Recent ATLAS results on jet suppression and modification in Pb+Pb collisions

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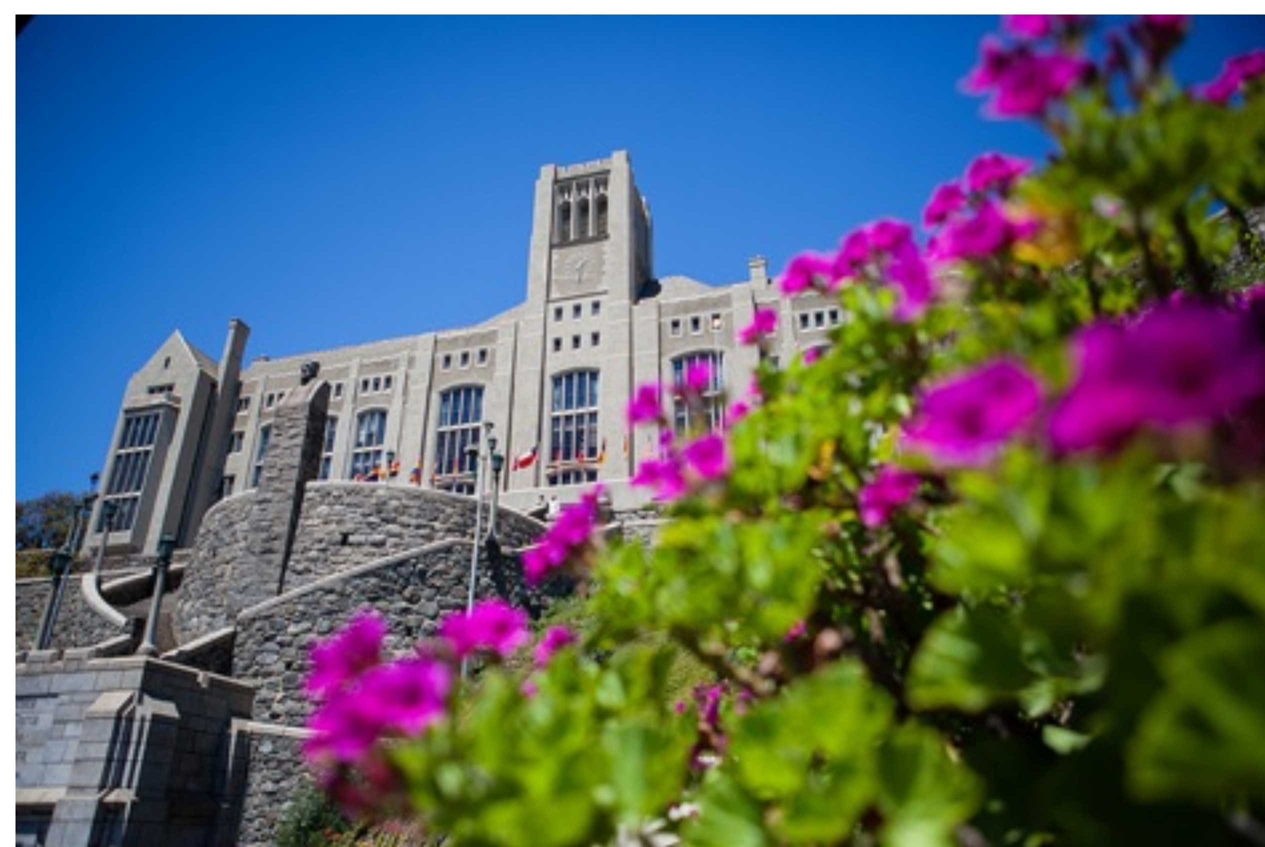
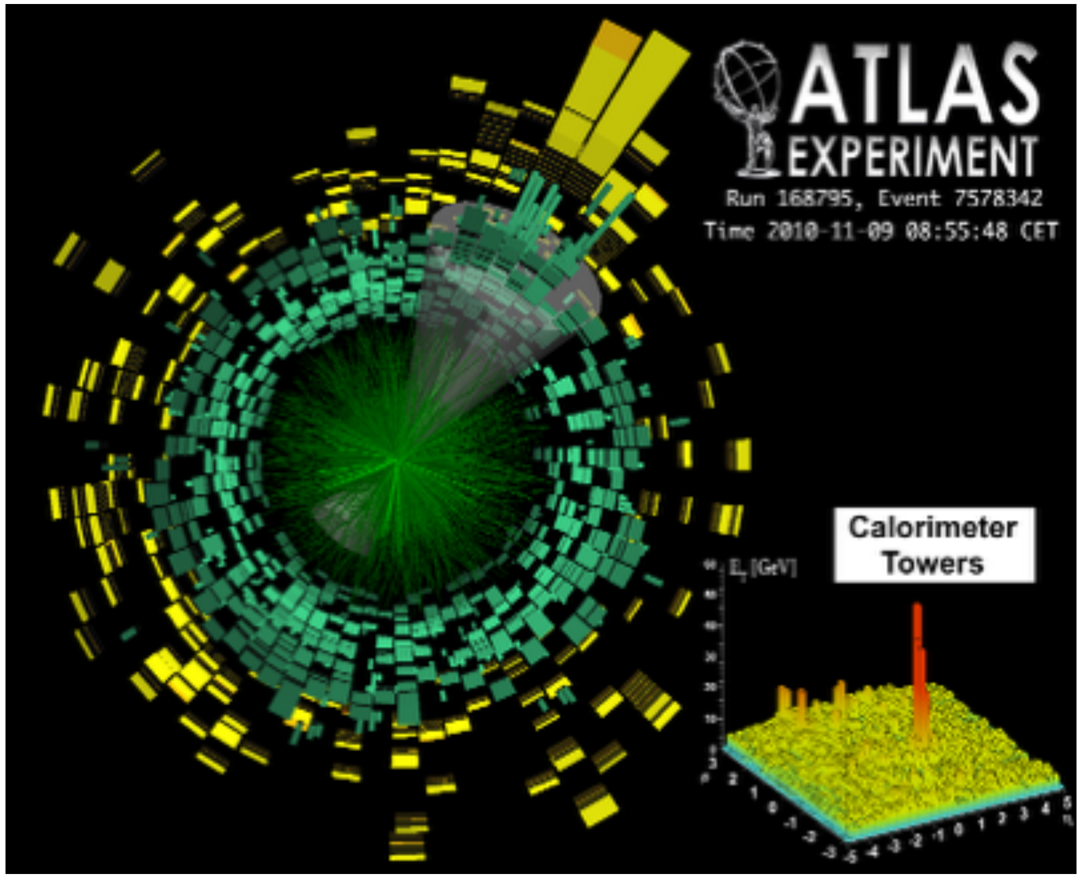
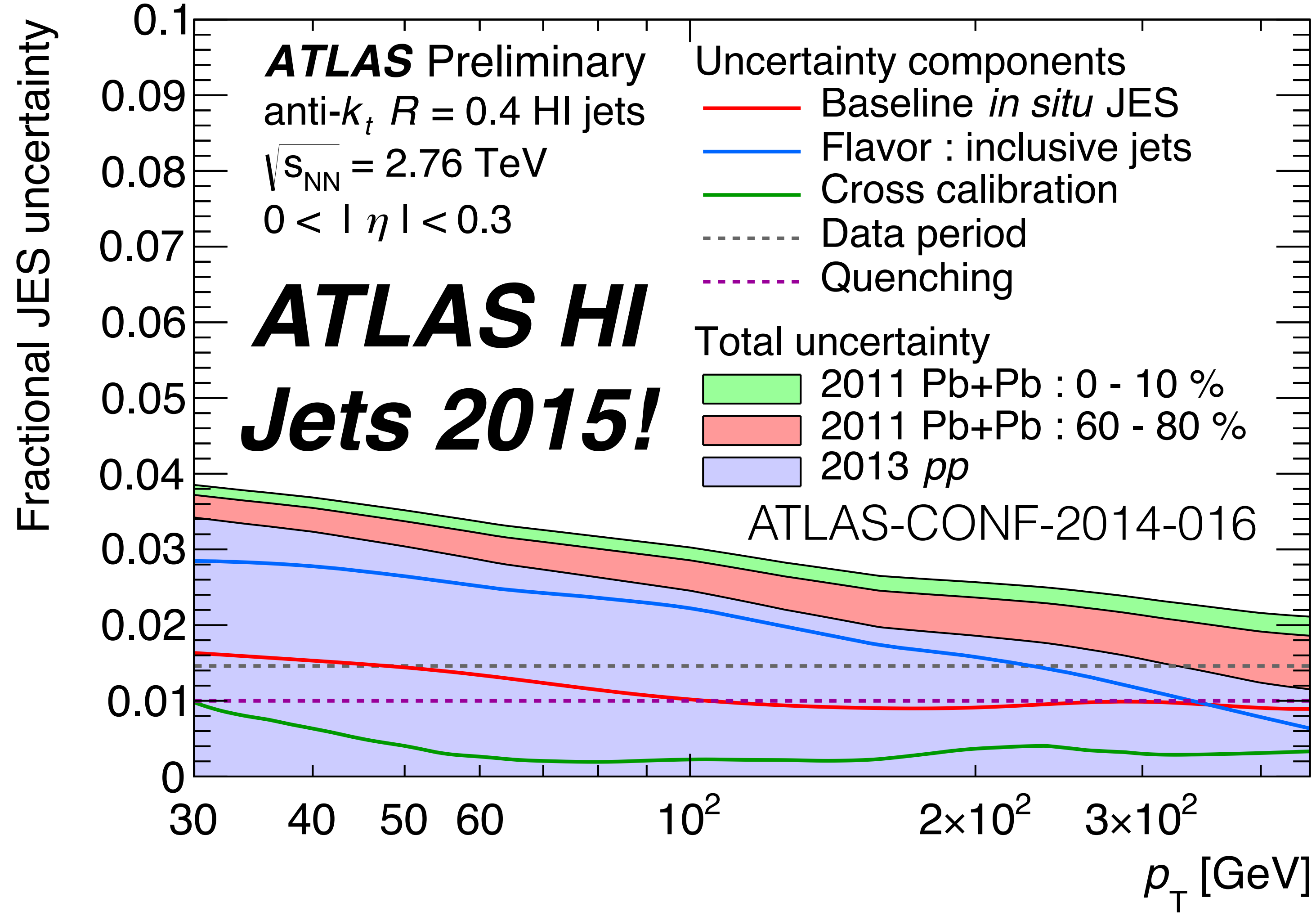


