Measurement of the centrality-dependence of inclusive jet production in p+Pb data at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV with the ATLAS detector

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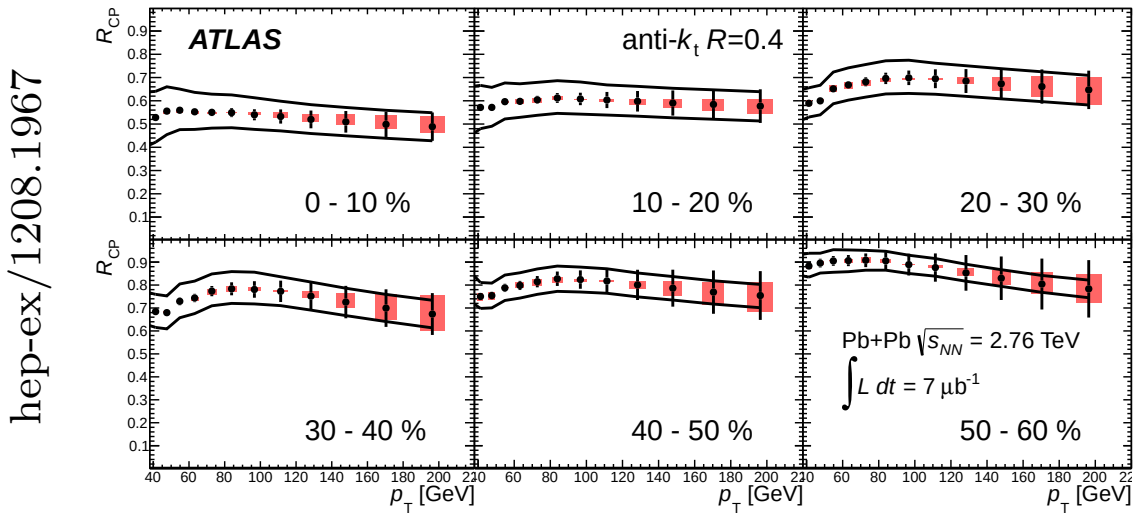
Hard probes of p+Pb collisions

- Exploratory measurement of the partonic structure of Pb
- *How are partons in the nucleus affected by the high-density environment?*

  $\Rightarrow$ basic QCD observable: *inclusive jet production*

  $\Rightarrow$ sensitive to nuclear modifications to the pdfs



- Benchmark needed for measurements of jet suppression $\uparrow$

  $\Rightarrow$ puts effects of the hot QGP into a quantitative context

Nuclear modification factors

- Basic observable: double differential per-event yield

  $\Rightarrow$ $(1/N_{\rm evt})(d^2N/dp_{\rm T}dy)$

- Yields are compared as a function of position in the nucleus

  $\Rightarrow$ between central events (small-b) and peripheral events (large-b)

$$R_{\rm CP} = \frac{(1/N_{\rm coll}^{\rm cent})(1/N_{\rm evt}^{\rm cent})(d^2N/dp_{\rm T}dy)\big|_{\rm cent}}{(1/N_{\rm coll}^{\rm peri})(1/N_{\rm evt}^{\rm peri})(d^2N/dp_{\rm T}dy)\big|_{\rm peri}}$$

  $\Rightarrow$ tests deviations from the null hypothesis p+Pb $= N_{\rm coll} \times pp$

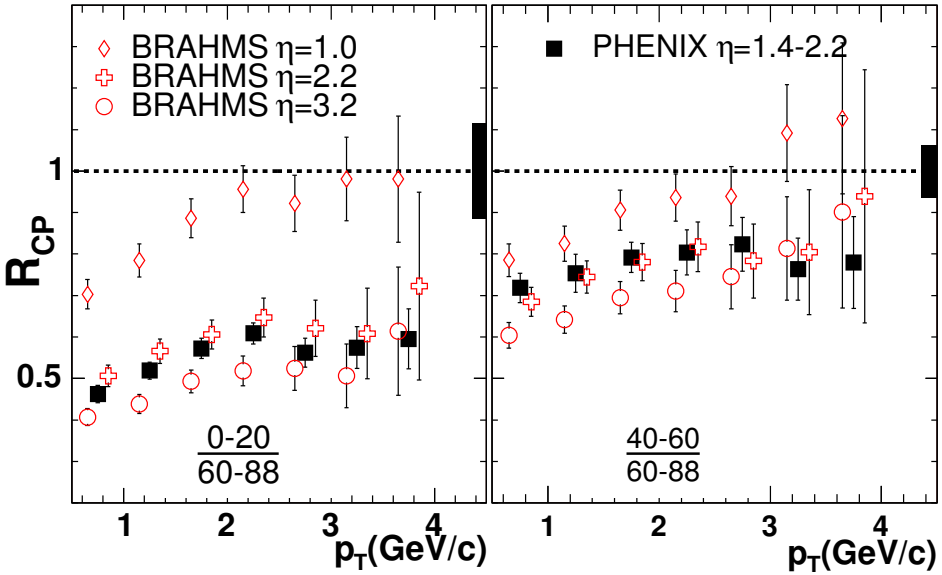
- p+Pb yields compared vs. pp reference directly

$$R_{\rm pPb} = \frac{(1/N_{\rm evt}^{\rm cent})(d^2N^{\rm cent}/dp_{\rm T}dy)\big|_{\rm cent}}{\langle T_{\rm AB}^{\rm cent}\rangle\,(d\sigma_{pp}^2/dp_{\rm T}dy)}$$

  $\Rightarrow$ results shown here use PYTHIA reference, $R_{\rm pPb}^{\rm PYTHIA}$

Previous Measurements in d+Au at RHIC

- d+Au collisions, $\sqrt{s_{\mathrm{NN}}} = 200$ GeV, data collected in 2003 and 2008



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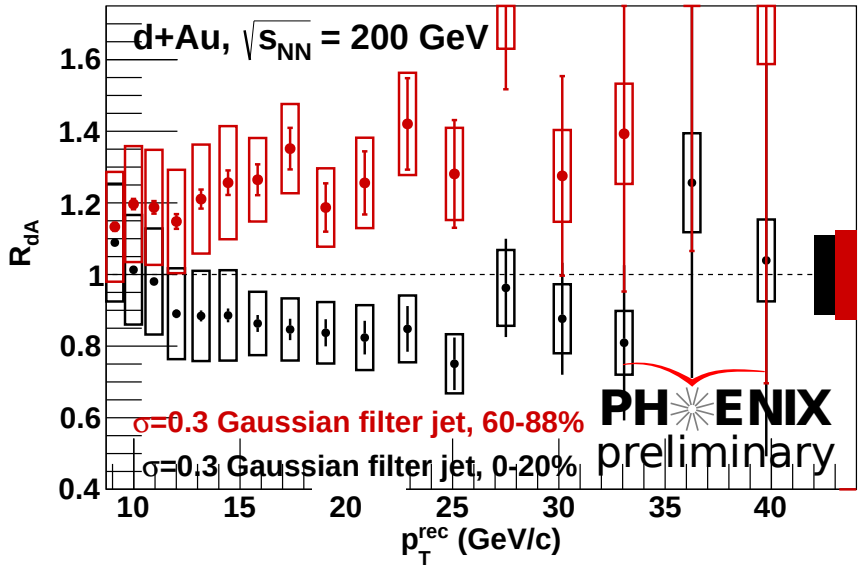

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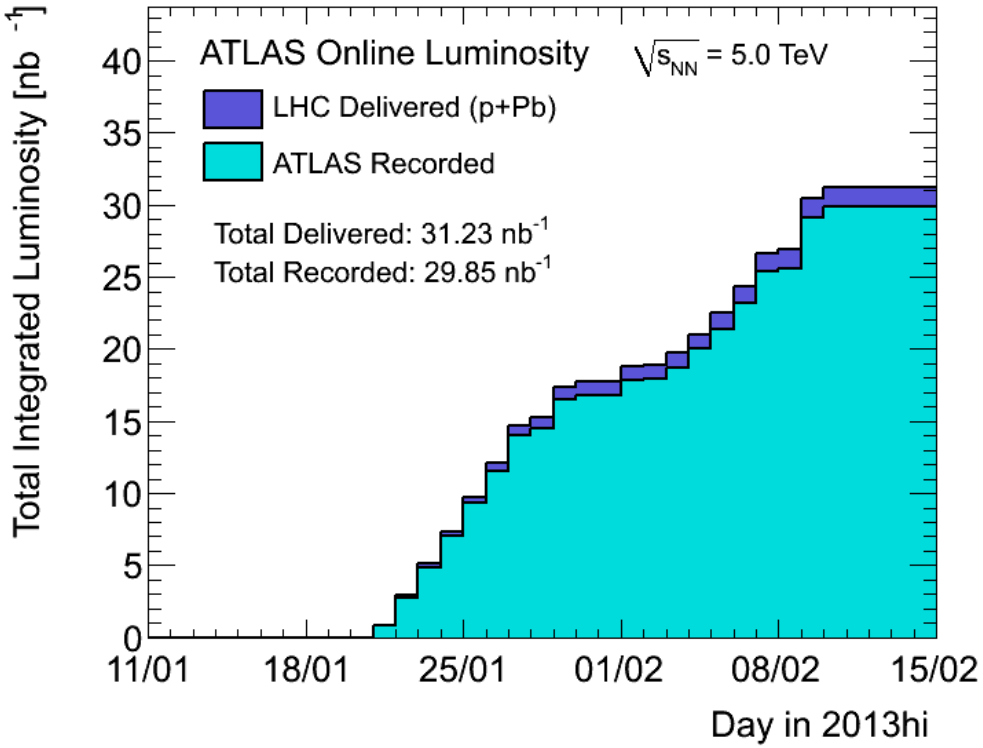
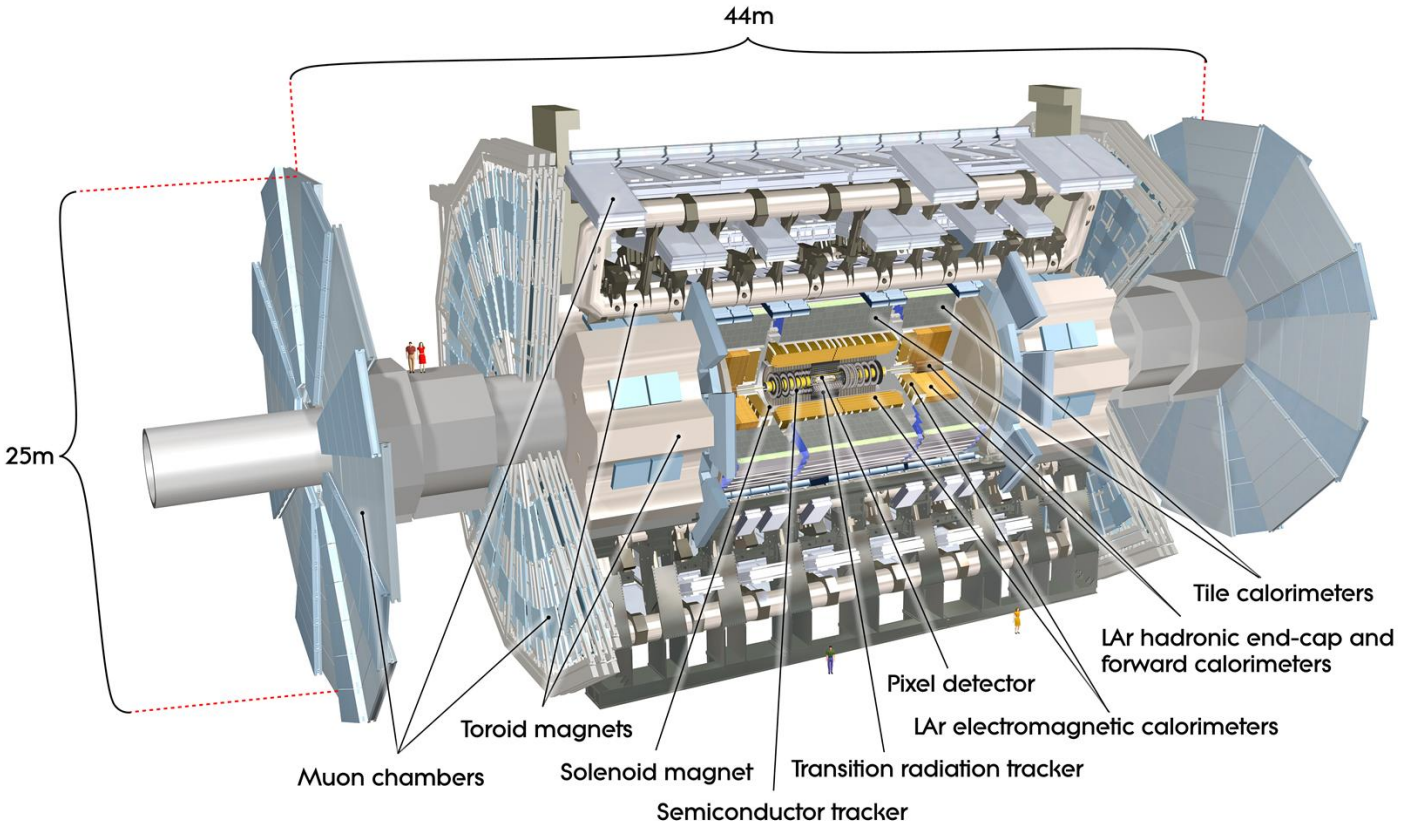
- Strong suppression of forward hadrons
  - $\Rightarrow$ attributed to nuclear shadowing / partonic saturation effects
- Modification for high-p_{T} jets at mid-rapidity
  - $\Rightarrow$ **suppression**/**enhancement** in **central**/**peripheral** events
  - $\Rightarrow$ not fully understood
- ATLAS can investigate these kinematic ranges *simultaneously*

