Recent results from the ATLAS heavy ion program

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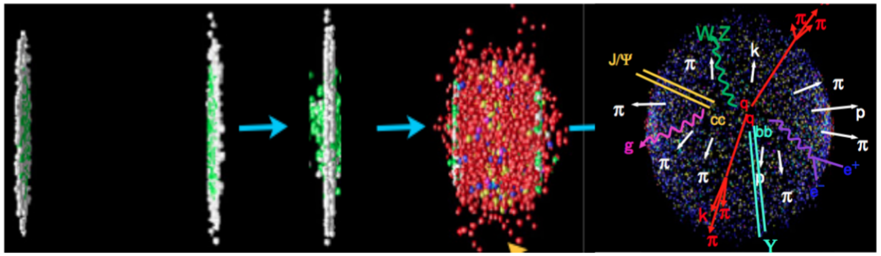
On behalf of the ATLAS Collaboration

Charles University in Prague

55. International Winter Meeting on Nuclear Physics

Bormio, Italy

Introduction

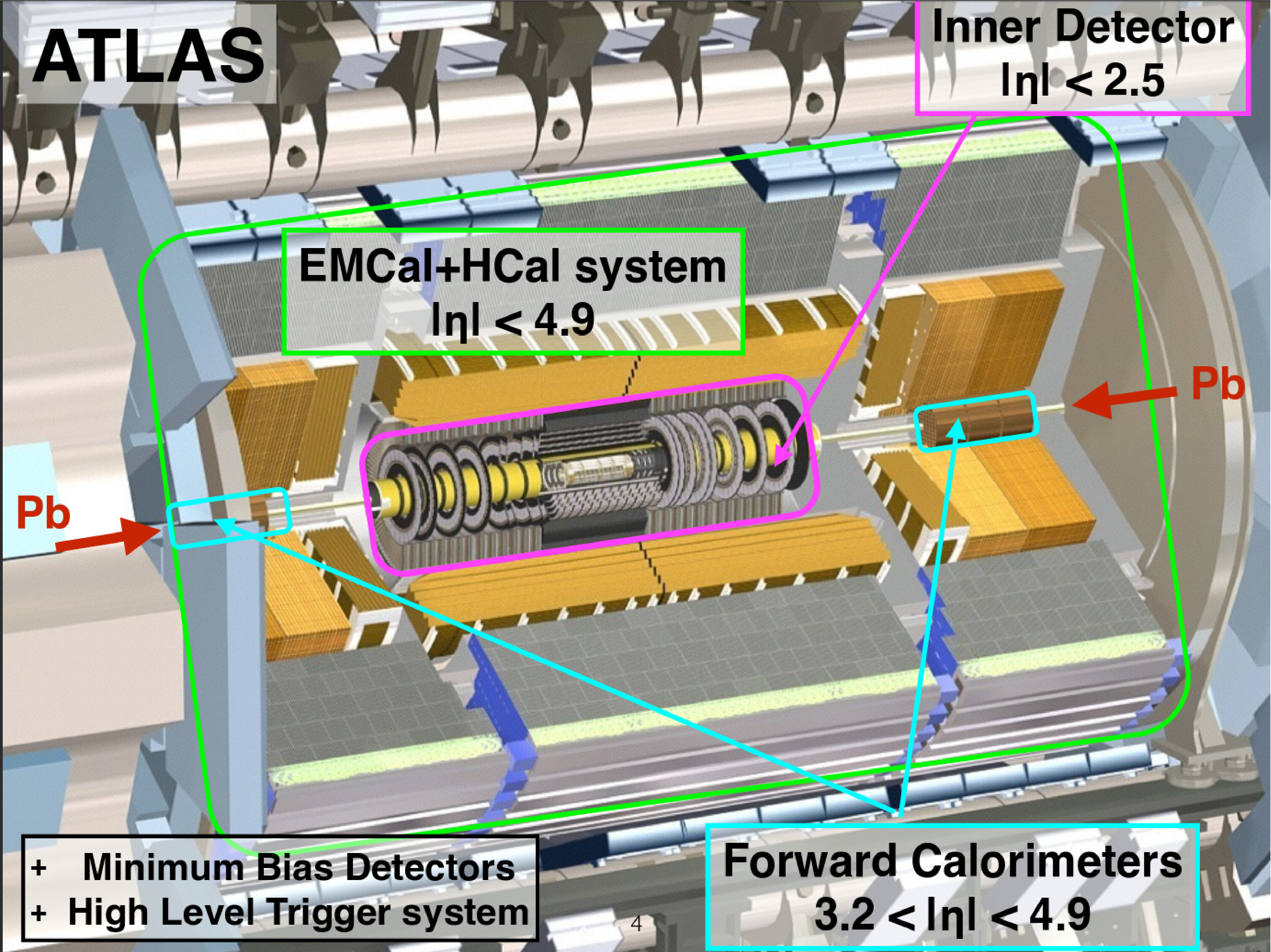


One of the main goals of heavy-ions physics is to study the QGP

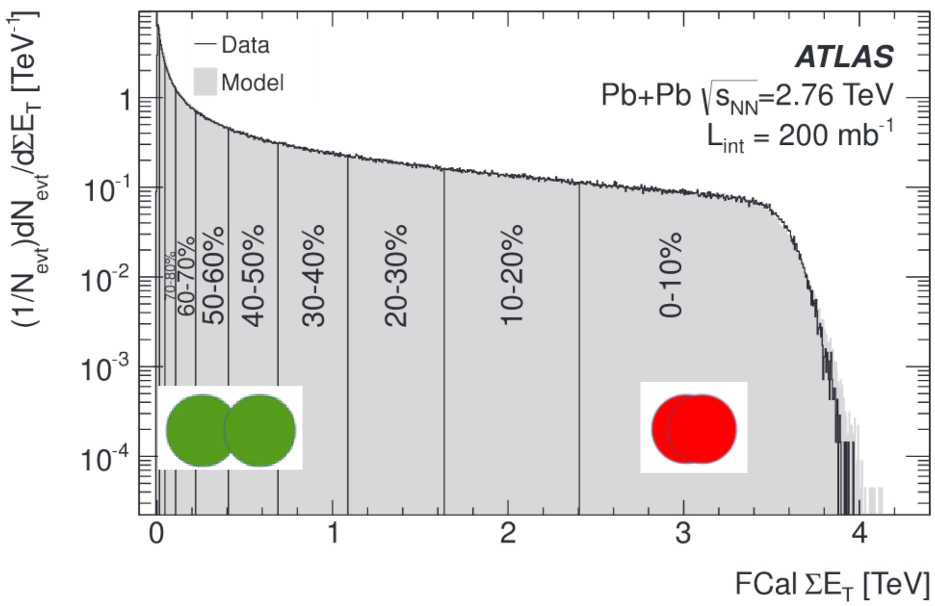
Use variety of final states to provide insight into various stages of heavy-ion collisions:

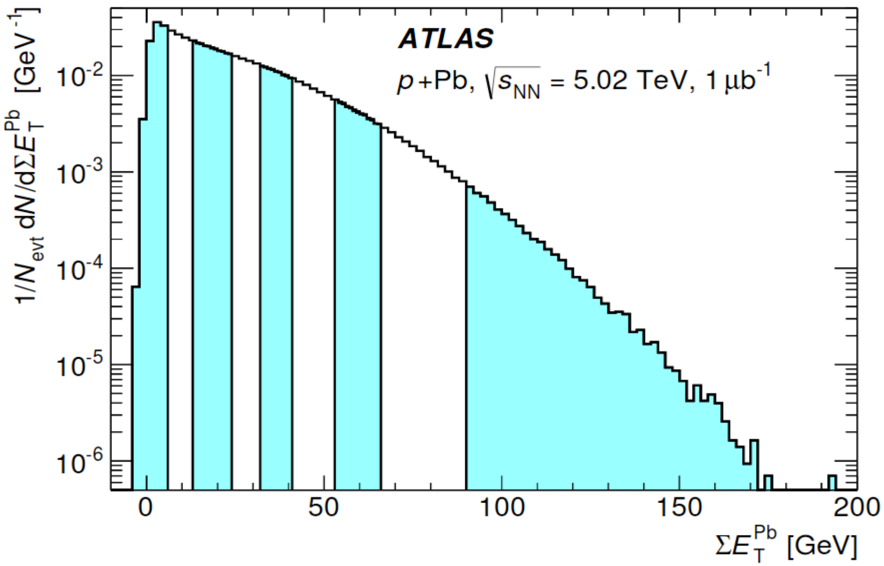
- Hard Probes:
  - Colorless objects e.g. electroweak bosons – standart candle in the medium
  - Color objects e.g. jets, hadrons – insight into partonic energy loss in QGP
- Bulk particle production:
  - Sensitivity to initial geometry, initial conditions, collective behaviour, etc.
- Disentangle initial- and final-state effects using p+Pb and *pp* systems

- LHC heavy ion runs at ATLAS: (not the full list)
  - Run 1: Pb+Pb: $\sqrt{s_{NN}}$ = 2.76 TeV, L_{int} = 0.15 nb^{-1}
    pp: $\sqrt{s}$ = 2.76 TeV, L_{int} = 4.2 nb^{-1}
    p+Pb: $\sqrt{s_{NN}}$ = 5.02 TeV, L_{int} = 29 nb^{-1}
  - Run 2: Pb+Pb: $\sqrt{s_{NN}}$ = 5.02 TeV, L_{int} = 0.5 nb^{-1}
    pp: $\sqrt{s}$ = 5.02 TeV, L_{int} = 28 pb^{-1}


ATLAS
Inner Detector
|η| < 2.5
EMCal+HCal system
|η| < 4.9
Pb
Pb
+ Minimum Bias Detectors
+ High Level Trigger system
Forward Calorimeters
3.2 < |η| < 4.9

Centality in Pb+Pb



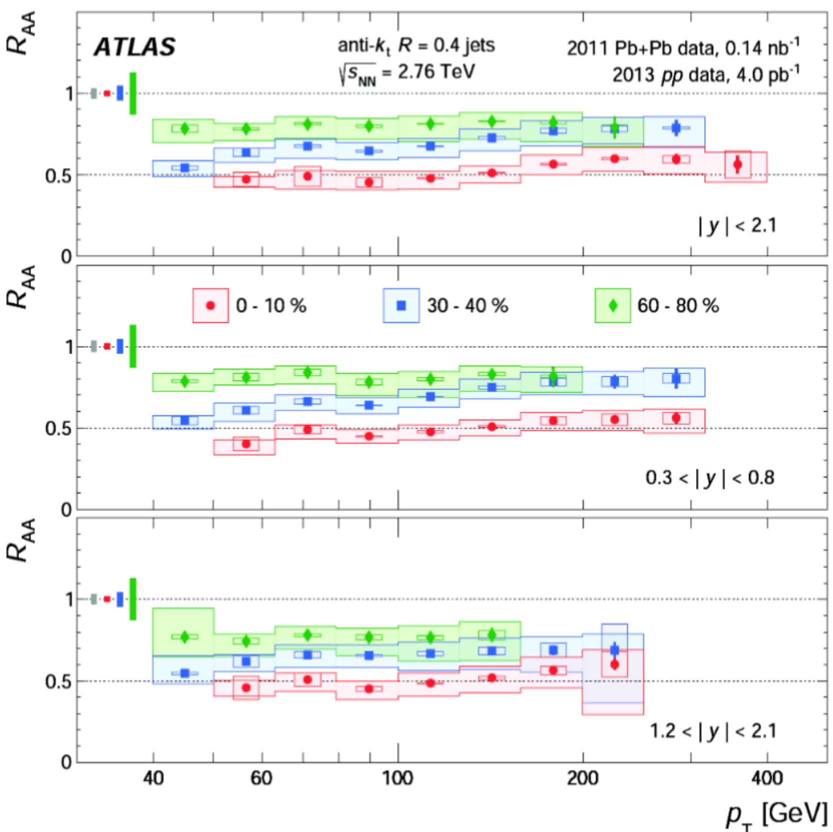


- Centrality express measure of everlap of two colliding nuclei
- Determined by the sum of the transverse energy deposited in the Forward calorimeters
- It is closely related to the average number of participant nucleons and number of binary inelastic collisions
- Events divided into succesive percintiles of the $\sum E_T^{\mathrm{FCal}}$

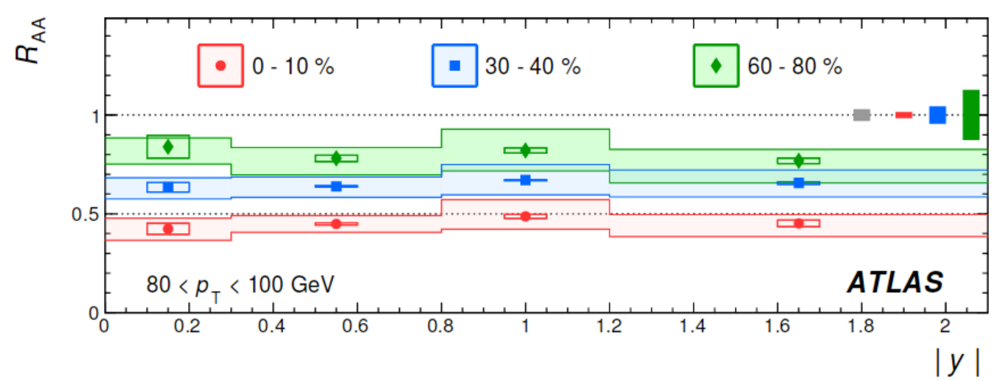
- In Pb+Pb collisions use sum of the transverse energy in both sides
- In p+Pb collisions use sum of the transverse energy on Pb-going side only

