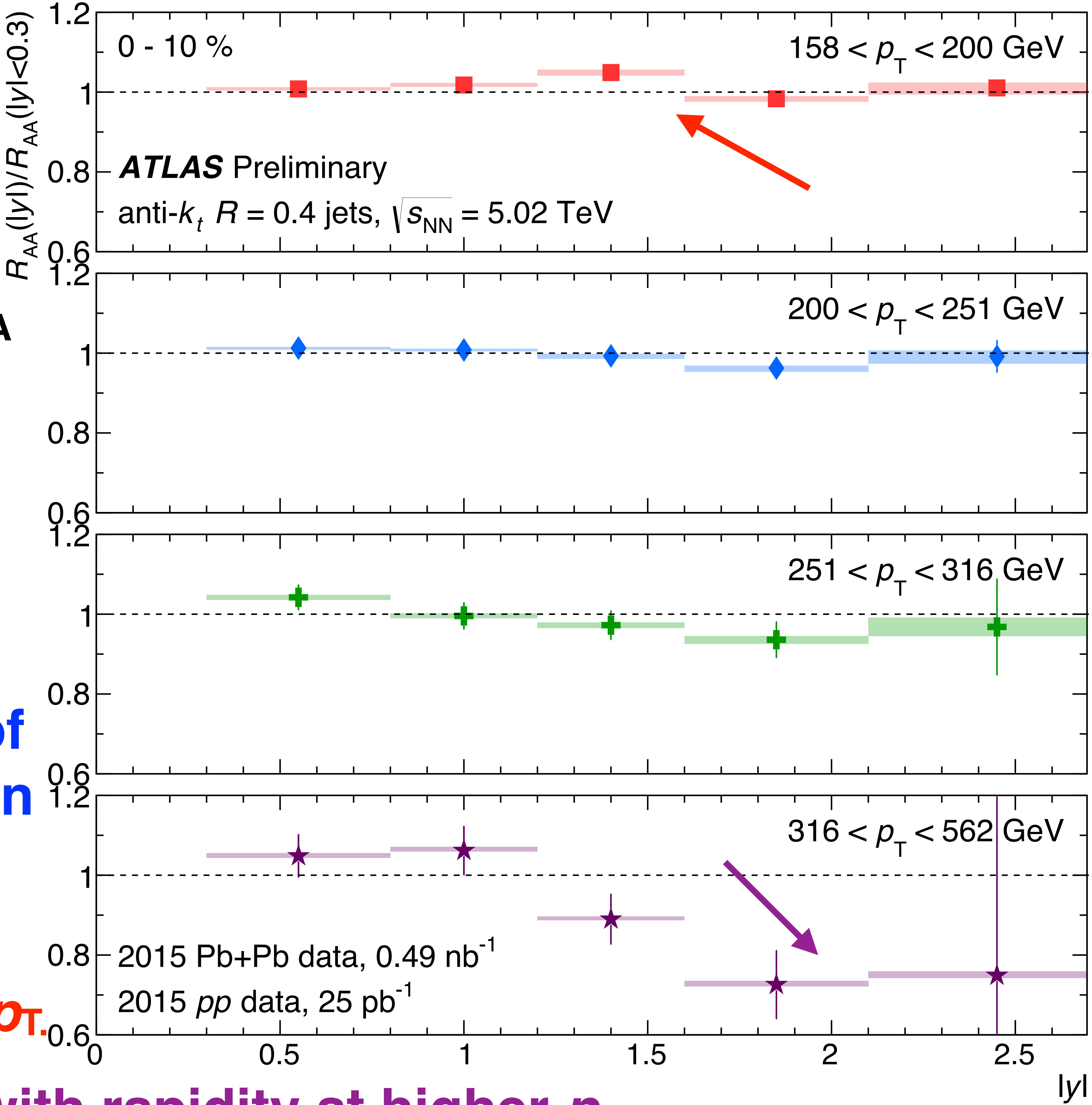
➡ **lower R_{AA}**

Quark and gluon fraction changes with rapidity and p_T with more quarks at forward rapidity which should be quenched less.

➡ **higher R_{AA}**

- ***Competing effects: which one wins or do they cancel?***

R_{AA} vs. rapidity



- **Ratio of the R_{AA} vs. y to the R_{AA} for $|y| < 0.3$ in different p_T ranges.**
  - **Large cancelation of systematics in ratio.**
- **R_{AA} is flat with rapidity at low p_T.**
- **R_{AA} decreases with rapidity at higher p_T.**

ATLAS-CONF-2017-009

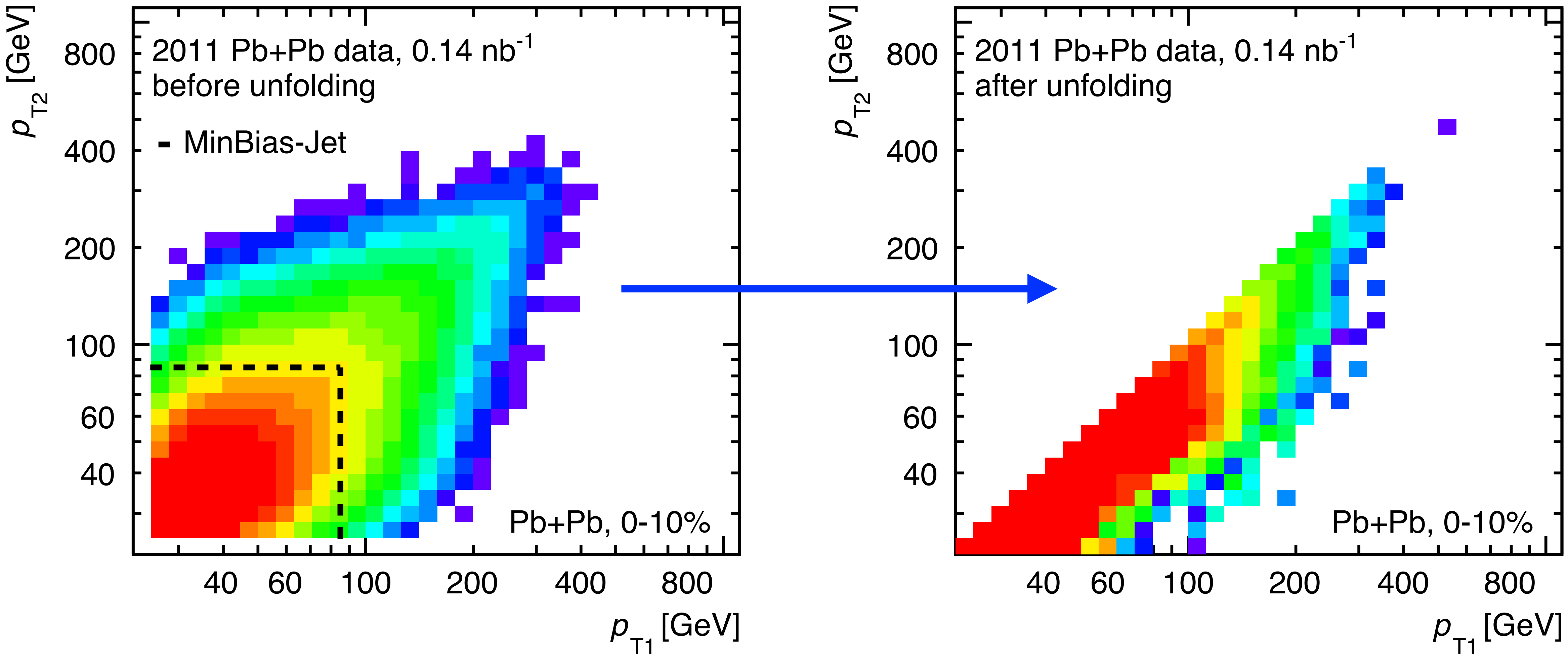
Effect of unfolding

PLB 774 (2017) 379

- **Unfolded using 2D Bayesian unfolding in p_{T1} and p_{T2}.**

2D distribution *before* unfolding, symmetrized to account for bin migration across the diagonal

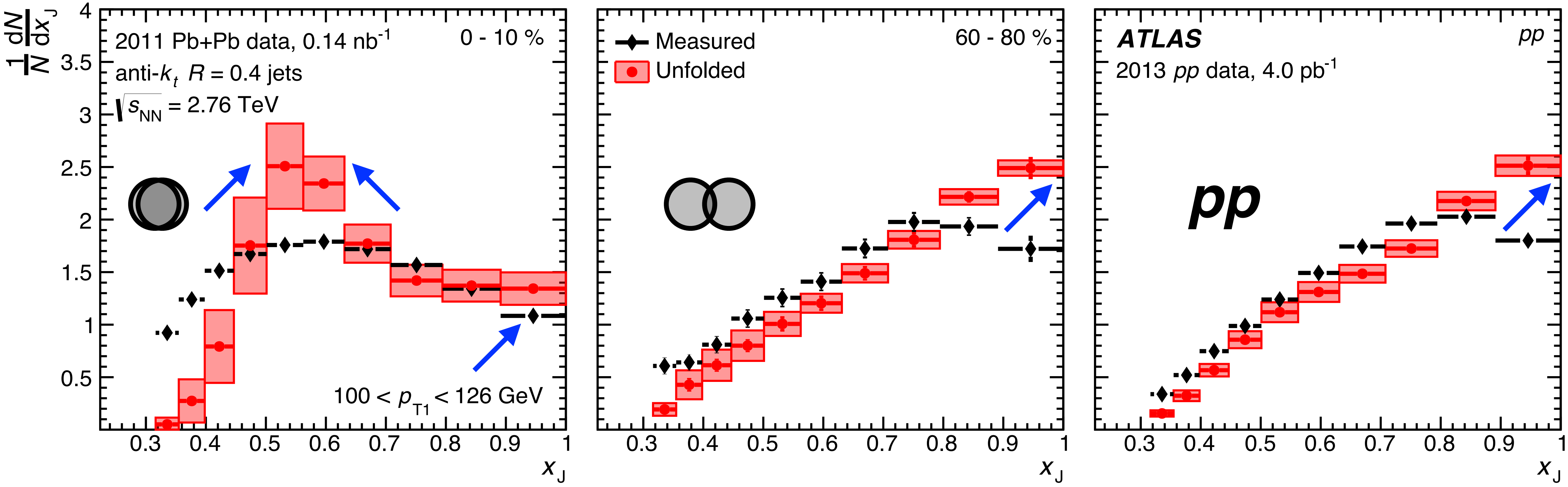
2D distribution *after* unfolding, projected over the diagonal to restore to leading/sub-leading distribution



PLB 774 (2017) 379

Effect of unfolding

- **Project 2D distribution into x_J distribution**



- **Moves jets in pp and peripheral to more balanced configurations and jets in central to both more balanced and asymmetric configurations at x_J ~0.5**

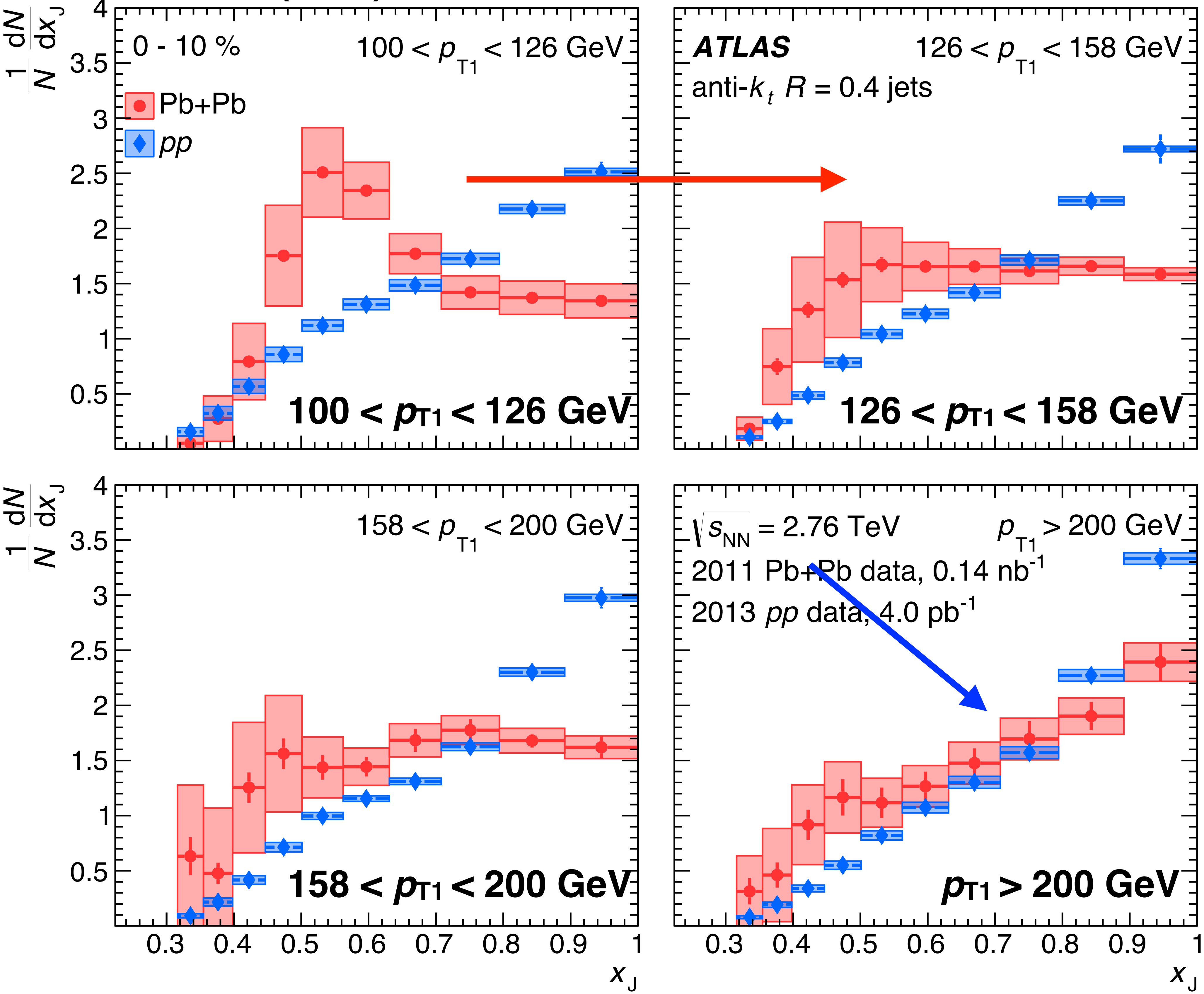
► ***Unfolded result can be compared directly to theory***

