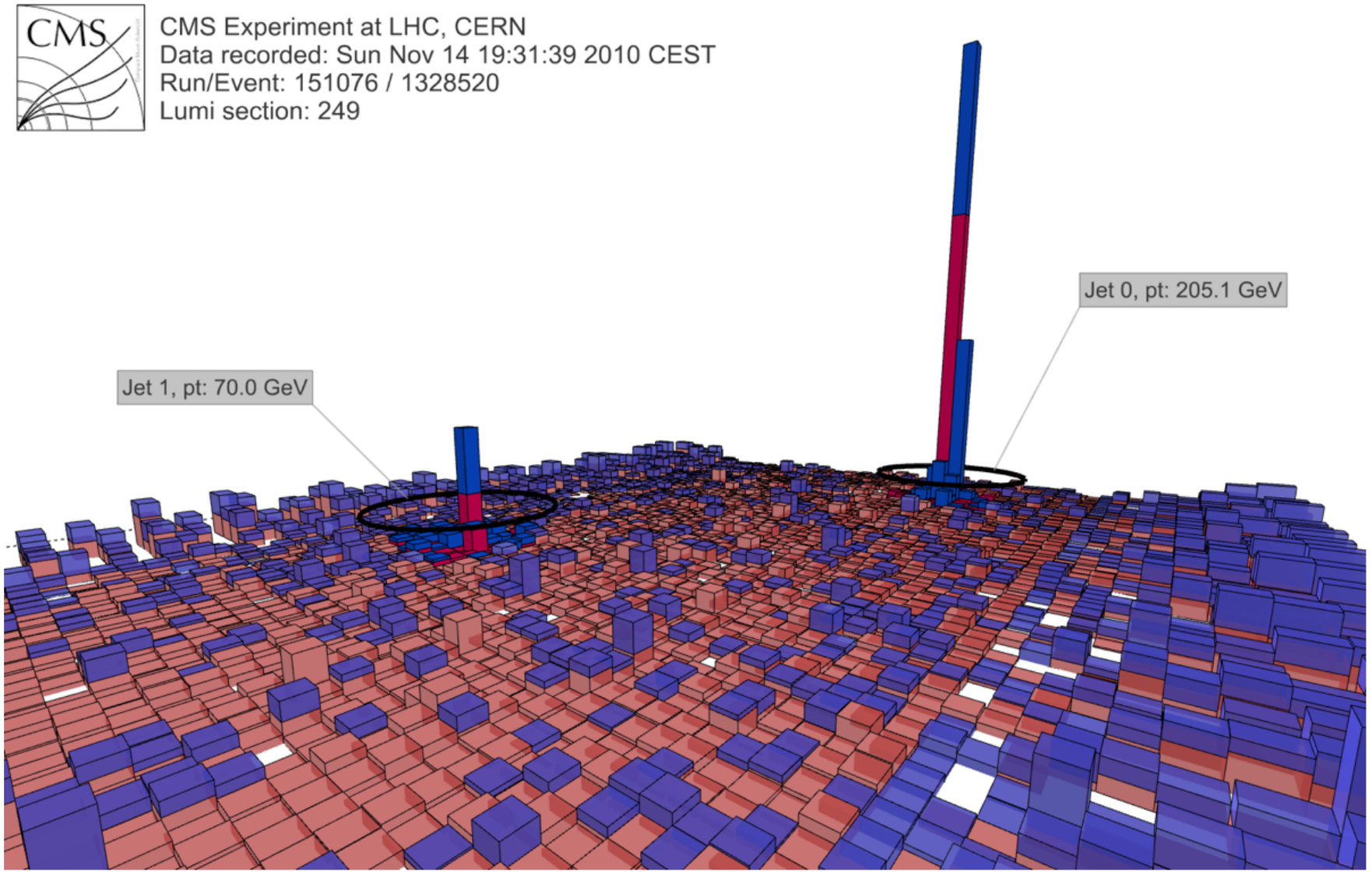
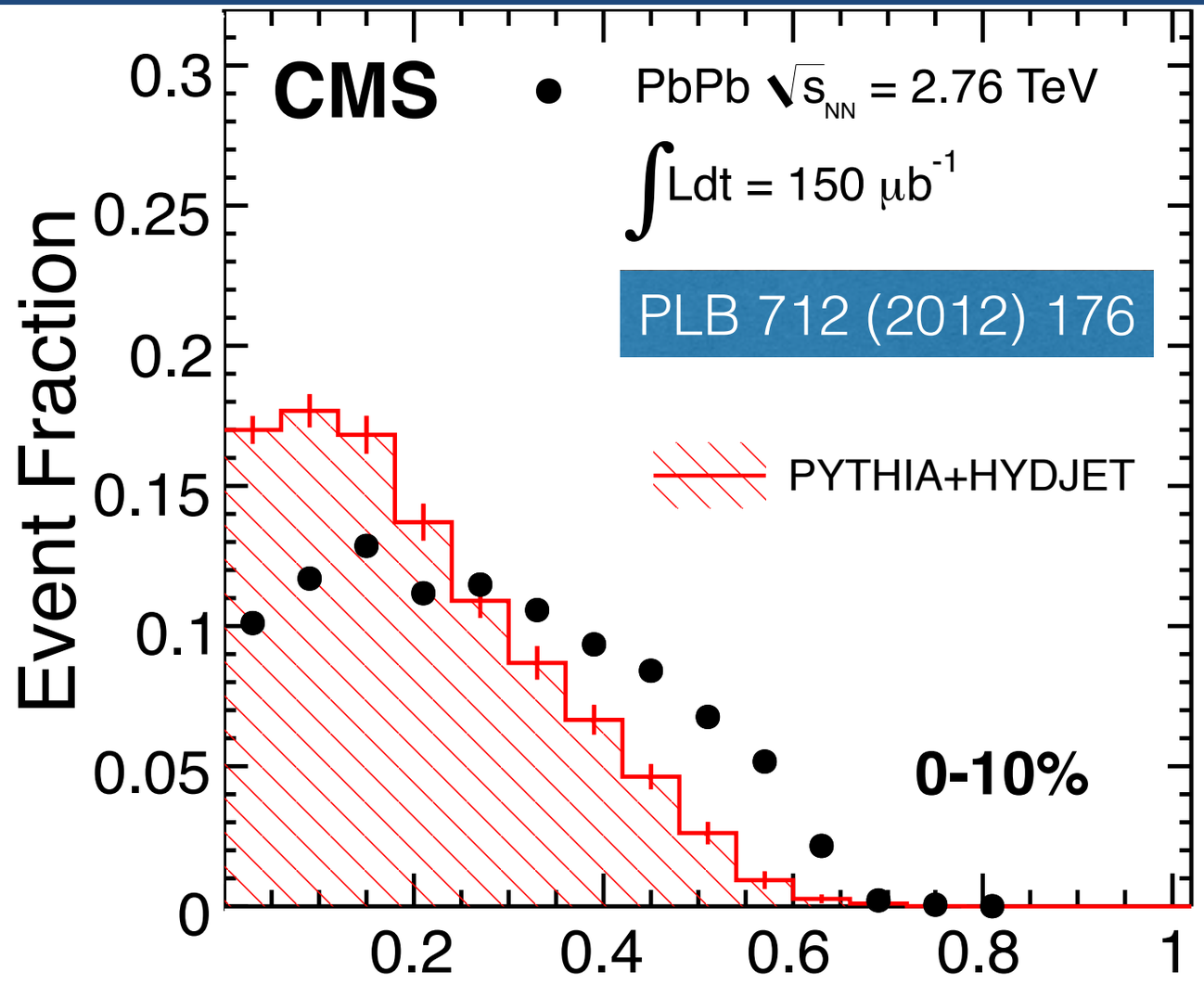


What have we learned from missing transverse momentum measurements?

4th Heavy Ion Jet Workshop
Ecole Polytechnique in Palaiseau, France
On behalf of the CMS experiment at the LHC

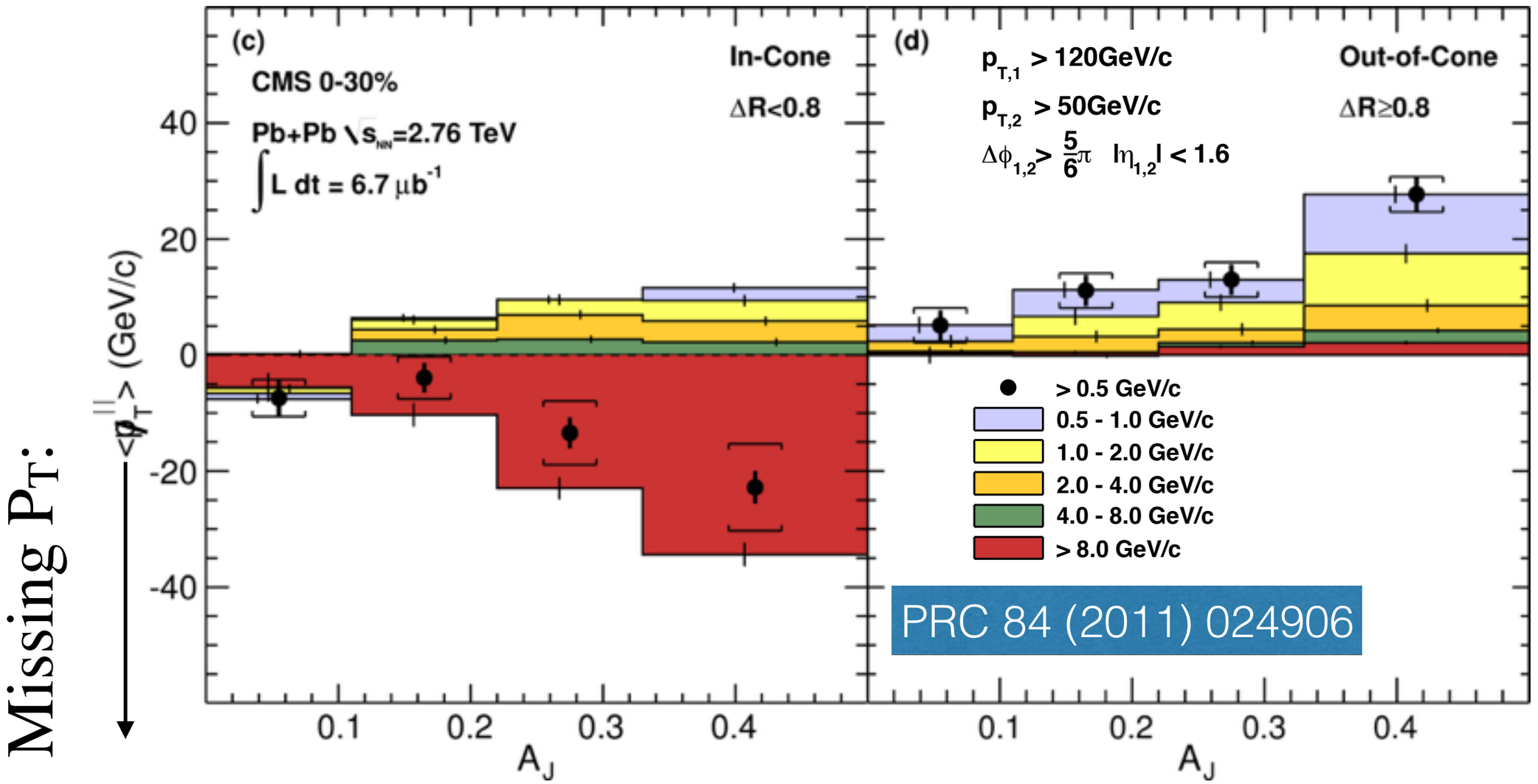
Observation of Dijet Asymmetry in PbPb



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

- Central PbPb A_J modification relative to pp and MC
  - Look outside the jets for the missing momentum

Initial Study of Missing Momentum



$$\not{p}_{\mathrm{T}}^{\parallel} = \sum_{\mathrm{i}} -p_{\mathrm{T}}^{\mathrm{i}} \cos\left(\phi_{\mathrm{i}} - \phi_{\mathrm{Dijet}}\right)$$

- Balancing (Missing p_T > 0) spectrum softer
- Large contribution found far from jet cones

New Study of Dijet Missing P_T

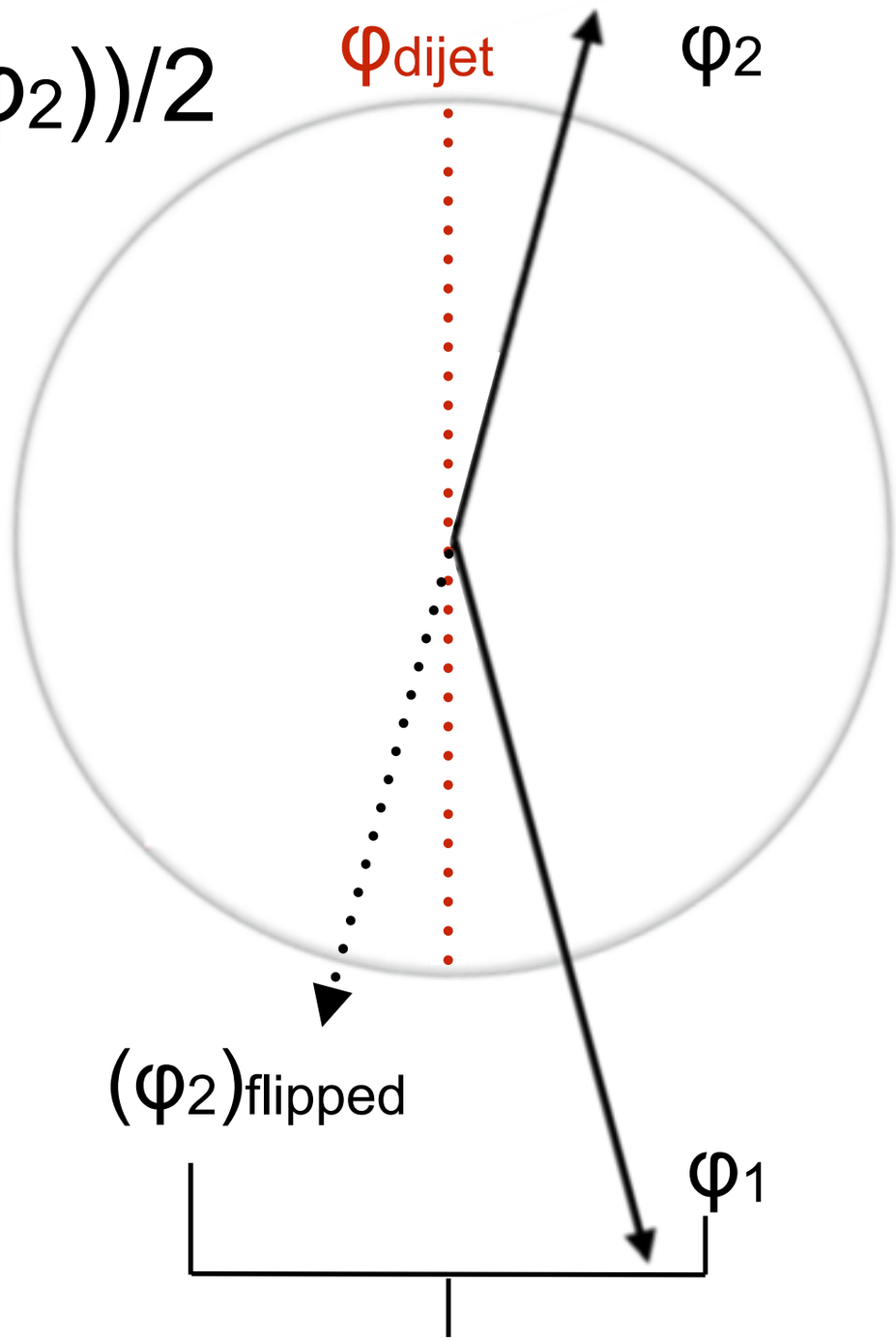
- pp: 5.3 pb^{-1} at 2.76 TeV
- PbPb: 166 μb^{-1} at 2.76 TeV — Increase from initial 6.7 μb^{-1}
- Dijet selection:
  - $p_{T,1} > 120$ GeV
  - $p_{T,2} > 50$ GeV
  - $|\eta_1|, |\eta_2| < 1.6$ (0.6)
  - $\Delta\varphi_{1,2} > 5\pi/6$

  — anti-k_t calorimeter jets (See backup slide here)
- Track Selection:
  - $p_T > 0.5$ GeV
  - $|\eta| < 2.4$

  — Corrected for efficiency/fake rate (See backup slides here and here)

Analysis: The Dijet Axis

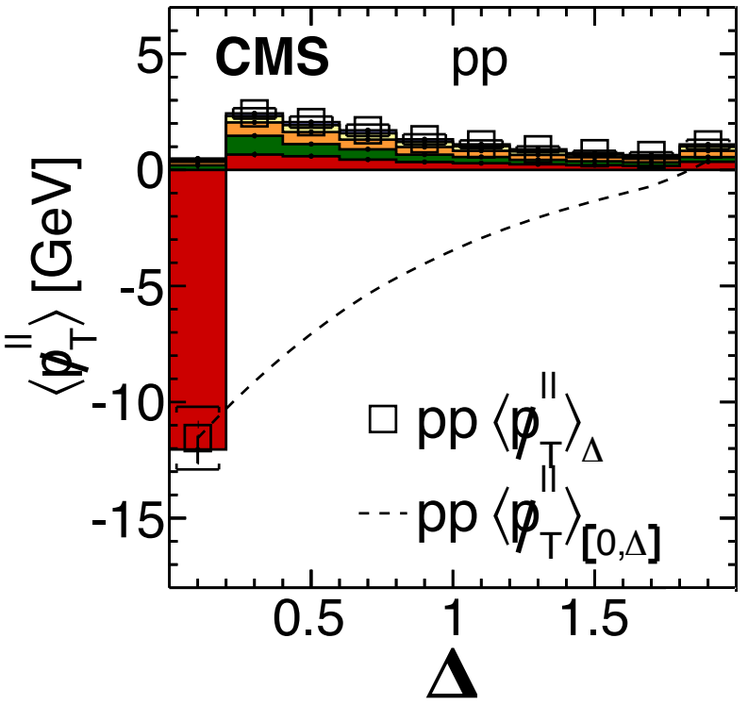
$\varphi_{dijet} = (\varphi_1 + (\pi - \varphi_2))/2$

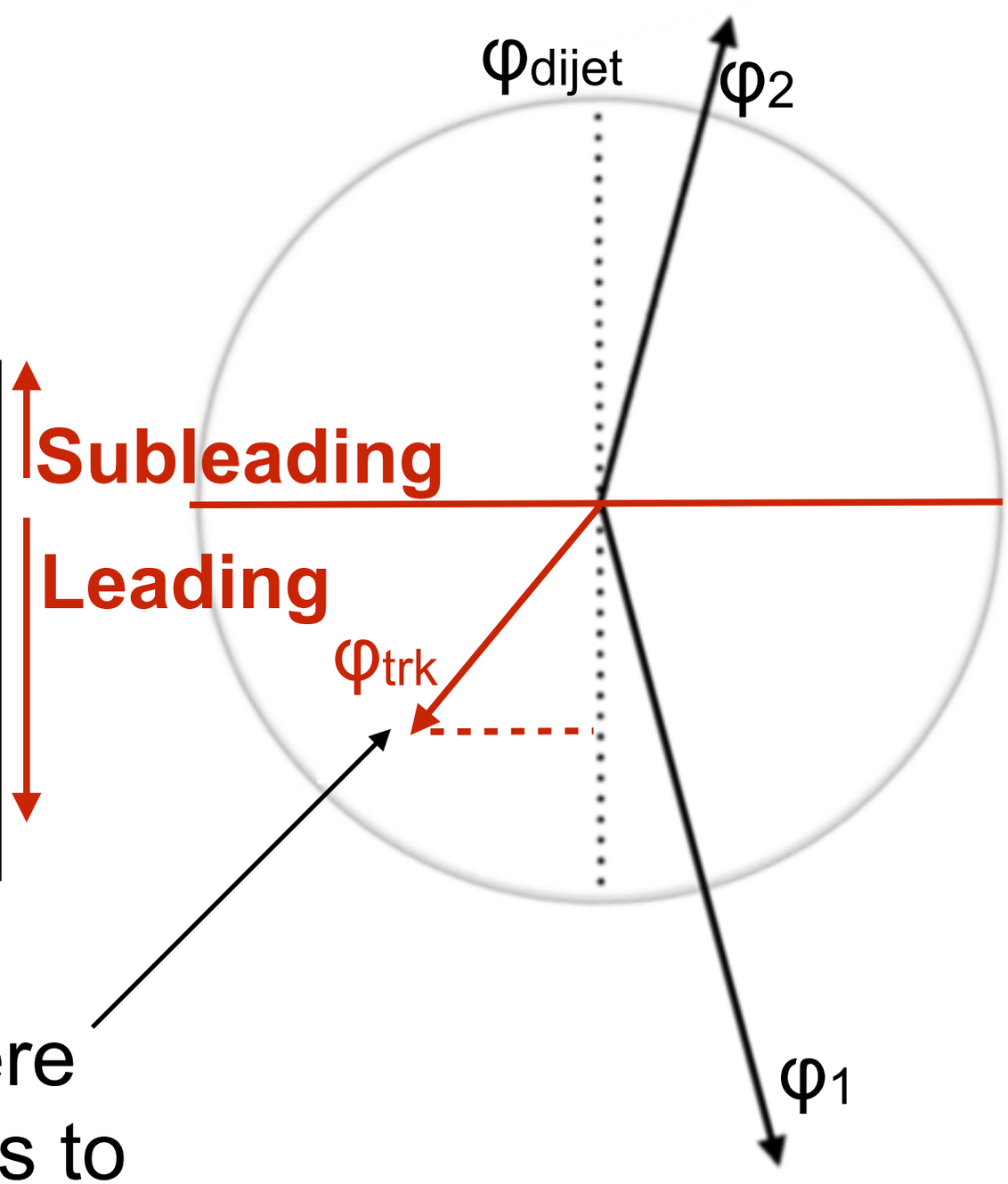


φ-dijet eliminates non-closures in Δ (see backup)