Heavy ion jet measurements

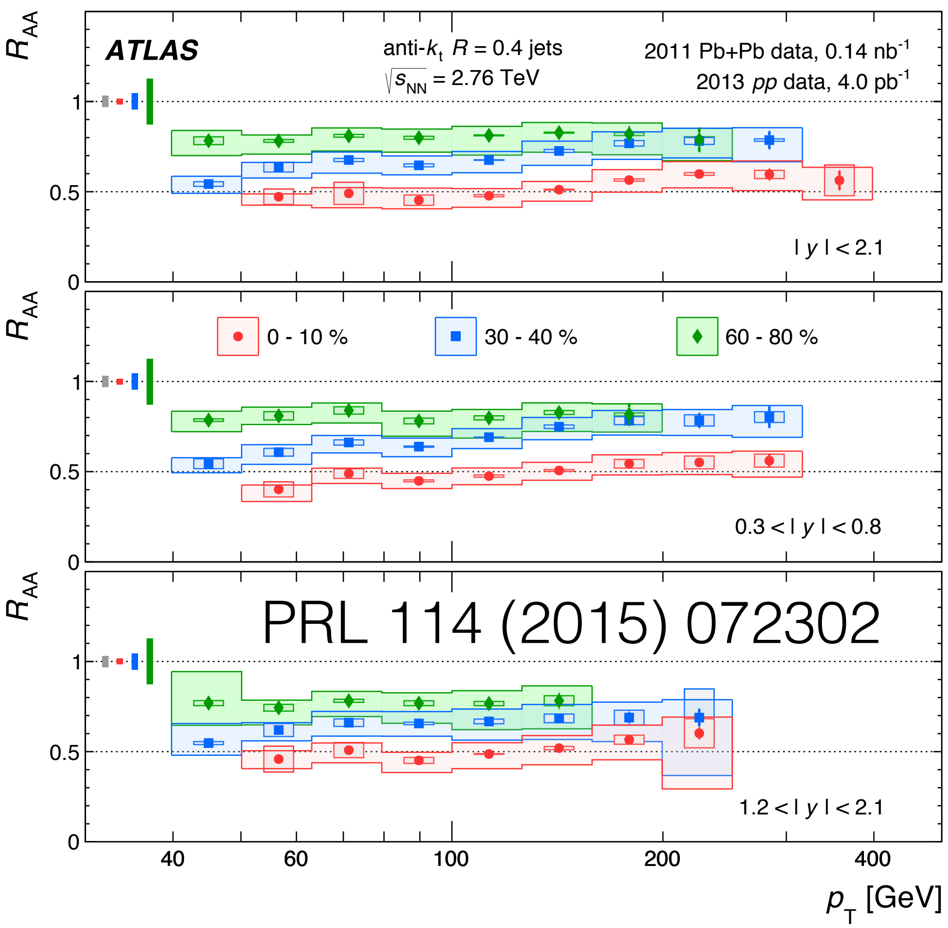


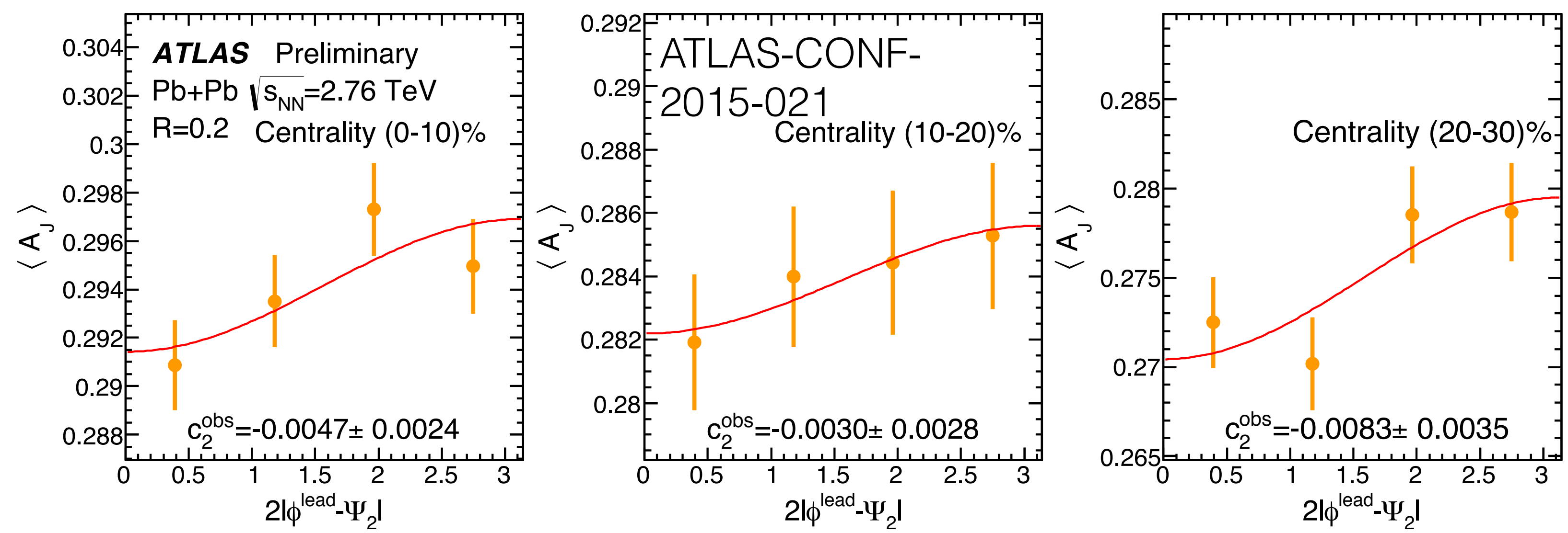
ATLAS HI Jets 2010



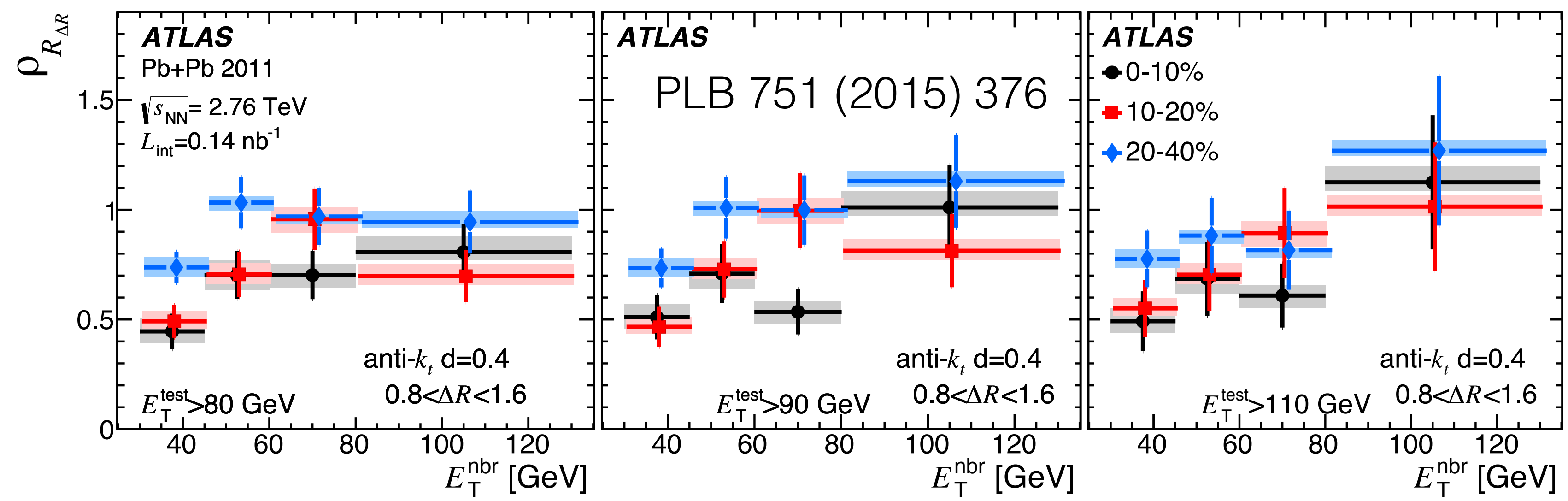
- Reconstructed jets are a sophisticated tool for exploring *parton energy loss* in the hot nuclear medium created in Pb+Pb collisions
  - ➡ substantial evolution within ATLAS from *first "observations"* of dijet energy imbalance…
  - ➡ … to detailed understanding of *jet performance* and HEP-style in situ constraints on energy scale

dijet asymmetry vs. reaction plane



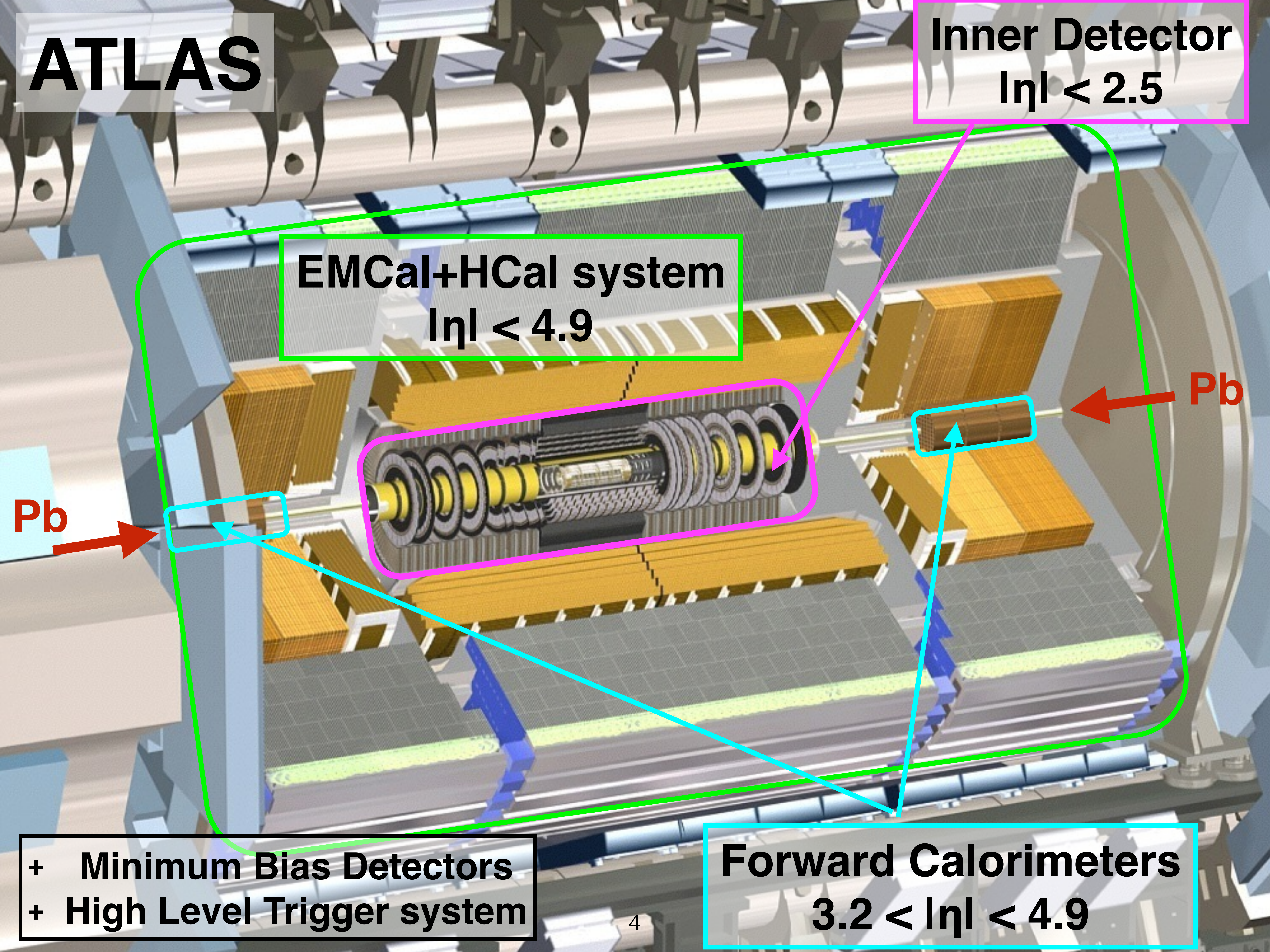


inclusive jet suppression



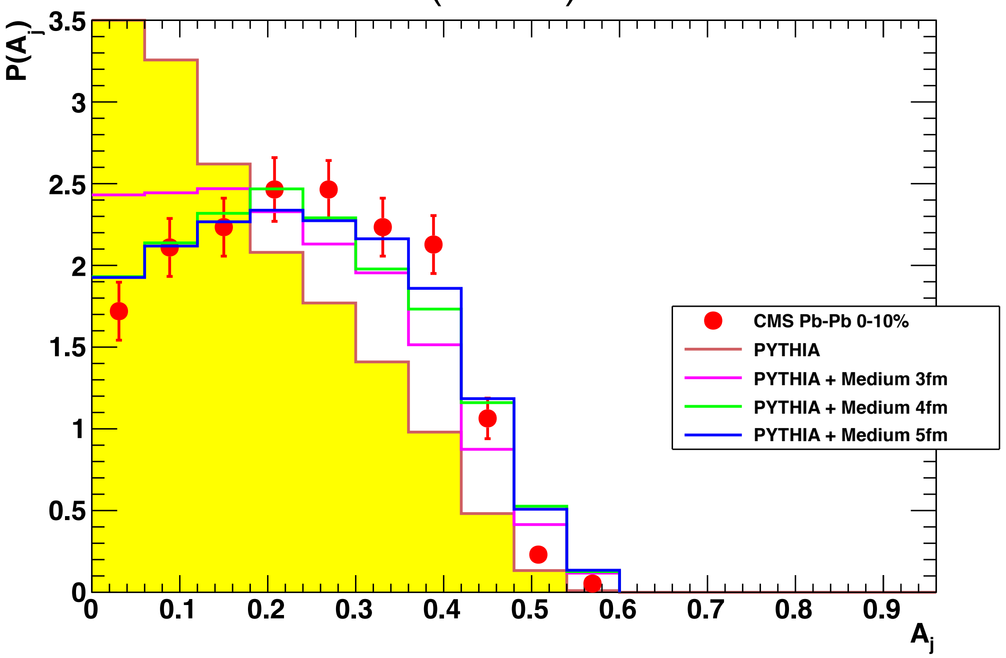
modification of multi-jet correlations

- Broad program of jet suppression and modification measurements in Pb+Pb collisions by ATLAS
  - ➡ in this talk, focus on two new measurements of **dijet energy balance (ATLAS-CONF-2015-052)** and **inclusive jet fragmentation functions (ATLAS-CONF-2015-055)**

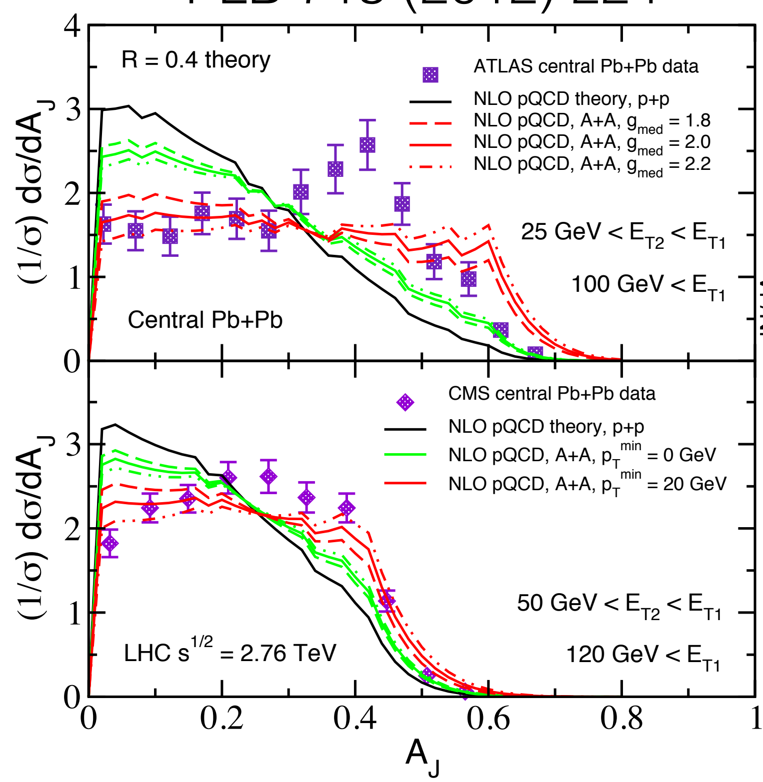

ATLAS
Inner Detector
|η| < 2.5
EMCal+HCal system
|η| < 4.9
Pb
Pb
+ Minimum Bias Detectors
+ High Level Trigger system
Forward Calorimeters
3.2 < |η| < 4.9

