Jet and high-p_T measurements in p+A collisions

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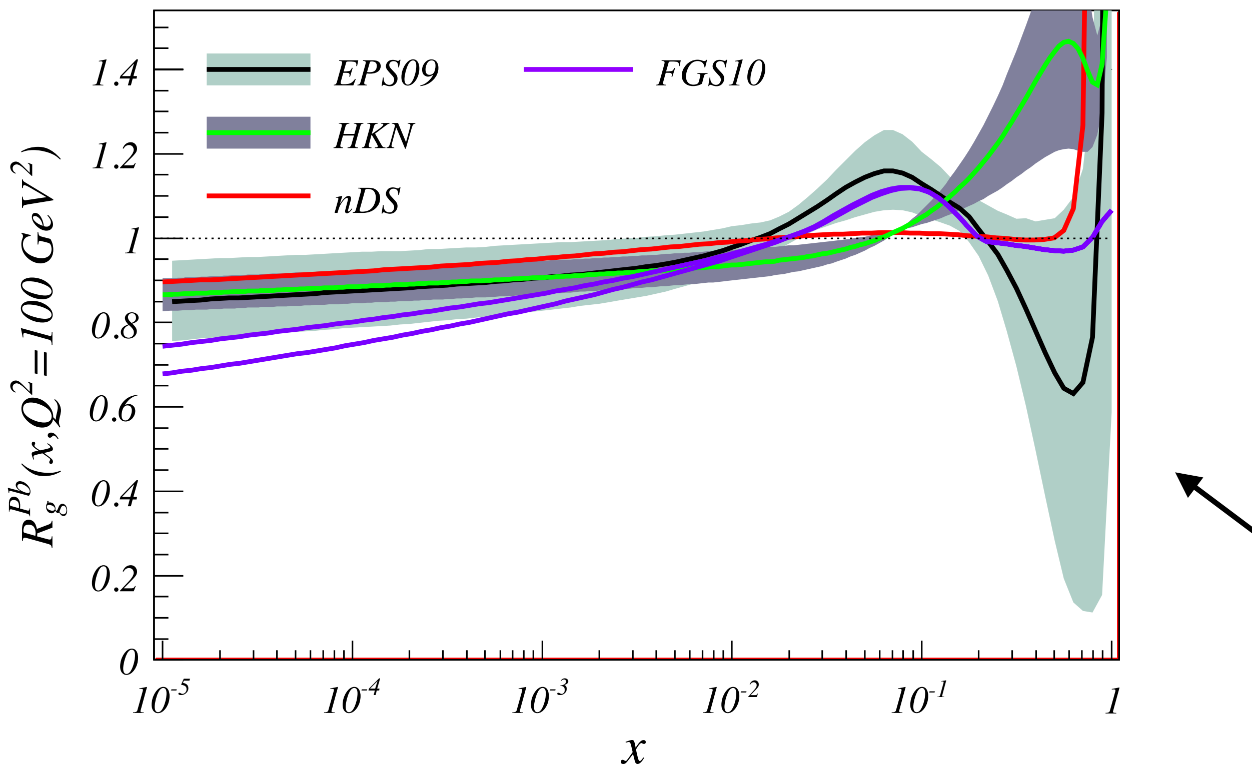
18 August 2014
3rd Workshop on Jet Modification in the RHIC and LHC Era
Wayne State University, Detroit, MI

What physics can p+A data explore?



Salgado et al., hep-ph/1105.3919
example of different nPDF sets

How are parton densities modified in nuclei?

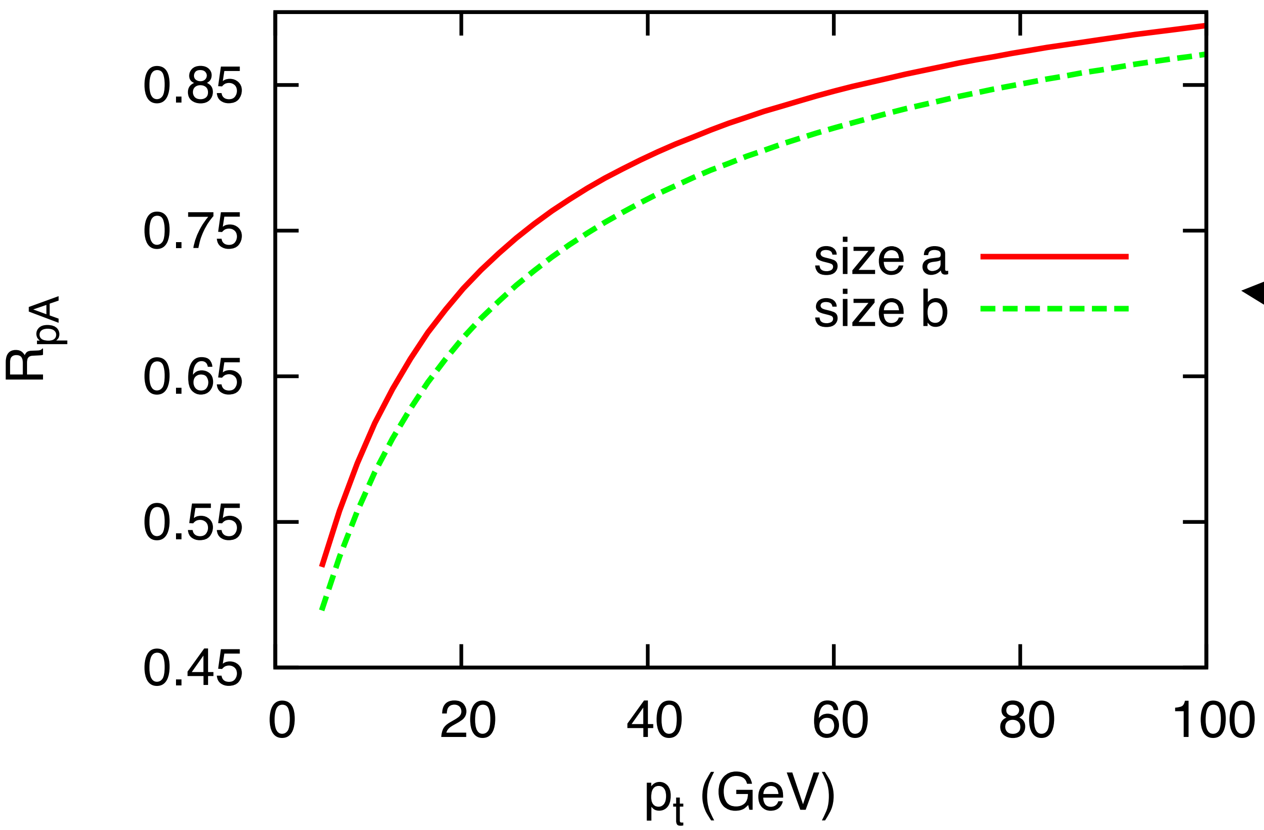
high-p_T processes access
the partonic content of the nucleus

and serve as a test of factorization
and pQCD-based nPDF frameworks

What physics can p+A data explore?

Zhang and Liao, nucl-th/1311.5463
final state effects in p+Pb

predictions of a suppressed R_{pPb}
due to quenching in a small QGP



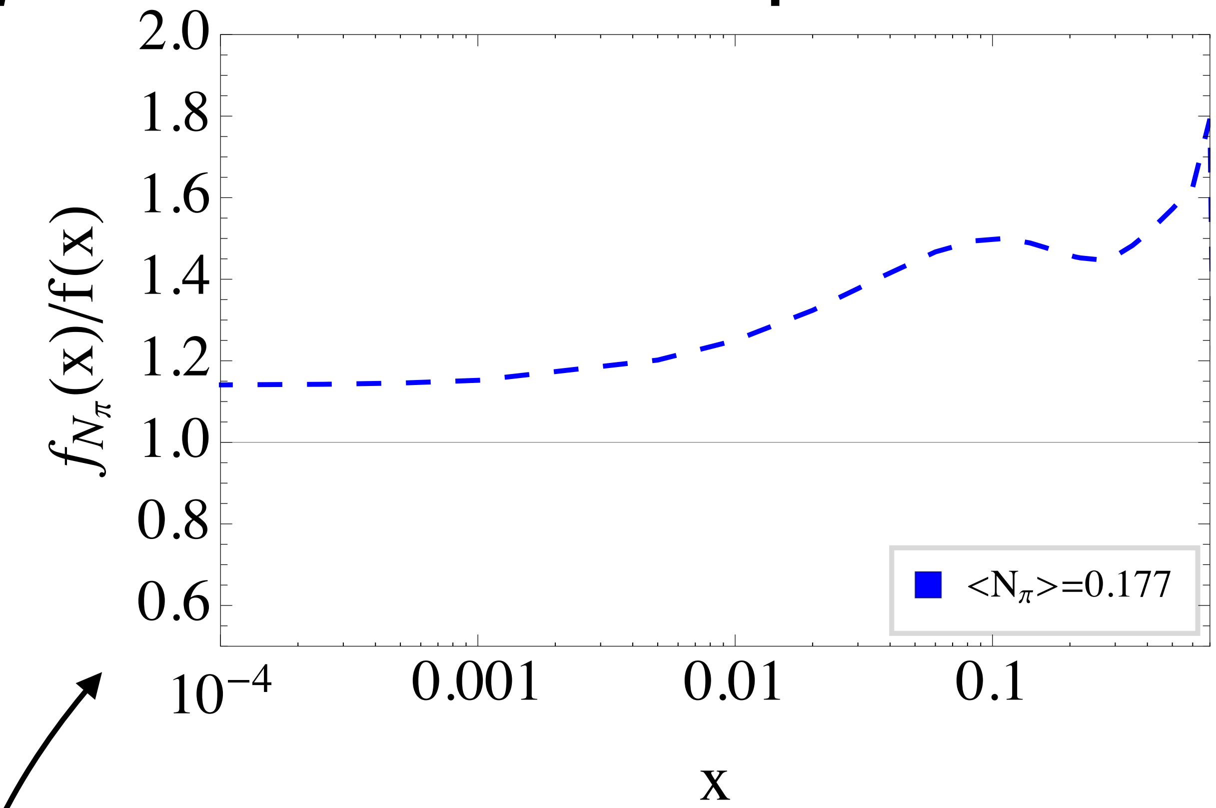
How are parton densities
modified in nuclei?

<u>Is there jet quenching
in small systems?</u>

What physics can *p*+A data explore?

Coleman-Smith, Mueller,
hep-ph/1307.5911
cloudy proton model

enhanced antiquark PDF
from the possibility of "proton
+pion" configurations



How are parton densities
modified in nuclei?

Is there jet quenching
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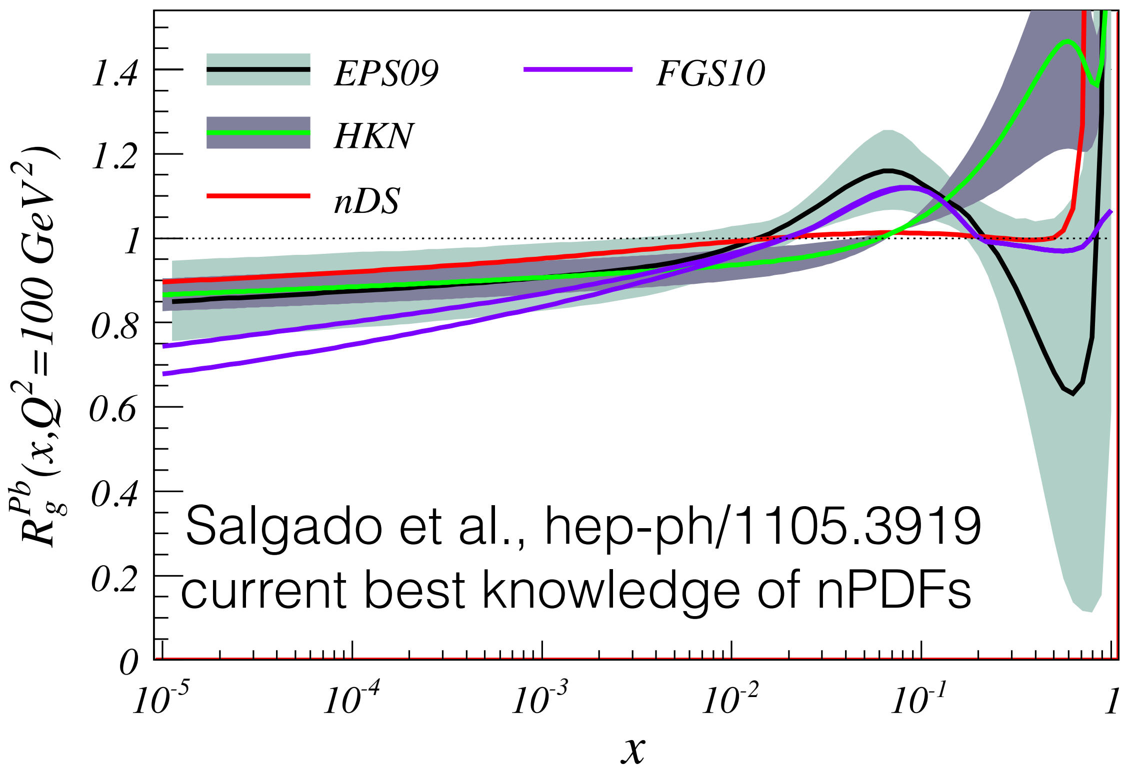
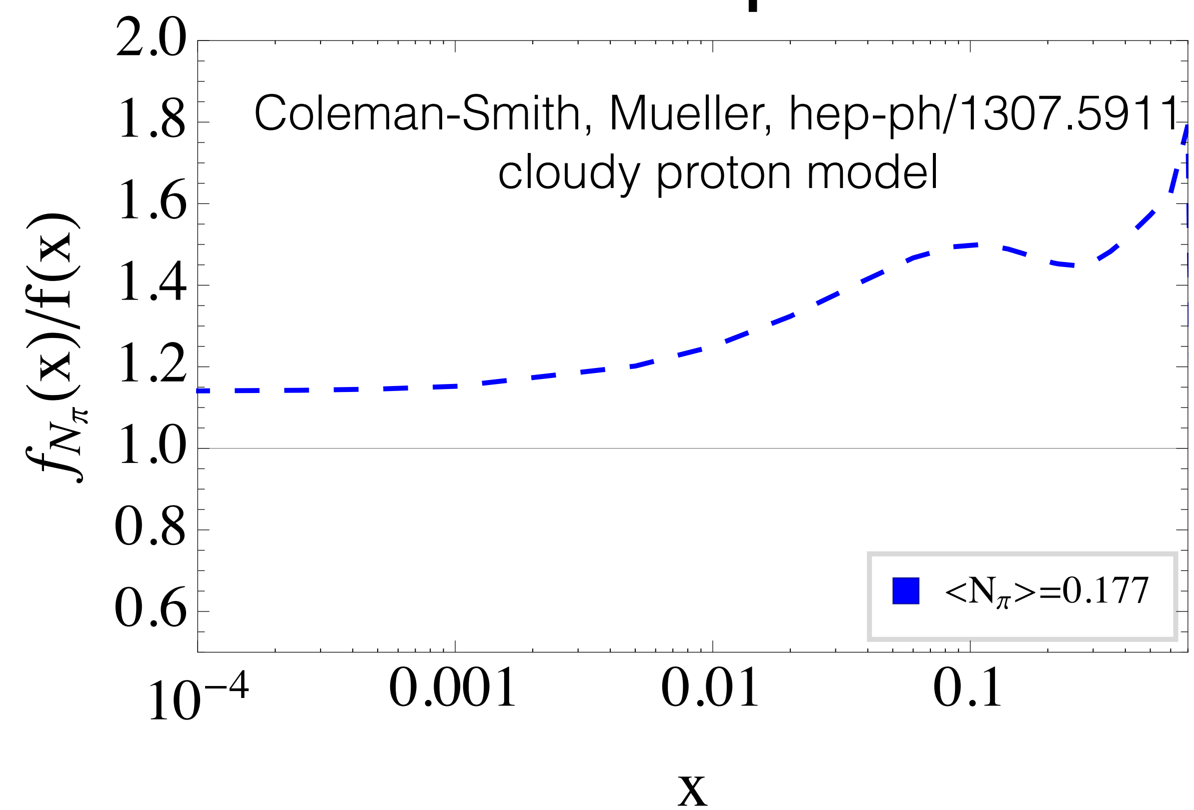
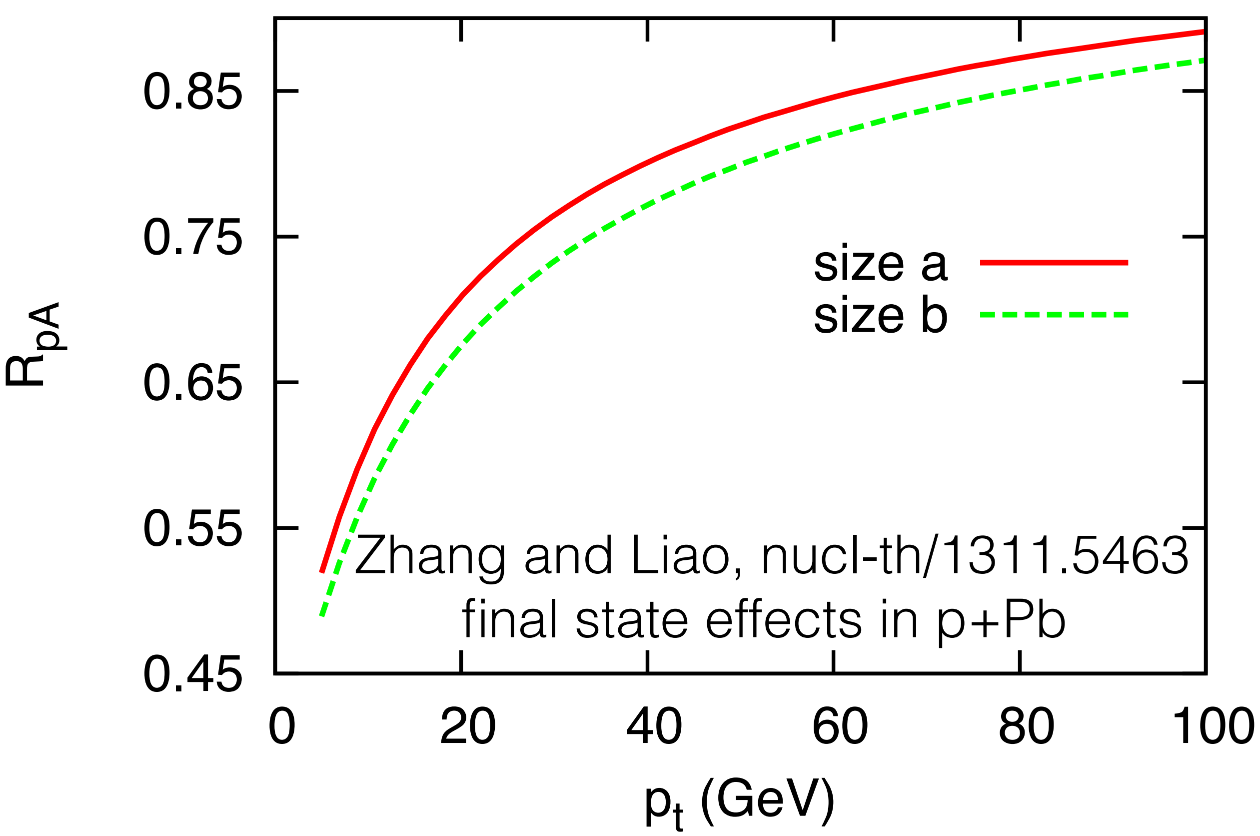
<u>Can we observe rare configurations of
the proton wavefunction?</u>

What physics can *p*+A data explore?







How are parton densities modified in nuclei?

Is there jet quenching in small systems?

Can we observe rare configurations of the proton wavefunction?

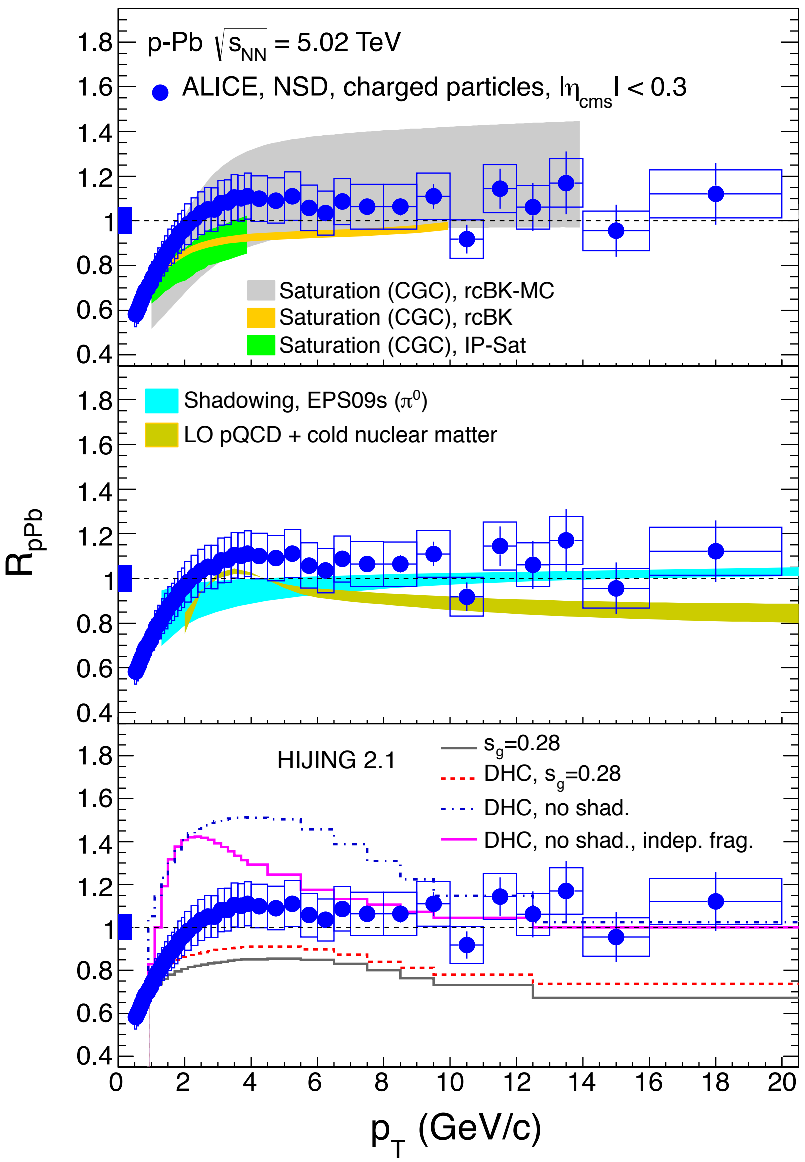
<u>But also: what has the LHC taught us about RHIC data?</u>

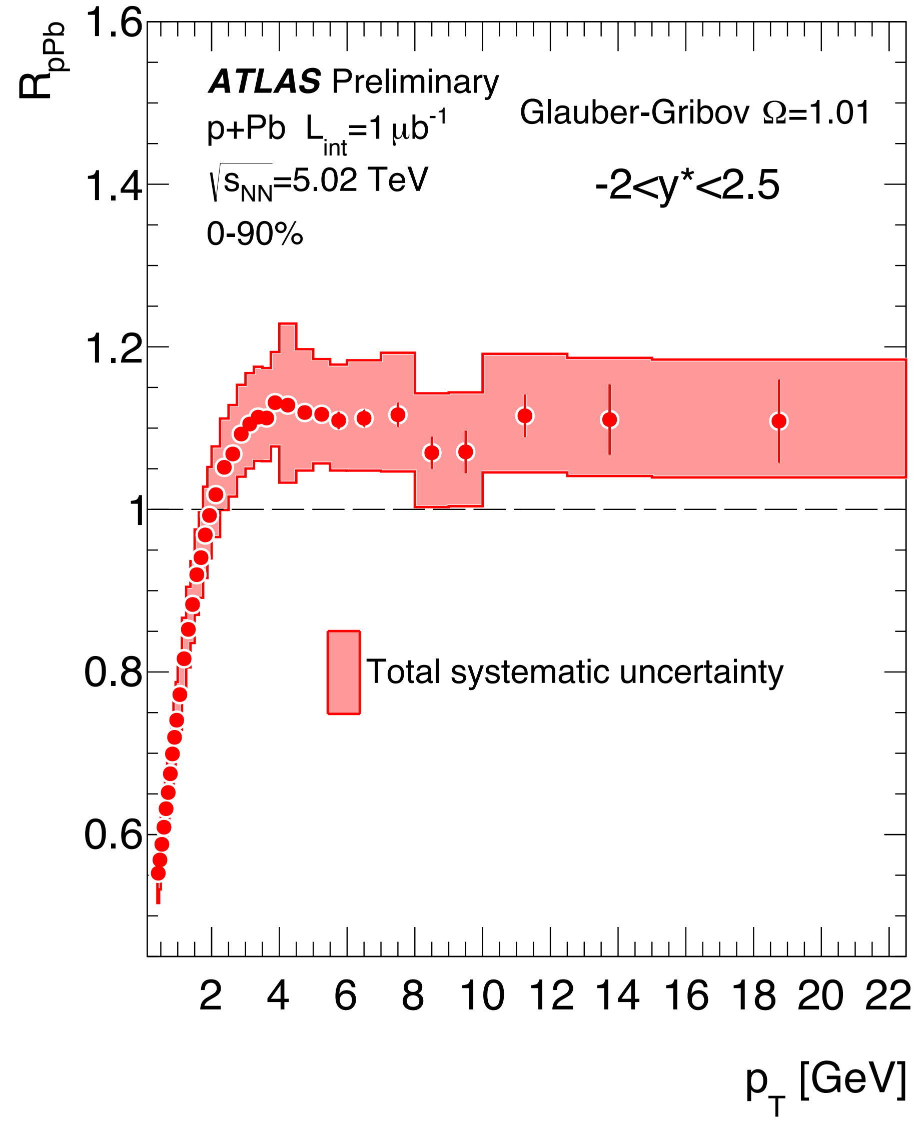
Minimum bias *p*+Pb data

How are parton densities modified in the nucleus?

