Overview of experimental results on jets in heavy-ion collisions

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Overview

- Experimental results using reconstructed jets in AuAu and PbPb collisions from QM’11 and QM’12
- No survey of models
- Brief discussion of jet finding performance and backgrounds
- Survey of results
  - Considerations for comparison to theory?
  - Consistency of experimental results?

Overview, part II

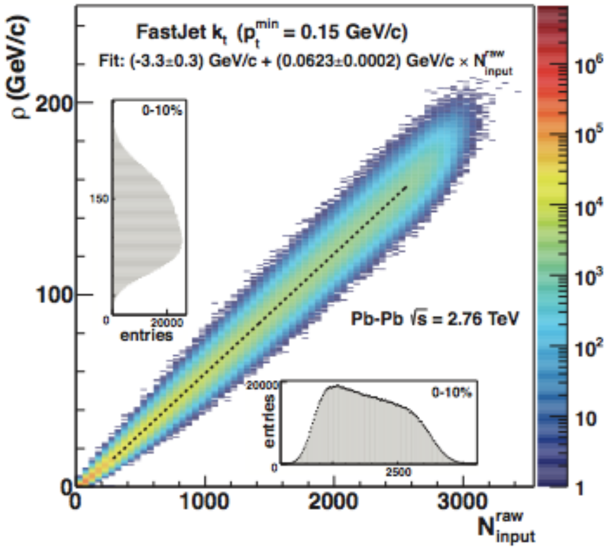
- Inclusive Jet R_{AA} and R_{CP}
  - ALICE: R. Reed, QM'12, ATLAS: arXiv:1208.1967; CMS: HIN-12-004; STAR: H. Caines, QM'11
- Dijet asymmetries
  - ATLAS: Phys.Rev.Lett. 105 (2010) 252303, M. Rybar, HP 2012; CMS:PRC 84 (2011) 024906, PLB 712 (2012) 176
- Inclusive jet v_2
  - ATLAS-CONF-2012-116; STAR: A. Ohlson, QM'12
- Jet anatomy: Jet shapes and fragmentation functions
  - ATLAS-CONF-2012-115; CMS-PAS-HIN-12-010
- Lost energy: Missing p_T and jet-track correlations
  - CMS:PRC 84 (2011) 024906, H. Caines, QM'11
- Into the future:
  - gamma-jet: ATLAS-CONF-2012-121. CMS arXiv:1205.0206
  - b-jets: CMS PAS HIN-12-003

Backgrounds and jet finding performance

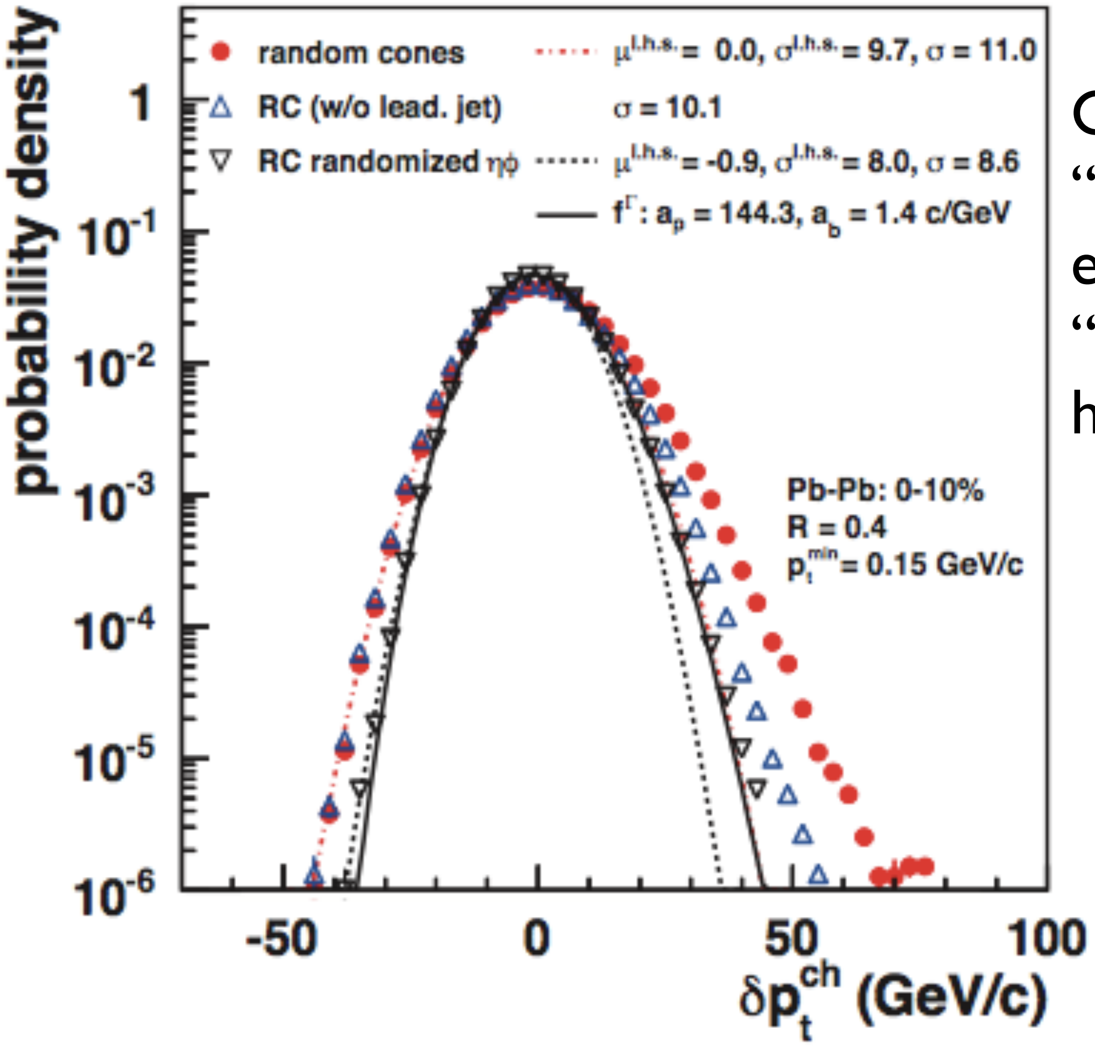
Some basic info

- Jet finding algo: Anti-k_T , using R from 0.2 to 0.5
- Background subtraction
  - ALICE, STAR: ρ x Area
  - ATLAS, CMS: iterative background subtraction in eta-rings
- Jet constituents
  - ALICE: tracks; tracks + ECAL matching
    - tracks from p_T > 0.15 GeV/c (R-independent)
  - ATLAS: calorimeter (ECAL+HCAL) towers; tracks
    - calo jets from p_T > 0.5-1GeV (??) (R-dependent)
  - CMS: Particle flow (combined tracks, ECAL, HCAL); calorimeter towers
    - PF objects from p_T > 1 GeV (R-independent)

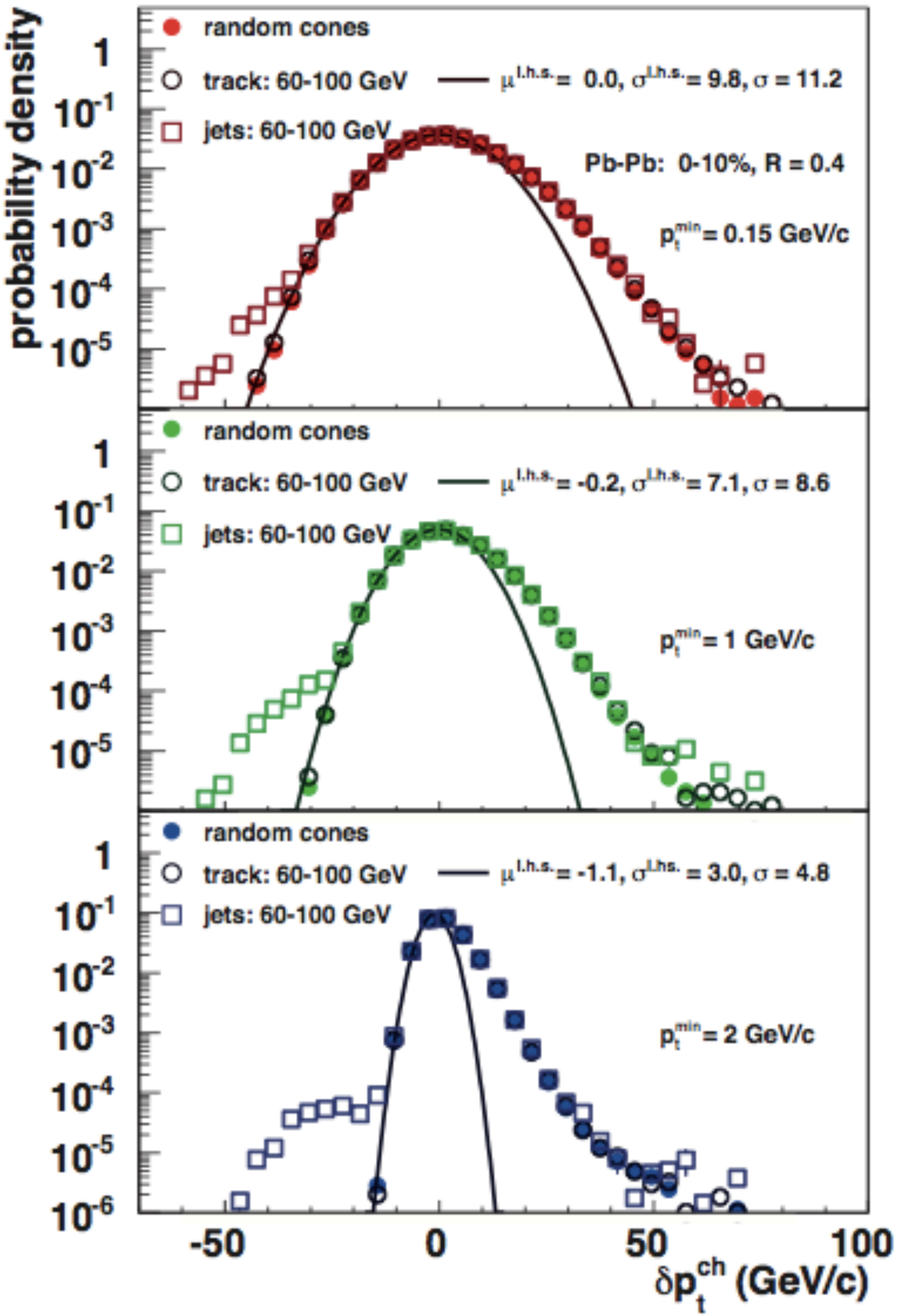
ALICE jet background studies



Large background per unit area

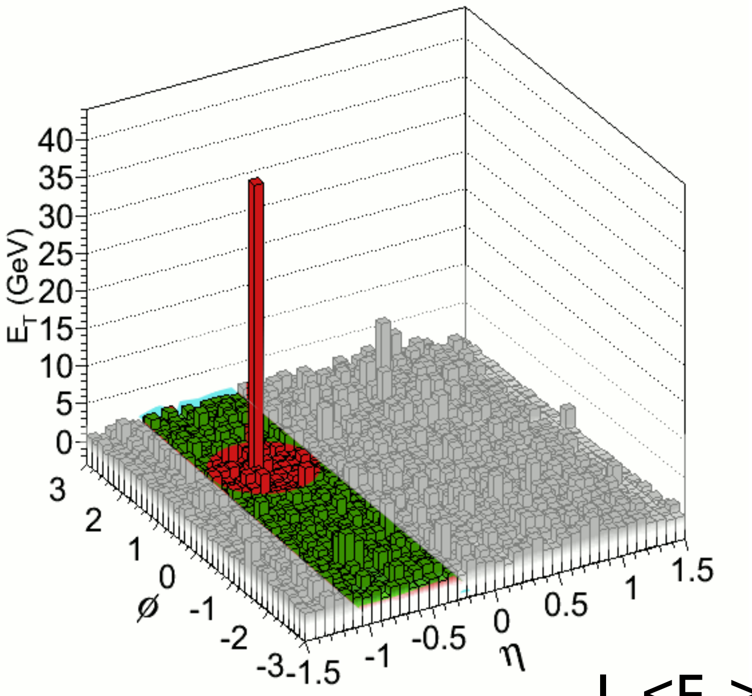


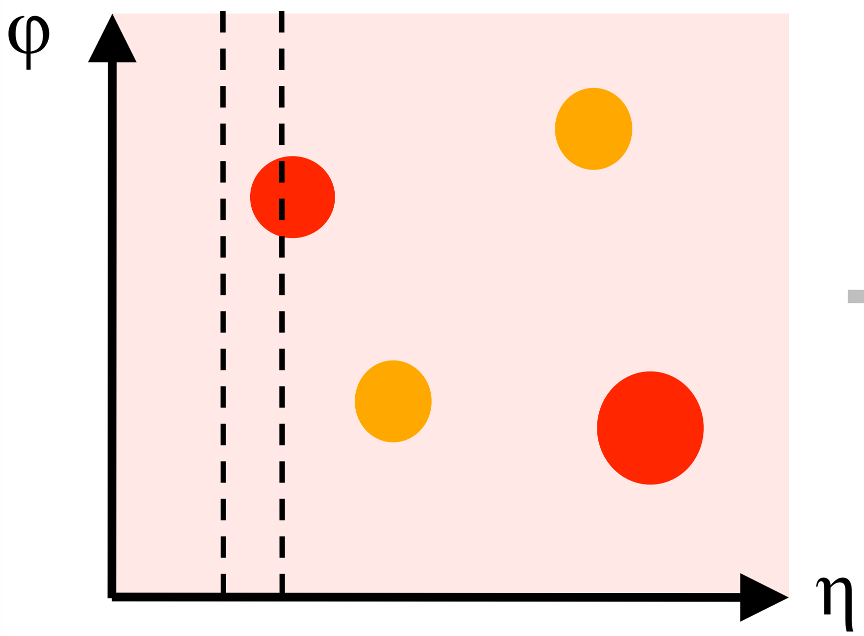
Combination of "soft" underlying event and "coincidence" with hard scattering



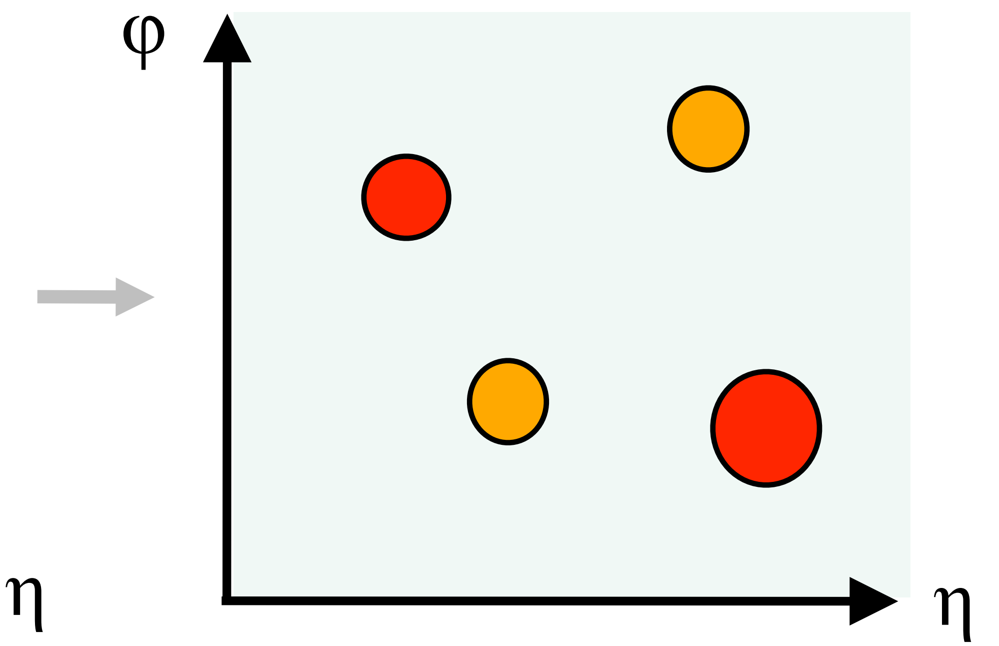
Background fluctuations depend ***strongly*** on p_T threshold and cone size

Underlying Event Subtraction (CMS)

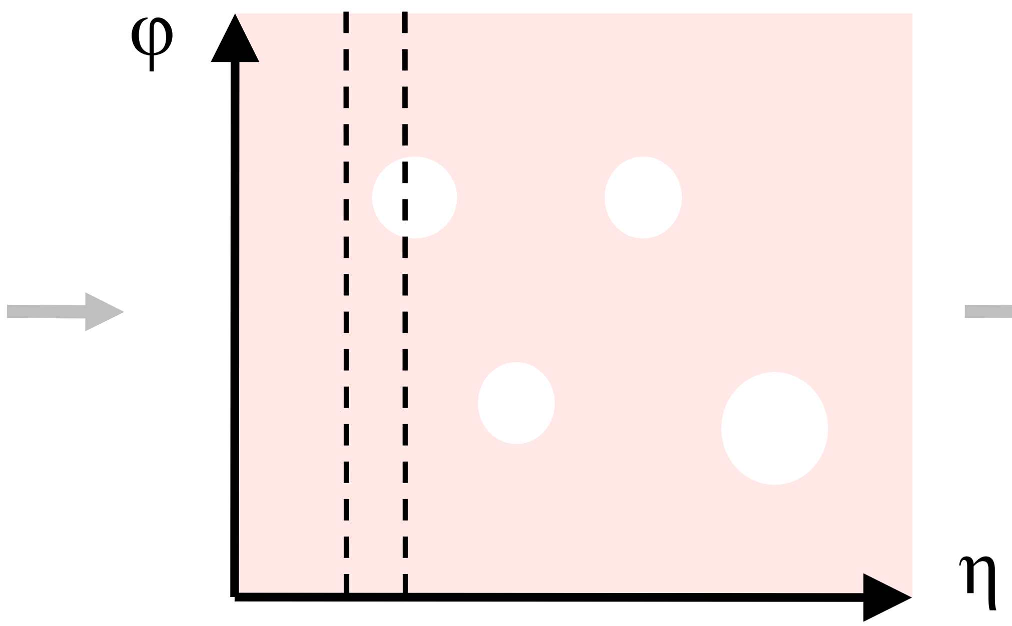




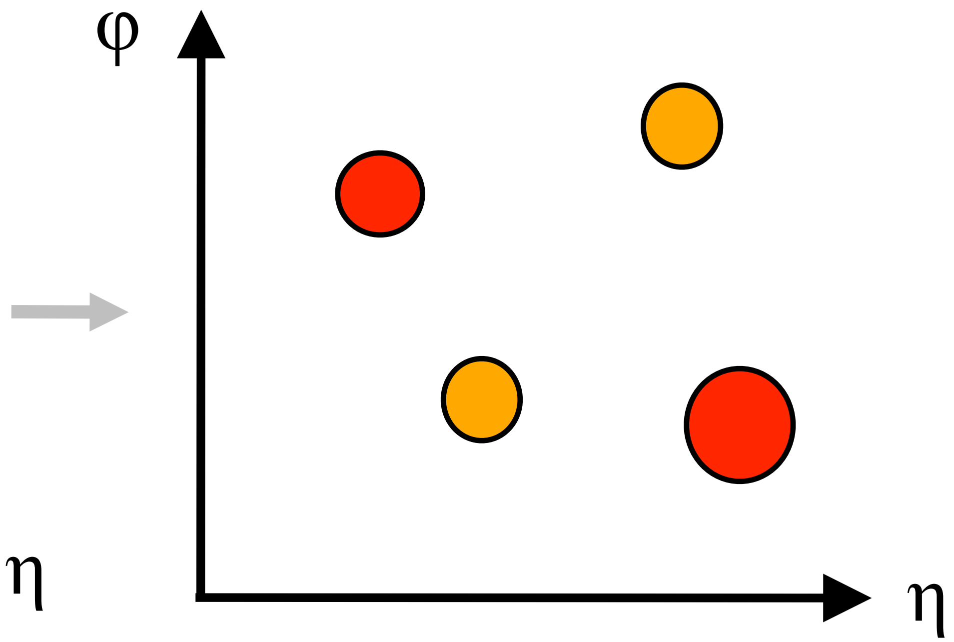
1. $\langle E_T \rangle$ calculated in strips of η. Subtract $\langle E_T \rangle + \sigma$



2. Run anti-k_T algorithm on background-subtracted towers



3. Exclude reconstructed jets and re-estimate background

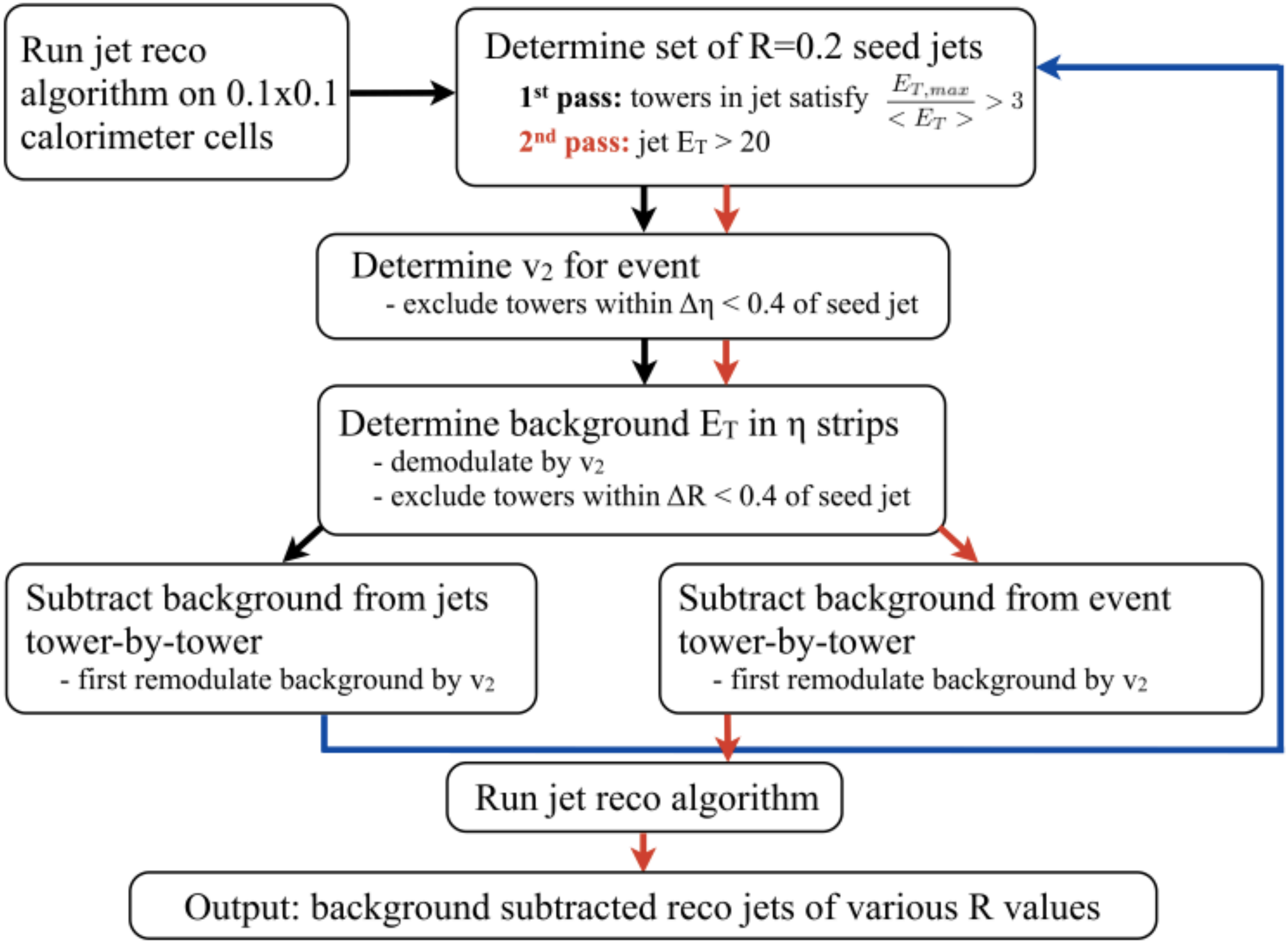


4. Re-run anti-k_T algorithm to get final jets

For details see:

- CMS, arXiv:1102.1957
- Kodolova et al., EPJC 50 (2007) 117

Underlying event subtraction (ATLAS)



Run jet reco algorithm on 0.1x0.1 calorimeter cells

Determine set of R=0.2 seed jets

1st pass: towers in jet satisfy $\frac{E_{T,max}}{< E_T >} > 3$

2nd pass: jet $E_T > 20$

Determine v_2 for event

- exclude towers within $\Delta\eta < 0.4$ of seed jet

Determine background E_T in η strips

- demodulate by v_2
- exclude towers within $\Delta R < 0.4$ of seed jet

Subtract background from jets tower-by-tower

- first remodulate background by v_2

Subtract background from event tower-by-tower

- first remodulate background by v_2

Run jet reco algorithm

Output: background subtracted reco jets of various R values

"Closure tests"

- Some CMS jargon
  - "**gen level**": final state particle truth info of event generators (e.g. PYTHIA) before decay of long-live particles ($c\tau > 1$cm)

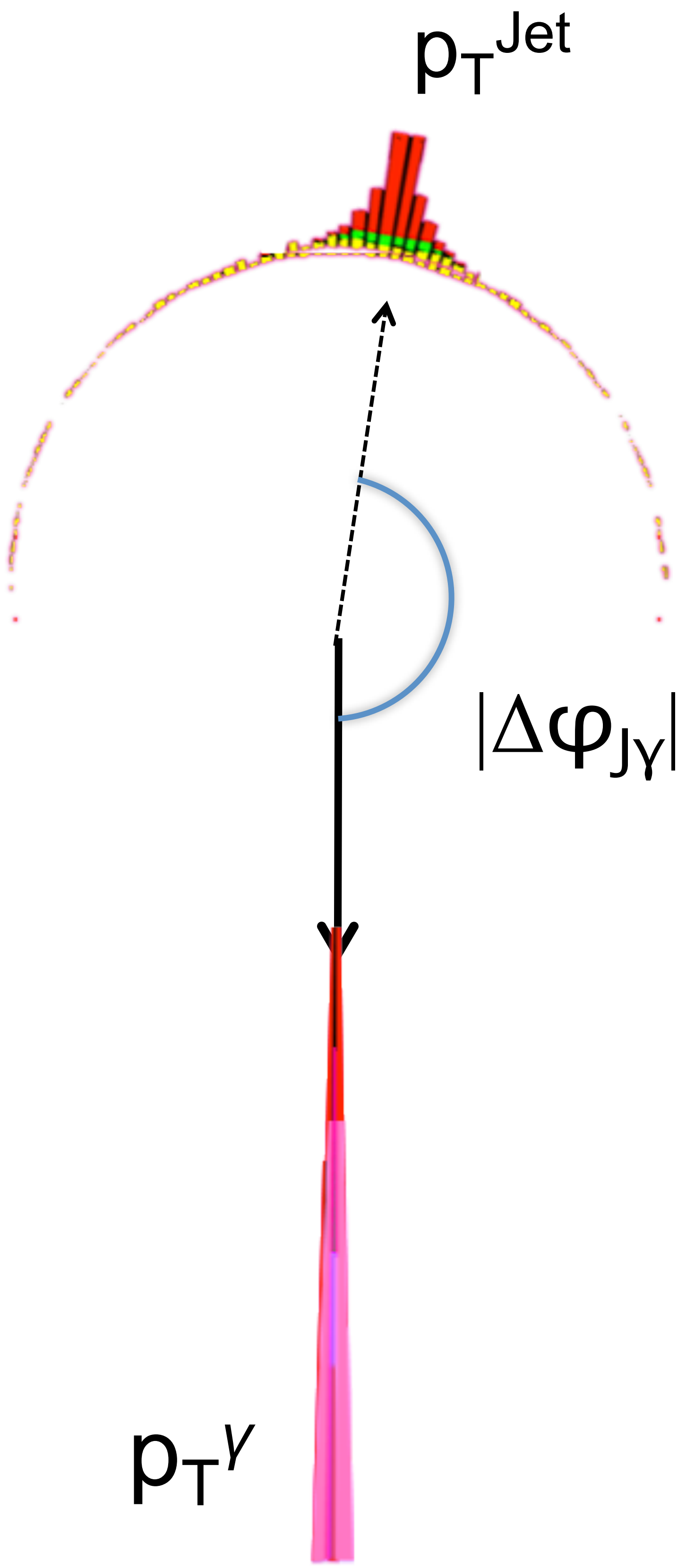
  - "**reco level**": after simulation of all decays, full simulation (GEANT 4) and reconstruction of tracks, photons, jets etc

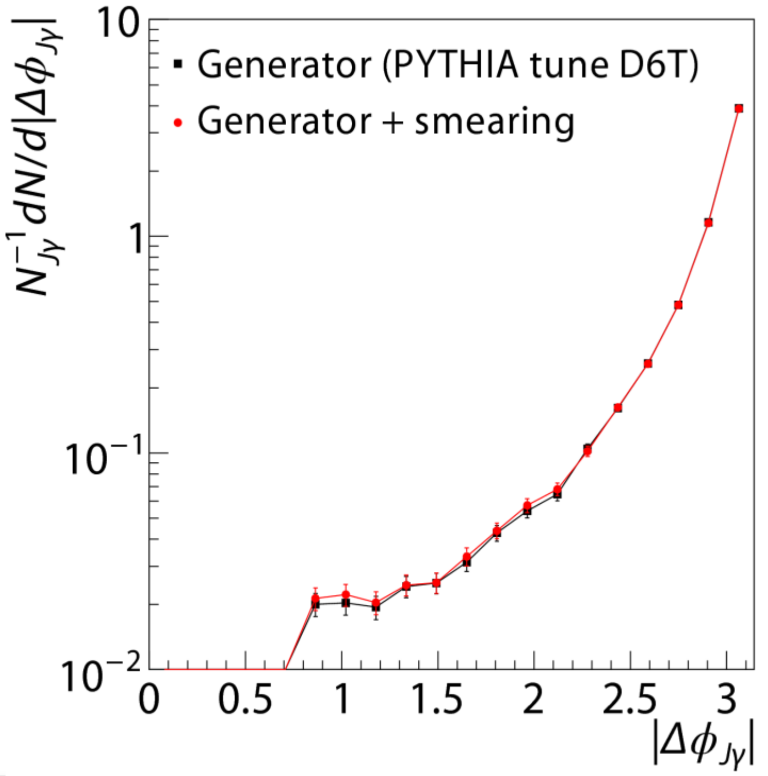
  - "**embedding**": combining a single generator hard scattering event (e.g. a PYTHIA pp dijet event) with the heavy-ion underlying event (from data or from HYDJET). Called "**overlay**" by ATLAS

