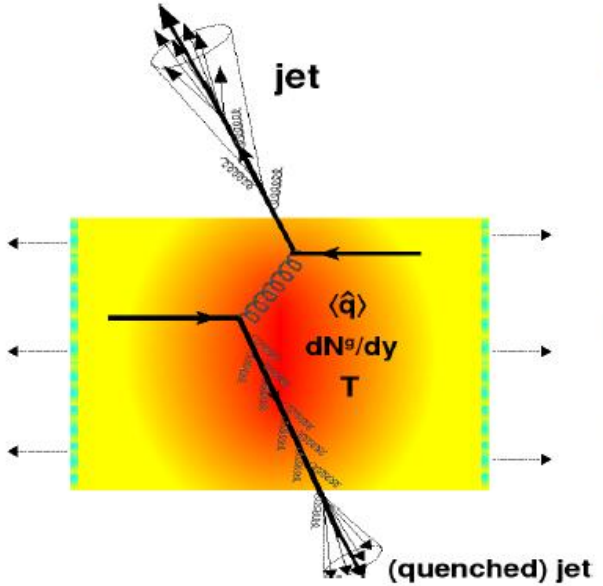
COLUMBIA UNIVERSITY

Jets in ATLAS

Martin Spousta
on behalf of the ATLAS Collaboration

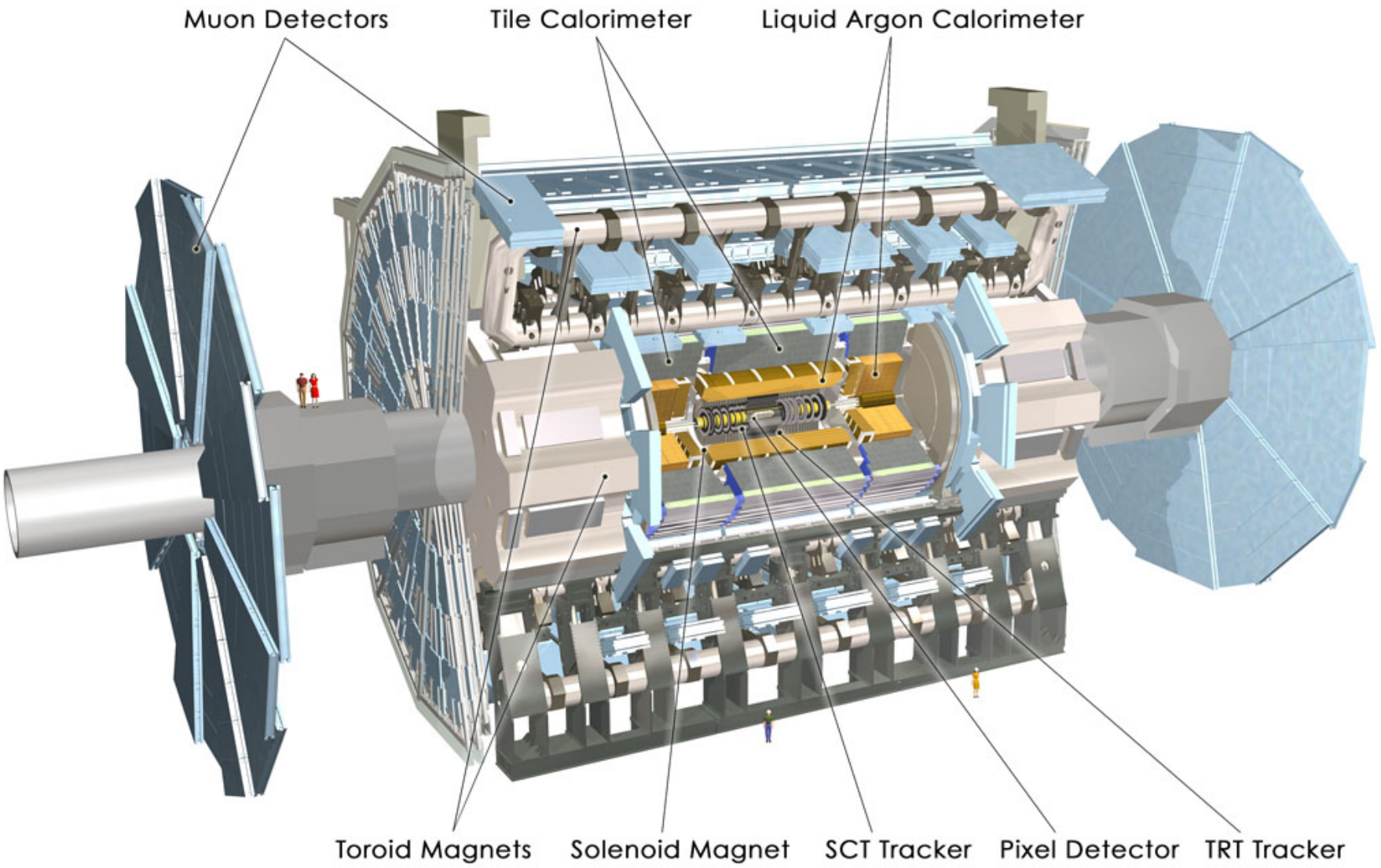
Columbia University
and
Charles University

Jet suppression and parton energy loss



- General motivation: Detailed understanding of the parton energy loss means better understanding of QCD in the limit of high densities and temperatures.
- Key question: How does the medium modify the parton showering?
- More questions:
  - Does the energy remain inside the jet but redistributed among fragments?
    - ⇒ Is the jet fragmentation function modified?
    - ⇒ Is the transverse structure of jet modified?
  - Or is the energy rather redistributed out of the jet cone?
    - ⇒ Is the jet yield suppressed?
    - ⇒ How does the suppression depend on jet radius?

ATLAS Detector

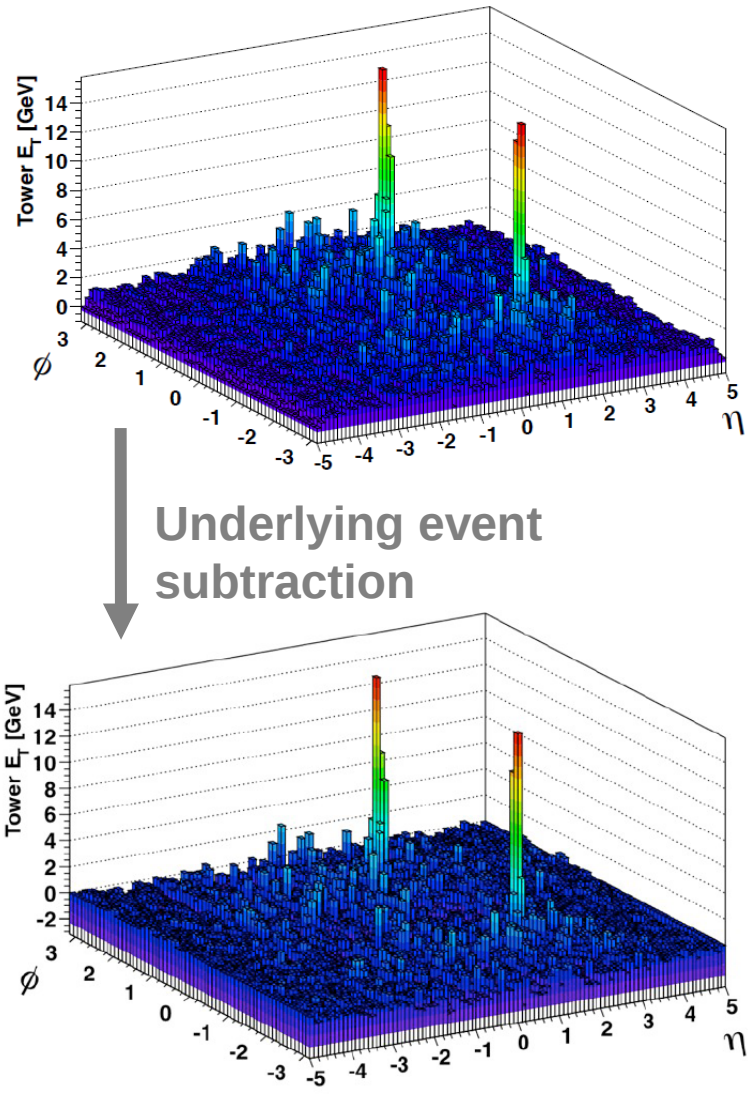


Jet reconstruction

- 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.

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

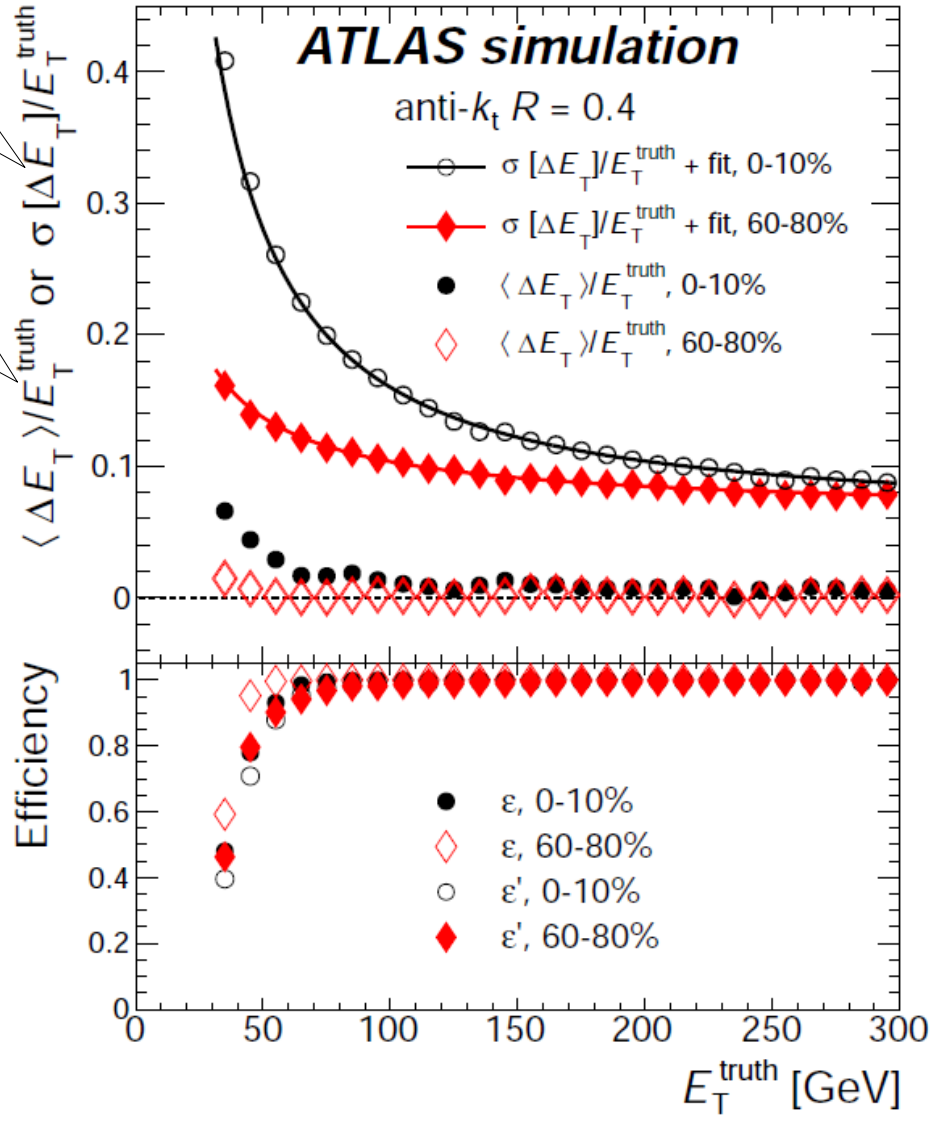
- Jets are corrected for the elliptic flow contribution.
- The subtraction is done in two iterations to avoid a bias of the background estimate by the presence of jets.



Performance

Jet energy resolution

Jet energy scale

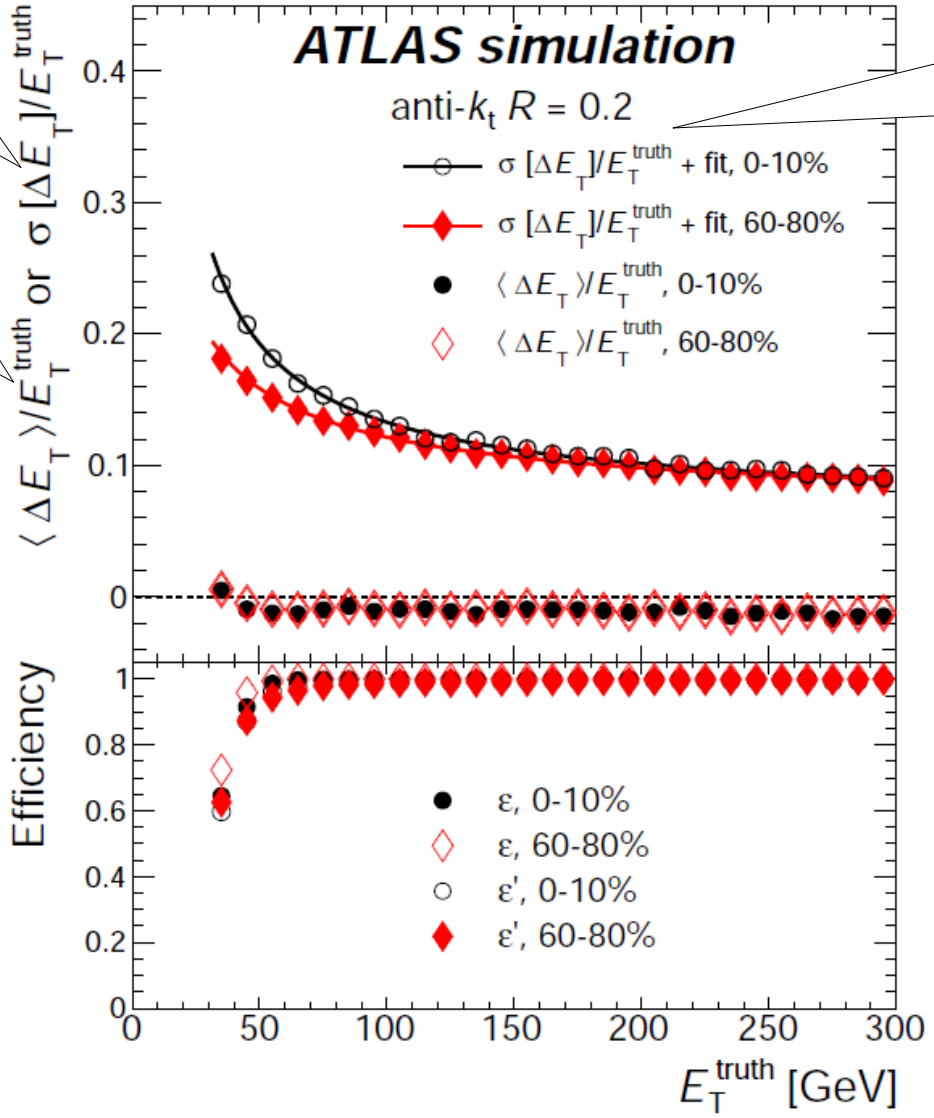


- Detailed evaluation of the performance.
- Data-driven checks of jet energy resolution using the evaluation of fluctuations in minimum bias event and HIJING.
- Data-driven check of jet energy scale using jets reconstructed from tracks (“track jets”).
- Fake rejection using track jets or electromagnetic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

Performance

Jet energy resolution

Jet energy scale

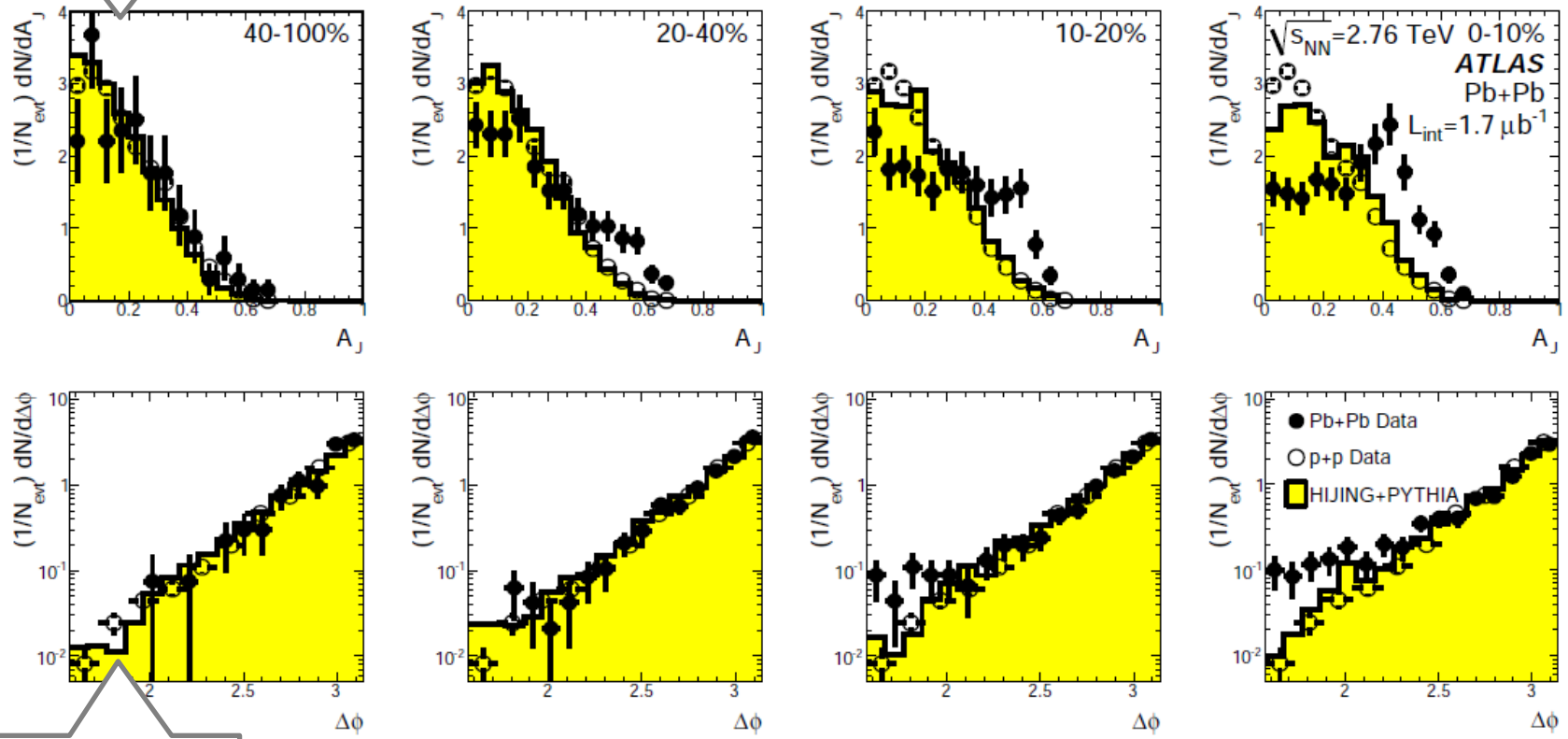


R=0.2 jets: very small difference in the performance between central and peripheral collisions

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

Beyond the asymmetry

Asymmetry is the observation measurement. Alone, it cannot provide information about details of parton energy loss … More detailed questions we want to answer:

- 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

- 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

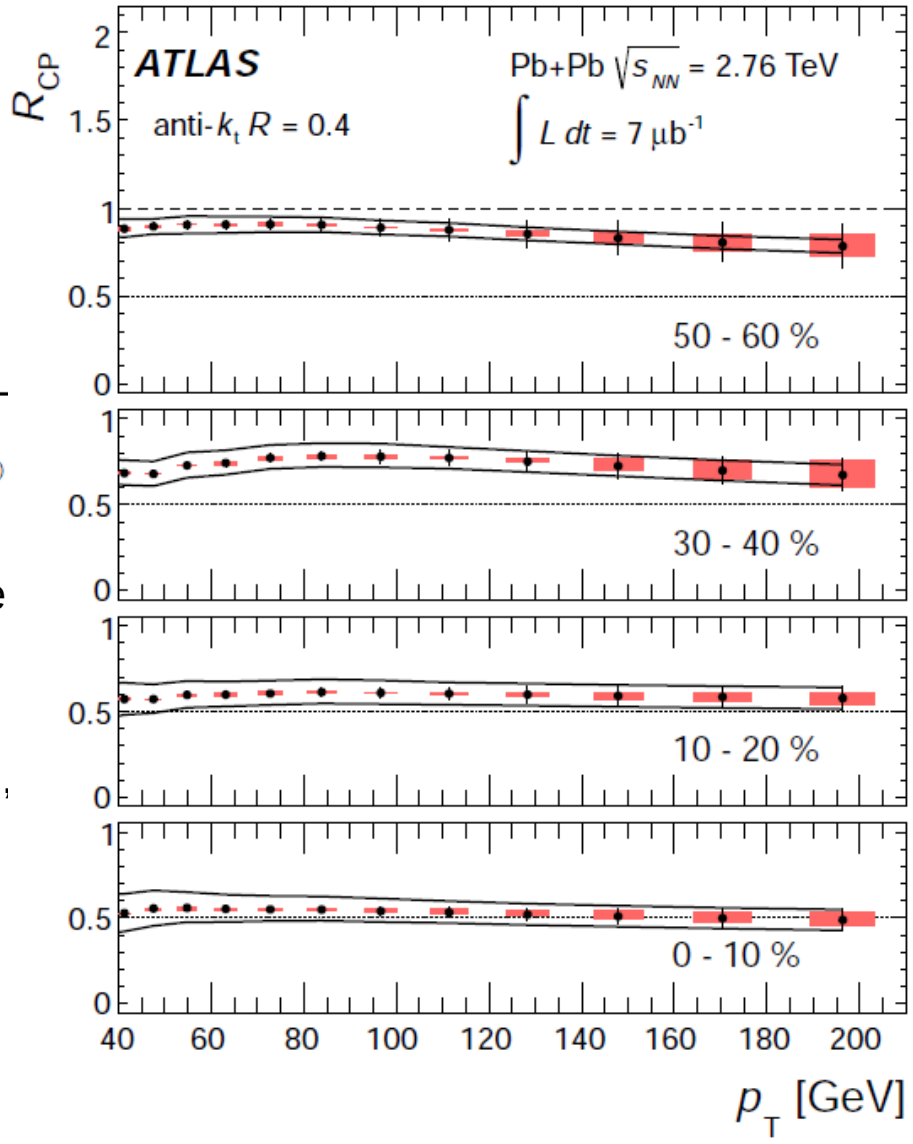
Jet R_{CP}

Q: How are the inclusive jet yields suppressed?

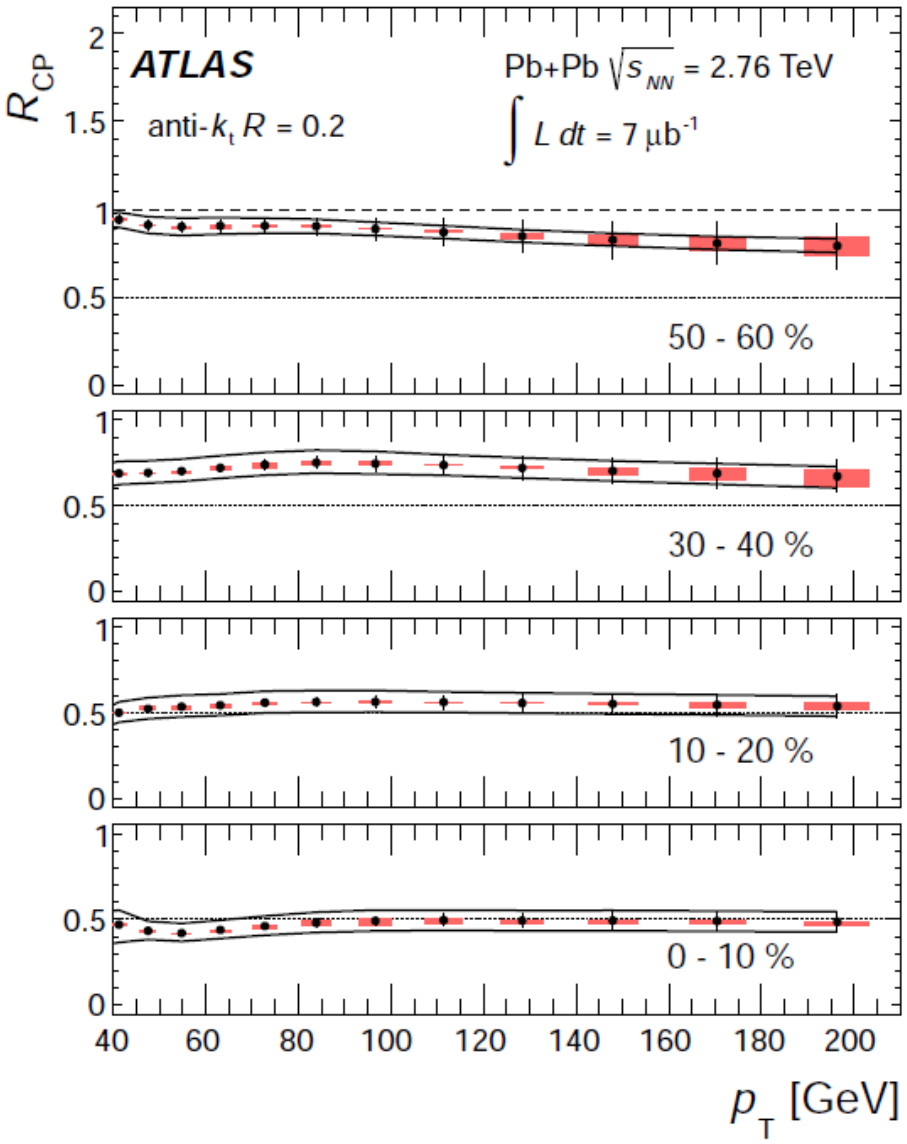
- Jet R_{CP} – ratio of central to peripheral collisions,

