High p_T probes of proton-lead collisions with the ATLAS detector

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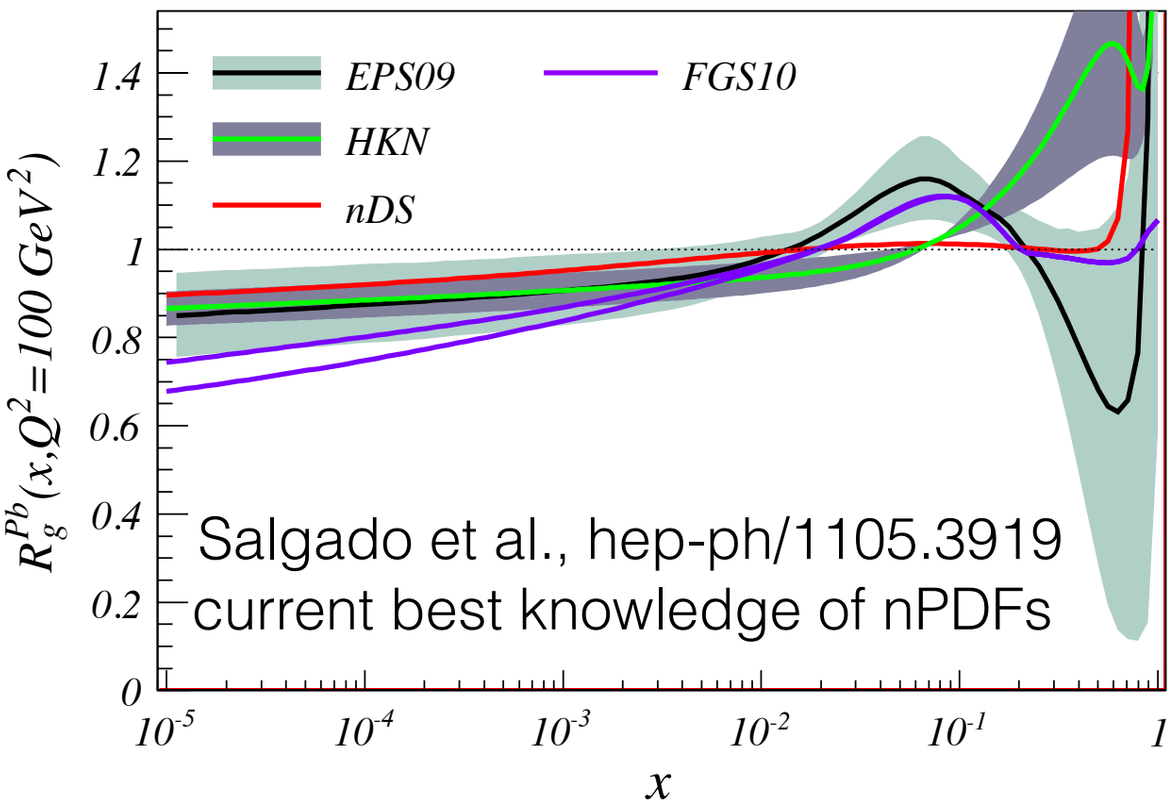
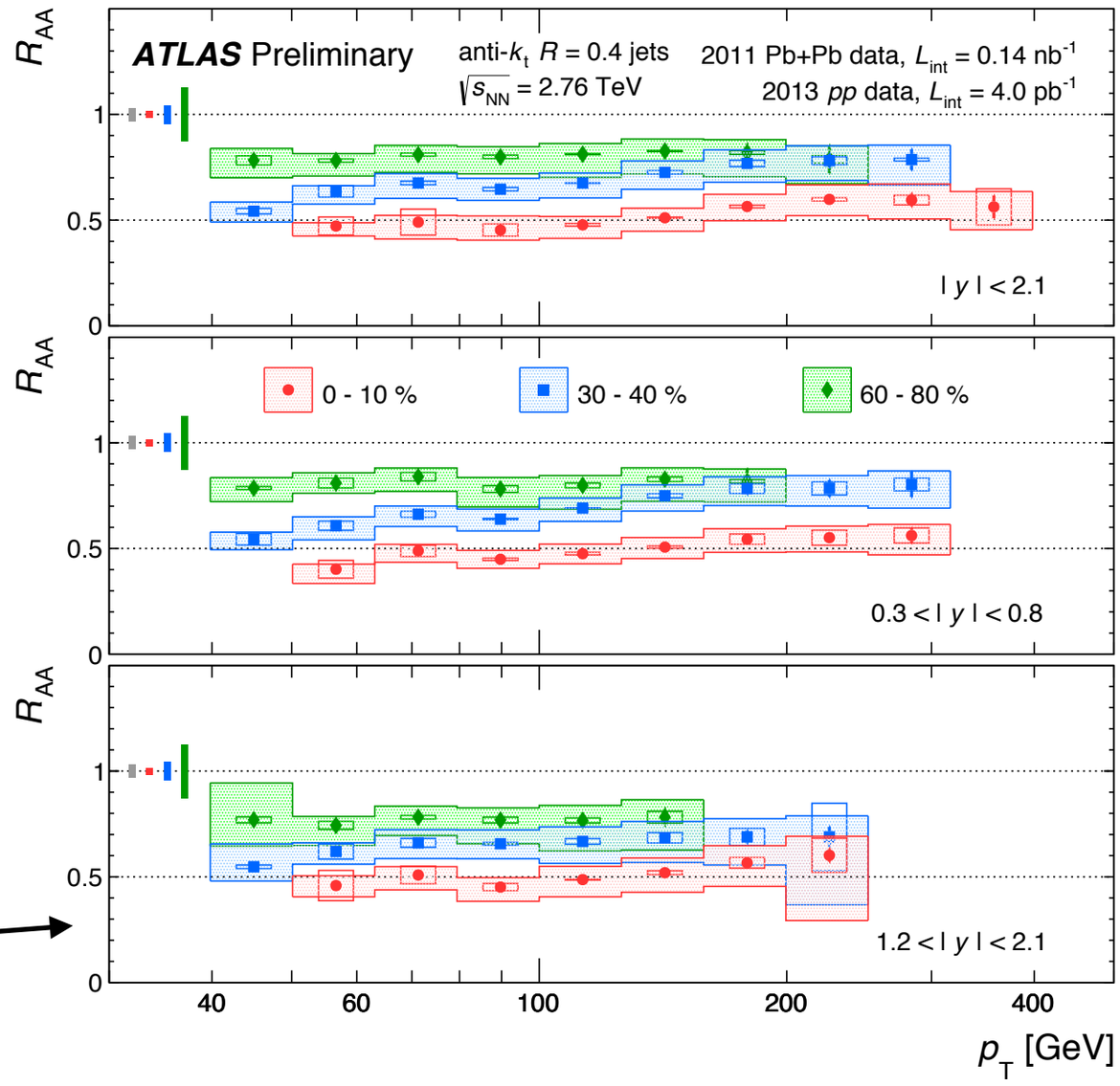
Hard probes of *p*+Pb



quenching in Pb+Pb, 2.76 TeV →



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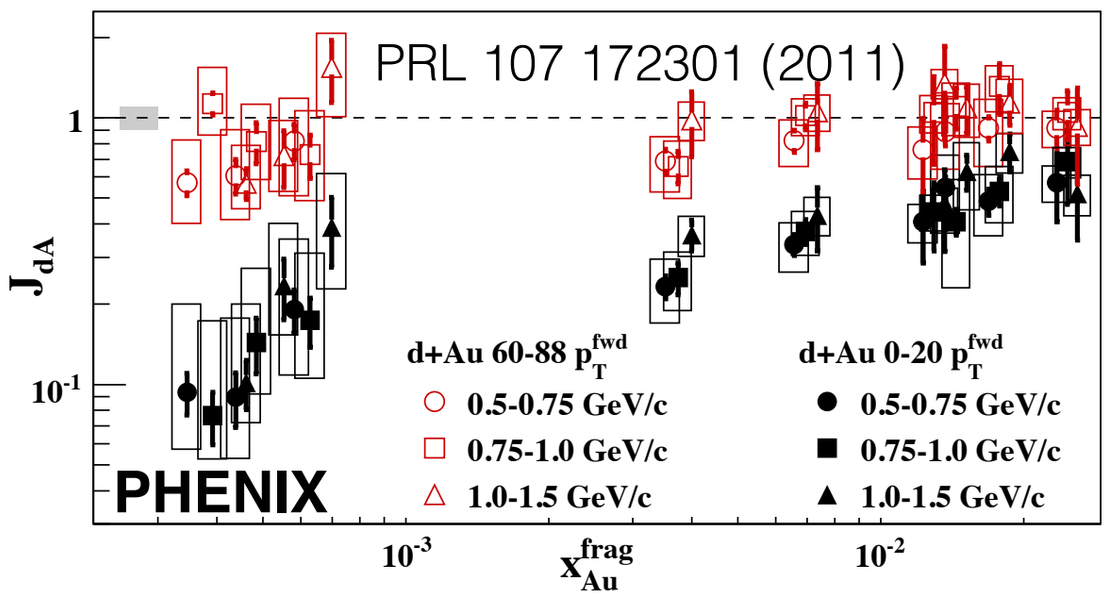
- Hard probes access the partonic structure of the nucleus
  - Can probe *b*-dependent nPDFs, initial state energy loss, saturation phenomena, etc.
  - Provide a crucial baseline within which to interpret the strong suppression observed in Pb+Pb collisions

Hard probes of *d*+Au @ RHIC

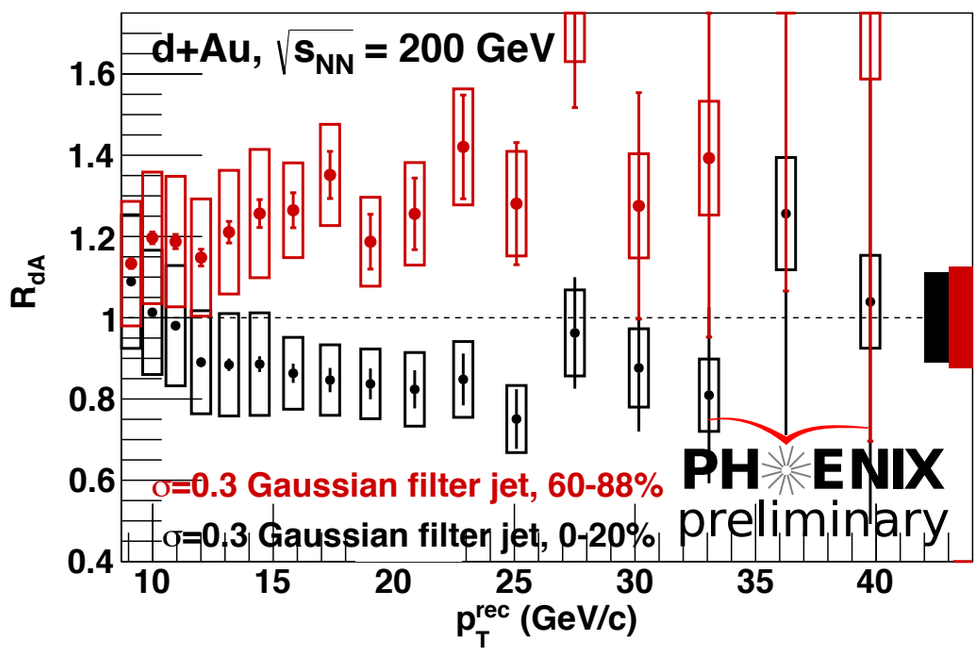
di-hadron J_{dA}



60-88%

0-20%

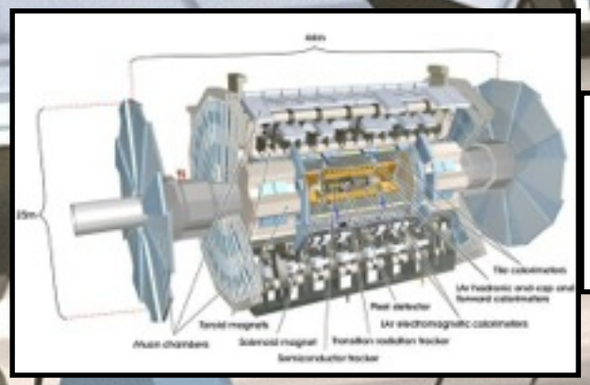
jet R_{dAu}



10.1016/j.nuclphysa.2013.02.184

- At forward rapidity, large centrality dependent suppression
  - single- and di-hadrons
  - attributed to shadowing / saturation / CGC phenomena
- At mid-rapidity, anomalous centrality dependence
  - for high-p_T jets
  - **central** suppression
  - enhanced **peripheral** (!?)

- What happens in central & peripheral collisions in between?
  - ➡ full jets in ATLAS can explore the wide kinematic range in the middle



ATLAS detector

Inner Detector
$-2.5 < \eta < +2.5$

Convention: $y^* > 0$ is *proton*-going

p

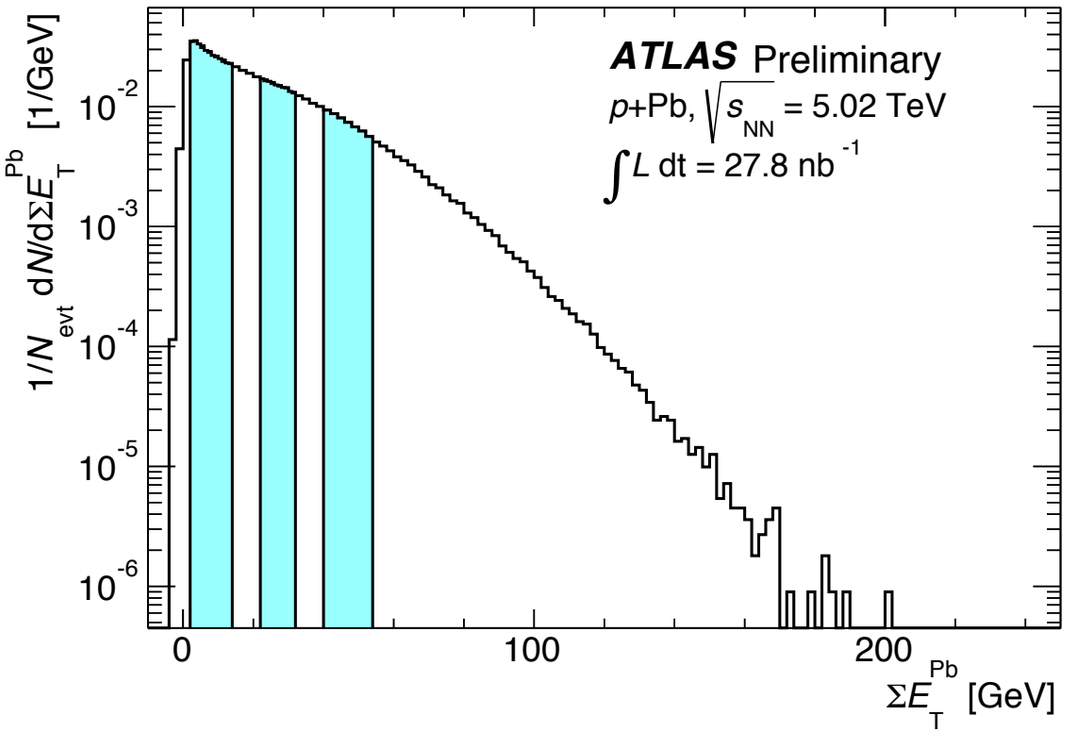
Pb

EMCal+HCal system
$-4.9 < \eta < +4.9$

Pb-going Forward Calorimeter
$-4.9 < \eta < -3.2$

+ High Level Trigger system

p+Pb collisions & centrality



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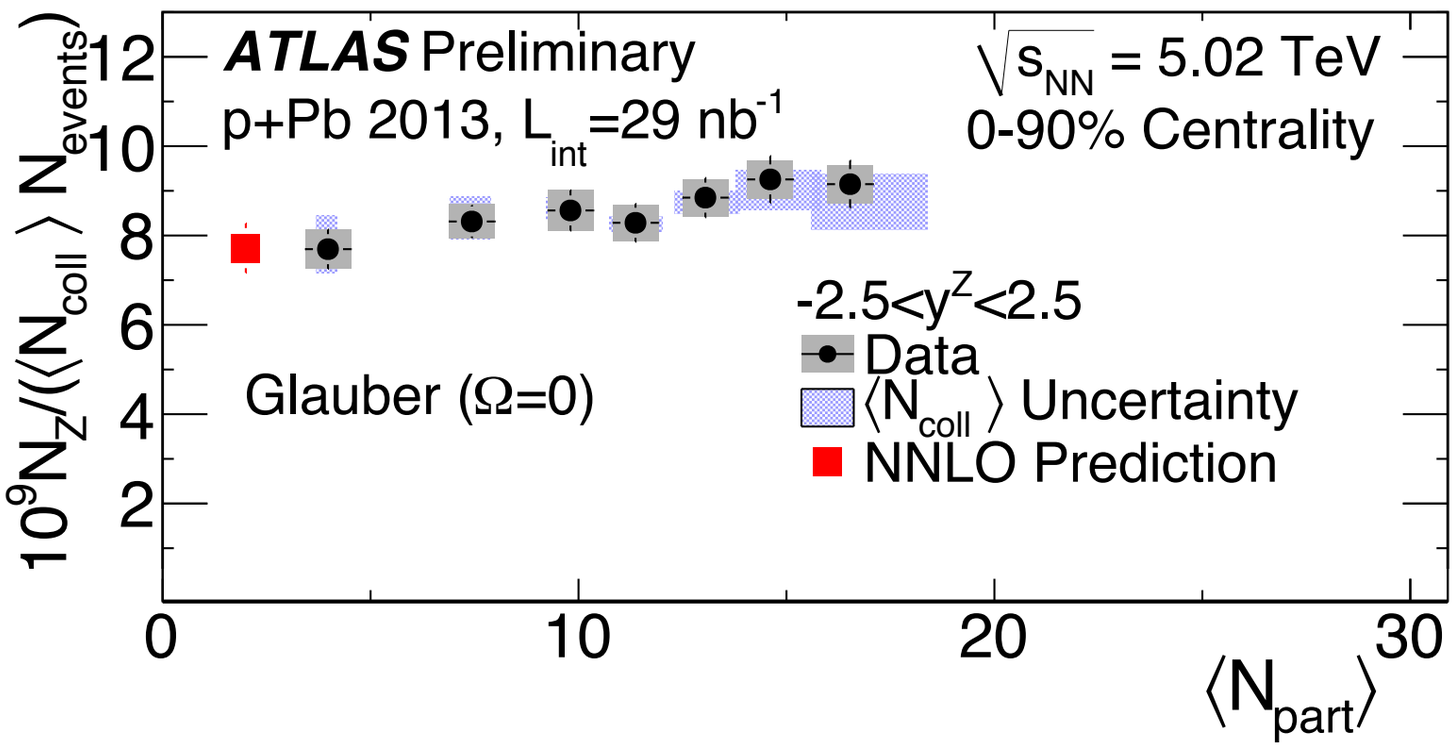