p+Pb data



- ≈ 31 nb^{-1} data to experiments
  - $\Rightarrow$ we use data from both beam orientations
- $E = 4$ TeV protons on $E = 4 \times \frac{Z}{A} = 1.58$ GeV / nucleon Pb
- $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV, with a enter of mass shift $\Delta y^{\mathrm{COM}\to\mathrm{lab}} = -0.465$
  - $\Rightarrow$ **Convention: $y^* < 0$ denotes p-going direction**
  - $\Rightarrow$ **"forward rapidity" / small-x_{Pb} / large-x_p**

ATLAS Detector

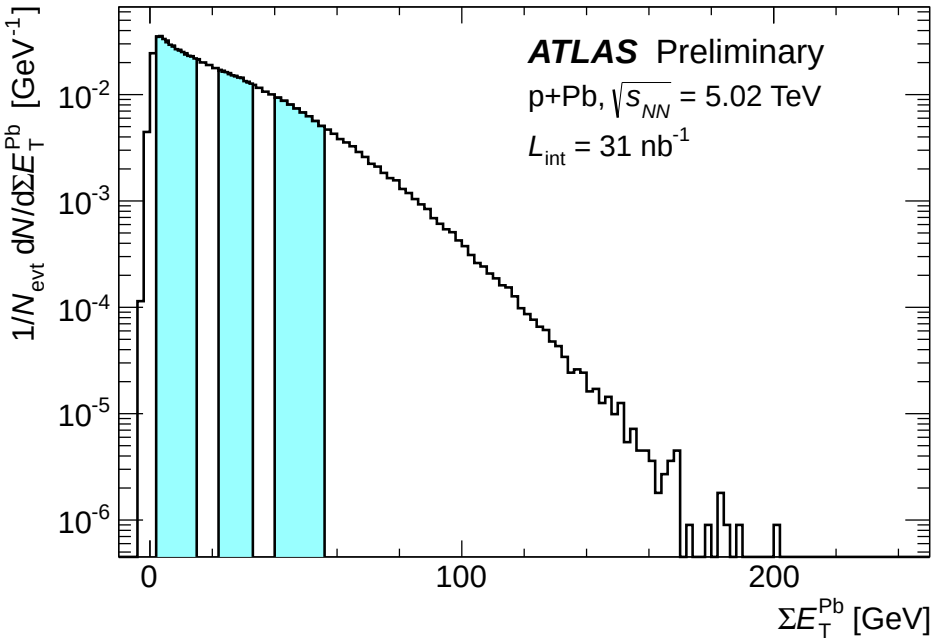


- Minimum Bias Trigger Scintillators, $2.1 < |\eta| < 3.8$: MB trigger
- Calorimeter, $|\eta| < 4.9$
- Online trigger for high-level objects

  $\Rightarrow$ jets selected with mid- and forward-rapidity jet triggers

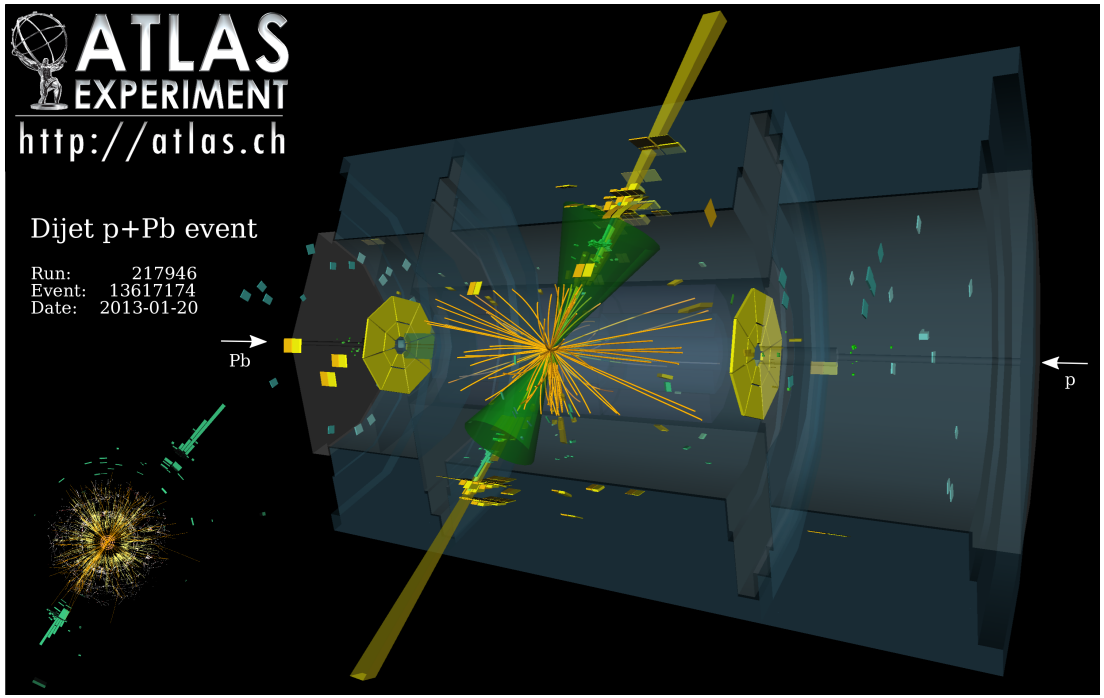
Centrality selection in p+Pb

- p+Pb event centrality determined using Pb-going Forward Calorimeter ($3.1 < \eta < 4.9$)
  - $\Rightarrow$ "central" events have the 0-10% highest $\Sigma E_{\mathrm{T}}^{\mathrm{Pb}}$
  - $\Rightarrow$ "peripheral" events have the 60-90% highest $\Sigma E_{\mathrm{T}}^{\mathrm{Pb}}$



- # of nucleon-nucleon collisions $\langle N_{\mathrm{coll}} \rangle$ & nucleonic luminosity T_{AB} determined with default Glauber analysis
  - $\Rightarrow$ as reported in a recent measurement of charged particle multiplicity, `ATLAS-CONF-2013-096`

Jet reconstruction



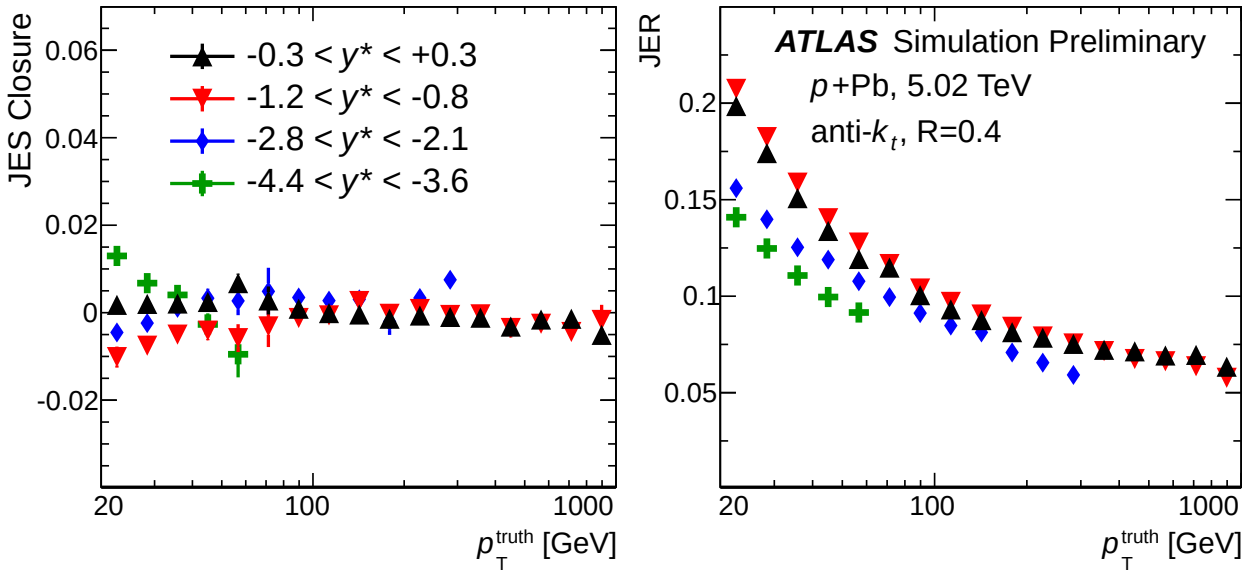
- Standard HI Jet Reconstruction procedure
  - $\Rightarrow$ successfully developed for Pb+Pb & benchmarked in pp
  - $\Rightarrow$ effects from the UE are much milder in p+Pb than Pb+Pb
- Iterative subtraction of the underlying event (UE) pedestal
- All results use anti-k_{T} algorithm, R=0.4
  - $\Rightarrow$ clusters calorimeter towers at the EM scale