x_J distribution

p_{T1} dependence

0-10%

PLB 774 (2017) 379



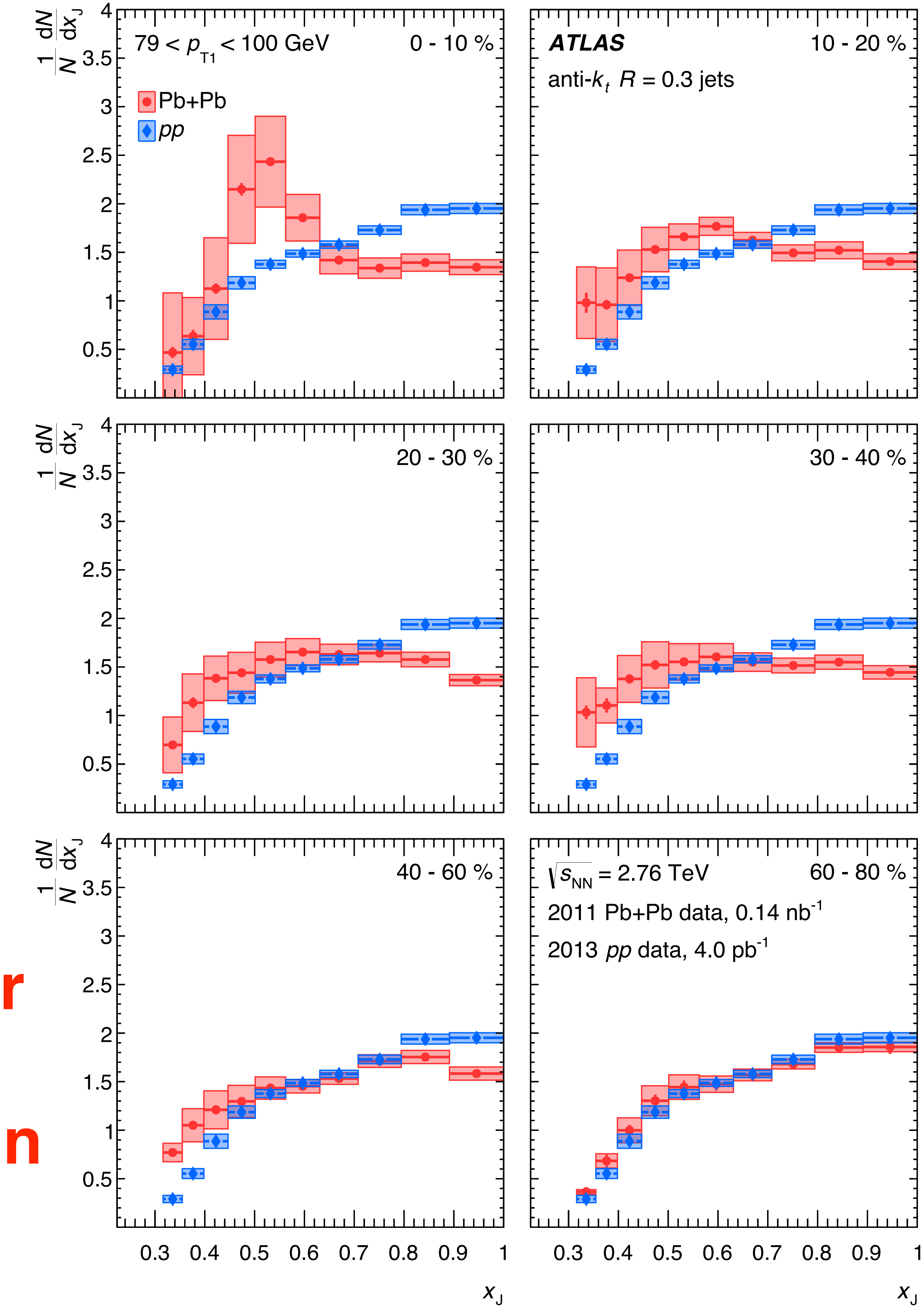
- **Strong p_{T1} dependence**
- **Pb+Pb becomes like *pp* at high p_{T1}**
- ***Flavor dependence probe since quark/gluon fractions change with p_T?***

PLB 774 (2017) 379

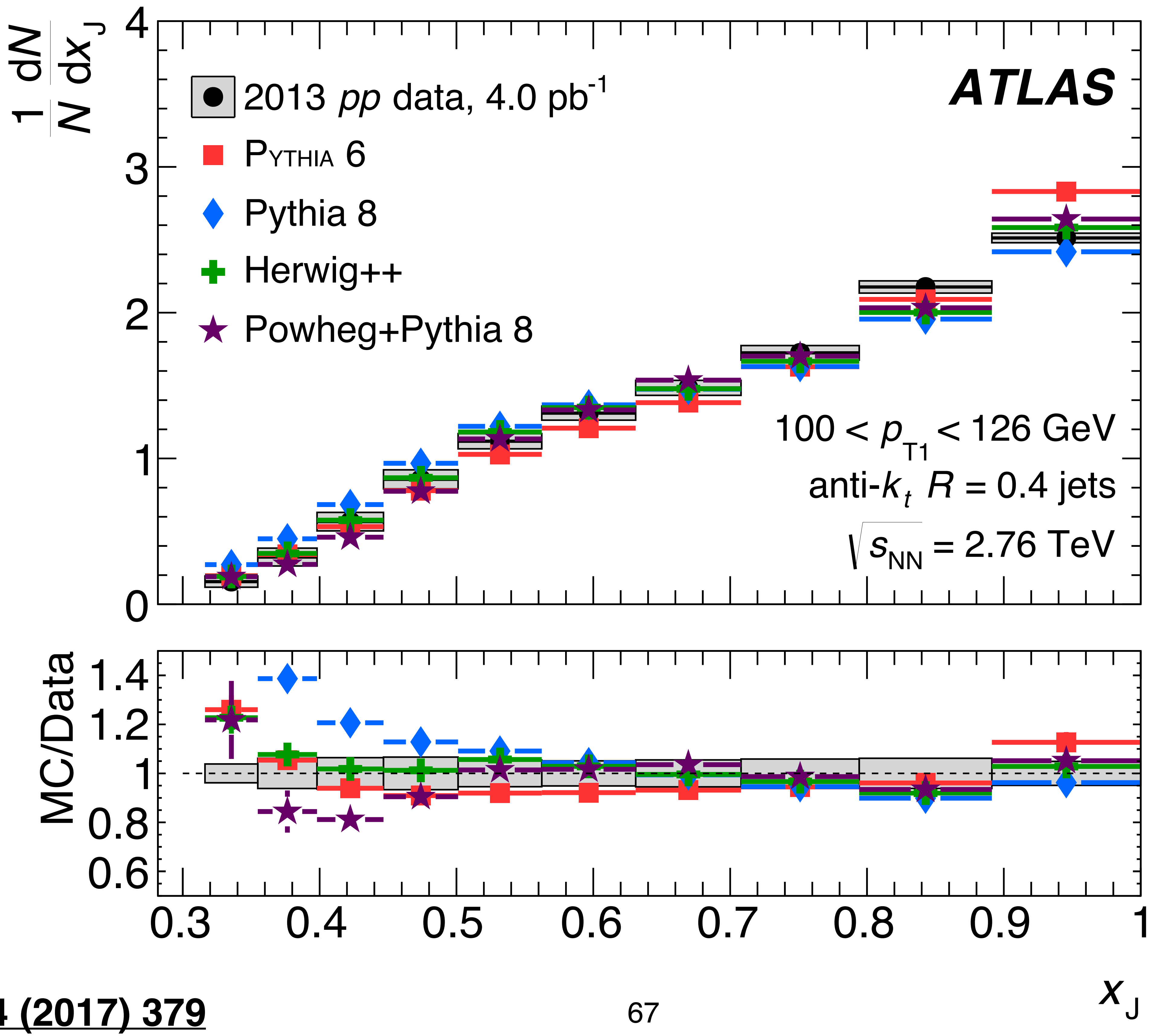
R=0.3 x_J

Centrality dependence of Pb+Pb compared to *pp* dijets for 79<p_{T1}<100 GeV.

- Same analysis for R=0.3 jets since effects of the JER and the background are much less
- R=0.3 jets correspond to R=0.4 jets at a larger energy due to the smaller jet cone so the R=0.3 are shifted to one bin lower in leading jet p_T.