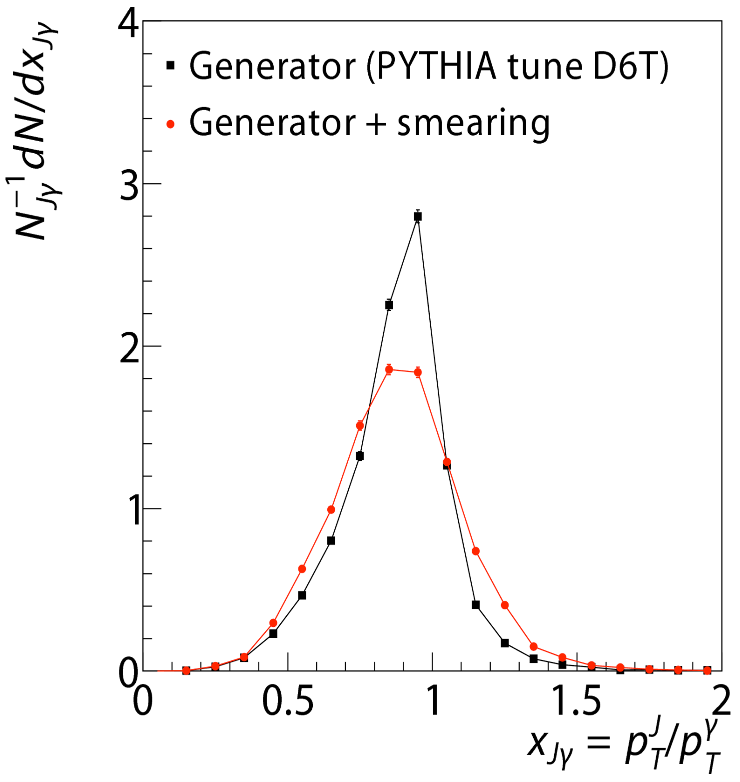
  - "**closure test**": comparison of an observable (e.g. dijet A_j) for e.g. PYTHIA gen level truth vs reco level result after embedding for the same set of PYTHIA events

Example: photon-jet closure test

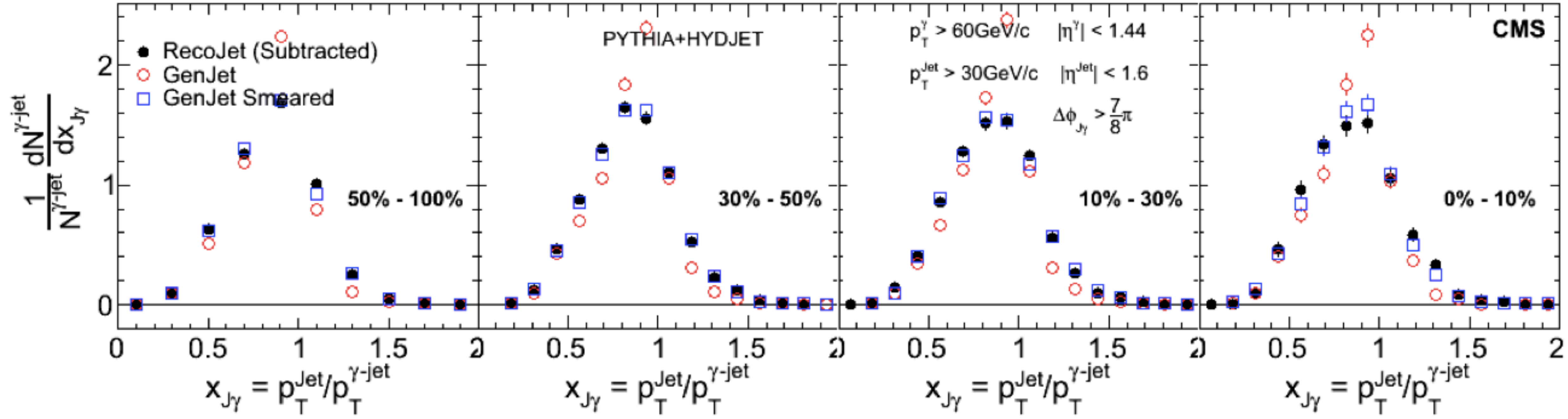
- Azimuthal decorrelation:
  $|\Delta\varphi_{J\gamma}|$, and its parametrized width $\sigma(|\Delta\varphi_{J\gamma}|)$
- Transverse momentum ratio:
  $x_{J\gamma} = p_T^{Jet} / p_T^{\gamma}$, and its mean $\langle x_{J\gamma} \rangle$
- Fraction of photons with associated jets: $R_{J\gamma}$
- $p_T^{\gamma} > 60$ GeV/c (to have sufficient $x_{J\gamma}$ phase space)
- $p_T^{Jet} > 30$ GeV/c (constrained by efficiency)

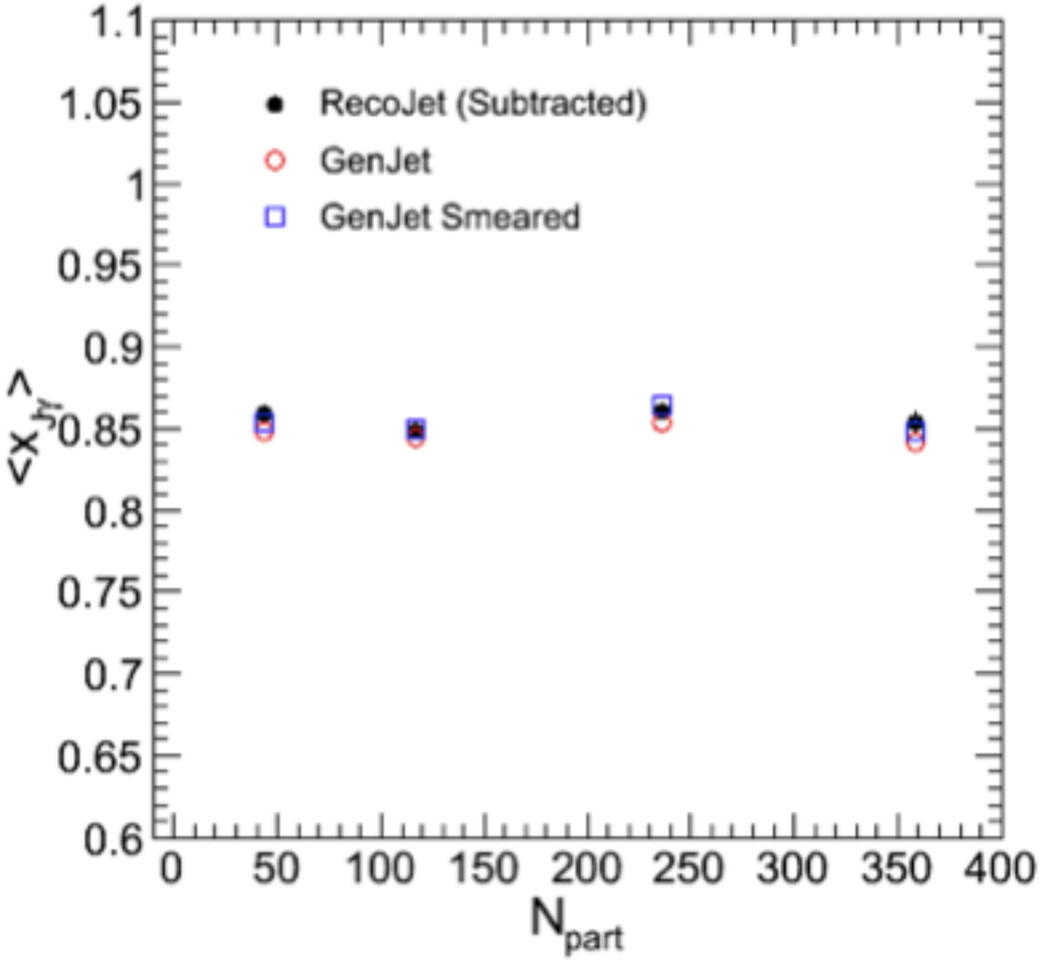






Example: photon-jet closure test



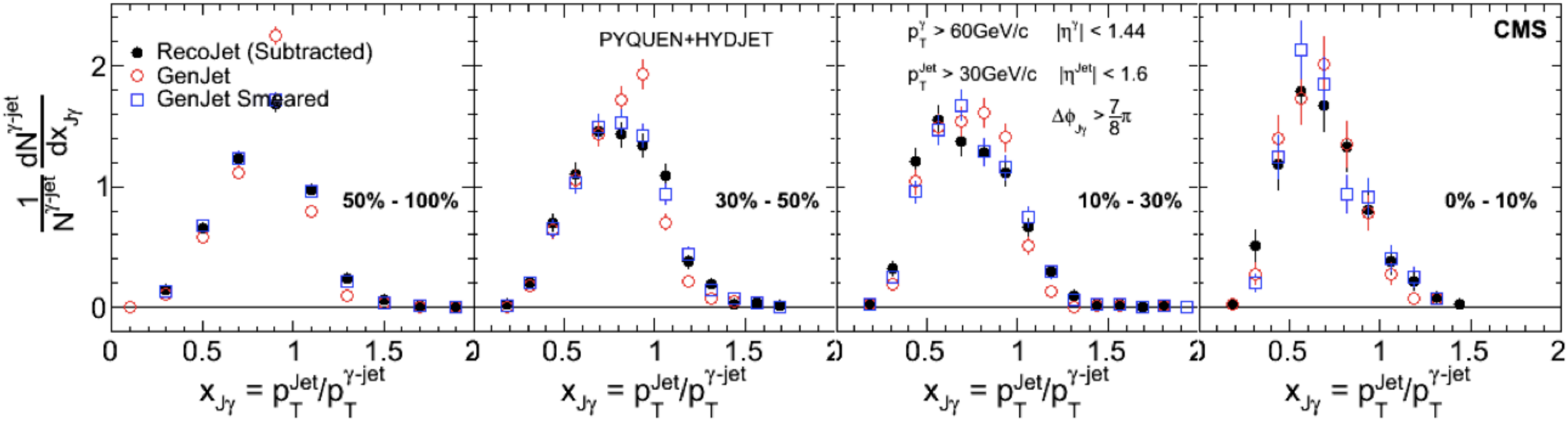


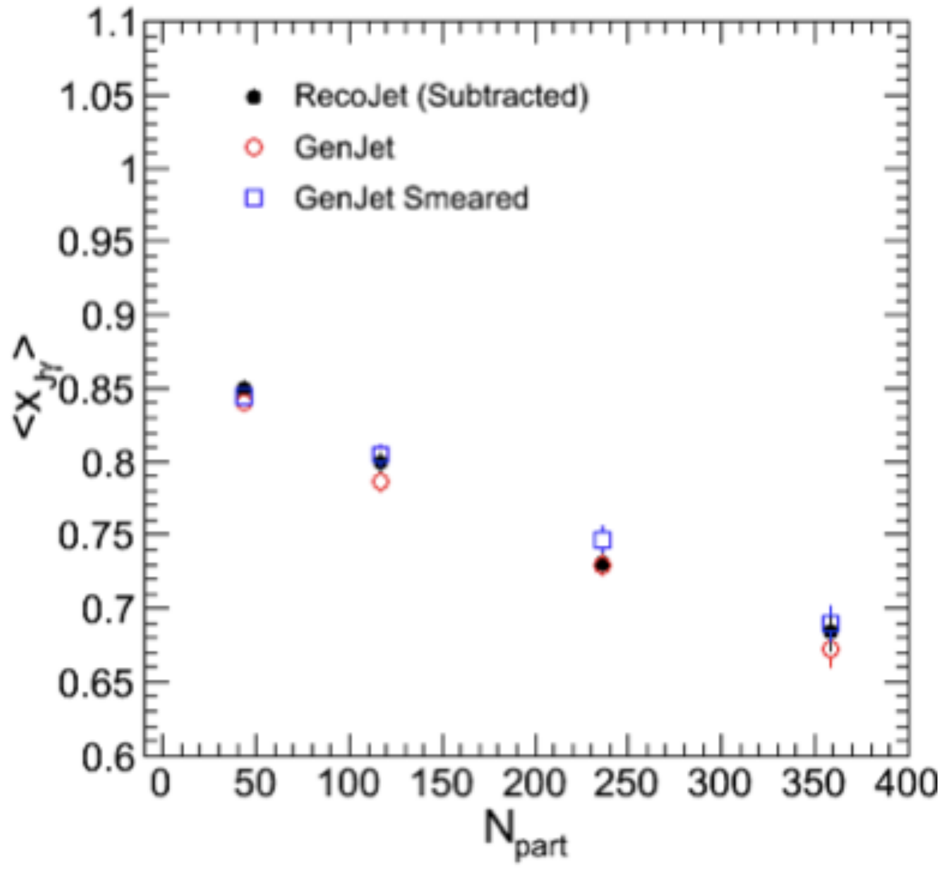
C	*S*	*N* (pp)	*N* (50–100%)	*N* (30–50%)	*N* (10–30%)	*N* (0–10%)
0.0246	1.213	0.001	0.001	3.88	5.10	5.23

$$\sigma\left(\frac{p_T^{\text{Reco}}}{p_T^{\text{Gen}}}\right) = C \oplus \frac{S}{\sqrt{p_T^{\text{Gen}}}} \oplus \frac{N}{p_T^{\text{Gen}}},$$

For this analysis, the effect of background fluctuations, UE background subtraction, jet finding, photon isolation, background jets etc etc etc is fully accounted for by simple Gaussian smearing of jet energy

Closure test for modified jets (PYQUEN)

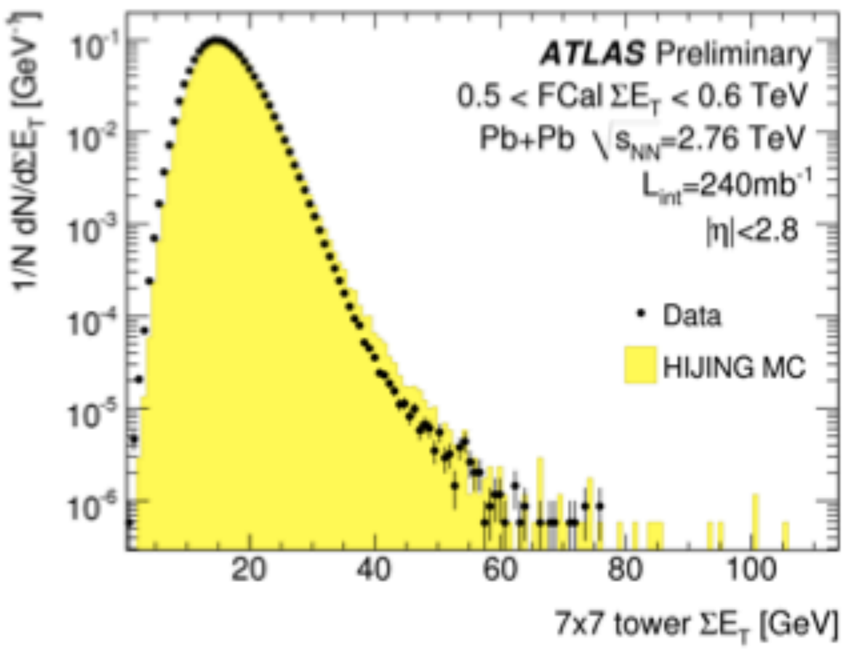


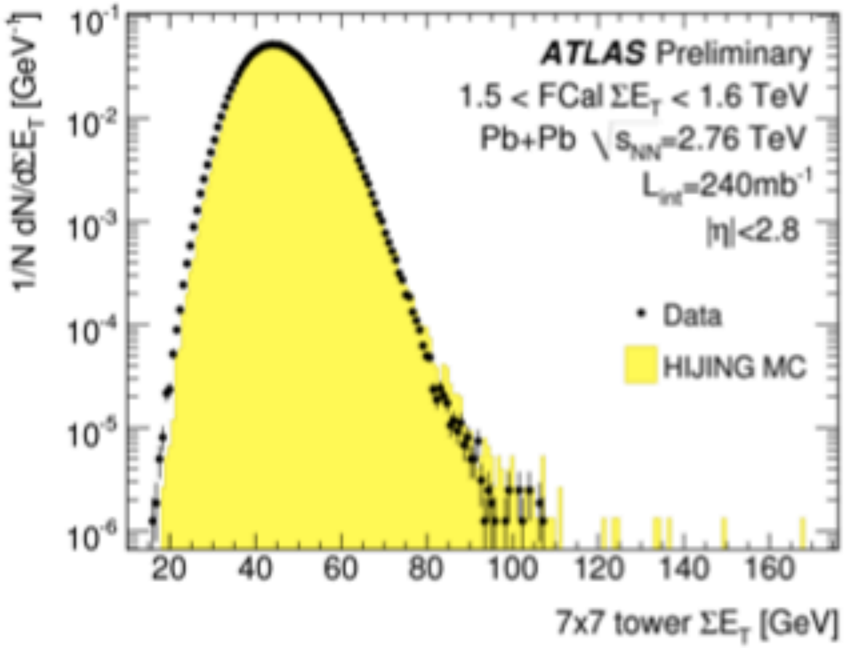


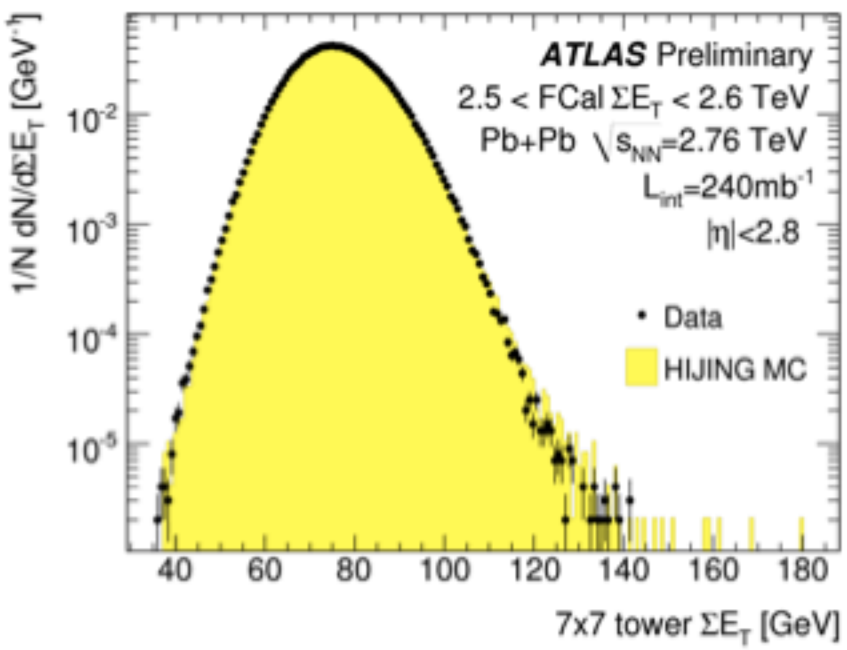
For this analysis, the effect of background fluctuations, UE background subtraction, jet finding, photon isolation, background jets etc etc etc is fully accounted for by simple Gaussian smearing of jet energy

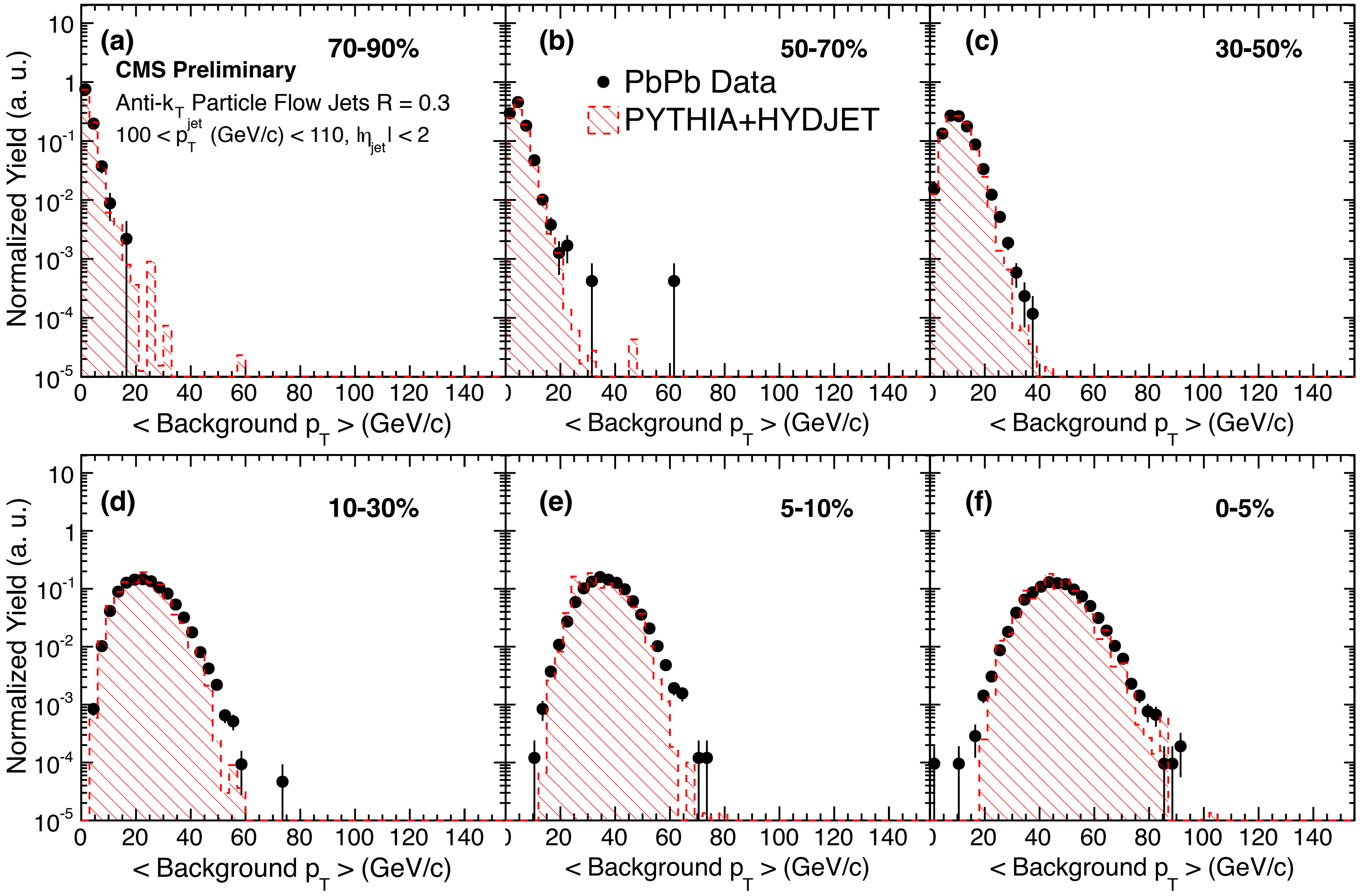
True also for models that show a strong quenching effect (e.g. PYQUEN)