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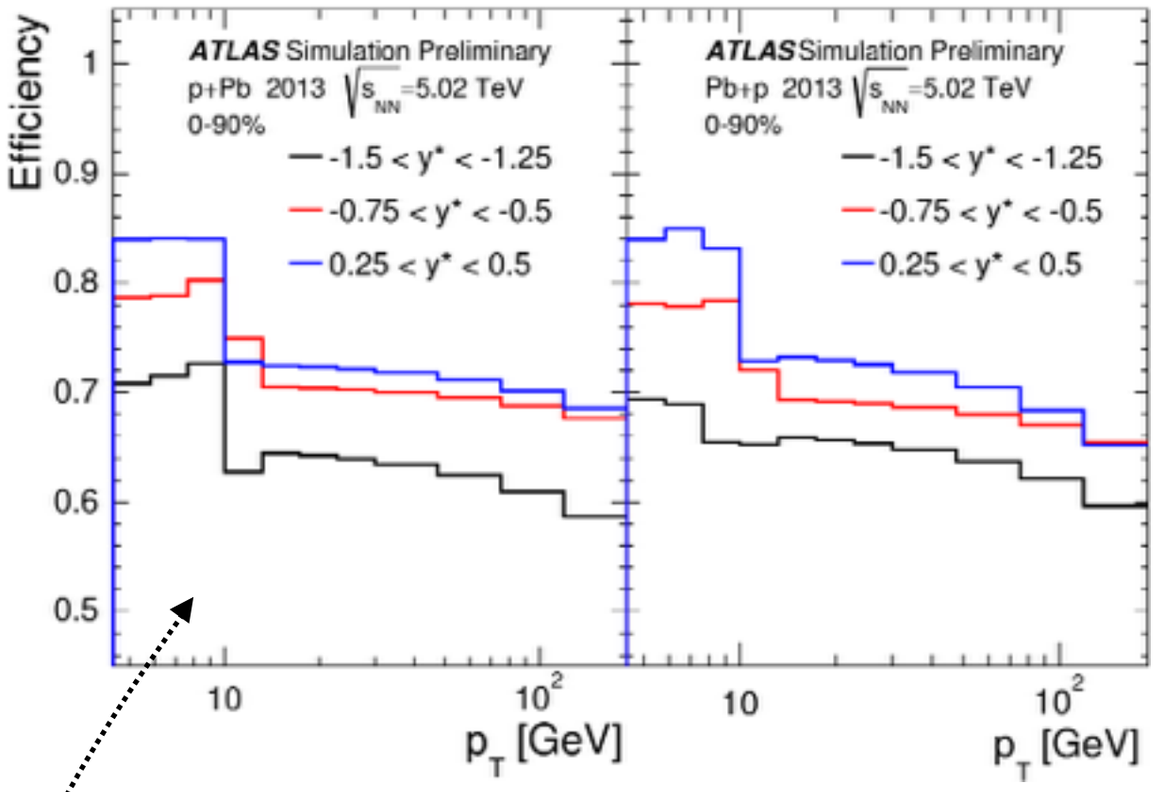
- 28 nb^{-1} of *p*+Pb/Pb+*p* data @ 5.02 TeV, shift of $\Delta y = -0.465$ w.r.t. lab frame
- Centrality determined using ΣE_T in Pb-going FCal, $-4.9 < \eta < -3.2$
  - best sensitivity to collision geometry
  - allows measurements of very forward jets
- Centrality method results in reasonable behavior in **soft** & **hard** observables
  - e.g. N_{coll}-scaling of Z production in *p*+Pb (right plot)

High-p_T charged particles in p+Pb

Charged particle spectra



- Reconstructed tracks in the inner detector are selected according to a set of quality criteria
  - reconstruction efficiency shown above
  - other corrections for: “fake” tracks from secondaries, p_T resolution and $\eta^{lab} \rightarrow y^*$ transformation
- Example of fully corrected spectra

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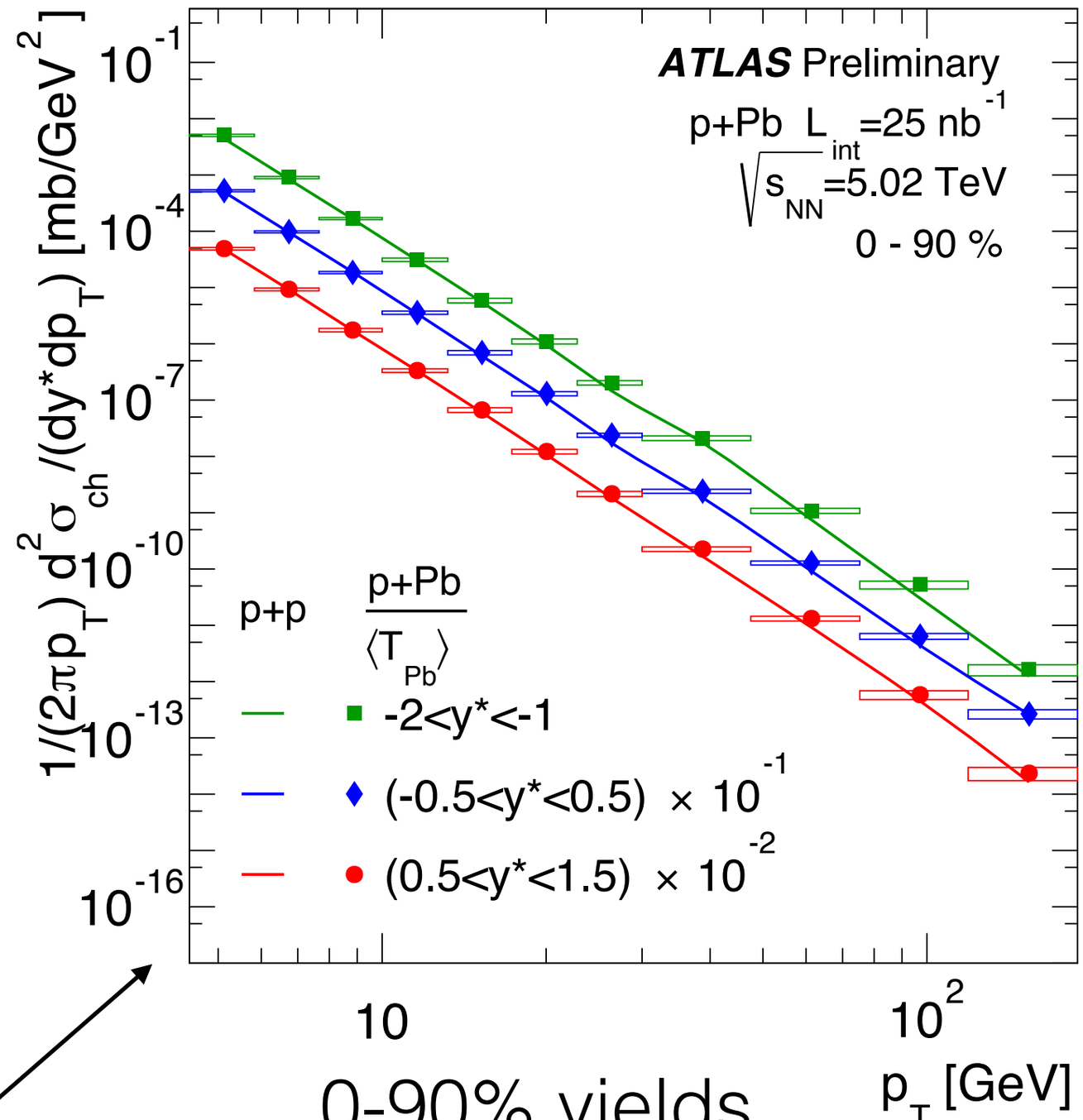


0-90% yields, three rapidity bins

Charged particle R_{pPb}

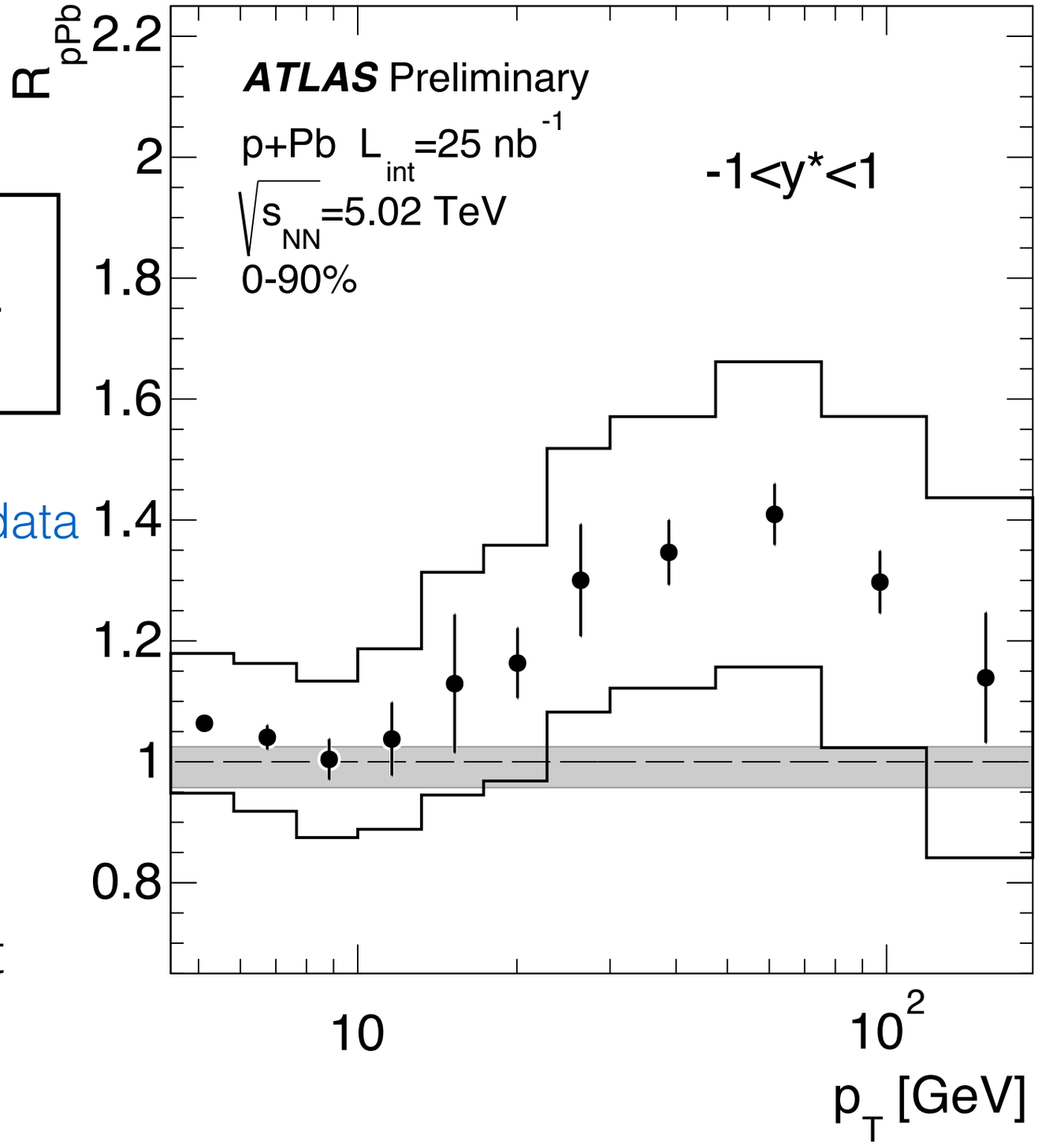
yield in p+Pb

$$R_{\mathrm{pPb}} = \frac{(1/N_{\mathrm{evt}})\, \mathrm{d}^2N/\mathrm{d}p_{\mathrm{T}}\mathrm{d}y^*}{\langle T_{\mathrm{pA}} \rangle\, \mathrm{d}^2\sigma/\mathrm{d}p_{\mathrm{T}}\mathrm{d}y^*}$$

Pb nucleon flux seen by proton

log(√s)-interpolated 2.76 TeV and 7 TeV pp data

- R_{pPb} for 0-90% events
  - $|y^*| < 1$, 5-200 GeV
- At low p_{T}, geometric scaling
- At high p_{T}, systematic enhancement
  - with a non-trivial p_{T} dependence
  - reaching a 40% effect at ≈60 GeV
  - challenging for nPDF pictures!