Performance

- Jet energy scale (JES) closure & resolution (JER) determined in MC

  $\Rightarrow$ 6.5m PYTHIA dijets, $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV, with p+Pb kinematics

  $\Rightarrow$ Reconstruction efficiency $> 99\%$ for $p_{\mathrm{T}} > 25$ GeV



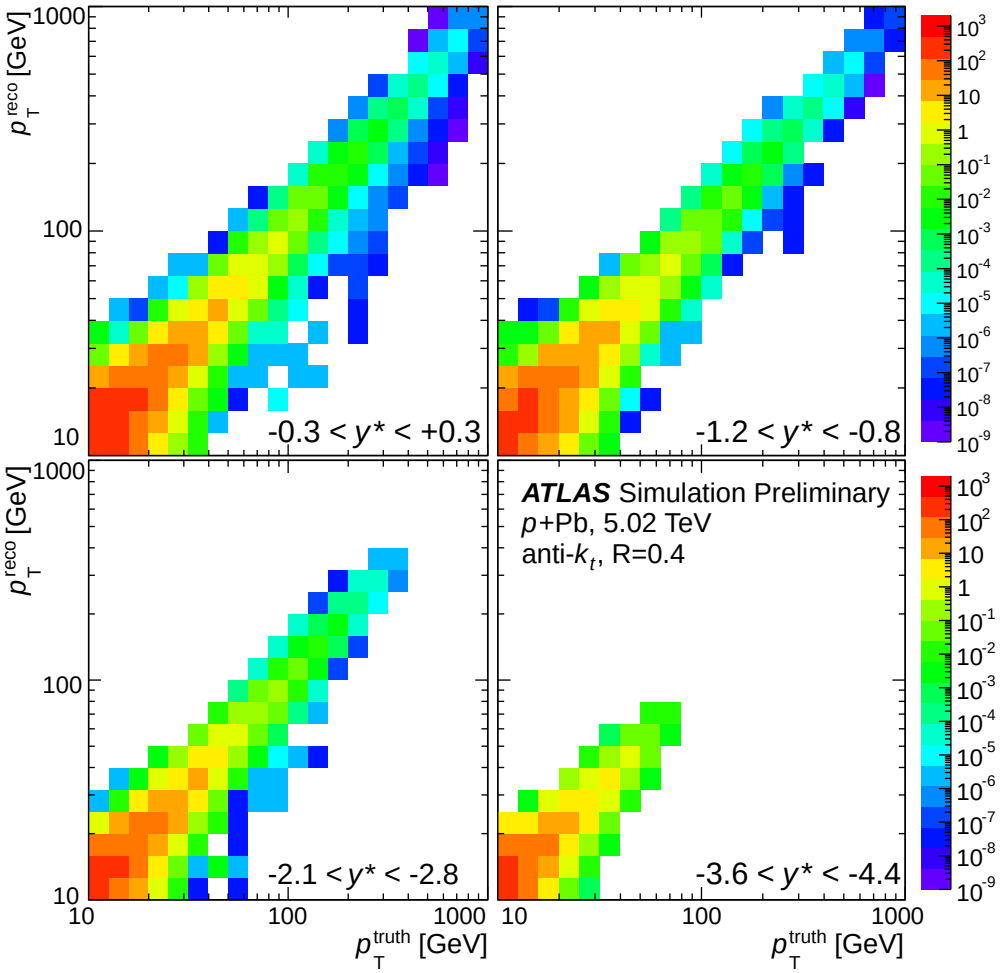
- Separate MC sample of PYTHIA embedded into real minimum bias p+Pb data

  $\Rightarrow$ used to determine centrality-dependence in response

  $\Rightarrow$ p+Pb yields only measured where response is *UE-independent*

  $\Rightarrow$ $\boldsymbol{p_{\mathrm{T}} > 100}$ **GeV at** $\boldsymbol{y^* = 0}$, $\boldsymbol{p_{\mathrm{T}} > 25}$ **GeV at** $\boldsymbol{y^* = -4}$

Correction for detector effects



- p+Pb yields are corrected for bin migration effects
  - $\Rightarrow$ Bin-by-bin correction factors $C_i = T_i/R_i$
  - $\Rightarrow$ MC reweighted to match data in each p+Pb centrality
- 10%-20% corrections
  - $\Rightarrow$ which largely cancel in the R_{CP}
  - $\Rightarrow$ (but not in $R_{\mathrm{pPb}}^{\mathrm{PYTHIA}}$)

R_{CP}, at fixed rapidity

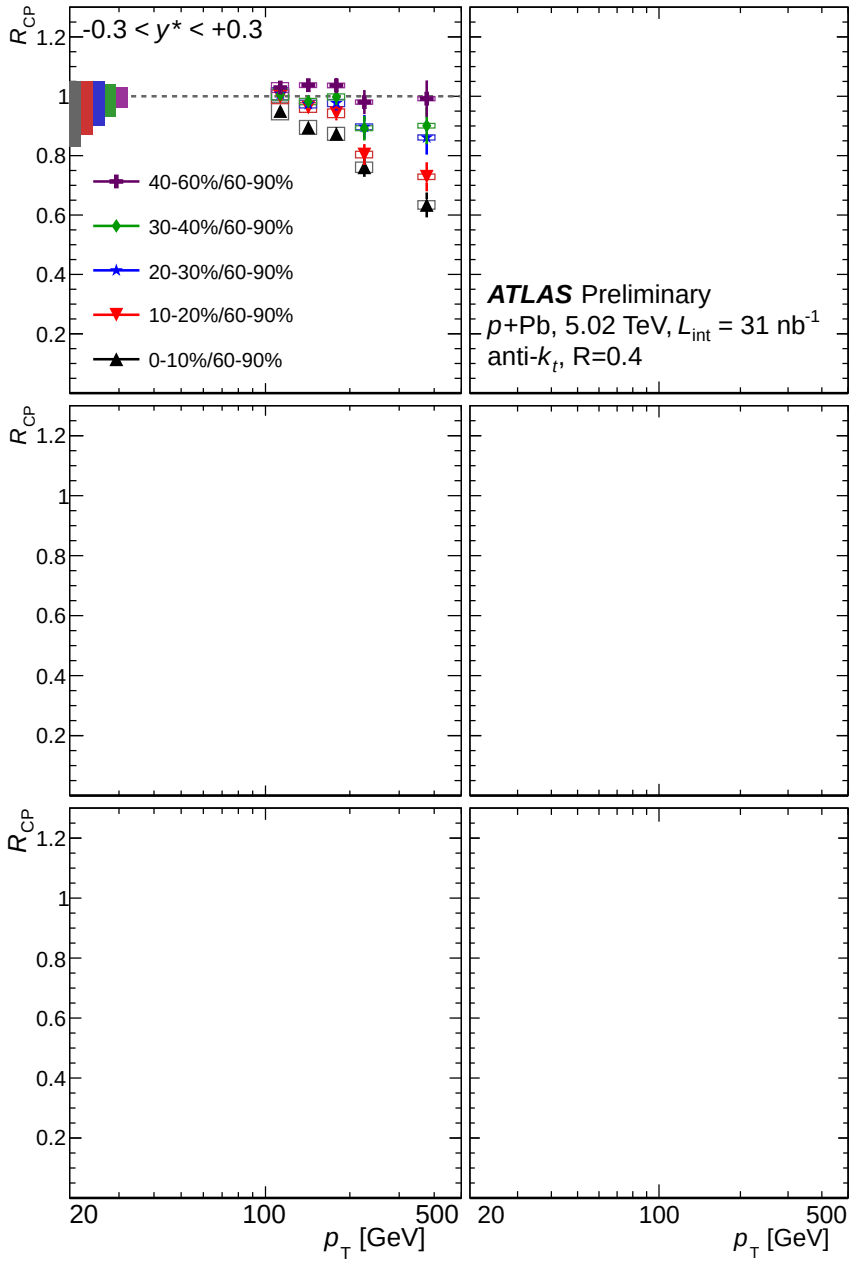
$$R_{\mathrm{CP}} = \frac{1}{R_{\mathrm{coll}}^{\mathrm{cent/peri}}} \frac{\frac{1}{N_{\mathrm{evt}}} \frac{d^2 N_{\mathrm{jet}}}{dp_{\mathrm{T}} dy}\Big|_{\mathrm{cent}}}{\frac{1}{N_{\mathrm{evt}}} \frac{d^2 N_{\mathrm{jet}}}{dp_{\mathrm{T}} dy}\Big|_{\mathrm{peri}}}$$