1. Dijet asymmetries

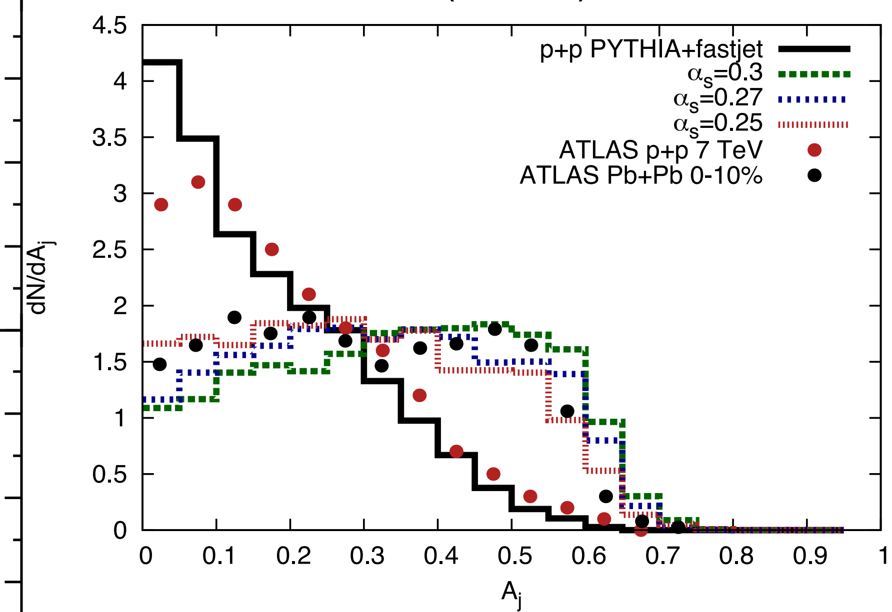
PRC 86 (2012) 054901



PLB 713 (2012) 224



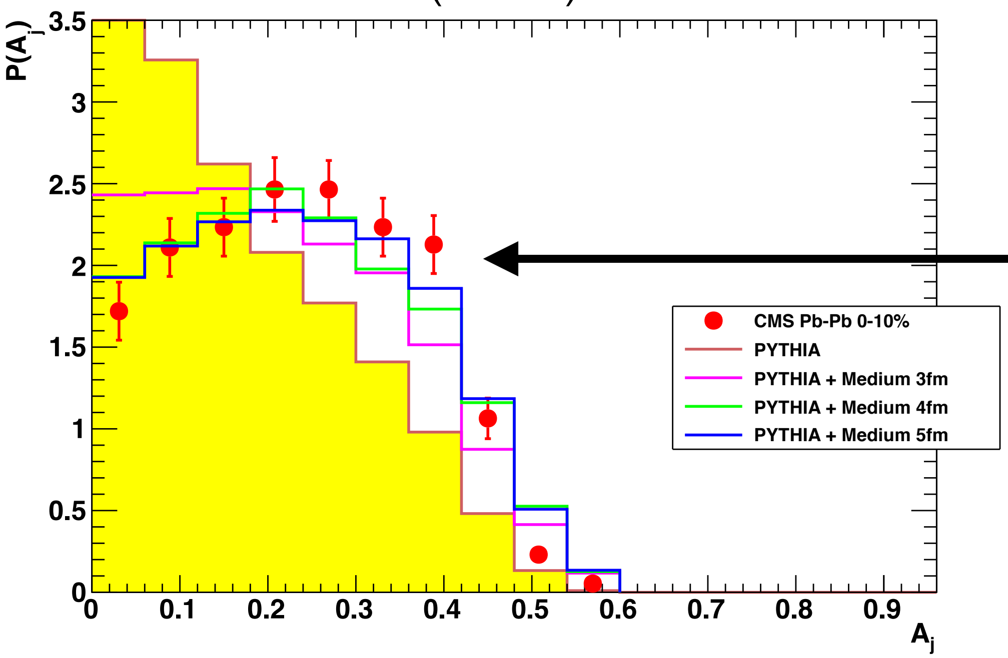
PRC 84 (2011) 024907



- Back to back jets see different path lengths, destroying the expected p_T-balance, $A_J = (p_{T,1} - p_{T,2})/(p_{T,1} + p_{T,2}) \gg 0$
  ➡ insightful probe of **differential energy loss** within an event
- Much **theoretical interest** and activity in this observable
  ➡ published results typically **not corrected to particle-level**, making direct comparisons ambiguous

1. Dijet asymmetries

PRC 86 (2012) 054901



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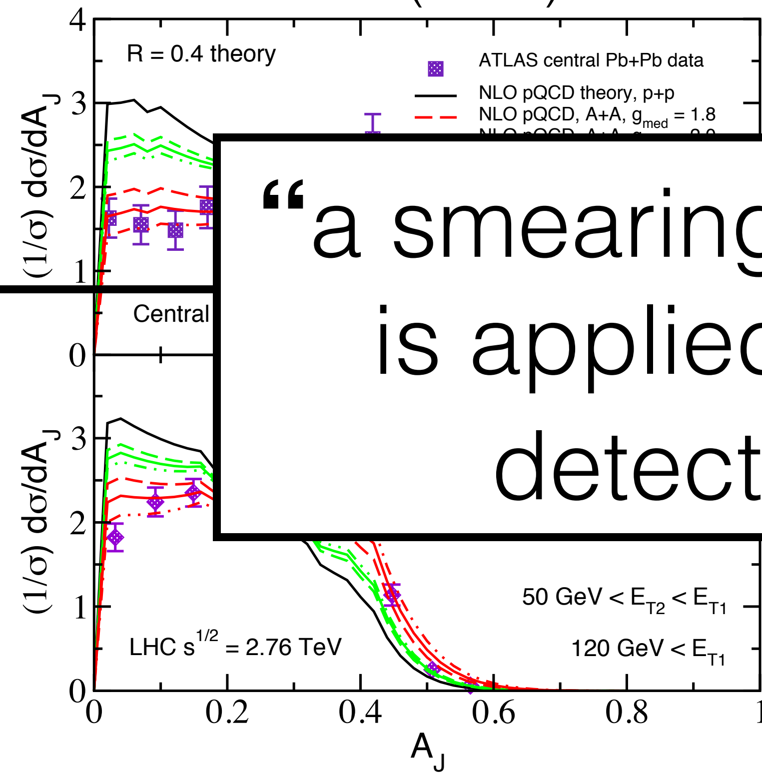
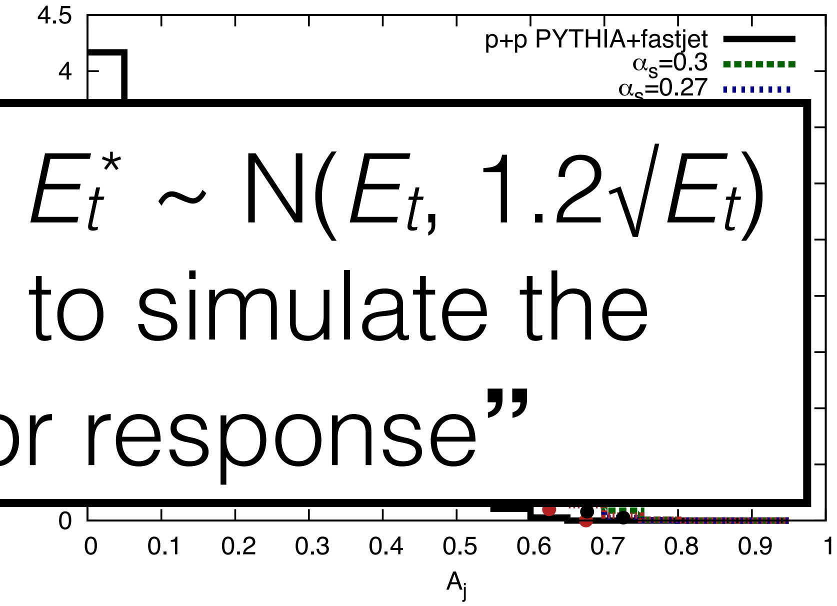


PRC 84 (2011) 024907



"a smearing $E_t^* \sim \mathrm{N}(E_t,\ 1.2\sqrt{E_t})$ is applied to simulate the detector response"

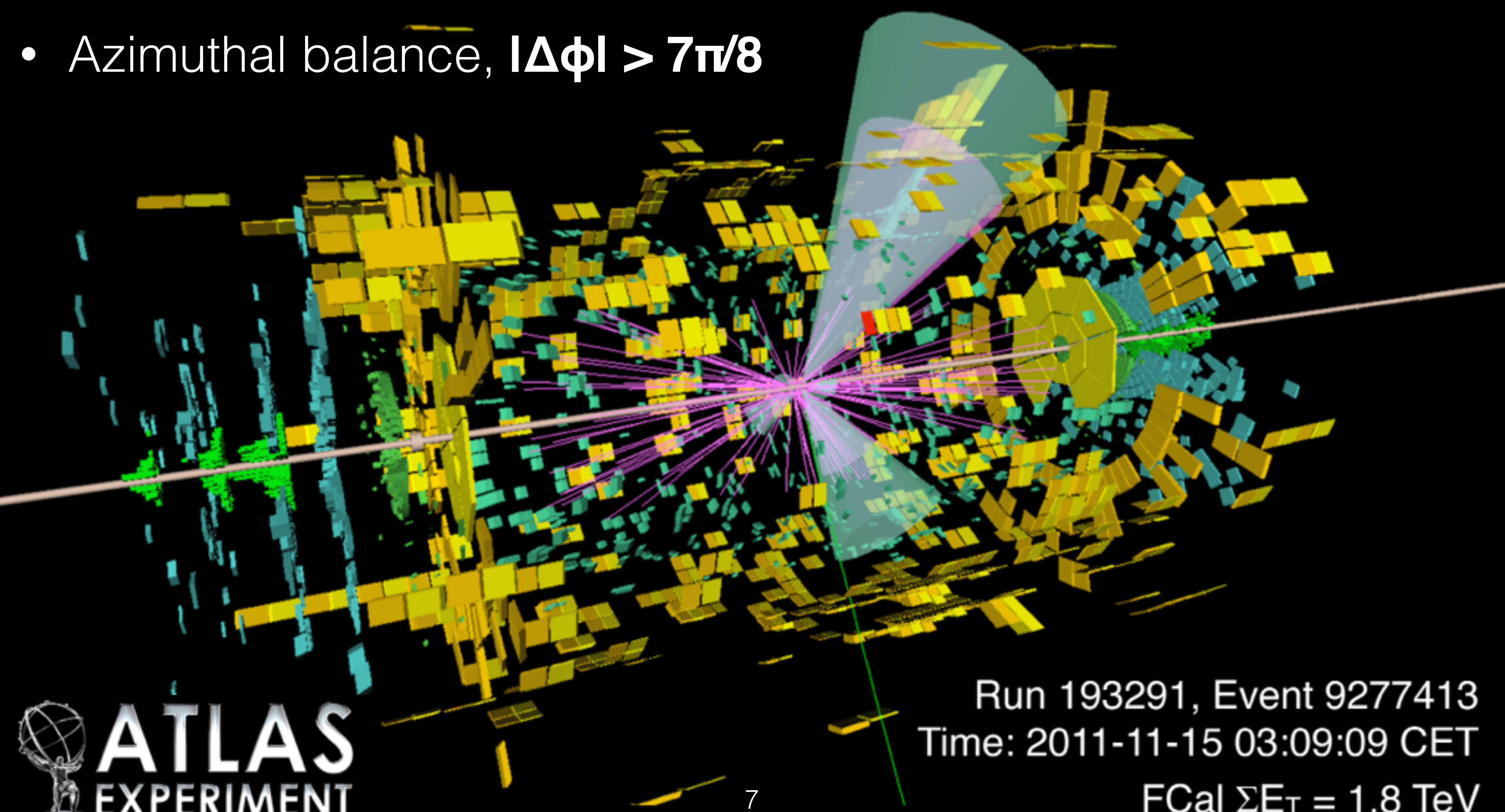
- Back to back jets see different path lengths, destroying the expected p_T-balance, $A_\mathrm{J} = (p_{\mathrm{T},1} - p_{\mathrm{T},2})/(p_{\mathrm{T},1} + p_{\mathrm{T},2}) \gg 0$
  - ➡ insightful probe of **differential energy loss** within an event
- Much **theoretical interest** and activity in this observable
  - ➡ published results typically **not corrected to particle-level**, making direct comparisons ambiguous

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, **$|\Delta\phi| > 7\pi/8$**