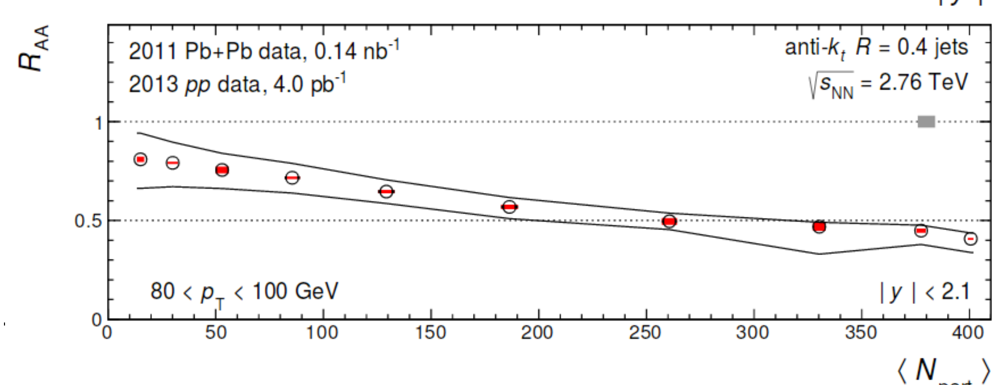
Jet R_{AA}

$$R_{AA} = \frac{\frac{1}{N_{\rm evnt}} \frac{d^2 N_{\rm jet}^{PbPb}}{dp_{\rm T} dy}\Big|_{\rm cent}}{\langle T_{AA} \rangle_{\rm cent} \times \frac{d^2 \sigma_{\rm jet}^{pp}}{dp_{\rm T} dy}}$$



- High transverse momentum partons, produced in hard scattering process, propagating through the medium of strongly interacting nuclear matter lose energy, resulting in the phenomenon of ‘jet quenching’
- Magnitude of the suppresion is expected to depend on both the p_T dependence of energy loss as well as the shape of initial jet p_T spectrum

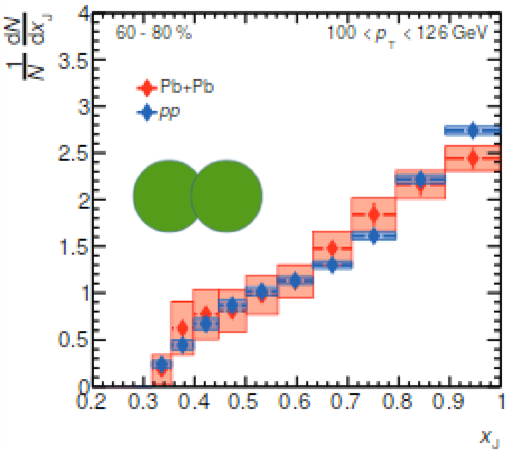


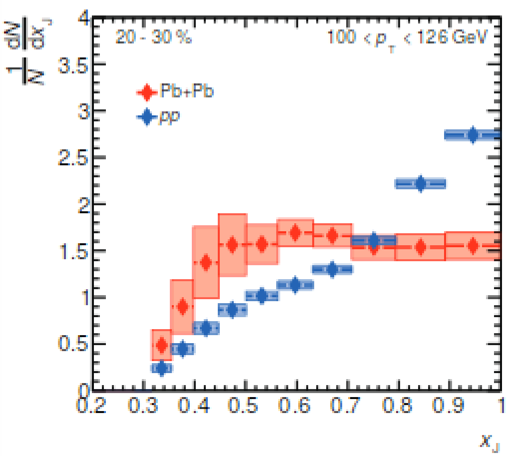


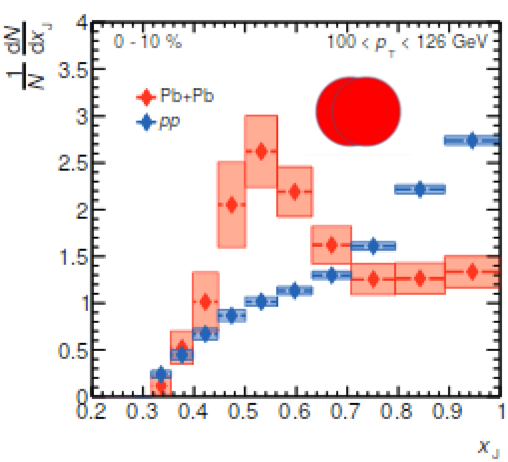
- A modest grow of jet R_{AA} with increasing jet p_T
- Still a significant suppression even for 60-80% centrality bin
- Practically no rapidity dependence

PRL114 (2015) 072302

New dijet asymmetry measurement







- Dijets - the jets originating from the same hard scattering can loose different amounts of energy in the medium depending on the path lengths traveled or by fluctuations.

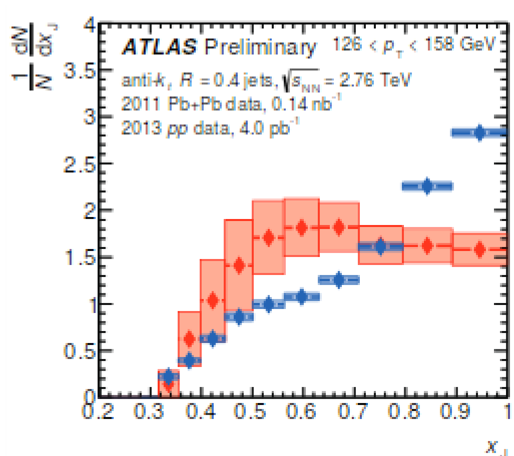
- New measurement of the unfolded asymmetry in Pb+Pb collisions compared to *pp* at 2.76 TeV as a function of centrality for R=0.4 jets

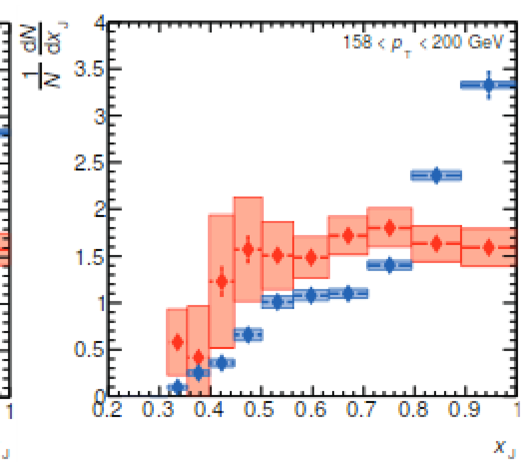
- Dijets were corrected for jet energy resolution by 2D Bayesian unfolding to account for bin migration in $p_{T,1}$ and $p_{T,2}$ silmultaneously

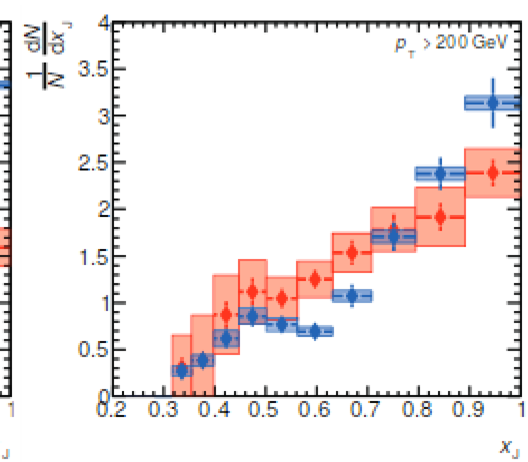
$$x_J = \frac{p_{T,1}}{p_{T,2}}$$

- Increase of asymmetry with centrality of HI collisions.
- Asymmetry much less pronounced in high p_T jets sample

ATLAS-CONF-2015-52







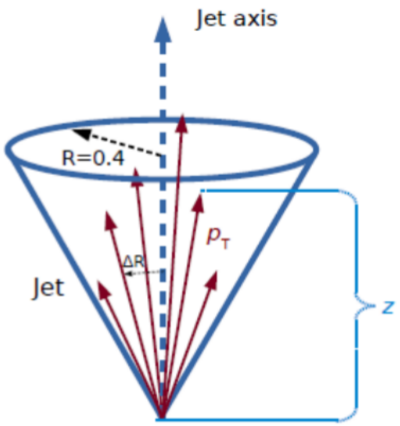
Jet fragmentation

ATLAS-CONF-2015-055

- How much is the jet structure modified?

- Jet fragmentation functions (FF) are defined as:

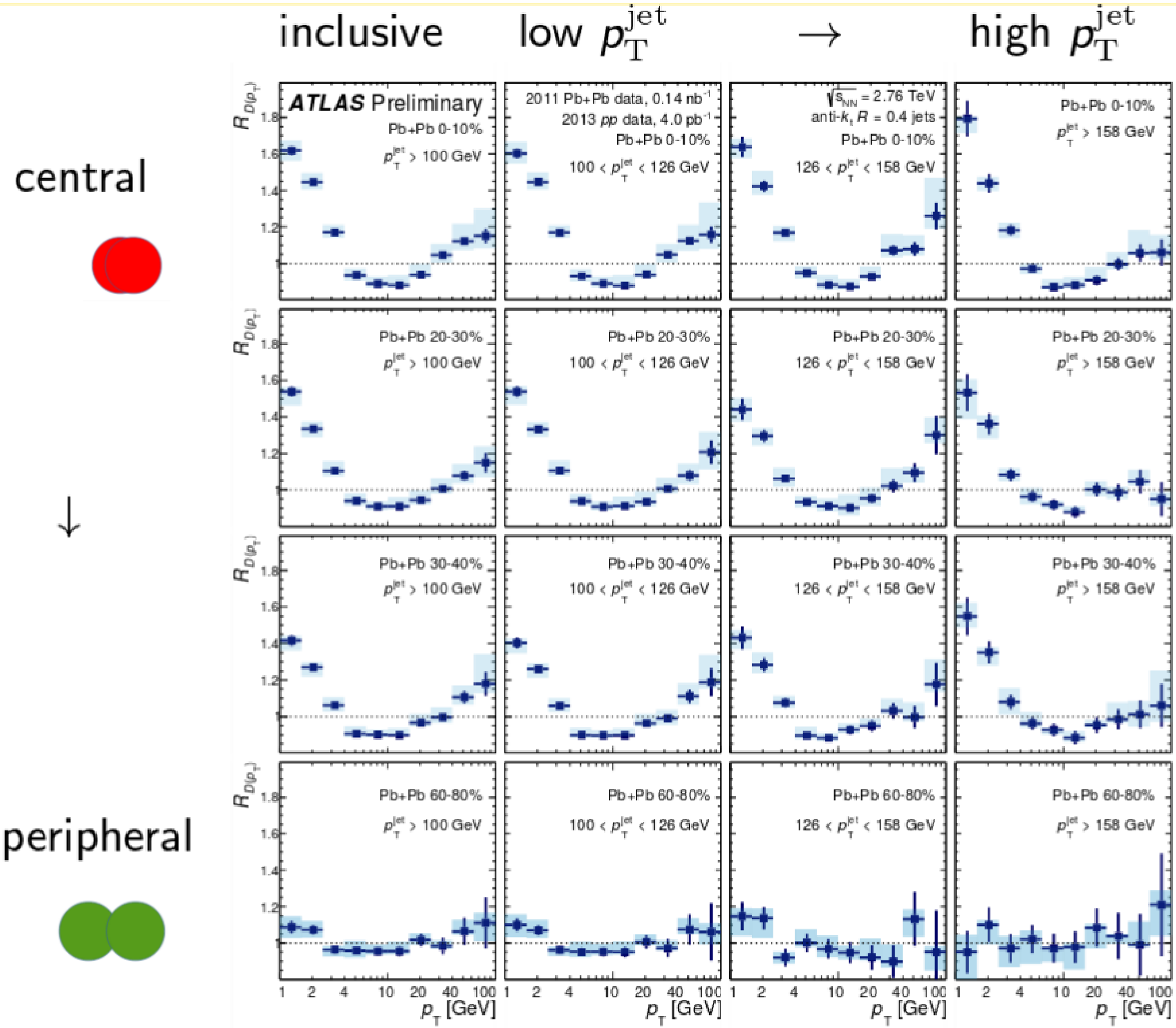
$$D(p_T) = \frac{1}{N_{\mathrm{jet}}}\frac{\mathrm{d}N_{\mathrm{ch}}}{\mathrm{d}p_T^{\mathrm{ch}}} \qquad D(z) = \frac{1}{N_{\mathrm{jet}}}\frac{\mathrm{d}N_{\mathrm{ch}}}{\mathrm{d}z} \qquad z = \frac{p_T}{p_T^{\mathrm{jet}}}\cos\Delta R$$



- N_{ch} is the number of charged particles associated to a jet
- Measurement was done for R = 0.4 jets differentially in η and p_T
- Jet substructure measured using charged tracks starting at p_T = 1 GeV
- FF are background subtracted, corrected for tracking efficiency and fully unfolded with 2D Bayesian unfolding