$$\mathbf{R}_{\mathrm{coll}}^{\mathbf{0-10\%/60-90\%}} = \mathbf{4.9}$$

$$\mathbf{R}_{\mathrm{coll}}^{\mathbf{40-60\%/60-90\%}} = \mathbf{2.2}$$

Each panel at fixed y^*

- R_{CP} is suppressed (< 1) at high-p_{T} at mid-rapidity



R_{CP}, at fixed rapidity

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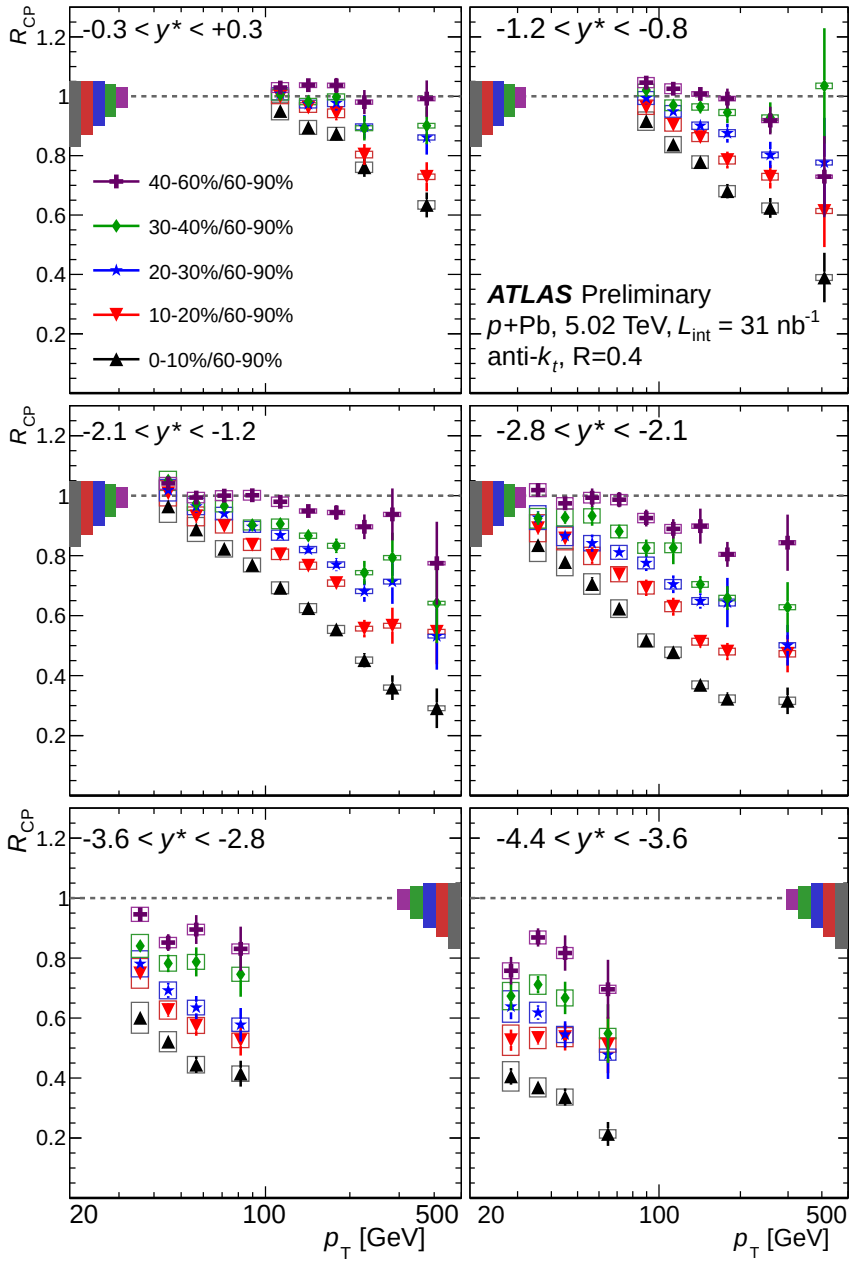
Each panel at fixed y^*

- R_{CP} is suppressed (< 1) at high-p_{T} at mid-rapidity

  $\mathbf{y^* < 0 \rightarrow p-going}$

  $\Rightarrow$ and all p_{T} at forward-rapidity

- Suppression increases with p_{T}!
- Strong effects in most forward bin!



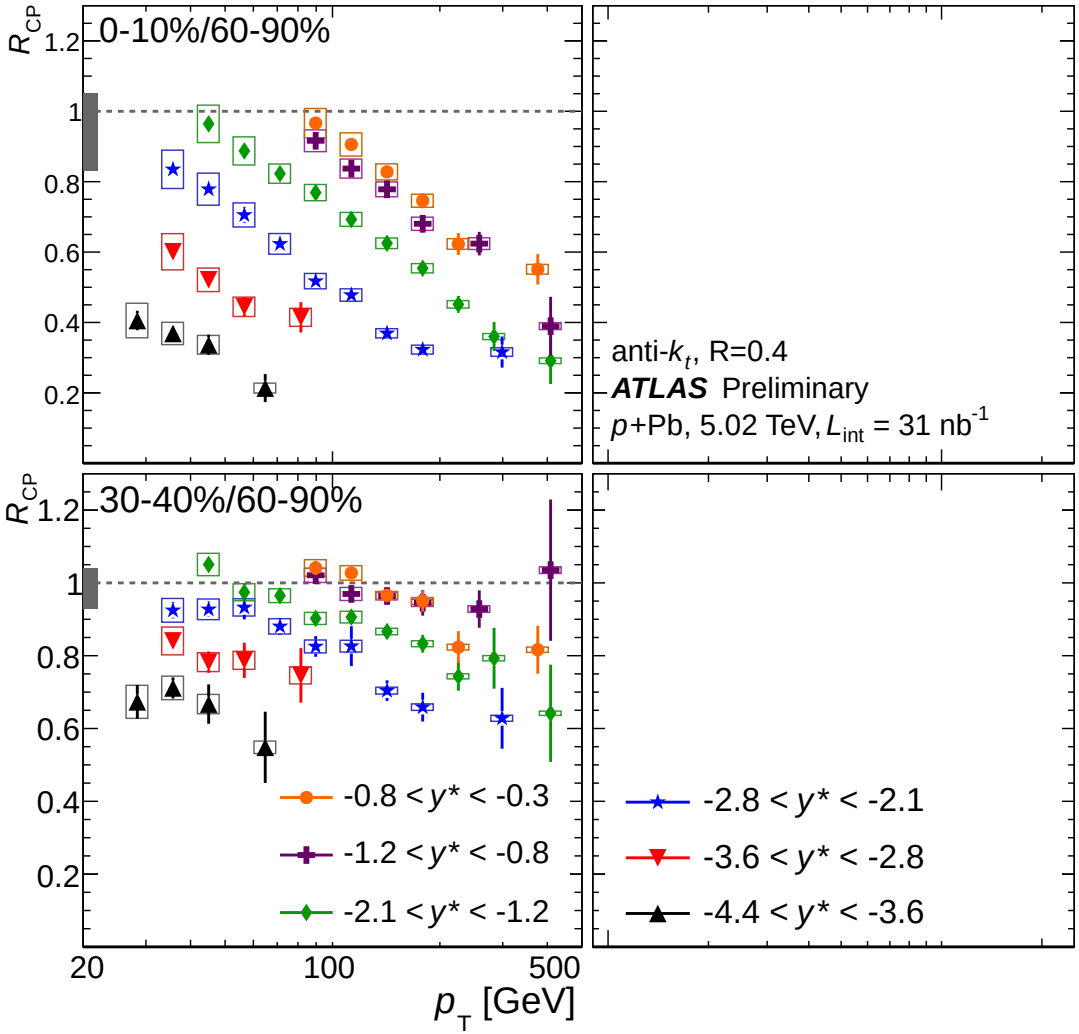
R_{CP}, rapidity dependence

$$R_{\mathrm{CP}} = \frac{1}{R_{\mathrm{coll}}^{\mathrm{cent/peri}}} \frac{\frac{1}{N_{\mathrm{evt}}} \frac{d^2 N_{\mathrm{jet}}}{dp_{\mathrm{T}} dy}\Big|_{\mathrm{cent}}}{\frac{1}{N_{\mathrm{evt}}} \frac{d^2 N_{\mathrm{jet}}}{dp_{\mathrm{T}} dy}\Big|_{\mathrm{peri}}}$$

$\mathbf{y^* < 0 \rightarrow p-going}$

Each panel at fixed centrality

- Multiple y^* bins overlaid
- Possible to find a simple kinematic dependence?



R_{CP}, rapidity dependence

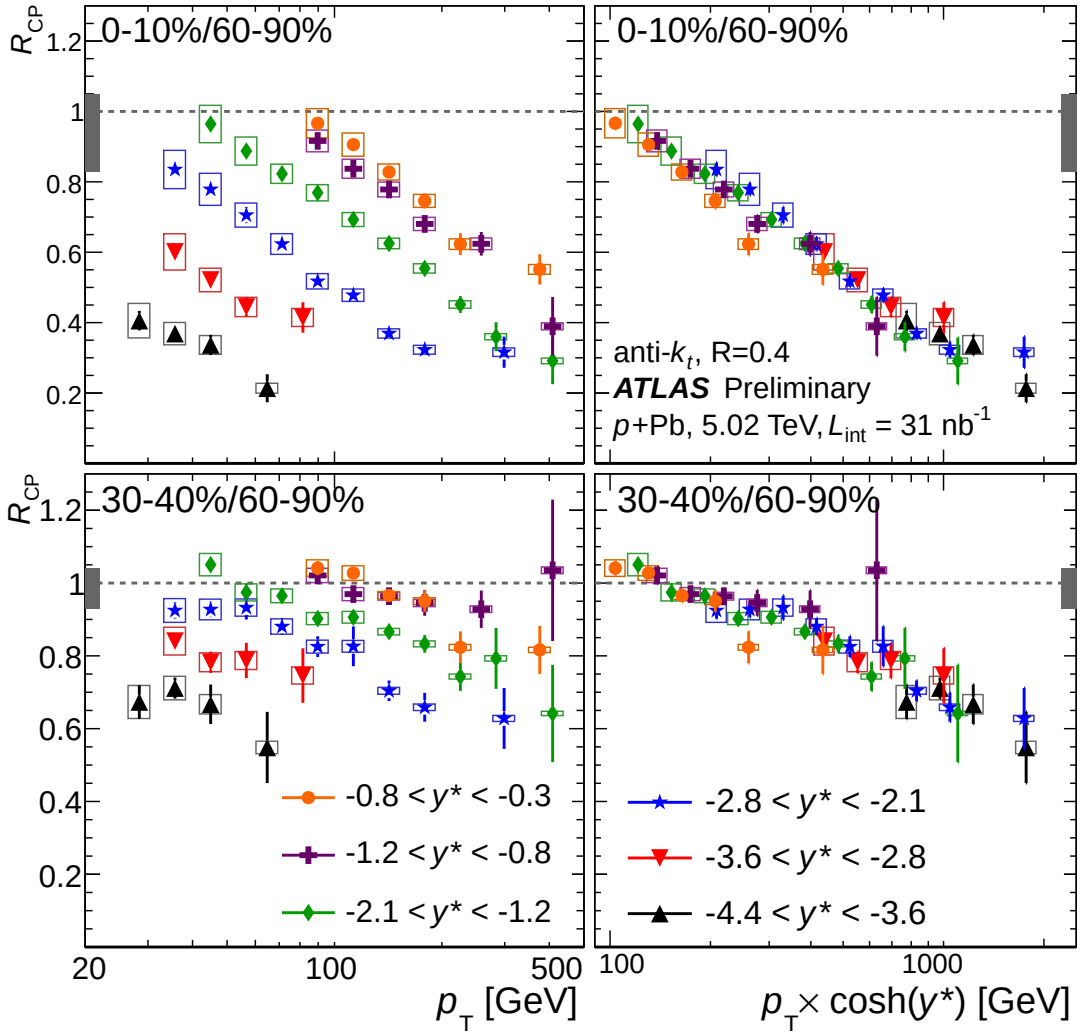
$$R_{\mathrm{CP}} = \frac{1}{R_{\mathrm{coll}}^{\mathrm{cent/peri}}} \frac{\frac{1}{N_{\mathrm{evt}}} \frac{d^2 N_{\mathrm{jet}}}{dp_{\mathrm{T}} dy}\Big|_{\mathrm{cent}}}{\frac{1}{N_{\mathrm{evt}}} \frac{d^2 N_{\mathrm{jet}}}{dp_{\mathrm{T}} dy}\Big|_{\mathrm{peri}}}$$

$\mathbf{y^* < 0 \rightarrow p-going}$

Each panel at fixed centrality

- Multiple y^* bins overlaid
- Possible to find a simple kinematic dependence?