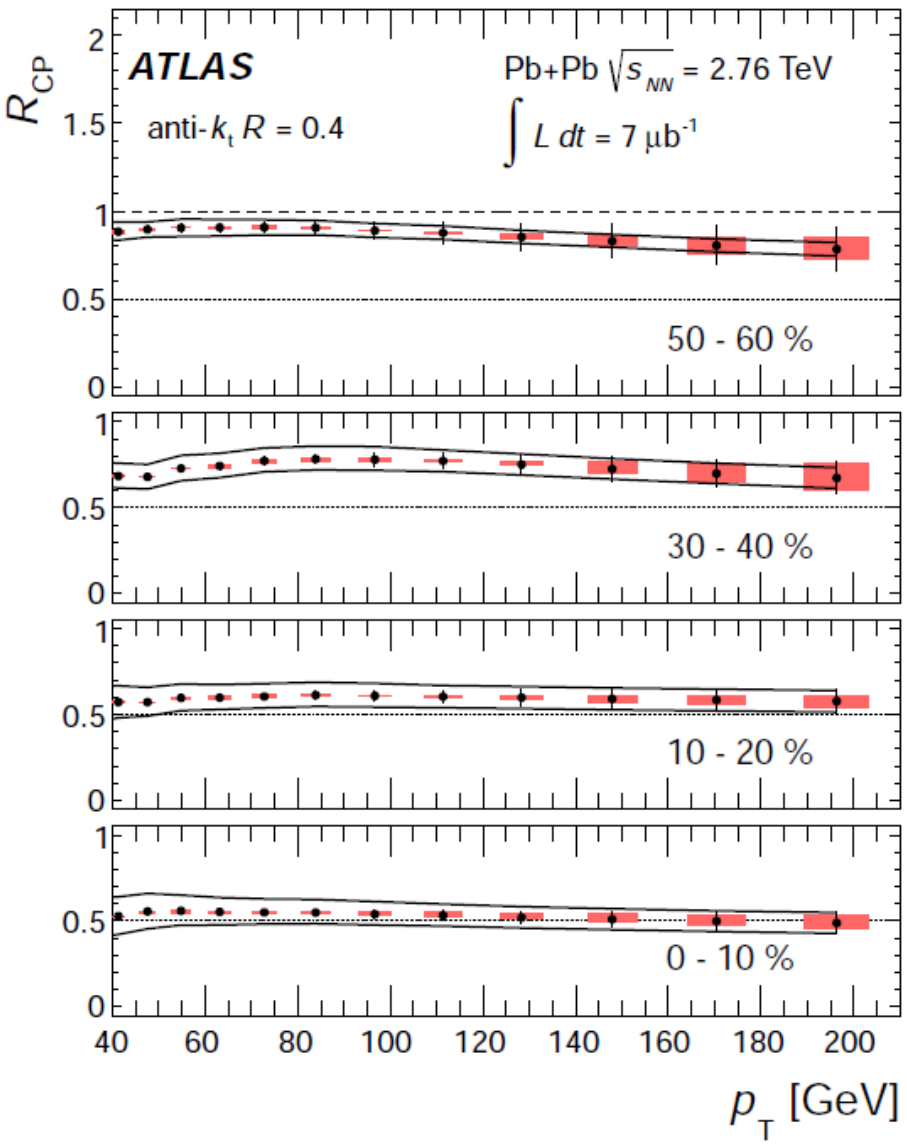
$$R_{\mathrm{CP}} = \frac{\frac{1}{N_{\mathrm{coll}}}\frac{1}{N_{\mathrm{evt}}}\frac{\mathrm{d}N}{\mathrm{d}p_{\mathrm{T}}}|_{cent}}{\frac{1}{N_{\mathrm{coll}}}\frac{1}{N_{\mathrm{evt}}}\frac{\mathrm{d}N}{\mathrm{d}p_{\mathrm{T}}}|_{60-80\%}}$$

- 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


ATLAS
Pb+Pb $\sqrt{s_{NN}}$ = 2.76 TeV
anti-k_t R = 0.2
$\int L\,dt$ = 7 μb^{-1}
50 - 60 %
30 - 40 %
10 - 20 %
0 - 10 %
R_{CP}
p_T [GeV]


ATLAS
Pb+Pb $\sqrt{s_{NN}}$ = 2.76 TeV
anti-k_t R = 0.4
$\int L\,dt$ = 7 μb^{-1}
50 - 60 %
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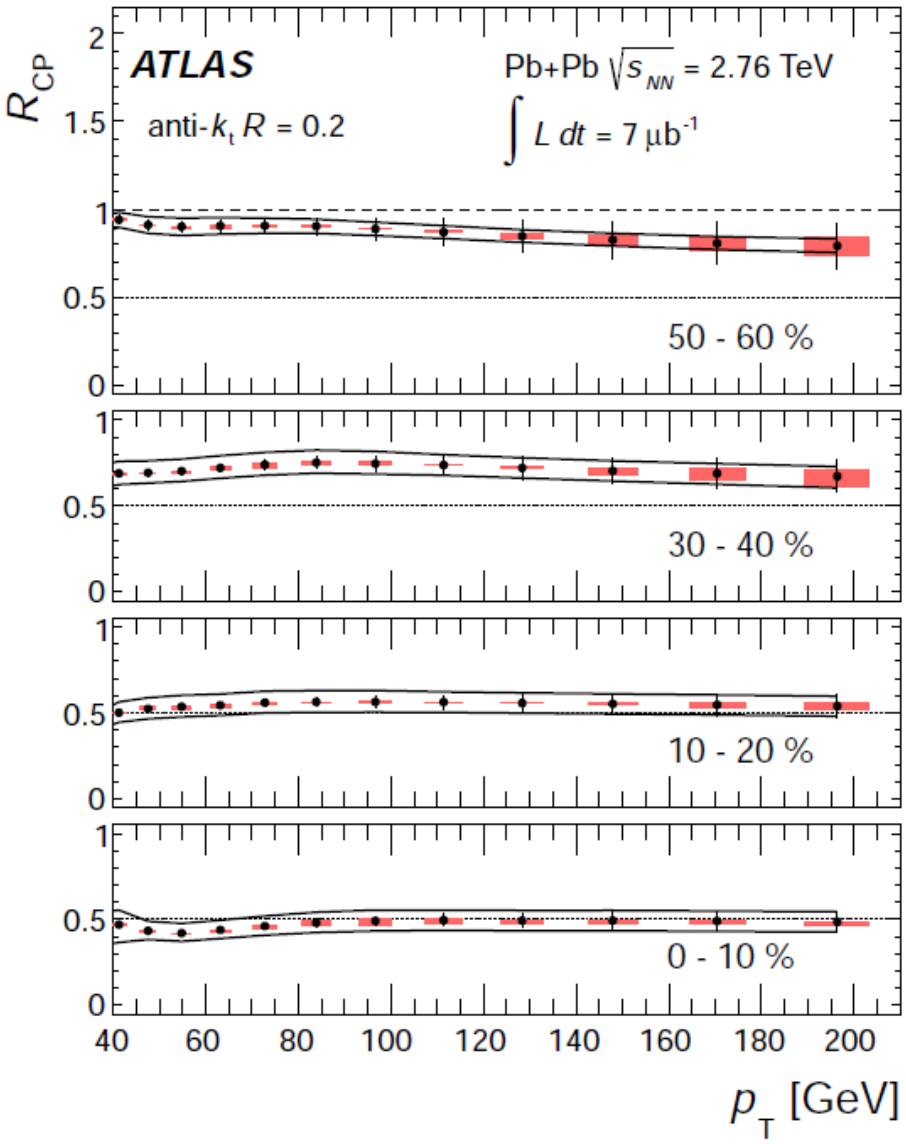
0 - 10 %
R_{CP}
p_T [GeV]

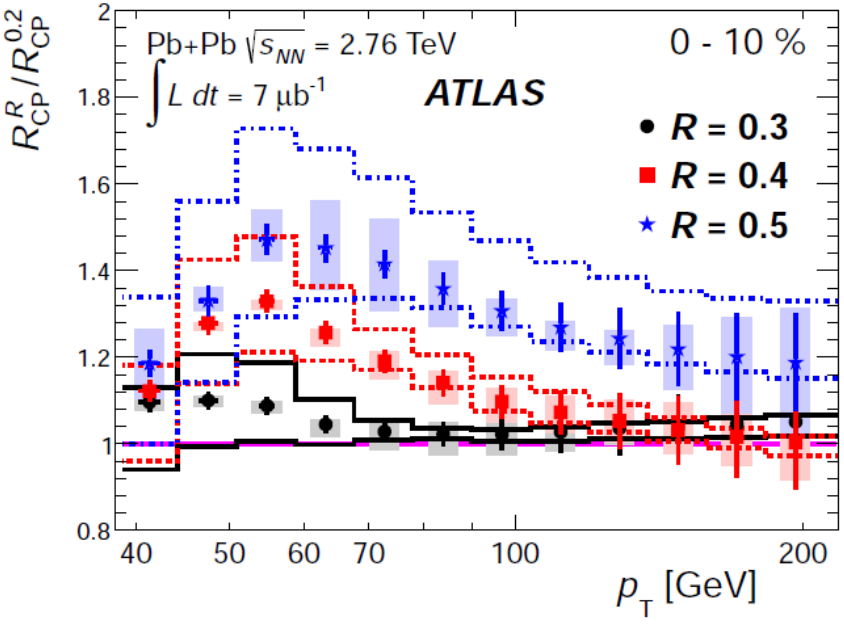
Jet R_{CP} vs p_T

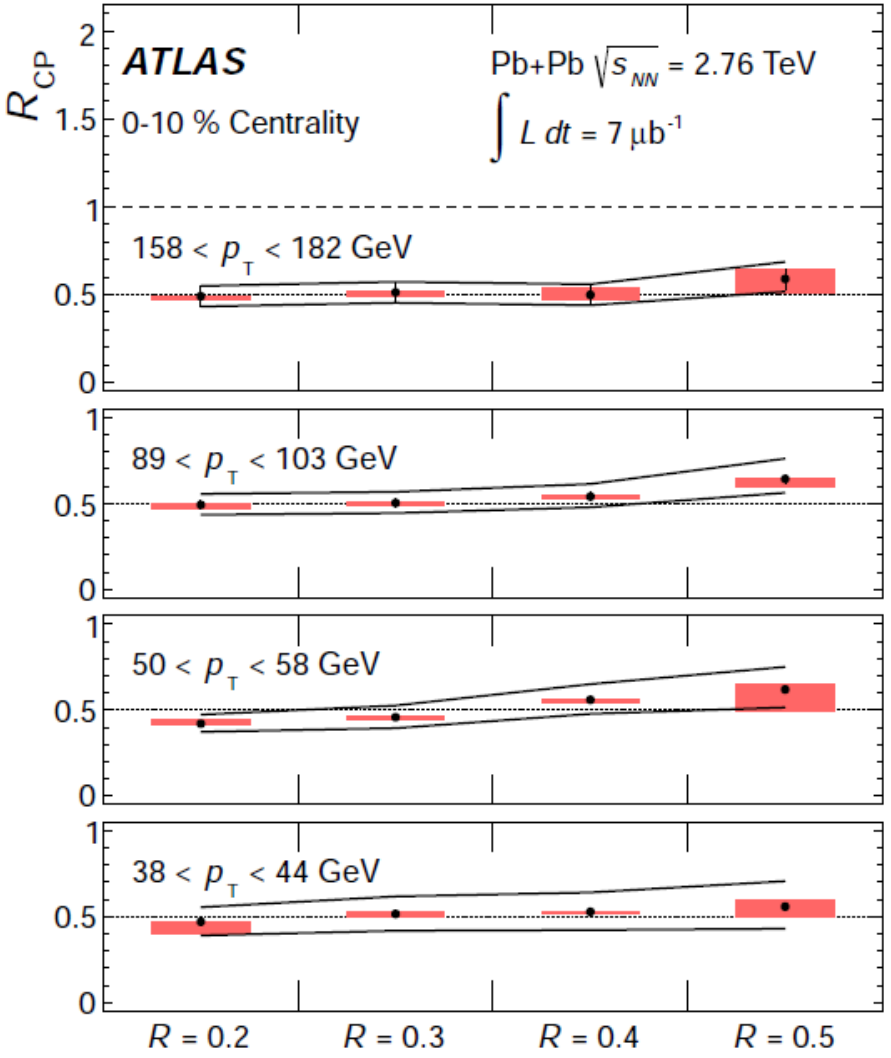


A: Suppression by a factor of 2 in central comparing to peripheral collisions. Suppression is almost independent on p_T.

Jet R_{CP} vs jet size

Q: Does the suppression depend on the jet radius?

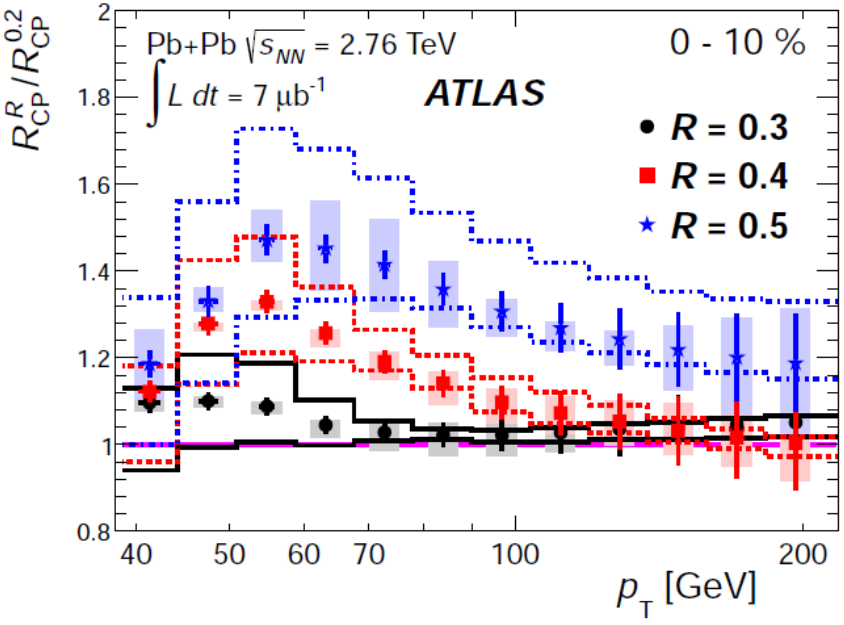


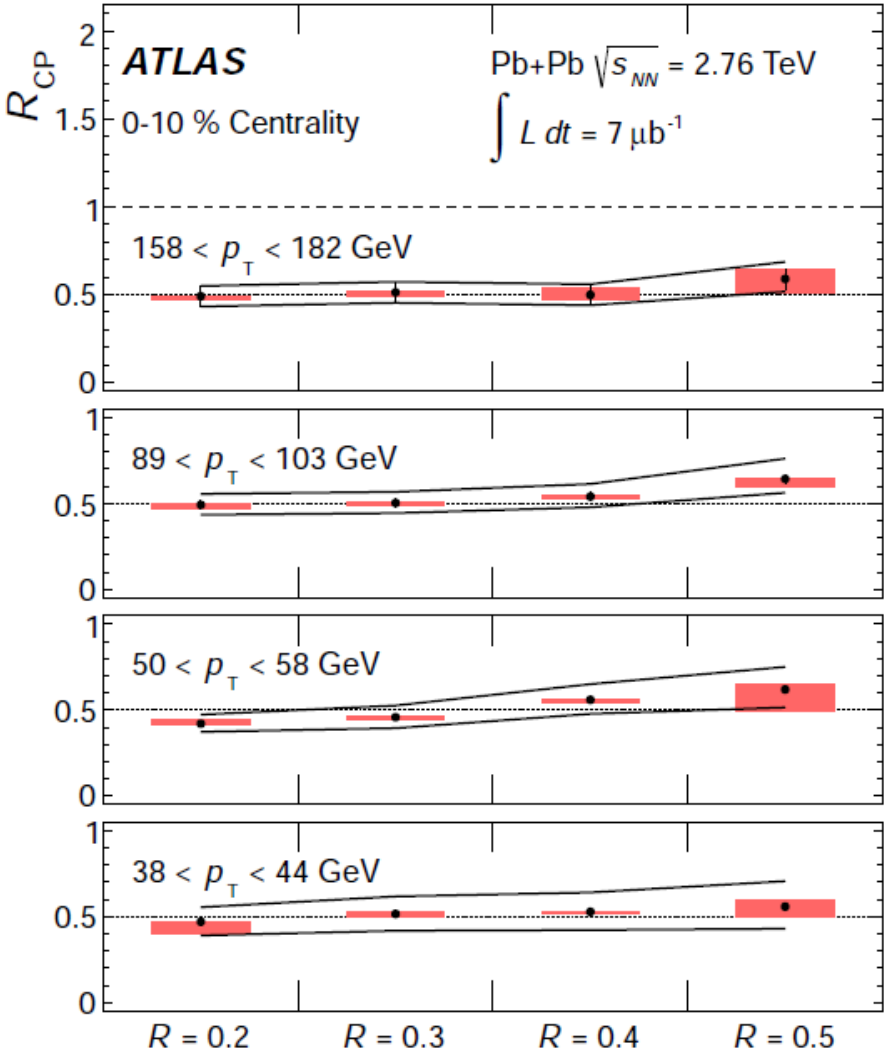


Jet R_{CP} vs jet size

A: Hint of slightly stronger suppression of smaller jets.

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





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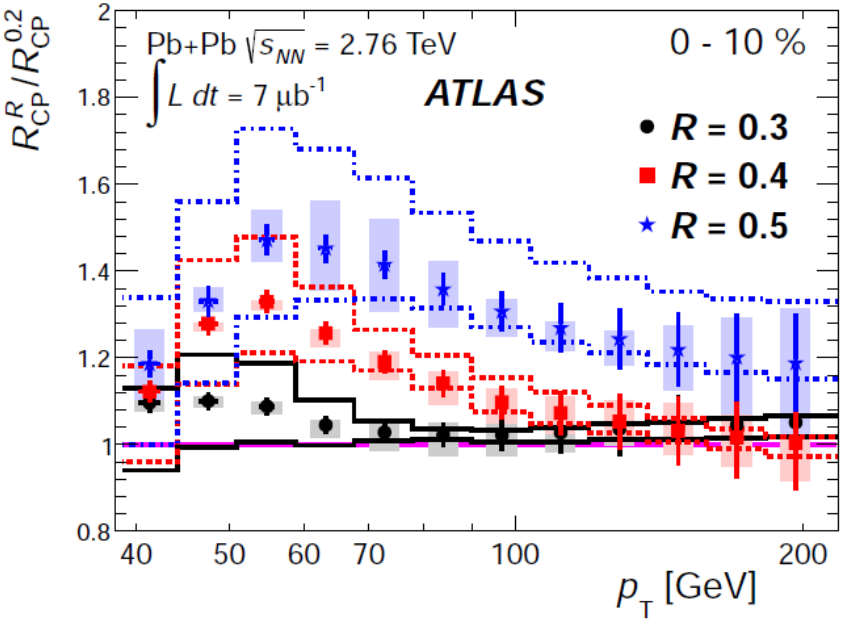

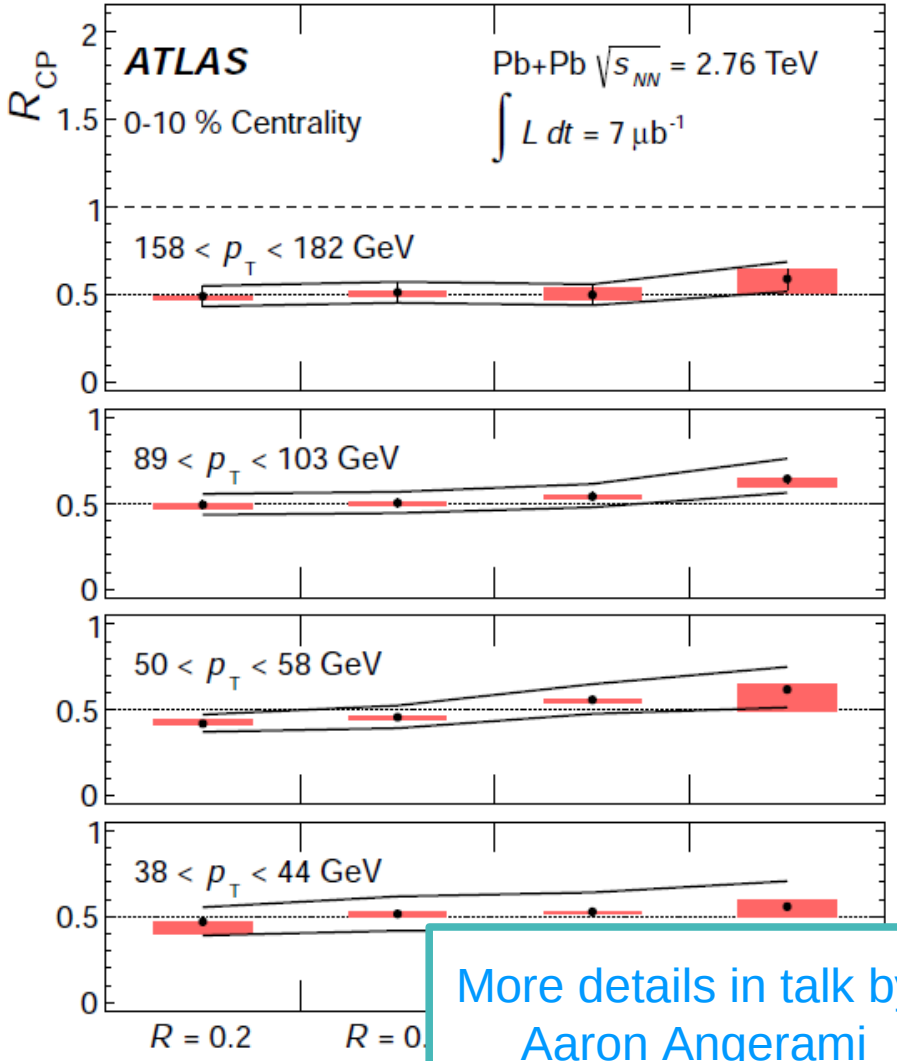

More details in talk by Aaron Angerami (Tue 5pm)

Jet suppression in other final states

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

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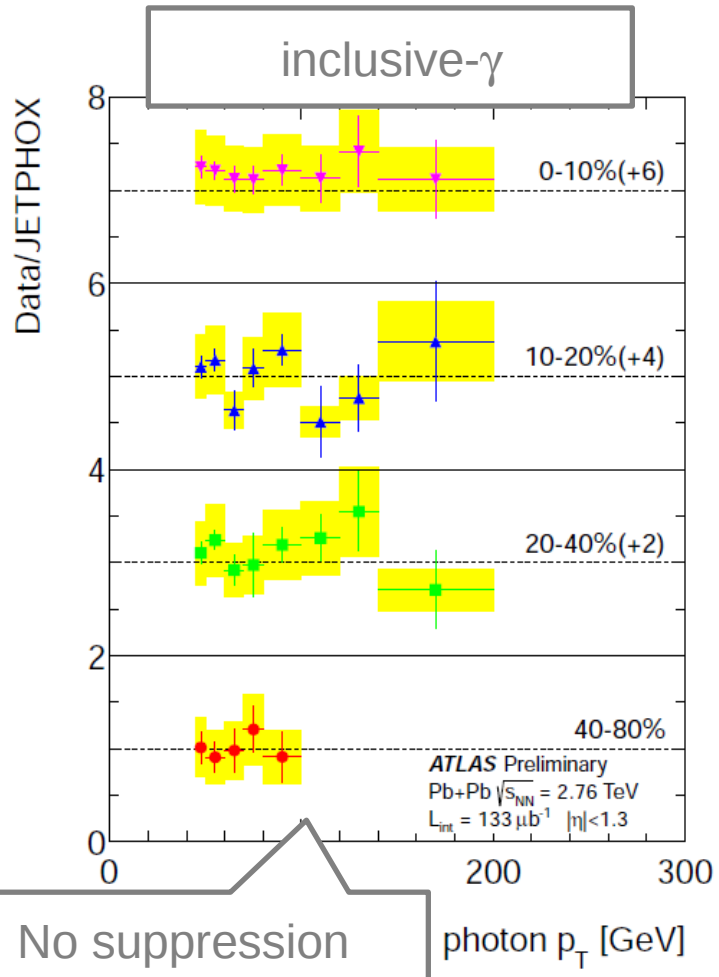
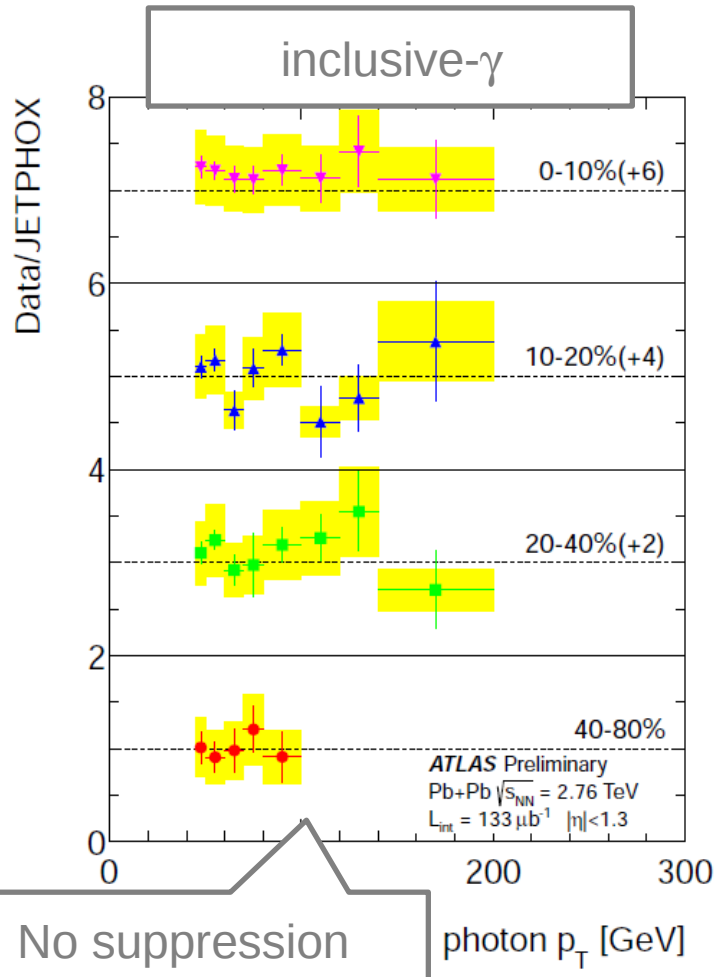
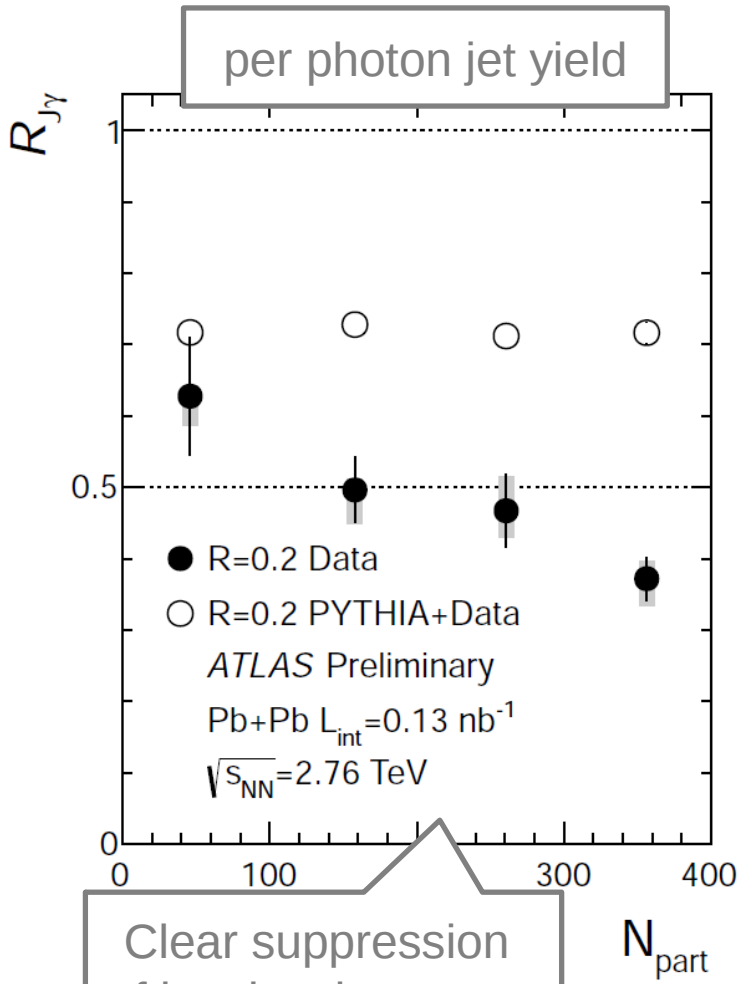


No suppression wrt to MC reference

Jet suppression in other final states

A: Yes. Inclusive-γ yields not suppressed but jets in γ-jet events suppressed.