Single particles: early look in p+Pb

nucl-ex/1210.4520

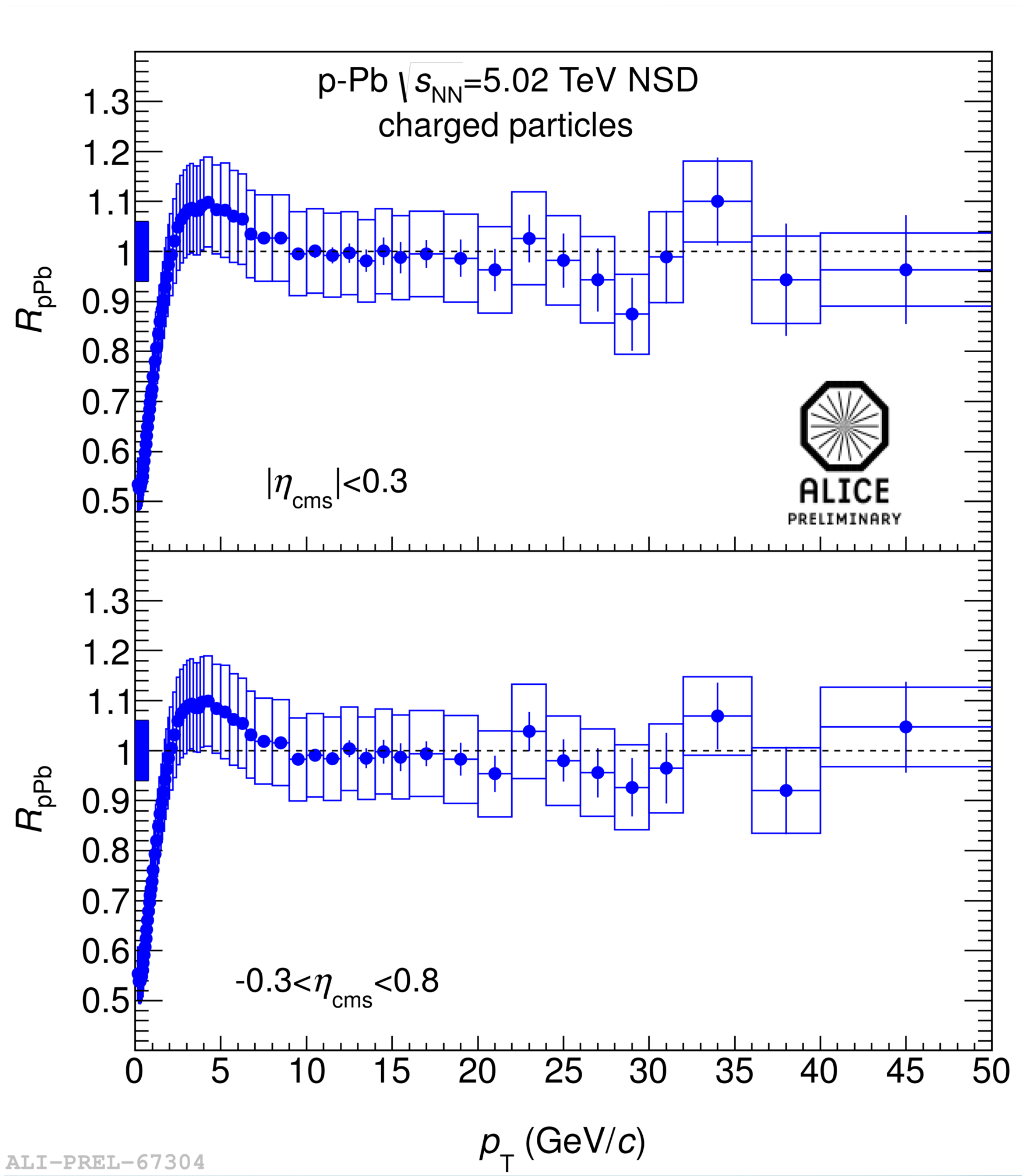




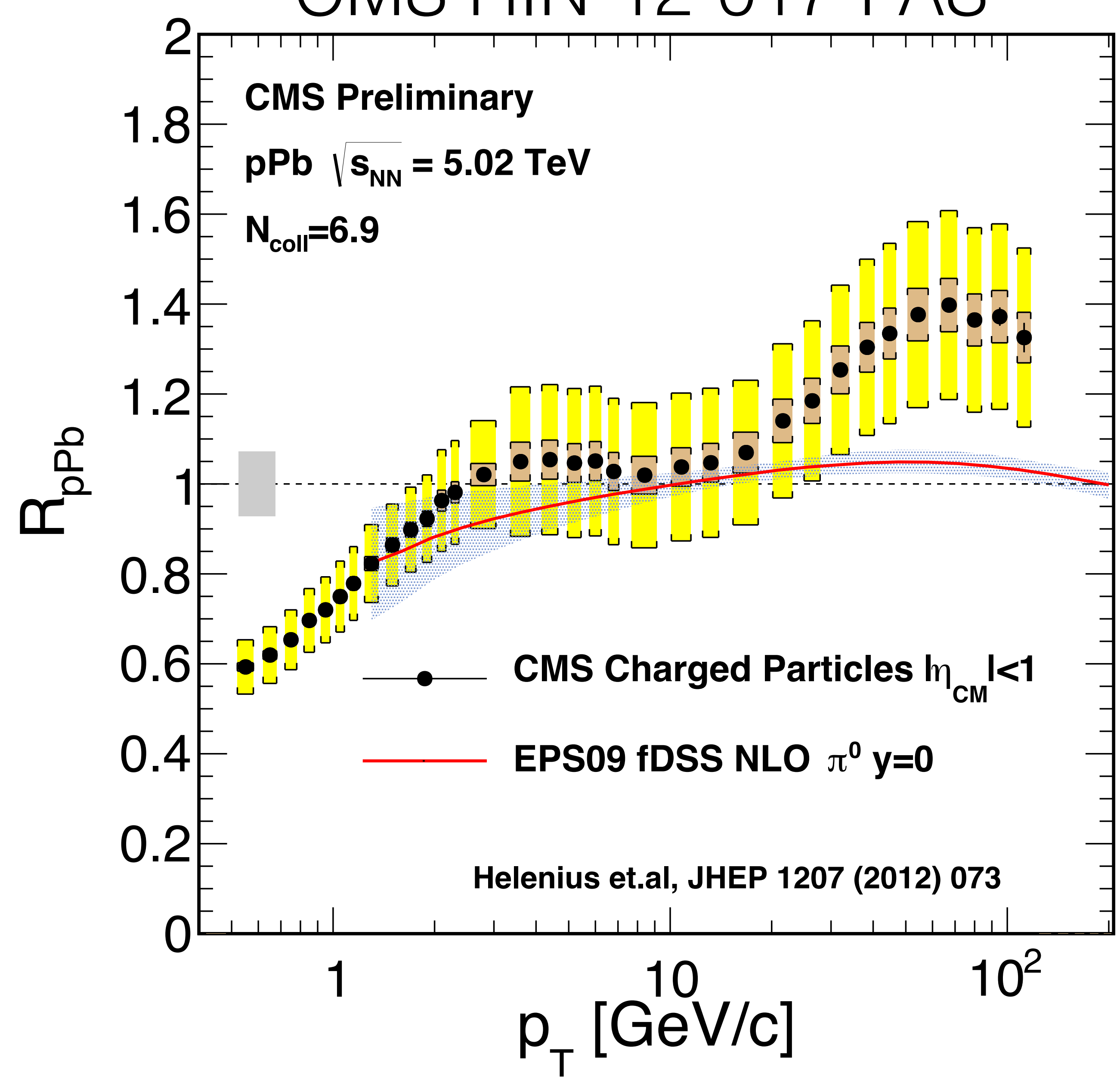
ATLAS-CONF-2013-107

- Measurements of the R_{pPb} in 2012 pilot data
    - geometric expectation out to 20 GeV
    - no visible enhancement in the "Cronin" region
- Major challenge: constructing a 5.02 TeV *pp* reference

Single particles: confusion at very high-p_T



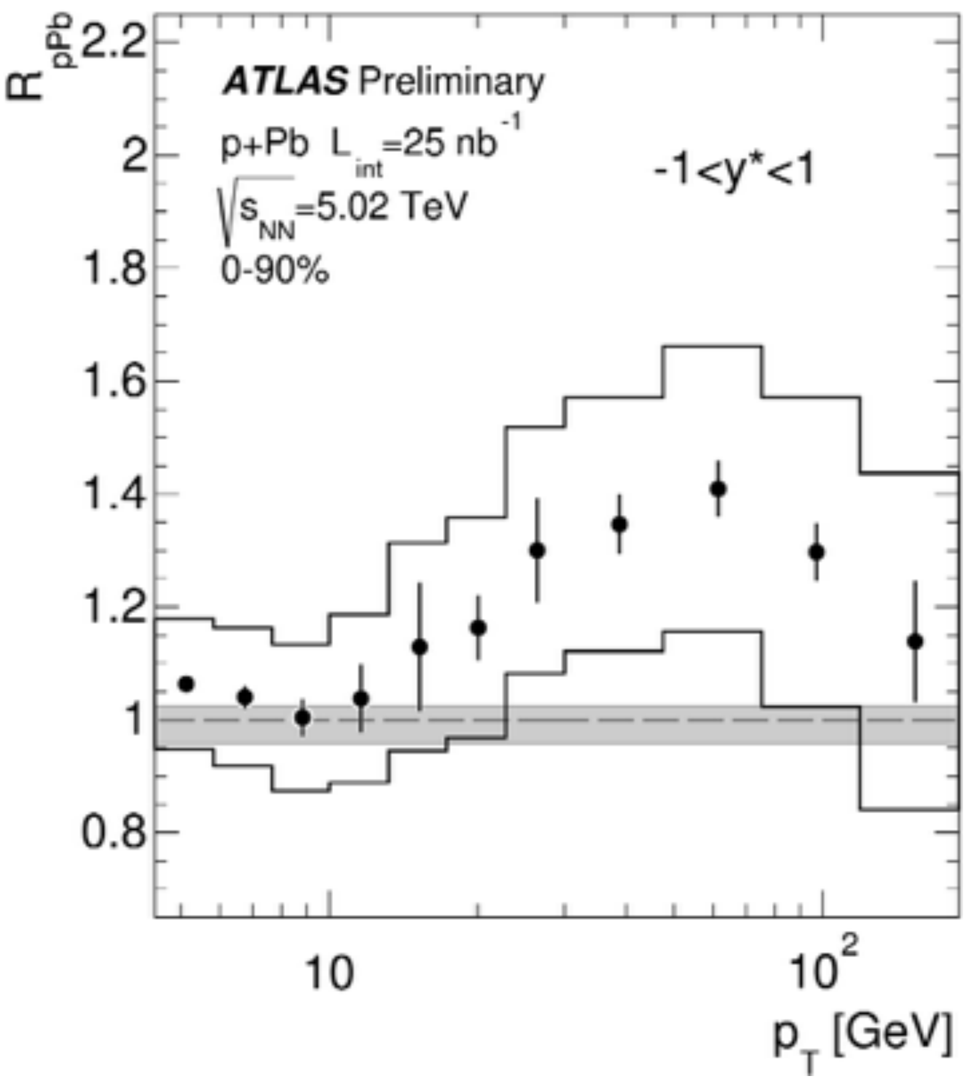
CMS HIN-12-017-PAS



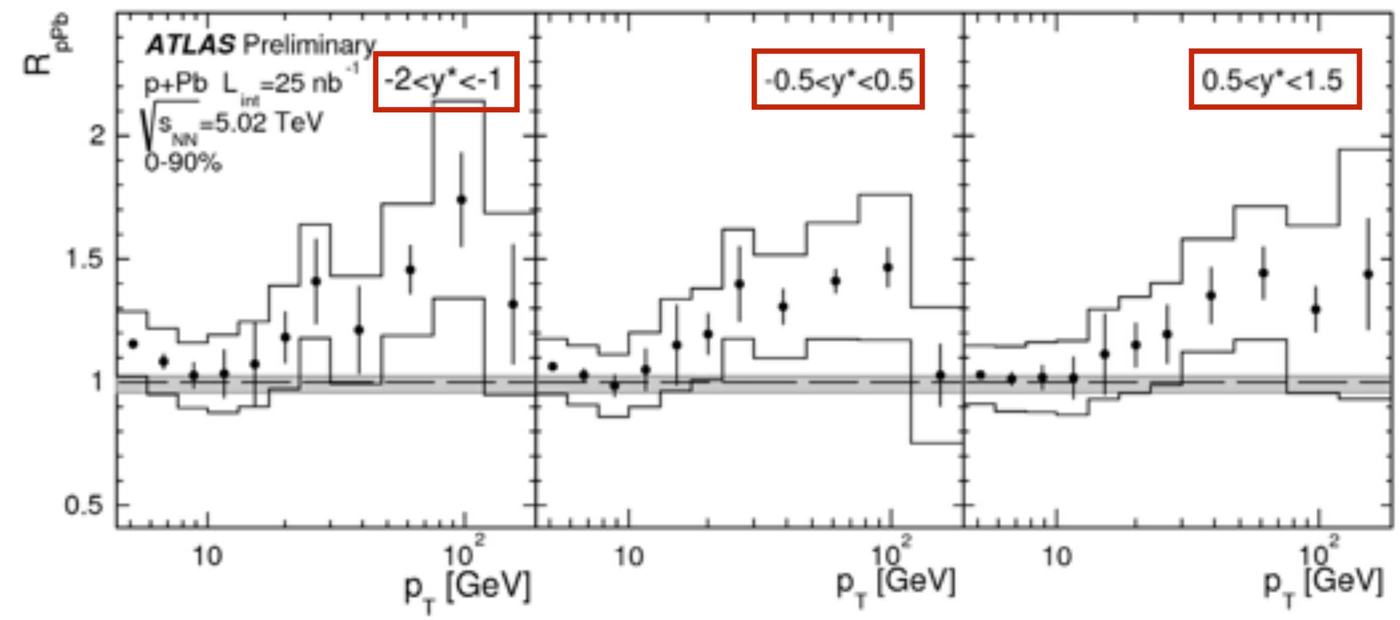
- ALICE reports no effect out to 50 GeV…
- CMS shows a 40% enhancement above 20 GeV!
    - challenging to accommodate within nPDF frameworks

Single particles: a tie breaker?

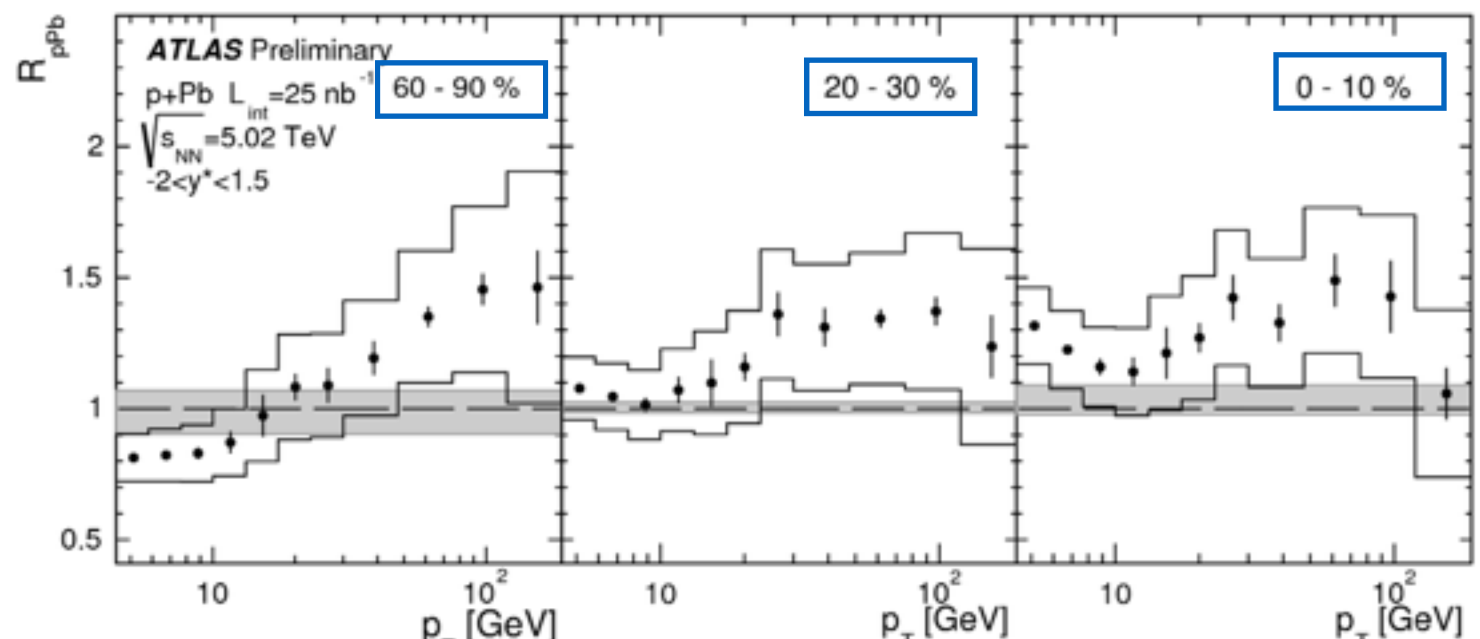
ATLAS-CONF-2014-029



Enhancement is insensitive to **rapidity**

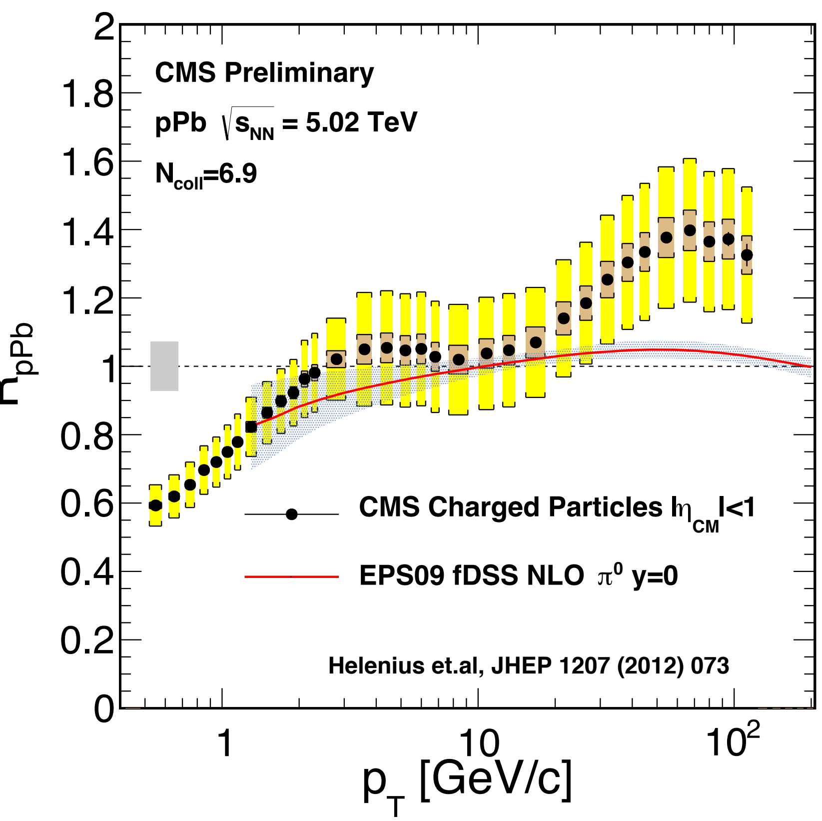


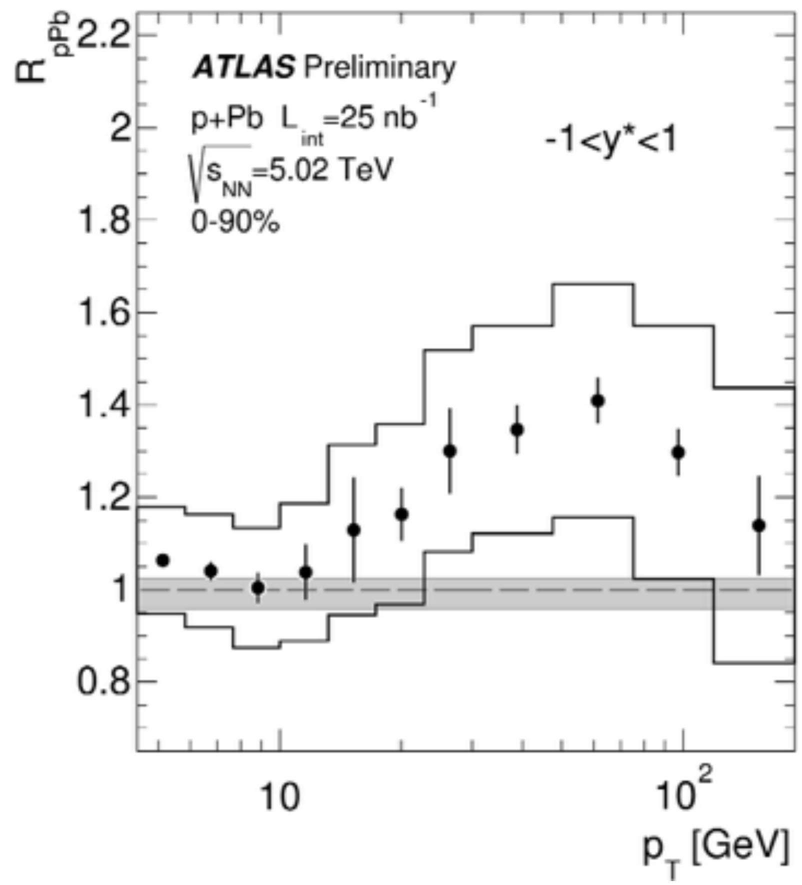
Enhancement is insensitive to **centrality**

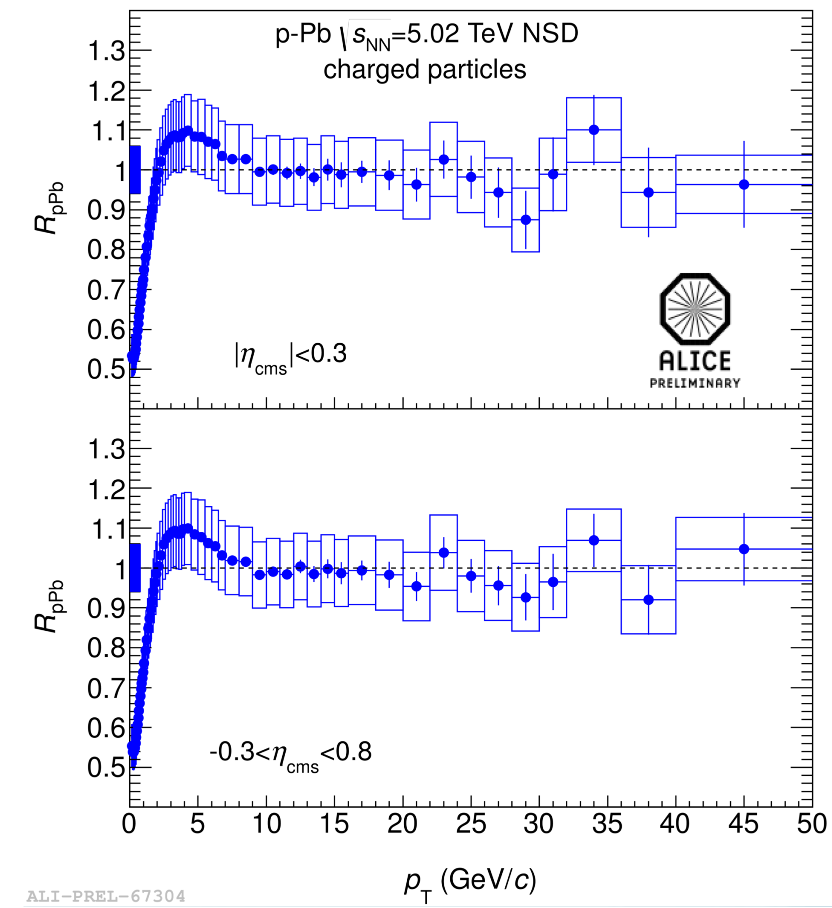


- Enhancement (tentatively) confirmed by ATLAS at QM'14
- Similar size of effect as CMS, similar kinematic region

