Recent ATLAS results on HI collisions

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on behalf of the ATLAS Collaboration

Charles University

Heavy ion physics at ATLAS

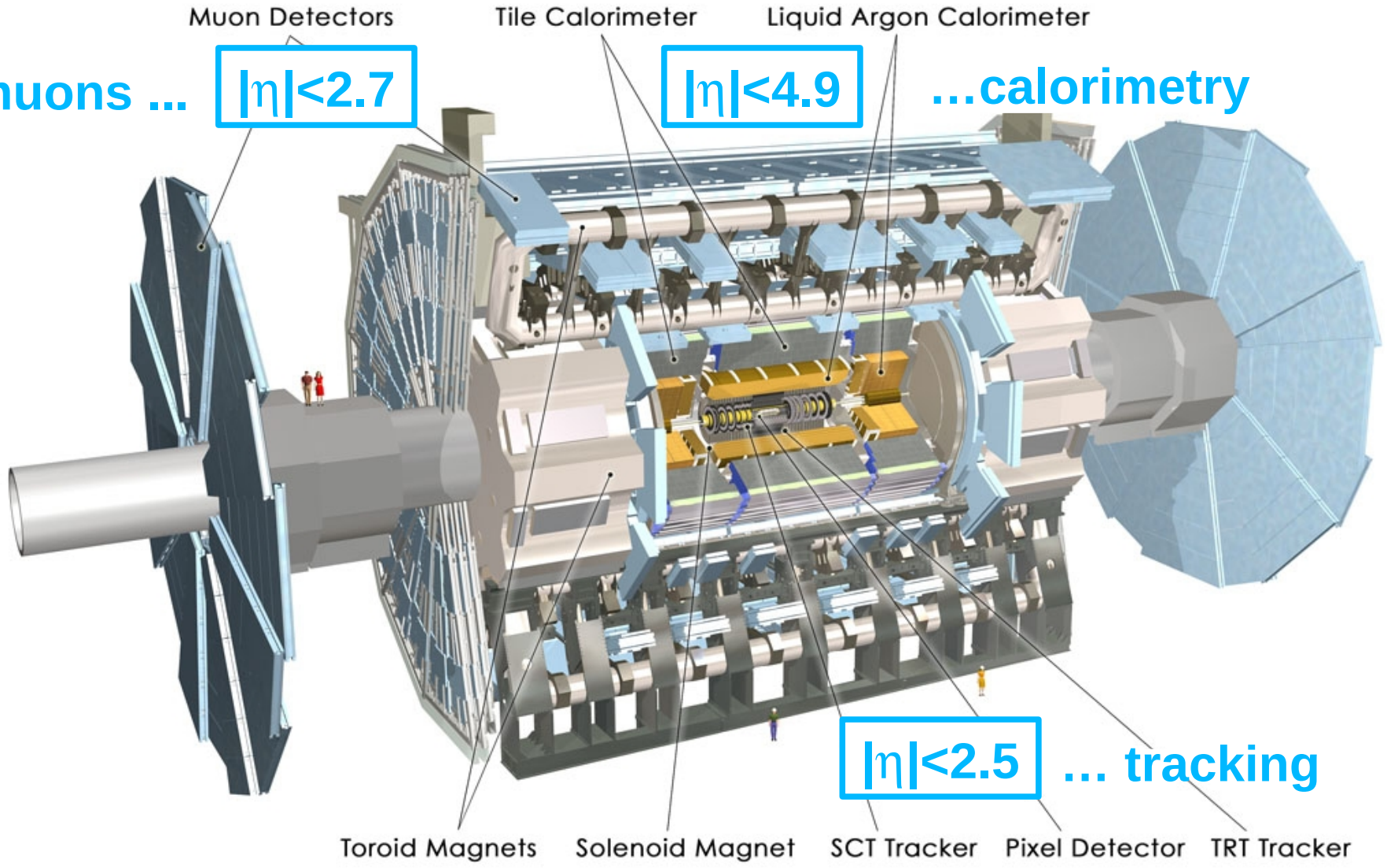
- **Soft physics** – lesson from RHIC: hot and dense QCD matter created in heavy ion collisions can be described by viscous hydrodynamics and it exhibits behavior of nearly perfect fluid. ATLAS confirms and extends this view by:
  - measurements of higher order flow harmonics
  - measurements of flow fluctuations
  - correlations in p+Pb events

  } **Talk by Jiangyong Jia**

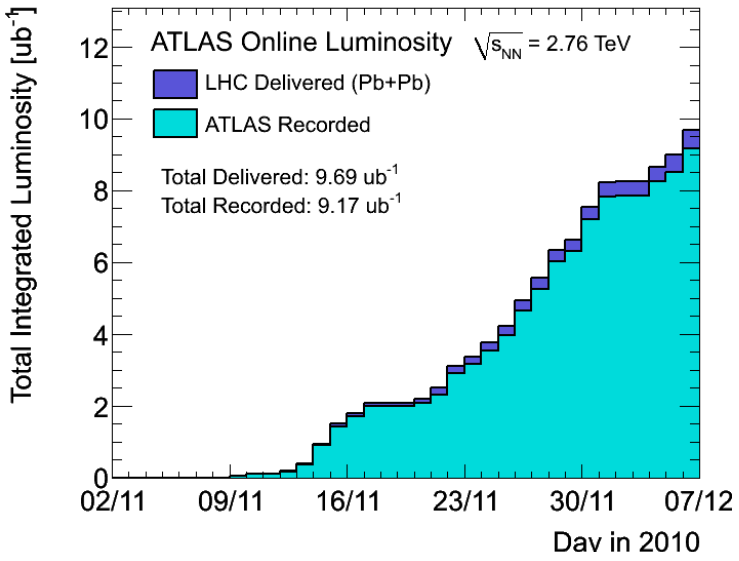
- **Hard physics** – lesson from RHIC: high-pt hadrons are strongly suppressed due to the jet quenching = energy loss of partons passing through the dense colored medium. ATLAS further extends this view by:
  - various measurements of fully reconstructed jets,
  - measurements of high-pt photons and vector bosons,
  - measurements of jet internal structure

  } **… this talk**

ATLAS Detector



Data-taking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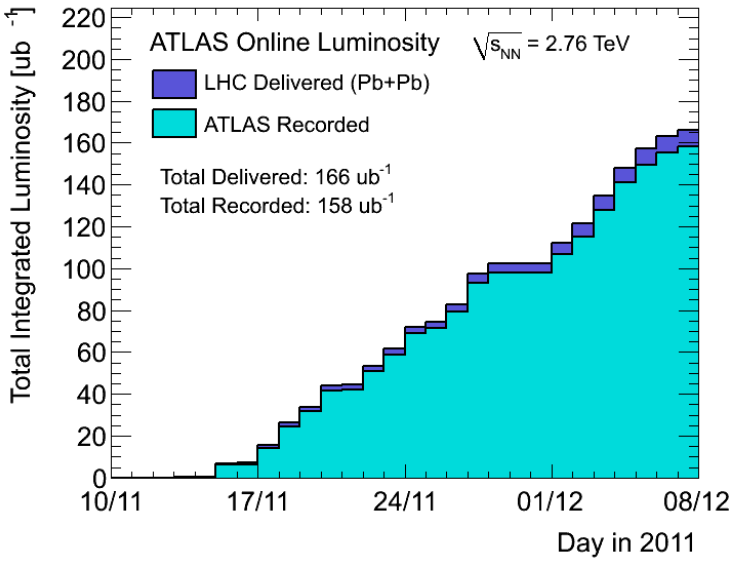
$\sqrt{s_{NN}}$ = 2.76 TeV
LHC Delivered (Pb+Pb)
ATLAS Recorded
Total Delivered: 9.69 ub^{-1}
Total Recorded: 9.17 ub^{-1}
Total Integrated Luminosity [ub^{-1}]
0 2 4 6 8 10 12
02/11 09/11 16/11 23/11 30/11 07/12
Dav in 2010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ATLAS Recorded
Total Delivered: 166 ub^{-1}
Total Recorded: 158 ub^{-1}
Total Integrated Luminosity [ub^{-1}]
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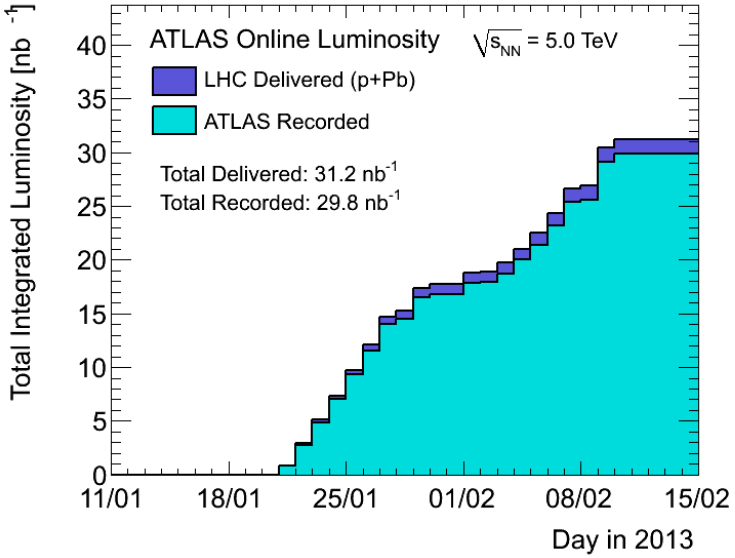
10/11 17/11 24/11 01/12 08/12
Day in 2011


ATLAS Online Luminosity
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LHC Delivered (p+Pb)
ATLAS Recorded
Total Delivered: 31.2 nb^{-1}
Total Recorded: 29.8 nb^{-1}
Total Integrated Luminosity [nb^{-1}]
0 5 10 15 20 25 30 35 40
11/01 18/01 25/01 01/02 08/02 15/02
Day in 2013

How does the parton lose its energy?

How does the parton lose its energy? To answer this fundamental question we need to ask further detailed questions:

- How are the inclusive jet yields suppressed?
- How does the suppression depend on jet energy and collisions centrality?
- Does the suppression depend on the size of the jet?

jet R_{CP} measurement

- Can we quantify the impact of initial state effects on jet the suppression? Can we see the jet suppression in other final states as well?

measurements of vector bosons

- Does the suppression depend on the flavor of initial parton?

measurement of direct muons

- Does the suppression depend on the path-length of a parton traversing the medium?
- What is the jet v_2?

measurement of jet yields with respect to reaction plane

- Is the structure of jets modified? How do the spectra of particles inside jets differ in central HI collisions?

measurement of jet fragmentation

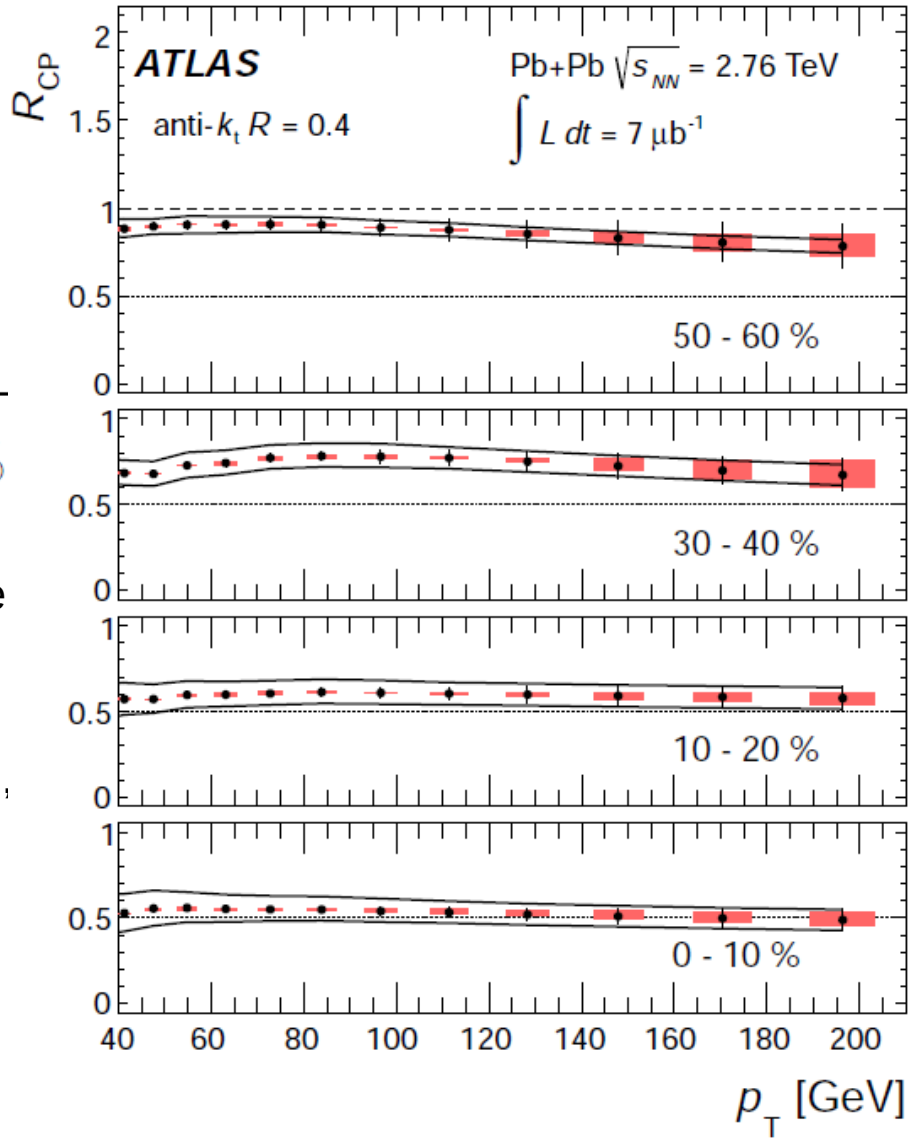
Jet R_{CP}

Q: How are the inclusive jet yields suppressed?

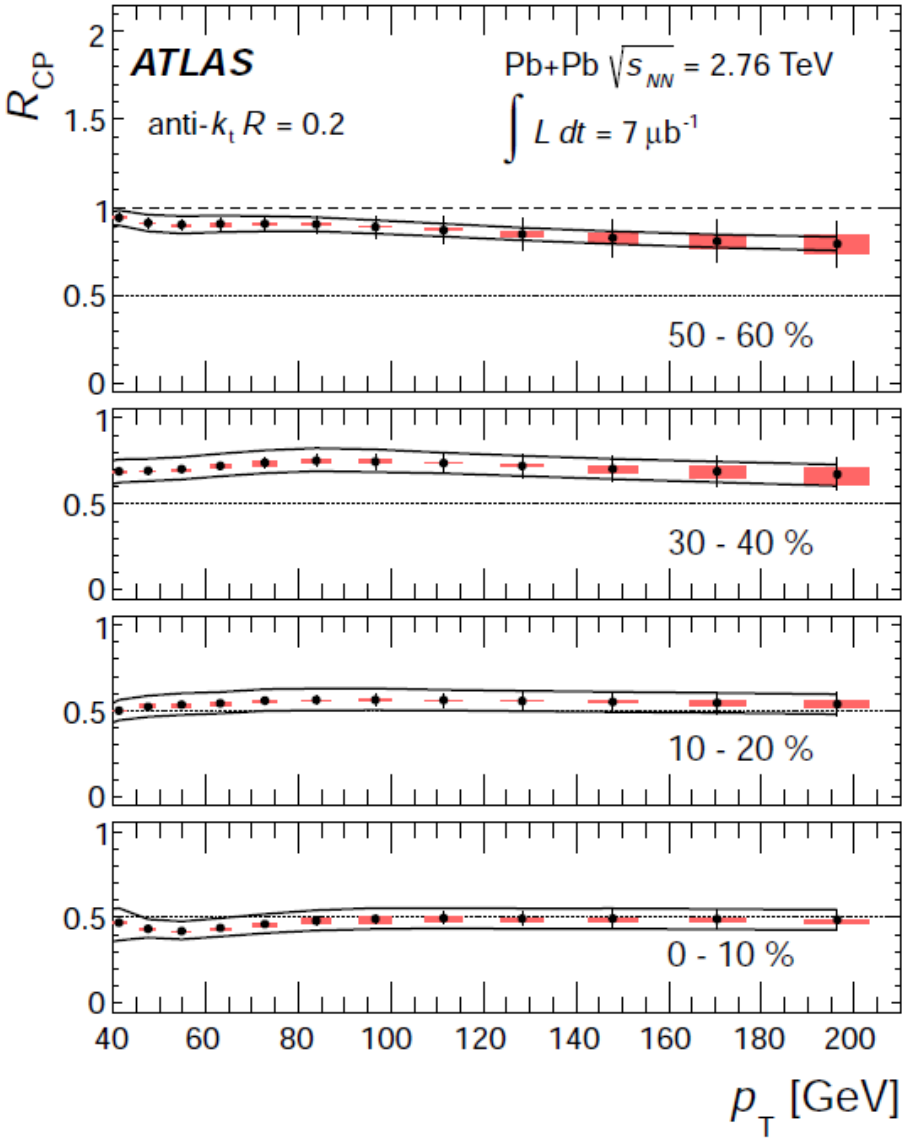
- Jet R_{CP} – ratio of central to peripheral collisions,

$$R_{\mathrm{CP}} = \frac{\frac{1}{N_{\mathrm{coll}}}\frac{1}{N_{\mathrm{evt}}}\frac{\mathrm{d}N}{\mathrm{d}p_{\mathrm{T}}}\Big|_{cent}}{\frac{1}{N_{\mathrm{coll}}}\frac{1}{N_{\mathrm{evt}}}\frac{\mathrm{d}N}{\mathrm{d}p_{\mathrm{T}}}\Big|_{60-80\%}}$$

- Result unfolded using SVD unfolding to remove detector effects (e.g. jet energy resolution).
- Systematic uncertainties:
  - black band: fully bin-wise correlated (R_{coll}, jet energy scale, jet energy resolution, efficiency, parametrization of truth distribution)
  - red boxes: partially correlated (choice of regularization parameter in unfolding)
- Statistical uncertainty by error bars.



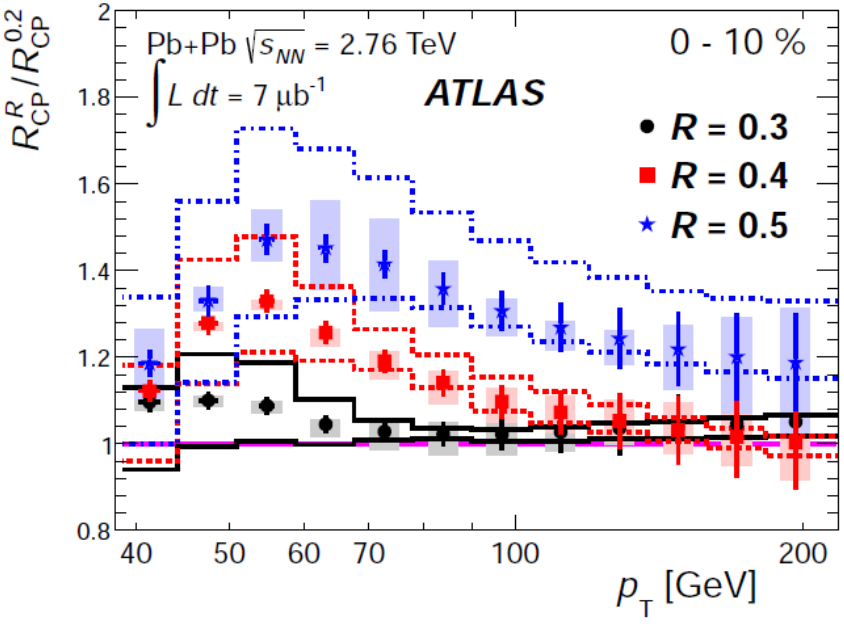
Jet R_{CP} vs p_T

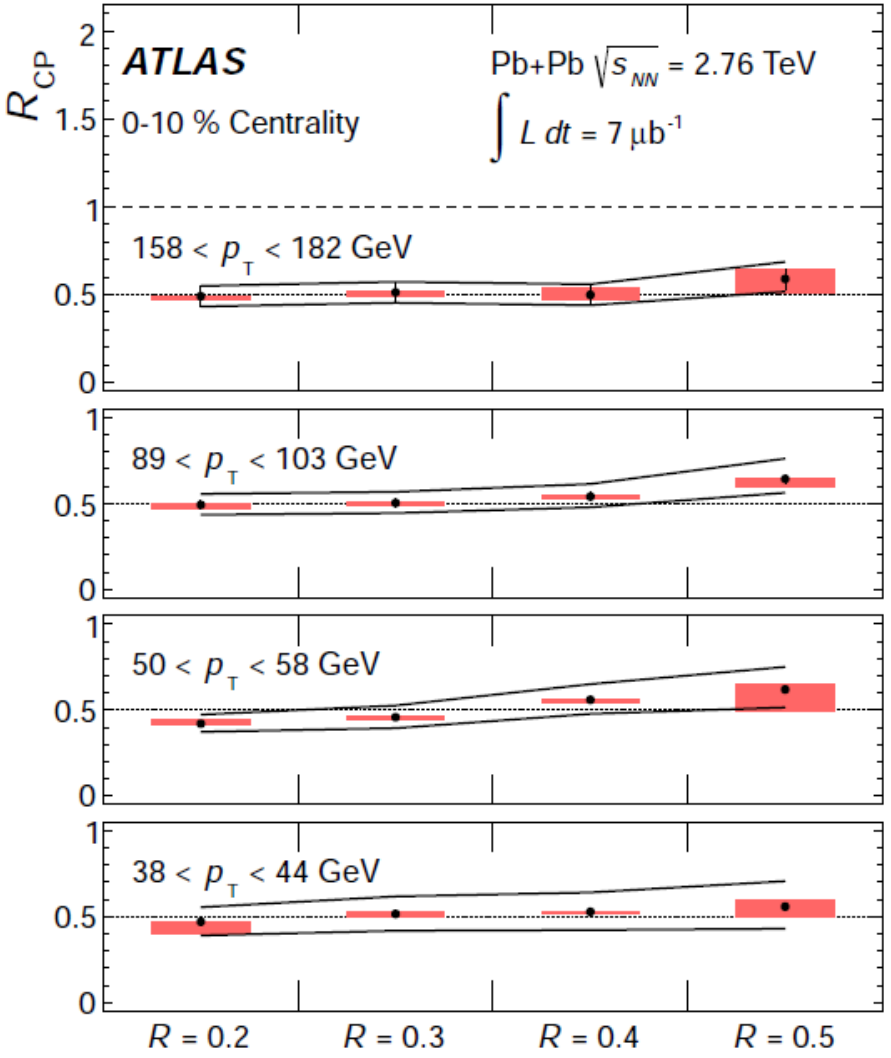


A: Suppression by a factor of 2 in central comparing to peripheral collisions. Suppression is almost independent on p_T.

Jet R_{CP} vs jet size

Q: Does the suppression depend on the jet radius?