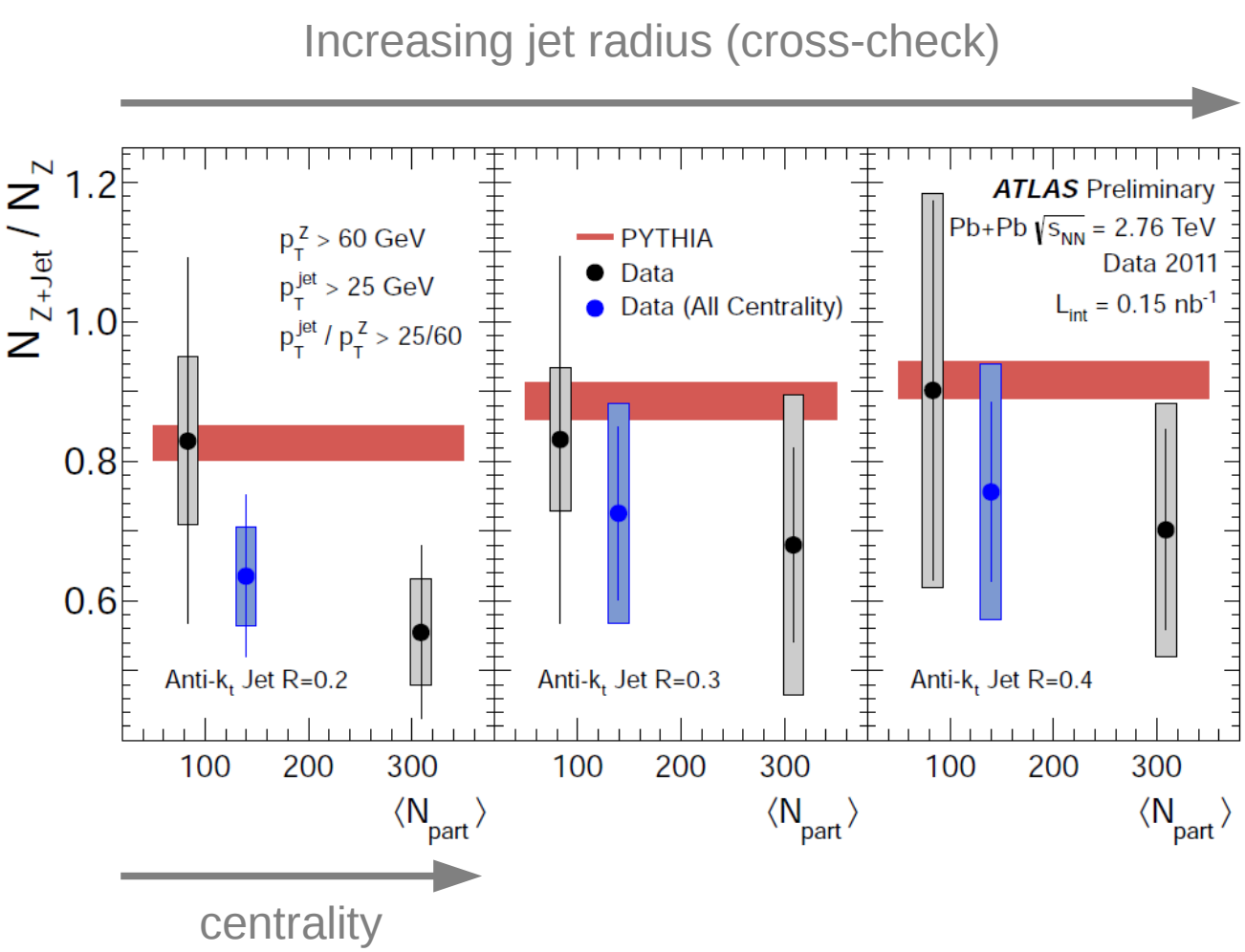




No suppression wrt to MC reference

Clear suppression of jets in γ-jet events

Jet suppression in other final states



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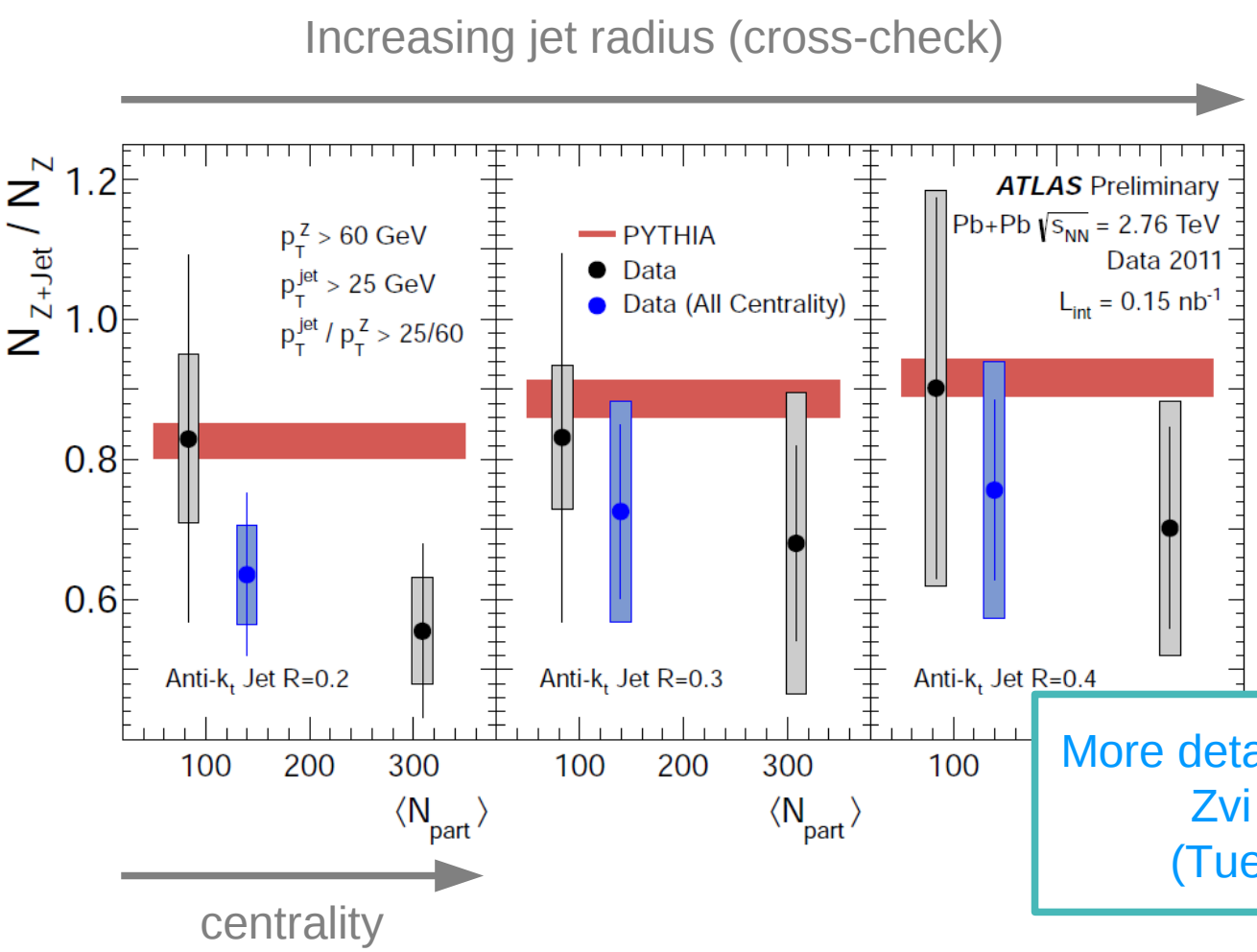


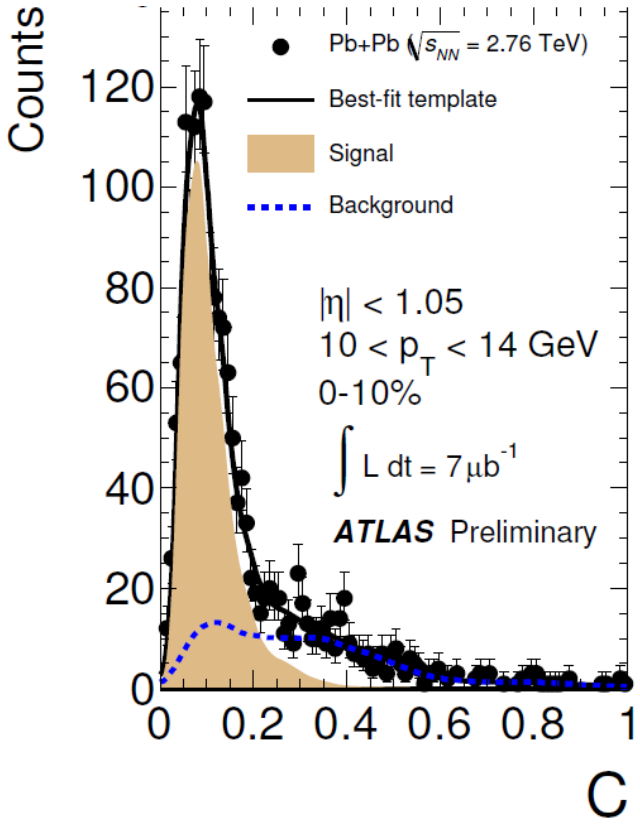
More details in talk by Zvi Citron (Tue 14:35)

… similar story seen for Z^0-jets

Heavy flavor

Q: Does the suppression depend on the flavor?

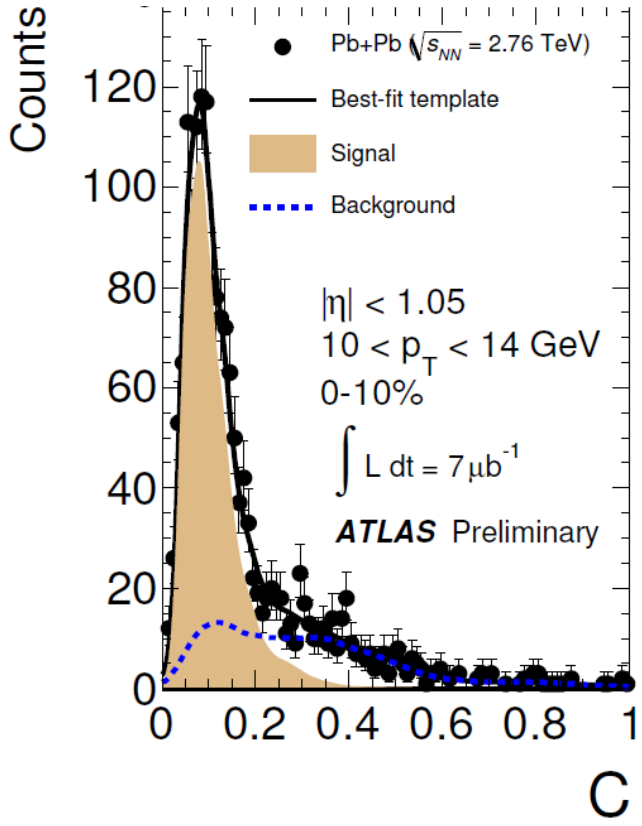
Heavy flavor

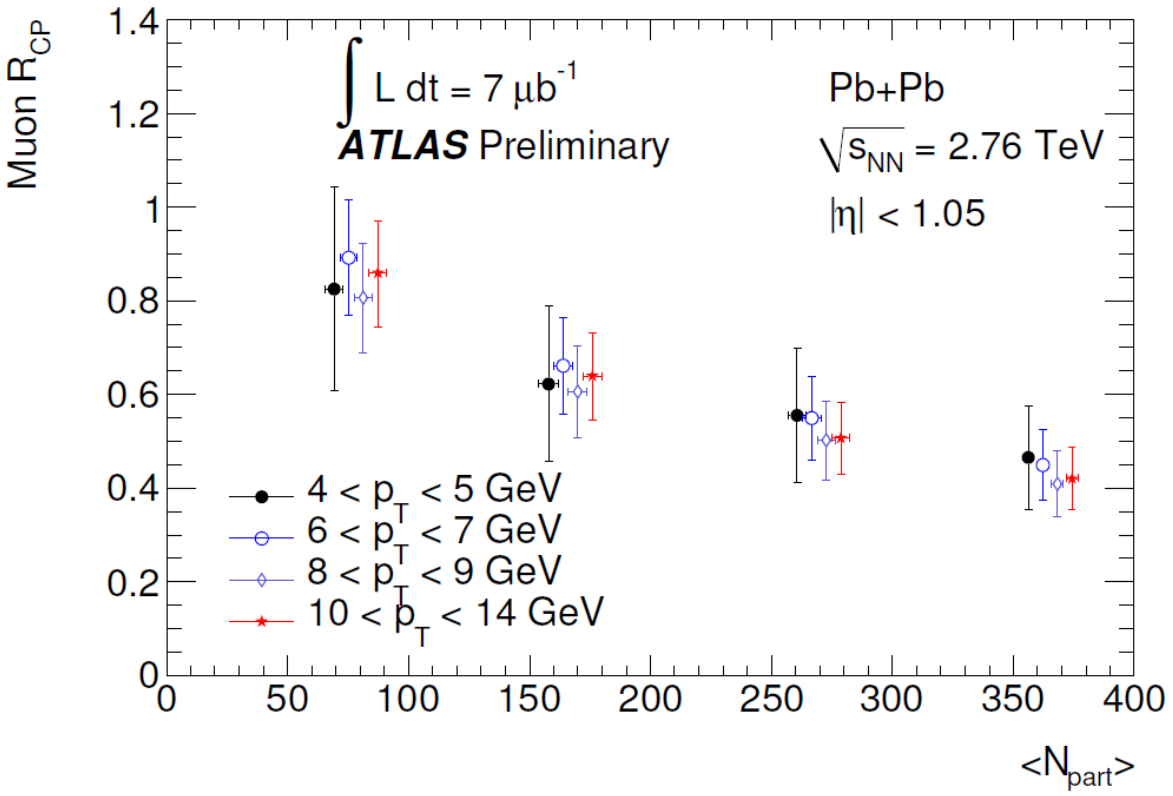


Q: Does the suppression depend on the flavor?

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

Heavy flavor



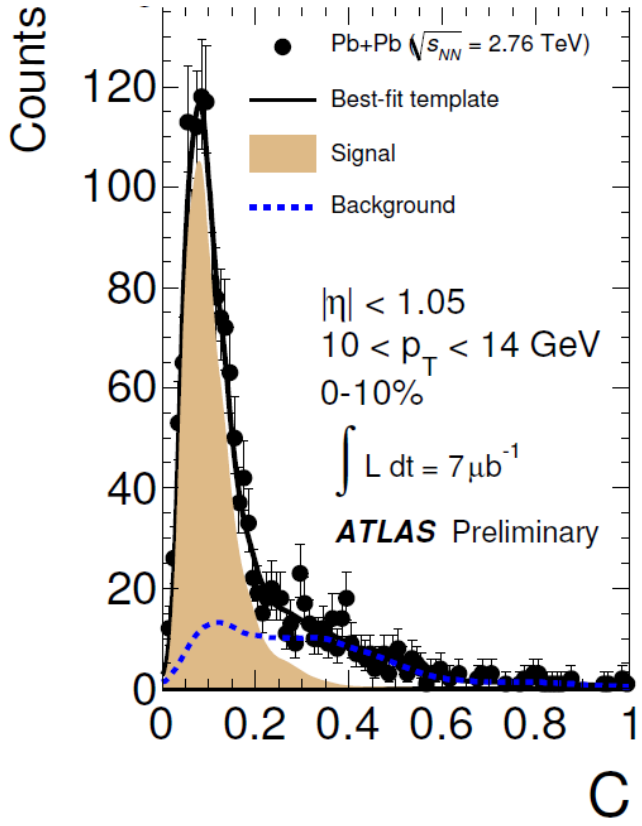


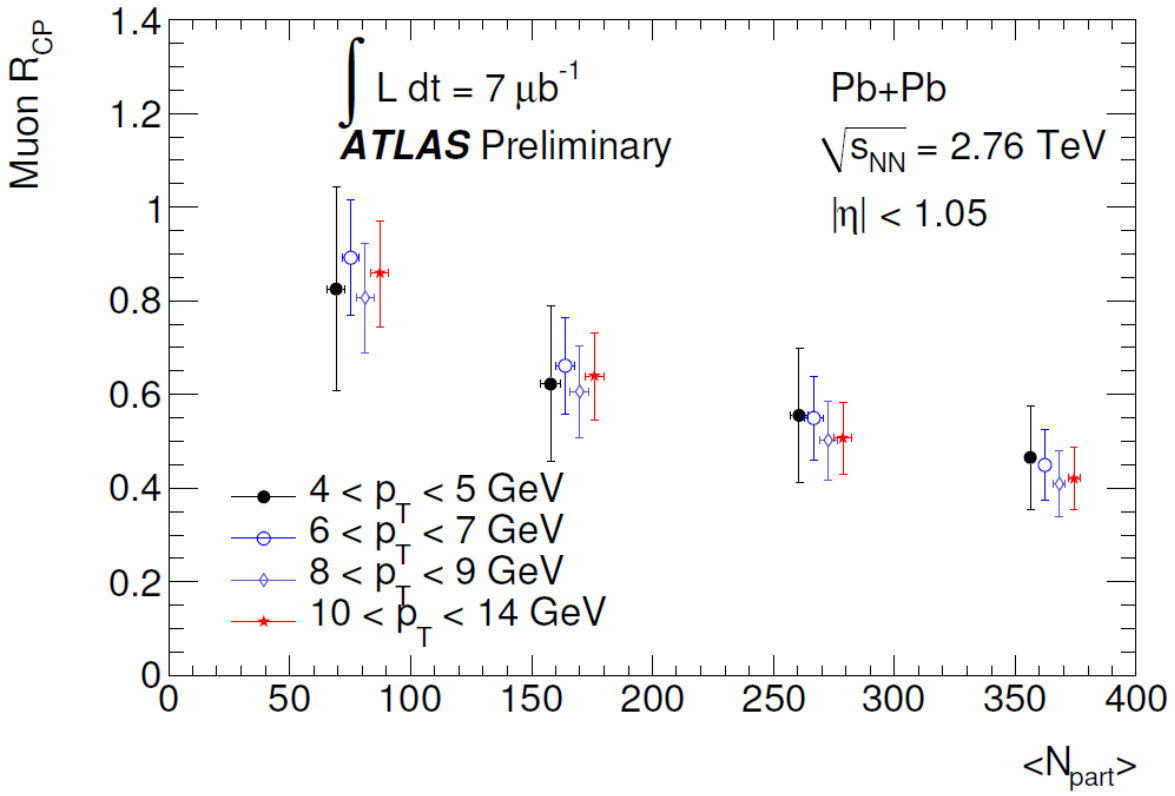
A: – R_{CP} of HF decreases smoothly from peripheral to central collisions.

– R_{CP} is p_T independent.

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

Heavy flavor





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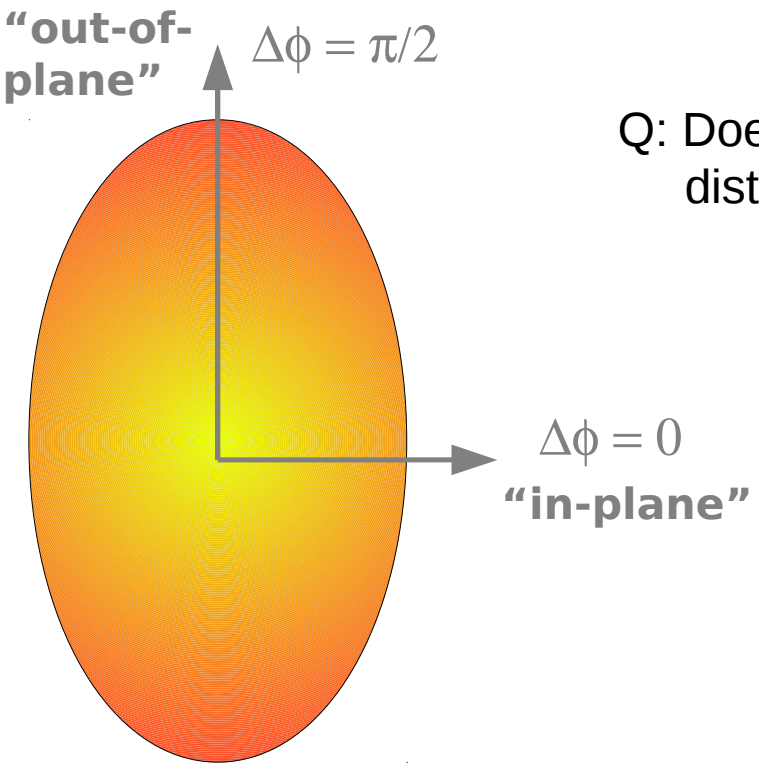
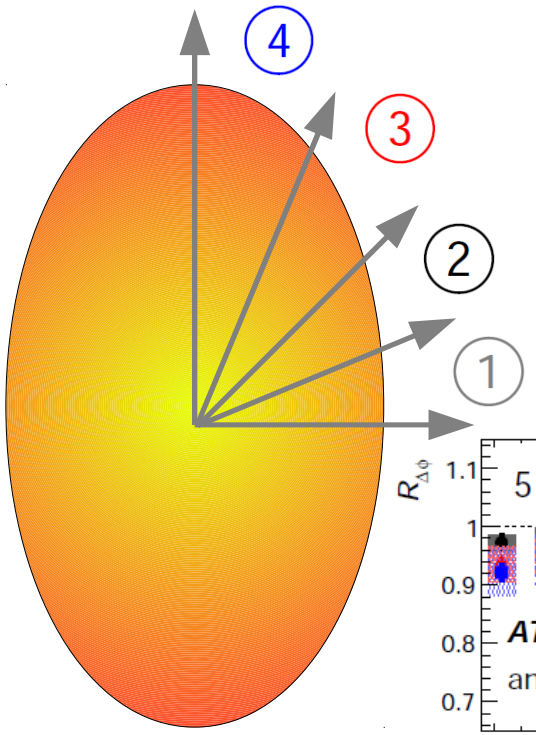
More details in talk by Dennis Perepelitsa (Fri 5pm)

Ψ dependence of jet suppression

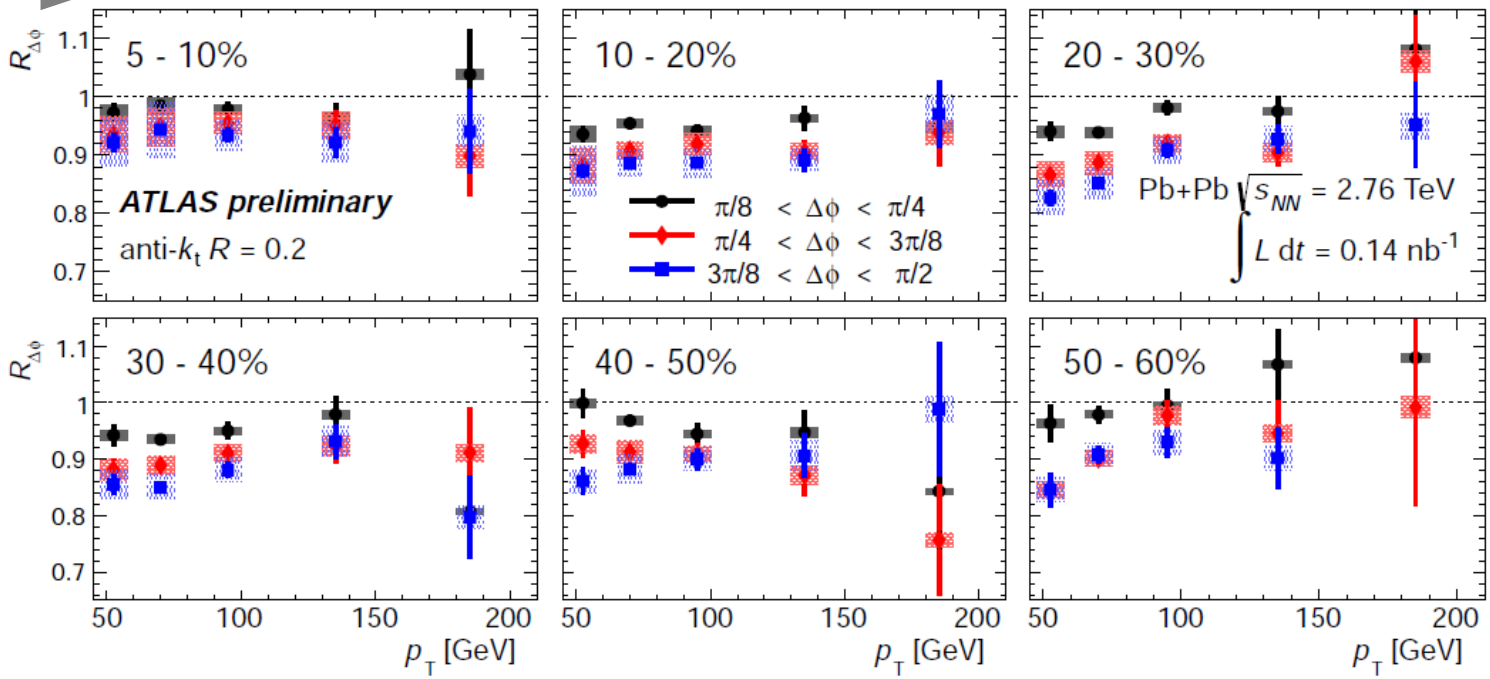


Q: Does the jet suppression depend on the azimuthal distance from the reaction plane? What is the jet v_2?