Single particles: summary

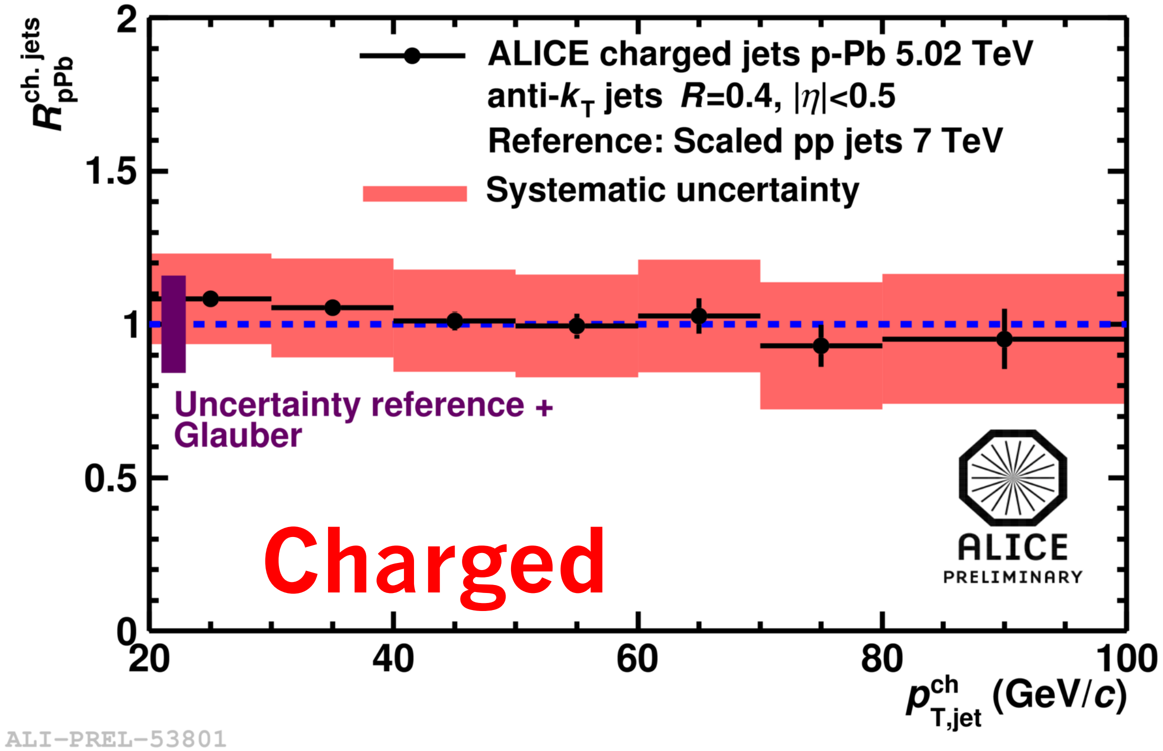


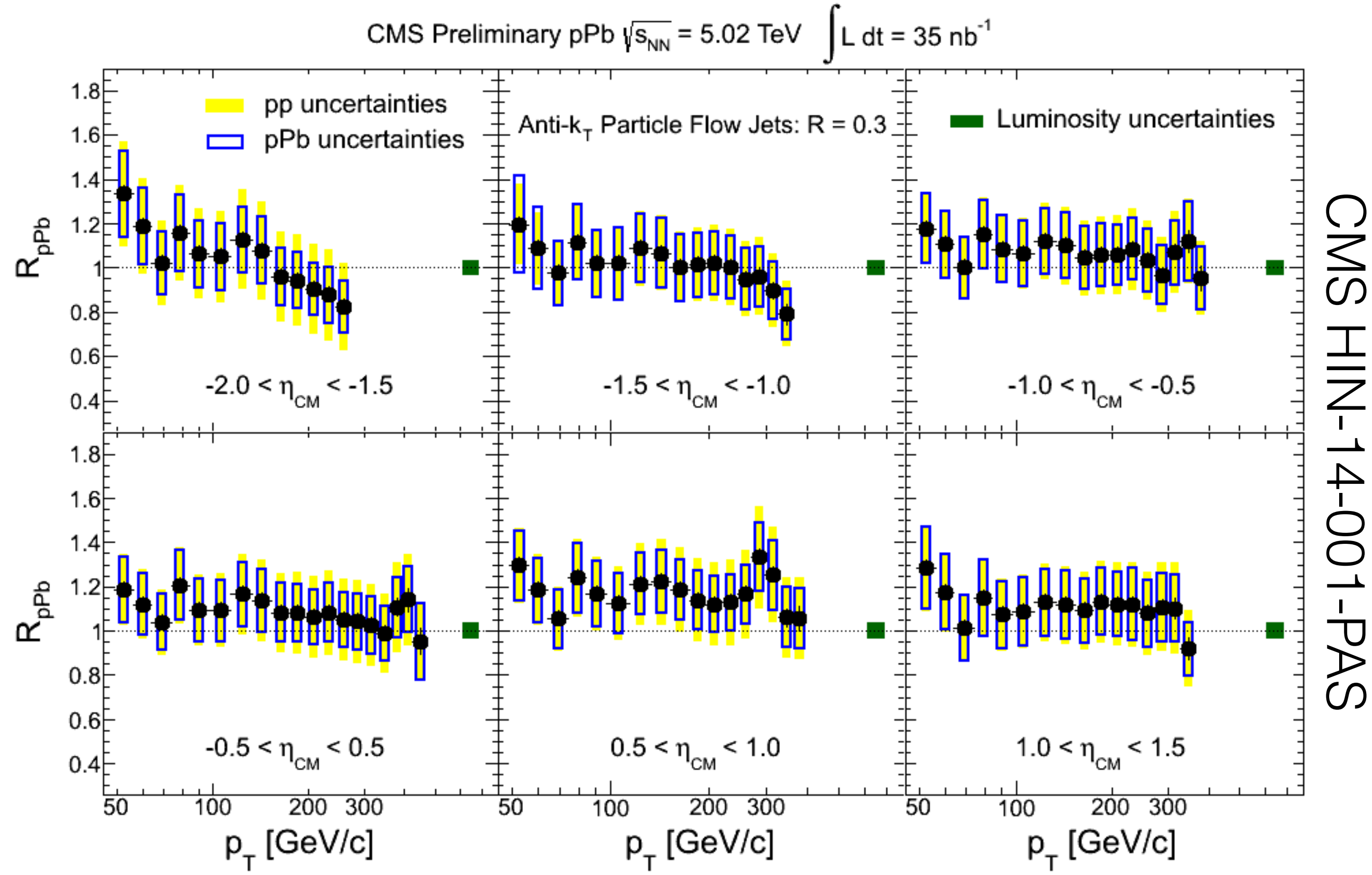




- CMS/ATLAS give a very different visual impression than ALICE
    - but we must take the error bars seriously
- Much discussion has focused on differences in the *pp* reference
    - another way to proceed: do we have a consistent measurement *p*+Pb yields in the *numerator*?
- Fortunately, it's plausible the LHC will run 5.5 TeV *pp* in Run 2

Jets in minimum bias p+Pb collisions, I



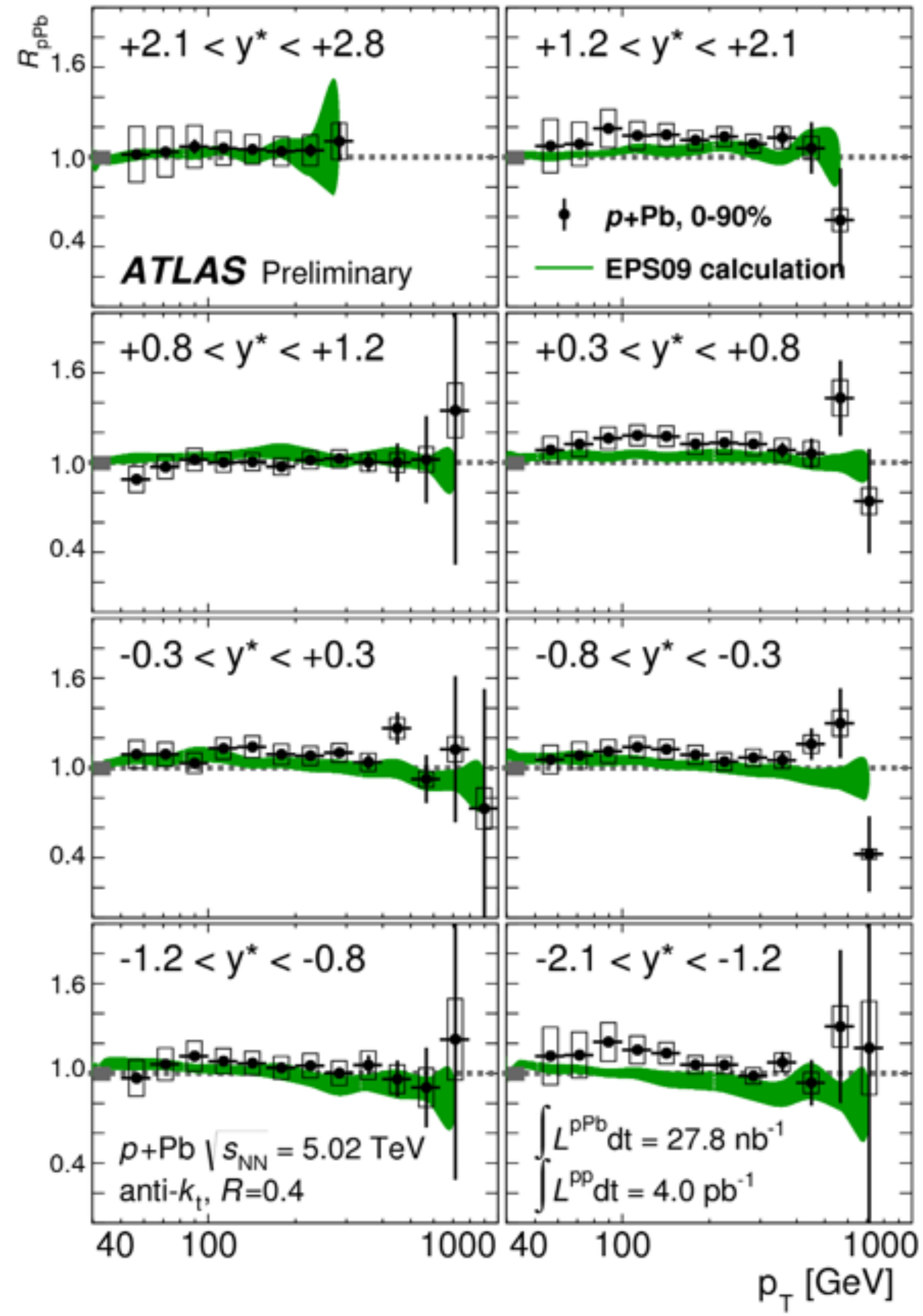


- ALICE jet spectrum
  - compared to 7 TeV *pp* data
  - “doubly interpolated” with MC in √s and in rapidity
- First measurement of <u>geometric scaling</u> in jets

- CMS jet cross-section ($d\sigma/dp_T$)
  - compared to 7 TeV *pp* data
  - “doubly interpolated” with MC in √s and *cone size*
  - systematics from unfolding & *pp* reference

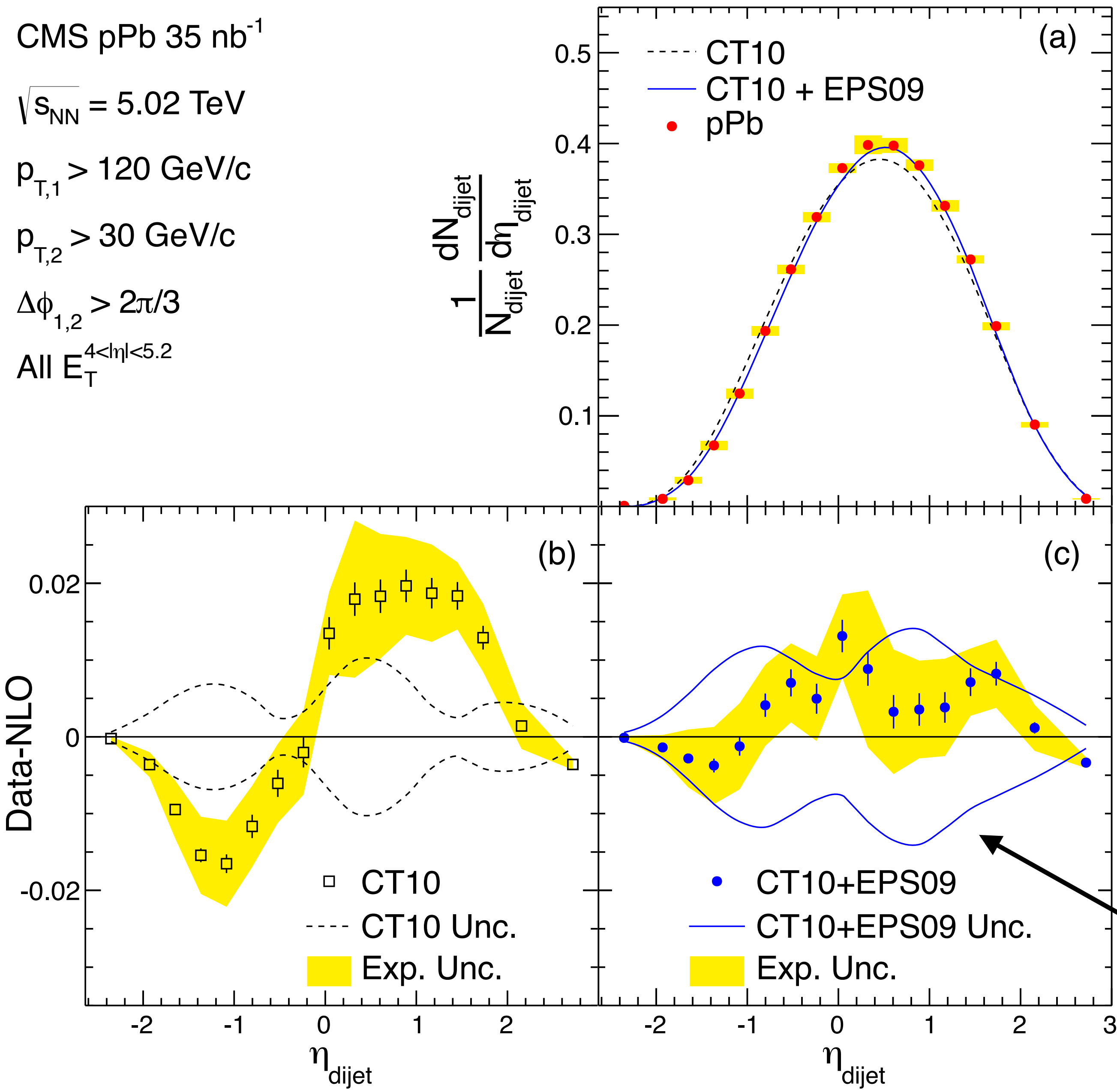
Jets in minimum bias *p*+Pb collisions, II

- ATLAS jets in 0-90% *p*+Pb
  - 5 units of rapidity, 40-1000 GeV
- *pp* reference is 2.76 TeV data
  - same running conditions, same reconstruction procedure & corrections
  - x_T-scaled using previous ATLAS data at 2.76 & 7 TeV
  - resulting systematics are small
- Data in line with (or only slightly above) **EPS09** predictions



ATLAS-CONF-2014-024

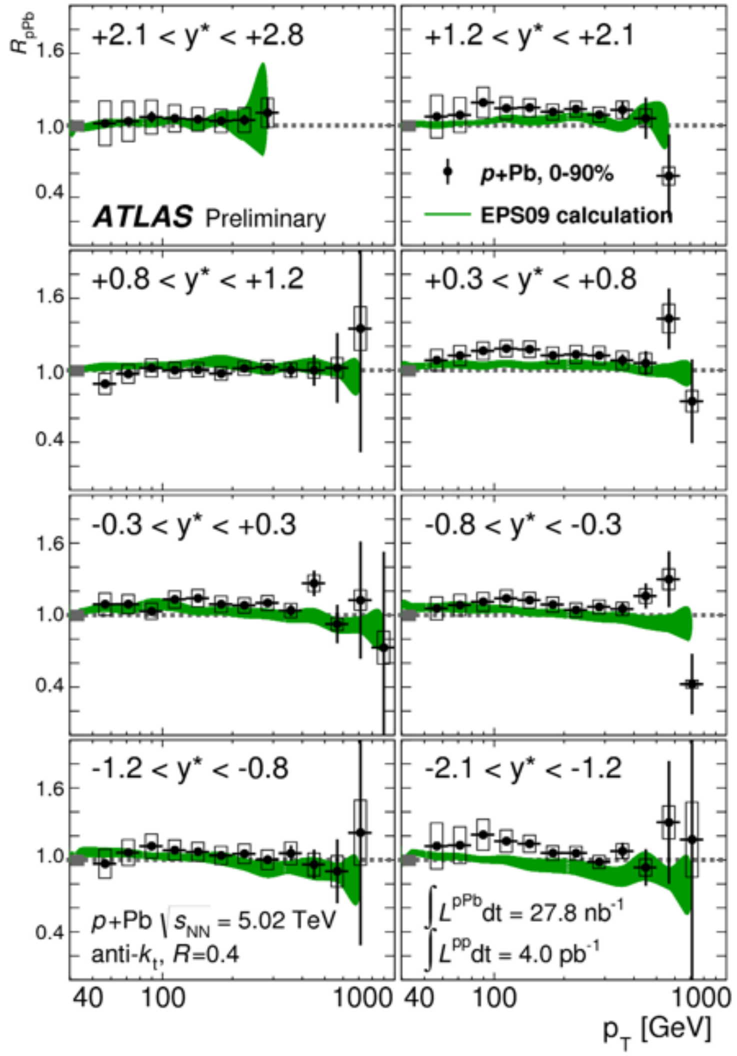
Jets in minimum bias *p*+Pb collisions, III



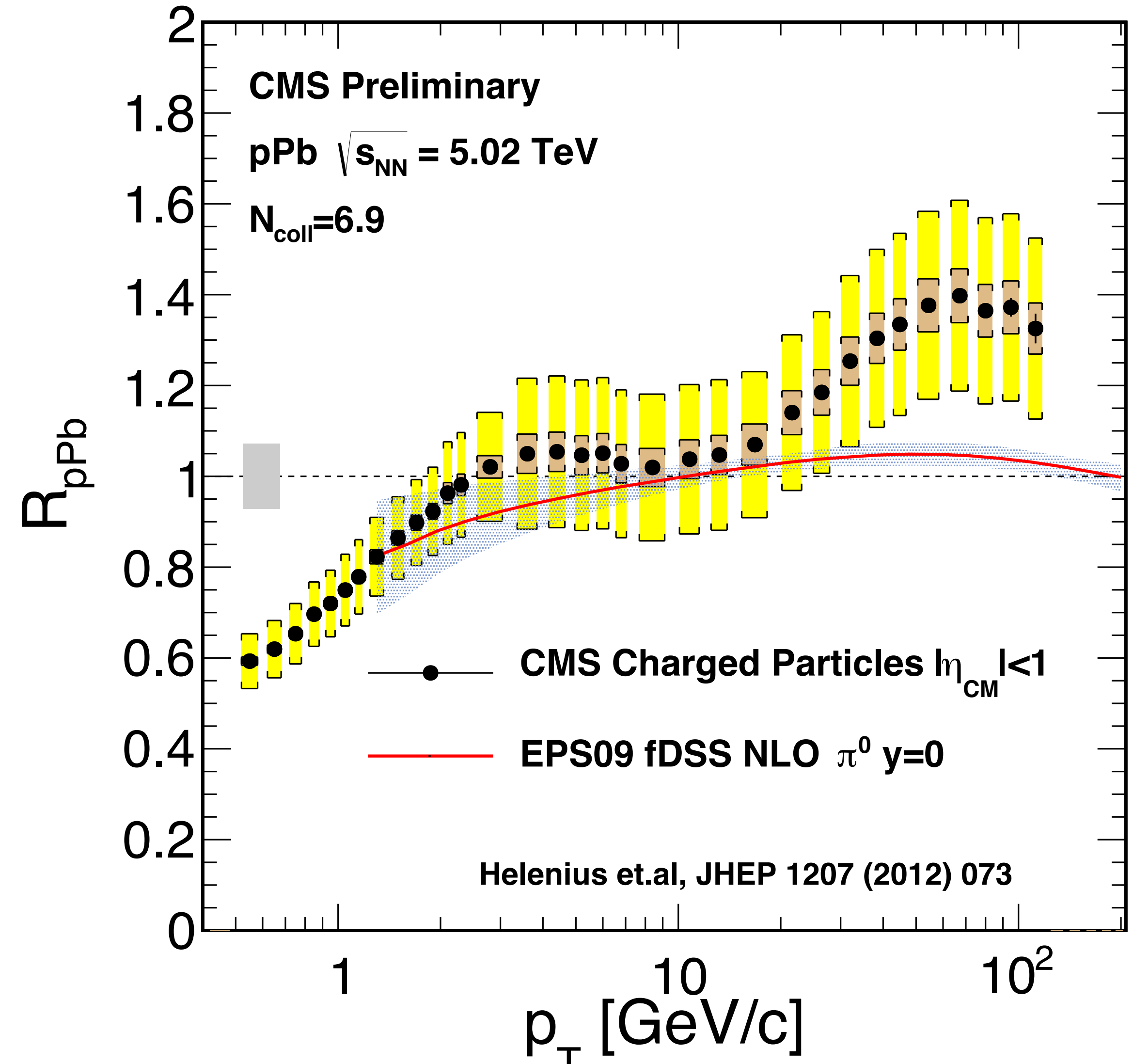
CMS HIN-13-001-PAS

- CMS dijets in minimum bias *p*+Pb collisions
- shape of the dijet system dN/dη distribution used to probe nPDF effects
  - modifications favor **EPS09** over *pp* PDF's

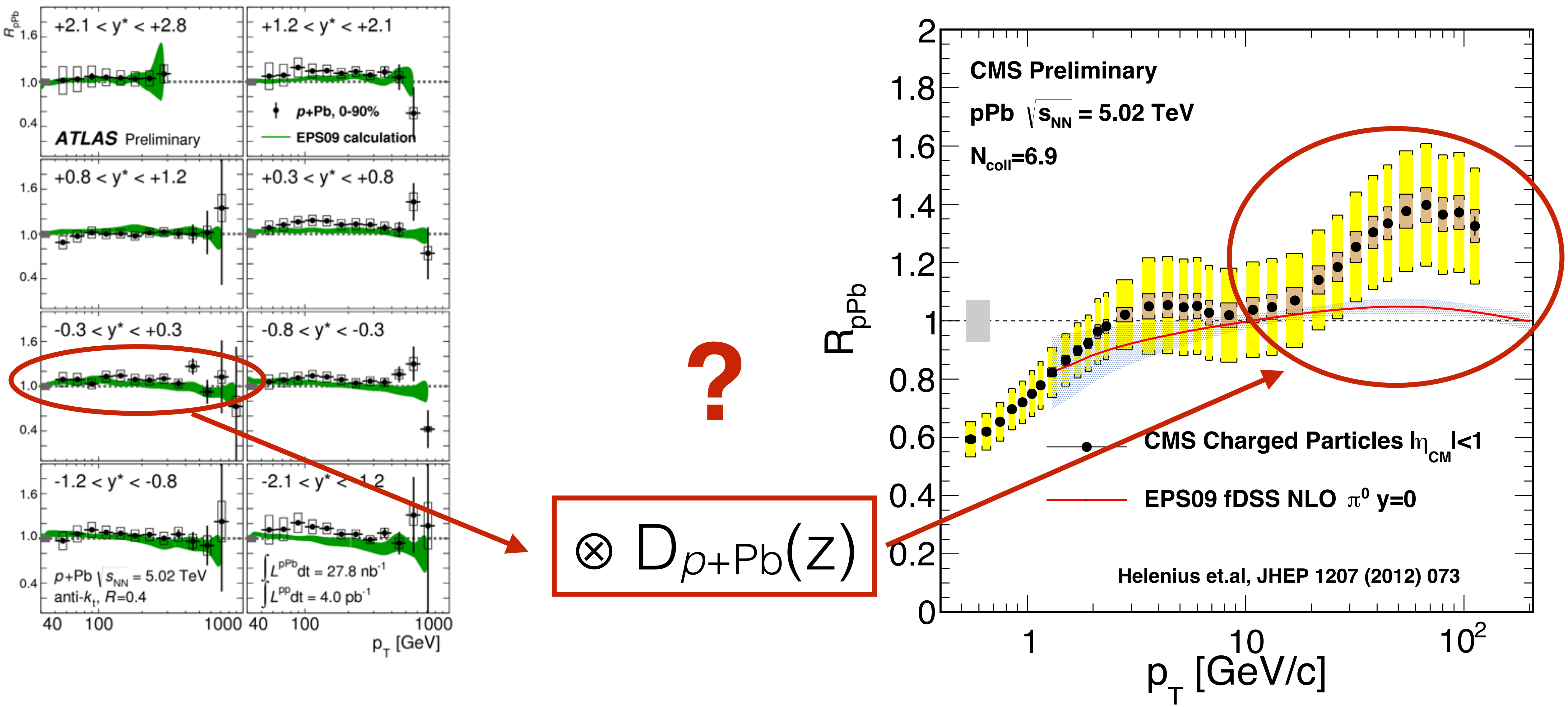
Jets vs. particles?



vs.