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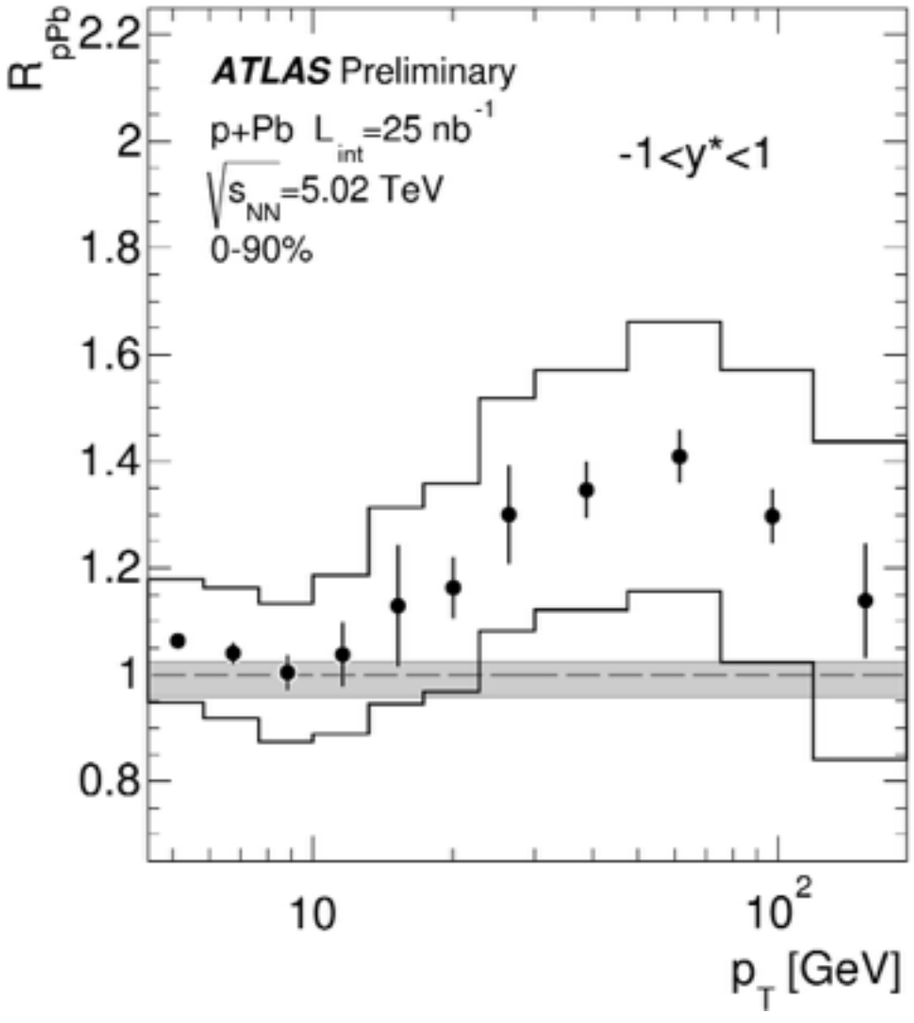
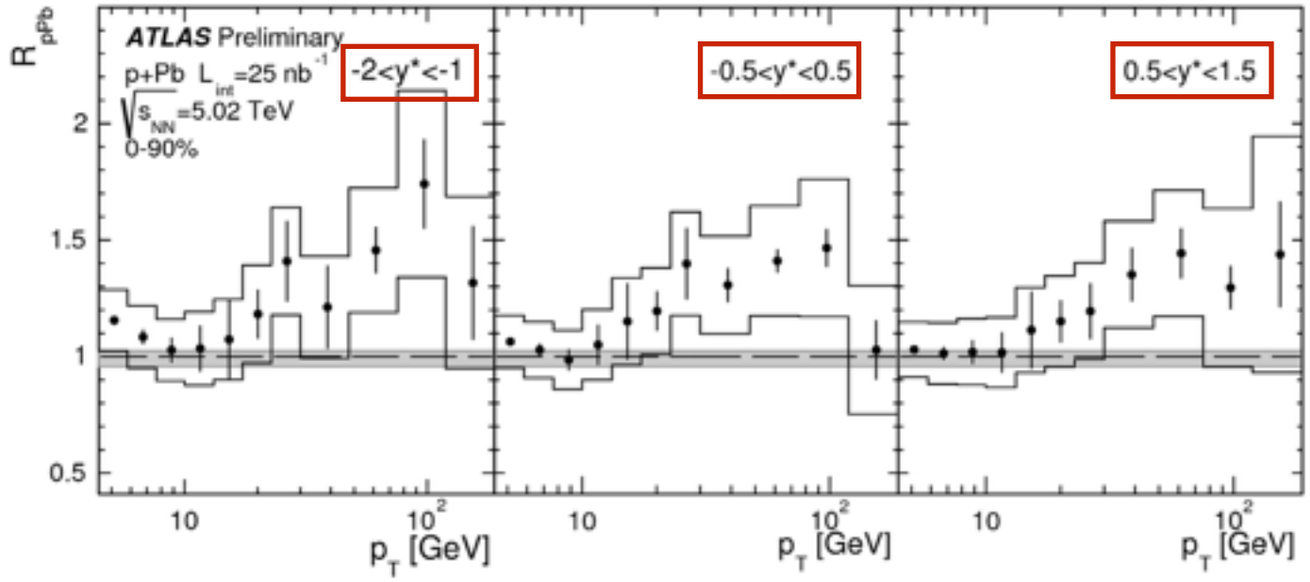
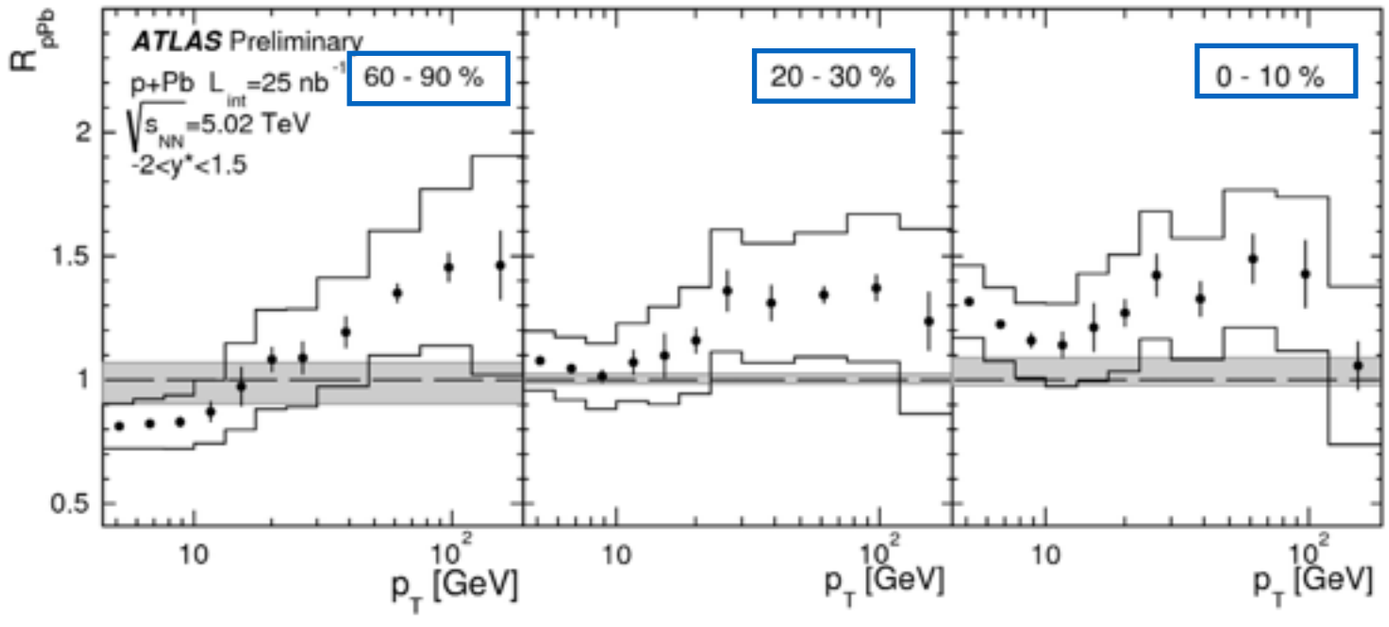
R_{pPb} vs. η and centrality

Enhancement is insensitive to **rapidity**





Enhancement is insensitive to **centrality**



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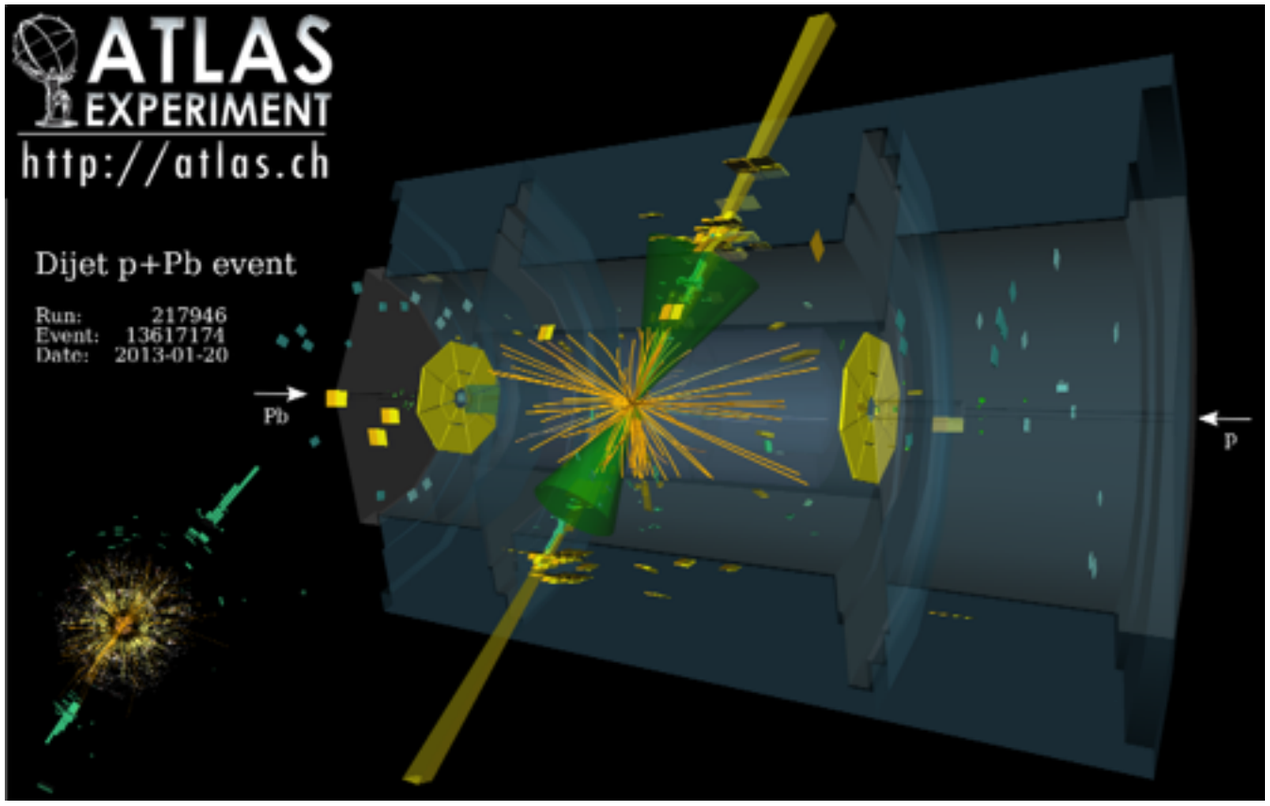
Jets in *p*+Pb

Jet spectra



- anti-k_t, R=0.4 calorimeter jets
  - UE estimation & subtraction
  - designed for Pb+Pb, cross-checked in *pp*
- Selected by level-1 + high-level jet triggers
- Monte Carlo: 36m PYTHIA *pp* hard scatter events overlaid onto real *p*+Pb data
  - unfolding corrections for the finite jet energy resolution are modest (10-30%)
    - and mostly cancel in the R_{CP} and R_{pPb}

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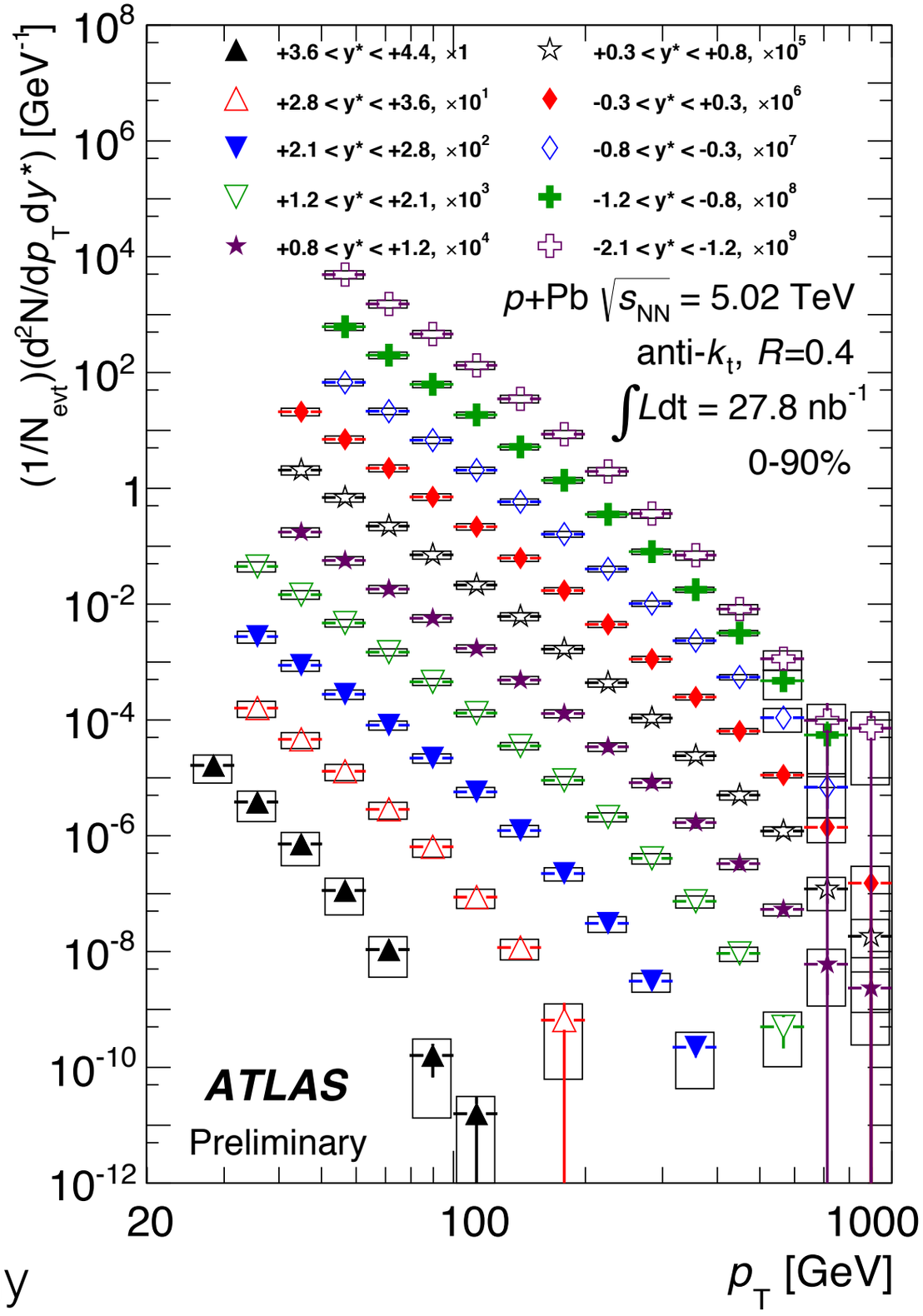

0-90% yields

Jet R_{pPb}

jet yield in p+Pb

$$R_{\mathrm{pPb}} = \frac{(1/N_{\mathrm{evt}})\, \mathrm{d}^2N/\mathrm{d}p_{\mathrm{T}}\mathrm{d}y^*}{\langle T_{\mathrm{pA}} \rangle\, \mathrm{d}^2\sigma/\mathrm{d}p_{\mathrm{T}}\mathrm{d}y^*}$$

Pb nucleon flux seen by proton

2013 pp data @ 2.76 TeV (x_{T}-scaled to 5.02 TeV)

- R_{pPb} for 0-90% events
  - ≈5 units of rapidity, 40-1000 GeV
- 5-10% enhancement
  - weak p_{T} dependence?
  - consistent with **EPS09** prediction (provided by N. Armesto)

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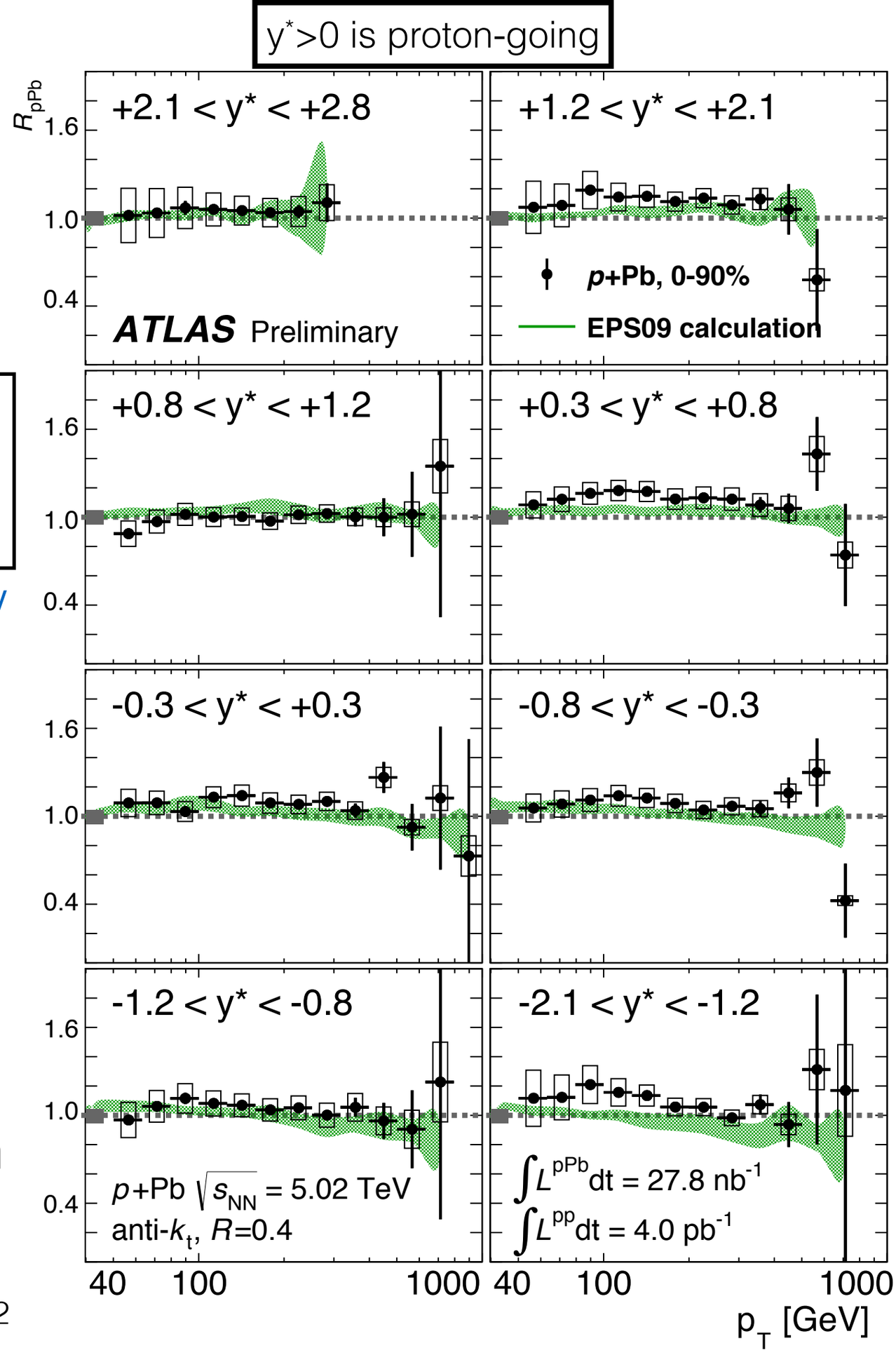

Jets vs. particles?