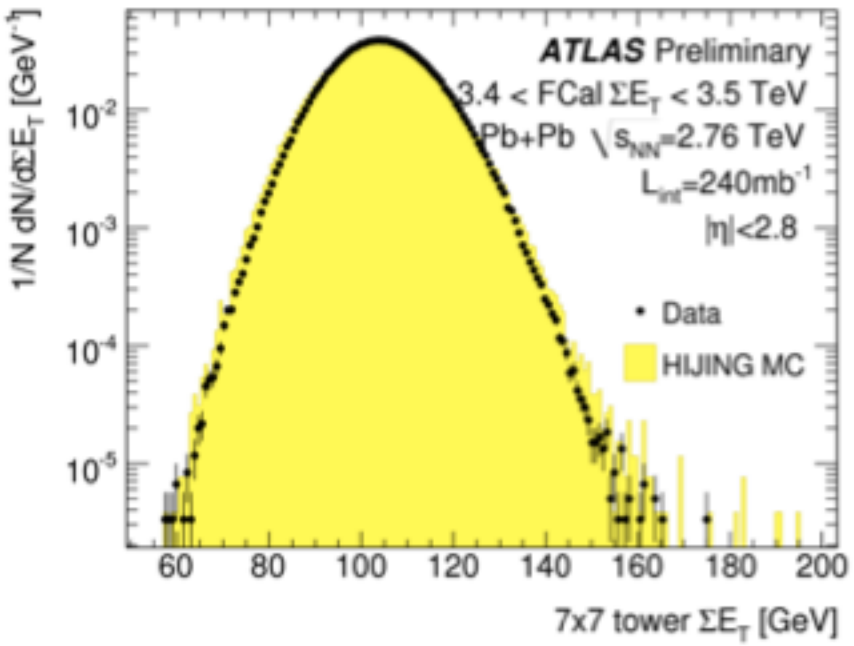
Background in data and MC





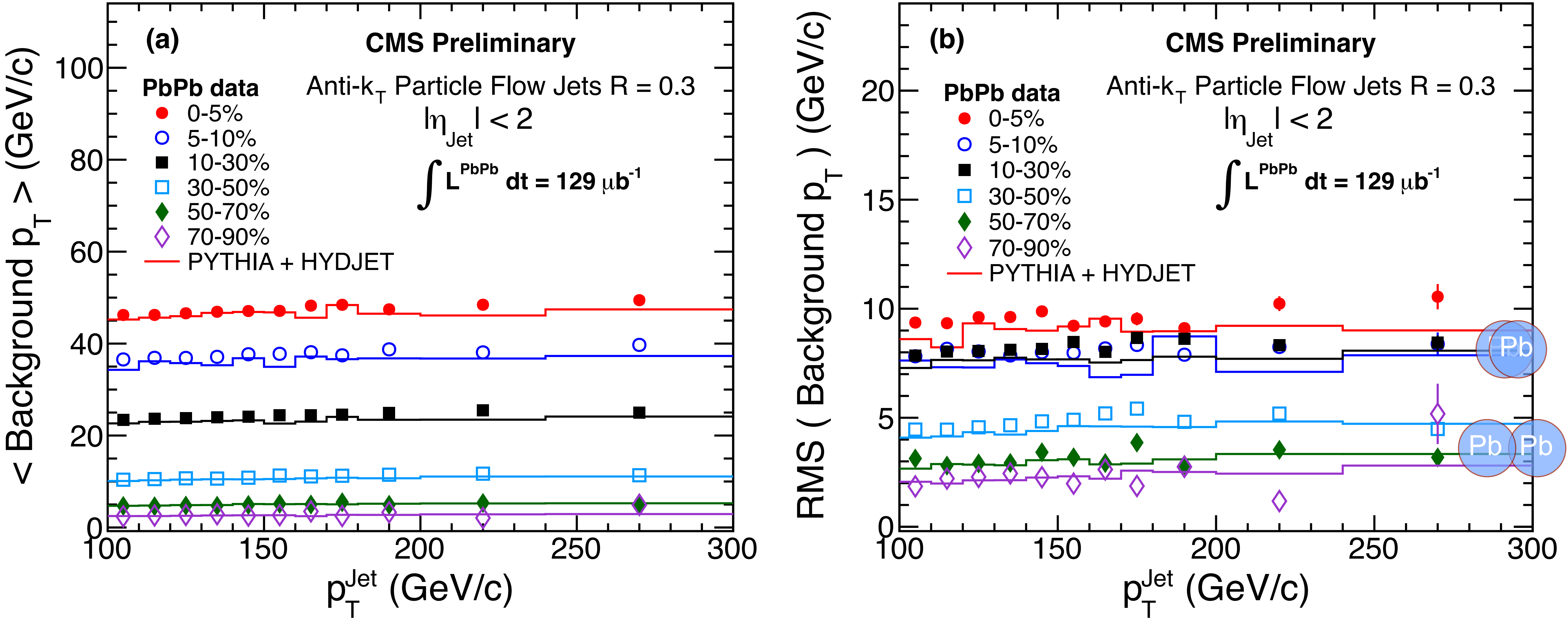






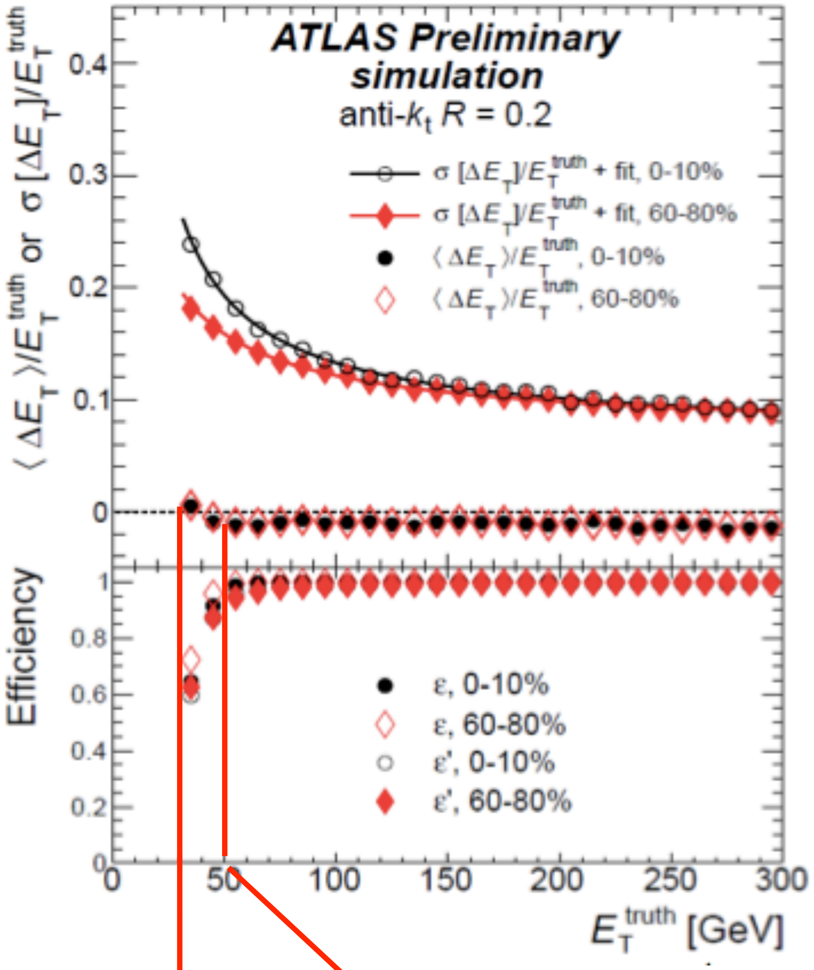
Crucial test of validity of procedure

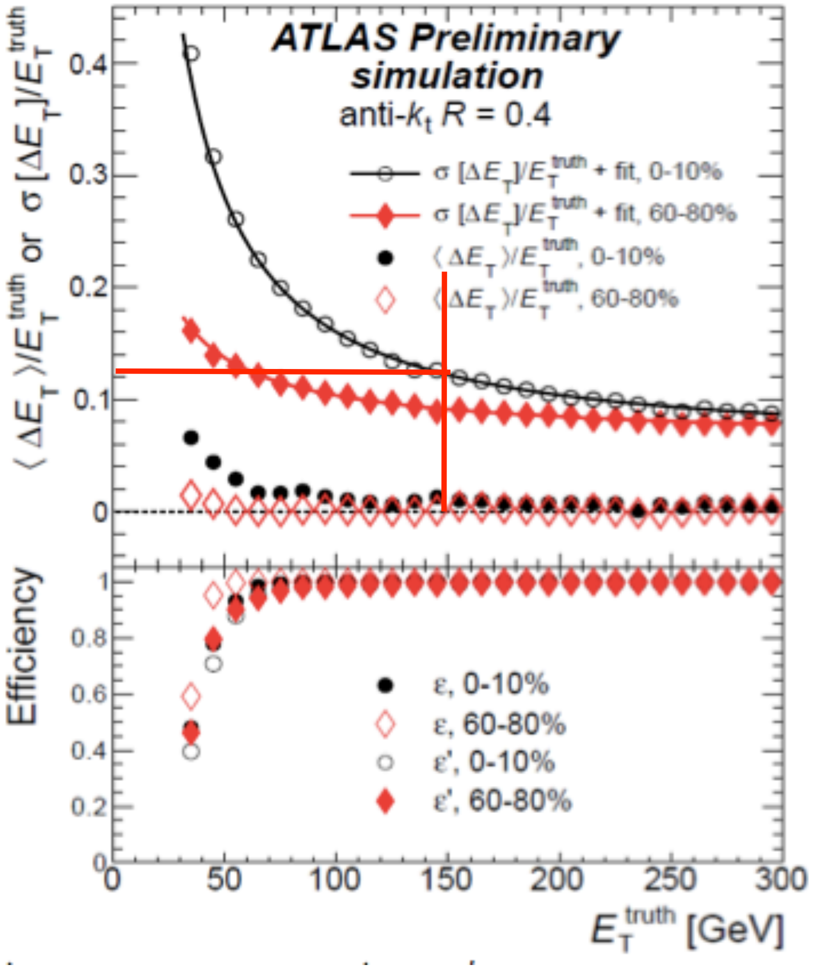
Jet background in PbPb

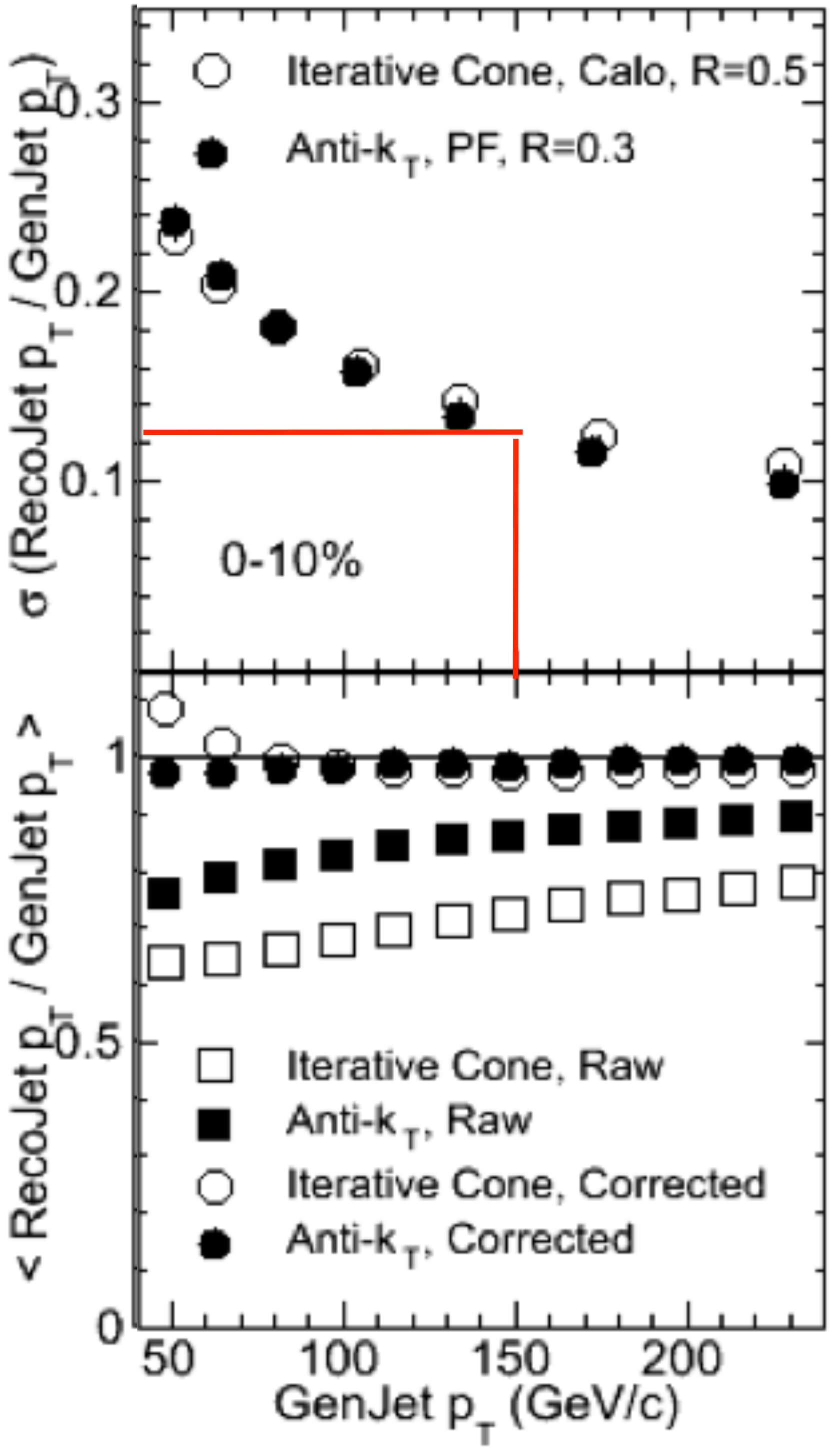


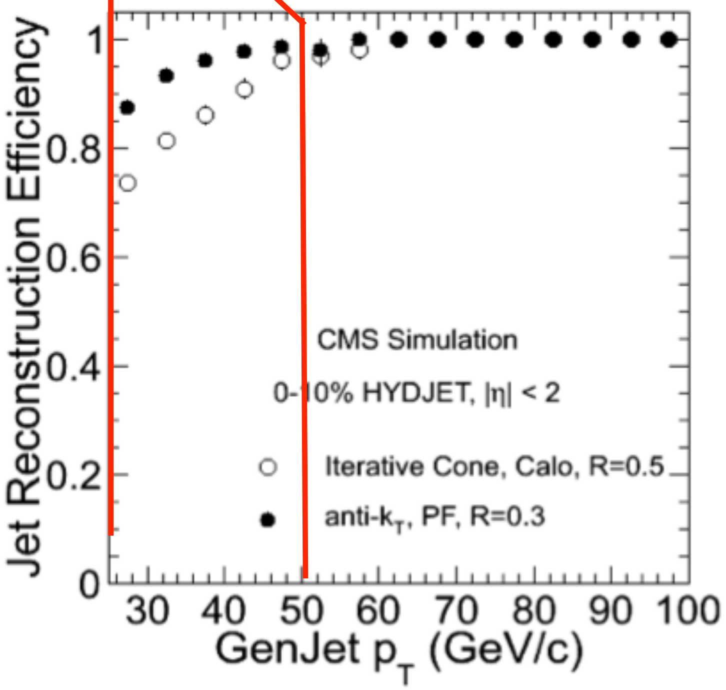
- Mean and width for background p$_T$ subtracted from jets
  - before jet energy correction
- Again, data and MC agree

Jet finding performance: ATLAS vs CMS



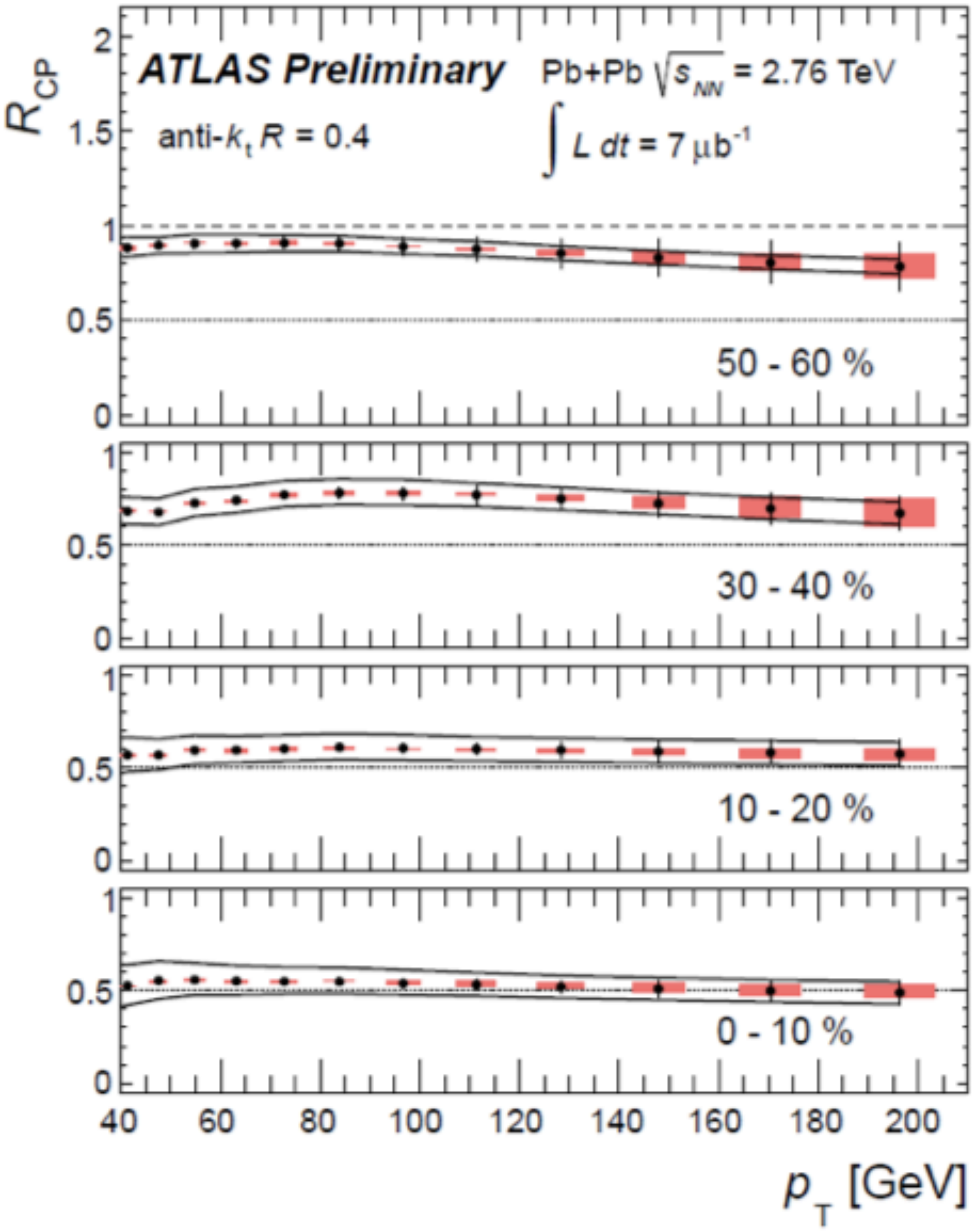






Jet R_{CP} and R_{AA}

ATLAS unfolded jet R_{CP}

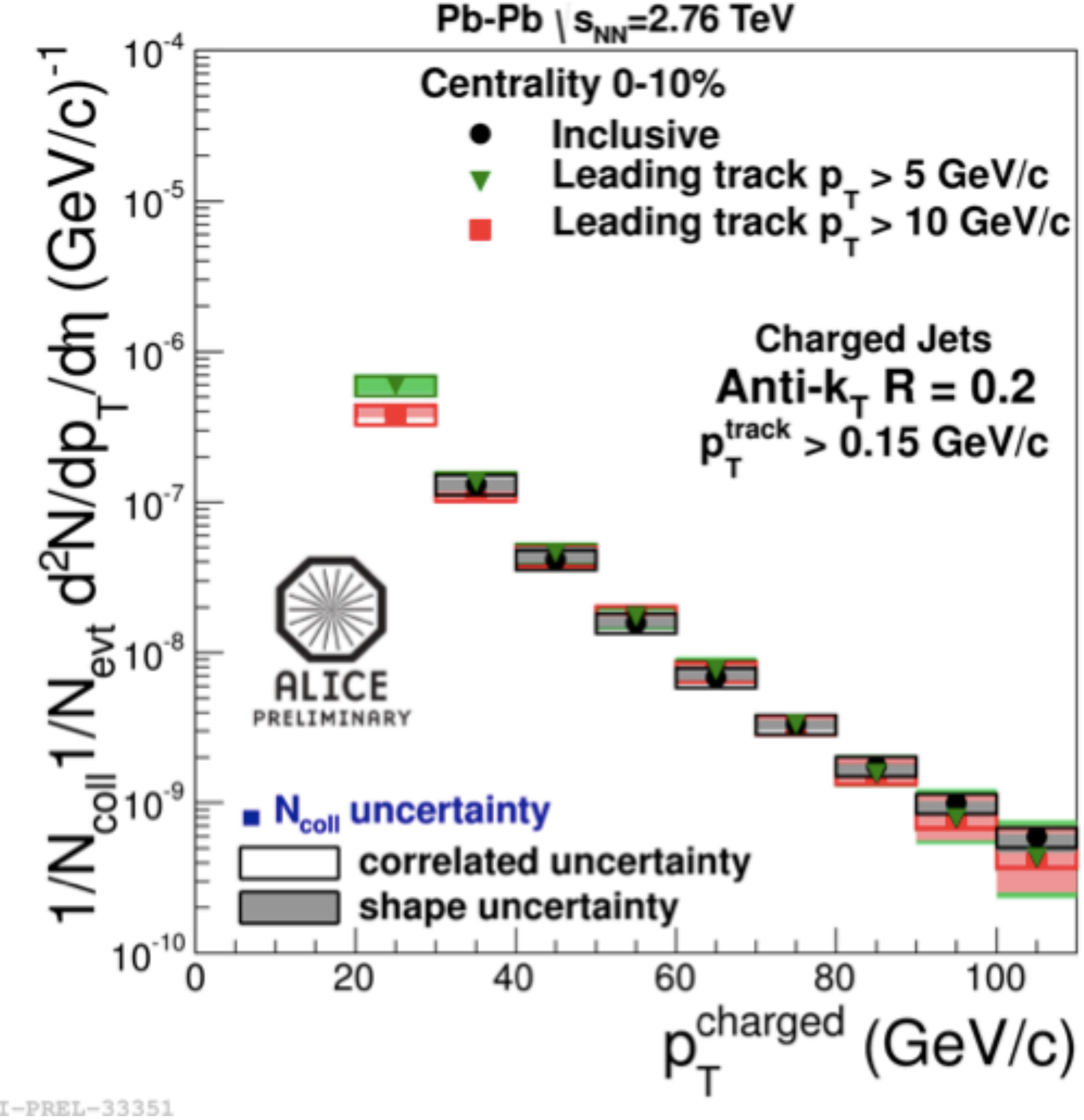


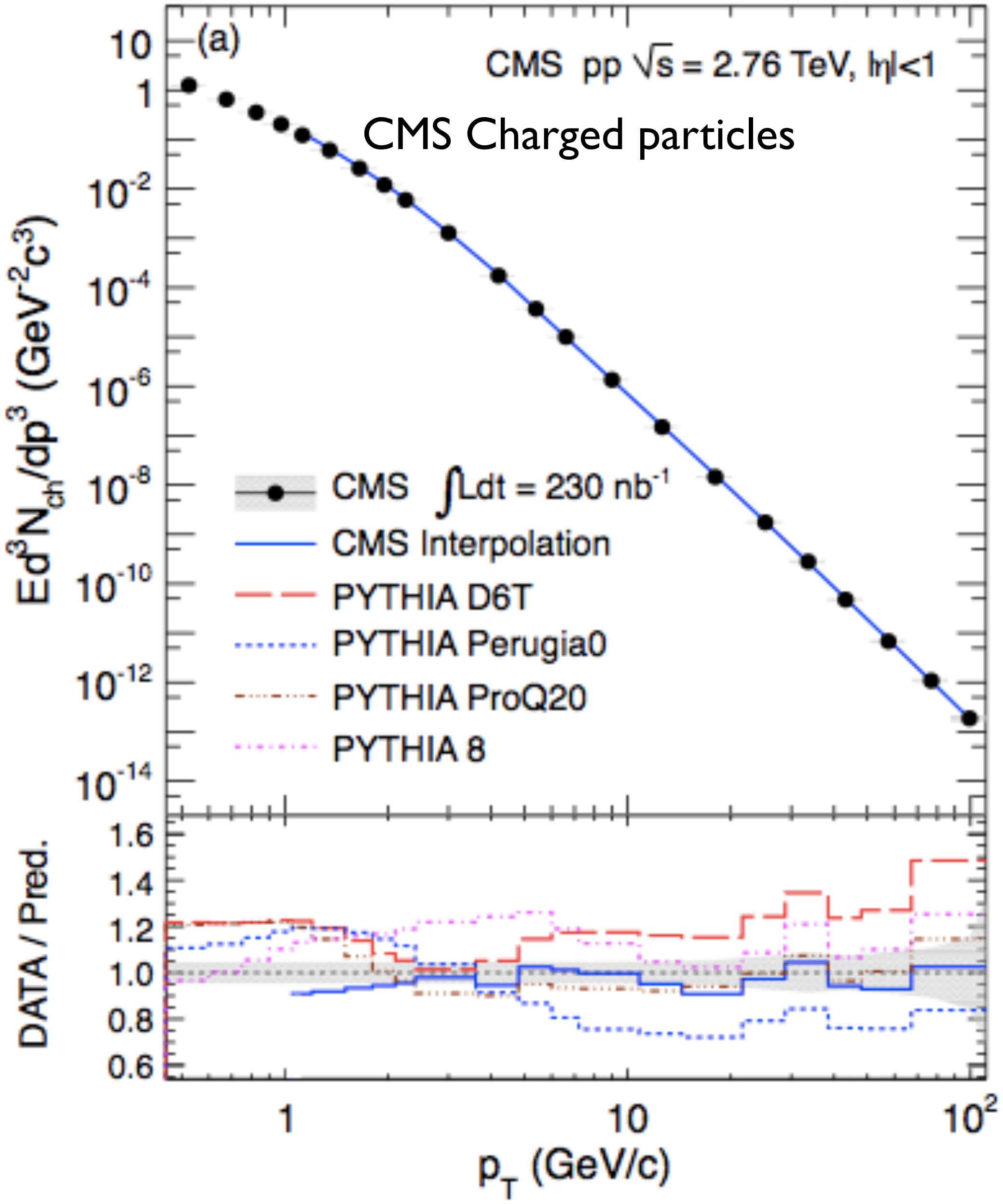
Anti-k_T w/ iterative background subtraction

R_{CP}: relative to 60-80% centrality

Flat at ~ 0.5

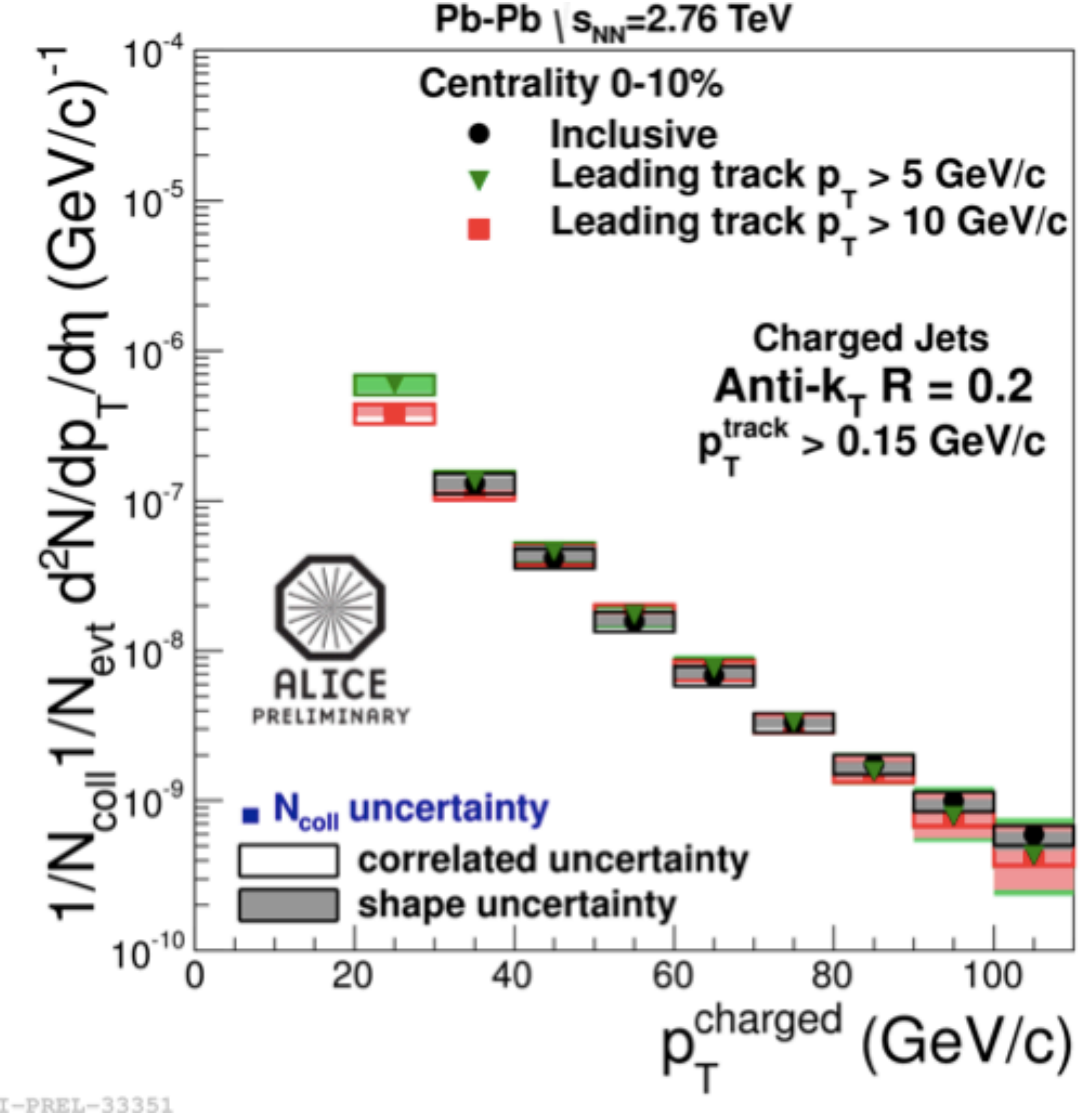
ALICE unfolded jet spectra in PbPb

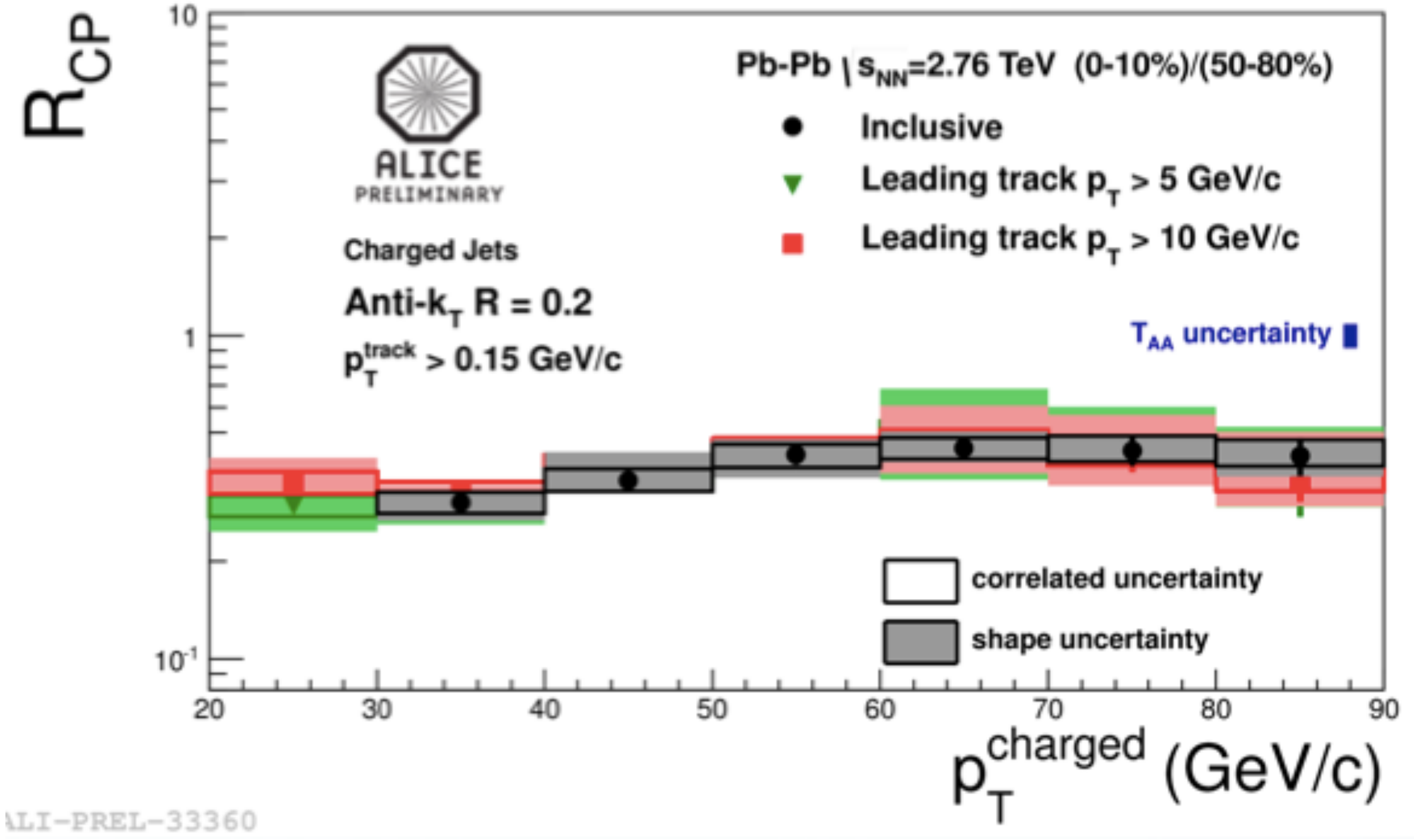




Charged track jets
Anti-KT with fastjet bkg subtraction
Leading-track requirement to suppress UE jets