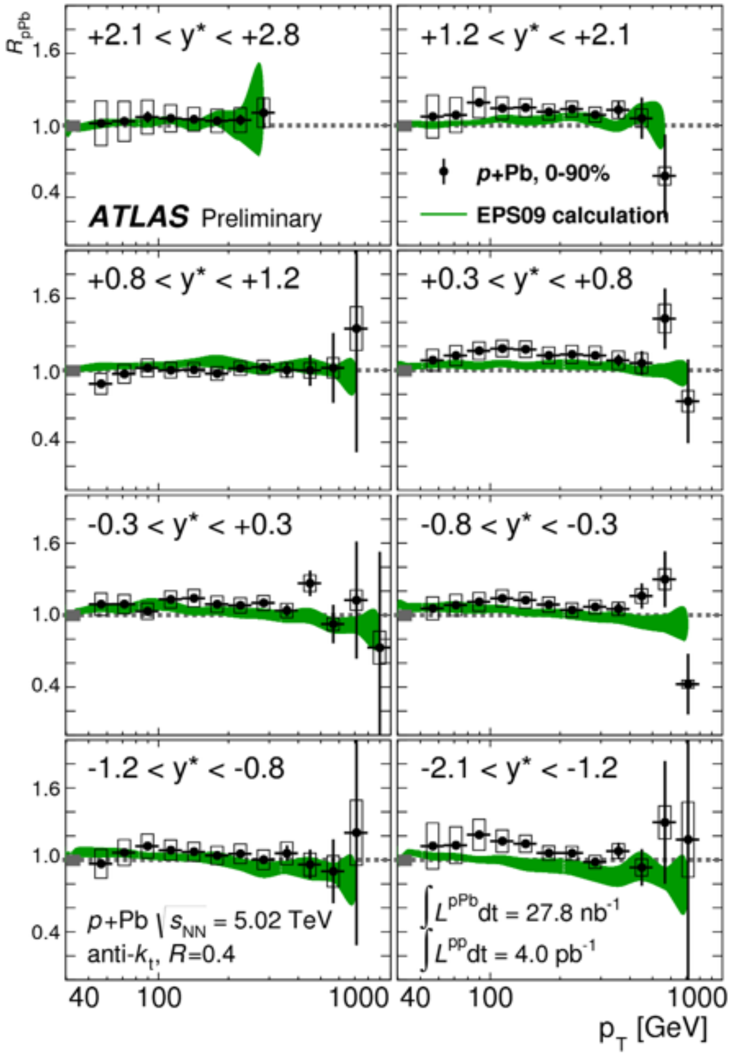


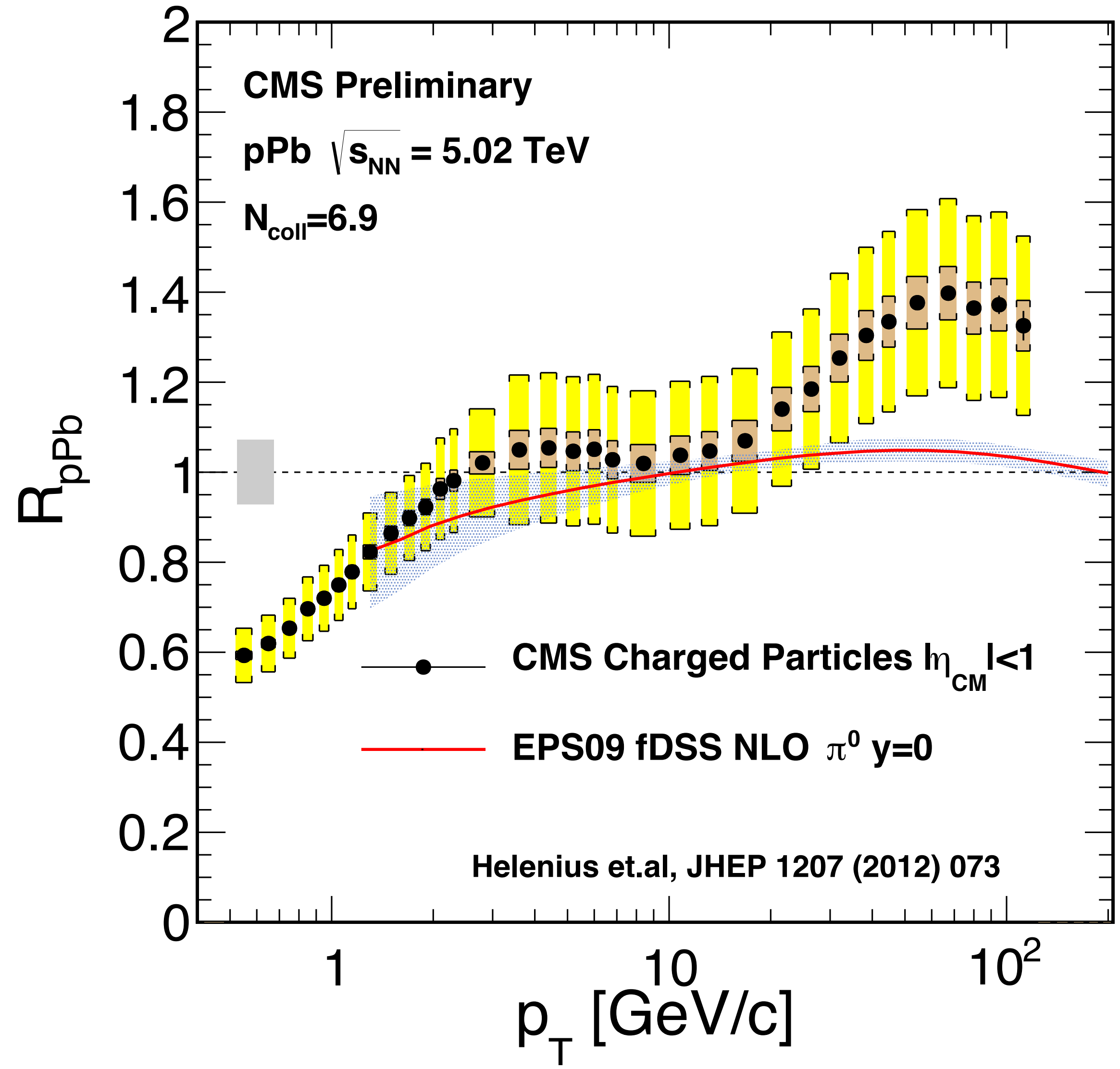
- Jets and hadrons are different QCD objects
  - no reason they must give the same R_{pPb}
- <u>How can we understand these results together?</u>
- Popular idea: particles are more sensitive to a change in q/g fraction
  - example: what if anti-shadowing is all quarks?



- <u>What measurements can provide additional input?</u>

1. Could measure fragmentation function in *p*+Pb
   - what type/size of modification could reproduce this effect?
   - need control over the *pp* reference
   - any insight from identified particle R_{pPb} (from ALICE)?





+

W's & Z's?

photons?

***b*-jets?**

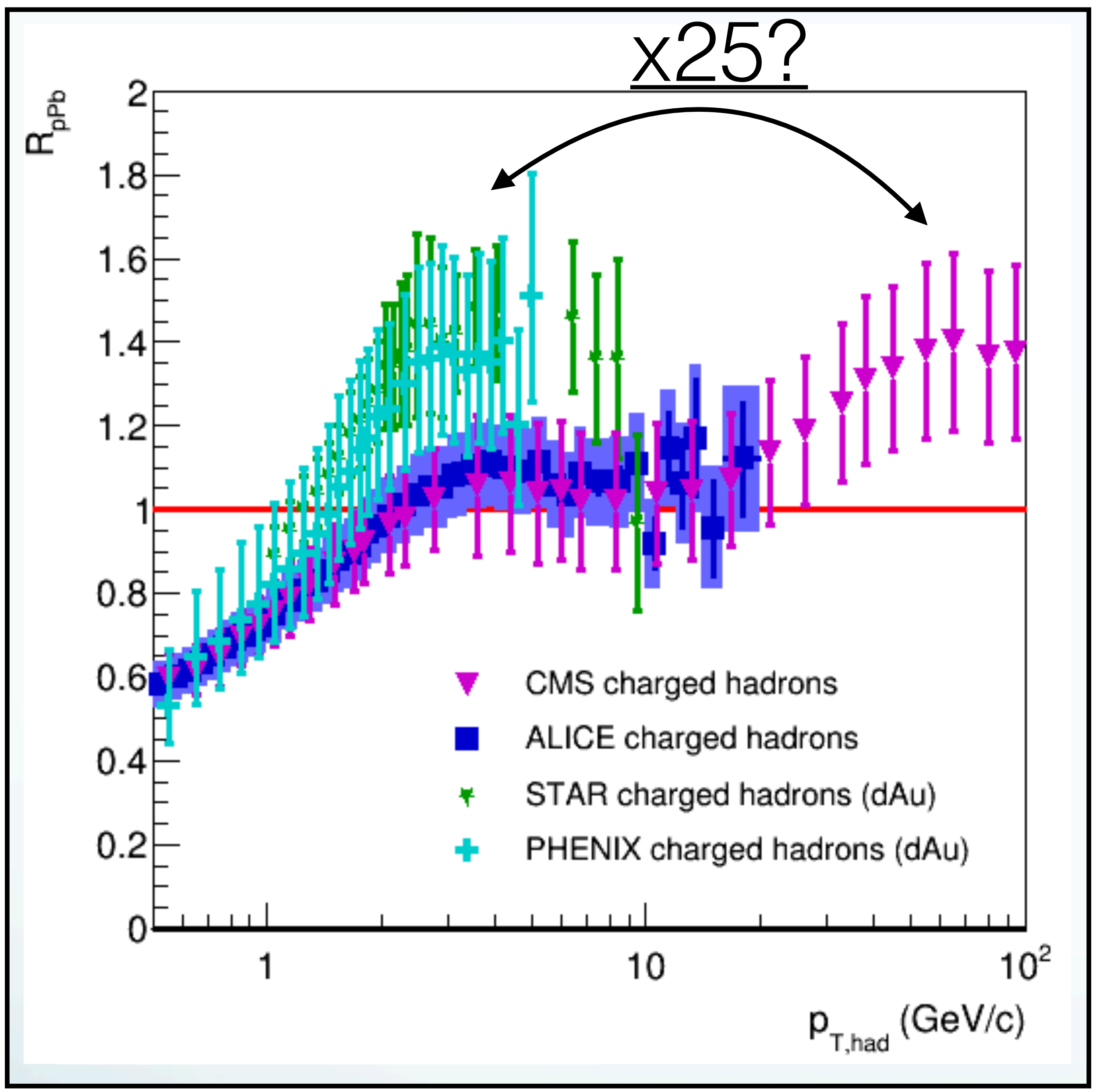
- What measurements can provide additional input?

2. Could access a different mixture of quarks and gluons
   - need a set of hard probes data that can scan in *flavor*
   - with systematic uncertainties small enough to distinguish small deviations

- for example: what if tomorrow we saw a photon R_{pPb} of 1.0? of 1.4?

Where was this effect at RHIC?

- Compilation of *d*+Au and *p*+Pb results in R. Reed's BNL Nuclear Physics Seminar, 7 April 2014

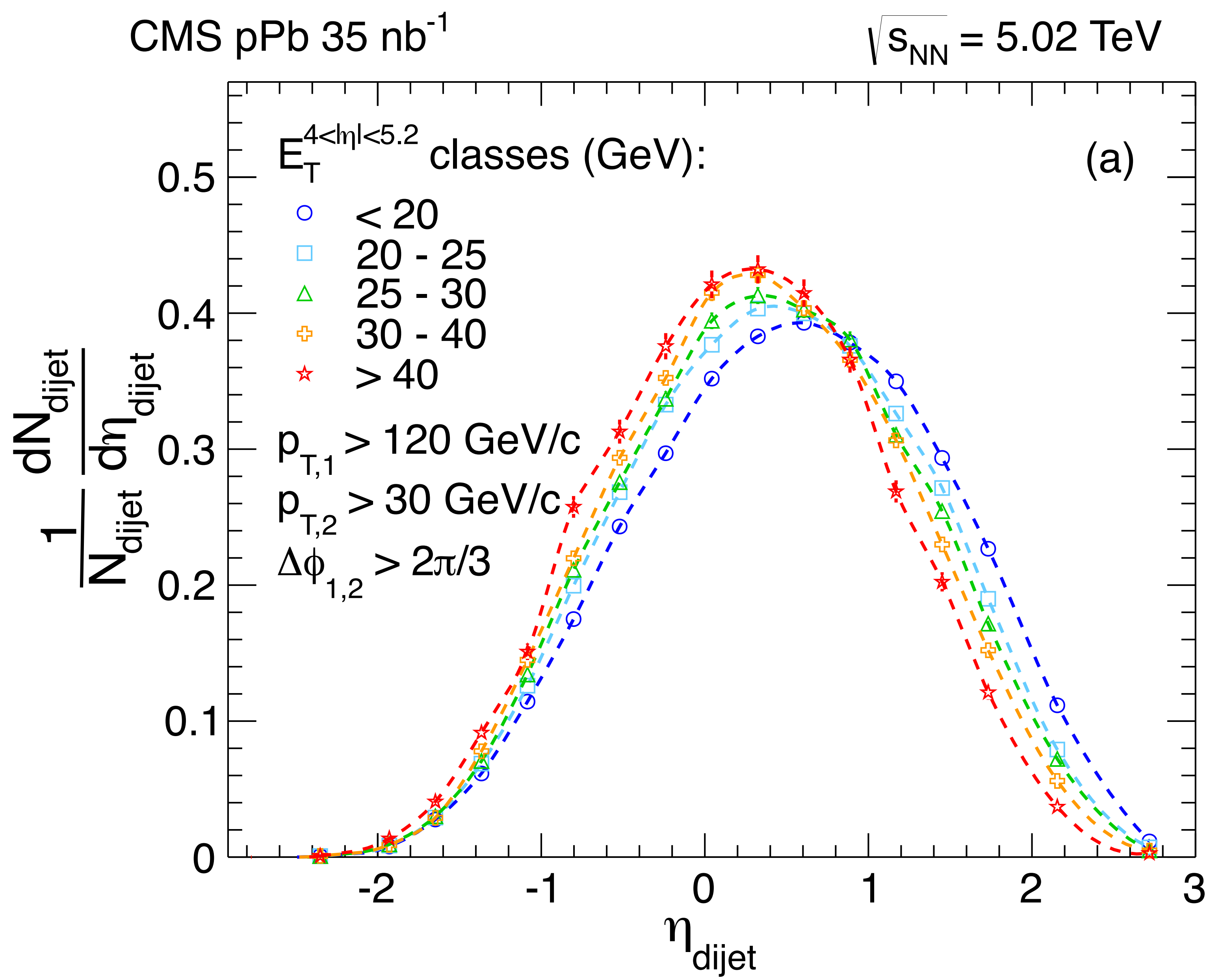


- R_{dAu} does reach 1.4, but at a much lower p_T…
  - 200 GeV / 5.02 TeV = 25
- Could this be the same effect?
  - a 40% excess at $x \approx 0.02$!
  - however, there are competing interpretations of this enhancement in *d*+Au…

Centrality-dependent *p*+Pb data

Dijet η distributions

- <u>CMS</u>: "event activity" measured in *p* and Pb-going HF's, 4 < |η| < 5
  - no extraction of geometric quantities (yet)

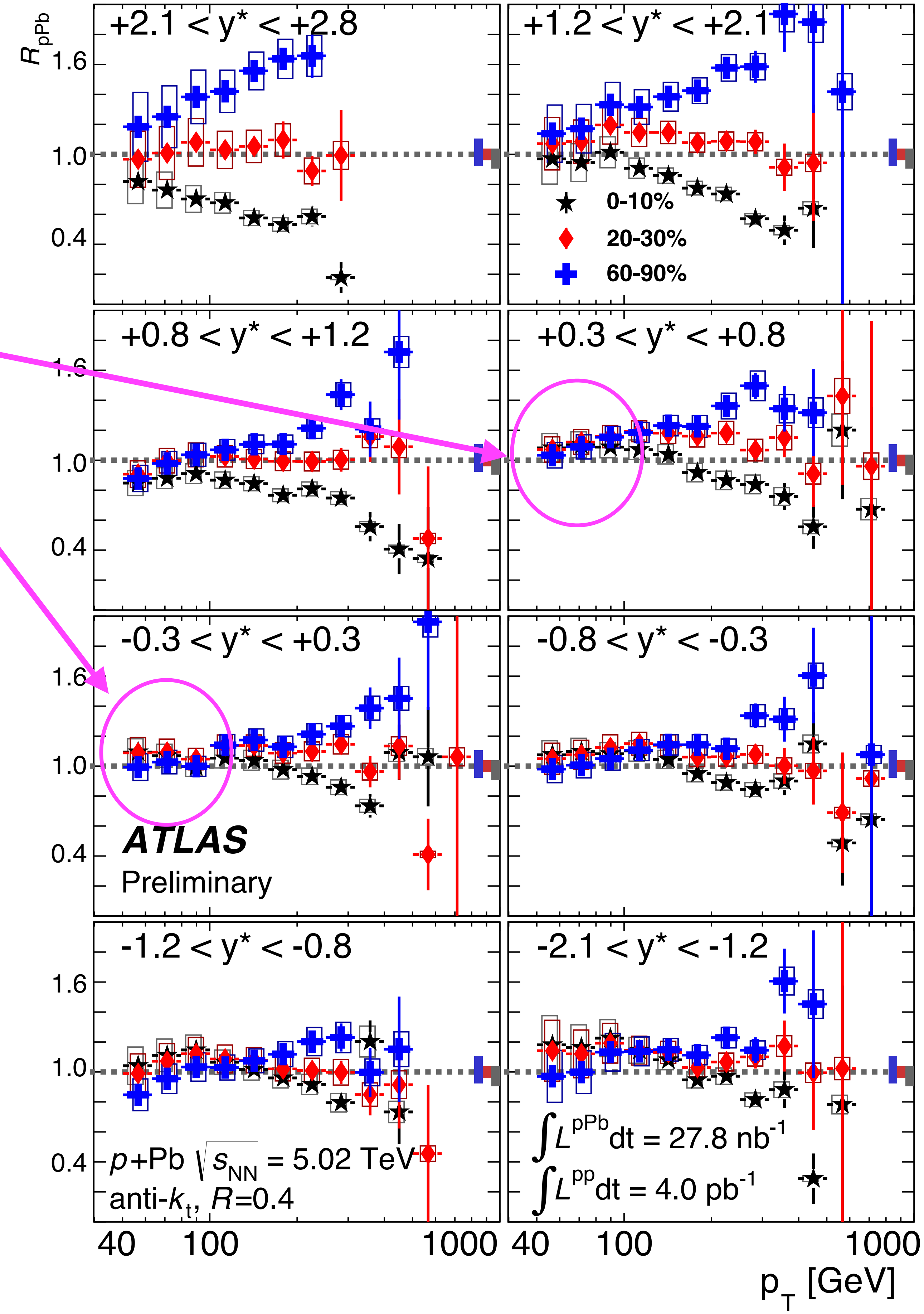


- Systematic shift of the dijet dN/dη distribution with event activity
  - challenging to find mechanisms in pQCD frameworks to produce such a rapidity shift!
- <u>Non-trivial interplay between hard and soft processes…</u>

Jet spectra, I

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

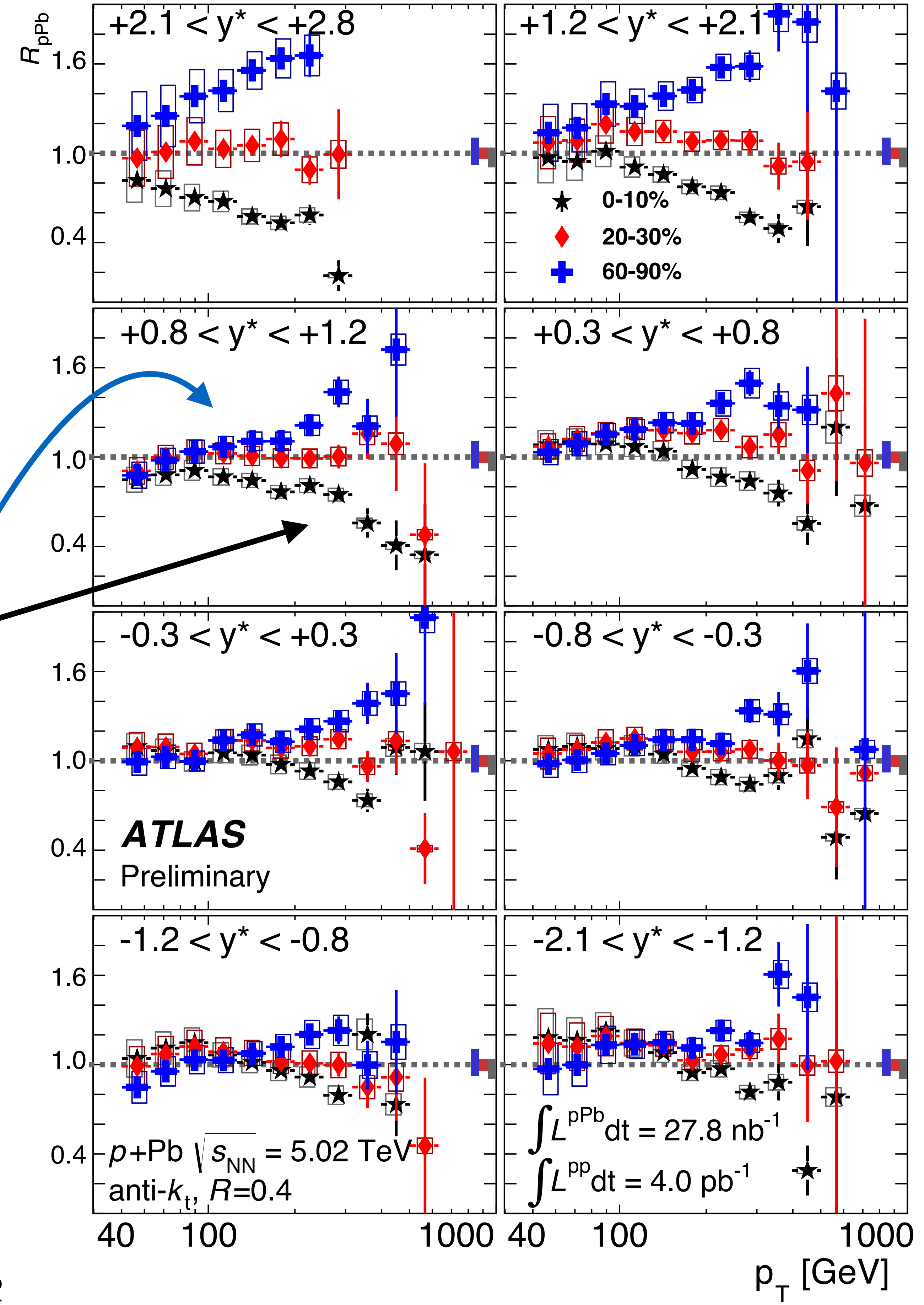
ATLAS-CONF-2014-024



Jet spectra, II

- Centrality-selected R_{pPb}
  - 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