Jet fragmentation ratios

Ratios of $D(p_T)$ for 4 centralities in 4 p_T bins



ATLAS-CONF-2015-055

Centrality dependence

- Enhancement at low and high p_T
- Suppression at intermediate p_T

Jet p_T dependence

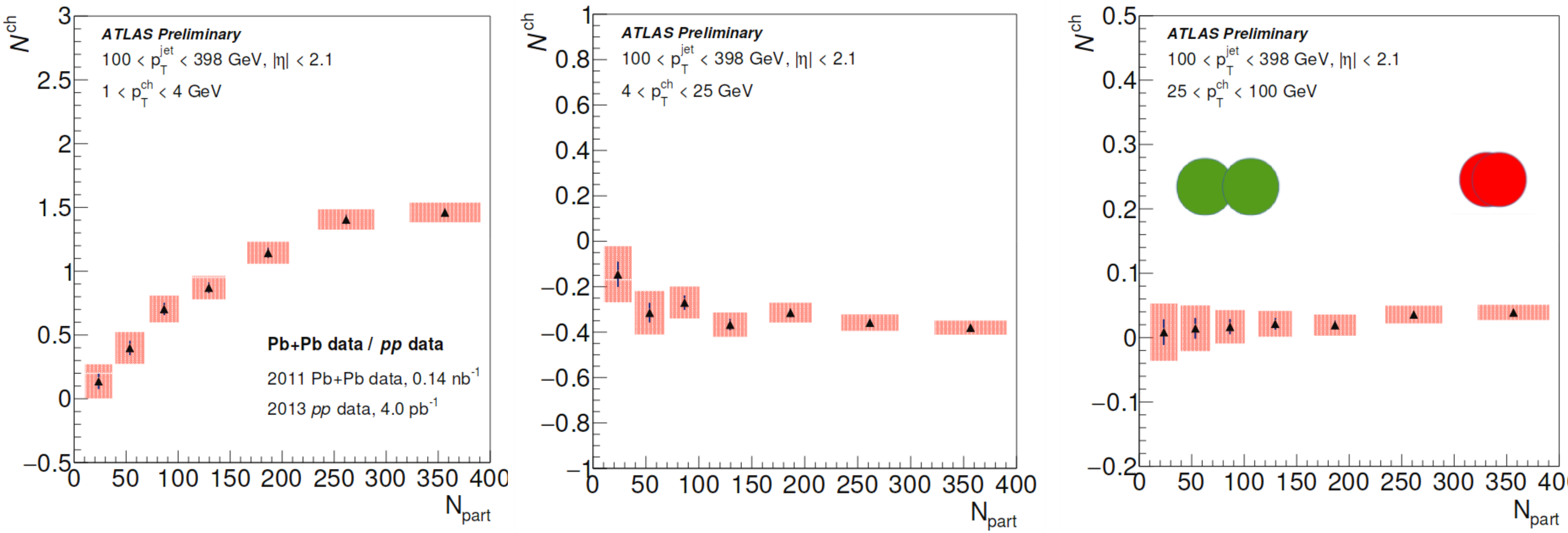
- No significant dependence on jet p_T

Rapidity dependence

- Hint of rapidity dependence

Jet fragmentation – flow of particles

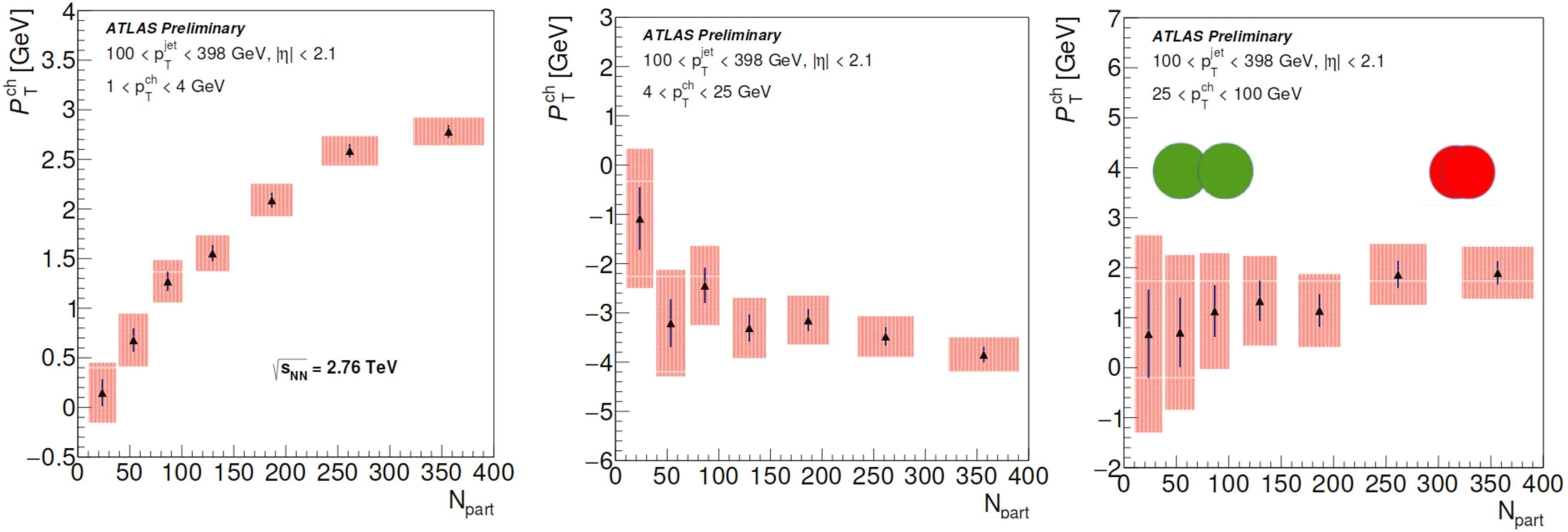
ATLAS-CONF-2015-055



- To quantify the flow of particles as a function of N_{part}: $N^{\mathrm{ch}} \equiv \int_{p_{\mathrm{T,min}}}^{p_{\mathrm{T,max}}} \left(D(p_{\mathrm{T}})|_{\mathrm{cent}} - D(p_{\mathrm{T}})|_{\mathrm{pp}} \right) \mathrm{d}p_{\mathrm{T}}$
- Tells us how many extra/missing particles are present in a given p_T range
- Observed a clear increase of yields of particles with low tranverse momenta as the collision's centrality increases
- Particles with p_T > 4 GeV do not exhibit noticeable variations with centrality

Jet fragmentation – flow of energy

ATLAS-CONF-2015-055



- To quantify the flow of momentum as a function of N_{part}:

$$P_{\mathrm{T}}^{\mathrm{ch}} \equiv \int_{p_{\mathrm{T,min}}}^{p_{\mathrm{T,max}}} \left(D(p_{\mathrm{T}})|_{\mathrm{cent}} - D(p_{\mathrm{T}})|_{\mathrm{pp}} \right) p_{\mathrm{T}} \, \mathrm{d}p_{\mathrm{T}}$$

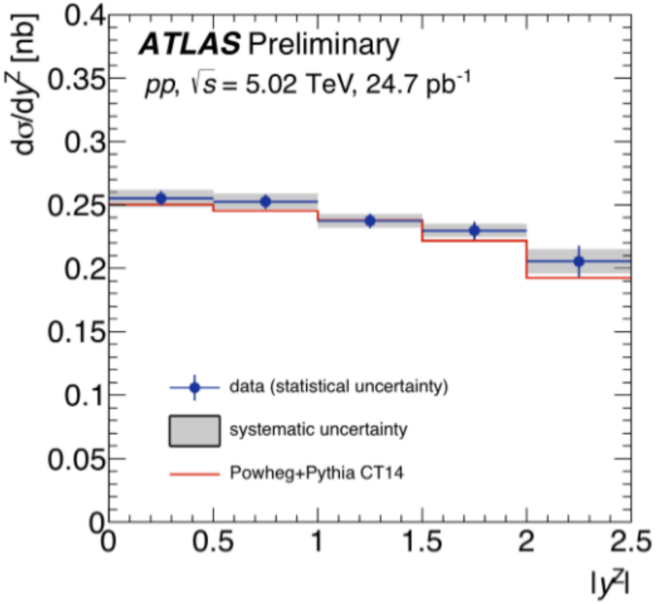
- Tells us how much p_T is carried by extra/missing particles in a given p_T range

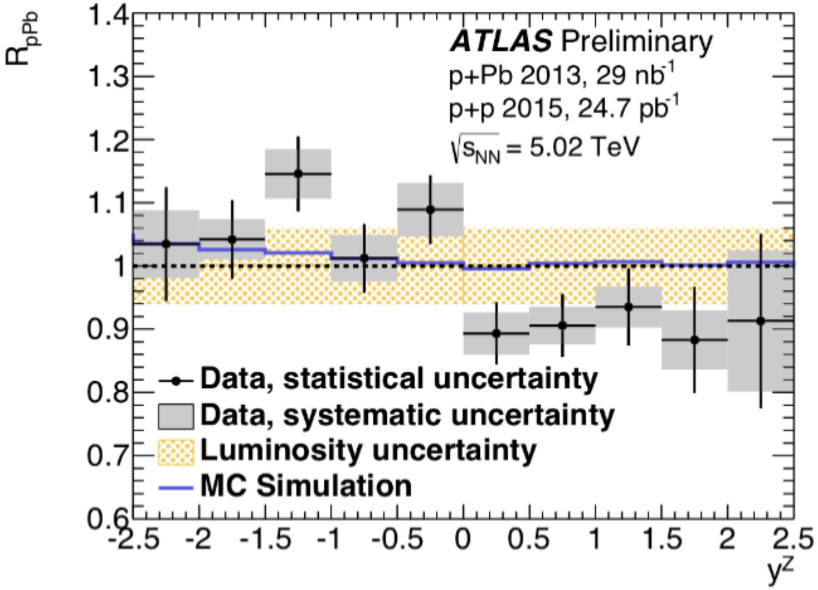
Z boson

ATLAS-CONF-2016-107
Phys. Rev C92, 044915(2015)

- Motivaton of measuring the EW probes:
  - Since EW boson don't interact with the strong interaction, they aren't influenced by the medium modifications
  - We can look at the EM boson + jet event – is p_T balanced?
  - Or we can test modification of the PDF's caused by the nuclear efects

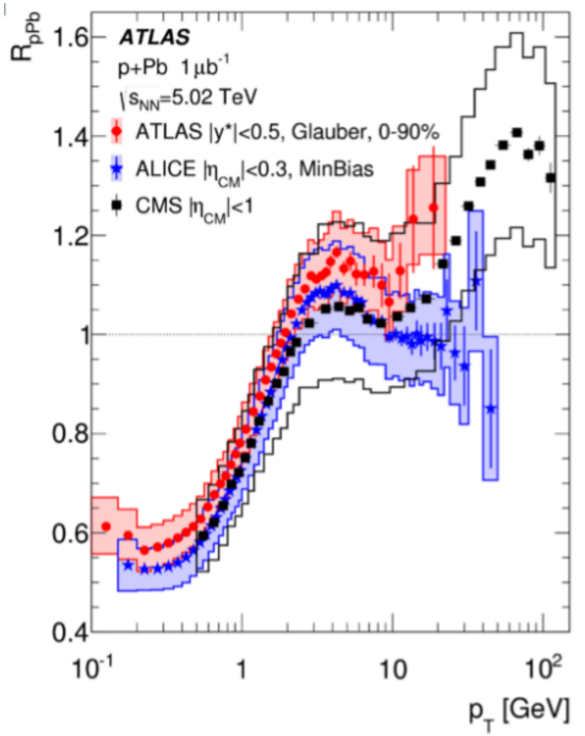
- Z boson measured in *pp* and p+Pb collisions
- Z boson production studied with decay via muon channels in *pp* 5 TeV data
- Cross section in the fidicial region of $66<M_{\mu\mu}<116$ GeV, $|y^Z| < 2.5$ is:
  - 590 ± 9 (stat.) ± 11 (syst.) ± 32 (lumi) pb
- In good agreement with the NNLO calculation using the CT14 PDF:
  $573.77^{+13.94}_{-15.96}$ pb
- R_{pPb} extracted using the old p+Pb result and new *pp* reference data

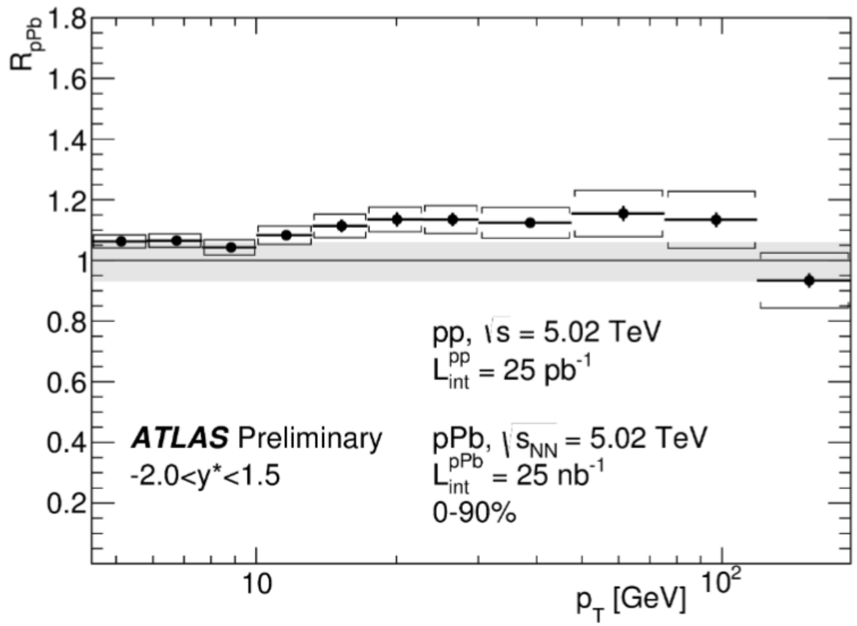


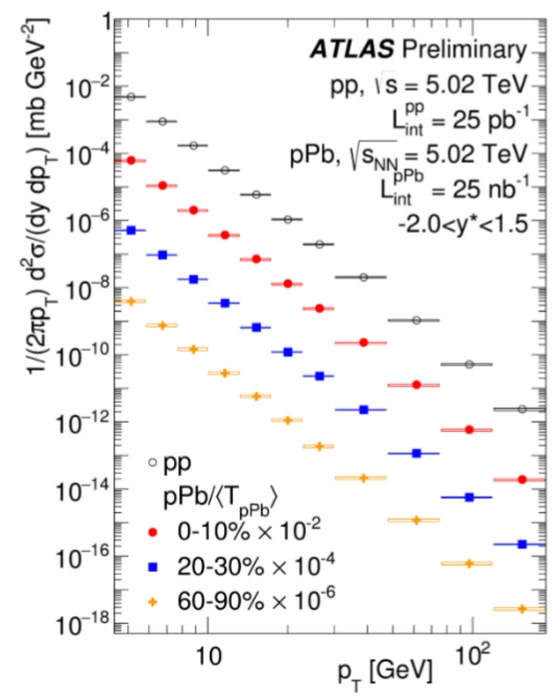


R_{pPb} of high-p_T hadrons

- Hint of enhancement of particle production at high-p_T in Run1 data where *pp* yield were interpolated from 2.76 and 7 TeV
- Nuclear modification faktor R_{pPb} for old p+Pb data extracted using *pp* reference
- Now with new 5 TeV *pp* data, we measured spectra of charged particles with p_T up to 100 GeV
- Huge improvement in reducing systematics uncertainties
- R_{pPb} flat and consistent with unity