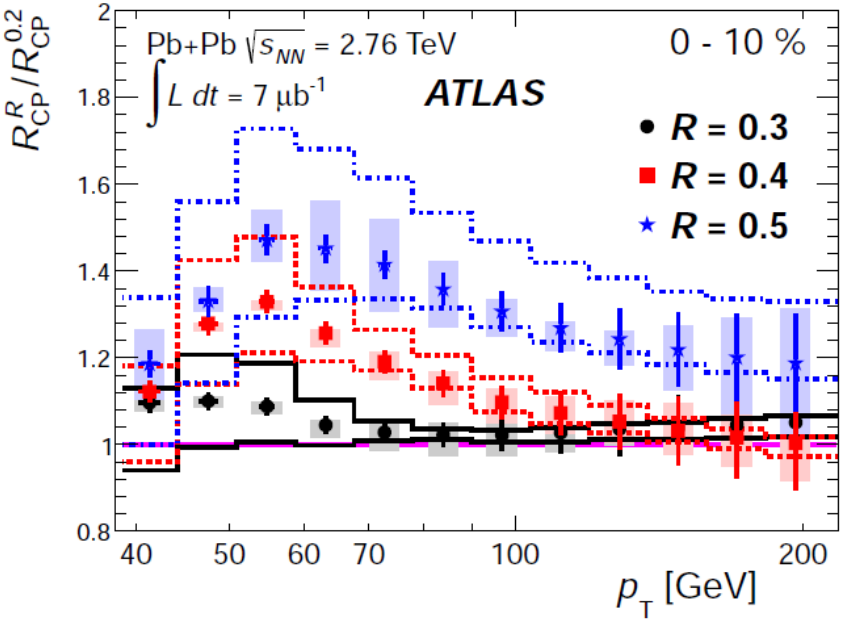


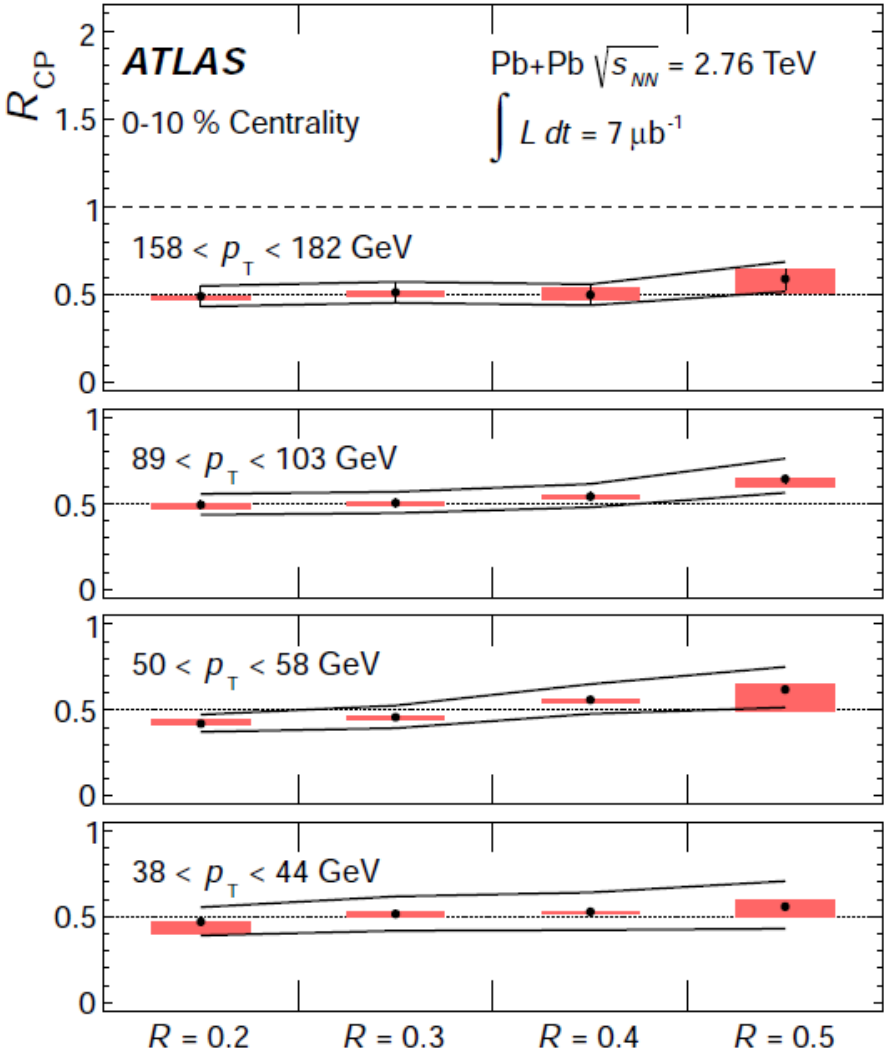


Jet R_{CP} vs jet size

A: Clear evidence for stronger suppression of smaller jets.

(Consistent with a picture of energy being recovered out of cone.)



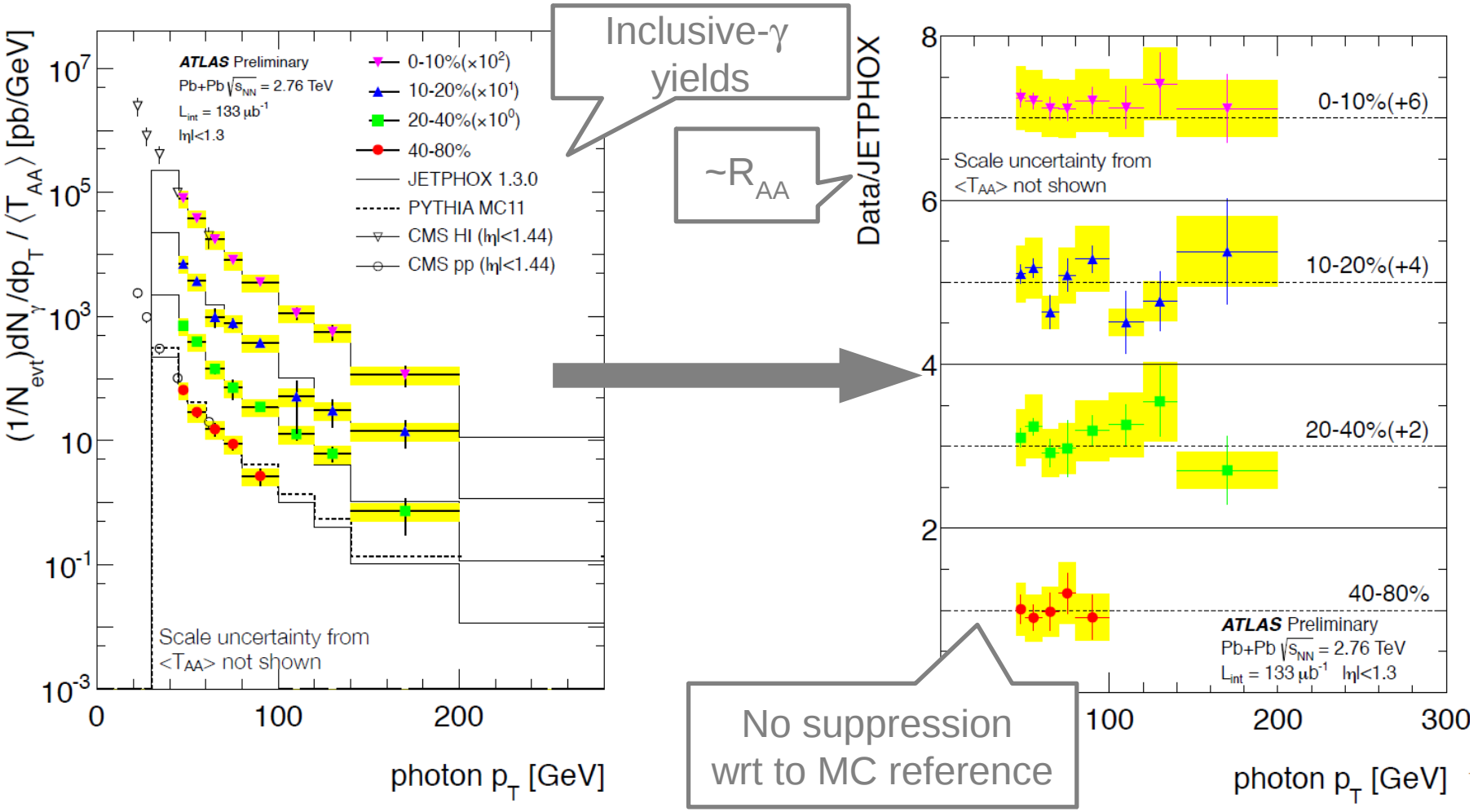


Is suppression final state effect?

Q: Can we verify that the jet suppression is really the final state effect?

Is suppression final state effect?

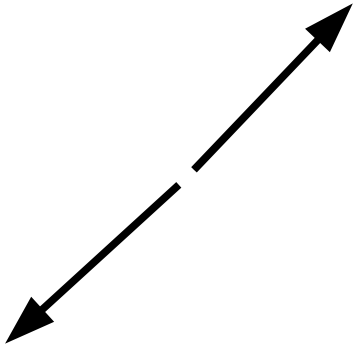
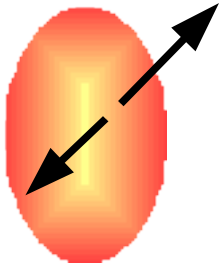
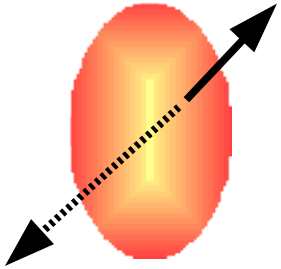
A: Yes. Yields of high-pt γ are not suppressed.



Jet suppression in other final states

Q: Can we see the jet suppression in other final states as well?

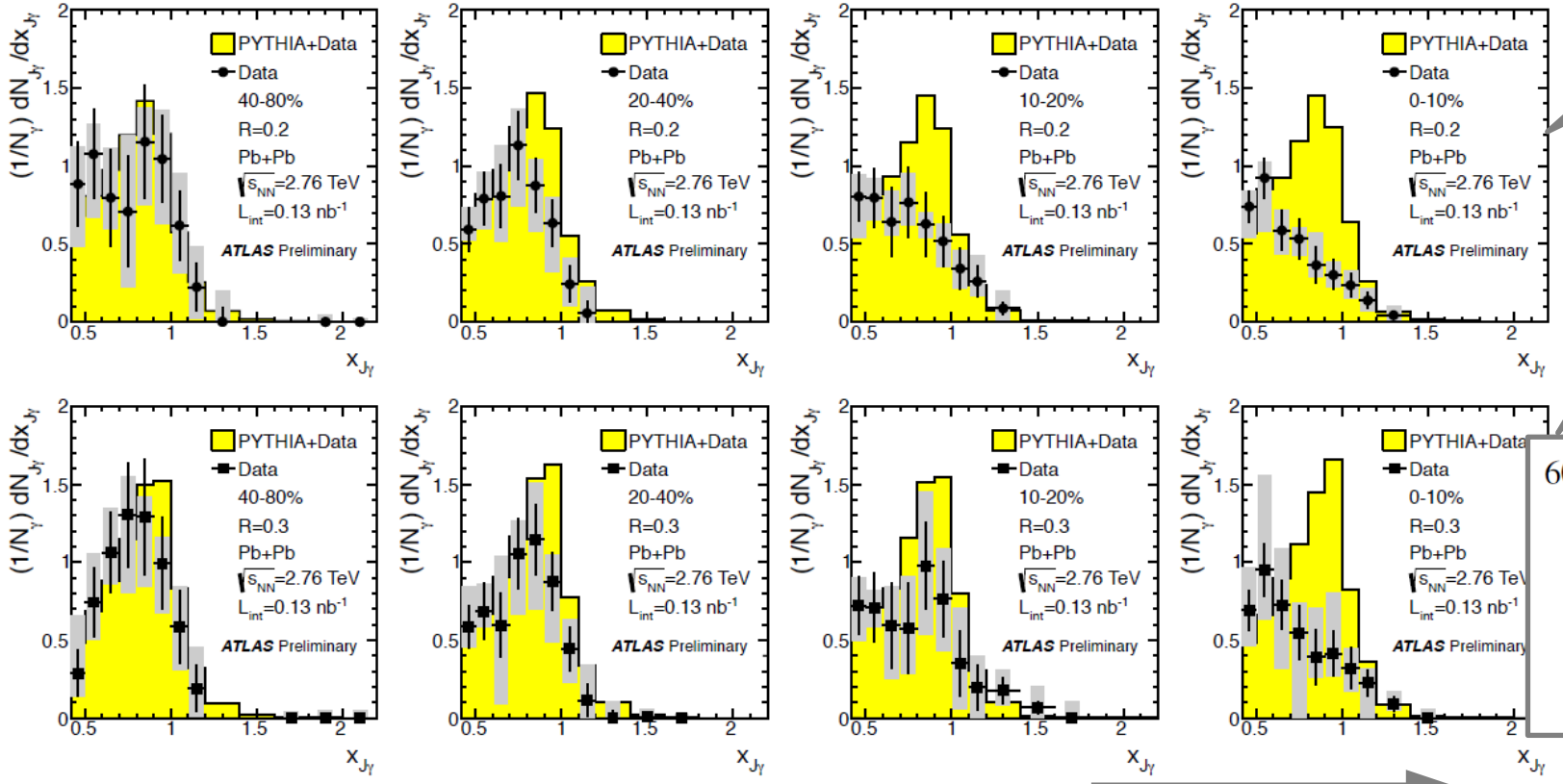
A: Yes. Measuring the jet suppression in final states with vector bosons can help us to quantify the size of the jet energy loss.

Di-jets in vacuum	Di-jets in medium	γ/Z^0-jets in medium
		
on average jets are balanced	**both jets are be modified**	**medium is transparent for EW vector bosons**

Imbalance in momentum between γ and jet can be quantified by:

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

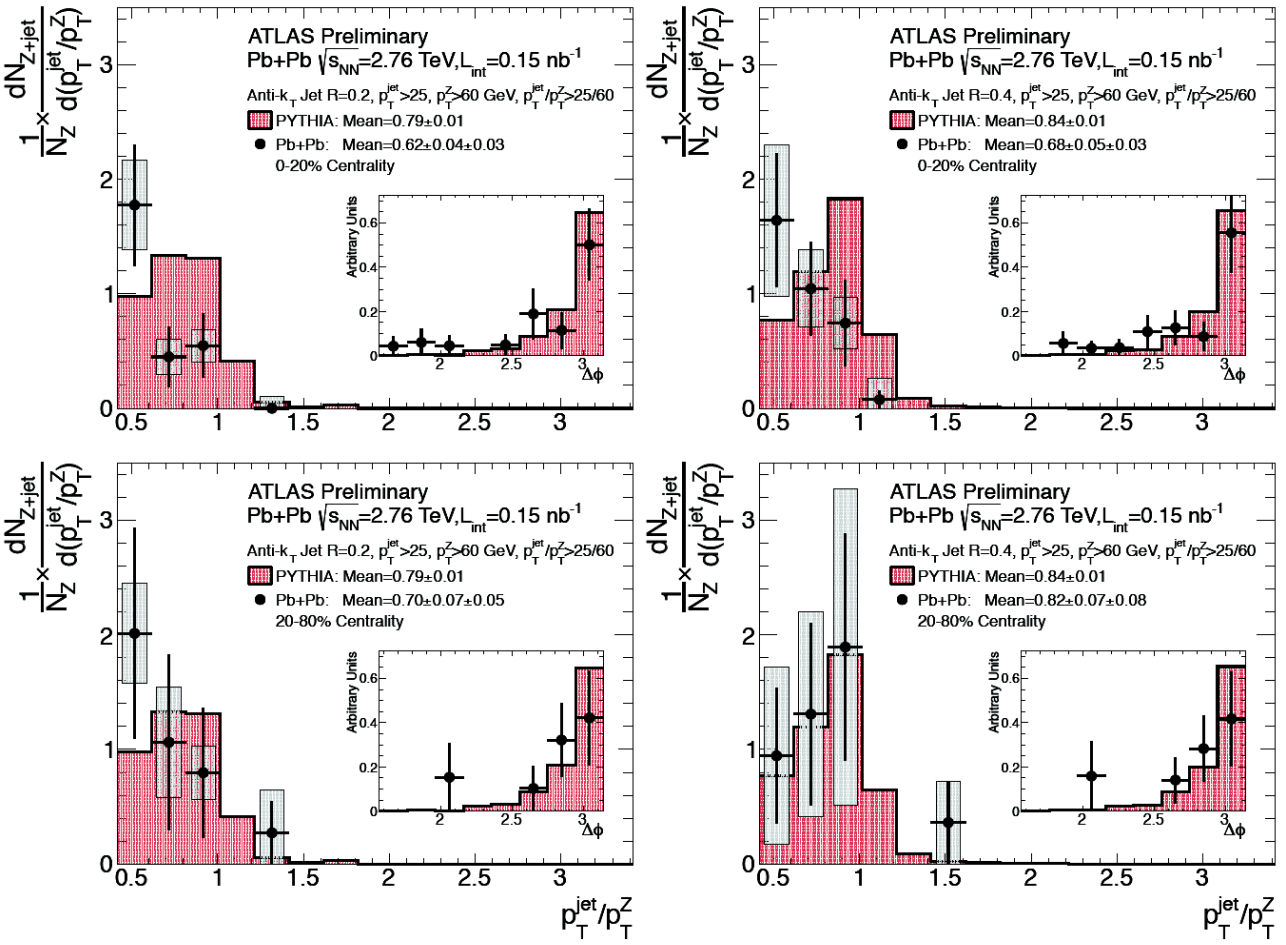
Jet suppression in other final states



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

- Per-photon normalized distributions, fully unfolded.
- Sizable suppression of jets in g-jet events seen.

Jet suppression in other final states



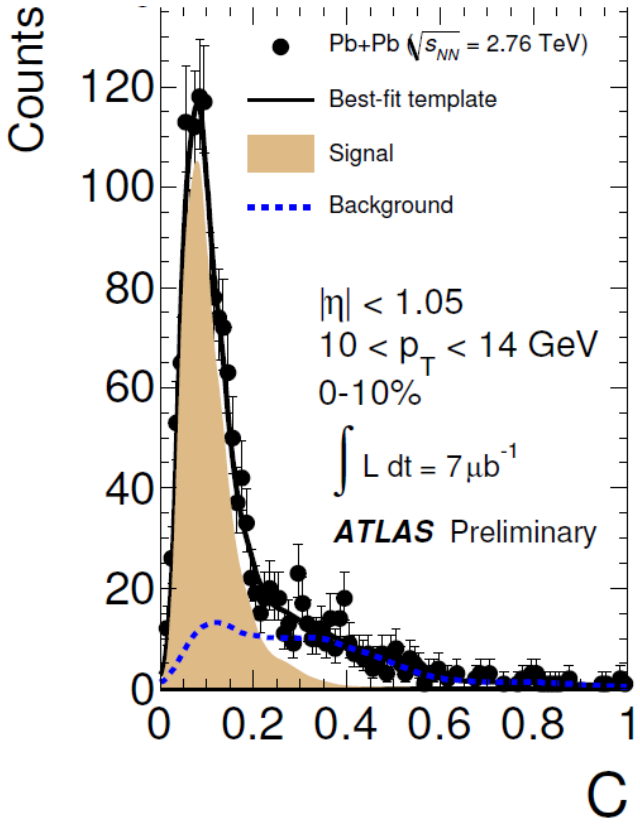
centrality

… similar behavior seen in Z^0-jet events, though the statistics is limited

Heavy flavor

Q: Does the suppression depend on the flavor?

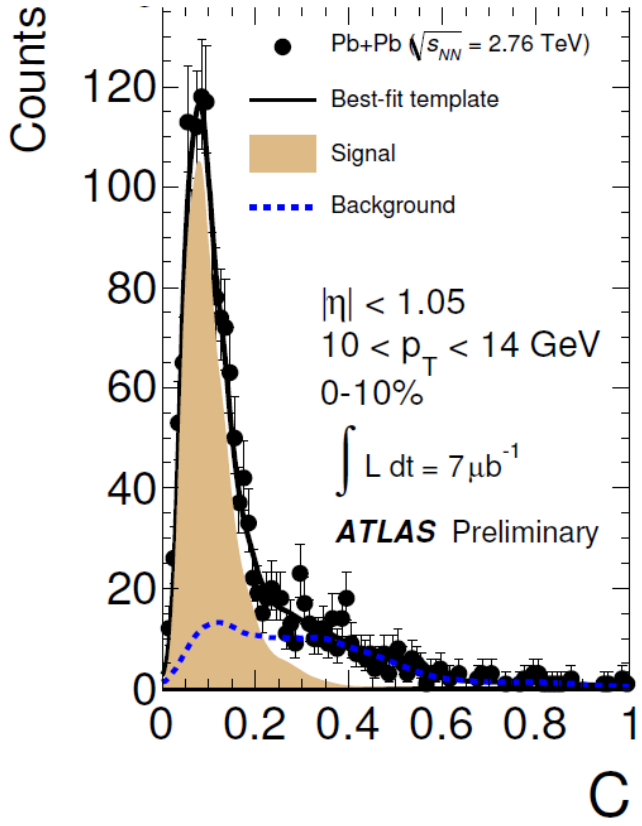
Heavy flavor

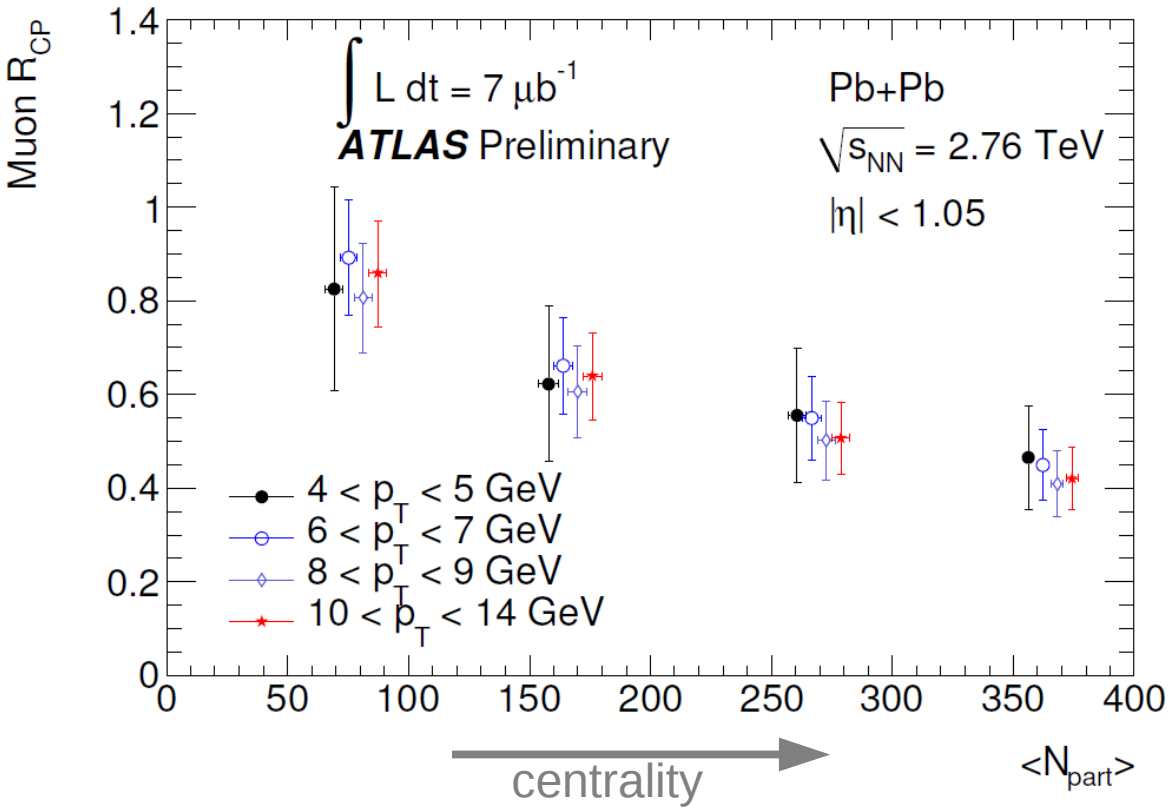


Q: Does the suppression depend on the flavor?

