Jets in small systems

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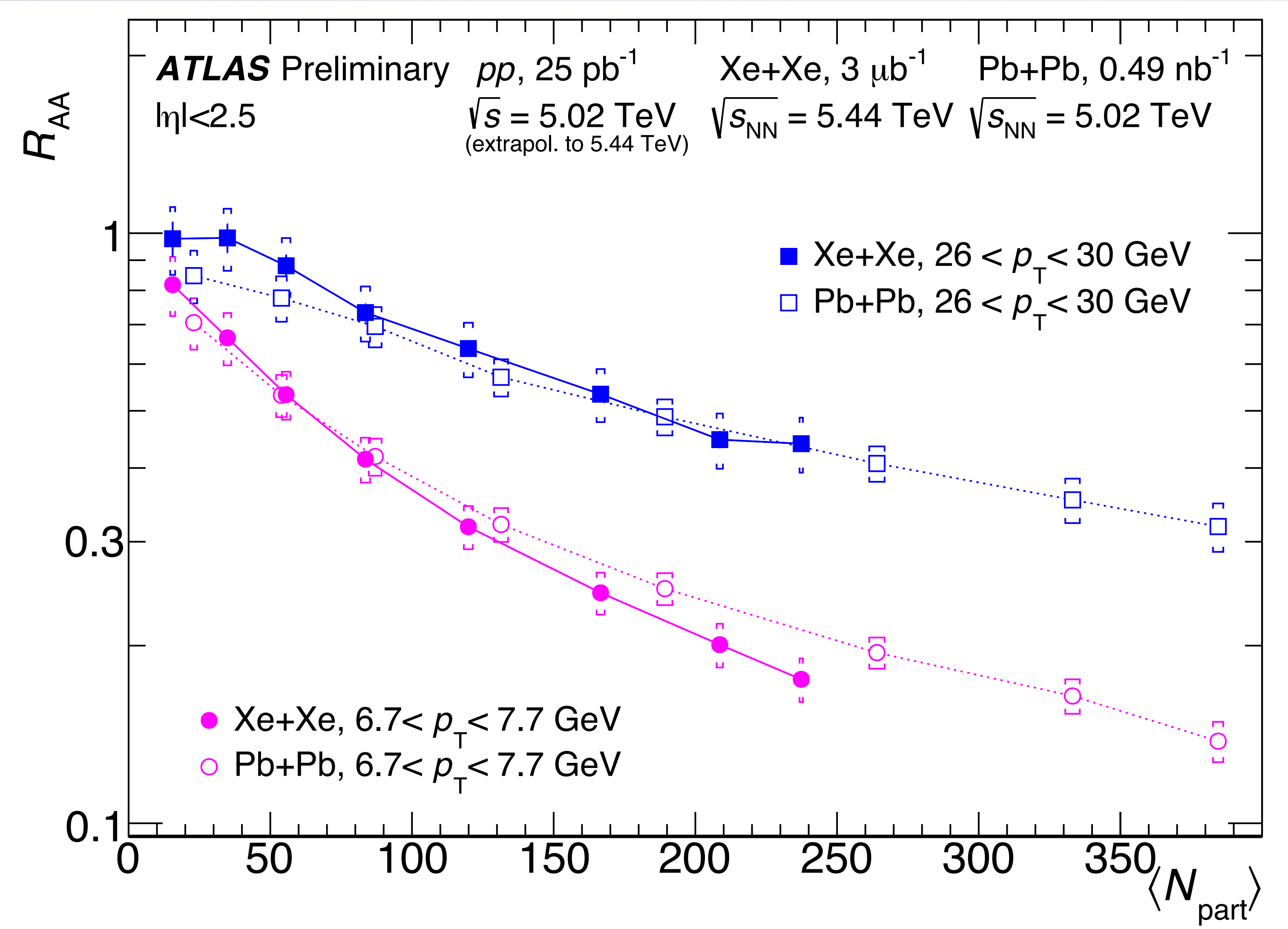
24 July 2018

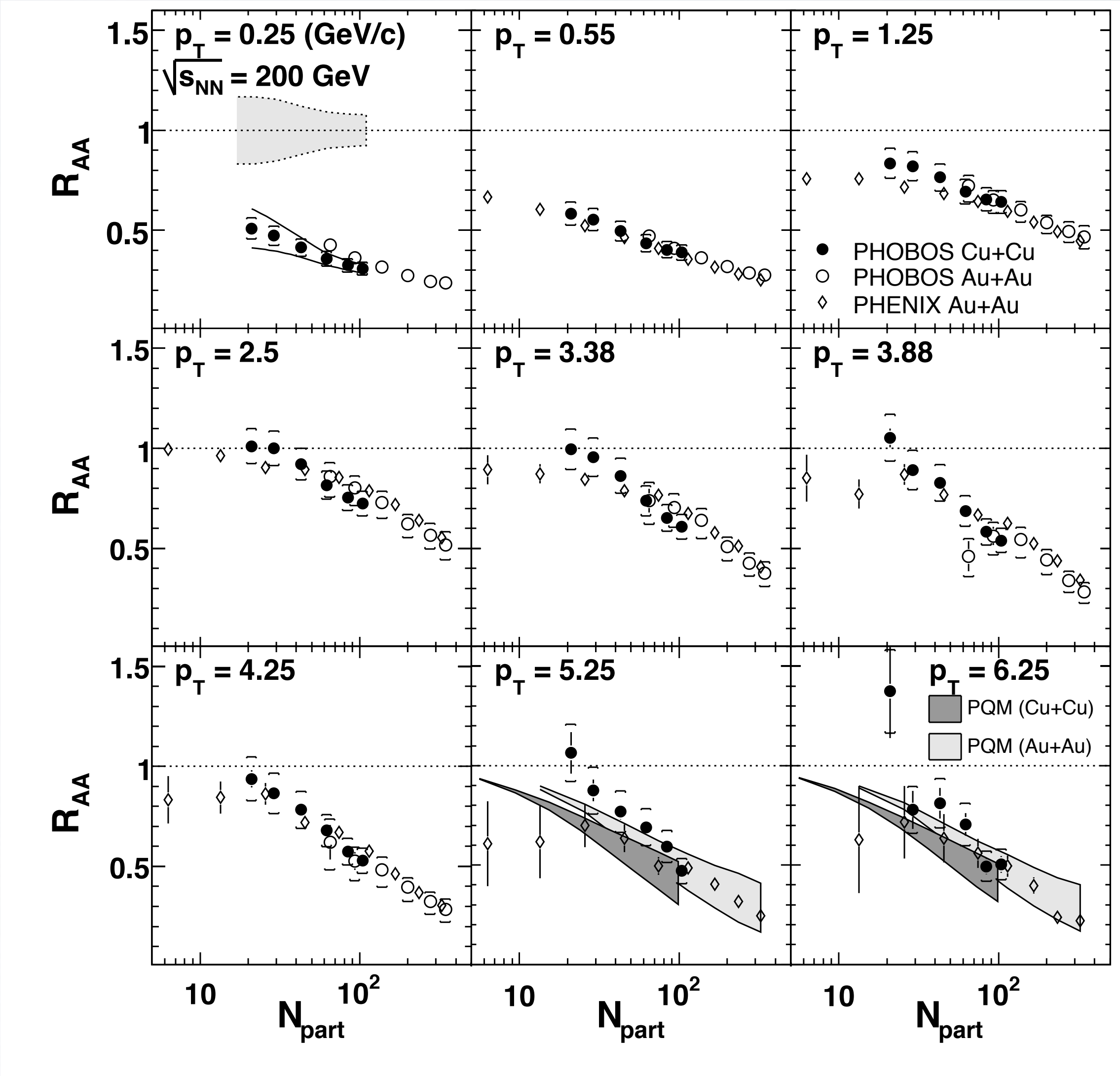
BROOKHAVEN NATIONAL LABORATORY

Workshop on "Probing Quark-Gluon Matter with Jets"
23-27 July 2018, Brookhaven National Laboratory

Center for Frontiers in Nuclear Science

context: jet quenching in AA



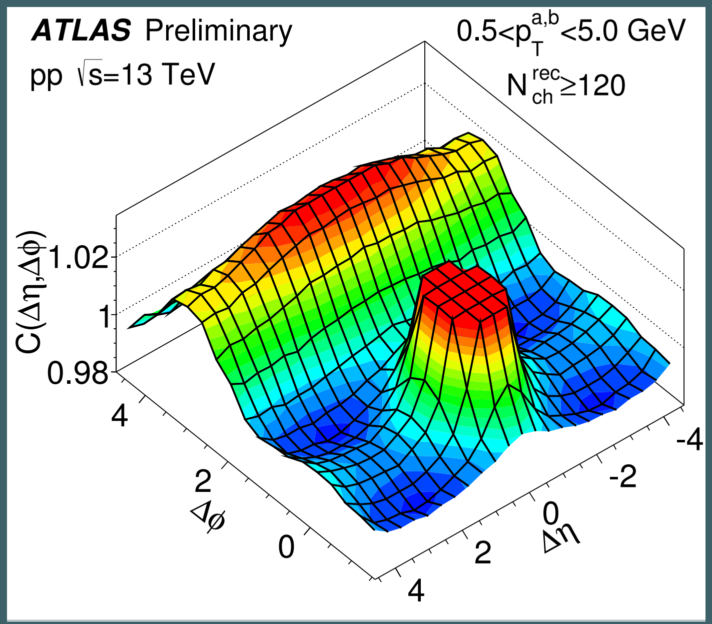


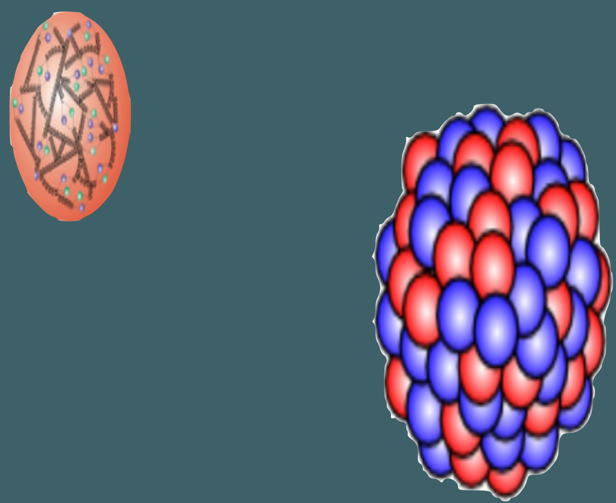
Clear indications of jet quenching in central events: where exactly does it turn off?

Influence/contribution of initial state (nPDF/shadowing) effects?

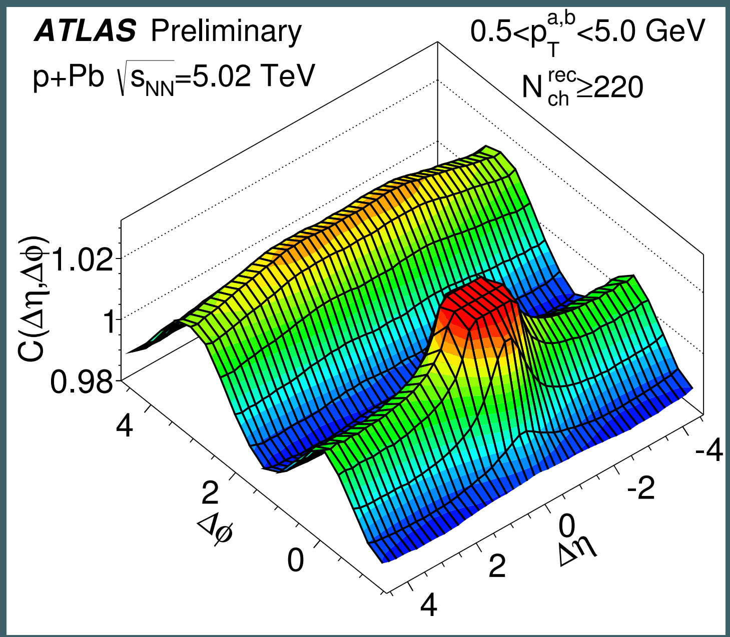
context: collectivity in pp/pPb/PbPb

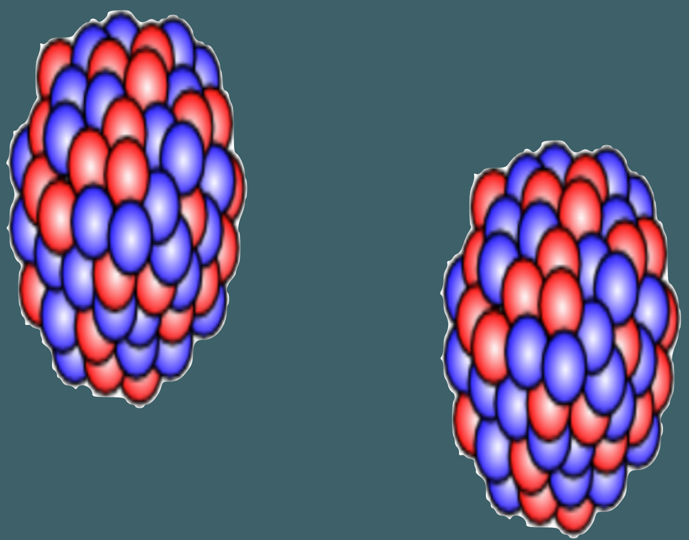
p+p



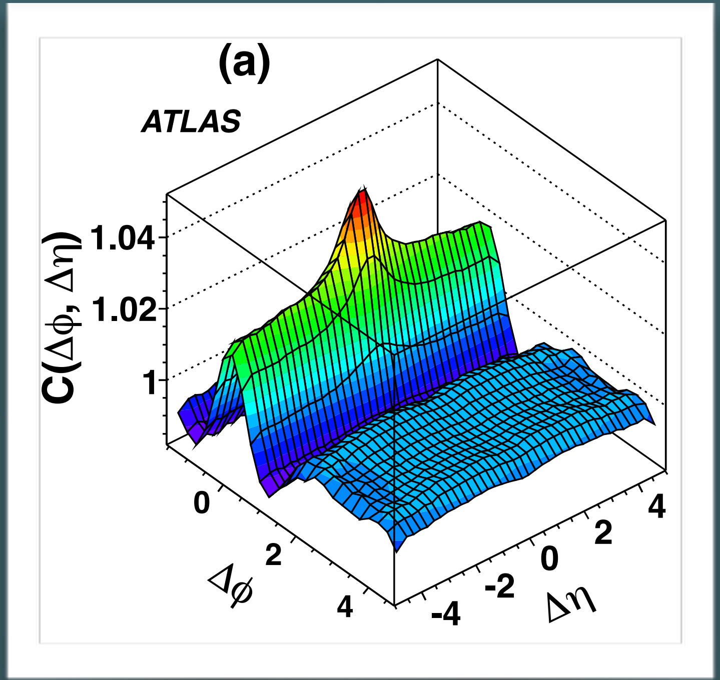


p+Pb



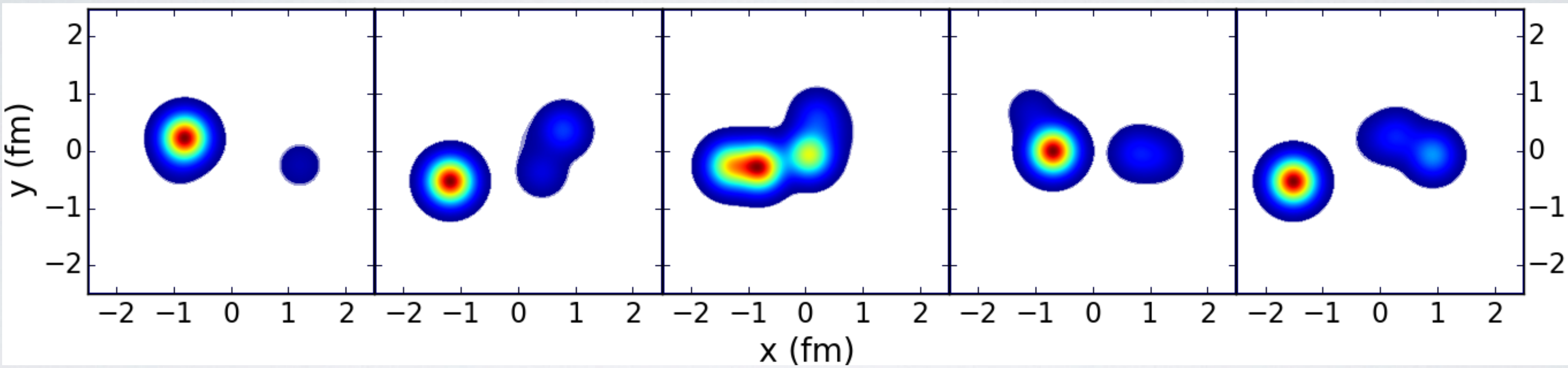


Pb+Pb

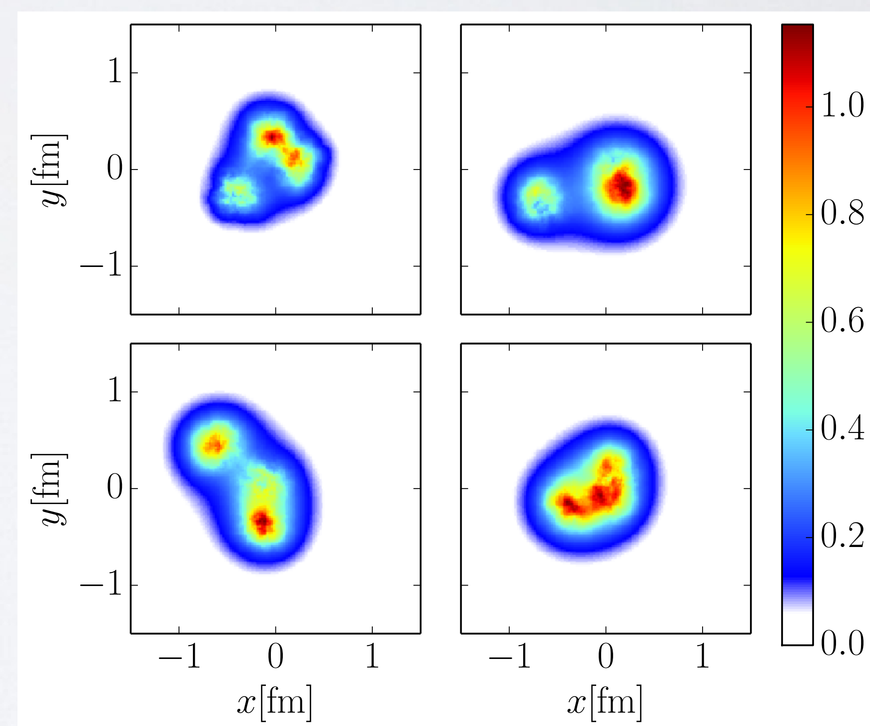


Geometry in pp

Welsh, Singer, Heinz (2016)



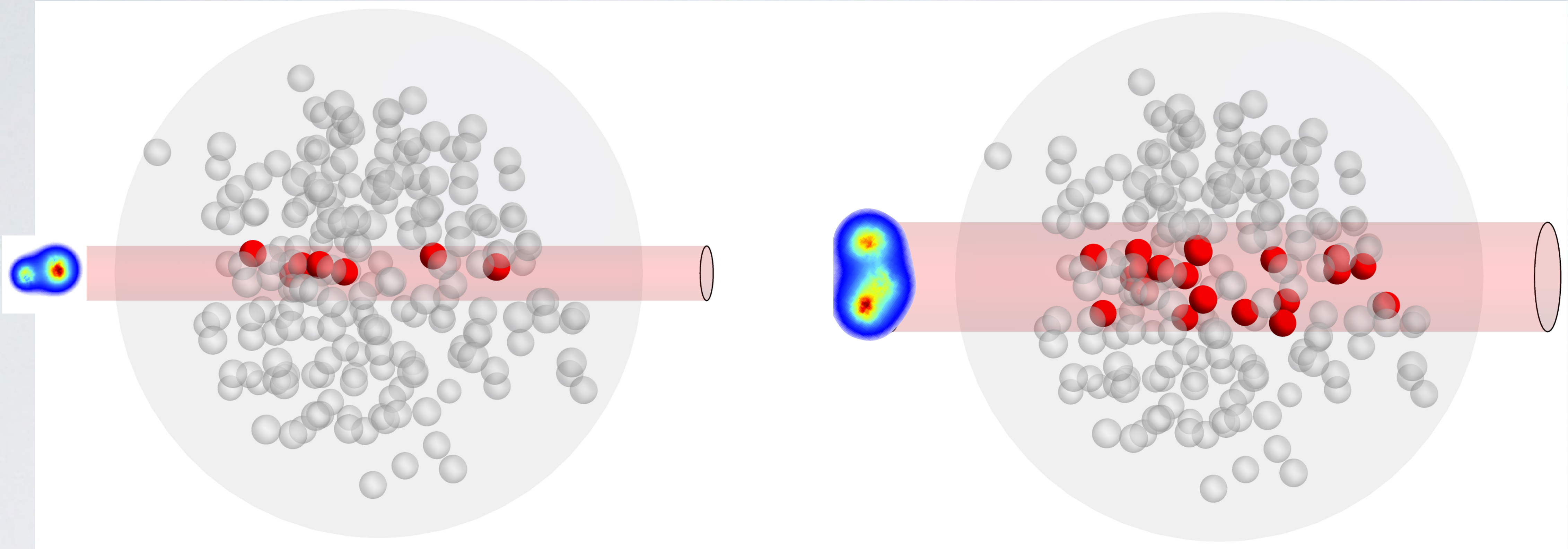
Many glauber calculations assumed smooth, round nucleons: many phenomena (MPI, ridge) have implied need for geometric picture of proton: implications for pp and p+Pb



Mantysaari & Schenke (2016)

Nucleon geometry in p+Pb

Mark's talk today

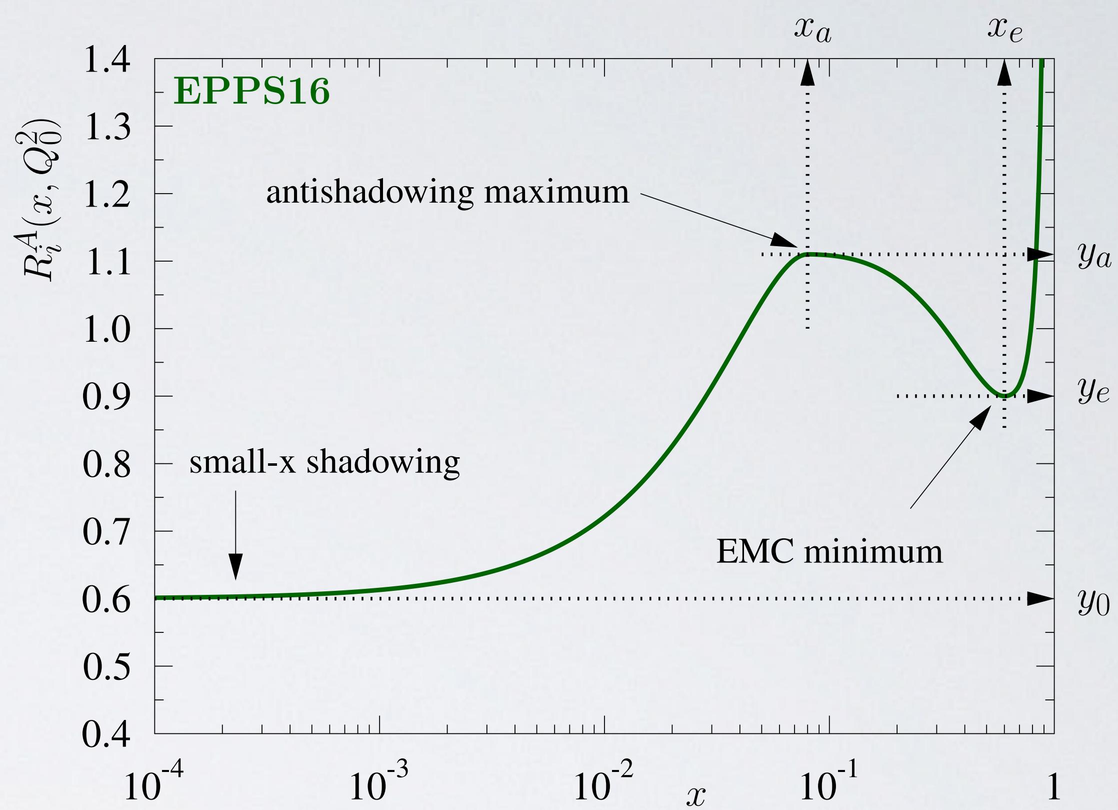


Substructure of nucleon can have measurable impact p+Pb:
color fluctuations lead to cross-section fluctuations (Mark's talk)
"Glauber-gribov" parameter characterizes width of fluctuations

Affects centrality estimation, since smaller proton configurations see fewer nucleons in nucleus

Nuclear PDFs

Embedding nucleons in nuclear medium known to change observed structure, relative to free nucleons