Flip subleading jet and bisect axes

Analysis: Binning Tracks by Δ

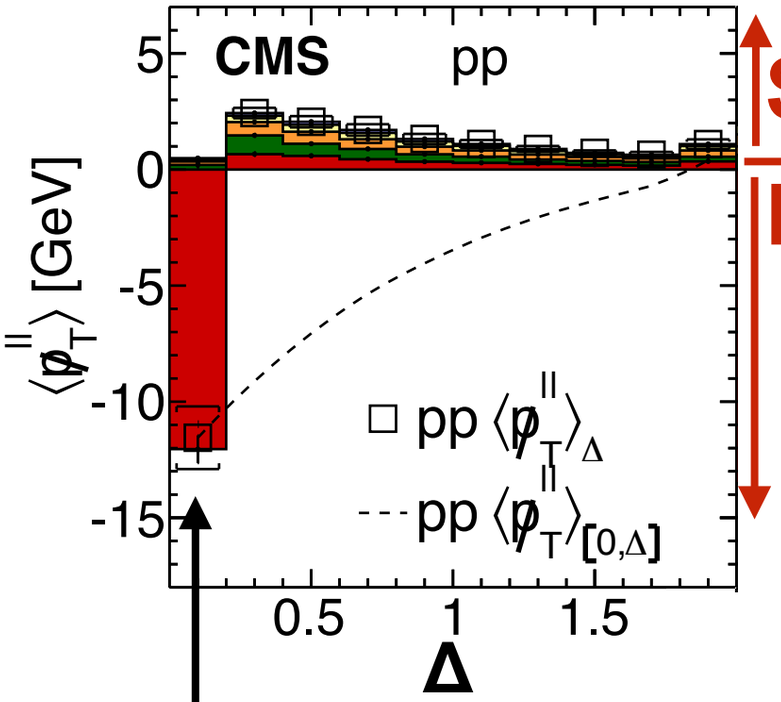




Track here contributes to Leading side:

$$p_{\mathrm{T}}^{\parallel} = -\mathrm{c}^{\mathrm{trk}} \times p_{\mathrm{T}}^{\mathrm{trk}} \times \cos\left(\phi_{\mathrm{trk}} - \phi_{\mathrm{dijet}}\right)$$

Analysis: Binning Tracks by Δ

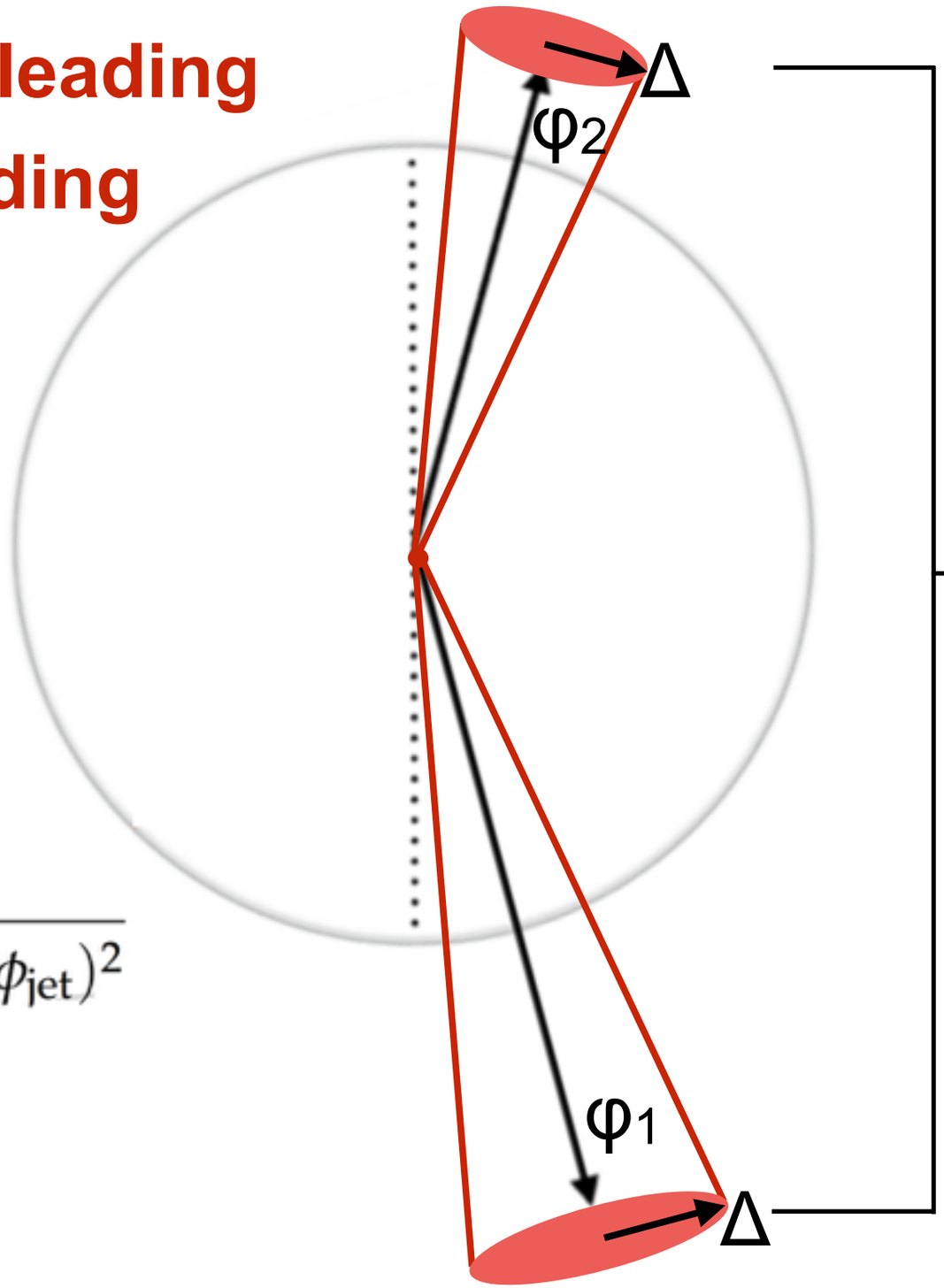


Subleading

Leading

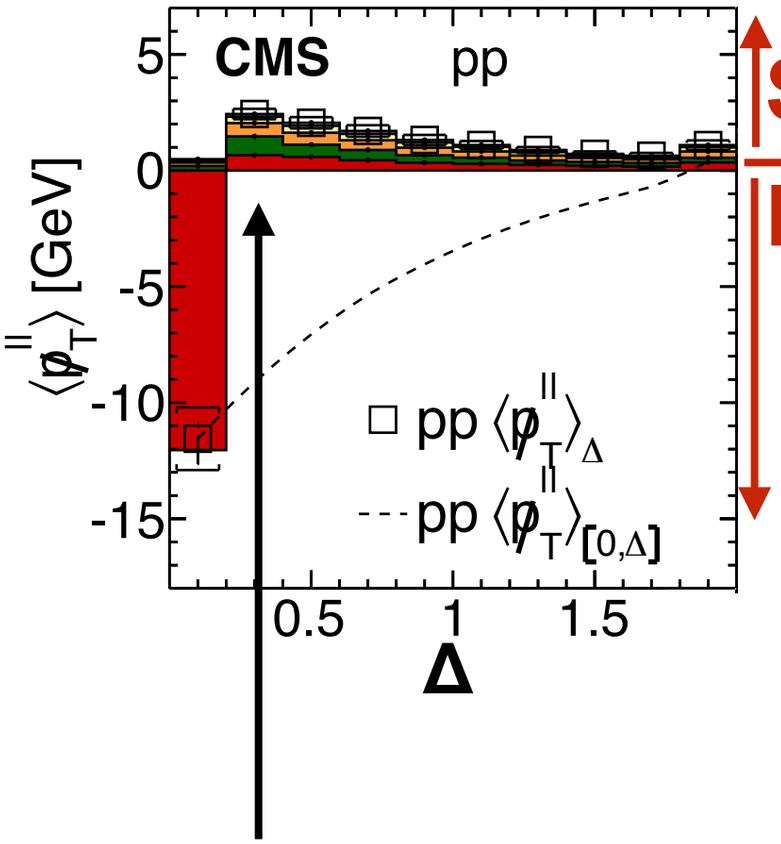
First bin Δ

$$\Delta = \sqrt{(\eta_{\text{trk}} - \eta_{\text{jet}})^2 + (\phi_{\text{trk}} - \phi_{\text{jet}})^2}$$



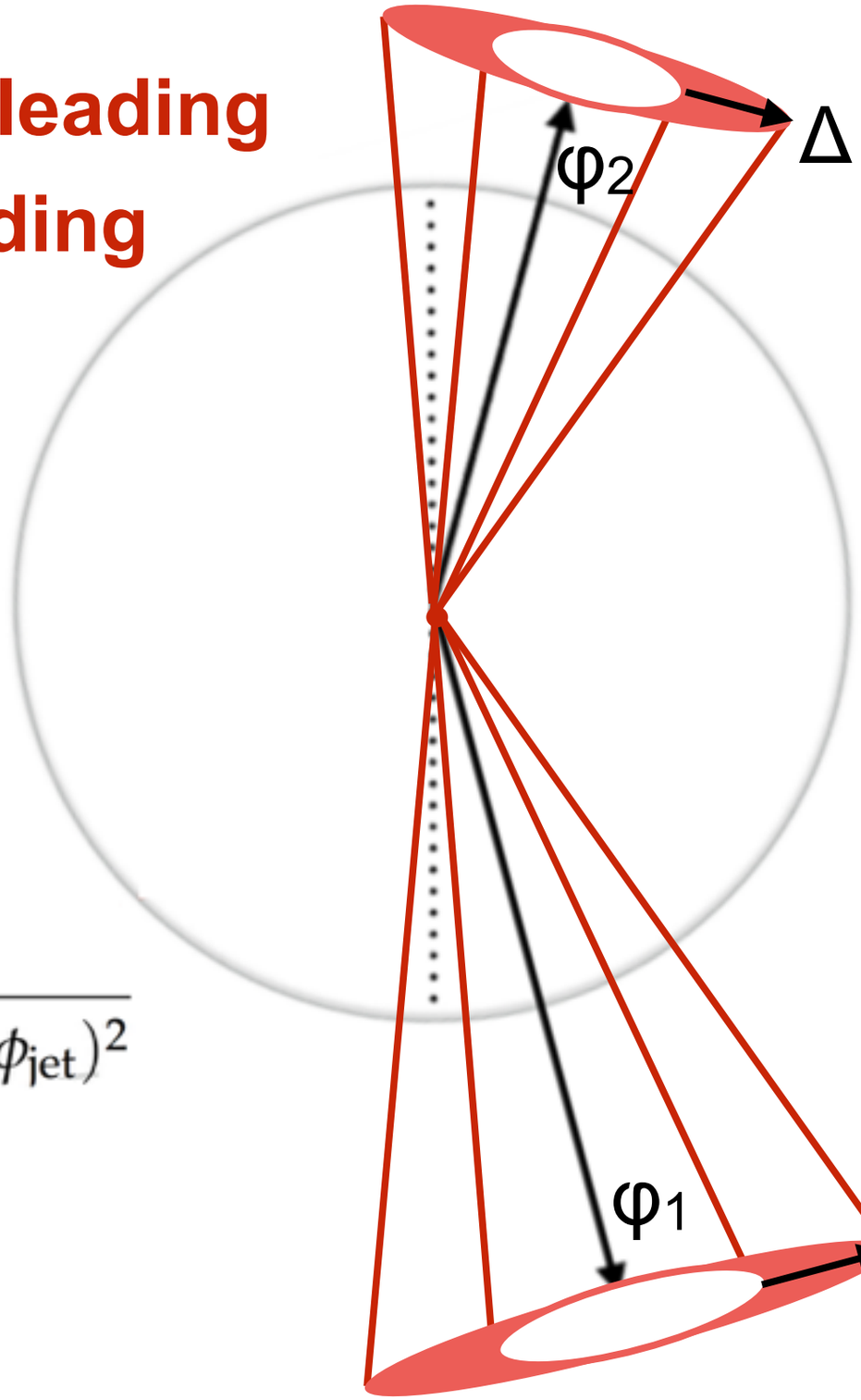
First bin Δ **NOT** same as jet cone

Analysis: Binning Tracks by Δ



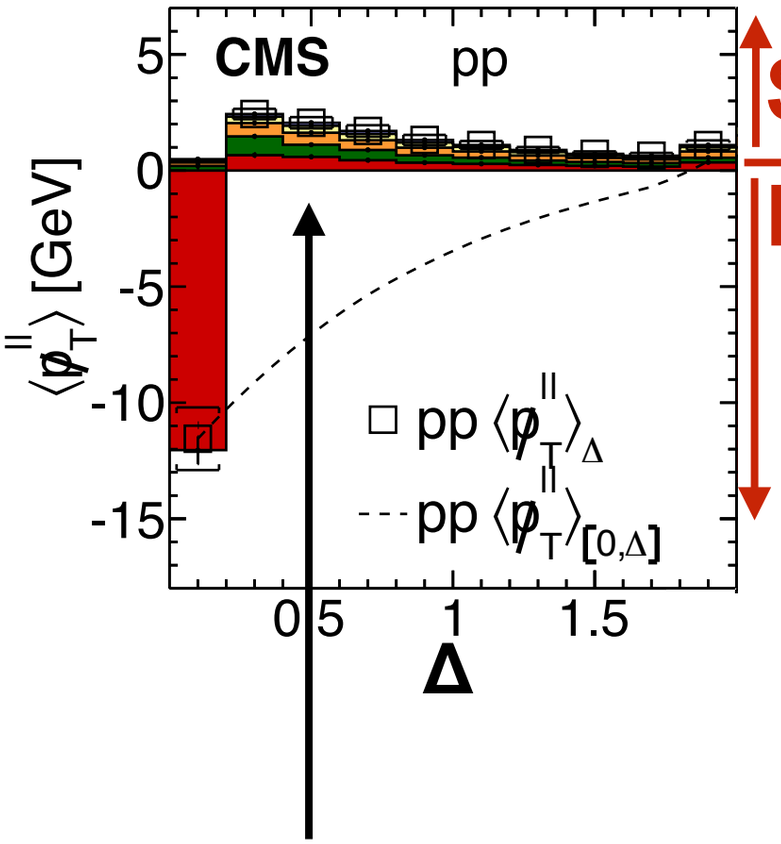
Second bin Δ

$$\Delta = \sqrt{(\eta_{\text{trk}} - \eta_{\text{jet}})^2 + (\phi_{\text{trk}} - \phi_{\text{jet}})^2}$$



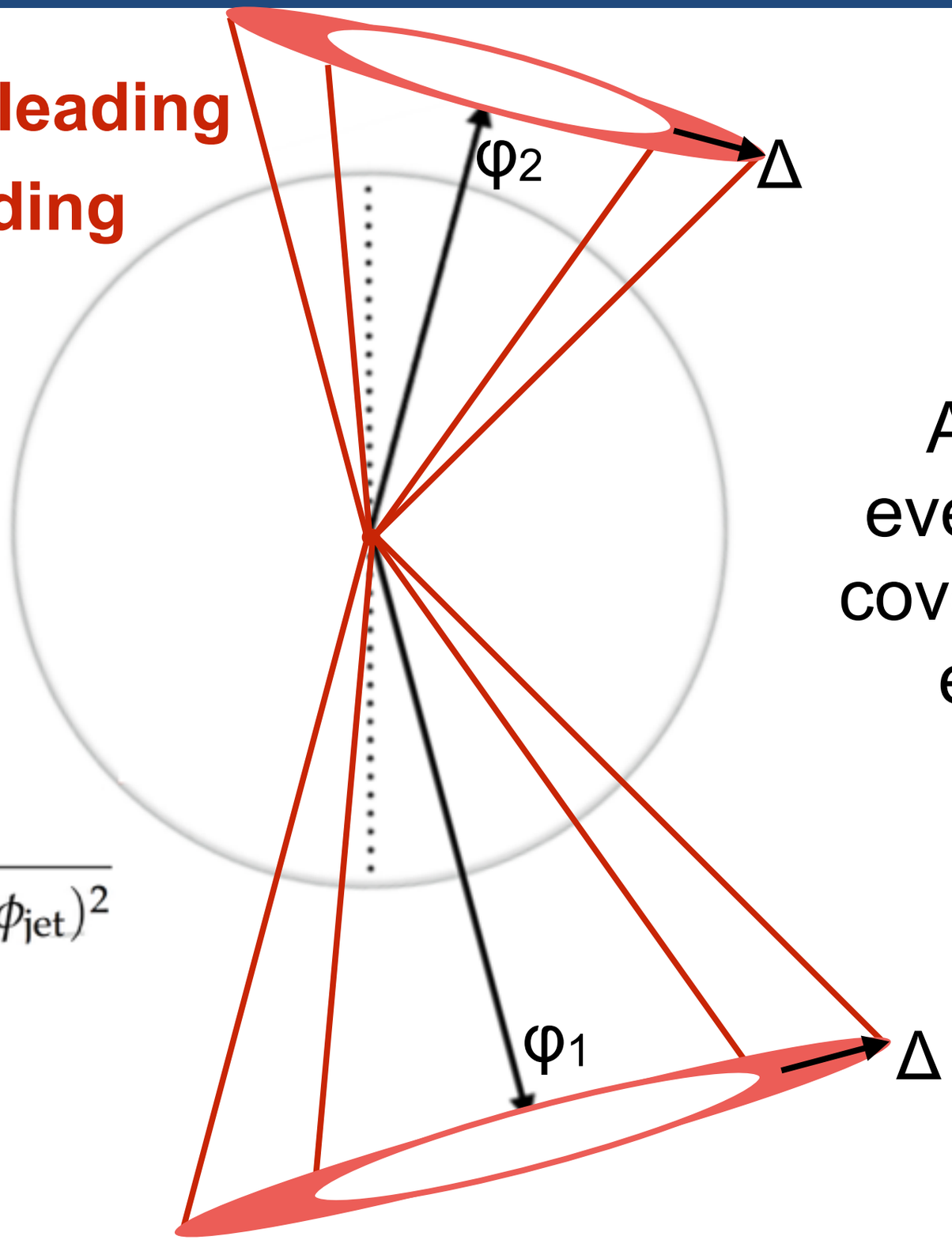
Increasing Δ -> Move away from leading and subleading jets

Analysis: Binning Tracks by Δ



Third bin Δ

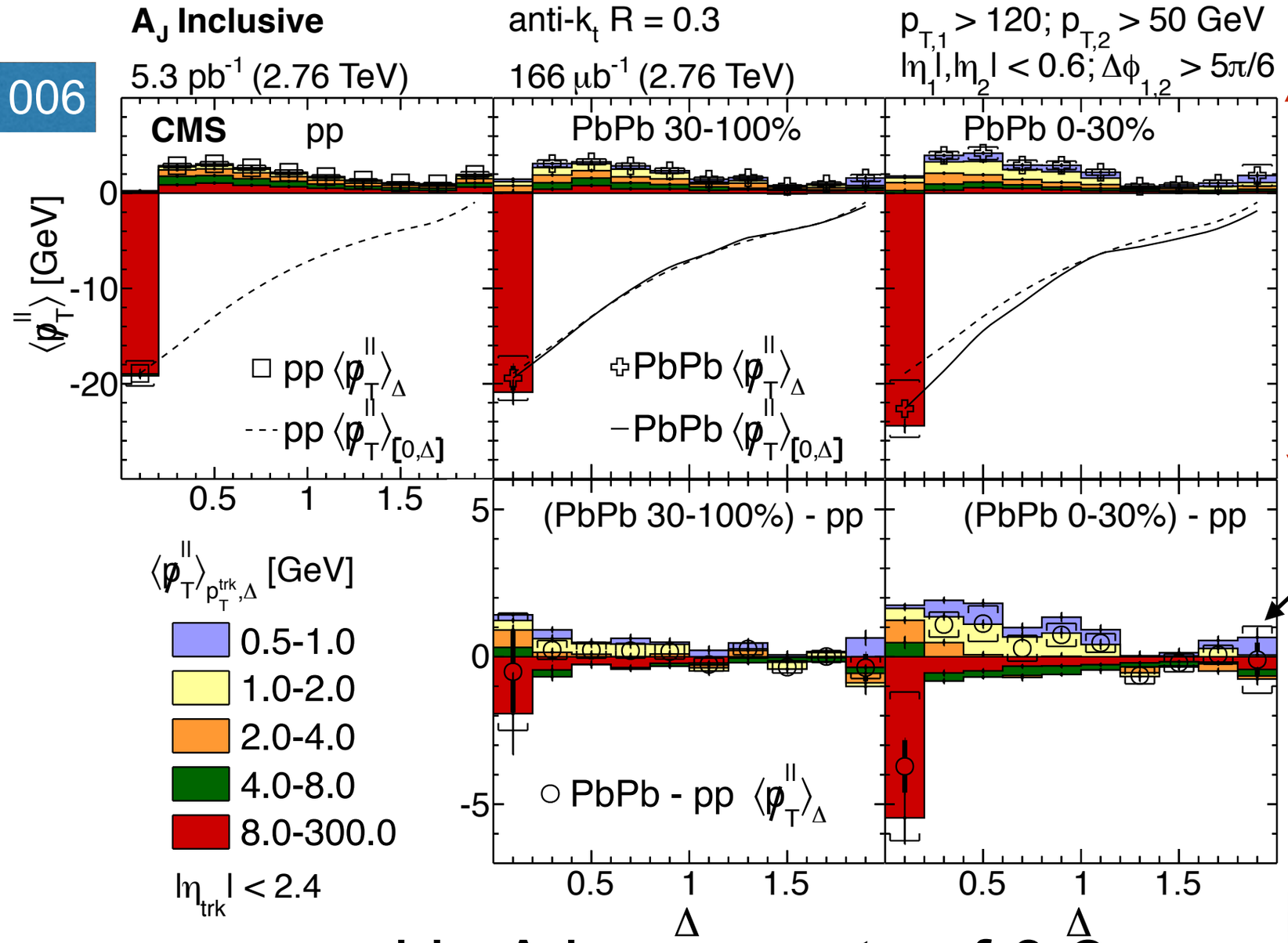
$$\Delta = \sqrt{(\eta_{\text{trk}} - \eta_{\text{jet}})^2 + (\phi_{\text{trk}} - \phi_{\text{jet}})^2}$$