- Measurement of direct muons with p_T=4-14 GeV.
- Two component template fitting to separate the prompt muons from non-prompt.

Heavy flavor



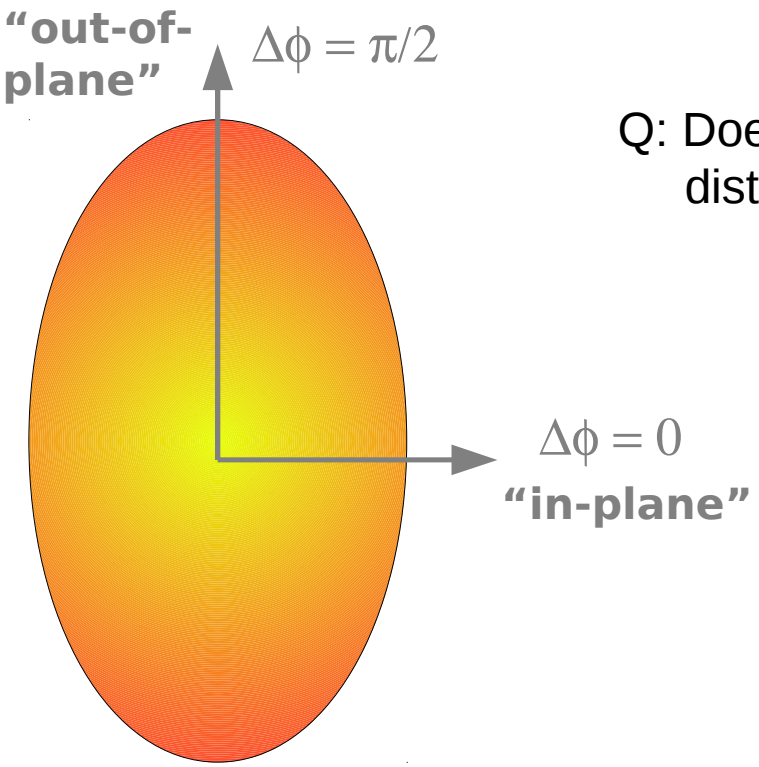


A: – R_{CP} of HF decreases smoothly from peripheral to central collisions.

– R_{CP} is p_T independent.

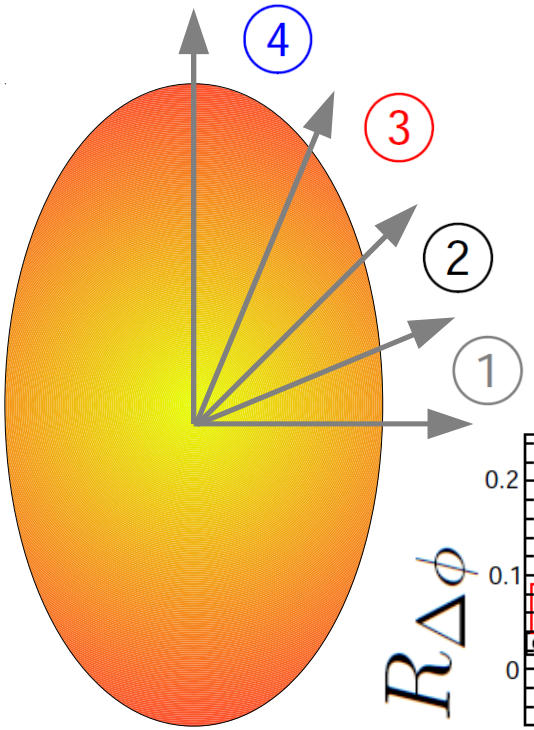
– R_{CP} in 0-10%/60-80% of 0.45 – comparable result to R_{CP} measured in jets.

Ψ dependence of jet suppression

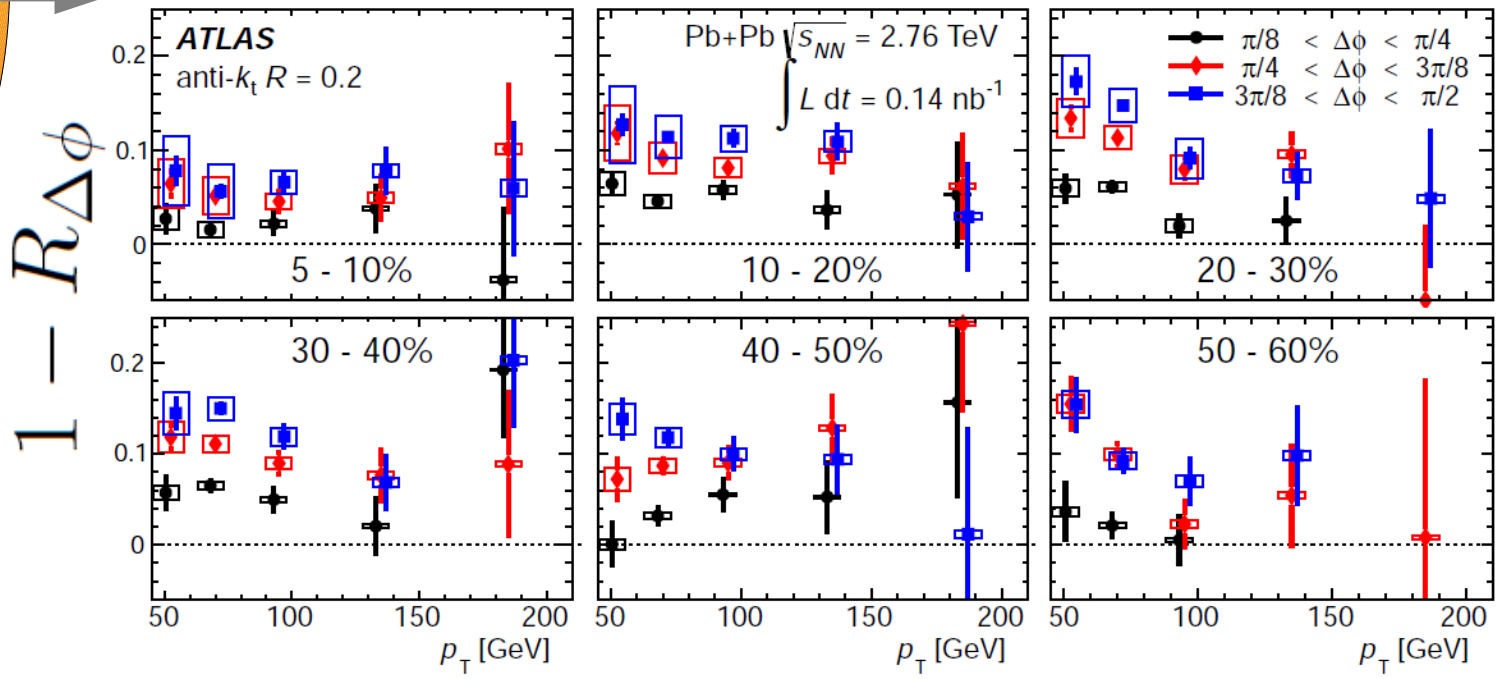


Q: Does the jet suppression depend on the azimuthal distance from the reaction plane? What is the jet v_2?

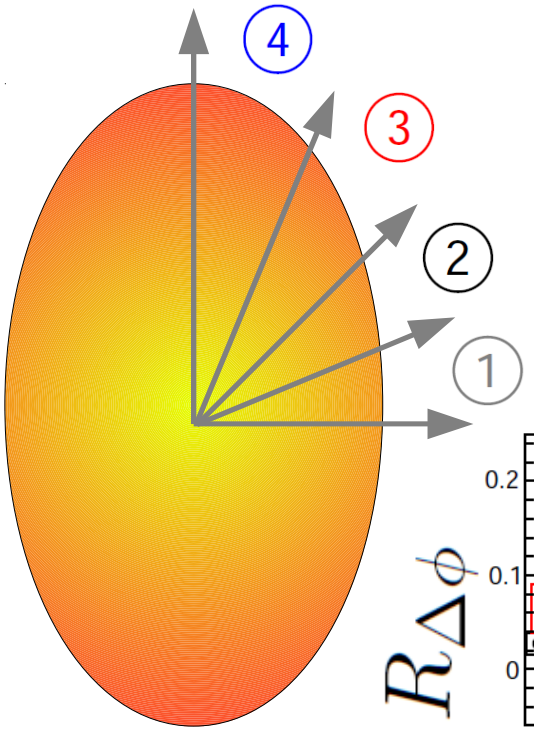
Ψ dependence of jet suppression



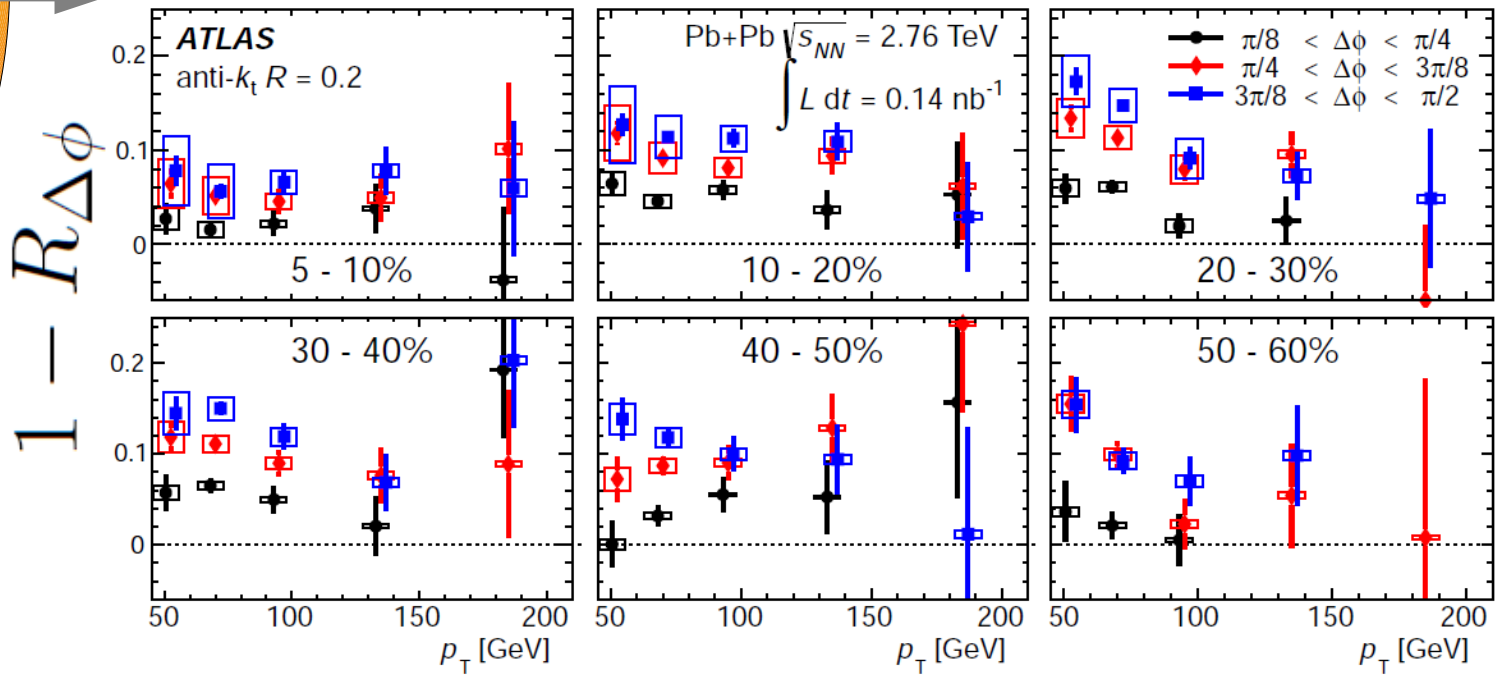
$$R_{\Delta\phi} = \frac{\left.\frac{\mathrm{d}^2 N_{\mathrm{jet}}}{\mathrm{d}p_T \mathrm{d}\Delta\phi}\right|_{\Delta\phi=2,3,4}}{\left.\frac{\mathrm{d}^2 N_{\mathrm{jet}}}{\mathrm{d}p_T \mathrm{d}\Delta\phi}\right|_{\Delta\phi=1}}$$



Ψ dependence of jet suppression



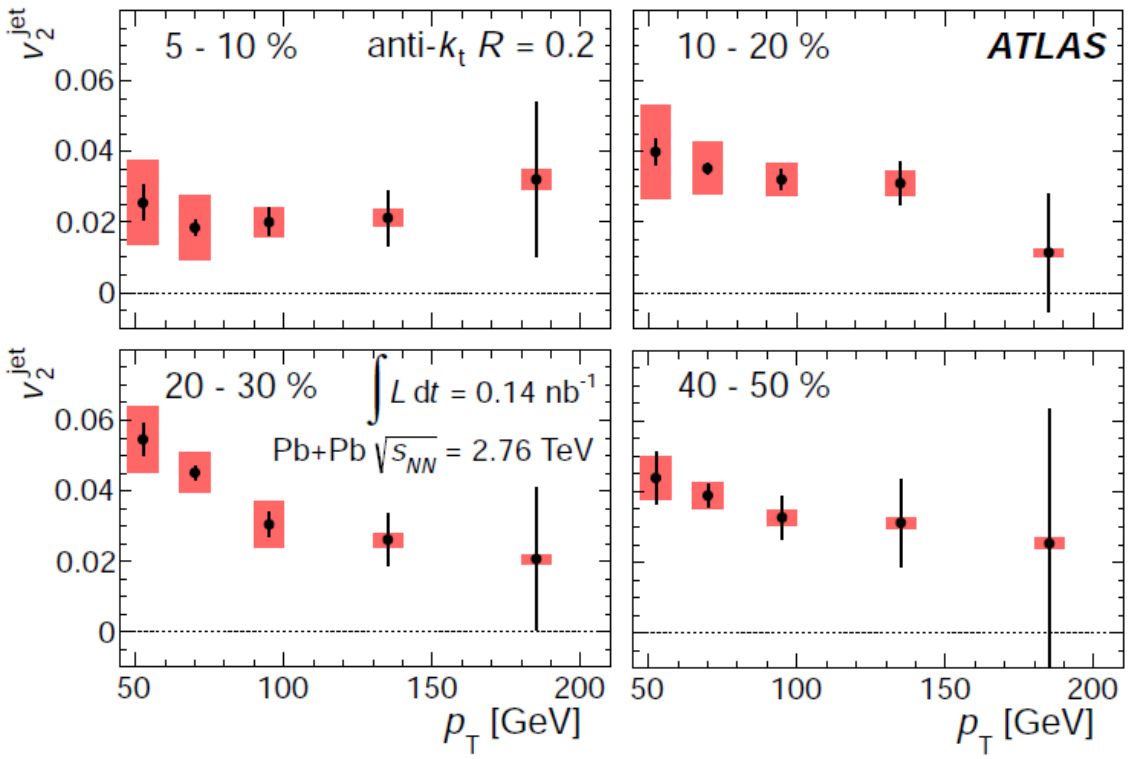
A: A suppression by as much as 15% seen for out-of-plane jets comparing to in-plane jets.

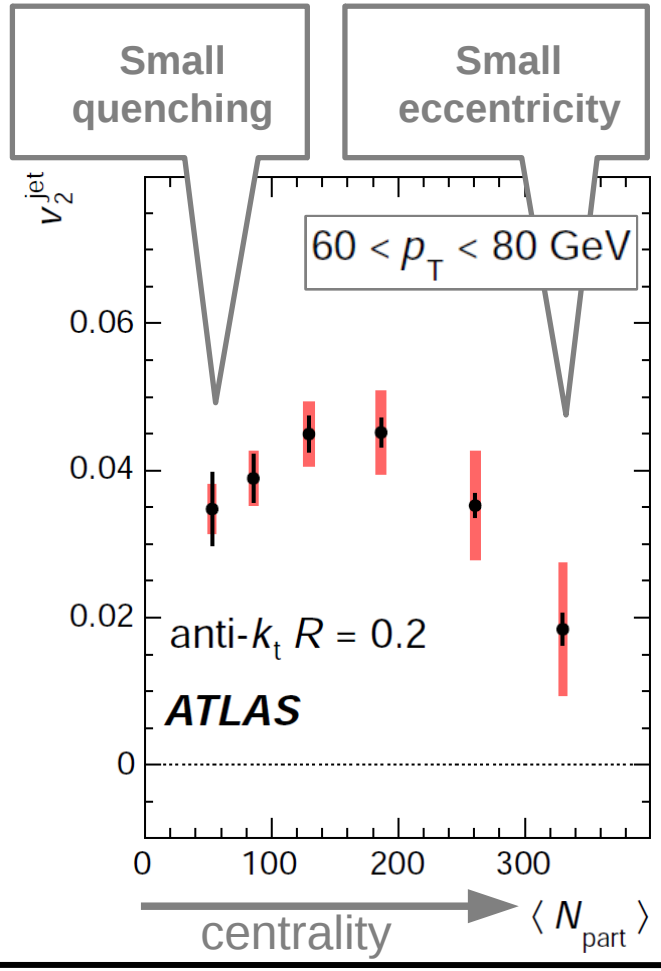


Ψ dependence of jet suppression

Q: If the suppression is different for in-plane and out-of-plane jets, what is the jet v_2?

$$\frac{dN}{d\phi} \propto 1 + 2v_2 \cos 2(\phi - \Psi_2)$$



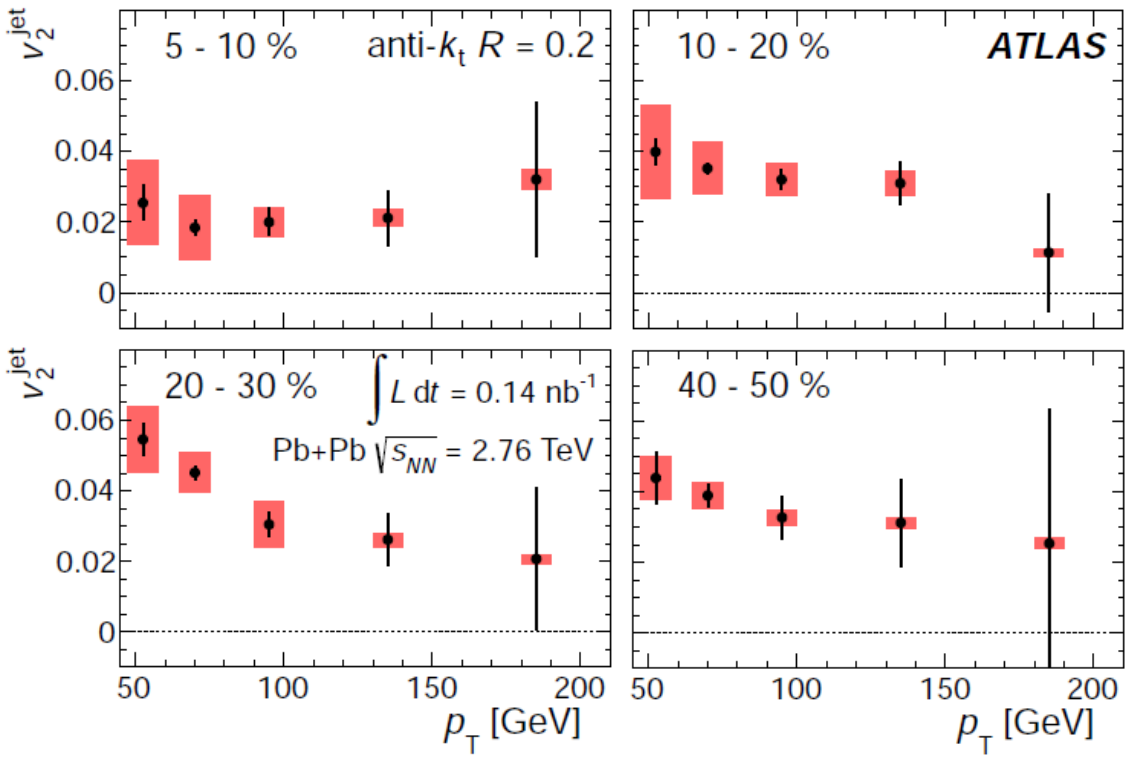


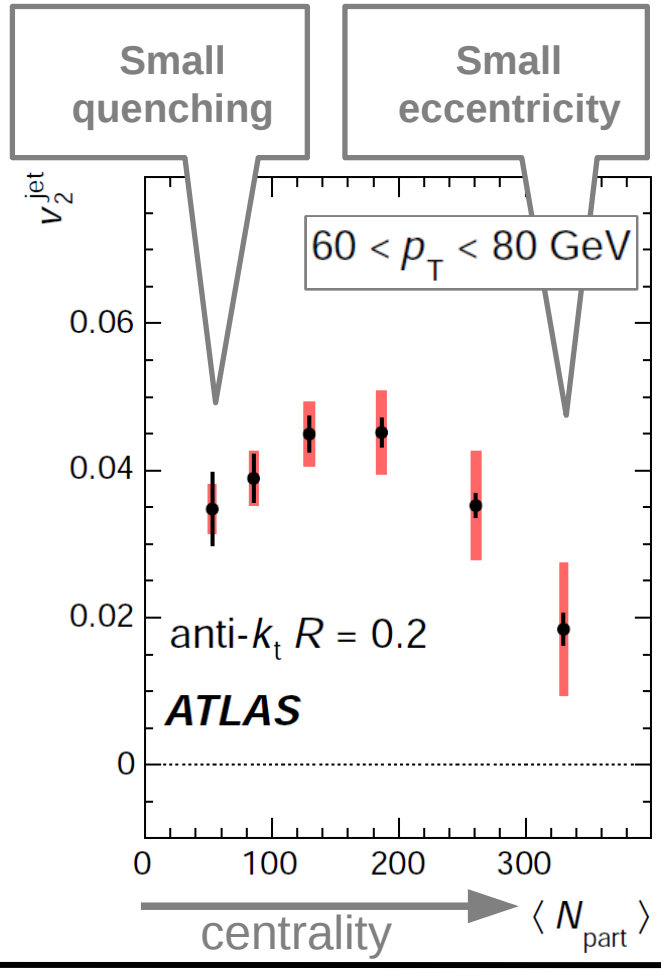
Ψ dependence of jet suppression

A: – jet v_2 of 0.02-0.04

– no jet p_T dependence observed for v_2

$$\frac{dN}{d\phi} \propto 1 + 2v_2 \cos 2(\phi - \Psi_2)$$





Jet fragmentation

$$D(p_{\mathrm{T}})(p_{\mathrm{T}}^{jet}) = \frac{1}{N_{jet}} \frac{1}{\epsilon} \frac{dN}{dp_{\mathrm{T}}} (p_{\mathrm{T}}^{jet}) =$$

Spectra of charged particles in jets

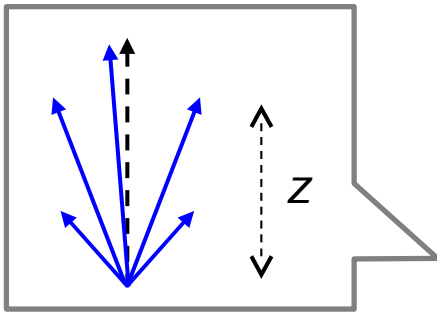
$$= \frac{1}{N_{jet}(p_{\mathrm{T}}^{jet})} \frac{1}{\epsilon(p_{\mathrm{T}}, \eta)} \left(\frac{\Delta N_{ch}(p_{\mathrm{T}}, p_{\mathrm{T}}^{jet})}{\Delta p_{\mathrm{T}}} - \frac{\Delta N_{ch}^{UE}(p_{\mathrm{T}}, p_{\mathrm{T}}^{jet})}{\Delta p_{\mathrm{T}}} \right)$$