x_J *pp* data to MC comparison

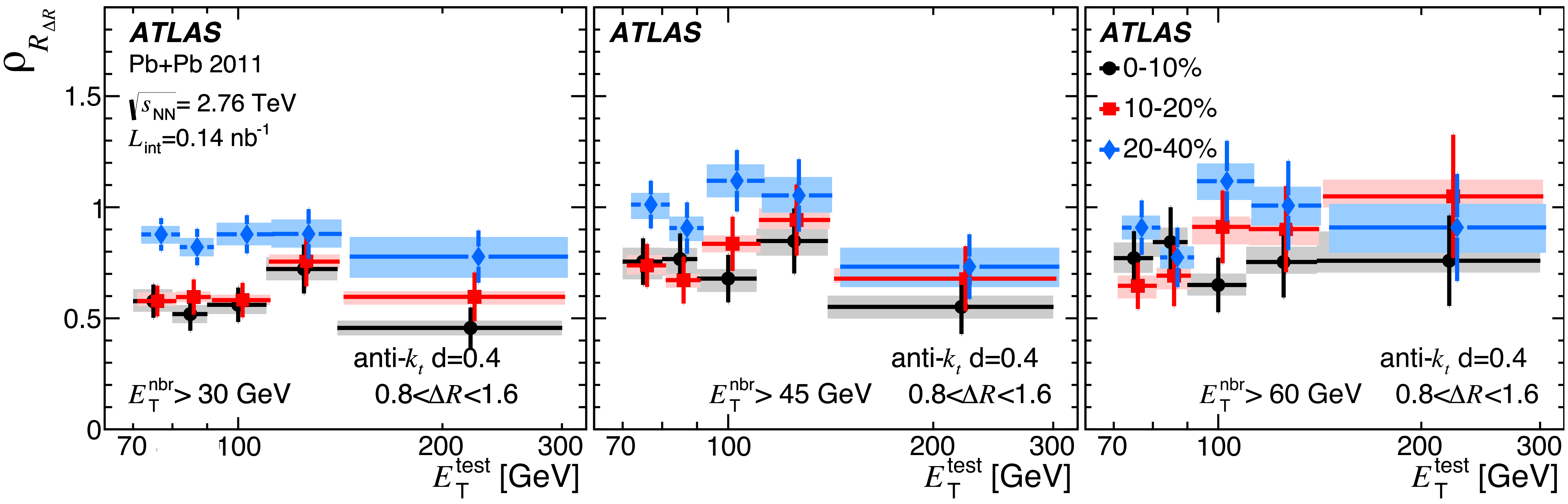


PLB 774 (2017) 379

x_J 3rd jet

- **See less nearby jets in more central collisions.**

PLB 751 (2015) 376

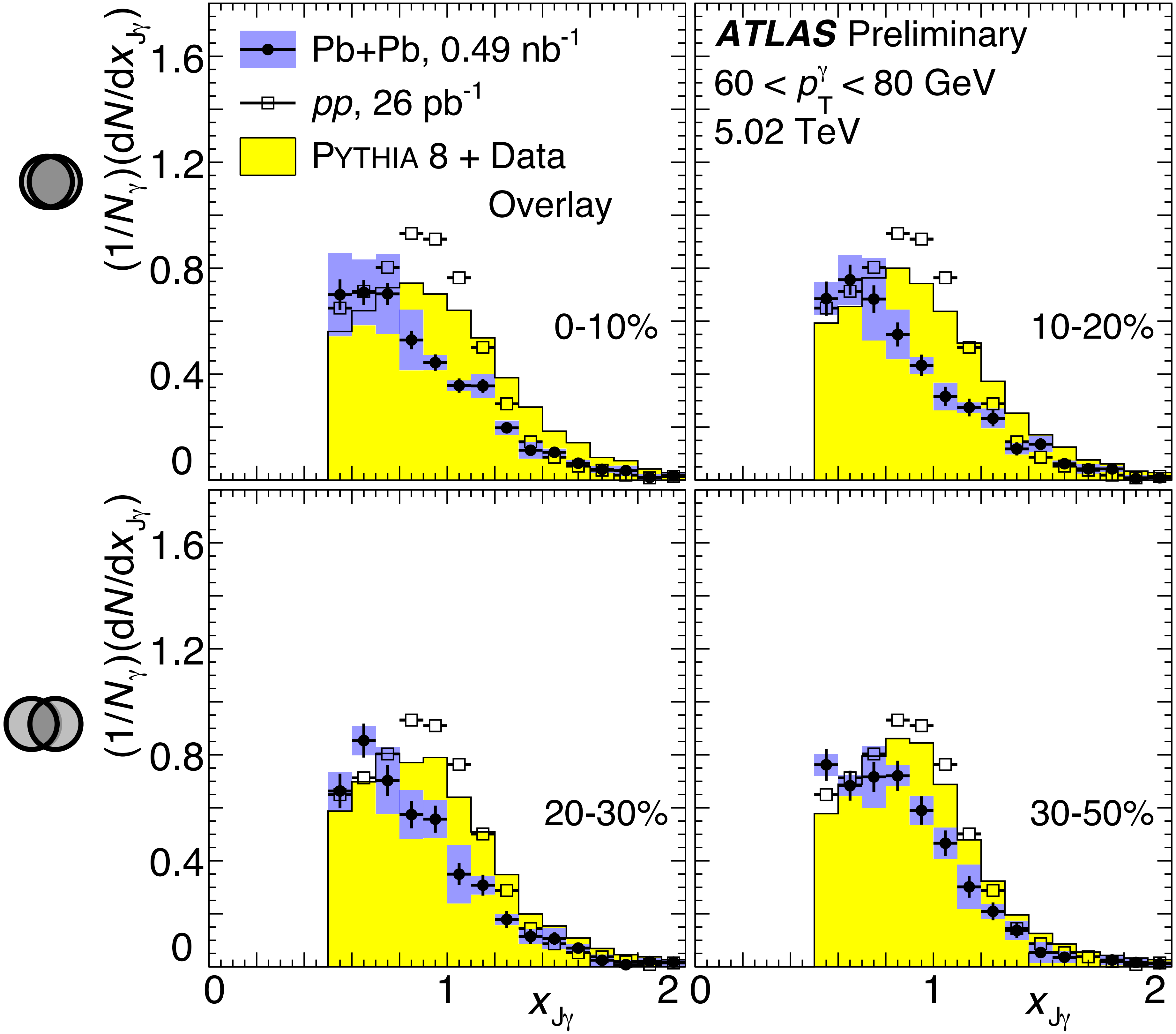


- **Tested this by unfolding with a new response that takes into account the contribution to the 3rd jet with a weighting applied to match the 3rd jet distribution in data**

➡ **Deviations from the result was well within the systematics of the measurement**

ATLAS-CONF-2016-110

γ-jet asymmetry



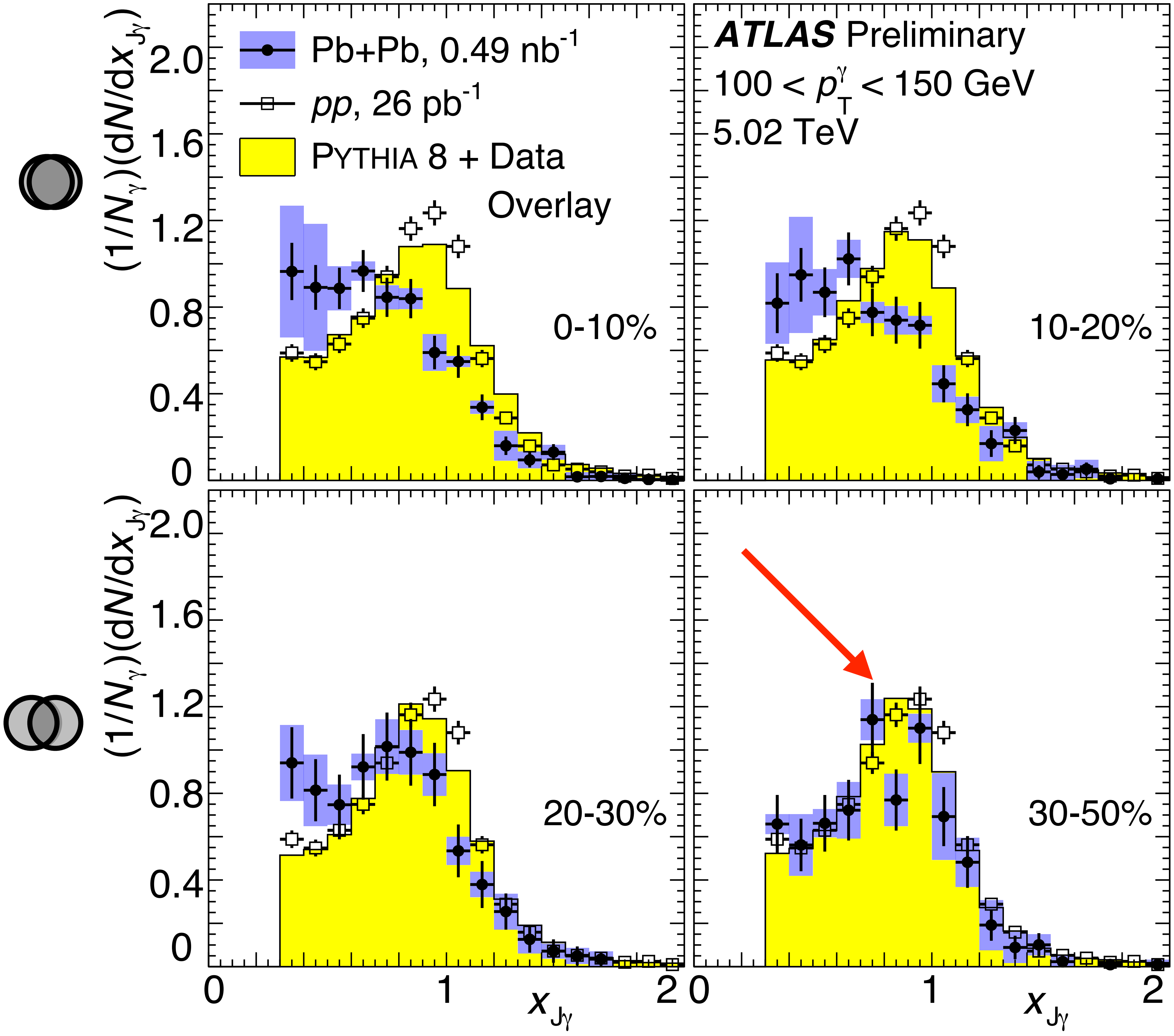
centrality dependence

$60 < p_{T\gamma} < 80$ GeV

- **The distributions become less asymmetric with decreasing centrality.**

ATLAS-CONF-2016-110

γ-jet asymmetry



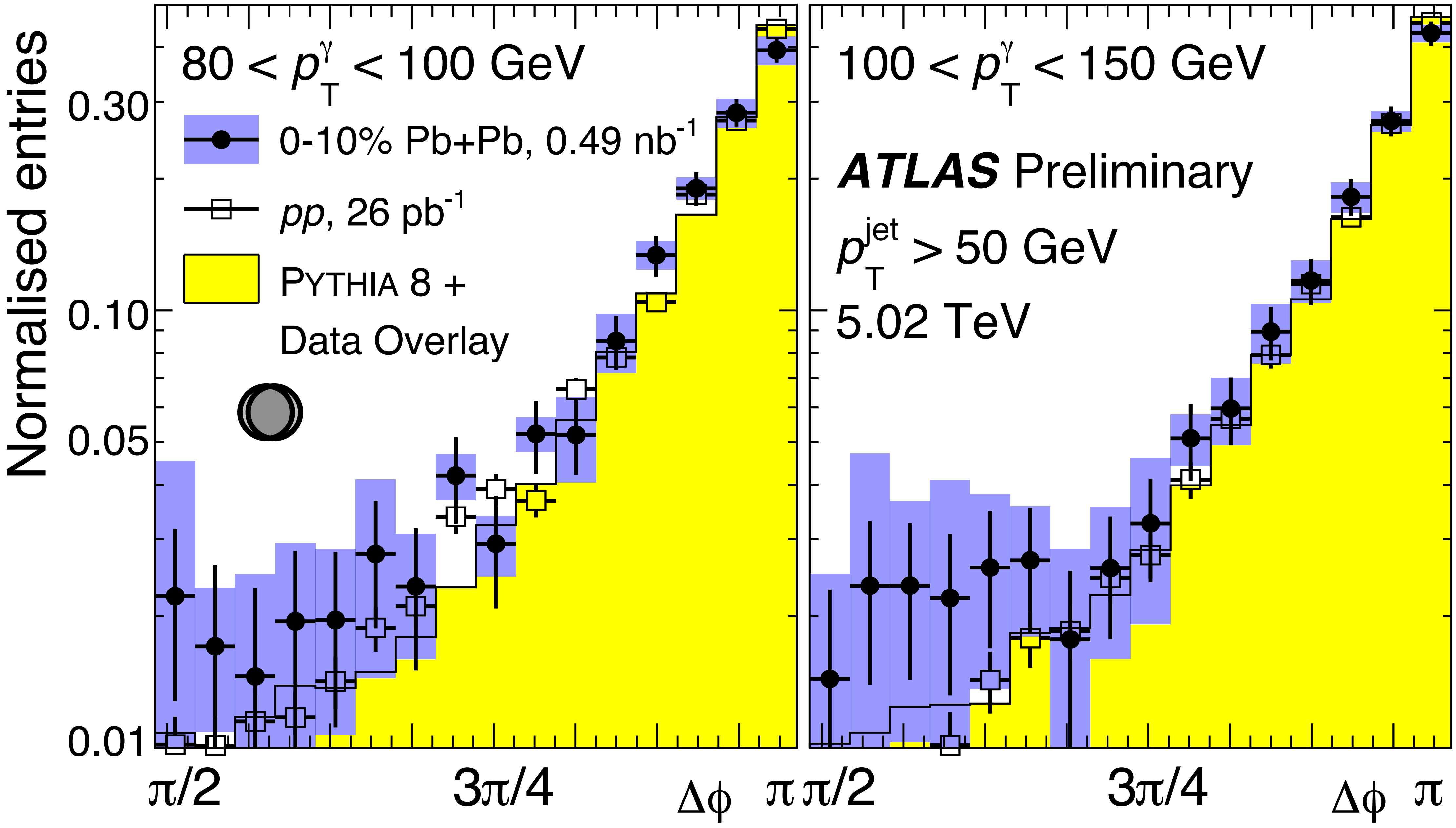
centrality dependence

$100 < p_{T\gamma} < 150$ GeV

- **The distribution becomes like simulation for 30-50% suggesting that the fraction of energy loss decreases with parton p_T.**

γ-jet angular correlations

- **No evidence for large modifications of angular distributions in Pb+Pb compared to *pp* collisions for photon+jet.**



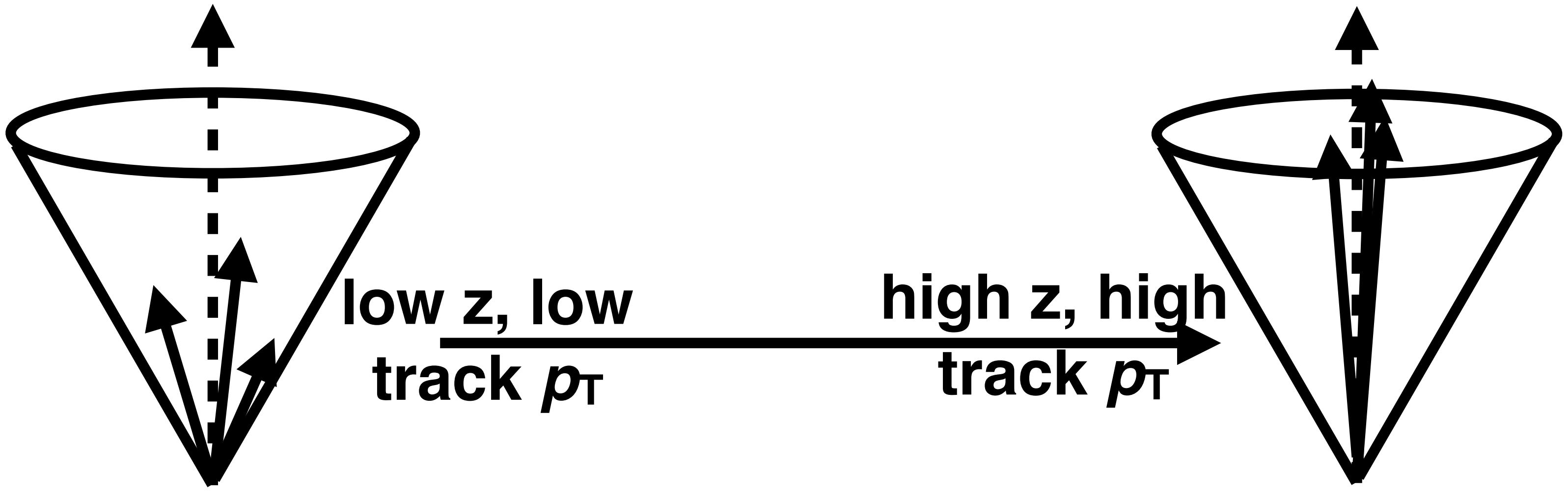
Jet fragmentation functions (FF)