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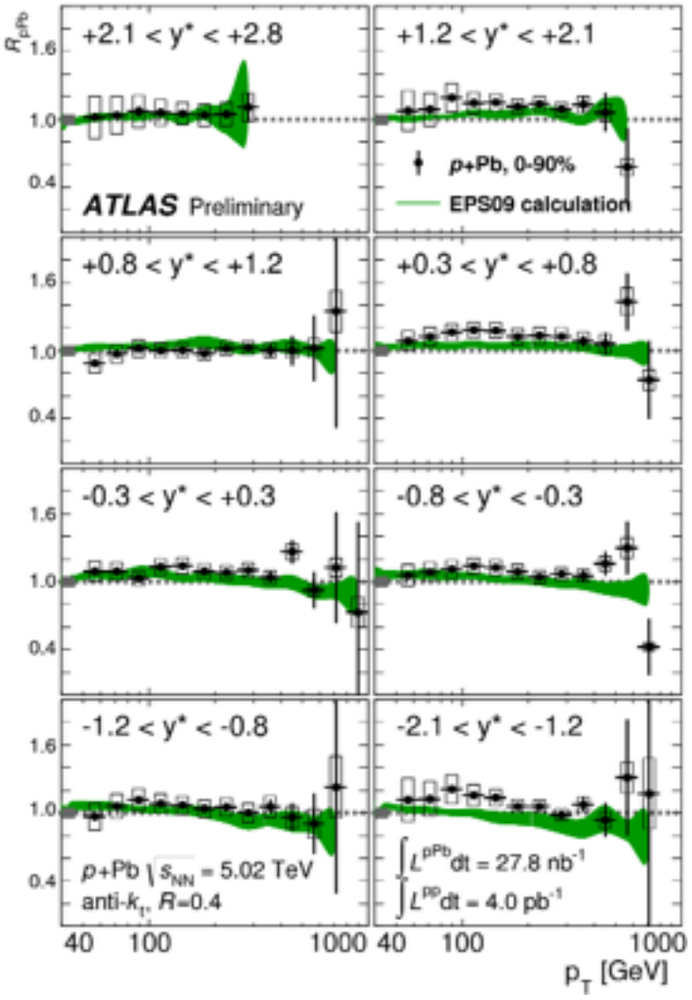
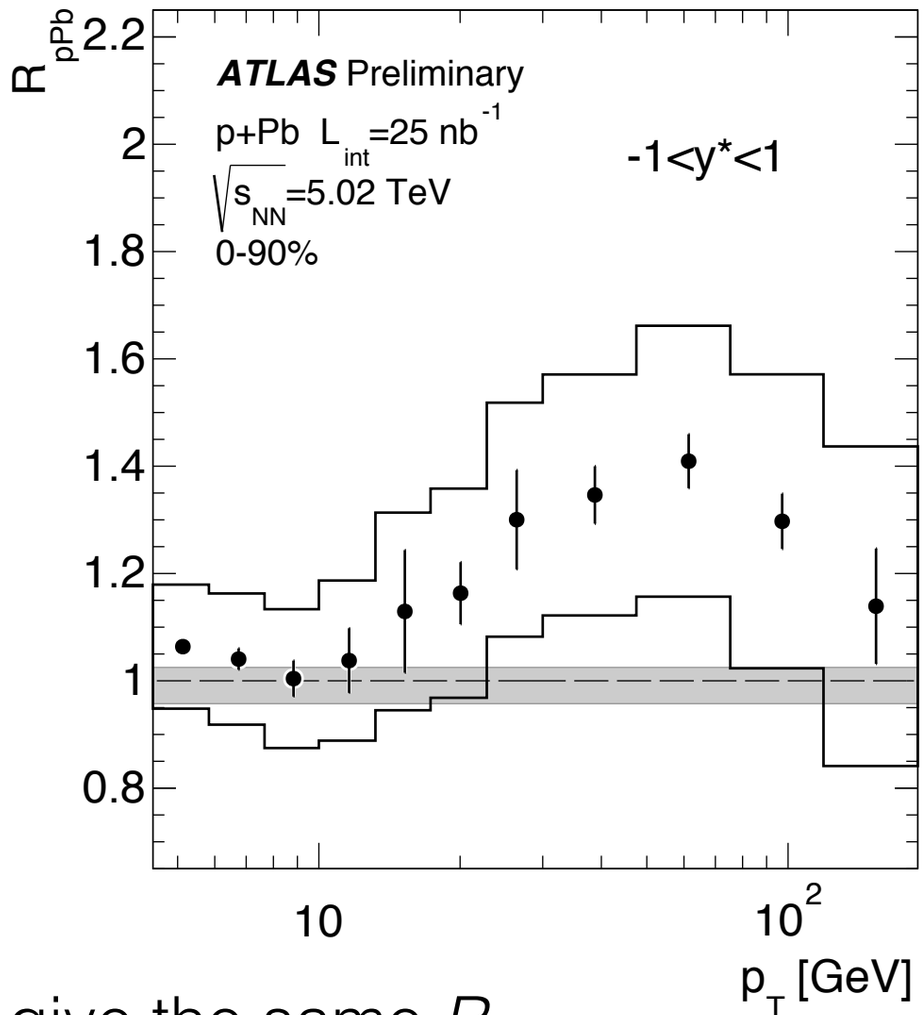


vs.



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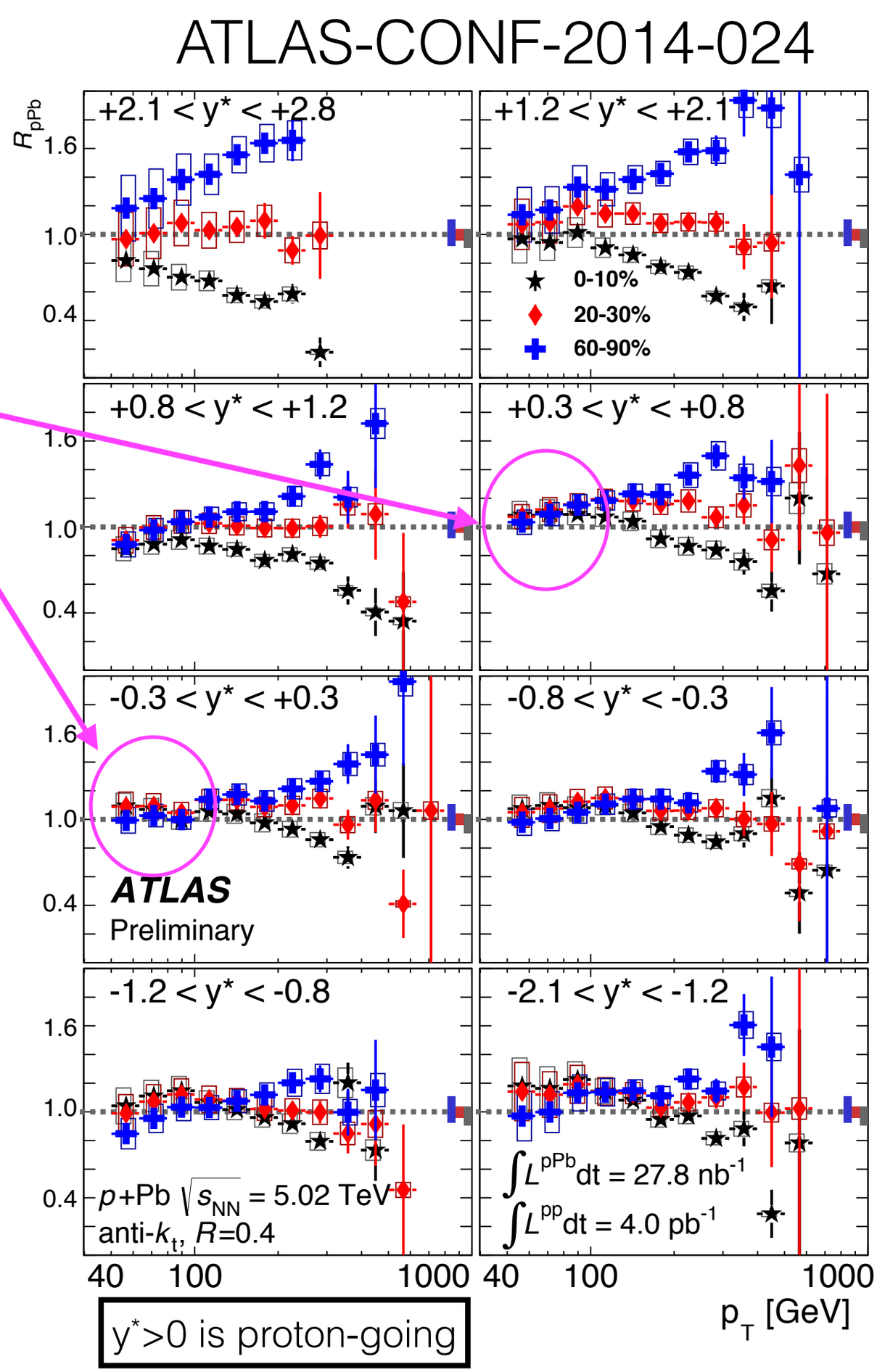
- Naively, one may expect that these should give the same R_{pPb}
  - but jets and hadrons are different QCD objects
  - we observe the expected number of *jets* but a change in the number of *fragments*
- <u>How can we understand these results together?</u>
  - measurement of the fragmentation function? (inclusive, γ-jet)
  - hard probes which access a different combination of initial state quarks and gluons?

Jet R_{pPb} vs. centrality

- Centrality-selected R_{pPb}
  - at intermediate p_{T}, jets show geometric scaling



Jet R_{pPb} vs. centrality

- Centrality-selected R_{pPb}
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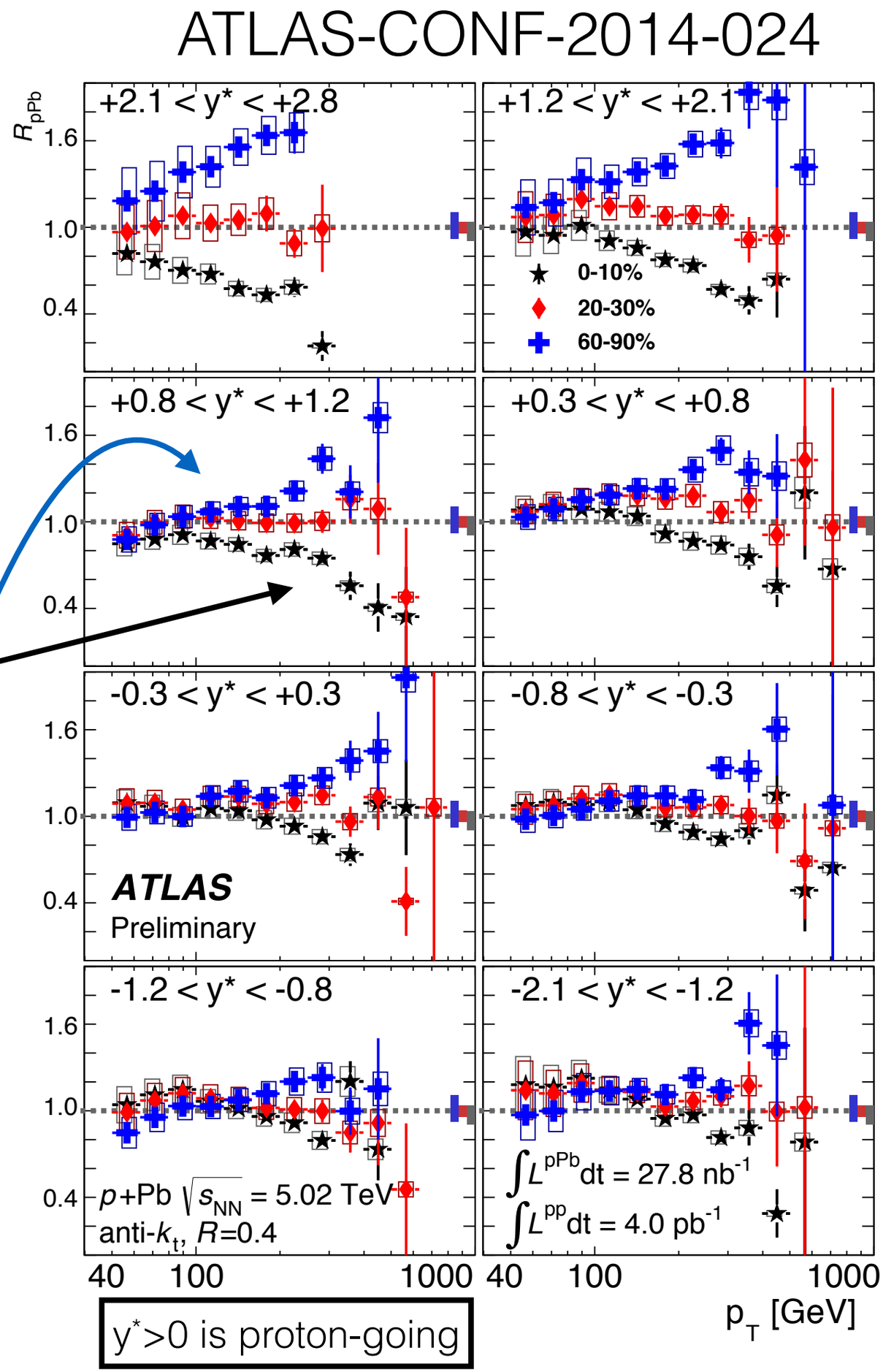
- At high p_{T}, strong deviations from geometric expectation
  - suppression in **central** events
  - enhancement(?) in **peripheral** events