Tracking efficiency corrected

Underlying event subtracted

"Fragmentation function"

$$D(z)(p_{\mathrm{T}}^{jet}) = \frac{1}{N_{jet}} \frac{1}{\epsilon} \frac{dN}{dz} (p_{\mathrm{T}}^{jet}) =$$



$$= \frac{1}{N_{jet}(p_{\mathrm{T}}^{jet})} \frac{1}{\epsilon(p_{\mathrm{T}}, \eta)} \left(\frac{\Delta N_{ch}(z, p_{\mathrm{T}}^{jet})}{\Delta z} - \frac{\Delta N_{ch}^{UE}(z, p_{\mathrm{T}}^{jet})}{\Delta z} \right)$$

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

Jet fragmentation

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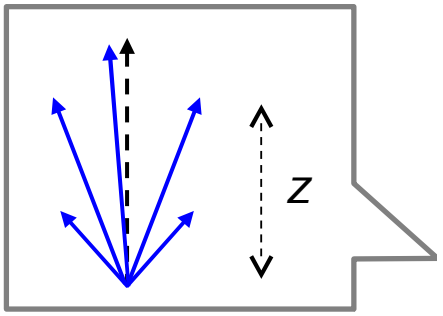

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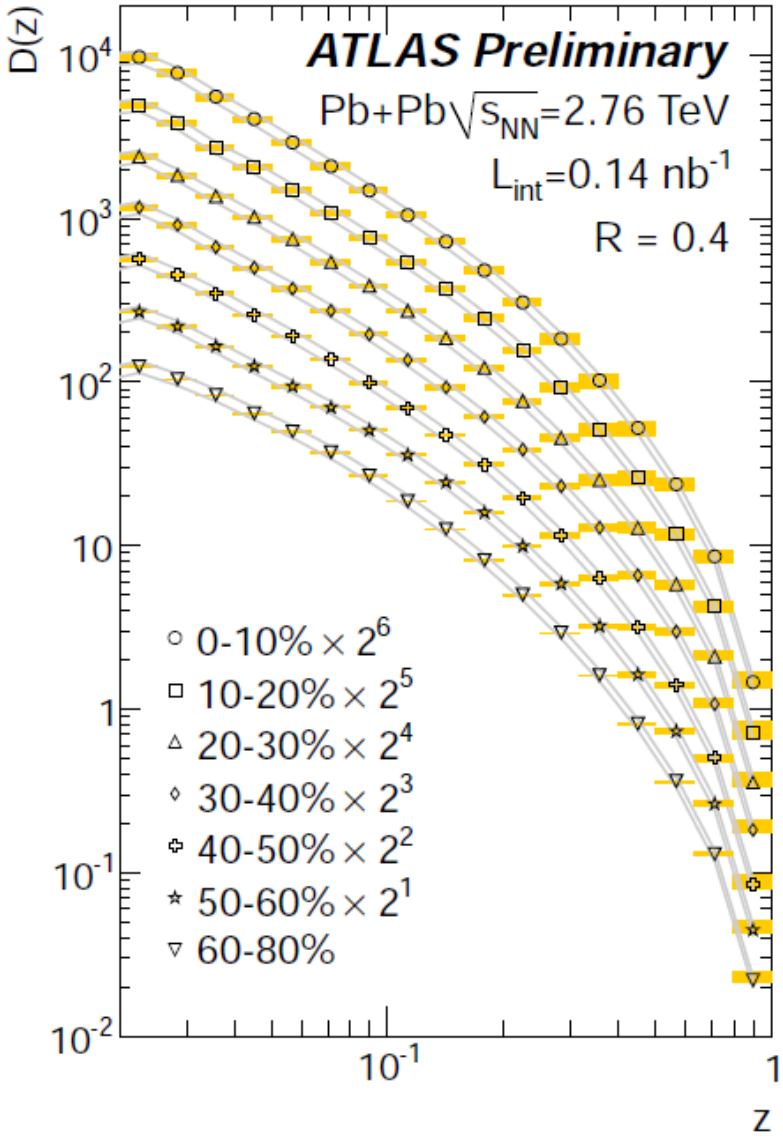
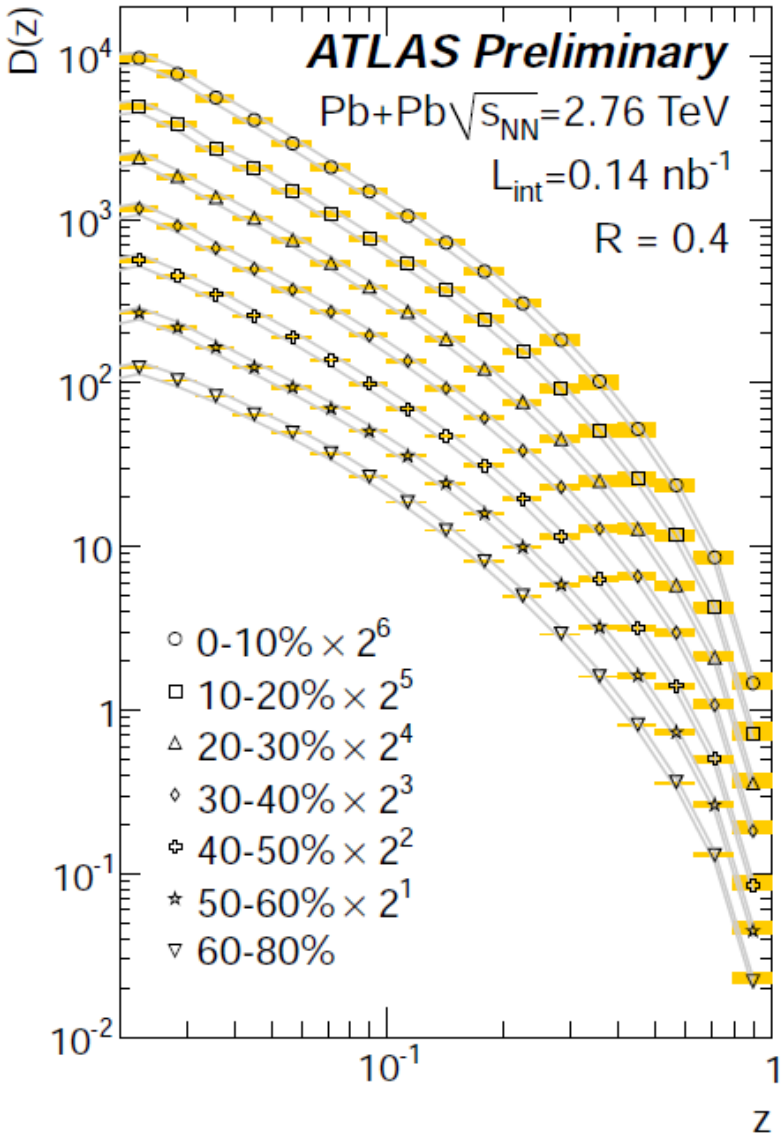
Q: Is the jet structure modified?

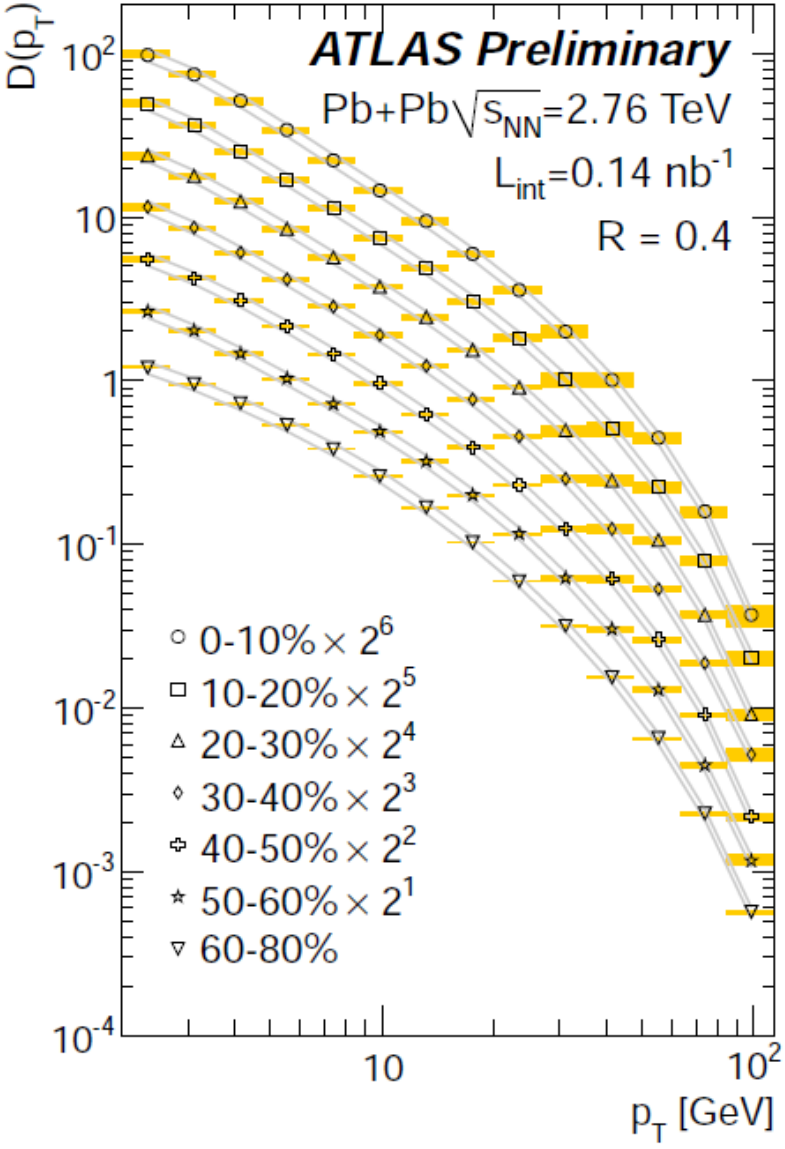
Jet fragmentation



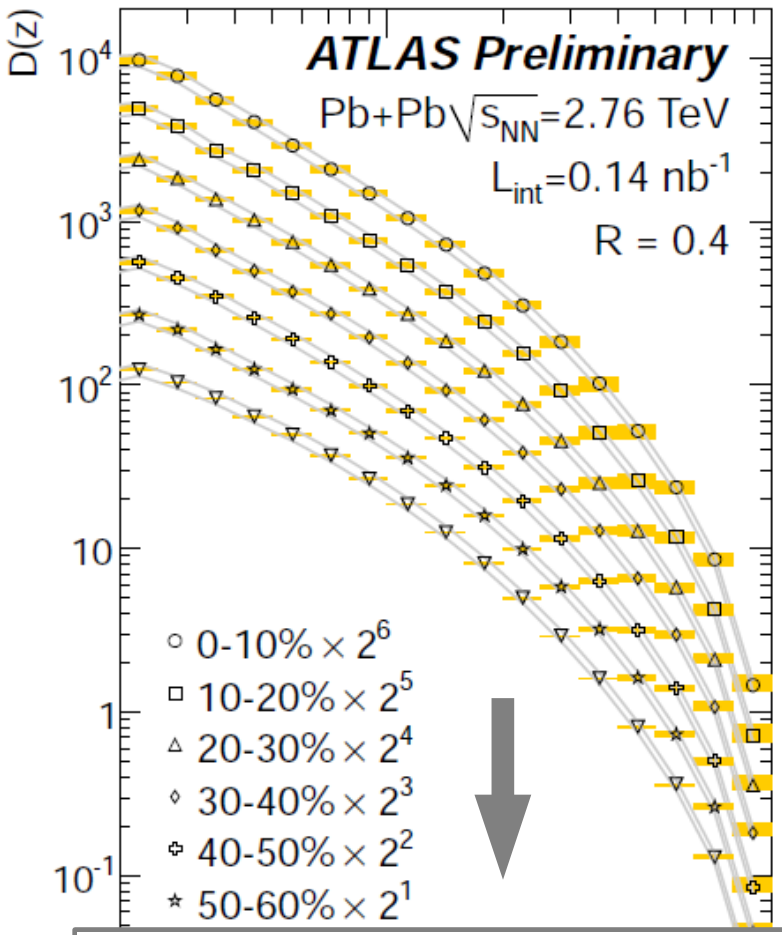
- Result unfolded using SVD unfolding to remove detector effects (e.g. jet energy resolution, tracking momentum resolution).
- Systematic uncertainties:
  - gray band: fully bin-wise correlated (tracking efficiency)
  - yellow boxes: partially correlated (jet energy scale and resolution, tracking efficiency, choice of regularization parameter in unfolding, parametrization of truth distributions, ...)
- Statistical error by error bars.

Jet fragmentation

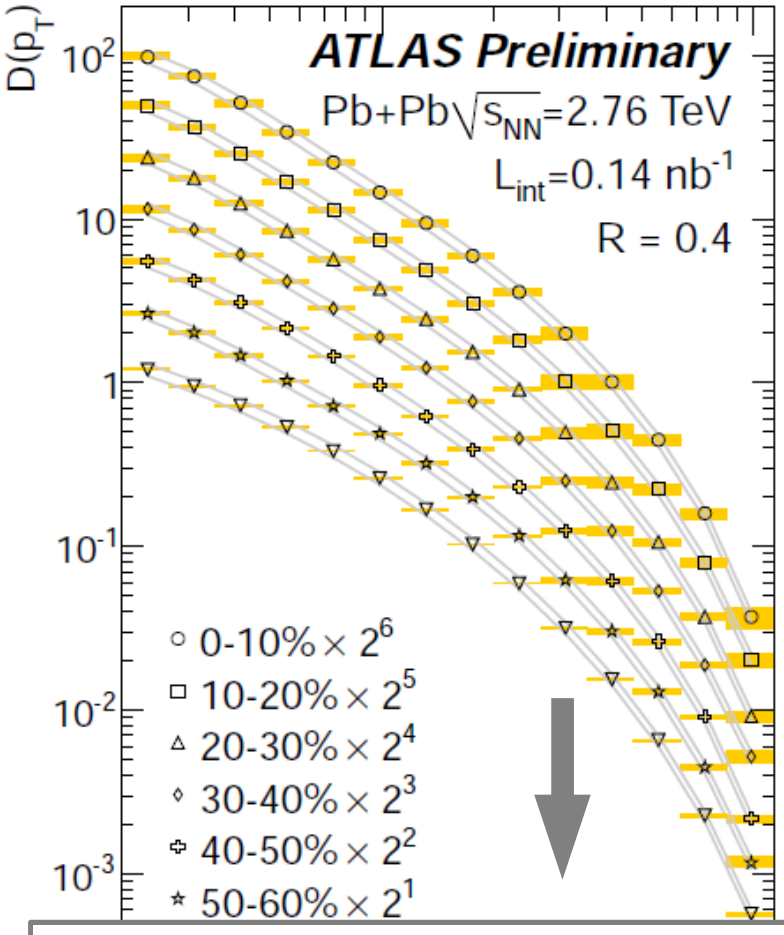




Jet fragmentation



$$R_{\mathrm{D(z)}} = \frac{\mathrm{D}(z)|_{\mathrm{cent}}}{\mathrm{D}(z)|_{60-80\%}}$$



$$R_{\mathrm{D(p_T)}} = \frac{\mathrm{D}(p_T)|_{\mathrm{cent}}}{\mathrm{D}(p_T)|_{60-80\%}}$$

Jet fragmentation

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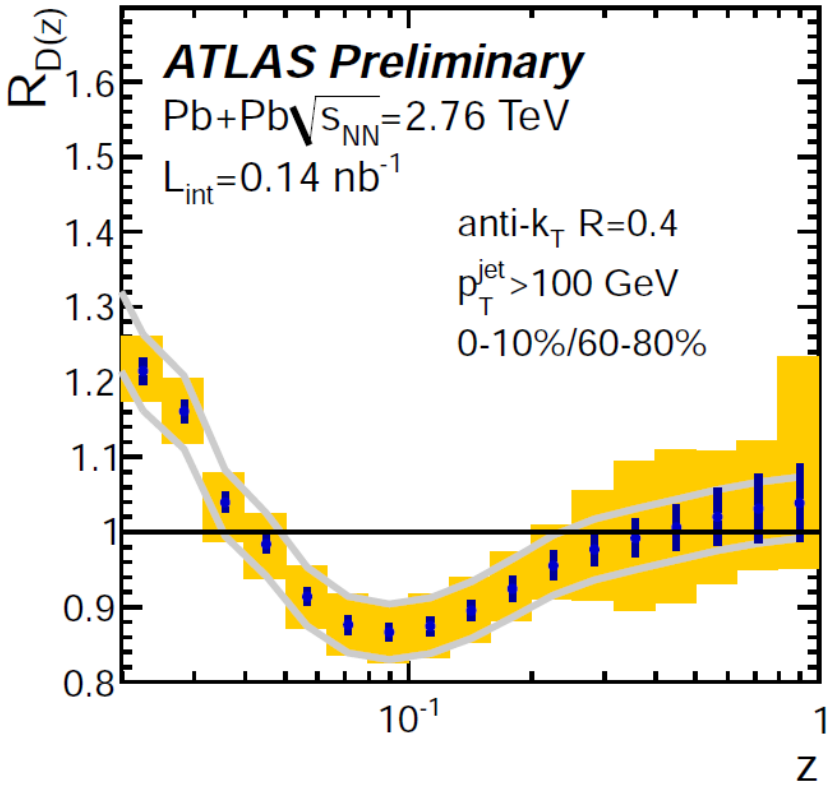
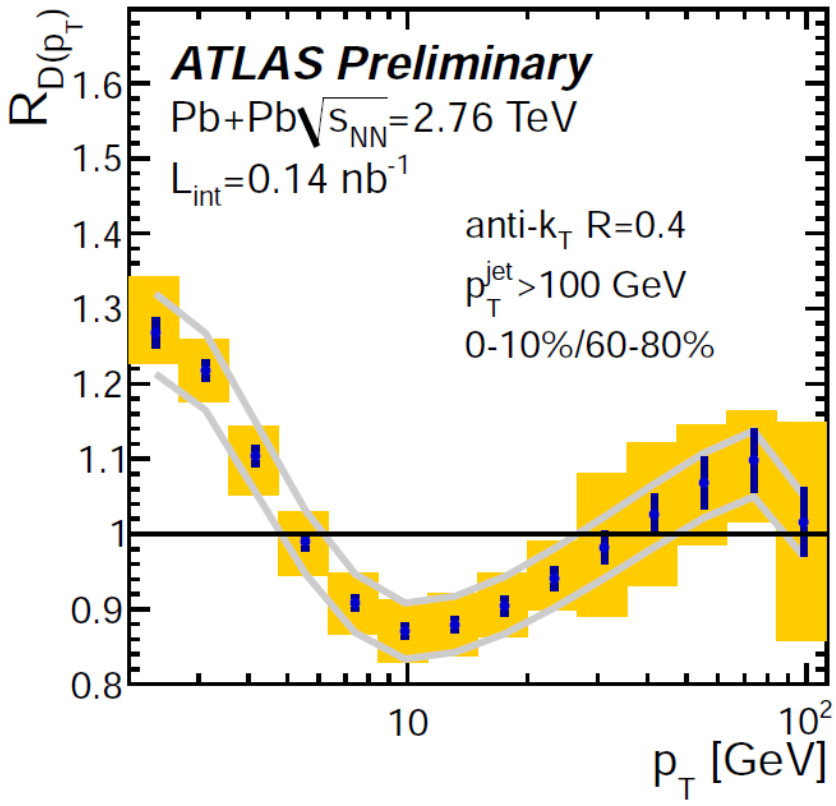
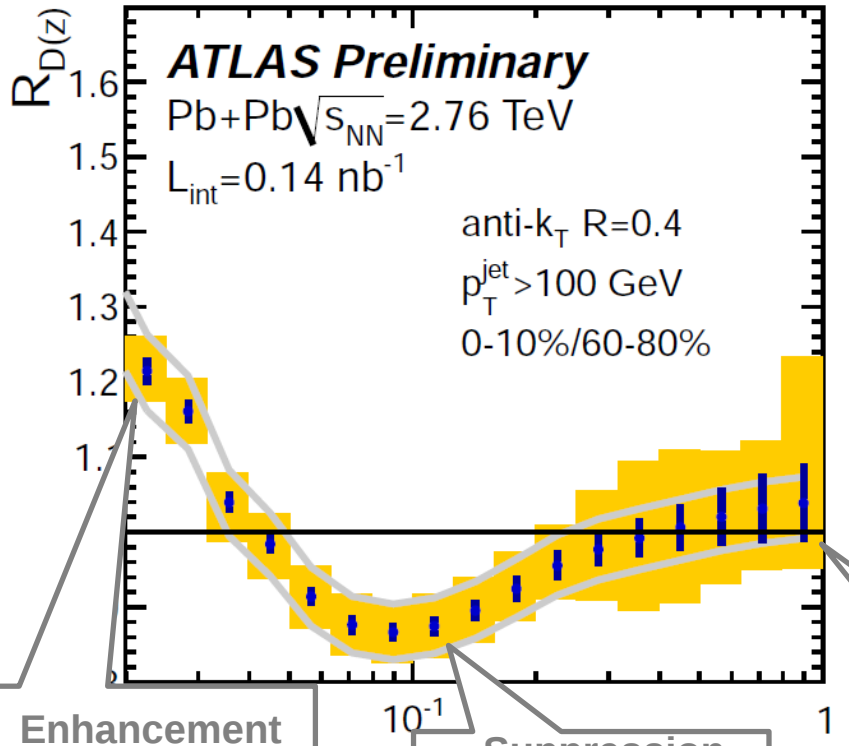


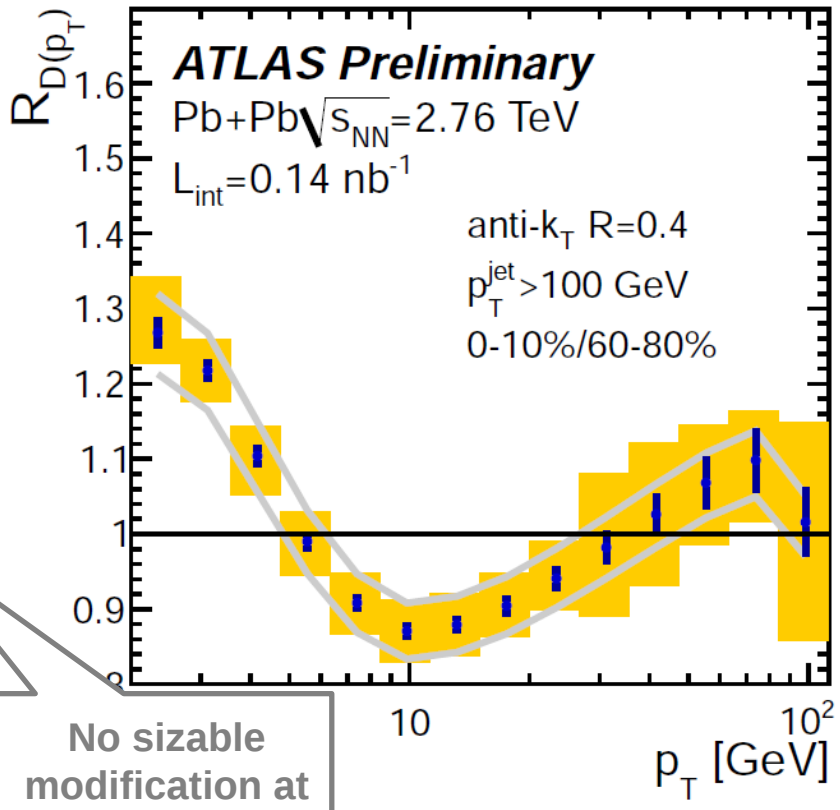


Jet fragmentation

$$R_{\mathrm{D(z)}} = \frac{\mathrm{D}(z)|_{\mathrm{cent}}}{\mathrm{D}(z)|_{60-80\%}}$$

$$R_{\mathrm{D(p_T)}} = \frac{\mathrm{D}(p_T)|_{\mathrm{cent}}}{\mathrm{D}(p_T)|_{60-80\%}}$$