- **Measures how the particles within the jet are distributed by looking at number of charged particles in jets (N_{ch})**

$$D(z) = \frac{1}{N_{\mathrm{jet}}} \frac{\mathrm{d}N_{ch}}{\mathrm{d}z}$$

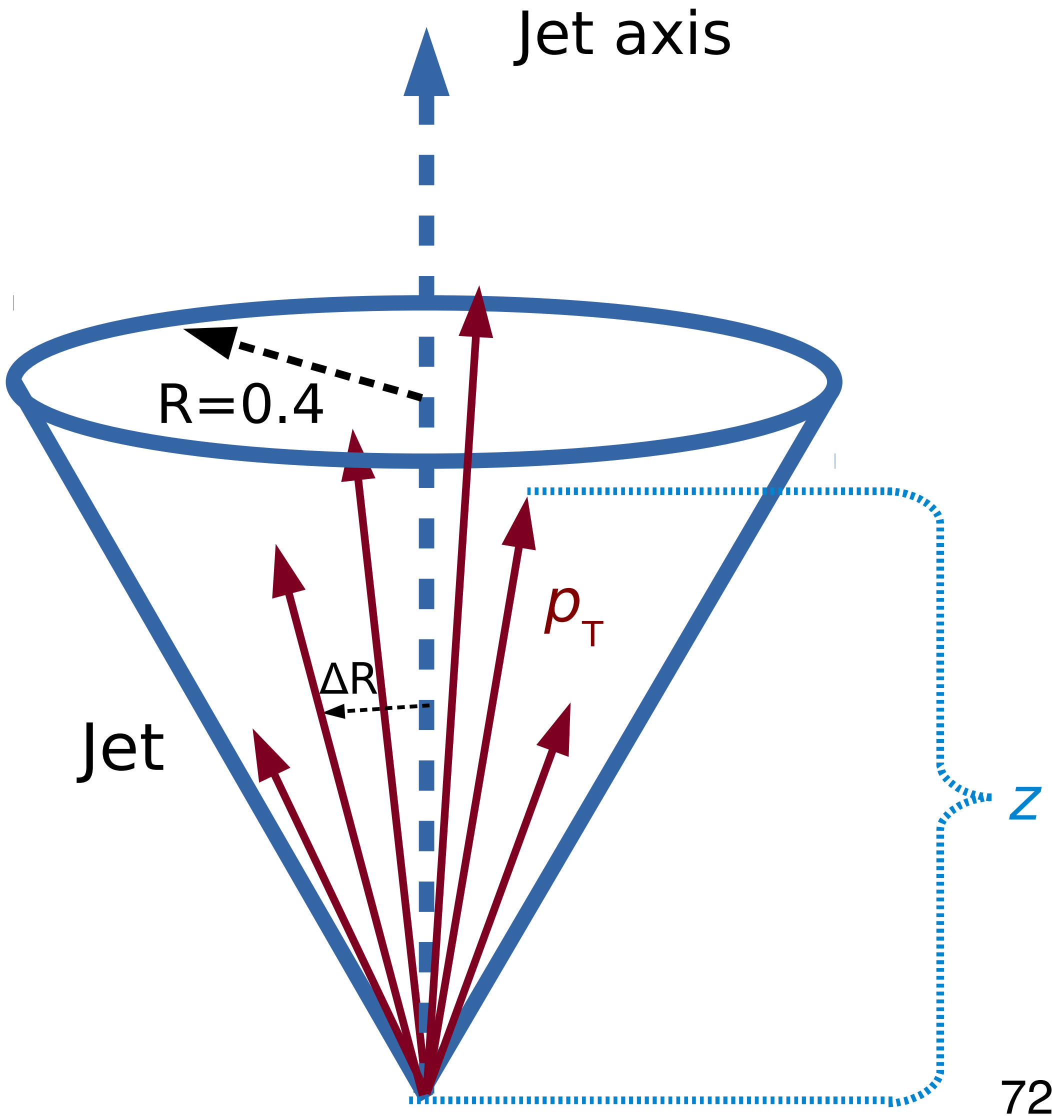
➡ **z measures the fraction of the track momentum in the jet momentum**