Ψ dependence of jet suppression



$$R_{\Delta\phi} = \frac{\frac{\mathrm{d}^2 N_{\mathrm{jet}}}{\mathrm{d}p_T \mathrm{d}\Delta\phi}\Big|_{\Delta\phi=(2),(3),(4)}}{\frac{\mathrm{d}^2 N_{\mathrm{jet}}}{\mathrm{d}p_T \mathrm{d}\Delta\phi}\Big|_{\Delta\phi=(1)}}$$



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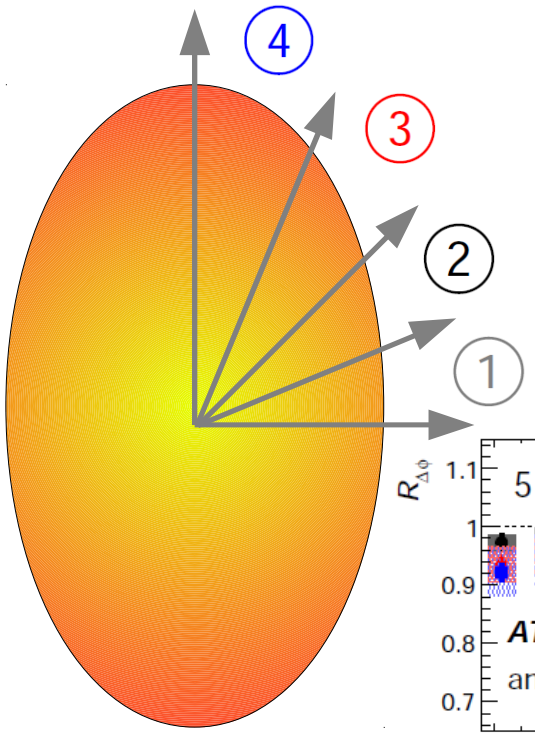
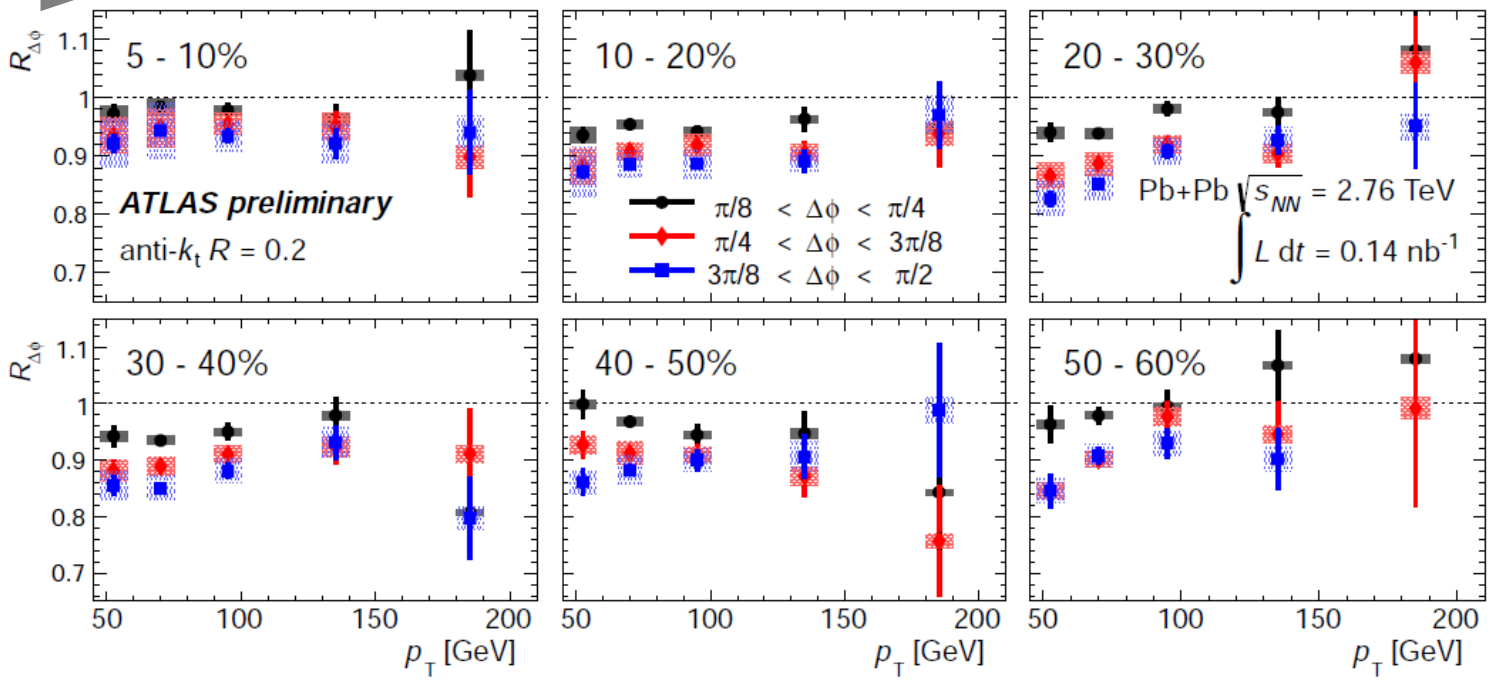
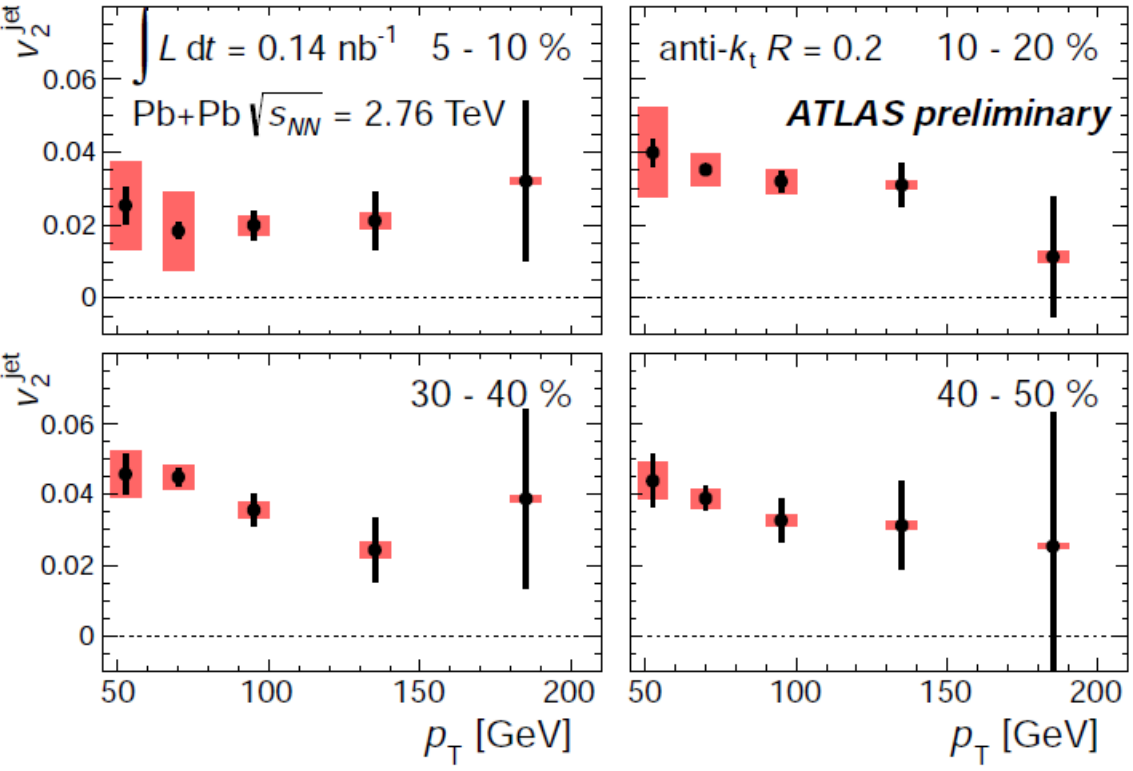


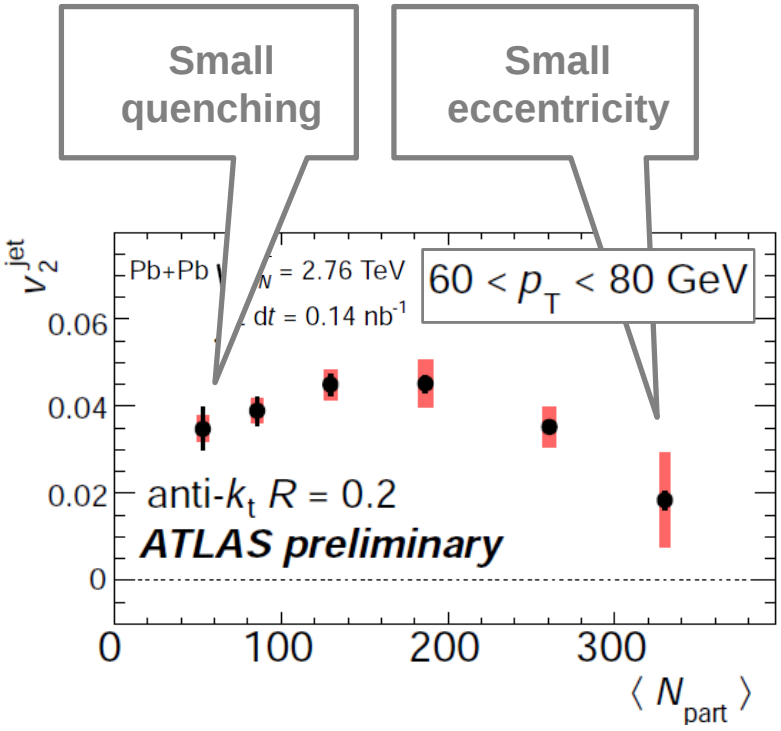
A: A suppression by as much as 15% seen for out-of-plane jets comparing to in-plane jets.



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?

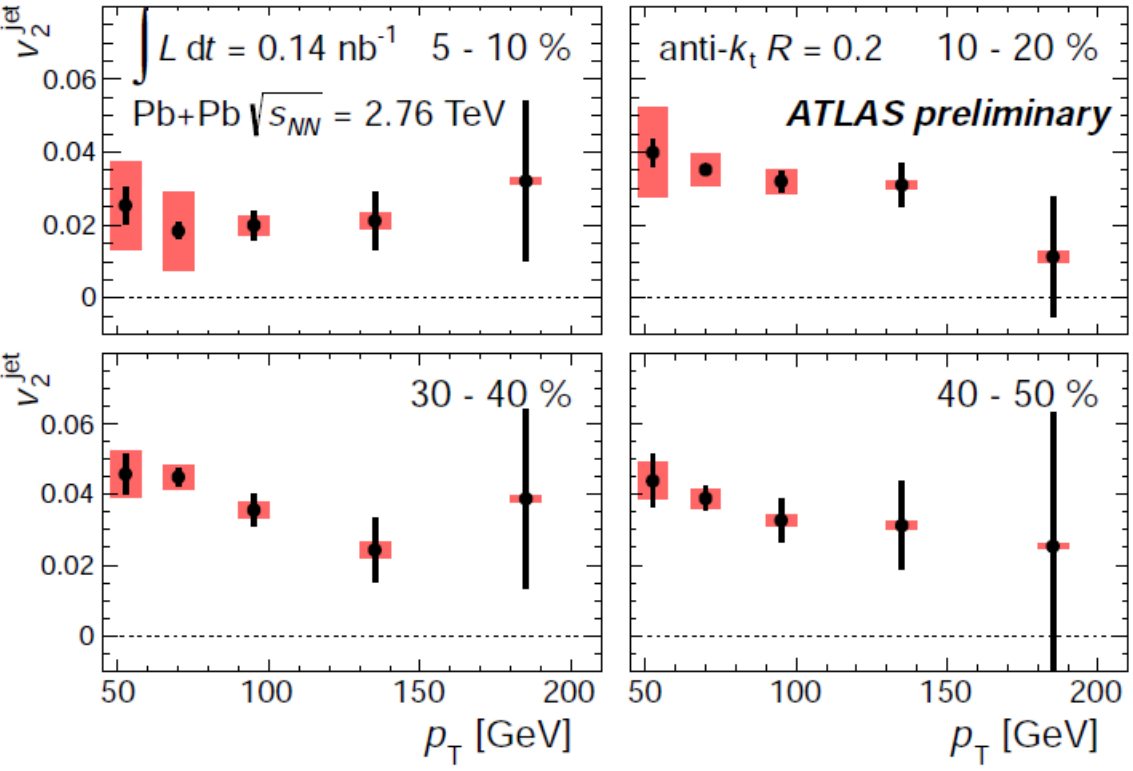


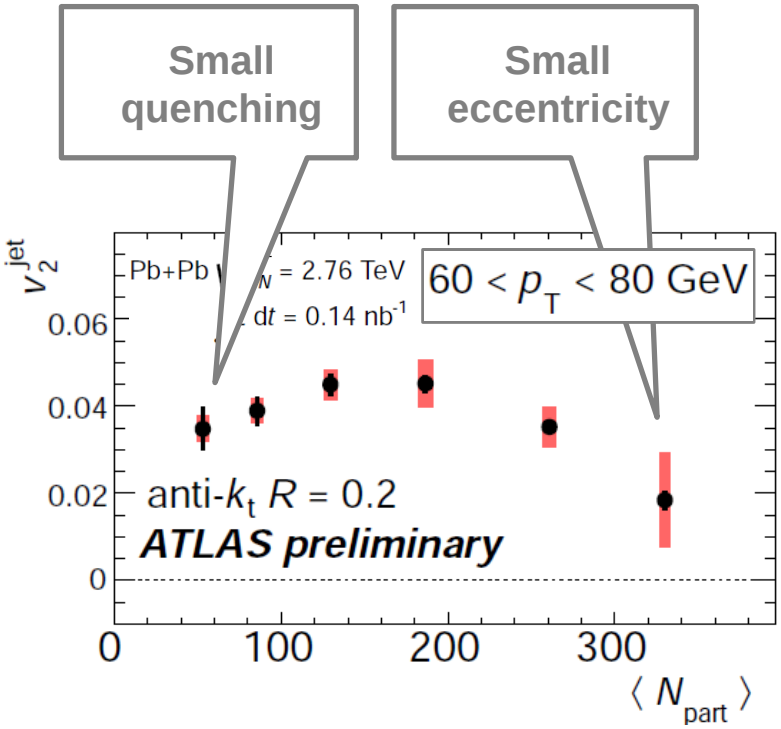


Ψ dependence of jet suppression

A: – jet v_2 of 0.02-0.04

– no jet p_T dependence observed for v_2





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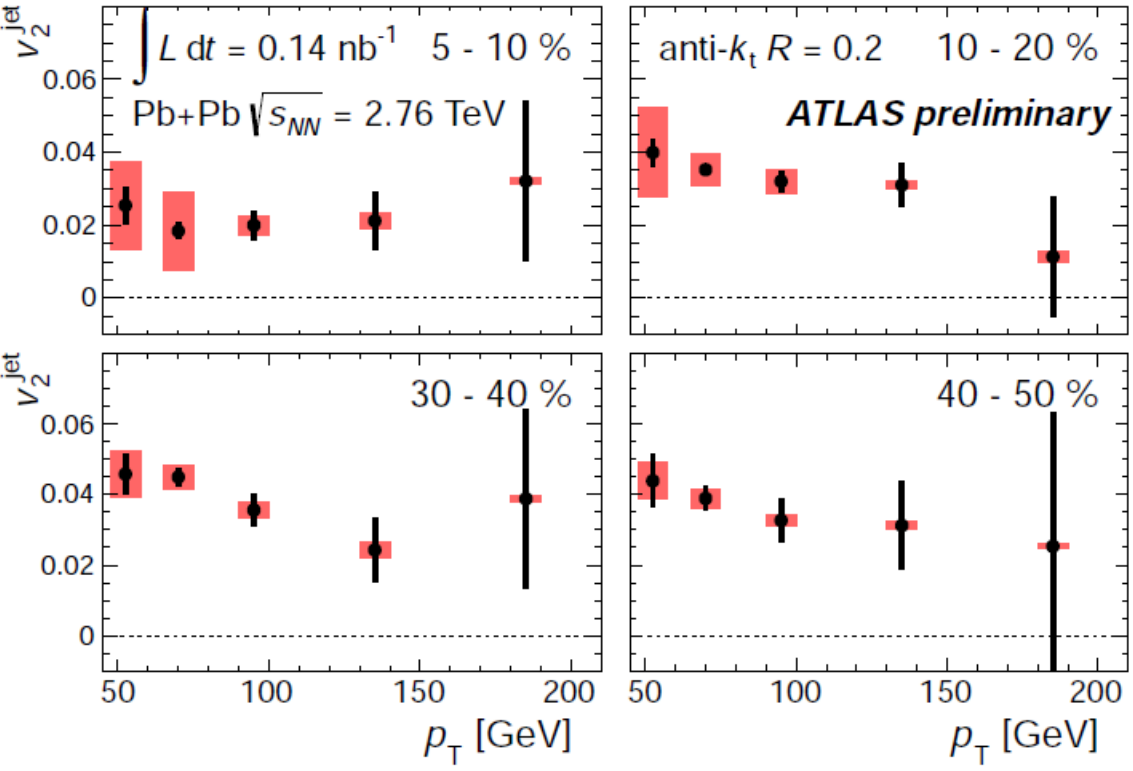
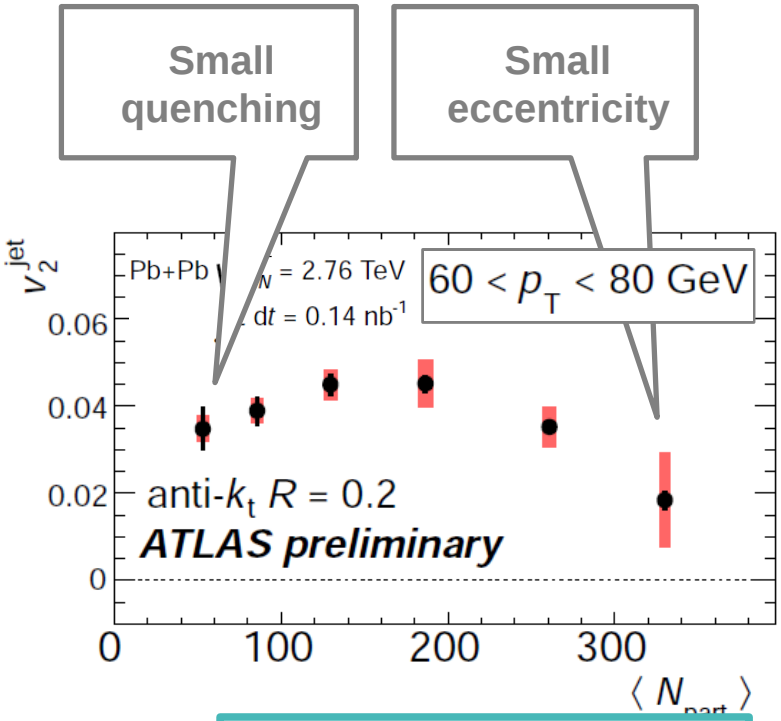




More details in talk by Aaron Angerami (Tue 5pm)

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

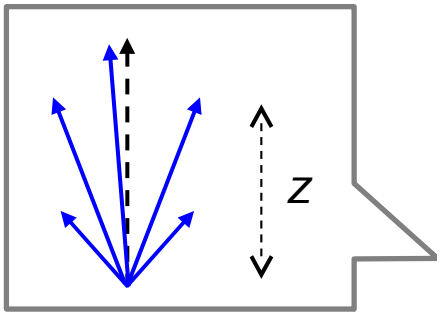
$$= \frac{1}{N_{jet}(p_{\mathrm{T}}^{jet})} \frac{1}{\epsilon(p_{\mathrm{T}}, \eta)} \left(\frac{\Delta N_{ch}(p_{\mathrm{T}}, p_{\mathrm{T}}^{jet})}{\Delta p_{\mathrm{T}}} - \frac{\Delta N_{ch}^{UE}(p_{\mathrm{T}}, p_{\mathrm{T}}^{jet})}{\Delta p_{\mathrm{T}}} \right)$$

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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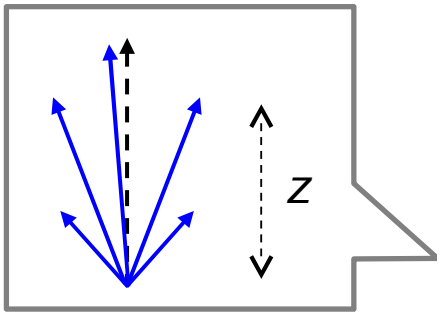
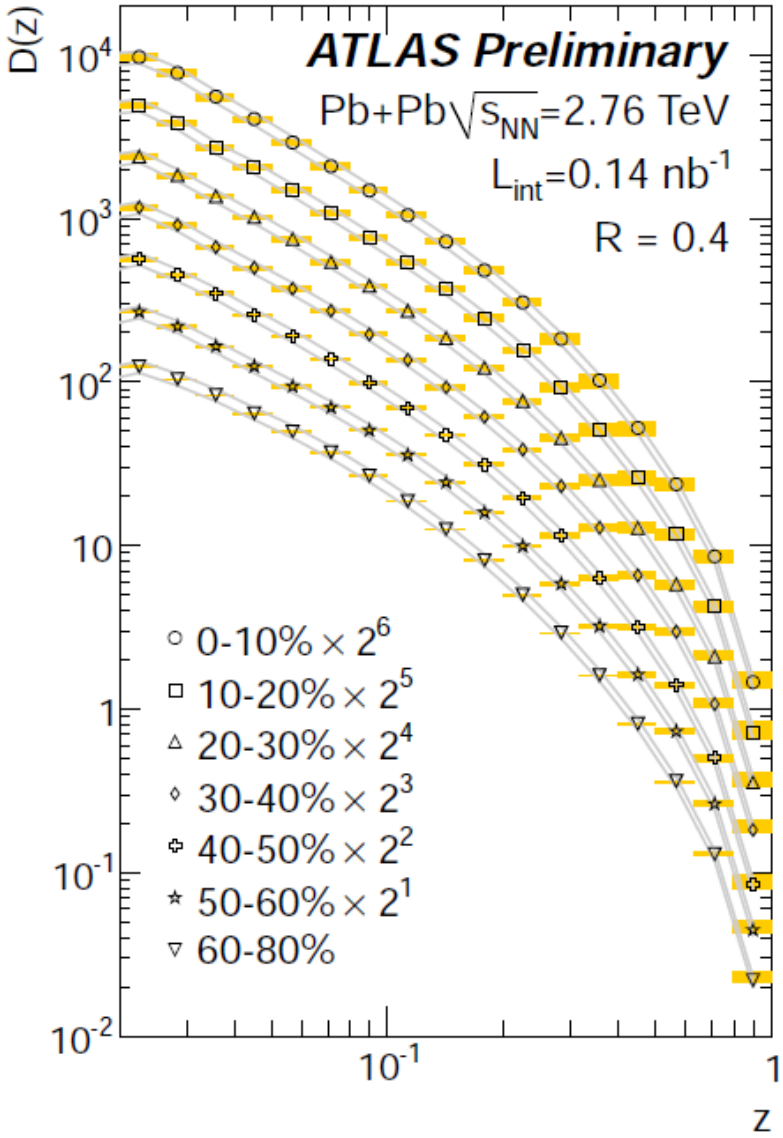


$$z = p_{\mathrm{T}} / p_{\mathrm{T}}^{jet} \cos \Delta R$$

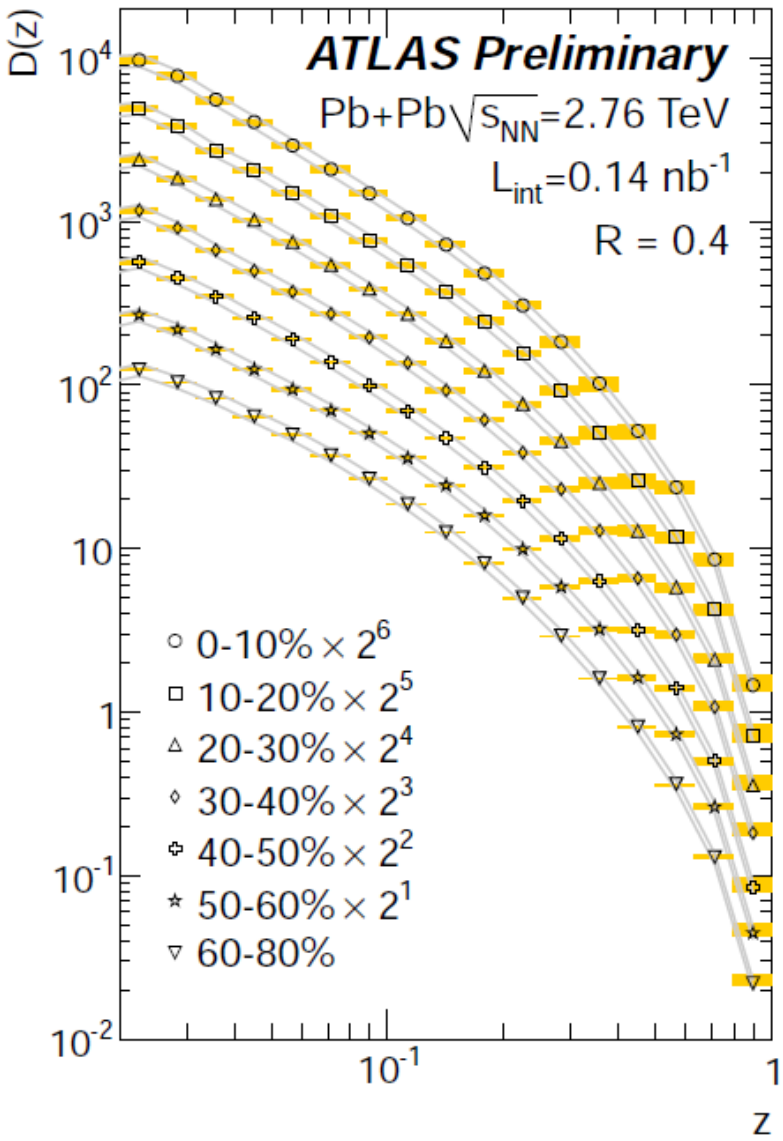
Q: Is the jet structure modified?