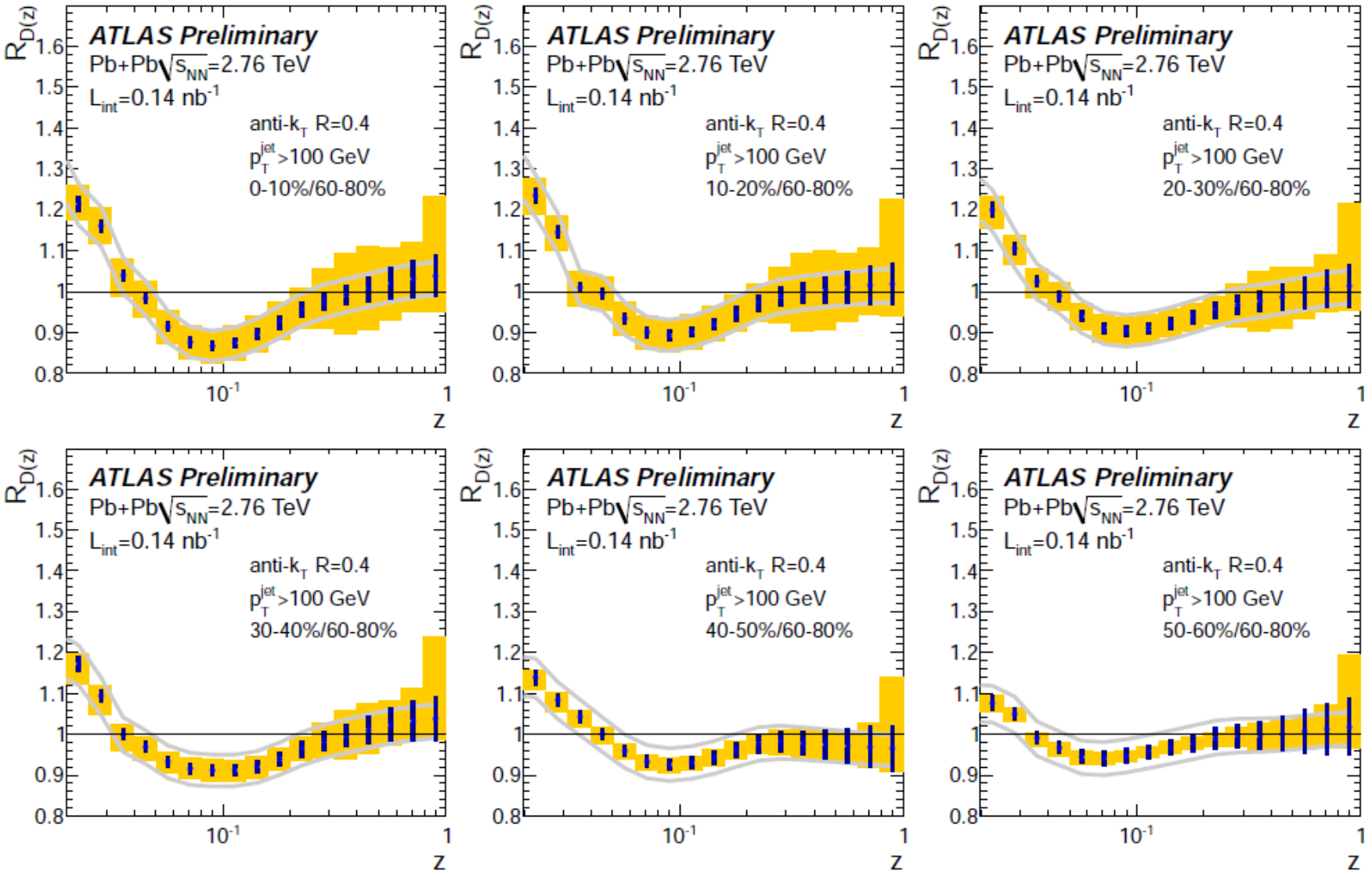


Enhancement at low-z (or low- p_T)

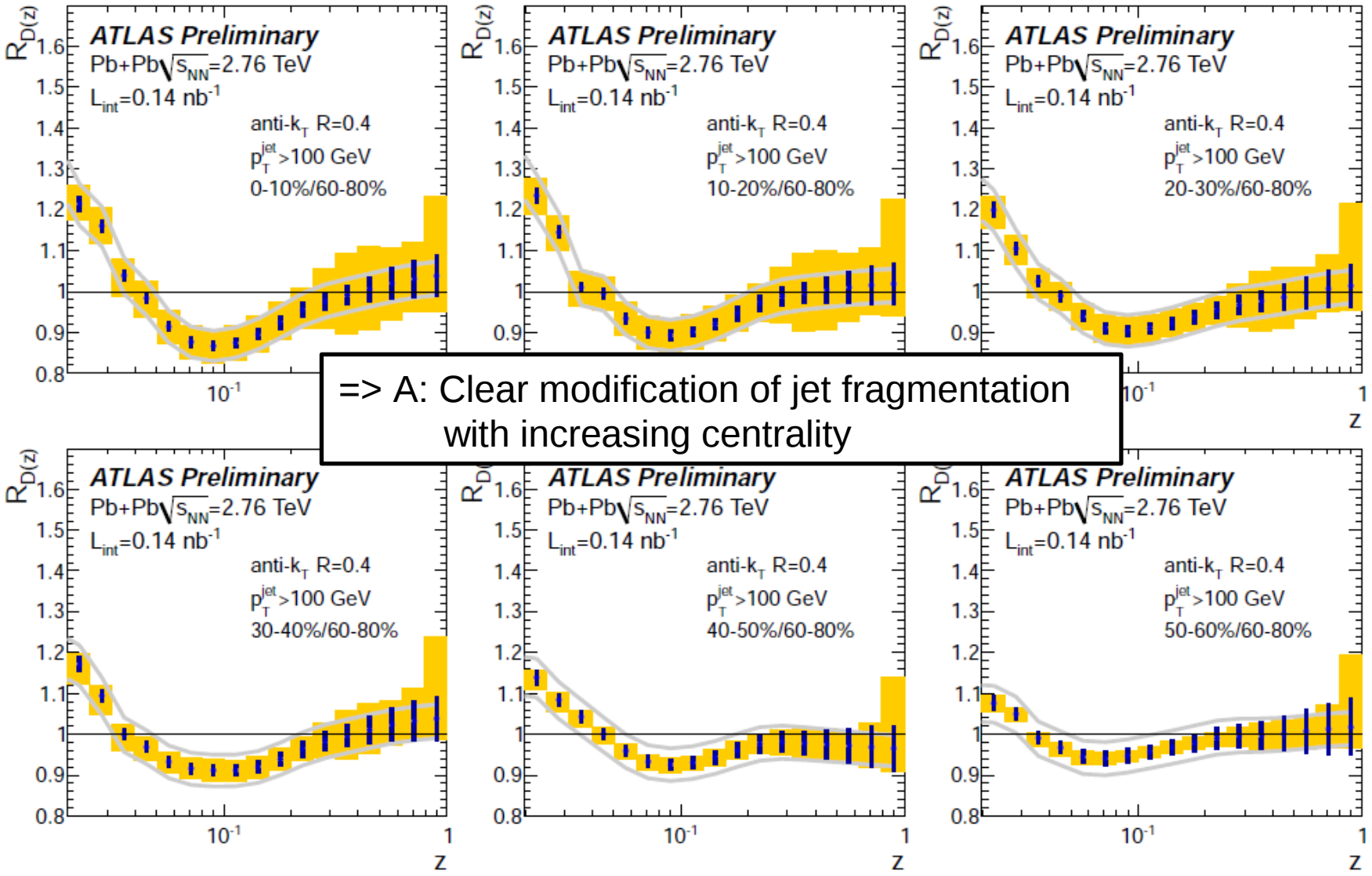
Suppression at intermediate-z (or p_T)

No sizable modification at high-z (or p_T)

Jet fragmentation



Jet fragmentation



=> A: Clear modification of jet fragmentation with increasing centrality

Conclusions

- No modification of high-pt photons and electroweak vector bosons.
- Suppression of inclusive jet yields by a factor of two in central compared to peripheral collisions.
- Suppression of jets in γ-jet events.
- Indirect measurement of suppression of b-jets consistent with the measurement of the suppression of inclusive jets.
- Suppression of ~15% of jets oriented out-of-plane comparing to jets oriented in plane.
- Enhancement of particles in jets at low-p_T, suppression of particles at intermediate p_T, no sizable modification of particles in jets at high-p_T.
- … many more to come

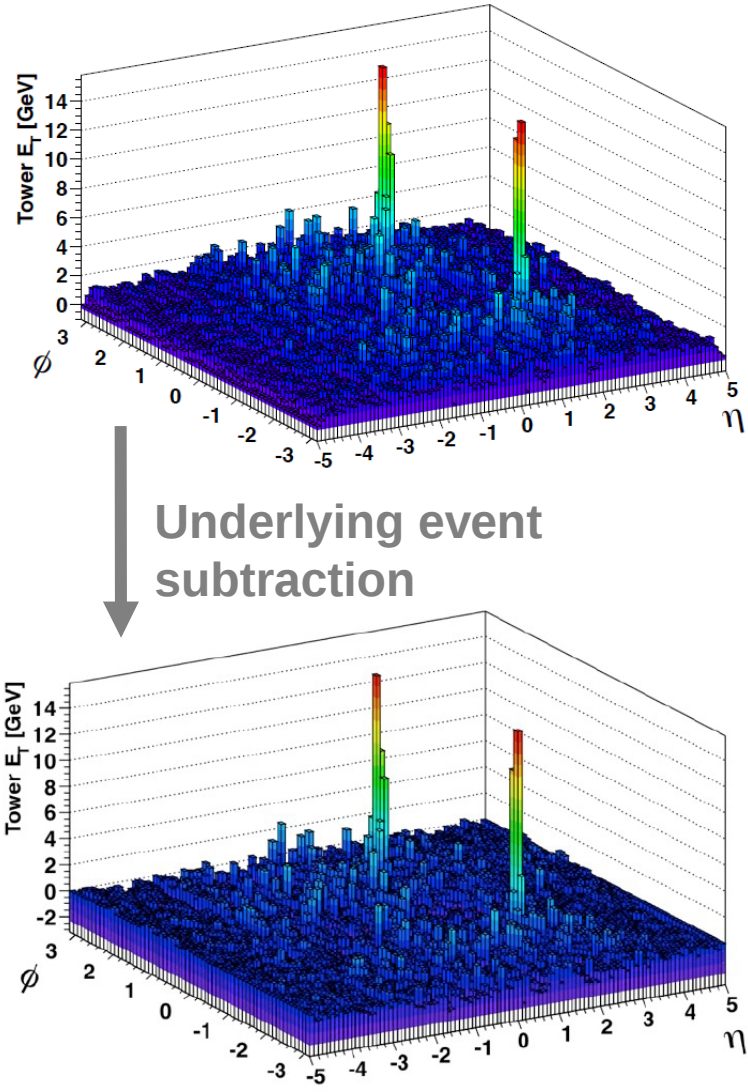
Additional Information

Jet reconstruction

- Jets reconstructed using anti-k_T algorithm with different distance parameters R=0.2-0.5.
- The underlying event contribution ("background") subtracted from jets on an event-by-event basis.

$$E_{T,j}^{\mathrm{sub}} = E_{T,j} - A_j \rho_j(\eta_j)(1 + 2v_{2,i}\cos[2(\phi_j - \Psi_2)])$$

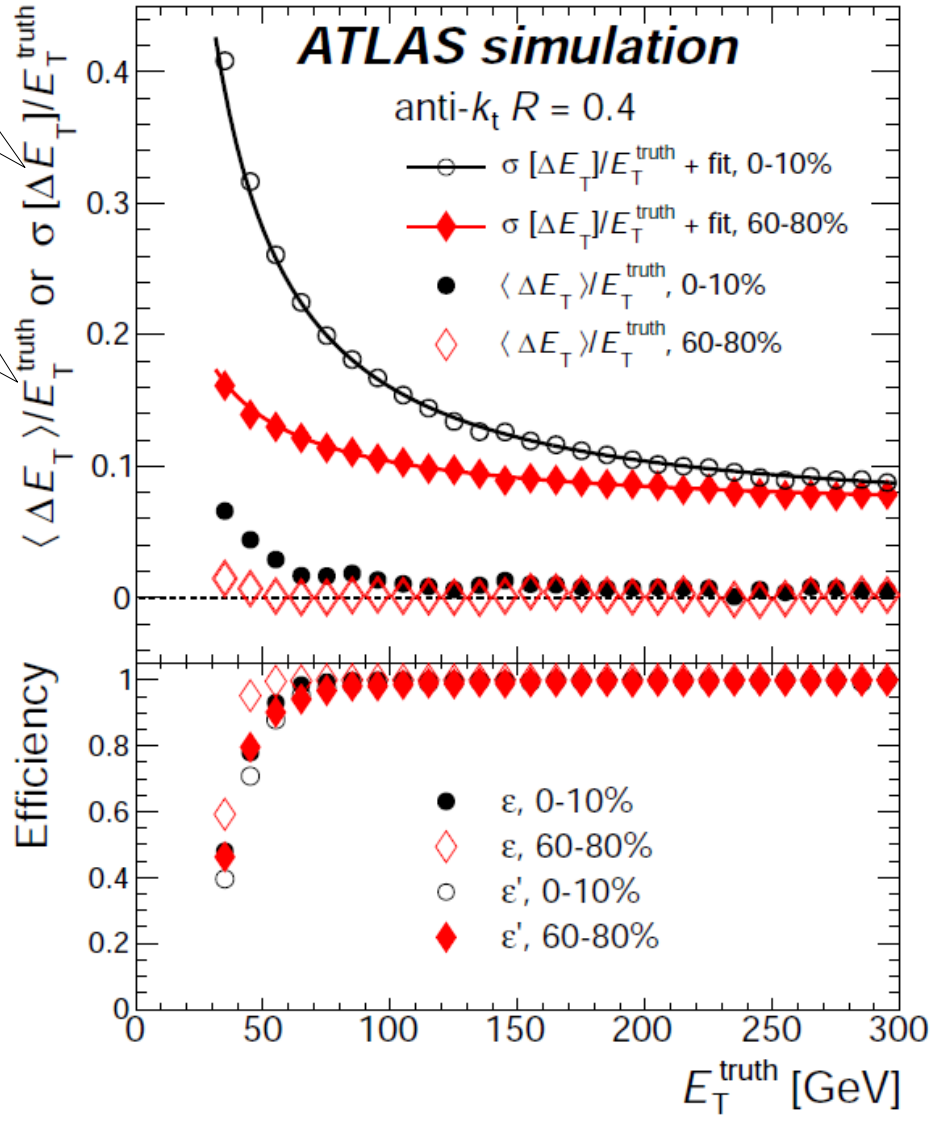
- Jets are corrected for the elliptic flow contribution.
- The subtraction is done in two iterations to avoid a bias of the background estimate by the presence of jets.



Performance

Jet energy resolution

Jet energy scale

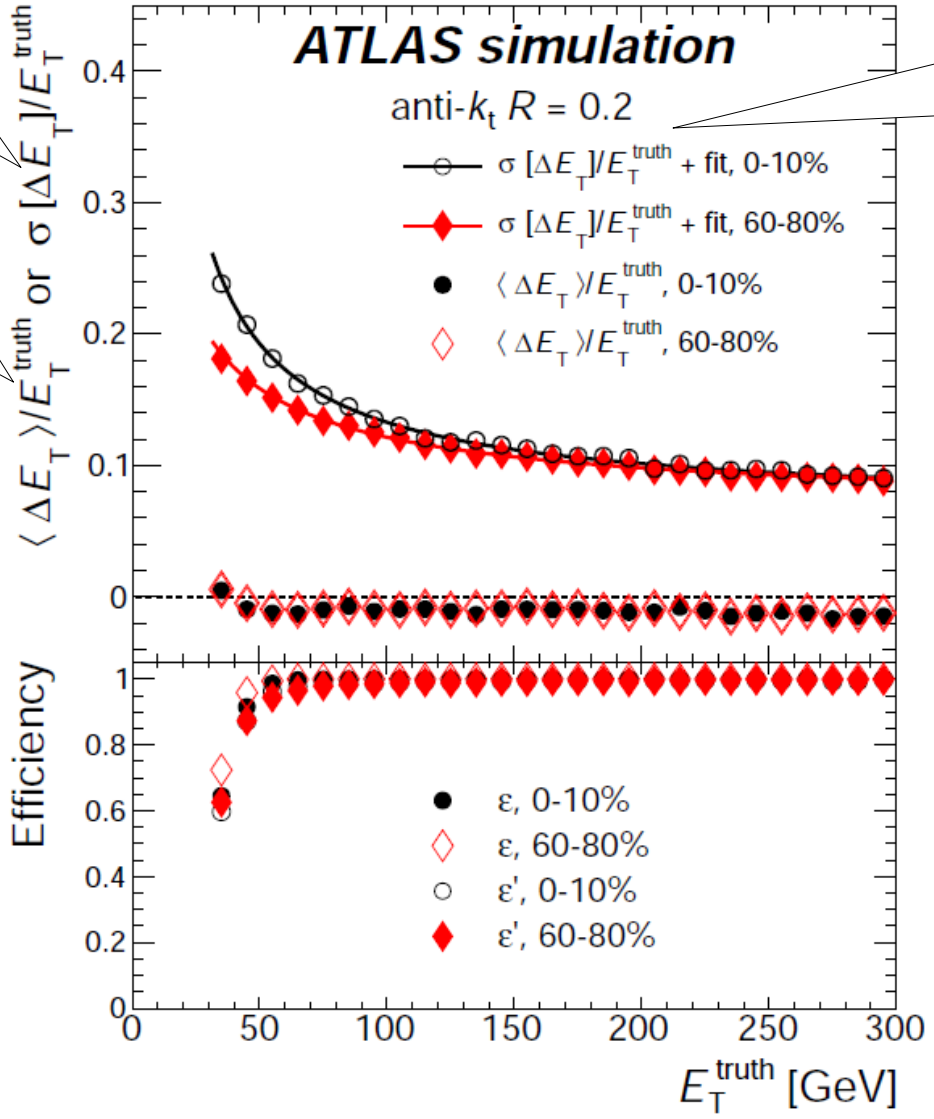


- Detailed evaluation of the performance.
- Data-driven checks of jet energy resolution using the evaluation of fluctuations in minimum bias event and HIJING.
- Data-driven check of jet energy scale using jets reconstructed from tracks (“track jets”).
- Fake rejection using track jets or electromagnetic clusters.

Performance

Jet energy resolution

Jet energy scale

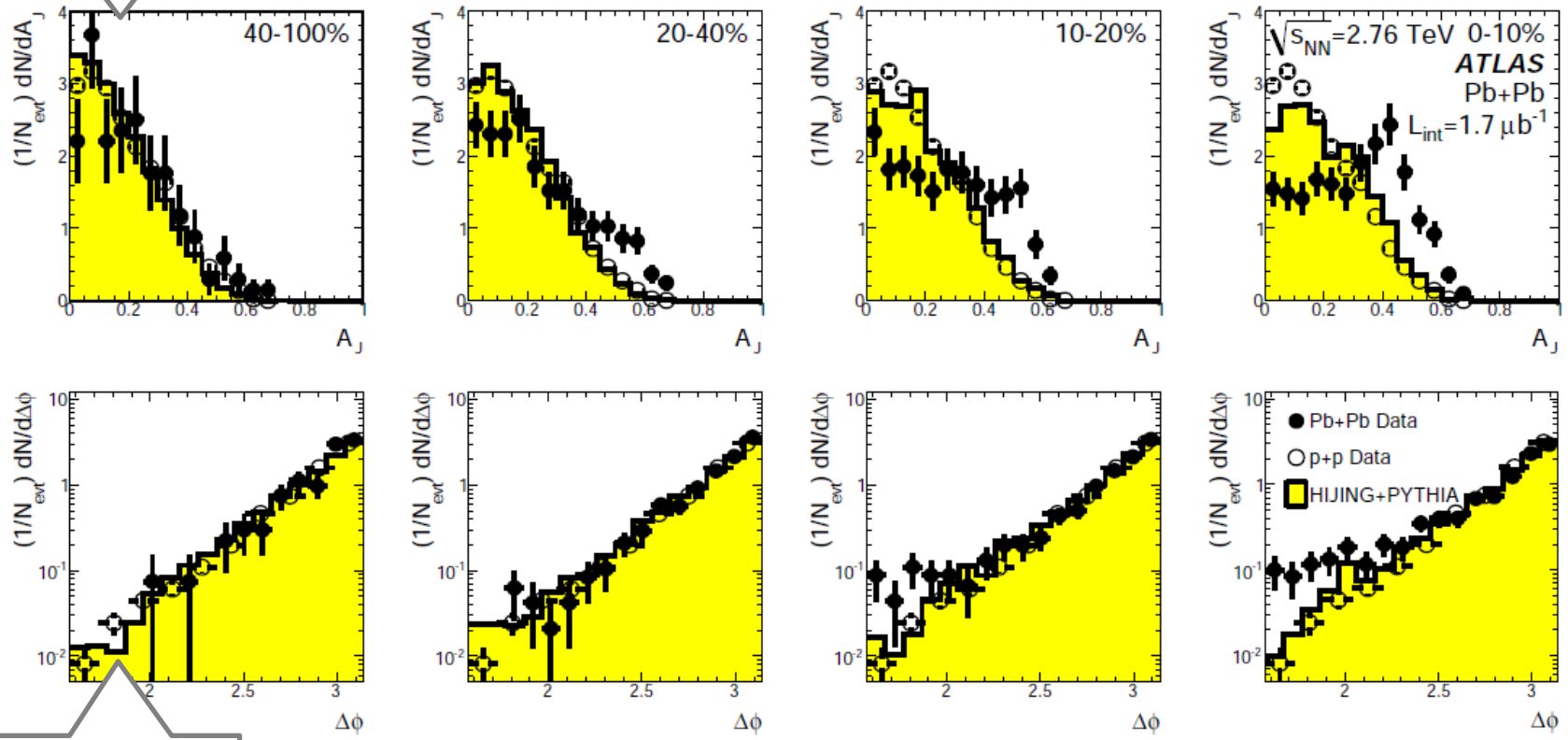


R=0.2 jets: very small difference in the performance between central and peripheral collisions