ATLAS-CONF-2014-024

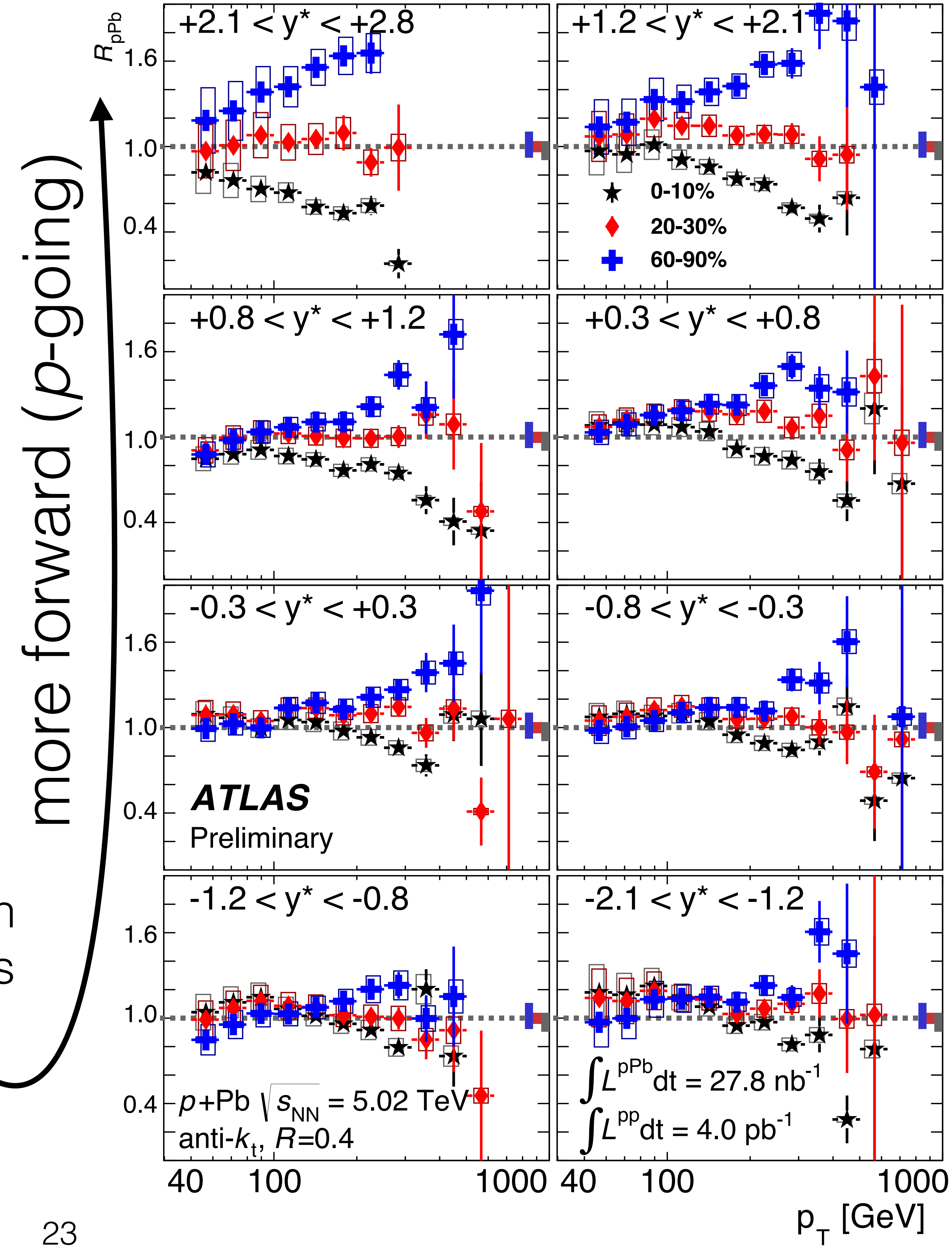


Jet spectra, III

- Centrality-selected R_{pPb}
  - 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

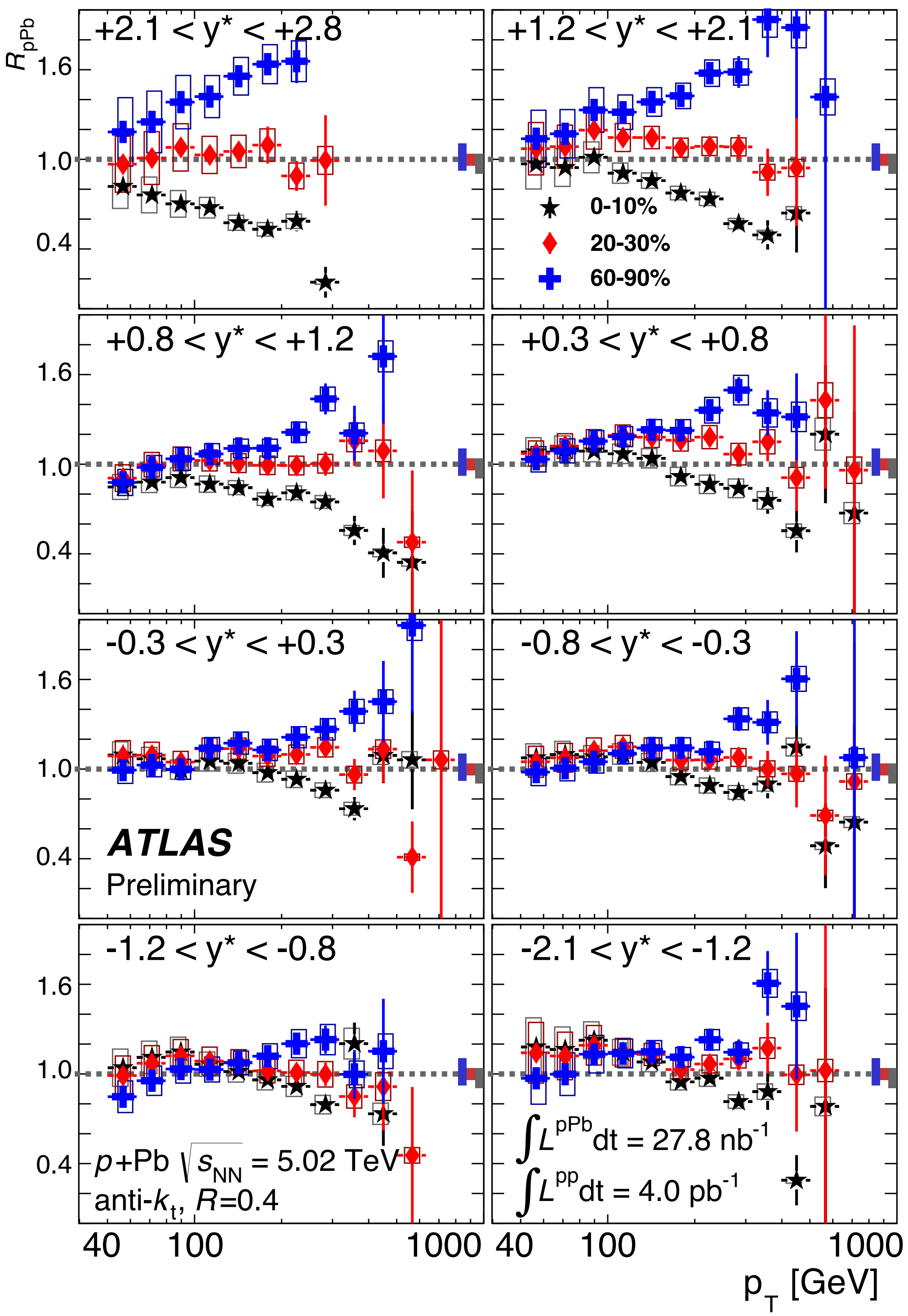
Just like in CMS dijets, large violations of hard/soft factorization!

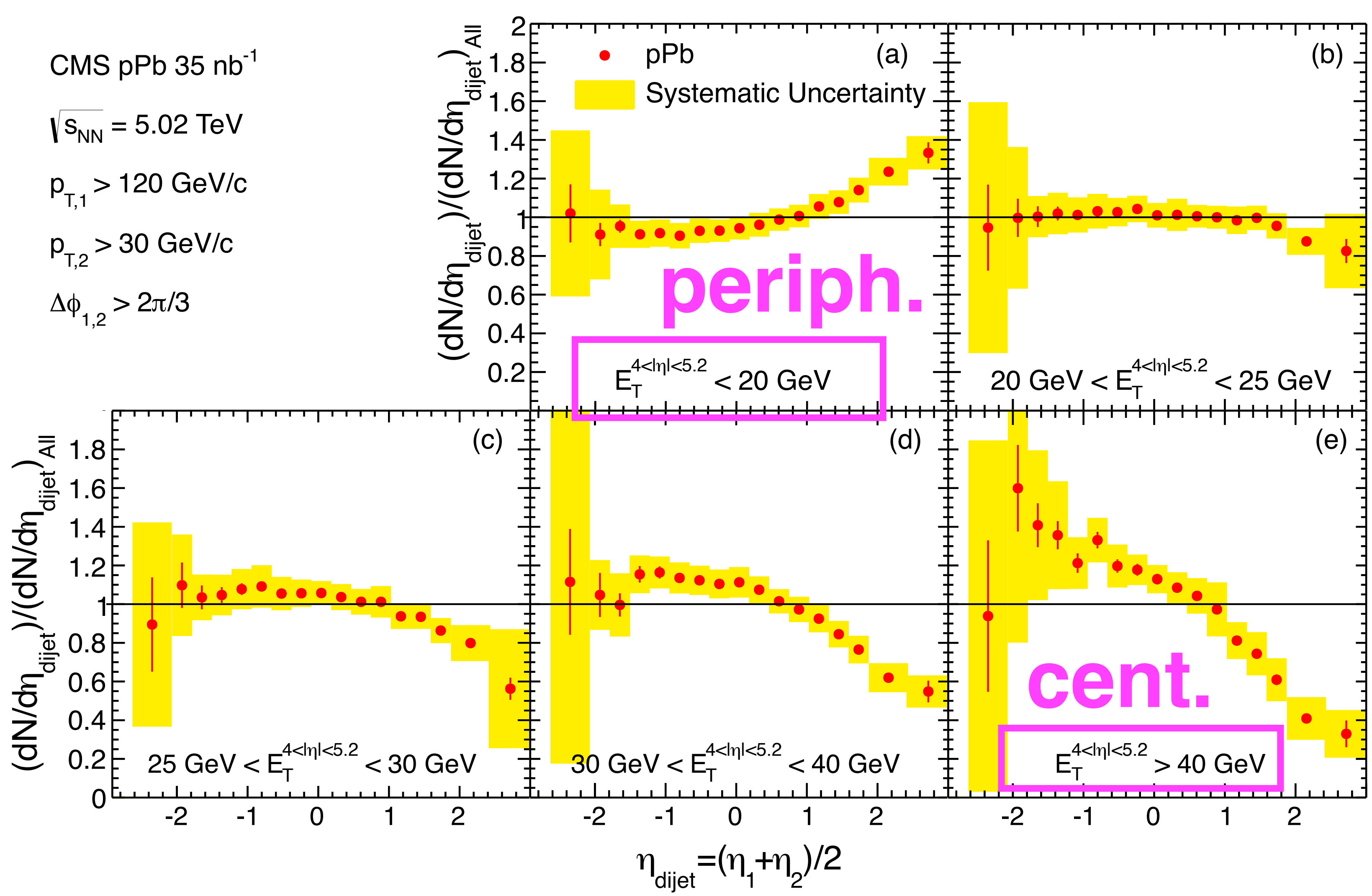
ATLAS-CONF-2014-024



Where is this in the CMS data?

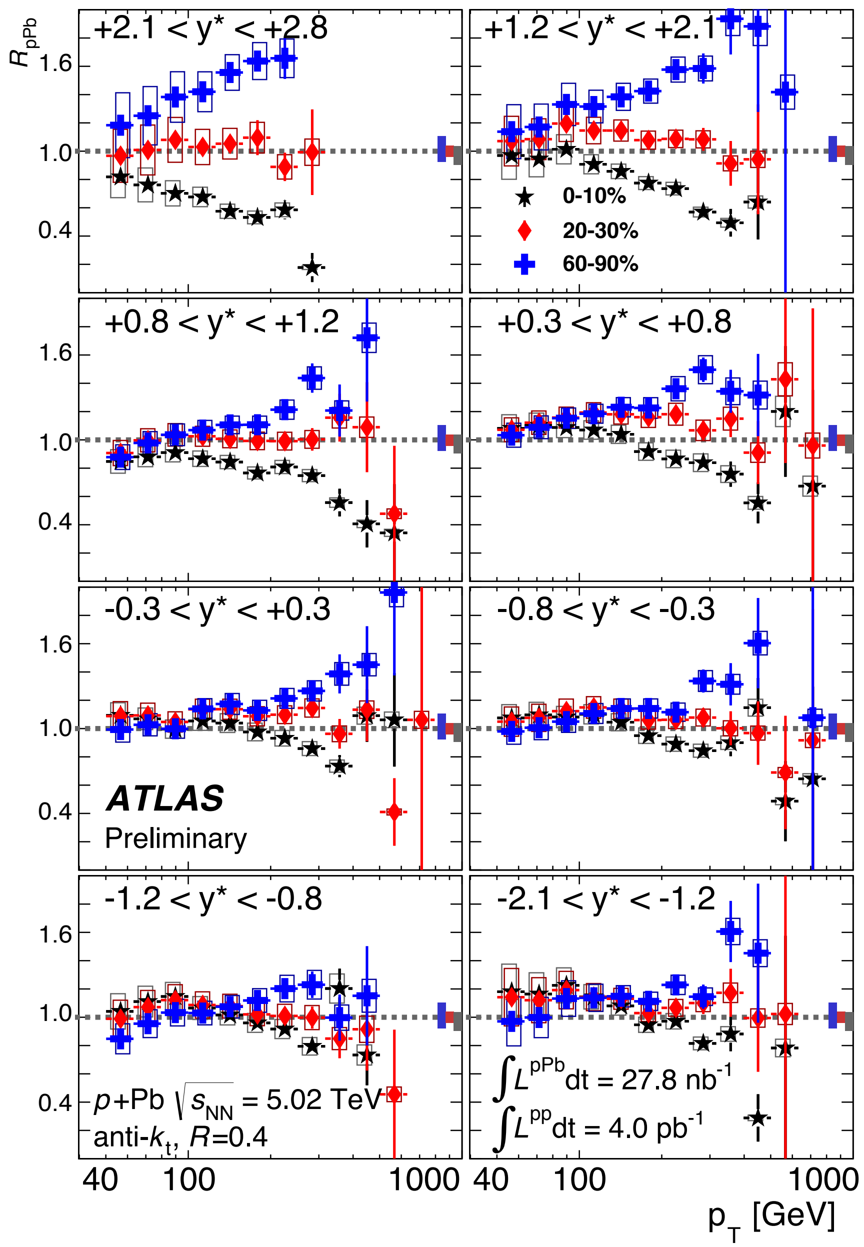
- Same effect visible in the CMS dijet $R_{C/MB}(\eta)$
  - enhancement in peripheral / suppression in central
  - increasing modification for more forward dijet systems





CMS HIN-13-001-PAS

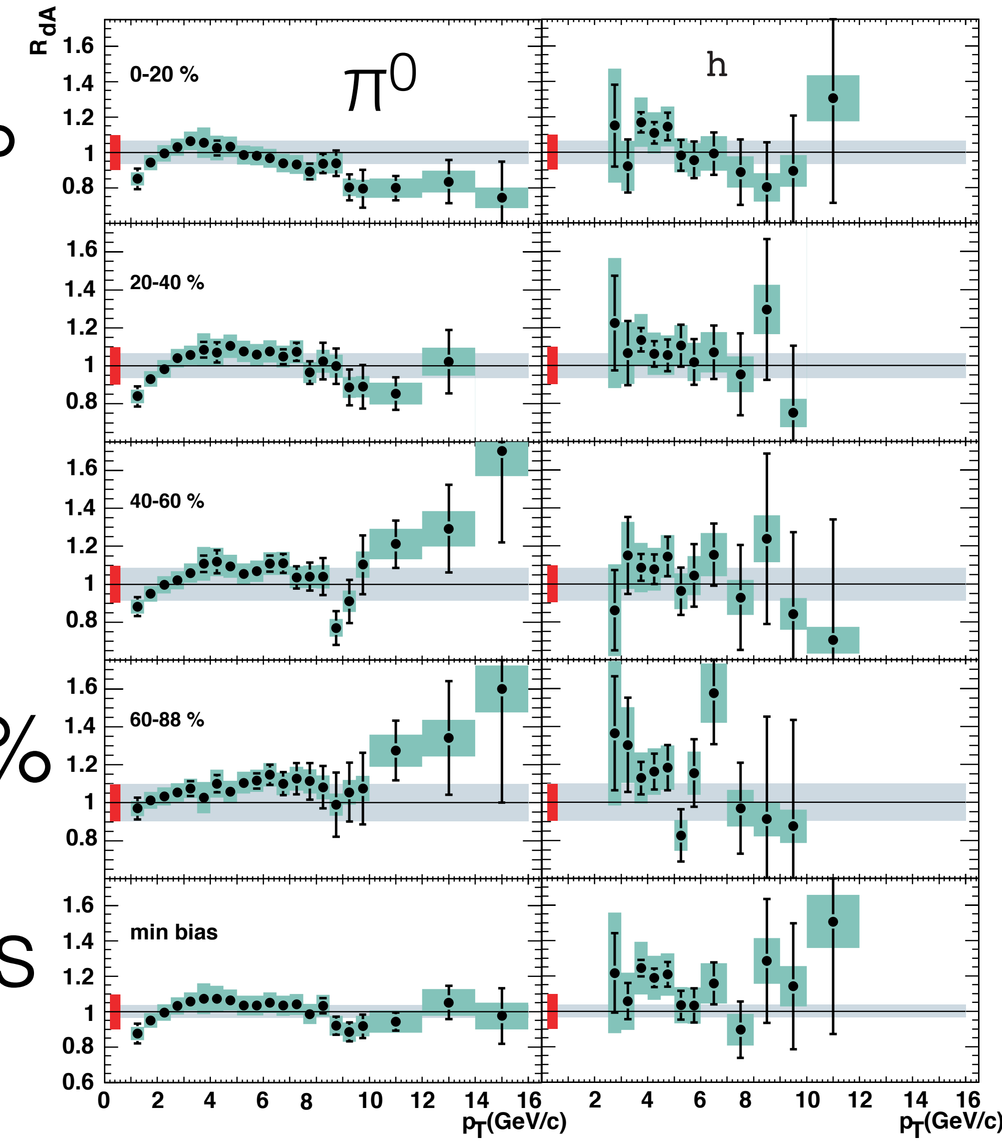
… and at RHIC?



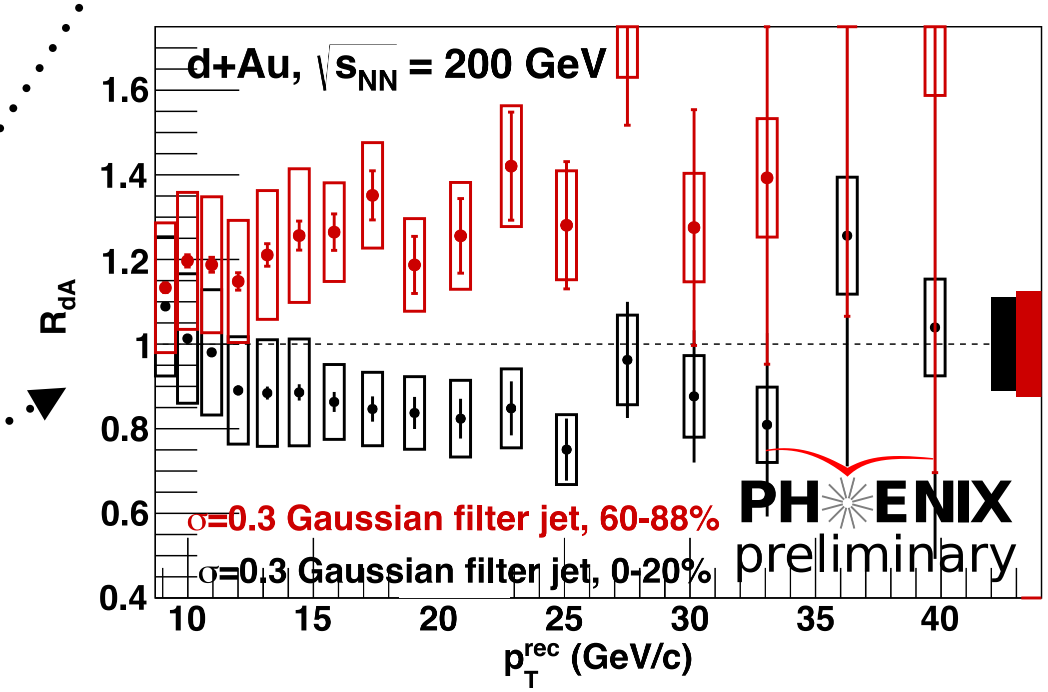
0-20%

60-88%

min. bias



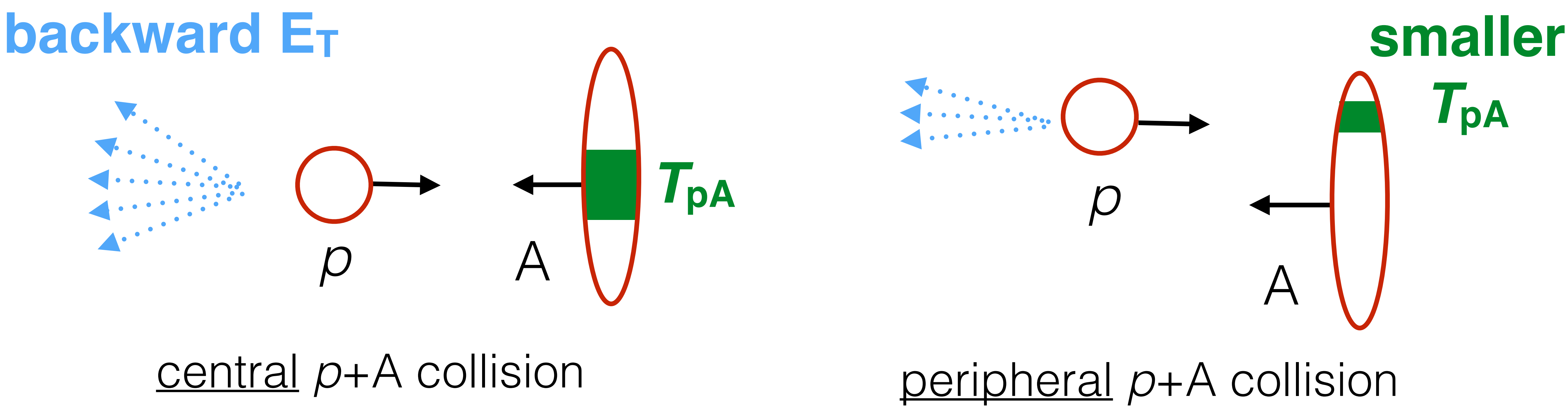
PHENIX, nucl-ex/0610036



10.1016/j.nuclphysa.2013.02.184

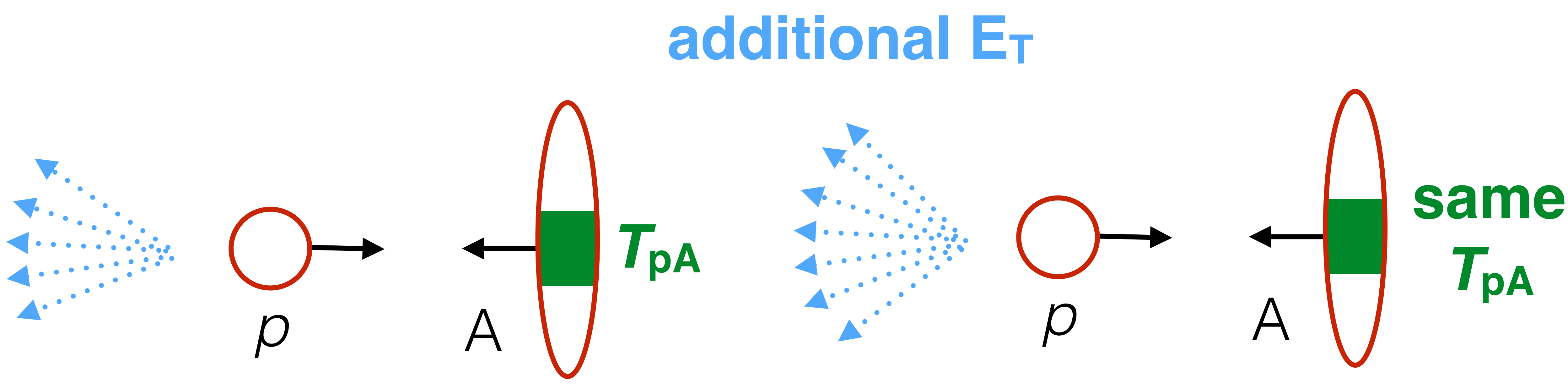
- Qualitatively similar to what has been observed (but not understood) by PHENIX
  - geometric scaling at intermediate p_T
  - central/peripheral "split" at high p_T

Geometric pictures of *p*+A collisions: I



- Simple picture of *p*+A geometry:
  - soft particle production in the downstream A direction grows with successive number of p-N collisions
  - thus, selecting on a range of E_T (or, e.g. multiplicity) picks out a set of collision geometries with N_{part}, N_{coll}, T_{pA}, etc., that we can estimate