Several nPDF sets exist, all based on NLO pQCD calculations

EPS09 - l+A experiments, DY from FNAL, pi0 from RHIC
EPPS16 - uses dijets, W/Z from p+Pb at LHC
nCTEQ15 - extension of CTEQ to nuclei (up to Pb)
DSSZ - incorporates RHIC high p_T pion data

integrate over impact parameter: only EPS09s encodes centrality

Nuclear effects & centrality

- Until relatively recent (~pre-LHC) days, protons were assigned a simple spatial structure, while nuclei were considered in more detail
  - *RHIC & LHC data immediately pointed to need for better spatial understanding of proton structure*

- Now details of hard - and soft - processes can stem from several factors
  - *Geometry of nucleus (Glauber)*
  - *Geometry of nucleon (Glauber-Gribov)*
  - *Structure of nucleons within a nucleus (nPDFs)*

- Worse, centrality estimation itself can be influenced by these effects
  - *Our assumptions can lead to different values of N_{part}, N_{coll}*

Outline

- Centrality-inclusive physics in p+Pb (nPDFs)
  - *Electroweak probes*
  - *Jet rates*

- “Centrality"-dependent physics in p+Pb
  - *Electroweak physics*
  - *Jet rates*

- Along the way: several issues arise pertaining to centrality in p+Pb, and small systems in general

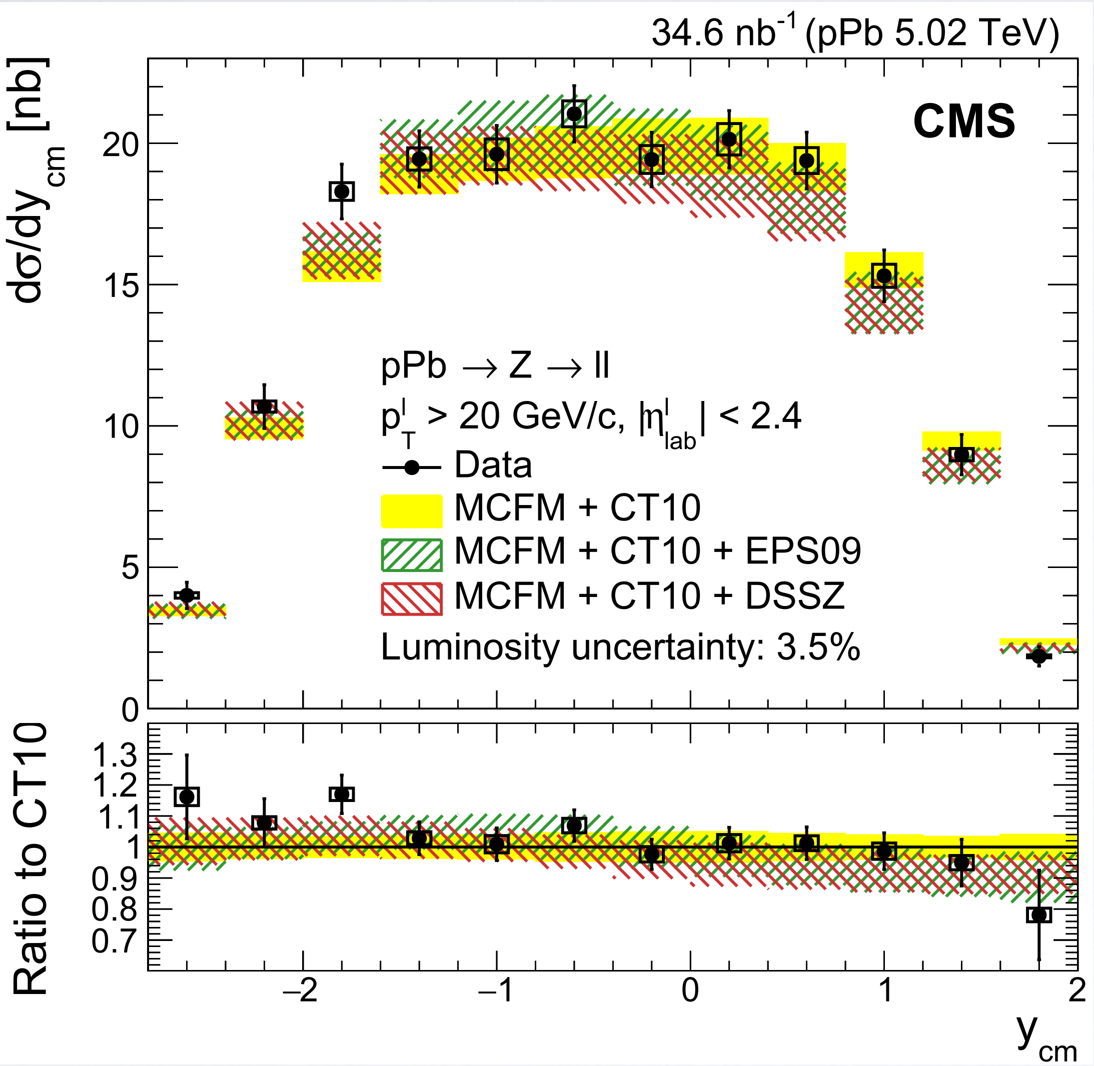
nPDFs via electroweak & jet probes

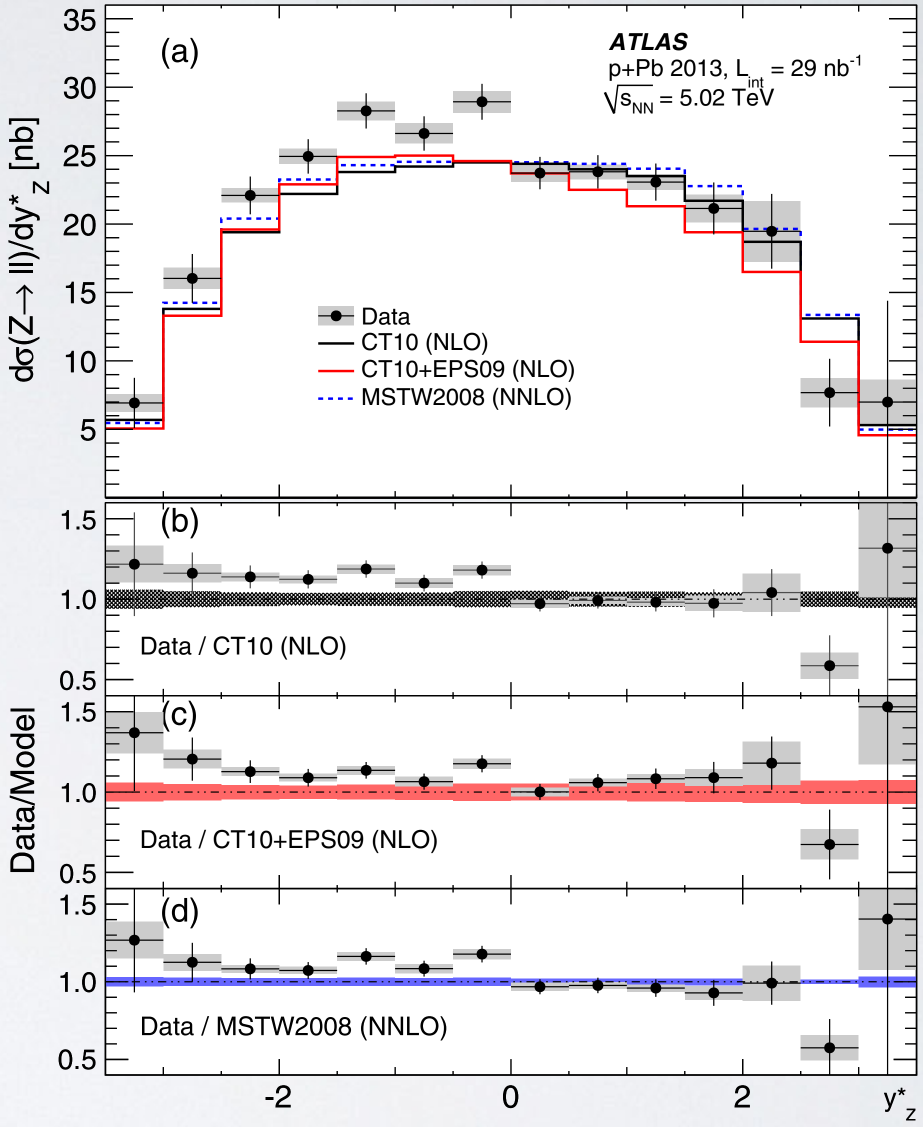
W Z γ

uds cb t

Centrality-inclusive measurements…

Inclusive p+Pb: Z boson



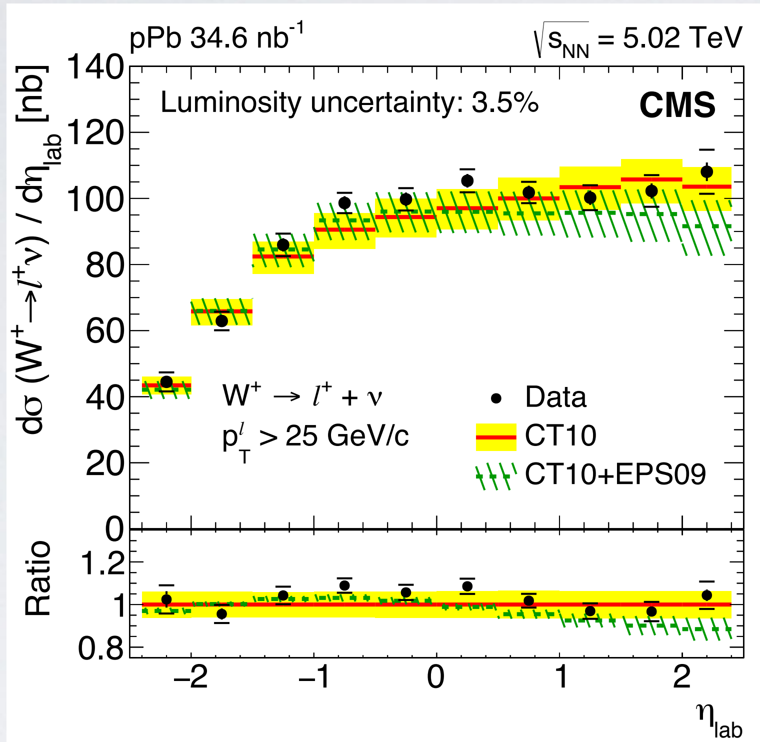


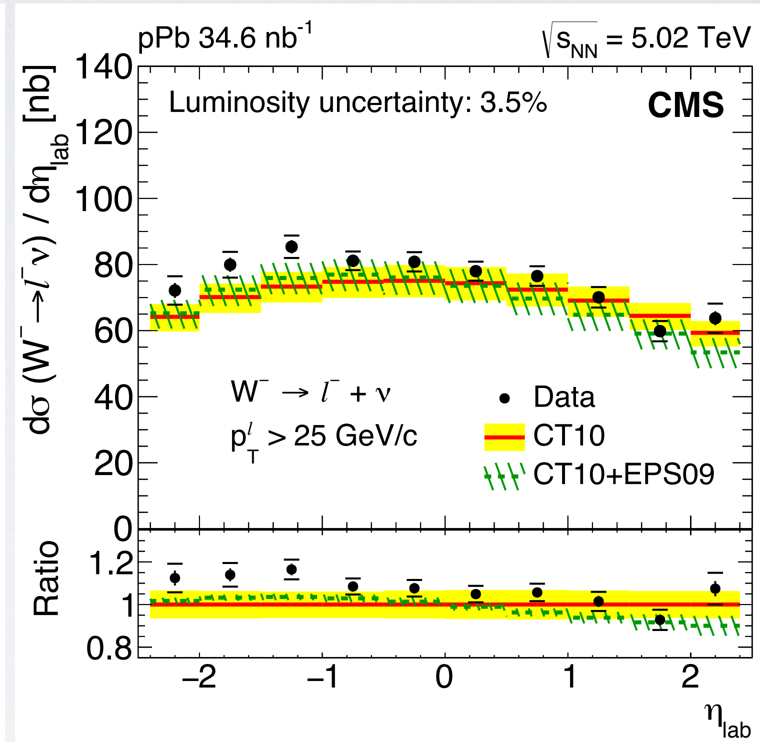
Z bosons in p+Pb give slight preference to nPDFs, without distinguishing between them: Both tend to be enhanced in Pb-going direction

Inclusive p+Pb: W boson

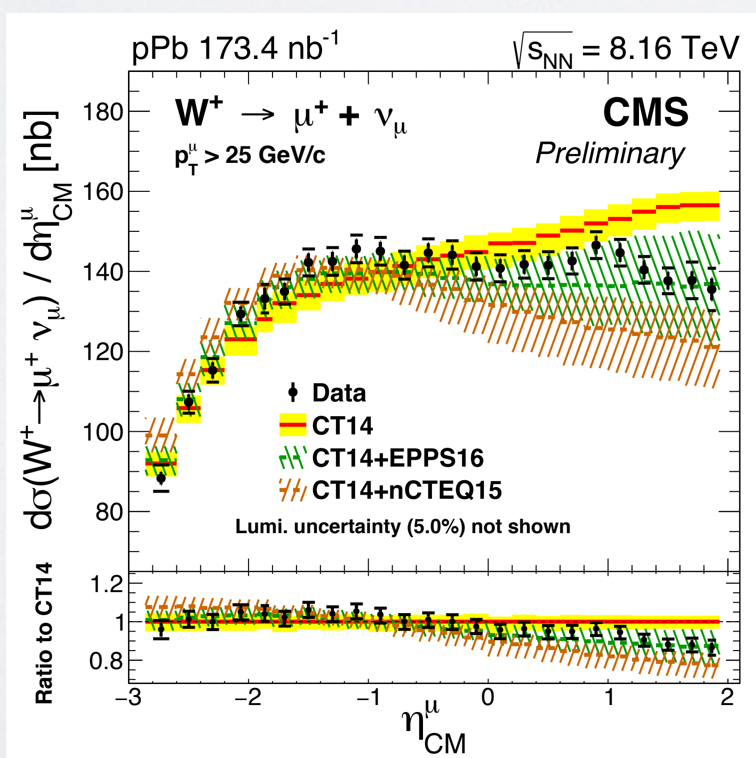
W+ W-

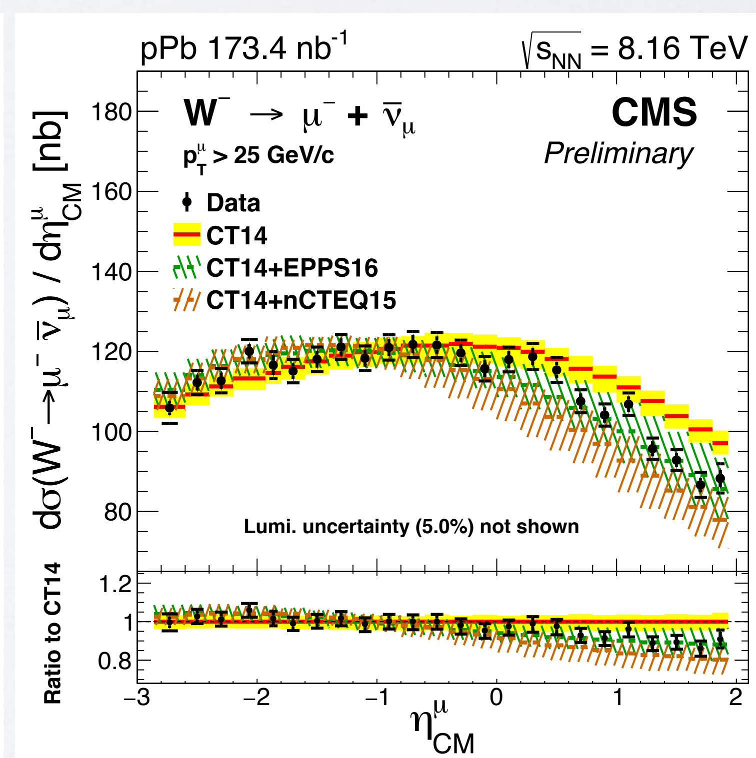
5.02 TeV





8.16 TeV



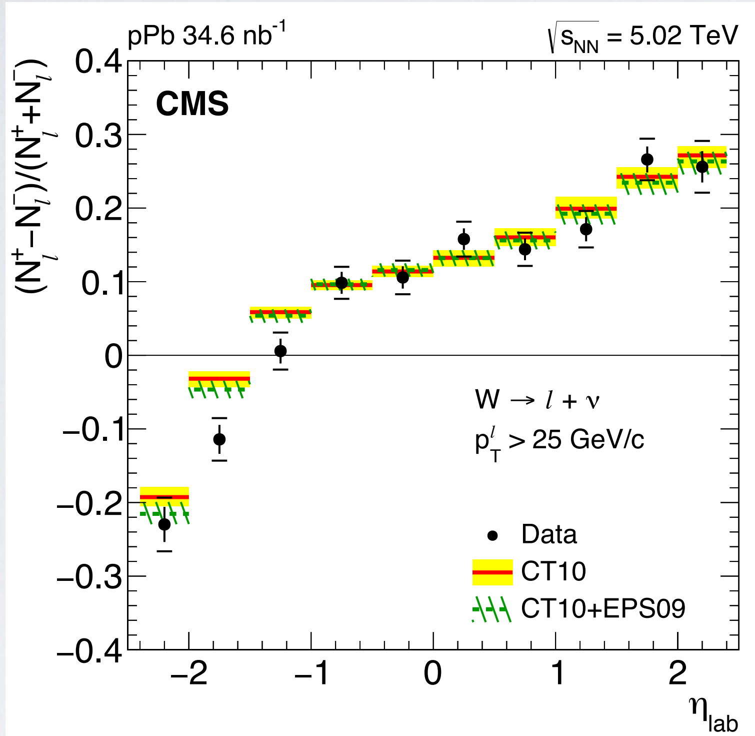


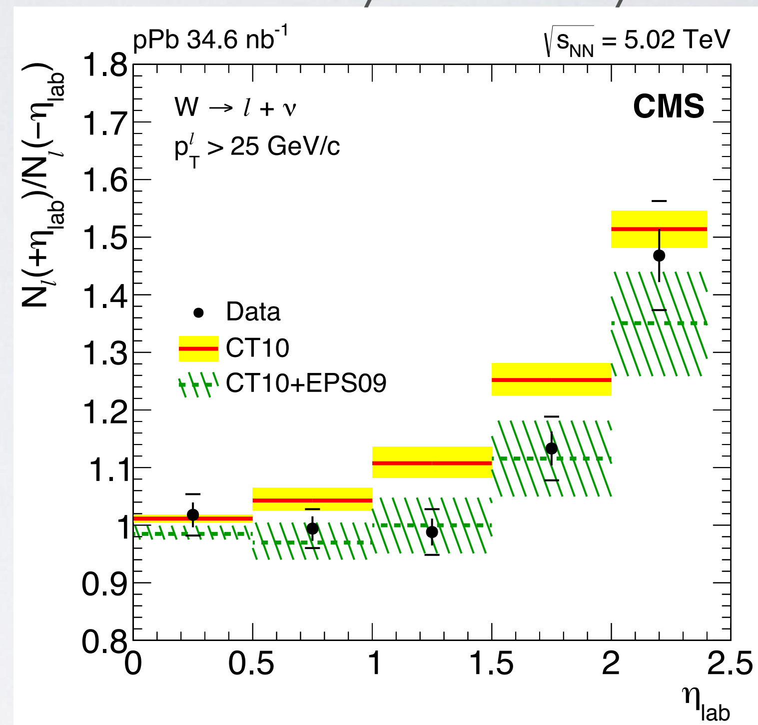
Inclusive p+Pb: W boson

Charge asymmetry | FB asymmetry

5.02 TeV

Deviations from CT10 in backward direction

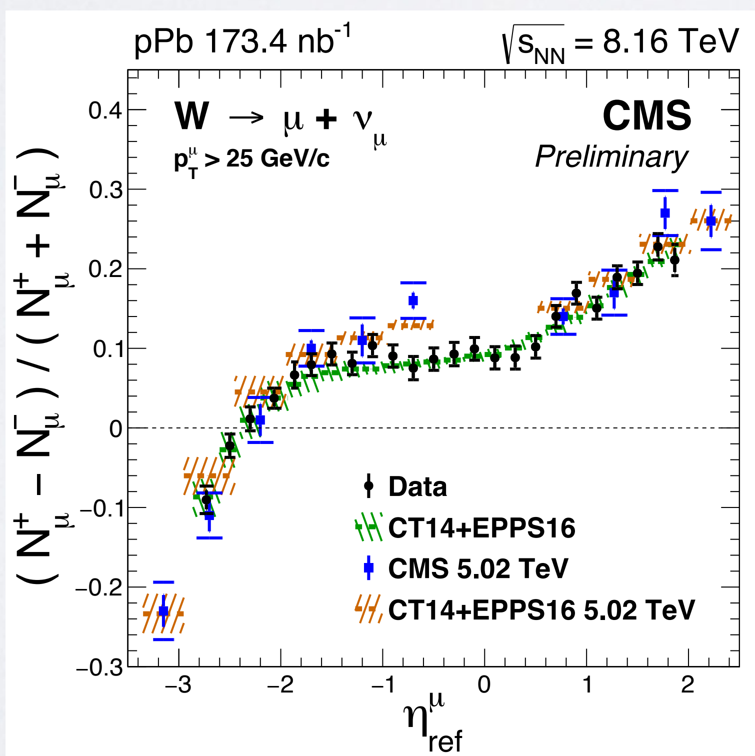


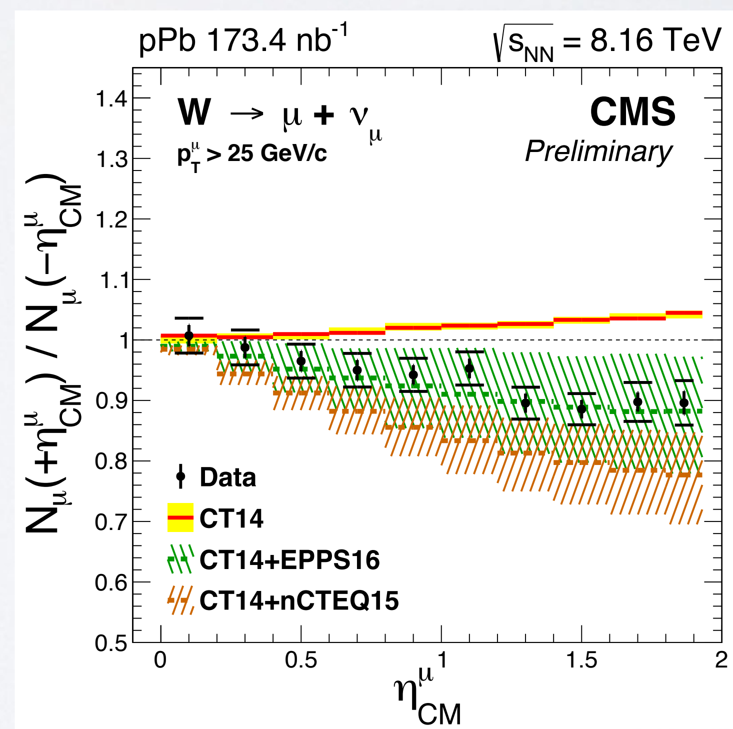


Clear preference for nPDFs

8.16 TeV

Deviation no longer seen: charge asym. insensitive to nPDF



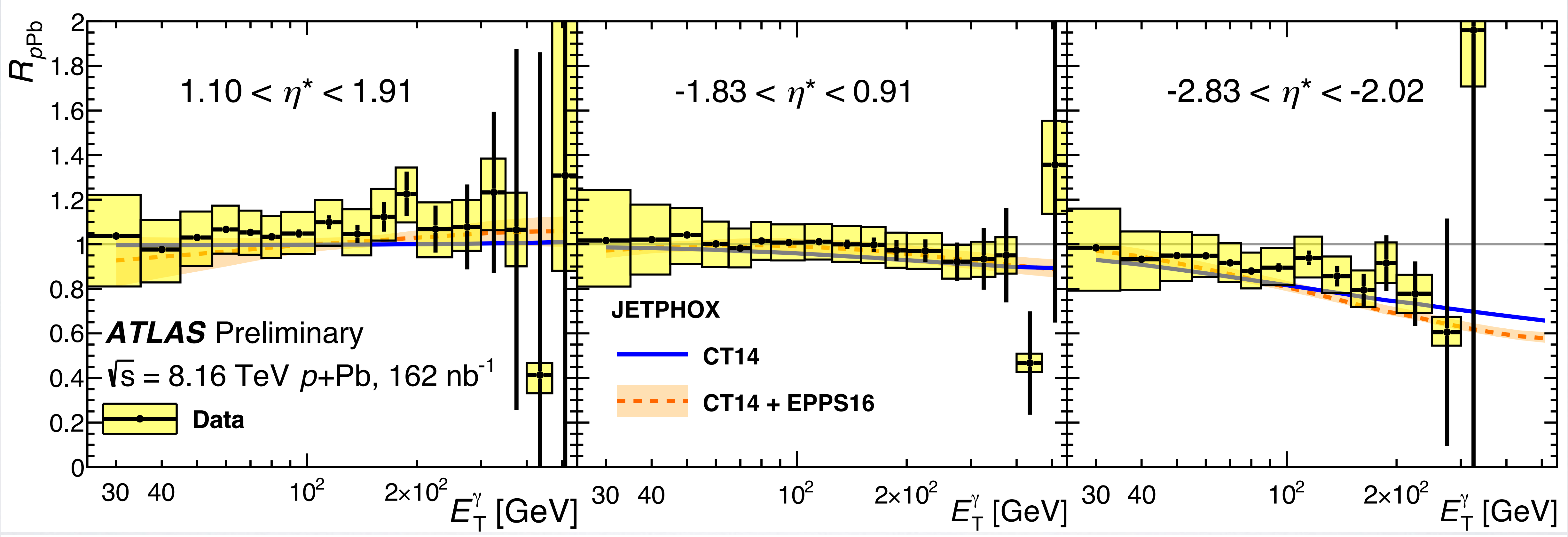


Clear preference for nPDFs

$$\eta_{ref}^{\mu} = \eta_{CM}^{\mu} \pm \ln\left(8.16\ \text{TeV}/\sqrt{s_{NN}}\right)$$