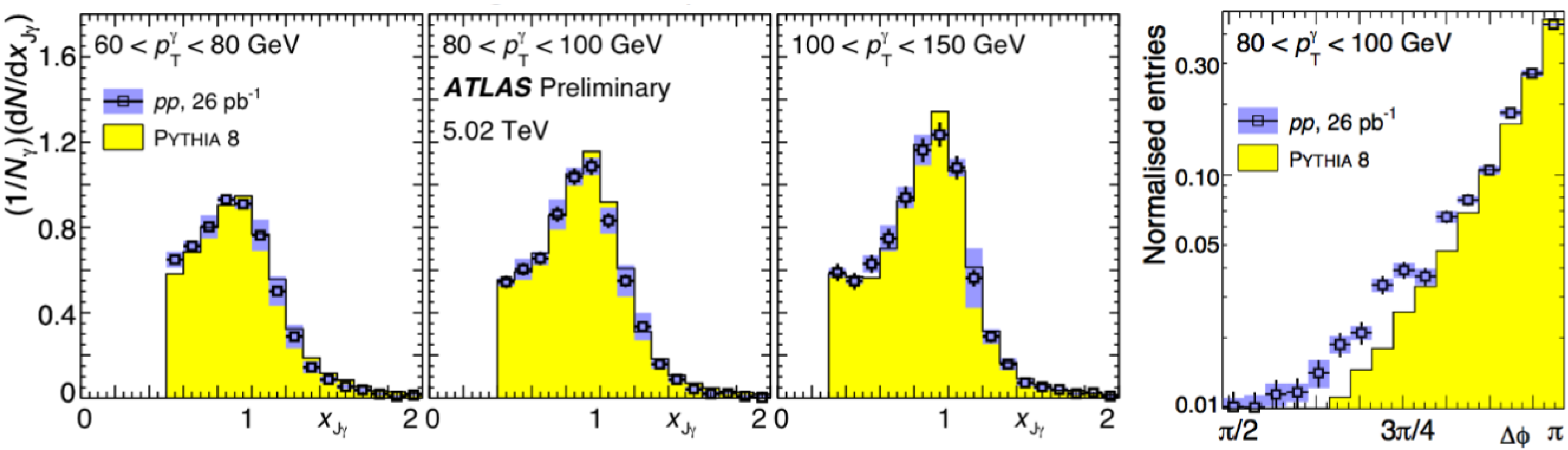
- Radim Slovak

Photon+jet correlation

- Run 1 data established: isolated photon yields are not affected by the medium
  - Use jet+photon events to measure jet energy loss in the QGP

- Two observables:
  - Per photon $x_{J\gamma}$ = jet p_T / photon p_T
  - $\Delta\Phi$ = difference in azimuthal angle between photon and jet
  - In *pp* : for $x_{J\gamma}$ good agreement of data with PYTHIA8 simulation

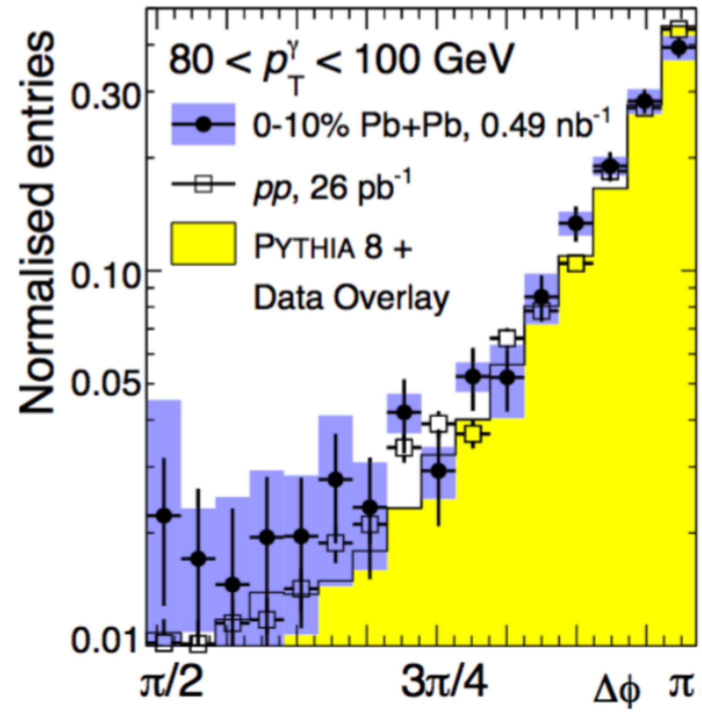
    for $\Delta\Phi$ good agreement for larger $\Delta\Phi$, smaller $\Delta\Phi$ does not describe the data due to lack of fragmentation photons in the MC

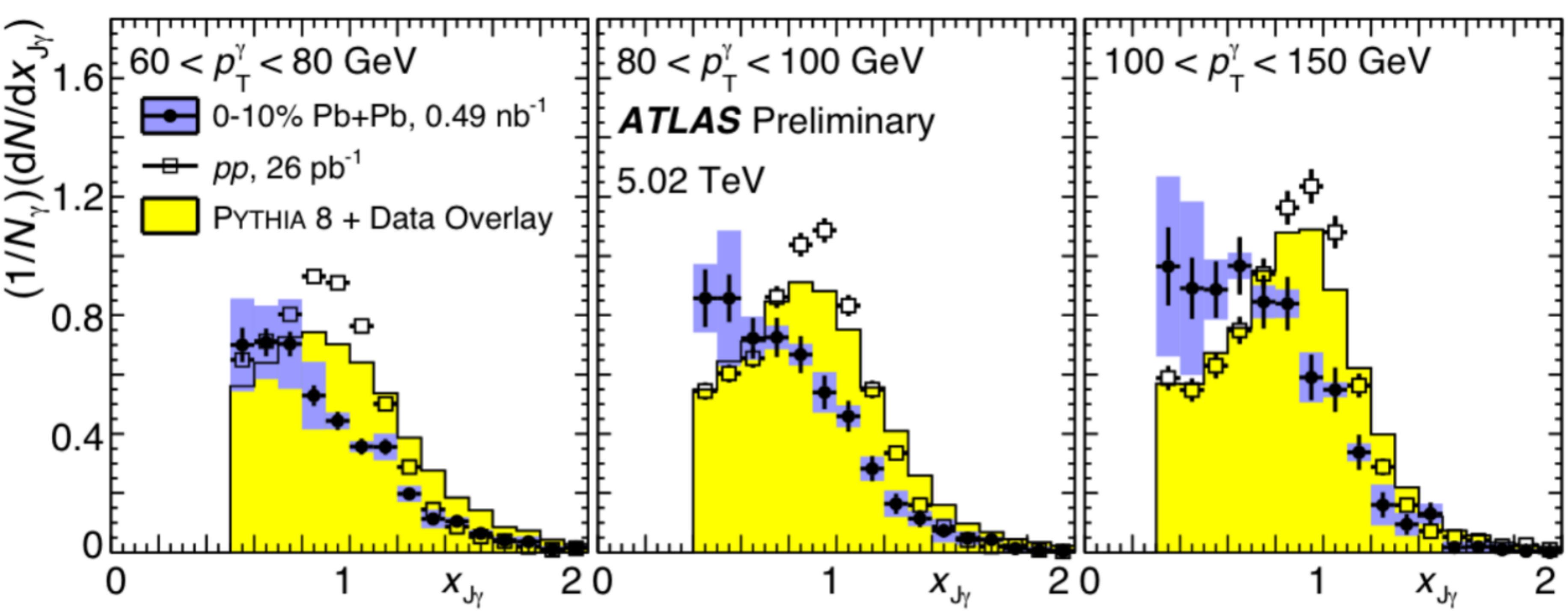


Photon+jet correlation

ATLAS-CONF-2016-110

- In the most central (0 - 10%) events in Pb+Pb:
  - $x_{j\gamma}$ is shifted towards lower values and shape is modified wrt predictions for all photon p_T bins
  - Shape of the ΔΦ distribution is consistent with that in *pp* collisions and in simulated Pb+Pb events
  - Observation qualitatively consistent with results at 2.76TeV

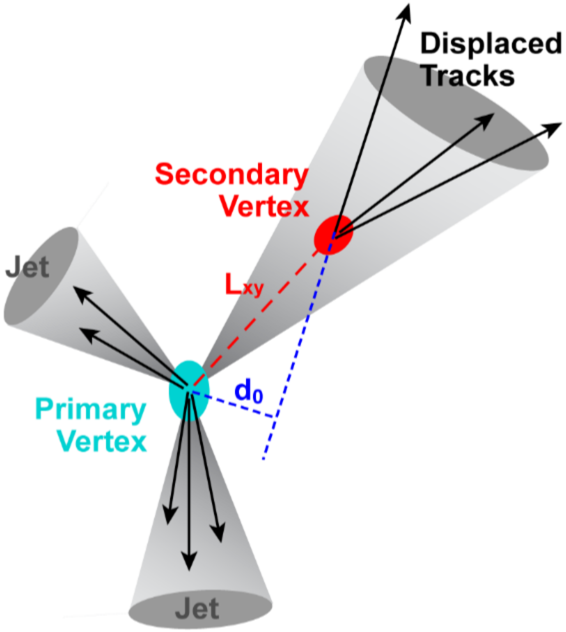




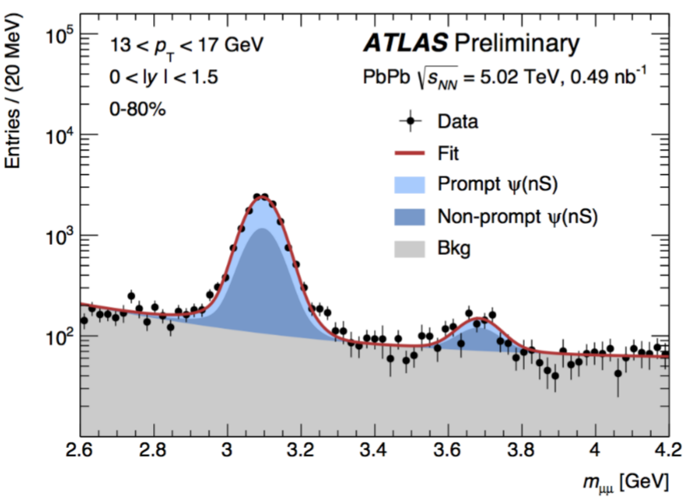
Charmonium production

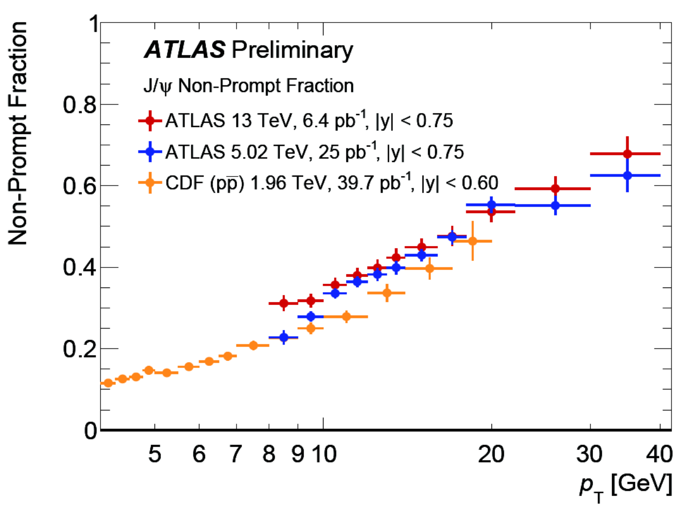
ATLAS-CONF-2016-124

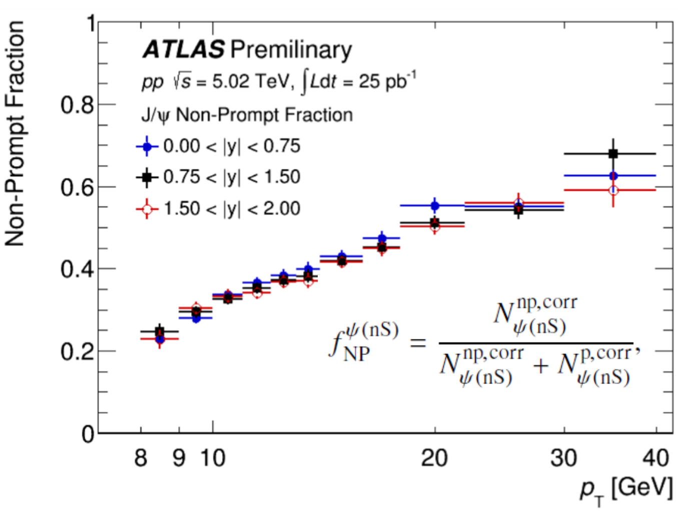
- Tool to provide information on temperature and degree of deconfinement of the QGP
- J/Ψ and Ψ(2S) production measured in *pp* and Pb+Pb collisions at 5 TeV
- Test response of medium to **prompt** (cc-bar) and **non-prompt** (b-decay) components
- Kinematic region: $9 < p_T < 40$ GeV, $|y| < 2$
- Use pseudo-proper decay time (τ) to distinguish between two production mechanisms
- Non-prompt fraction consistent between three rapidity intervals in *pp* and also between 5 and 13TeV data