  $\Rightarrow$ total jet energy $\boldsymbol{p = p_{\mathrm{T}} \cosh(y^*)}$



- R_{CP} at all rapidities follow a single trend vs. p

$$R_{\mathrm{CP}}(p_{\mathrm{T}}, y^*) = R_{\mathrm{CP}}(p)$$

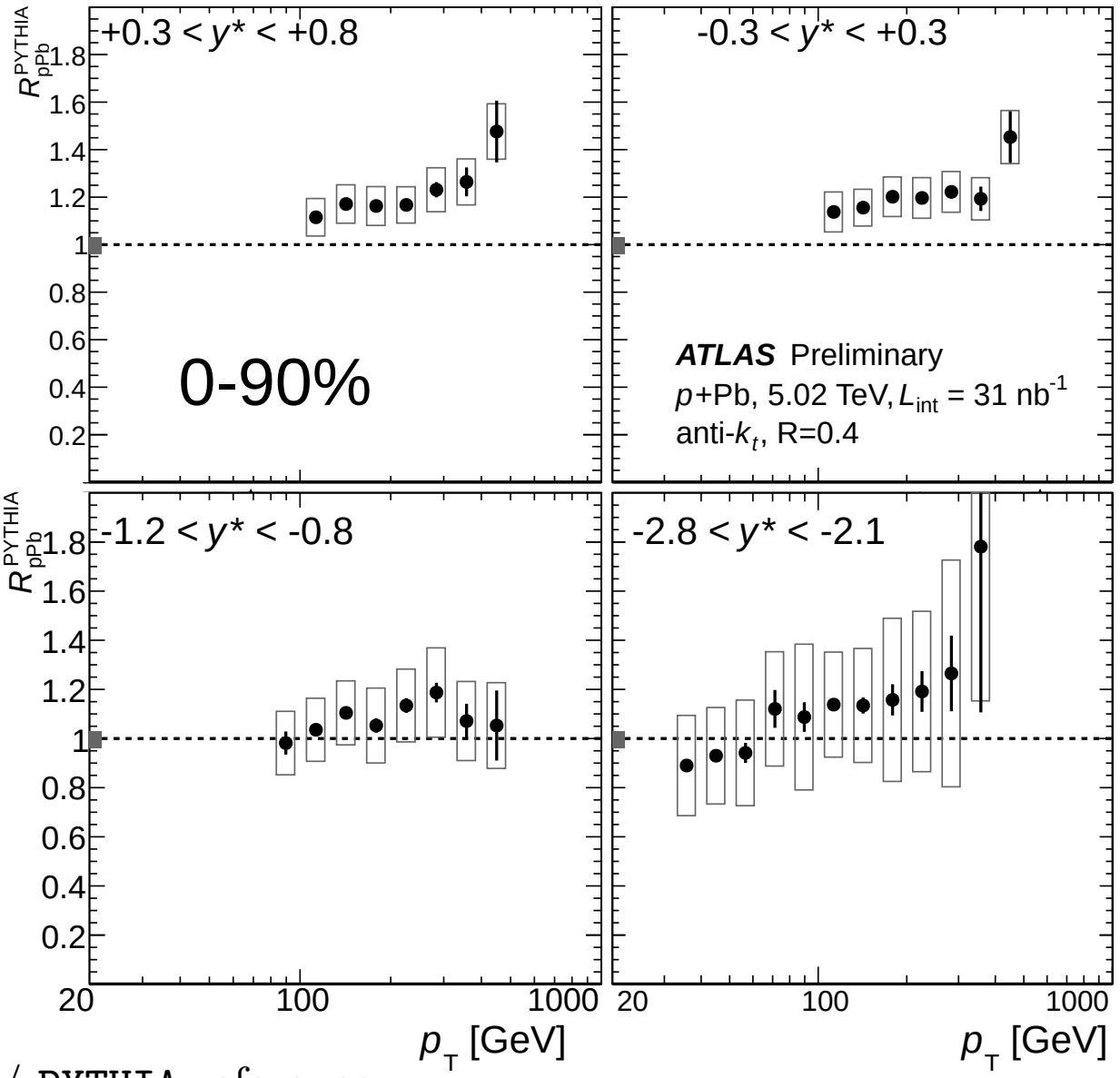
Inclusive $R_{\mathrm{pPb}}^{\mathrm{PYTHIA}}$

$$R_{\mathrm{pPb}}^{\mathrm{PYTHIA}} = \frac{\frac{1}{N_{\mathrm{evt}}}\frac{d^2N_{\mathrm{jet}}}{dp_{\mathrm{T}}dy}}{\langle T_{\mathrm{AB}}\rangle \frac{d^2\sigma_{\mathrm{jet}}^{\mathrm{pp}}}{dp_{\mathrm{T}}dy}}$$

$$\mathbf{T_{AB}^{0-90\%} = 7.4/\sigma_{NN}}$$

$R_{\mathrm{pPb}}^{\mathrm{PYTHIA}}$ for inclusive (0-90%) p+Pb events

Each panel at fixed y^*



- Reminder: R_{pPb} w/ `PYTHIA` reference
- **No strong p_{T} dependence** in the inclusive $R_{\mathrm{pPb}}^{\mathrm{PYTHIA}}$

$R_{\mathrm{pPb}}^{\mathrm{PYTHIA}}$

$$R_{\mathrm{pPb}}^{\mathrm{PYTHIA}} = \frac{\frac{1}{N_{\mathrm{evt}}} \frac{d^2 N_{\mathrm{jet}}}{dp_{\mathrm{T}} dy}}{\langle T_{\mathrm{AB}} \rangle \frac{d^2 \sigma_{\mathrm{jet}}^{\mathrm{pp}}}{dp_{\mathrm{T}} dy}}$$

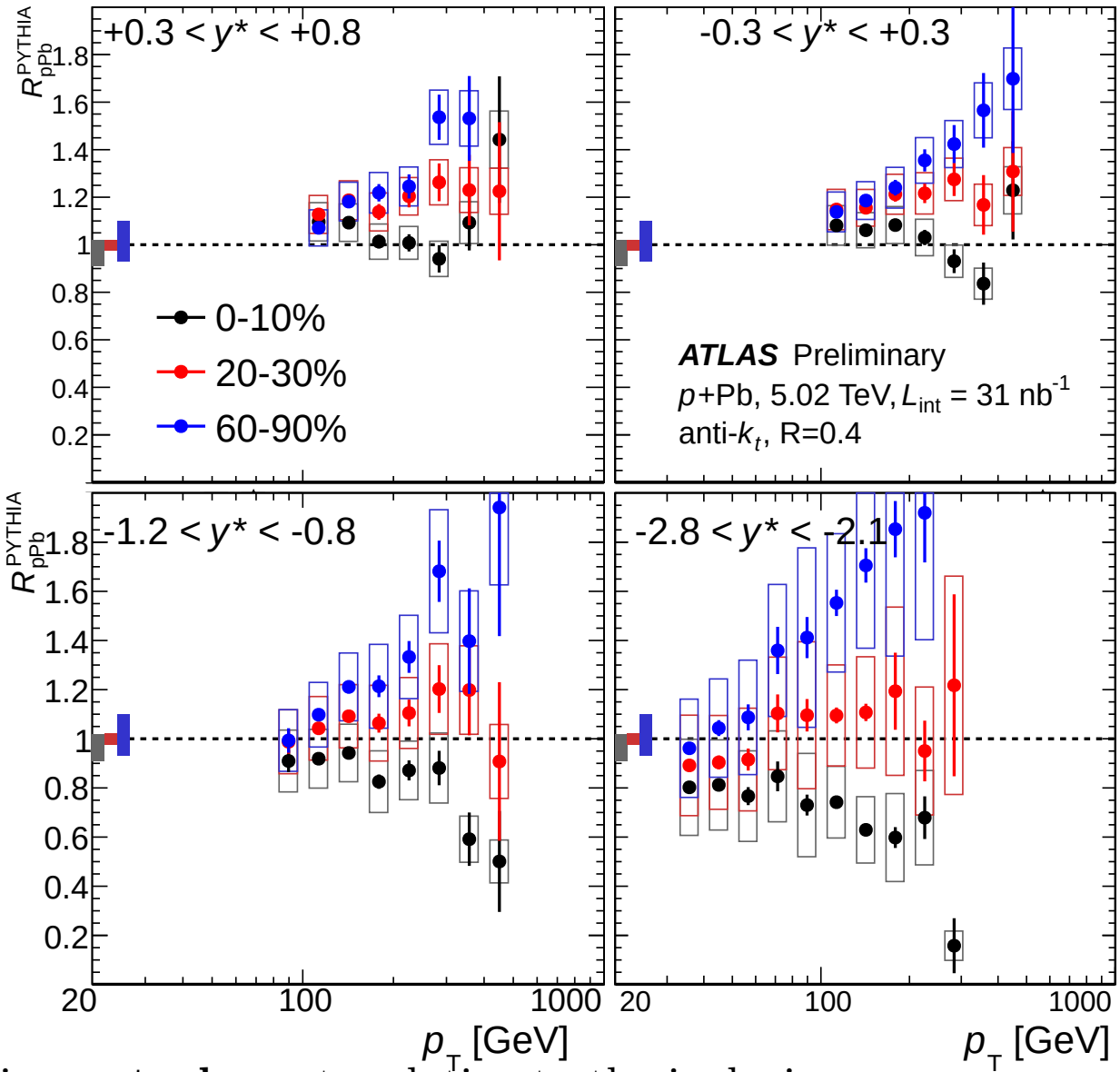
$\mathbf{T_{AB}^{60-90\%} = 3.0/\sigma_{NN}}$

$\mathbf{T_{AB}^{20-30\%} = 10.4/\sigma_{NN}}$

$\mathbf{T_{AB}^{0-10\%} = 14.5/\sigma_{NN}}$

$R_{\mathrm{pPb}}^{\mathrm{PYTHIA}}$, selecting on three p+Pb centralities

Each panel at fixed y^*



- Suppression (< 1) in **central** events relative to the inclusive
- Enhancement (> 1) in **peripheral** events relative to the inclusive

Discussion

- Suppression in central events

  $\Rightarrow$ initial state E-loss?