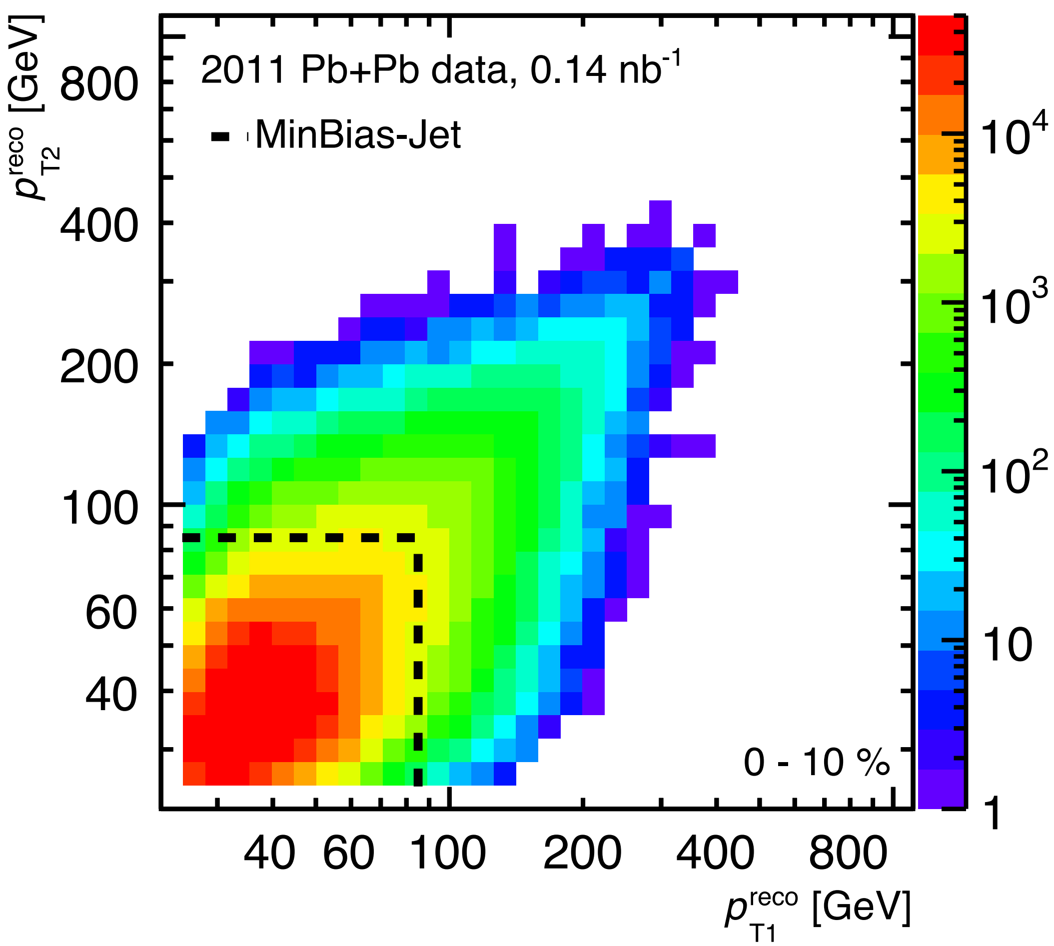
➡ $x_J = p_{T,2} / p_{T,1}$



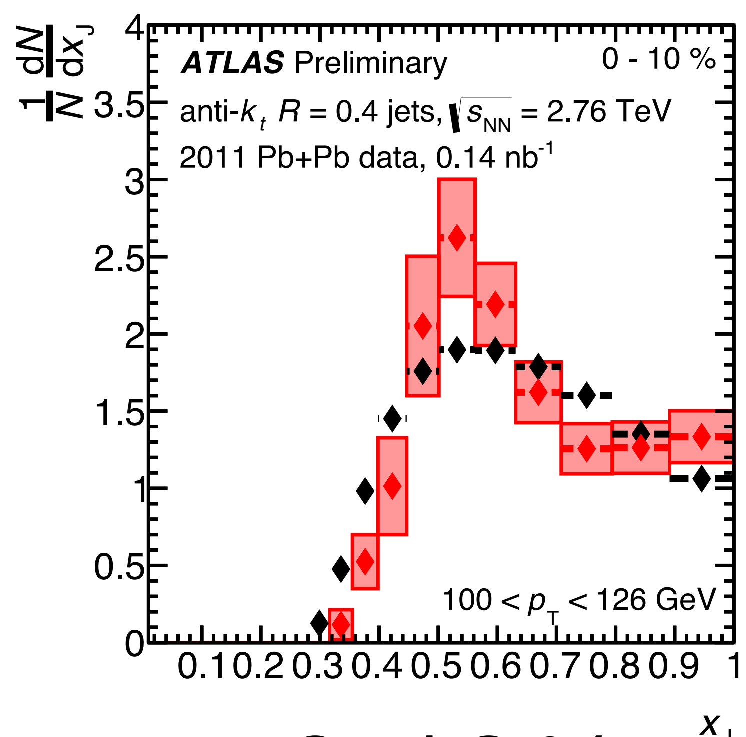
1. Data selection & corrections

- **Unbiased two-jet ($p_{T,1}$, $p_{T,2}$) spectrum** in 2.76 TeV *pp* and Pb+Pb collisions efficiently filled by MB + jet triggers

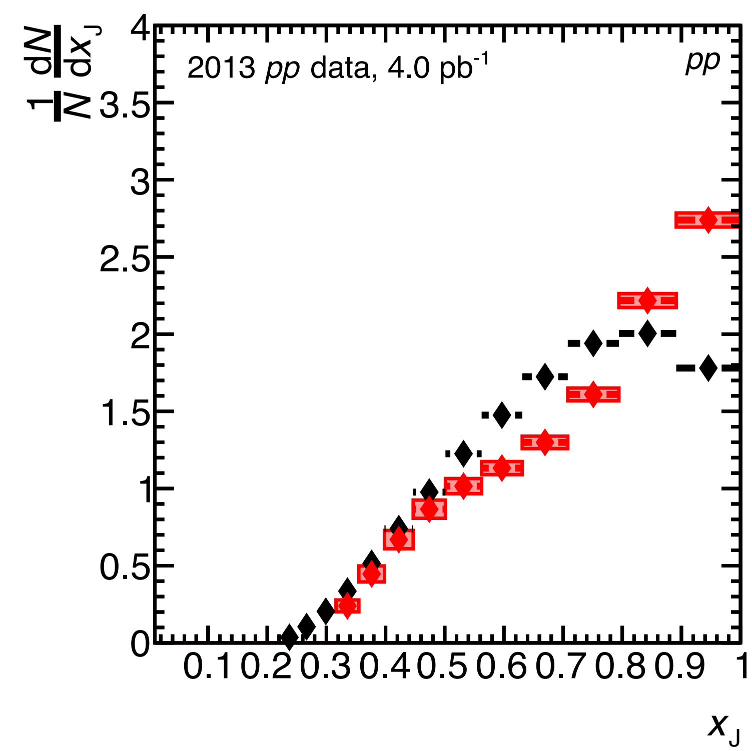
  ➡ **unfold in both simultaneously** to account for important event-by-event correlations in the response