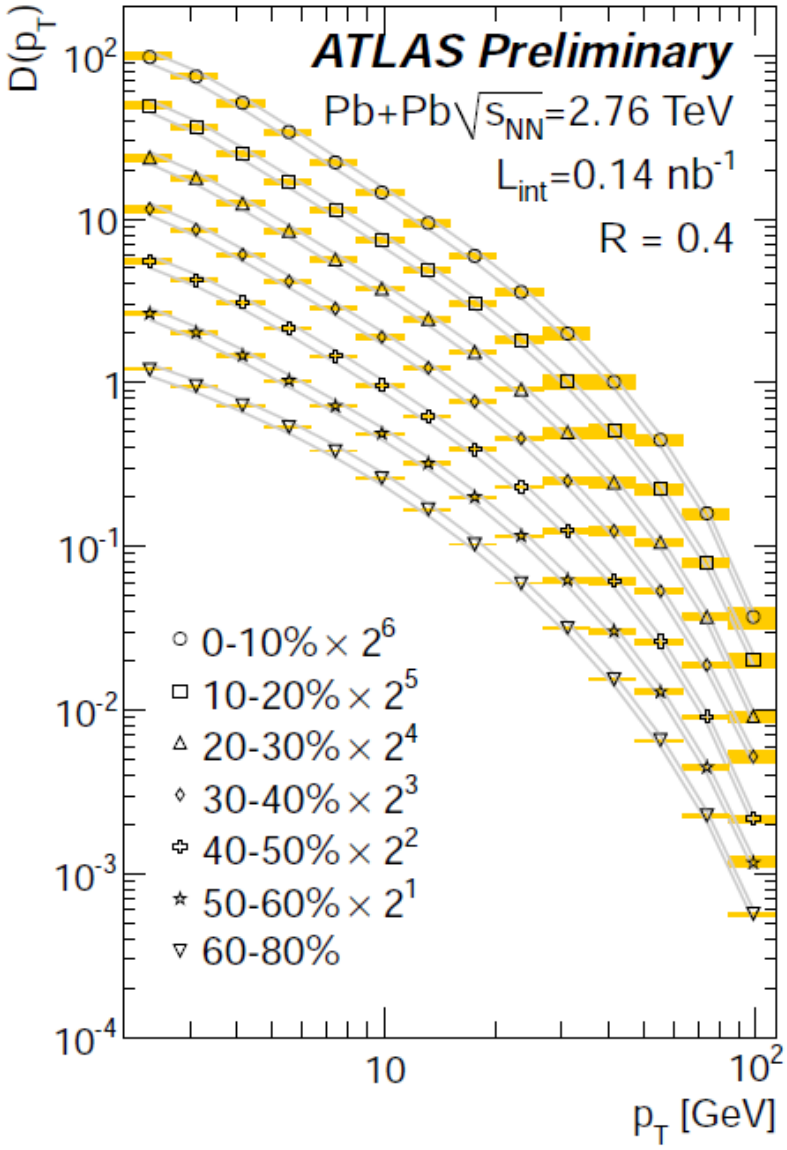
Jet fragmentation



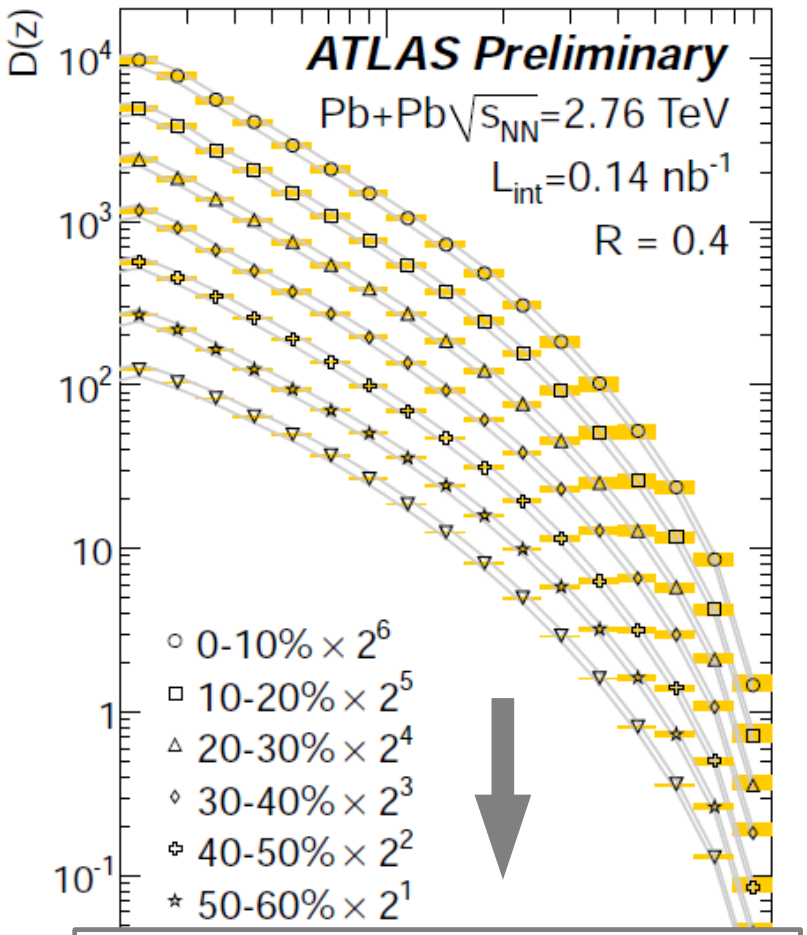
- Result unfolded using SVD unfolding to remove detector effects (e.g. jet energy resolution, tracking momentum resolution).
- Systematic uncertainties:
  - gray band: fully bin-wise correlated (tracking efficiency)
  - yellow boxes: partially correlated (jet energy scale and resolution, tracking efficiency,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

Jet fragmentation

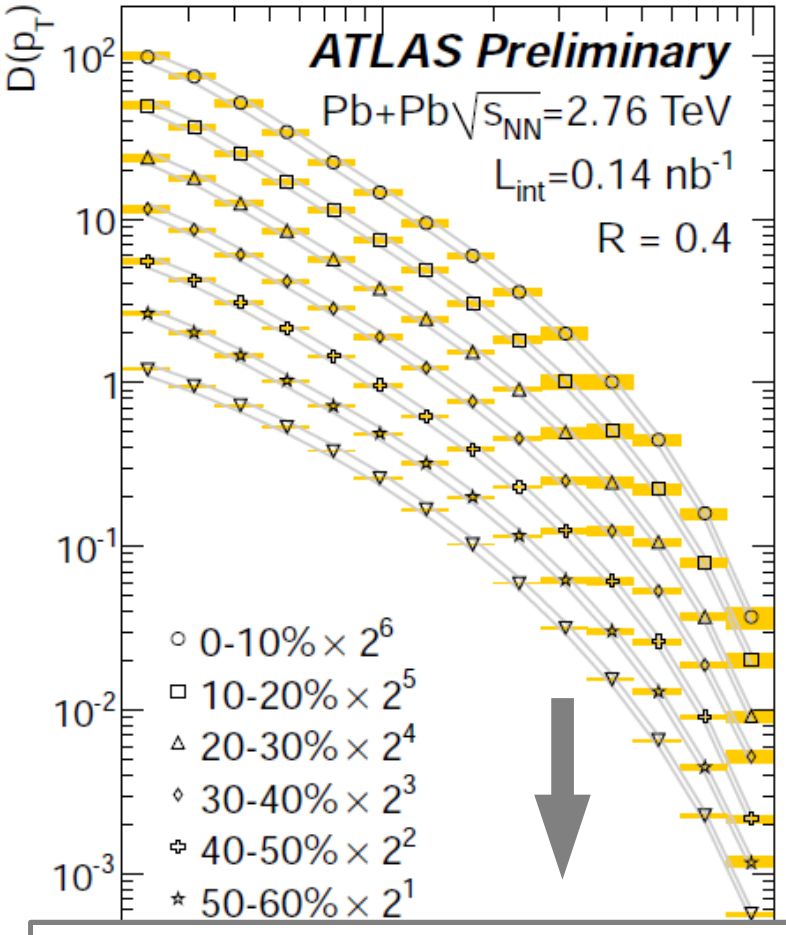




Jet fragmentation



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

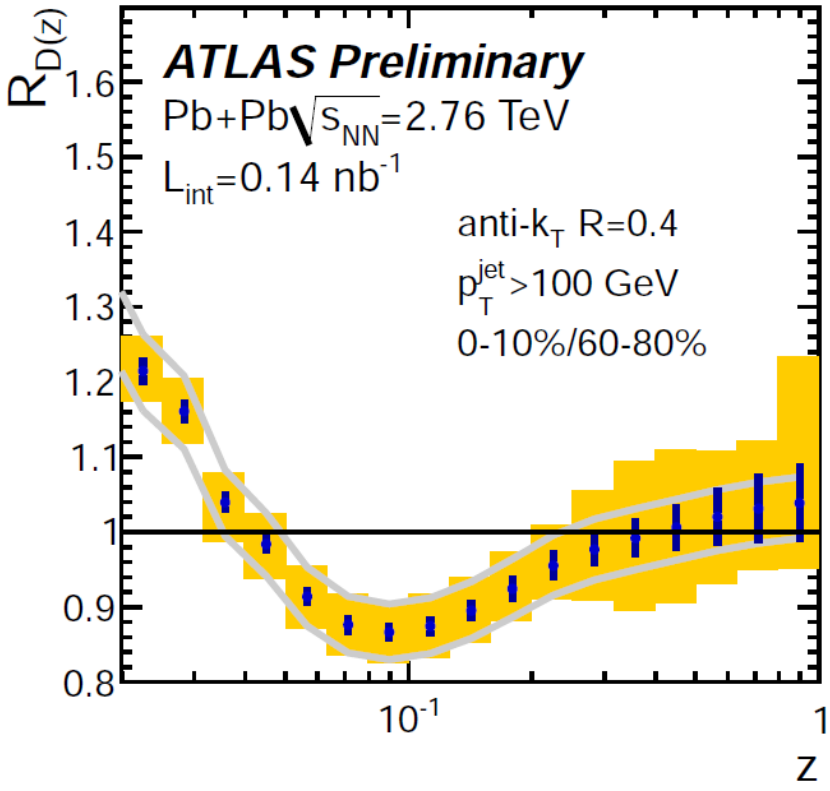


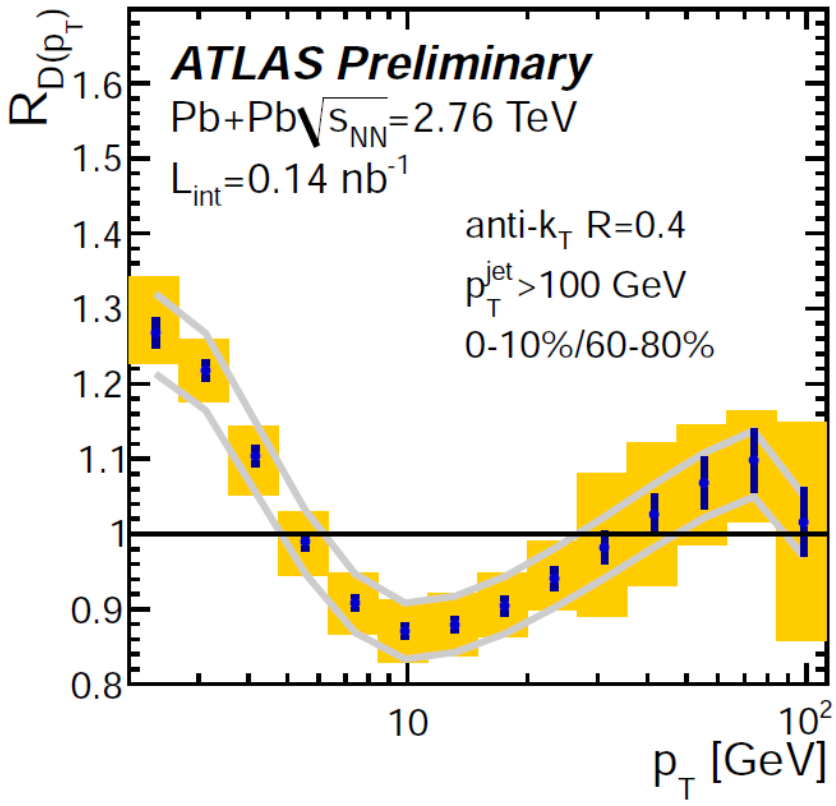
$$R_{\mathrm{D(p_T)}} = \frac{\mathrm{D}(p_T)|_{\mathrm{cent}}}{\mathrm{D}(p_T)|_{60-80\%}}$$

Jet fragmentation

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

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

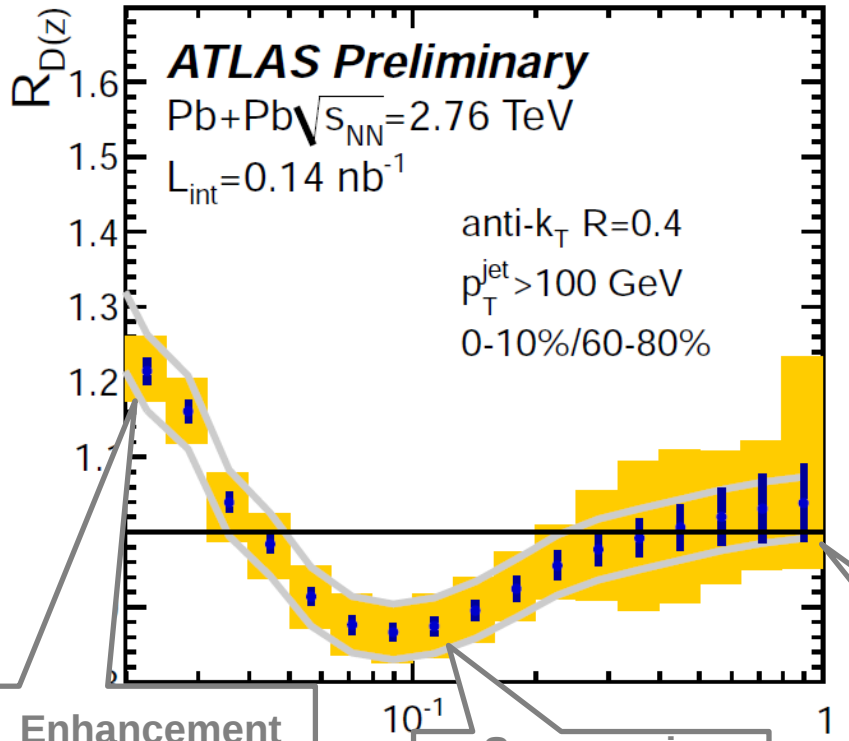


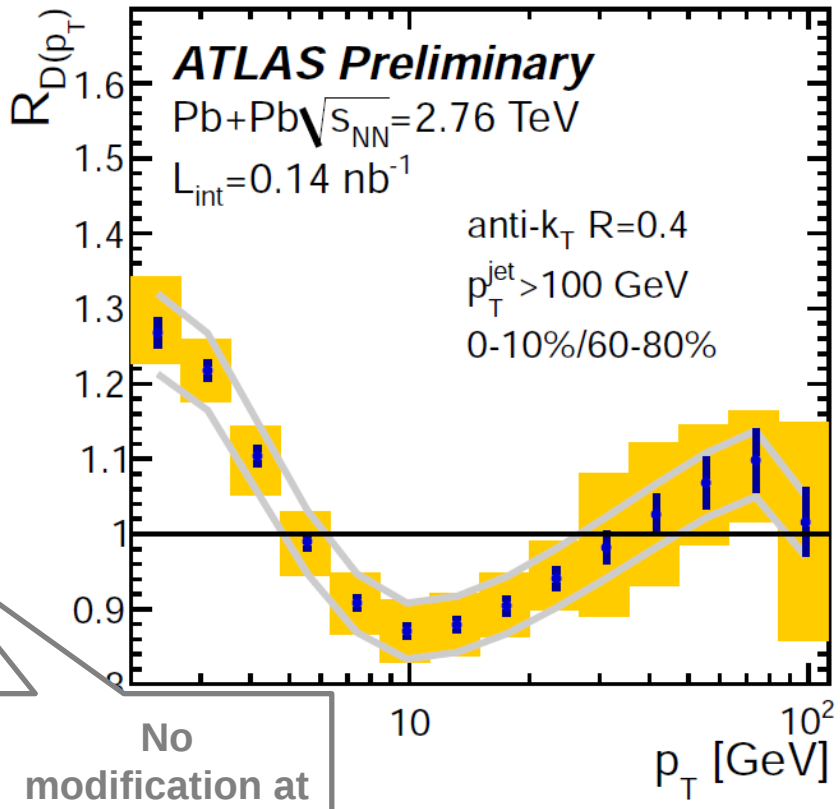


Jet fragmentation

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

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



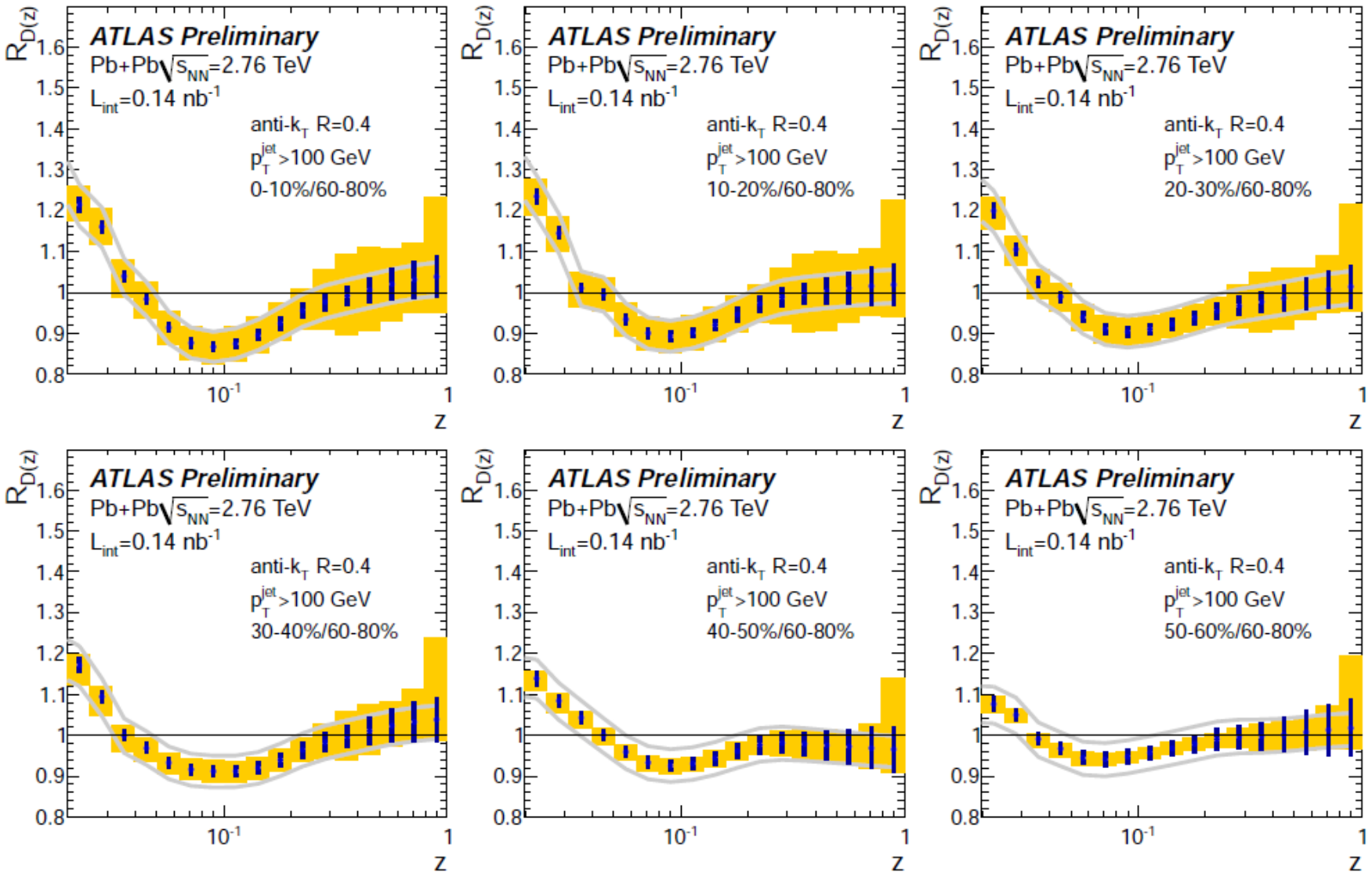


Enhancement at low-z (or low- p_T)

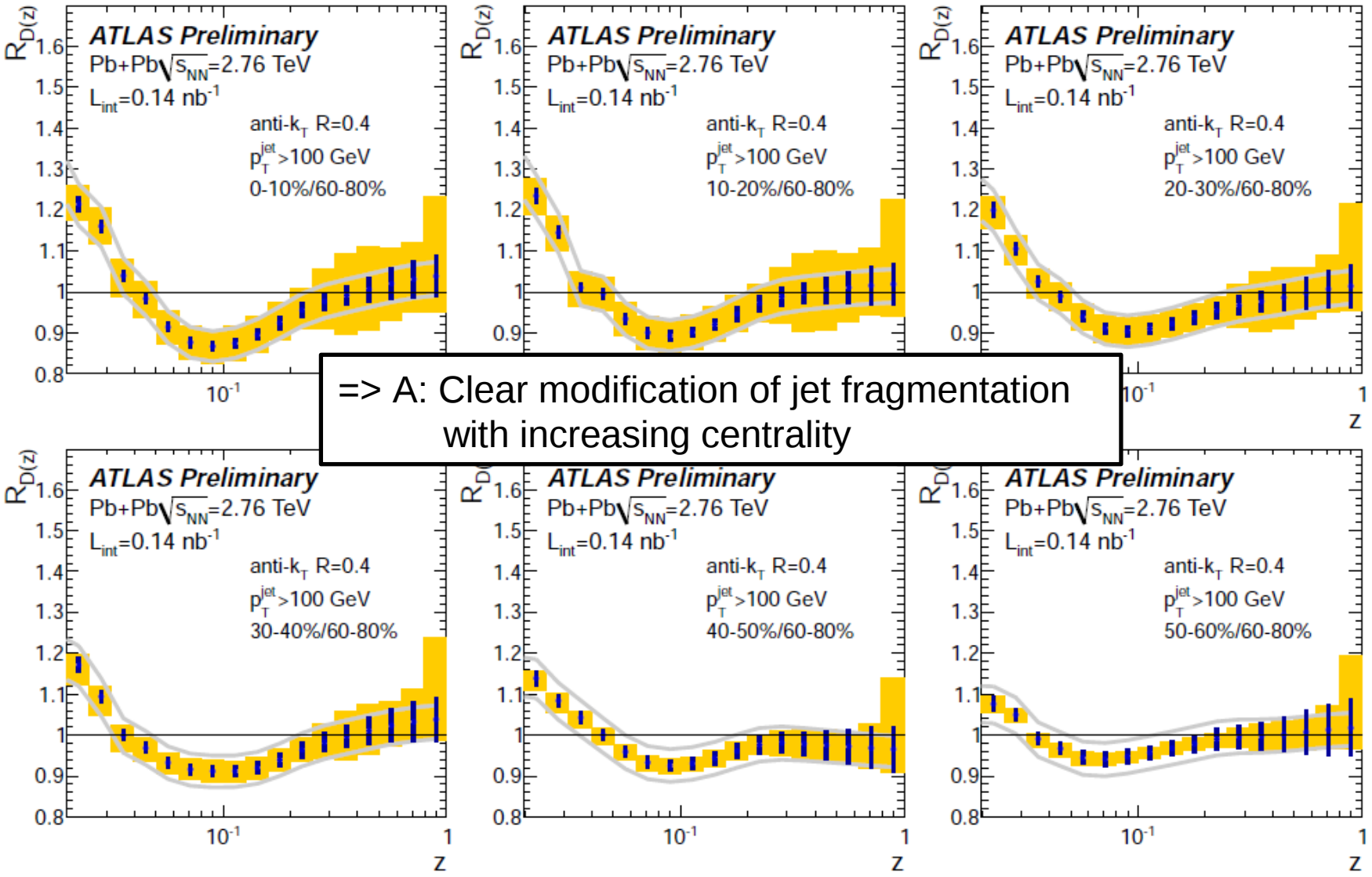
Suppression at intermediate-z (or p_T)

No modification at high-z (or p_T)

Jet fragmentation

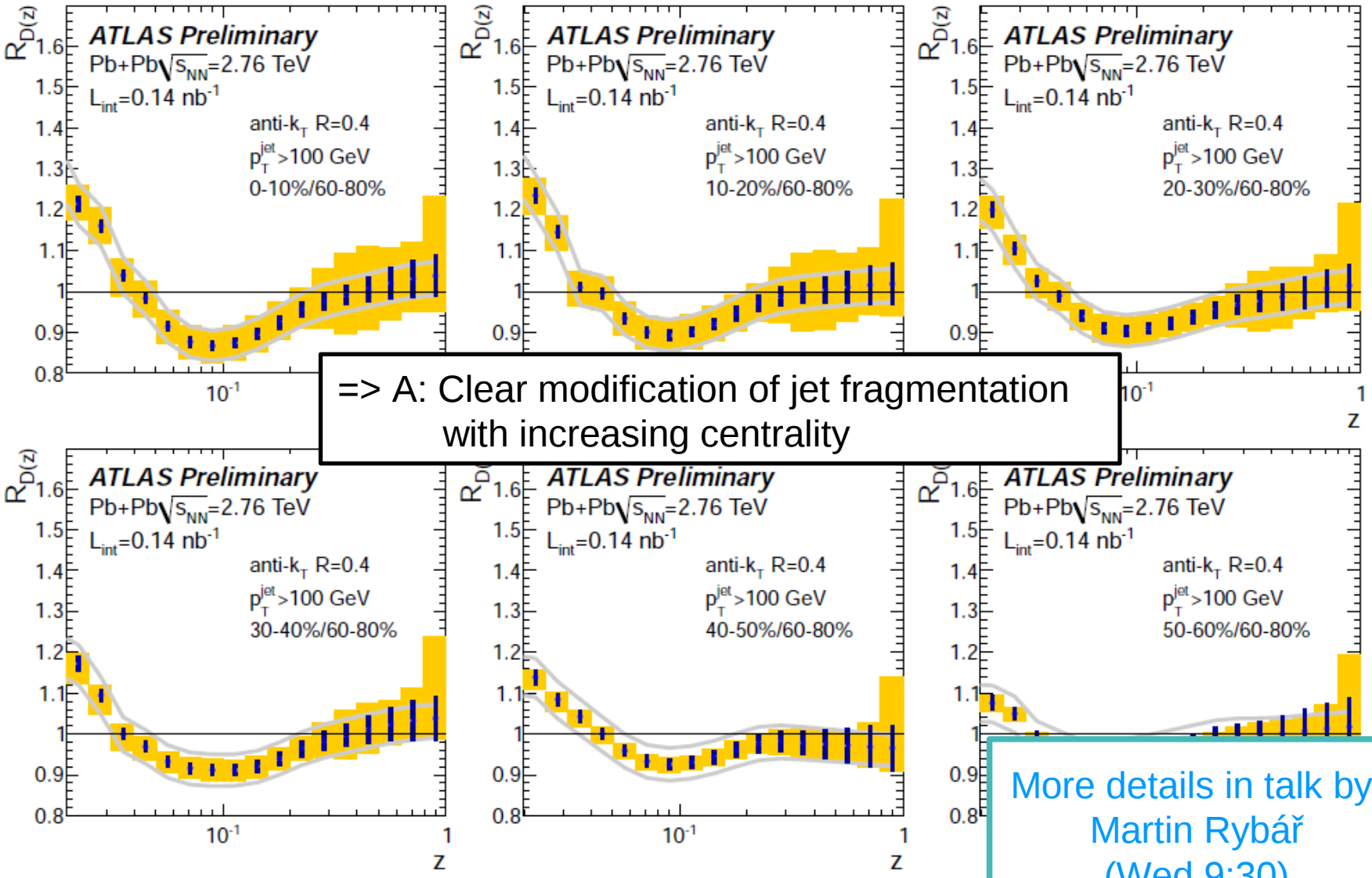


Jet fragmentation



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

Jet fragmentation

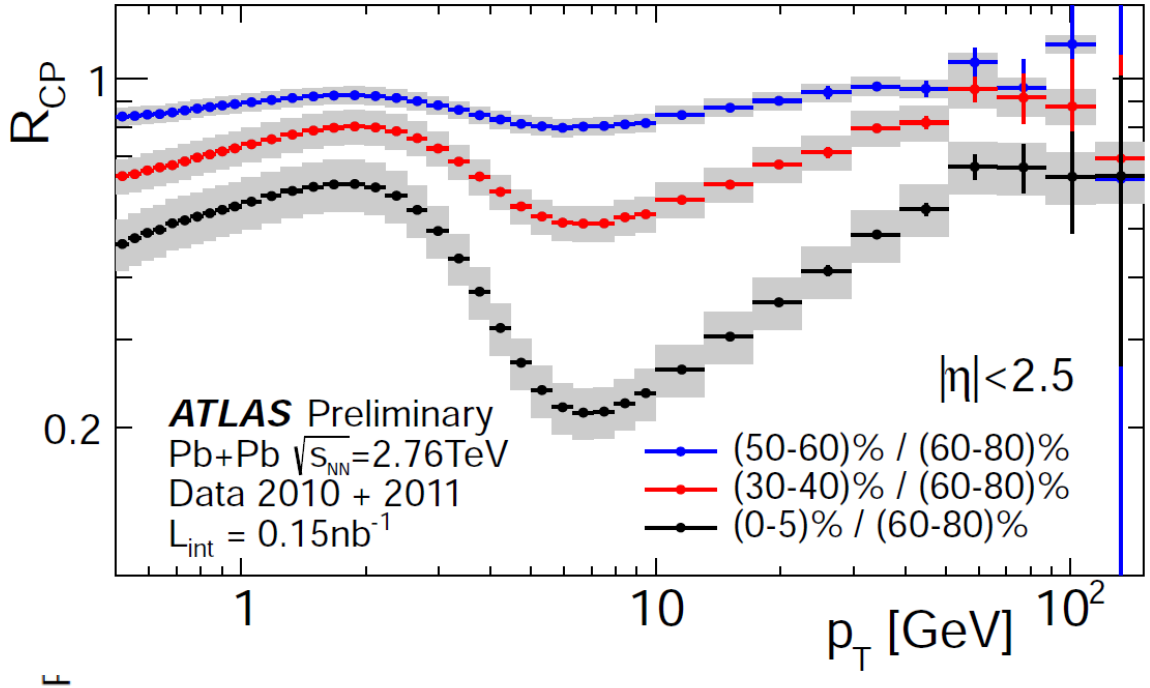


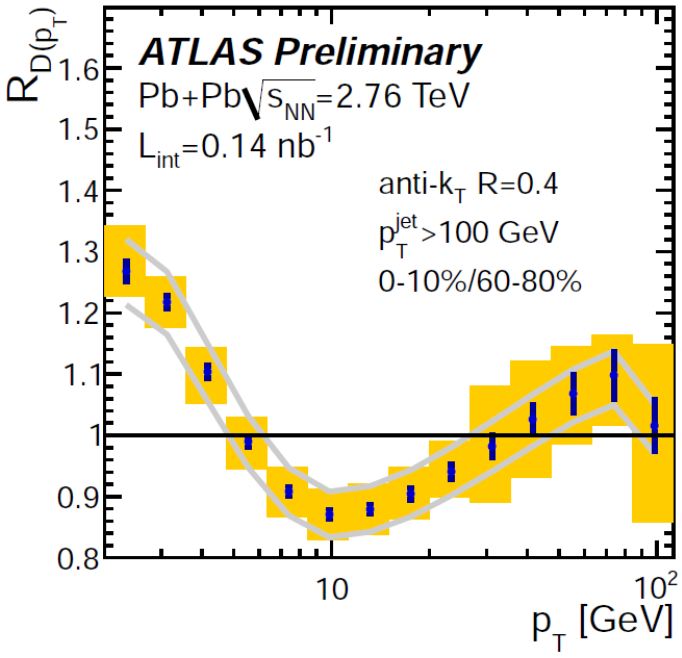
=> A: Clear modification of jet fragmentation with increasing centrality

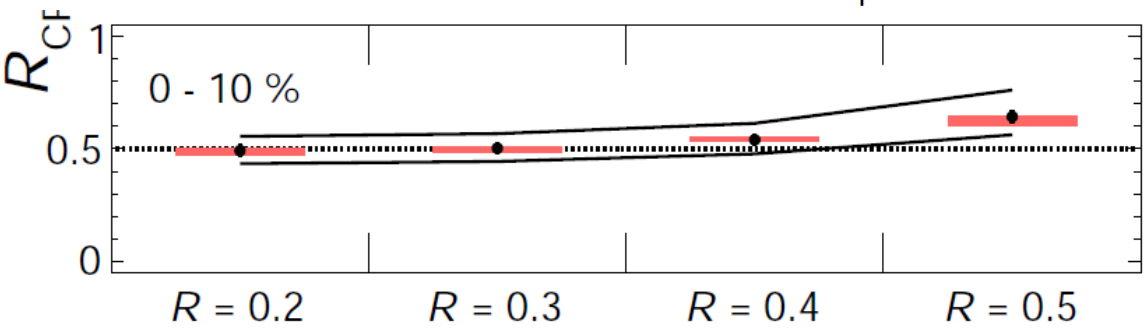
More details in talk by Martin Rybář (Wed 9:30)

Charged particle R_{CP} and jet suppression

Q: Can we built a bridge between charged particle R_{CP} and observed jet suppression?