$$\tau = \frac{L_{xy} m_{\mu\mu}}{p_T^{\mu\mu}}$$







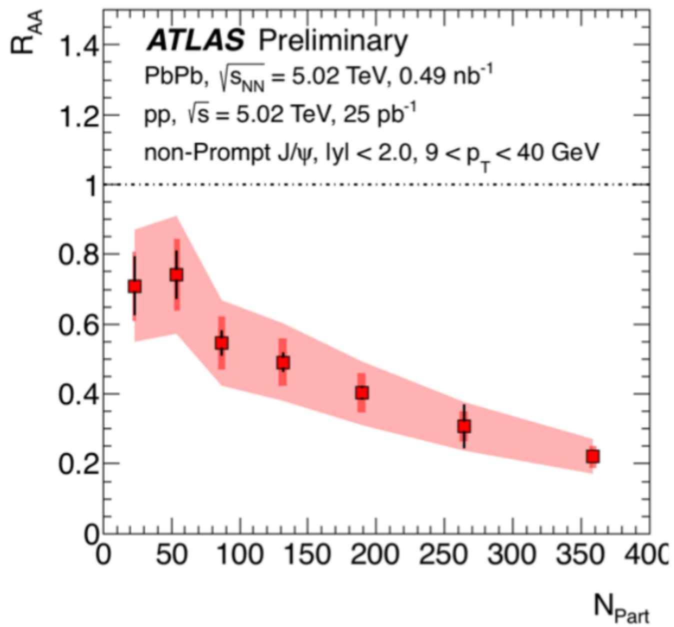
R_{AA} for J/Ψ

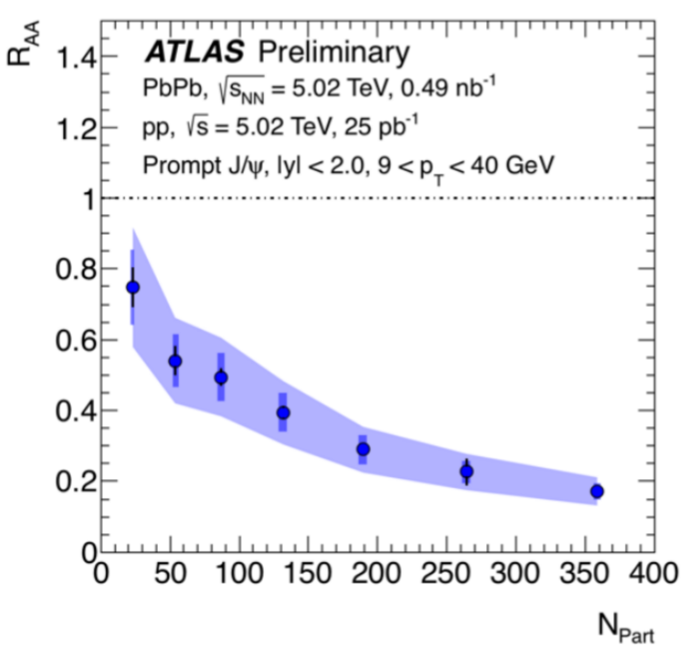
ATLAS-CONF-2016-124

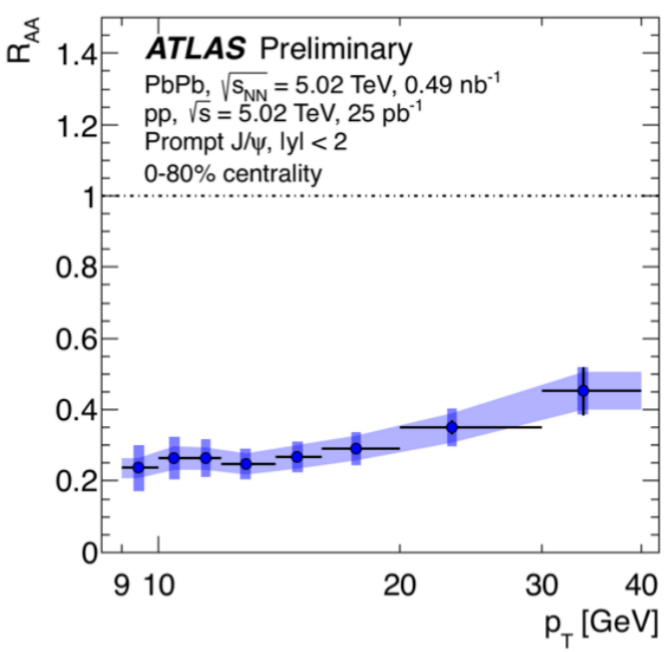
- R_{AA} measured for **promt** and **non-promt** J/Ψ production
- Strong J/Ψ suppression

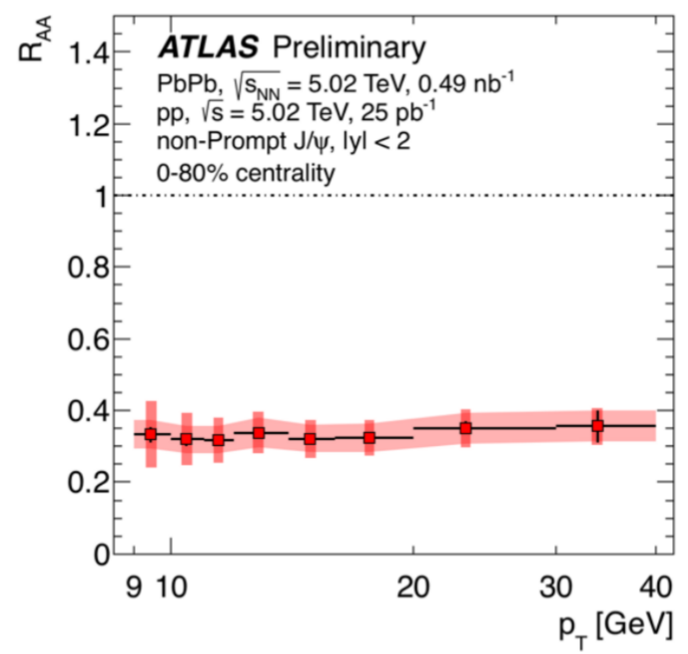
- As a function of p_T: 0.2-0.4 for **promt** (small rise for high p_T), 0.3 for **non-promt**

- As a function of N_{part} : drop from 0.8-0.2 with a similar trend for both components



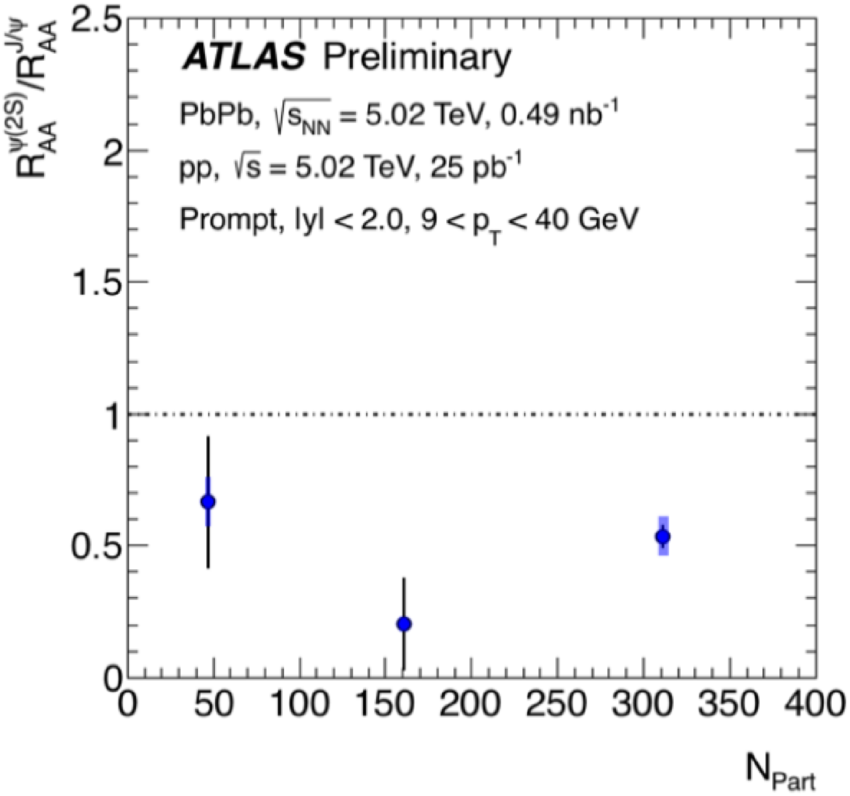


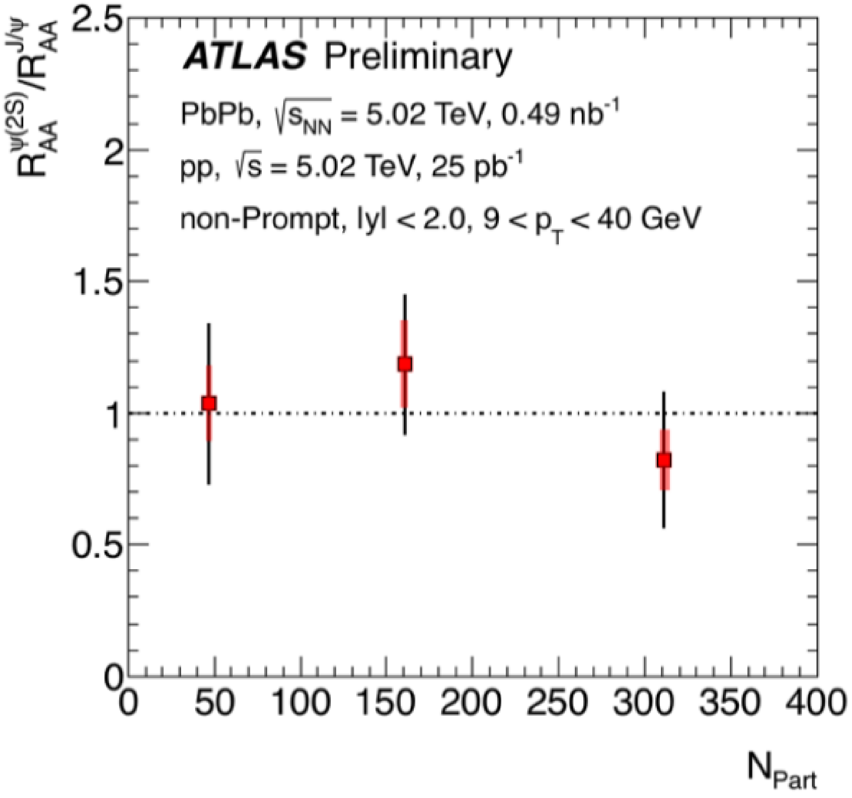




Supperssion of Ψ(2S) vs J/Ψ

- Ratio of R_{AA} for Ψ(2S) to J/Ψ measured for promt and non-promt production
  - **Promt**: ratio ~ 0.5, Ψ(2S) is suppperessed more than J/Ψ due to lower biding energy, less sensitivity to the recombination due to p_T > 9 GeV requirement
  - **Non-promt:** ratio consistent with unity and consistent with production outside the medium

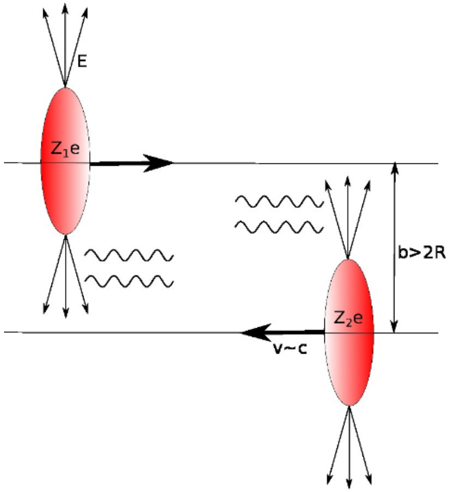




Light-by-light scattering in UPC events

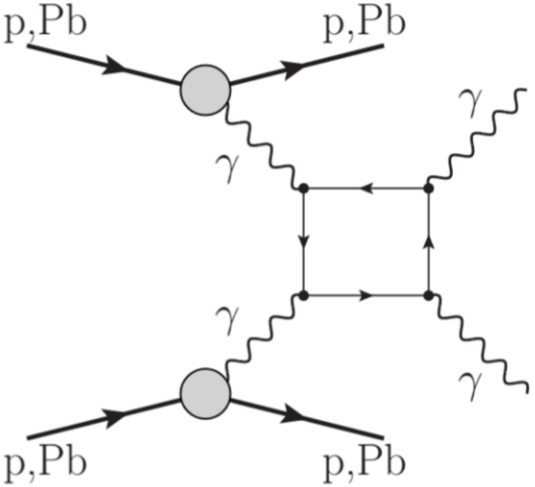
ATLAS-CONF-2016-111

- Ultra-peripheral collisions (UPS): **b > 2R**
  - hadronic interactions strongly suppressed
  - intense source of photons (~ Z^2)