Geometric pictures of *p*+A collisions: II

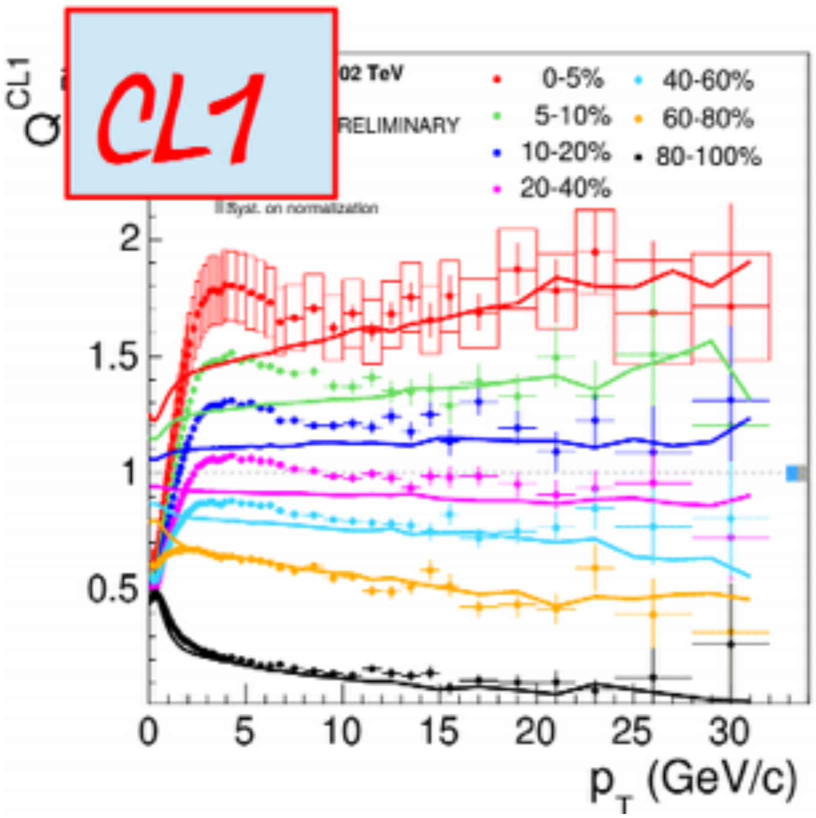


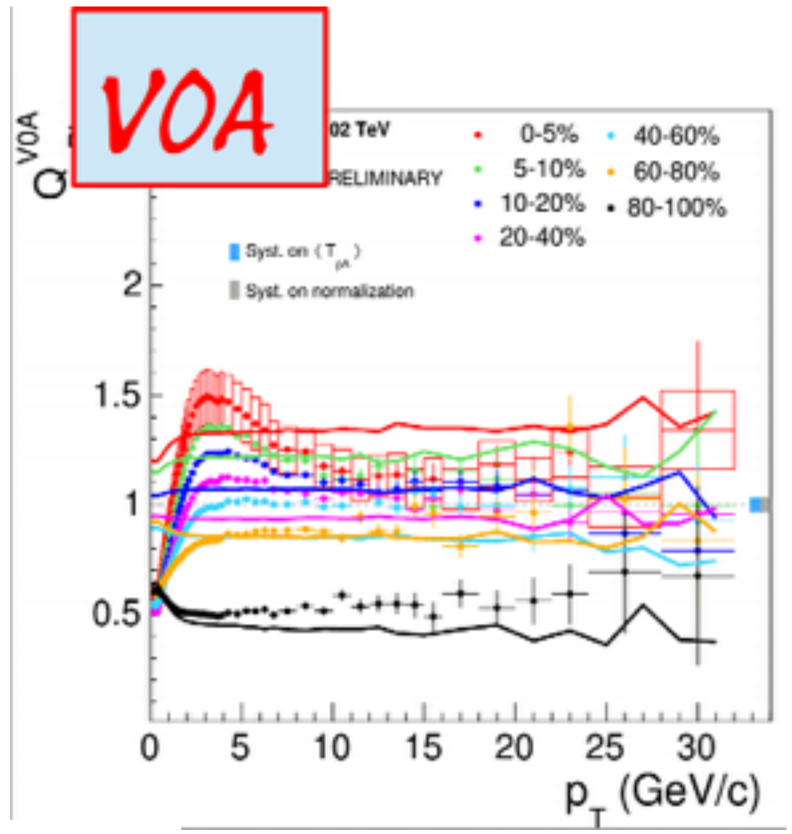
<u>central</u> *p*+A collision

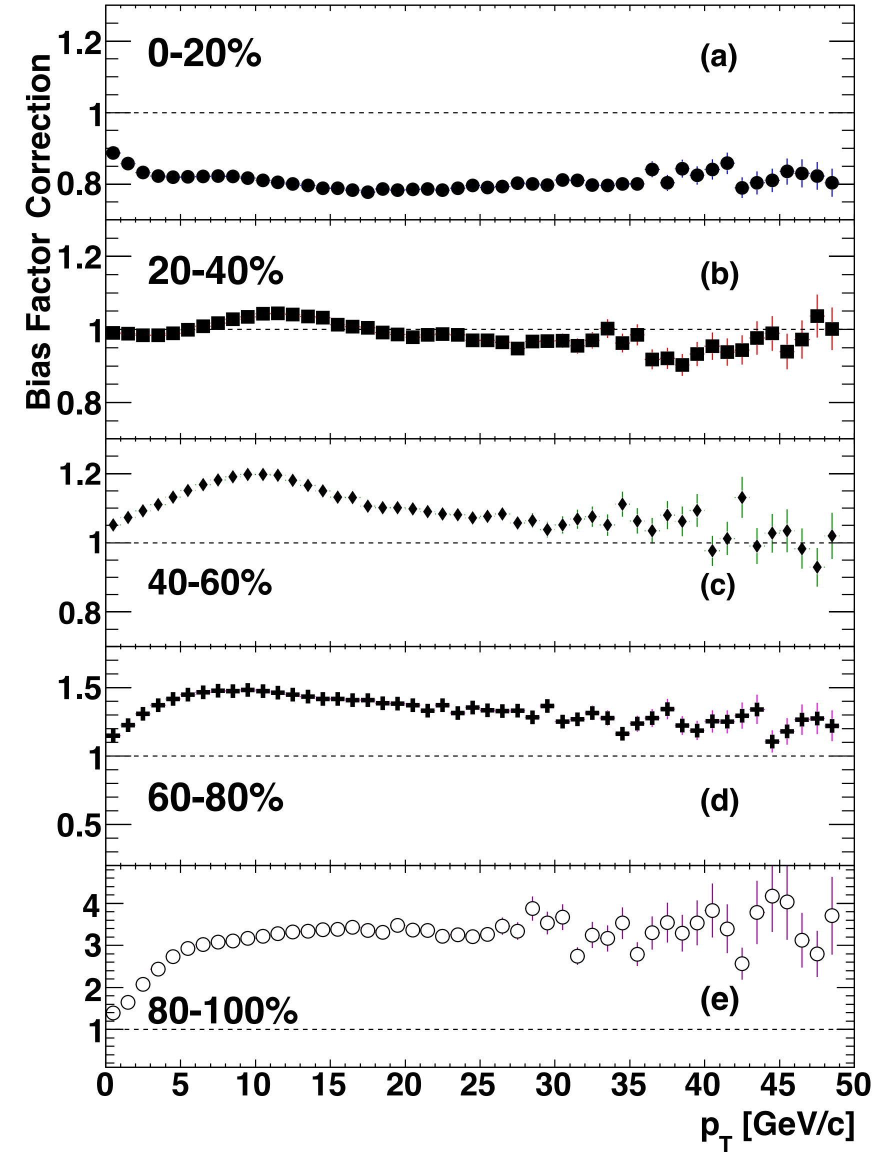
<u>central</u> *p*+A collision
with a hard process

- But the event activity can reflect the presence of a hard process in additional to just the collision geometry
  - known to be true in individual nucleon-nucleon collisions
- So selecting on high ΣE_T preferentially selects hard processes
  - this "autocorrelation" results in a slight mis-estimation of the true <N_{coll}>

Studies of centrality "bias"







PHENIX, nucl-ex/1310.4793

- Q_{pPb} spread between centrality

Reduces with increasing rapidity gap: CL1→V0M→V0A

A. Toia, QM14 talk

- 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

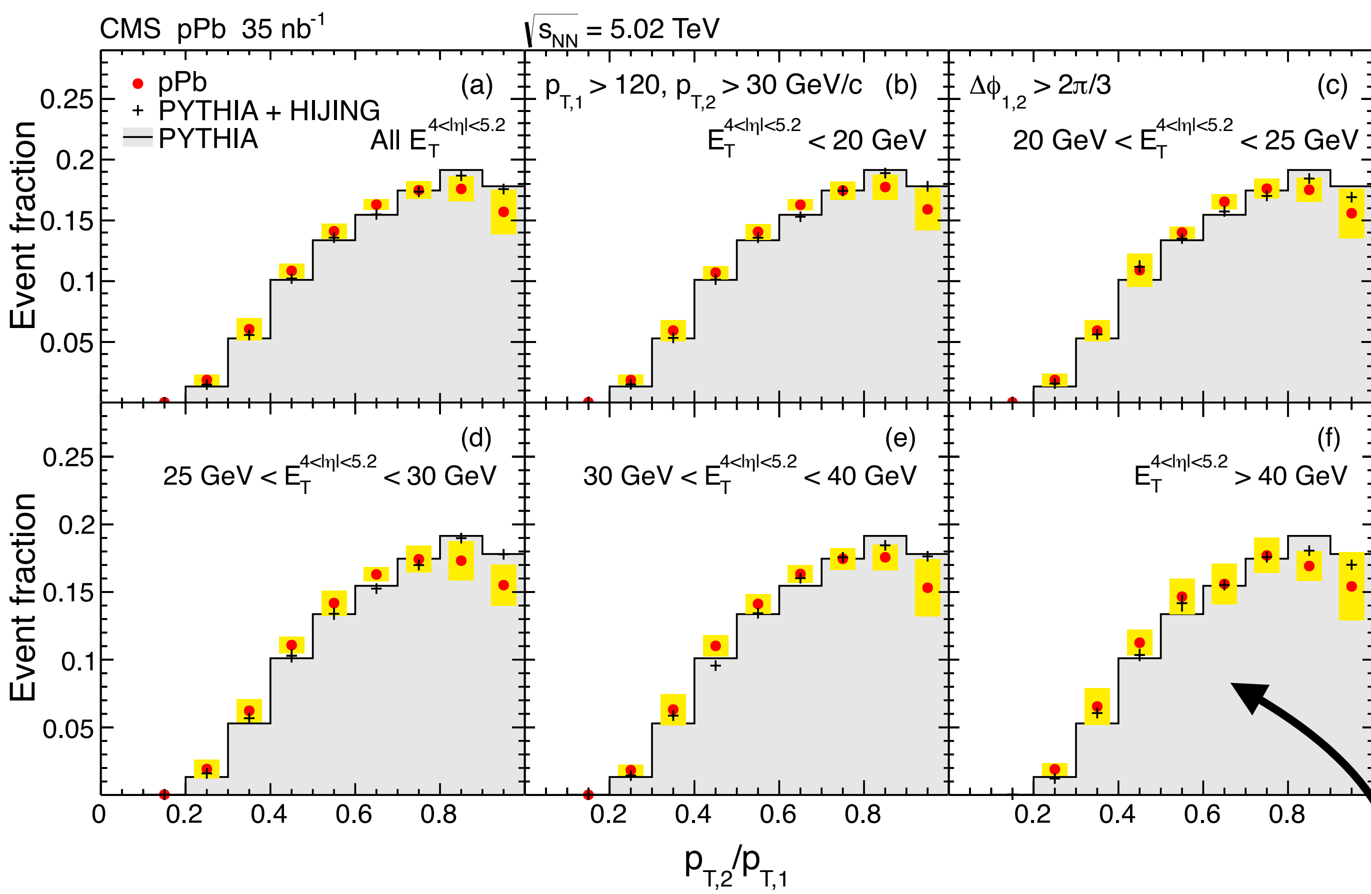
➡ the high-p_T LHC data show the <u>opposite</u> effects!

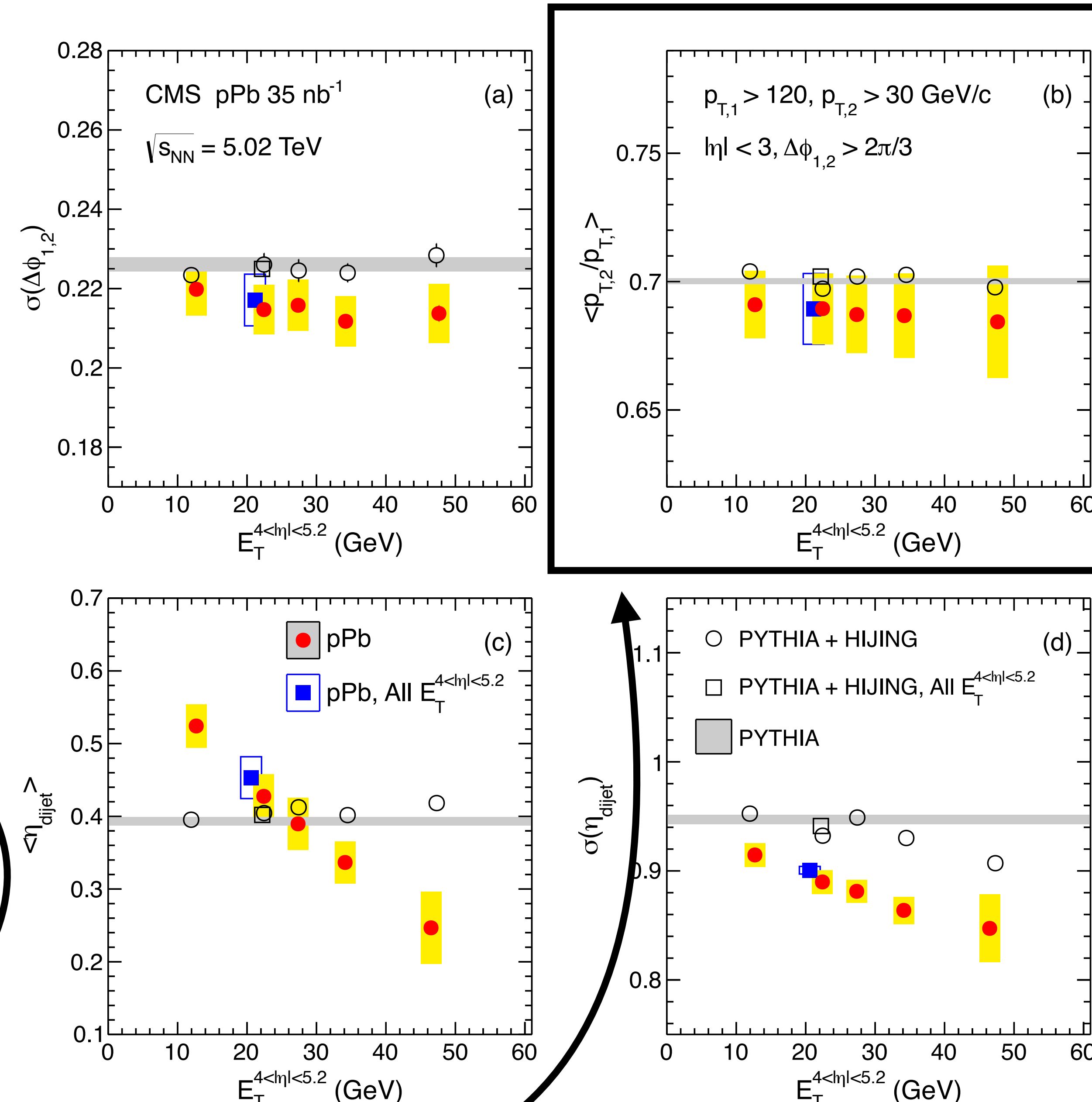
Is there jet quenching in small systems?

Final state effects in p+Pb?

CMS HIN-13-001-PAS

CMS di-jet





$p_T^{subleading}/p_T^{leading}$ distributions

mean p_T ratio vs. centrality

- No discernable signal of quenching for <u>> 120 GeV jets</u>

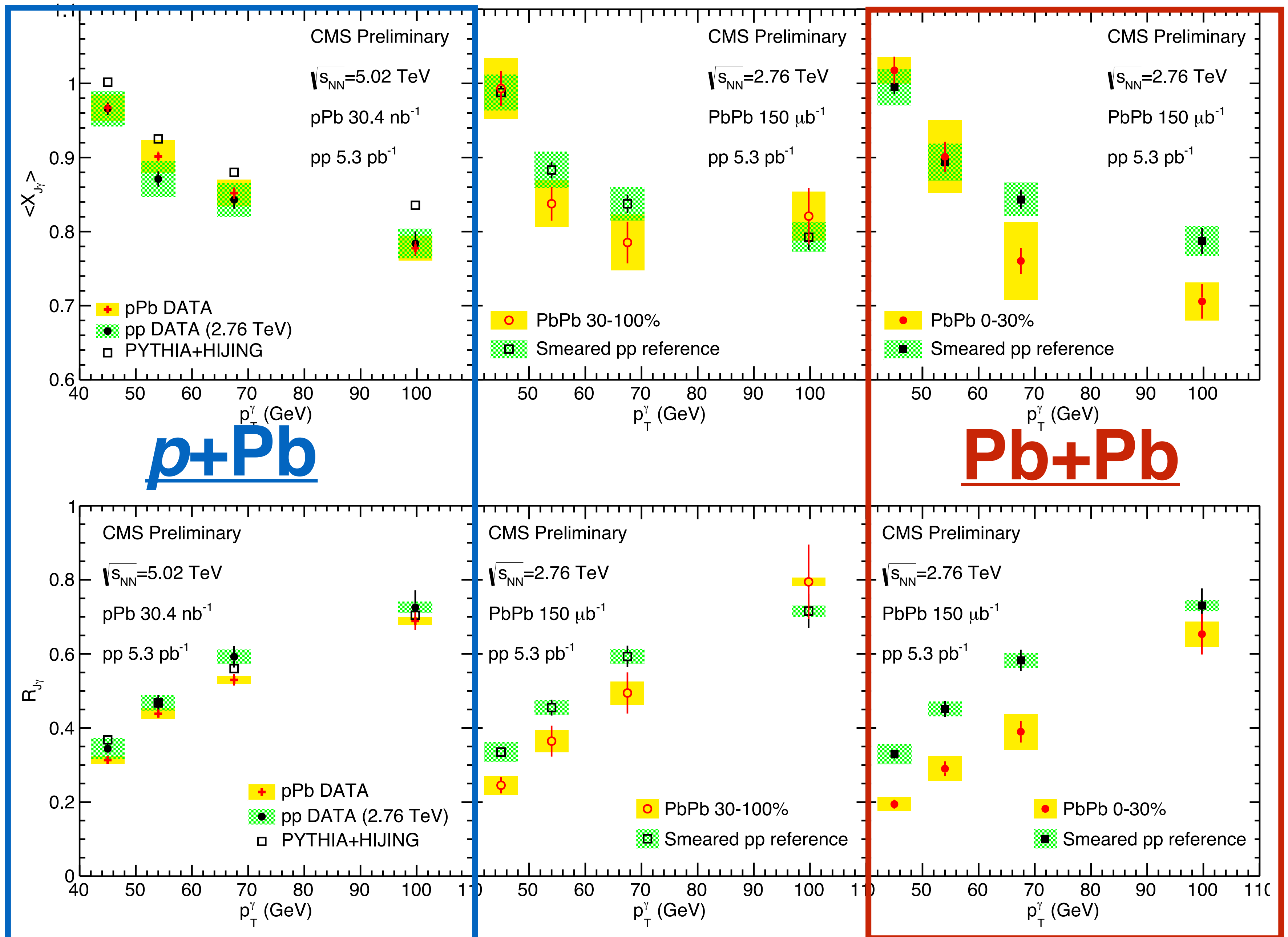
Final state effects in *p*+Pb?

CMS HIN-13-006-PAS

CMS ɣ-jet

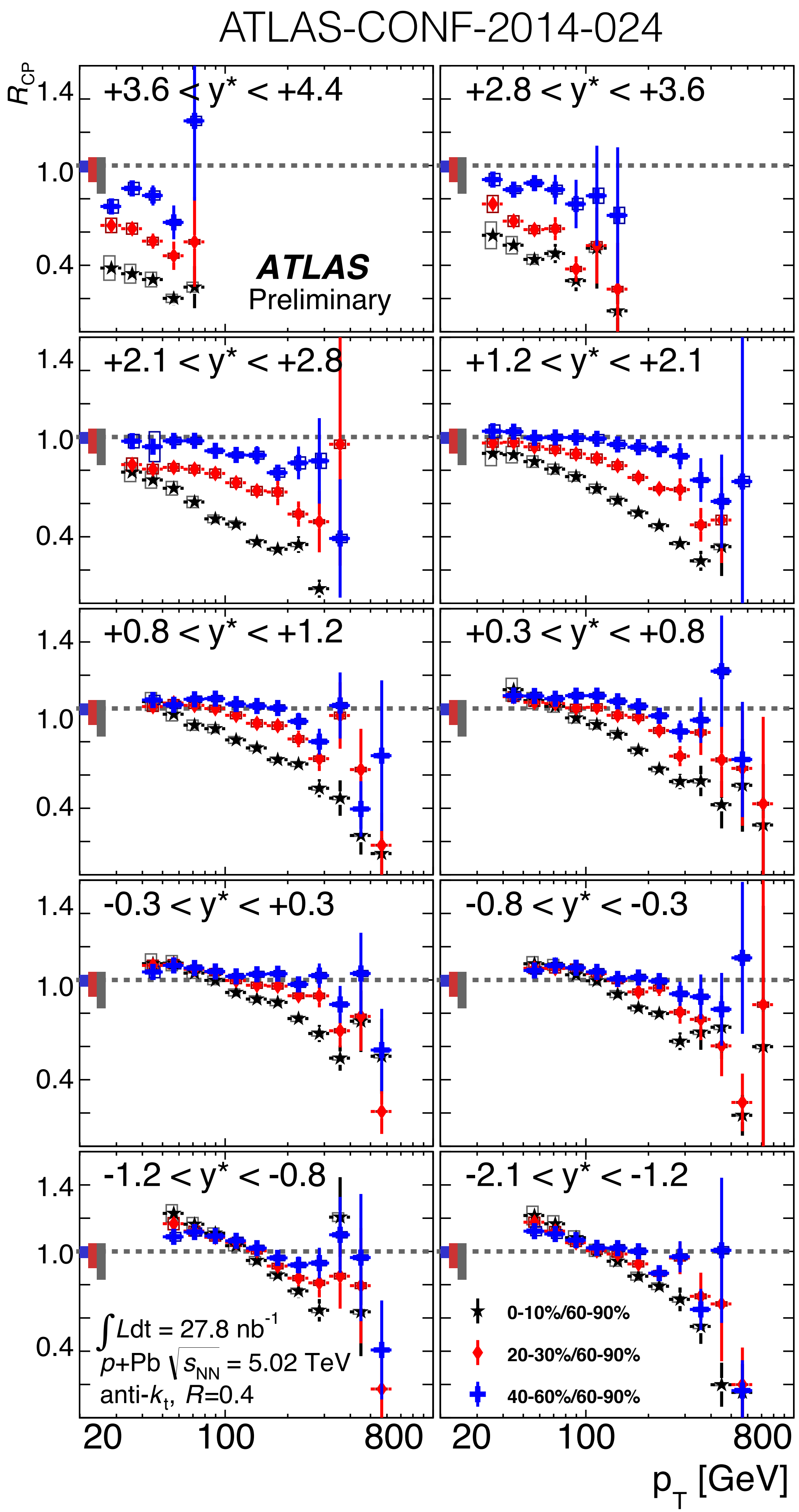
mean p_T^{jet}/p_T^{γ} ratio

fraction of photons with a jet



- No discernable signal of quenching for 40-100 GeV jets

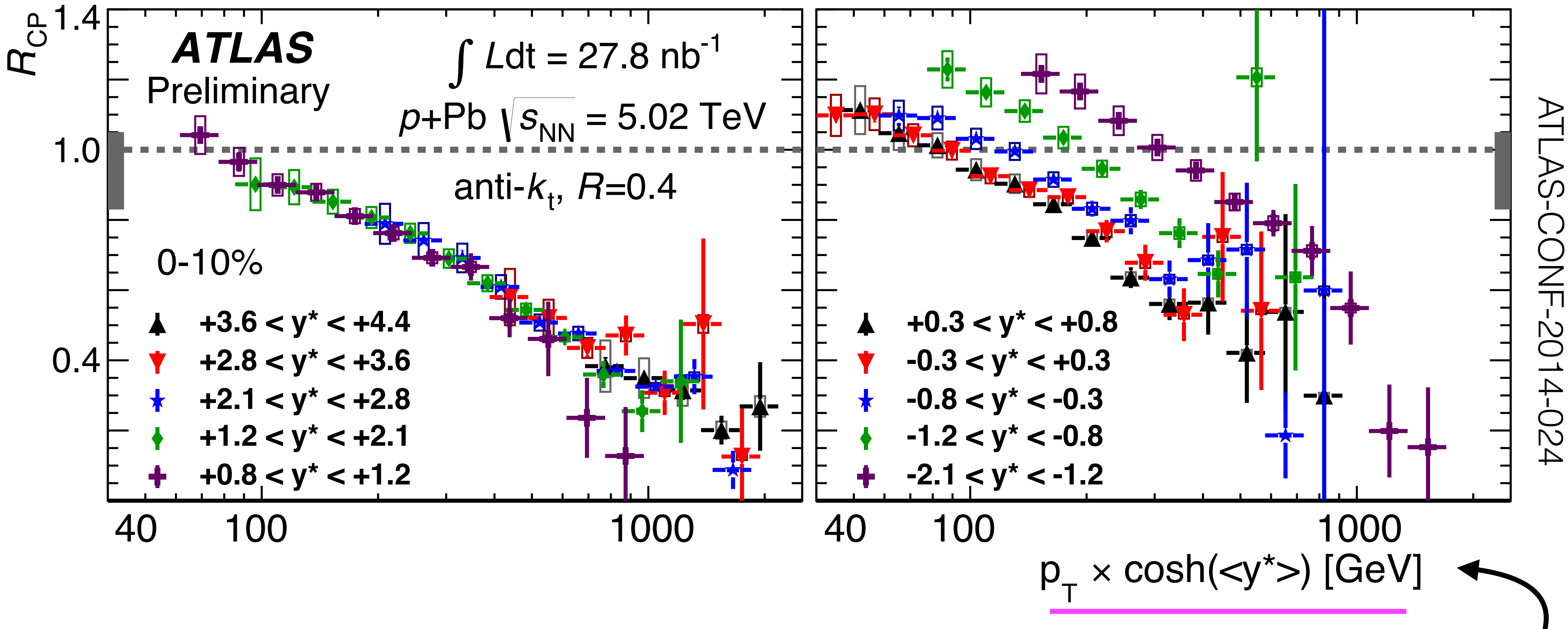
Can we observe rare configurations of the proton wavefunction?