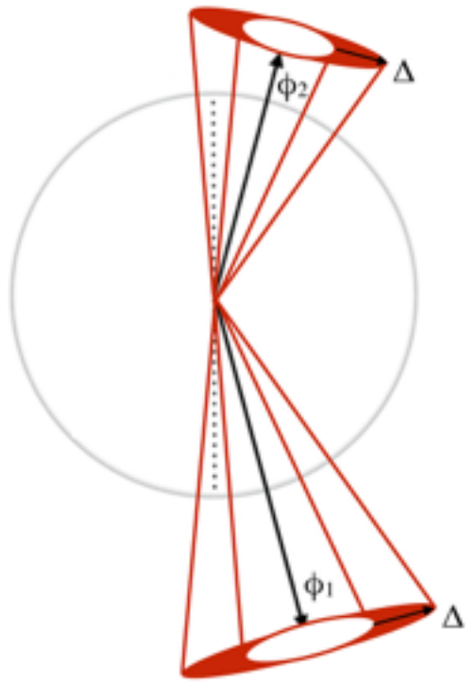


Annuli eventually cover entire event

Missing P_T vs. Δ with R = 0.3

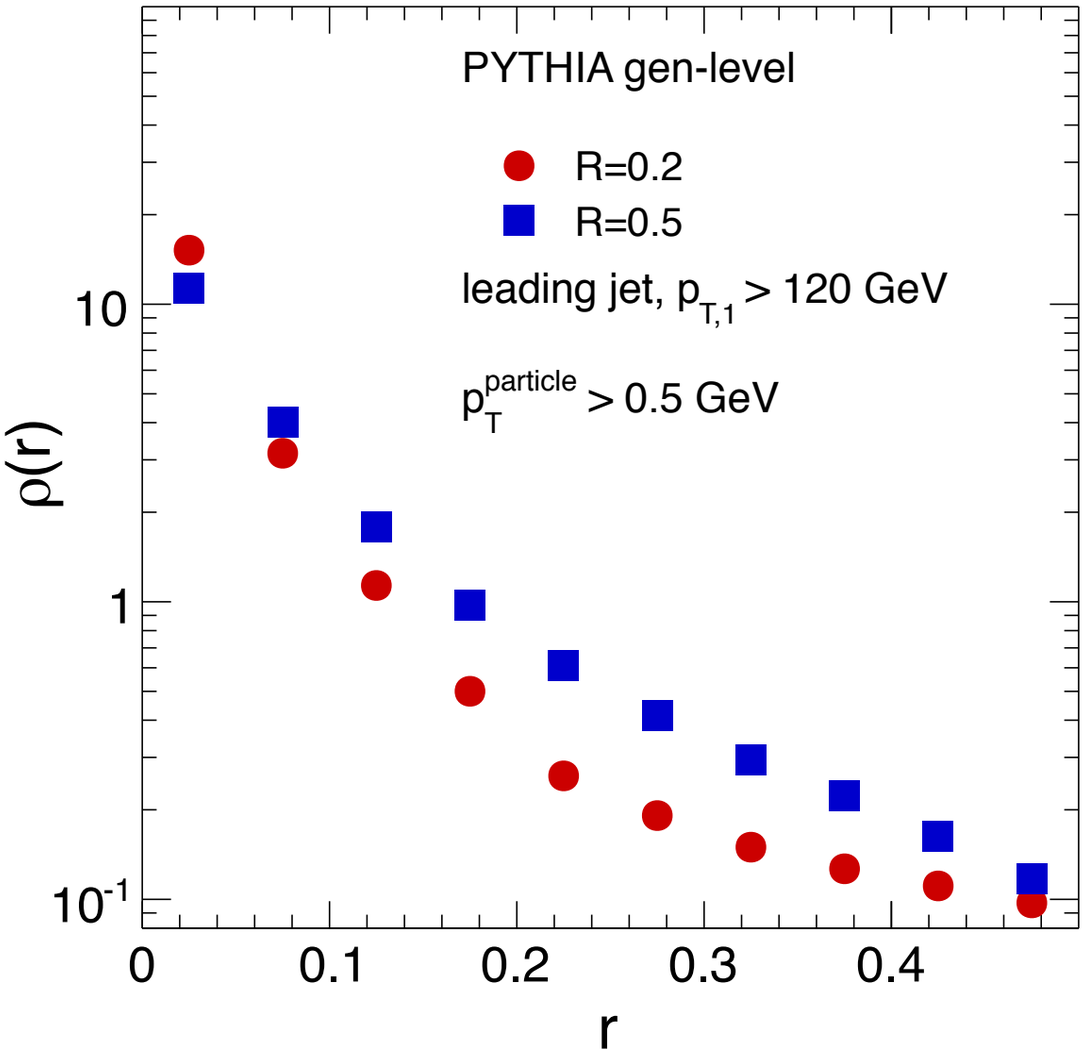
JHEP 01 (2016) 006

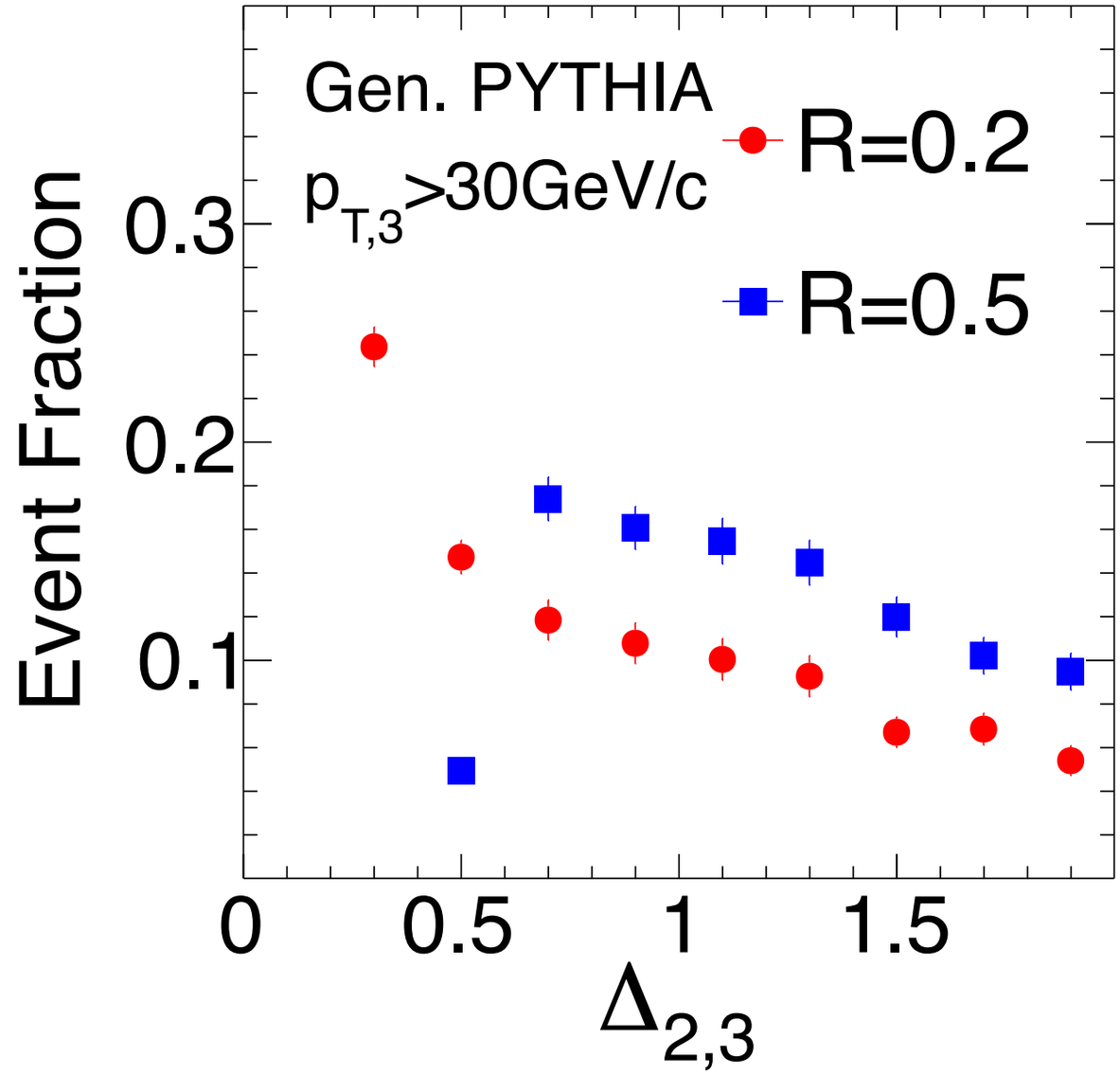




- Missing p_T measured in Δ increments of 0.2
- In central PbPb, balanced by lower p_T particles

Missing P_T and Jet Radius Motivation





- Left: Jet shape in Gen. PYTHIA for different R
- Right: Shifting third jet position in Gen. PYTHIA relative to subleading jet for different R

Multiple R Missing P_T vs. Δ

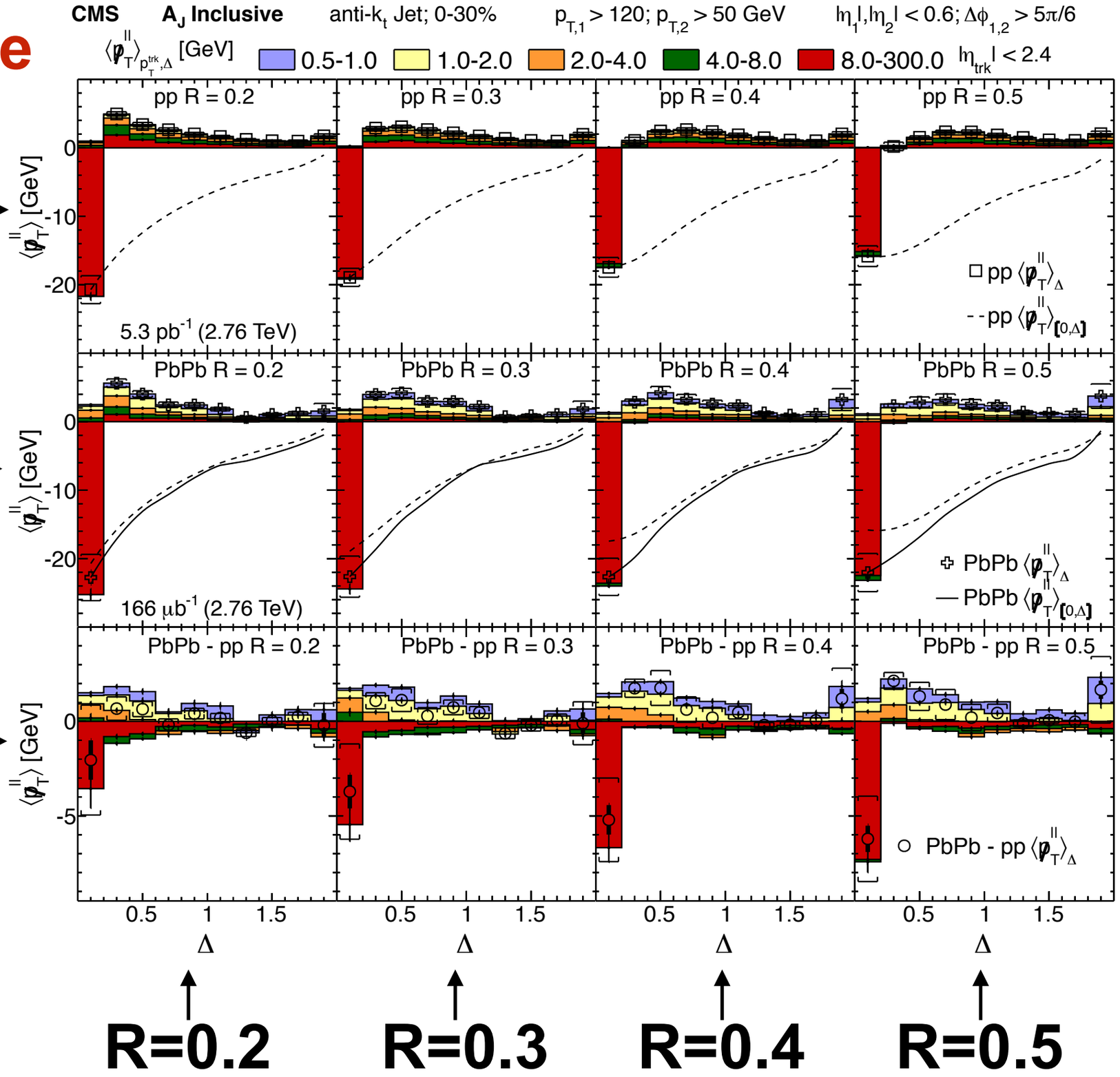
A_J Inclusive

JHEP 01 (2016) 006

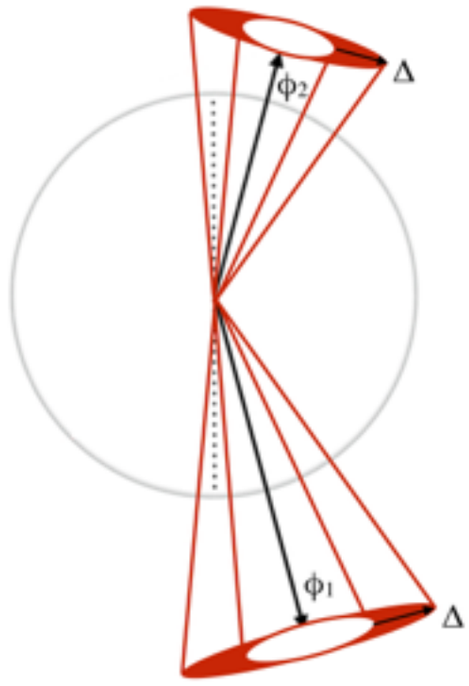
pp

PbPb (0-30%)

PbPb - pp



R=0.2 **R=0.3** **R=0.4** **R=0.5**



Zoom on pp and PbPb Distributions (I)

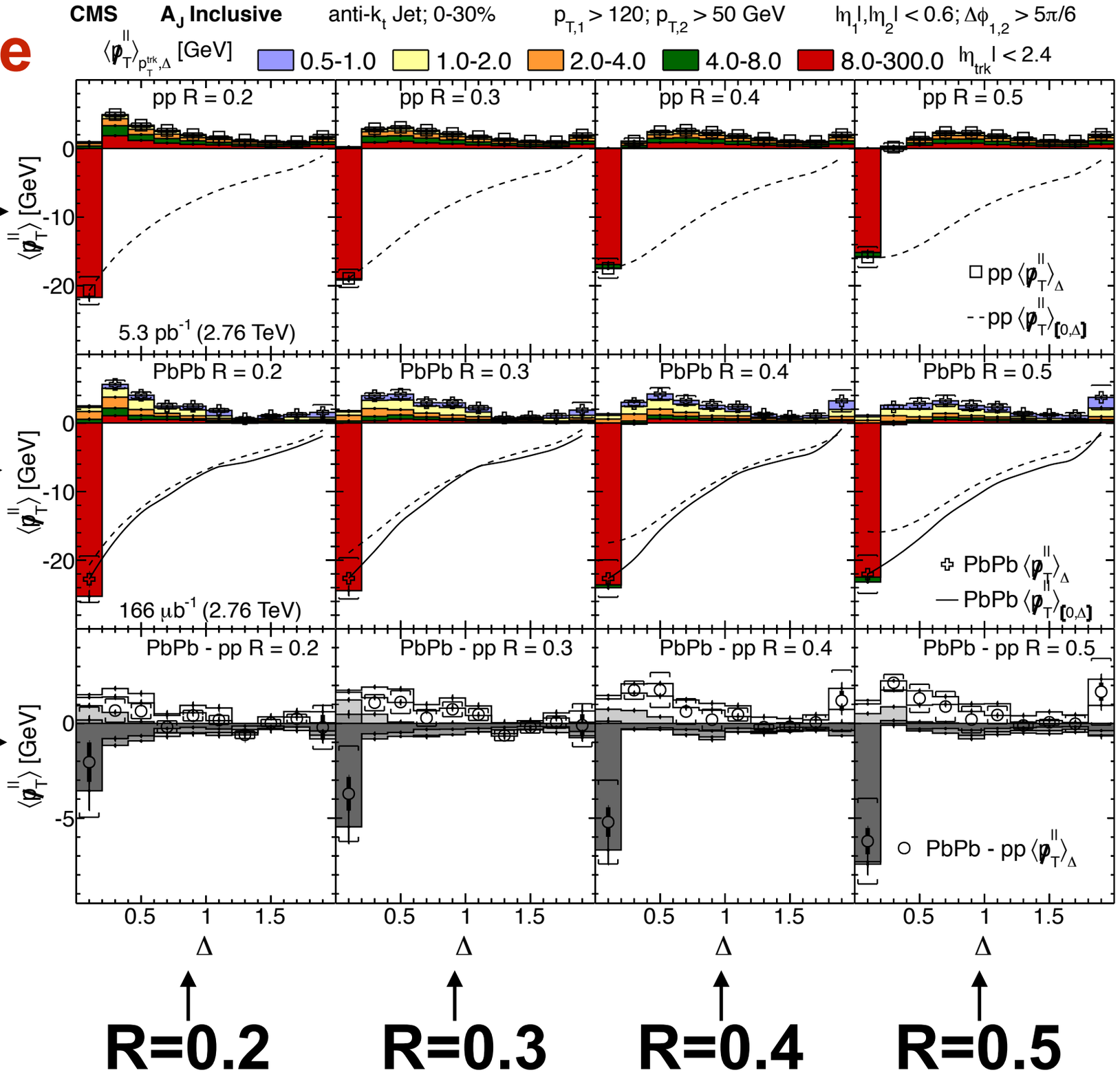
A_J Inclusive

JHEP 01 (2016) 006

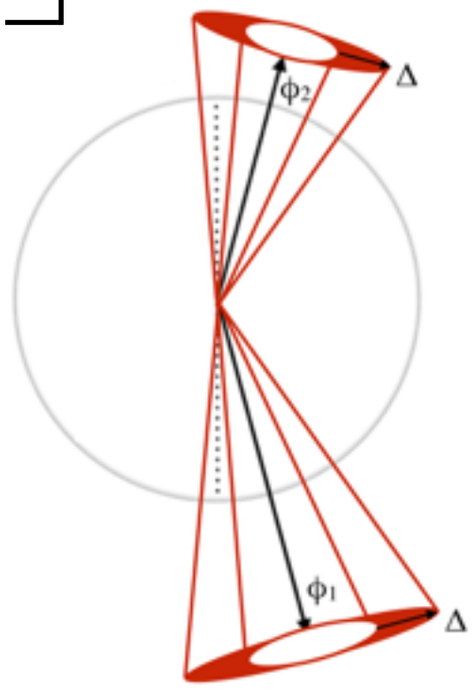
pp →

PbPb → (0-30%)