- Light-by-light (γγ → γγ) scattering: elastic scattering of two photons
  - Tested indirectly in measurements of the anomalous magnetic moment of the electron and muon
  - Despite its fundamental simplicity, no direct observation so far due to very small cross section

- Proposed as a possible channel to study:
  - Anomalous gauge couplings
  - Contributions from charged SUSY partners of SM particles



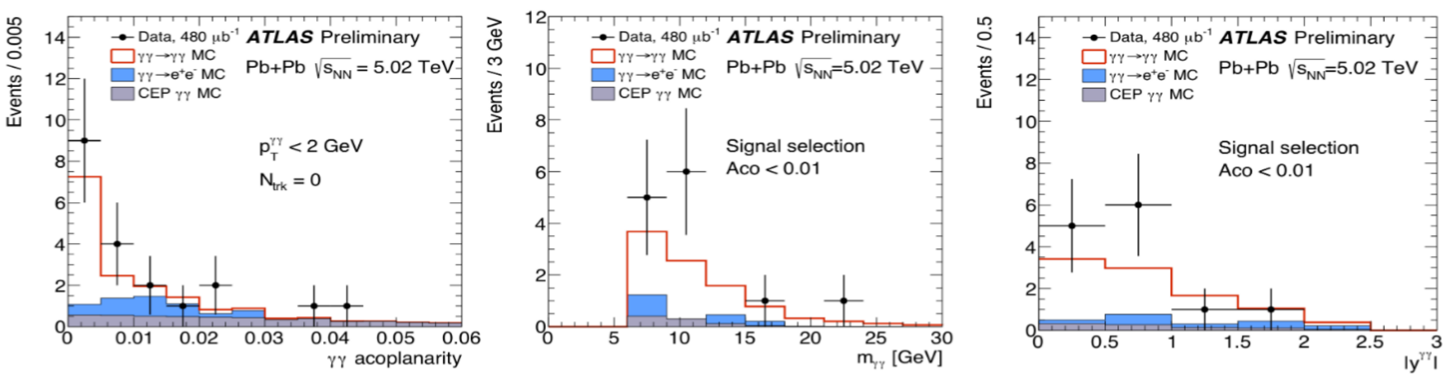
- p,Pb is a source of EM fields
- Very small Q^2 of initial photons for Pb+Pb so outgoing diphotons produced at small $p_T(\gamma\gamma)$
- Box diagrams involve charged fermions (leptons or quarks) and W bosons

ATLAS EXPERIMENT

Light-by-light scattering in UPC events

ATLAS-CONF-2016-111

- Search for signal diphoton candidates using:
  - Dedicated trigger: little activity in the calorimeter, no activity in the forward direction, little activity in the tracker
  - Two photons with E_T > 3 GeV, $M_{\gamma\gamma}$ > 6 GeV, $Aco = (1 - \Delta\varphi_{\gamma\gamma}/\pi) < 0.01$
  - Exclusivity requirement: no tracks originating from the primary vertex
- Excess in the data consistent with the light-by-light signal (arxiv:1601.07001)
- First direct observation of the light-by-light signal



Measured cross section:

σ_{fid}=70±20(stat)±17(syst)nb

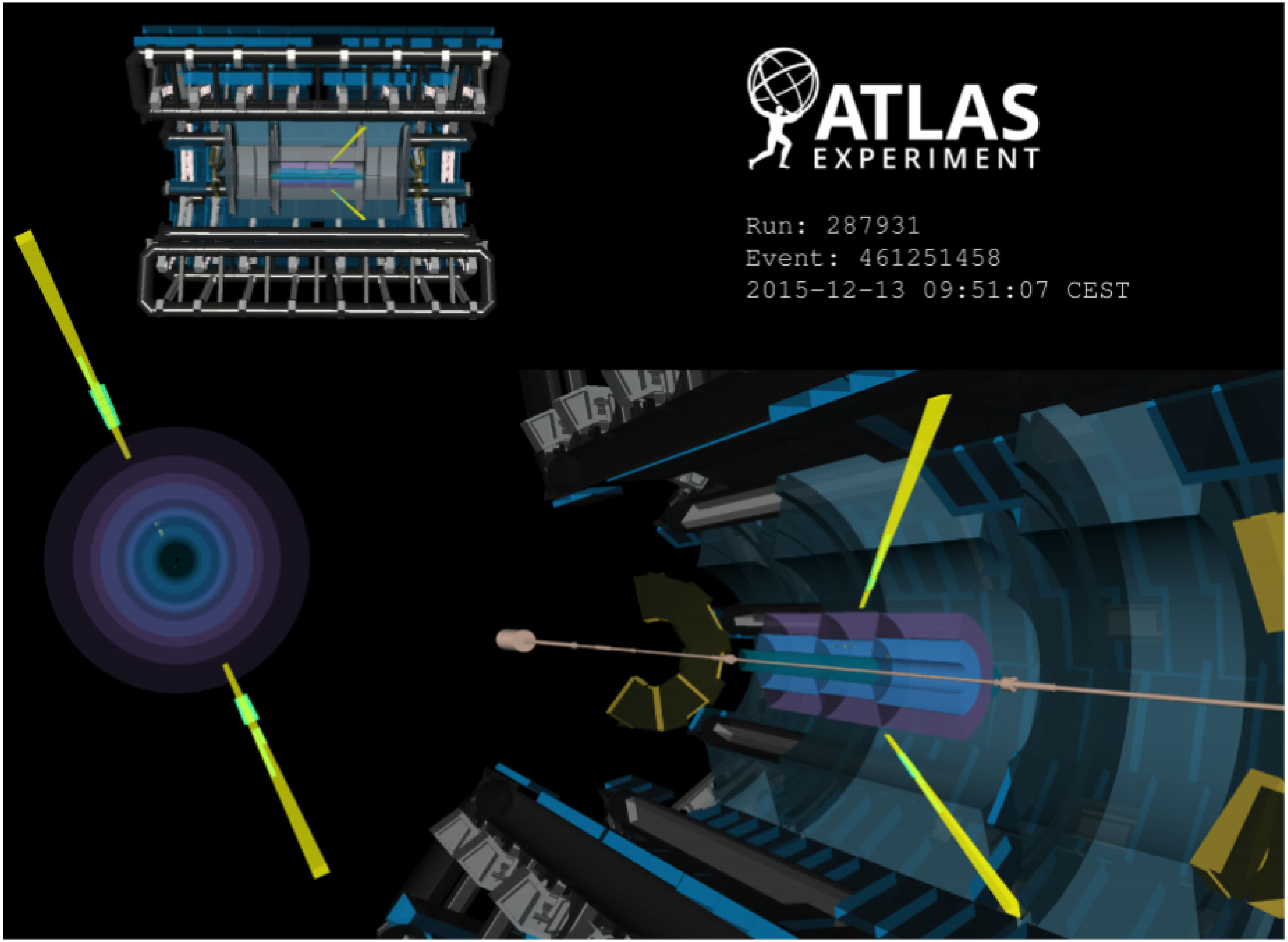
Predictions (arxiv:1601.07001):

σ_{fid} = 49 ± 10 nb

Selection	Data	Signal	$\gamma\gamma \to e^+e^-$	CEP $gg \to \gamma\gamma$	Hadronic fakes	Other fakes	Total expected
Preselection	105	9.1	74	4.7	6	19	113
$N_{\mathrm{trk}} = 0$	39	8.7	4.0	4.5	6	19	42
$p_T^{\gamma\gamma} < 2$ GeV	21	8.5	3.5	4.4	3	1.3	21
Aco < 0.01	13	7.3	1.3	0.9	0.3	0.1	9.9
Uncertainty		1.5	0.3	0.5	0.3	0.1	

Light-by-light scattering in UPC events

Two back-to-back photons (E_T = 12 GeV and E_T = 11 GeV) with $M_{\gamma\gamma}$ = 24 GeV with no aditional activity



Summary

- Broad program of jet-based imaging of the hot nuclear medium in ATLAS
- Inclusive jets in Pb+Pb are suppressed relatively to *pp* by up to a factor of 2, no dependence on rapidity
- First fully corrected dijet measurement provided
  - Enhancement in Pb+Pb, relatively to *pp* as the centrality increases
  - Clear dependence on the p_T of the leading jet in contrast to inclusive jets
- Jet internal structure measured differentially in jet p_T and rapidity, observed modest but significant modification of jet fragmentation functions

Summary

- R_{pPb} for charged hadrons is consistent with unity up to p_T~100GeV
- Photon-jet correlations confirm strong modification of $x_{J\gamma}$ with event centrality
- Prompt and non-prompt J/ψ and ψ(2S) production shows a different suppression pattern
- First direct observation of light-by-light scattering in UPC collisions, good agreement with SM predictions
- https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HeavyIonsPublicResults

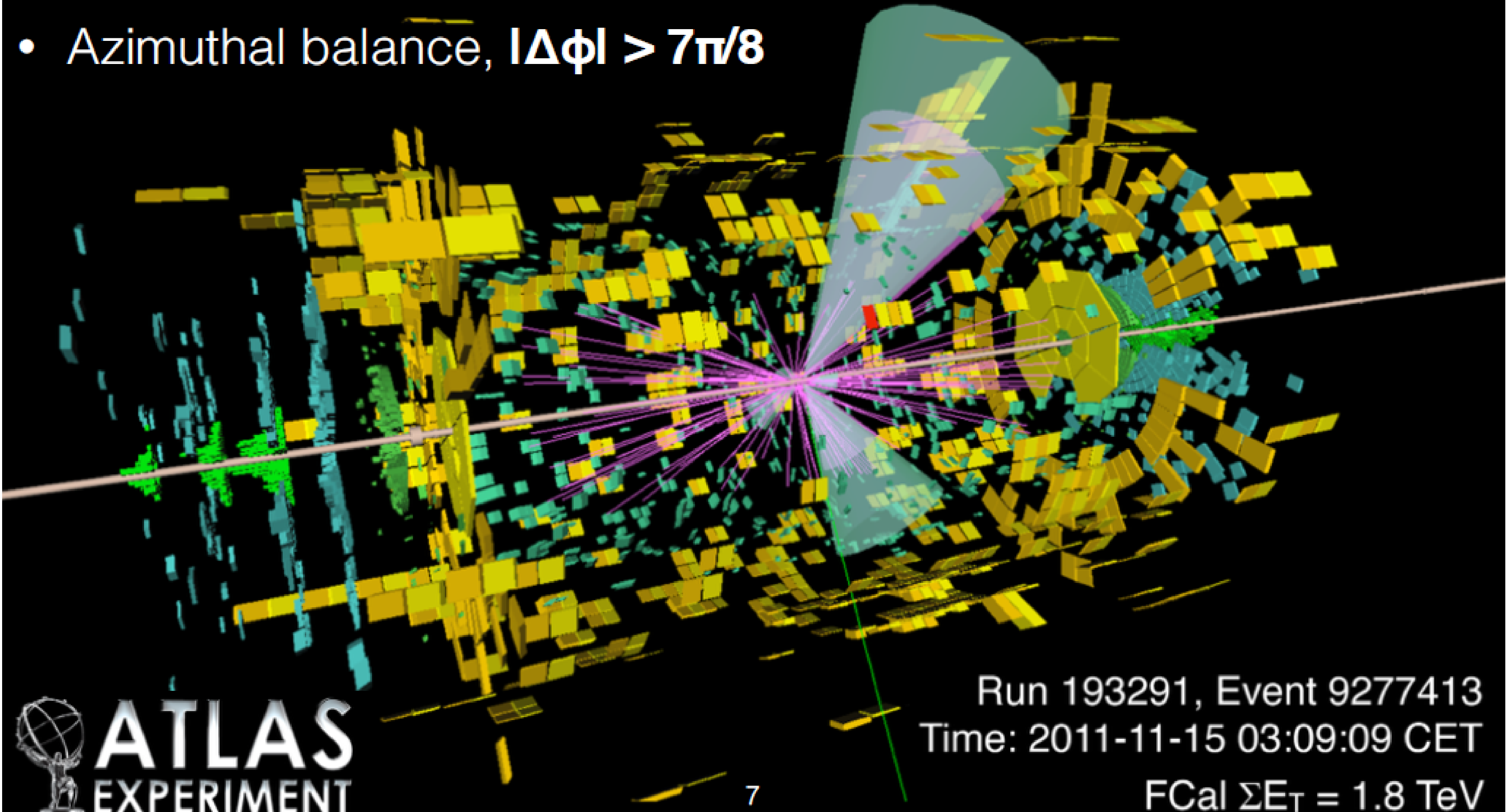
Back up

New Dijet Asymmetry

(ATLAS-CONF-2015-052)