$$\eta_{lab} = \eta_{CM} + 0.465$$

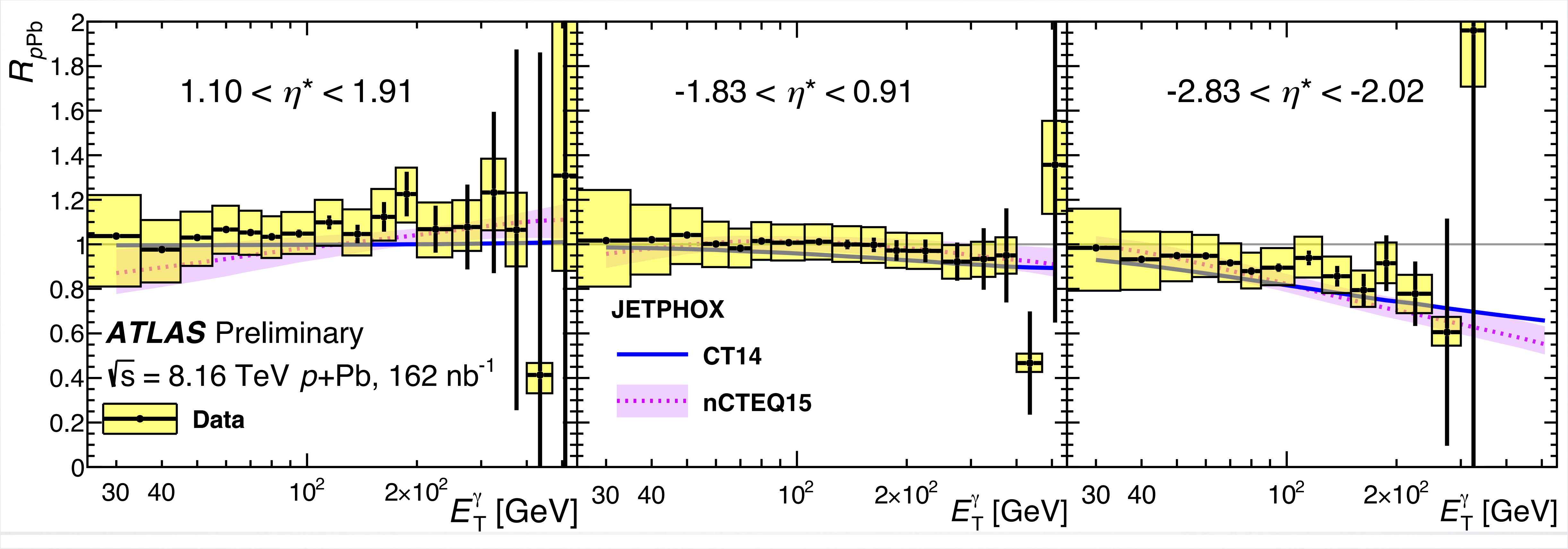
ATLAS p+Pb photons: EPPS



Errors still much larger than differences between CT14 & CT14+EPPS16

Clear observation of isospin effects from Pb in backward region.

ATLAS p+Pb photons: nCTEQ

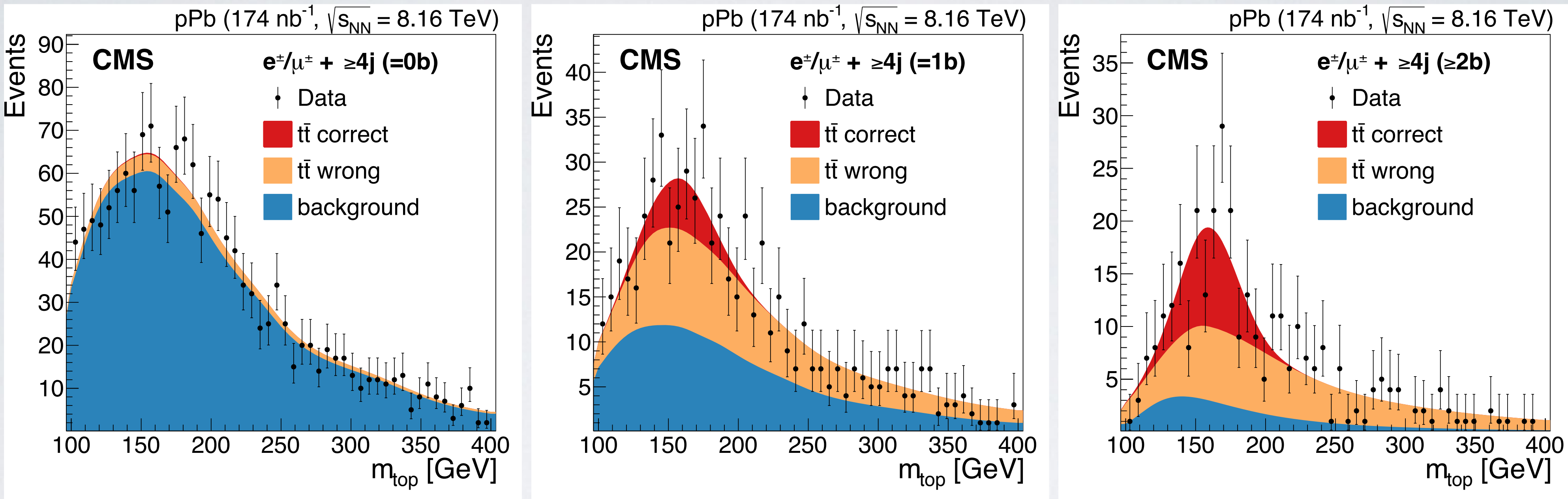


Errors still much larger than differences between CT14 & CT14+nCTEQ15

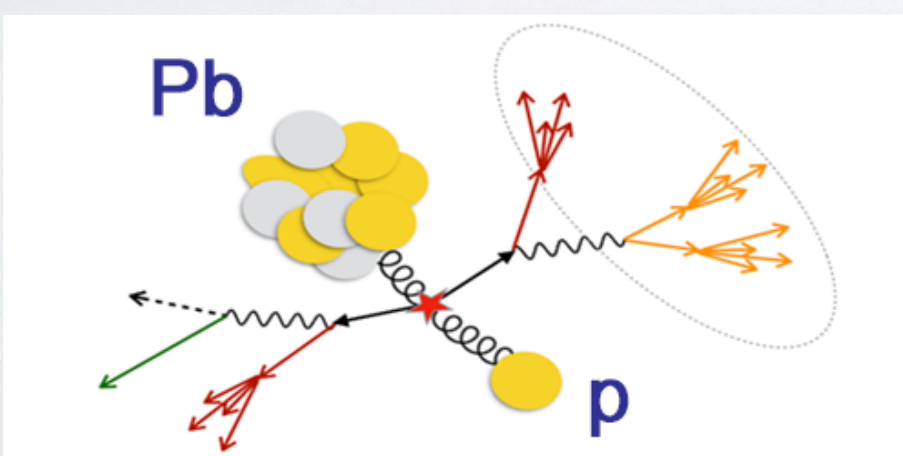
Clear observation of isospin effects from Pb in backward region.

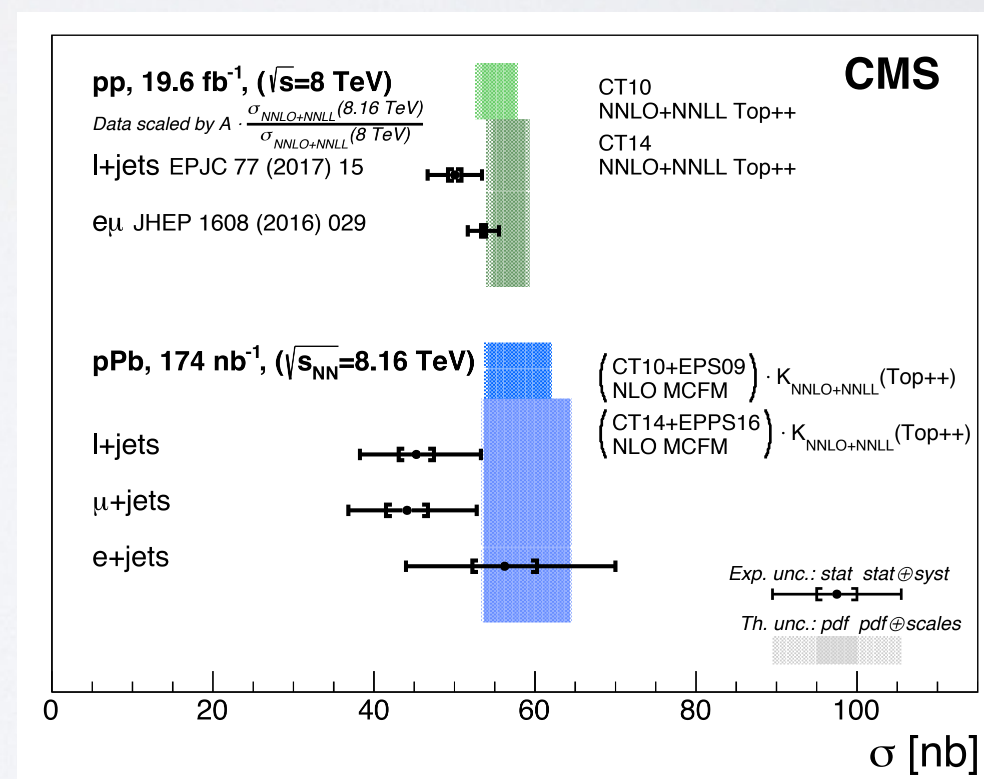
tt production in p+Pb

PhysRevLett.119.242001 (2017)



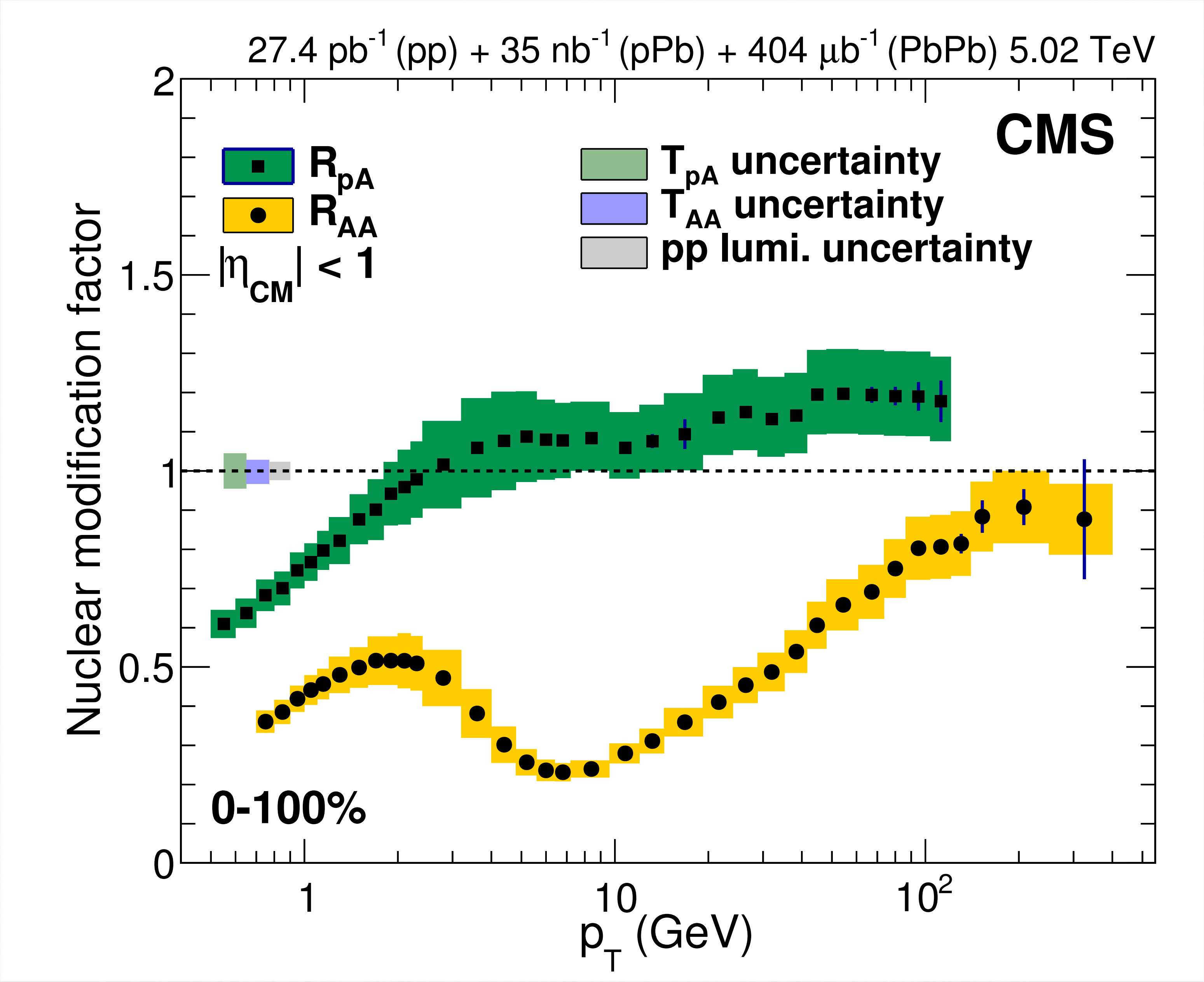
ttbar signal extracted in
8.16 TeV p+Pb data
using 1 lepton+4 jets channel:
sensitive to gluon PDF @ high-x (>0.05)!





CMS high p_T charged hadrons

JHEP04(2017)039



Charged hadrons offer preliminary look at basic differences in jet suppression between p+Pb and Pb+Pb

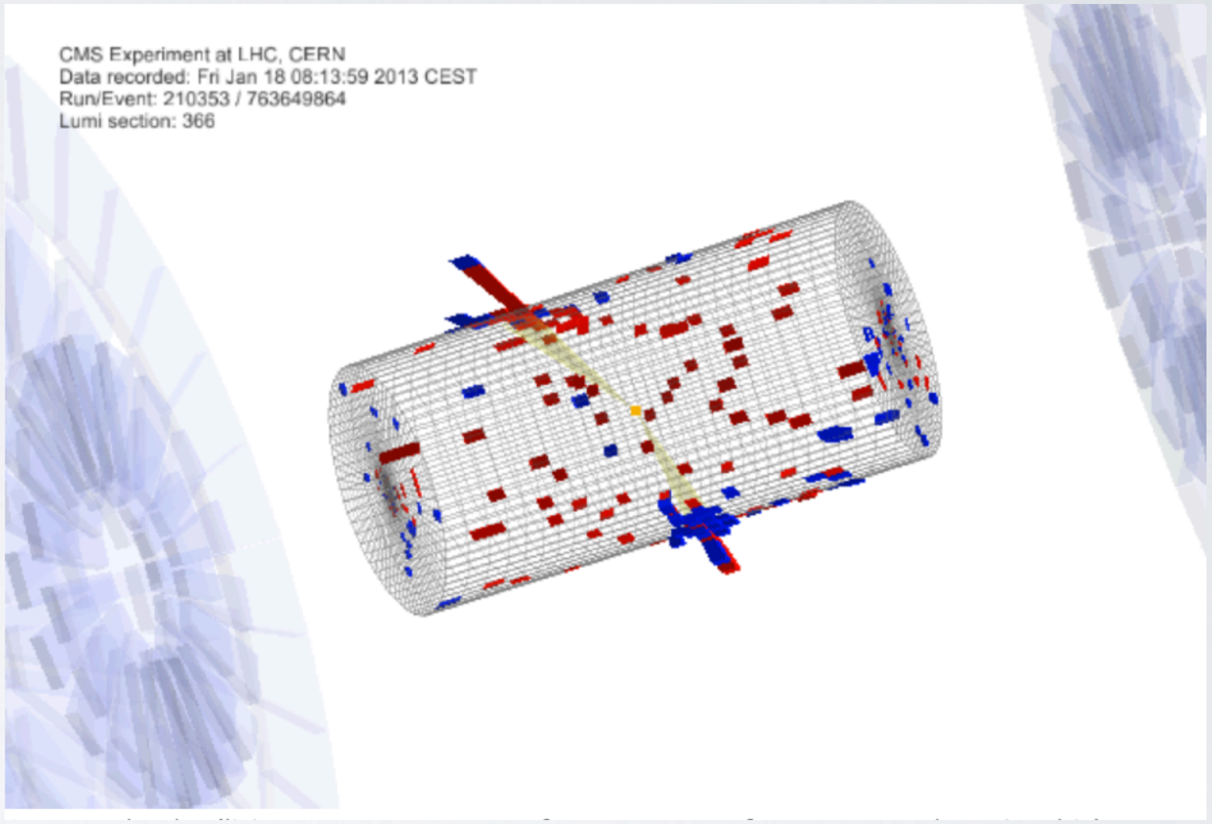
Jets in p+Pb

Much more straightforward than in Pb+Pb

Background subtraction issues far less severe

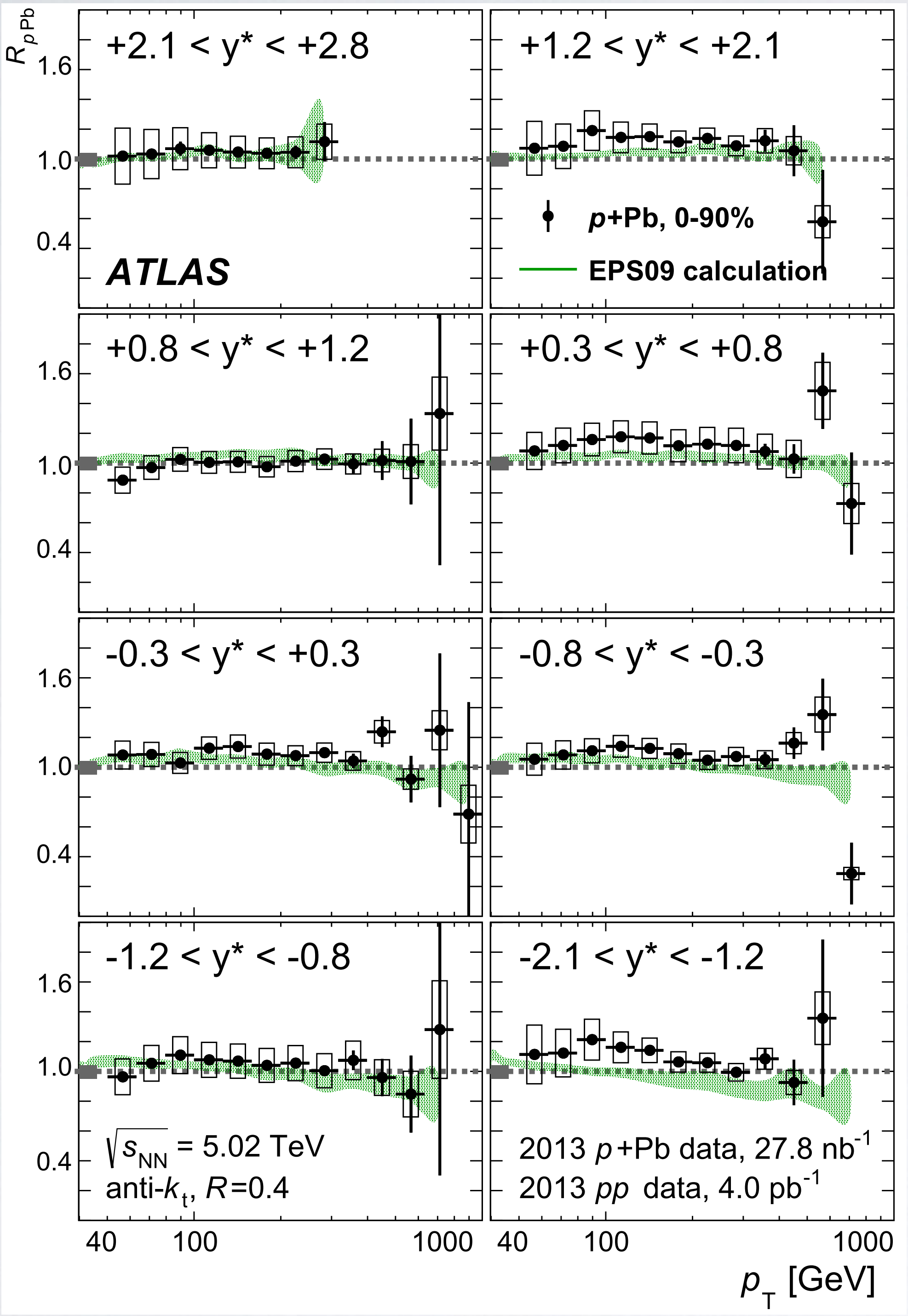
Measurements exist for:

1) **full jets**
2) **charged jets**
3) **HF (charm) jets**
4) **dijets**



Full jets from ATLAS & CMS

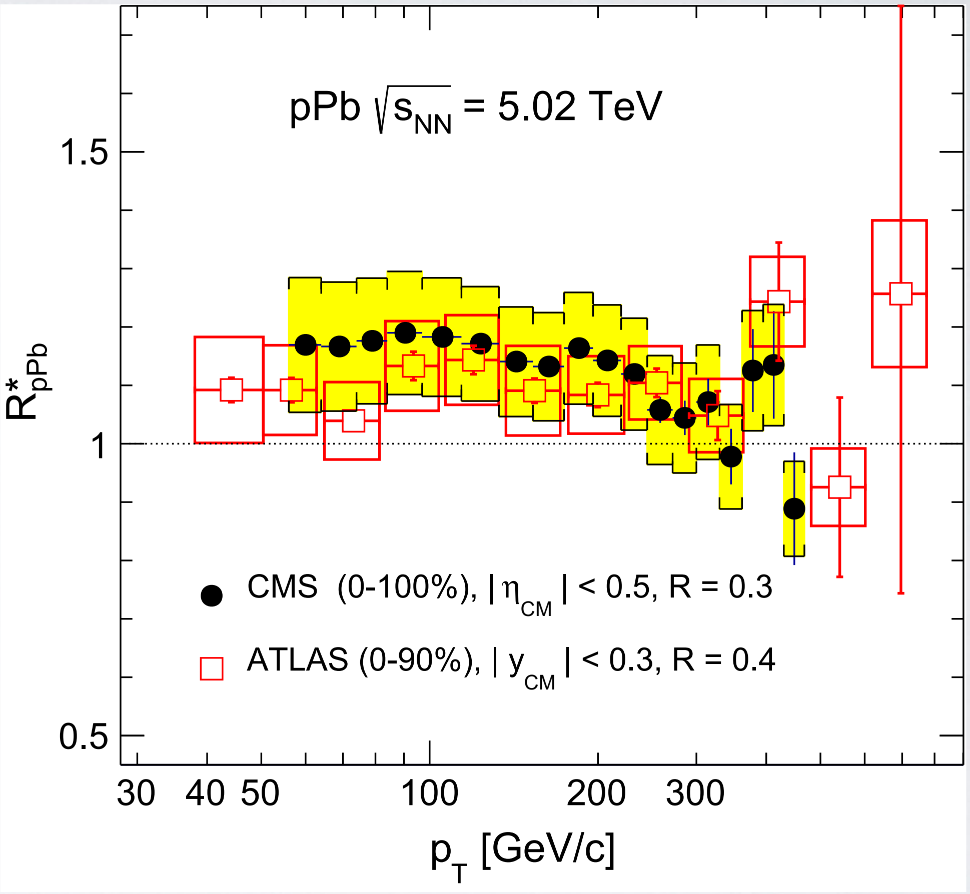
Physics Letters B 748 (2015) 392–413



ATLAS

Eur. Phys. J. C (2016) 76:372

CMS

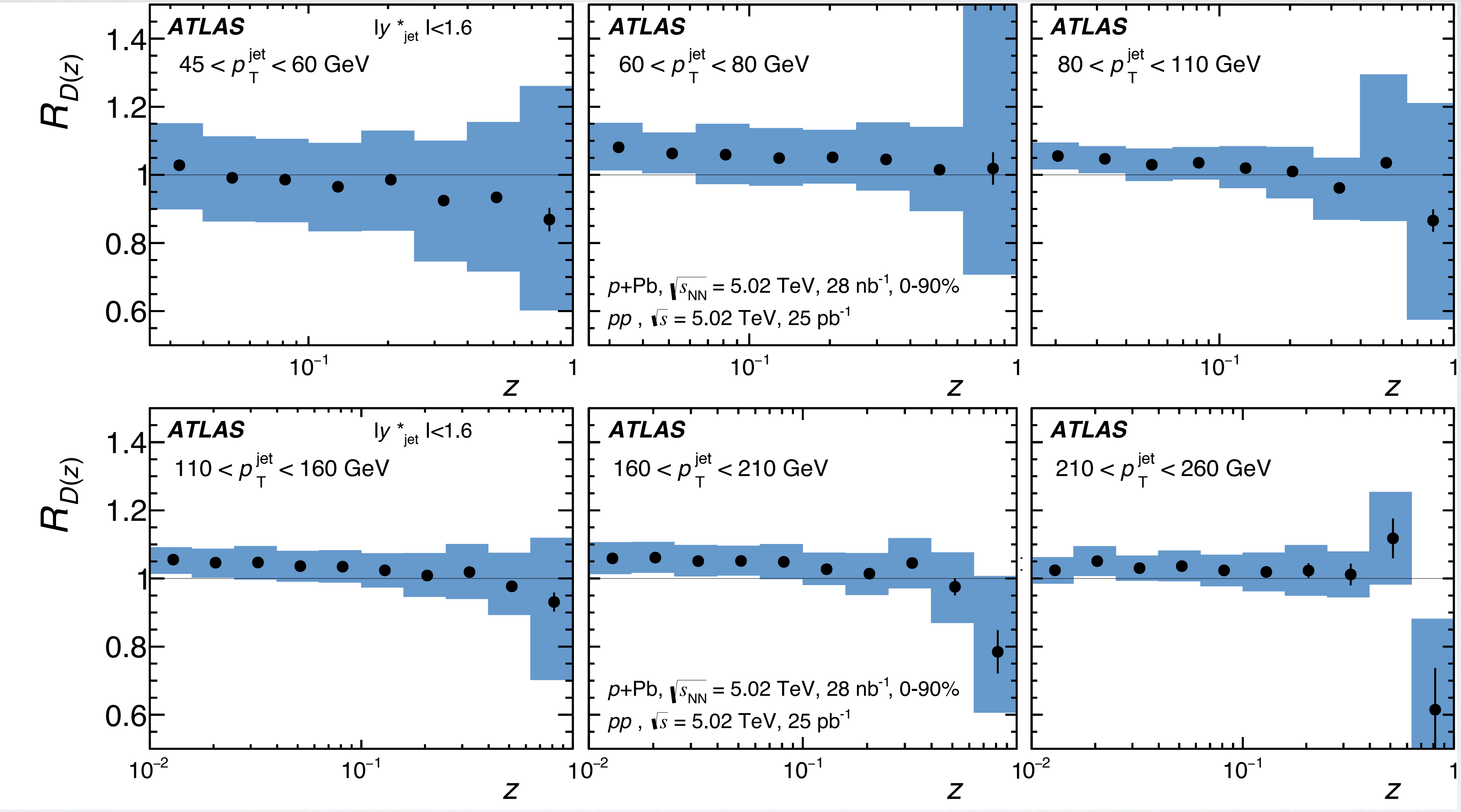


Unlike in Pb+Pb, inclusive jets are not suppressed but slightly **enhanced**

nPDF effects are modest/negligible in this kinematic range

ATLAS p+Pb jet fragmentation

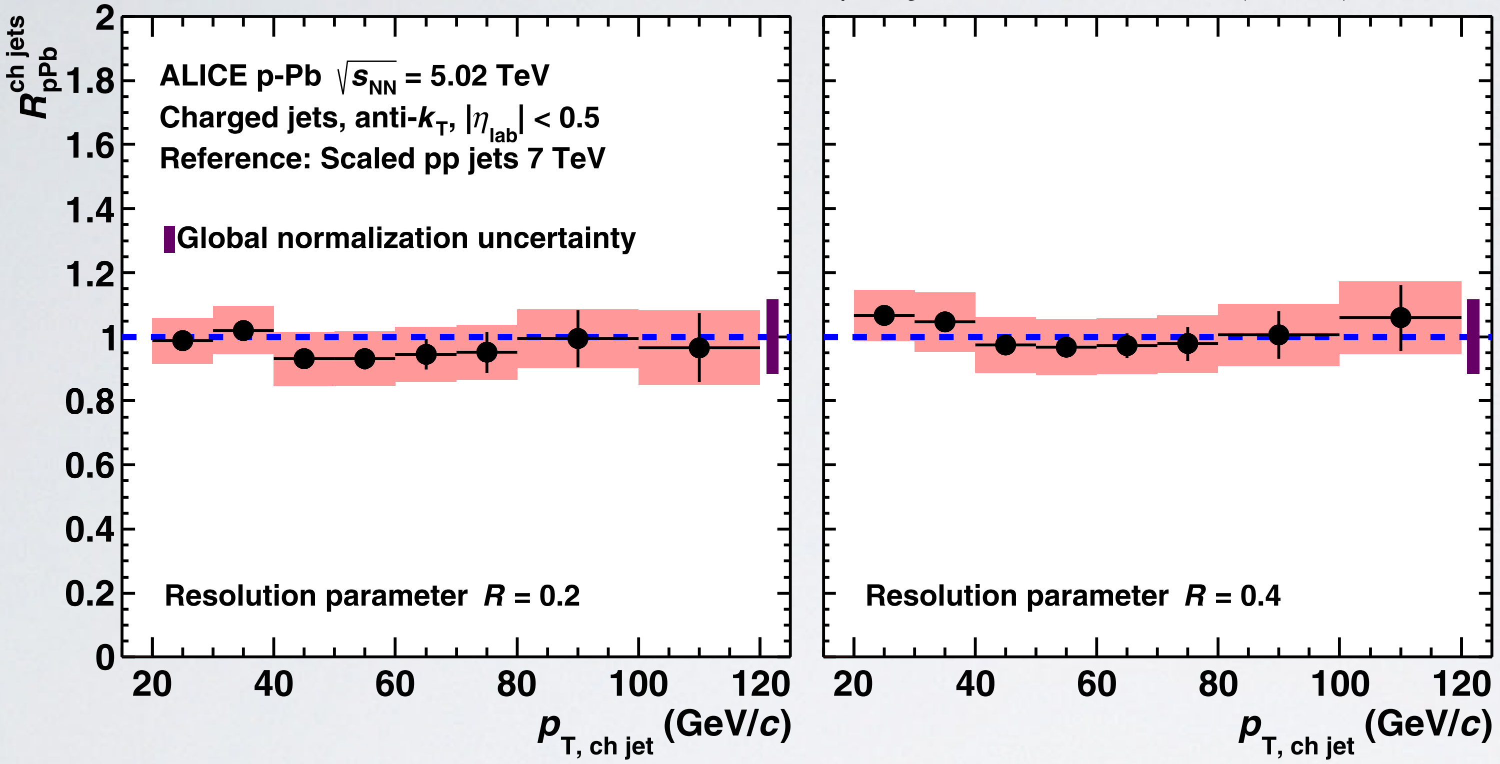
arxiv:1706.02859, accepted to NPA



p+Pb inclusive jet fragmentation functions show no substantial modifications

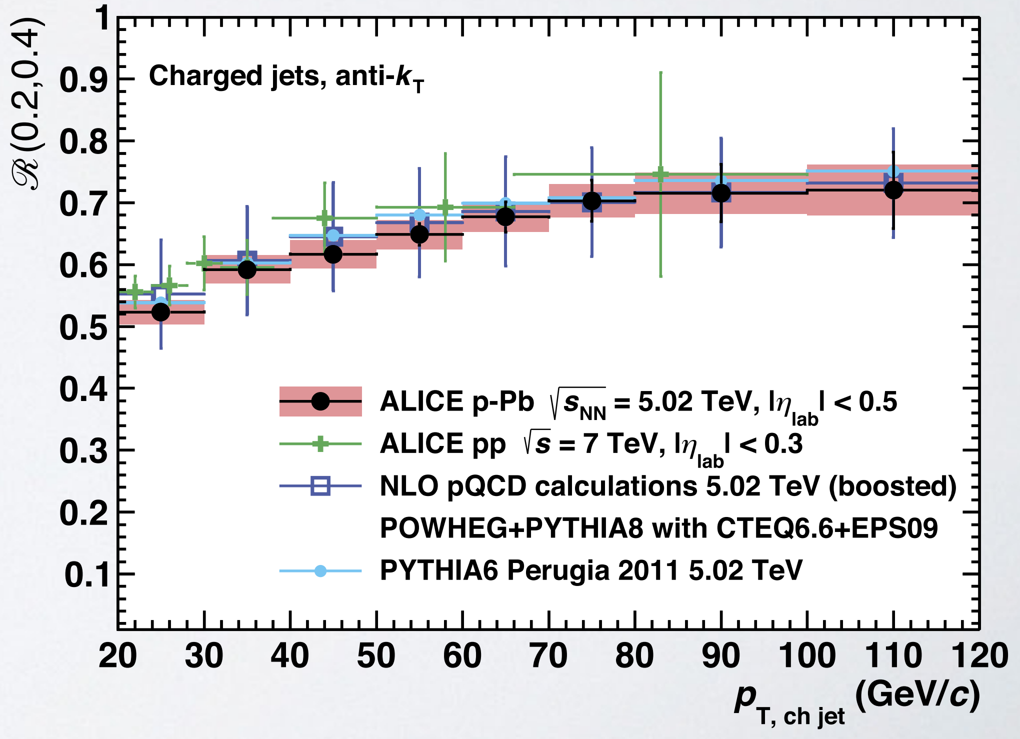
ALICE charged jets

ALICE Collaboration / Physics Letters B 749 (2015) 68–81

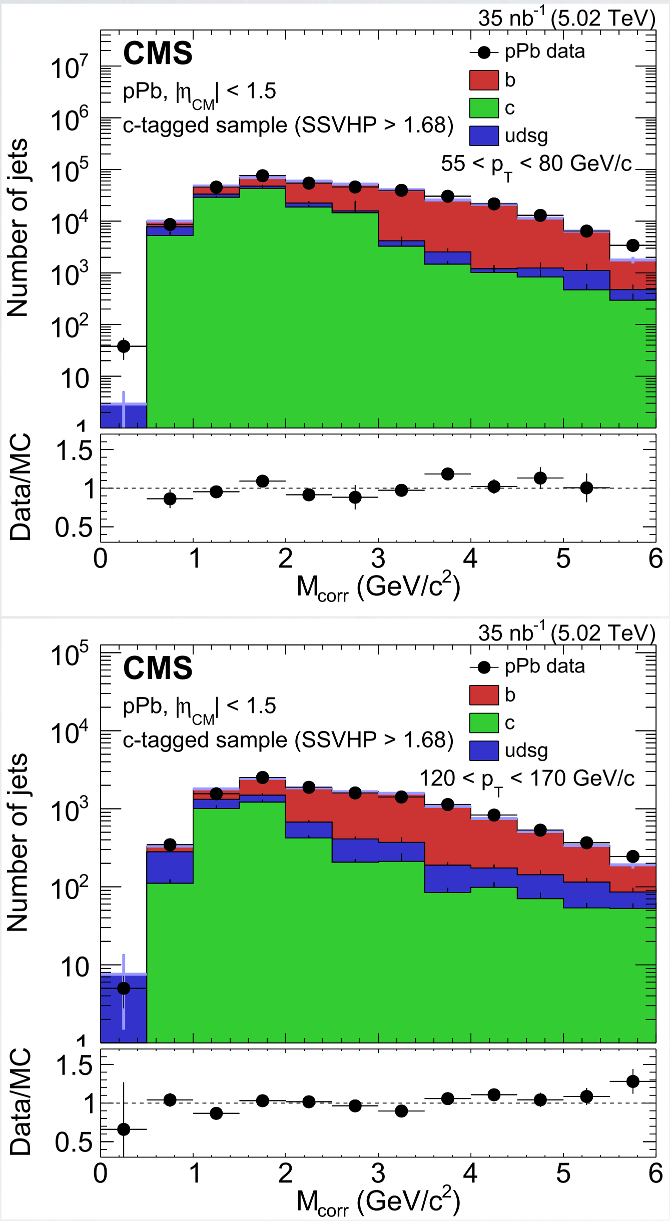


Charged jets show no modification either, relative to pp: no suppression, no PDF effects

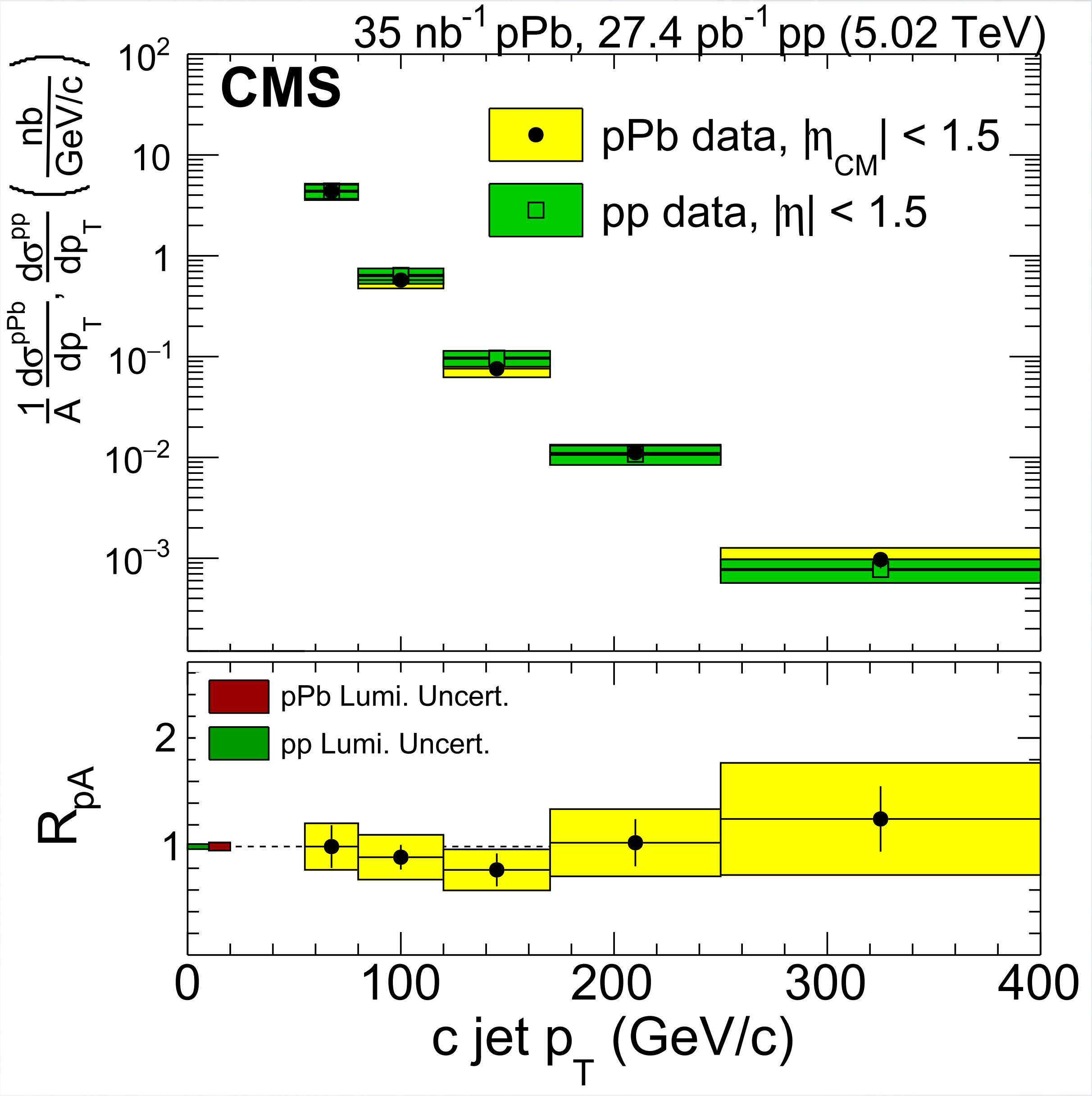
Even more detailed studies, such as comparing R=0.4 w/ R=0.2 are well modeled by pQCD & PYTHIA



CMS charm jets

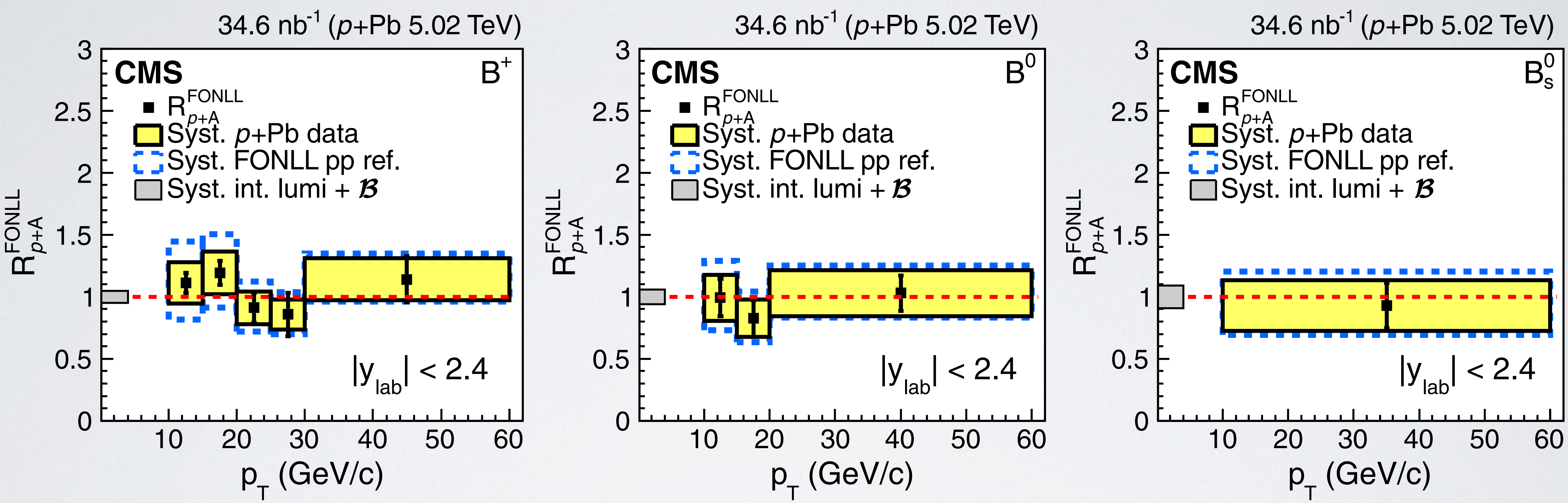


The CMS Collaboration / Physics Letters B 772 (2017) 306–329



CMS has extracted contribution from charm-induced jets via tagging: also no modification relative to pp (modulo large uncertainties)

CMS B mesons in p+Pb

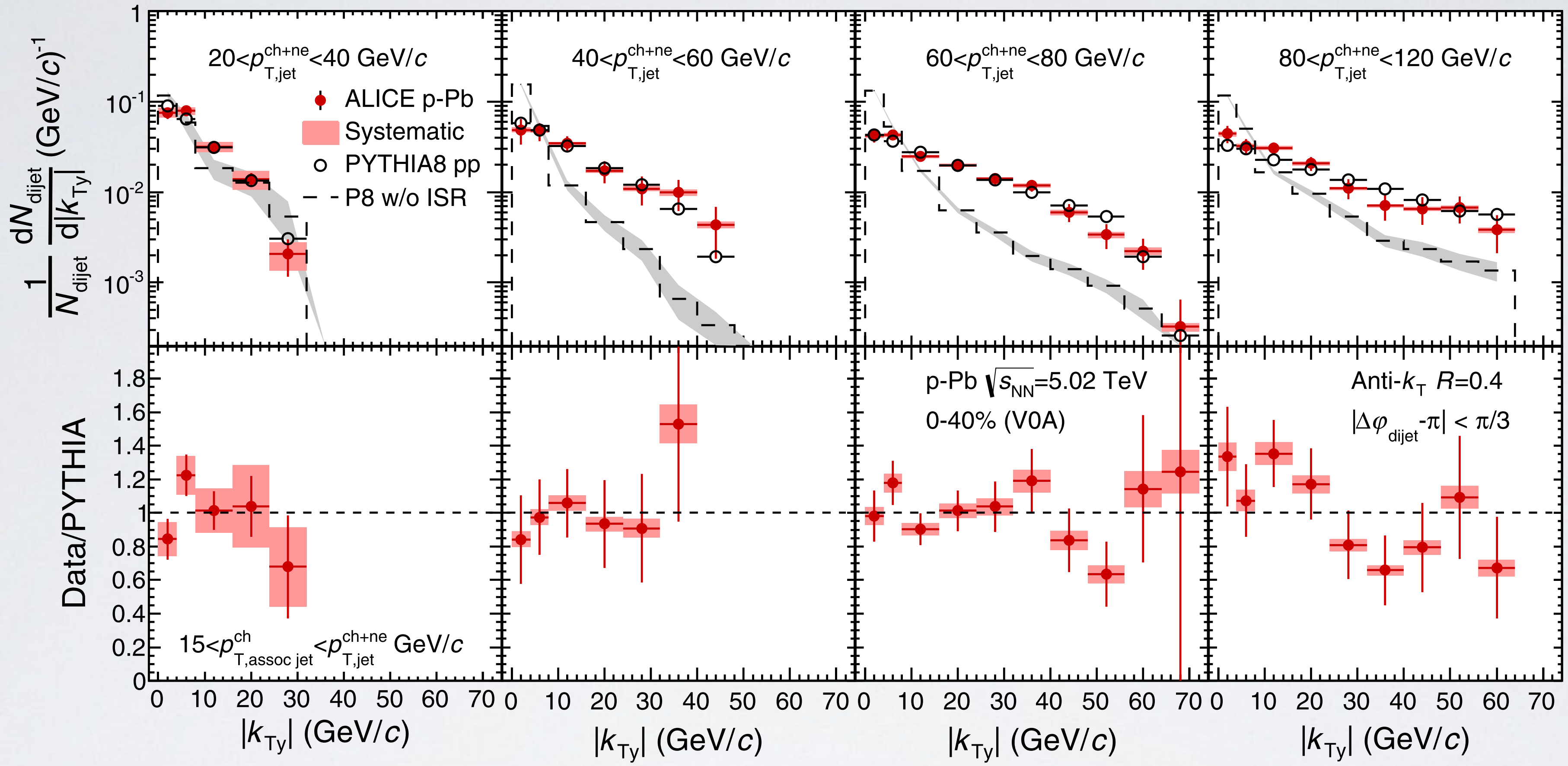


PRL **116,** 032301 (2016)

Fully-reconstructed bottom hadrons also show no modifiaction, within the limited statistical and systematic precision