First observation of jet quenching at LHC

Dijet asymmetry
=> imbalance in E_T

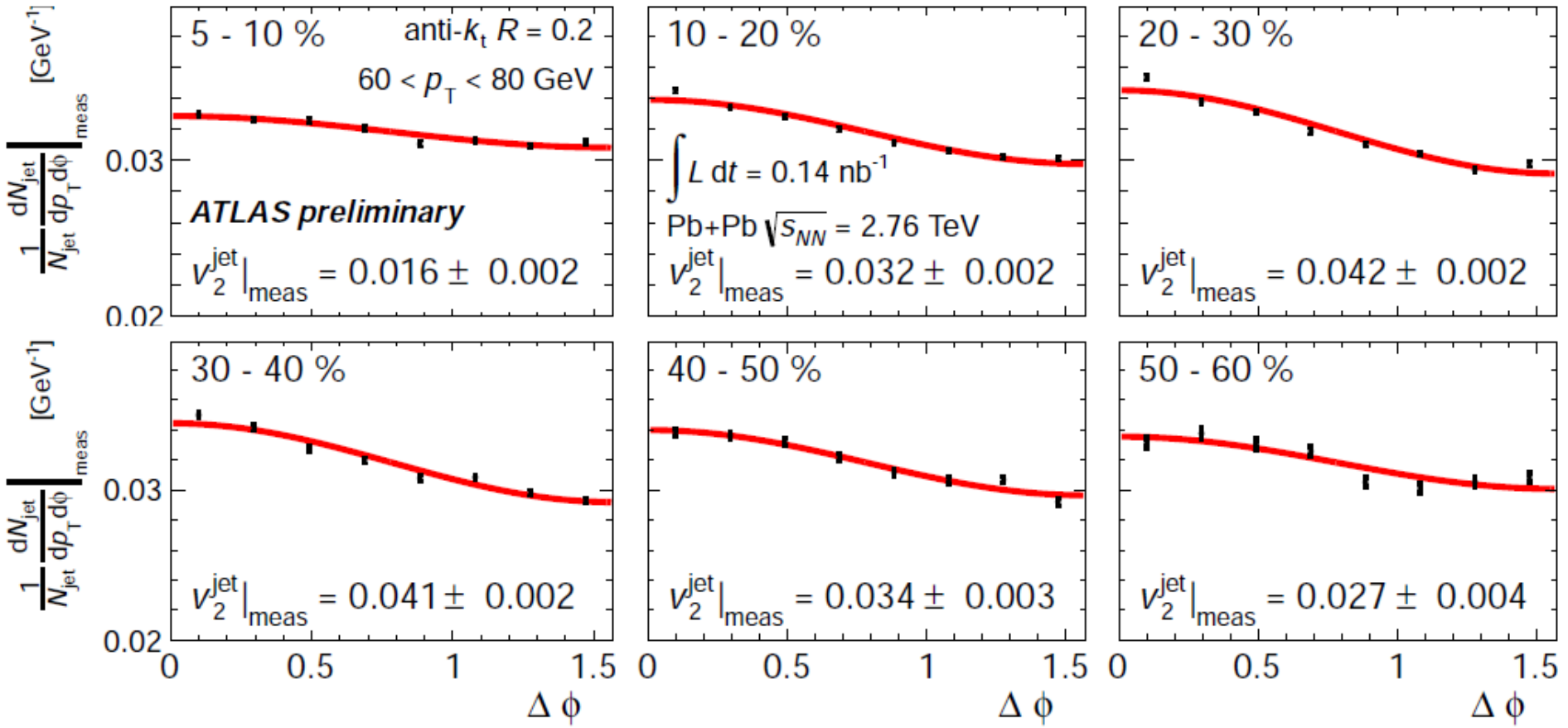
Centrality



Dijet $|\Delta\phi|$
=> balance in E_T

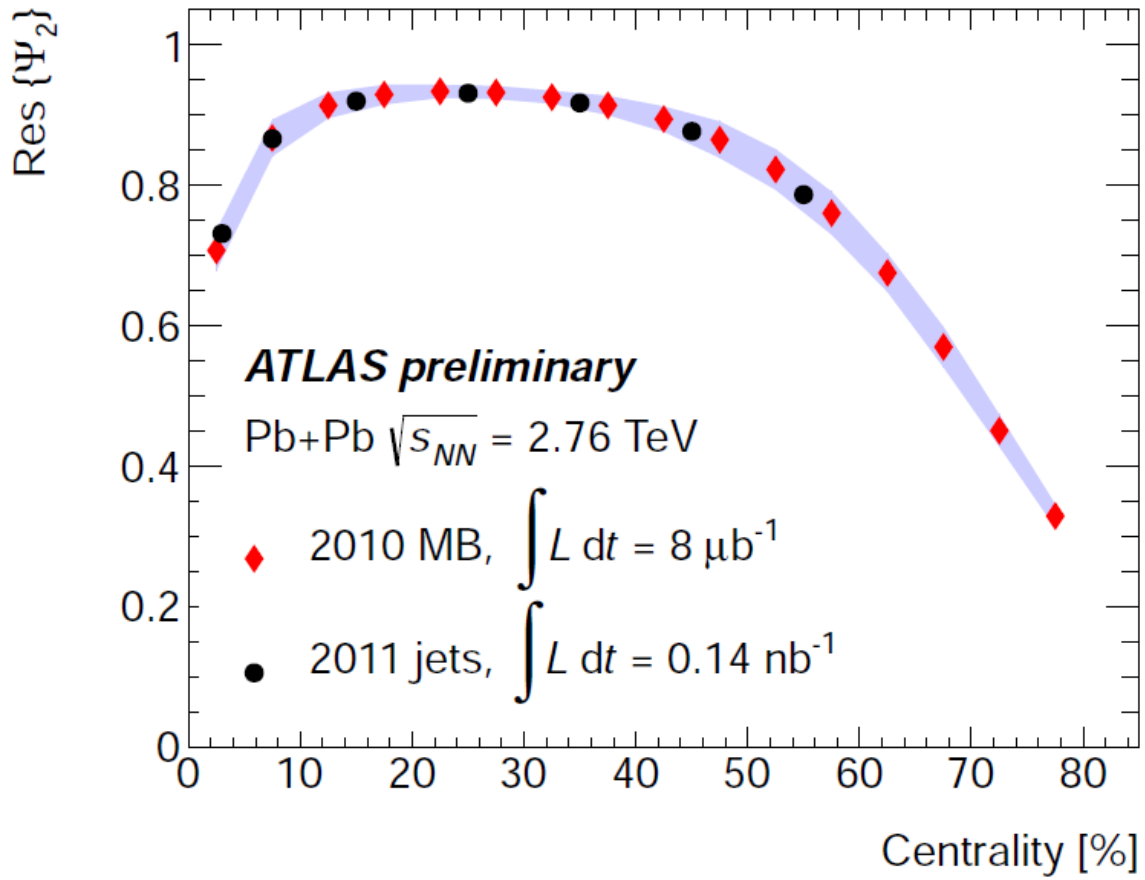
Original observation measurement of dijet asymmetry using ~2 μb^{-1} of 2010 Pb+Pb collisions

Jet v_2



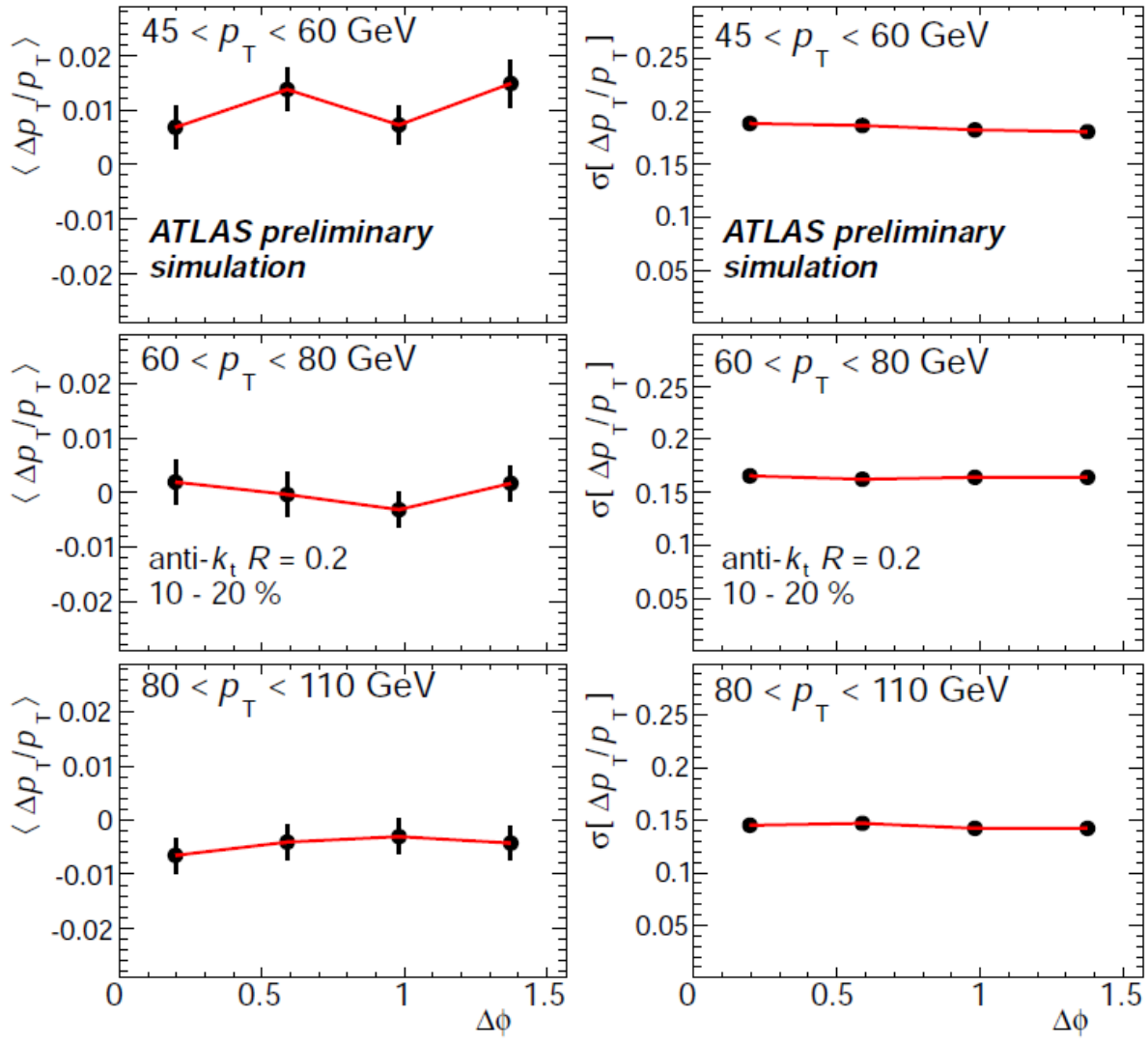
$$\frac{dN}{d\phi} = A\left(1 + 2v_2 \cos\left[2(\phi - \Psi_2)\right]\right)$$

Jet v_2

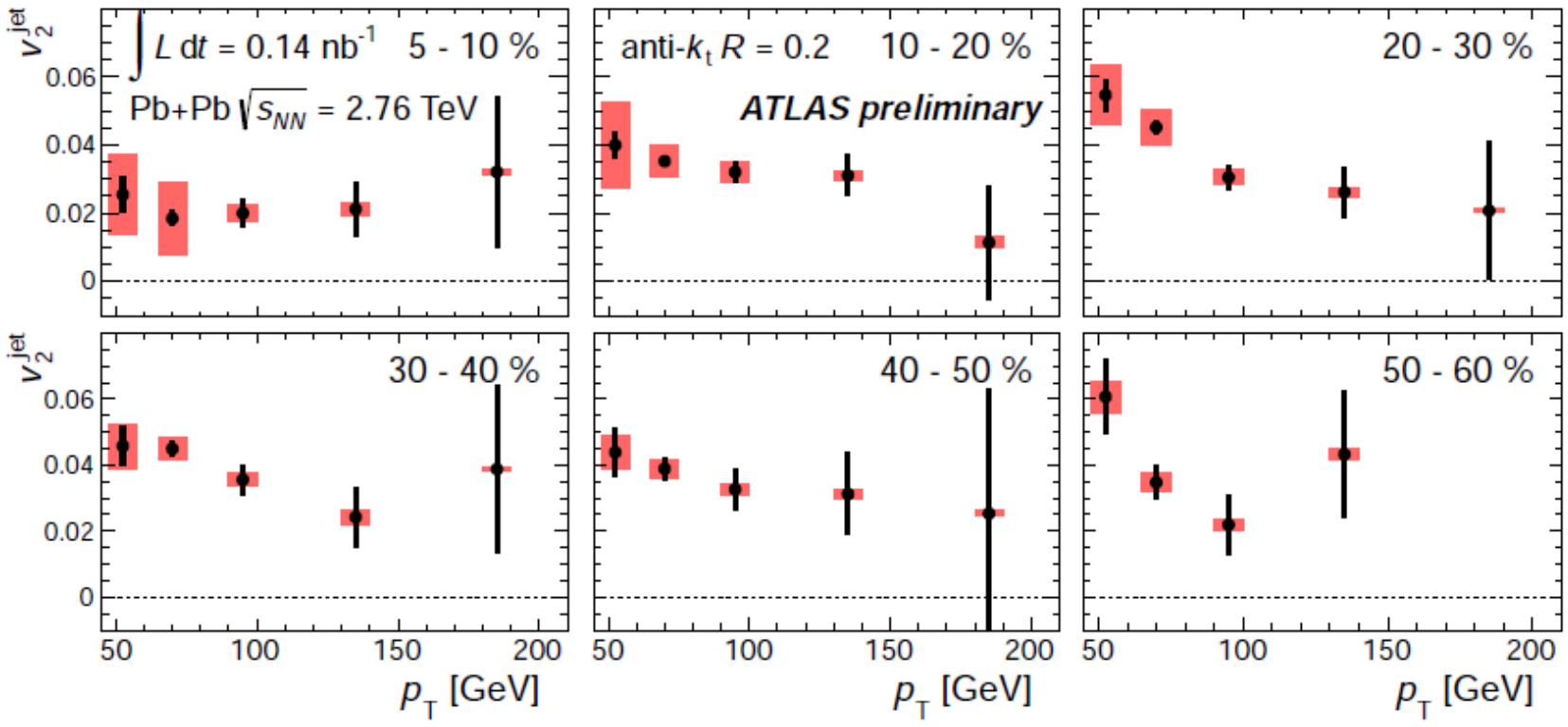


$$\Psi_2 = \frac{1}{2}\tan^{-1}\left\{\frac{\sum w_i E_{\mathrm{T}\,i}\sin 2\phi_i}{\sum w_i E_{\mathrm{T}\,i}\cos 2\phi_i}\right\}$$

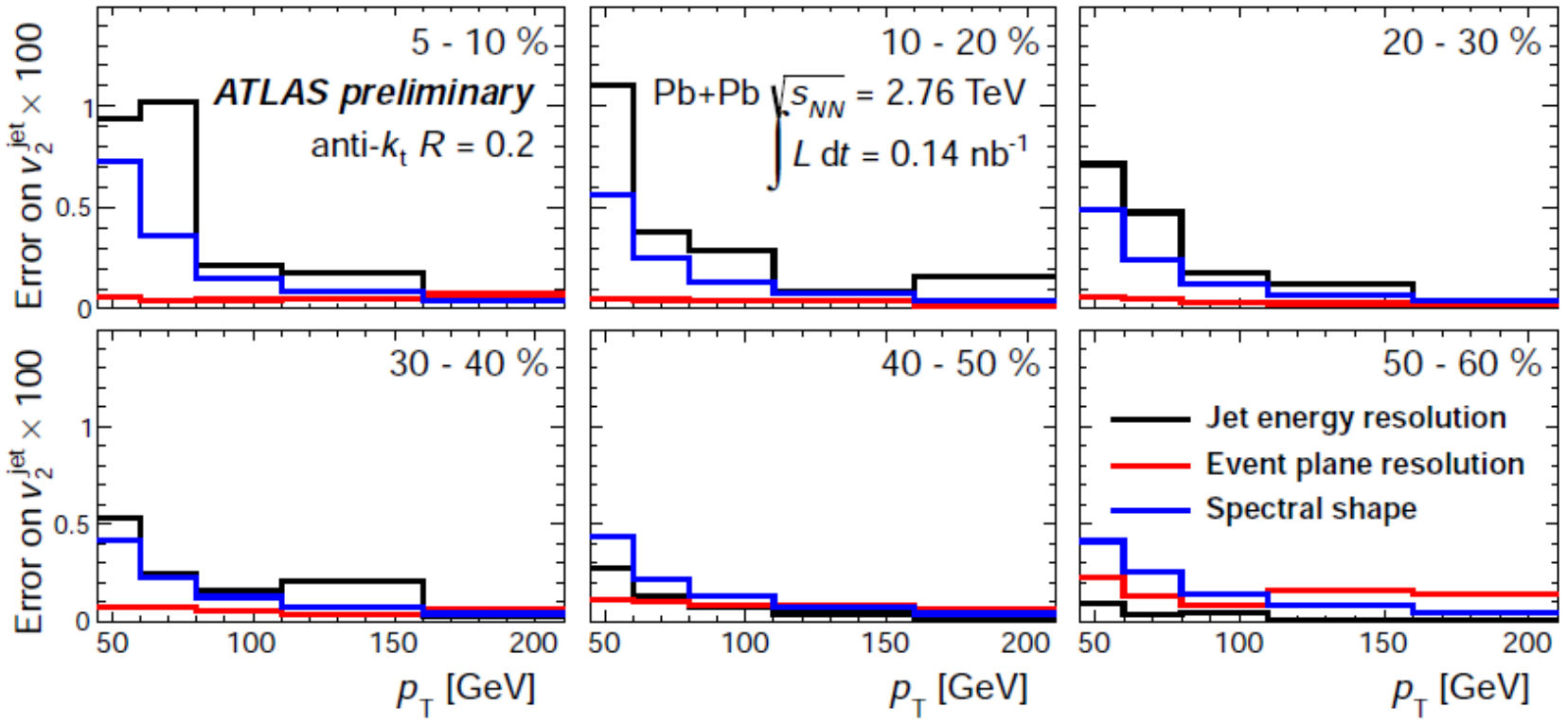
Jet v_2


45 < p_T < 60 GeV
ATLAS preliminary
simulation
60 < p_T < 80 GeV
anti-k_t R = 0.2
10 - 20 %
80 < p_T < 110 GeV
$\langle \Delta p_T / p_T \rangle$
$\sigma[\Delta p_T / p_T]$
$\Delta\phi$

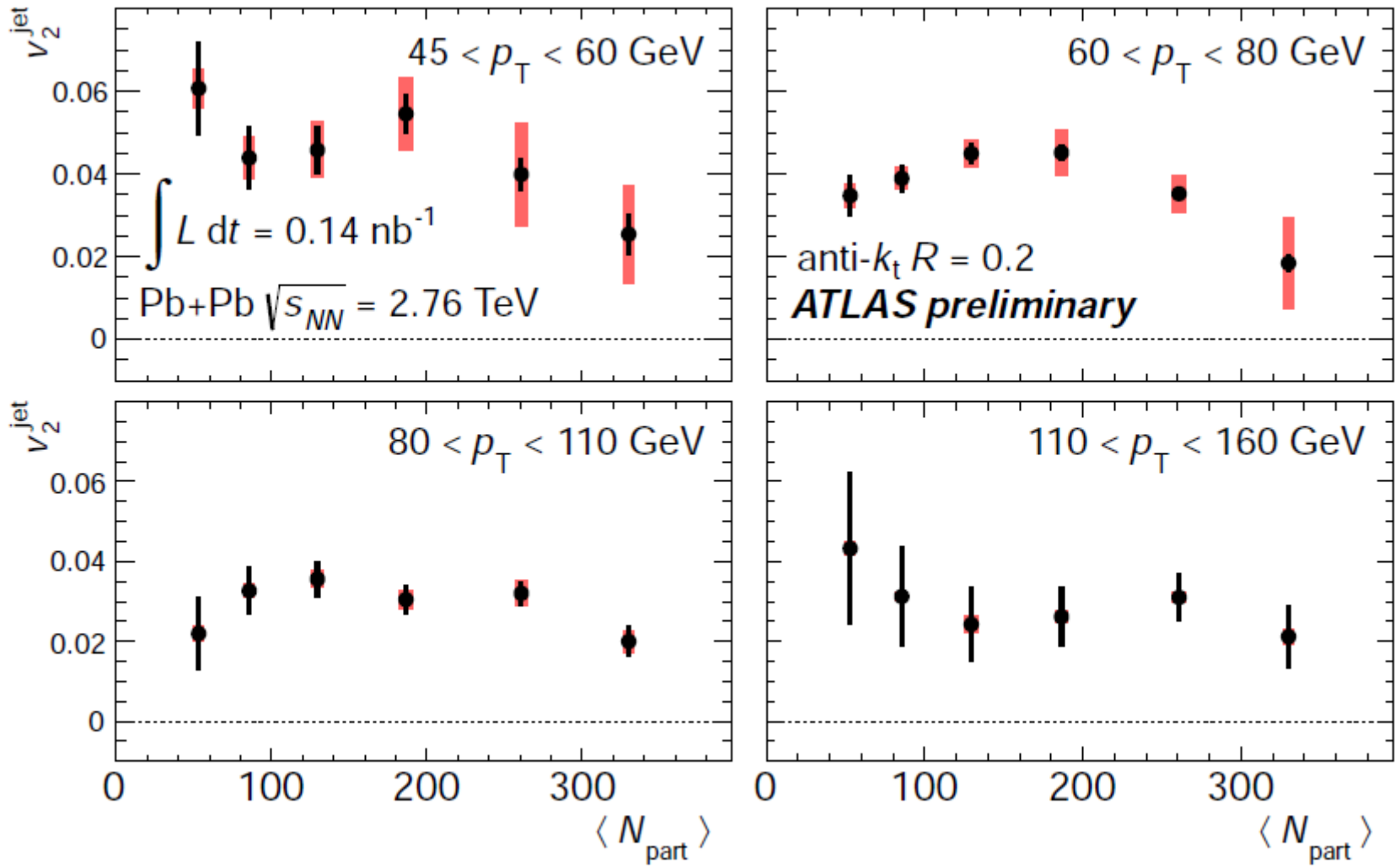
Jet v_2


$\int L\,dt$ = 0.14 nb^{-1}
Pb+Pb $\sqrt{s_{NN}}$ = 2.76 TeV
anti-k_t R = 0.2
ATLAS preliminary
5 - 10 %
10 - 20 %
20 - 30 %
30 - 40 %
40 - 50 %
50 - 60 %
v_2^{jet}
p_T [GeV]