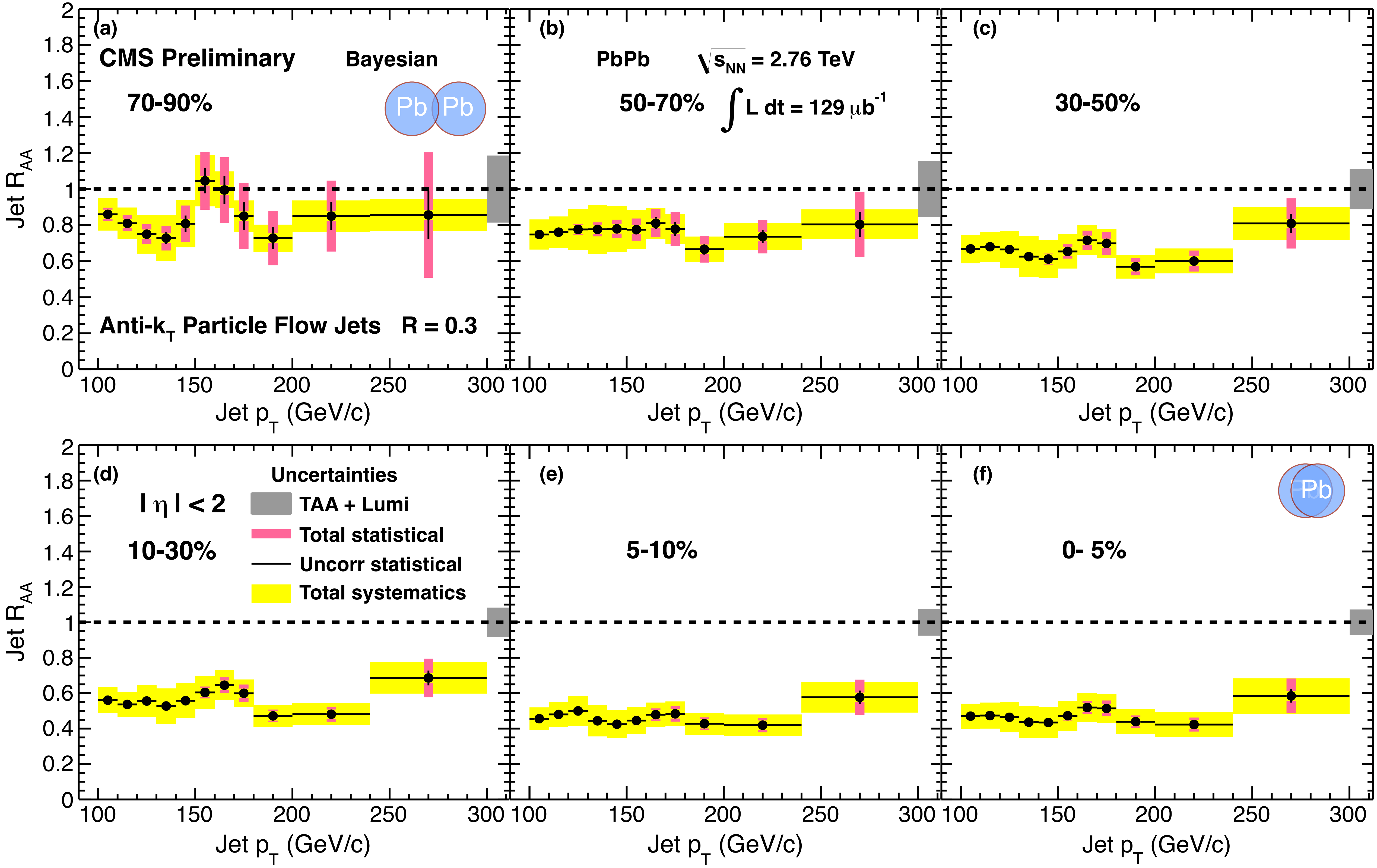
ALICE unfolded jet spectra in PbPb



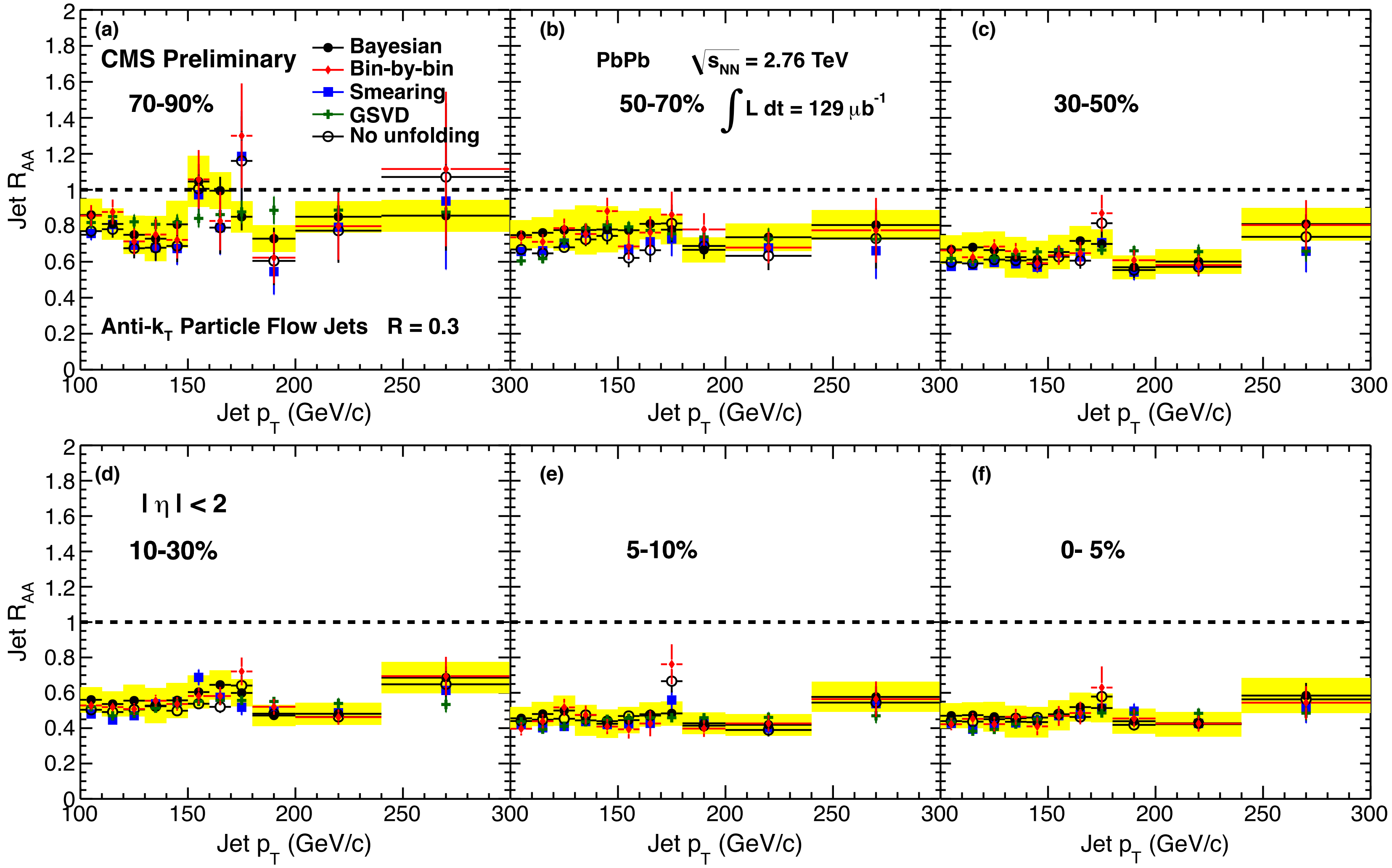


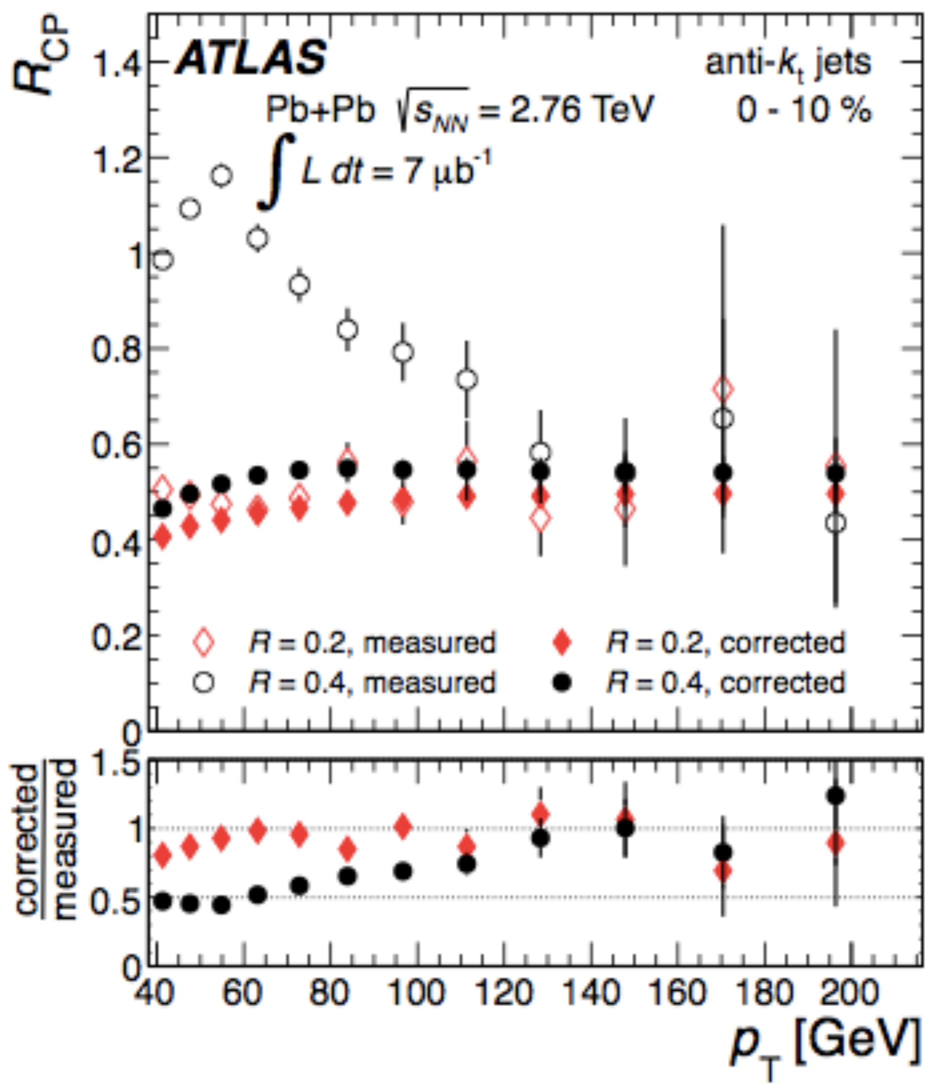
Charged track jets
Anti-KT with fastjet bkg subtraction
Leading-track requirement to suppress UE jets
R_{CP}: relative to 50-80% centrality

R_{AA} from unfolded jet spectra



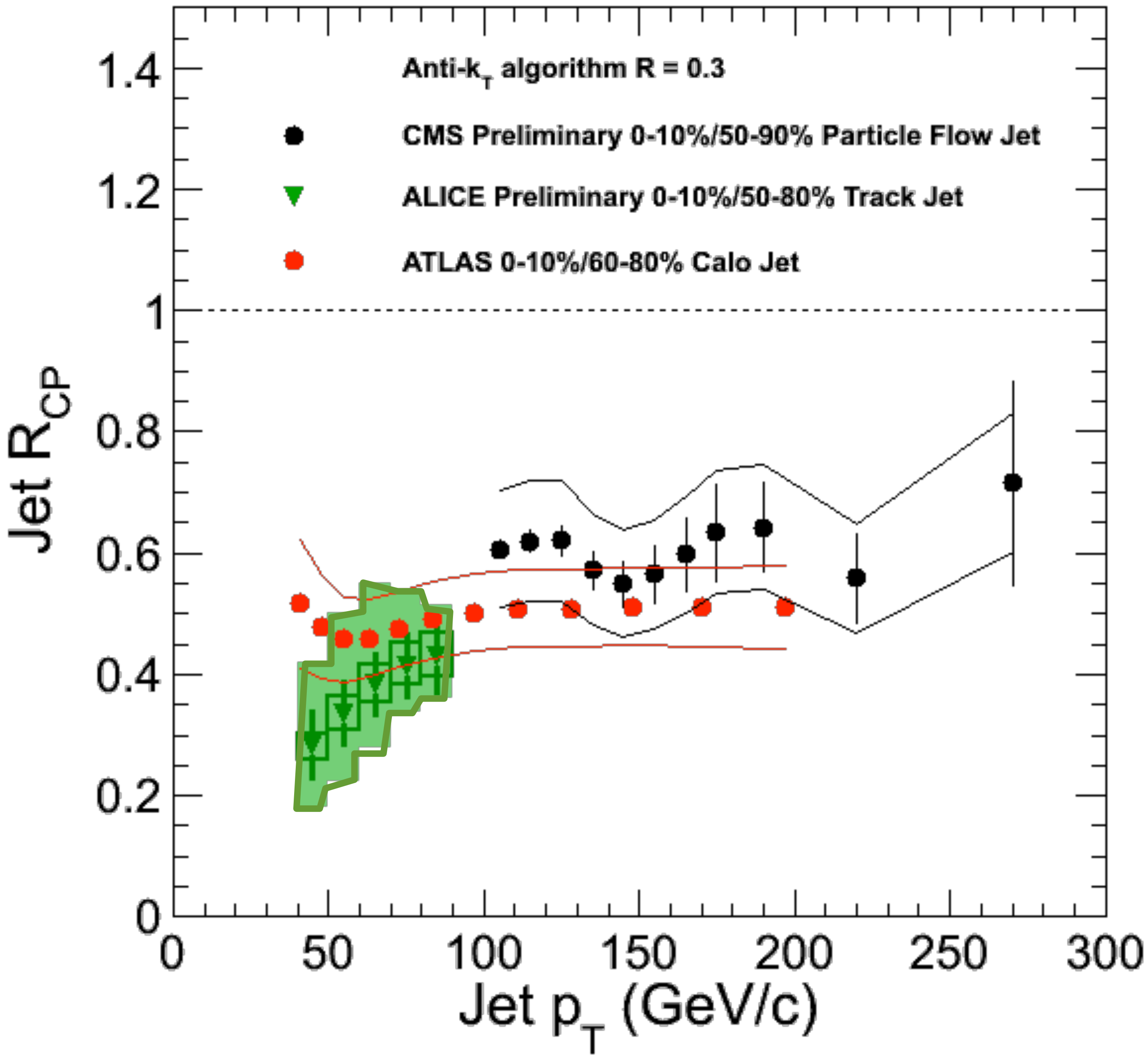
Unfolding





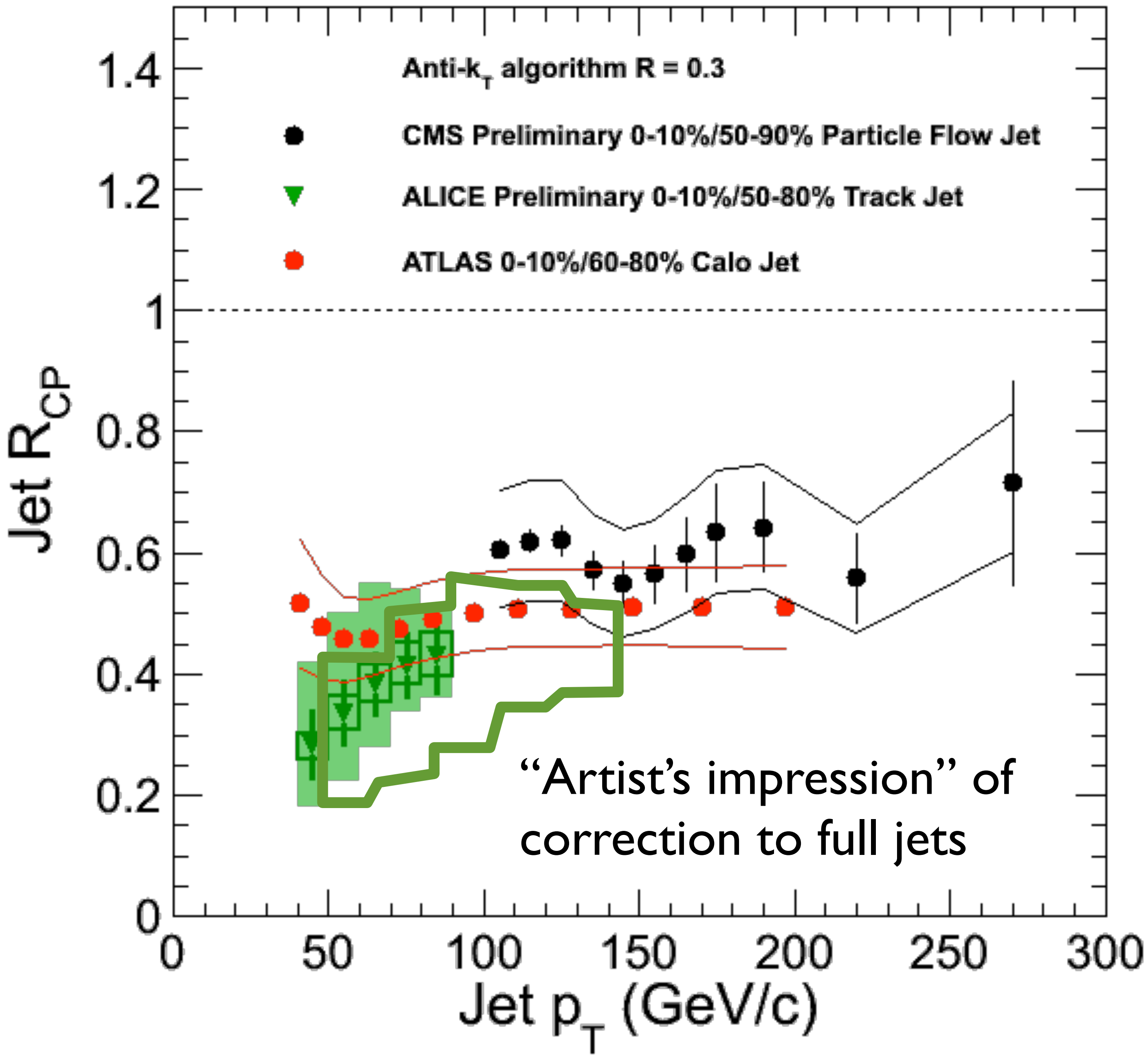
- Good agreement between 4 different methods in CMS
- Unfolding only makes a small difference in jet R_{AA} above pT > 100GeV

Consistency of jet R_{CP} results



- Experiments agree (barely) within systematic uncertainties
- Flat (ATLAS, CMS) vs rising R_{CP} is important

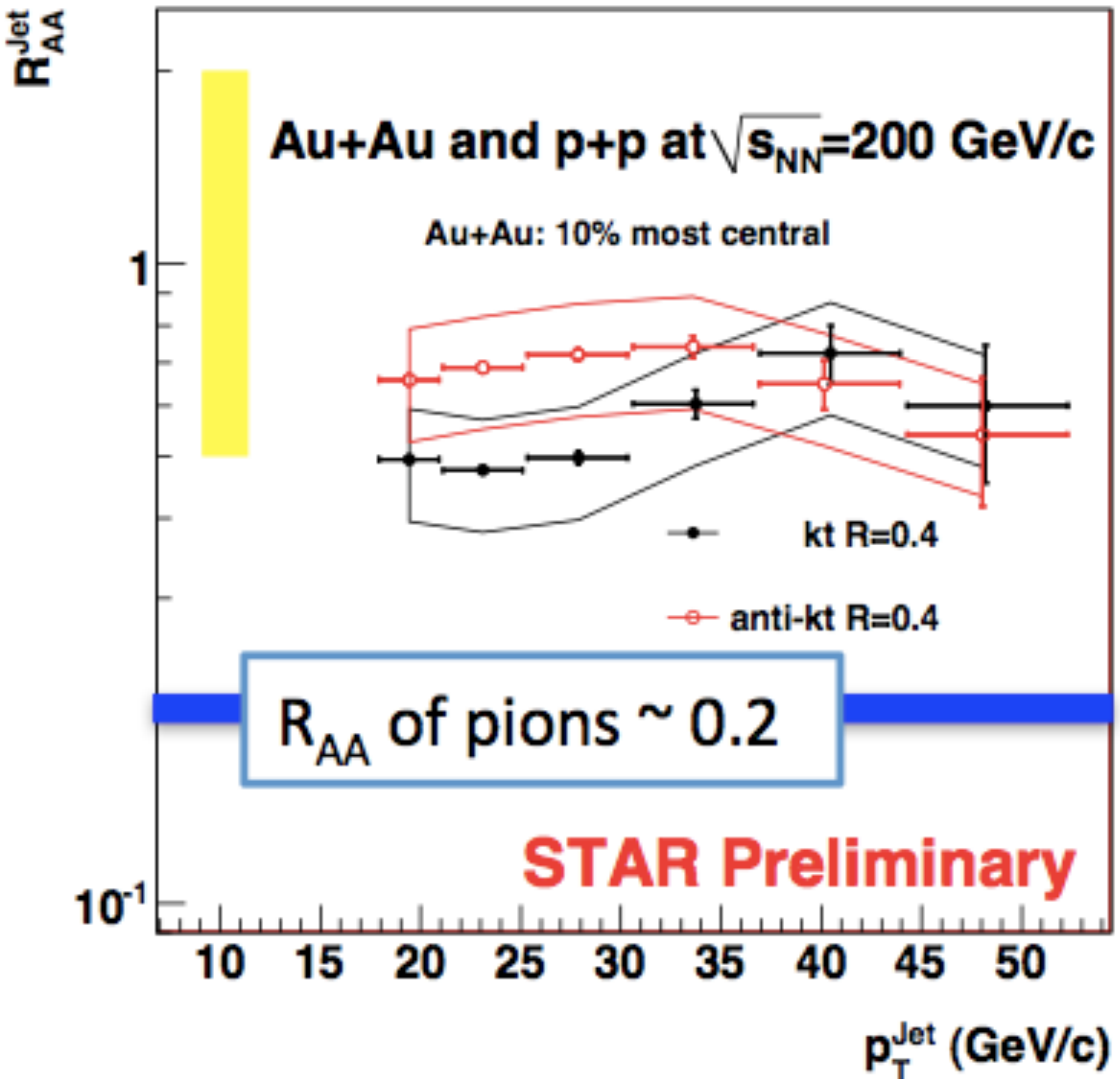
Consistency of jet R_{CP} results



"Artist's impression" of correction to full jets

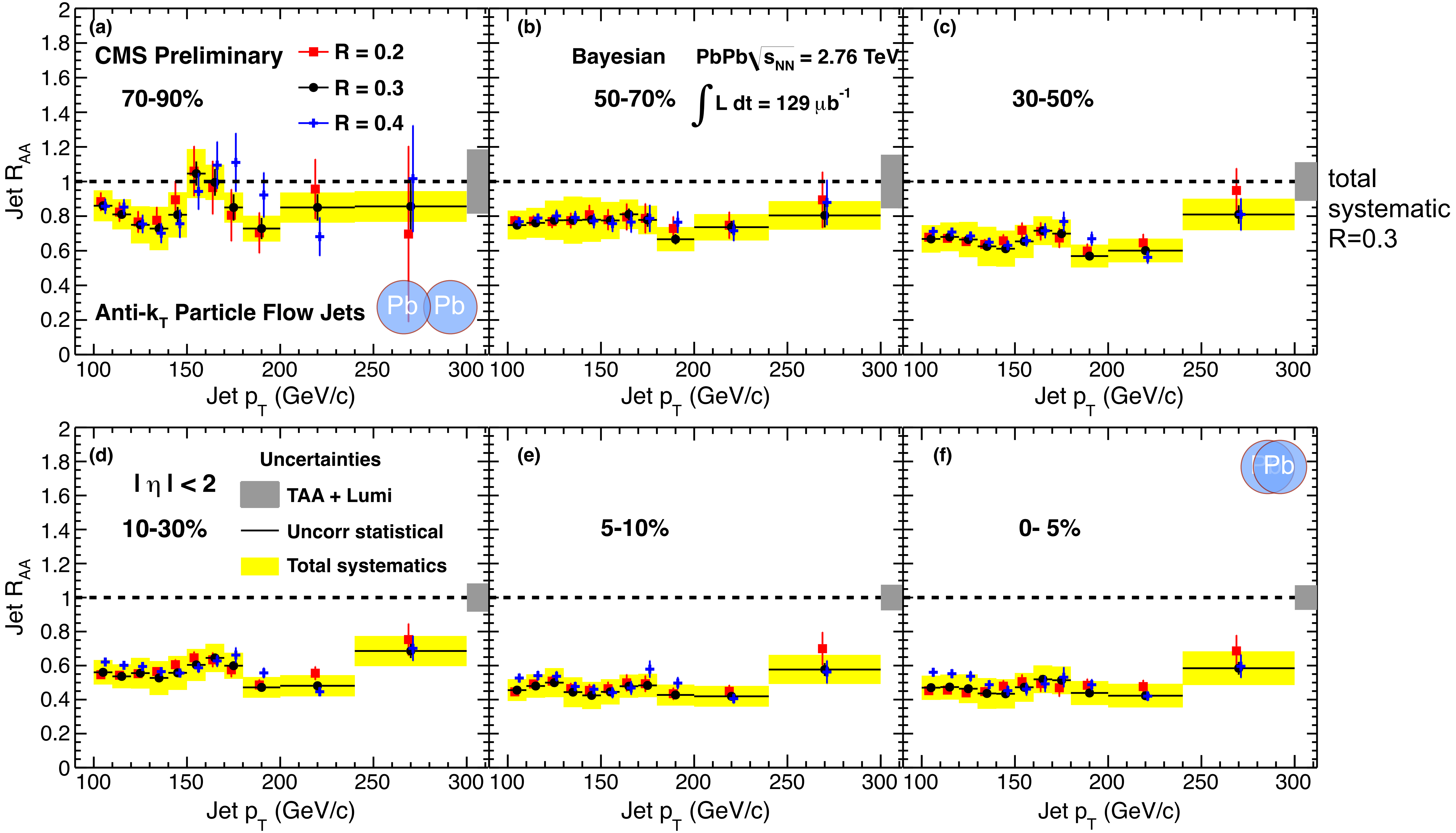
- Experiments agree (barely) within systematic uncertainties
- Flat (ATLAS, CMS) vs rising R_{CP} is important

Jet R_{AA} in AuAu at RHIC



- Large difference between jet and pion R_{AA} (unlike LHC)
- Large uncertatainty

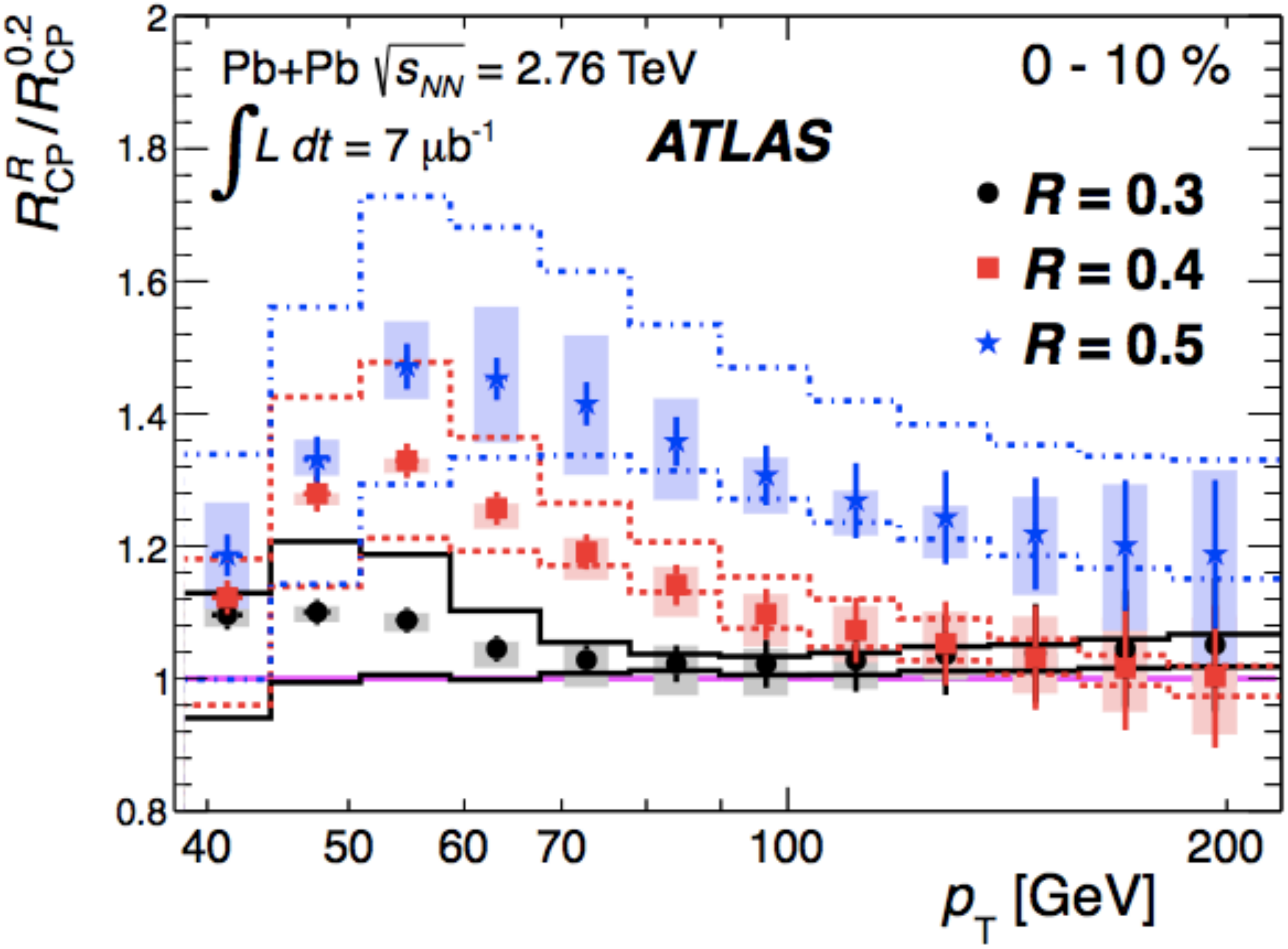
Suppression vs cone size



total systematic R=0.3

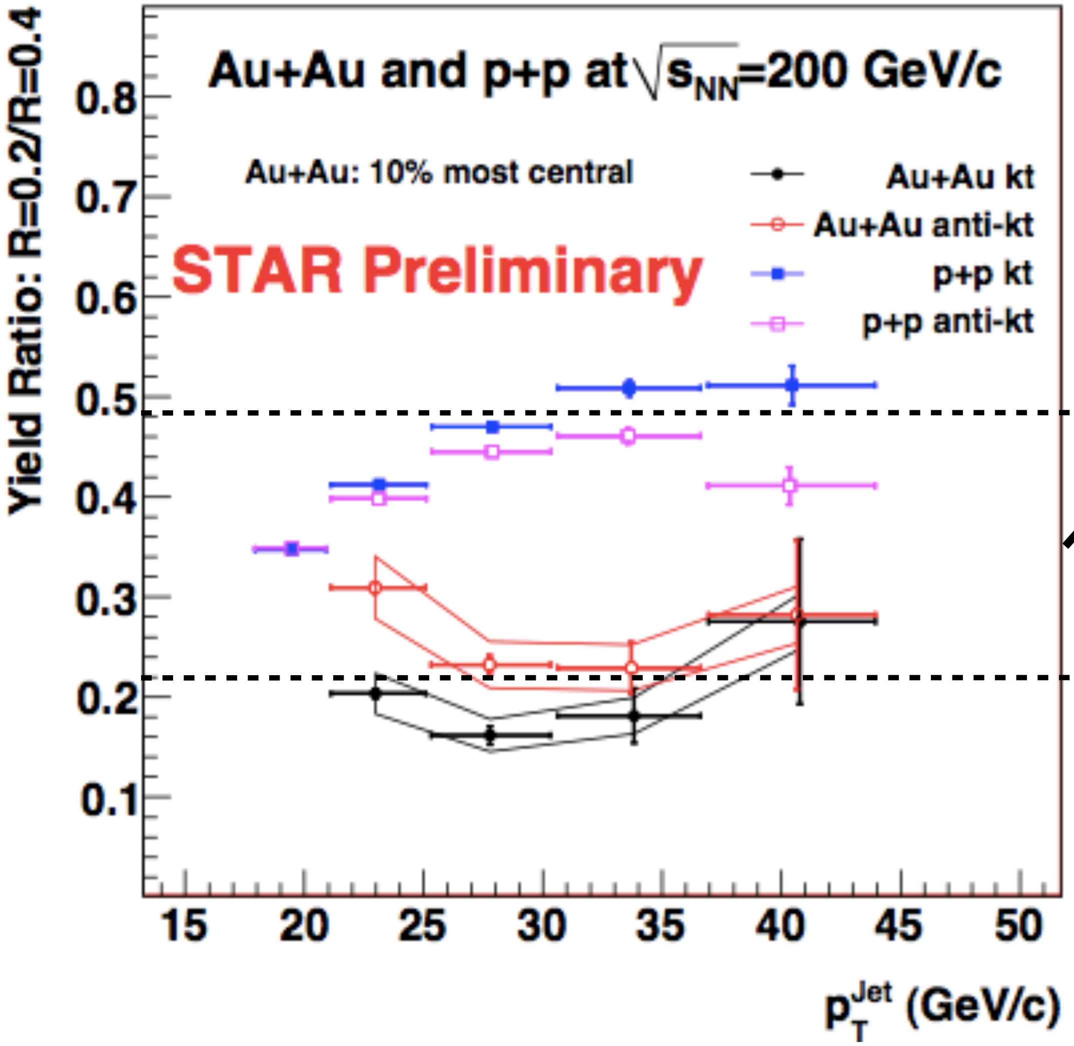
- No strong dependence on jet radius

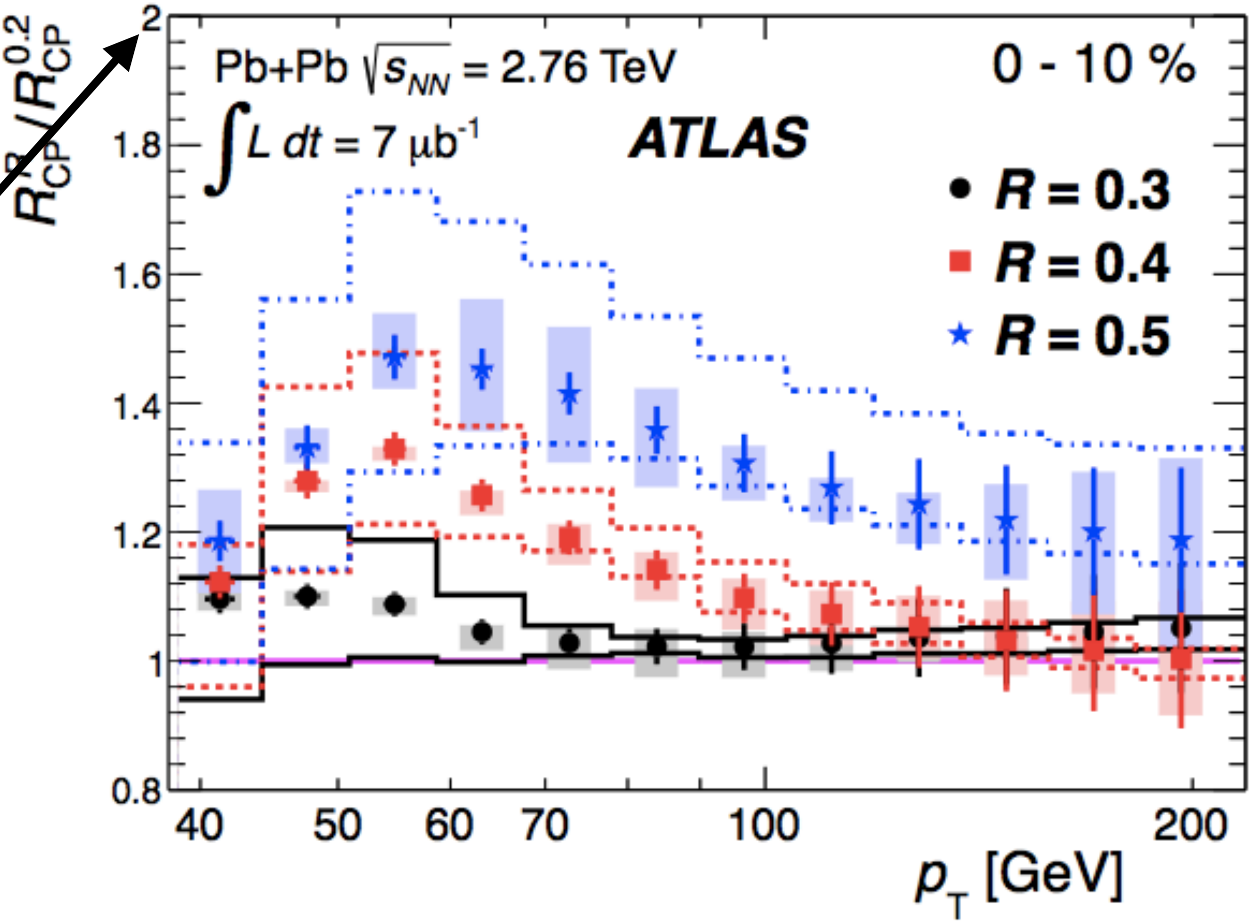
Suppression vs cone size



- Moderate, but significant R dependence of jet suppression, rising from ~0.4 to ~0.6 for R from 0.2 to 0.5