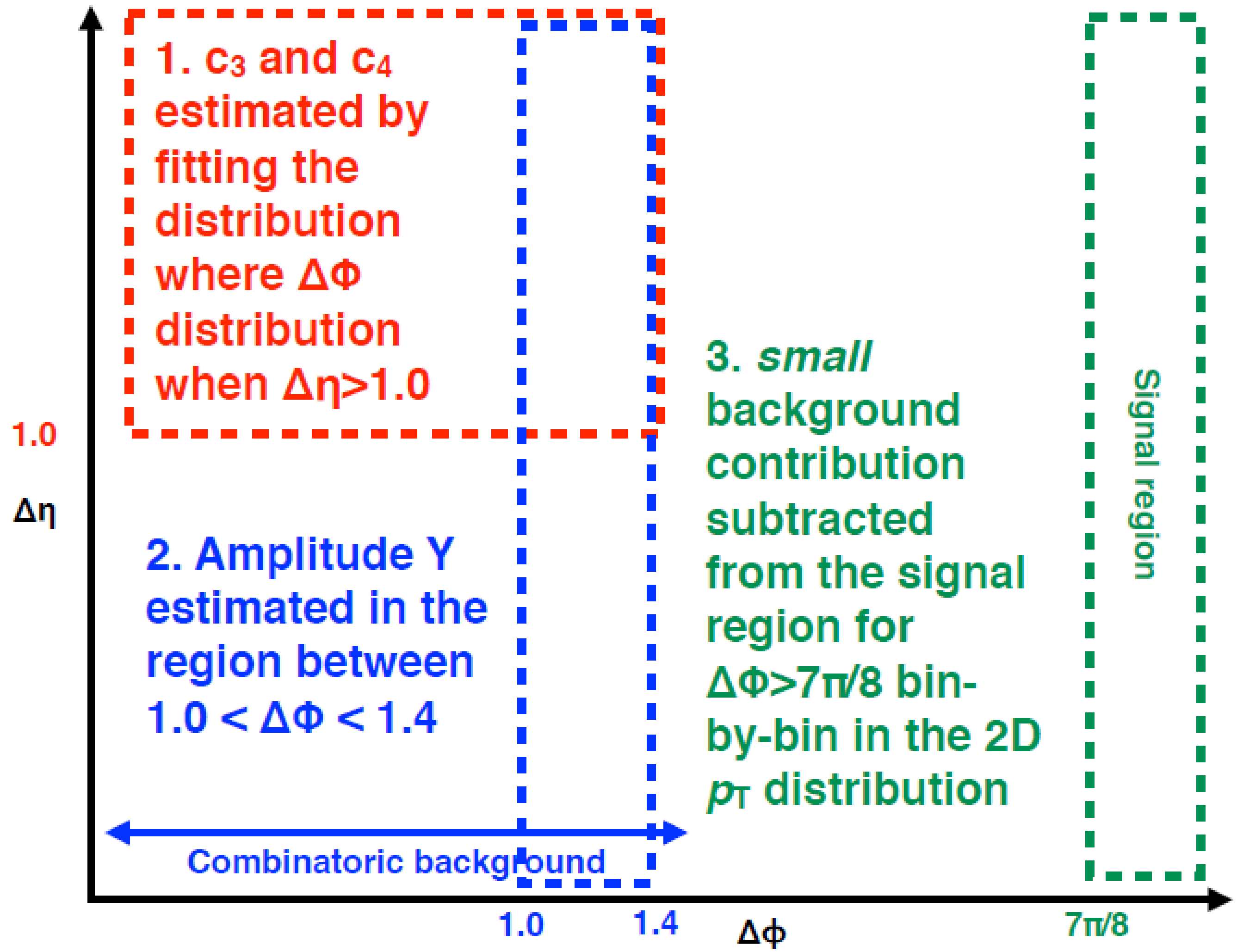
- Jets within $|\eta| < 2.1$
- Leading $p_{T,1} > 100$ GeV
- Subleading $p_{T,2} > 25$ GeV
- Azimuthal balance, $|\Delta\phi| > 7\pi/8$

$$\boxed{\Rightarrow\ x_J = p_{T,2} \,/\, p_{T,1}}$$



ΔΦ combinatoric subtraction

- Significant contribution of pairs arise from jets not originating from the same hard scattering
- combinatoric pairs expected to be uncorrelated in $\Delta\Phi < \pi/2$
  - ➡ except for small harmonic modulation from imperfect removal of flow effects in the reconstruction
  - ➡ v_2 contribution to the ΔΦ distribution was observed to be fully removed by the UE subtraction



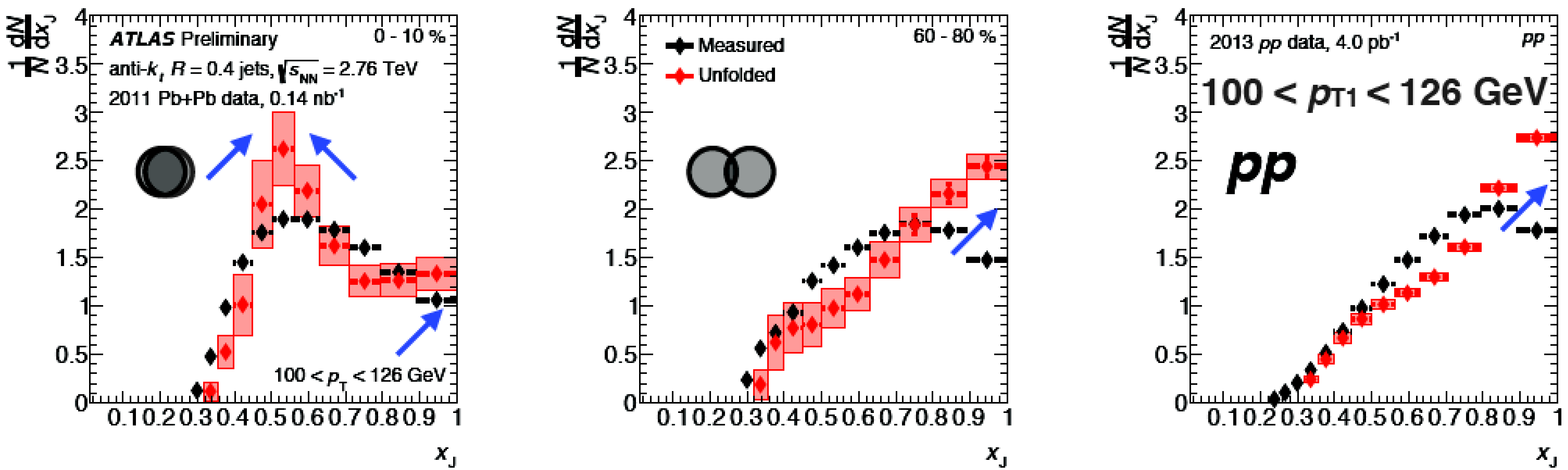
$$C(\Delta\phi) = Y(1+2c_3\cos 3\Delta\phi+2c_4\cos 4\Delta\phi)$$

Unfolding

- Unfolded to correct for the Jet Energy Scale (JES) and Resolution (JER) in the detector which is the mean (< 1%) and width (~40% in central low p_T) of the measured jet p_T distributions at a given value of p_T true
- 2D Bayesian unfolding to account for bin migration in p_{T1} and p_{T2} simultaneously

➡ Filled response symmetrically from MC in p_{T1}^{true}, p_{T2}^{true}, p_{T1}^{reco}, and p_{T2}^{reco}

➡ MC sample is pythia dijet events run through a GEANT simulation of ATLAS and then embedded into real minimum bias HI data



▸ *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*

Unfolding details

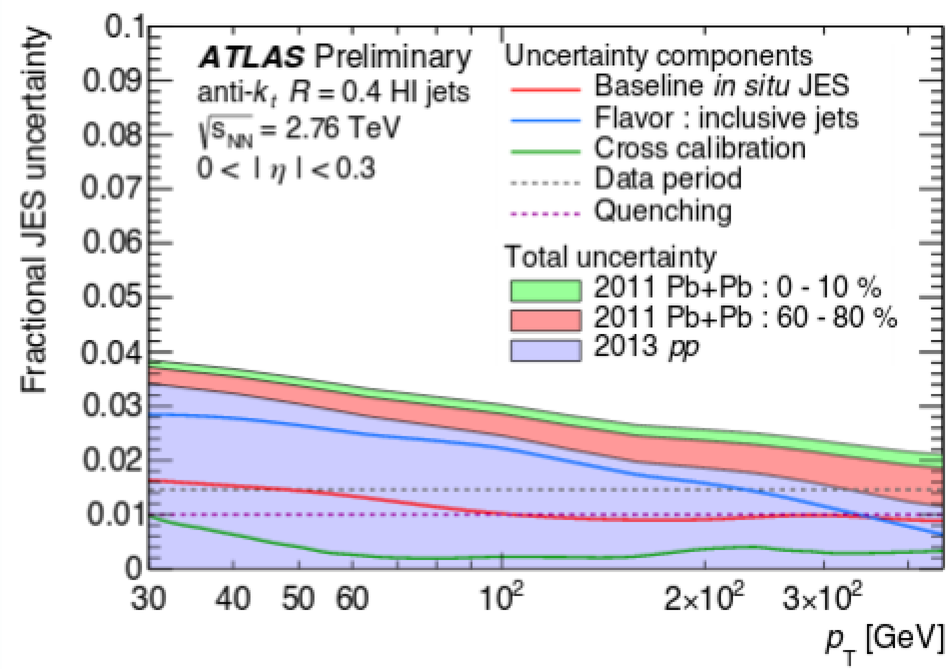
- Filled a response symmetrically in p_{T1}^{true}, p_{T2}^{true}, p_{T1}^{reco}, and p_{T2}^{reco}
- Response is generated from the MC in the Pb+Pb and the p+p separately
  - ➡ Truth pair with pT>25 GeV, $|\eta|<2.1$, and $|\Delta\phi|>7\pi/8$
  - ➡ Match each truth jet to a reconstructed jet for pT>25 GeV and $|\eta|<2.1$ with $\Delta R<0.3$
  - ➡ Reconstructed pair must be within $|\Delta\phi|>7\pi/8$
- Decide the number of iterations in the unfolding based on 3 criteria:
  - ➡ stability against number of iterations
  - ➡ closure in refolding (putting the unfolded distribution back though the response)
  - ➡ Monitor the fluctuations in the statistical errors with unfolding

▶ *Number of iteration chosen to be 26 for Pb+Pb and 15 for p+p.*

JES/JER uncertainty

JES:

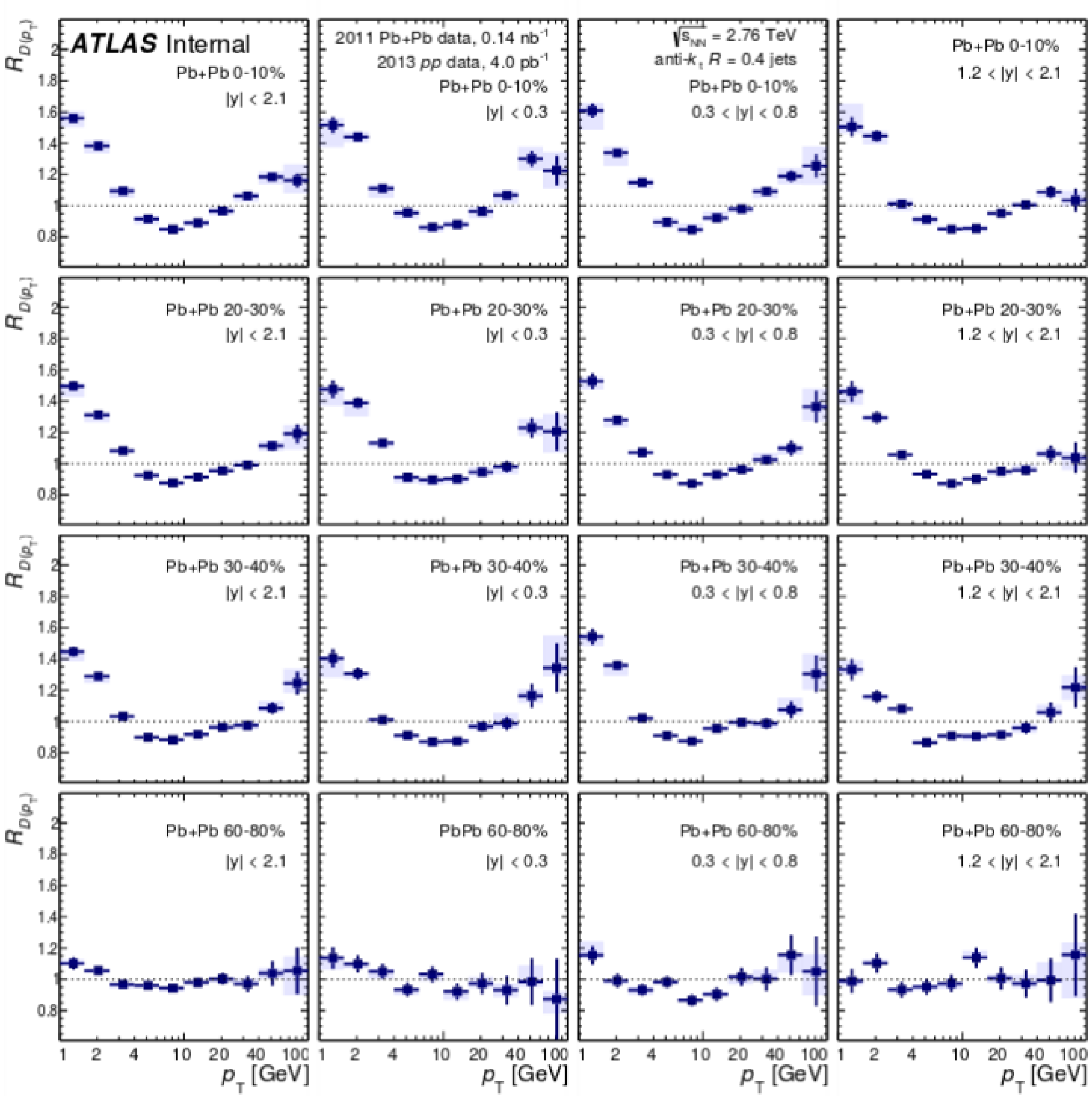
- Use the baseline 8 nuisance parameters from *in situ* calibration
- Additional parameters due to flavor responce and composition and cross calibration
- Two addition parameters for Pb+Pb due to the difference in the data taking period and detector responce to quenched jets