$$z = \frac{p_{\mathrm{T}} \cos \Delta R}{p_{\mathrm{T}}^{\mathrm{jet}}}$$

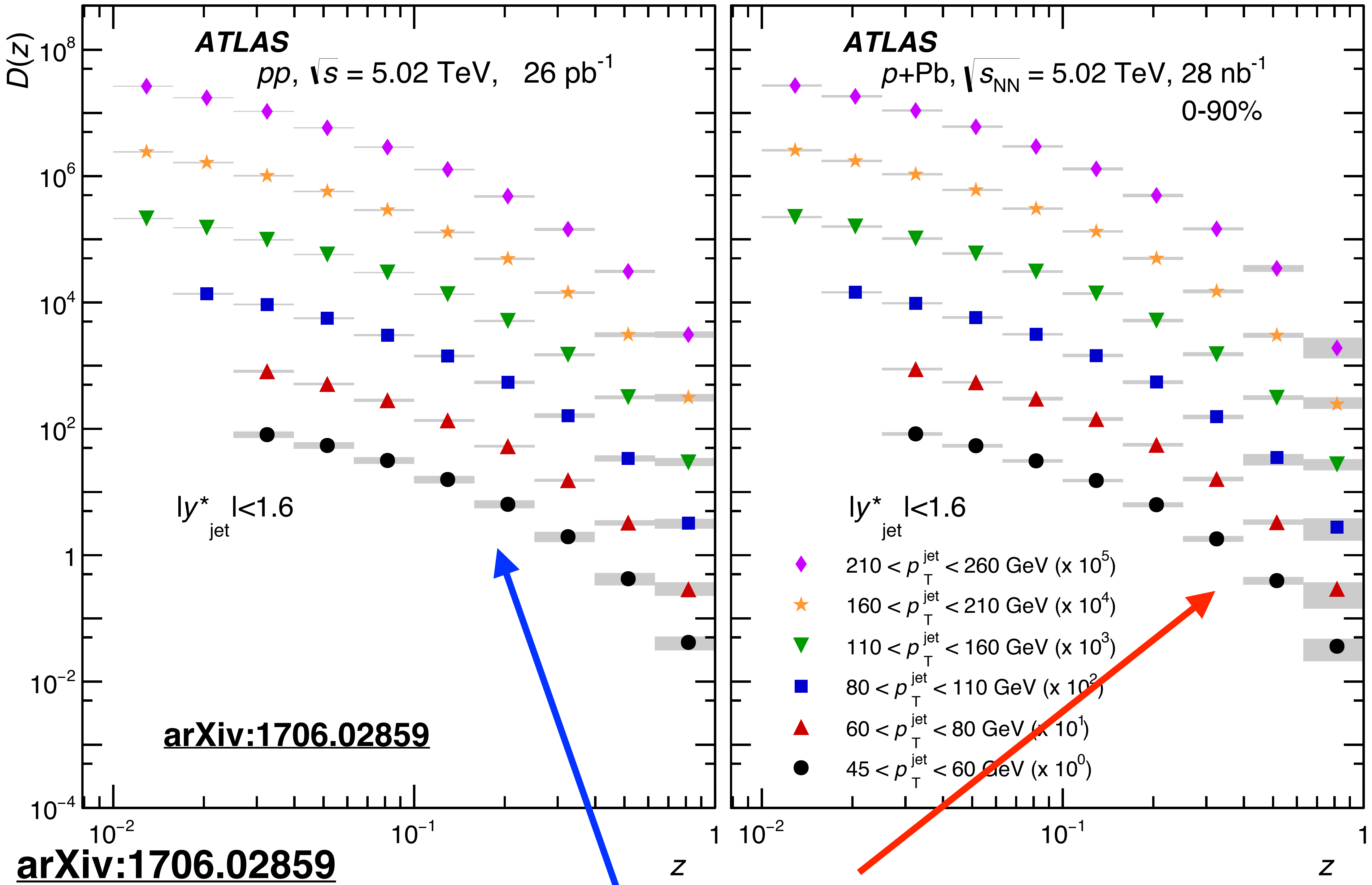


- **Ratio of FF needed to see modification**

$$R_{\mathrm{D(z)}} = \frac{D(z)_{\mathrm{PbPb}}}{D(z)_{\mathrm{pp}}}$$



Jet fragmentation: *pp* and *p*+Pb



arXiv:1706.02859

- **Ratio needed to see modification.**

$$R_{D(z)} = \frac{\boxed{D(z)_{pPb}}}{\boxed{D(z)_{pp}}}$$

$$D(z) = \frac{1}{N_{jet}} \frac{dN_{ch}}{dz}$$

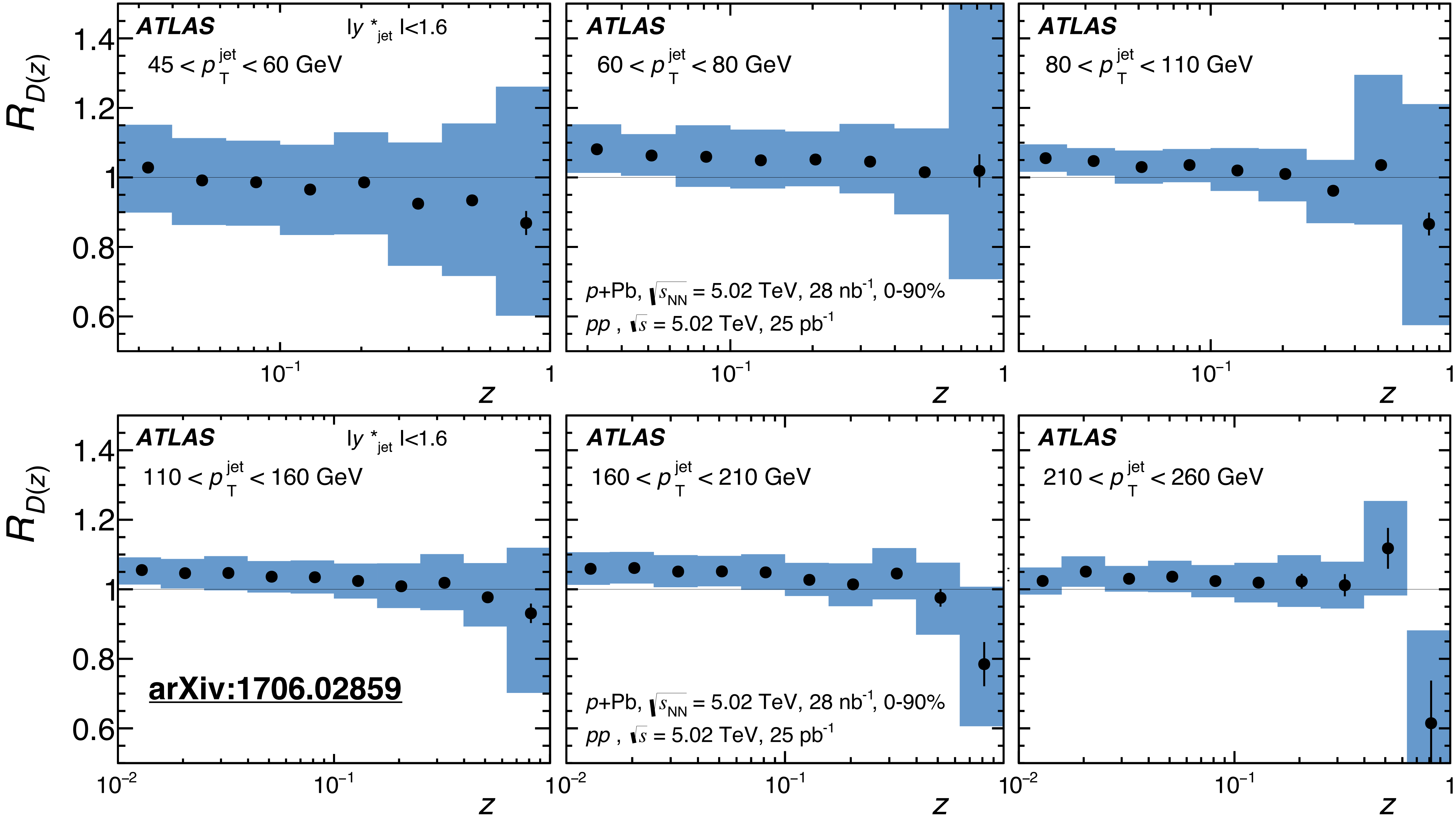
Internal structure: *p*+Pb

- **Ratio needed to see modification.**

***p*+Pb $R_{D(z)}$ in jet p_T bins**

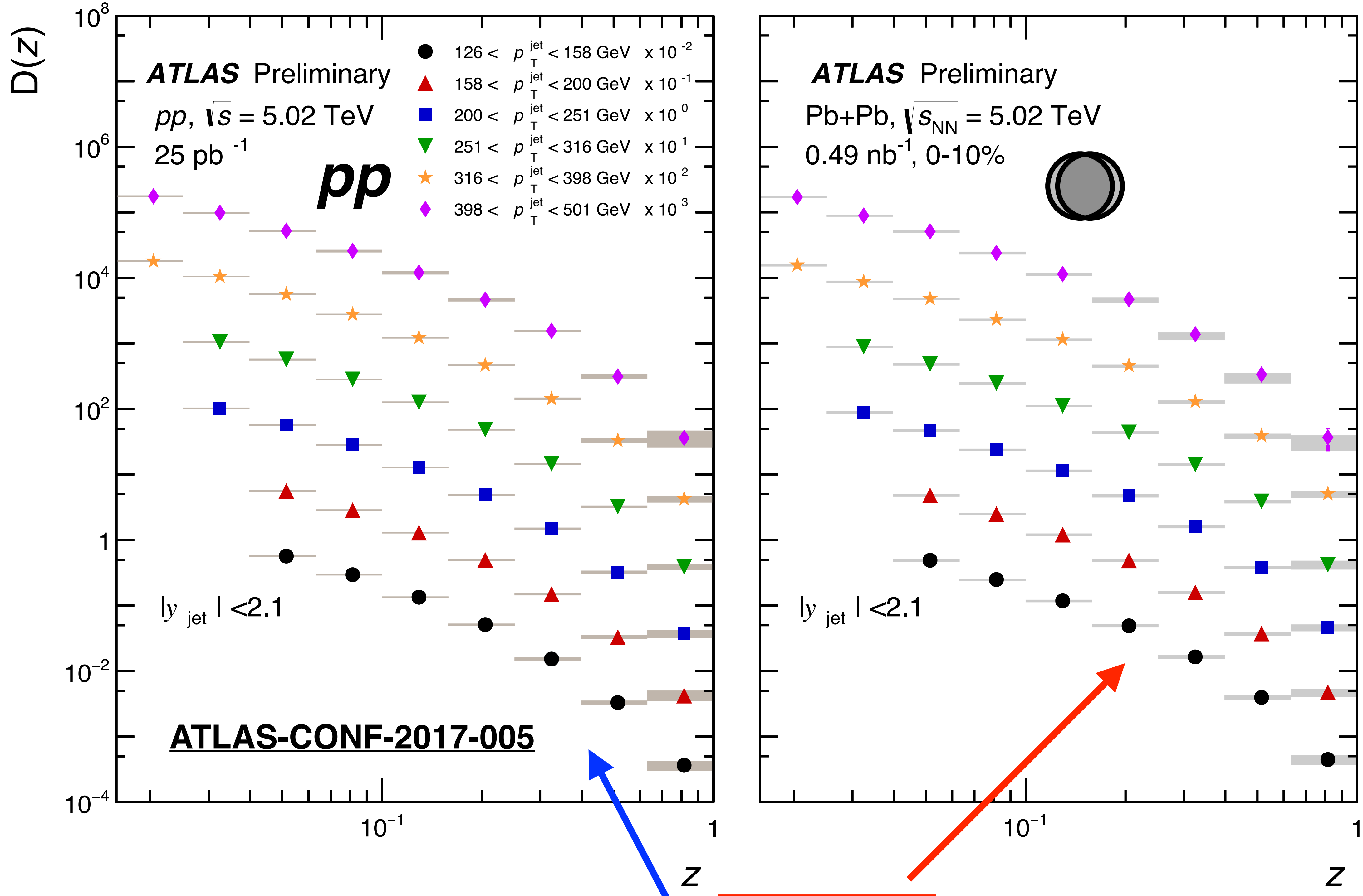
$$R_{D(z)} = \frac{D(z)_{\text{pPb}}}{D(z)_{\text{pp}}}$$

arXiv:1706.02859



➡ **No significant modification of jet structure in *p*+Pb.**

Jet fragmentation: Pb+Pb

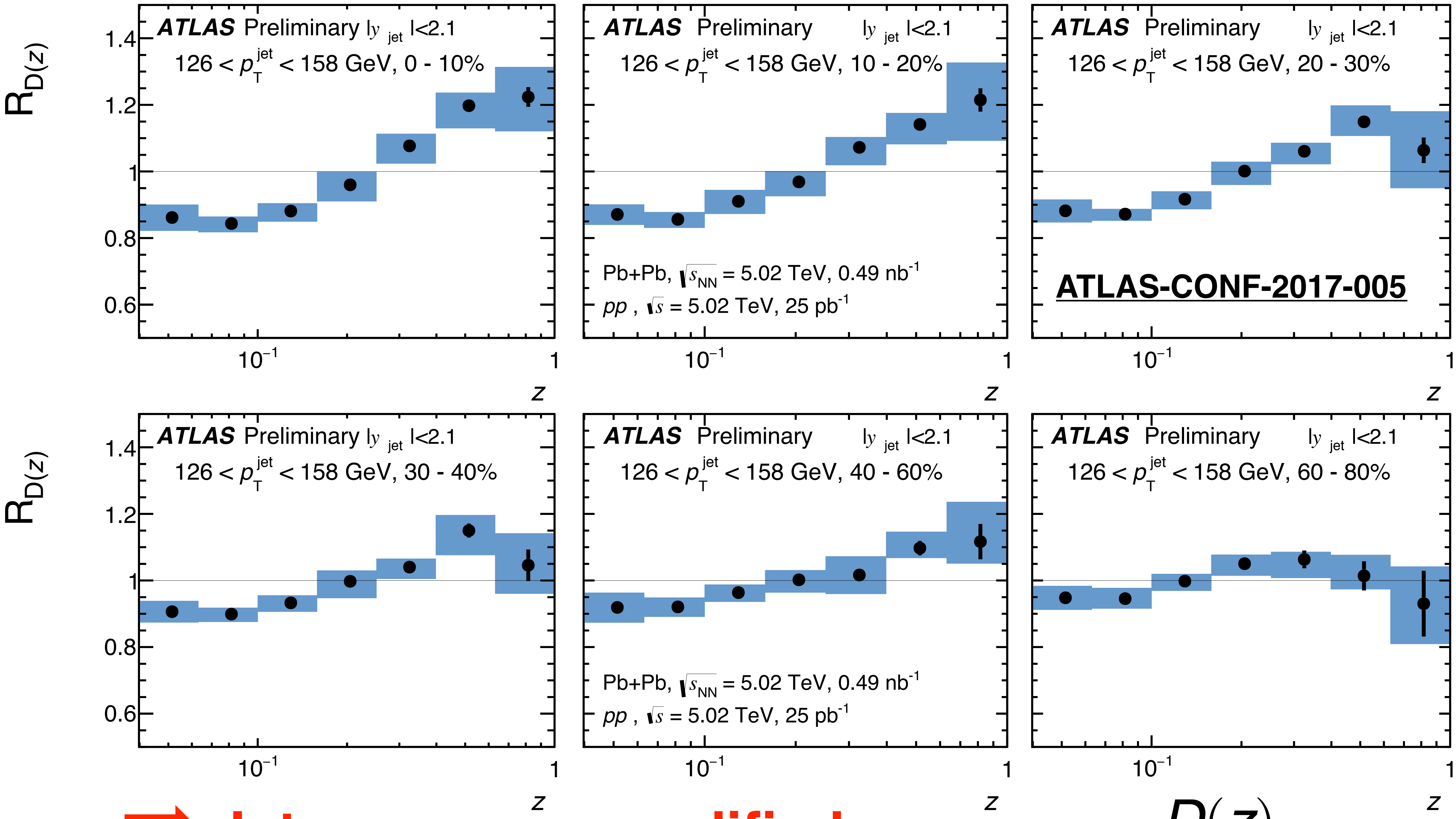


- **Need ratio to see modification.**

$$R_{D(z)} = \frac{\boxed{D(z)_{\mathrm{PbPb}}}}{\boxed{D(z)_{\mathrm{pp}}}} \qquad D(z) = \frac{1}{N_{\mathrm{jet}}}\frac{dN_{ch}}{dz}$$

Internal structure: Pb+Pb

Pb+Pb $R_{D(z)}$ in centrality bins



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➡ **Jets are more modified in central collisions**

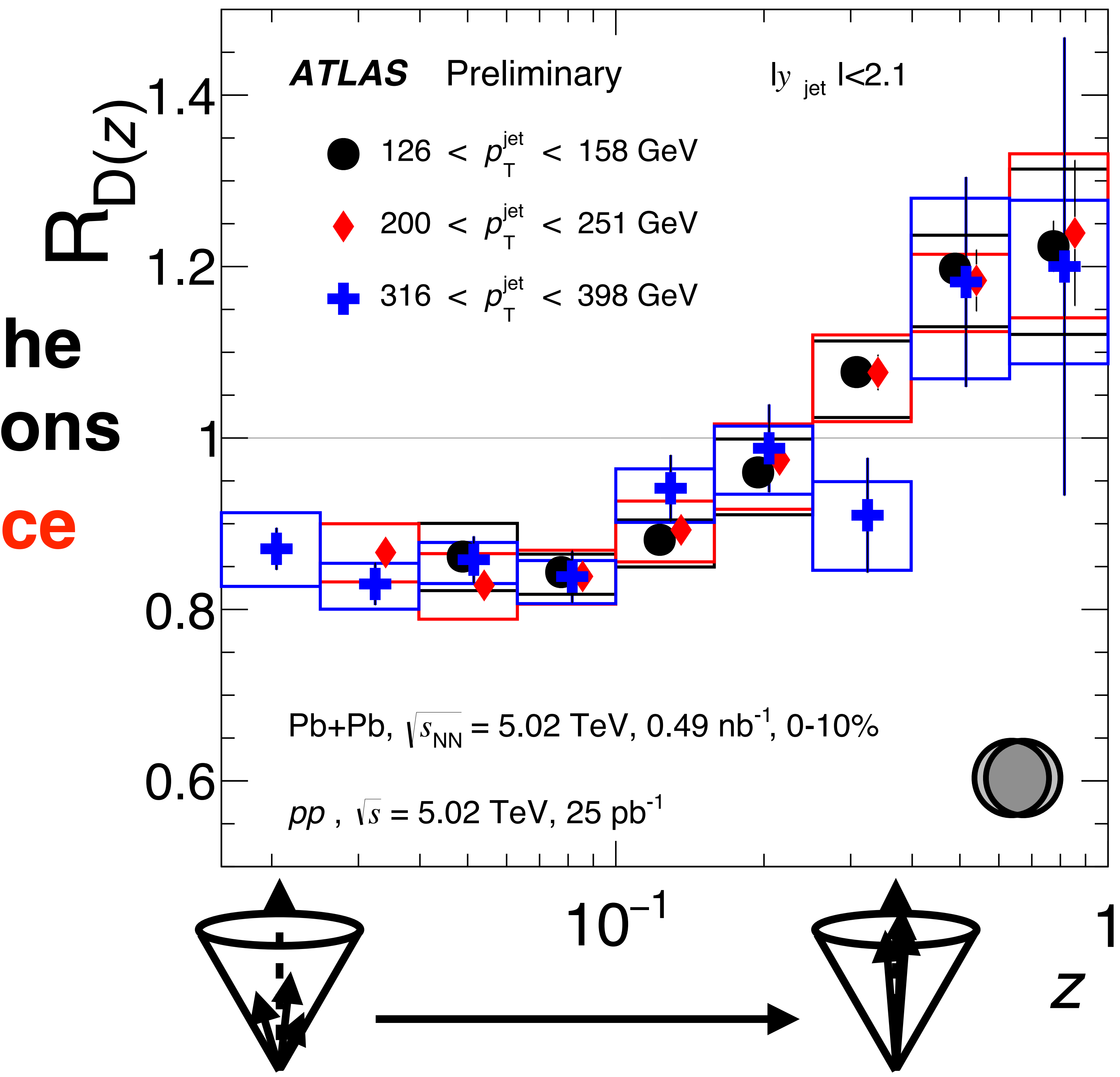
$$R_{D(z)} = \frac{D(z)_{PbPb}}{D(z)_{pp}}$$