Patterns in the *p*+Pb data?

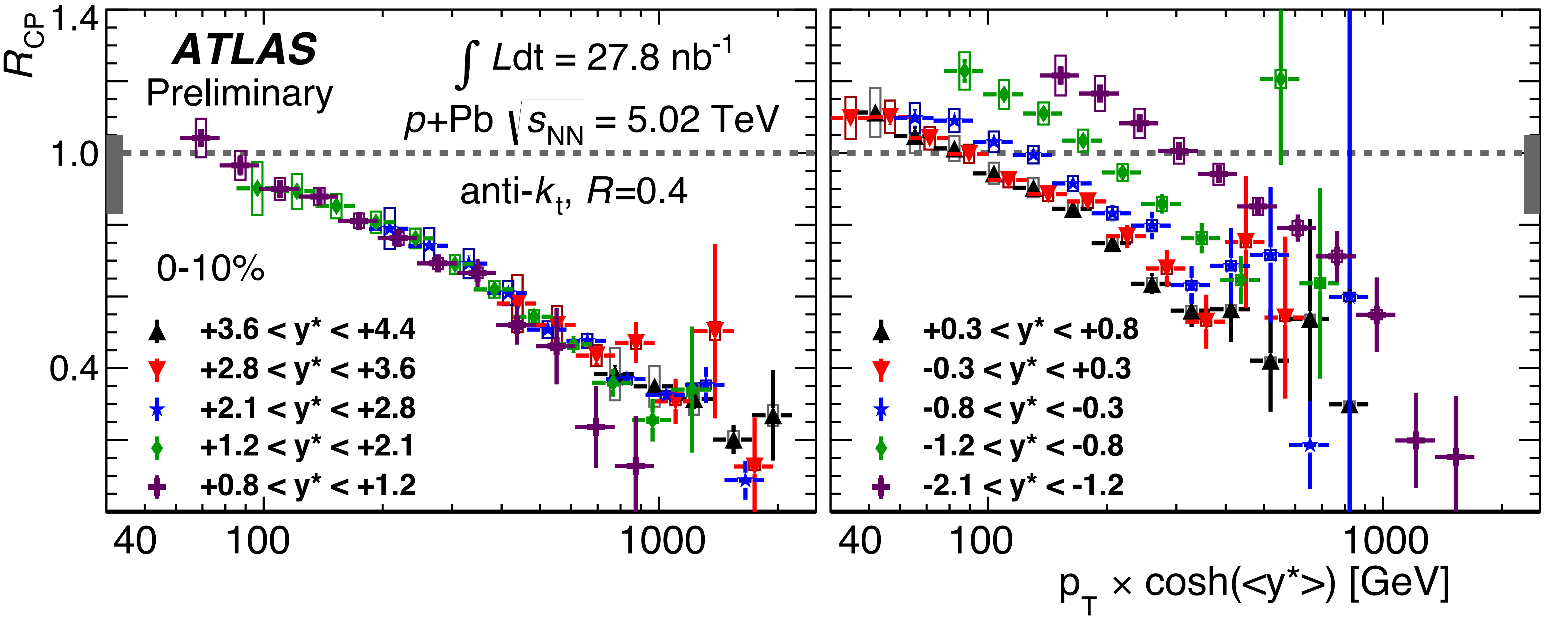
- Since this isn't a final state effect, perhaps it is an initial state one?
  - taken at face value, this implies large, impact parameter-dependent modifications to the nPDFs
- But maybe there is more information hidden in the pattern or modifications…
  - Another look at trends in the data: ATLAS jet R_{CP}
  - smooth evolution in p_T, centrality, y^*

Initial state effects in *p*+Pb?



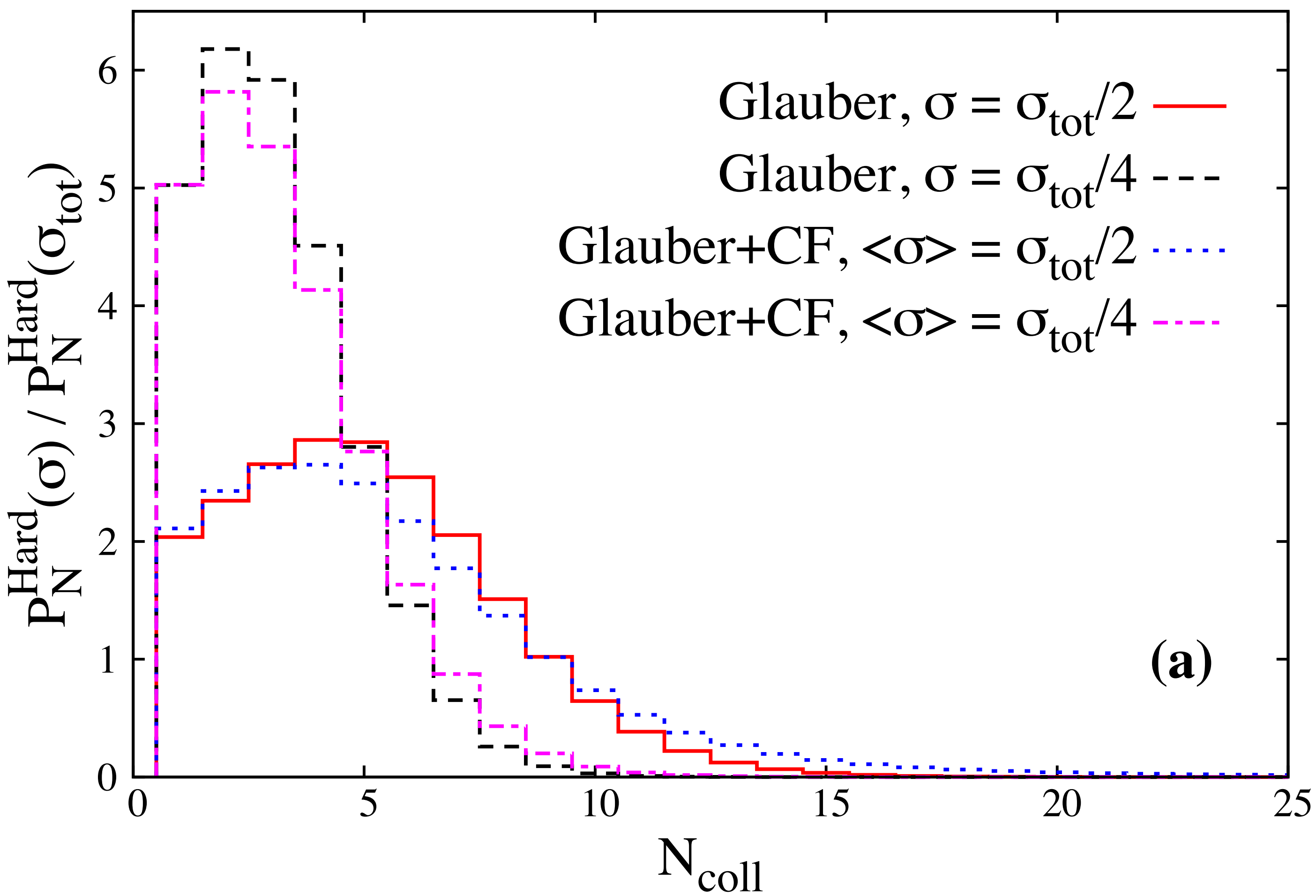
- Replot the ATLAS data at multiple rapidities vs. the <u>total jet energy</u> *p*
  - R_{CP} at forward & mid-rapidity falls along a common curve!
    - Modifications at all y^* are part of the same phenomenon
- Simplest explanation: the modifications are related to x_p
  - $R_{CP}(p_T, y) = R_{CP}(p)$ (or, $= R_{CP}(x_p)$)

Initial state effects in p+Pb?



An initial state effect … in the *proton*!

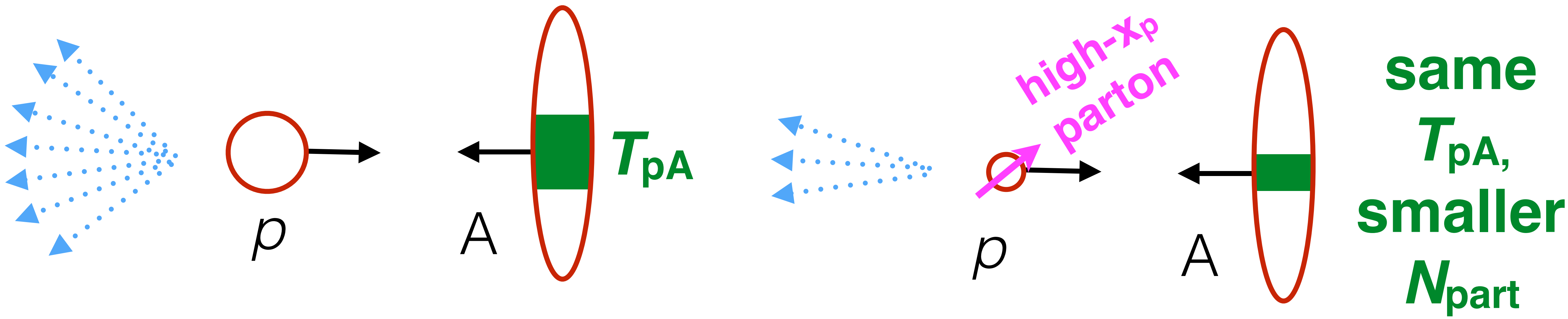
Proton "size" effects



fluctuating proton interaction strength
Alvioli, Frankfurt, Guzey, Strikman
hep-ph/1402.2868

- Idea: anti-correlation between high x_p-parton and proton interaction strength
  - asking for high x_p processes pick out "smaller" proton configurations
  - or, high-x_p configurations have tighter spatial parton-parton correlations
- In the Glauber picture, this smaller interaction strength appears as a smaller effective σ_{NN} in high-x_p events

Geometric pictures of p+A collisions: III



"minimum bias" p+A collision at some b

same b, but proton wavefunction with large x_p

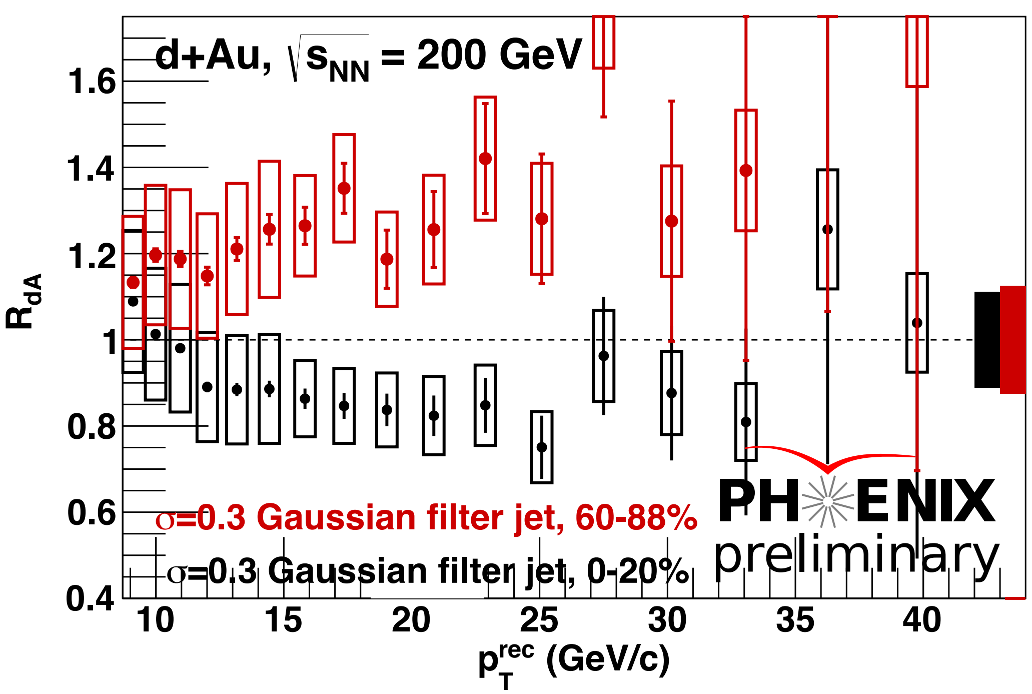
- At fixed b, a "smaller" (more weakly interacting) proton undergoes fewer collisions
  - and produces a smaller centrality signal
- Thus, the nucleus acts as a "filter" on the proton size
  - in the centrality framework, this *kinematic* signal appears as a *geometric* signal

What has the LHC taught us about RHIC data?

Shadowing in *d*+Au: R_{dAu}

- The *p*+Pb results suggest that modifications at low-p_T & y ≫ 0 are part of the same phenomenon as modifications at high-p_T & y = 0
  - because both kinematic regions are dominated by large x_p

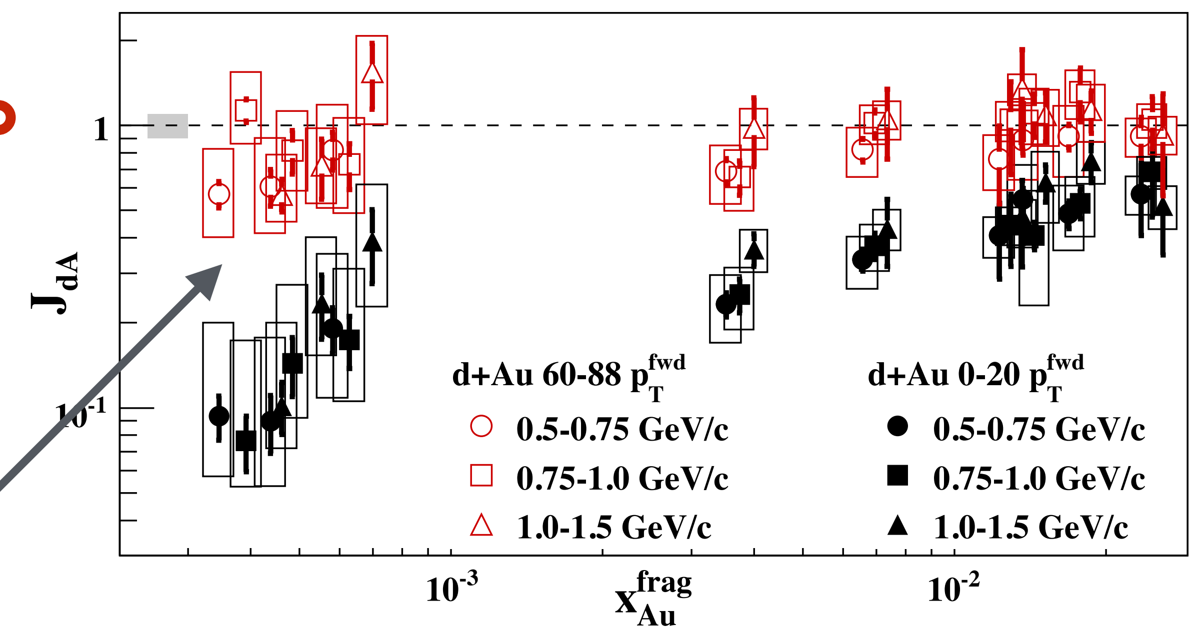
jet R_{dAu} 10.1016/j.nuclphysa.2013.02.184



60-88%

0-20%

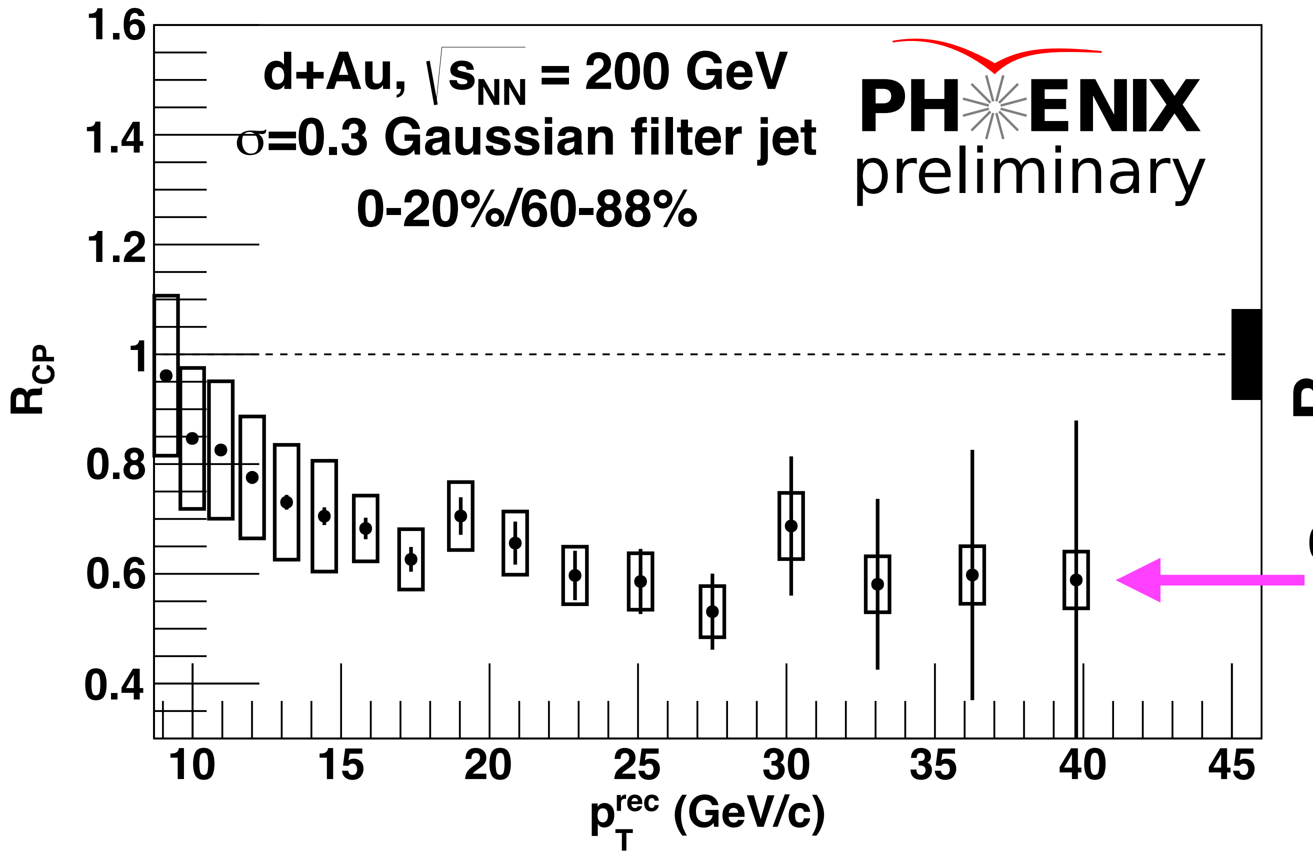
PRL 107 172301 (2011) **di-hadron J_{dA}**



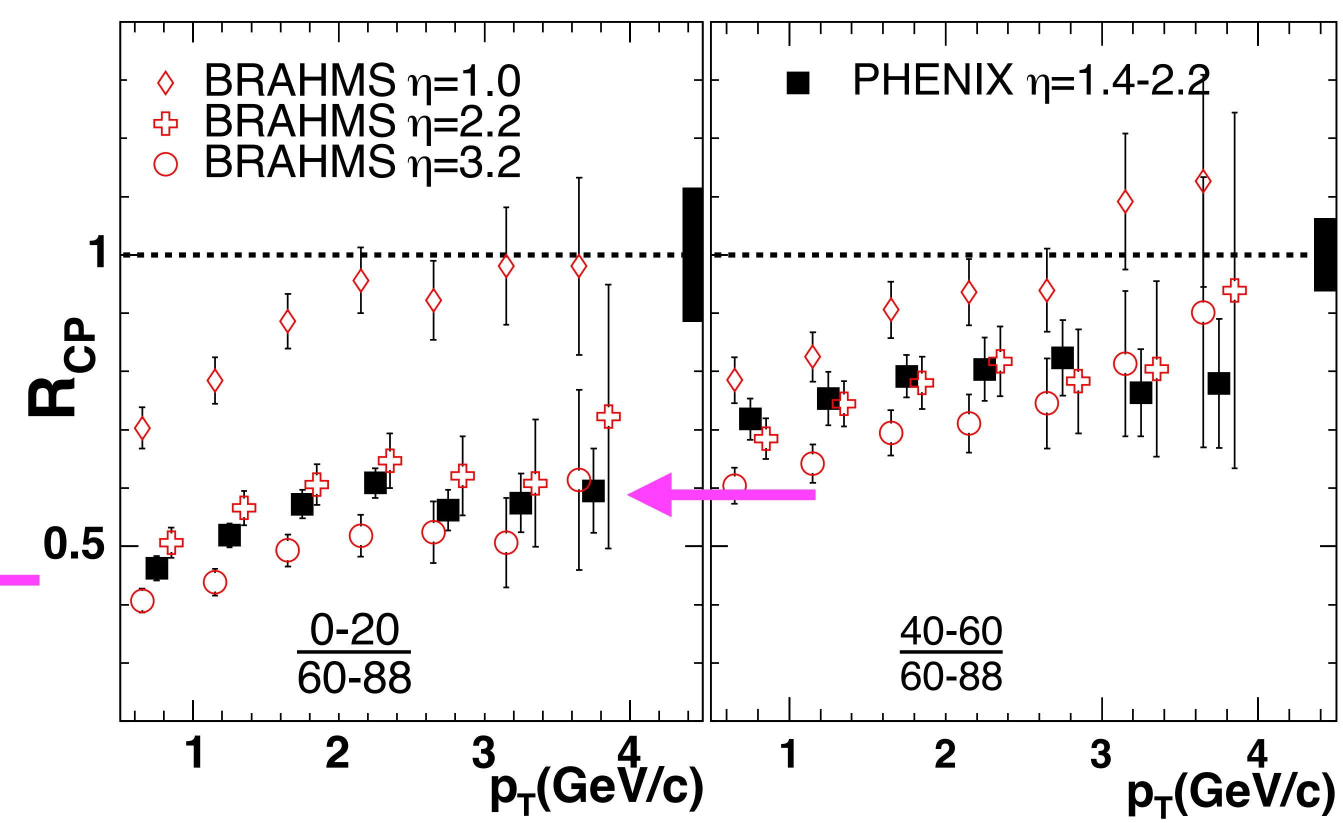
- Strong centrality dependence in forward *d*+Au measurements:
  - is it really *b*-dependent shadowing / saturation?
  - … or a proton size effect? what other measurements have new interpretations?

Shadowing in d+Au: R_{CP}

jet R_{CP} 10.1016/j.nuclphysa.2013.02.184



PRL 94 082302 (2005) **hadron R_{CP}**



- R_{CP} of ≈0.6 for p_T > 15 GeV jets at η≈0 at PHENIX
- R_{CP} of ≈0.6 for p_T > 2-3 GeV hadrons at η≈2 at PHENIX & BRAHMS
  - (e.g. the hadrons may originate from 3 GeV × cosh(2) / 0.7 ≈ 15 GeV jets)
- There may very well be real shadowing effects in the forward RHIC data
  - but the ATLAS results strongly imply that these kinematic regions are, at least partially, reflecting to the same phenomenon

What should we expect from *p*+Au?

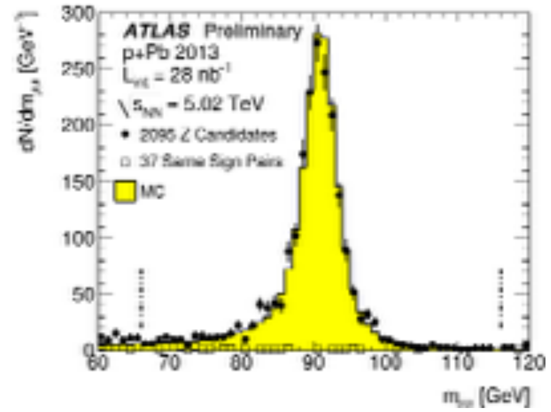
- RHIC will run 200 GeV *p*+Au in 2015
  - in particular, PHENIX will have substantial new capabilities in the forward direction with the MPC-EX
    - allowing the measurement of R_{pAu} at mid-and forward rapidity
- If these modifications are due to initial proton state effects,
  - *p*+Au will have larger effects than *d*+Au
    - since the other nucleon in the deuteron must certainly wash out the proton "size" effect to some extent
  - and there will be particularly large centrality-dependent modifications in the forward direction
    - but it will *not* be a nuclear initial state effect
- Any friendly bets?