JER:

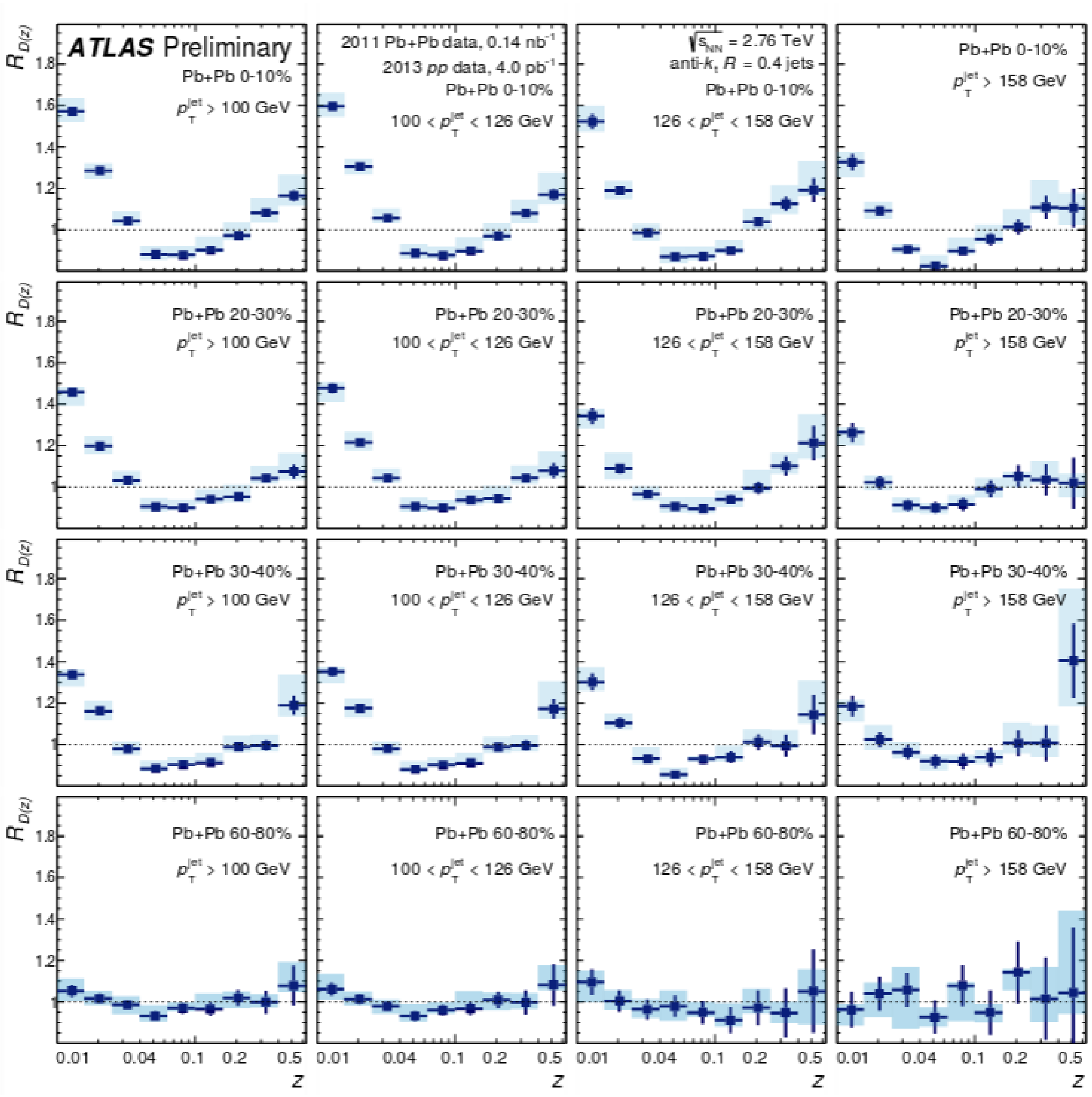
- Standart centrality-independent JER uncertainties
- Additional centrality dependent uncertaitny for possible disagreement between fluctuations term in JES in the MC independent analysis of fluctuations in data
- This is very small because MC sample is data everlay

Jet fragmentation



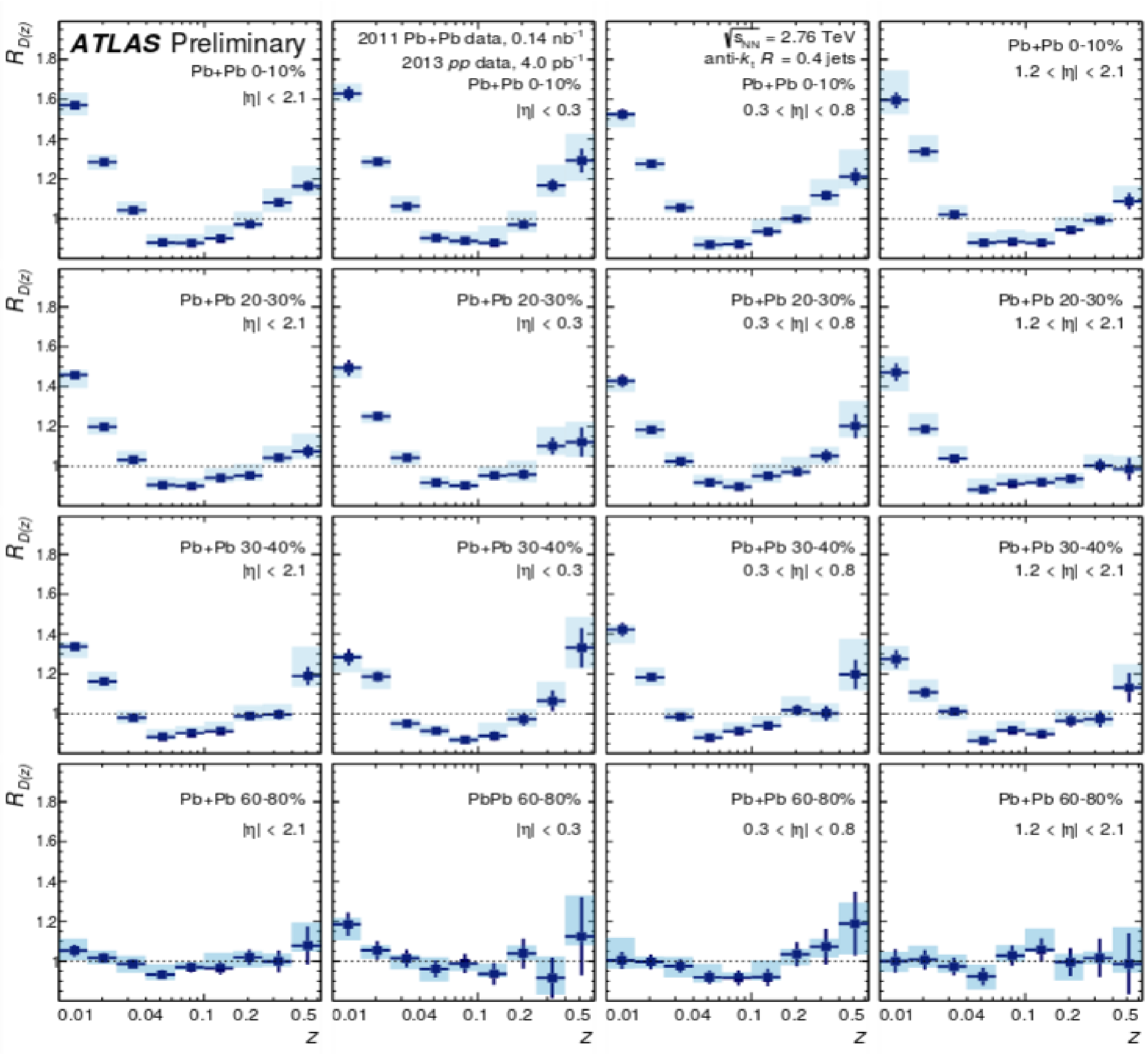
- Ratios of FF $D(p_T)$ for different centrality and rapidity bins

Jet fragmentation



- Ratios of FF $D(z)$ for different centrality and jet p_T bins

Jet fragmentation



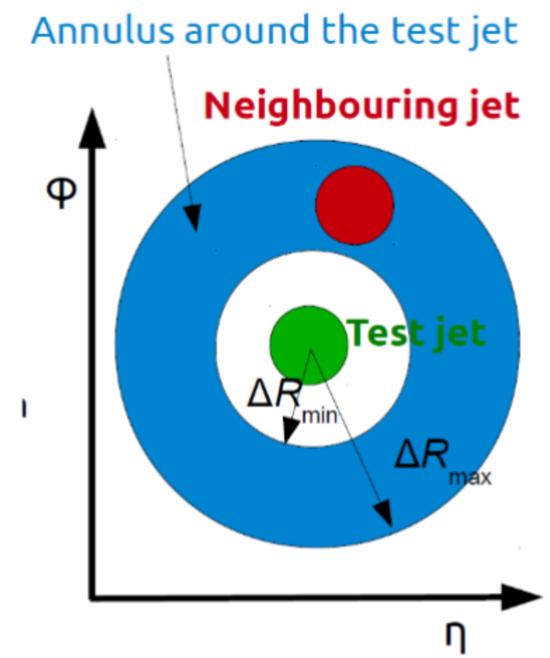
- Ratios of FF $D(z)$ for different centrality and rapidity bins

Nearby jets

PLB 751 (2015) 376

- The rate of the neighbouring jets that accompany a test jet was measured:

$$R_{\Delta R} = \frac{1}{\mathrm{d}N_{\mathrm{jet}}^{\mathrm{test}}/\mathrm{d}E_{\mathrm{T}}^{\mathrm{test}}} \sum_{i=1}^{N_{\mathrm{jet}}^{\mathrm{test}}} \frac{\mathrm{d}N_{\mathrm{jet},i}^{\mathrm{nbr}}}{\mathrm{d}E_{\mathrm{T}}^{\mathrm{test}}}(E_{\mathrm{T}}^{\mathrm{test}}, E_{\mathrm{T,min}}^{\mathrm{nbr}}, \Delta R)$$

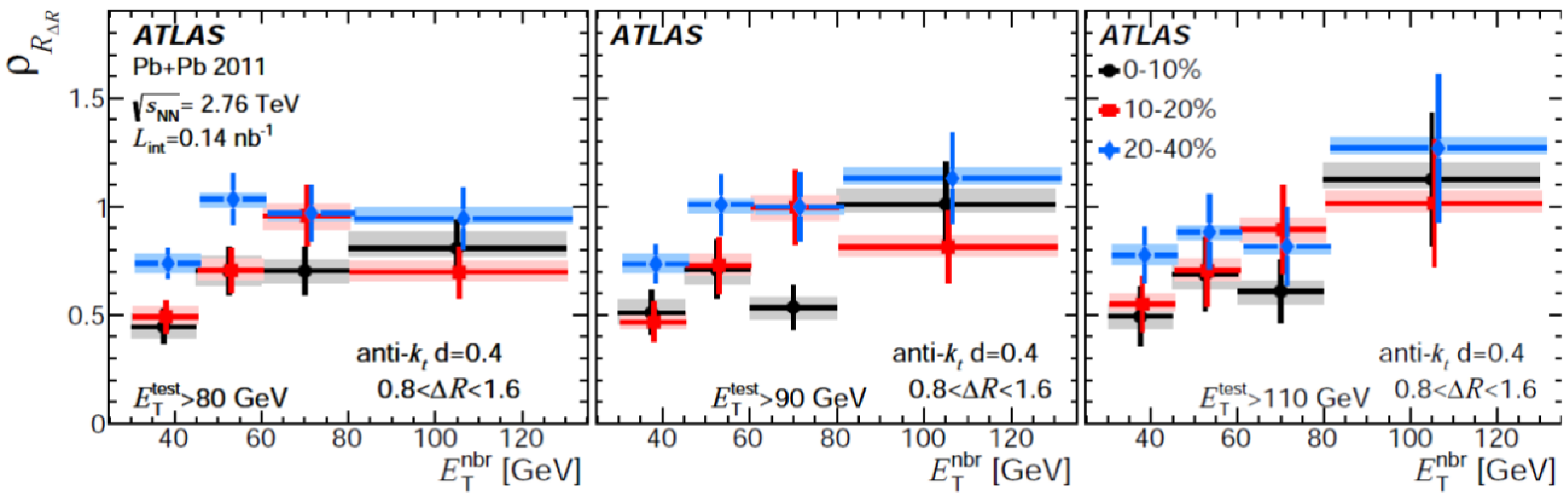


- Neighboring jet production quantified using this quantity previously measured at Tevatron

- To quantify the centrality dependence the central to peripheral ratios $\rho(R_{\Delta R})$ are evaluated

Nearby jets

PLB 751 (2015) 376



- Central to peripheral ratio of $R_{\Delta R}$ as a function of neighboring jet E_T
- Decrease of suppression (by a factor ≈ 2 in central collisions) with increasing neighbouring-jet E_T