Internal structure: Pb+Pb

ATLAS-CONF-2017-005

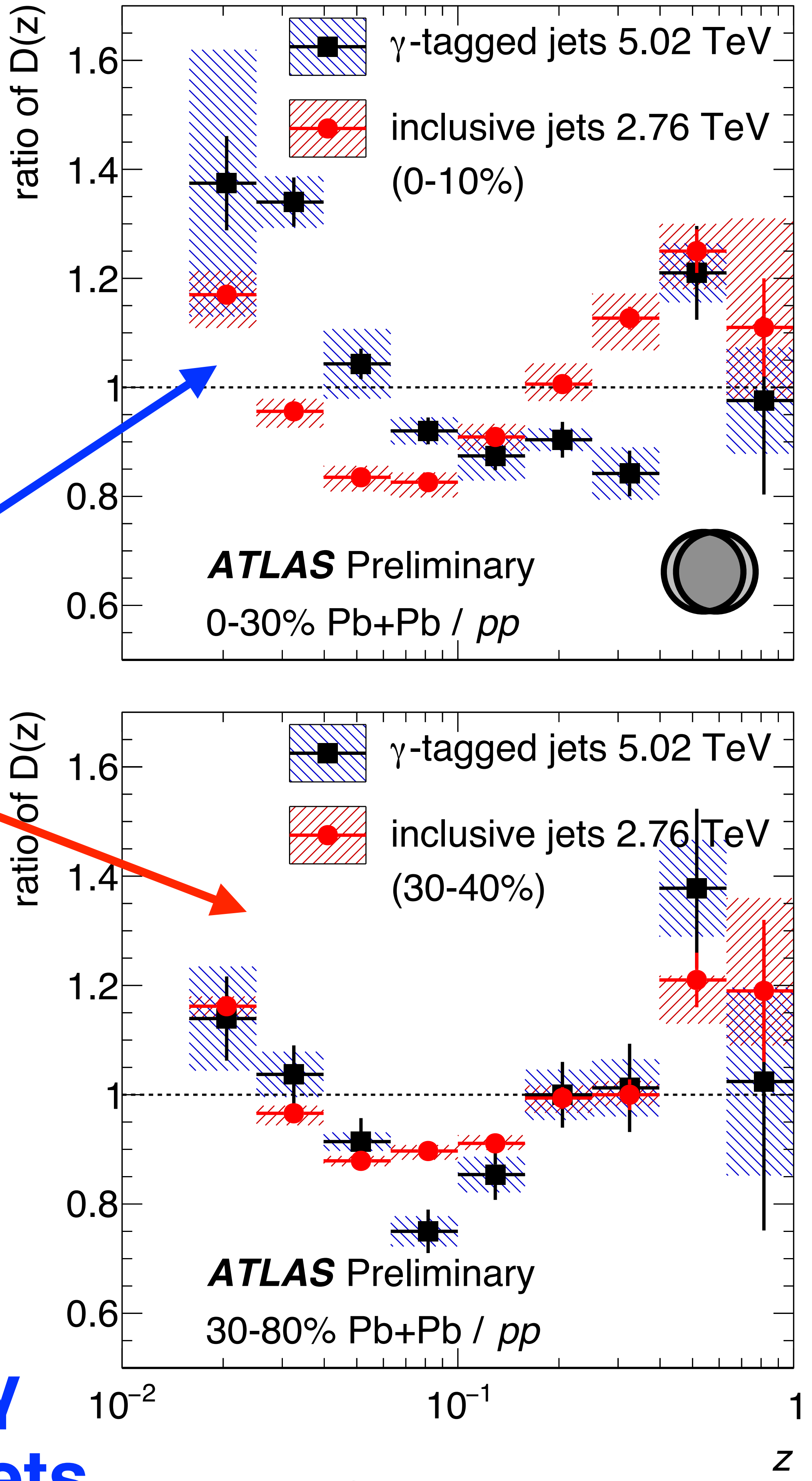
- **Dependence of the internal structure on the jet p_T in central collisions**

➡ **No jet p_T dependence to fragmentation functions**



Internal structure: photon tagged

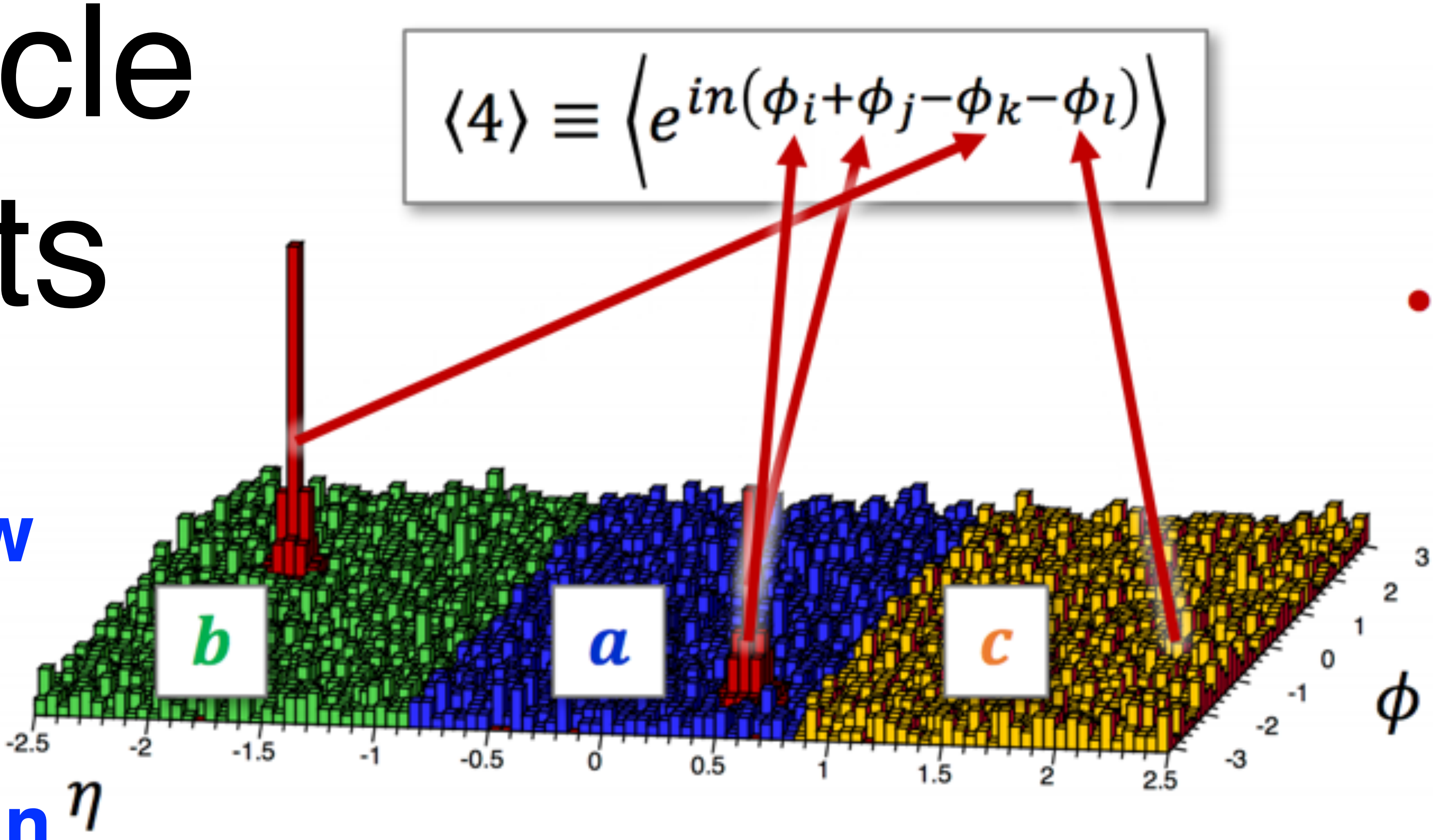
- **FF in γ-tagged jets compared to inclusive jets**
  - ➡ **γ-tagged jets have stronger modification in central**
  - ➡ **Better agreement in 30-40%**
- **This could be do to the effect of different jet p_{T} selections?**
- **Preferential selection of jets losing less energy in the inclusive case?**
- **Probes flavor dependence since γ +jets are more likely from quark jets**



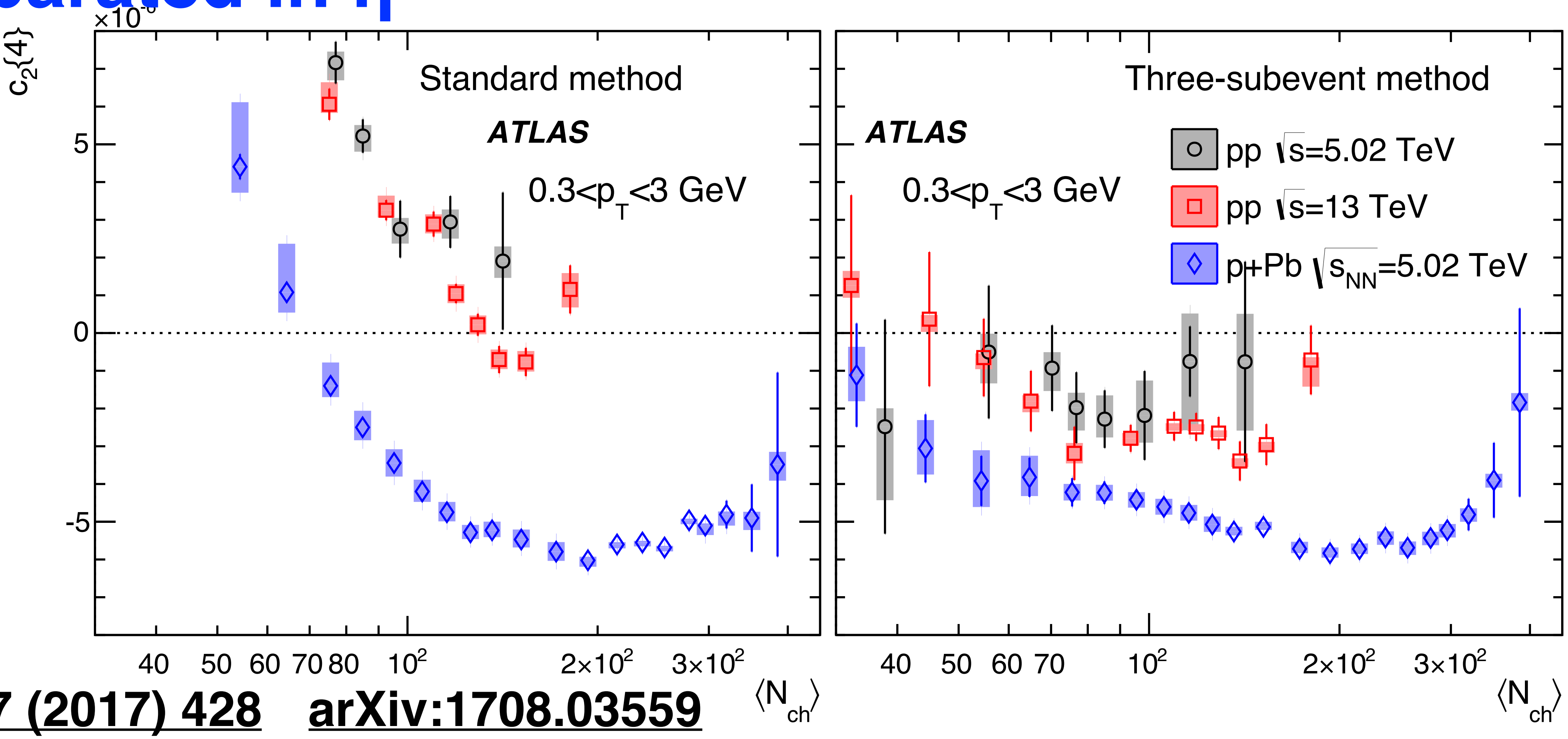
ATLAS-CONF-2017-074

Multi-particle cumulants

- **Sub-event method suppresses non-flow by using particles from different sub-events separated in η**