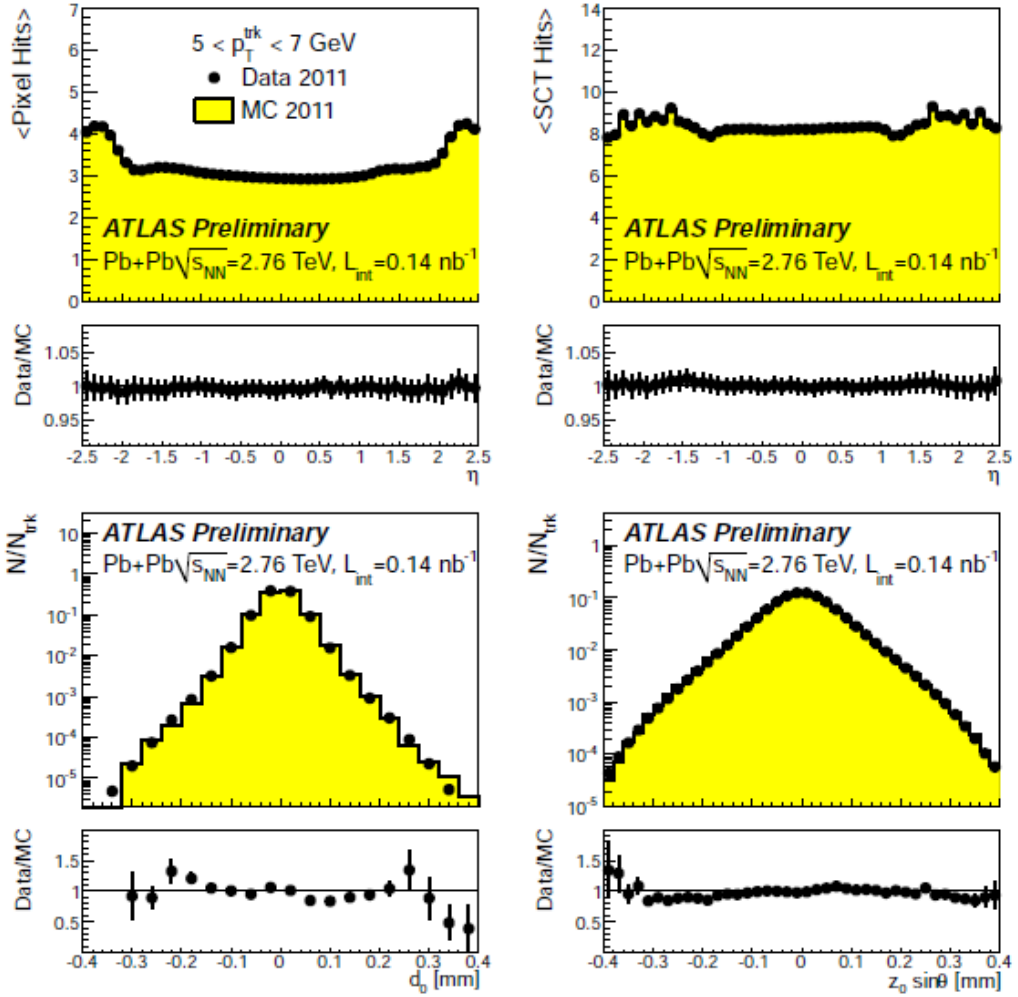
Jet v_2

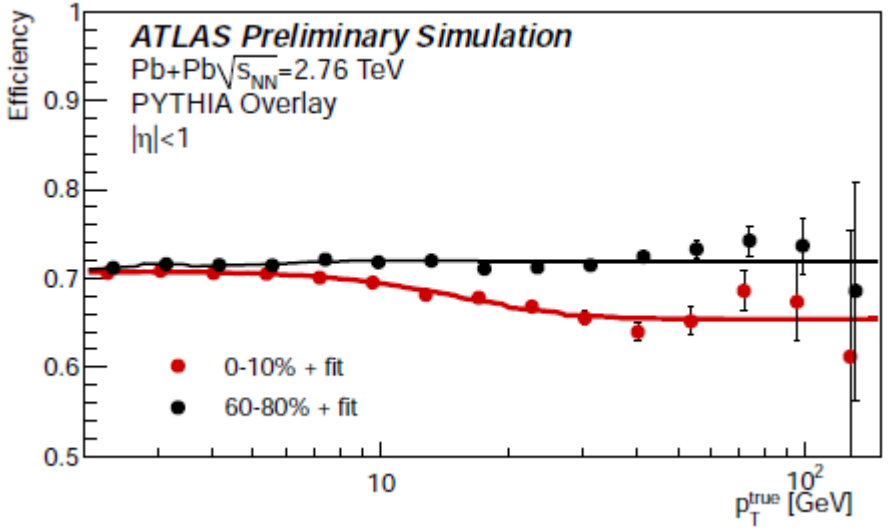

5 - 10 %
ATLAS preliminary
anti-k_t R = 0.2
10 - 20 %
Pb+Pb $\sqrt{s_{NN}}$ = 2.76 TeV
$\int L\,dt$ = 0.14 nb^{-1}
20 - 30 %
30 - 40 %
40 - 50 %
50 - 60 %
Jet energy resolution
Event plane resolution
Spectral shape
Error on $v_2^{jet} \times 100$
p_T [GeV]
0
0.5
1
50
100
150
200

Jet v_2

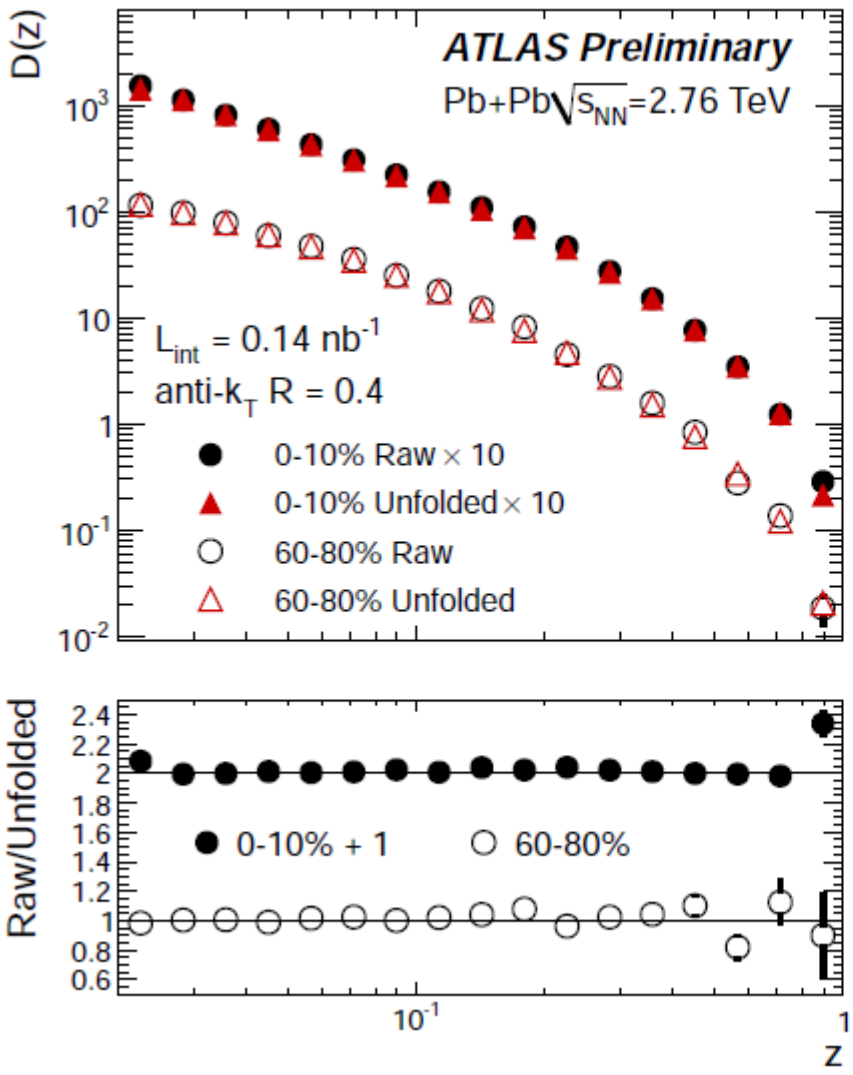

v_2^{jet}
45 < p_T < 60 GeV
60 < p_T < 80 GeV
80 < p_T < 110 GeV
110 < p_T < 160 GeV
$\int L\,dt$ = 0.14 nb^{-1}
Pb+Pb $\sqrt{s_{NN}}$ = 2.76 TeV
anti-k_t R = 0.2
ATLAS preliminary
0.06
0.04
0.02
0
0
100
200
300
⟨ N_{part} ⟩

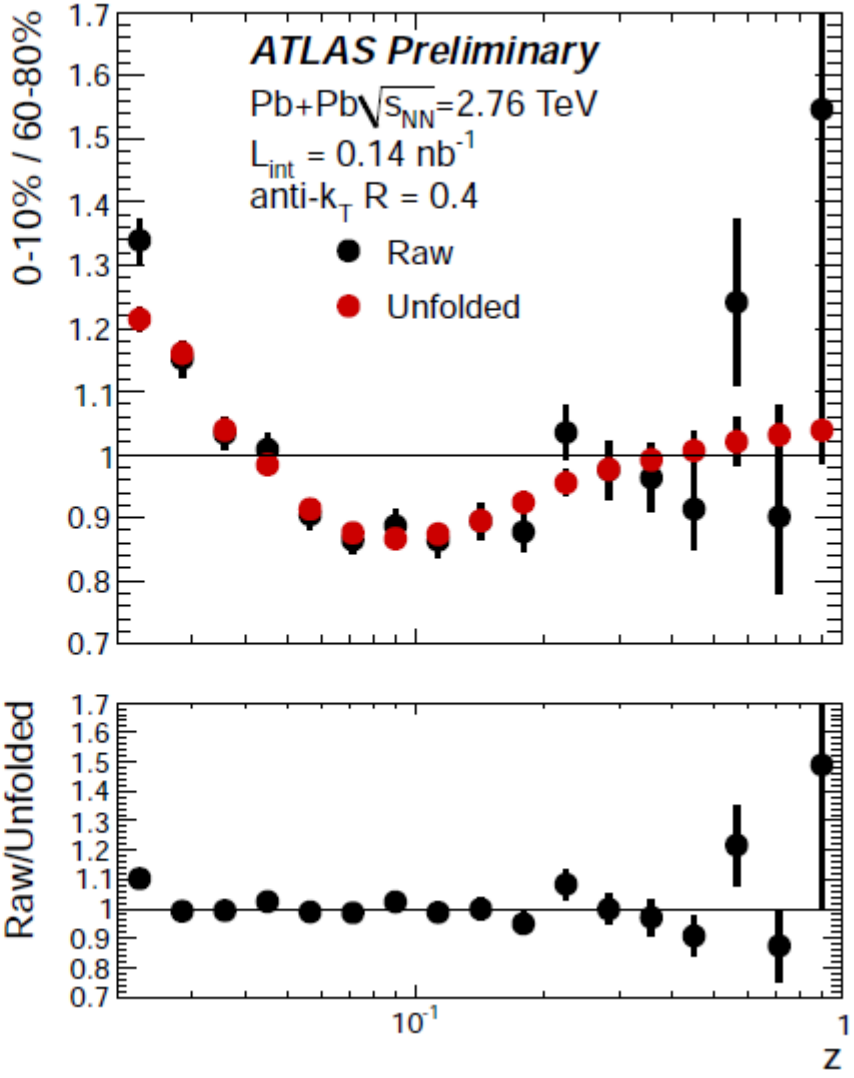
Jet Fragmentation



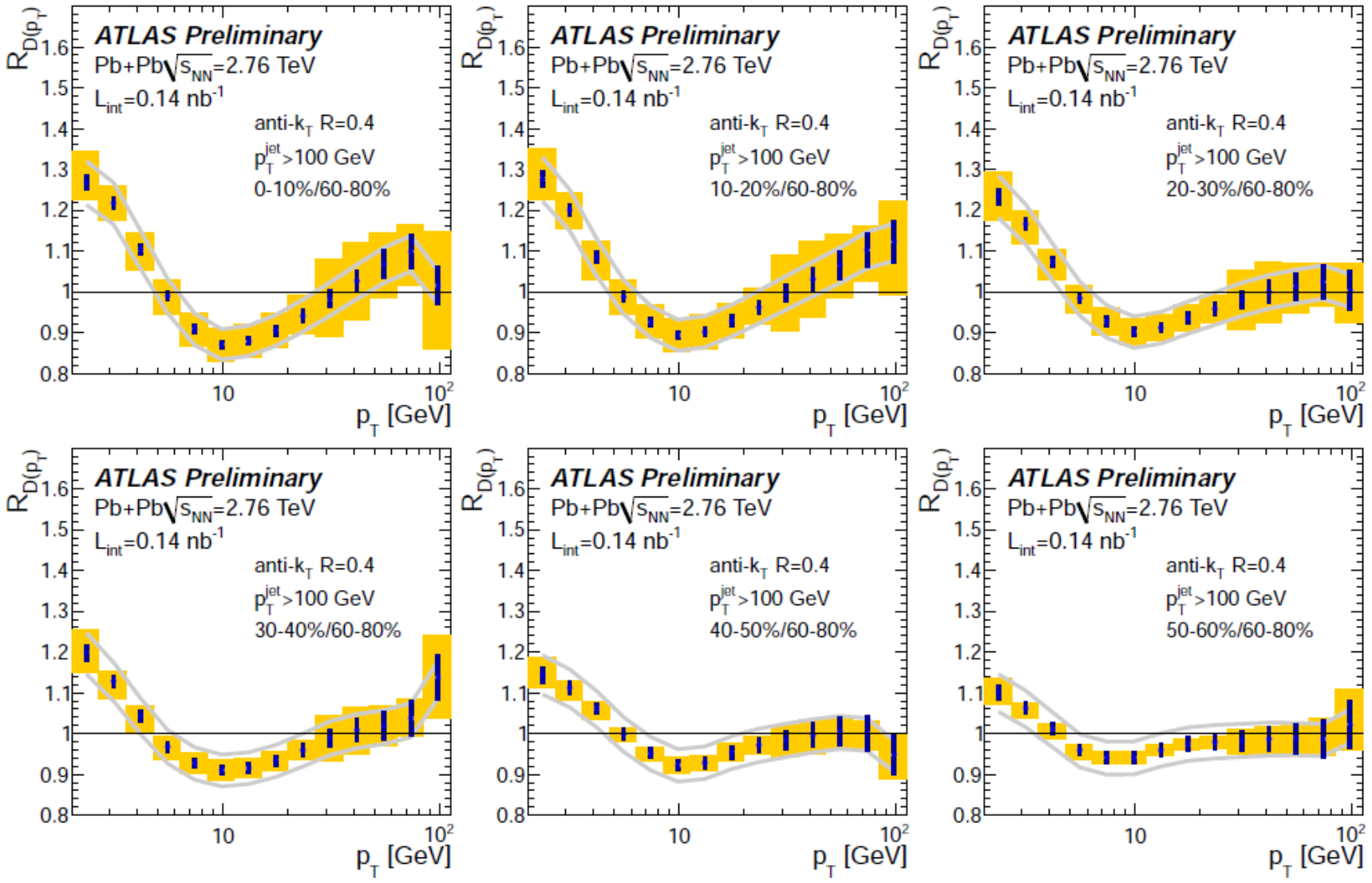


Jet Fragmentation

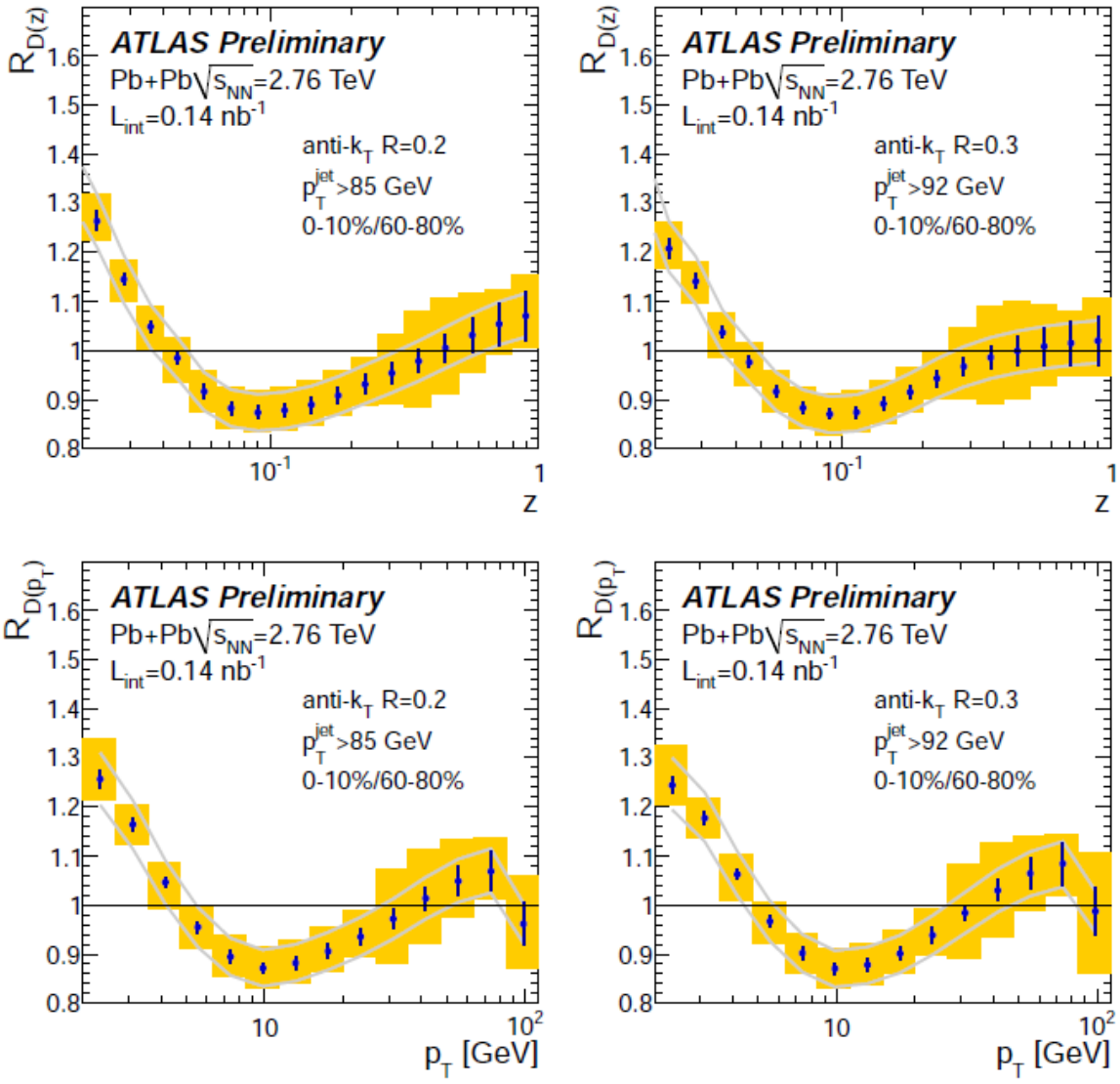




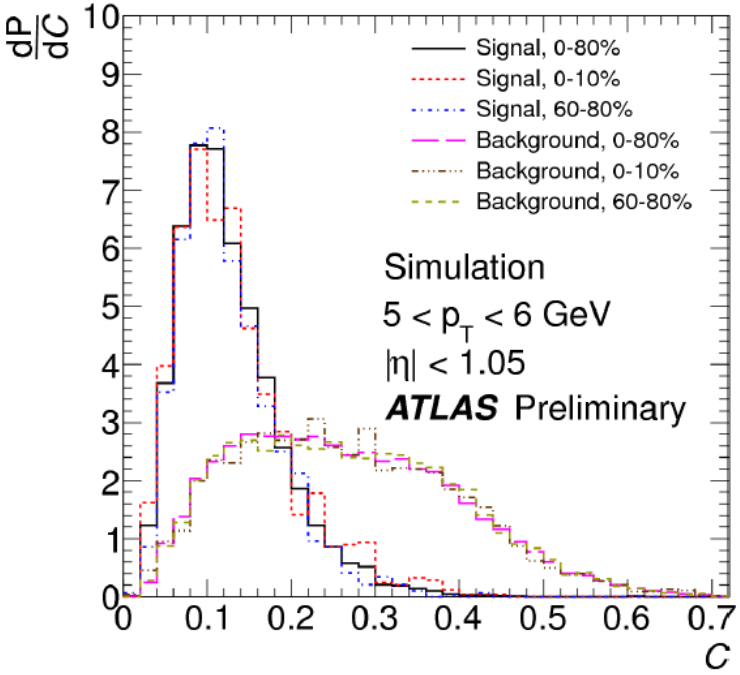
Jet Fragmentation

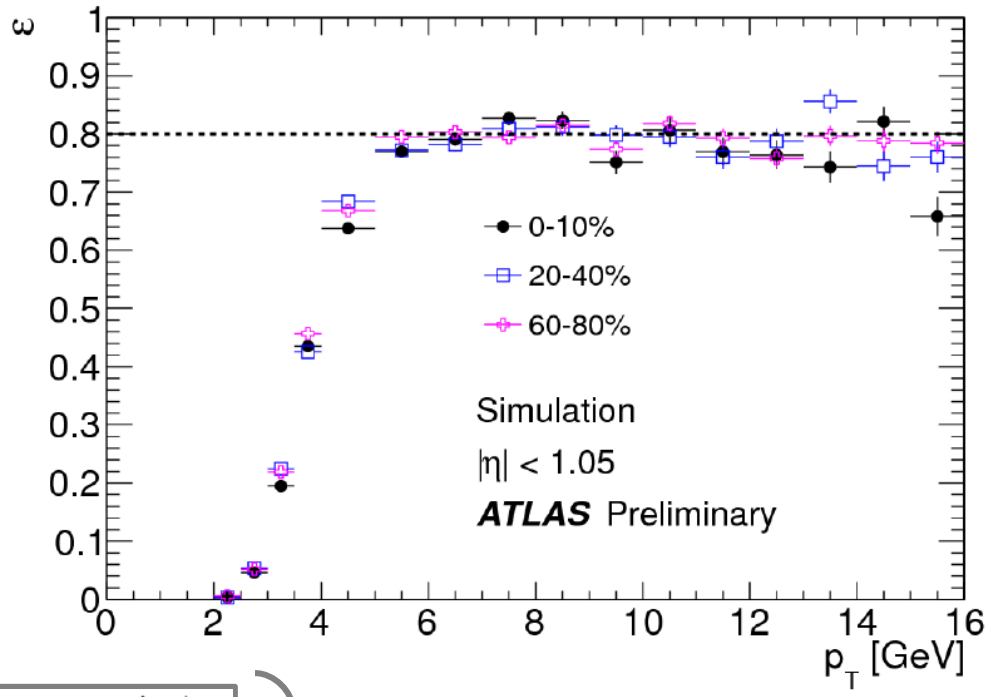


Jet Fragmentation



Heavy Flavor





$$\frac{\Delta p_{\text{loss}}}{p_{\text{ID}}} = \frac{p_{\text{ID}} - p_{\text{MS}} - \Delta p_{\text{calo}}(p,\eta,\phi)}{p_{\text{ID}}}$$

$$s_i = q\frac{\Delta\phi_i}{\phi_{\text{msc}}}$$

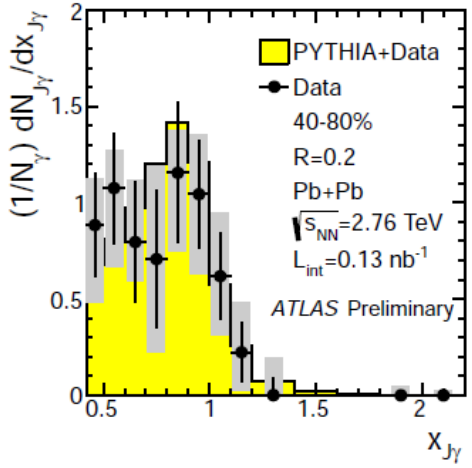
$$S(k) = \frac{1}{\sqrt{n}}\left(\sum_{i=1}^{k} s_i - \sum_{j=k+1}^{n} s_j\right)$$