PbPb - pp →



Zoom of Top Panels



R=0.2 **R=0.3** **R=0.4** **R=0.5**

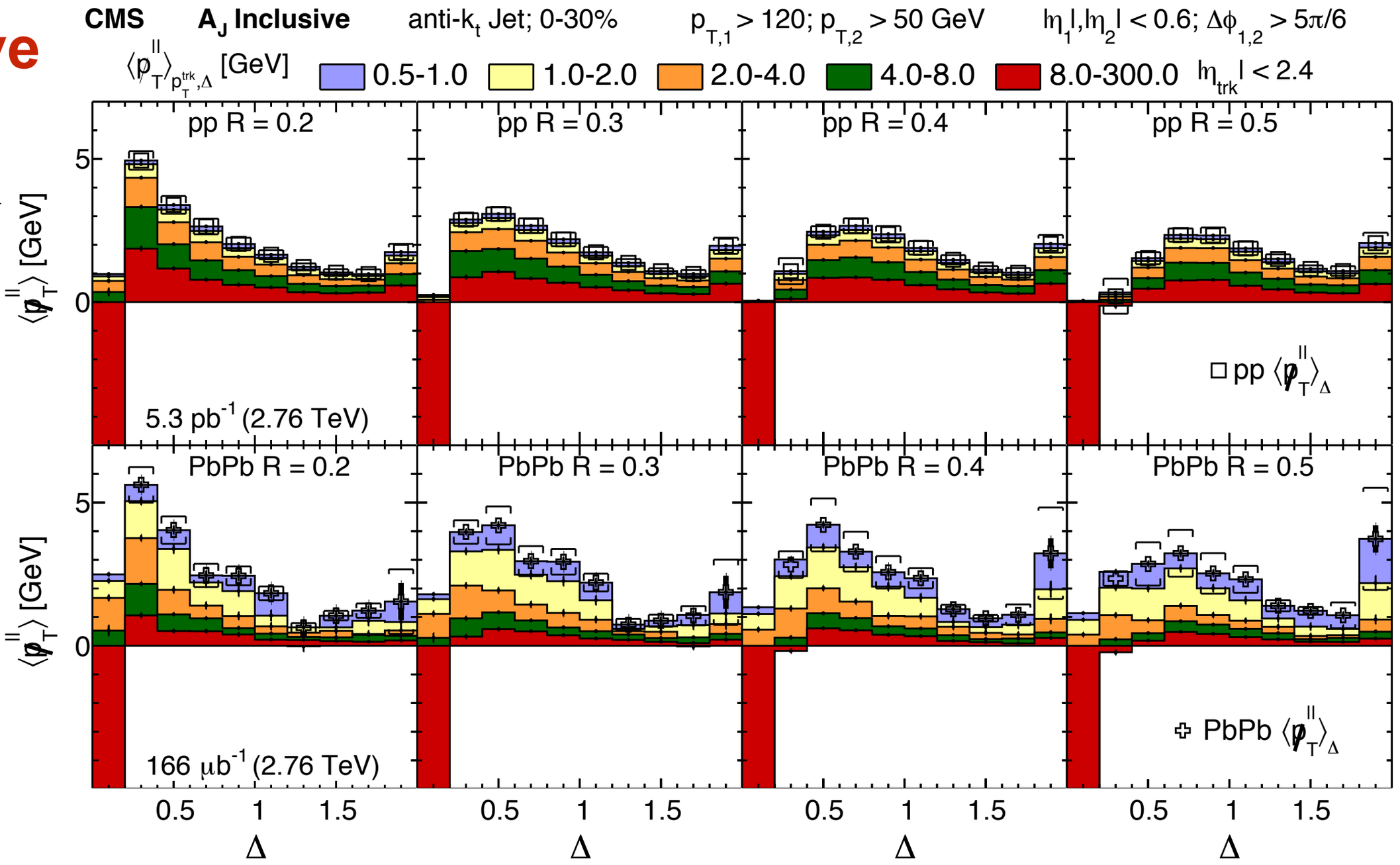
Zoom on pp and PbPb Distributions (II)

A_J Inclusive

pp →

PbPb (0-30%) →

JHEP 01 (2016) 006



- Subleading (> 0) peak shifts outward in Δ from R = 0.2->0.5
  - Third jet possible position pushed out with R increase

pp and PbPb Cumulative Curves (I)

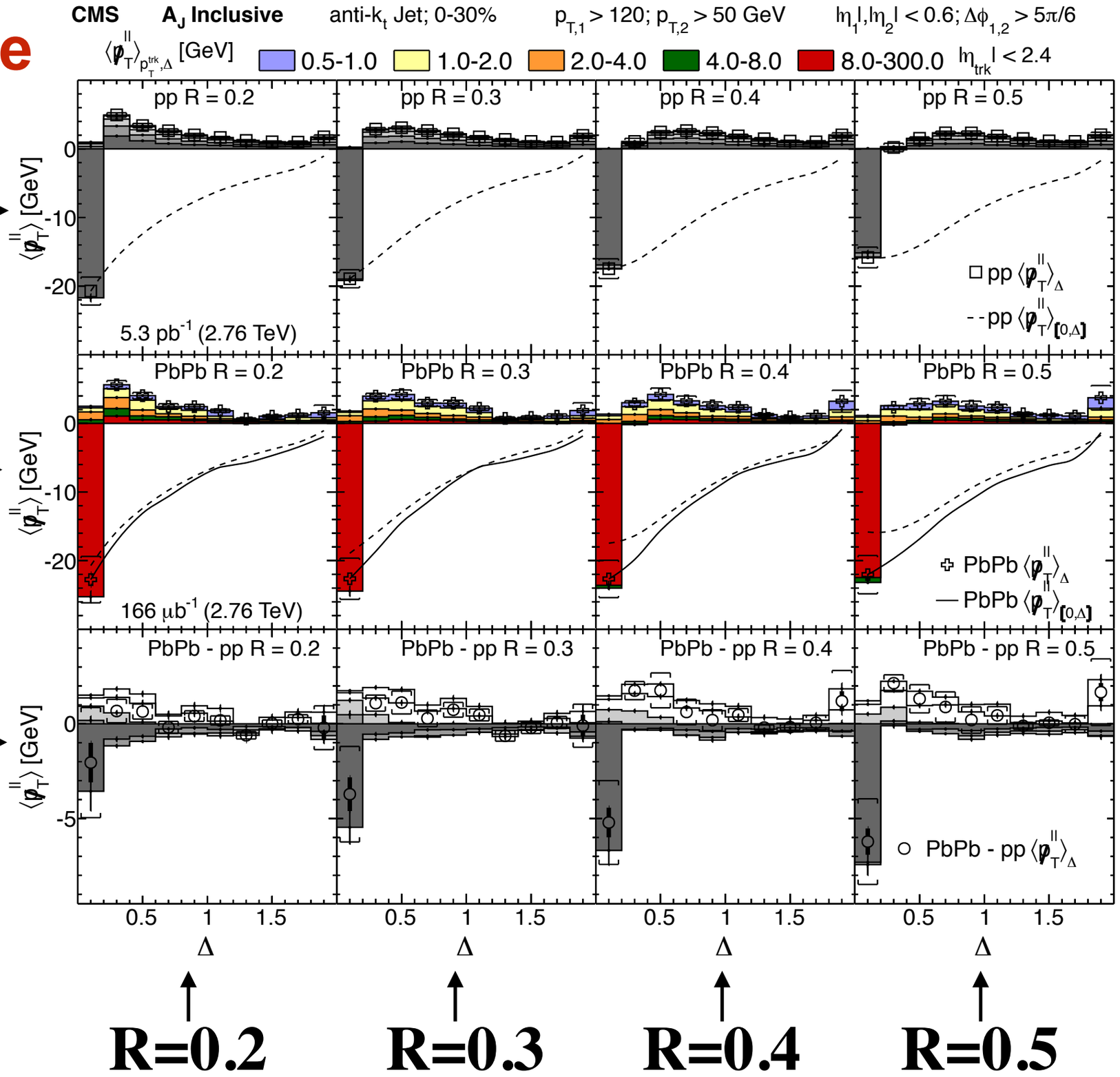
A_J Inclusive

JHEP 01 (2016) 006

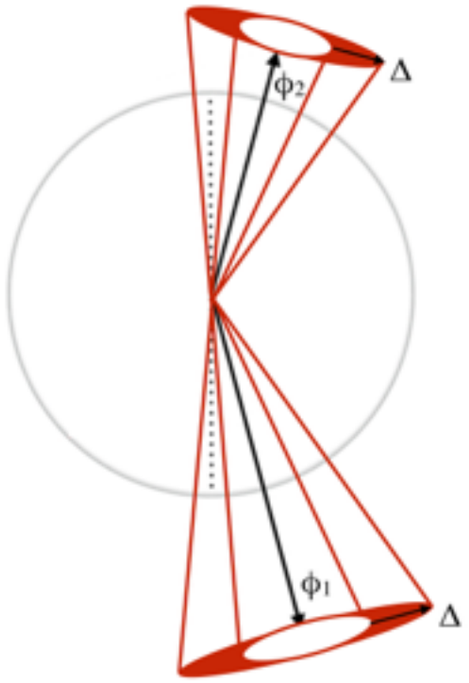
pp →

PbPb (0-30%) →

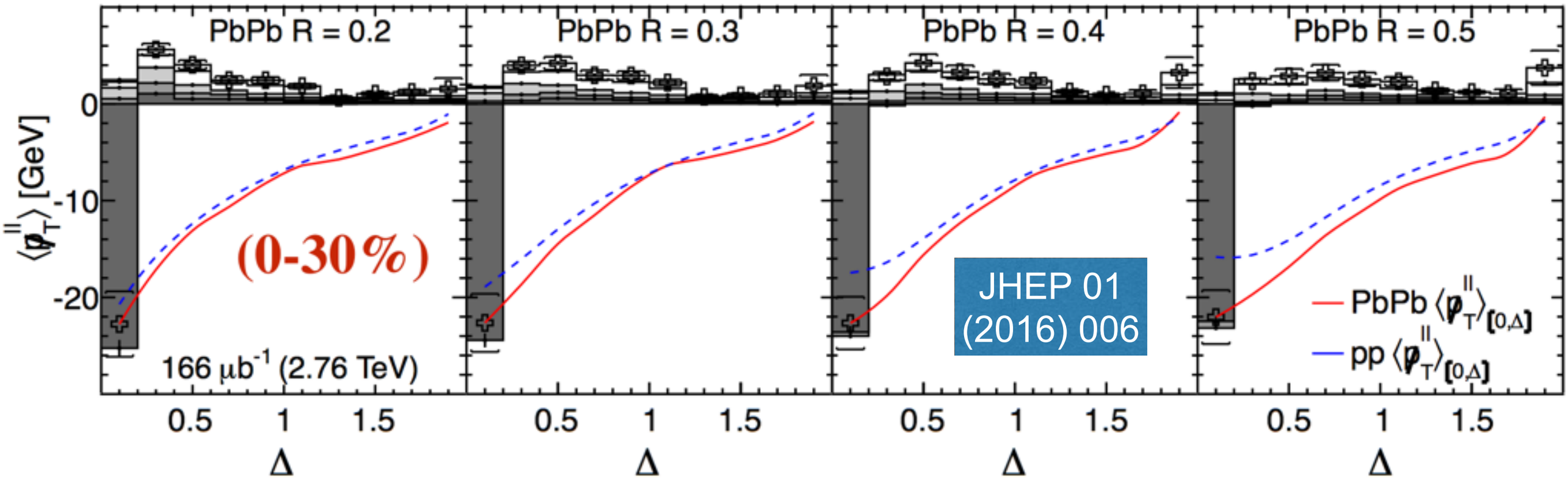
PbPb - pp →



Compare Curves



pp and PbPb Cumulative Curves (II)



- Curve difference between PbPb and pp in first bin Δ
- For all R, curves similar between PbPb and pp with Δ > 0.2
- Primary difference of PbPb and pp is in softening spectra

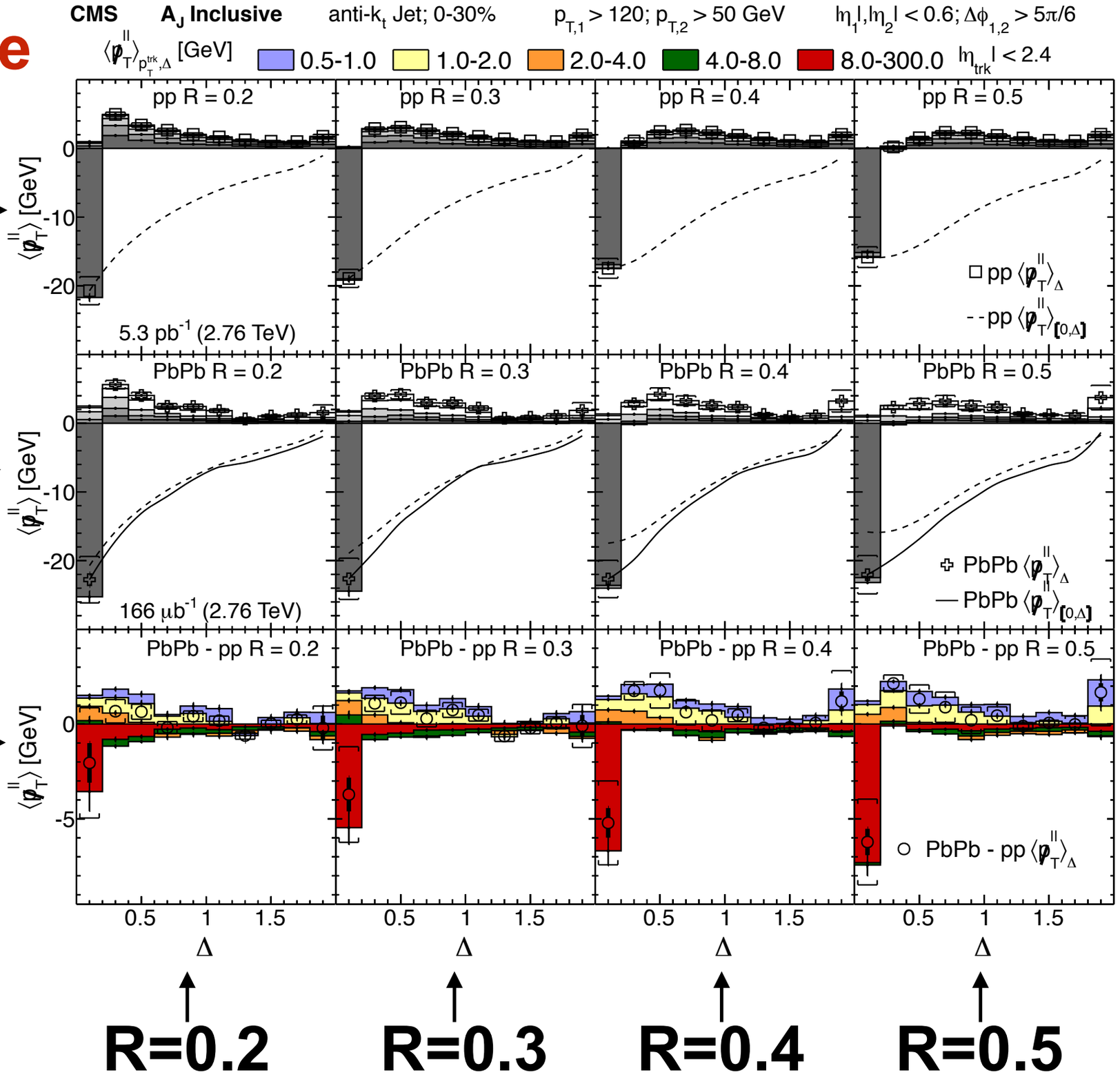
Difference of PbPb and pp (I)

A_J Inclusive

pp

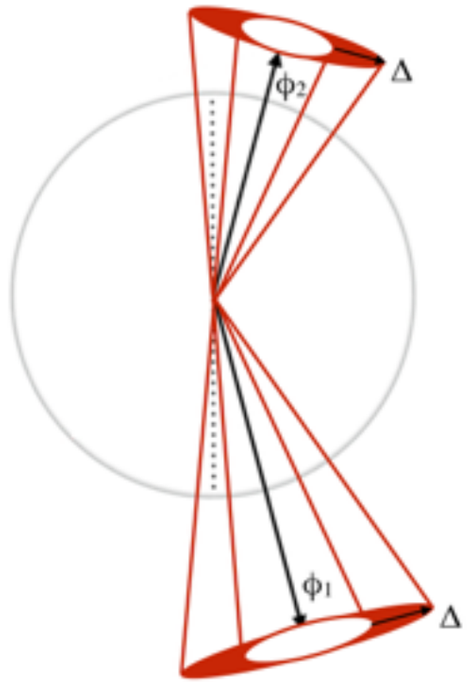
PbPb (0-30%)

PbPb - pp



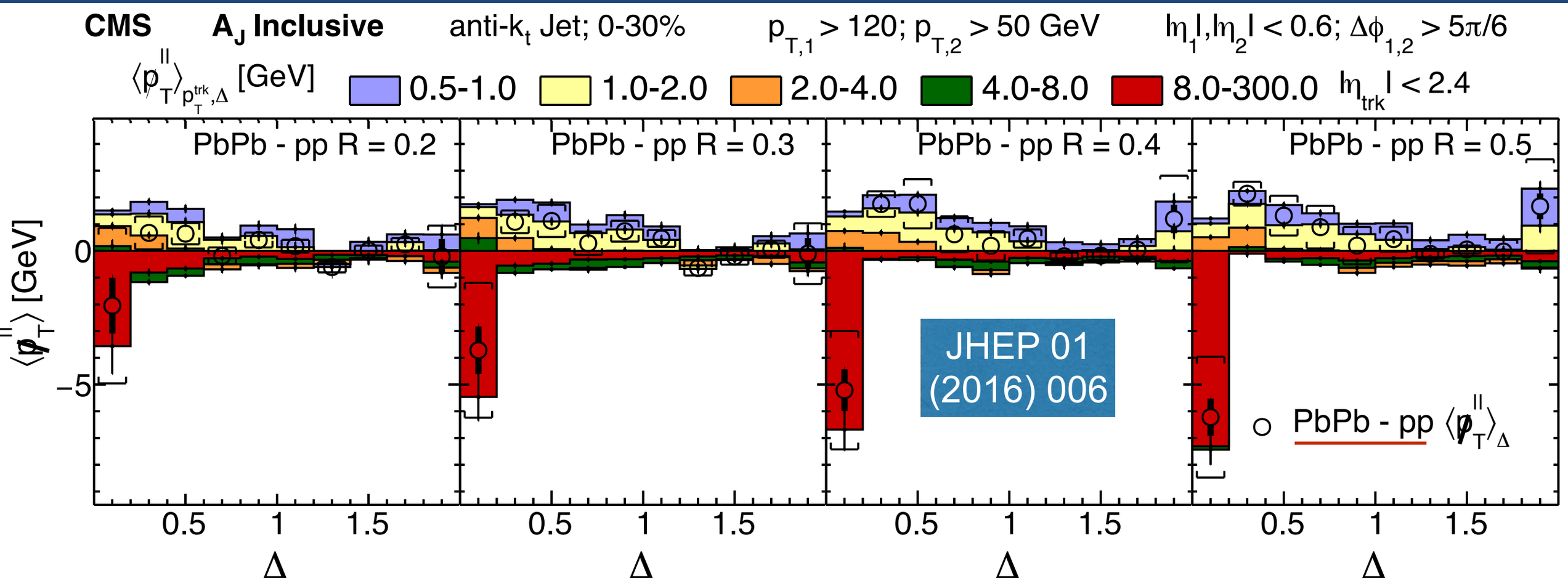
R=0.2 **R=0.3** **R=0.4** **R=0.5**

JHEP 01 (2016) 006



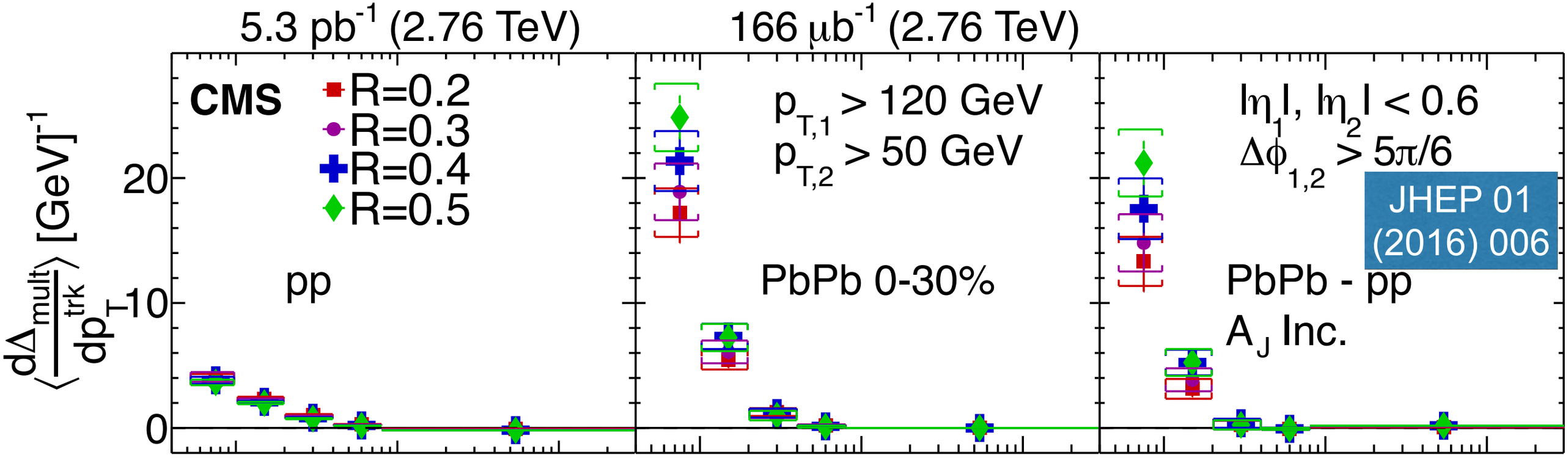
Zoom of Difference

Difference of PbPb and pp (II)