$p_{T,1}$-$p_{T,2}$ spectrum in 0-10% collisions



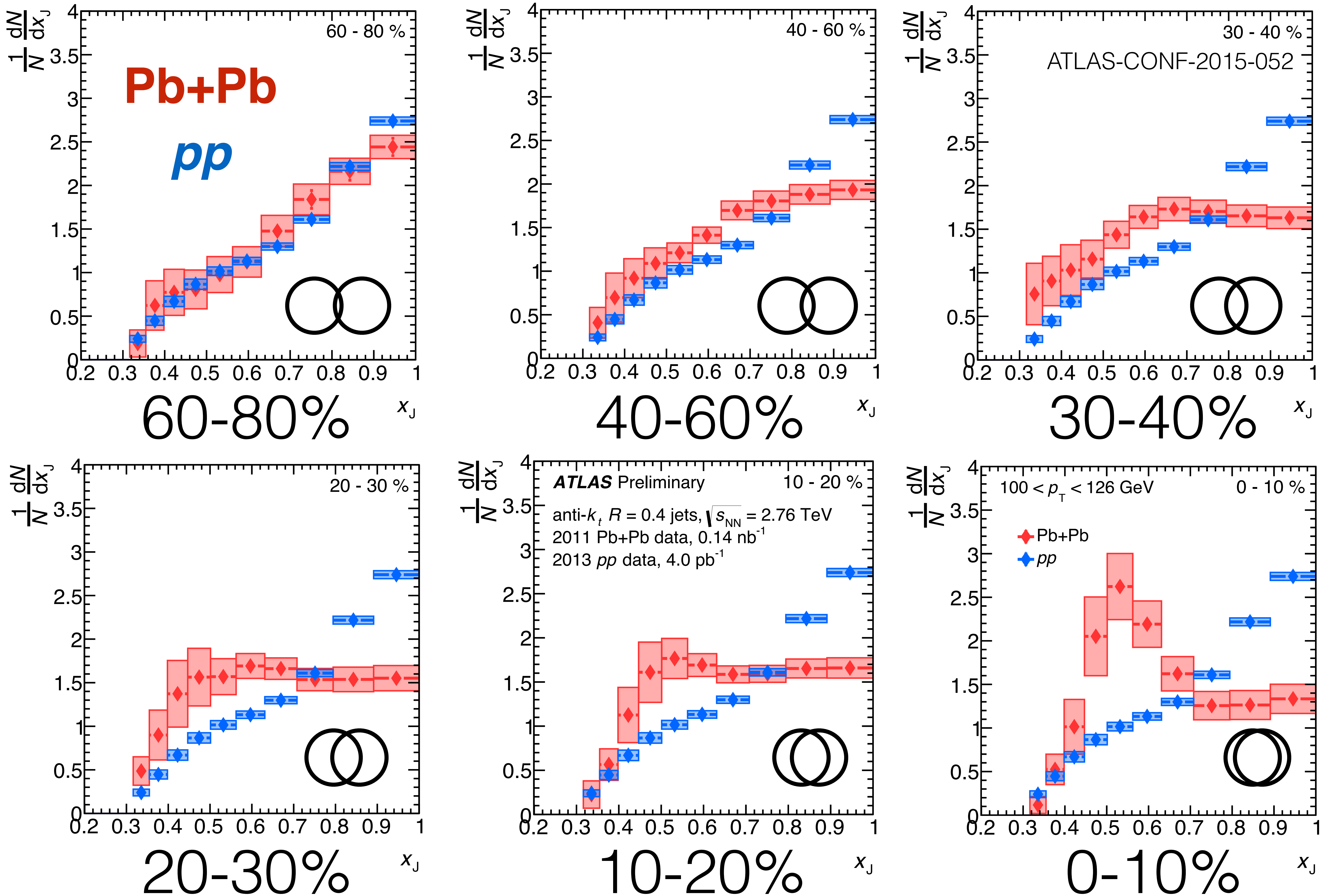
0-10%



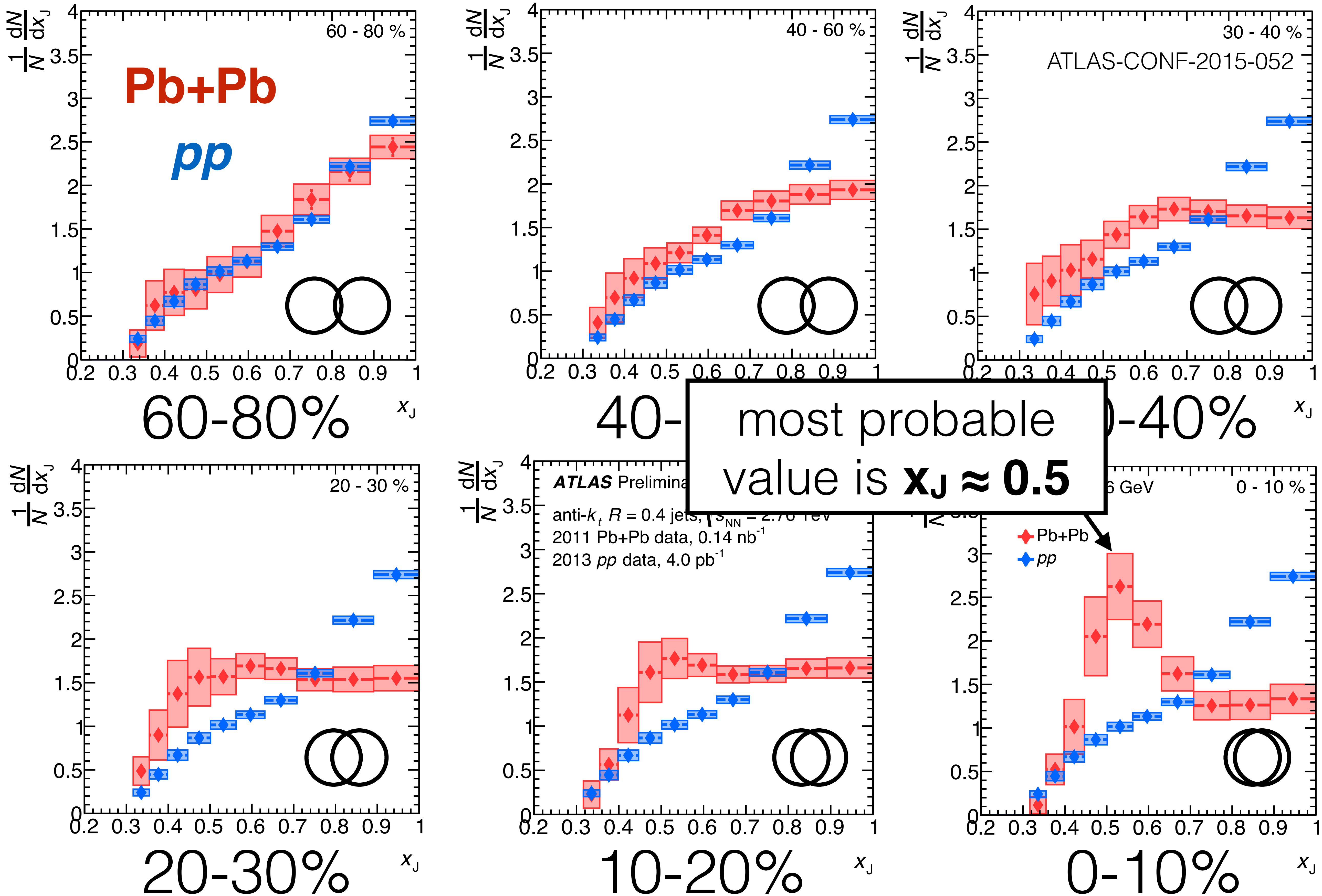
pp

Example **measured** and **unfolded** x_J distributions

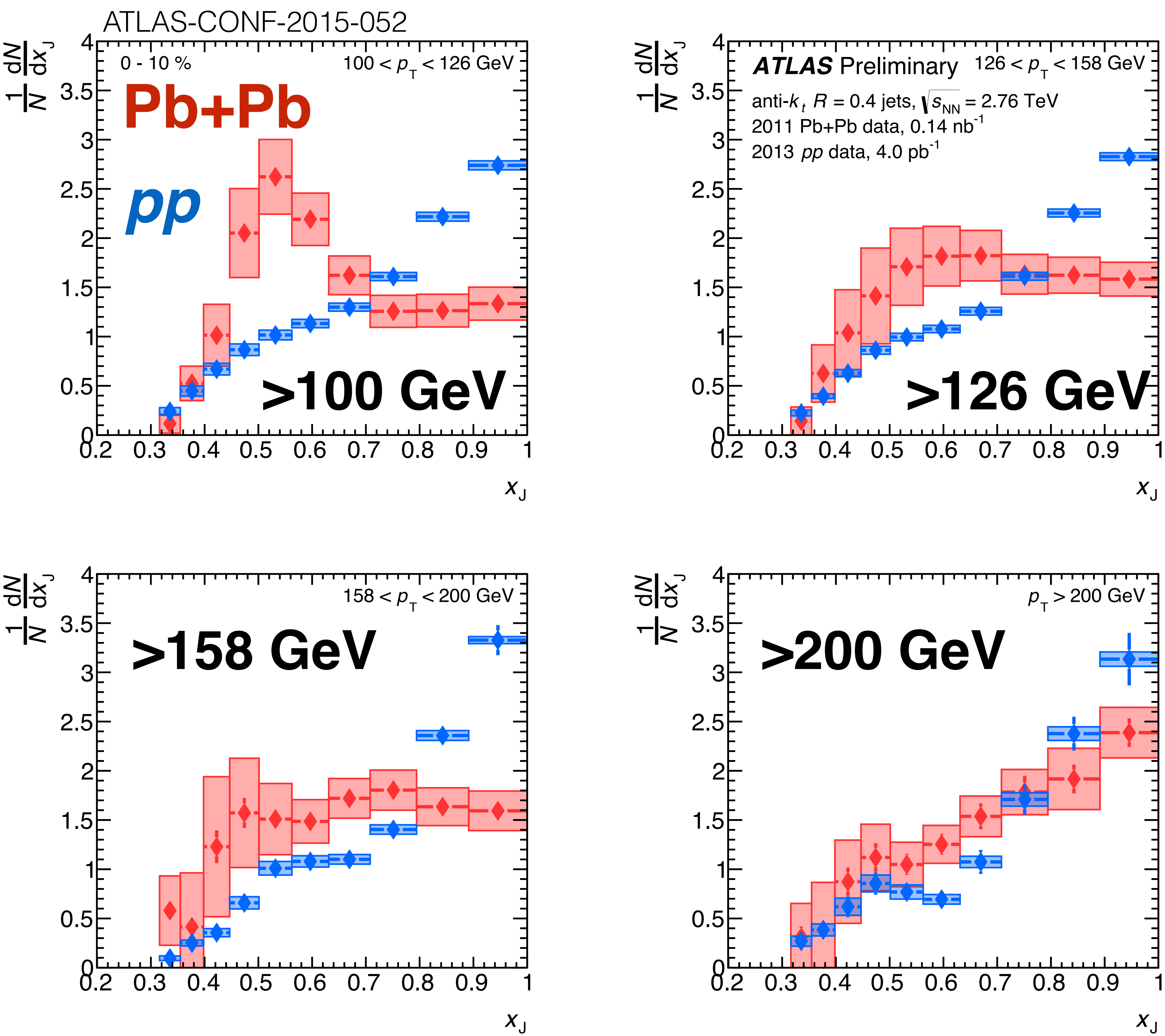
1. x_J for $p_{T,1}$ > 100 GeV, vs. centrality



1. x_J for $p_{T,1}$ > 100 GeV, vs. centrality



1. x_J for 0-10%, vs. $p_{T,1}$

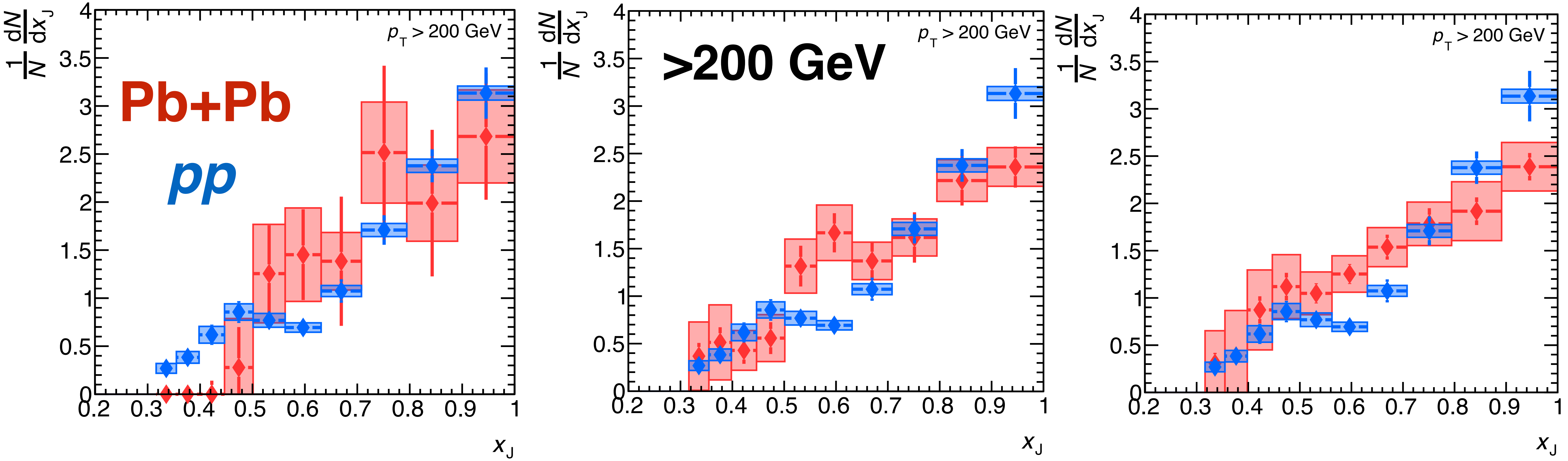


***pp*-like x_J** at high $p_{T,1}$!

fractional E-loss diff. between jets decreases w/ $p_{T,1}$?

1. x_J at high leading-p_T

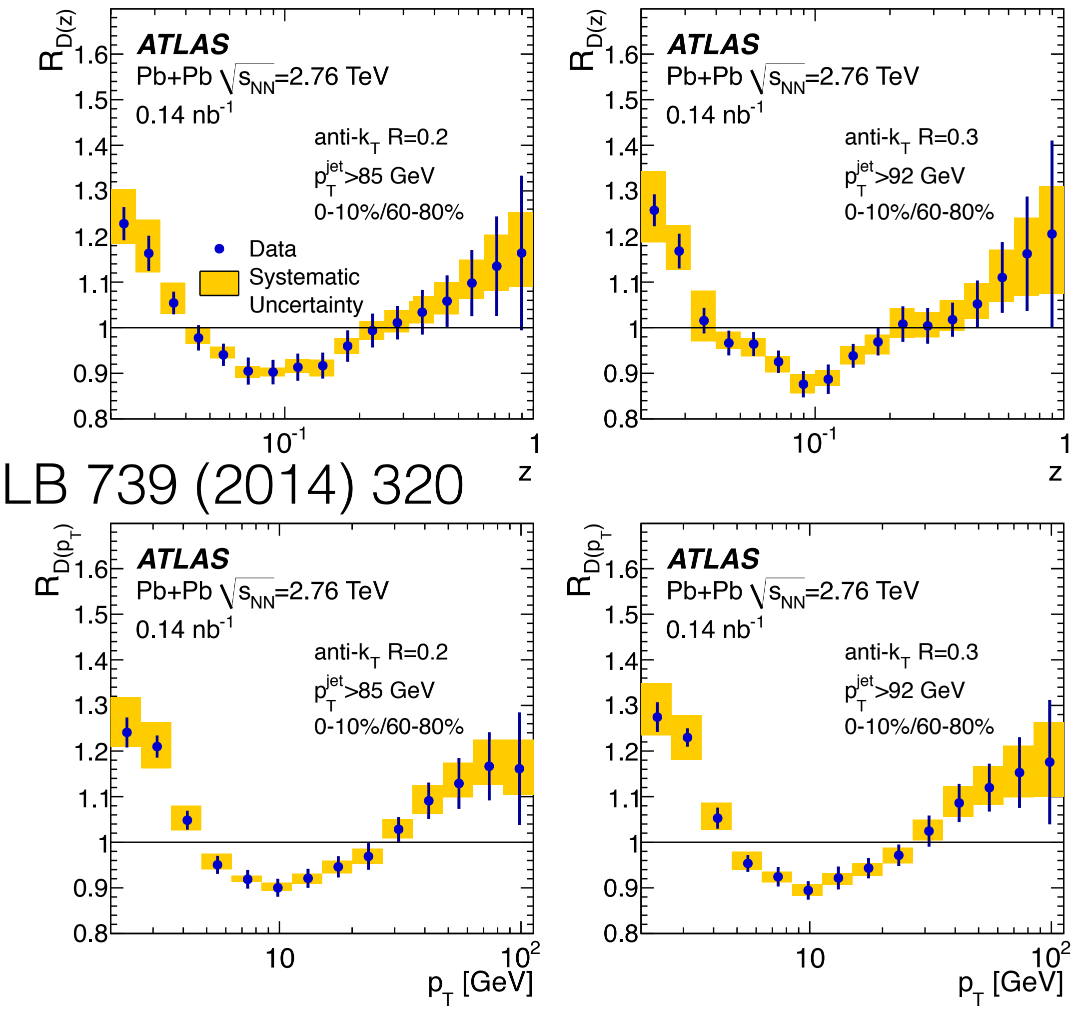
ATLAS-CONF-2015-052



60-80%   20-30%   0-10%

- Substantially **weaker centrality-dependence** for dijets with leading $\boldsymbol{p_{T,1}}$ **> 200 GeV**