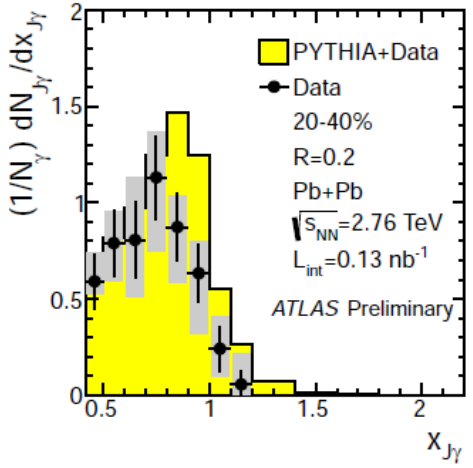
$$S = \max\{|S(k)|, k = 1, 2, ...\}$$

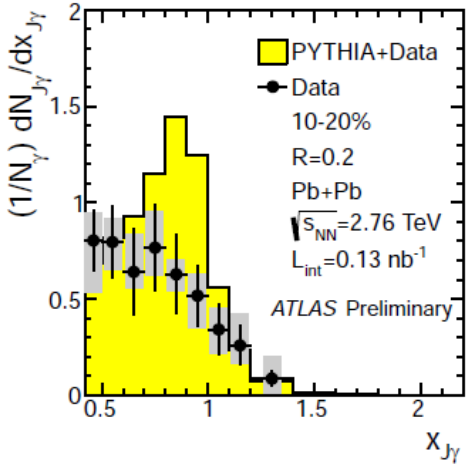
$$C = \left|\frac{\Delta p_{\text{loss}}}{p_{\text{ID}}}\right| + rS$$

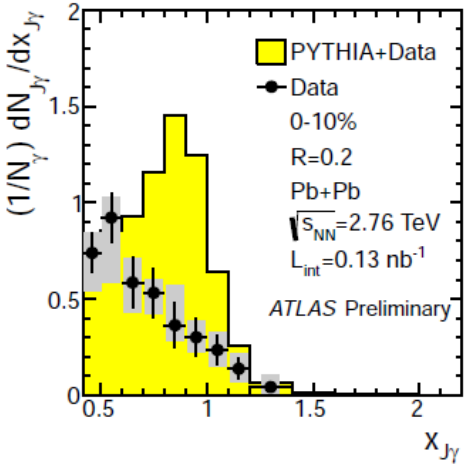
$$r = 0.07$$

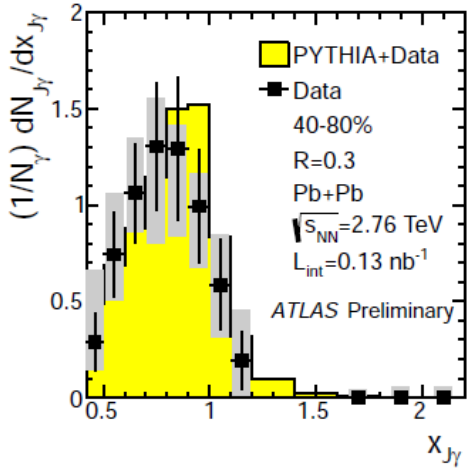
Gamma-jet

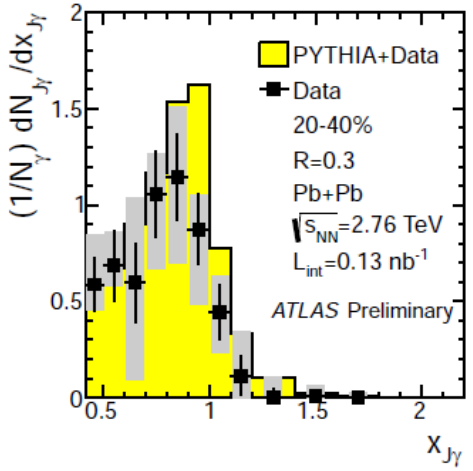

PYTHIA+Data
Data
40-80%
R=0.2
Pb+Pb
$\sqrt{s_{NN}}$=2.76 TeV
L_{int}=0.13 nb^{-1}
ATLAS Preliminary
$(1/N_{J\gamma})\, dN_{J\gamma}/dx_{J\gamma}$
$x_{J\gamma}$

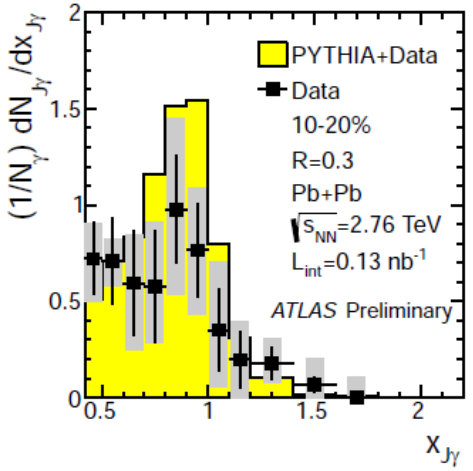

PYTHIA+Data
Data
20-40%
R=0.2
Pb+Pb
$\sqrt{s_{NN}}$=2.76 TeV
L_{int}=0.13 nb^{-1}
ATLAS Preliminary
$(1/N_{J\gamma})\, dN_{J\gamma}/dx_{J\gamma}$
$x_{J\gamma}$

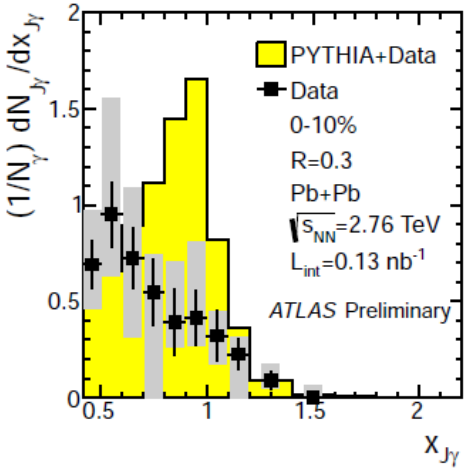

PYTHIA+Data
Data
10-20%
R=0.2
Pb+Pb
$\sqrt{s_{NN}}$=2.76 TeV
L_{int}=0.13 nb^{-1}
ATLAS Preliminary
$(1/N_{J\gamma})\, dN_{J\gamma}/dx_{J\gamma}$
$x_{J\gamma}$


PYTHIA+Data
Data
0-10%
R=0.2
Pb+Pb
$\sqrt{s_{NN}}$=2.76 TeV
L_{int}=0.13 nb^{-1}
ATLAS Preliminary
$(1/N_{J\gamma})\, dN_{J\gamma}/dx_{J\gamma}$
$x_{J\gamma}$

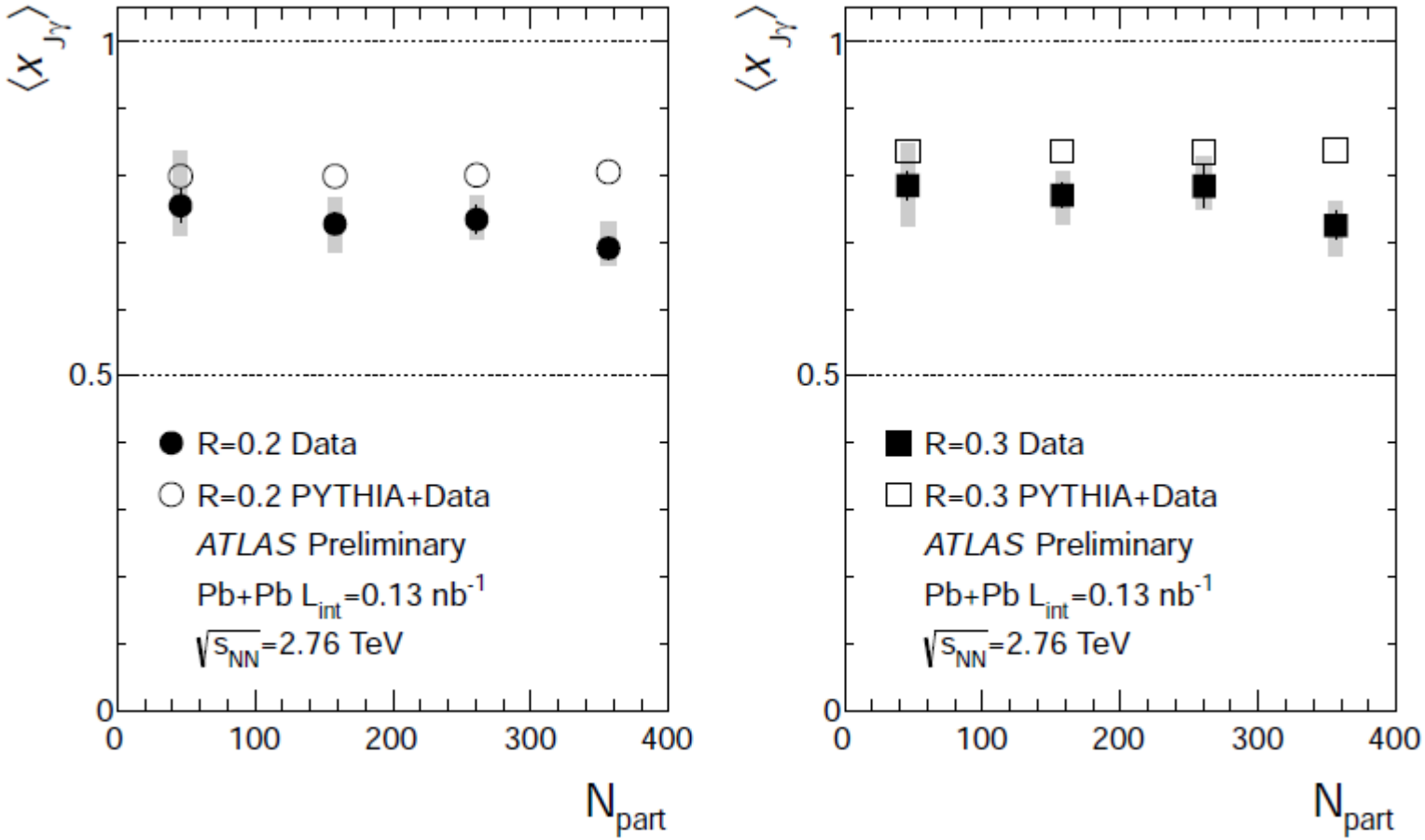

PYTHIA+Data
Data
40-80%
R=0.3
Pb+Pb
$\sqrt{s_{NN}}$=2.76 TeV
L_{int}=0.13 nb^{-1}
ATLAS Preliminary
$(1/N_{J\gamma})\, dN_{J\gamma}/dx_{J\gamma}$
$x_{J\gamma}$


PYTHIA+Data
Data
20-40%
R=0.3
Pb+Pb
$\sqrt{s_{NN}}$=2.76 TeV
L_{int}=0.13 nb^{-1}
ATLAS Preliminary
$(1/N_{J\gamma})\, dN_{J\gamma}/dx_{J\gamma}$
$x_{J\gamma}$

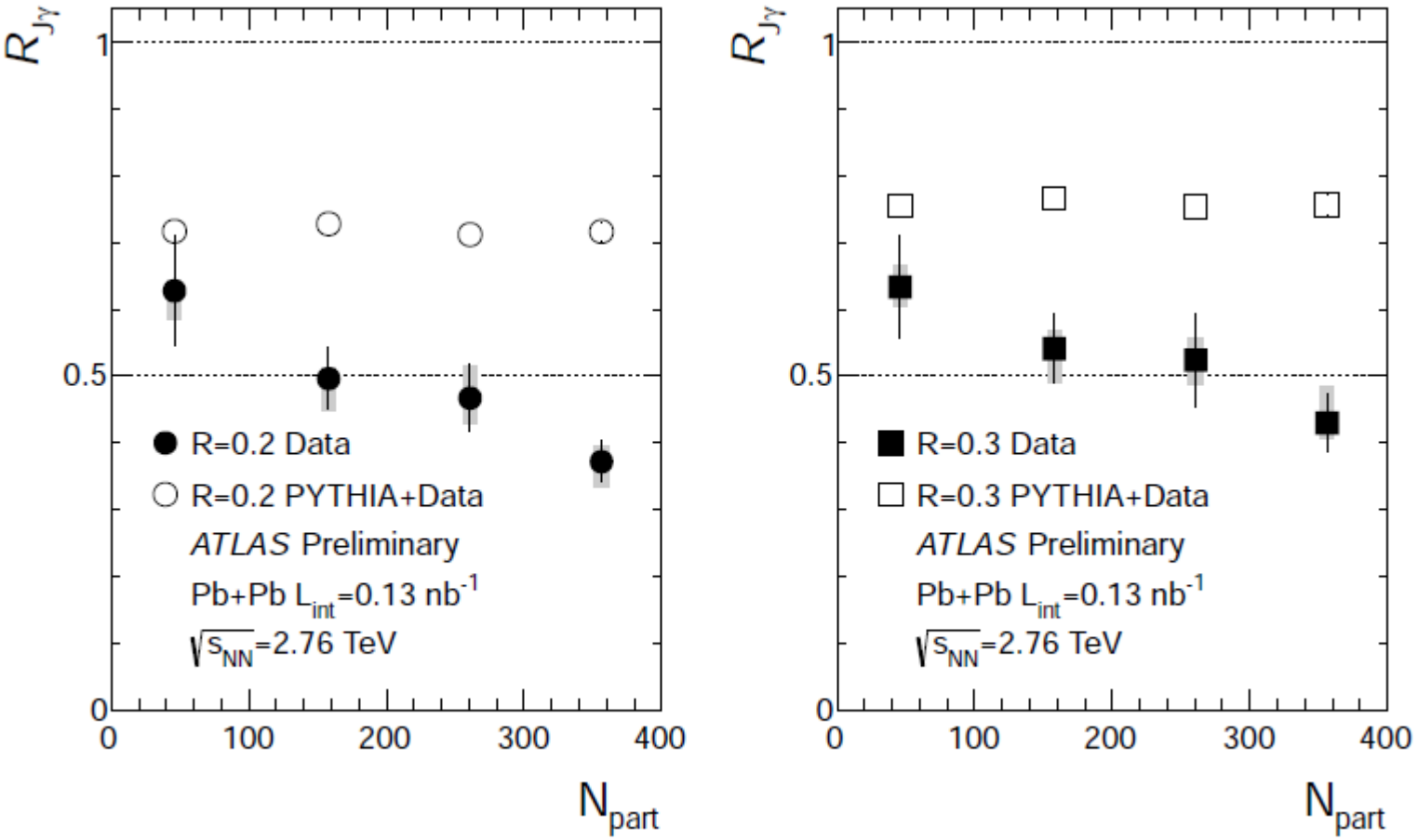

PYTHIA+Data
Data
10-20%
R=0.3
Pb+Pb
$\sqrt{s_{NN}}$=2.76 TeV
L_{int}=0.13 nb^{-1}
ATLAS Preliminary
$(1/N_{J\gamma})\, dN_{J\gamma}/dx_{J\gamma}$
$x_{J\gamma}$


PYTHIA+Data
Data
0-10%
R=0.3
Pb+Pb
$\sqrt{s_{NN}}$=2.76 TeV
L_{int}=0.13 nb^{-1}
ATLAS Preliminary
$(1/N_{J\gamma})\, dN_{J\gamma}/dx_{J\gamma}$
$x_{J\gamma}$

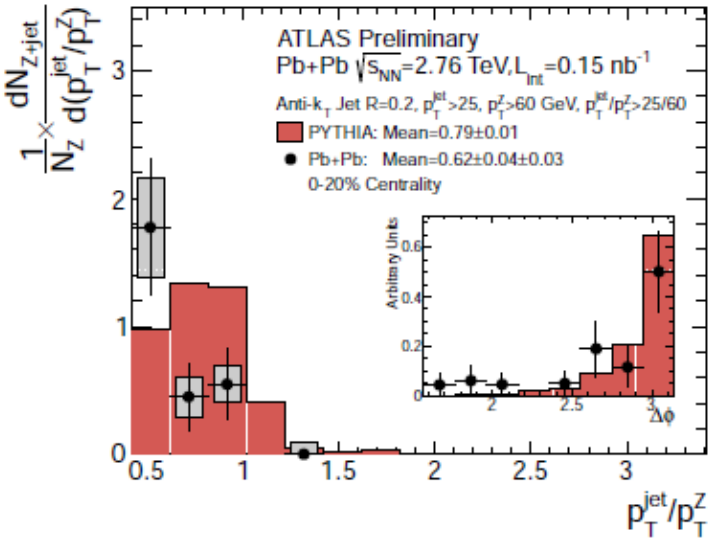
Gamma-jet

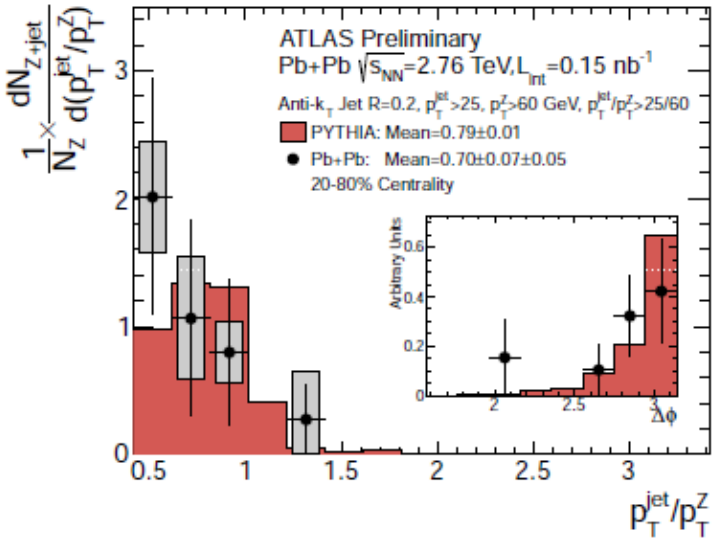

$\langle x_{J\gamma} \rangle$
1
0.5
0
0
100
200
300
400
N_{part}
R=0.2 Data
R=0.2 PYTHIA+Data
ATLAS Preliminary
Pb+Pb L_{int}=0.13 nb^{-1}
$\sqrt{s_{NN}}$=2.76 TeV
R=0.3 Data
R=0.3 PYTHIA+Data
ATLAS Preliminary
Pb+Pb L_{int}=0.13 nb^{-1}
$\sqrt{s_{NN}}$=2.76 TeV

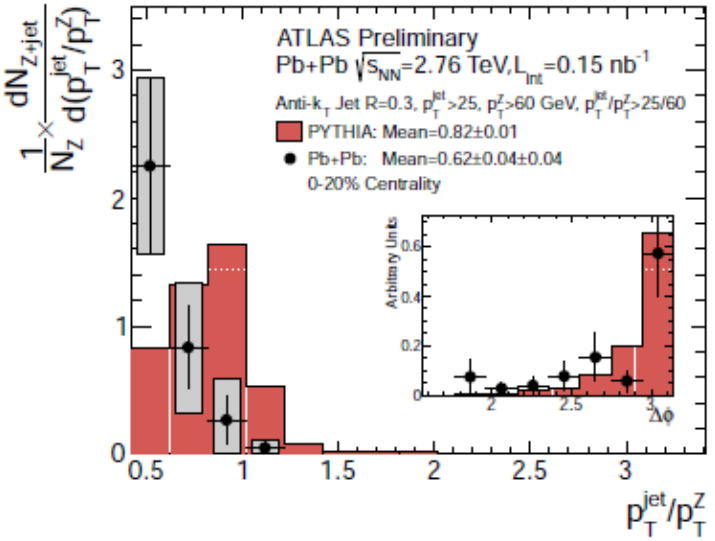
Gamma-jet

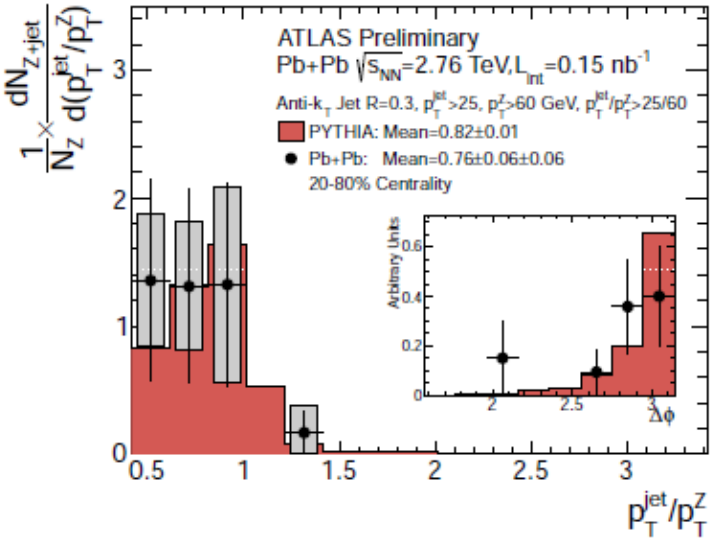

$R_{J\gamma}$
1
0.5
0
0
100
200
300
400
N_{part}
R=0.2 Data
R=0.2 PYTHIA+Data
ATLAS Preliminary
Pb+Pb L_{int}=0.13 nb^{-1}
$\sqrt{s_{NN}}$=2.76 TeV
$R_{J\gamma}$
1
0.5
0
0
100
200
300
400
N_{part}
R=0.3 Data
R=0.3 PYTHIA+Data
ATLAS Preliminary
Pb+Pb L_{int}=0.13 nb^{-1}
$\sqrt{s_{NN}}$=2.76 TeV

Z-jet


ATLAS Preliminary
Pb+Pb $\sqrt{s_{NN}}$=2.76 TeV, L_{int}=0.15 nb^{-1}
Anti-k$_t$ Jet R=0.2, p_T^{jet}>25, p_T^Z>60 GeV, p_T^{jet}/p_T^Z>25/60
PYTHIA: Mean=0.79±0.01
Pb+Pb: Mean=0.62±0.04±0.03
0-20% Centrality
$\frac{1}{N_Z}\frac{dN_{Z+jet}}{d(p_T^{jet}/p_T^Z)}$
p_T^{jet}/p_T^Z
Arbitrary Units
$\Delta\phi$


ATLAS Preliminary
Pb+Pb $\sqrt{s_{NN}}$=2.76 TeV, L_{int}=0.15 nb^{-1}
Anti-k$_t$ Jet R=0.2, p_T^{jet}>25, p_T^Z>60 GeV, p_T^{jet}/p_T^Z>25/60
PYTHIA: Mean=0.79±0.01
Pb+Pb: Mean=0.70±0.07±0.05
20-80% Centrality
$\frac{1}{N_Z}\frac{dN_{Z+jet}}{d(p_T^{jet}/p_T^Z)}$
p_T^{jet}/p_T^Z
Arbitrary Units
$\Delta\phi$


ATLAS Preliminary
Pb+Pb $\sqrt{s_{NN}}$=2.76 TeV, L_{int}=0.15 nb^{-1}
Anti-k$_t$ Jet R=0.3, p_T^{jet}>25, p_T^Z>60 GeV, p_T^{jet}/p_T^Z>25/60
PYTHIA: Mean=0.82±0.01
Pb+Pb: Mean=0.62±0.04±0.04
0-20% Centrality
$\frac{1}{N_Z}\frac{dN_{Z+jet}}{d(p_T^{jet}/p_T^Z)}$
p_T^{jet}/p_T^Z
Arbitrary Units
$\Delta\phi$


ATLAS Preliminary
Pb+Pb $\sqrt{s_{NN}}$=2.76 TeV, L_{int}=0.15 nb^{-1}
Anti-k$_t$ Jet R=0.3, p_T^{jet}>25, p_T^Z>60 GeV, p_T^{jet}/p_T^Z>25/60
PYTHIA: Mean=0.82±0.01
Pb+Pb: Mean=0.76±0.06±0.06
20-80% Centrality
$\frac{1}{N_Z}\frac{dN_{Z+jet}}{d(p_T^{jet}/p_T^Z)}$
p_T^{jet}/p_T^Z
Arbitrary Units
$\Delta\phi$