- High p_T change in first bin Δ from R=0.2->0.5 within systematic
- Low p_T excess increases in both magnitude and angle with R=0.2->0.5
  - Final bin is catch-all; increase w/ R suggests growing tail

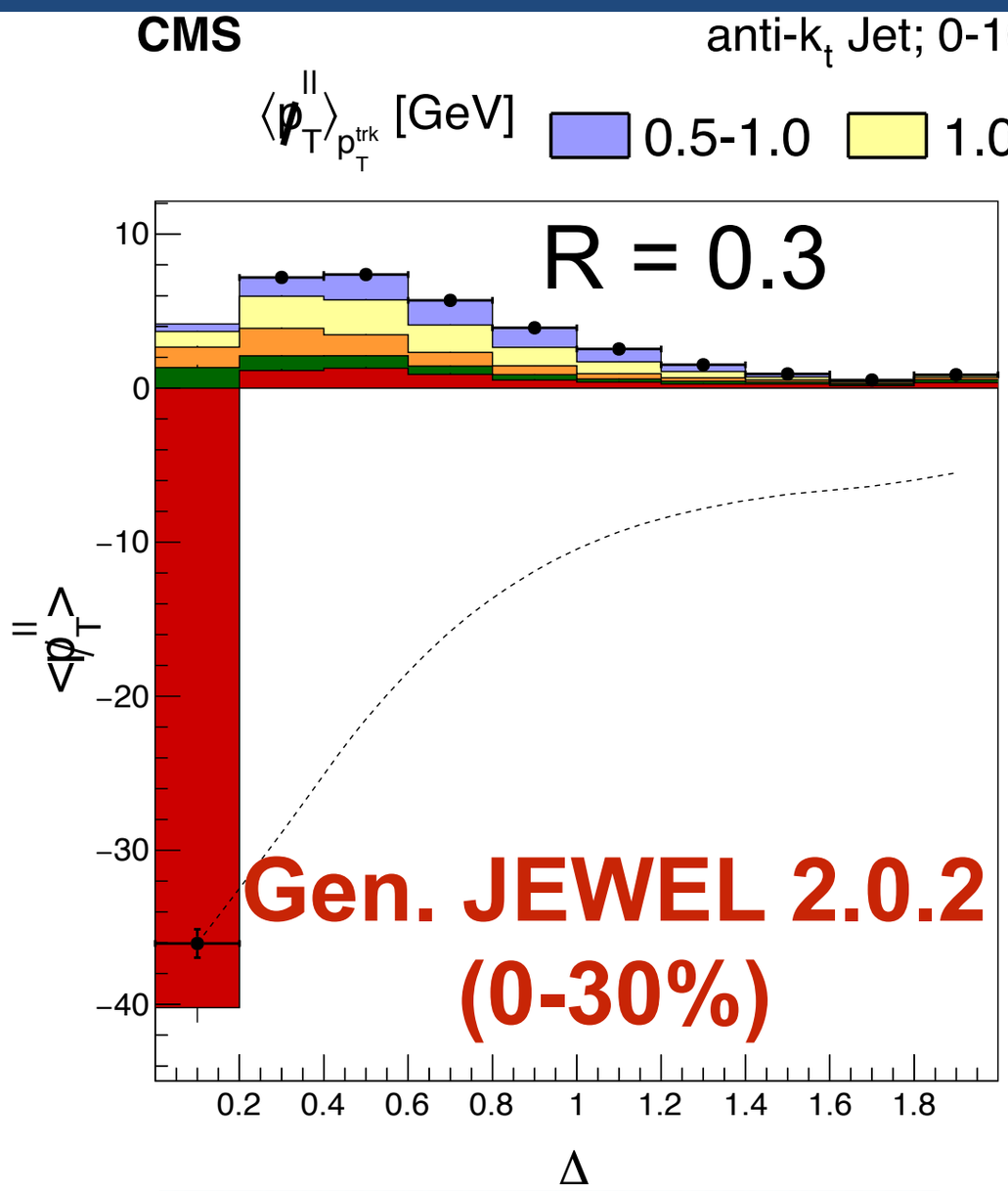
dN/dp_T for all R



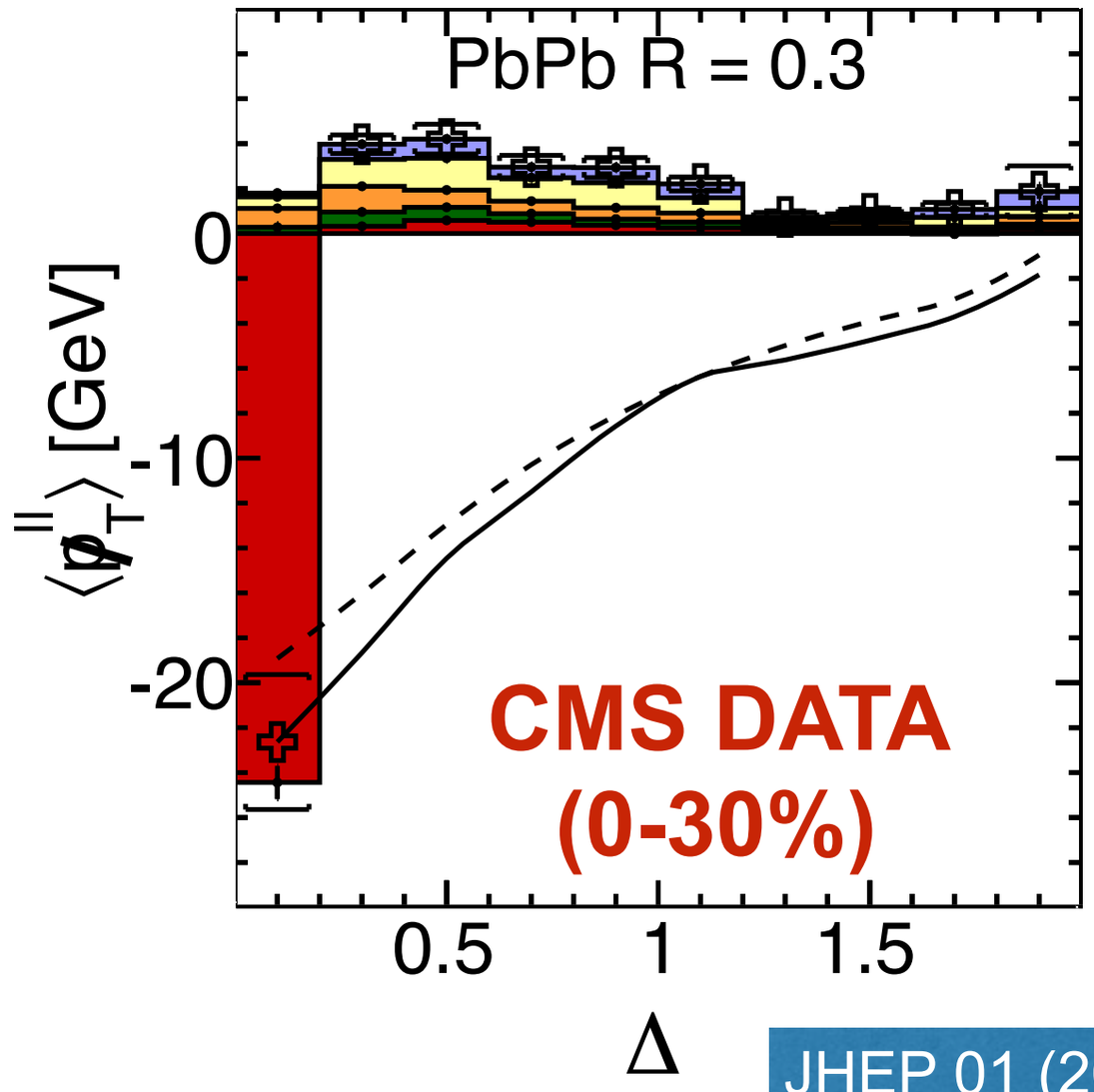
$$\langle d\Delta_{mult}/dp_T \rangle = -c^{trk} \times \cancel{p_T^{trk}} \times \cos(\phi_{trk} - \phi_{dijet}) \longrightarrow \text{(remove } p_T \text{ weight)}$$

- Low p_T contribution (0.5-1.0 GeV) ordered in R
- R = 0.2-> R = 0.5 difference greater than summed statistical and systematic error

Gen. JEWEL Missing p_T, R=0.3 (0-30%)



Eur.Phys.J. C74 (2014) 2762

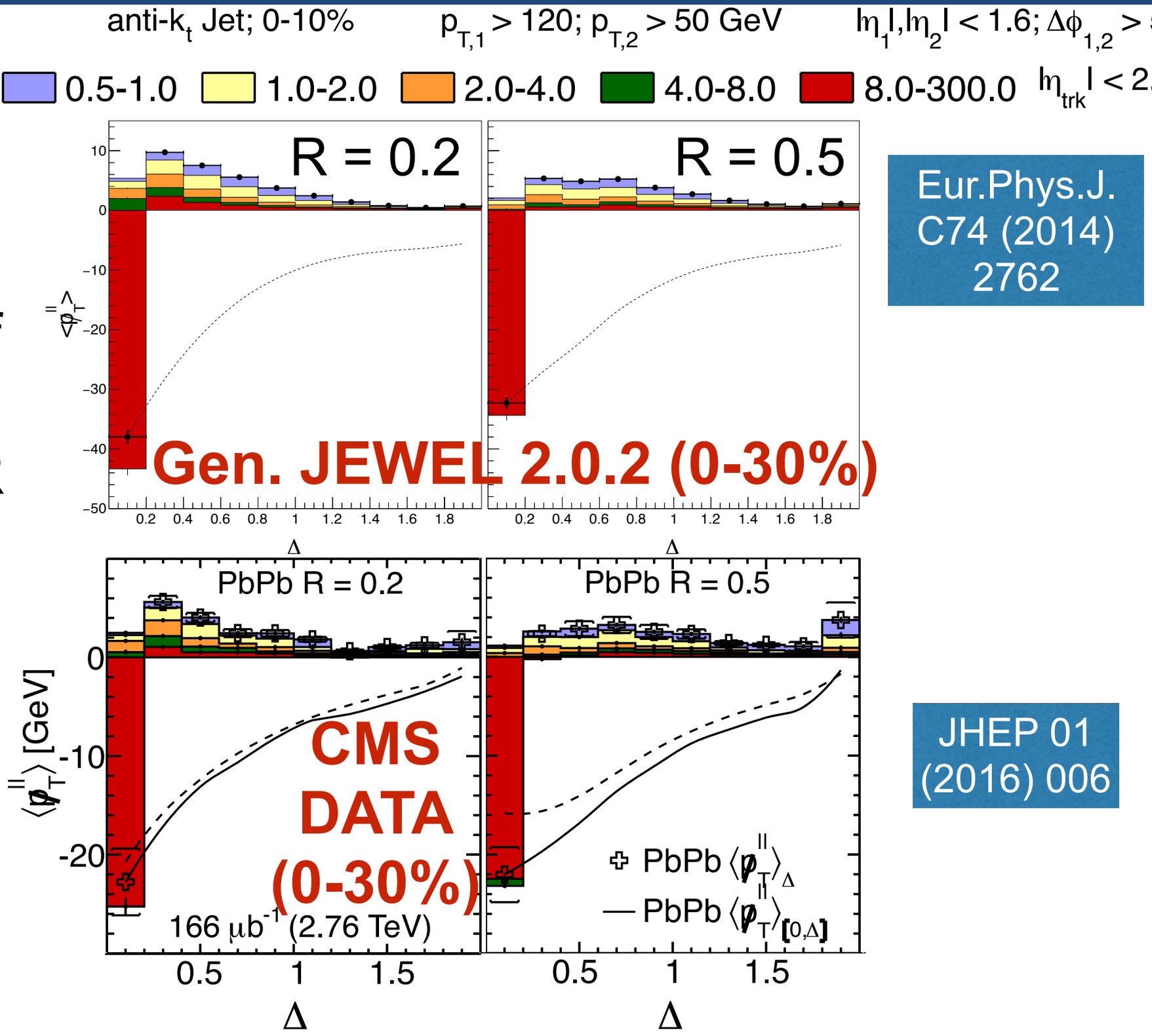


JHEP 01 (2016) 006

- Missing p_T curve using Gen. JEWEL w/ medium recoil, 0-30%, unsmeared
  - See backup for exact running parameters (here)

Gen. JEWEL Missing p_T, R=0.2 and 0.5

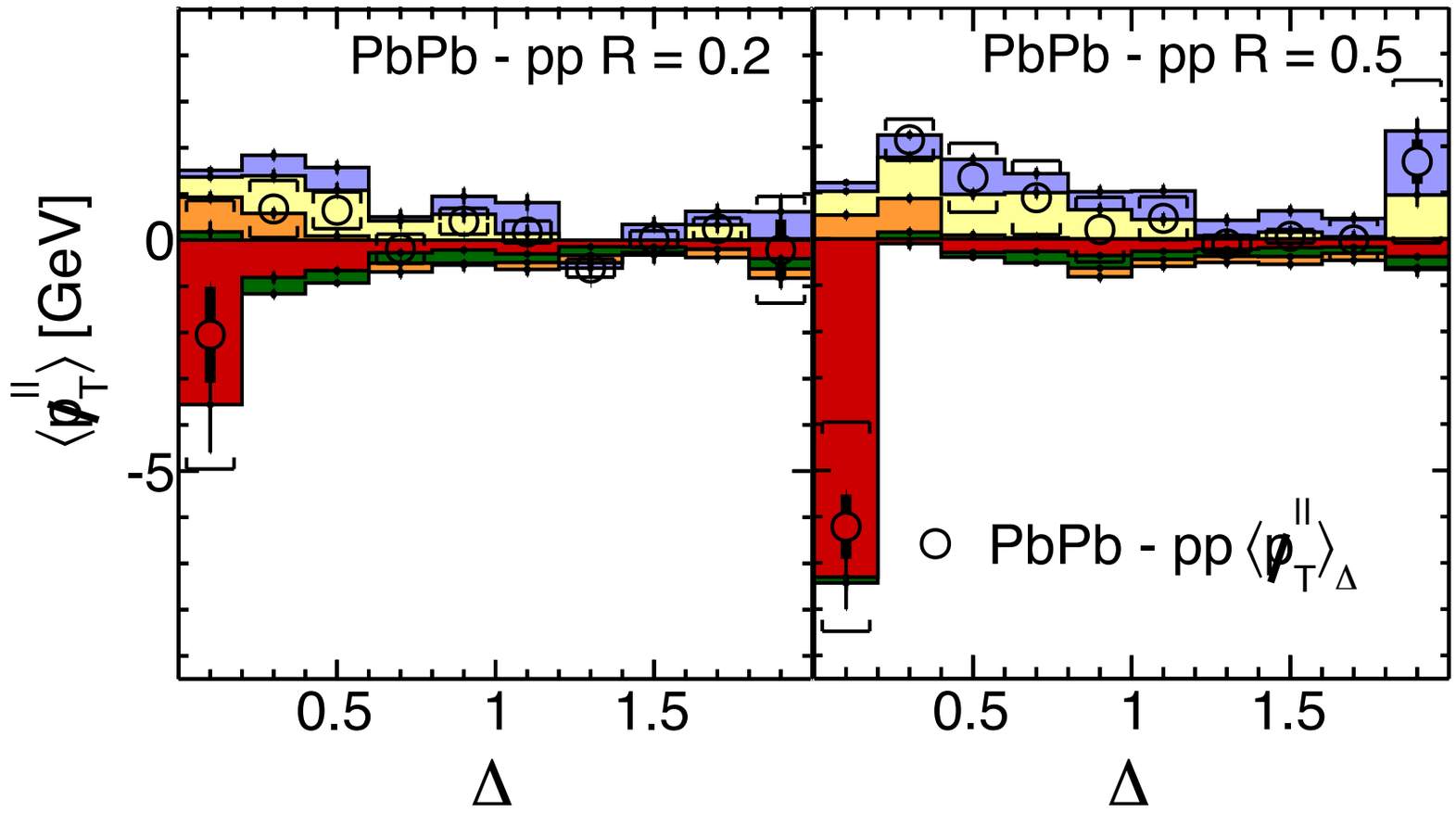
- Comparing the high and low cases of clustering parameter R



Eur.Phys.J. C74 (2014) 2762

JHEP 01 (2016) 006

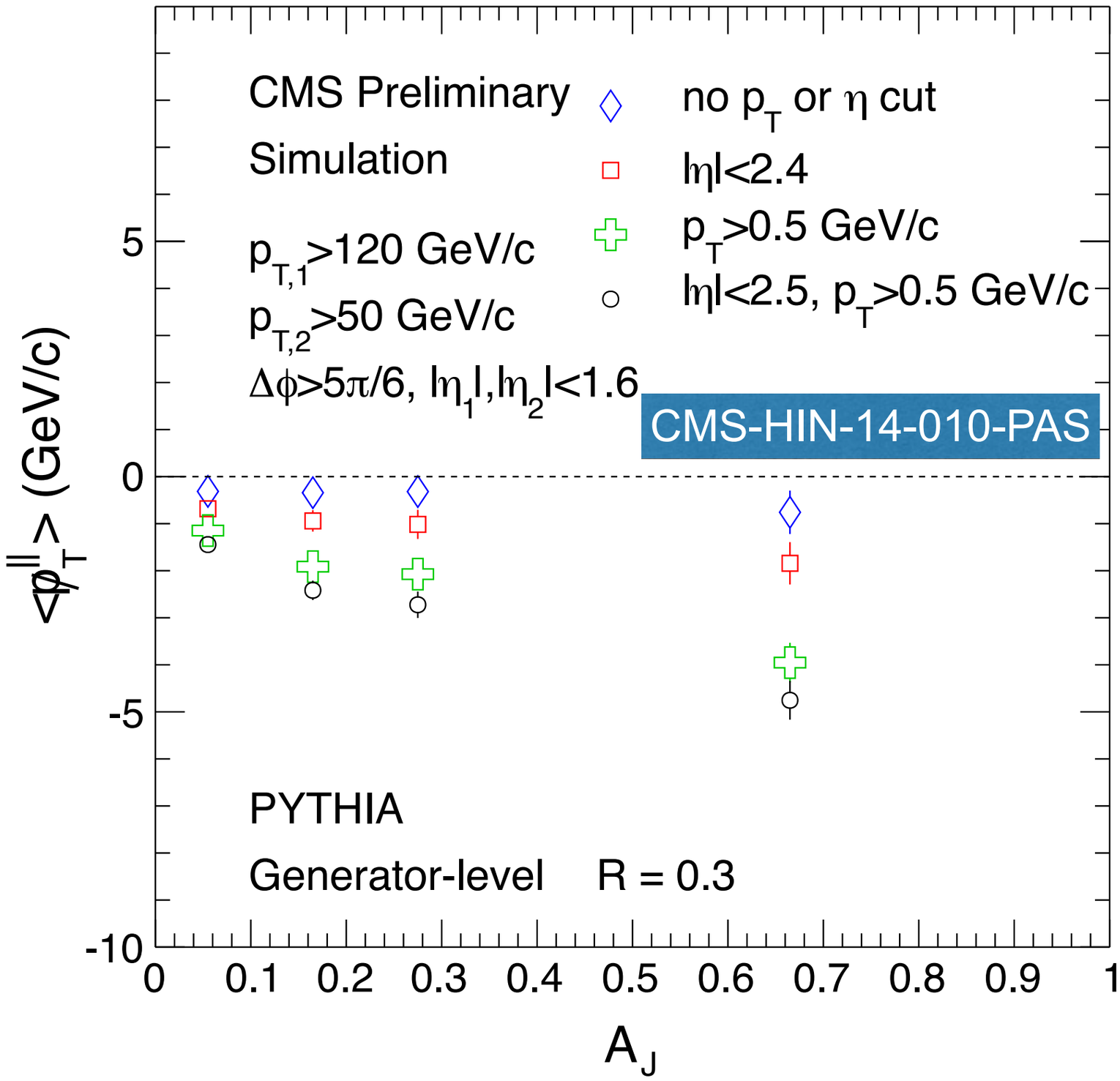
Summary



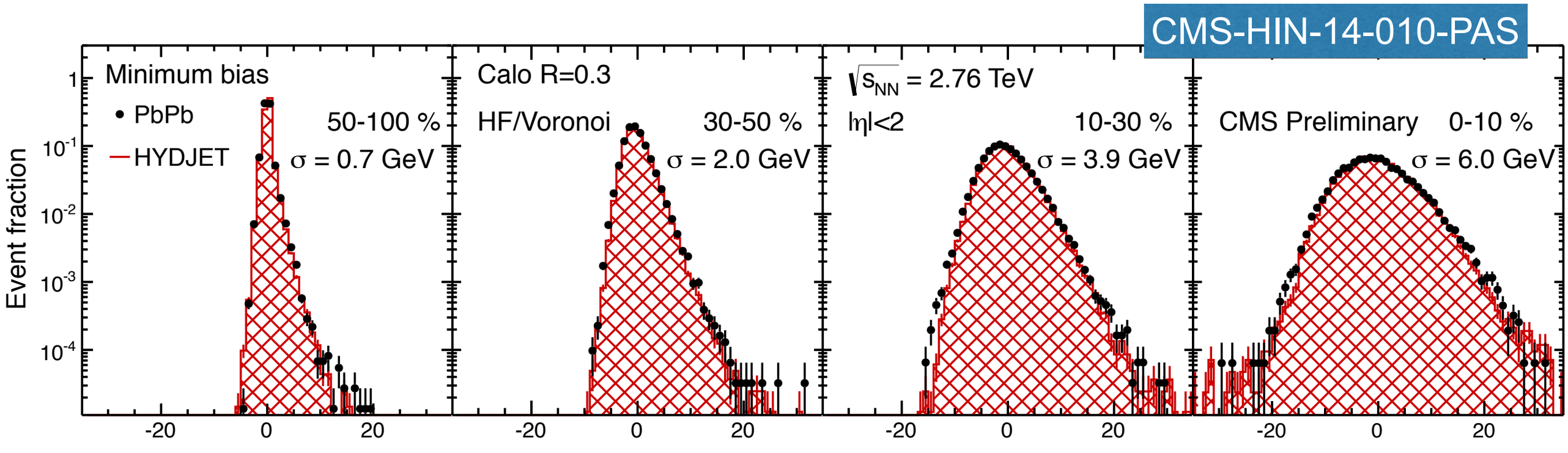
- Missing p_T finely measured through large angles Δ
  - Different dijet configurations were sampled by R variation
- Cumulative curves similar for all jet R in PbPb and pp
  - Modification primarily of constituents carrying momentum
- Future: look to generator comparisons and unquenched probes