ALICE dijet k_T

Physics Letters B 746 (2015) 385–395

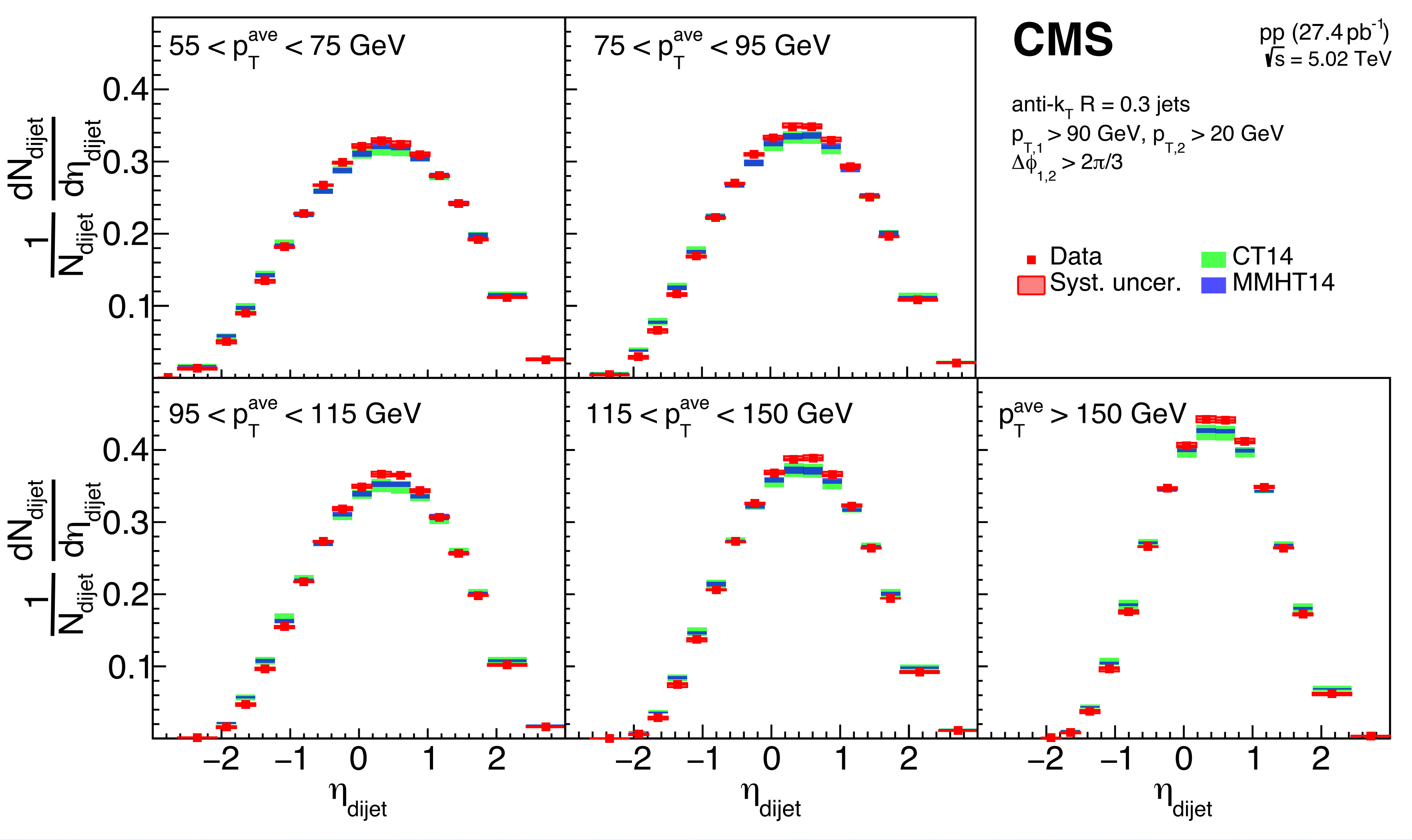


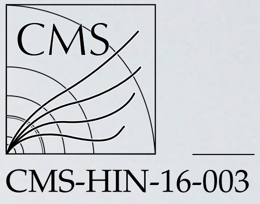
ALICE has measured the kT of full jets recoiling against charged jets, vs. full-jet p_T, well described by PYTHIA (including ISR)

$$k_{\mathrm{Ty}} = p_{\mathrm{T,jet}}^{\mathrm{ch+ne}} \sin(\Delta\varphi_{\mathrm{dijet}}),$$

No obvious dijet broadening in nuclear environment

CMS: probing nPDFs with dijets

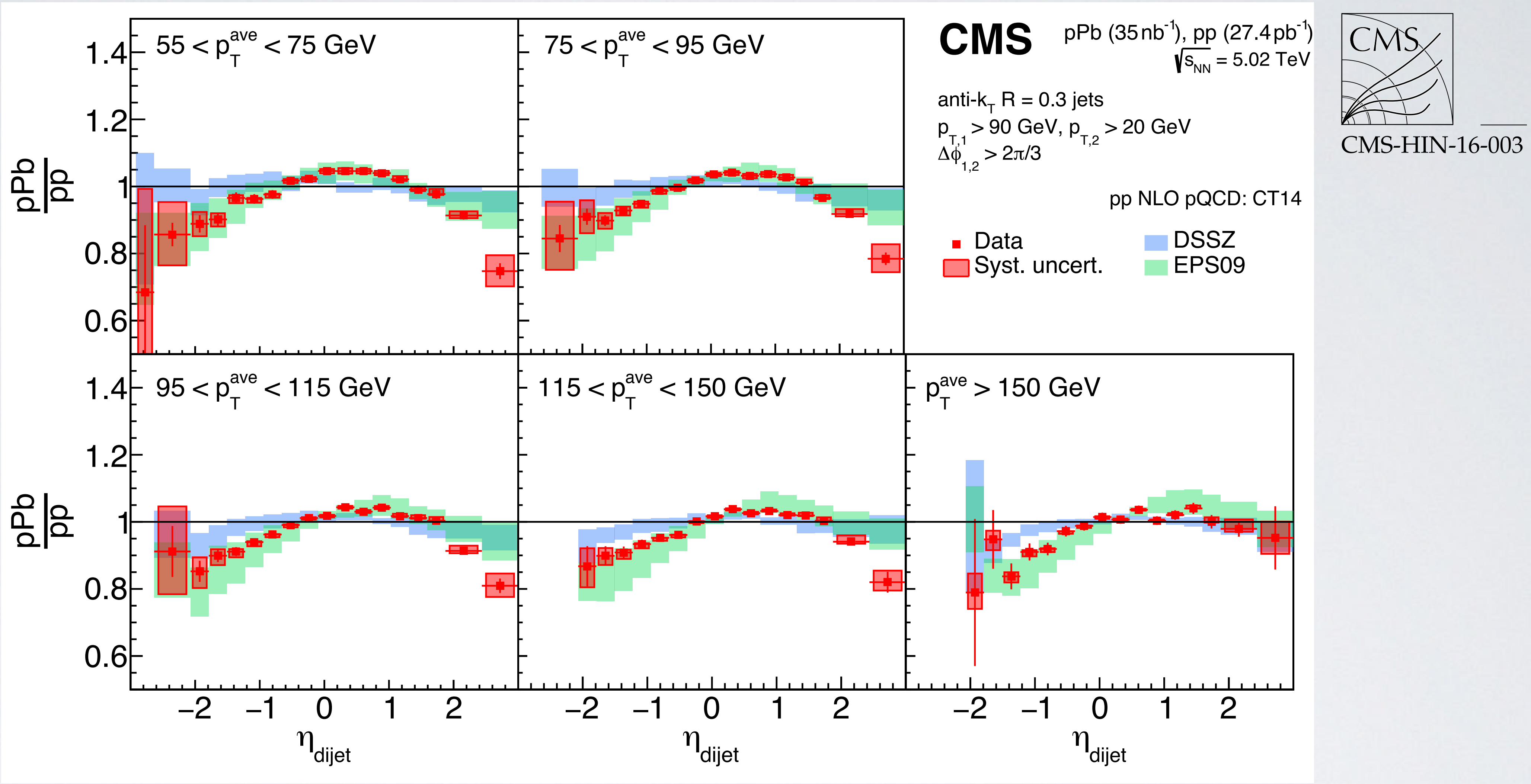




Dijet p_T balance observed to hold in p+Pb, unlike in Pb+Pb: no energy loss.
Self normalized dijet $\eta_{dijet}=(\eta_1+\eta_2)/2$ are very precise.

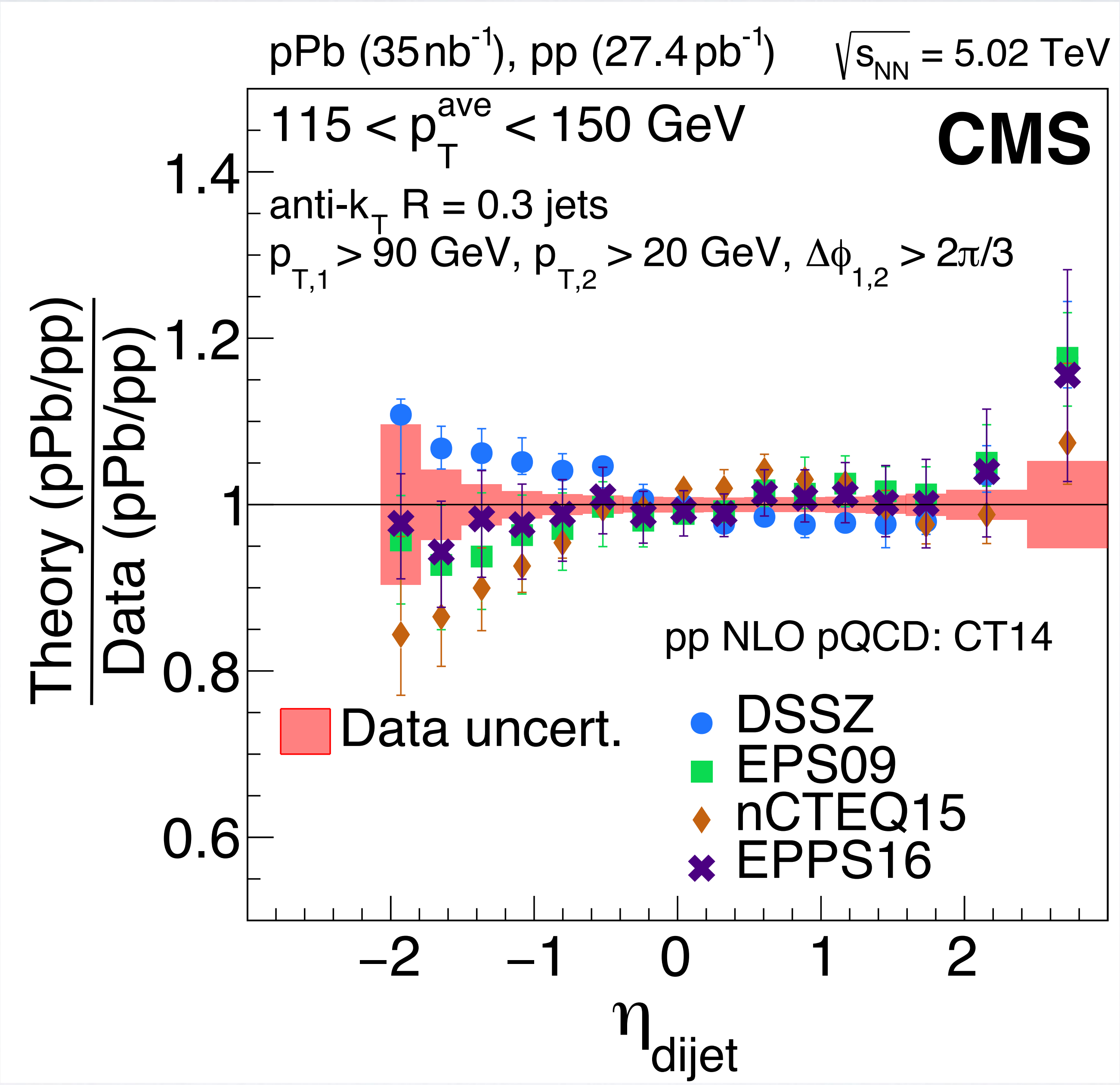
New measurements of 5.02 TeV pp used to compare with previous p+Pb (w/ $\Delta\eta$=0.465)
w/ $\eta_{dijet} \sim \ln(x_2/x_1)$ probing different regions of x_1, x_2

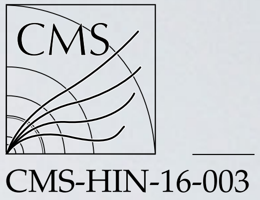
CMS: probing nPDFs with dijets



Ratios of p+Pb/pp demonstrate differences (up to 20%) in PDFs: nPDF implementations differ systematically (also up to 20%)

CMS: Theory/Data ratios





Centrality dependence

A parting of the ways

Inclusive p+Pb → **impact parameter dependence**

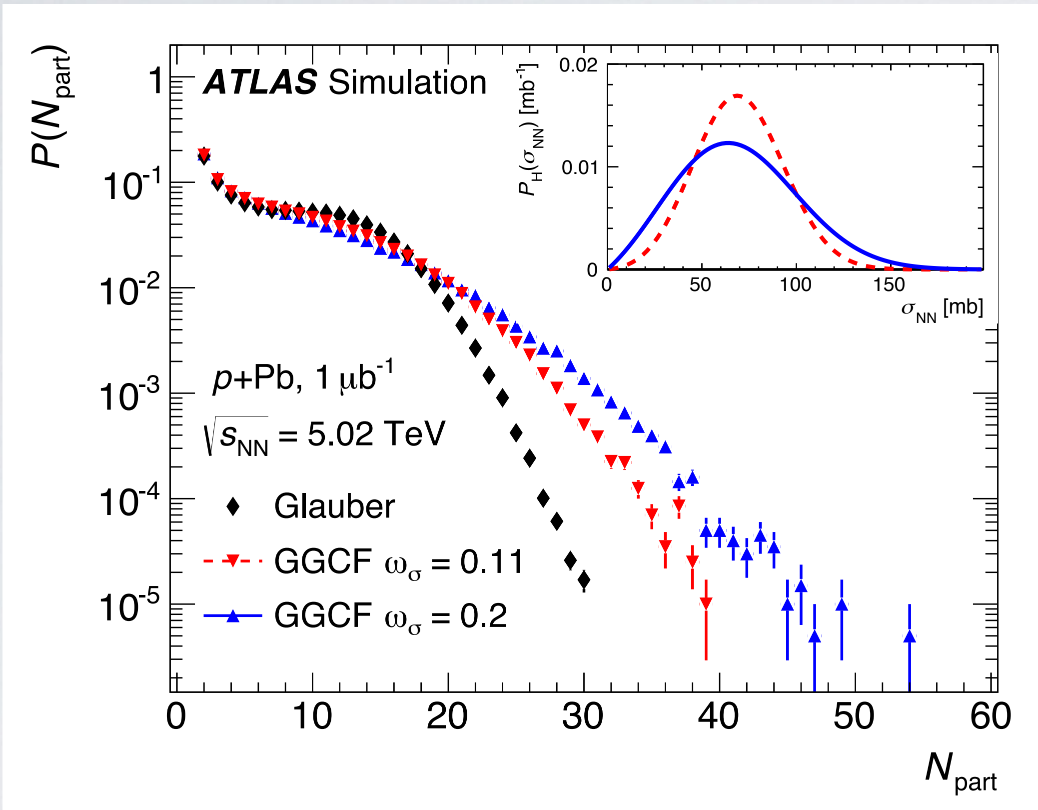
→ **ATLAS: Glauber + corrections**

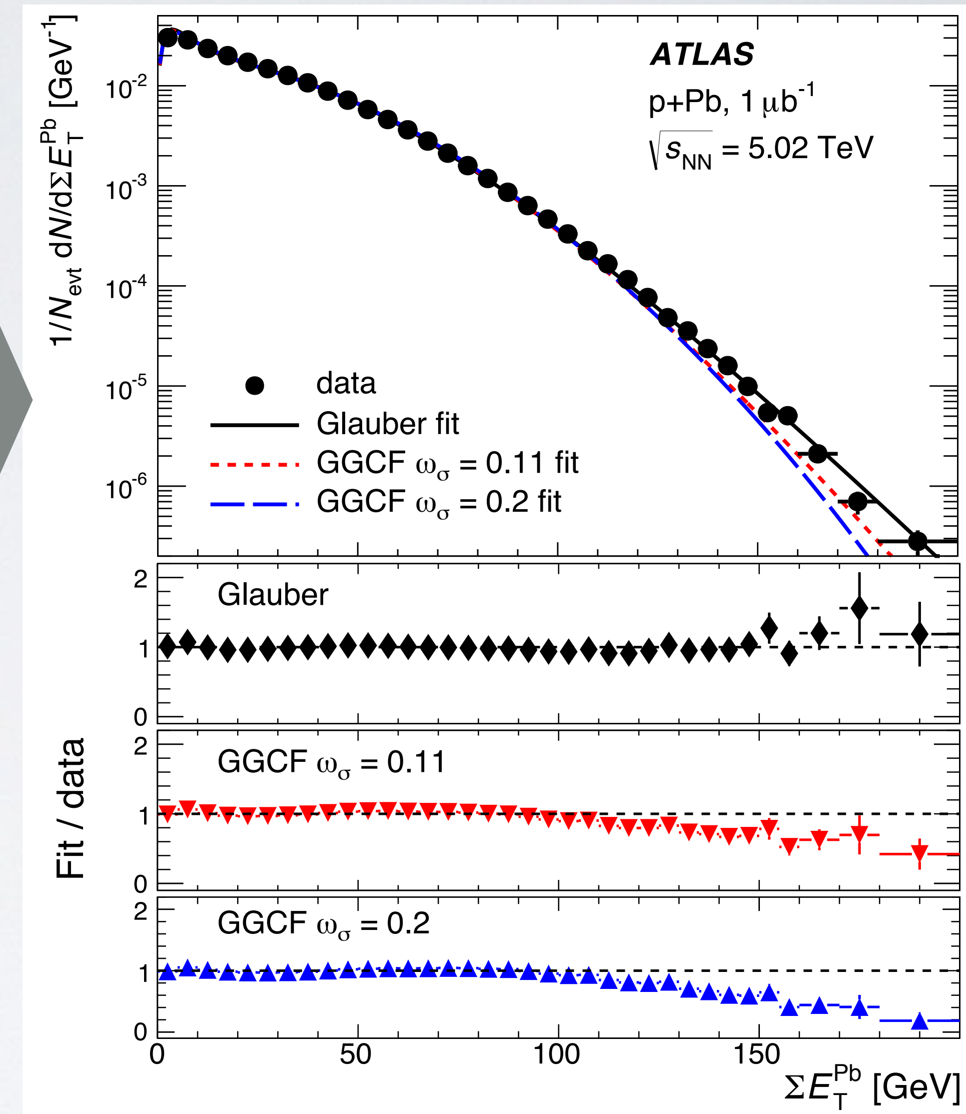
→ **ALICE: Hybrid method**

→ **CMS & ALICE: event activity (no geometry)**

Comments on p+Pb centrality

Eur. Phys. J. C (2016) 76:199





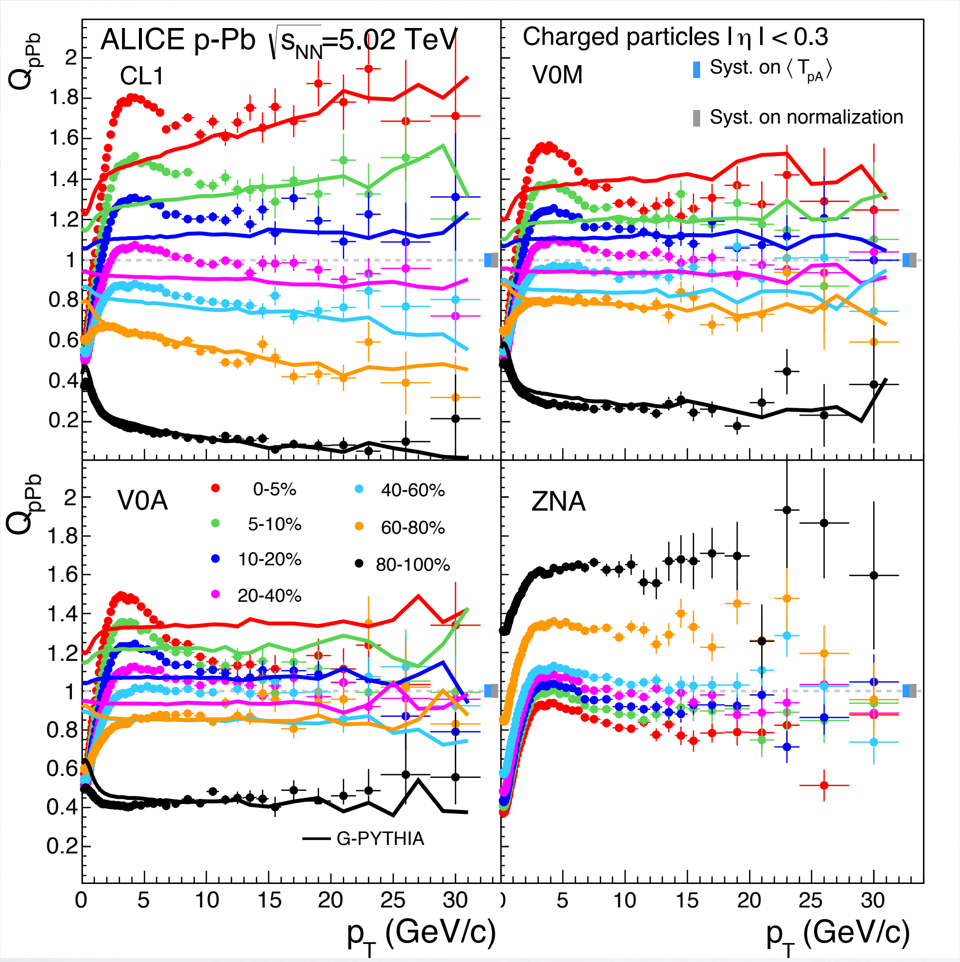
With many measurements demonstrating nucleonic substructure, nucleon size should vary event-to-event: **cross section fluctuations** ("Glauber Gribov Color Fluctuations")

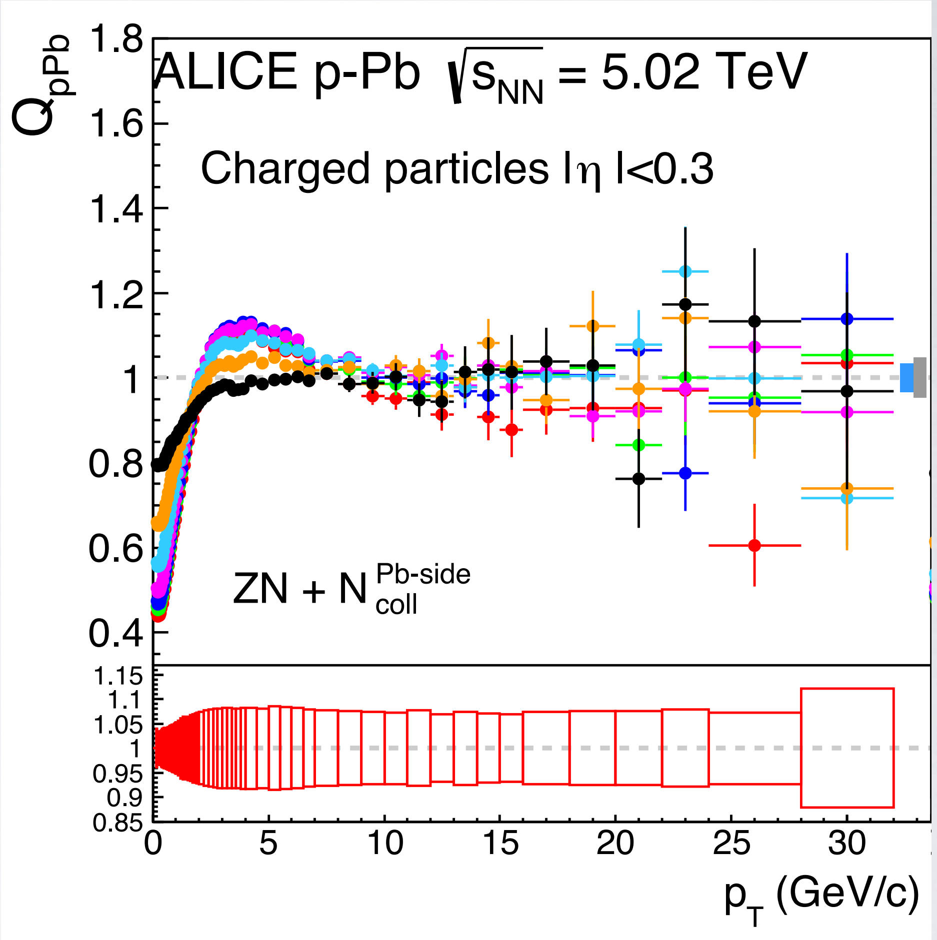
Following Alvioli et al, we implemented this in Glauber and tested fits to Pb-going E_T

While nominal Glauber gives good overall fit (with N_{part} dependent gamma function parameters) GGCF also works well, and "looks" more like data

ALICE Hybrid Method

PHYSICAL REVIEW C **91**, 064905 (2015)





$$Q_{\mathrm{pPb}}(p_{\mathrm{T}};\mathrm{cent}) = \frac{\mathrm{d}N^{\mathrm{pPb}}_{\mathrm{cent}}/\mathrm{d}p_{\mathrm{T}}}{\langle N^{\mathrm{Glauber}}_{\mathrm{coll}}\rangle \mathrm{d}N^{\mathrm{pp}}/\mathrm{d}p_{\mathrm{T}}} = \frac{\mathrm{d}N^{\mathrm{pPb}}_{\mathrm{cent}}/\mathrm{d}p_{\mathrm{T}}}{\langle T^{\mathrm{Glauber}}_{\mathrm{pPb}}\rangle \mathrm{d}\sigma^{\mathrm{pp}}/\mathrm{d}p_{\mathrm{T}}}$$