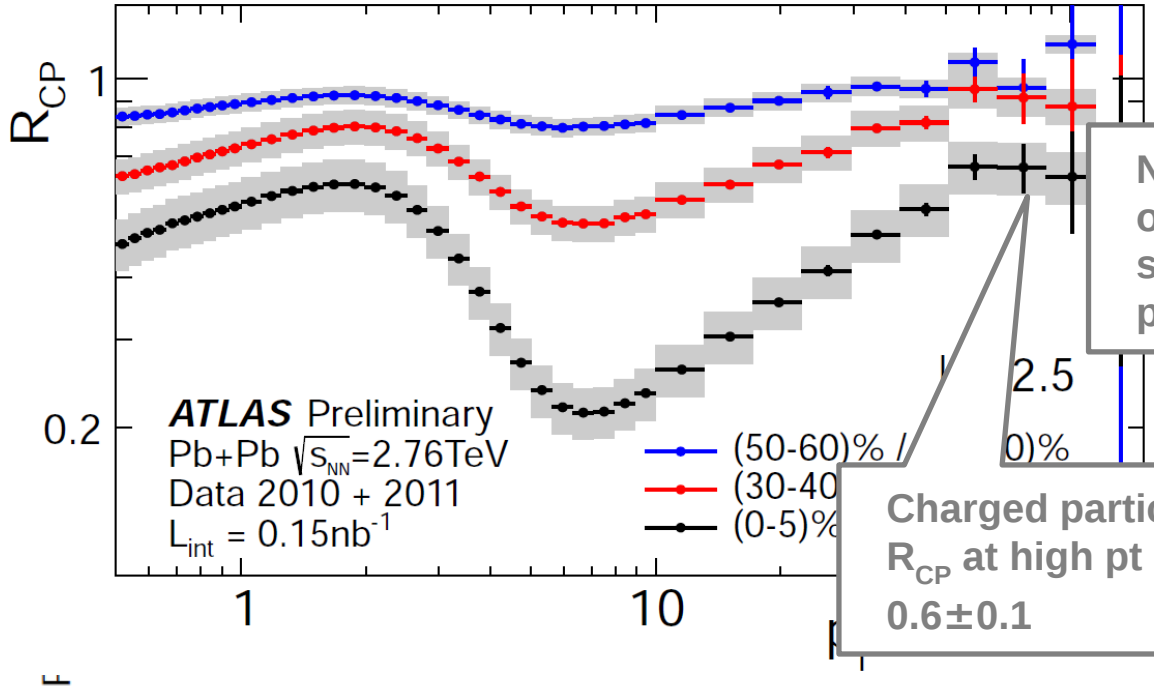


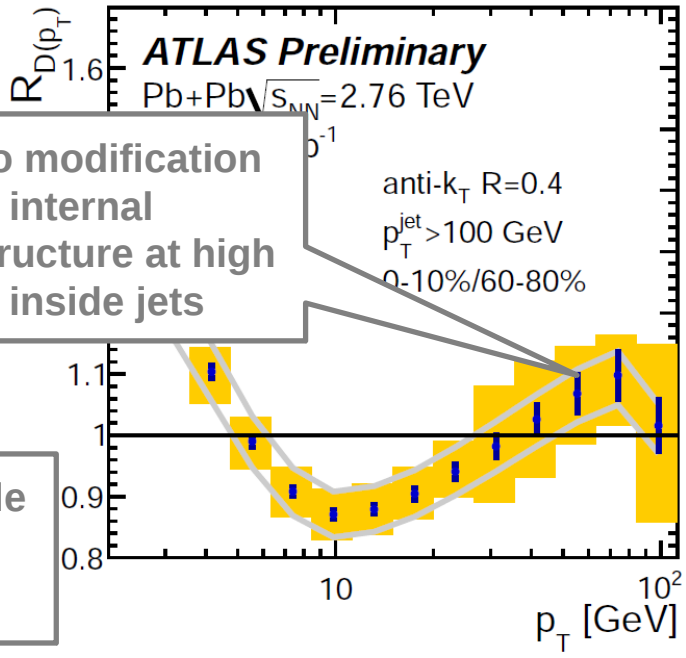


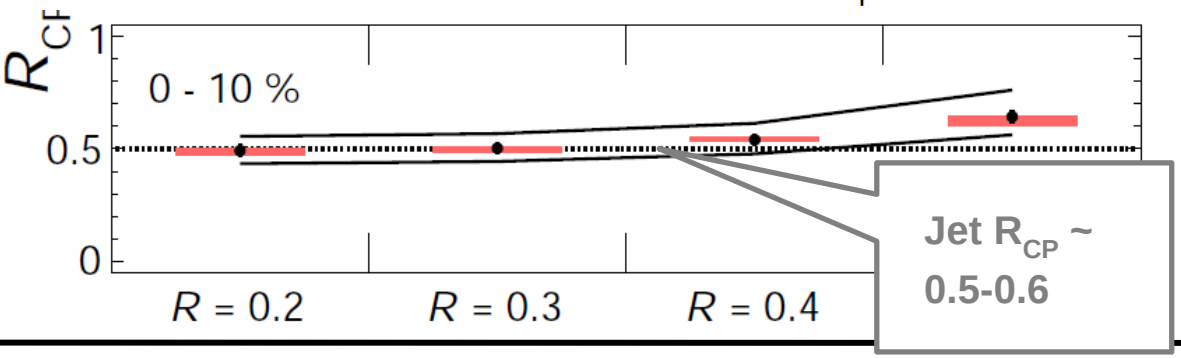


Charged particle R_{CP} and jet suppression

Q: Can we built a bridge between charged particle R_{CP} and observed jet suppression?







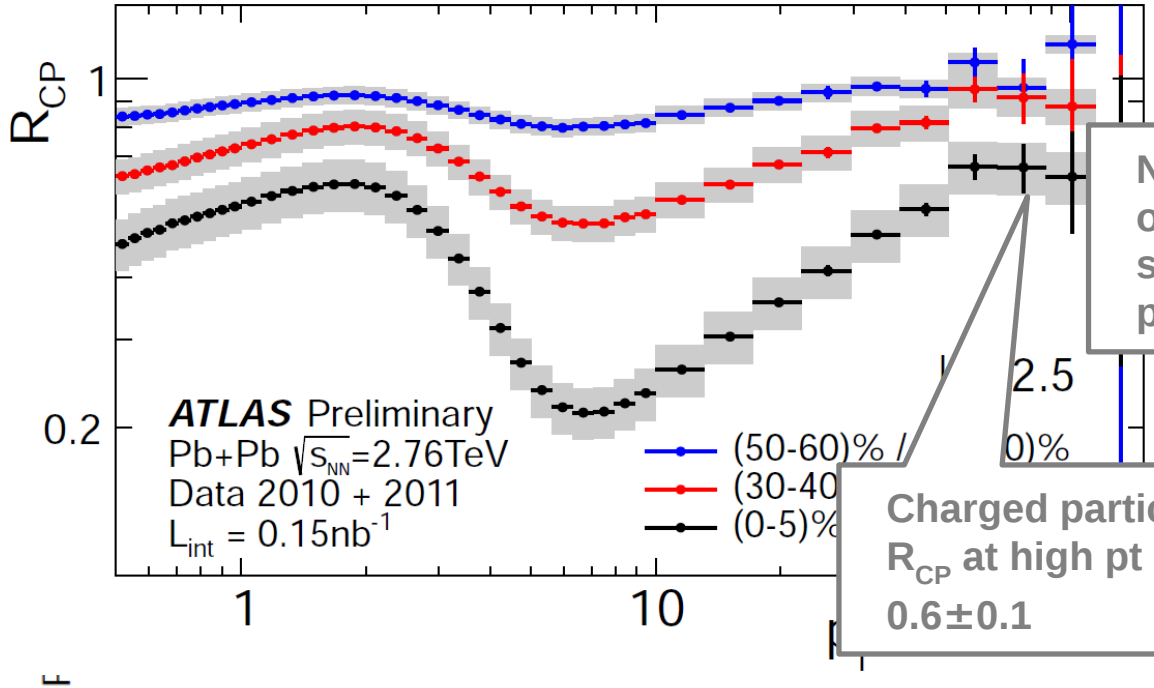
No modification of internal structure at high pt inside jets

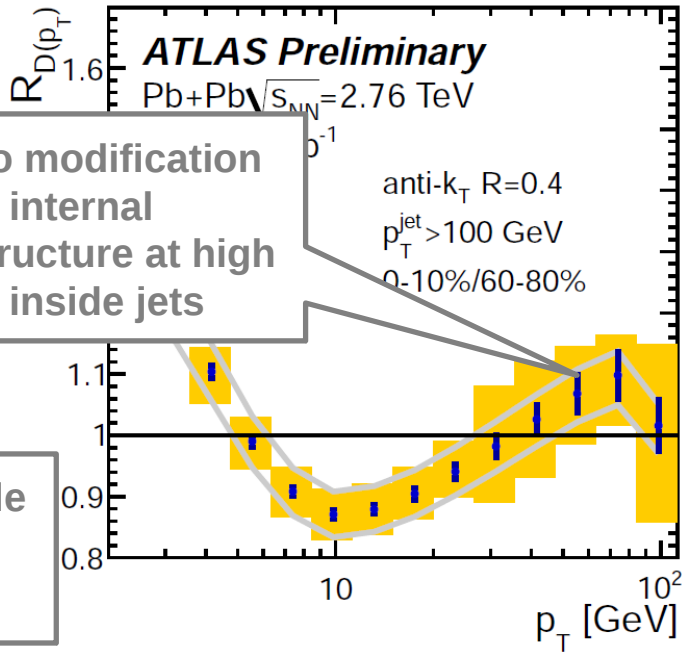
Charged particle R_{CP} at high pt ~ 0.6±0.1

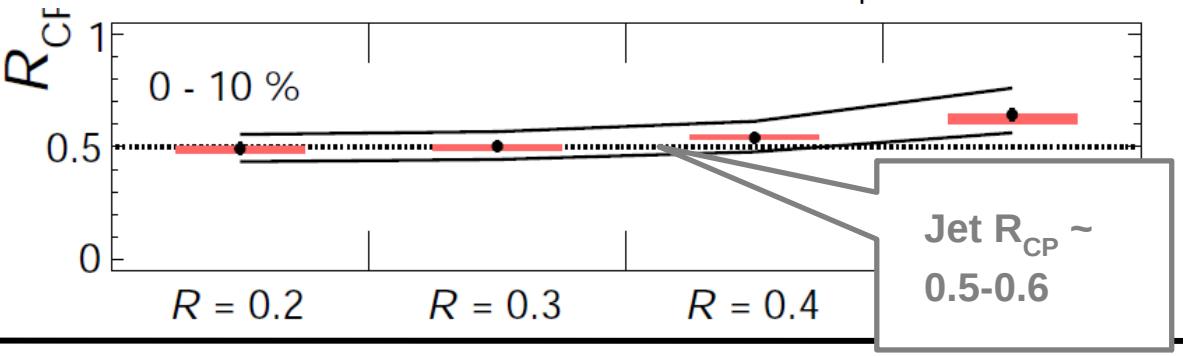
Jet R_{CP} ~ 0.5-0.6

Charged particle R_{CP} and jet suppression

Q: Can we built a bridge between charged particle R_{CP} and observed jet suppression?







No modification of internal structure at high pt inside jets

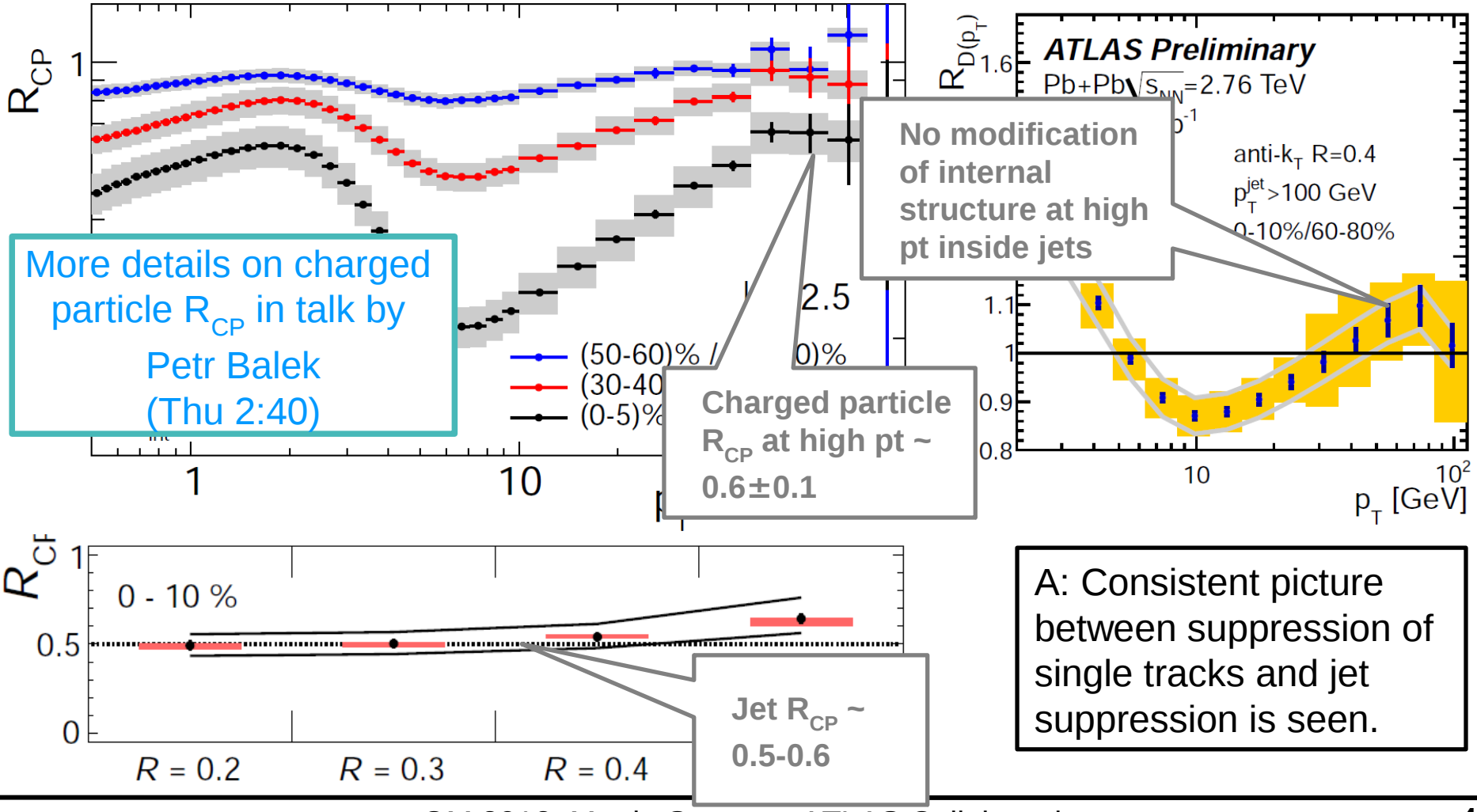
Charged particle R_{CP} at high pt ~ 0.6±0.1

Jet R_{CP} ~ 0.5-0.6

A: Consistent picture between suppression of single tracks and jet suppression is seen.

Charged particle R_{CP} and jet suppression

Q: Can we built a bridge between charged particle R_{CP} and observed jet suppression?



Conclusions

- Suppression of inclusive jet yields by a factor of two in central compared to peripheral collisions.
- 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 modification of particles in jets at high-p_T.
- We have provided a set of new measurements that goes beyond the original observation and that should shade more light into the jet energy loss in the QCD medium.

More information

https://twiki.cern.ch/twiki/bin/view/Atlas/AtlasResults … ATLAS Heavy Ion Public Results

http://arxiv.org/abs/1208.1967 … Jet size dependence of single jet suppression in lead-lead collisions at $\sqrt{s_{NN}}$= 2.76 TeV with the ATLAS detector at the LHC

ATLAS-CONF-2012-115 … Measurement of inclusive jet charged particle fragmentation functions in Pb+Pb collisions at $\sqrt{s_{NN}}$= 2.76 TeV with the ATLAS detector

ATLAS-CONF-2012-050 … Measurement of the centrality dependence of open heavy flavour production in lead-lead collisions at $\sqrt{s_{NN}}$= 2.76 TeV with the ATLAS detector

ATLAS-CONF-2012-116 … Measurement of the azimuthal dependence of inclusive jet suppression in Pb+Pb collisions at $\sqrt{s_{NN}}$= 2.76 TeV with the ATLAS detector

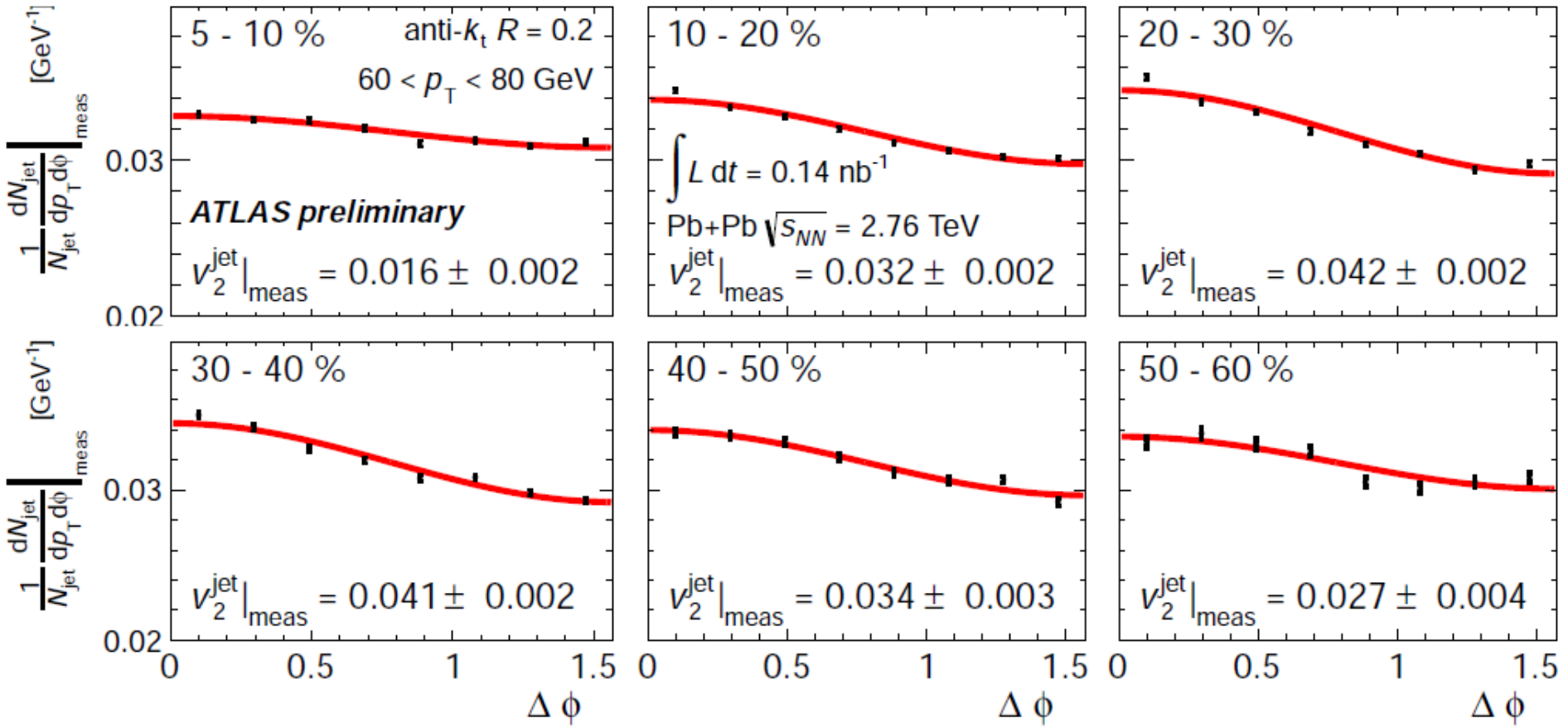
ATLAS-CONF-2012-121 … Measurement of the correlation of jets with high p_T isolated prompt photons in lead-lead collisions at $\sqrt{s_{NN}}$= 2.76 TeV with the ATLAS detector at the LHC

ATLAS-CONF-2012-119 … Measurement of momentum imbalance in Z –>ll+jet events in Pb+Pb collisions at $\sqrt{s_{NN}}$= 2.76 TeV with the ATLAS detector

ATLAS-CONF-2012-120` … Measurement of the charged particle spectra in Pb+Pb collisions at $\sqrt{s_{NN}}$= 2.76 TeV with the ATLAS detector at the LHC

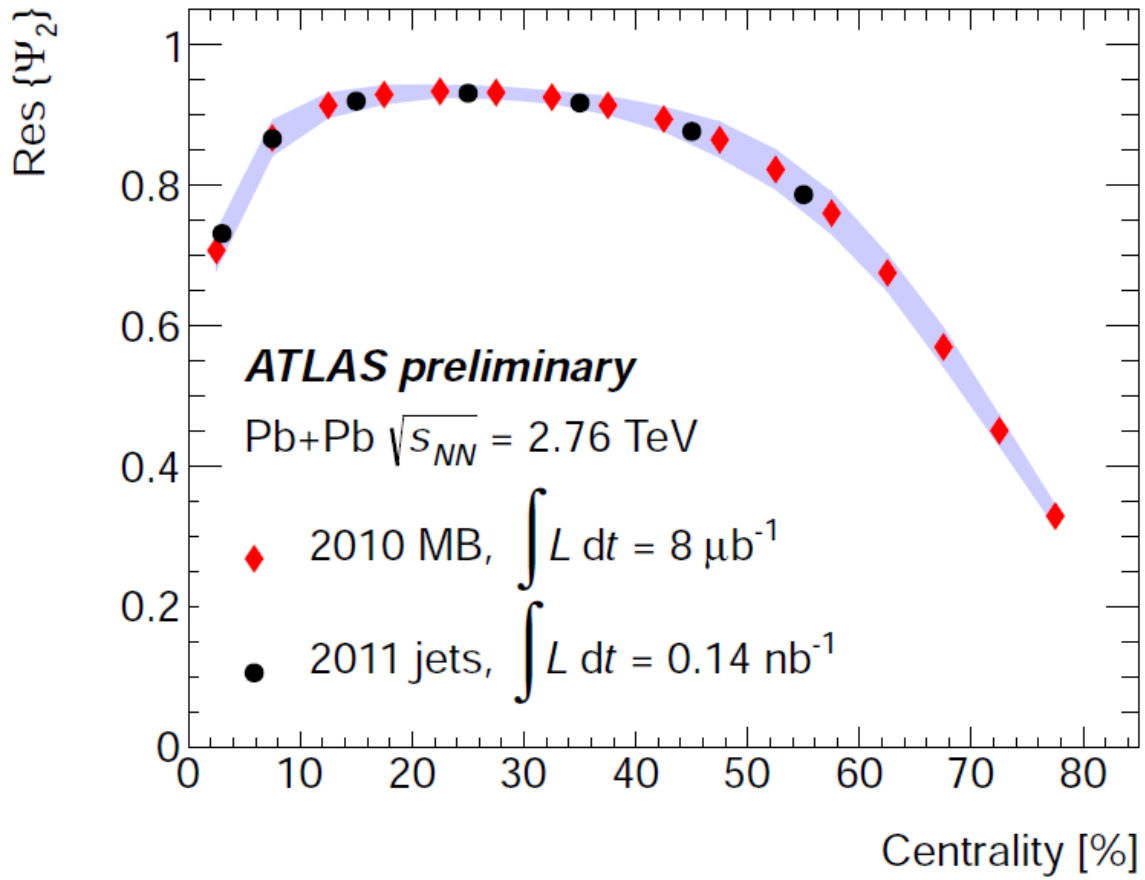
Additional Information

Jet v_2



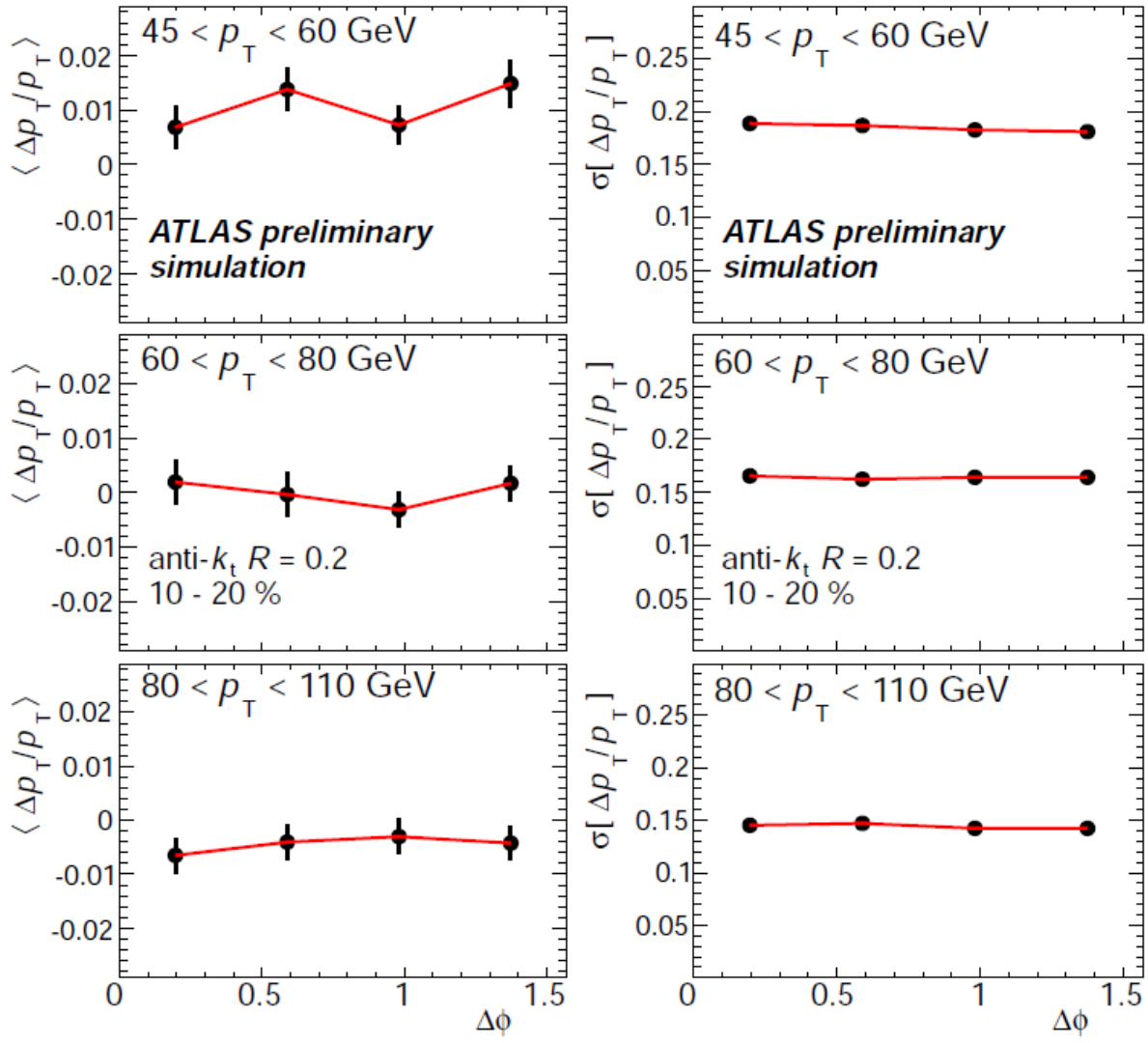
$$\frac{dN}{d\phi} = A\left(1 + 2v_2 \cos\left[2(\phi - \Psi_2)\right]\right)$$