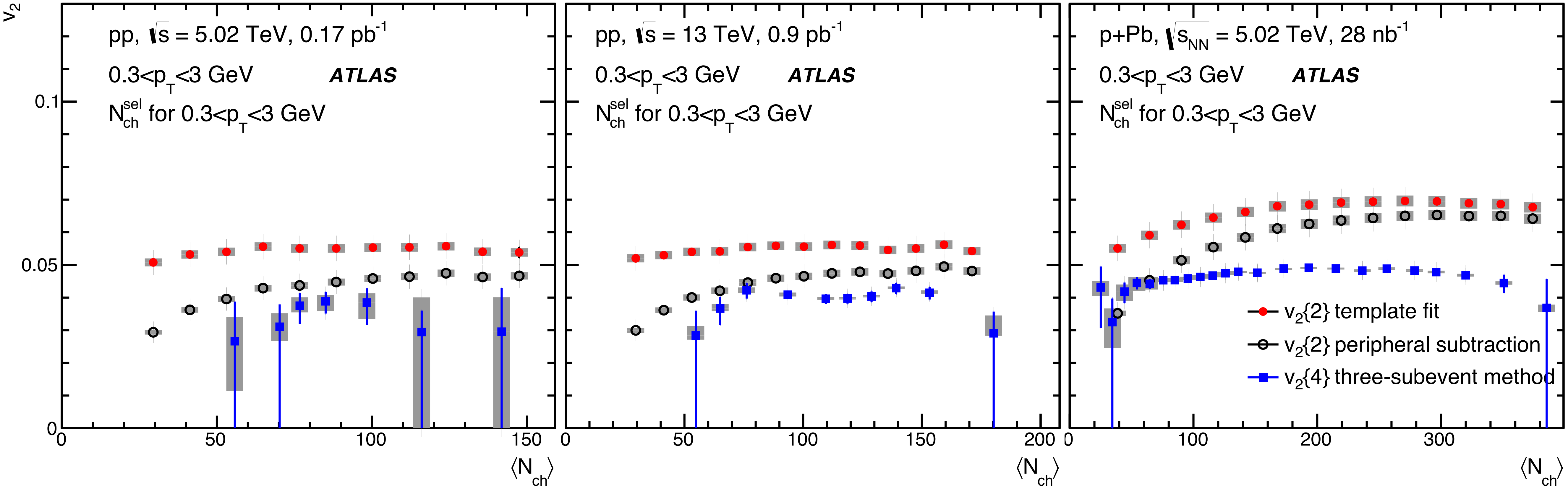
$$\langle 4\rangle \equiv \left\langle e^{in(\phi_i+\phi_j-\phi_k-\phi_l)}\right\rangle$$



Eur. Phys. J. C 77 (2017) 428 **arXiv:1708.03559**

Multi-particle cumulants

$$\frac{v_2\{4\}}{v_2\{2\}} = \left[\frac{4}{(3+N_s)}\right]^{1/4} \quad \text{or} \quad N_s = \frac{4v_2\{2\}^4}{v_2\{4\}^4} - 3\,.$$



- **c2{4} is an average event-by-event then over many events in each centrality**
- **centrality definition leads to flow fluctuations**
- **centrality smearing:ET not equal to Nch**

Eur. Phys. J. C 77 (2017) 428 **arXiv:1708.03559**

arXiv:1609.06213

Template fits

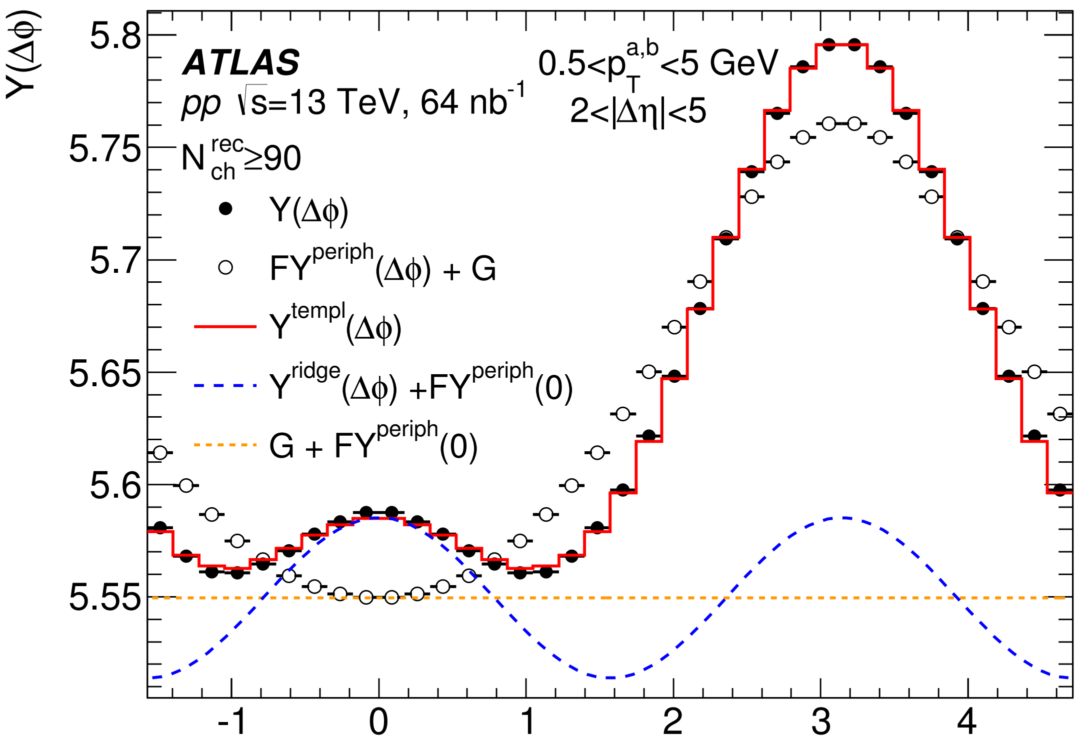
- ZYAM method similar to peripheral subtraction which removes the jet peak but depend on "zero yield at minimum" $Y^{\text{templ}}(\Delta\phi) = Y^{\text{ridge}}(\Delta\phi) + F\, Y^{\text{periph}}(\Delta\phi)$

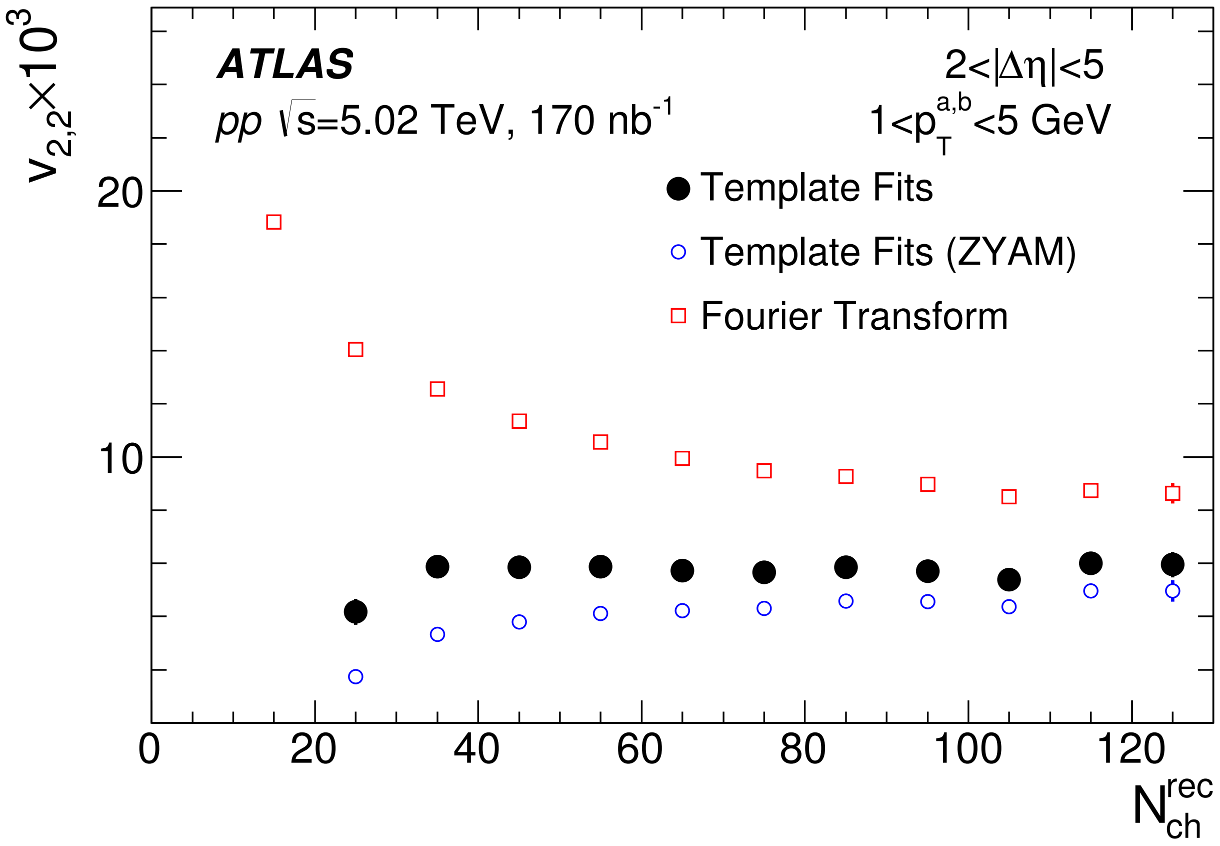
Template-vn,n overcomes this problem

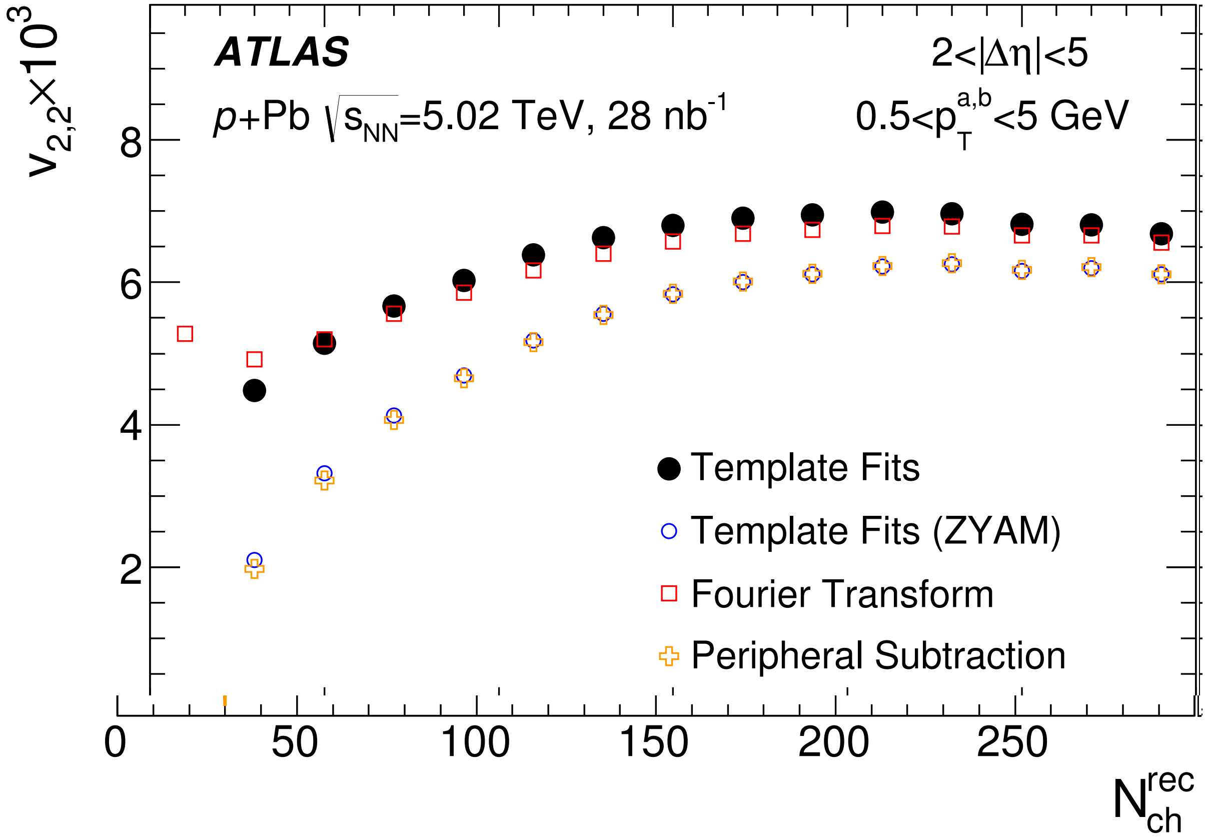
where

$$Y^{\text{ridge}}(\Delta\phi) = G\left(1 + \sum_{n=2}^{\infty} 2v_{n,n}\cos(n\Delta\phi)\right)$$

$v_{n,n}$ factories and v_n is extracted.