Radius dependence RHIC vs LHC

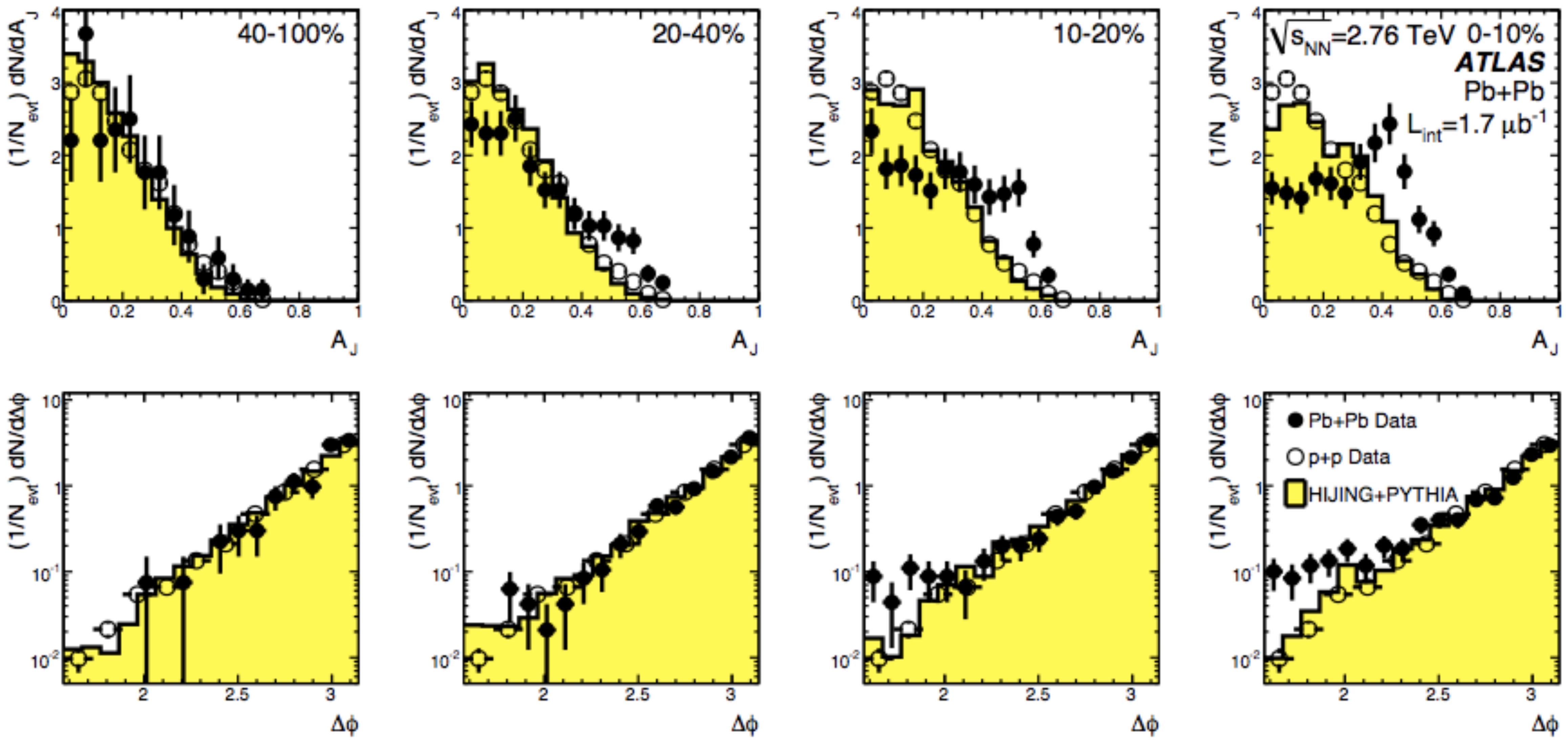




- Stronger dependence seen at RHIC?

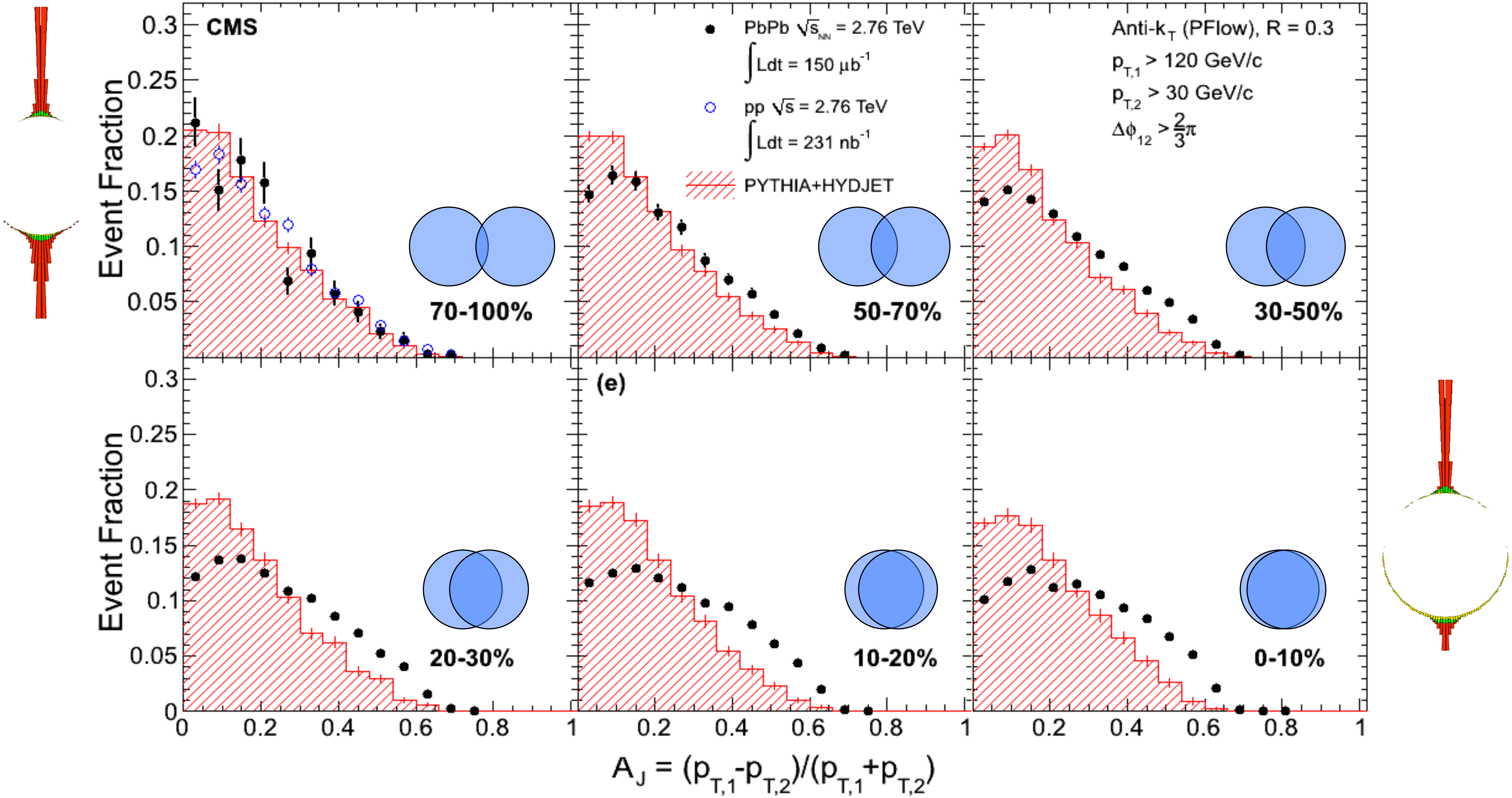
Dijet asymmetries

First observation of dijet asymmetries



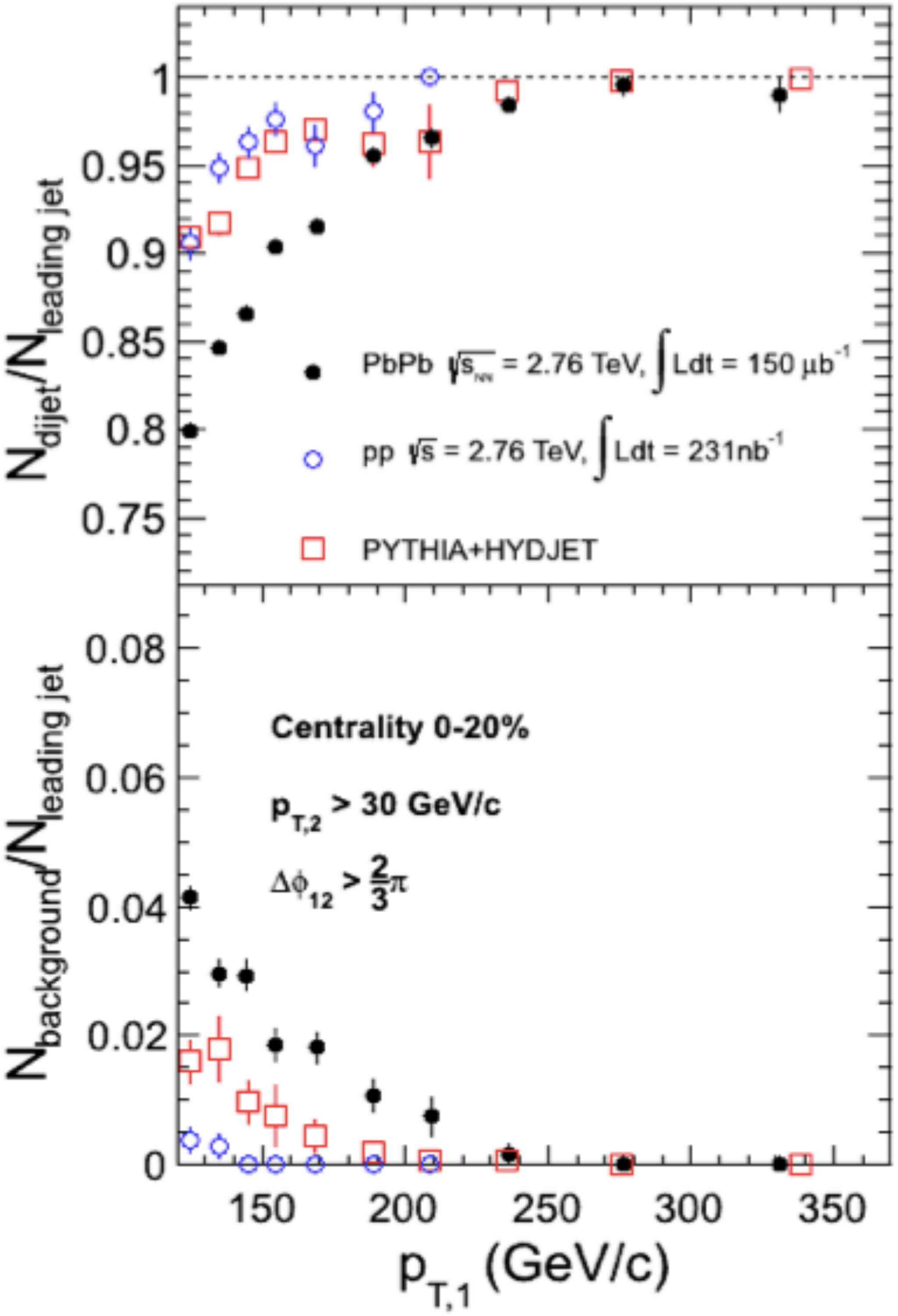
- For central events, a strong imbalance of leading vs subleading momentum develops
- Azimuthal back-to-back correlation remains

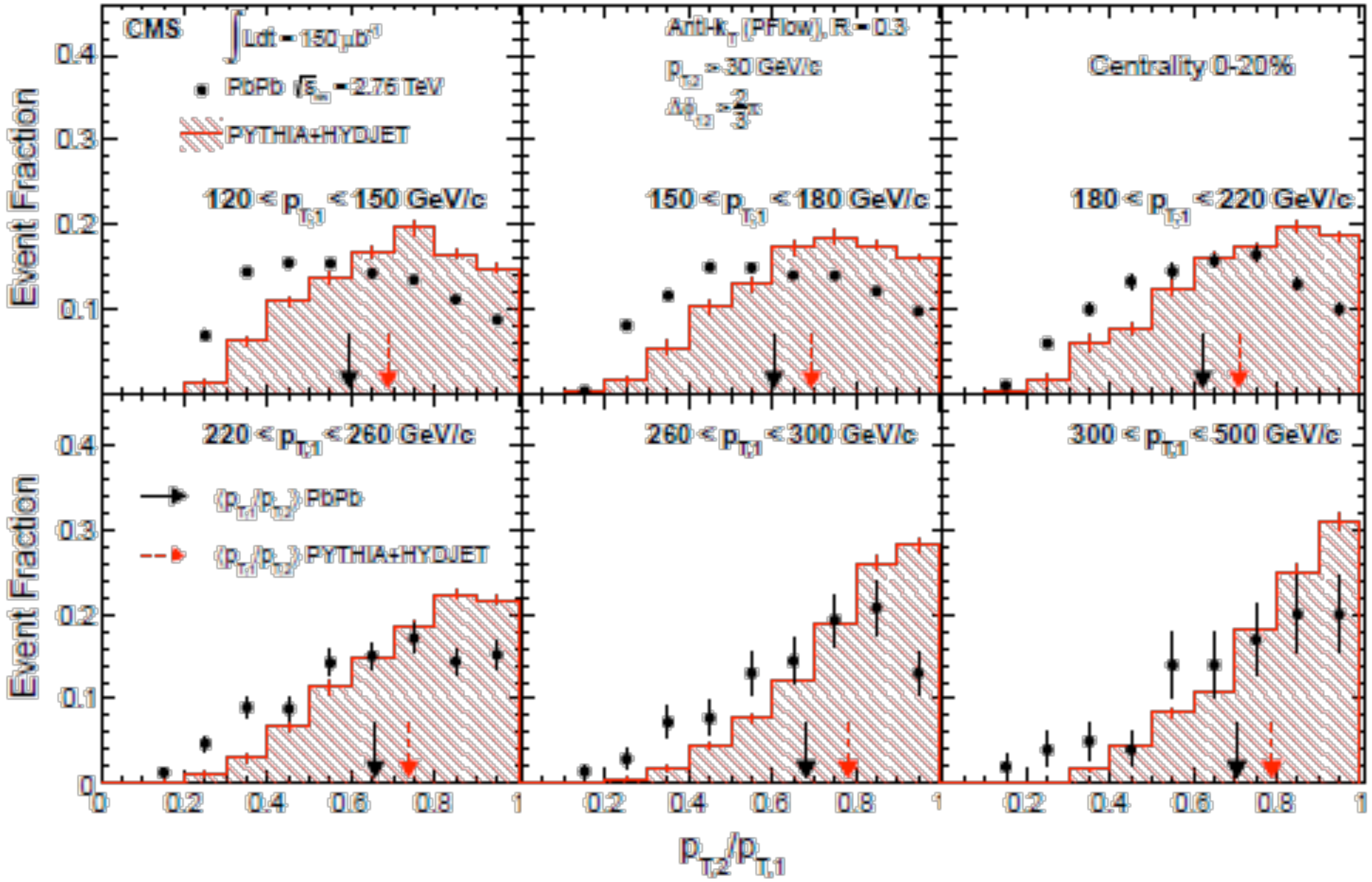
Fragmentation function comparison



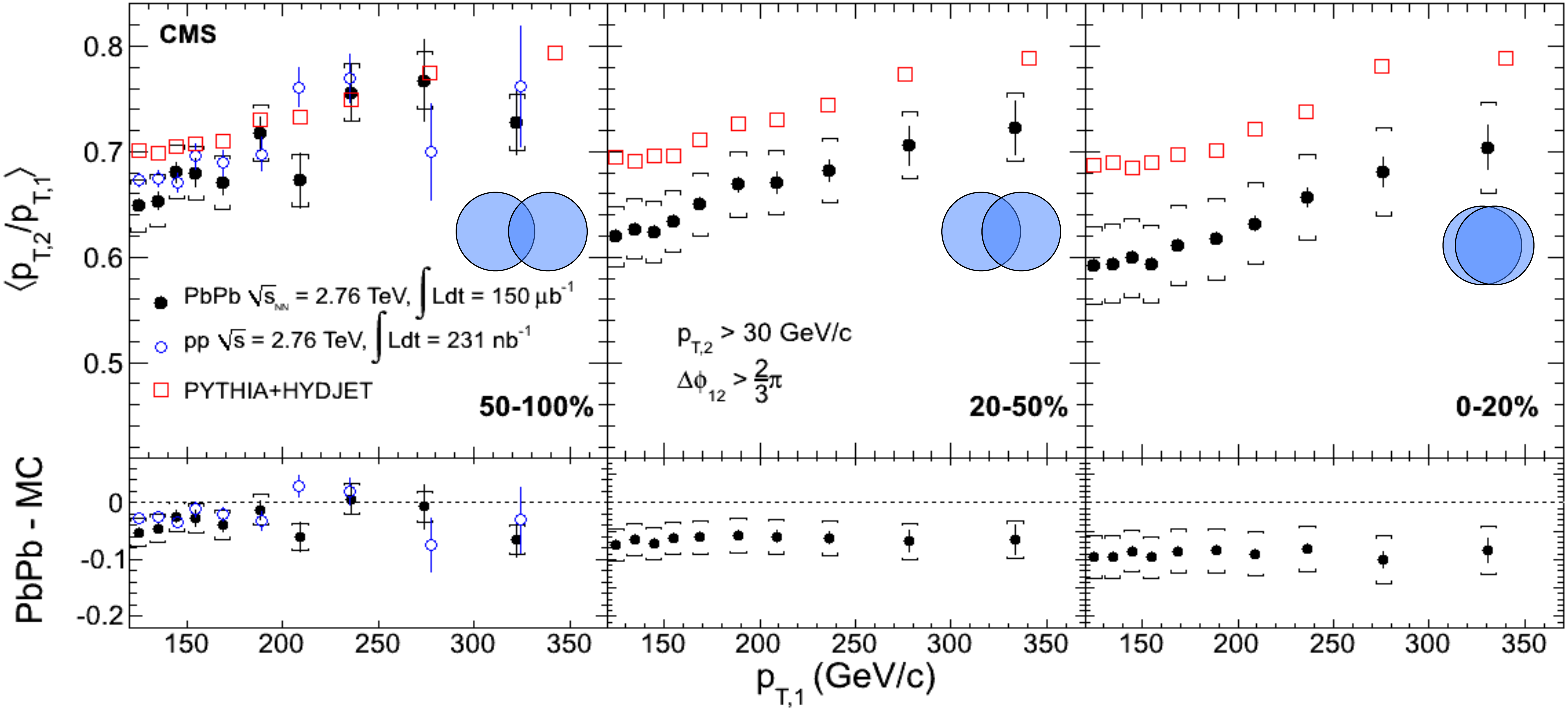
Dijet balance centrality evolution from 2011 data set

Fraction of matched jets





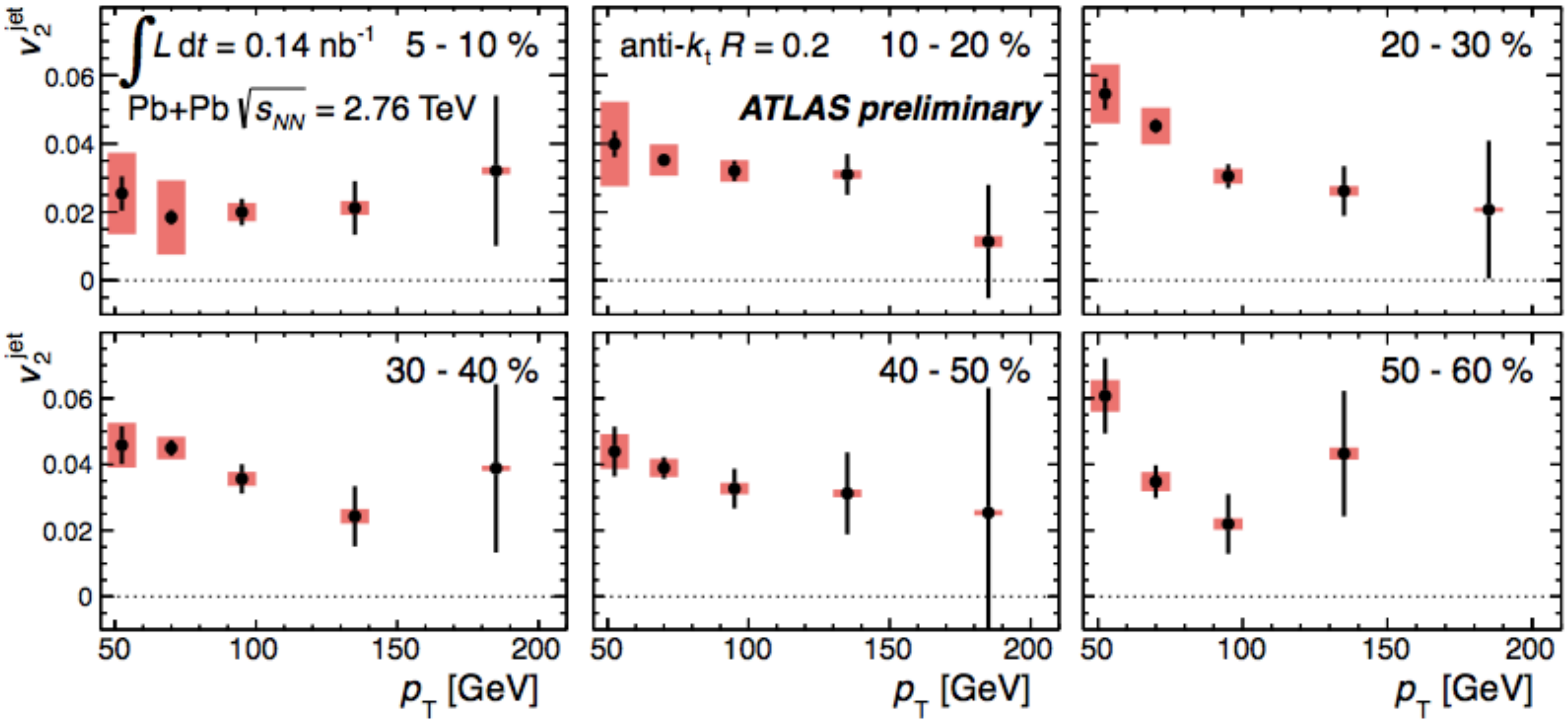
Dijet imbalance vs p_T

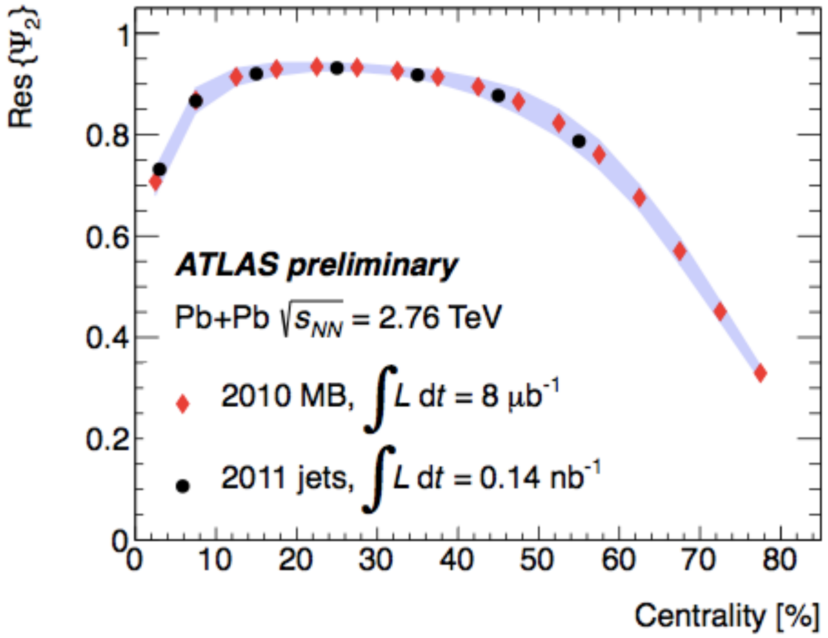


- Dijets in reference (pp, PYTHIA) more balanced with increasing p_T
- $<p_{T,2}/p_{T,1}>$ in PbPb consistent with a constant offset from reference MC