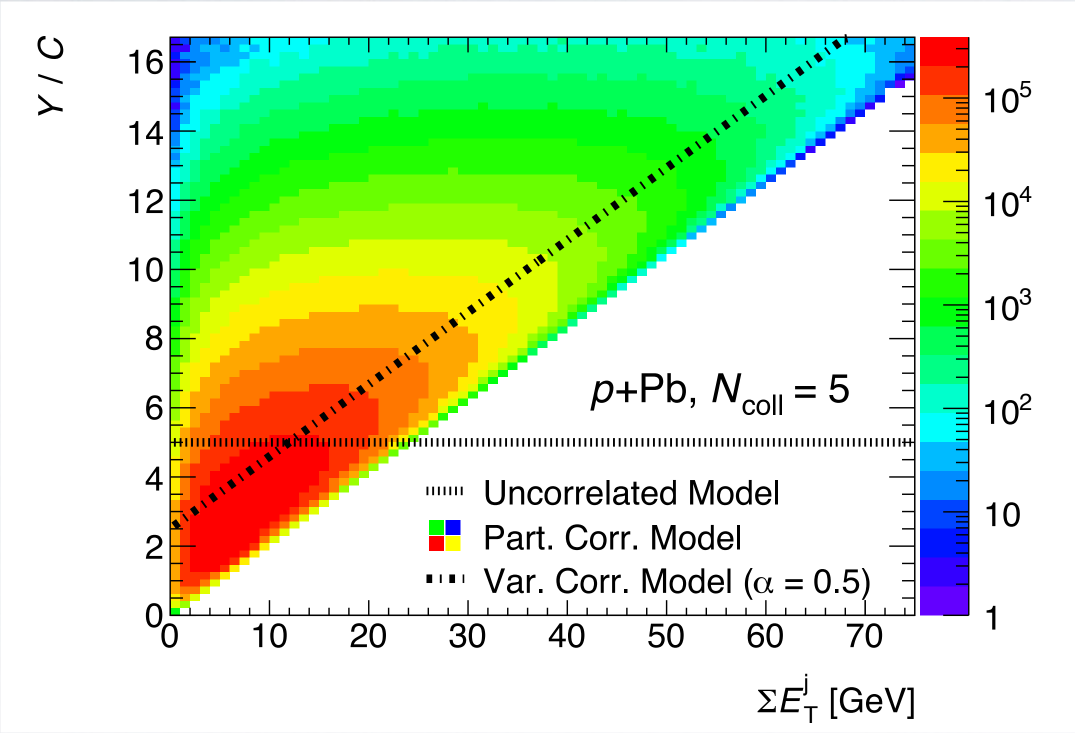
$$\langle N_{\mathrm{coll}}\rangle_{\mathrm{i}}^{\mathrm{Pb-side}} = \langle N_{\mathrm{coll}}\rangle_{MB} \cdot \frac{\langle S\rangle_{\mathrm{i}}}{\langle S\rangle_{MB}}$$

ALICE noticed clear centrality biases from estimators in different η regions

"**Hybrid method**": use ZDC as primary centrality, modified by event activity in regions assumed to scale with N_{coll} or N_{part}

Centrality bias corrections

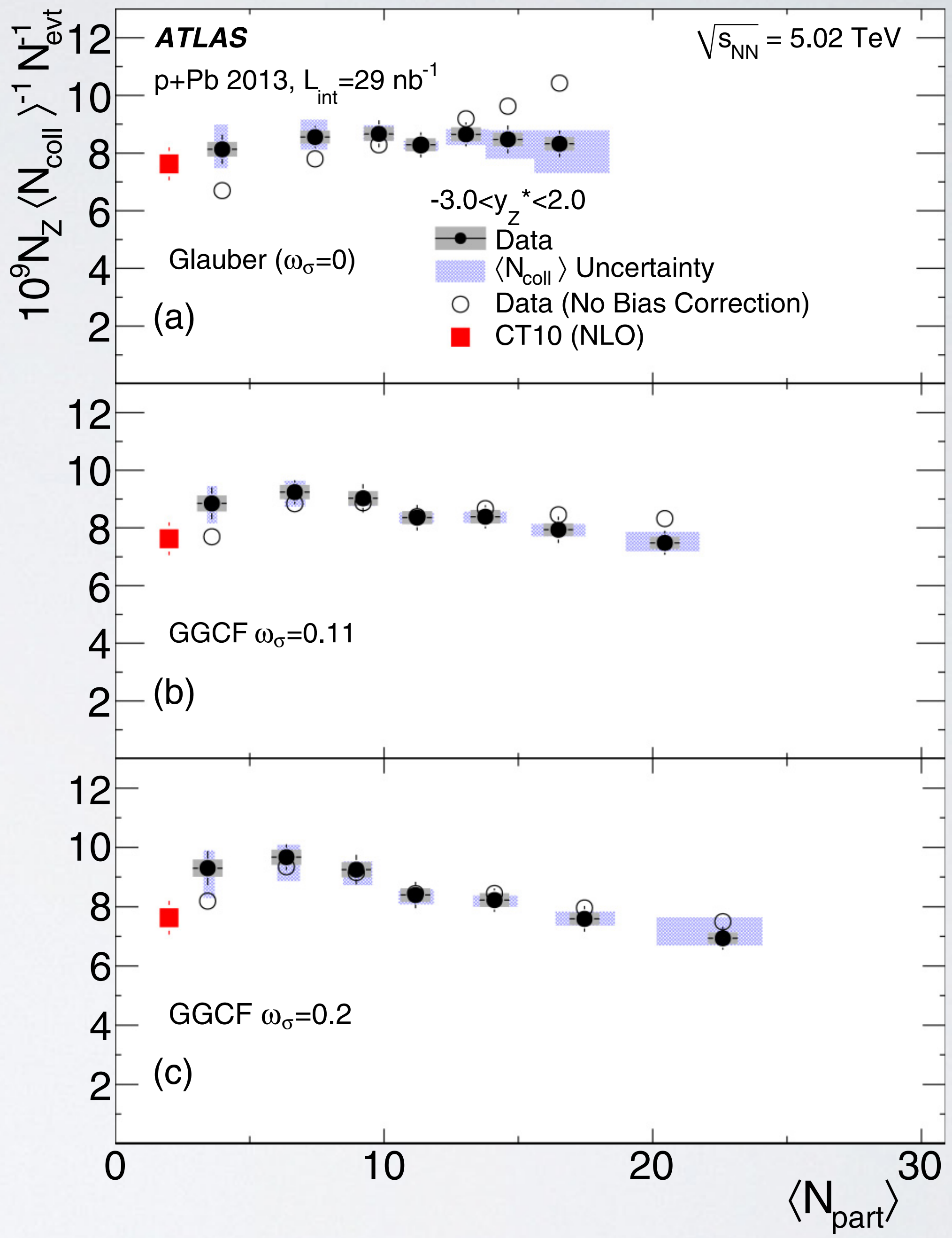
Perepelitsa & Steinberg, arxiv:1412.0976



Simple "centrality bias" model incorporating:
1) per NN ΣE_T fluctuations
2) hard process yield scaling with ΣE_T
Provides per bin corrections on raw yield to correct for misestimated N_{coll}

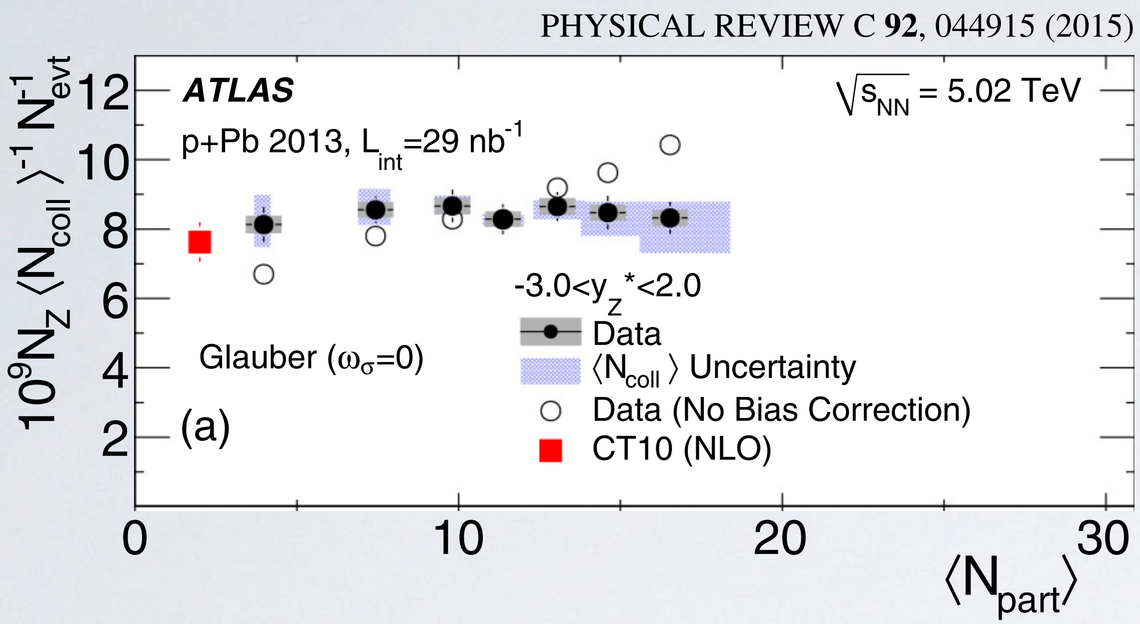
centrality	ρ (default)	ρ ($\Omega = 0.55$)	ρ ($\Omega = 1.01$)
0–10%	1.20 ± 0.10	1.09 ± 0.04	1.07 ± 0.03
10–20%	1.06 ± 0.03	1.03 ± 0.02	1.03 ± 0.01
20–30%	1.00 ± 0.01	1.00 ± 0.01	1.01 ± 0.01
30–40%	0.96 ± 0.02	0.98 ± 0.01	0.99 ± 0.01
40–60%	0.91 ± 0.04	0.96 ± 0.02	0.97 ± 0.02
60–90%	0.82 ± 0.07	0.87 ± 0.06	0.88 ± 0.06

PHYSICAL REVIEW C **92**, 044915 (2015)

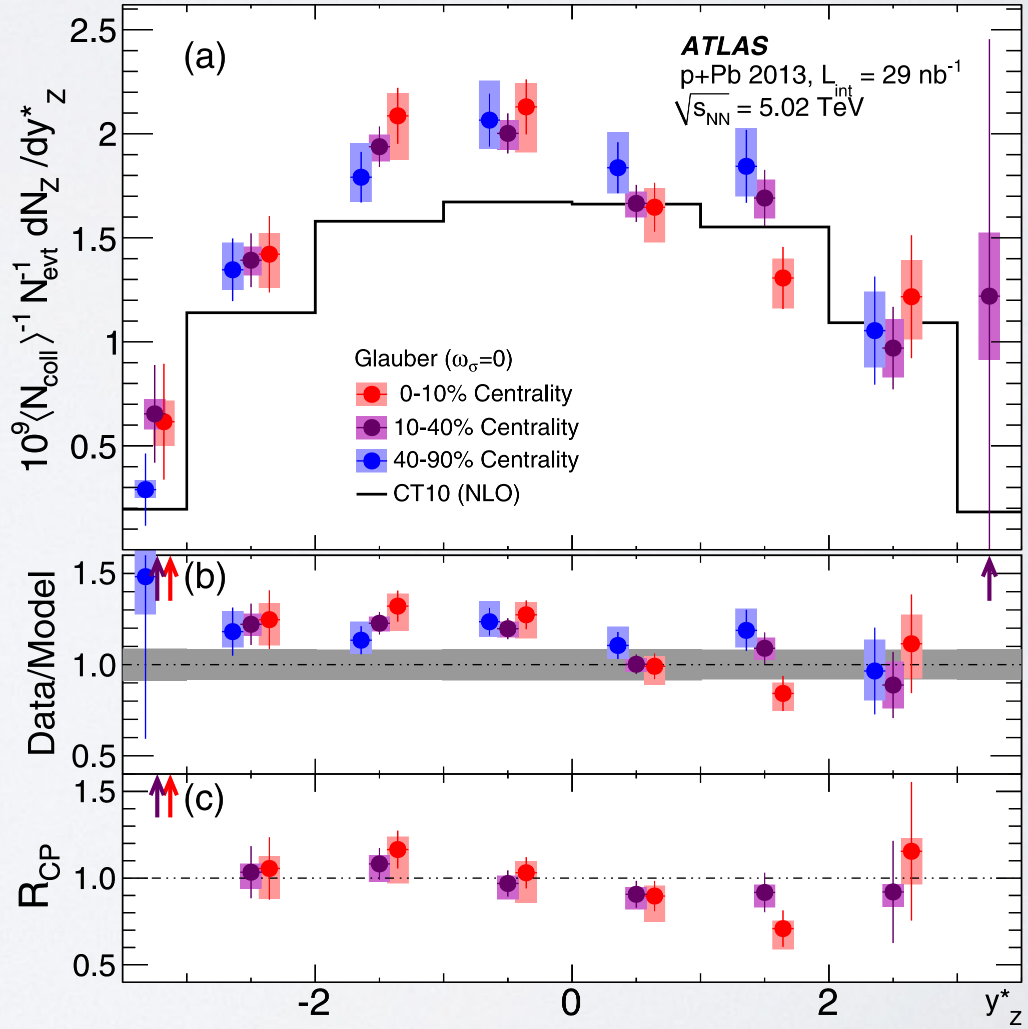


Used by ATLAS for Z boson: successfully "flattens" Z/<N_{coll}>

ATLAS Z yield vs. centrality



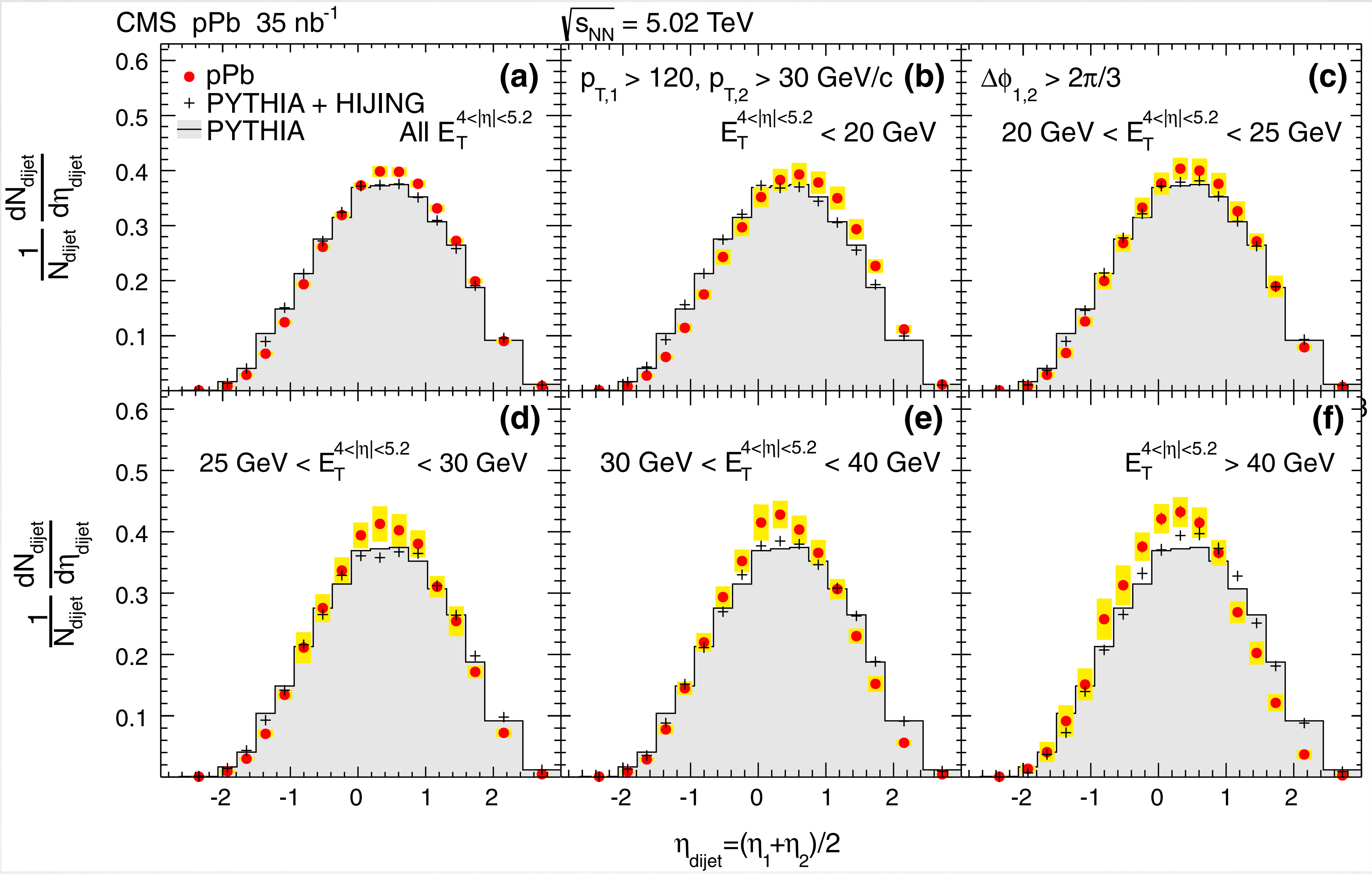
Already seen:
Z yields scale with $<T_{AB}>$,
but only after corrections



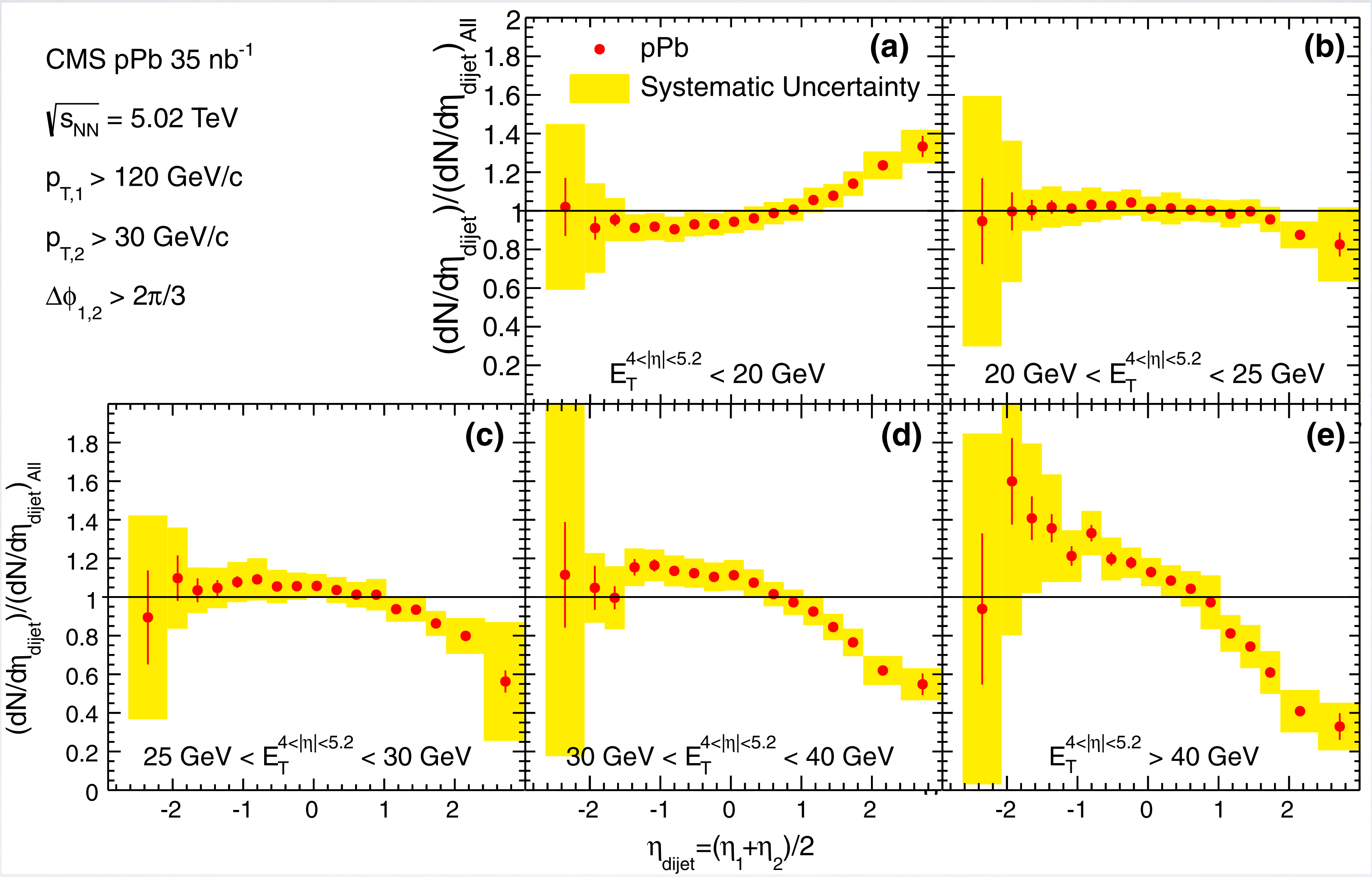
Rapidity distributions
shown for 3 centrality selections
(0-10, 10-40, 40-90%)

All centralities show a systematic
difference relative to CT10,
possible (2.5σ) linear slope to R_{CP}

CMS p+Pb dijets vs. event activity



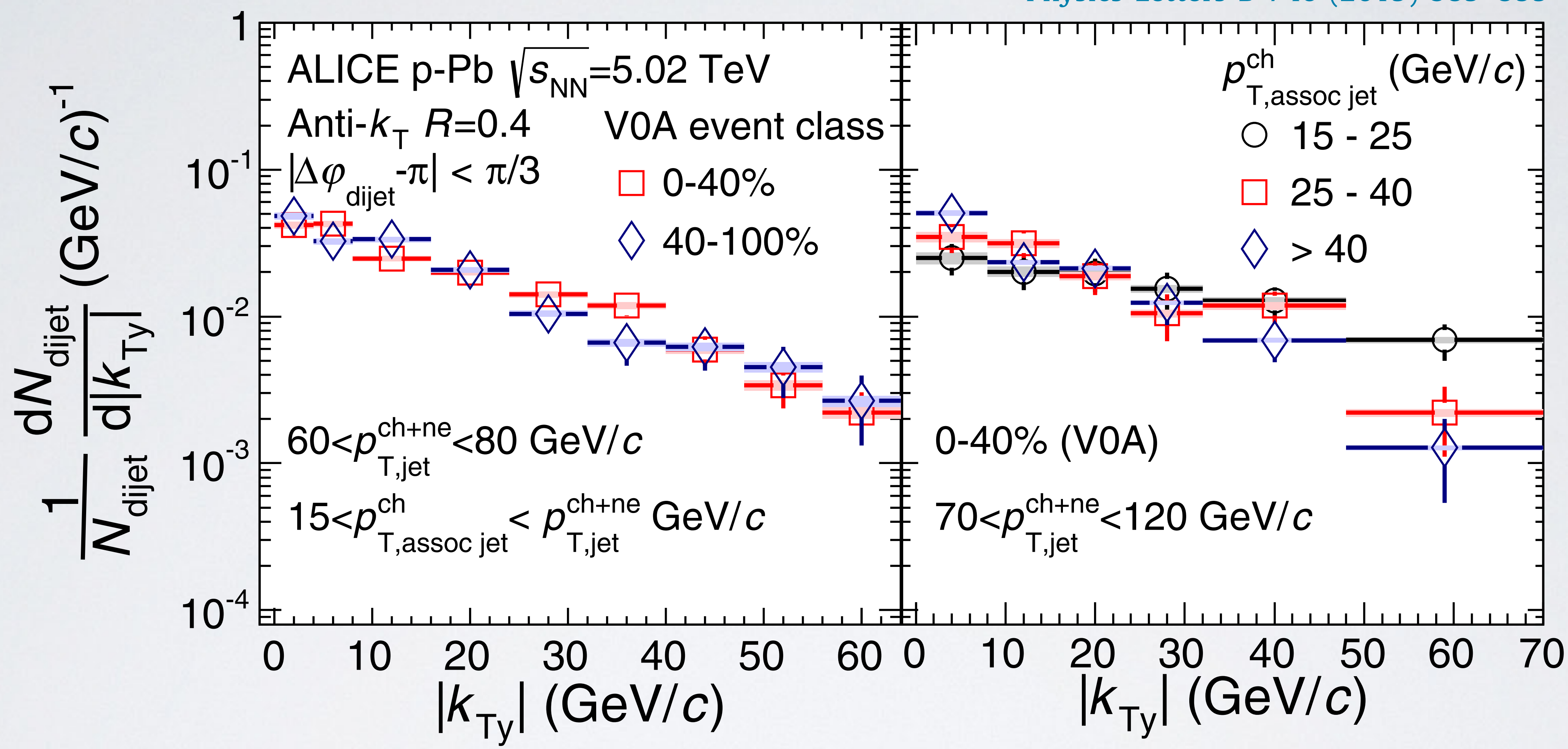
CMS p+Pb dijets vs. event activity



Clear modification (shift?) of $\eta_{\rm dijet}$ distributions vs. event activity: sensitivity of this variable to nPDFs suggest impact parameter dependence