Backup

Impact of Tracking Cuts on Missing P_T



Jet Reconstruction with HF/Voronoi Algorithm



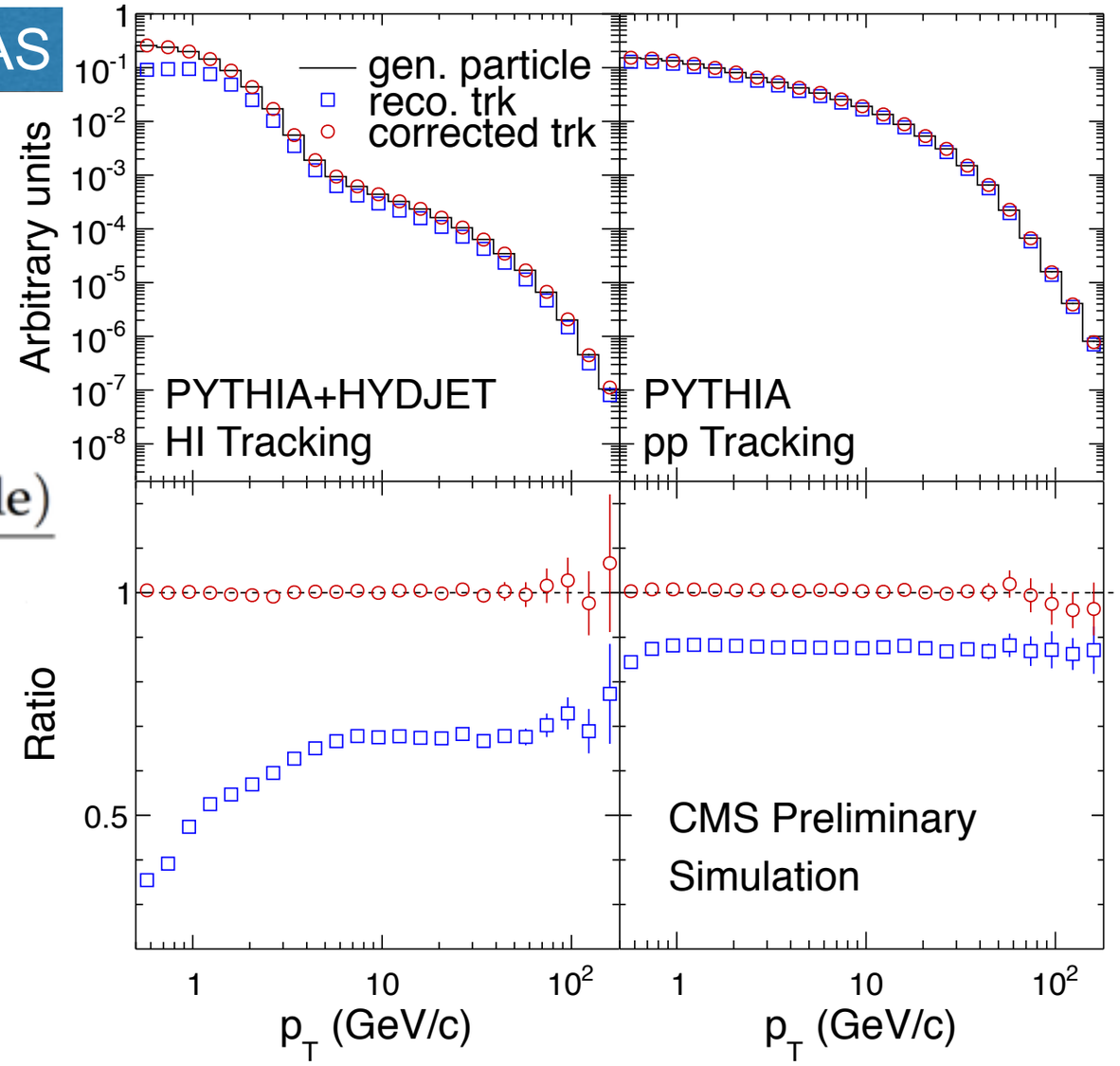
- UE at mid-η mapped by energy deposition at forward-η
- Equalization removes negative energy towers
  - Shifted from surrounding positive energy towers
- An energy correction based on fragmentation is applied to minimize bias from non-linear calorimeter response
  - Applied to pp and PbPb

Track Reconstruction and Correction

CMS-HIN-14-010-PAS

- Define tracking correction on track-by-track basis as:

$$c^{\mathrm{trk}} = \frac{(1 - \mathrm{misreconstruction}) \times (1 - \mathrm{secondary\text{-}particle})}{(\mathrm{efficiency}) \times (1 + \mathrm{multiple\text{-}reconstruction})}$$

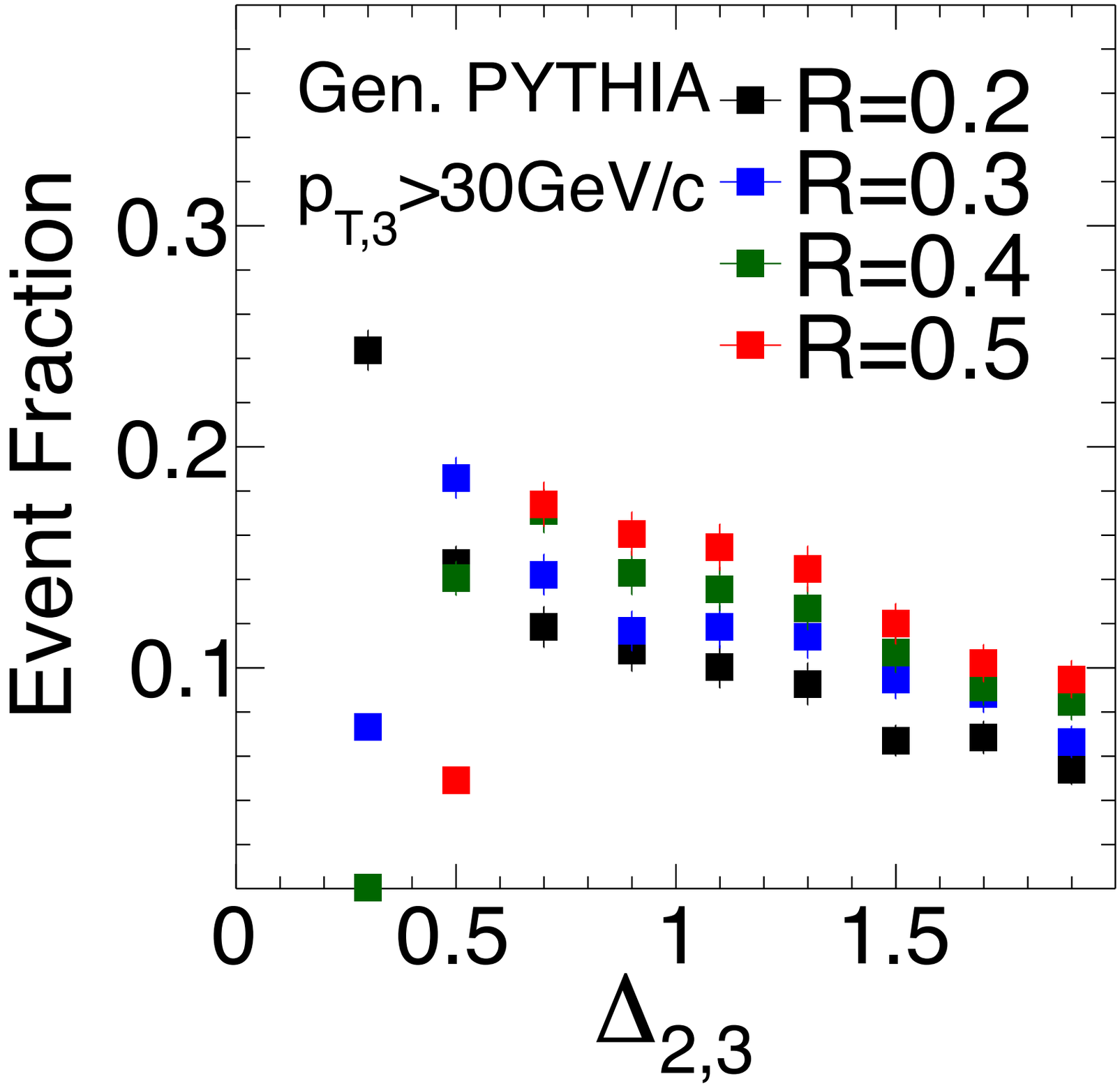


- Correct for efficiency/fake rate (+ secondary/multiple reco. in pp)
- Iterative tracking corrections in p_T, φ, η, centrality, and minimum jet distance

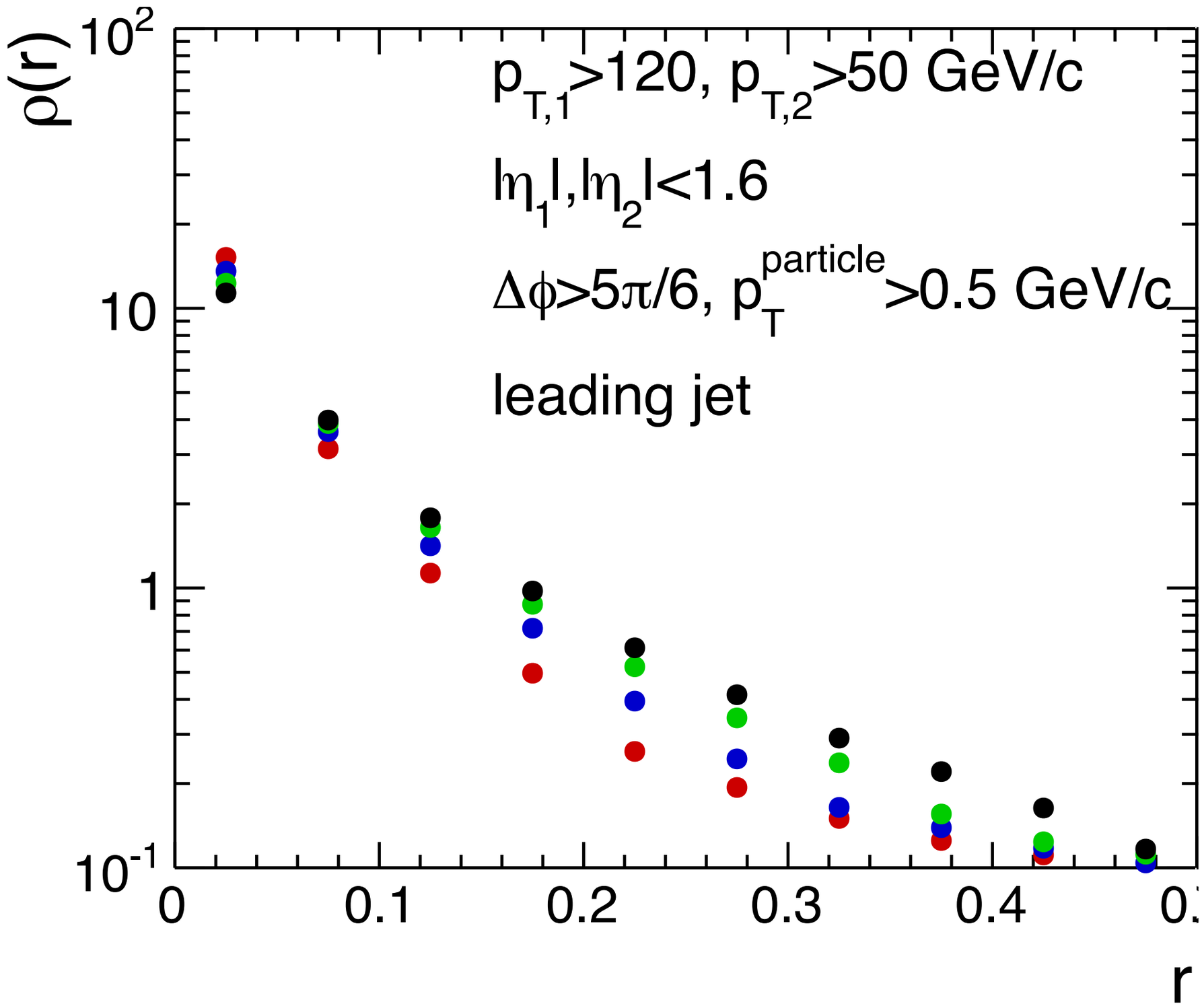
Summary of Systematics R = 0.2/0.4/0.5

	$R = 0.2$		$R = 0.4$		$R = 0.5$	
Δ	< 0.2	0.2–2.0	< 0.2	0.2–2.0	< 0.2	0.2–2.0
Jet reconstruction	1	0.1–0.4	1	0.1–0.5	1	0.1–0.7
Data/MC differences for JES	2	0.1–0.5	2	0.1–0.4	2	0.1–0.3
Fragmentation dependent JES	1	0.1–0.4	1	0.1–0.3	1	0.1–0.3
Track corrections	2	0.2–0.7	2	0.1–1.1	2	0.1–1.1
Data/MC differences for tracking	1	0.1–0.2	1	0.1	1	0.1
Total	3	0.2–0.9	3	0.3–1.1	3	0.2–1.1