Jet v_2

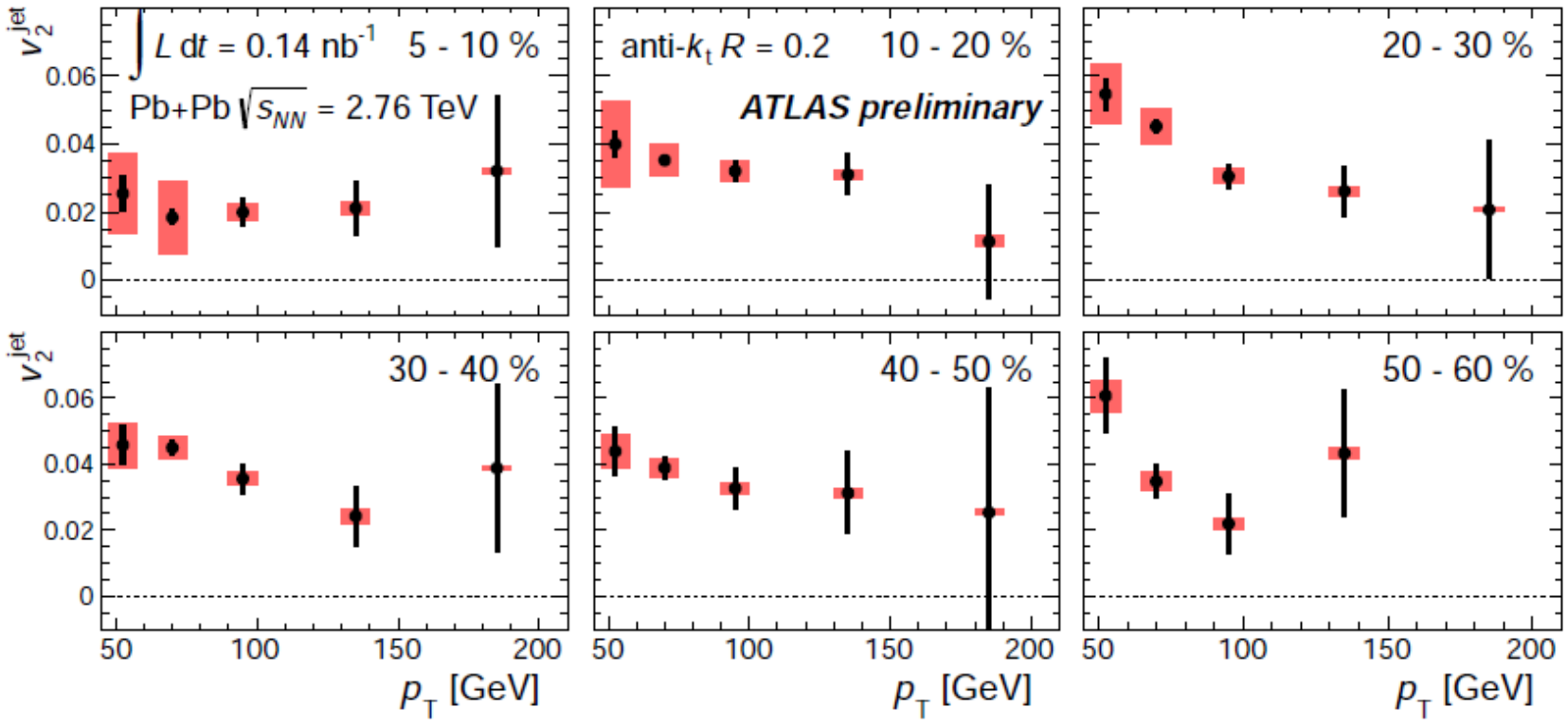


$$\Psi_2 = \frac{1}{2}\tan^{-1}\left\{\frac{\sum w_i E_{\mathrm{T}\,i}\sin 2\phi_i}{\sum w_i E_{\mathrm{T}\,i}\cos 2\phi_i}\right\}$$

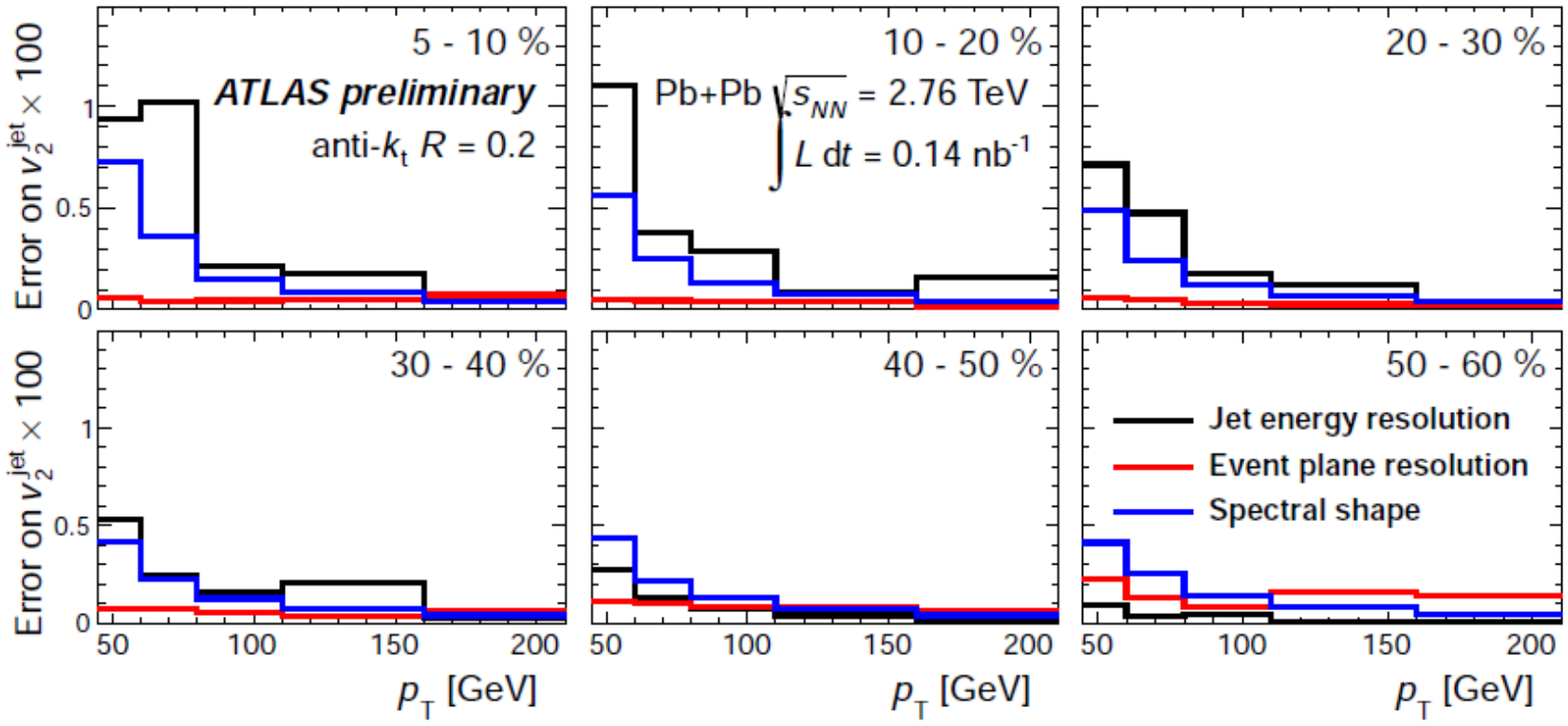
Jet v_2


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
$\langle \Delta p_T / p_T \rangle$
$\sigma[\Delta p_T / p_T]$
$\Delta\phi$

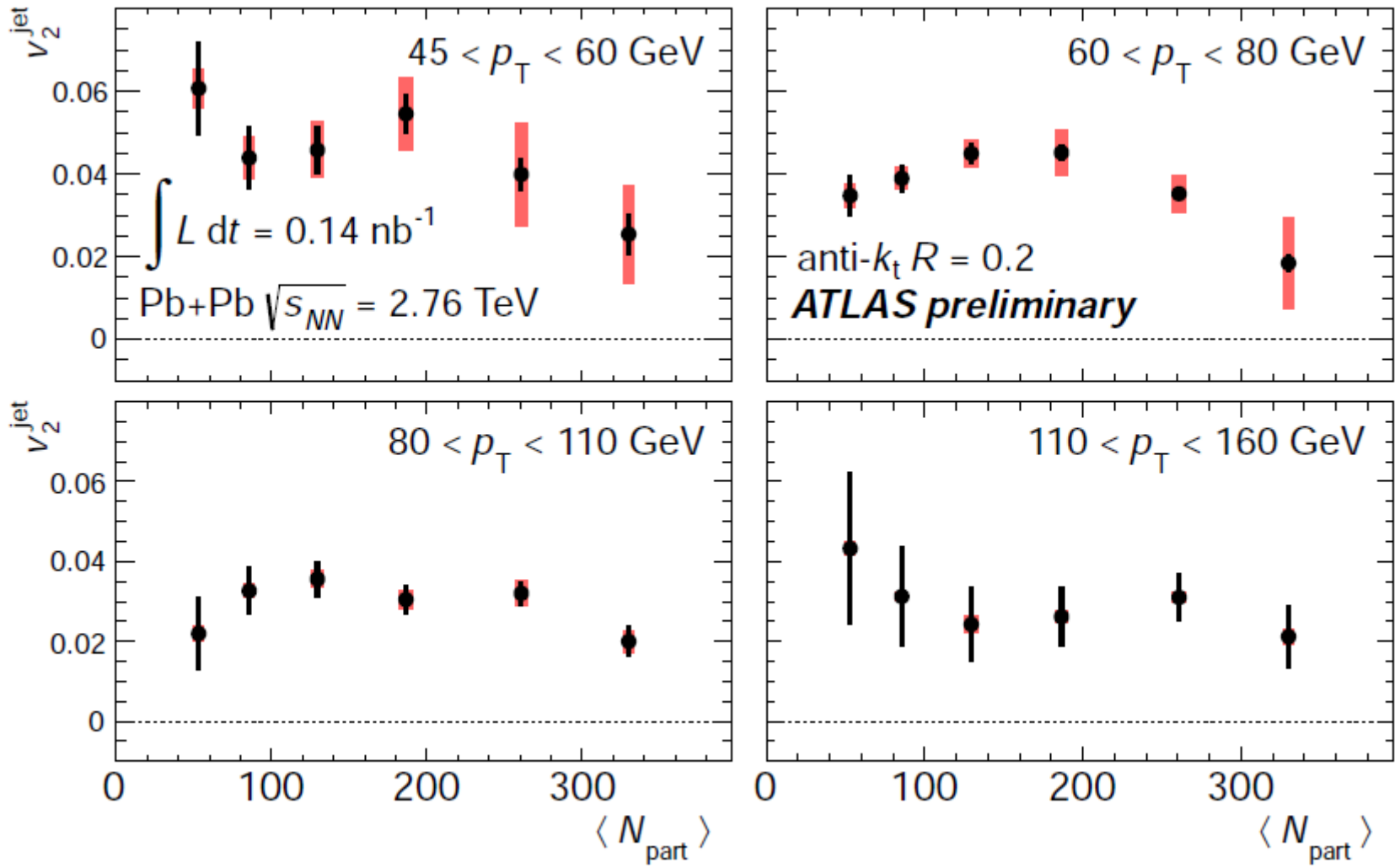
Jet v_2


v_2^{jet}
$\int L\,dt$ = 0.14 nb^{-1} 5 - 10 %
Pb+Pb $\sqrt{s_{NN}}$ = 2.76 TeV
anti-k_t R = 0.2 10 - 20 %
ATLAS preliminary
20 - 30 %
30 - 40 %
40 - 50 %
50 - 60 %
0.06
0.04
0.02
0
50
100
150
200
p_T [GeV]

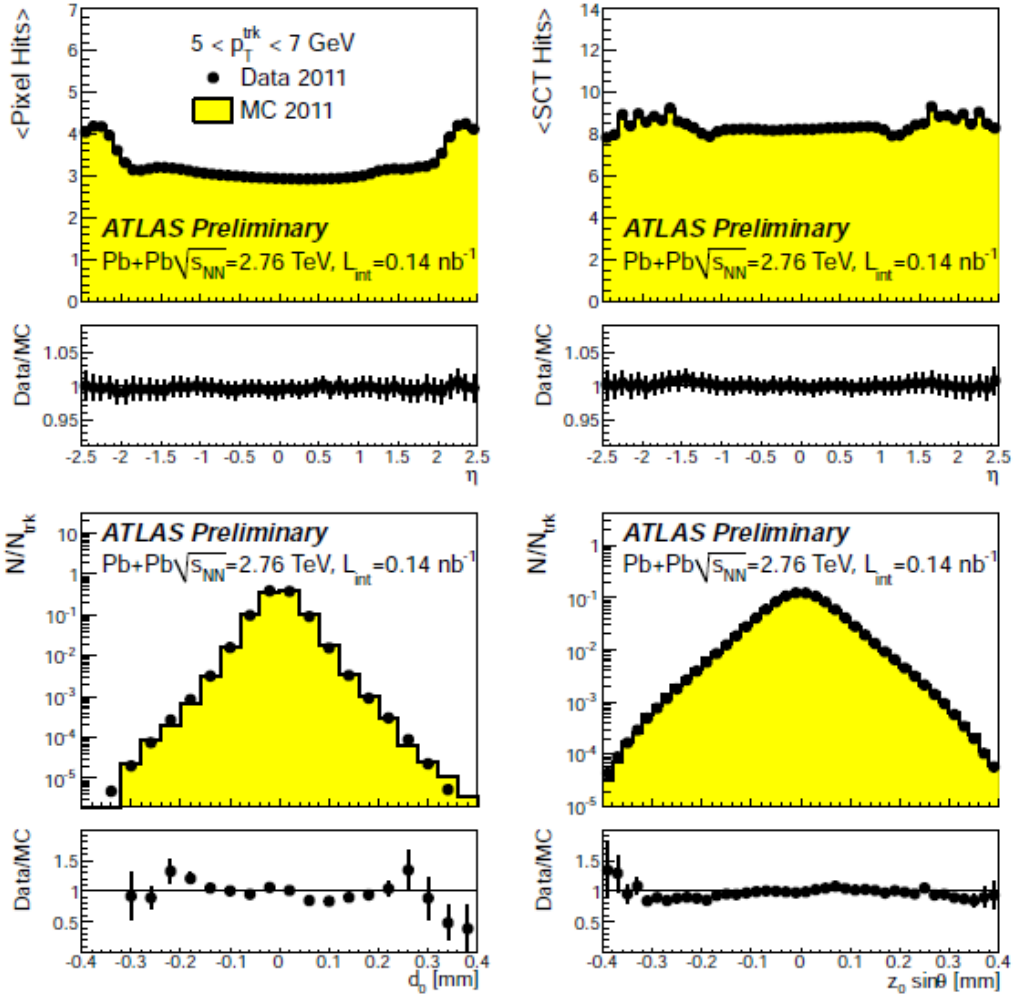
Jet v_2

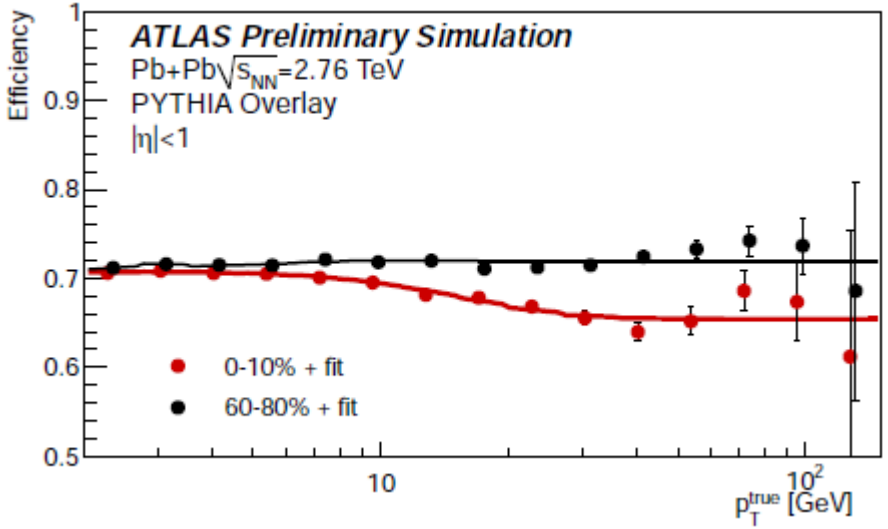

5 - 10 %
ATLAS preliminary
anti-k_t R = 0.2
10 - 20 %
Pb+Pb $\sqrt{s_{NN}}$ = 2.76 TeV
$\int L\,dt$ = 0.14 nb^{-1}
20 - 30 %
30 - 40 %
40 - 50 %
50 - 60 %
Jet energy resolution
Event plane resolution
Spectral shape
Error on $v_2^{jet} \times 100$
p_T [GeV]
0
0.5
1
50
100
150
200

Jet v_2

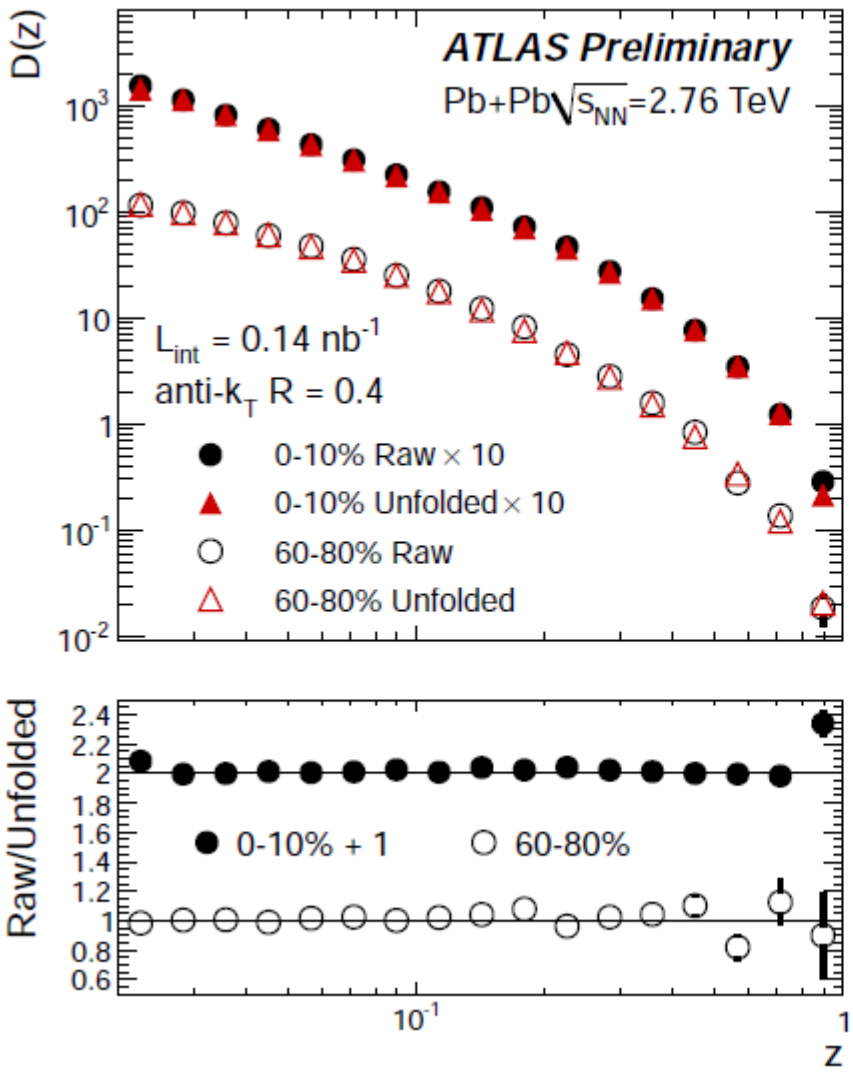

v_2^{jet}
45 < p_T < 60 GeV
60 < p_T < 80 GeV
80 < p_T < 110 GeV
110 < p_T < 160 GeV
$\int L\,dt$ = 0.14 nb^{-1}
Pb+Pb $\sqrt{s_{NN}}$ = 2.76 TeV
anti-k_t R = 0.2
ATLAS preliminary
0.06
0.04
0.02
0
0
100
200
300
⟨ N_{part} ⟩