2. Fragmentation functions



PLB 739 (2014) 320

$D(p_T^{\text{hadron}})$ *or*

$D(z)$, $z = p_T^{\text{hadron}} / p_T^{\text{jet}}$

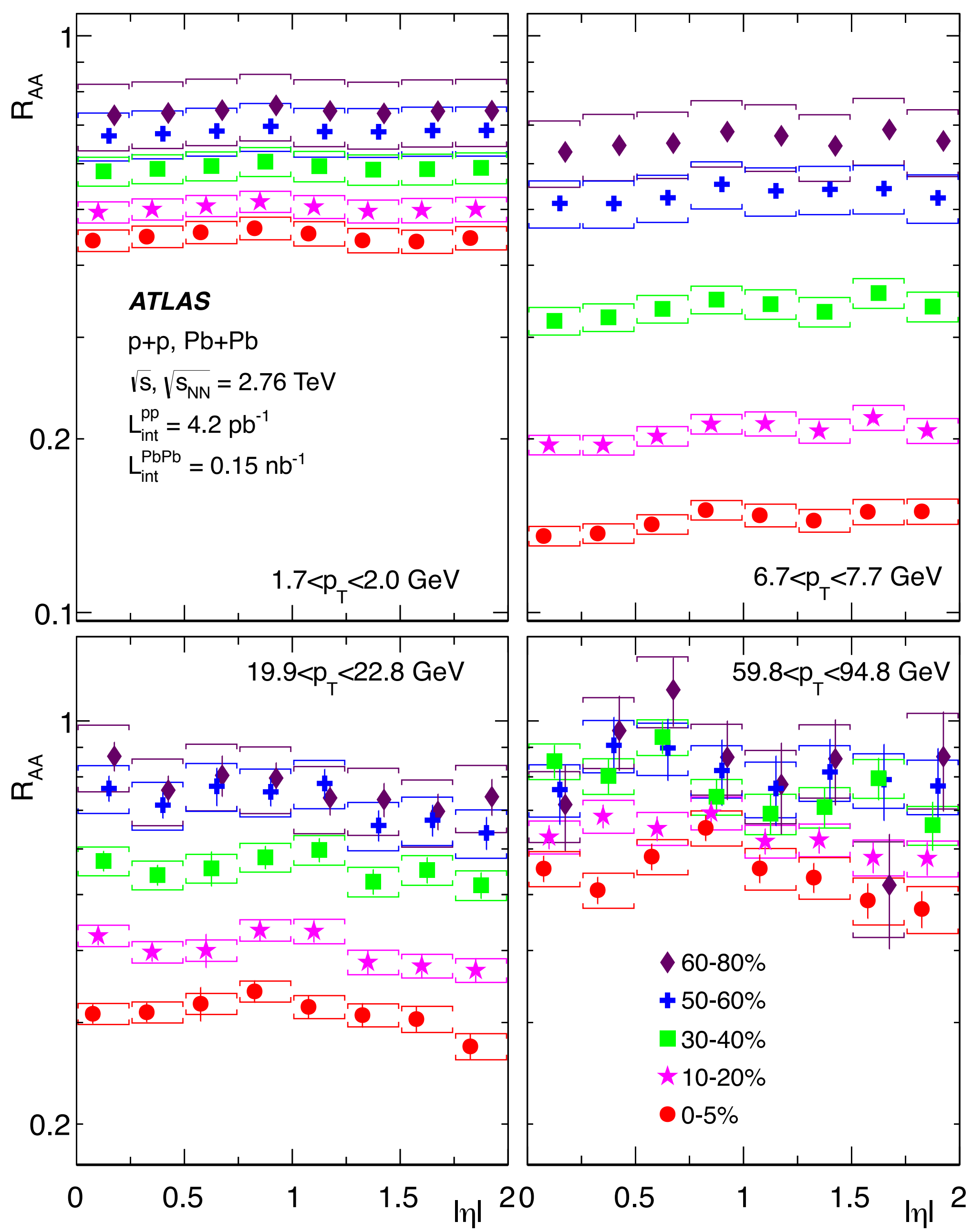
$\boldsymbol{R_{D(z)}} =$

$D(z)^{PbPb,central} / D(z)^{PbPb,peripheral}$

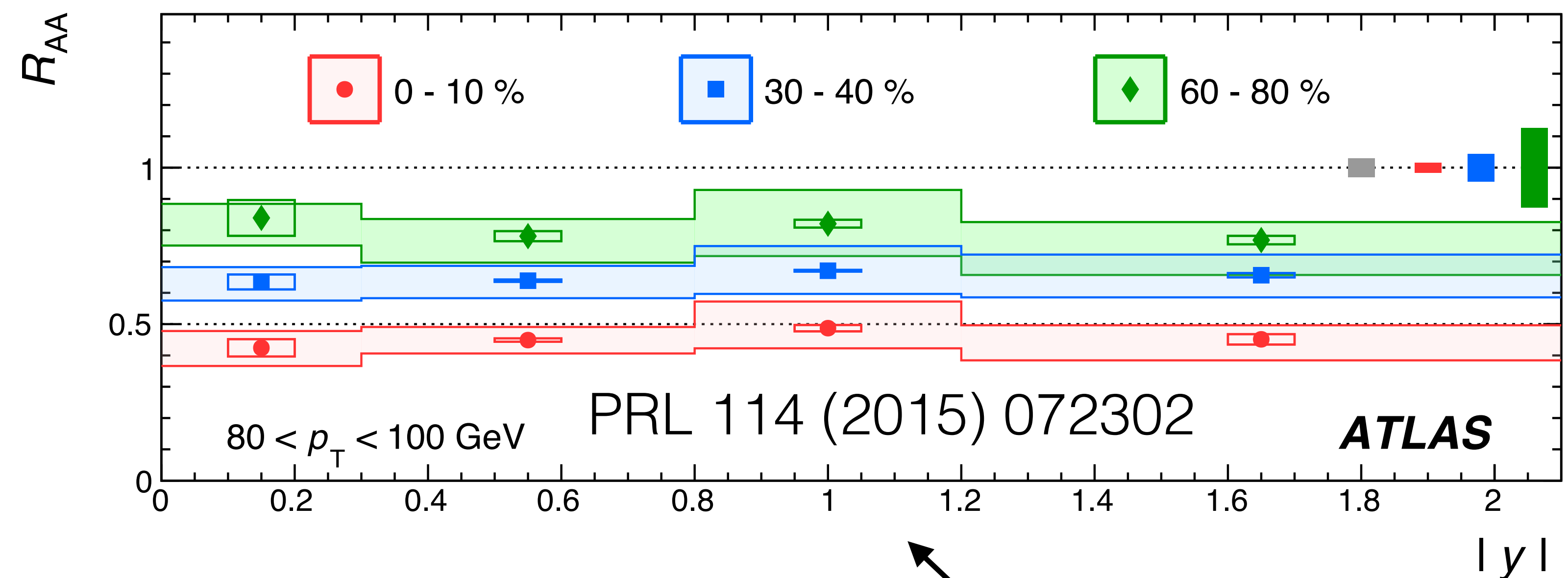
or $\boldsymbol{R_{D(p_T\text{hadron})}}$

- In addition to energy loss, jet internal structure can be modified
  - ➡ popularly, probe **longitudinal momentum structure** D(z)
- Much theoretical interest in early results
  - ➡ higher statistics & precision now allow for a *more differential look…*

JHEP 09 (2015) 050



2. η-dependence of quenching



jets

hadrons

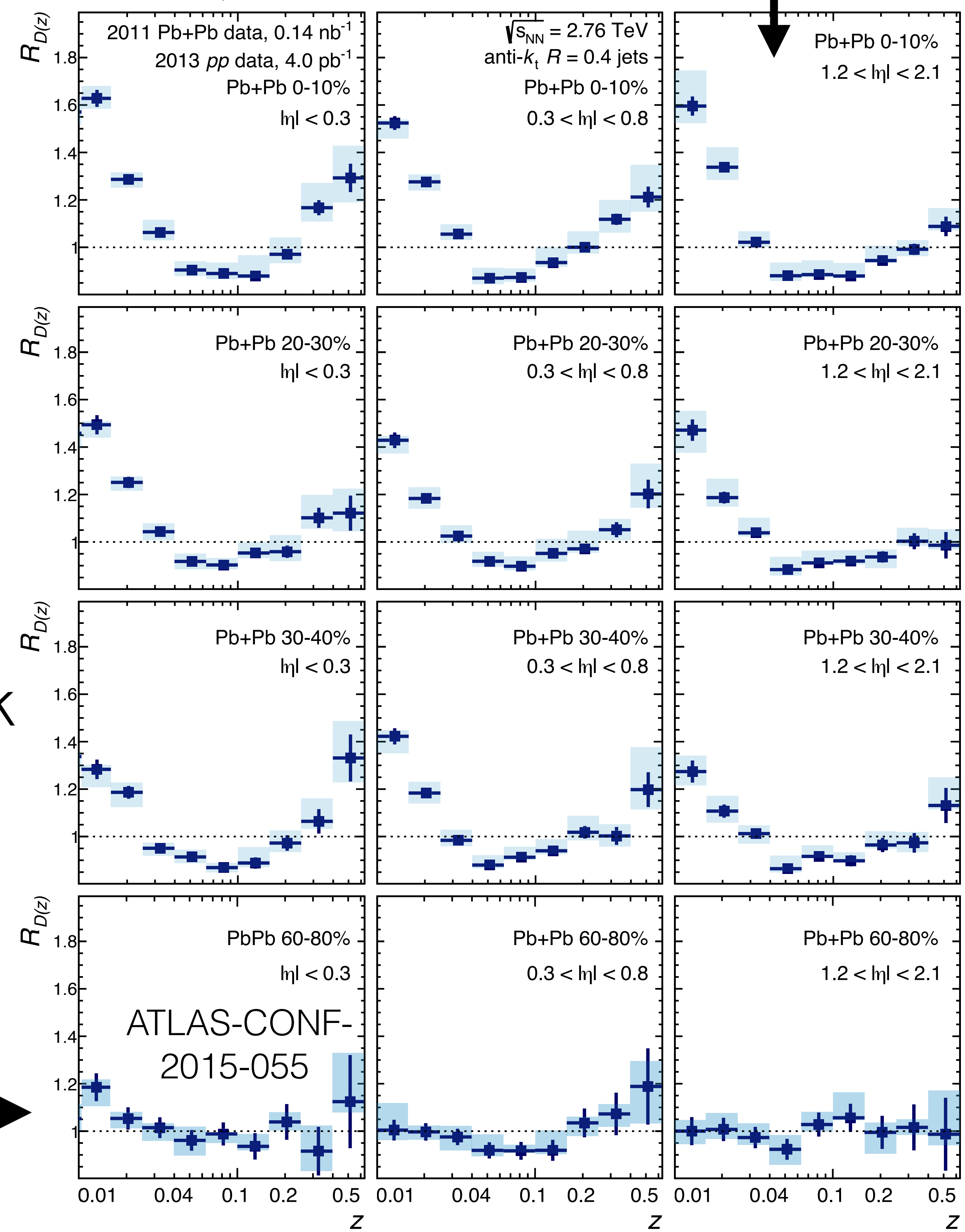
- Varying η range tests the interplay of several effects:
  - ➡ at fixed p_T, increased quark fraction at high η
  - ➡ at fixed p_T, (modestly) steeper spectrum at high η
  - ➡ at fixed p_T, smaller path length at high η

2. Fragmentation function vs. η

mid-rapidity

forward-rapidity

central



peripheral

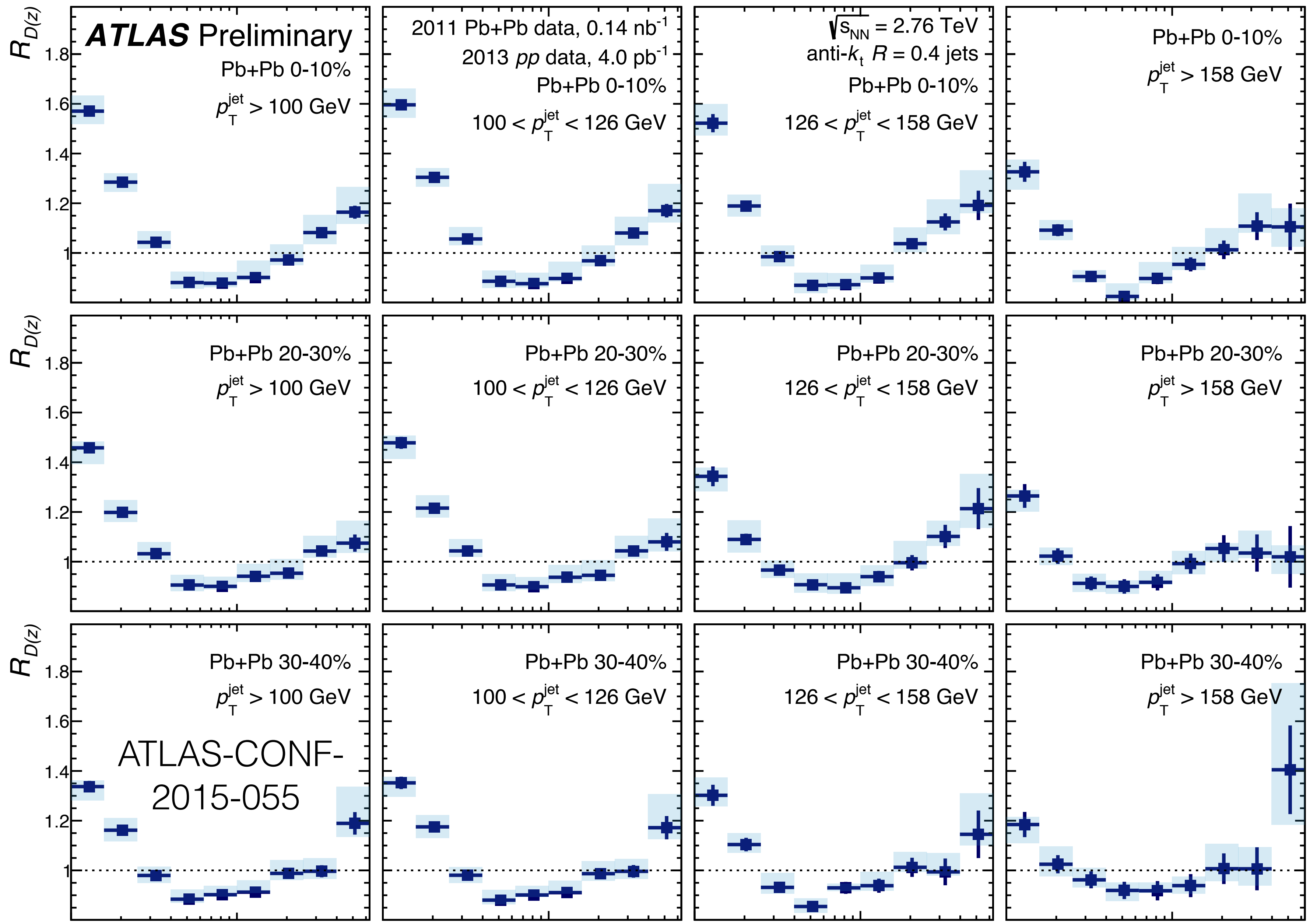
- $R_{D(z)} = D(z)^{\mathrm{Pb+Pb}} / D(z)^{\mathrm{pp}}$
  - ➡ plotted here vs. z
- *Moderate η dependence* at all centralities
  - ➡ suggests, e.g. higher quark fraction at forward rapidities? (hep-ph/1504.05169)

2. Fragmentation function vs. p_T

increasing p_T

central

semi-central



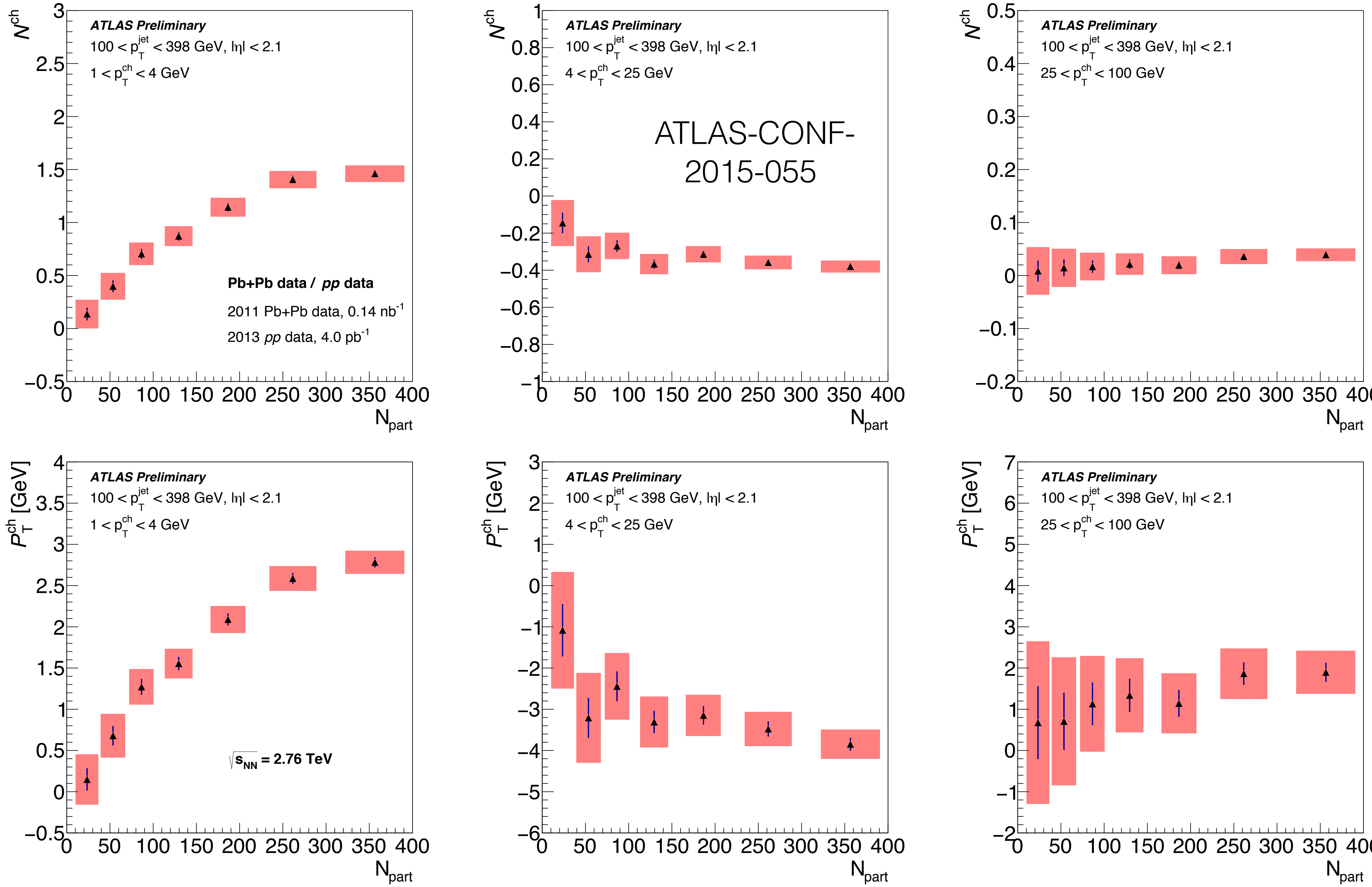
➡ Low and high-z excesses become <u>*systematically smaller*</u> with higher jet p_T…