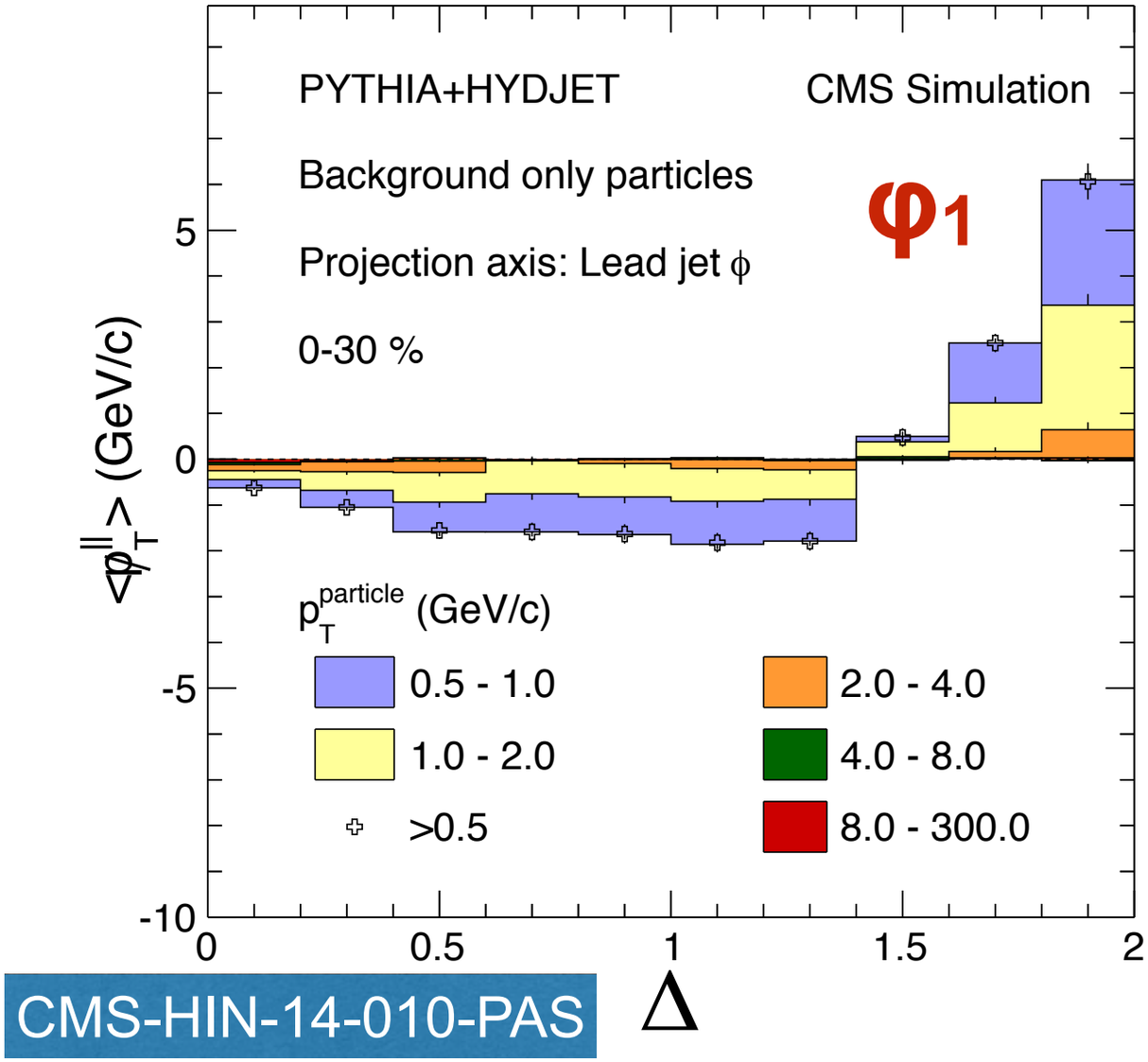
3rd Jet Position in Gen. PYTHIA

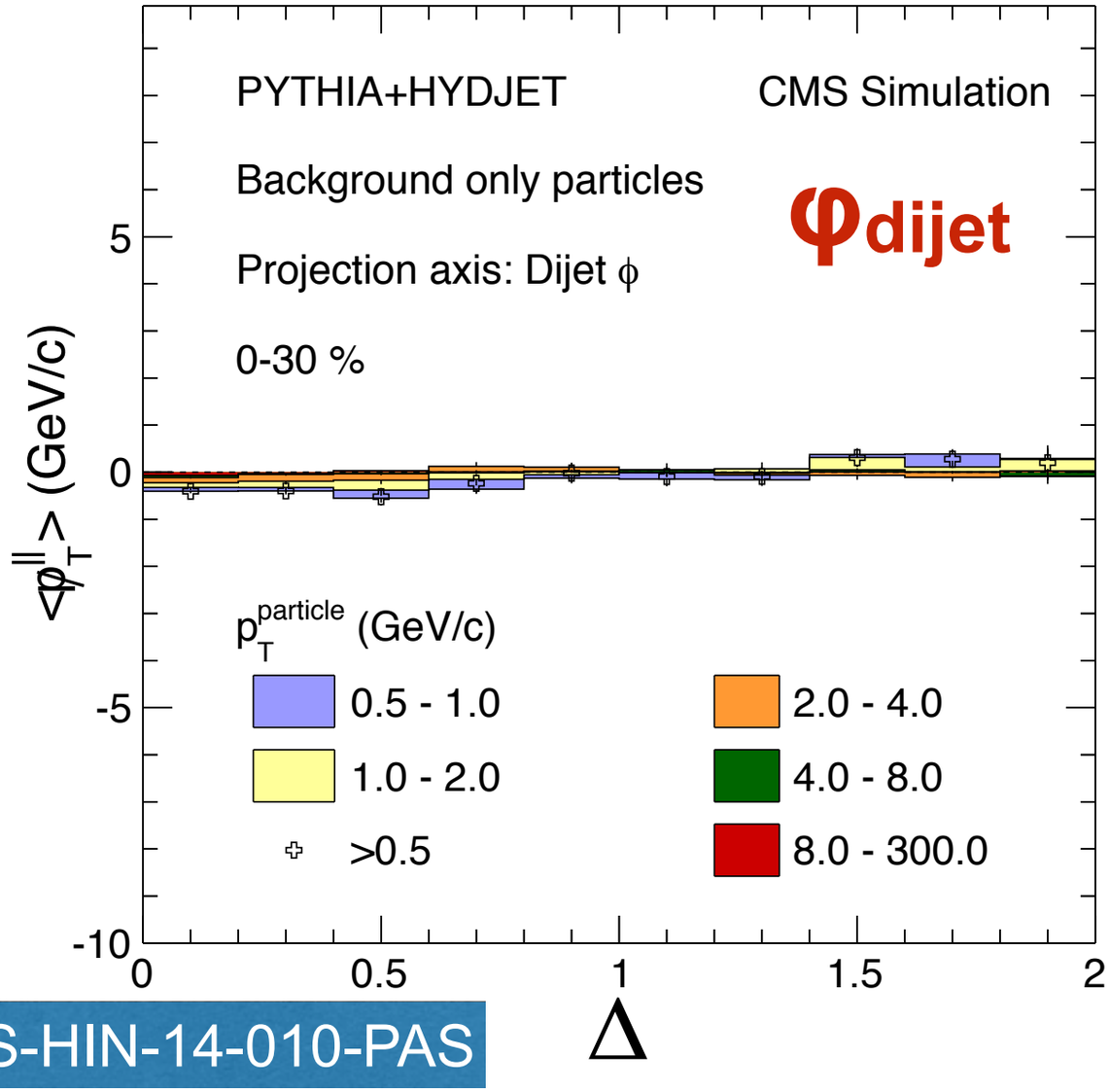


Gen. PYTHIA Jet Shapes



Dijet Axis and Non-Closure

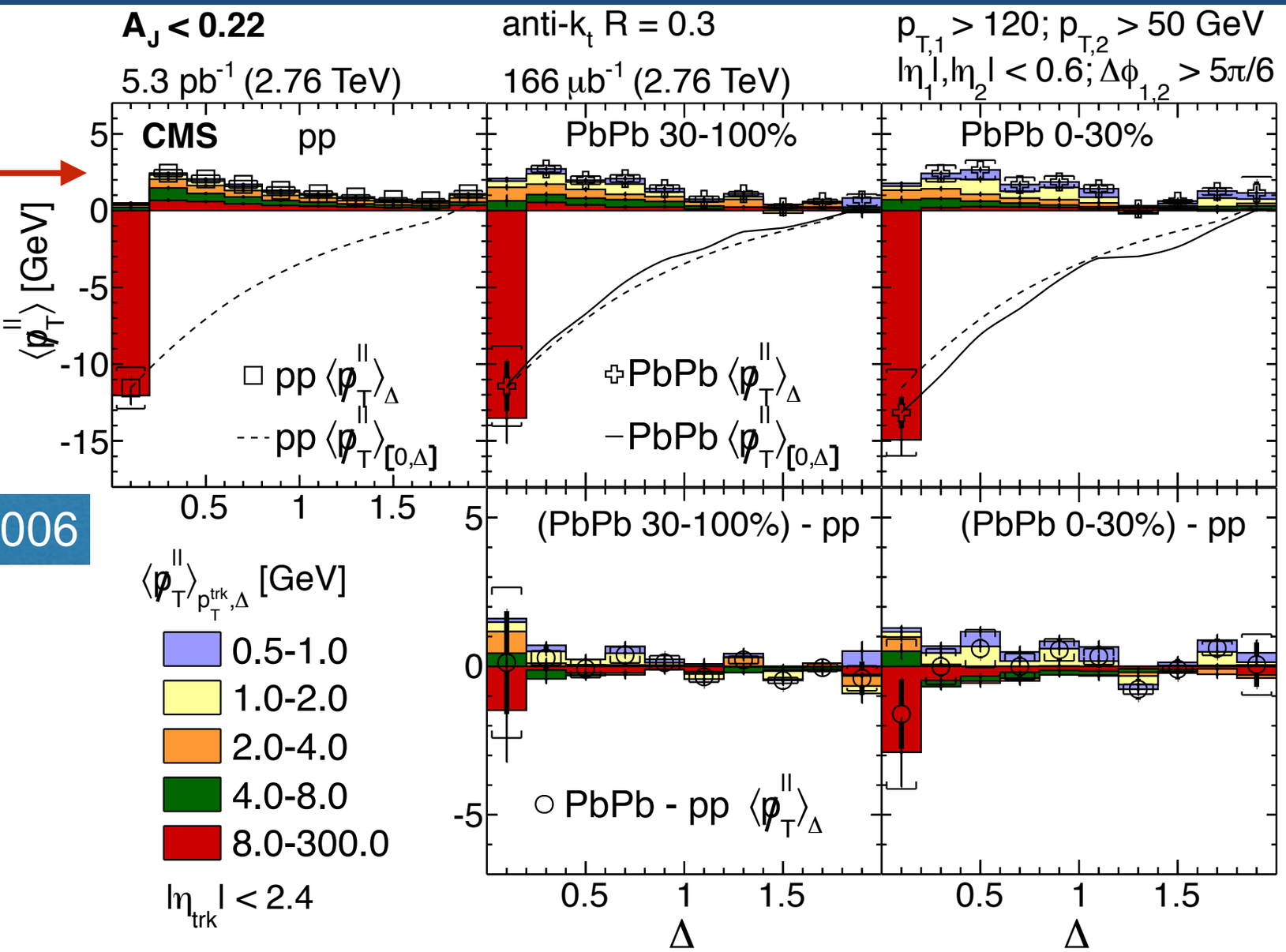


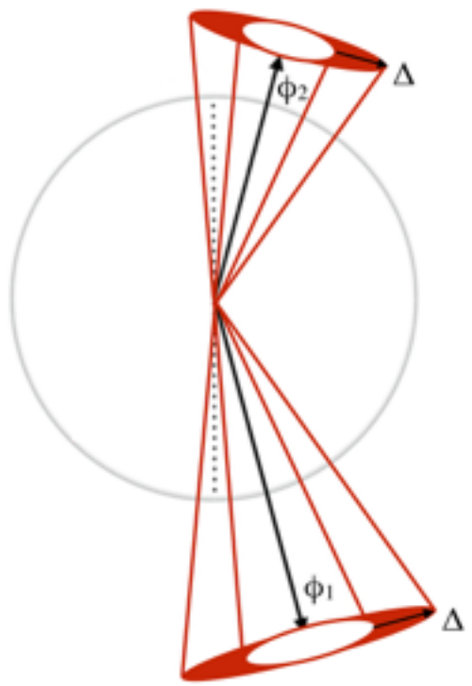


Missing P_T vs. Δ with R = 0.3 (A_J < 0.22)

Scale Change (Decrease)

JHEP 01 (2016) 006

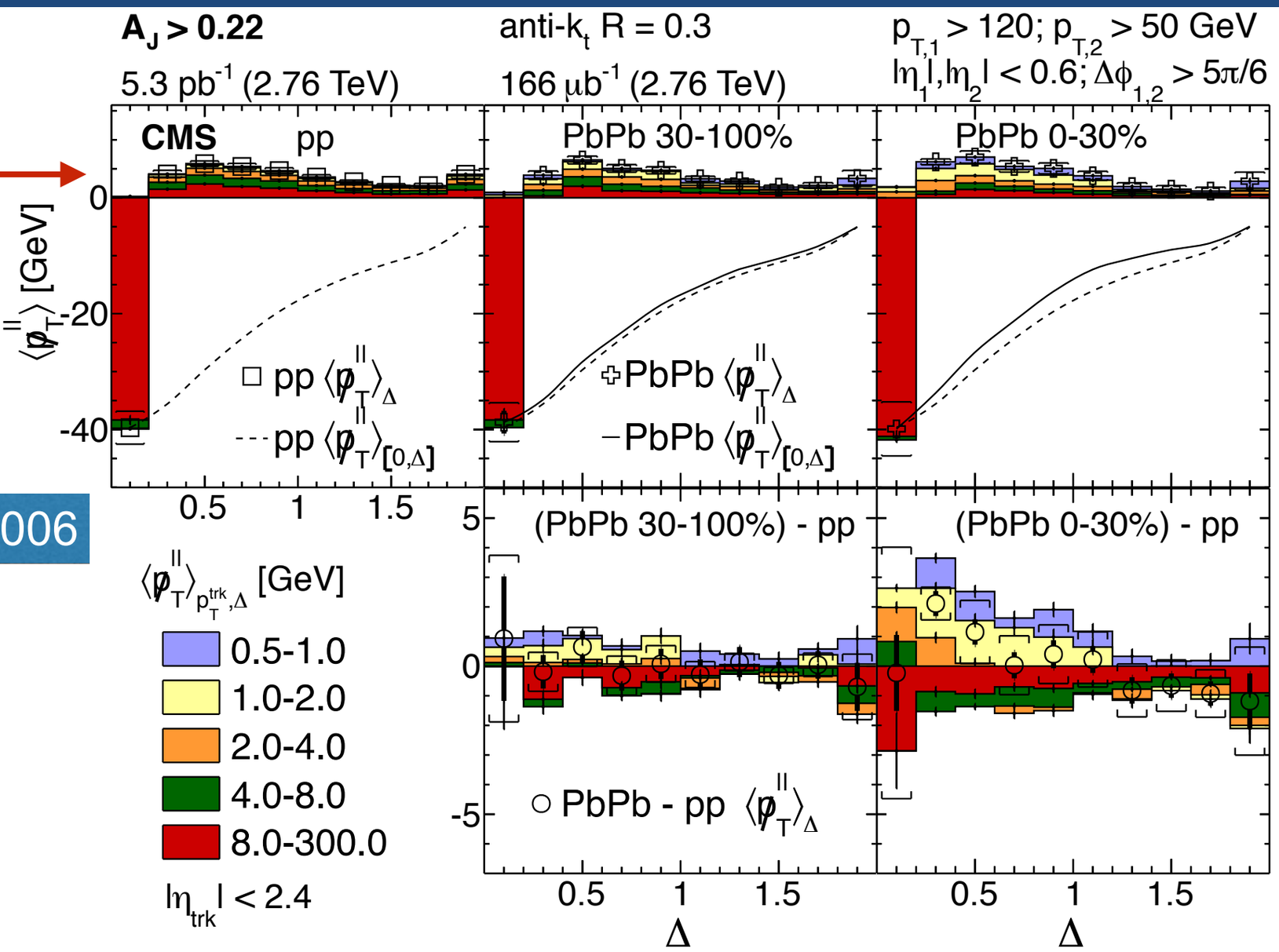


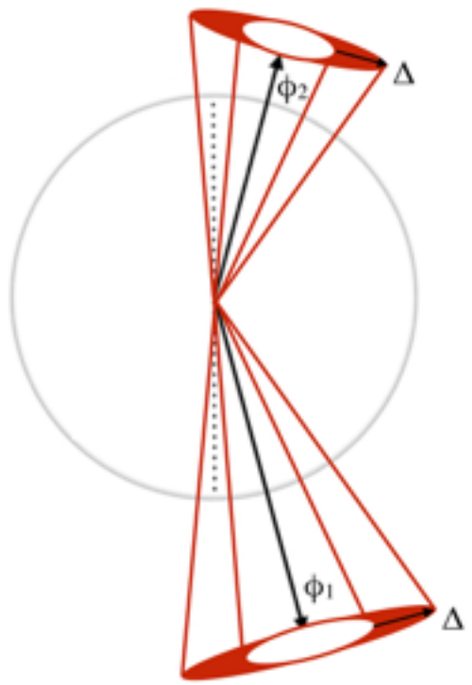


Missing P_T vs. Δ with R = 0.3 (A_J > 0.22)

Scale Change (Increase)

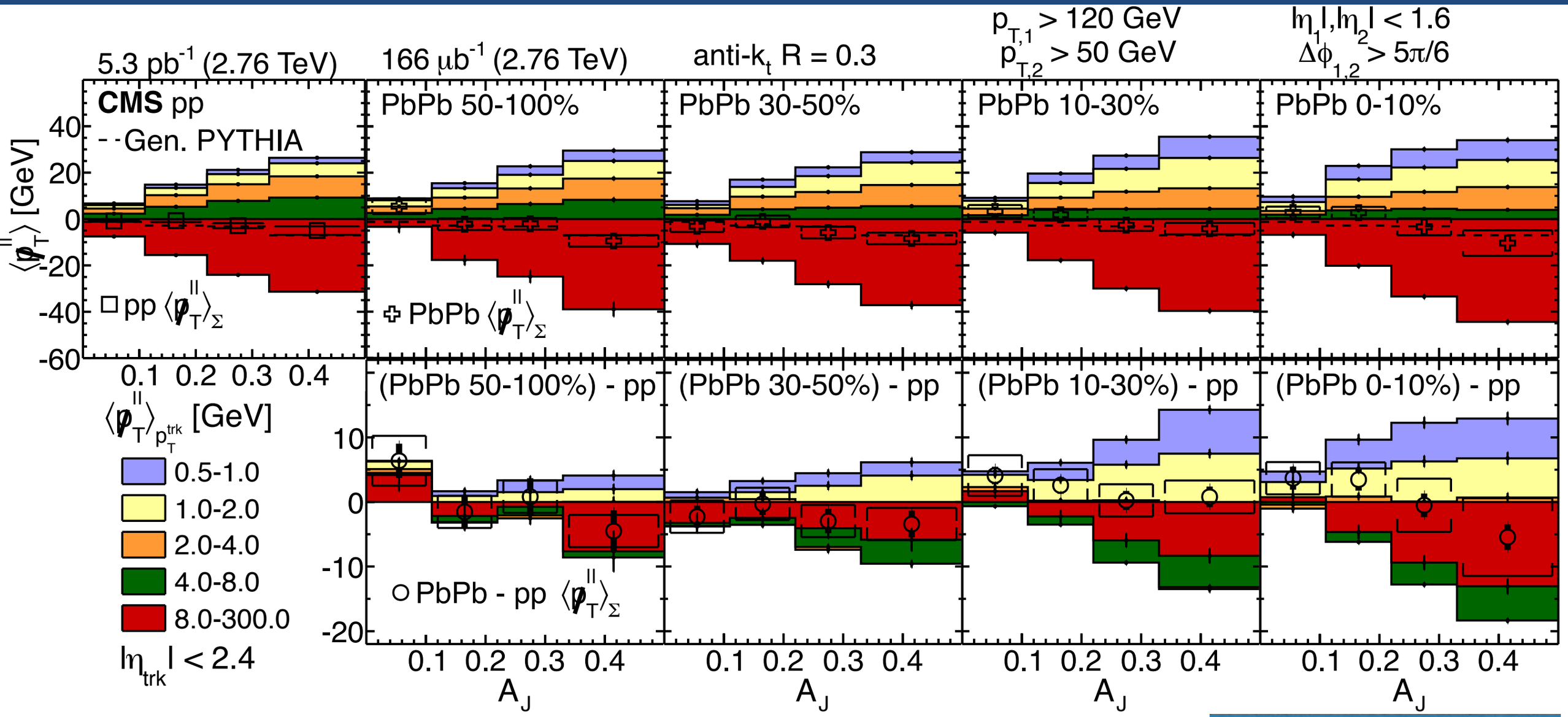
JHEP 01 (2016) 006





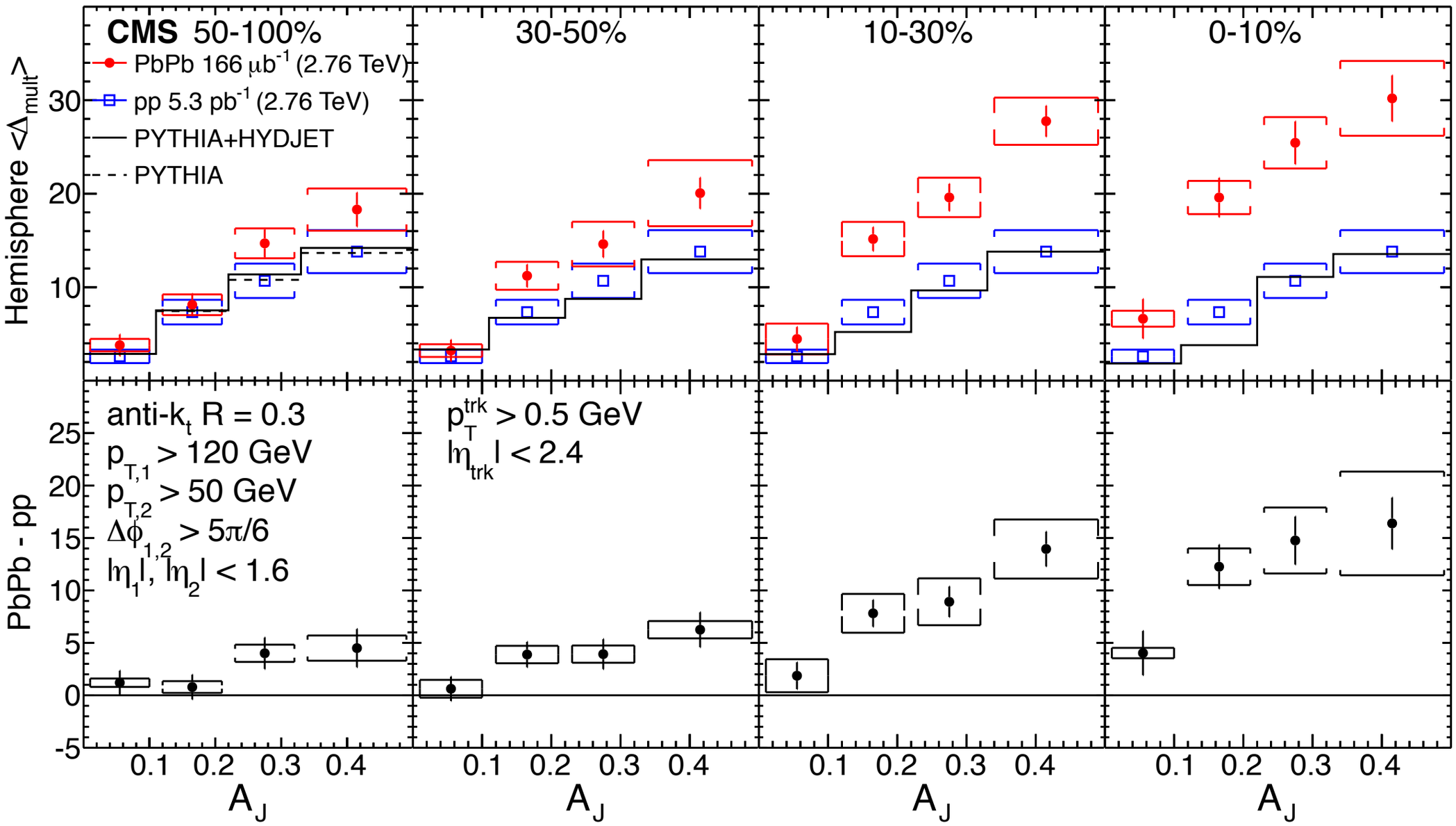
- Low p_T particles enhanced by cut on A_J > 0.22
- Cumulative curves track despite scale change

Missing P_T vs. A_J with R = 0.3



JHEP 01 (2016) 006

Hemisphere Multiplicity Difference



JHEP 01 (2016) 006

- Multiplicity excess towards subleading side shows centrality and A_J dependence

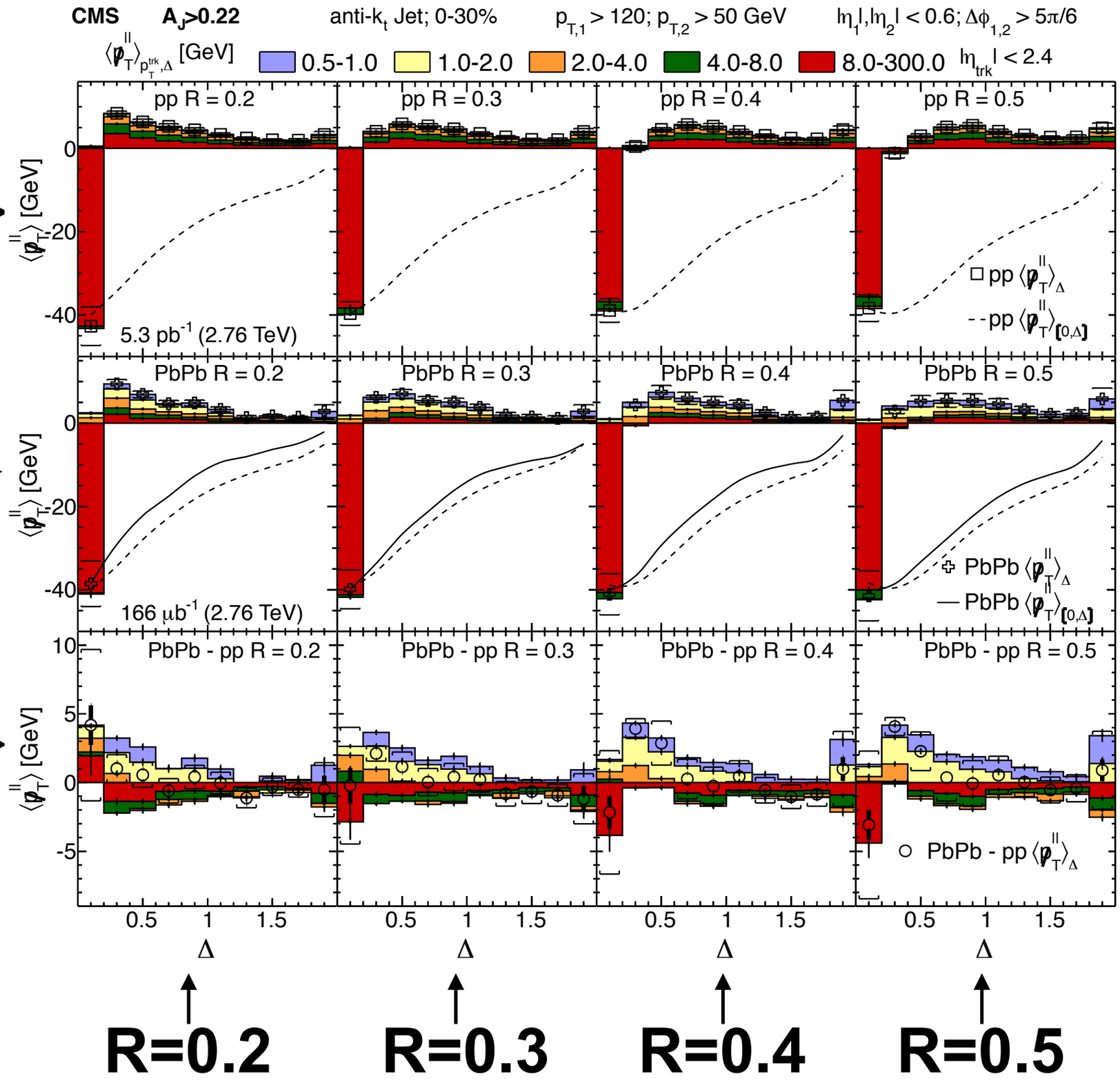
Multiple R Missing P_T vs. Δ (A_J > 0.22)