Inclusive jet v_2

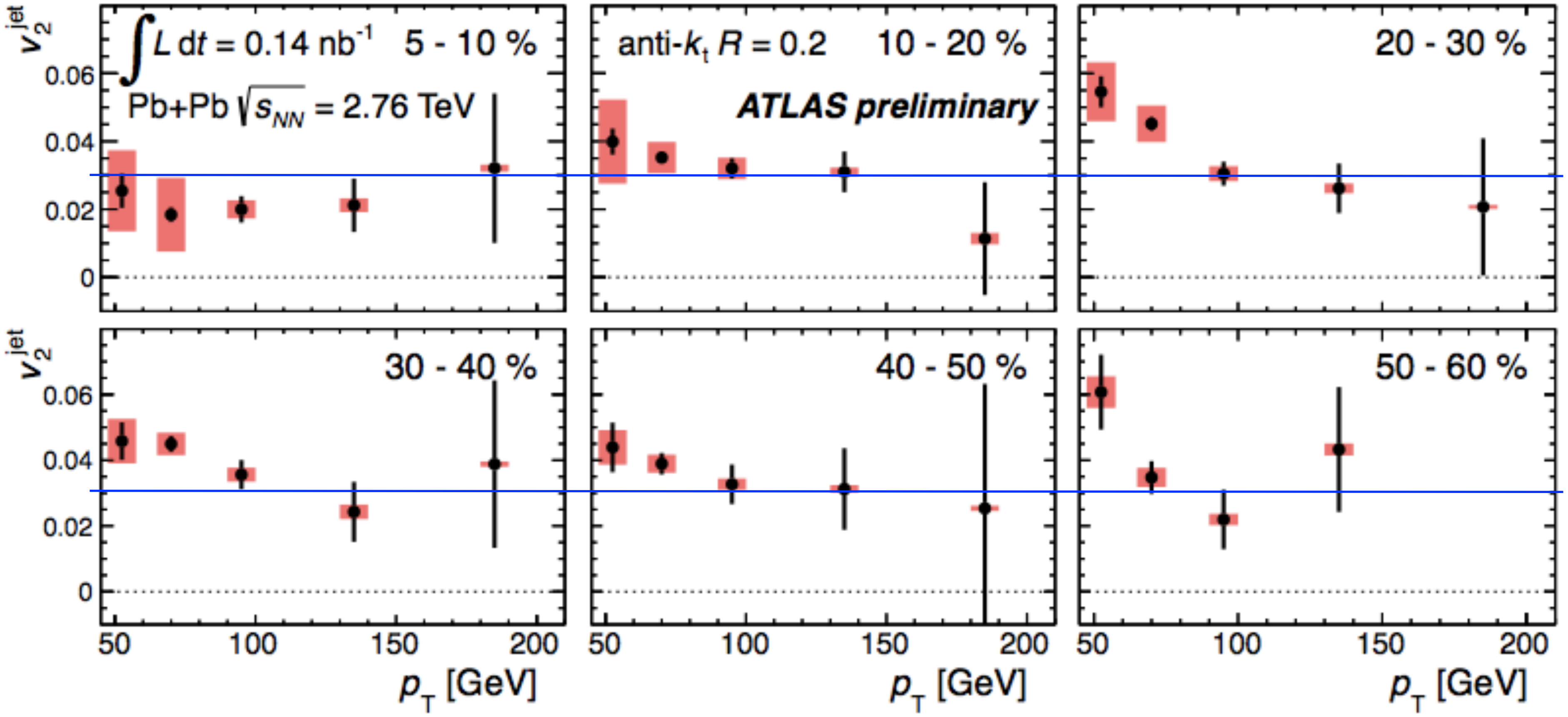
Jet v_2 in ATLAS

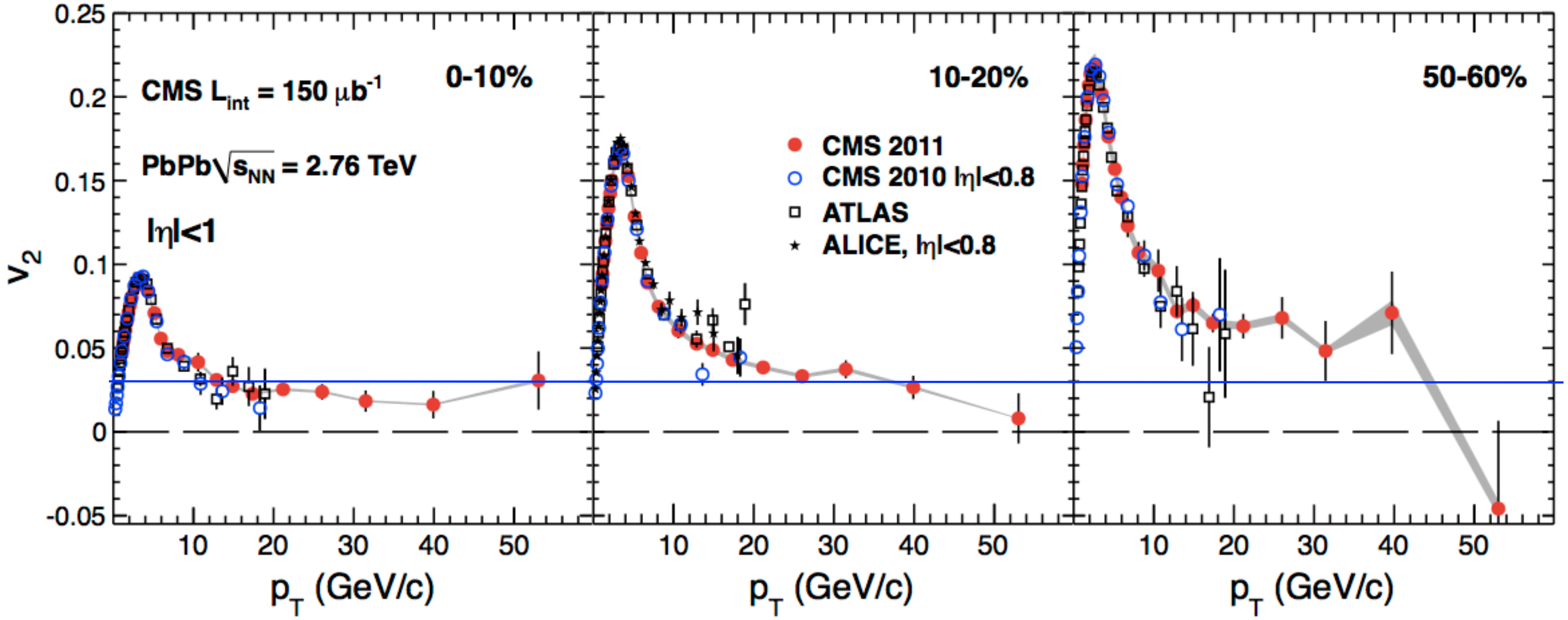




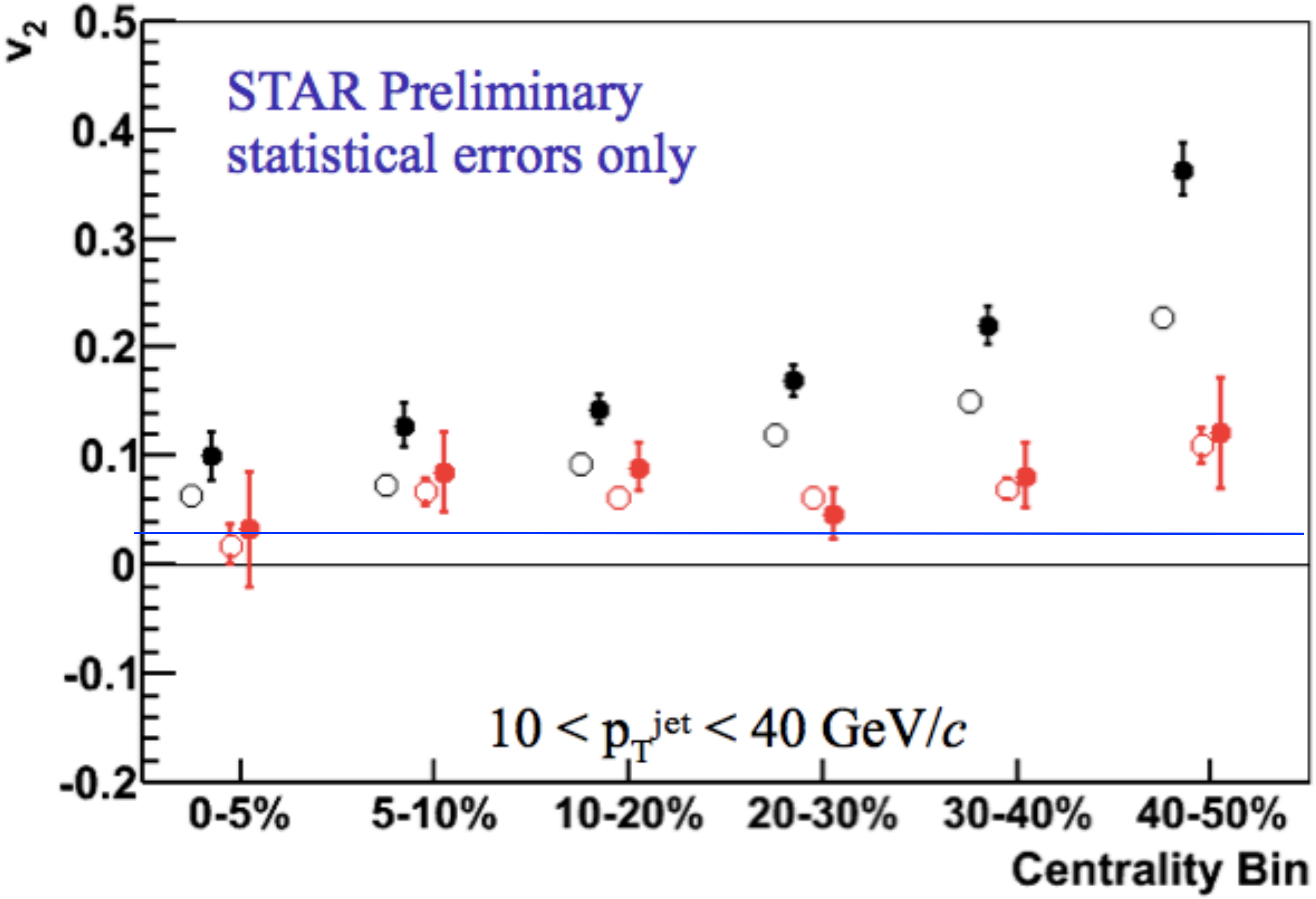
jet v2 measured wrt event plane from forward calorimeters

Jet v_2 vs charged particle v_2





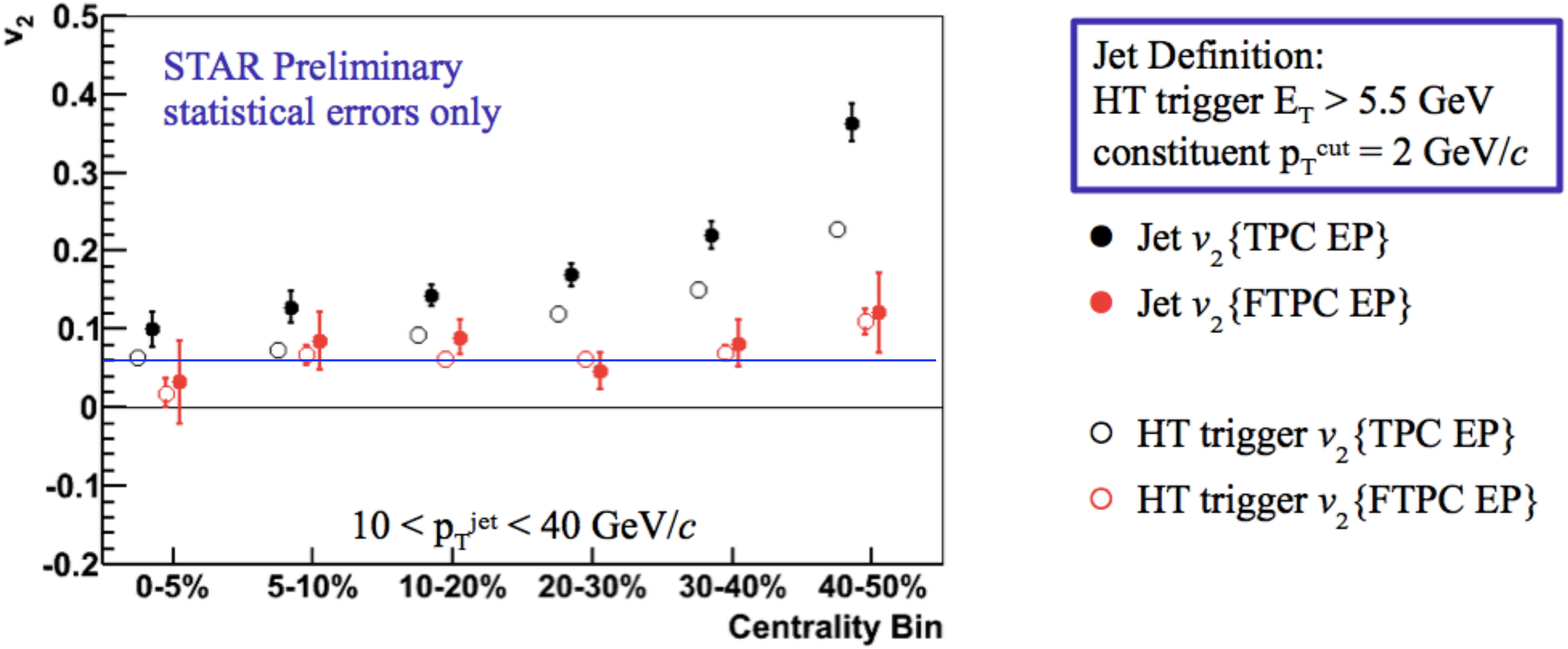
Jet v_2 in STAR



Jet Definition:
HT trigger $E_T > 5.5$ GeV
constituent $p_T^{cut} = 2$ GeV/c

- ● Jet v_2\{TPC EP\}
- ● Jet v_2\{FTPC EP\}
- ○ HT trigger v_2\{TPC EP\}
- ○ HT trigger v_2\{FTPC EP\}

Jet v_2 in STAR



Jet Definition:
HT trigger $E_T > 5.5$ GeV
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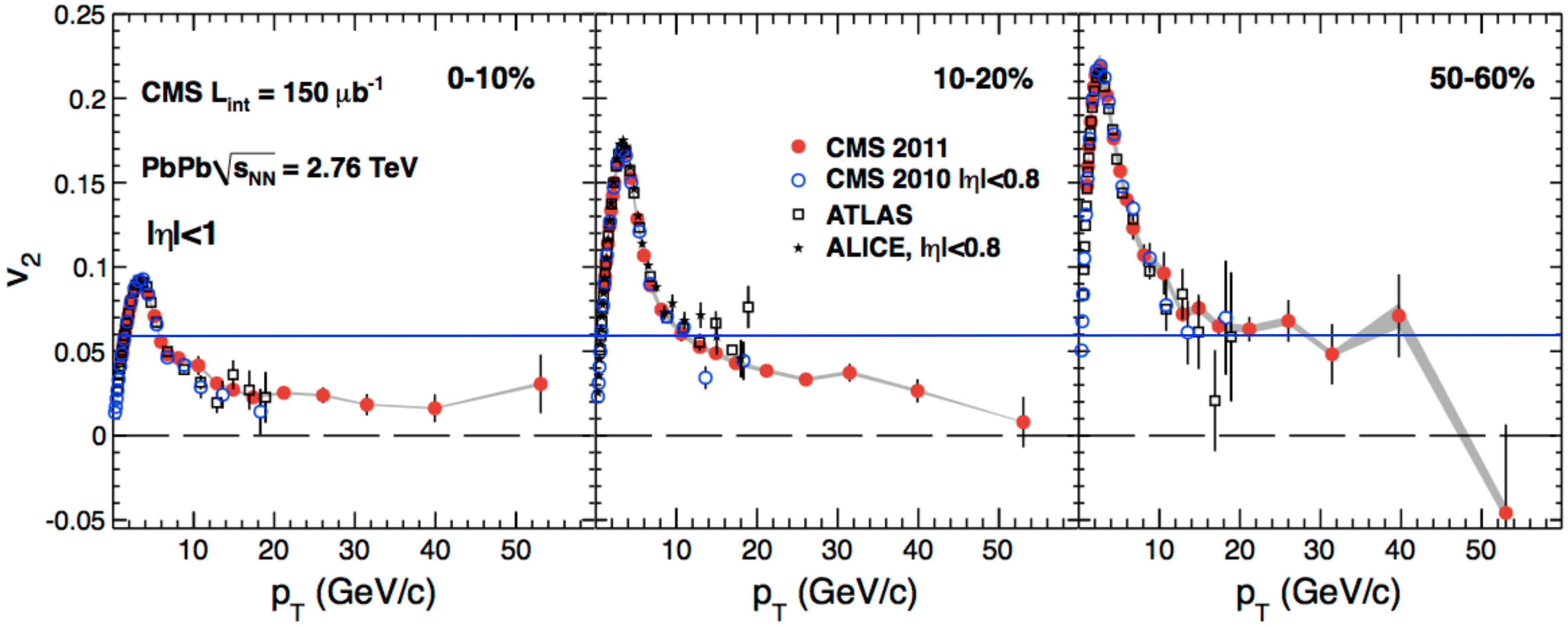
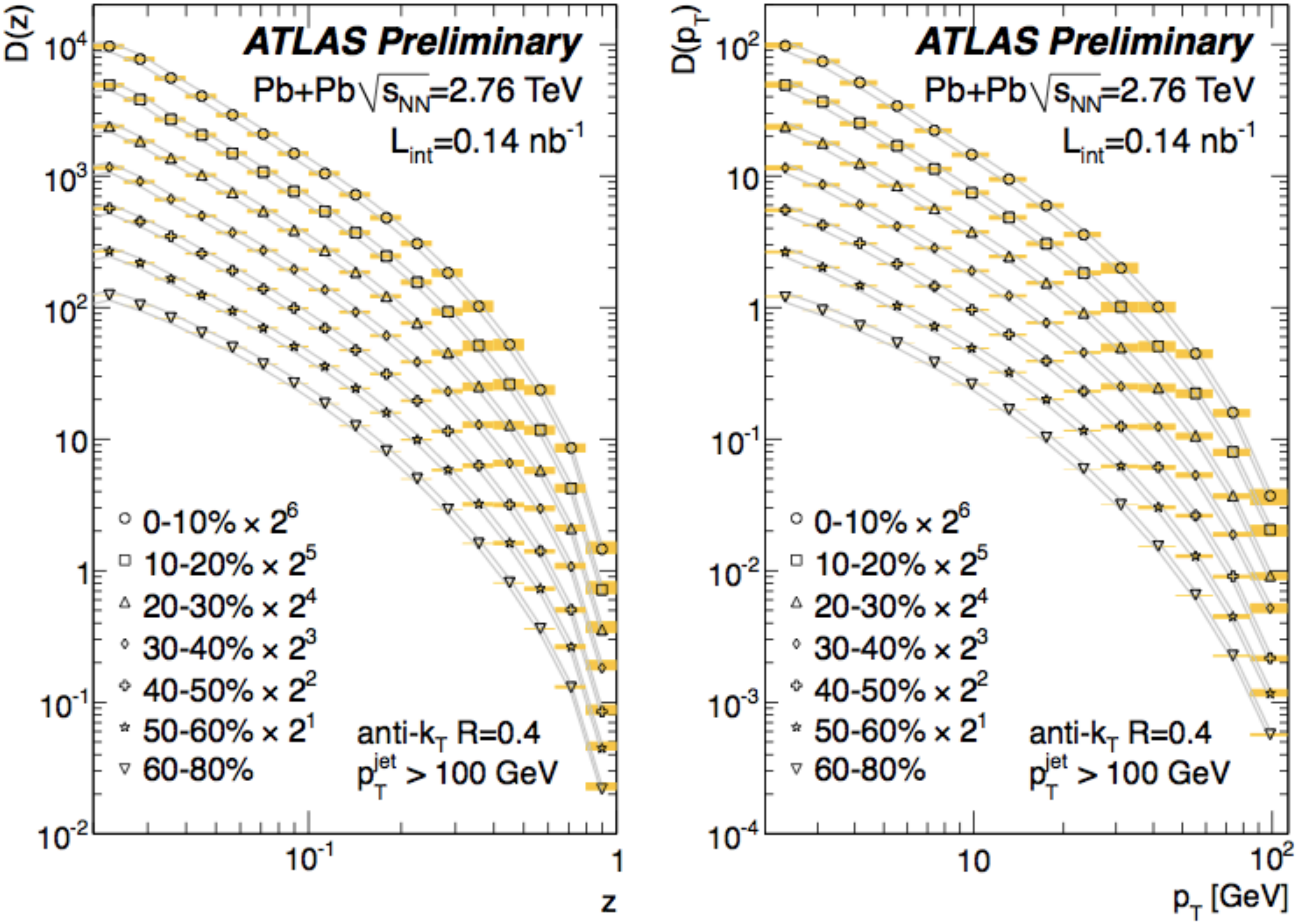


Fragmentation functions

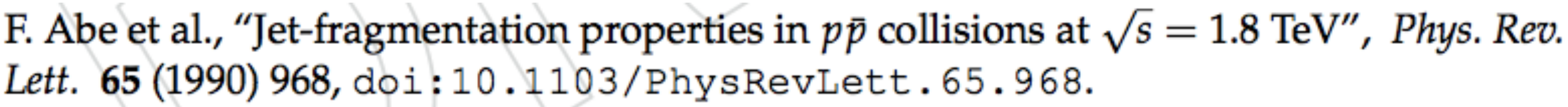
Fragmentation functions



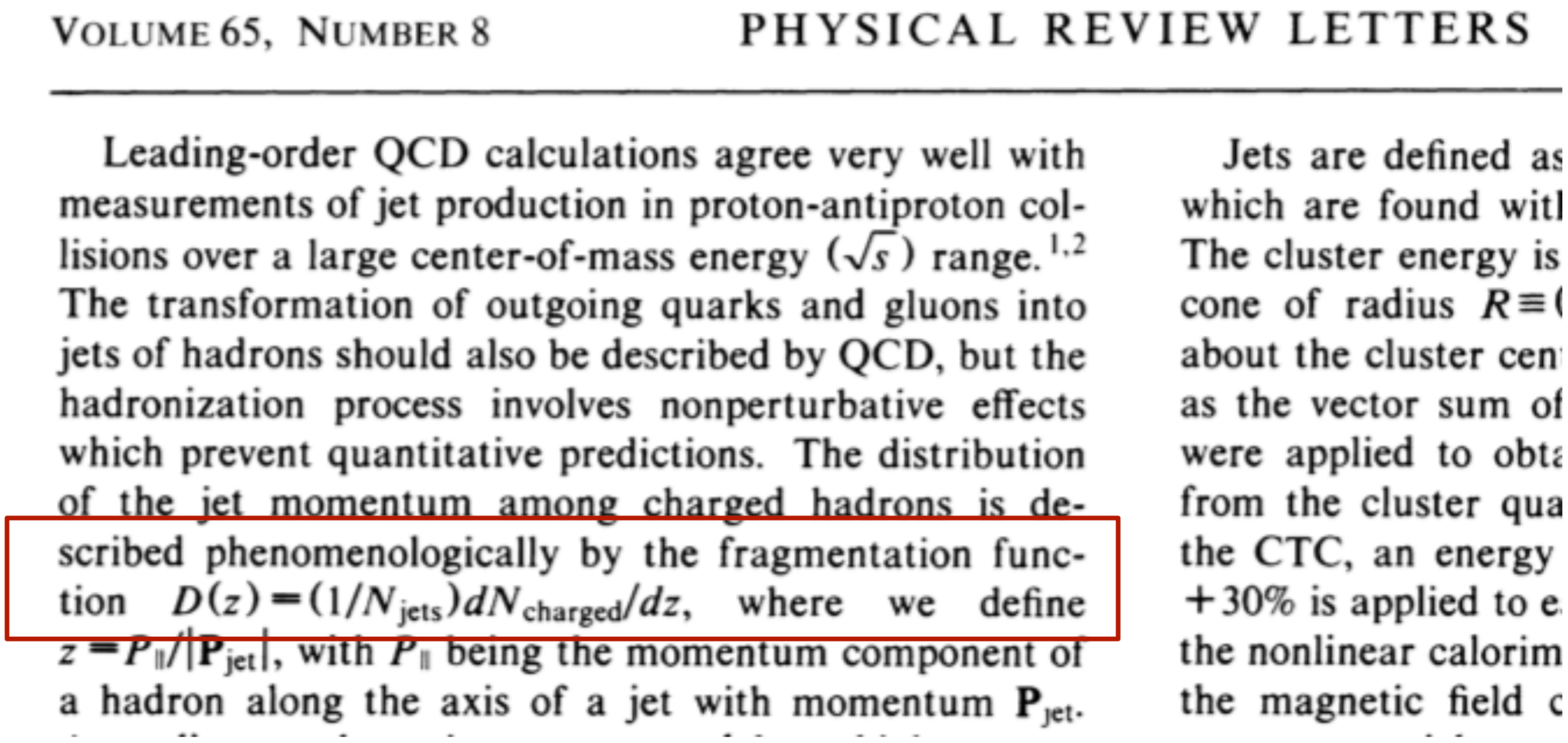
$$z = p_{\mathrm{T}}^{\mathrm{ch}} / p_{\mathrm{T}}^{\mathrm{jet}} \cos \Delta R$$

Fragmentation functions

- Distribution of associated track p_T in cone, relative to measured jet p_T
  - plot $Z = p_{T,\text{ track}}/p_{T,\text{jet}} \cos(\Delta R)$, $\xi = \ln(1/z)$ and track p_T
  - **No direct connection to parton p_T at scattering**



F. Abe et al., "Jet-fragmentation properties in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV", *Phys. Rev. Lett.* **65** (1990) 968, `doi:10.1103/PhysRevLett.65.968`.

- 

VOLUME 65, NUMBER 8 PHYSICAL REVIEW LETTERS

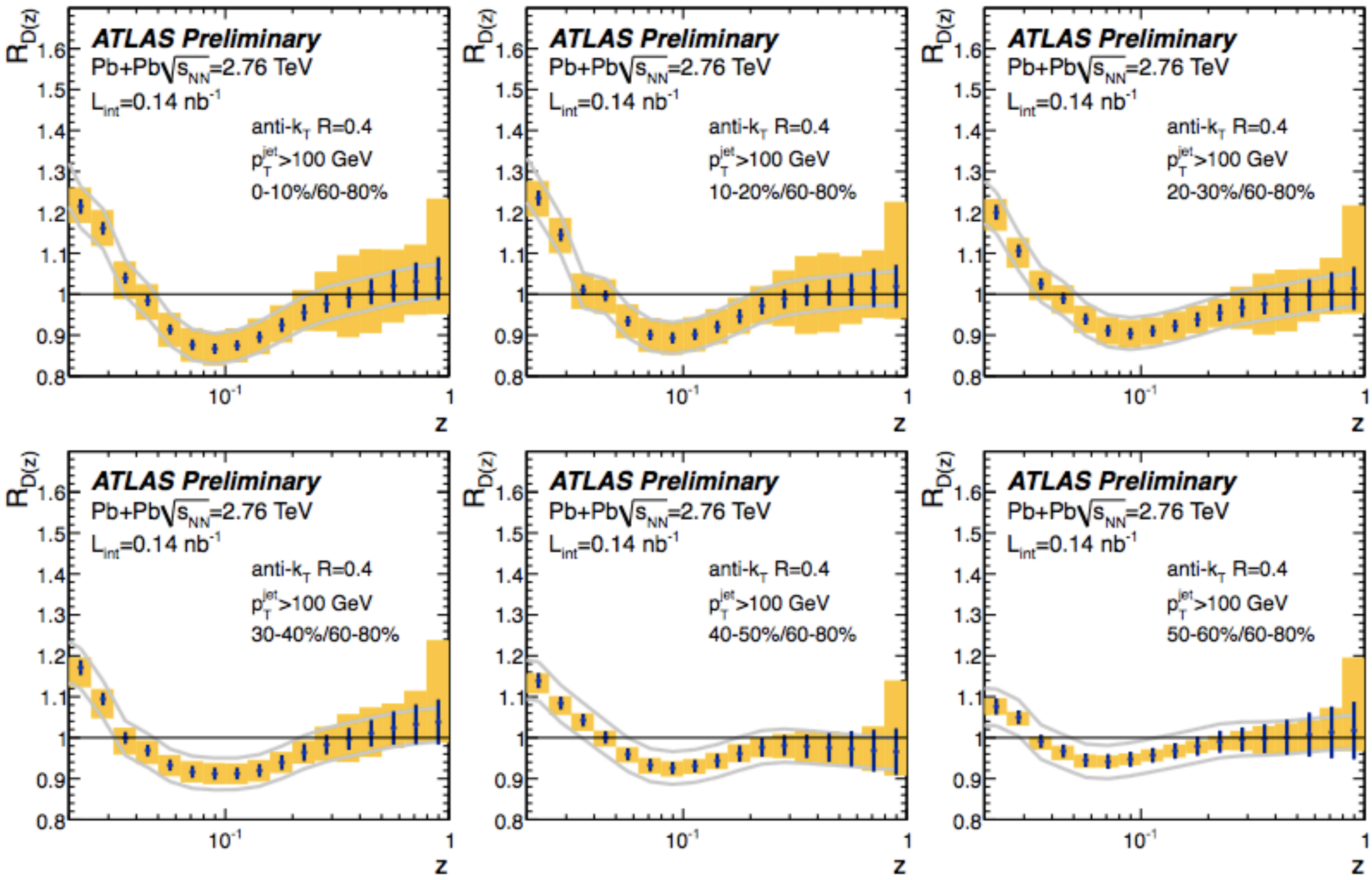
Leading-order QCD calculations agree very well with measurements of jet production in proton-antiproton collisions over a large center-of-mass energy ($\sqrt{s}$) range.[1,2] The transformation of outgoing quarks and gluons into jets of hadrons should also be described by QCD, but the hadronization process involves nonperturbative effects which prevent quantitative predictions. The distribution of the jet momentum among charged hadrons is described phenomenologically by the fragmentation function $D(z) = (1/N_{\text{jets}})dN_{\text{charged}}/dz$, where we define $z = P_{\parallel}/|\mathbf{P}_{\text{jet}}|$, with $P_{\parallel}$ being the momentum component of a hadron along the axis of a jet with momentum $\mathbf{P}_{\text{jet}}$.