2. Difference in fragment yield

$1 < p_T{}^h < 4$ GeV | $4 < p_T{}^h < 25$ GeV | $p_T{}^h > 25$ GeV

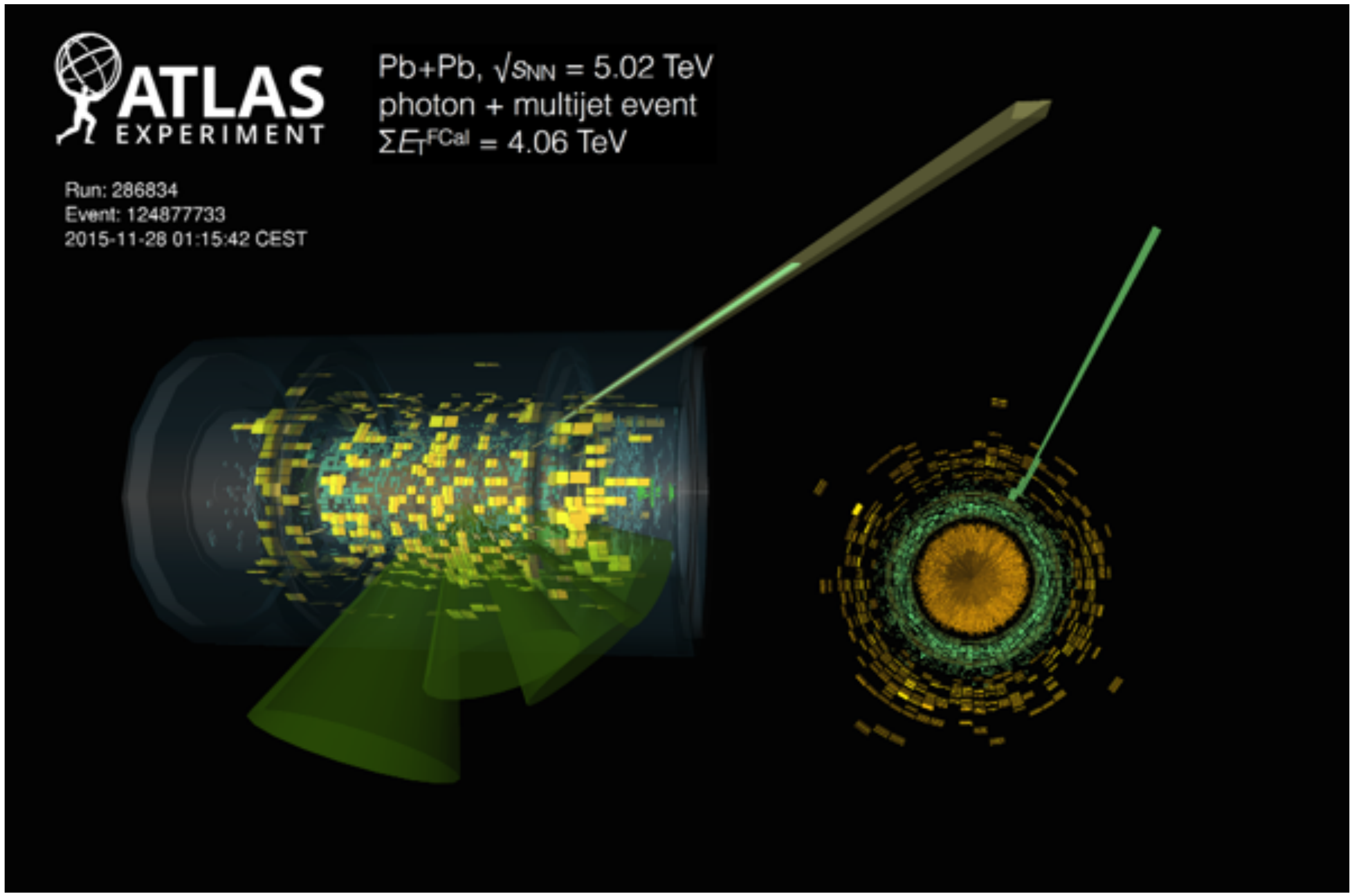
$\boldsymbol{\Delta N^{ch}} = N_{ch}{}^{Pb+Pb} - N_{ch}{}^{pp}$

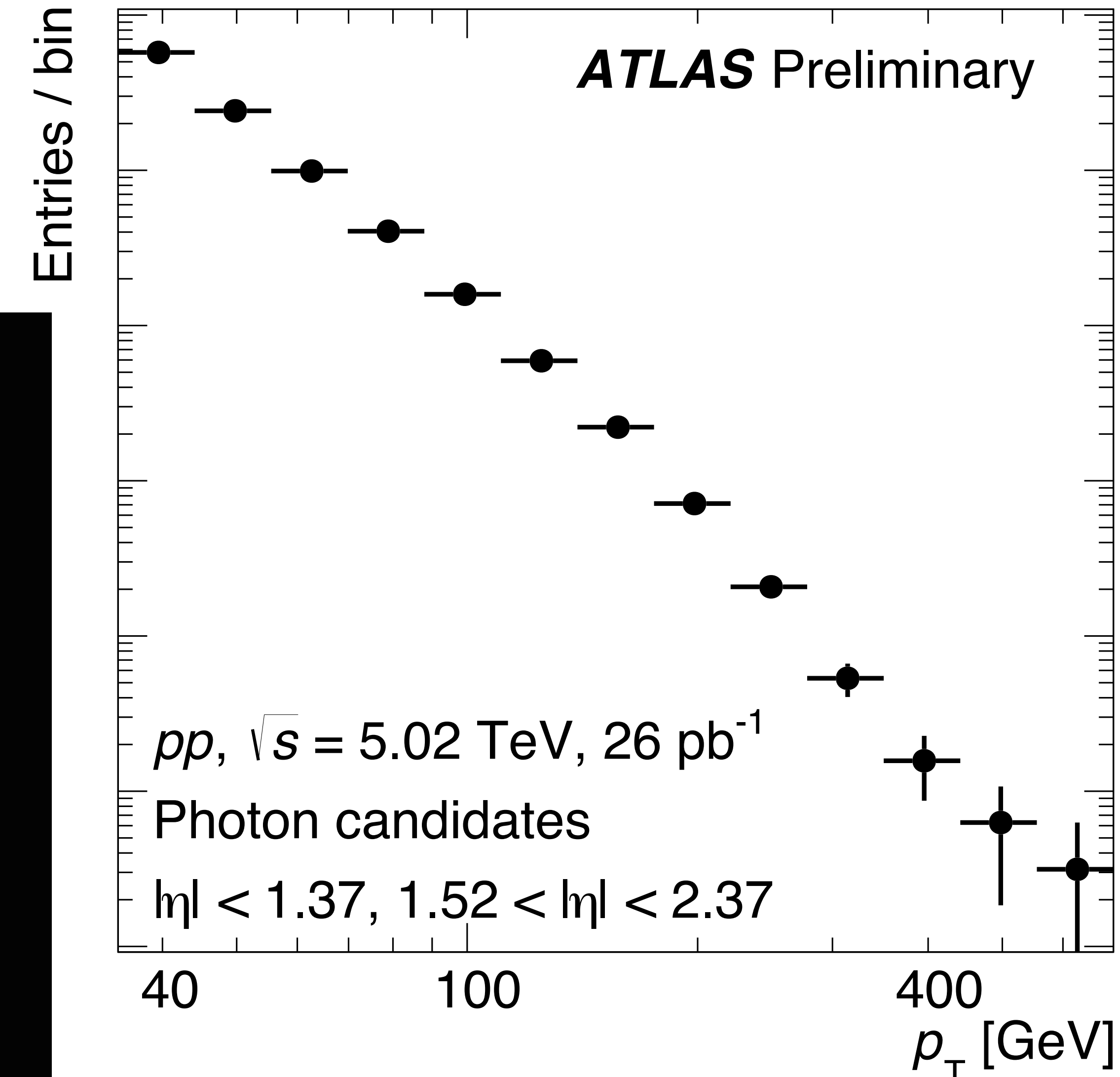
$\boldsymbol{\Delta \Sigma p_T{}^h} = (\Sigma p_T{}^h)^{Pb+Pb} - (\Sigma p_T{}^h)^{pp}$



➡ Modification may arise from << 1 particle/jet on average!

Prospects in Run 2





high-statistics gamma-jet in Run 2!

- ATLAS collected > 650 μb^{-1} of 5.02 TeV Pb+Pb data in November-December 2015
  - ➡ large statistics enables more differential looks at old observables
  - ➡ and entirely new measurements as well!

Summary

- Broad program of jet-based imaging of the hot nuclear medium in ATLAS
- New results on jet-jet p_T balance, x_J vs. $p_{T,1}$ and centrality
  - ➡ fully **corrected to particle-level** allow theory comparisons
  - ➡ non-trivial $p_{T,1}$- and centrality-dependent **evolution of x_J distribution**
- New results on inclusive fragmentation functions
  - ➡ full η-, p_T-, centrality-dependence can shed light on **flavor dependence of quenching**
- ATLAS is expecting to perform exciting high-statistics jet measurements in Run 2!

⇒ *https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HeavyIonsPublicResults* ⇐

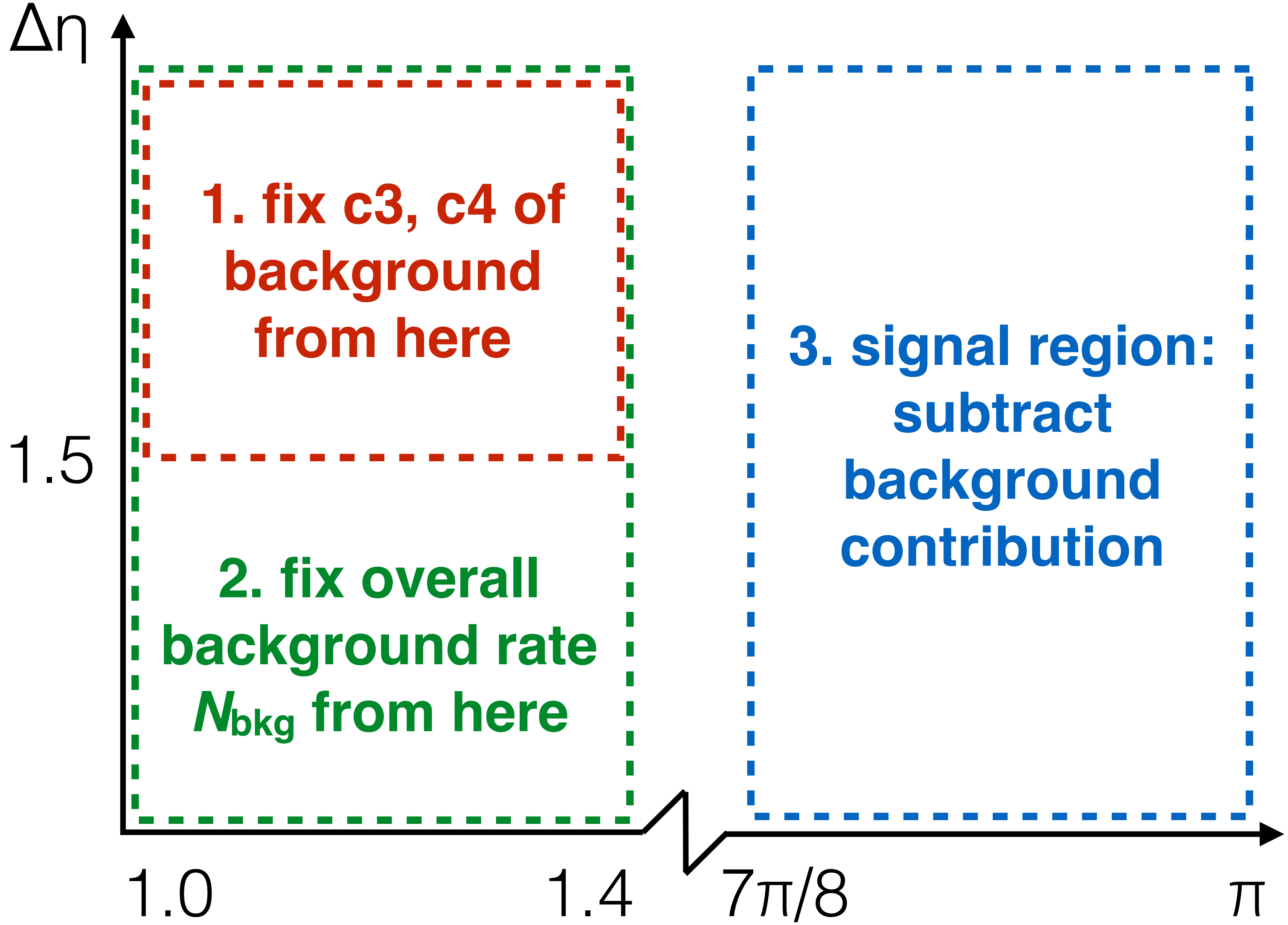
Backup

Systematic uncertainties

- Dominant at high-p_T and in peripheral collisions:
  - ➡ Response matrices regenerated with variations for each **jet energy scale** and **jet energy resolution** sub-uncertainty
- Dominant at lower-p_T and in central collisions:
  - ➡ **Unfolding procedure uncertainty**: # of Bayesian iterations, refolding test, large reweighting of x_J prior
- Subdominant effects evaluated:
  - ➡ Cross-check with **factorizing** two-jet response into the **product of the single jet response**
  - ➡ Variations in **combinatoric jet-jet subtraction** procedure