- Enhancement in peripheral events

  $\Rightarrow$ challenging to explain in theoretical frameworks

- No (large) modification in inclusive p+Pb events!

  $\Rightarrow$ qualitatively similar to PHENIX d+Au jets

- Modifications are smooth in centrality and *increase* with p_{T}

  $\Rightarrow$ only a function of the total energy $p = p_{\mathrm{T}} \cosh(y^*)$

  $\Rightarrow$ lots of ideas[1], but so far experimentally robust

- Key point: if $\boxed{R_{\mathrm{CP}}(p_{\mathrm{T}}, y^*) = R_{\mathrm{CP}}(p)}$ then at fixed jet p,

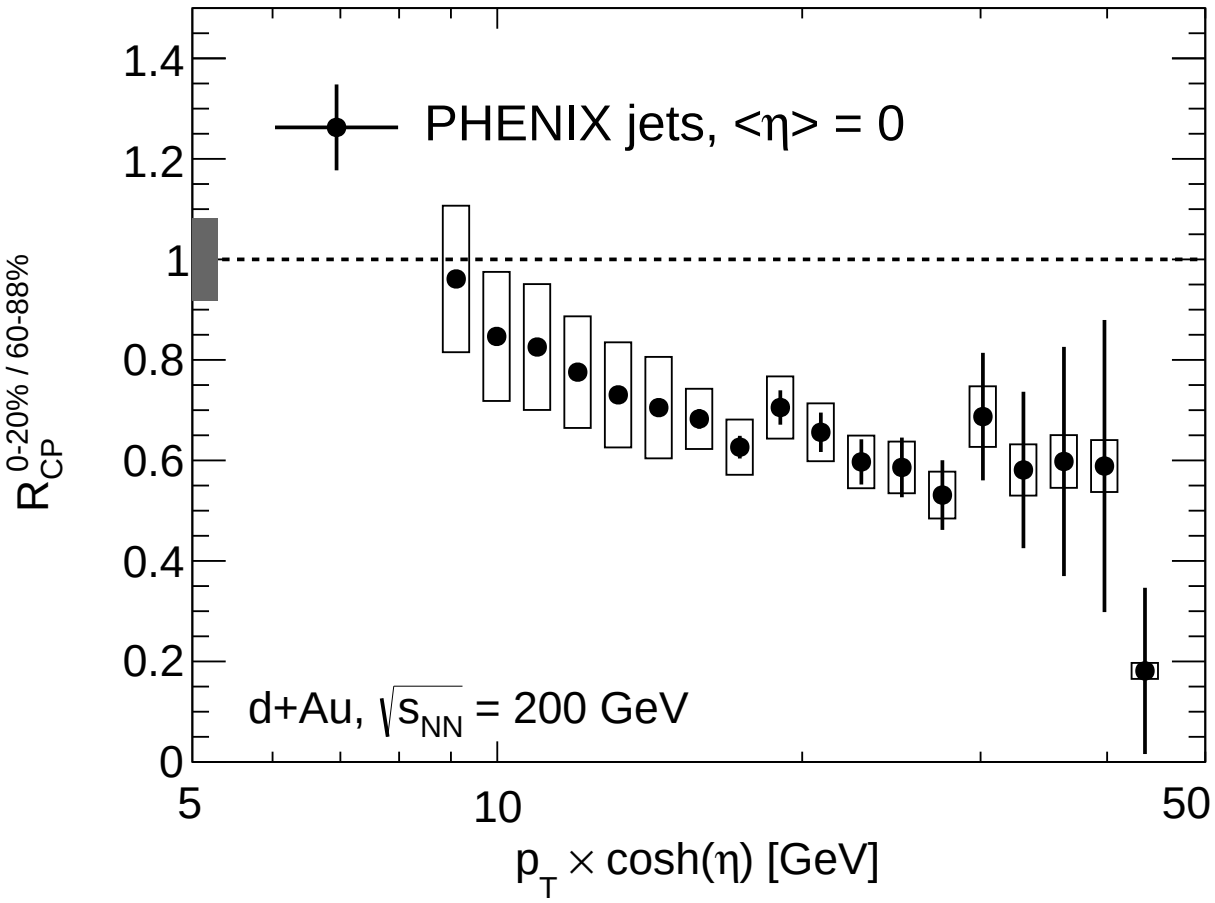
  $\boxed{(\text{high-}p_{\mathrm{T}}\ \&\ \text{mid-rapidity}) \xrightarrow{\text{connected}} (\text{low-}p_{\mathrm{T}}\ \&\ \text{forward rapidity})}$

  $\Rightarrow$ ... what if this is also true at RHIC?

  $\Rightarrow$ Compare different rapidities at RHIC vs. p.

[1] "energy conservation" / violation of hard process - UE factorization / selecting particular proton wavefunctions / centrality "bias" / etc. etc. etc.

RHIC suppression at mid- and forward rapidities



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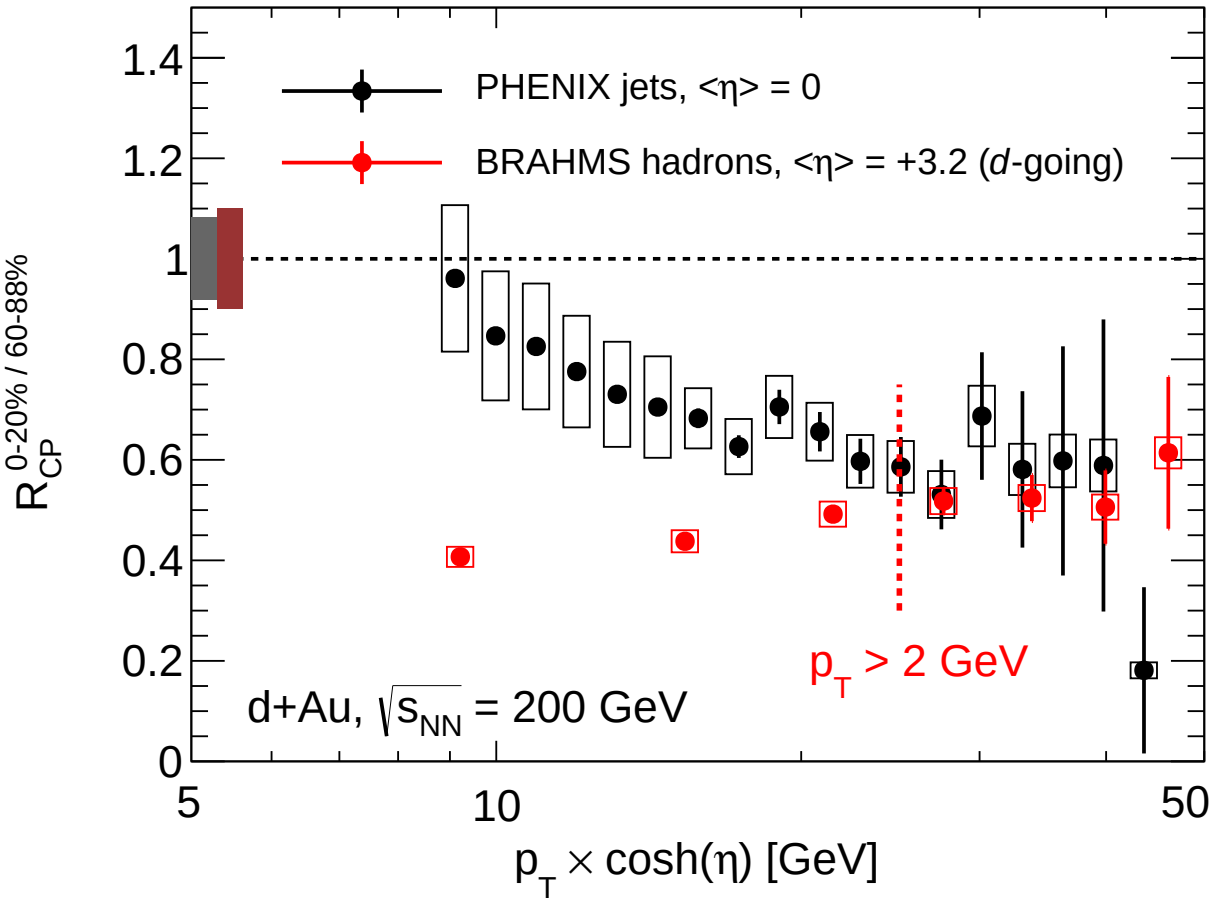
- Plot RHIC results vs. $p = p_{\mathrm{T}} \cosh(\eta)$

  $\Rightarrow$ **mid-rapidity jets**, PHENIX

RHIC suppression at mid- and forward rapidities



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- Plot RHIC results vs. $p = p_{\mathrm{T}} \cosh(\eta)$
  - $\Rightarrow$ **mid-rapidity jets**, PHENIX
  - $\Rightarrow$ **forward hadrons**, BRAHMS
    - $\Rightarrow$ hard-scattering dominates for $p_{\mathrm{T}} > 2$ GeV
- Consistent suppression when plotted vs. p ?

Conclusion

- We have measured the centrality-dependence of jet production in p+Pb collisions
  - $\Rightarrow$ $p_{\mathrm{T}} > 25$ GeV to ≈ 500 GeV, more than 5 units of rapidity
  - $\Rightarrow$ centrality determined using Pb-going FCal & Glauber model
  - $\Rightarrow$ first centrality-dependent $R_{\mathrm{CP}}/R_{\mathrm{pPb}}$ for jets in p+Pb
- Limits on any inclusive modification
  - $\Rightarrow$ jet rate in central events suppressed $\downarrow$
  - $\Rightarrow$ jet rate in peripheral events enhanced $\uparrow$
- We observe patterns in the nuclear modification
  - $\Rightarrow$ smooth in centrality
  - $\Rightarrow$ increasing modification at high-p_{T}
  - $\Rightarrow$ modification at all y^* $\rightarrow$ $\boxed{R_{\mathrm{CP}}(p_{\mathrm{T}}, y^*) = R_{\mathrm{CP}}(p)}$
- How can we understand this phenomena?
  - $\Rightarrow$ They complicate the extraction of b-dependent IS effects.
  - $\Rightarrow$ What are the consequences for future (and previous!) forward measurements in p+A?