Jets are defined as
which are found wit
The cluster energy is
cone of radius $R \equiv$
about the cluster cen
as the vector sum of
were applied to obt
from the cluster qua
the CTC, an energy
+30% is applied to e
the nonlinear calorim
the magnetic field

Fragmentation functions

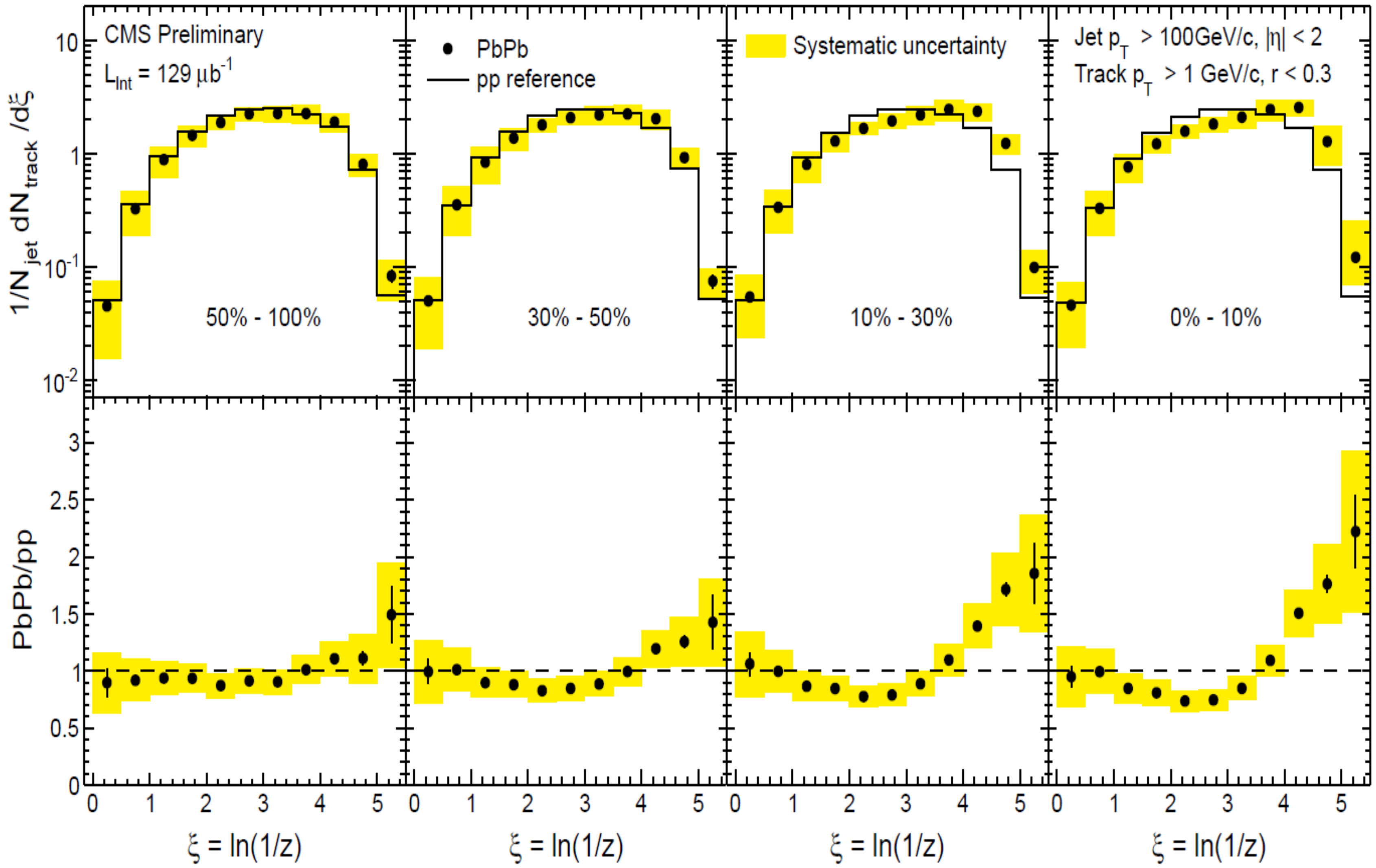
- Distribution of associated track p_T in cone, relative to measured jet p_T
  - plot $Z = p_{T,\text{ track}}/p_{T,\text{jet}} \cos(\Delta R)$, $\xi = \ln(1/z)$ and track p_T
  - **No direct connection to parton p_T at scattering**
- "Associated tracks" are defined relative to track population in same-event displaced cone
  - ATLAS: "cone grid"; CMS: "eta-reflected cone"
  - **No distinction between in-cone "associated tracks" from medium response or from hard-parton fragmentation**
- 1st point can be addressed with photon-jet

Fragmentation functions

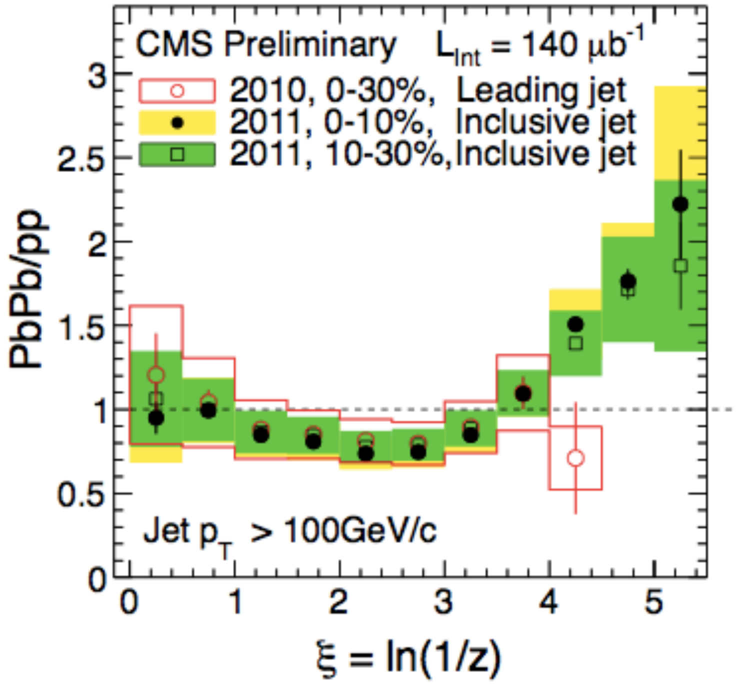


Unfolded for jet resolution (negligible effect except for lowest z bin)

Fragmentation functions

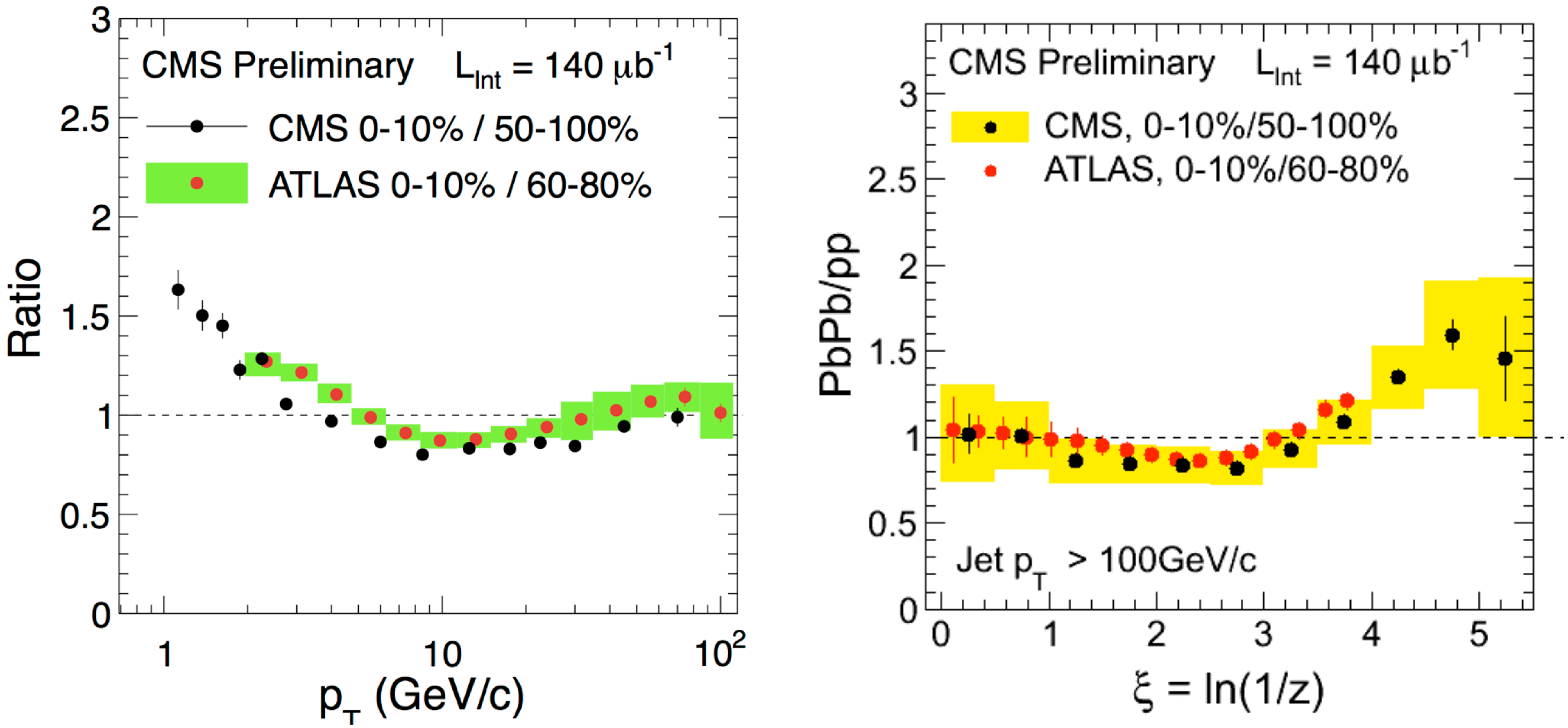


$$\xi = \ln\frac{1}{z}\ ;\ z = \frac{p_{\parallel}^{\text{track}}}{p^{\text{jet}}}$$



pp smeared and reweighted to match PbPb jet p_T spectrum

Fragmentation function comparison



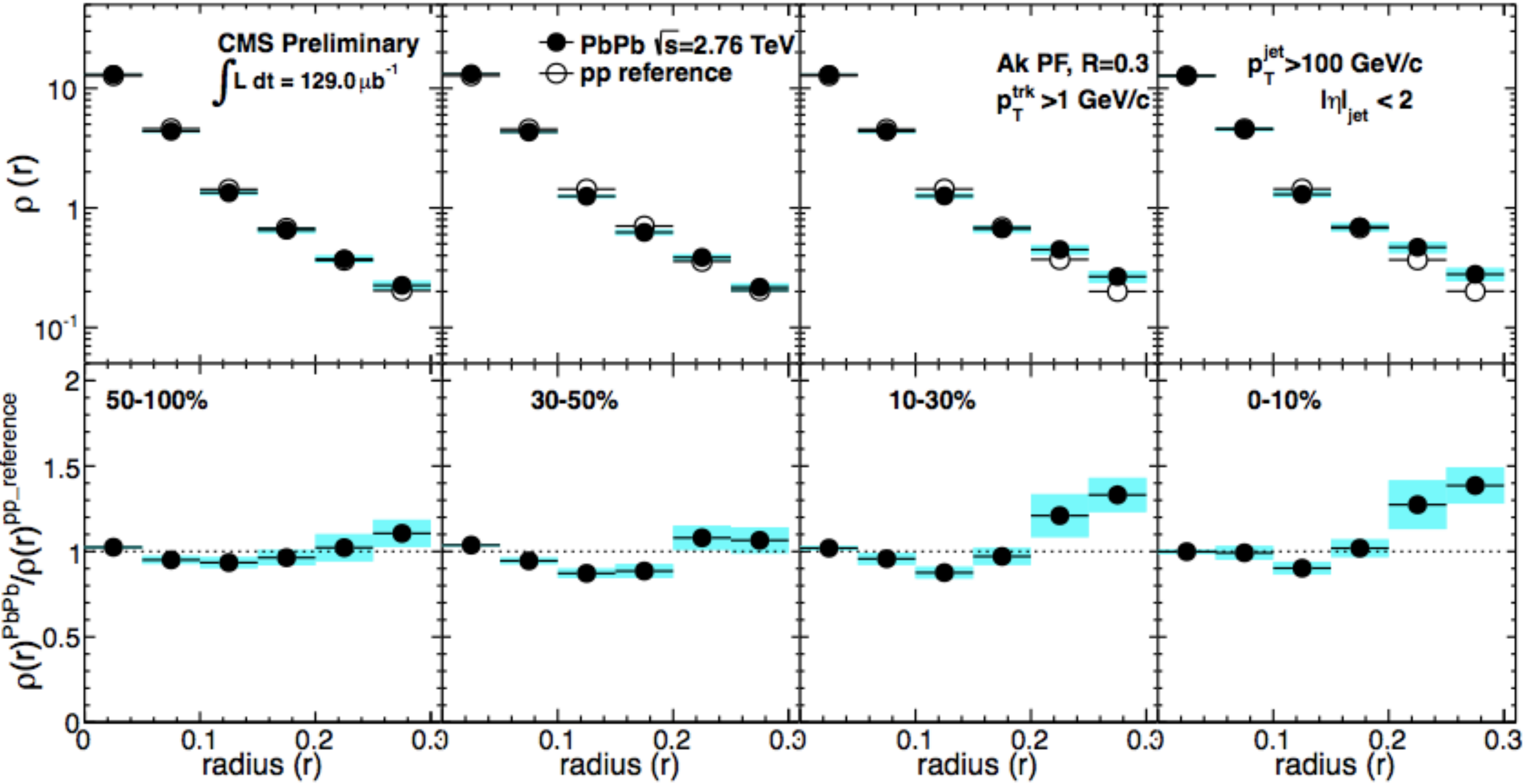
Note: Only one set of syst. uncertainties shown: Good agreement

Depletion from 3-4GeV to 40-50GeV (2-3% of total jet energy)

Enhancement below 3-4GeV (~ 2% of jet energy)

Differential jet shapes

$$\rho(r) = \frac{1}{f_{\mathrm{ch}}} \frac{1}{\delta r} \frac{1}{N_{\mathrm{jet}}} \sum_{\mathrm{jets}} \frac{p_{\mathrm{T}}(r - \delta r/2, r + \delta r/2)}{p_{\mathrm{T}}^{\mathrm{jet}}} \qquad f_{\mathrm{ch}} = \frac{1}{N_{\mathrm{jet}}} \sum_{\mathrm{jets}} \frac{p_{\mathrm{T}}(0,R)}{p_{\mathrm{T}}^{\mathrm{jet}}}$$

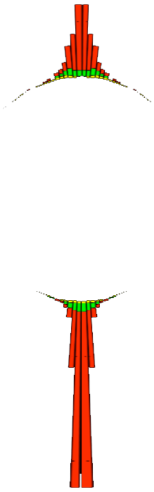


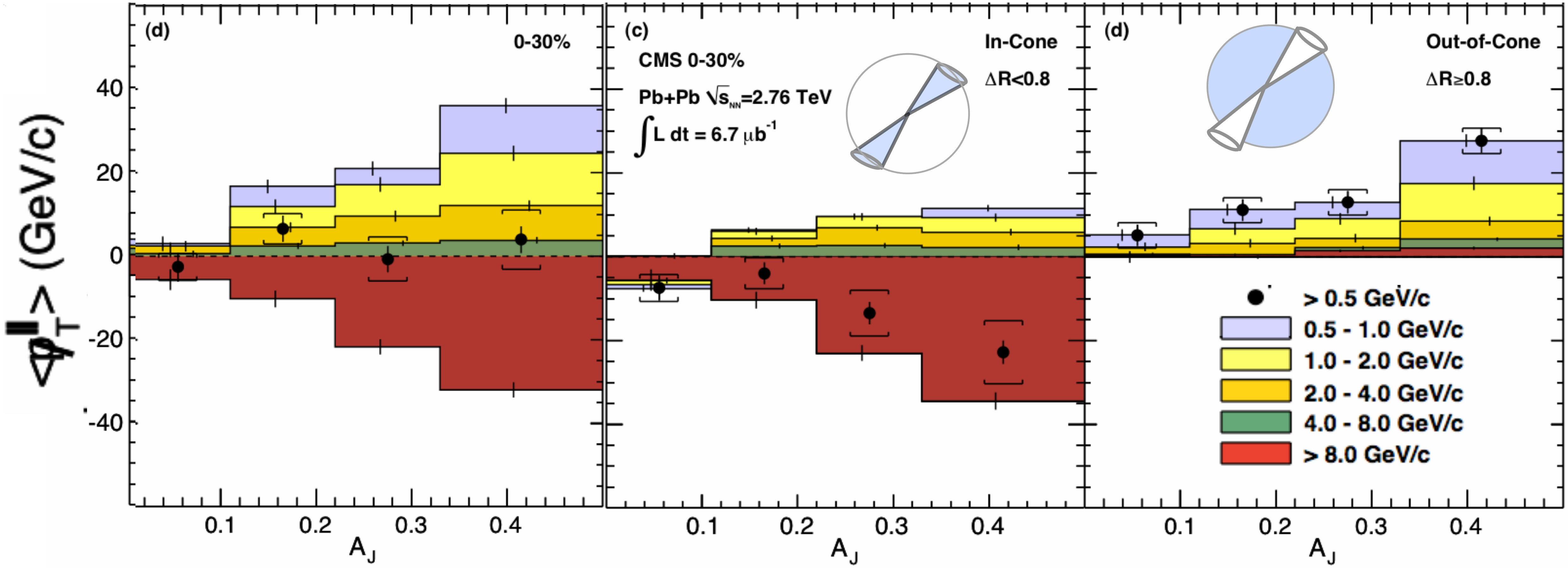
Again, depletion/enhancement pattern (correlation between fragment p_T and r)

Lost energy

Energy redistribution

The momentum difference in the dijet is balanced by low p_T particles mainly at large angles relative to the away side jet axis





$$A_J = (p_{T,1}-p_{T,2})/(p_{T,1}+p_{T,2})$$

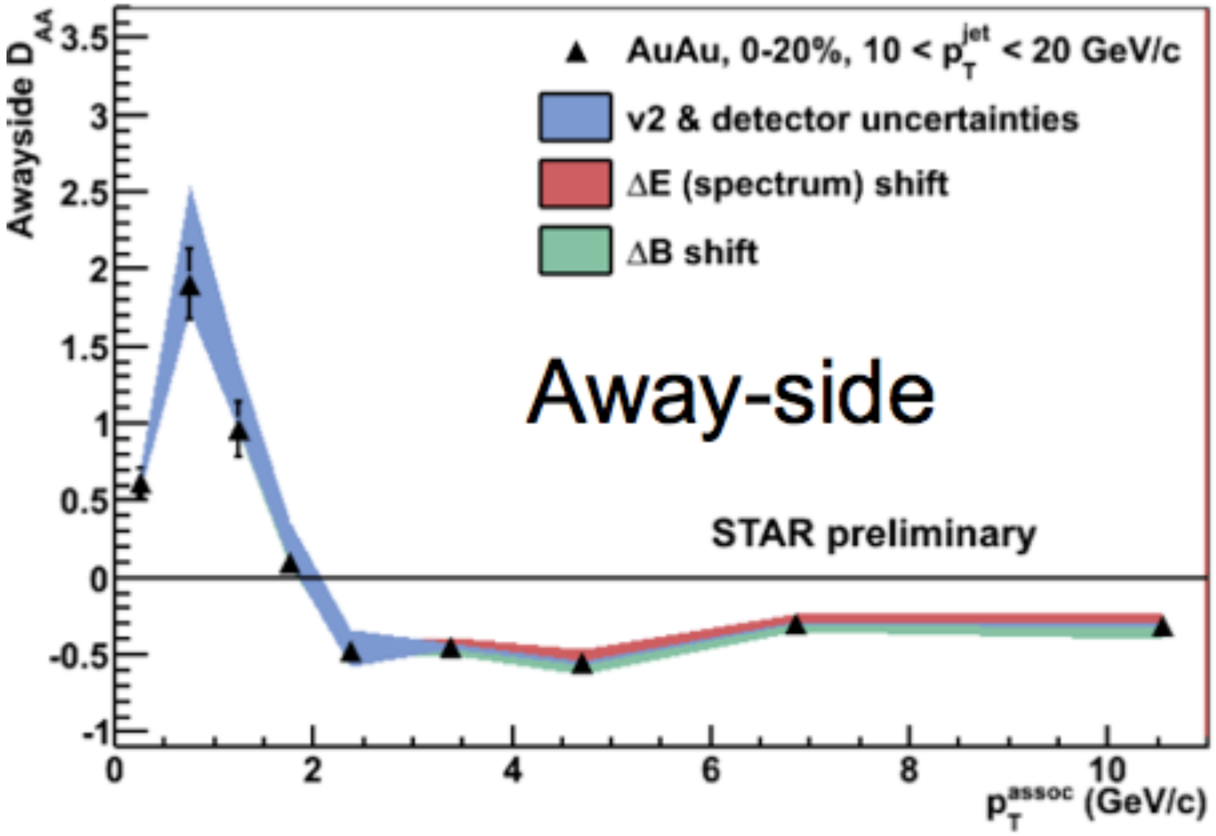
$$\not{p}_{\mathrm{T}}^{\|} = \sum_{\mathrm{Tracks}} -p_{\mathrm{T}}^{\mathrm{Track}} \cos\left(\phi_{\mathrm{Track}} - \phi_{\mathrm{Leading\ Jet}}\right)$$

Momentum balance from jet-track correlations

$$D_{AA}(p_T^{assoc}) = Y_{AA}(p_T^{assoc}) \cdot p_{T,AA}^{assoc} - Y_{pp}(p_T^{assoc}) \cdot p_{T,pp}^{assoc}$$

$$\Delta B = \int dp_T^{assoc} D_{AA}(p_T^{assoc})$$

STAR AuAu 200GeV preliminary

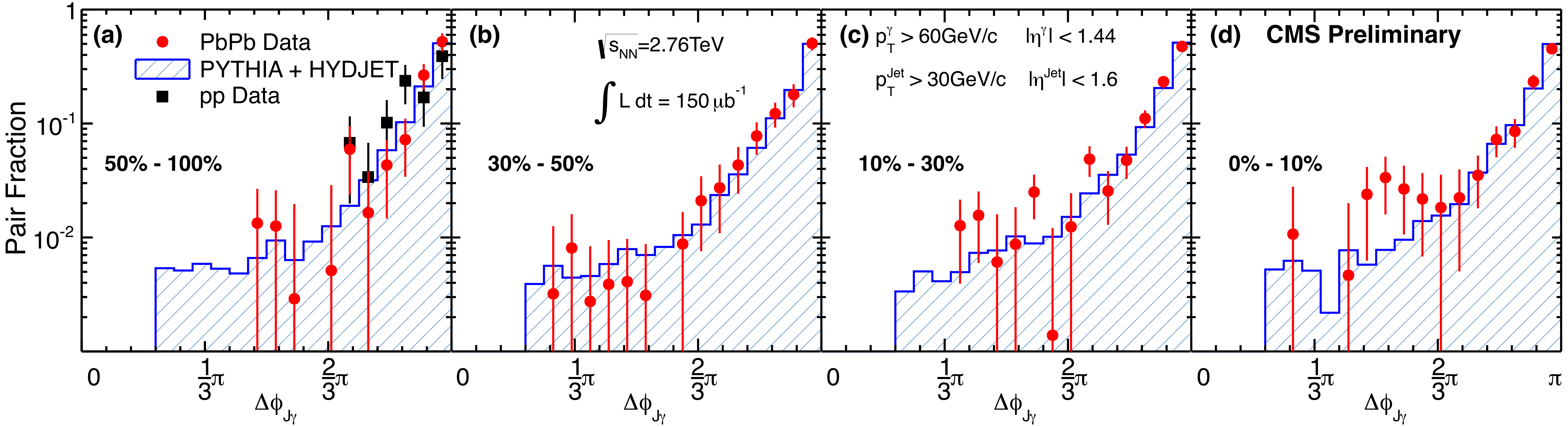


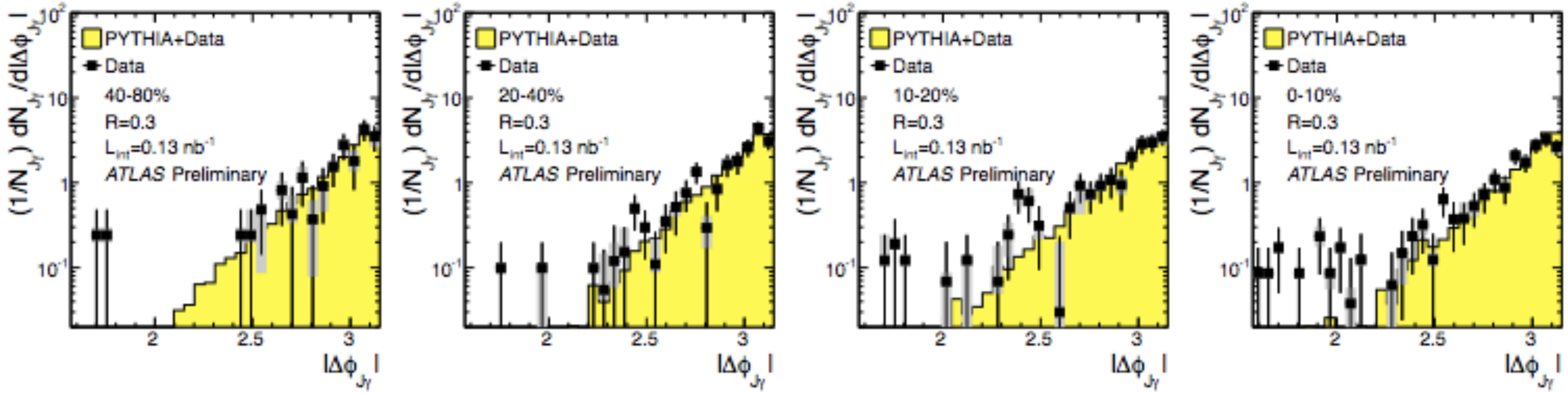
$$\Delta B = 1.5 \,{}^{+1.7}_{-0.4}\,{}^{+0.5}_{-0.4}\ (sys)\ \mathrm{GeV}/c$$

Energy lost at high p_T approximately recovered at low p_T and high R

Photon-jet

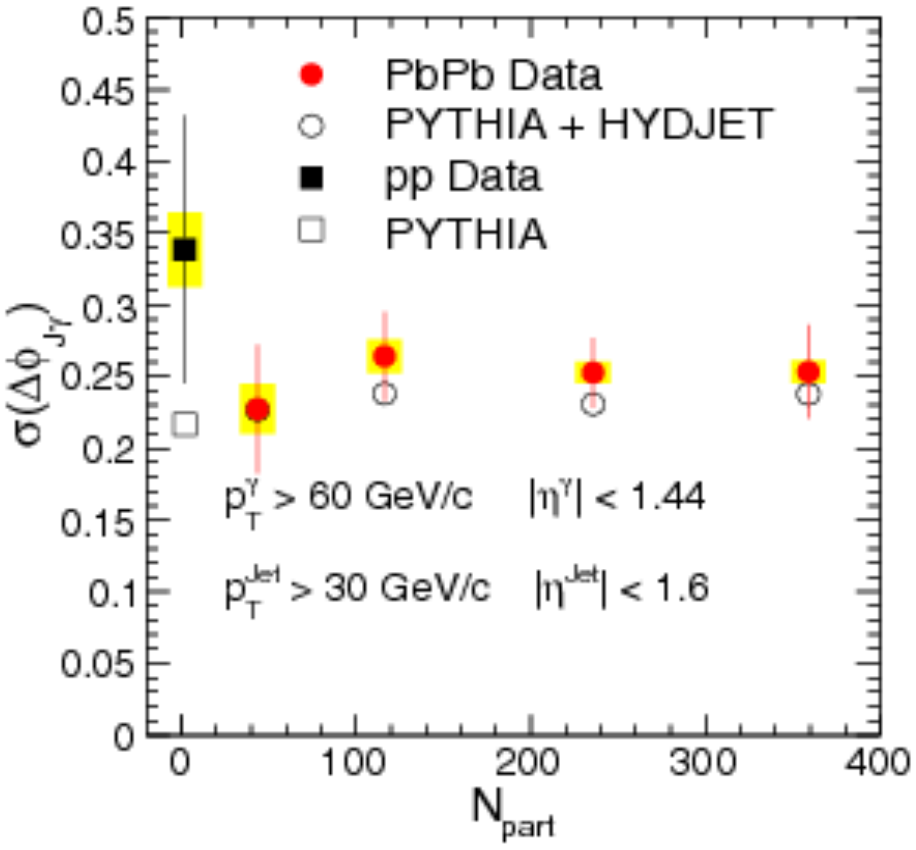
Photon-Jet Angular Correlation

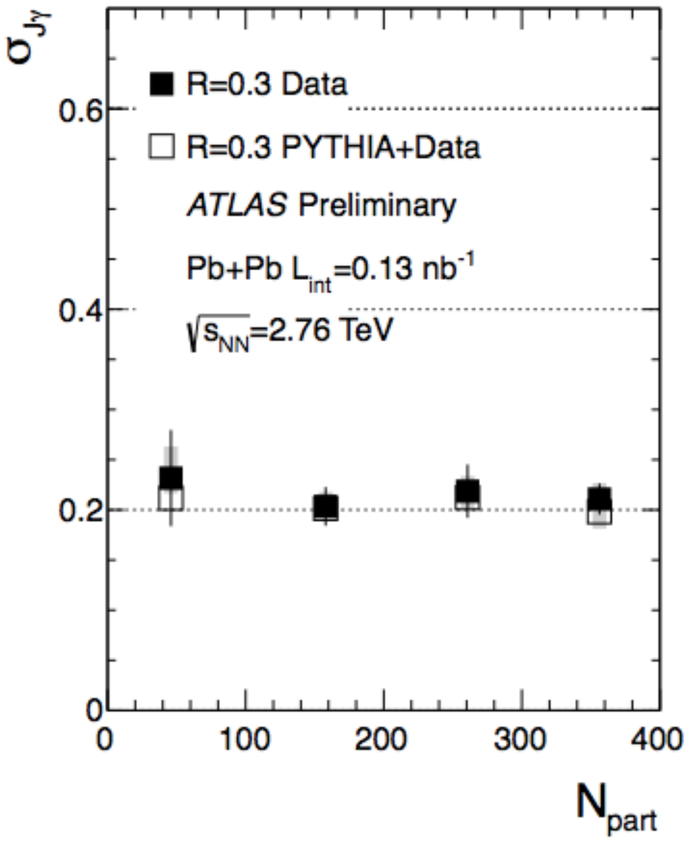


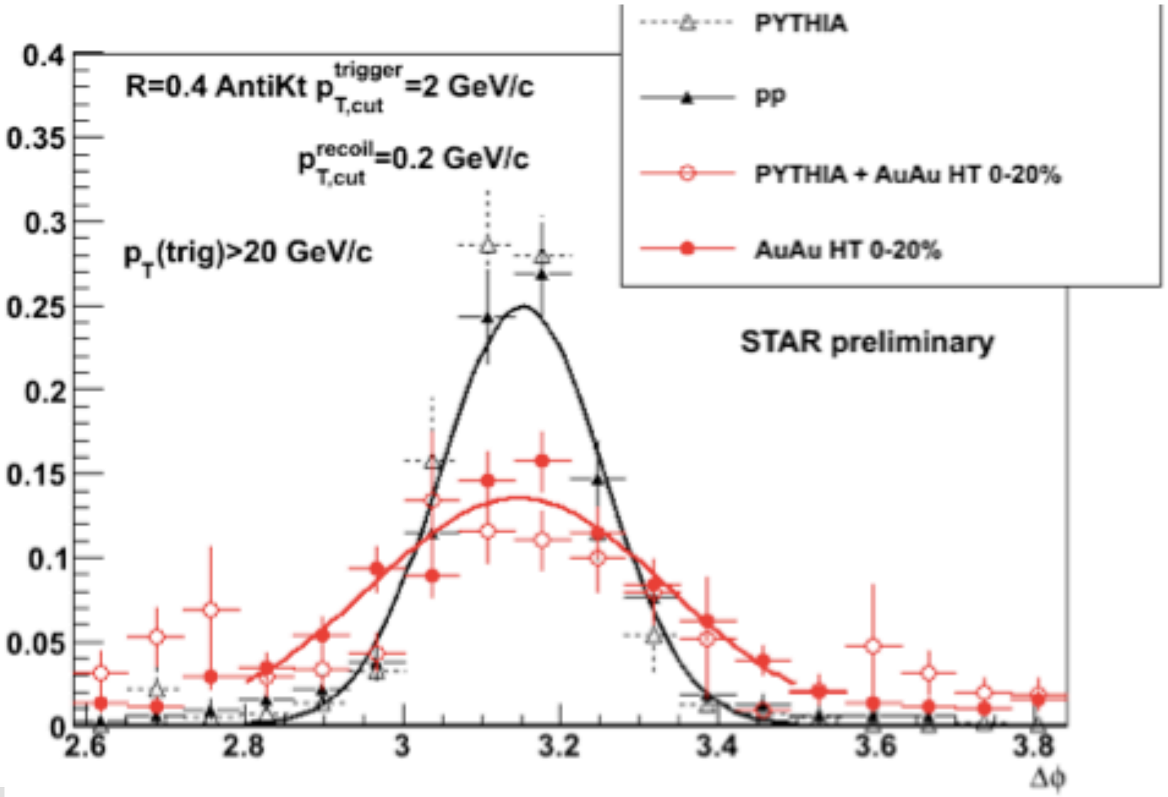


No angular decorrelation observed (now with much lower jet p_T)

Angular decorrelation?