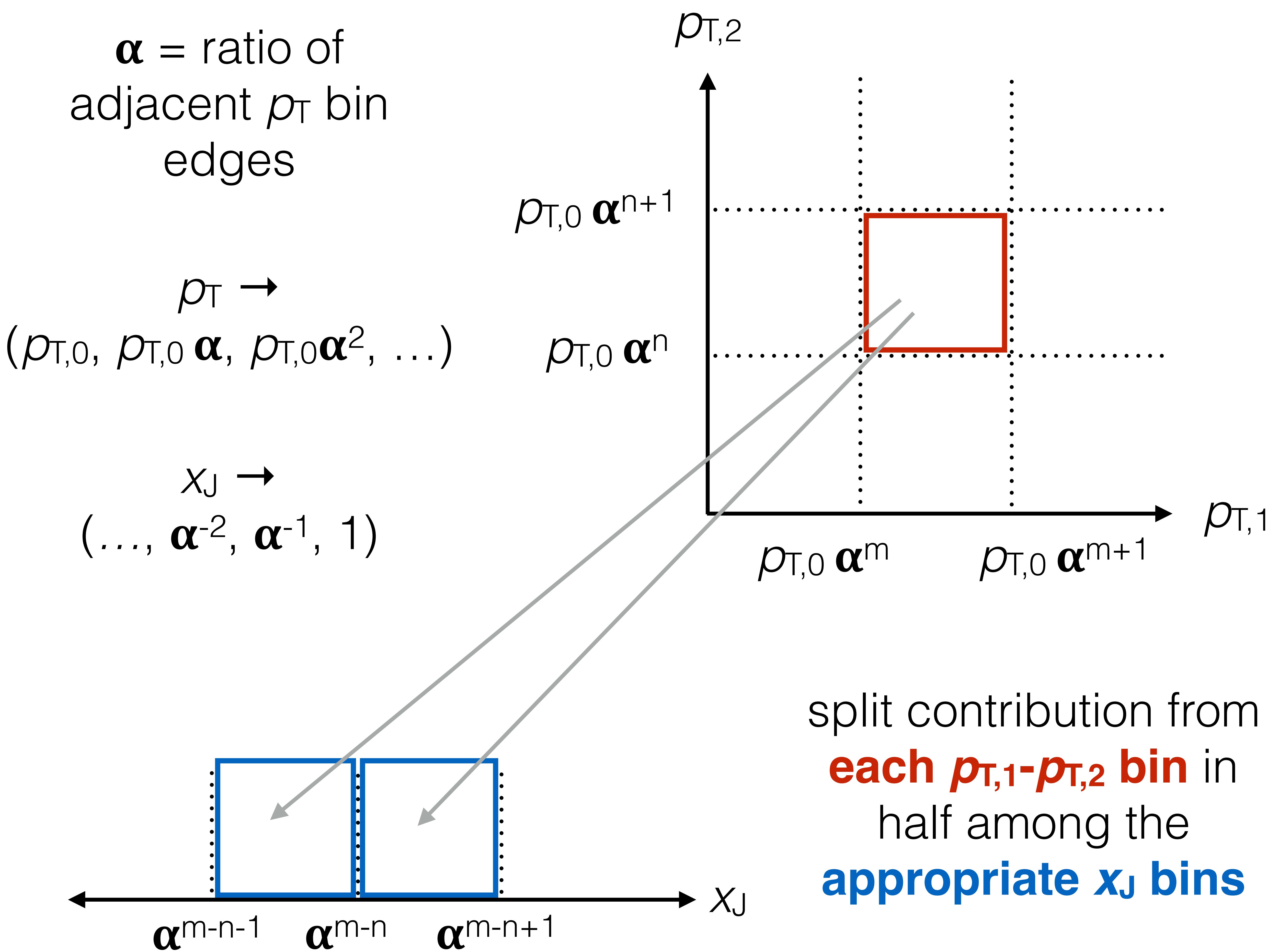
Combinatoric removal

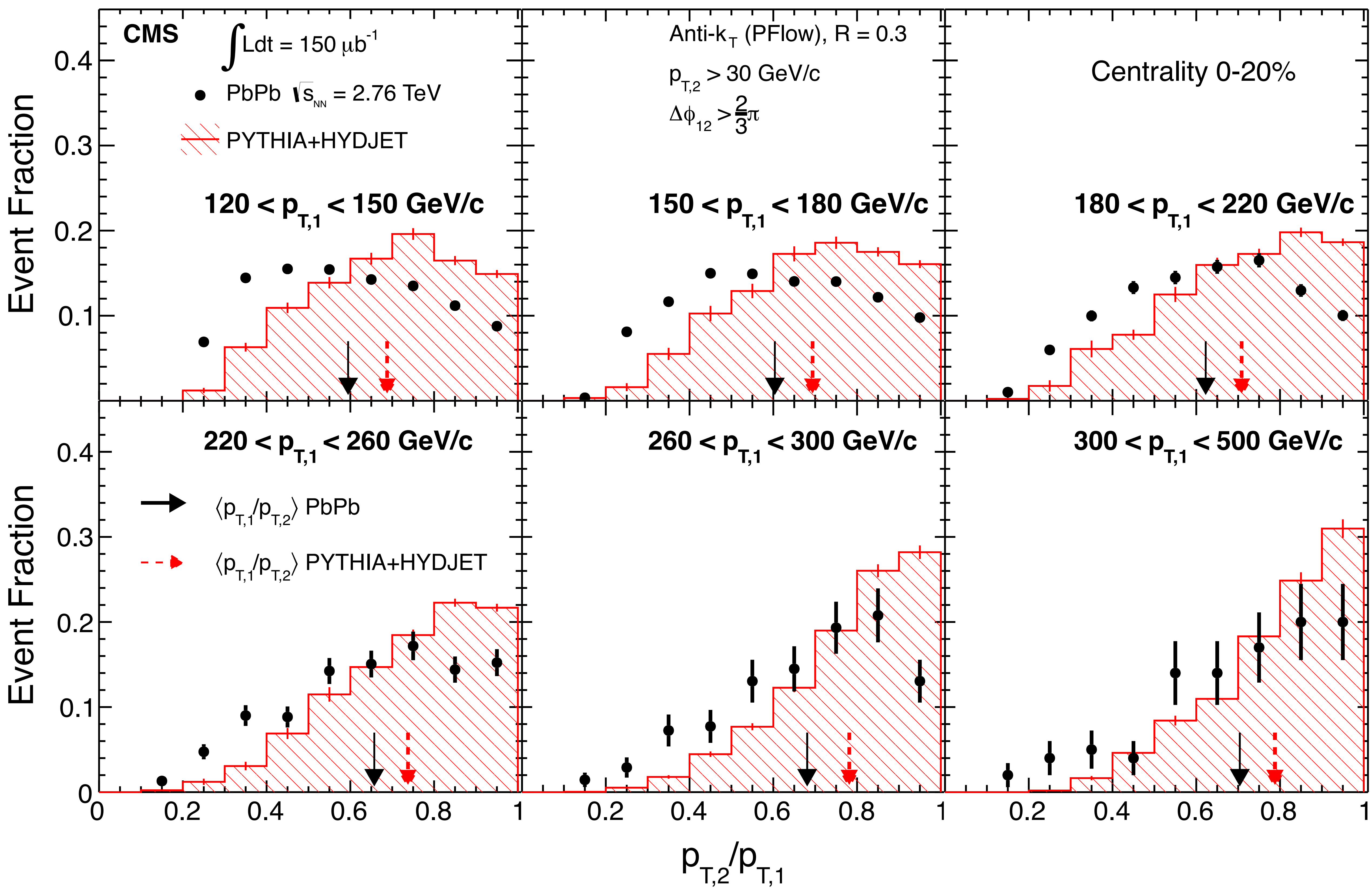
- Residual $p_{T,1}$-$p_{T,2}$ contribution from **combinatoric jet-jet correlations** pushed up by v_3- & v_4-modulated UE flow
  - ➡ of the form <u>$N_{bkg}(1 + 2\ c_3 \cos(3\Delta\phi) + 2\ c_4 \cos(4\ \Delta\phi)\ )$</u>



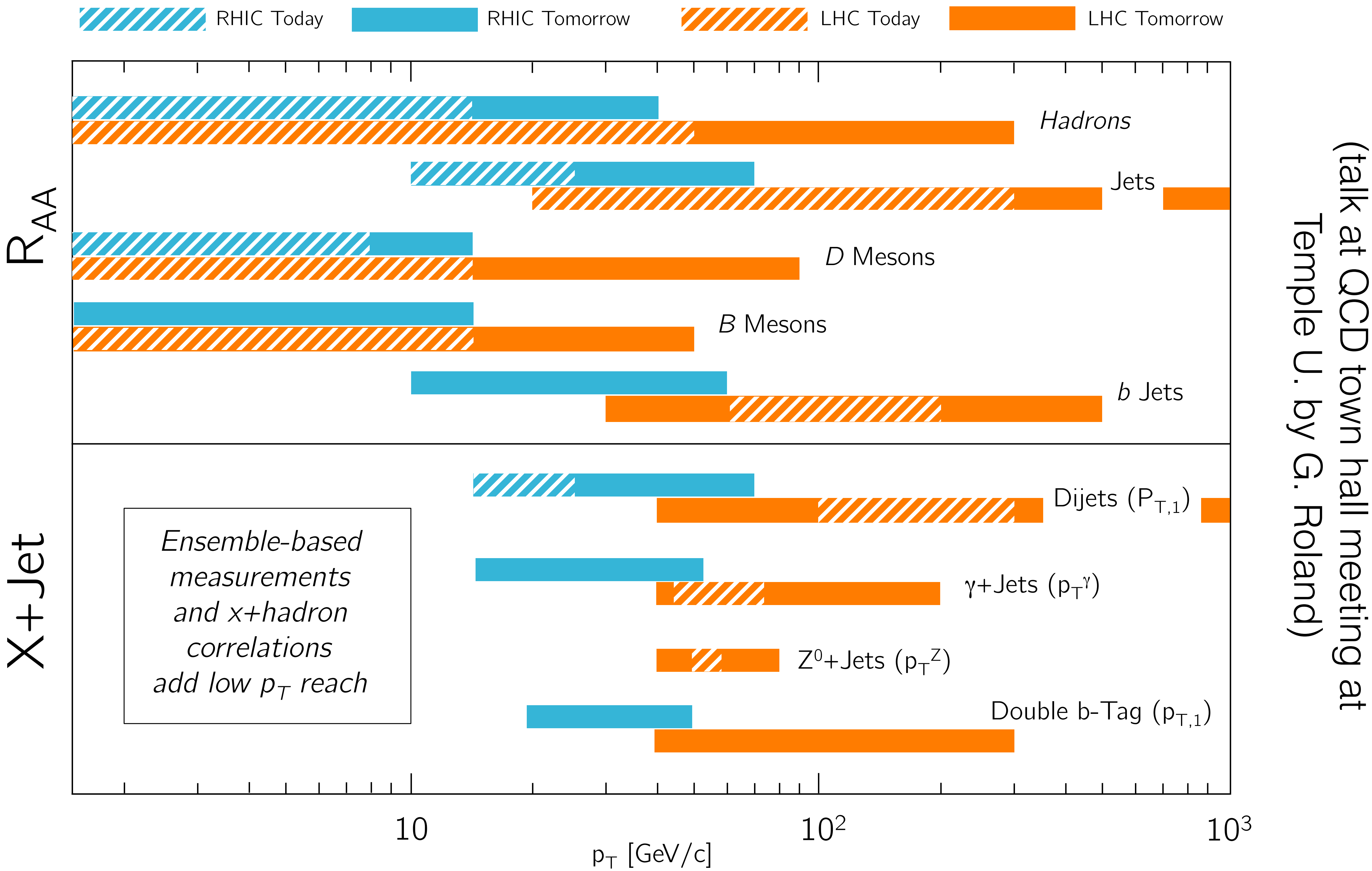
<u>≈10% effect</u> at smallest x_J in central collisions

typically <u>≈1% effect</u> elsewhere


α = ratio of adjacent pT bin edges
pT →
(pT,0, pT,0 α, pT,0α2, …)
xJ →
(…, α-2, α-1, 1)
pT,2
pT,0 αn+1
pT,0 αn
pT,1
pT,0 αm
pT,0 αm+1
xJ
αm-n-1
αm-n
αm-n+1
split contribution from each pT,1-pT,2 bin in half among the appropriate xJ bins


CMS
$\int Ldt = 150\ \mu b^{-1}$
PbPb $\sqrt{s_{NN}}$ = 2.76 TeV
PYTHIA+HYDJET
Anti-k_T (PFlow), R = 0.3
$p_{T,2} > 30$ GeV/c
$\Delta\phi_{12} > \frac{2}{3}\pi$
Centrality 0-20%
120 < $p_{T,1}$ < 150 GeV/c
150 < $p_{T,1}$ < 180 GeV/c
180 < $p_{T,1}$ < 220 GeV/c
220 < $p_{T,1}$ < 260 GeV/c
260 < $p_{T,1}$ < 300 GeV/c
300 < $p_{T,1}$ < 500 GeV/c
$\langle p_{T,1}/p_{T,2} \rangle$ PbPb
$\langle p_{T,1}/p_{T,2} \rangle$ PYTHIA+HYDJET
Event Fraction
$p_{T,2}/p_{T,1}$
0
0.1
0.2
0.3
0.4
0.6
0.8
1

Jet measurements in LHC Run 2



- 5 TeV Pb+Pb collisions, Nov. 2015: 30x the hard probe rate in Run I
- Differential looks at Run I quantities and entirely new Run 2 observables