A_J > 0.22

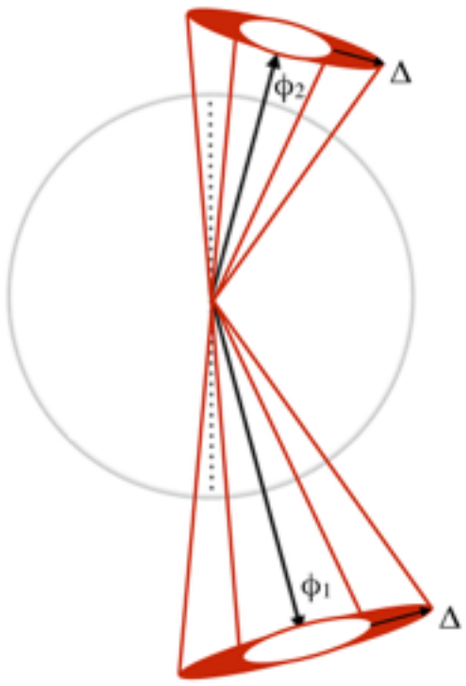
pp →

PbPb → (0-30%)

PbPb - pp →



JHEP 01 (2016) 006



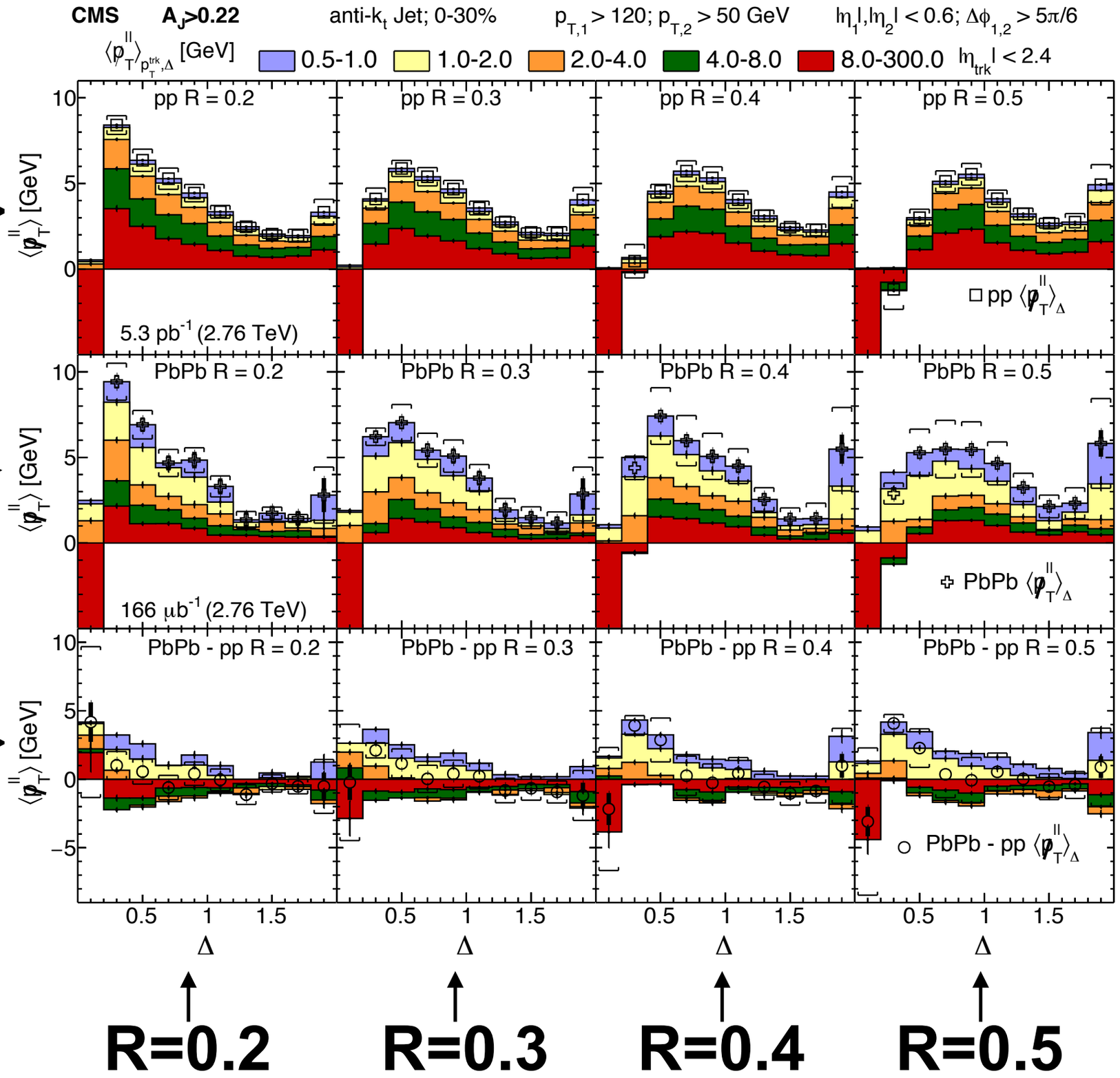
Multiple R Missing P_T vs. Δ (A_J > 0.22)

A_J > 0.22

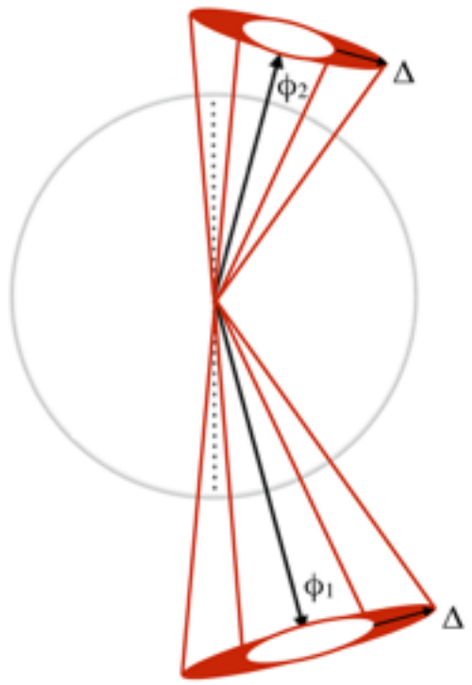
pp →

PbPb (0-30%) →

PbPb - pp →



JHEP 01 (2016) 006

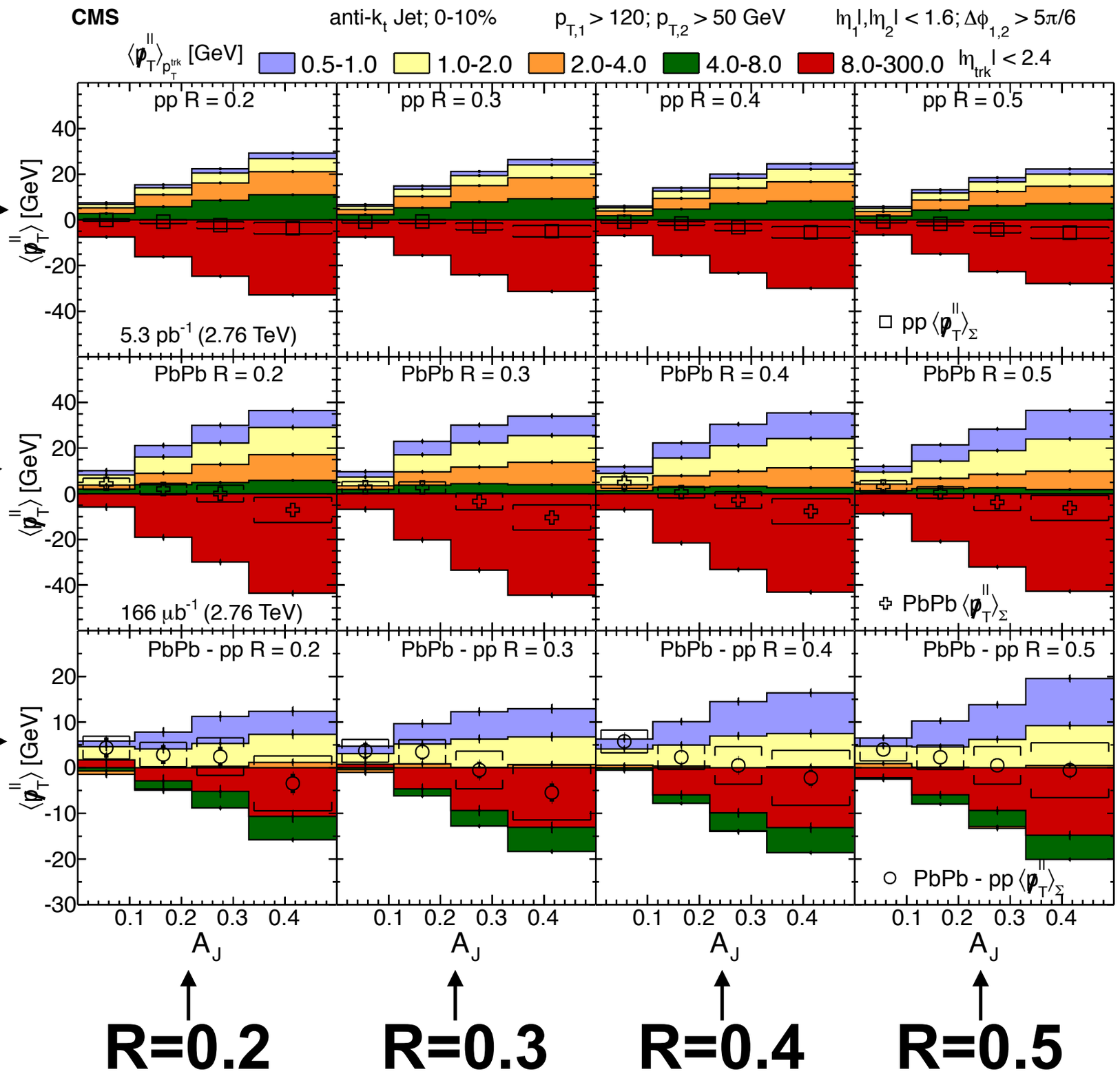


Multiple R Missing P_T vs. A_J

pp →

PbPb → **(0-10%)**

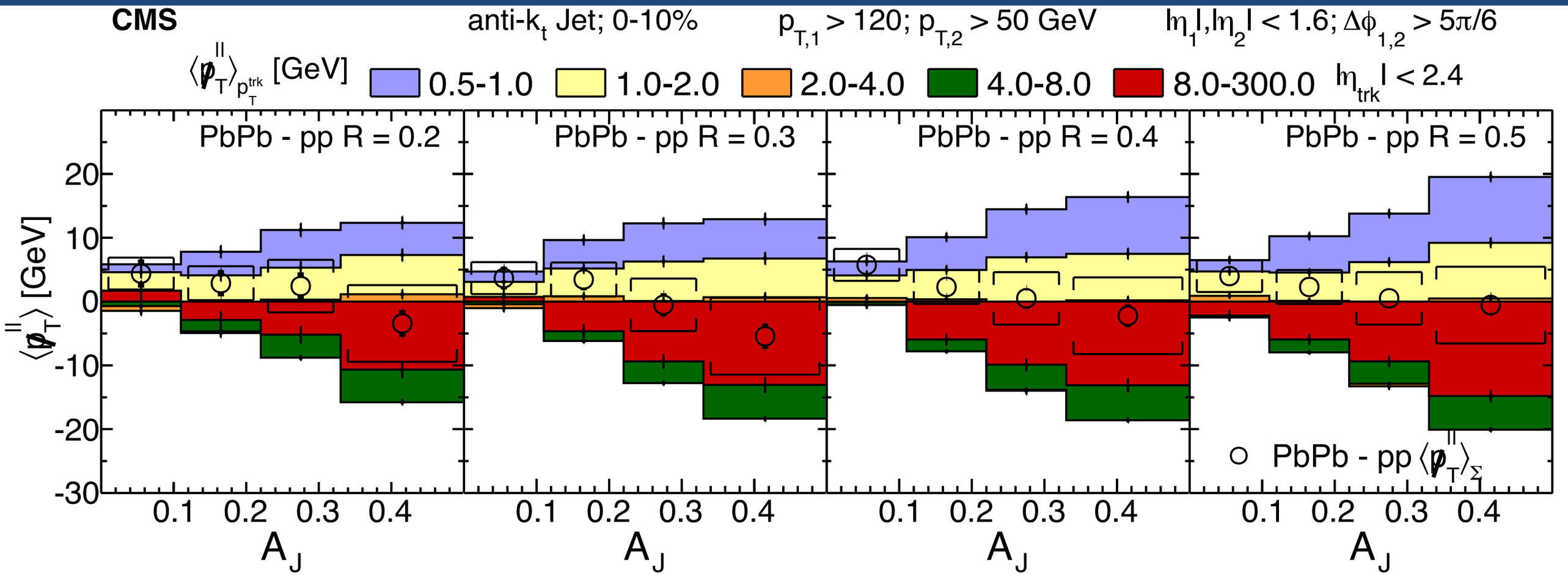
PbPb - pp →



JHEP 01 (2016) 006

R=0.2 **R=0.3** **R=0.4** **R=0.5**

Difference of PbPb and pp vs. A_J



JHEP 01 (2016) 006

- Potential R dependence in low p_T contribution (0.5-2.0 GeV)
- Total missing p_T between PbPb and pp shows no difference in each bin (within systematic)

JEWEL Parameters

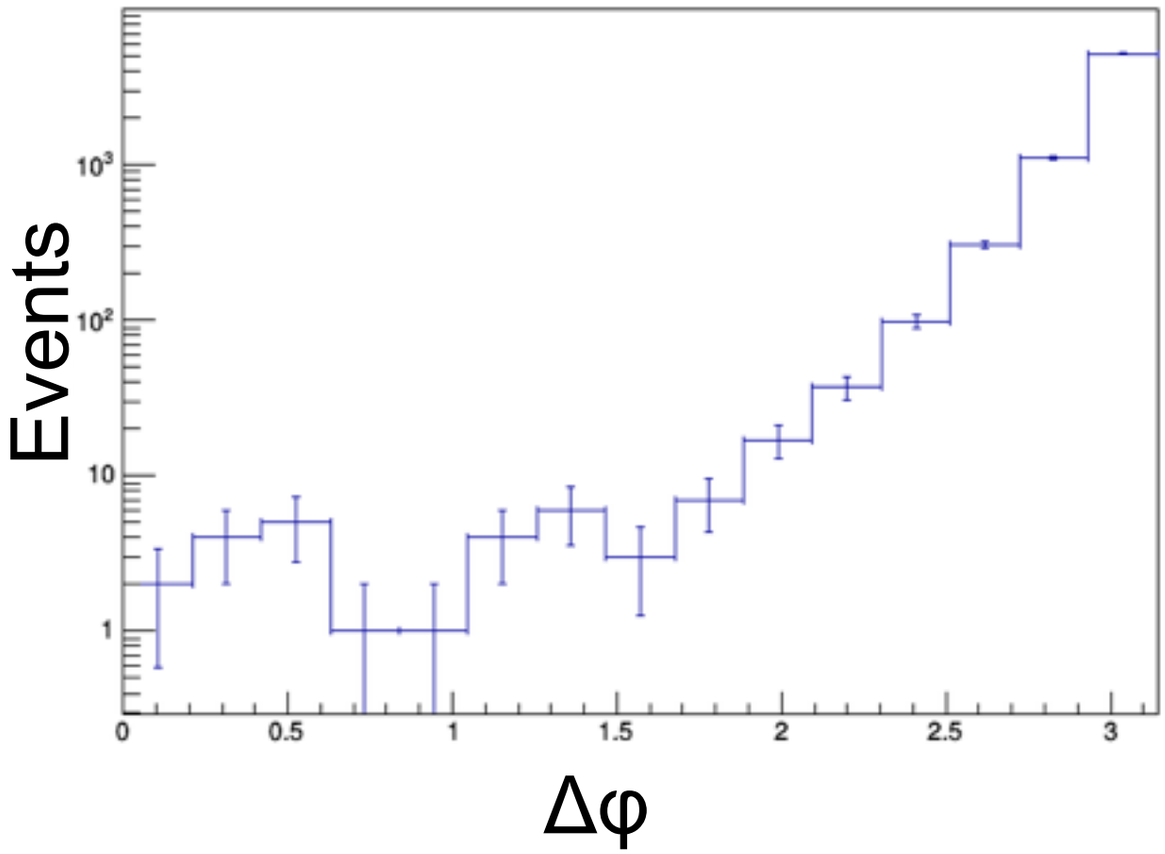
- params.job1.dat ->

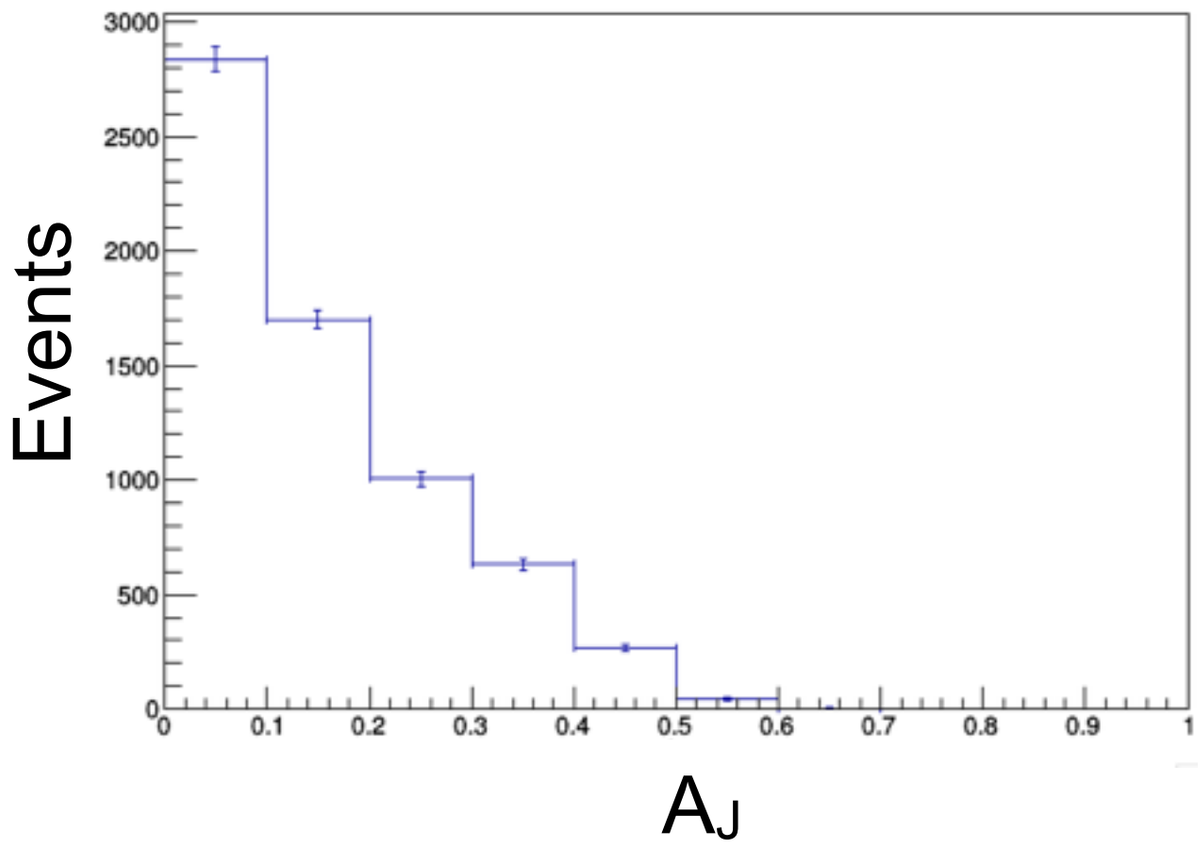
```
NEVENT 10000
PTMIN 90.
PTMAX -1.
ETAMAX 2.5
MEDIUMPARAMS medium.example.dat
KEEPRECOILS T
SQRTS 2760
SHORTHEPMC T
COMPRESS T
LOGFILE output/160722154039/job1.log
HEPMCFILE output/160722154039/job1.hepmc
NJOB 22154039
```

- medium.params.dat ->

```
TI 0.40
CENTRMIN 0.
CENTRMAX 30.
```

JEWEL Δφ and A_J sanity checks





- Distributions follow expectation if not necessarily mirroring data