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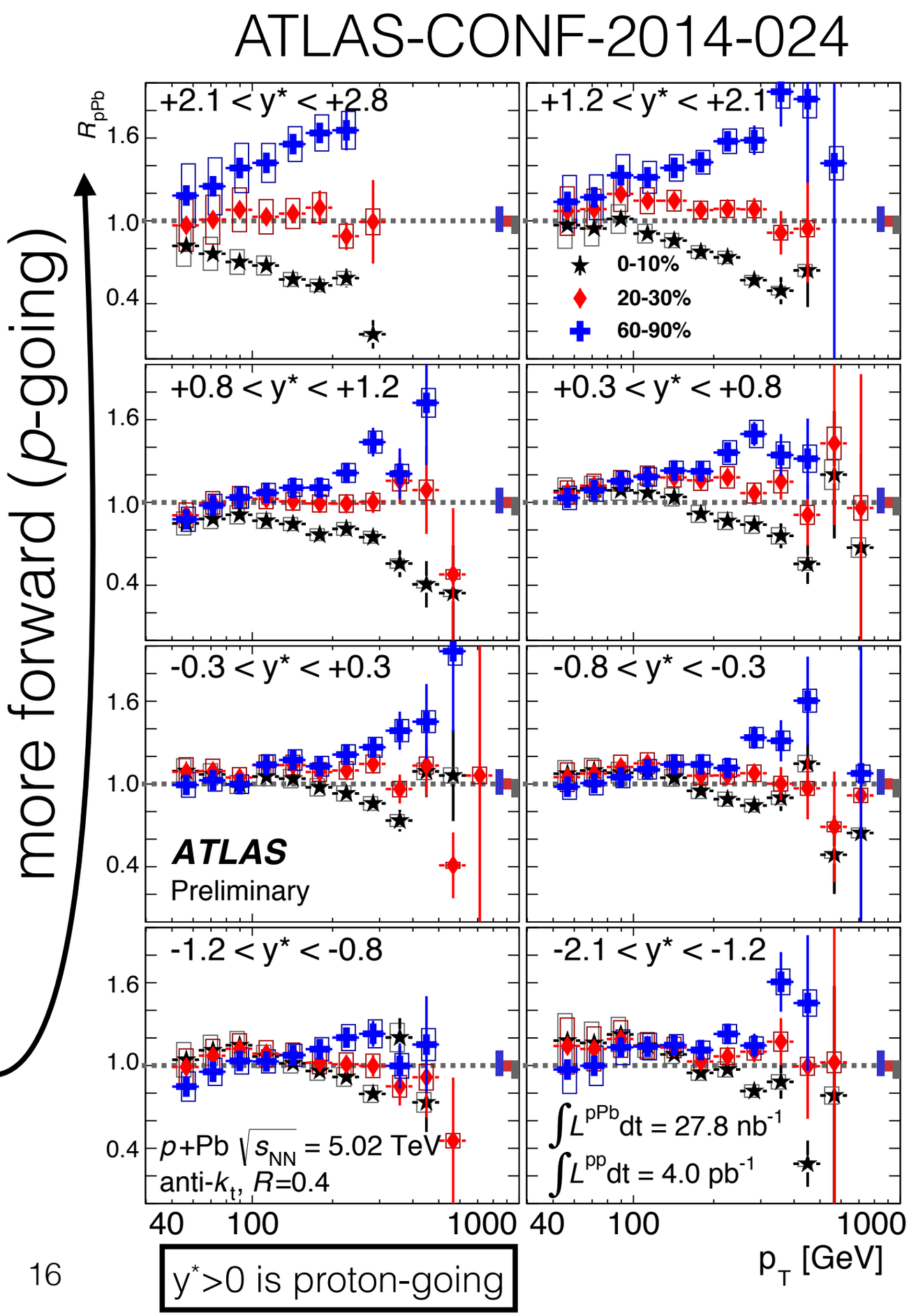
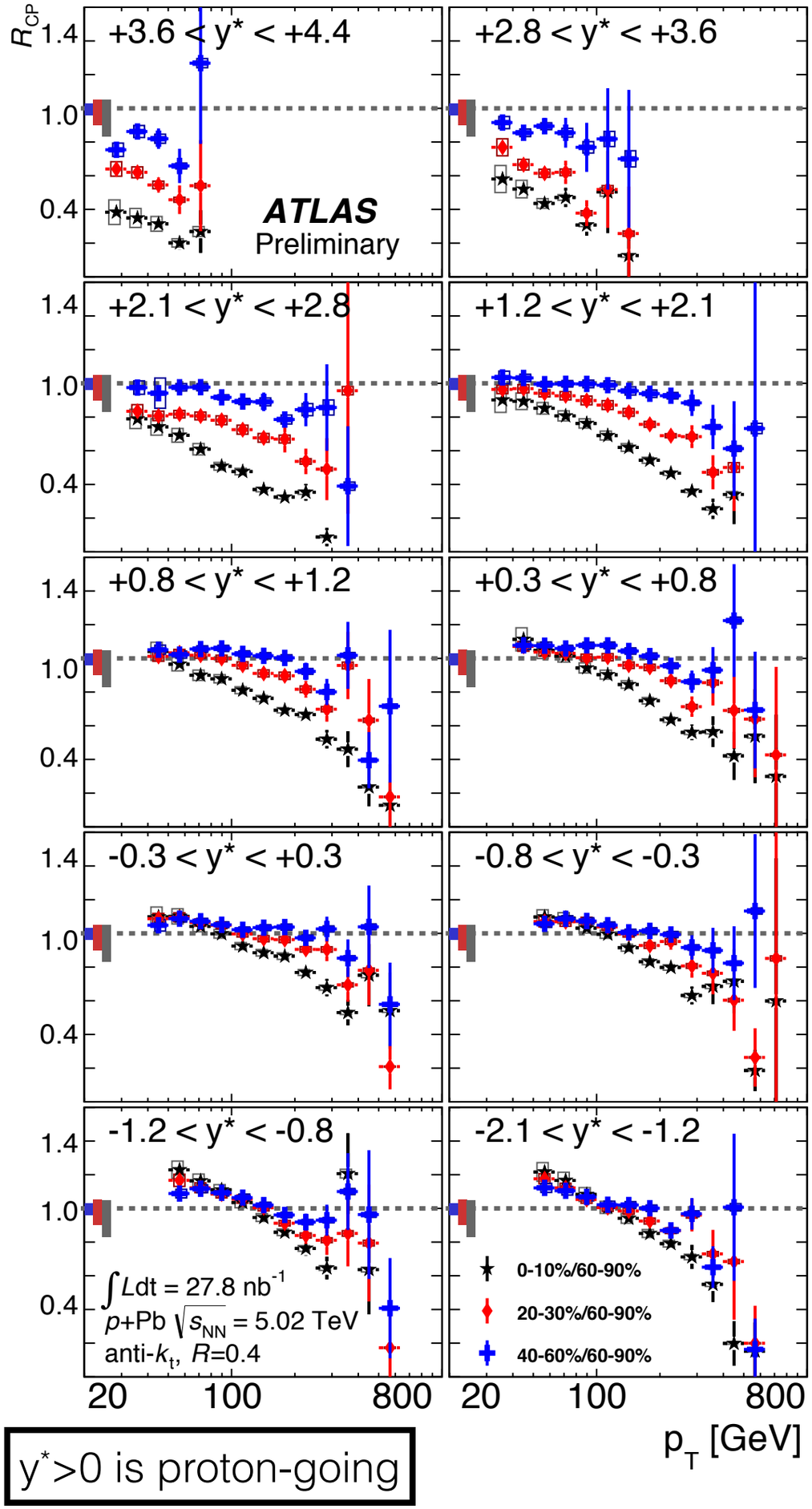
  - at intermediate p_{T}, jets show geometric scaling
- At high p_{T}, strong deviations from geometric expectation
  - suppression in **central** events
  - enhancement(?) in **peripheral** events
- Modifications are <u>stronger</u> and begin at <u>lower p_{T}</u> at more <u>forward</u> rapidities

Large, *b*-dependent changes in the nPDFs?
e.g. initial state <u>nuclear</u> effect?



Jet R_{CP}



y*>0 is proton-going

N_{coll} ratio

$$R_{CP} = R_{coll} \frac{(1/N_{evt})\, d^2N/dp_T dy^*}{(1/N_{evt})\, d^2N/dp_T dy^*}$$

central yield

peripheral yield

- R_{CP} allows a look at trends in the data from a different perspective
  - smaller systematics from the removal of the *pp* reference
- Smooth evolution in p_T, centrality, rapidity
  - how can we understand the rapidity dependence?

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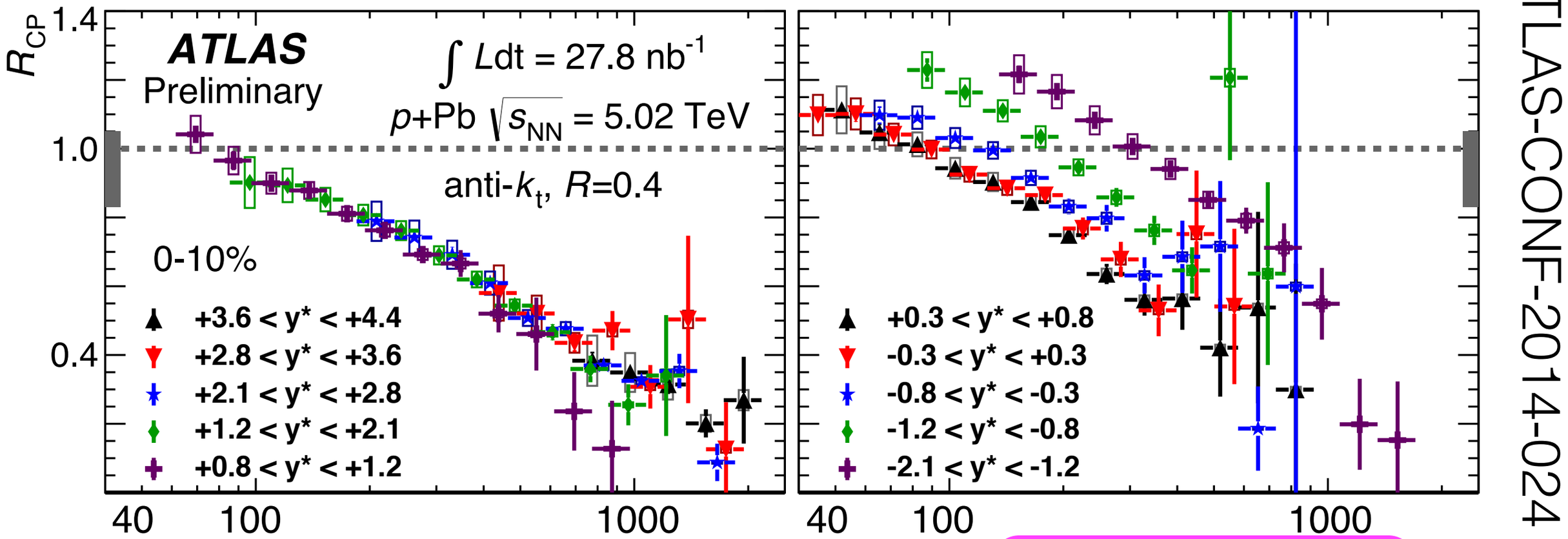
Scaling in the R_{CP} vs. p

- Replot the R_{CP} at all rapidities vs. $p = p_T \cosh(y^*)$
  - — e.g. **the total jet energy**

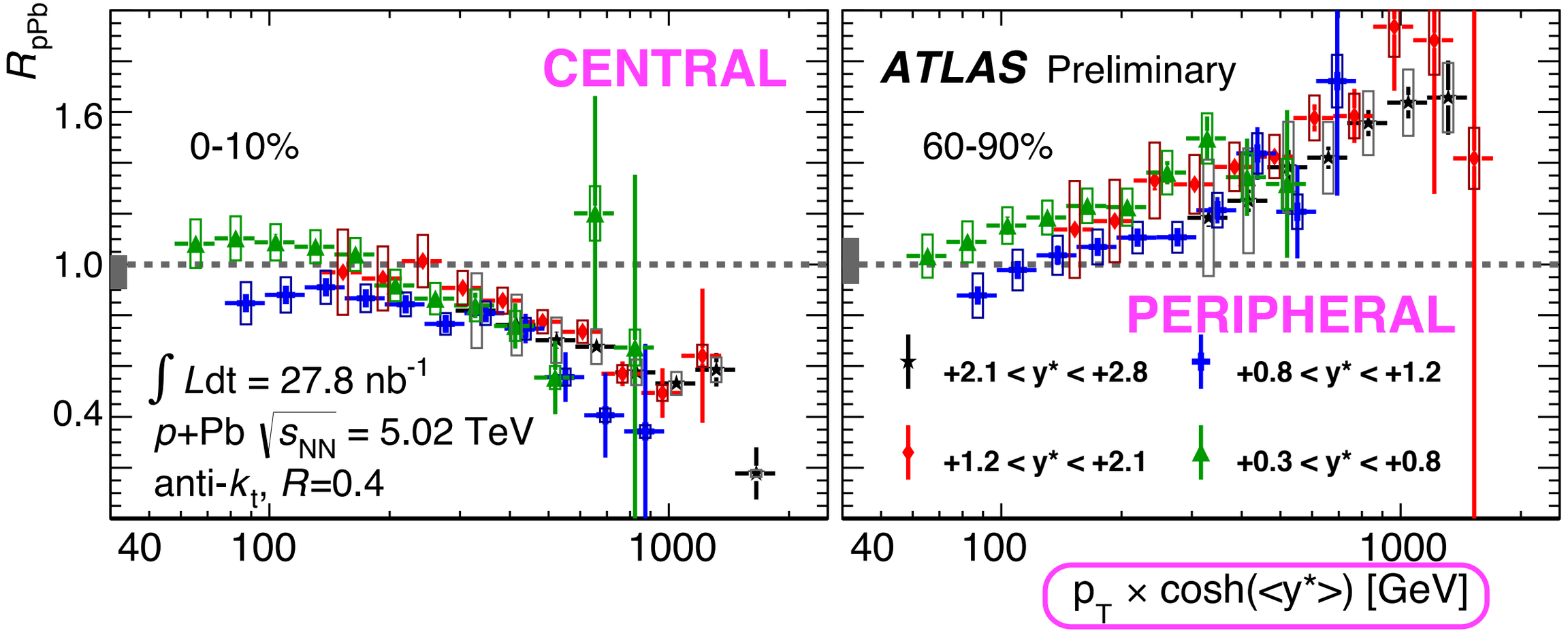


y* > 0 data
follow a single trend!
$R_{CP}(p_T, y^*) = R_{CP}(p)$

y* < 0 data do not…

What is this telling us about the suppression mechanism?

Scaling in the R_{pPb} vs. p



- At high p, central and peripheral R_{pPb} scale with p separately!
  - albeit with larger systematics from the introduction of the pp reference
- Events with a forward jet with energy p typically have $x_p = p / (\sqrt{s}/2)$
  - this implies the phenomenon is an initial state *proton* effect, and one that depends on parton kinematics
    - we are learning something about the proton wavefunction!