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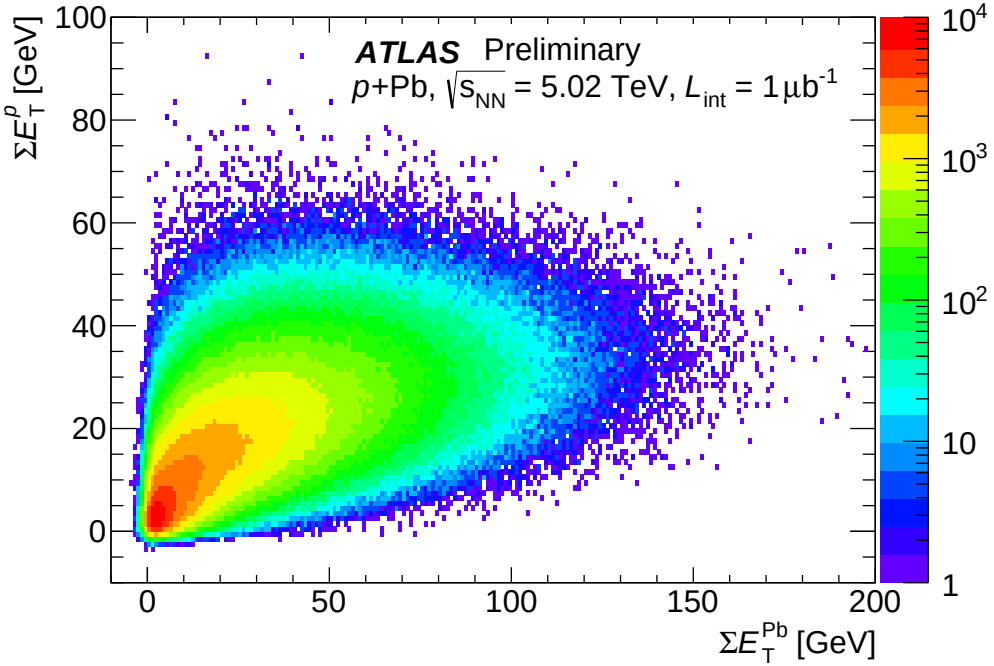
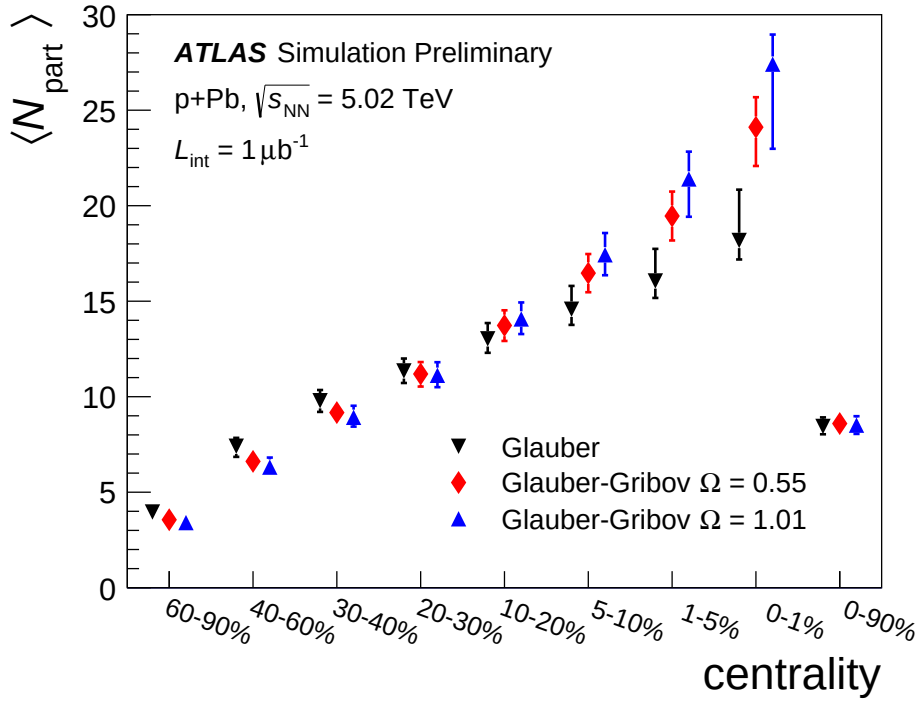
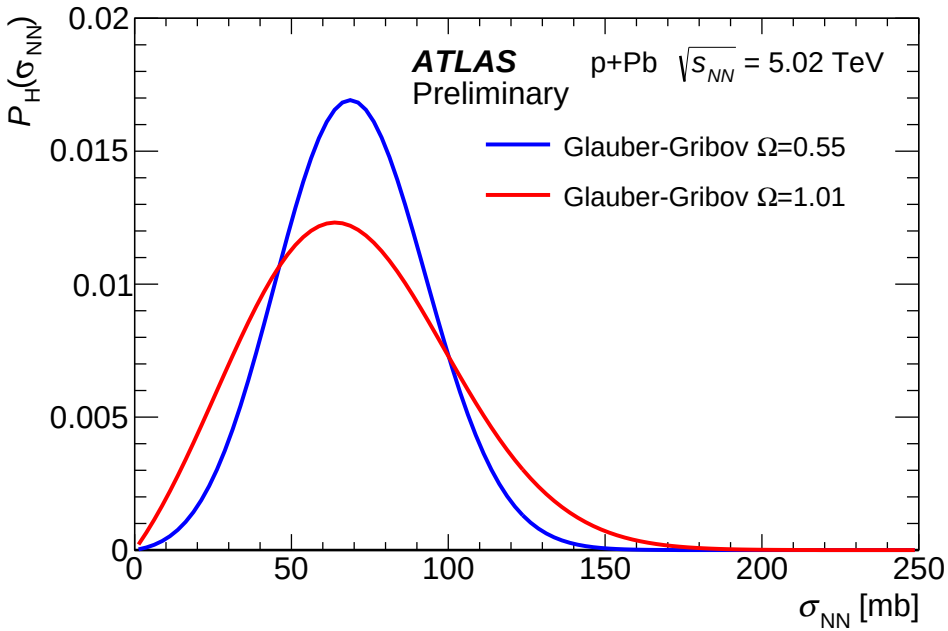
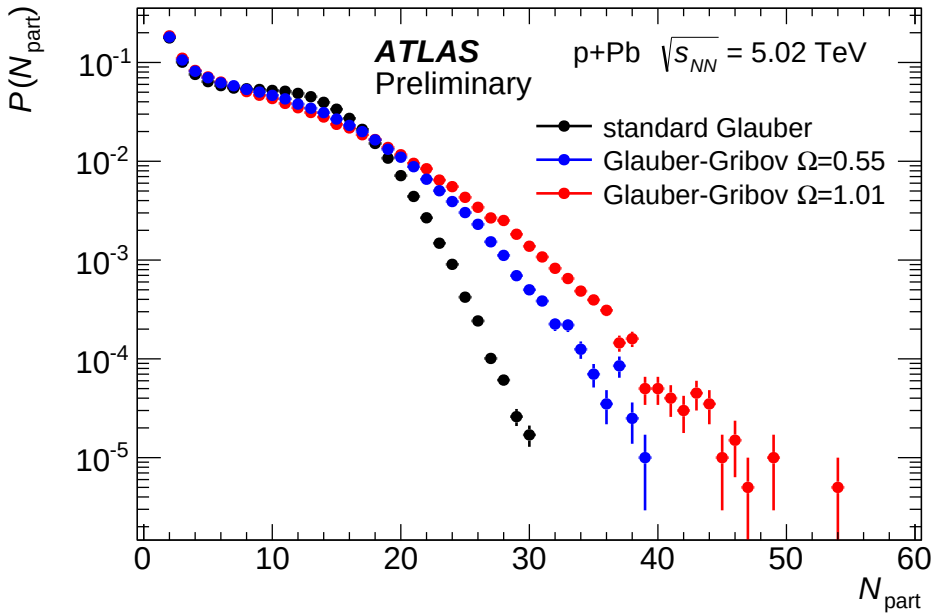
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2013-105/

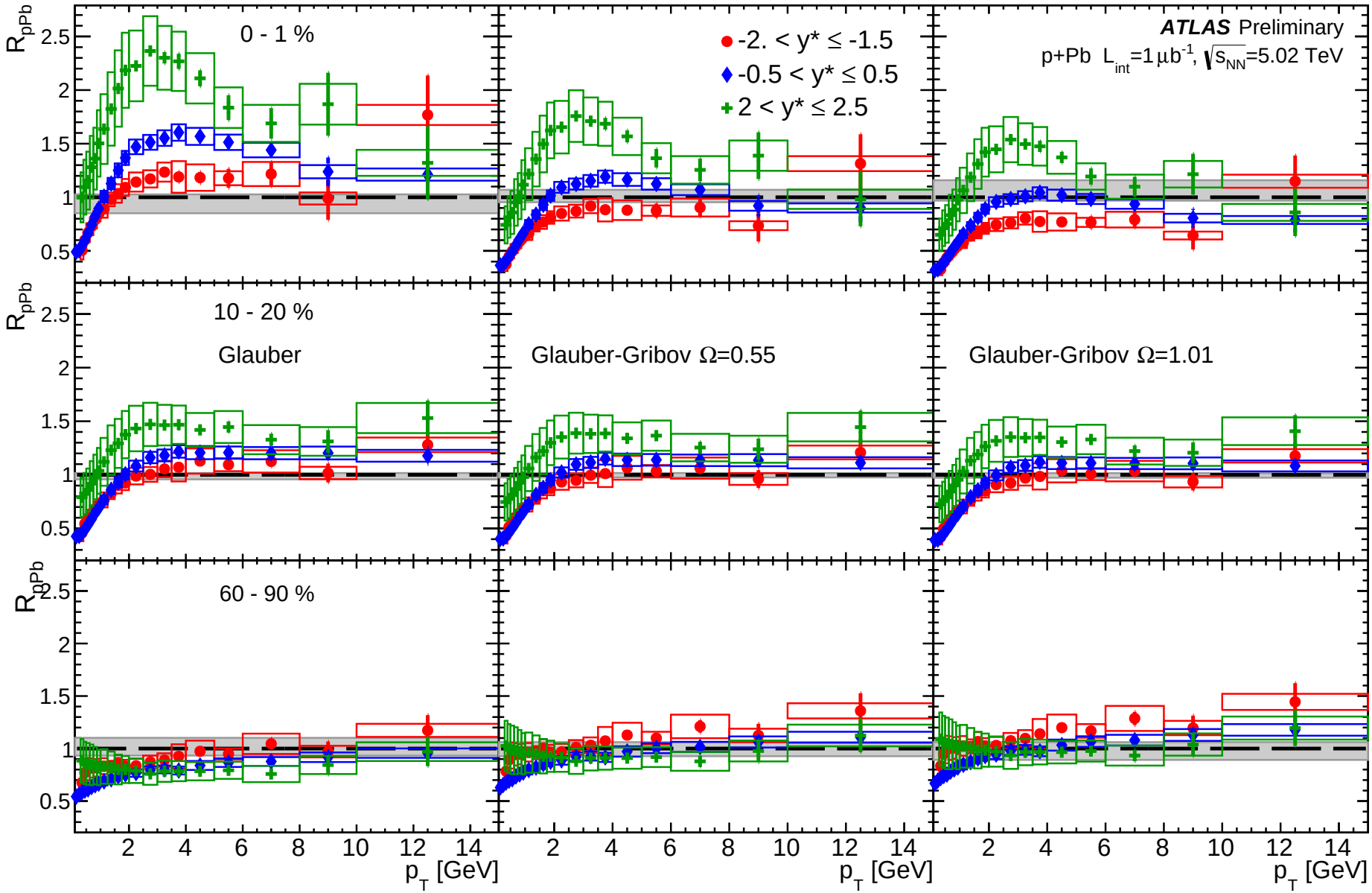
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HeavyIonsPublicResults