$p_{T\text{rec,jet}}$ > 20 GeV/c, $p_{T\text{rec,dijet}}$ > 10 GeV
Di-jet: highest p_T with $|\varphi_{jet}-\varphi_{dijet}| > 2.6$

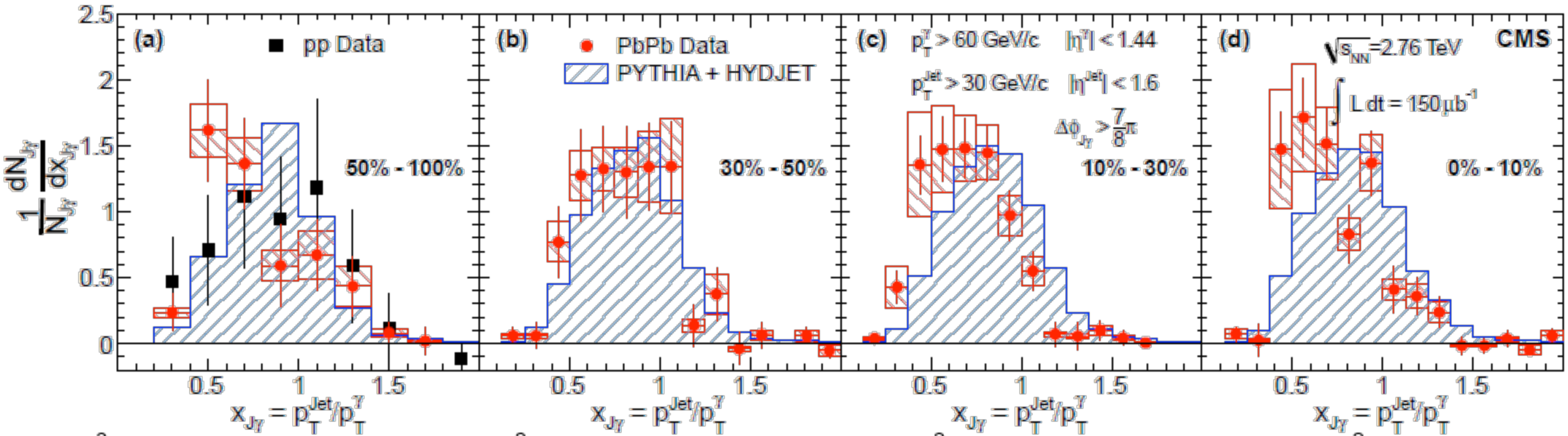
Δφ of identified di-jets

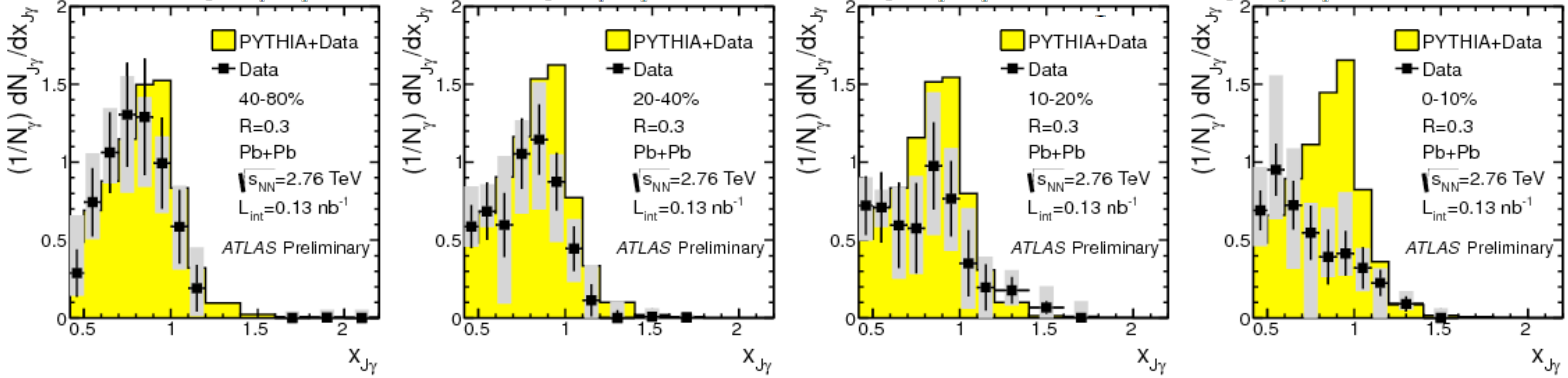
$\sigma_{Au\text{-}Au}$ ~ 0.2

$\sigma_{PYTHIA,Embed}$ ~ 0.14

$\sigma_{p\text{-}p} \sim \sigma_{PYTHIA}$ ~ 0.1

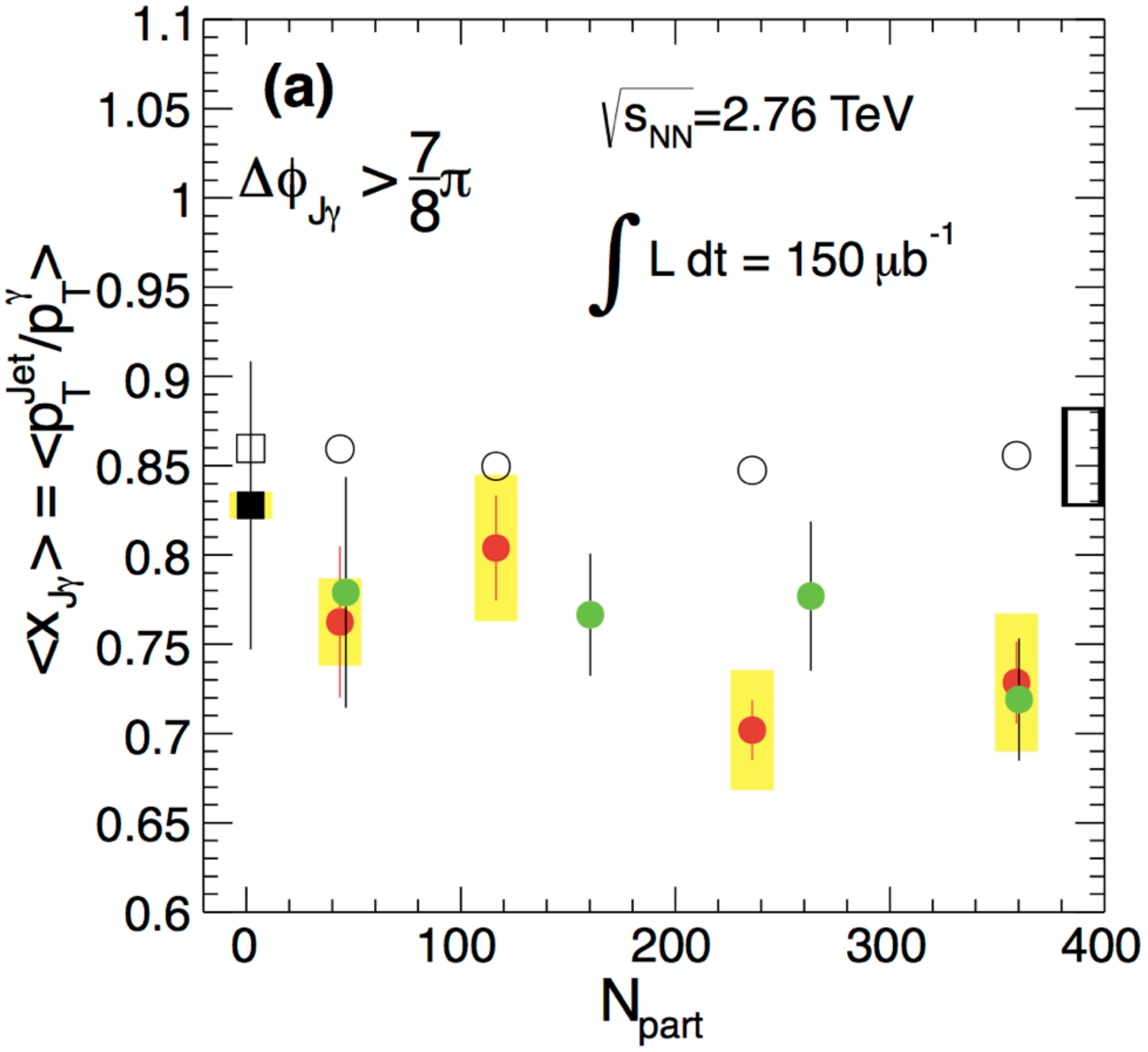
Photon-Jet Momentum Balance

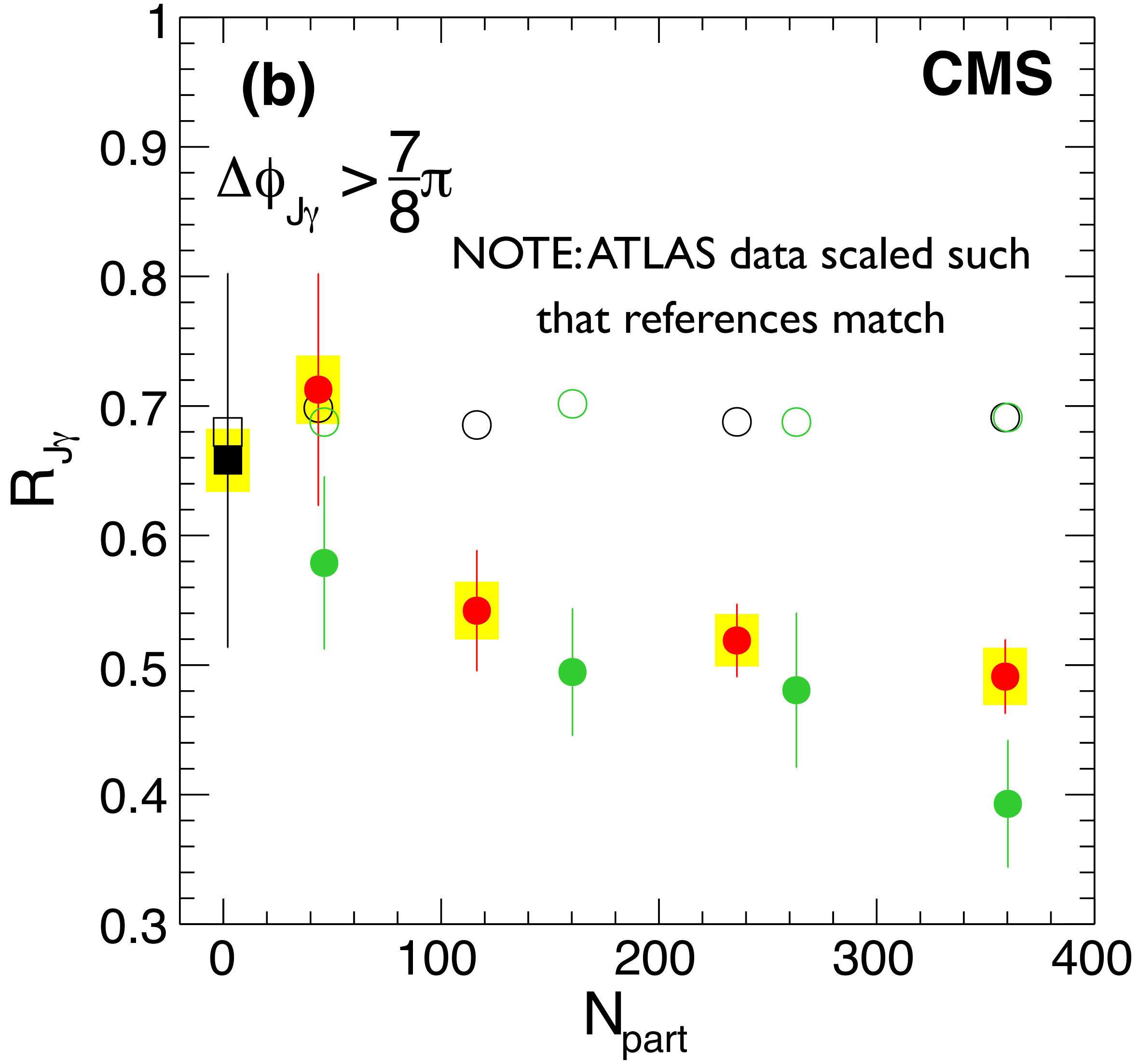




photon-jet momentum balance shifts in central events
(relative to PYTHIA reference, calibrated in 7GeV pp)

Photon-Jet Momentum Balance





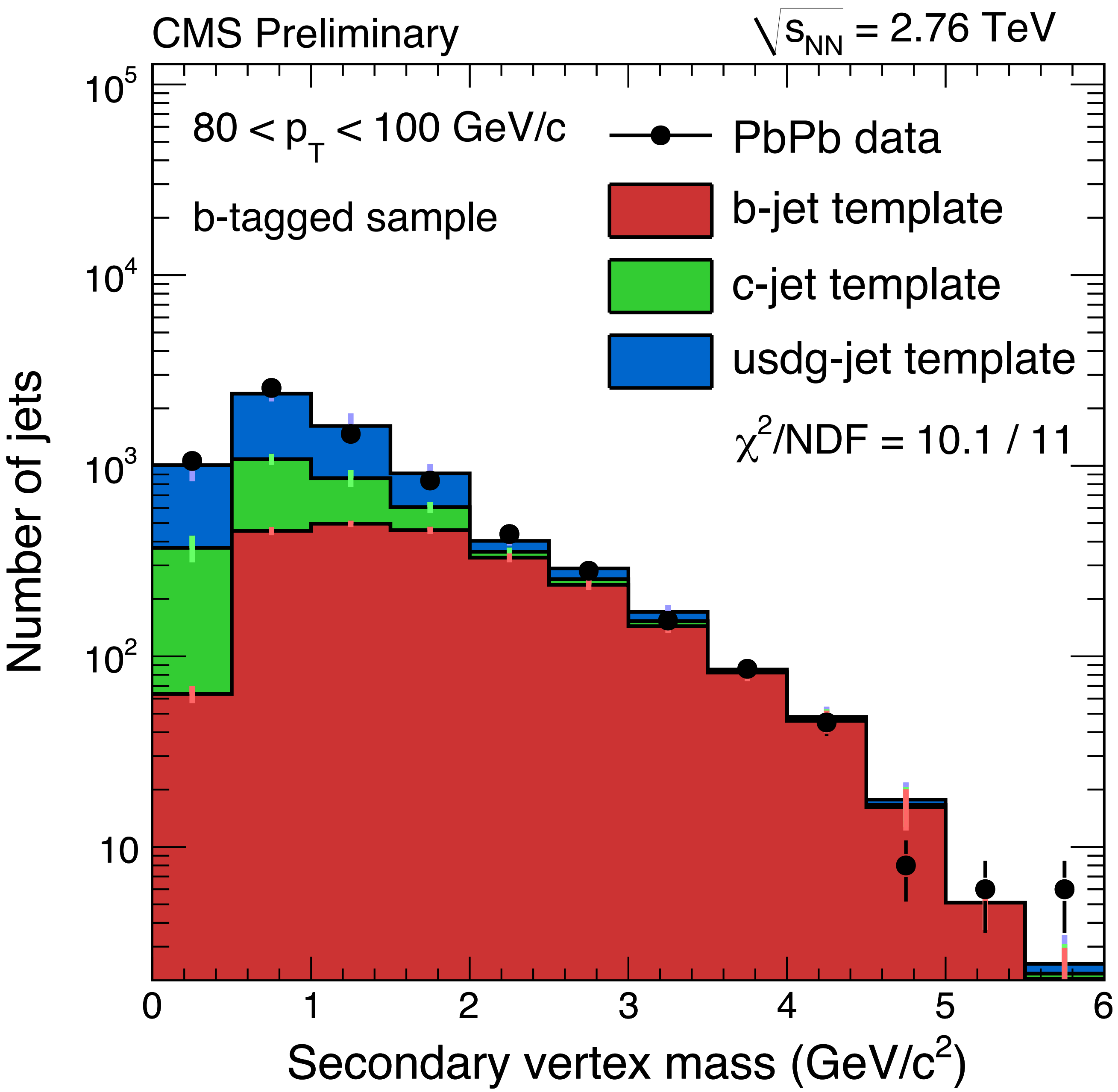
Reasonable agreement between ATLAS and CMS

NOTE: CMS correlates photon w/ associated jet, ATLAS w/ leading jet

b-tagging

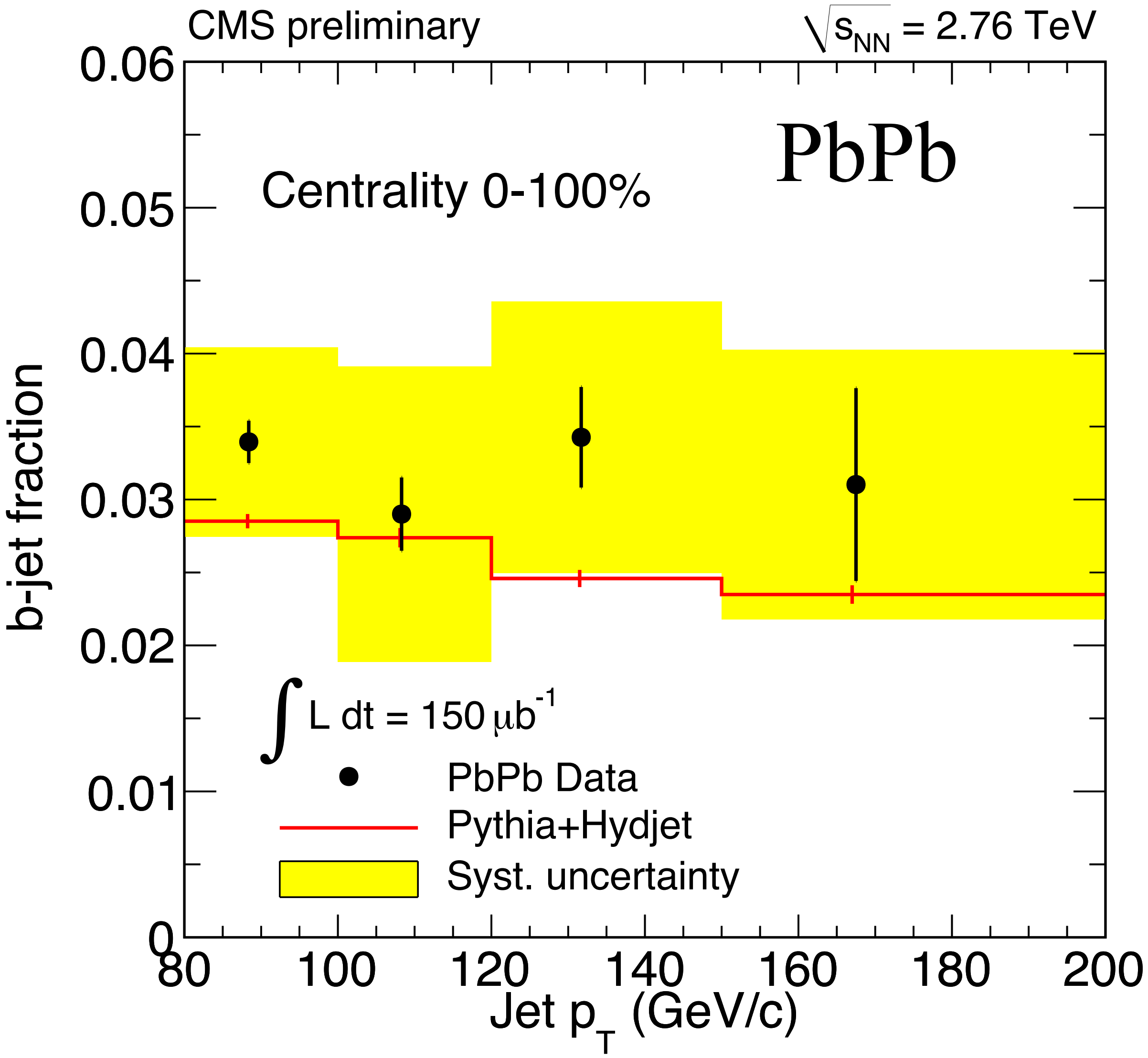
Secondary Vertex Mass Fits

- After enriching sample in b-jets with the SSVHE tagger, we fit the SV mass distribution
- Shapes of b and non-b templates taken from MC, normalizations allowed to float
- The shapes of the non-b templates are cross-checked with a data-driven method
- The stability of the fits and the shapes of the templates are the dominant sources of systematics uncertainty

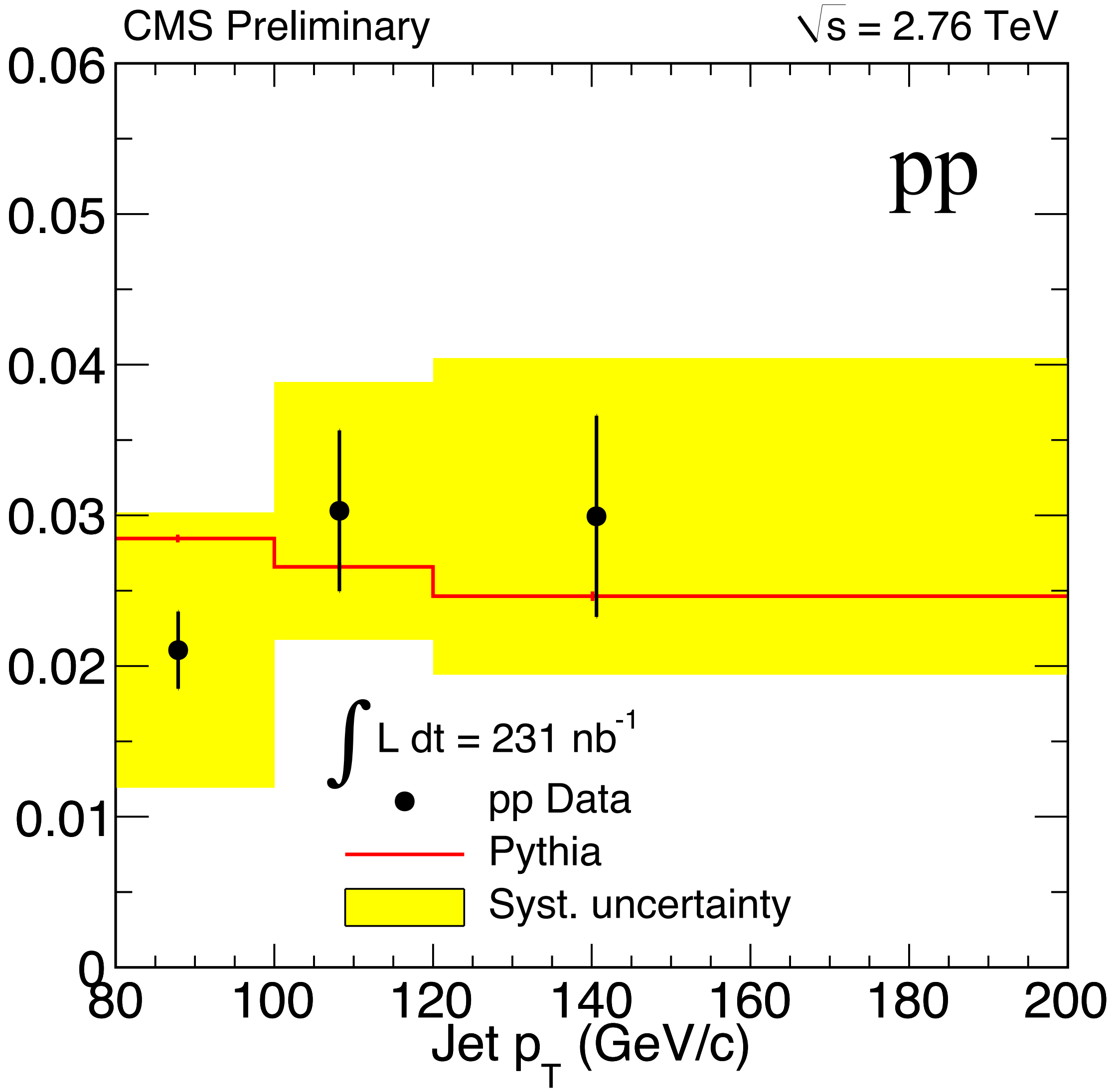


b-Tagging Purity and Efficiency

Purity: b-jet fraction in SV tagged sample extracted from SV mass fit

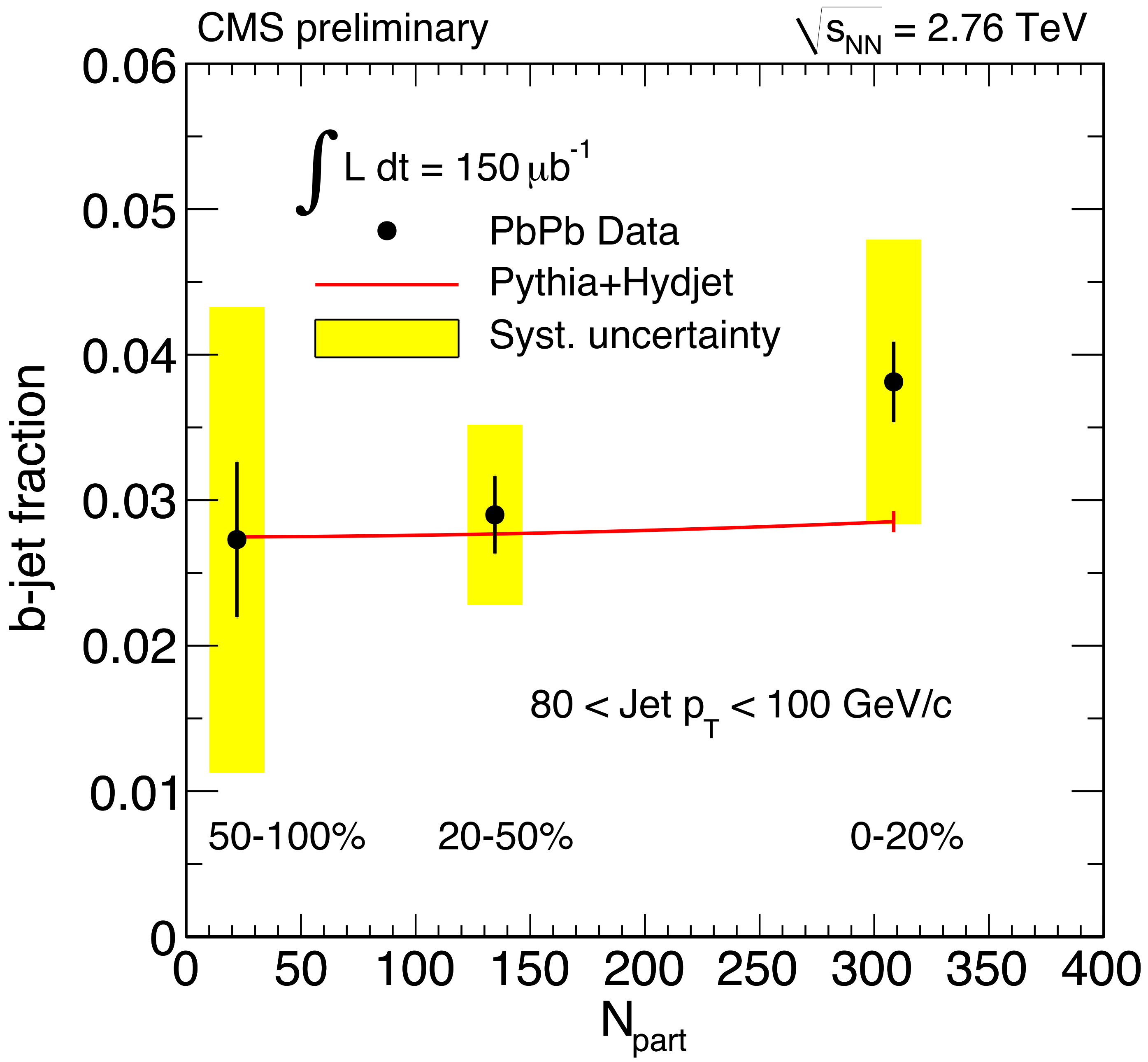


Efficiency: Fraction of b-jets which are tagged by their SV



- Efficiency is extracted from simulation and with a data-driven method using the JP tagger, i.e., w/o requiring a SV
- For both efficiency and purity, MC is fairly close to data "out of the box"

b-jet Fraction vs. Centrality



b-jet fraction does not show a strong centrality dependence

Summary

- Fantastic set of new results on jets from LHC and RHIC
- In general, good consistency between experiments
- Interface to theory needs to be refined:
  - unfolding?
  - folding?