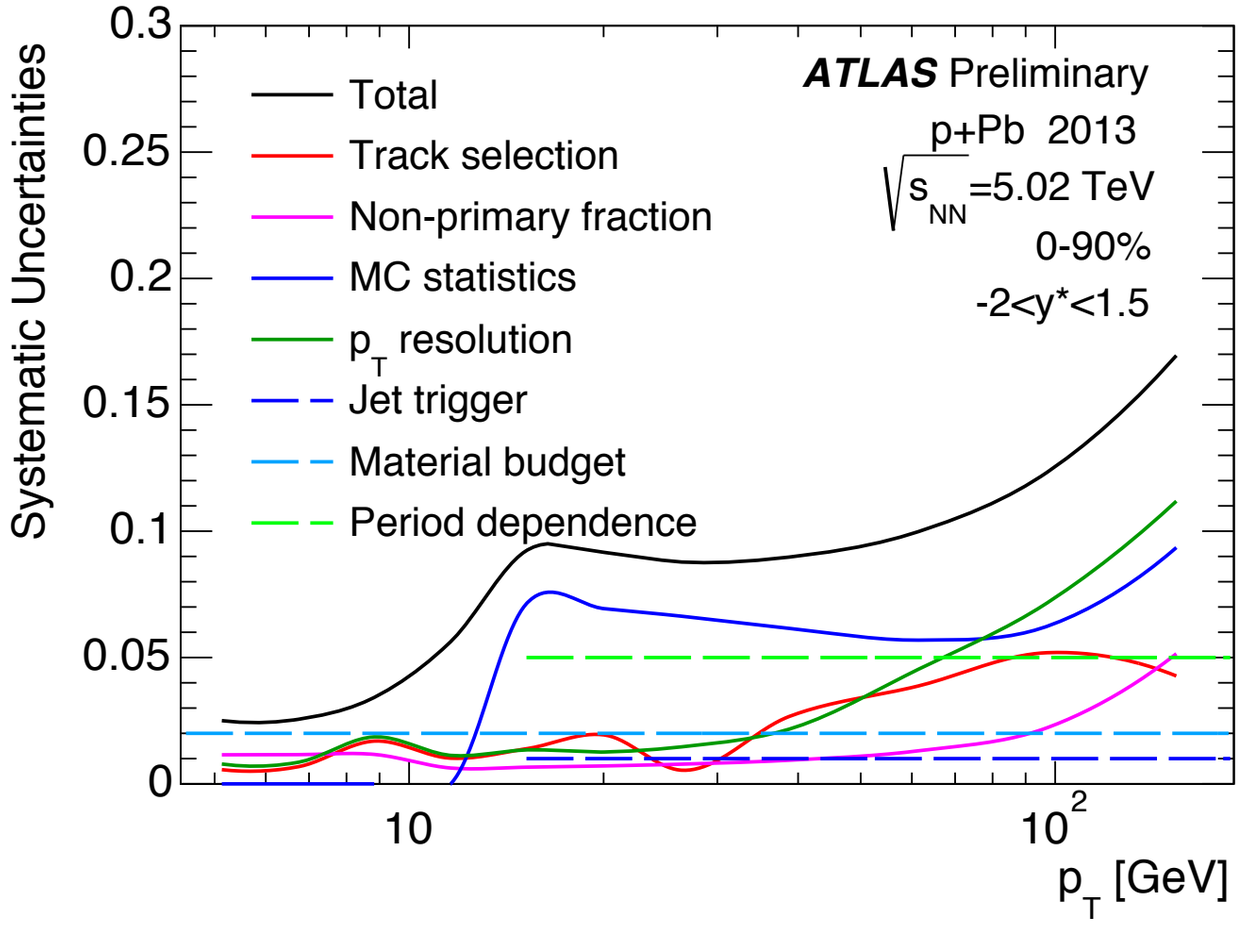
Conclusion

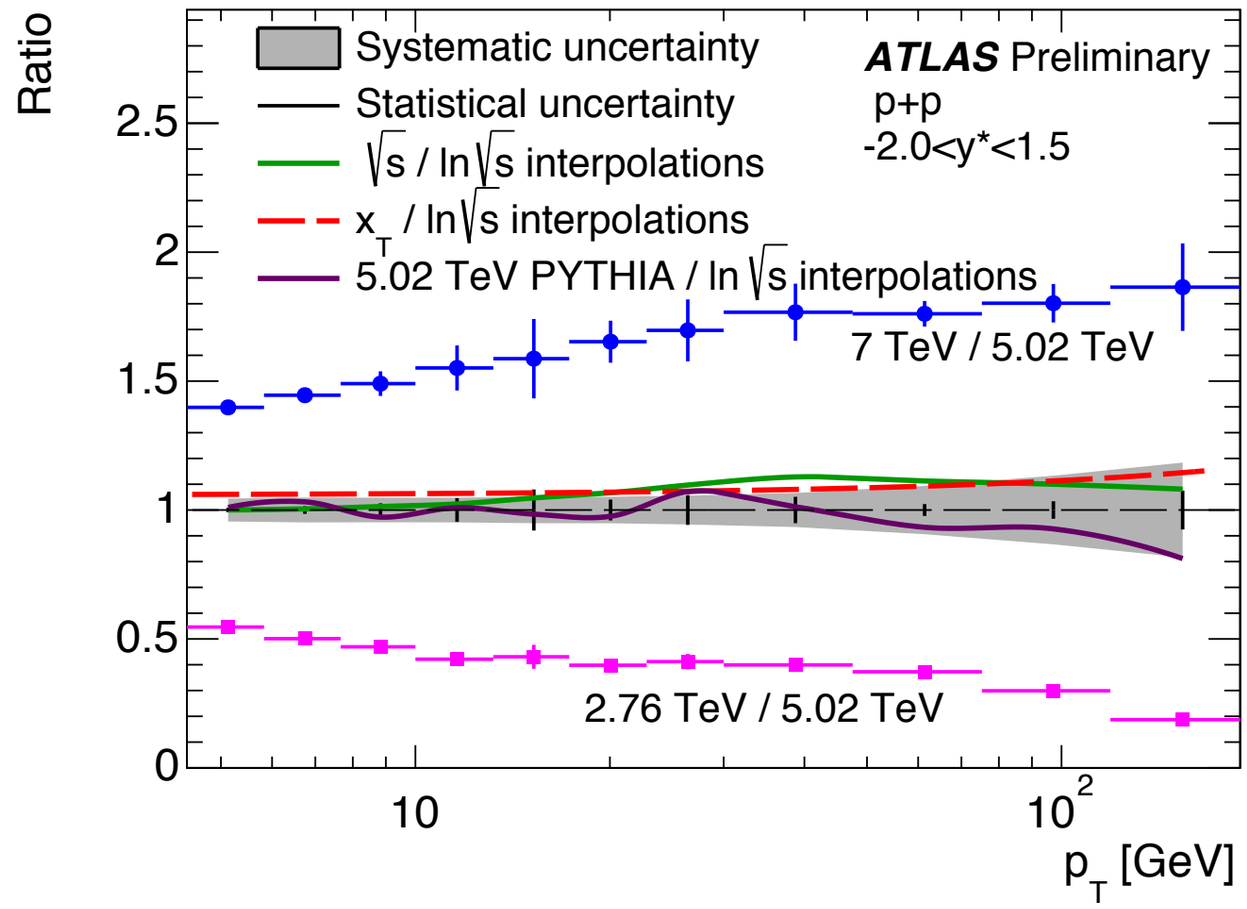
- ATLAS has measured inclusive jets and charged particles in *p*+Pb collisions
  - ➡ for particles, R_{pPb} up to 200 GeV, -2 < y* < +1.5
  - ➡ for jets, R_{pPb} for > 50 GeV, -2.1 < y* < +2.8 (larger y*, p_T range for R_{CP})
- Enhancement in the rate of charged particles with p_T > 20 GeV in minimum bias *p*+Pb collisions
  - ➡ the jet rate is mildly enhanced, in a way consistent with nPDF expectations
  - ➡ current challenge to experiment (and theory) is to understand how these data can be consistent
- Large, centrality dependent modifications in the jet R_{CP} & R_{pPb} at high-p_T & at forward rapidities
  - ➡ suppression/enhancement pattern in central/peripheral jet rate
  - ➡ indication of an initial state effect in the *proton* which depend on the underlying parton kinematics
  - ➡ challenging for factorization pictures of hard processes & soft particle production in *p*(*d*)+A collisions

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

Backup

Backup: systematic uncertainties in the charged particle R_{pPb}





- Systematic uncertainty breakdown for the *p*+Pb charged particle yields
- Dependence of the 5.02 TeV *pp* reference on choice of interpolation scheme
  - and systematic uncertainty envelope

Backup: 5.02 TeV *pp* jet reference

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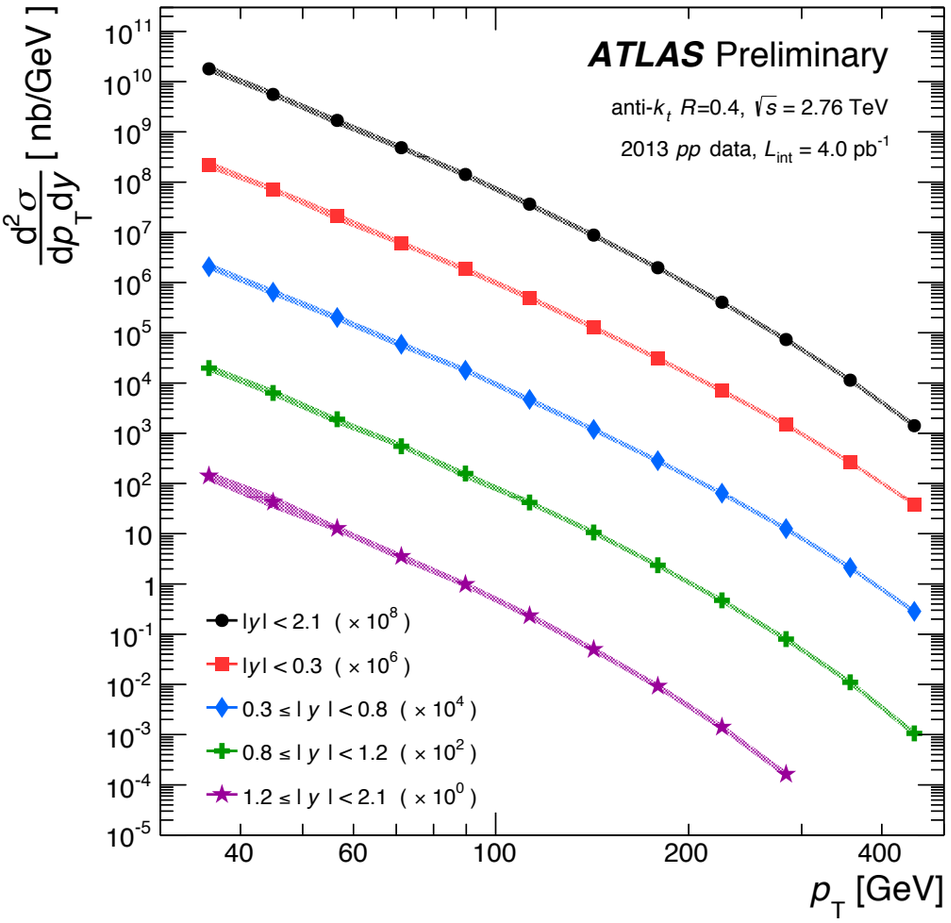
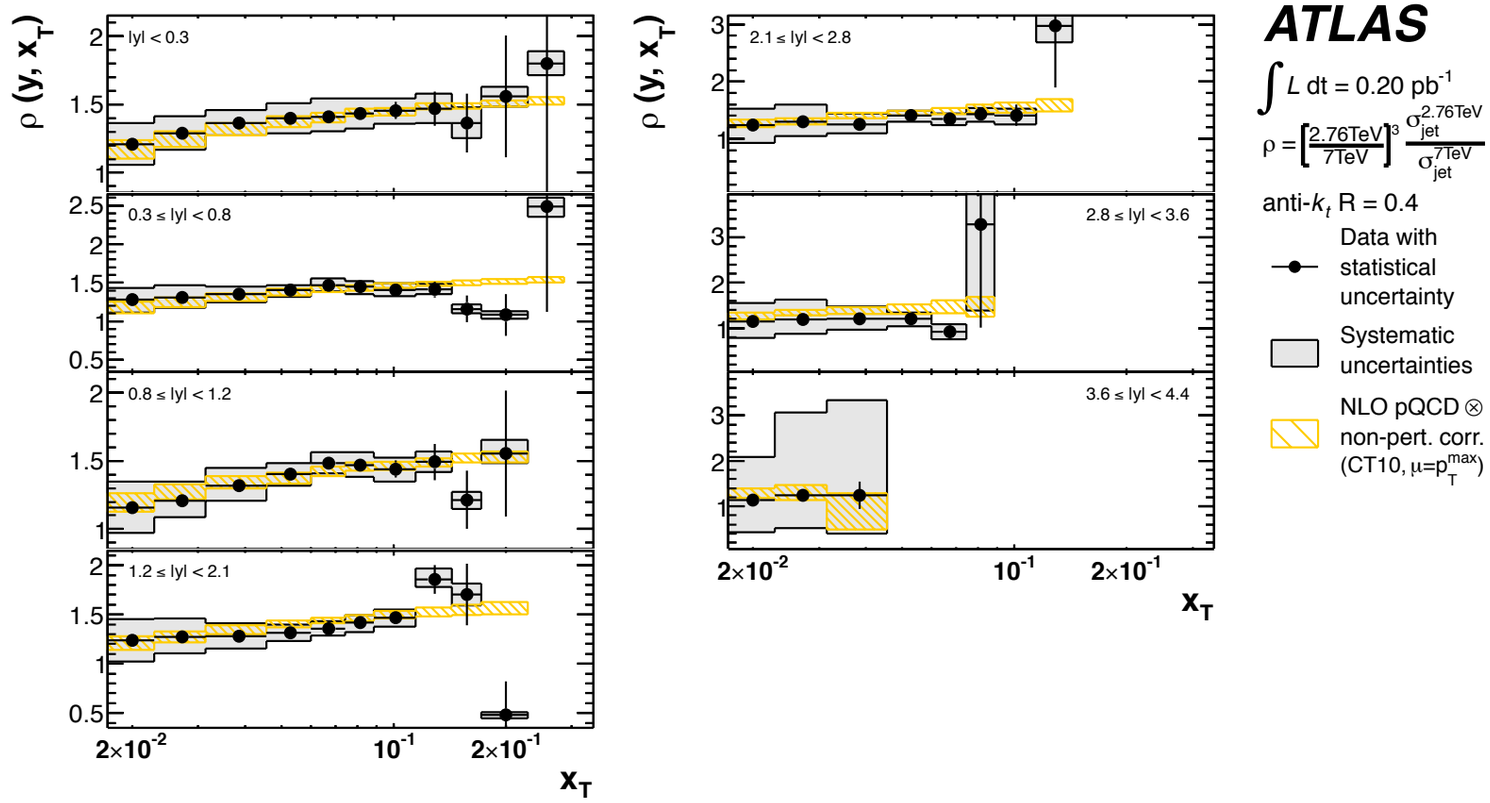
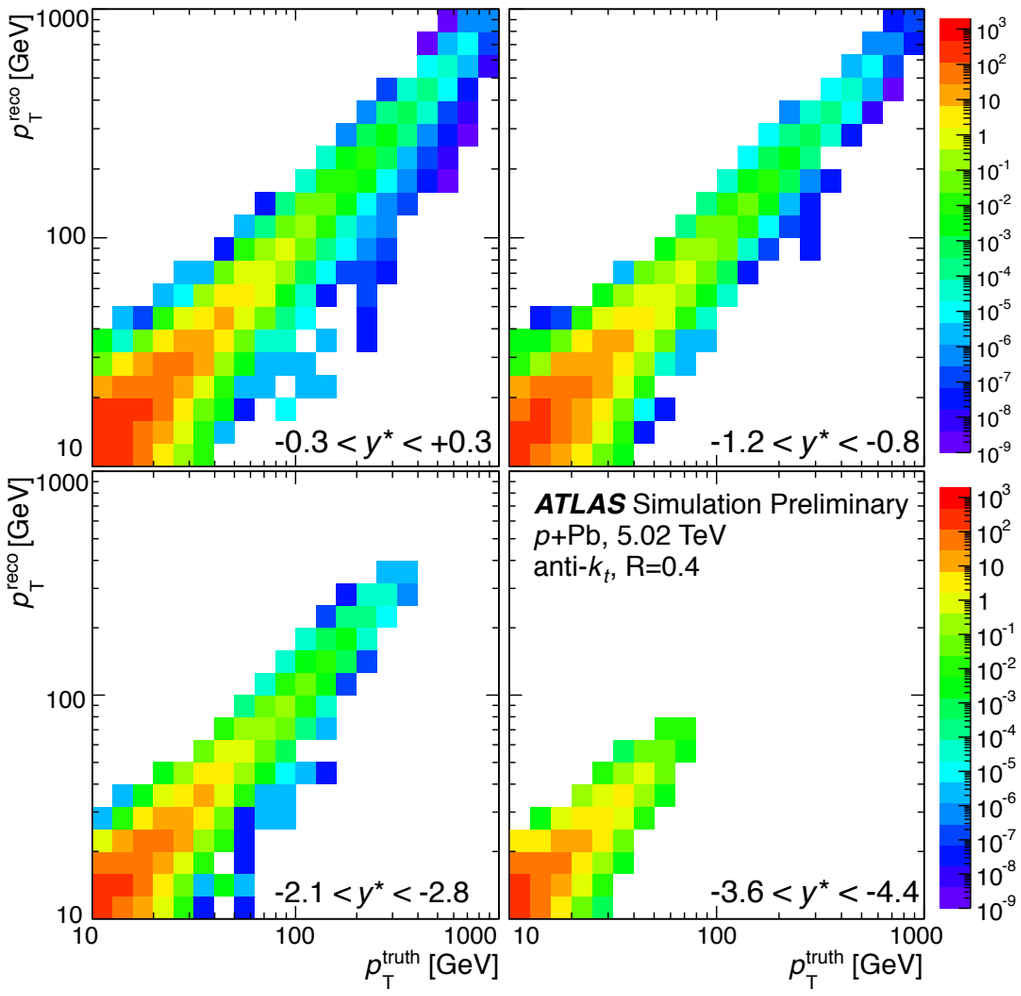


ATLAS, hep-ph/1304.4739



- *pp* jet cross-section, high-statistics February 2013 running
  - same reconstruction procedure & corrections as in *p*+Pb data
  - consistent with 2.76 TeV *pp* jet cross-section from 2011 running & NLO calculations
- ATLAS measurement of x_T scaling between 2.76 and 7 TeV
  - full treatment of correlations in systematic uncertainties
  - we interpolate to 5.02 TeV between two ATLAS data measurements