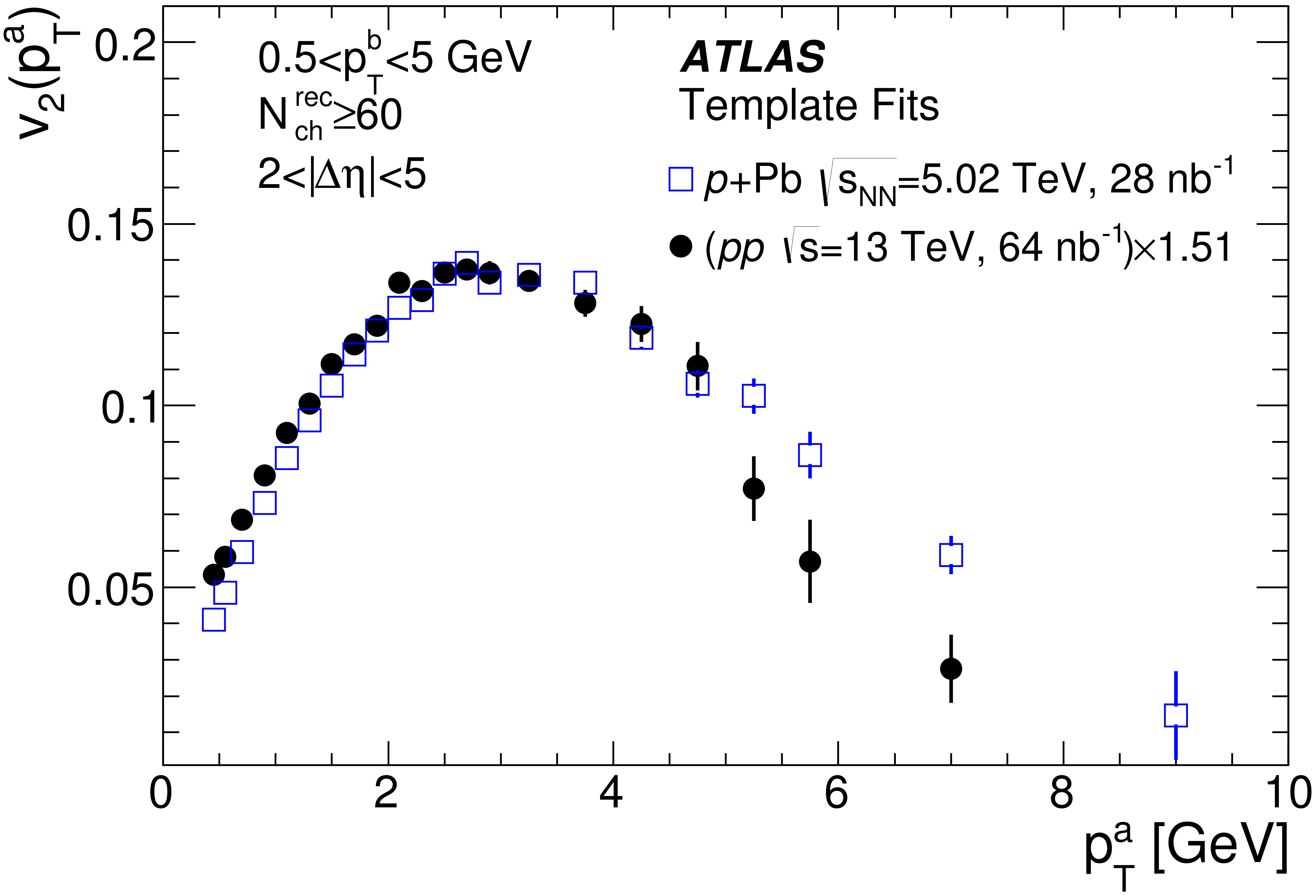






arXiv:1609.06213

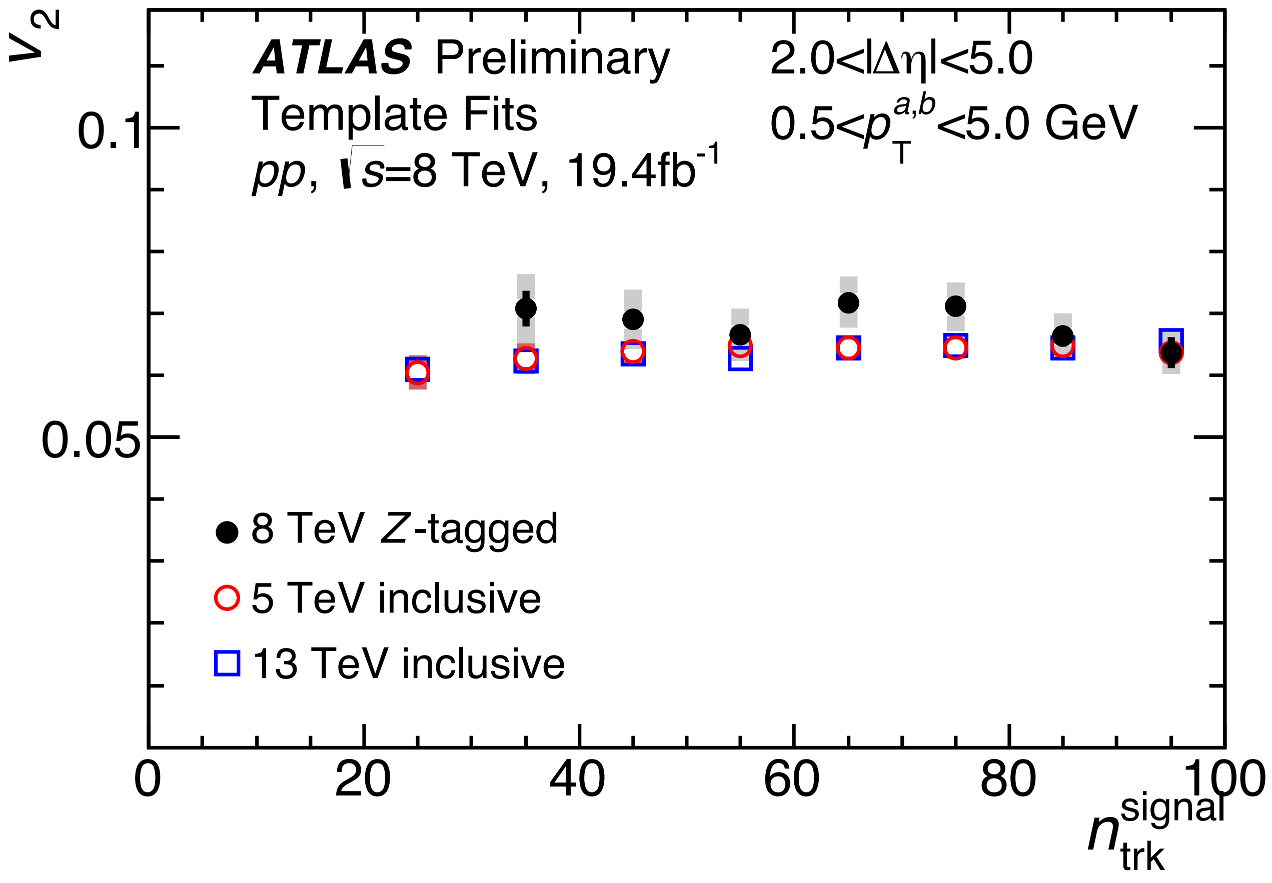
2P correlations

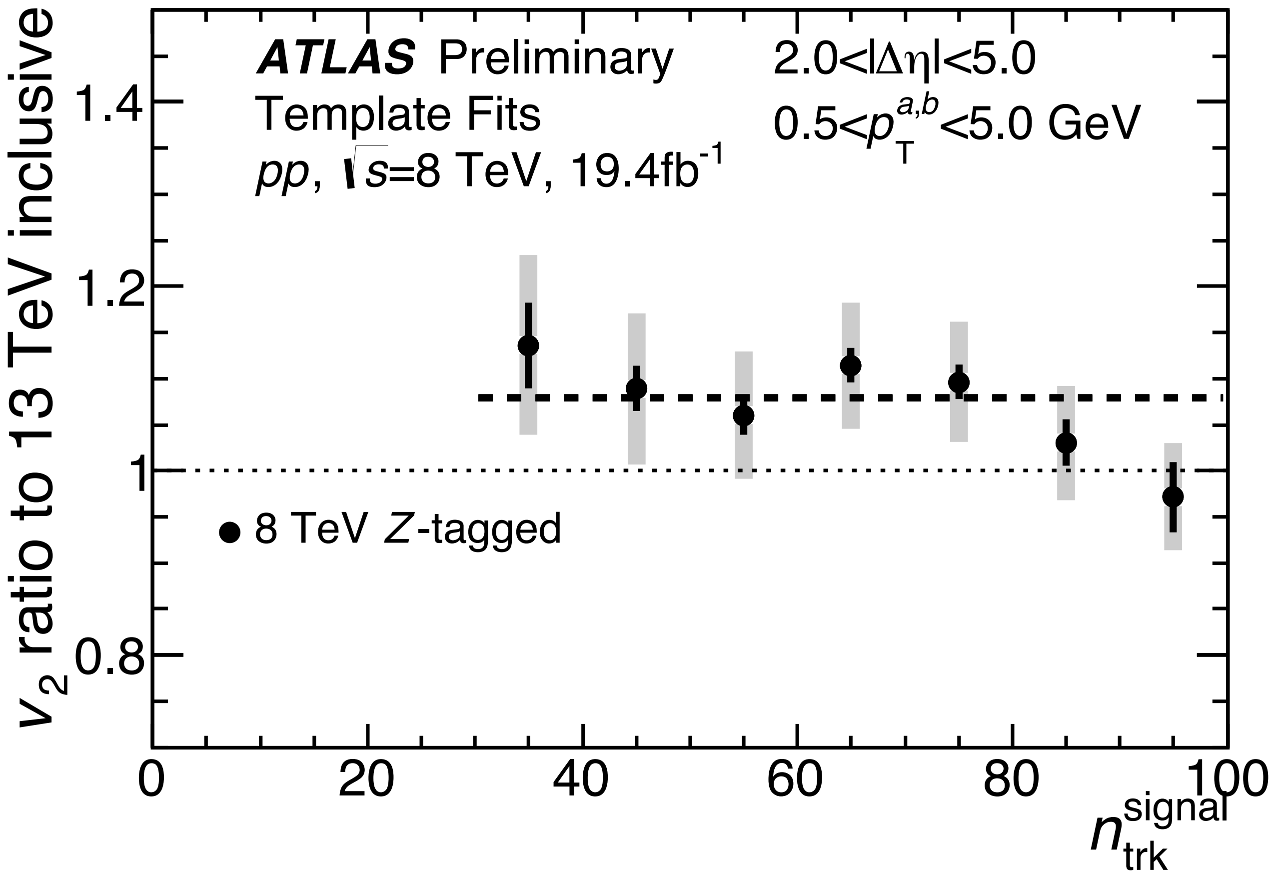


Z tagged ridge

- **2P correlations measured in 8 TeV *pp* collisions for hadrons in events with a Z boson**

➡ Control of the impact parameter in *pp* collisions by selecting at high Q^2 process





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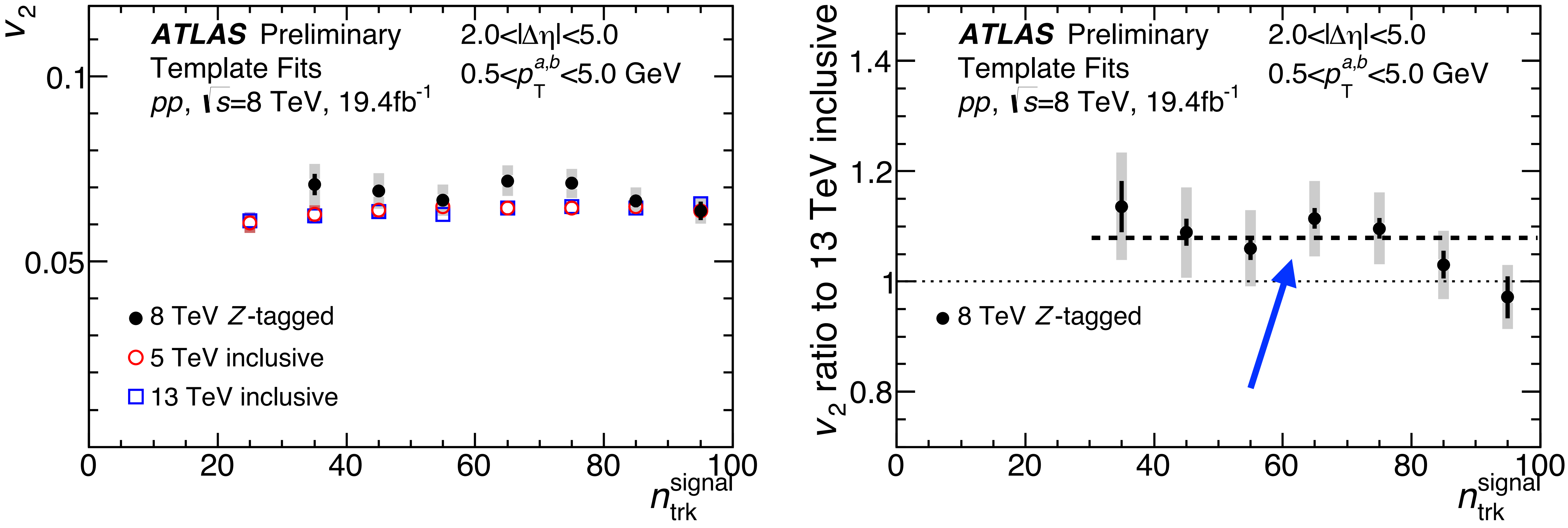
Z tagged ridge

- **2P correlations measured in 8 TeV *pp* collisions for hadrons in events with a Z boson**

➡ Control of the impact parameter in *pp* collisions by selecting at high Q^2 process

▶ v_2 found to be 8 ± 6 % higher than inclusive at 13 TeV



ATLAS-CONF-2017-068