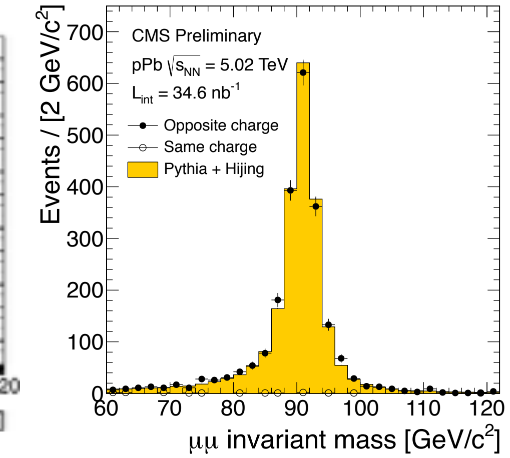
Conclusion

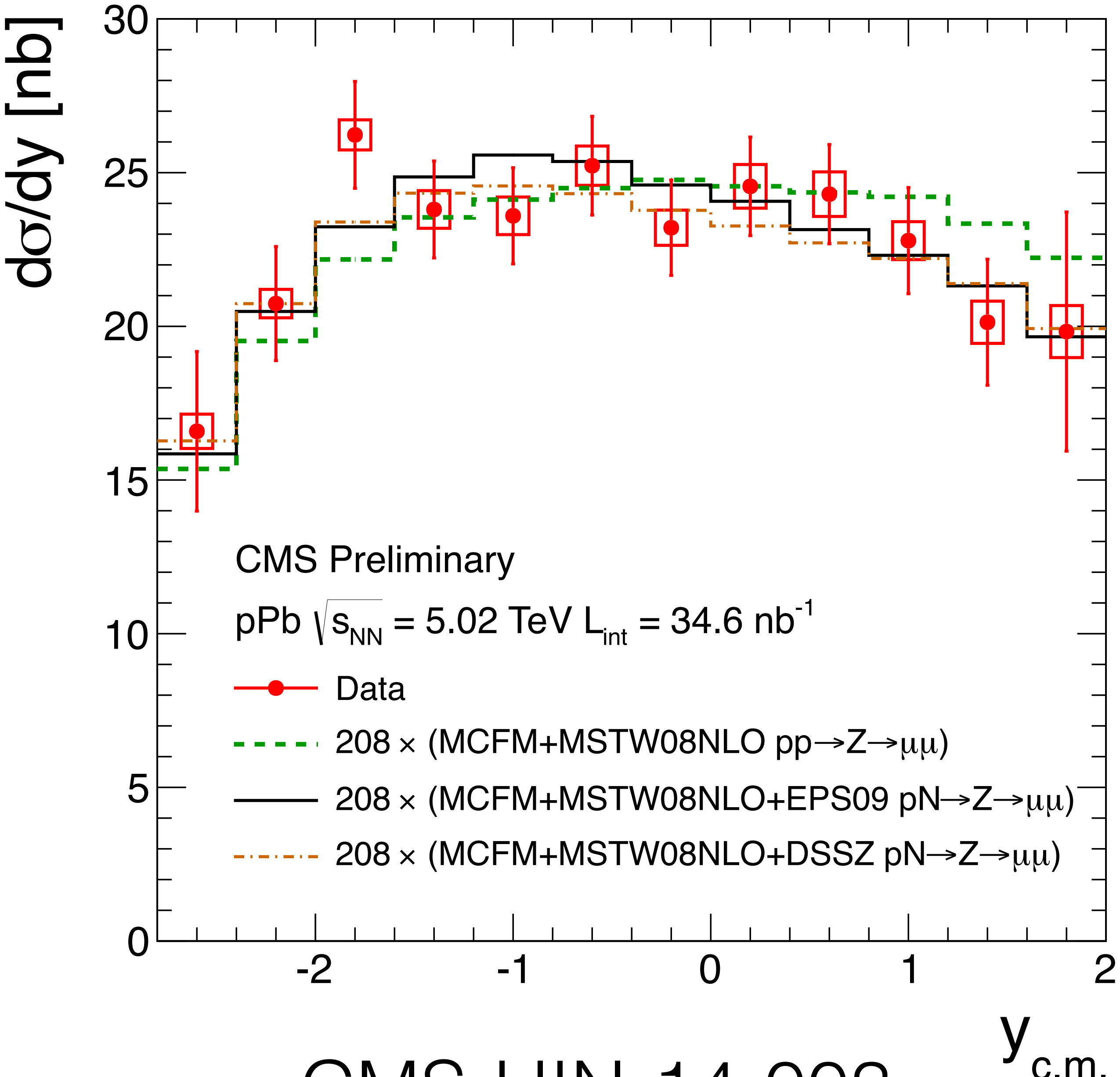
- Single particle and jet results are currently a challenge for nPDF-based frameworks
    - complicated by the lack of a clean *pp* reference
    - need more information (on flavor dependence, possible modification of fragmentation…)
- No evidence for jet quenching in *p*+Pb over a large kinematic range
- Proton initial state effects may play a role in all high-p_T centrality dependent measurements
    - and, especially, in low-p_T forward measurements
    - can be attributed to a smaller proton "size" associated with high-x_p configurations
- These give us new insight into understanding *d*+Au data, and interesting predictions for *p*+Au

Backup

Z production in *p*+Pb







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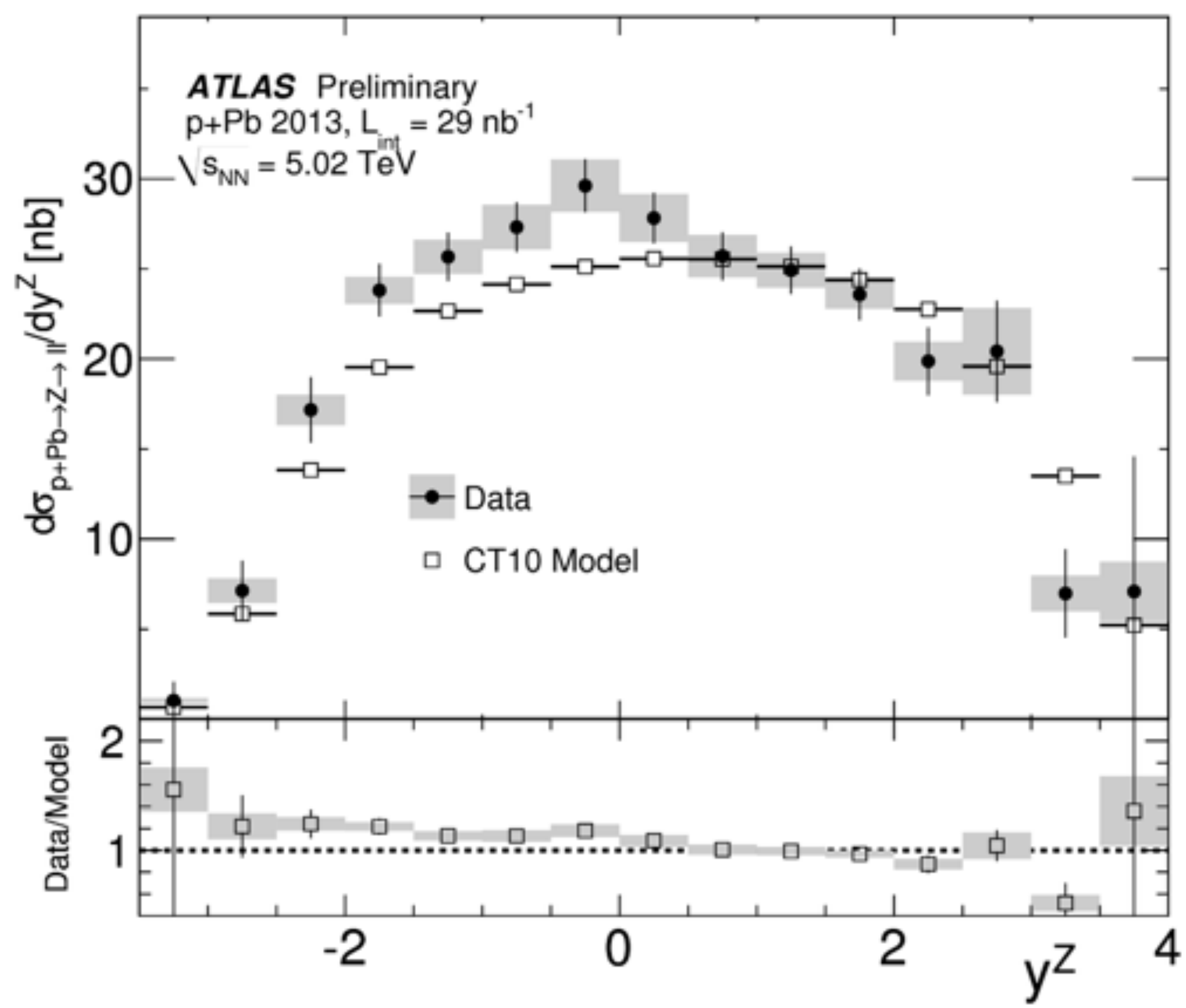
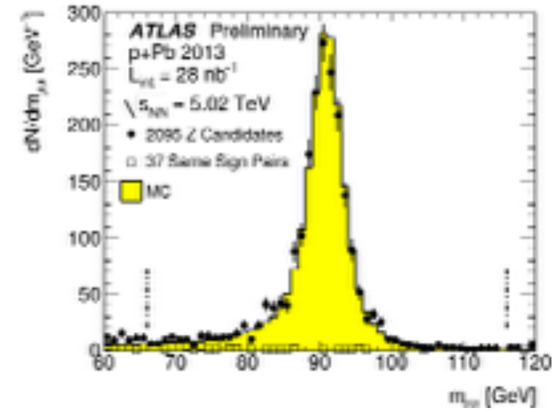
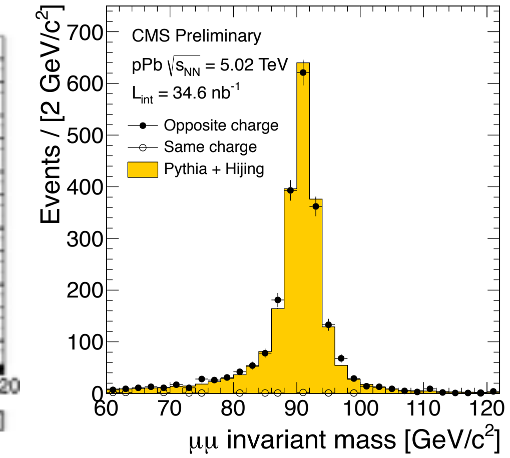
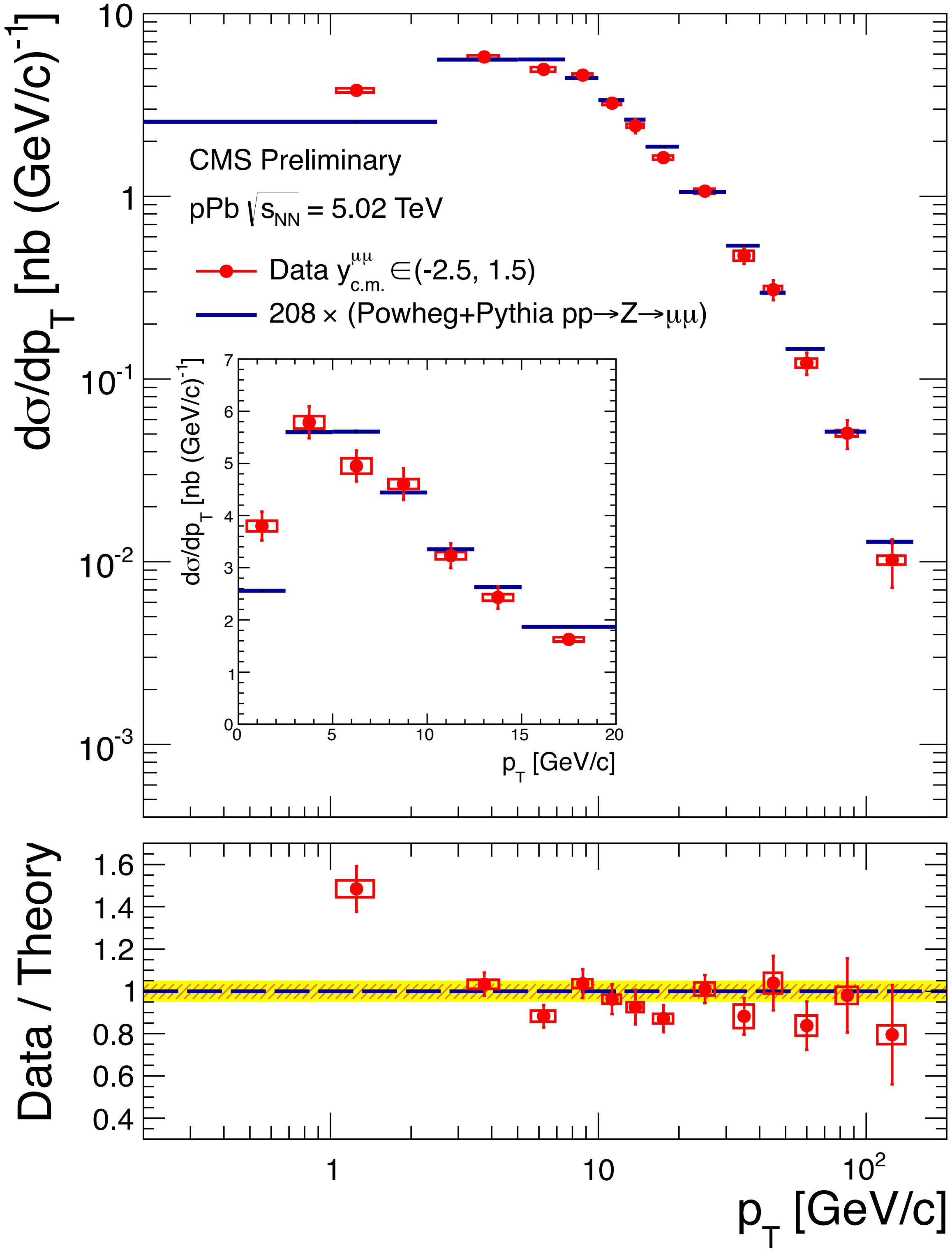


ATLAS-CONF-2014-020

Z production in *p*+Pb







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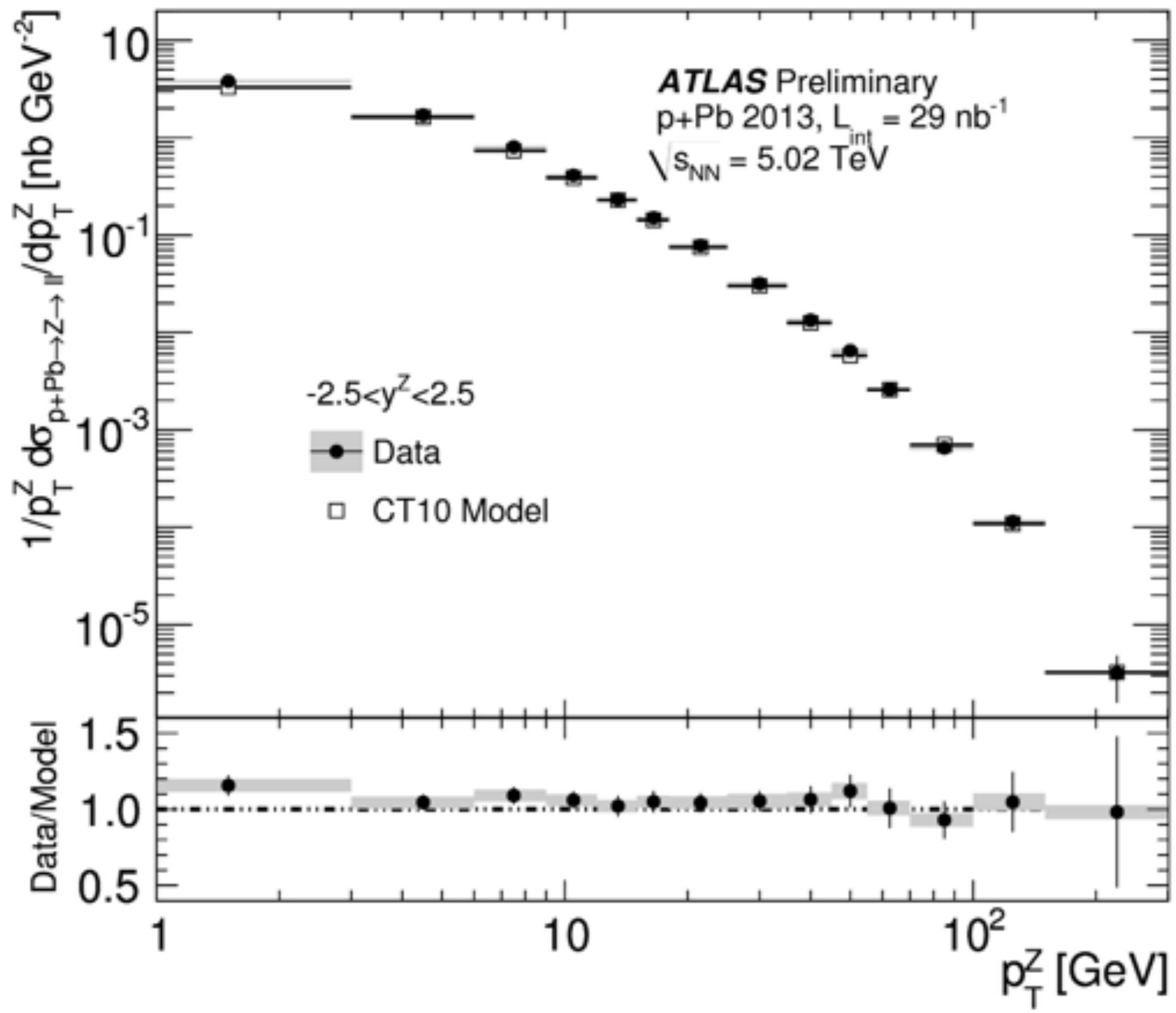

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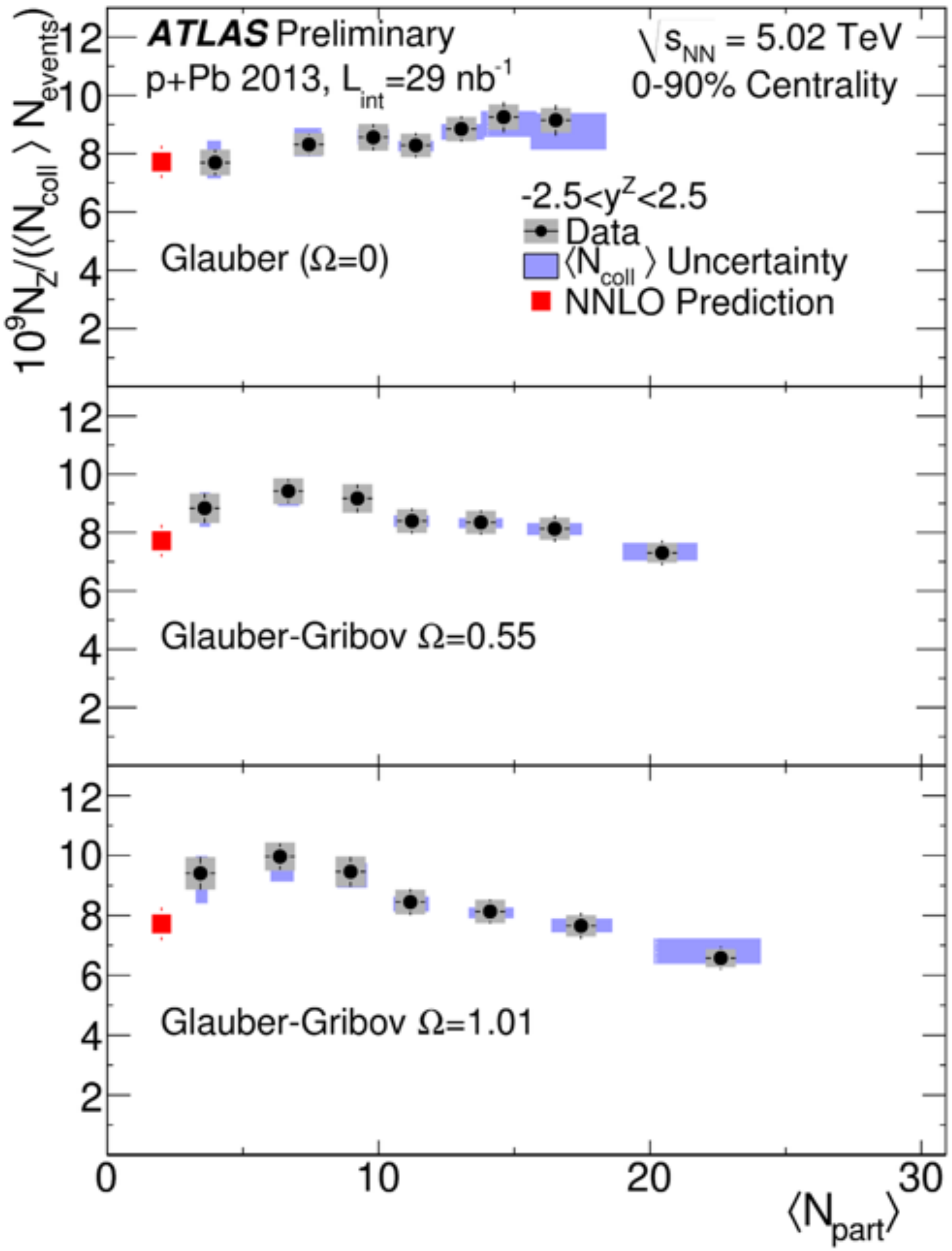
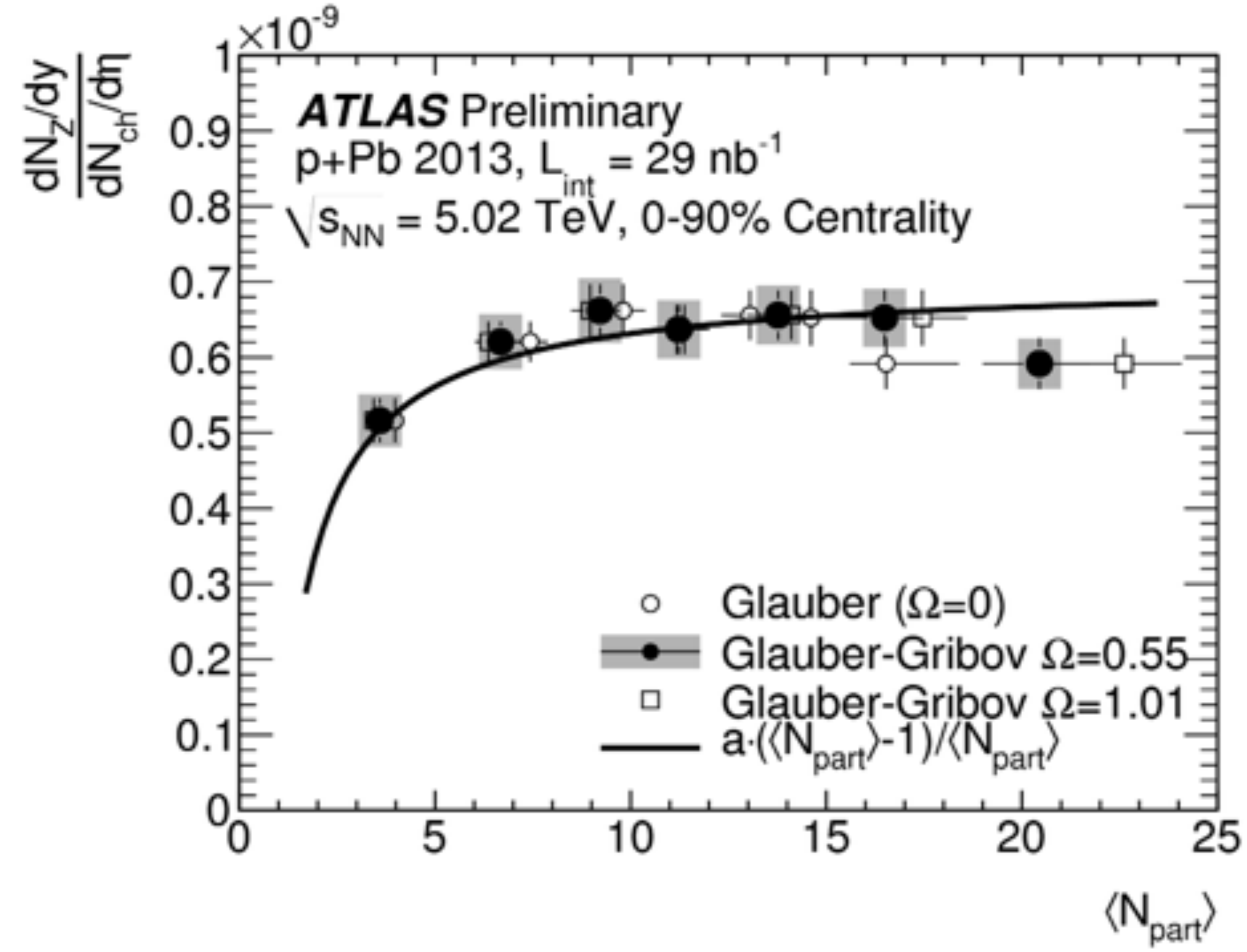
Z production in p+Pb





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W and *b*-jet production in *p*+Pb