ALICE dijet k_T vs. event activity

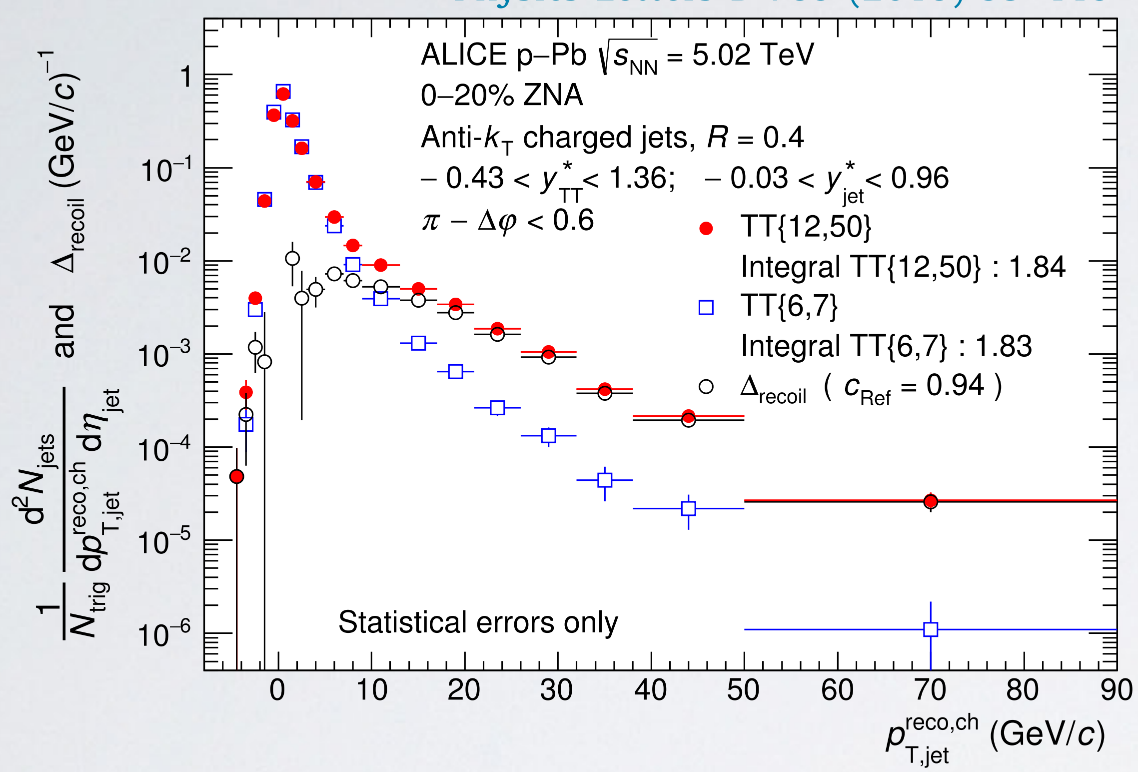
Physics Letters B 746 (2015) 385–395



Using forward scintillator, ALICE tests for modifications of dijet acoplanarity (changes in $\Delta\phi$): no significant change observed

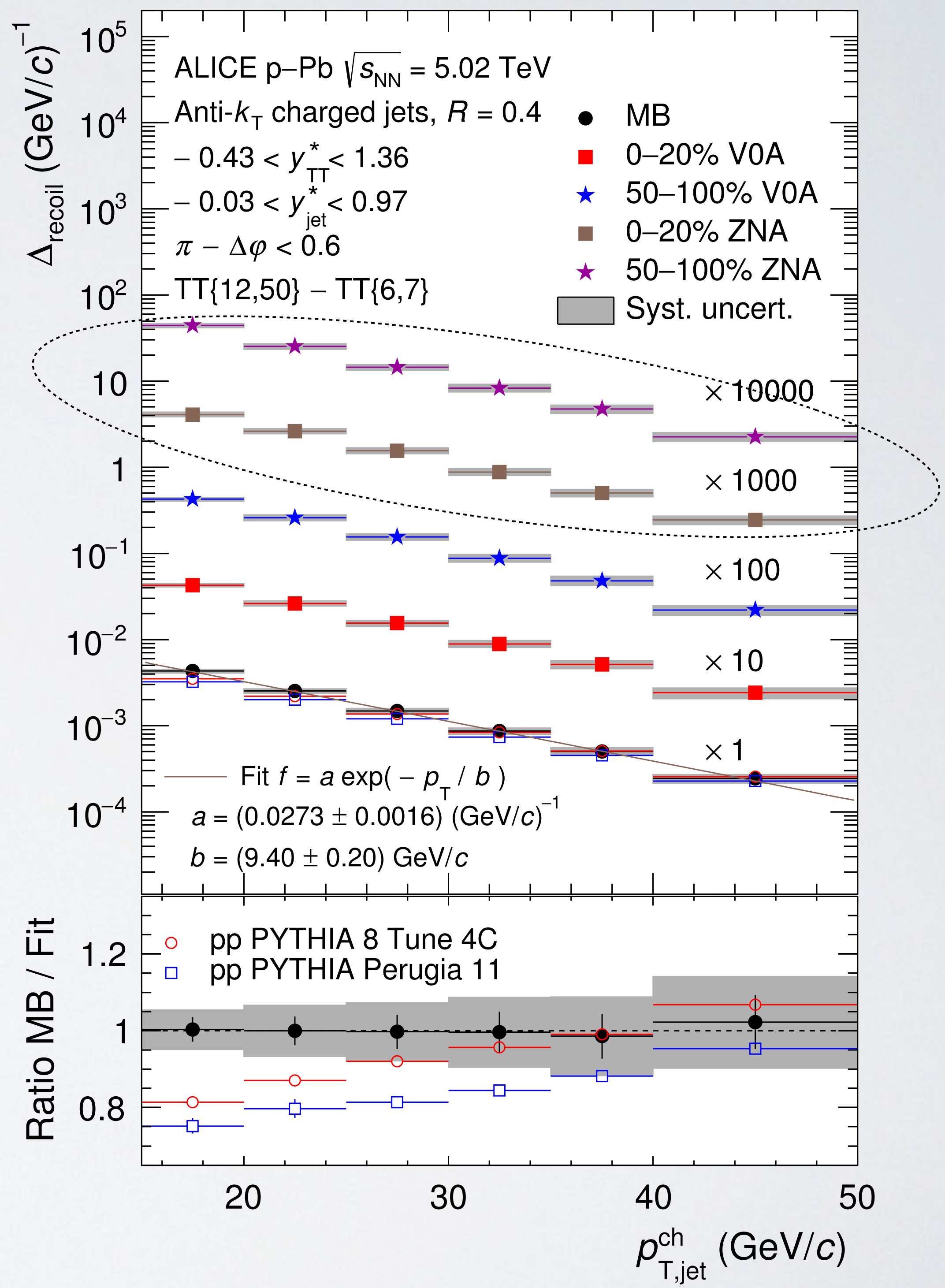
ALICE recoil vs. event activity

Physics Letters B 783 (2018) 95–113



Jets recoiling against trigger tracks (TT), with UE fluctuations removed statistically by selection on a lower p_T TT: "recoil" depends on two pT selections

$$\Delta_{recoil}\left(p^{ch}_{T,jet}\right) = \frac{1}{N_{trig}} \frac{d^2N_{jets}}{dp^{ch}_{T,jet}}\bigg|_{p_{T,trig} \in TT_{Sig}} - c_{Ref} \cdot \frac{1}{N_{trig}} \frac{d^2N_{jets}}{dp^{ch}_{T,jet}}\bigg|_{p_{T,trig} \in TT_{Ref}}$$

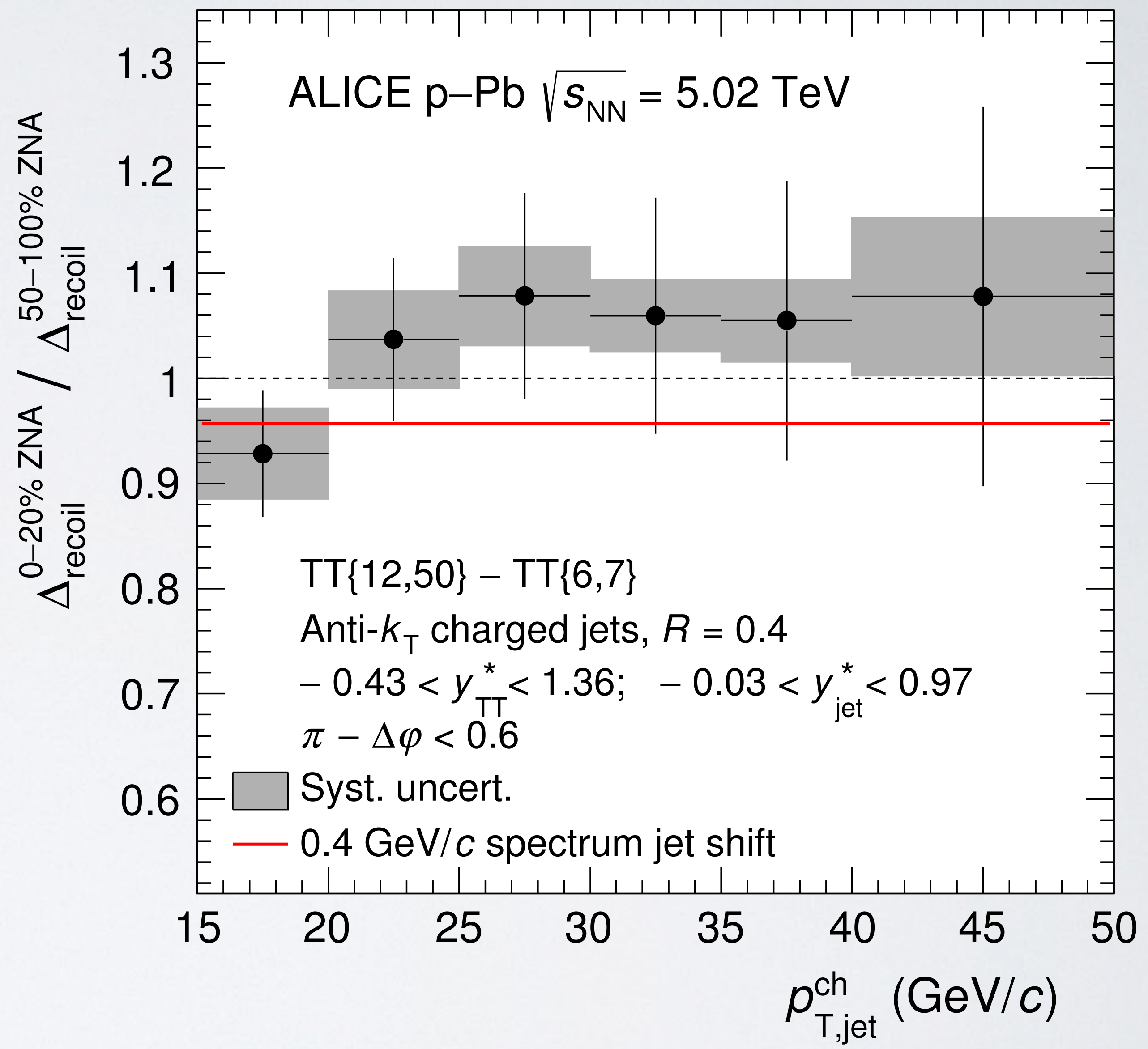


ALICE recoil vs. event activity

Recoil is self-normalized (effectively a dijet measurement) so just probes modifications vs. event activity

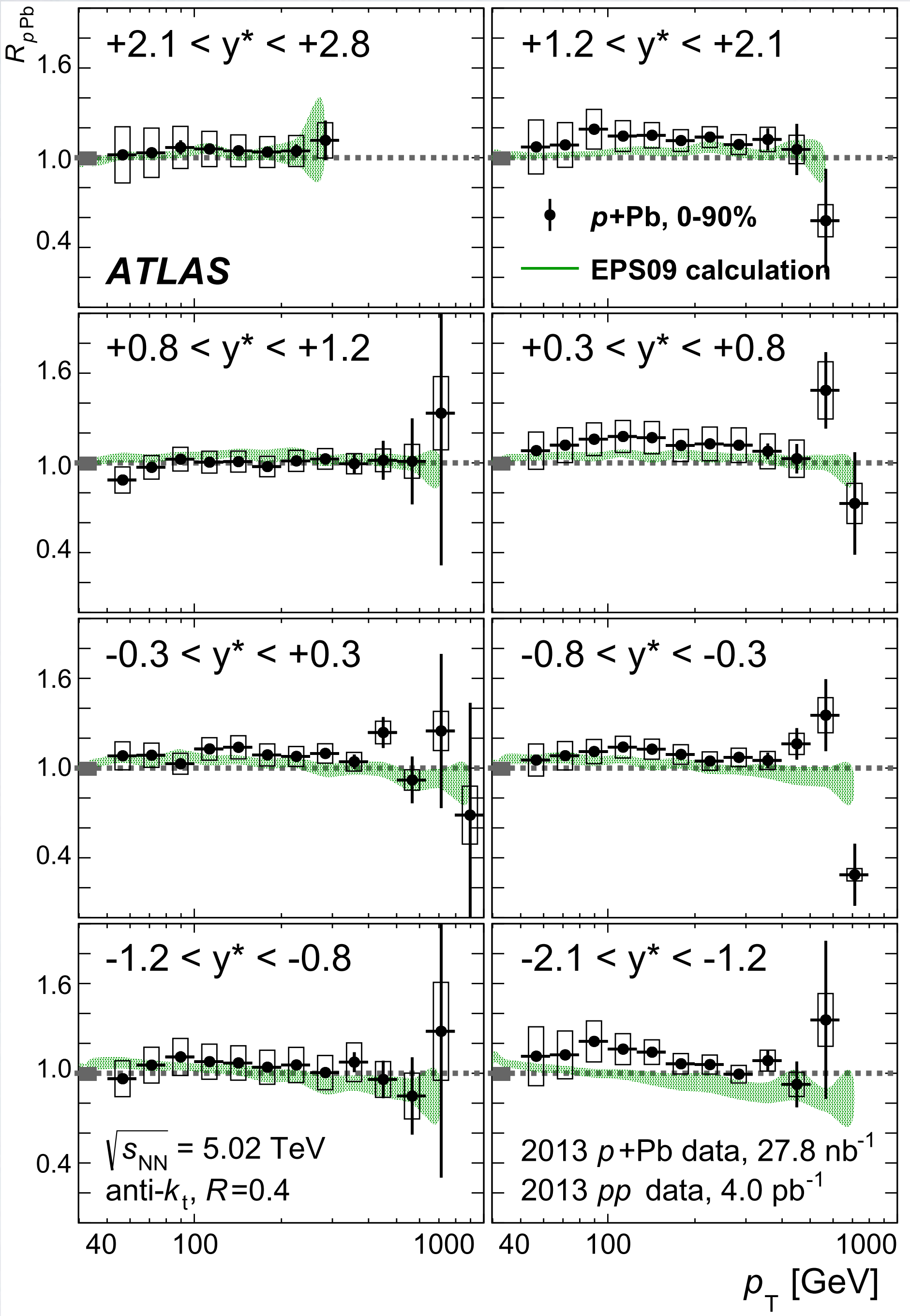
None-observed but combining systematic and statistical uncertainties provides an upper limit on shift of *charged* jet spectrum of 0.4 GeV

Physics Letters B 783 (2018) 95–113



ATLAS jets vs. centrality

Physics Letters B 748 (2015) 392–413

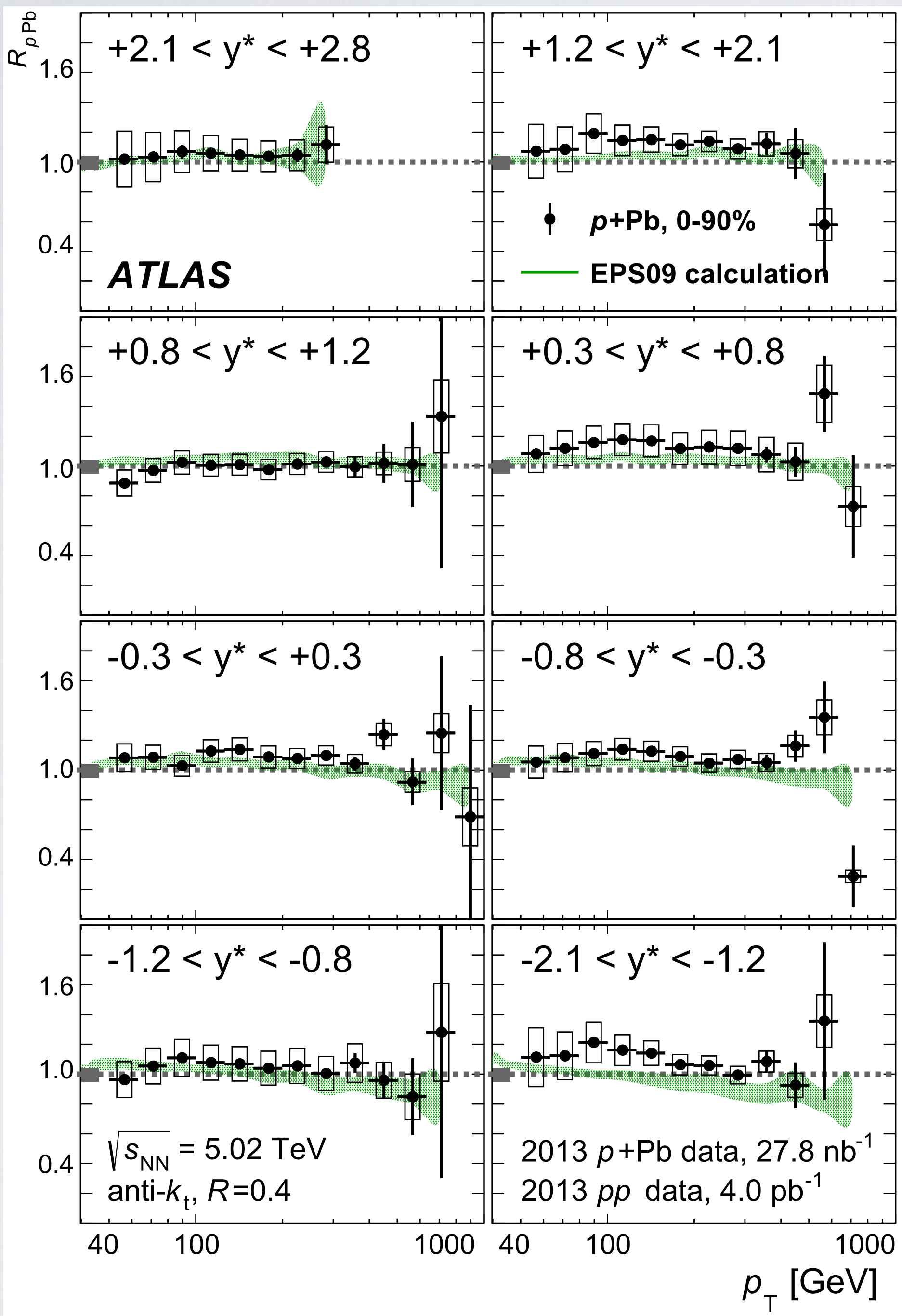


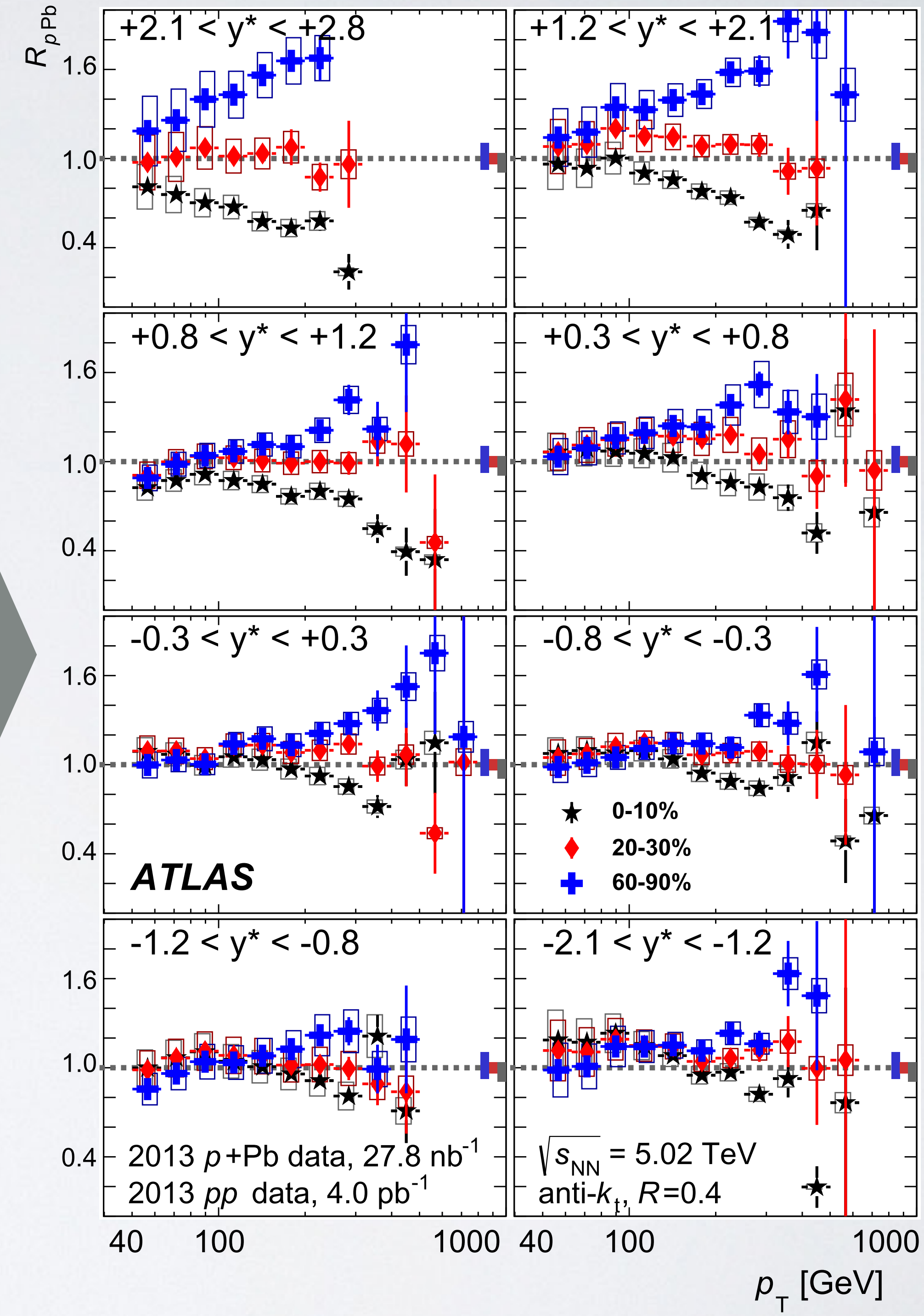
Inclusive jets show no obvious modification relative to x_T-scaled pp: nor do nPDFs predict much change

What if we impose centrality cuts?