Backup: jet performance



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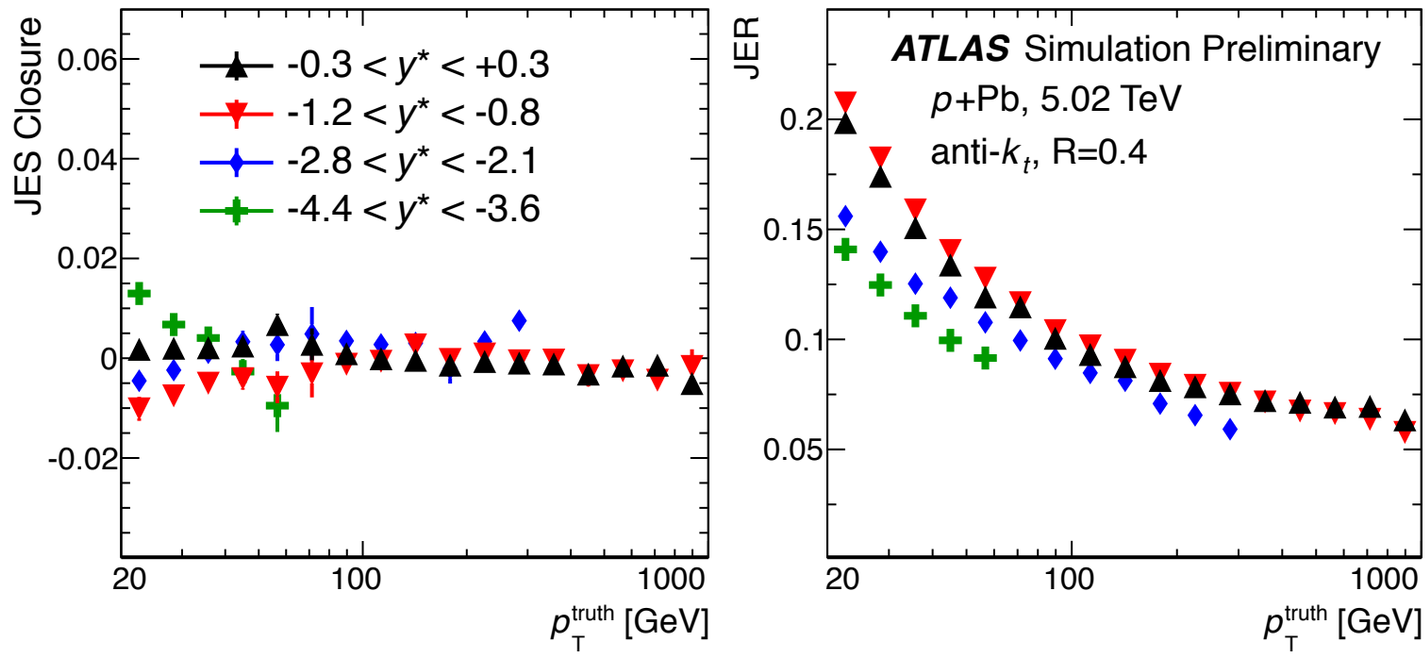
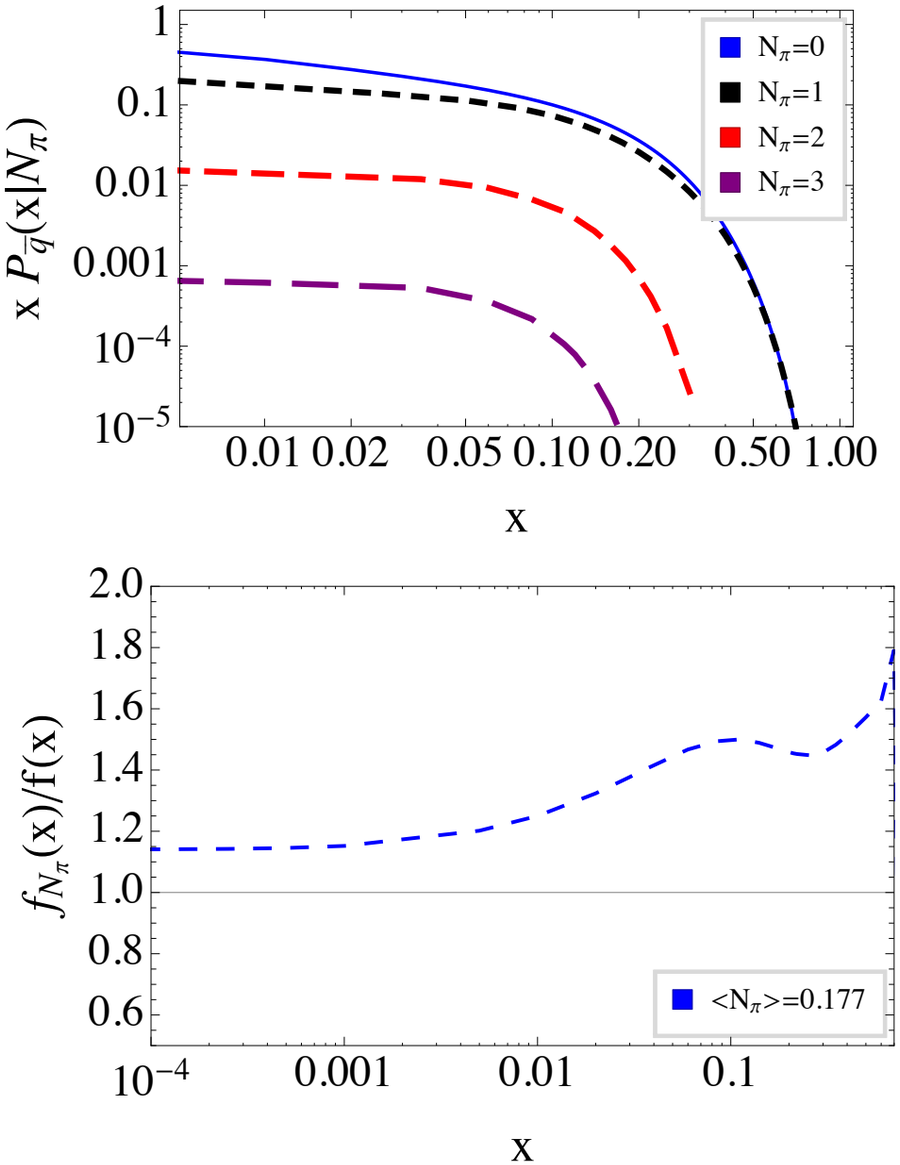


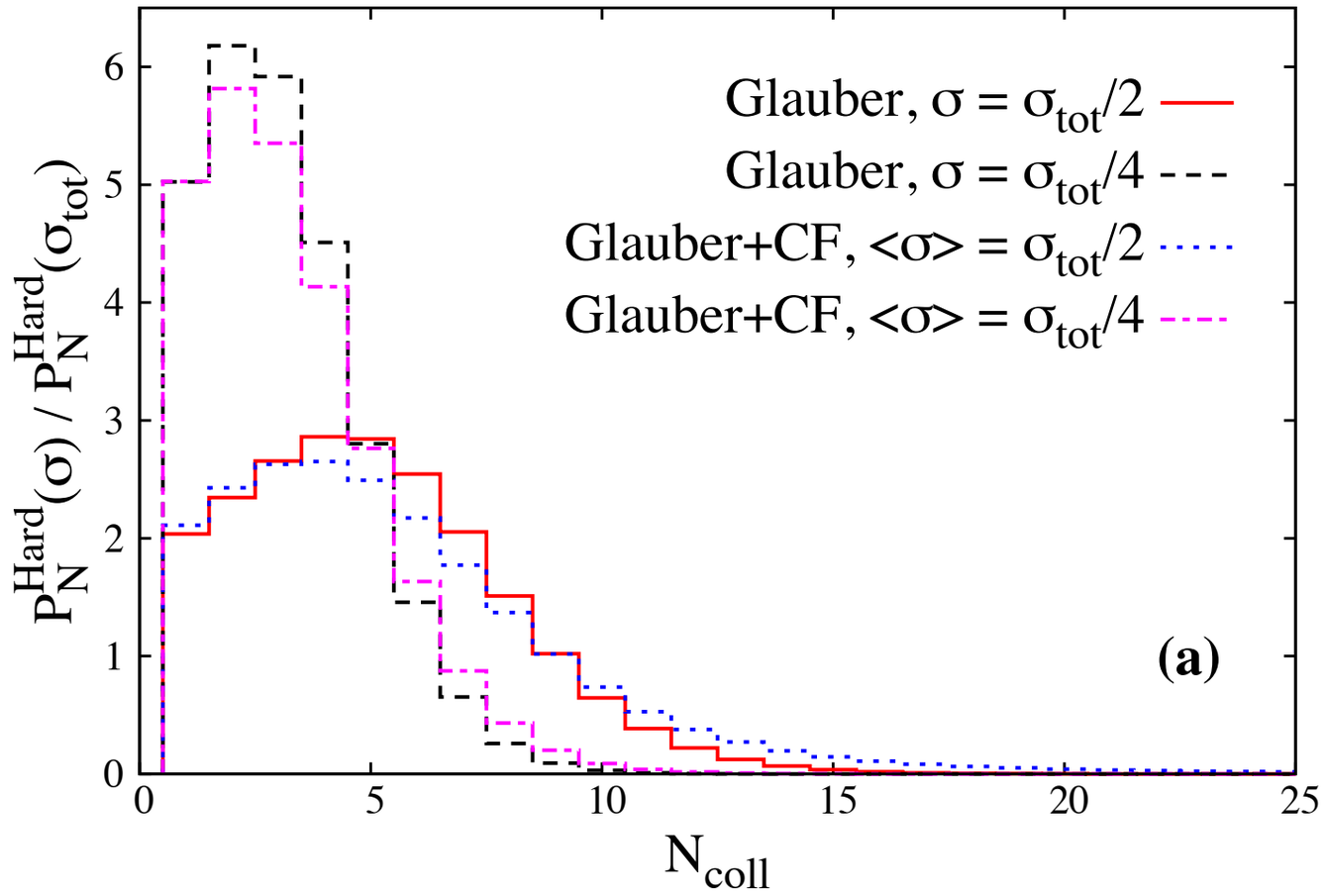
- Jet Energy Scale Closure (<p_T^{reco}/p_T^{truth} - 1>) always better than 2%
  - typically 1%, with small centrality-dependent differences at low p_T
- Jet Energy Resolution σ(p_T^{reco}/p_T^{truth} - 1), 7-20%, p_T and y^* dependent
- Bin-by-bin correction factors typically 10-30%, but largely cancel in the R_{CP} and R_{pPb} ratios anyway

Backup: x_p dependence?

Idea: (anti-)correlation between proton wave function with large transverse extent and high *x*?

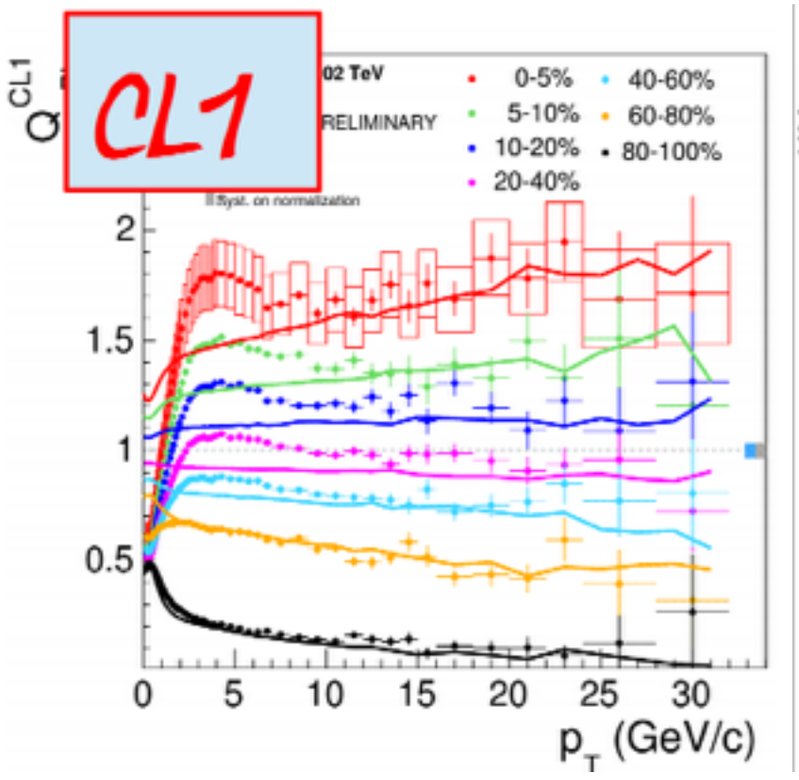


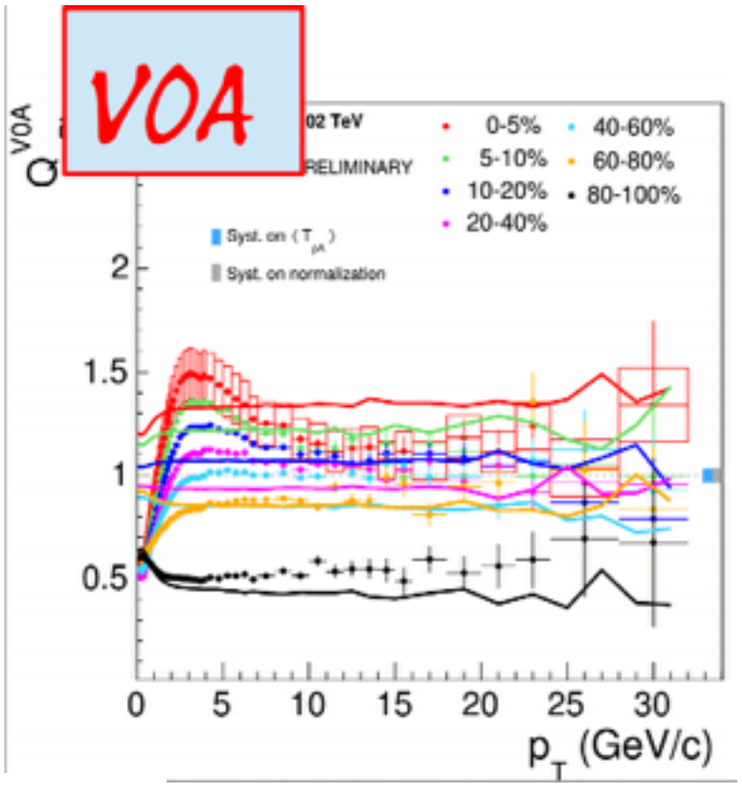
Coleman-Smith, Mueller
hep-ph/1307.5911



Alvioli, Frankfurt, Guzey, Strikman
hep-ph/1402.2868

Backup: studies of centrality "bias"

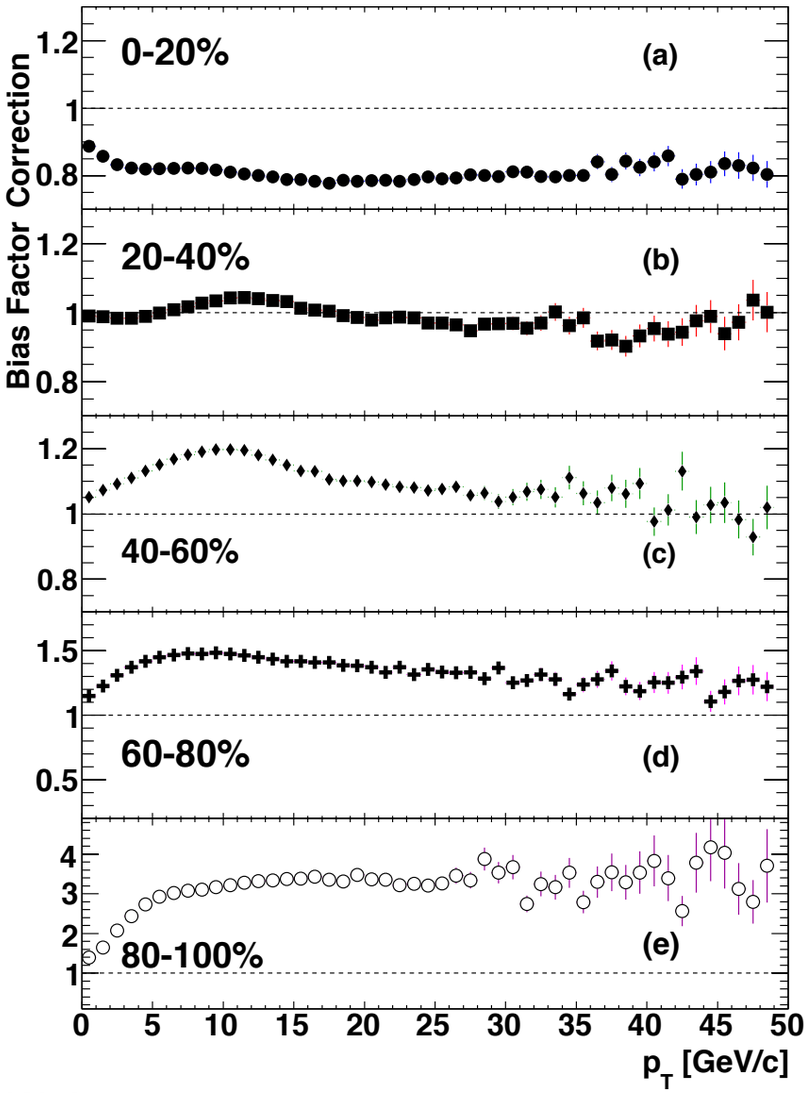




- Q_{pPb} spread between centrality

Reduces with increasing rapidity gap: CL1→V0M→V0A

A. Toia, QM14 talk



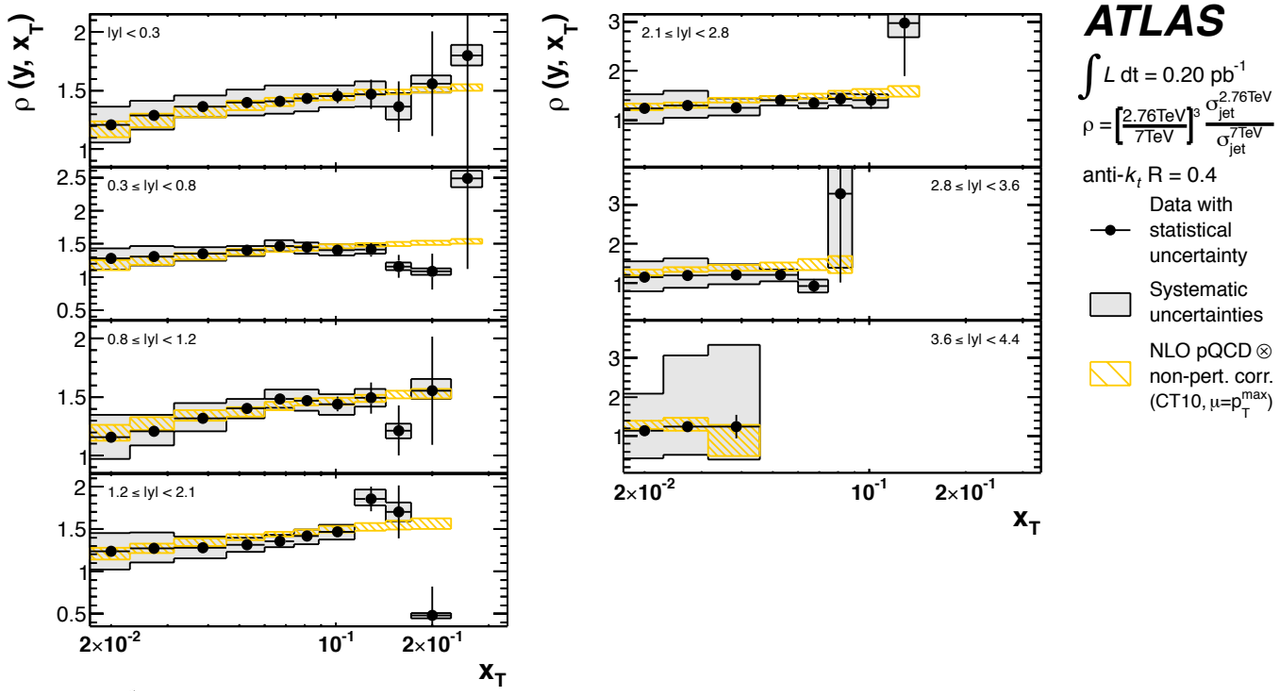
PHENIX, nucl-ex/1310.4793

- Detailed studies of this effect by ALICE and PHENIX
  1. All result in an *increased* (decreased) R_{pPb} in *central* (peripheral) events
  2. All show a weaker "bias" farther from the centrality-determining detector
     - ≈10-20% effect, depending on centrality cuts & centrality detector

➡ the high-p_T LHC data show the <u>opposite</u> effects!