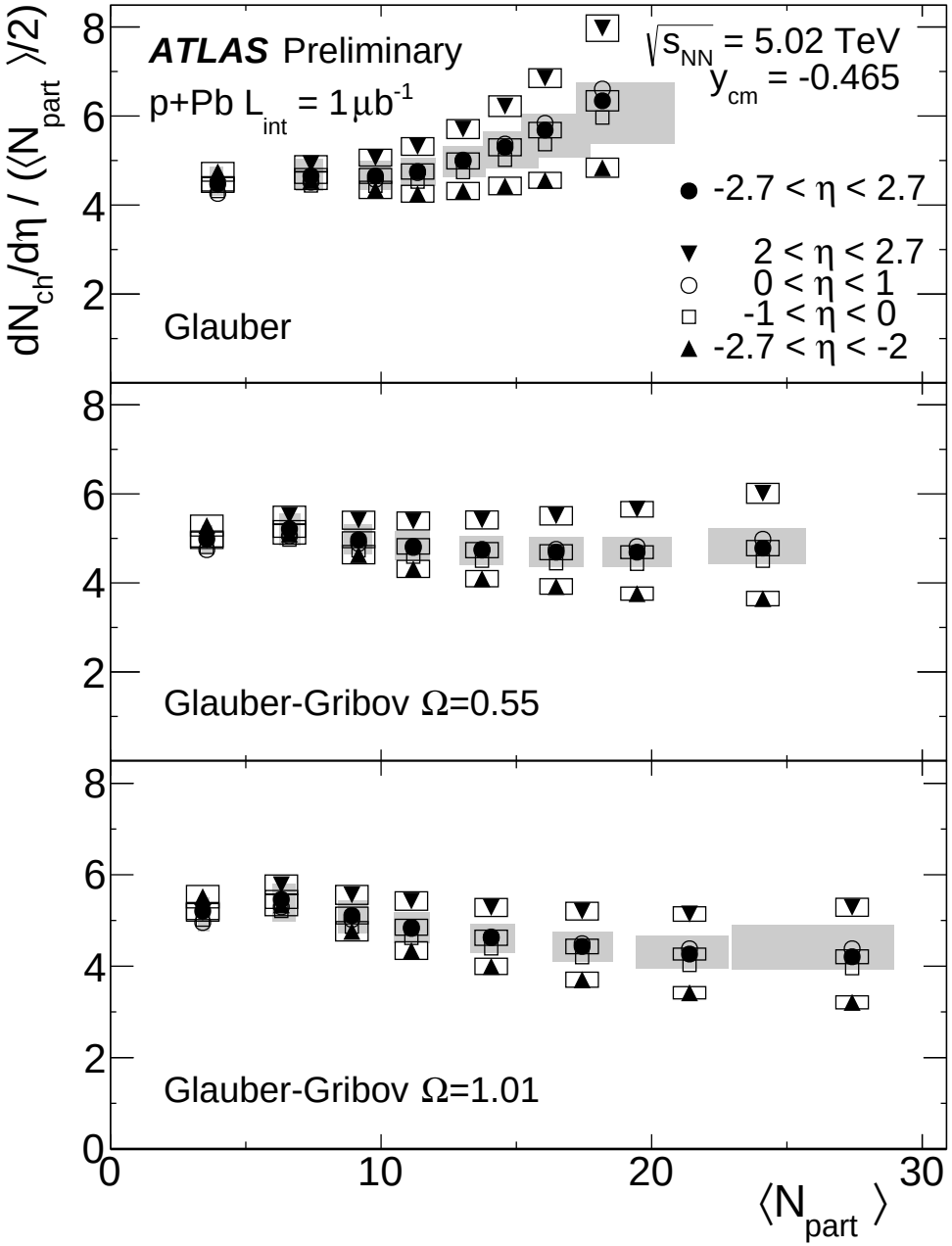

ATLAS Preliminary
p+Pb, √sNN = 5.02 TeV, Lint = 1 μb-1
ΣEpT [GeV]
ΣEPbT [GeV]

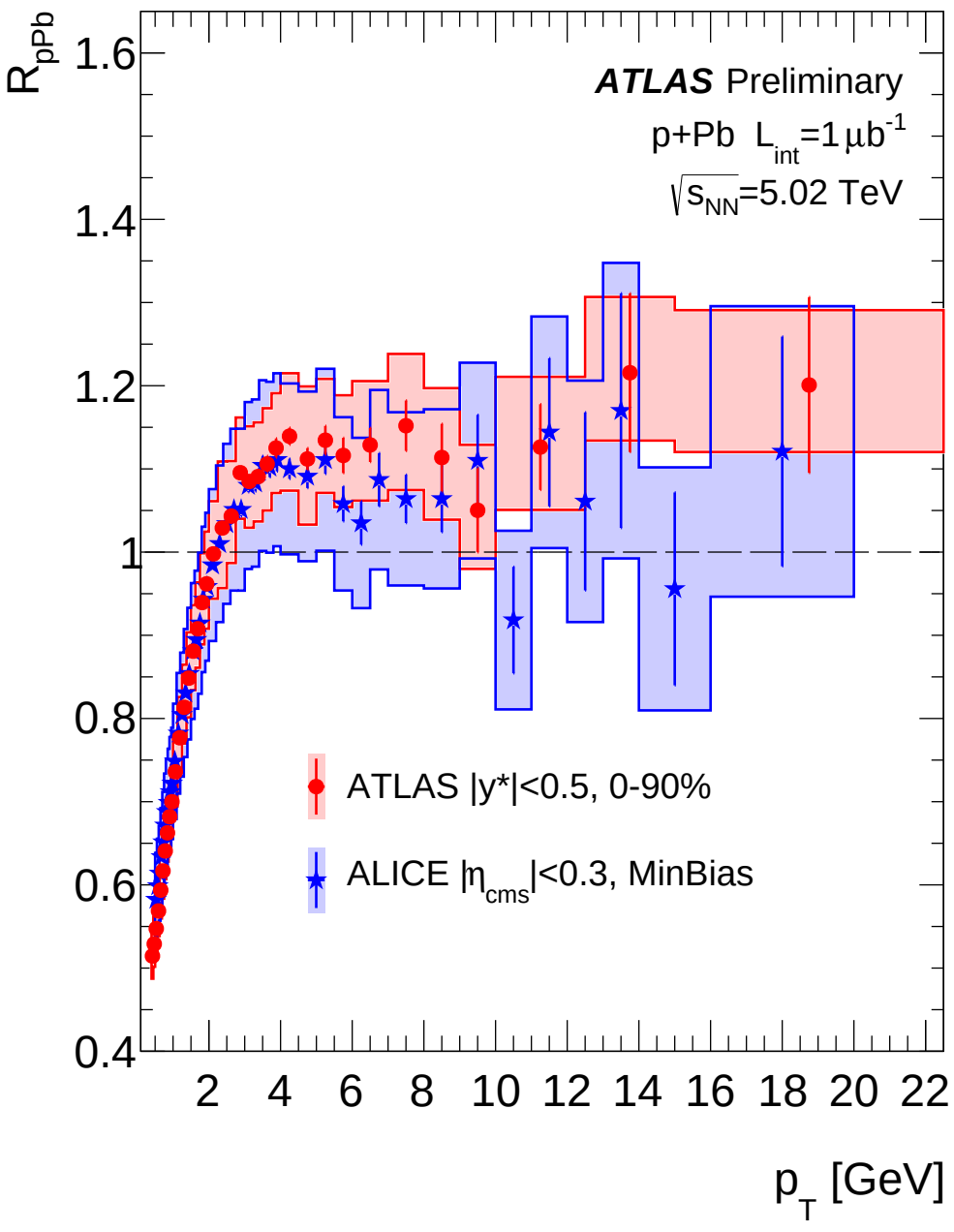

ATLAS Simulation Preliminary
p+Pb, √sNN = 5.02 TeV
Lint = 1 μb-1
⟨Npart⟩
Glauber
Glauber-Gribov Ω = 0.55
Glauber-Gribov Ω = 1.01
60-90%
40-60%
30-40%
20-30%
10-20%
5-10%
1-5%
0-1%
0-90%
centrality


ATLAS Preliminary
p+Pb √sNN = 5.02 TeV
Glauber-Gribov Ω=0.55
Glauber-Gribov Ω=1.01
PH(σNN)
σNN [mb]


ATLAS Preliminary
p+Pb √sNN = 5.02 TeV
standard Glauber
Glauber-Gribov Ω=0.55
Glauber-Gribov Ω=1.01
P(Npart)
Npart


ATLAS Preliminary
p+Pb L_int=1 μb^-1, √s_NN=5.02 TeV
-2. < y* ≤ -1.5
-0.5 < y* ≤ 0.5
2 < y* ≤ 2.5
0 - 1 %
10 - 20 %
60 - 90 %
Glauber
Glauber-Gribov Ω=0.55
Glauber-Gribov Ω=1.01
R_pPb
p_T [GeV]


ATLAS Preliminary
p+Pb L_int = 1 μb^-1
√s_NN = 5.02 TeV
y_cm = -0.465
-2.7 < η < 2.7
2 < η < 2.7
0 < η < 1
-1 < η < 0
-2.7 < η < -2
Glauber
Glauber-Gribov Ω=0.55
Glauber-Gribov Ω=1.01
dN_ch/dη / (⟨N_part⟩/2)
⟨N_part⟩


ATLAS Preliminary
p+Pb L_int=1 μb^-1
√s_NN=5.02 TeV
ATLAS |y*|<0.5, 0-90%
ALICE |η_cms|<0.3, MinBias
R_pPb
p_T [GeV]

Uncertainty source	$-0.3 < y^* < +0.3$		$-2.8 < y^* < -2.1$	
	R_{CP}	$R_{\mathrm{pPb}}^{\mathrm{PYTHIA}}$	R_{CP}	$R_{\mathrm{pPb}}^{\mathrm{PYTHIA}}$
Jet energy scale	1%	7-9%	2%	15-30%
Jet energy resolution	1%	1-2%	1-4%	4-16%
Shape uncertainty	2-3%	1-2%	3-4%	1-2%
Trigger selection	1%	1%	1%	1%

Table: Summary of the various sources of systematic uncertainty and their estimated impact on the R_{CP} and $R_{\mathrm{pPb}}^{\mathrm{PYTHIA}}$ measurement in two rapidity bins.