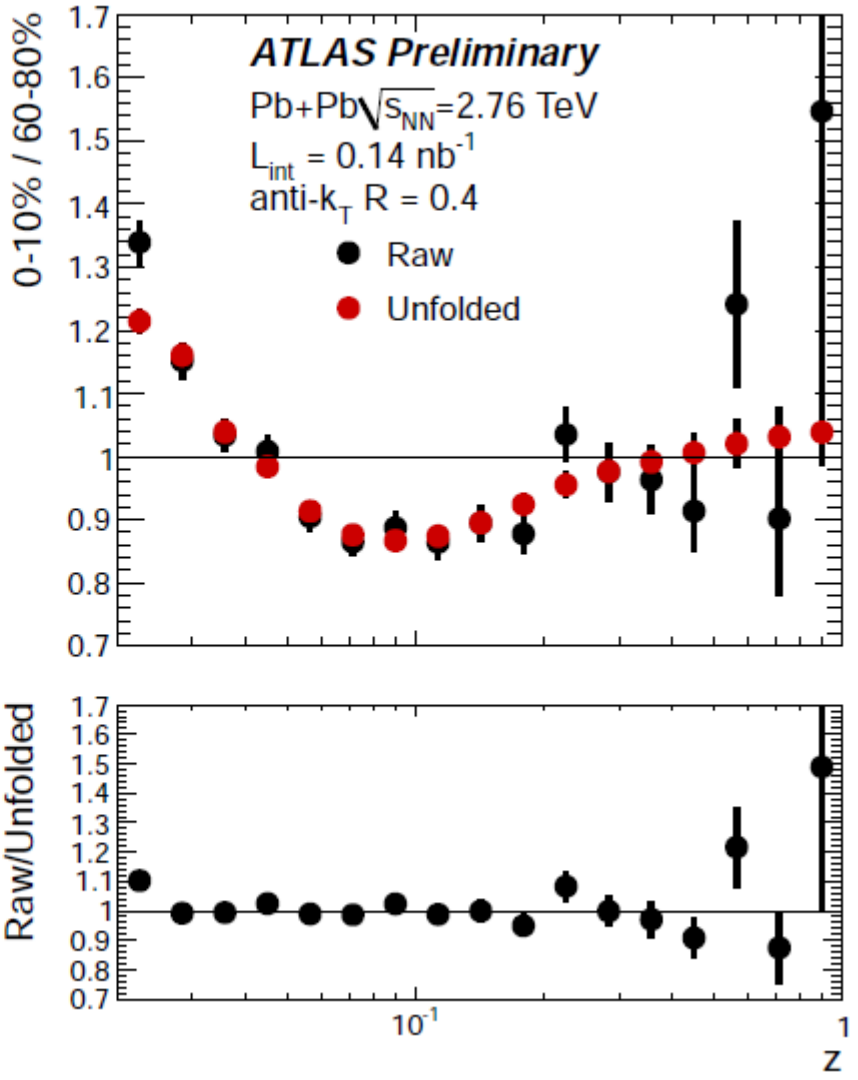
Jet Fragmentation



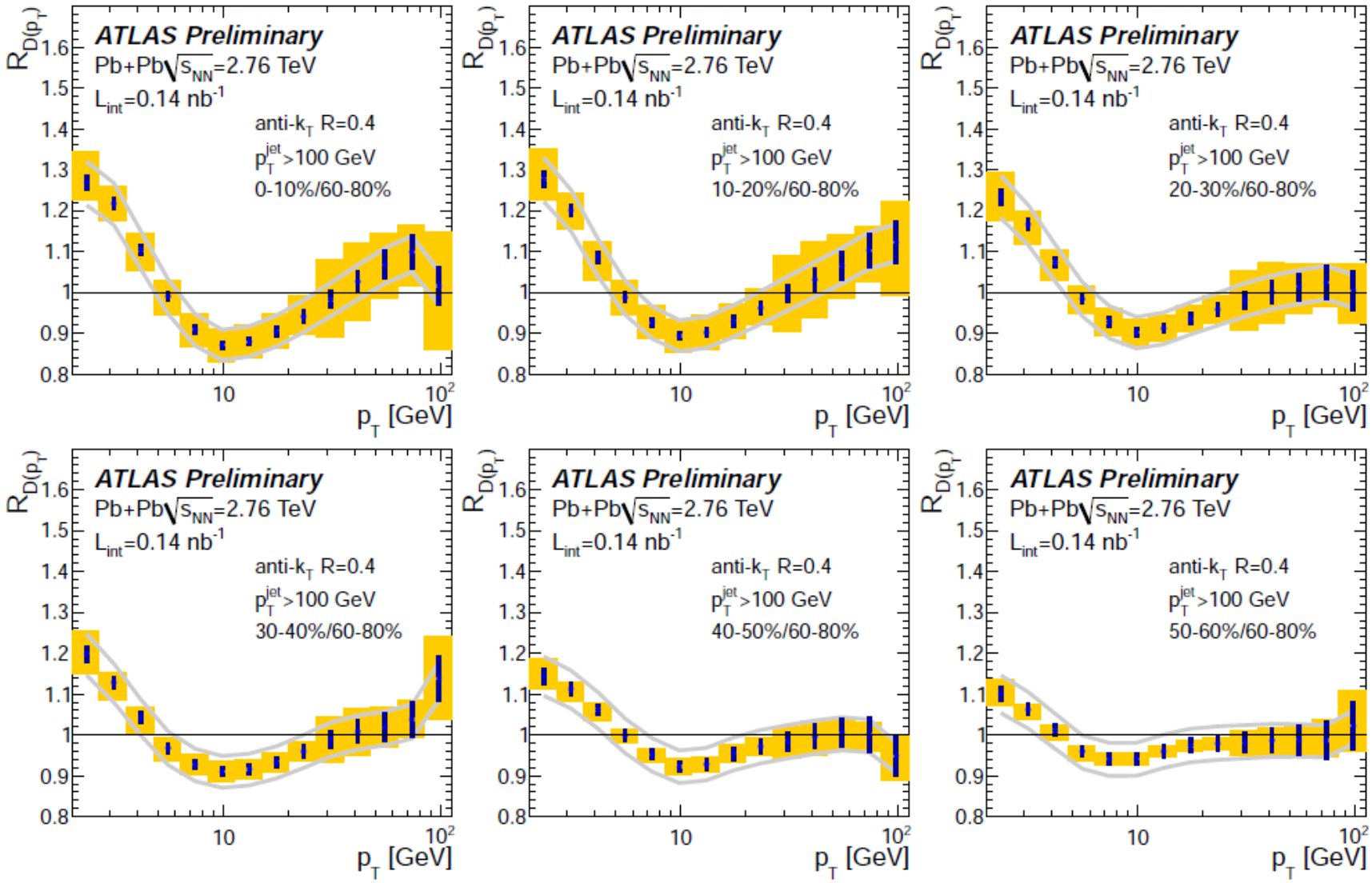


Jet Fragmentation

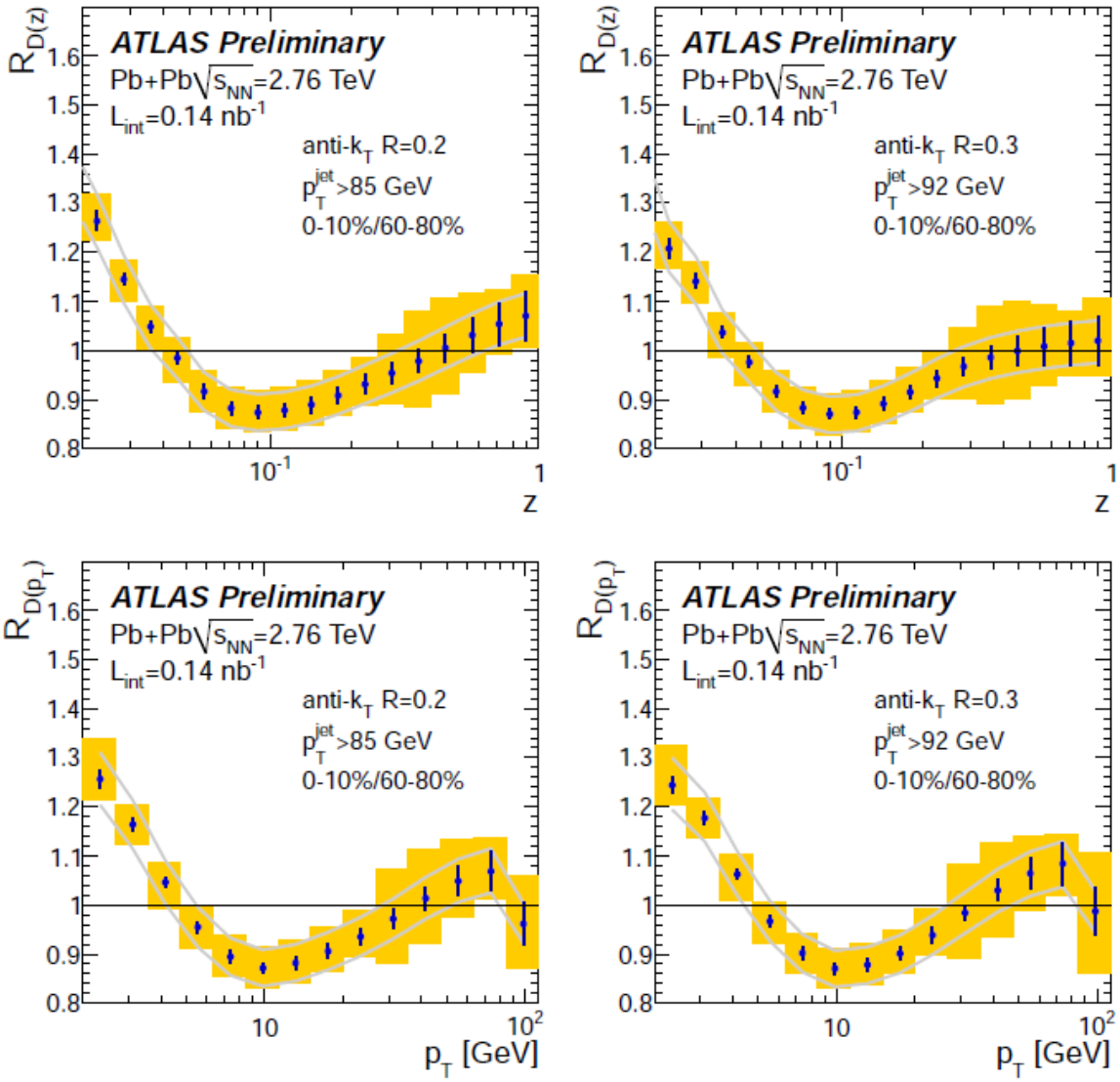




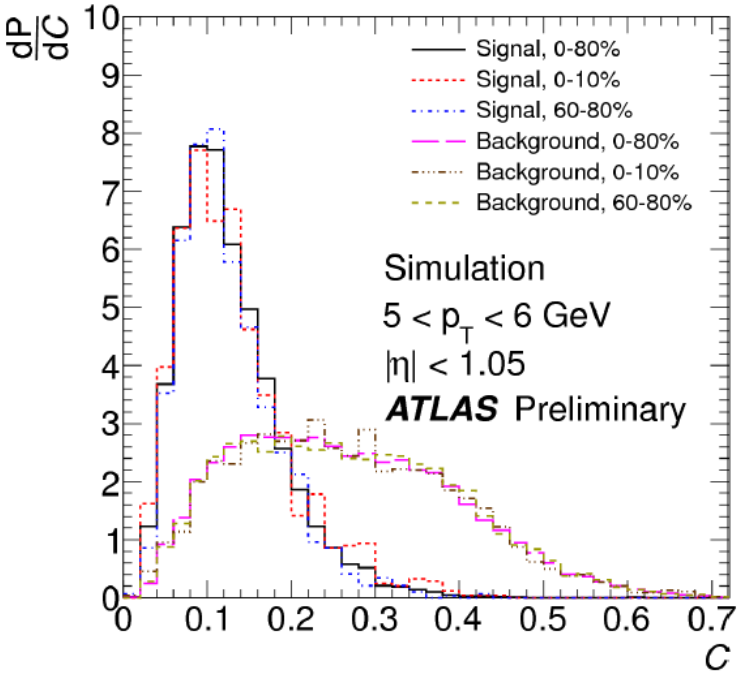
Jet Fragmentation

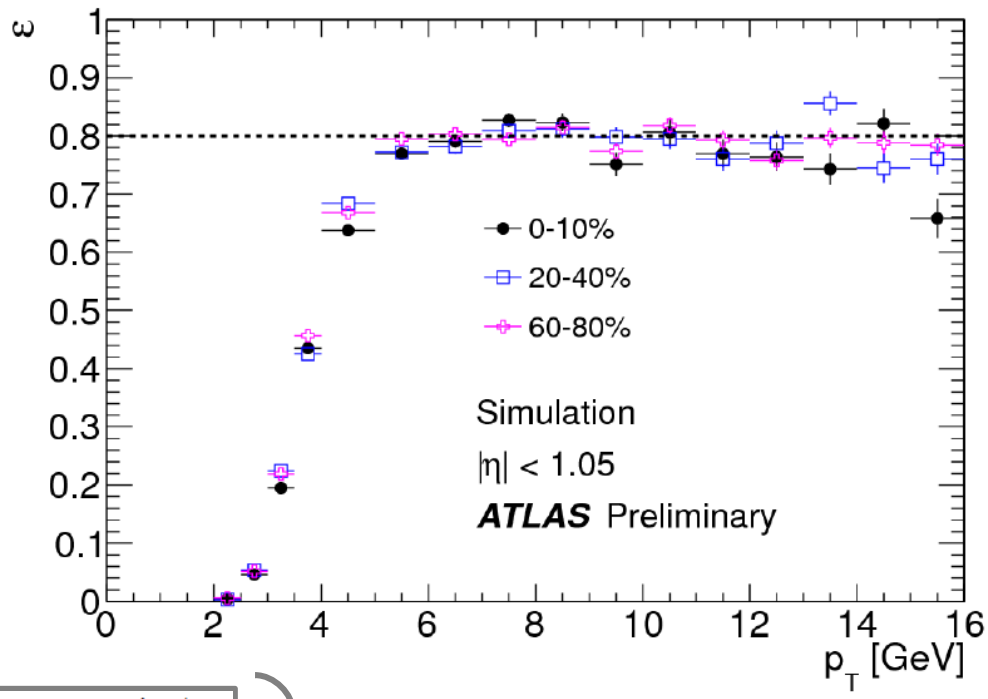


Jet Fragmentation



Heavy Flavor





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

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

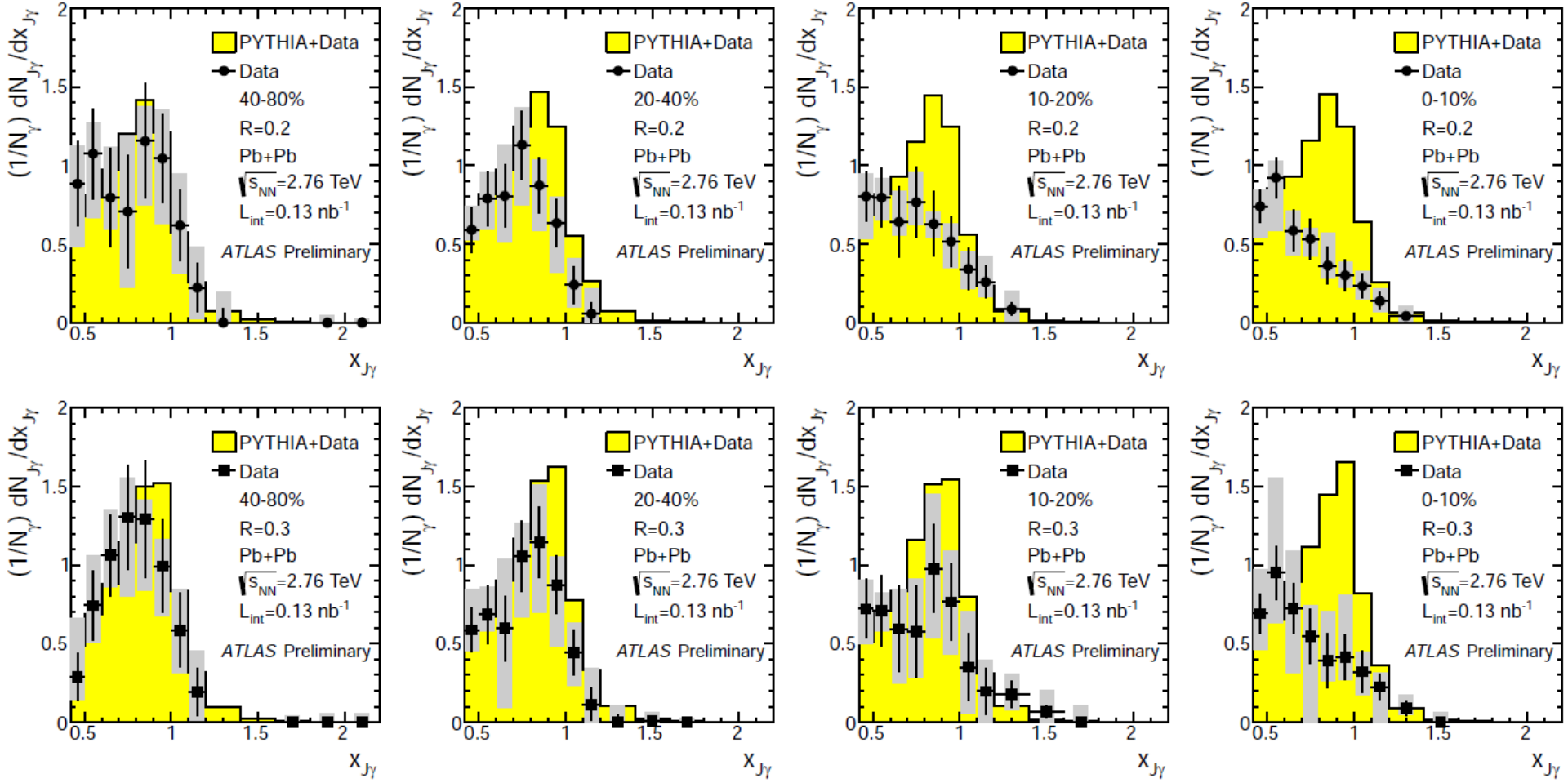
$$S(k) = \frac{1}{\sqrt{n}}\left(\sum_{i=1}^{k} s_i - \sum_{j=k+1}^{n} s_j\right)$$

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

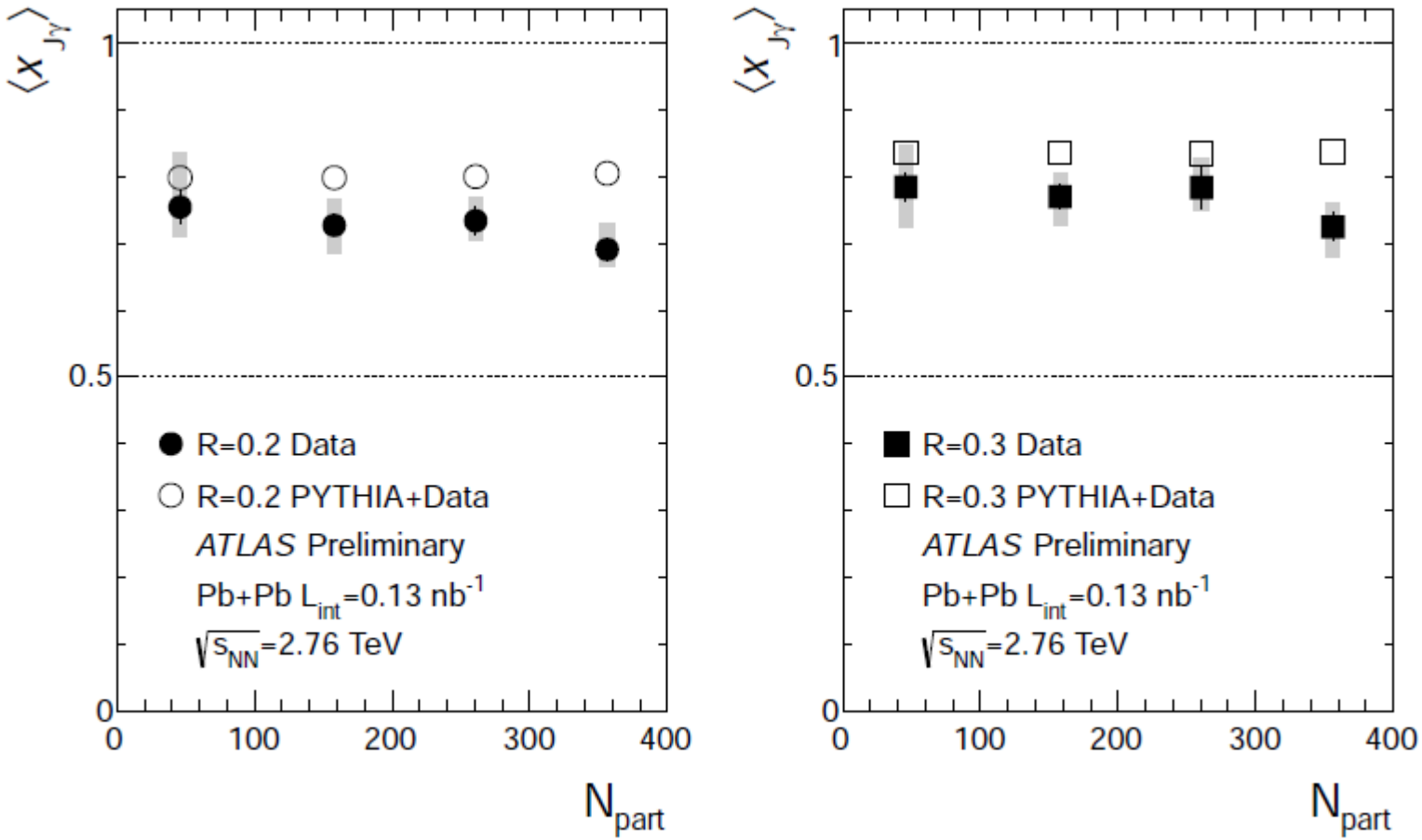
$$C = \left|\frac{\Delta p_{\text{loss}}}{p_{\text{ID}}}\right| + rS$$

$$r = 0.07$$

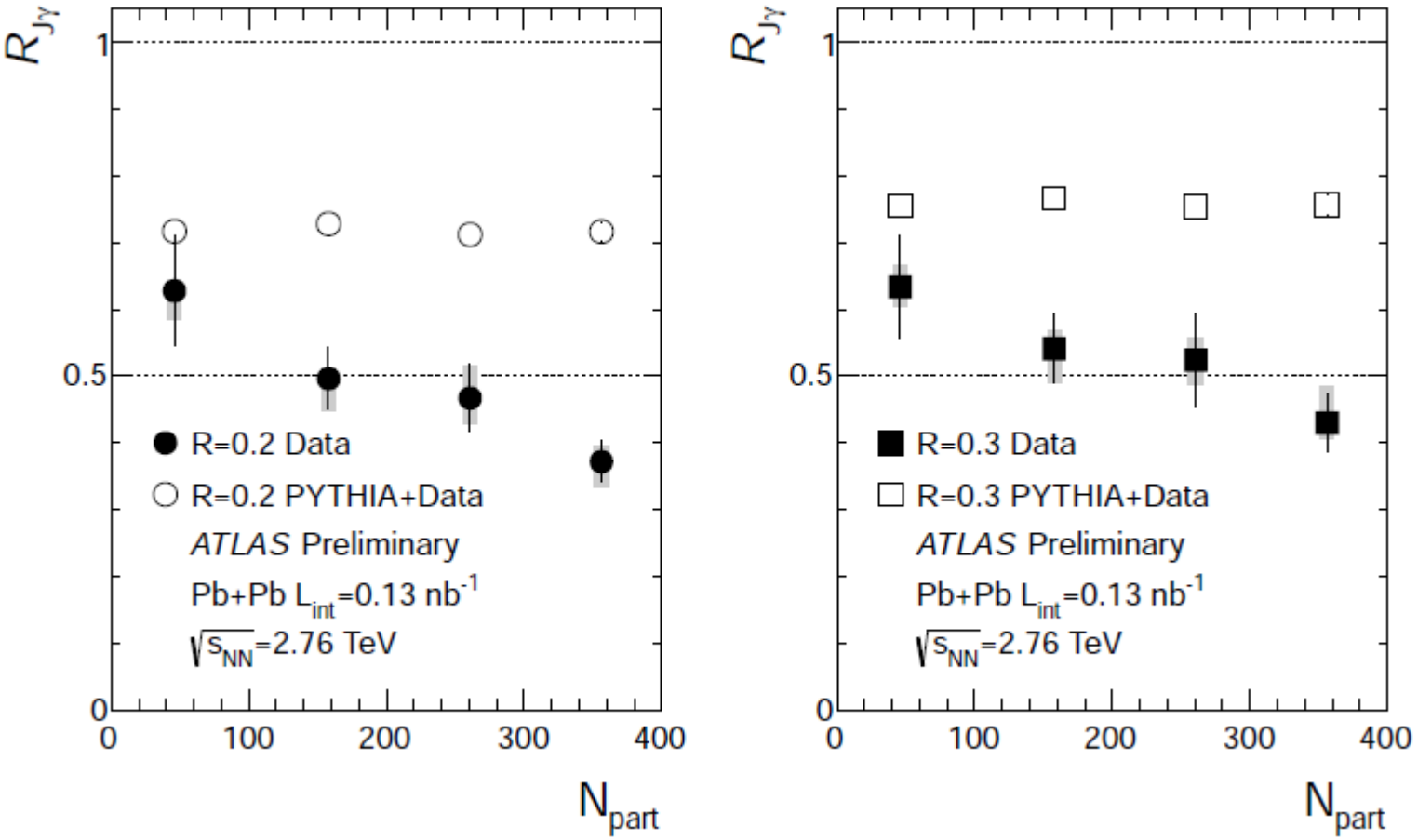
Gamma-jet


PYTHIA+Data
Data
40-80%
20-40%
10-20%
0-10%
R=0.2
R=0.3
Pb+Pb
$\sqrt{s_{NN}}$=2.76 TeV
L_{int}=0.13 nb^{-1}
ATLAS Preliminary
$(1/N_\gamma)\, dN_{J\gamma}/dx_{J\gamma}$
$x_{J\gamma}$

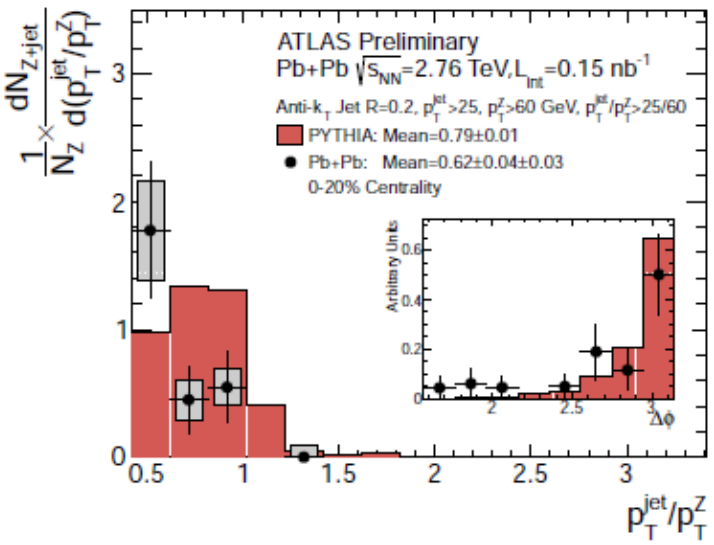
Gamma-jet

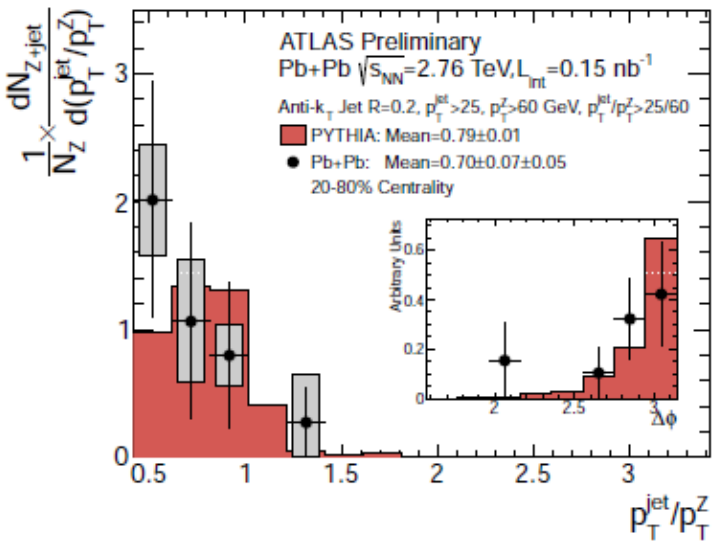

⟨x_Jγ⟩
1
0.5
0
0
100
200
300
400
N_part
R=0.2 Data
R=0.2 PYTHIA+Data
ATLAS Preliminary
Pb+Pb L_int=0.13 nb^-1
√s_NN=2.76 TeV
⟨x_Jγ⟩
1
0.5
0
0
100
200
300
400
N_part
R=0.3 Data
R=0.3 PYTHIA+Data
ATLAS Preliminary
Pb+Pb L_int=0.13 nb^-1
√s_NN=2.76 TeV

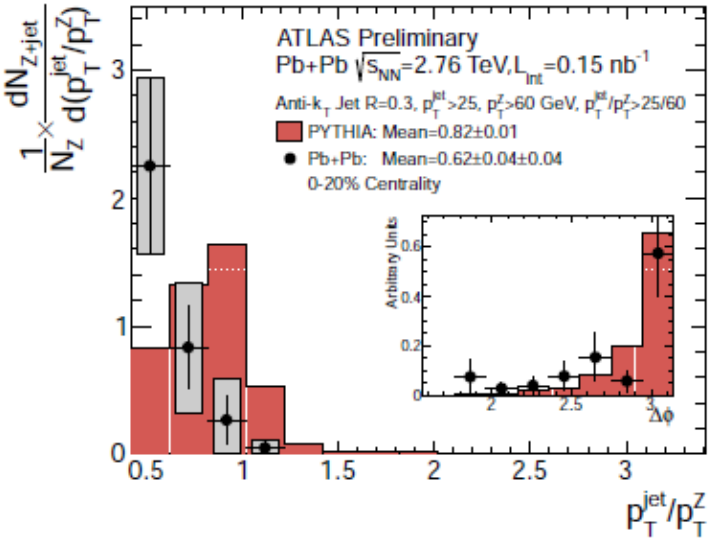
Gamma-jet

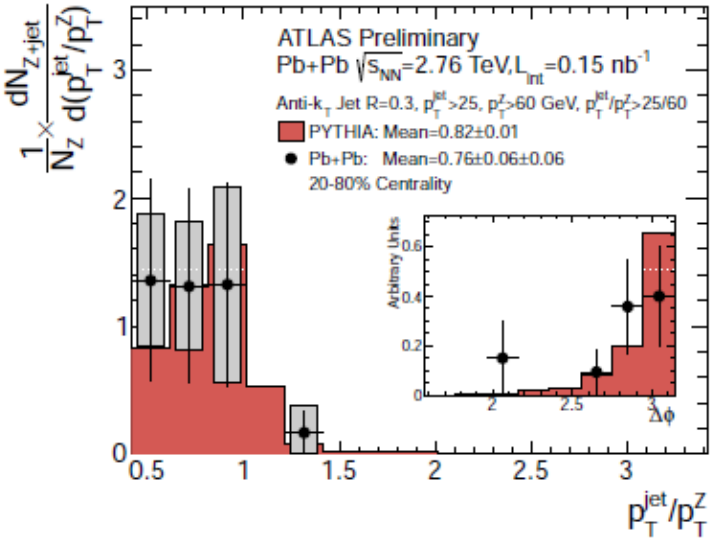

$R_{J\gamma}$
1
0.5
0
0
100
200
300
400
N_{part}
R=0.2 Data
R=0.2 PYTHIA+Data
ATLAS Preliminary
Pb+Pb L_{int}=0.13 nb^{-1}
$\sqrt{s_{NN}}$=2.76 TeV
$R_{J\gamma}$
1
0.5
0
0
100
200
300
400
N_{part}
R=0.3 Data
R=0.3 PYTHIA+Data
ATLAS Preliminary
Pb+Pb L_{int}=0.13 nb^{-1}
$\sqrt{s_{NN}}$=2.76 TeV

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
$\Delta\phi$