Backup: dominant systematics on the jet R_{pPb} and R_{CP}

ATLAS, hep-ph/1304.4739



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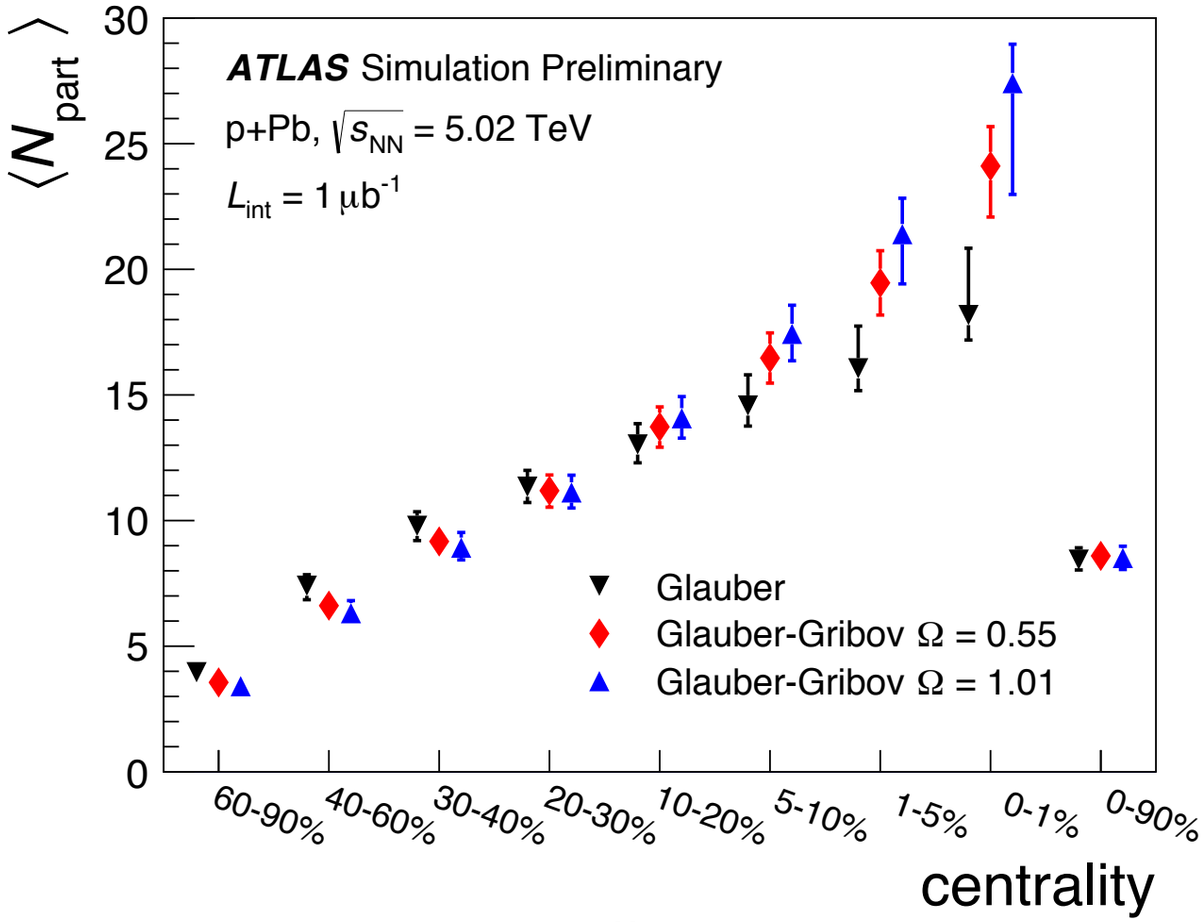
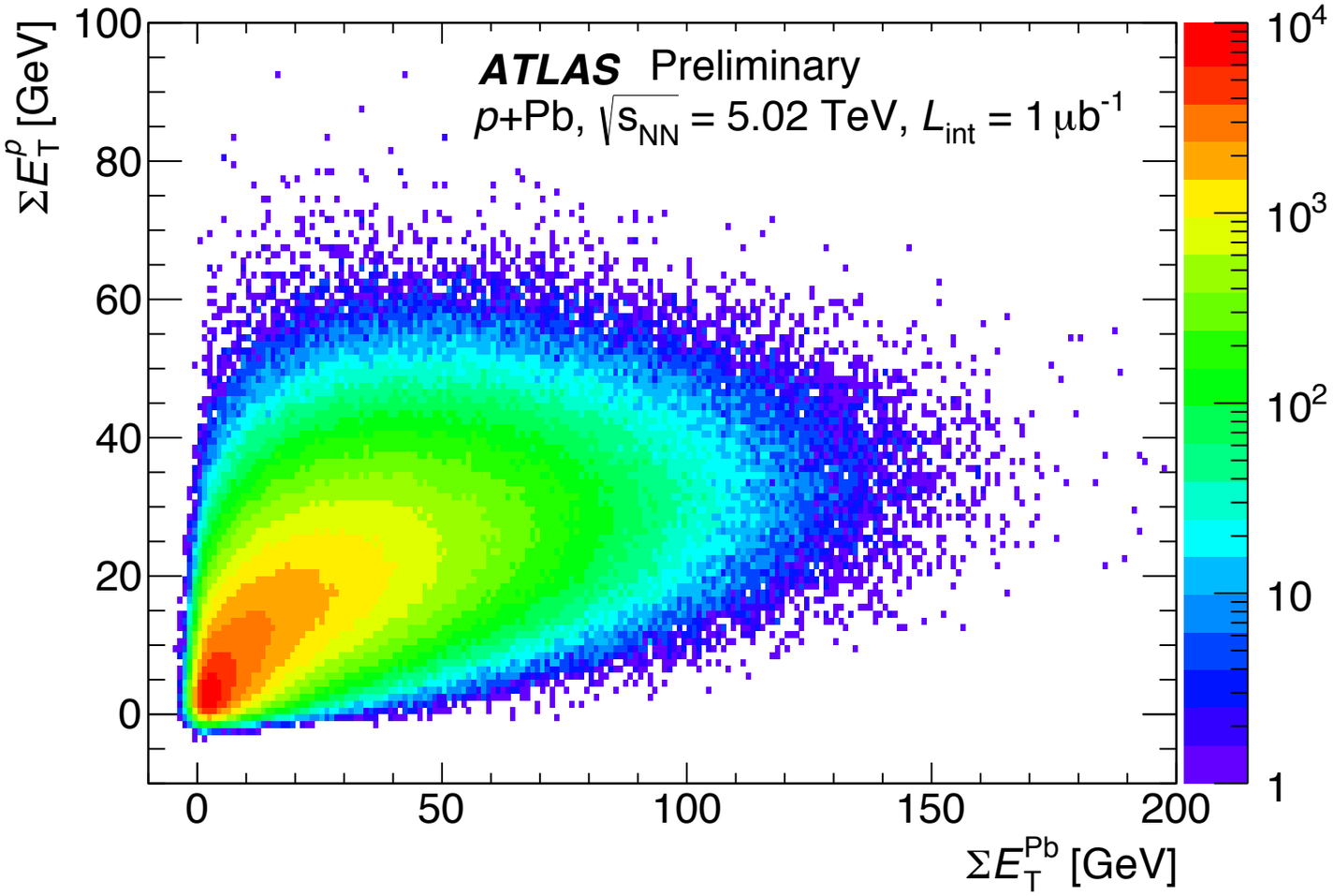
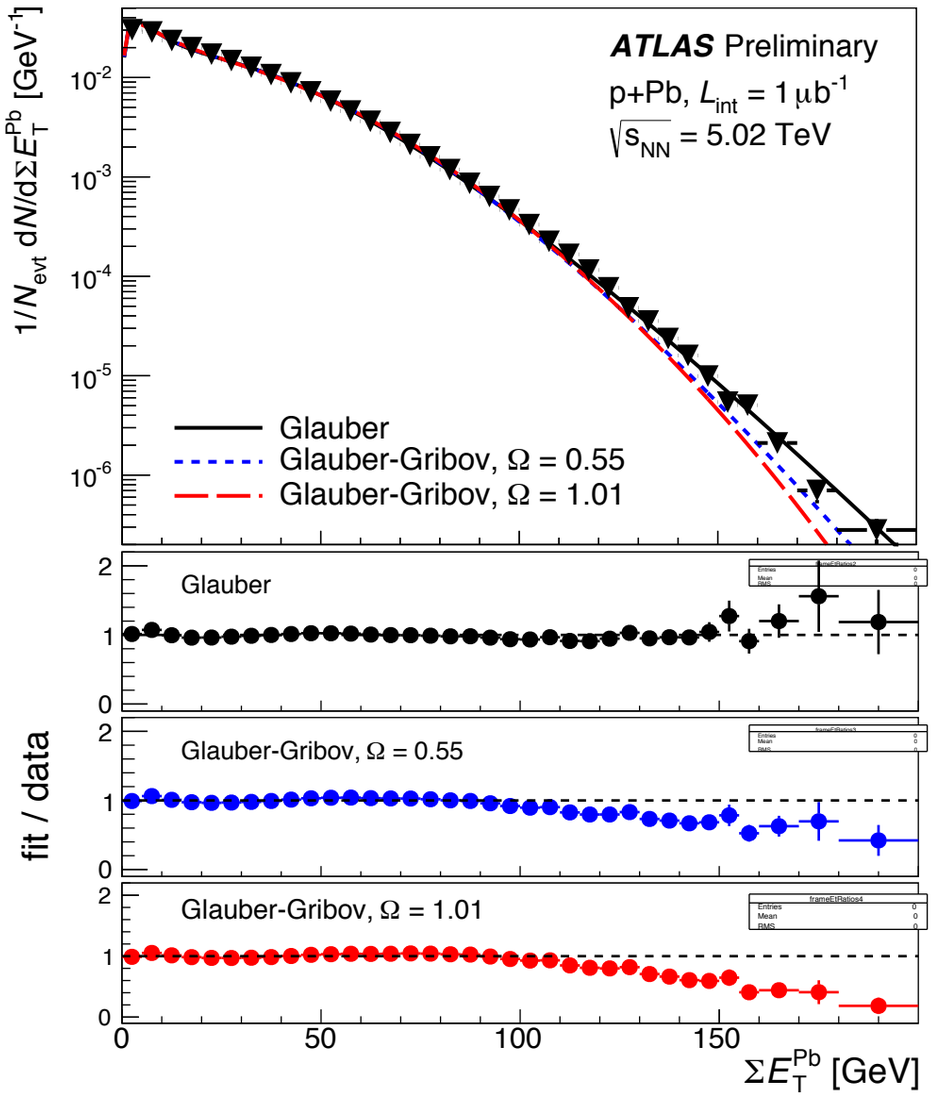


- Systematics on the ratios of *p*+Pb/*pp* spectra are small
  - same detector, same running period, same analysis procedure
- For R_{pPb}, dominant systematics are from the x_T interpolation (6-15%) and T_{pA}
- For R_{CP}, dominant systematics are actually from R_{coll}

Backup: centrality in *p*+Pb collisions

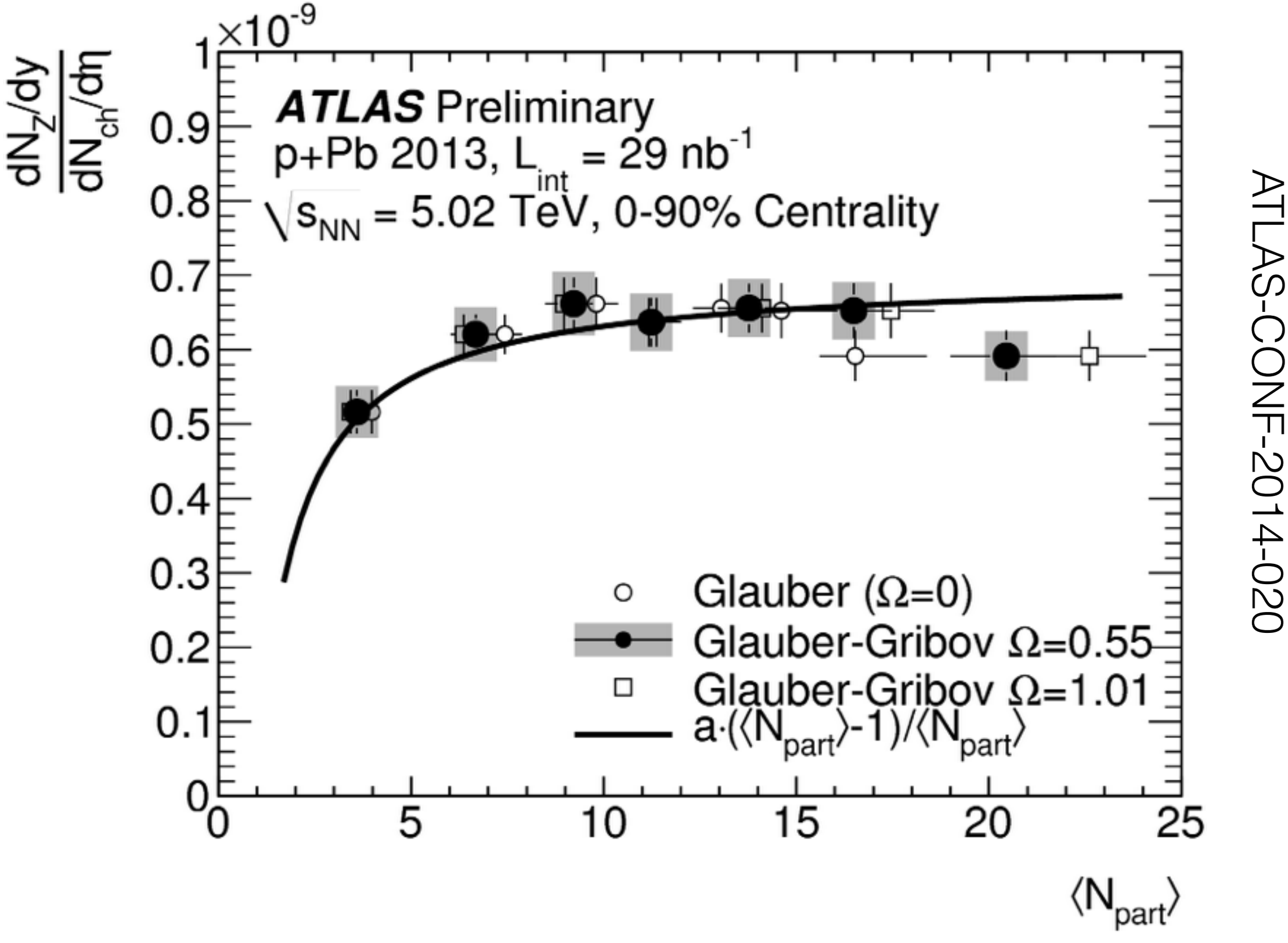
ATLAS-CONF-2013-096





- Centrality determined using ΣE_T in Pb-going FCal, $+3.2 < \eta < +4.9$
  - WN model of soft particle production, with modest modifications
  - default Glauber model gives reasonable fits to data
  - ATLAS has also explored Glauber-Gribov variants (not relevant for this talk)

Backup: Z yields vs. dN/dη



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Backup: high-p_T charged hadrons at the LHC