ATLAS jets vs. centrality

Physics Letters B 748 (2015) 392–413





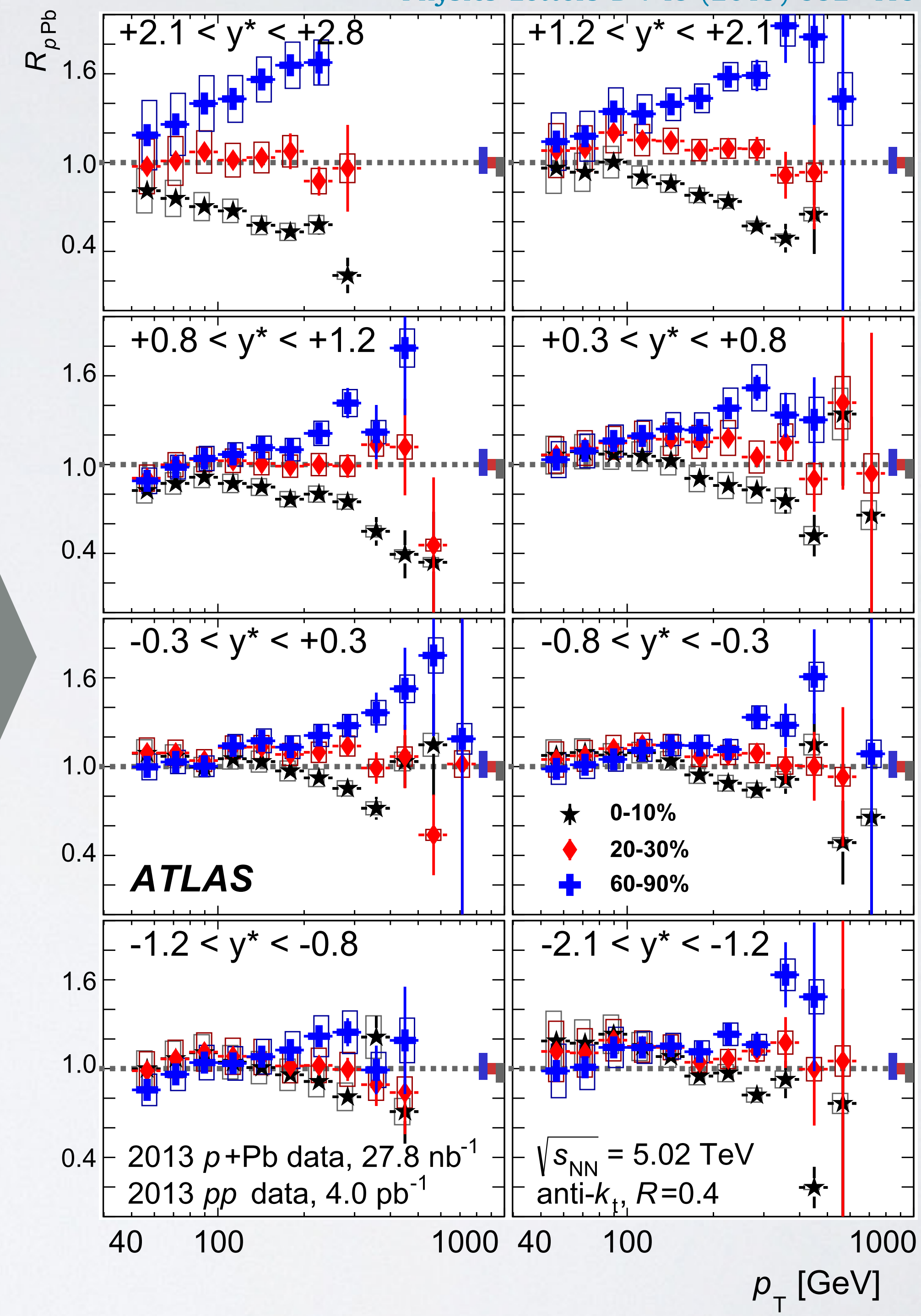
ATLAS p+Pb jets vs. centrality

Peripheral events show **enhanced** yield per binary collision

Mid-central events show **nominal** yield per binary collision

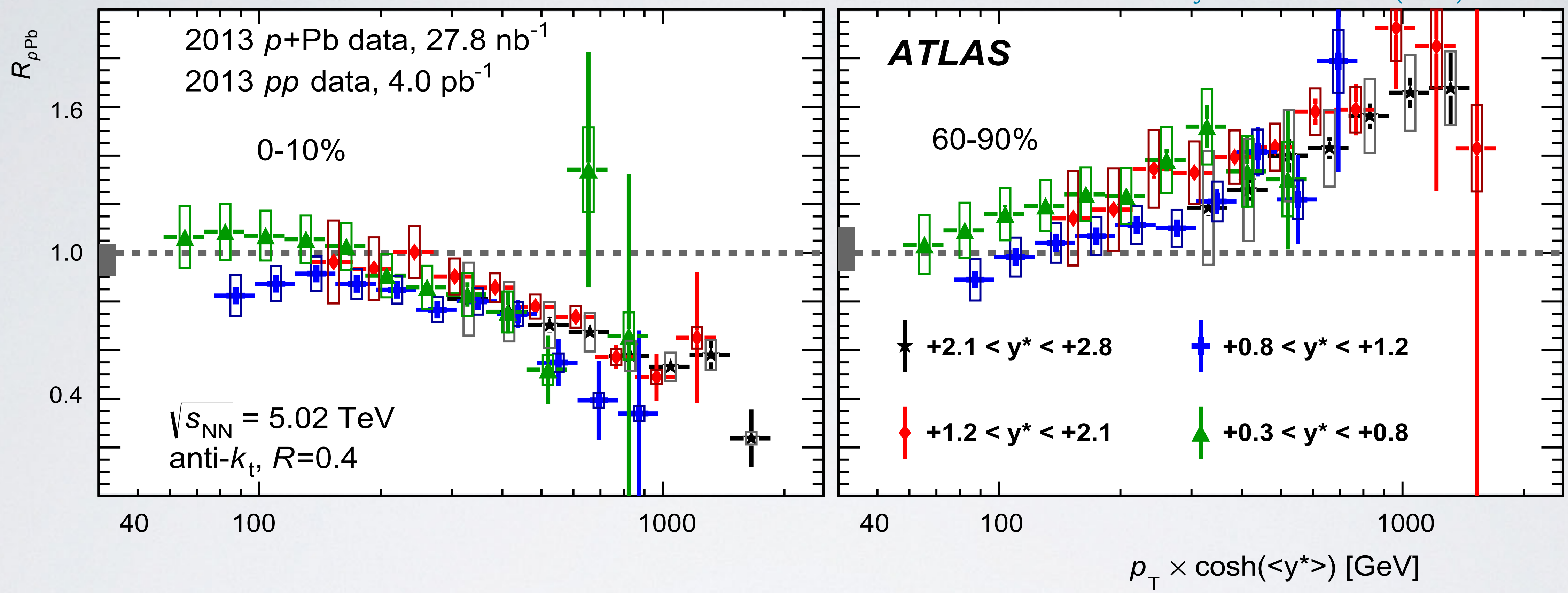
Central events show **suppressed** yield per binary collision

Physics Letters B 748 (2015) 392–413



ATLAS p+Pb jets vs. centrality

Physics Letters B 748 (2015) 392–413

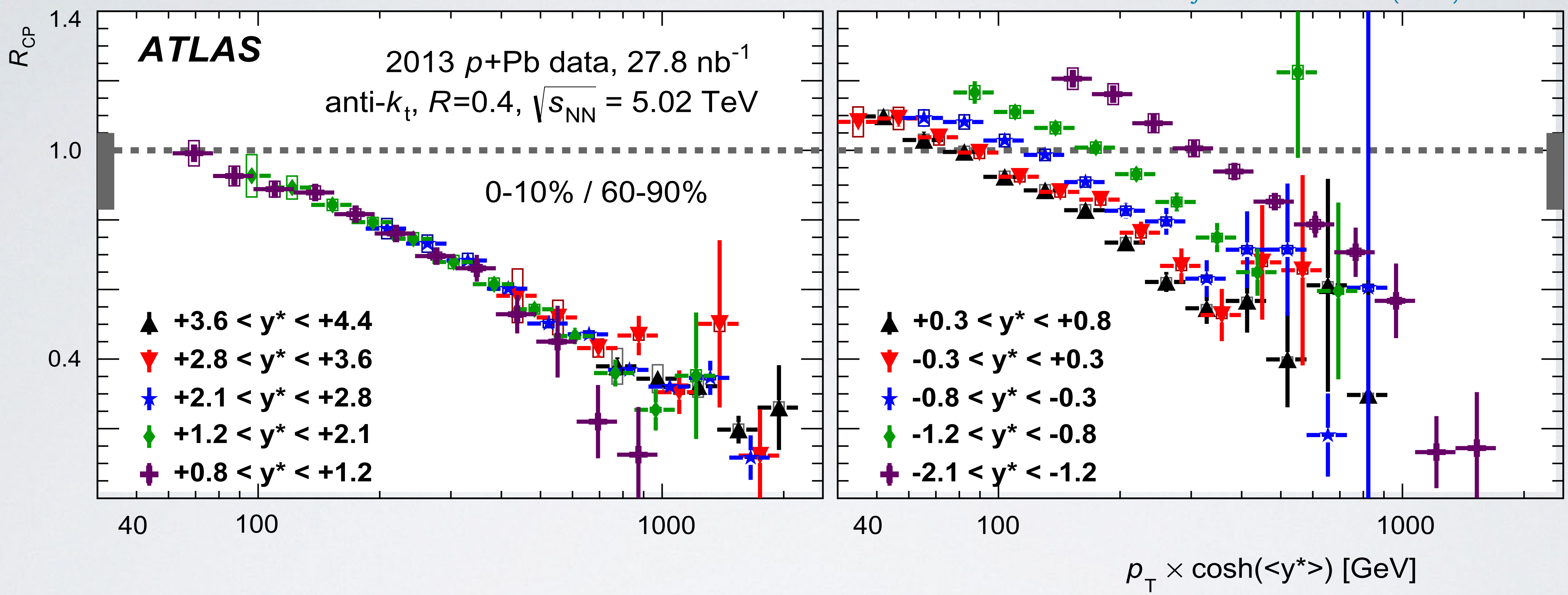


All rapidity bins show the same generic behavior, and show a rough scaling as a function of ***E*=*p*T x cosh(y*)**

what about detailed differences between peripheral and central (R_{CP})?

ATLAS p+Pb jets vs. centrality

Physics Letters B 748 (2015) 392–413



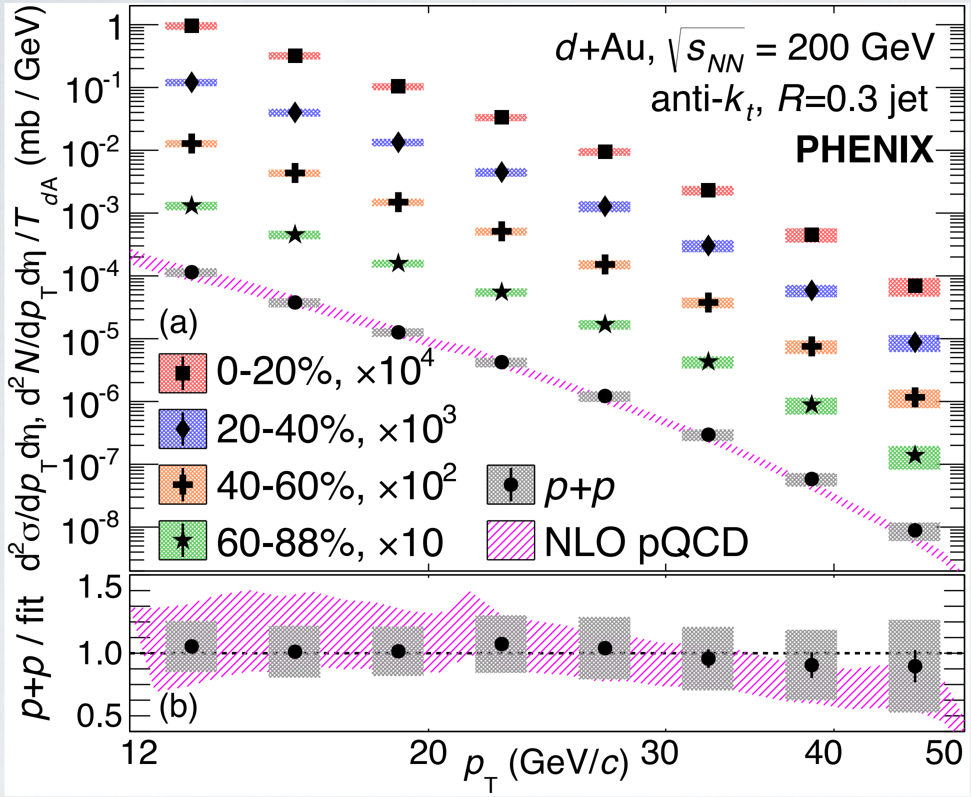
As function of ***E*=*p*$_T$ x cosh(y*):**

1) forward (proton-going) rapidities collapse onto universal function

2) backward (lead-going) show no particular scaling

Is this energy loss? (answer: probably not)

PHENIX d+Au inclusive jets

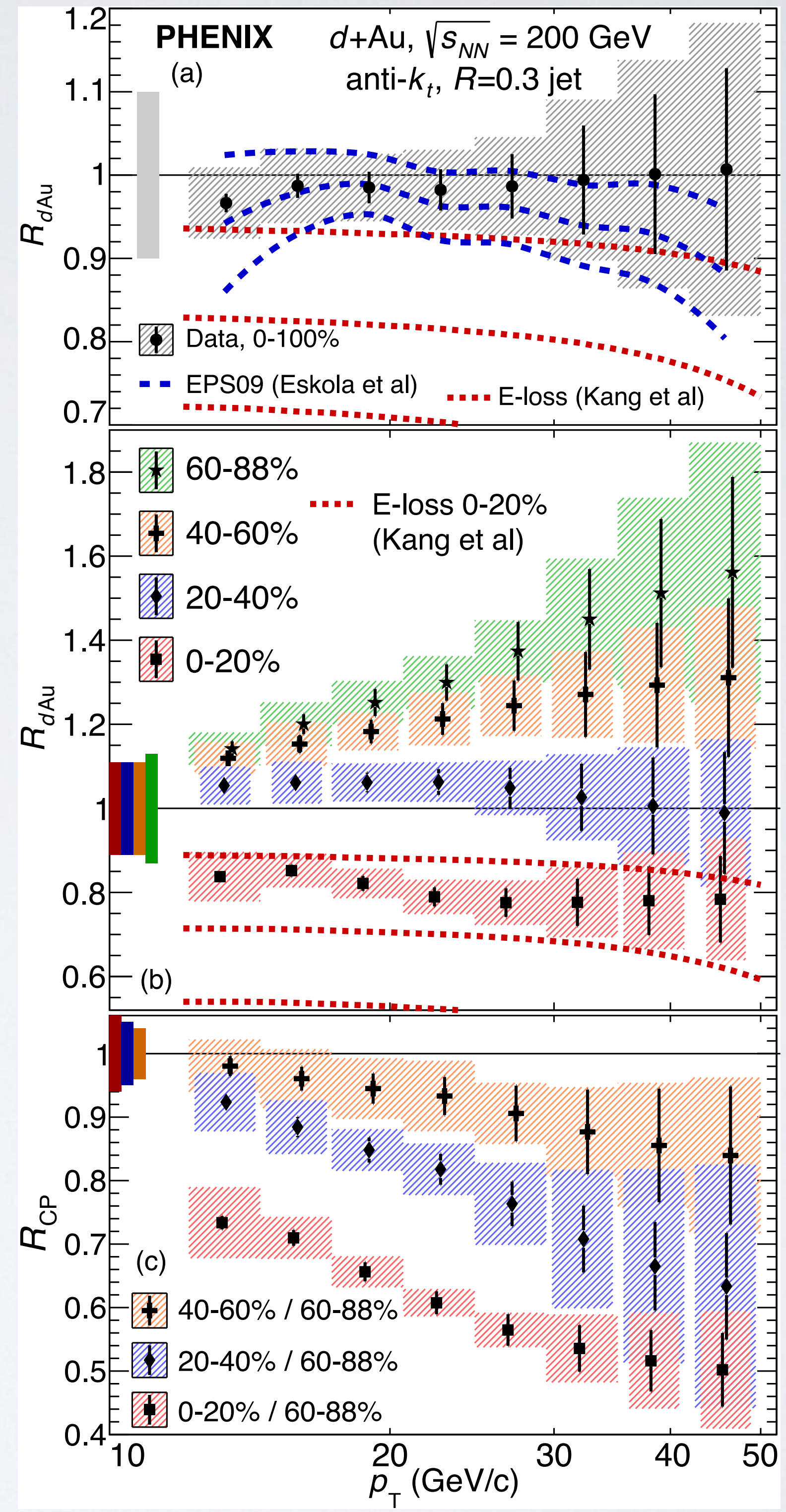


PHENIX data on centrality-dependent jets in d+Au show same phenomenon:

1) inclusive R_{dAu} ~ 1

2) centrality "splitting"

3) decrease of R_{CP} with p_T~E



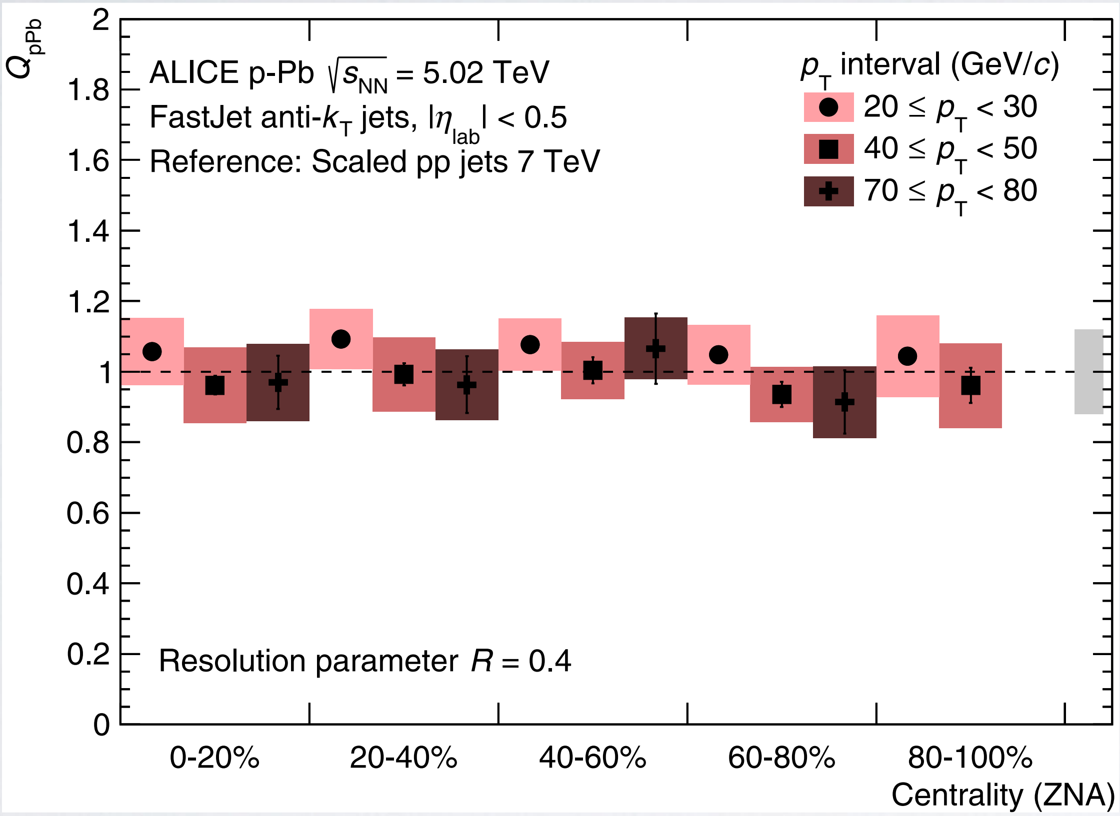
1

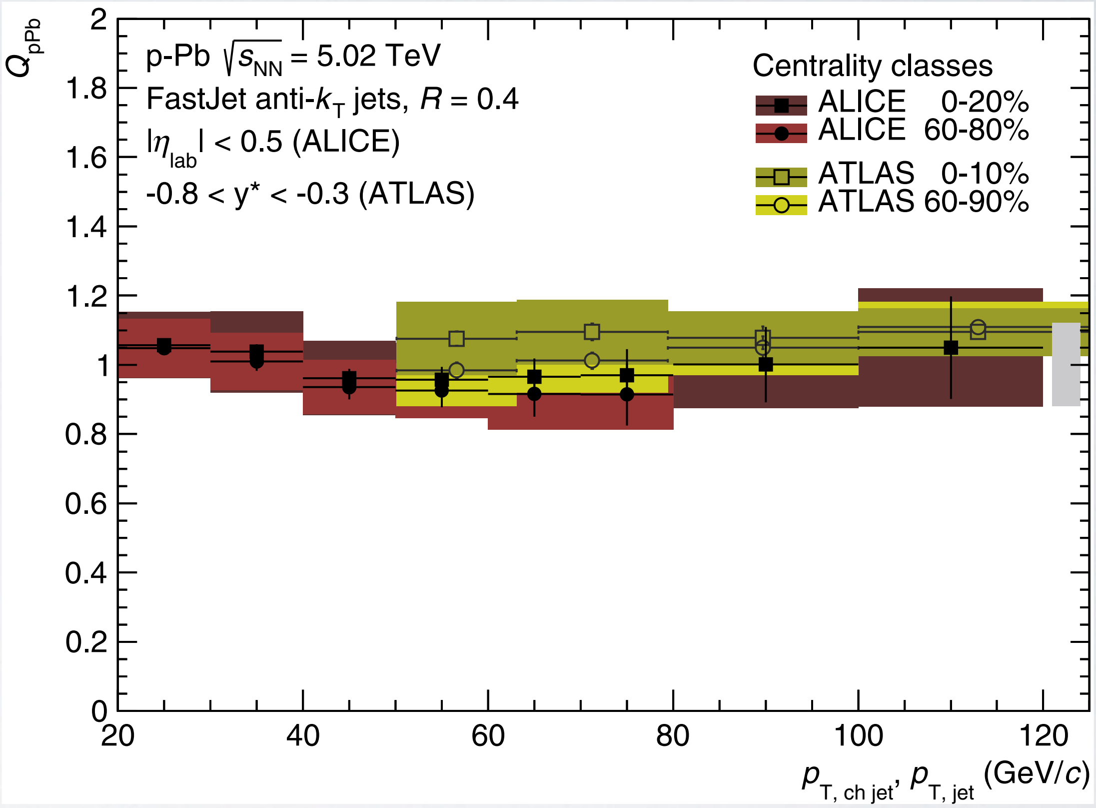
2

3

ALICE charged jets vs. centrality

Physics Letters B 749 (2015) 68–81



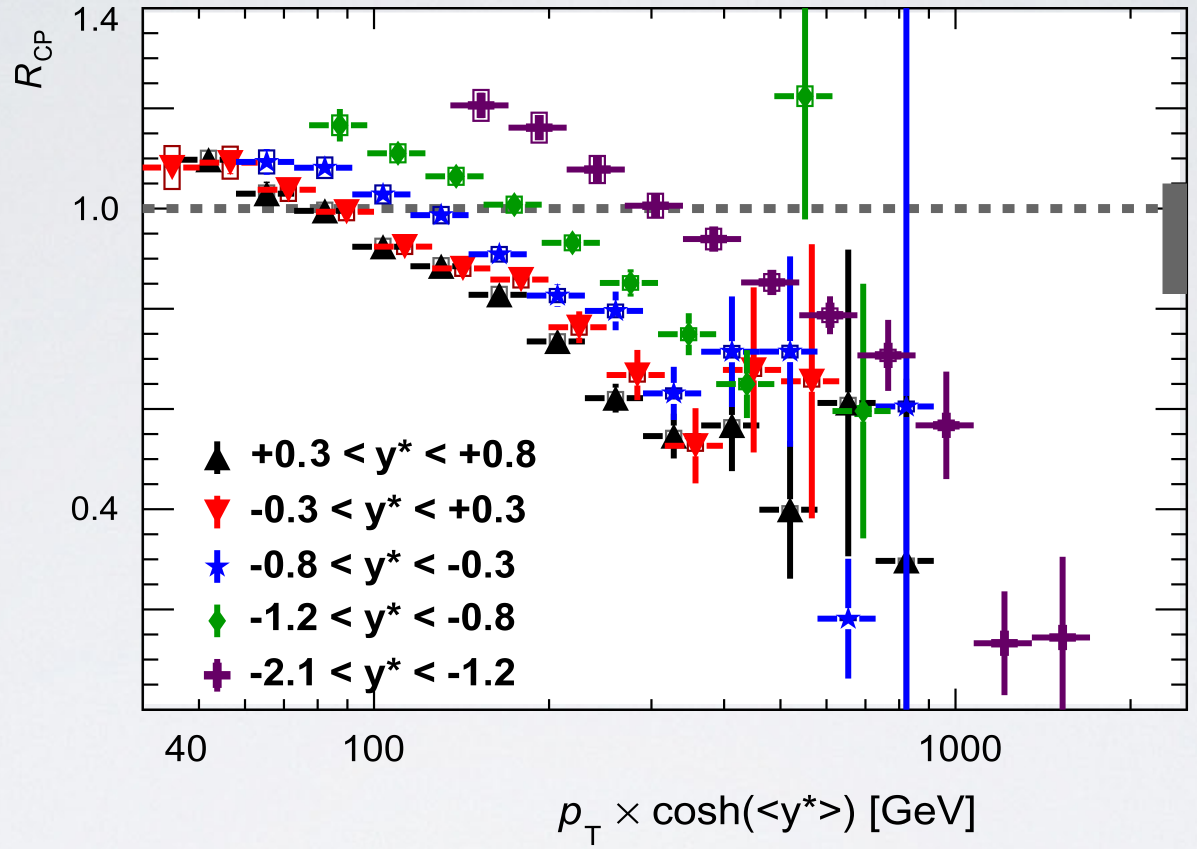


ALICE has performed a centrality dependence, using hybrid model: no substantial centrality dependence seen, nor splitting

Comparing with ATLAS, it is seen that ALICE measures in kinematic region where neither experiment observes any dependence

ATLAS in wonderland

Physics Letters B 748 (2015) 392–413



ALICE tested if ATLAS R_{CP} consistent with their upper limit (for $|y^*|<0.3$)

p–Pb $\sqrt{s_{NN}} = 5.02$ TeV $y^* = 0.3$ [66]	p–Pb 0–10%/60–90%	57 113	$R_{CP} = 1.09 \pm 0.02_{stat} \pm 0.03_{sys}$ $R_{CP} = 0.93 \pm 0.01_{stat} \pm 0.02_{sys}$
	p–Pb MB w/wo $-0.6\,\mathrm{GeV}/c$ shift	50 110	$R^*_{CP} = 0.95$ $R^*_{CP} = 0.97$

Physics Letters B 783 (2018) 95–113

In their checks, R_{CP} should **decrease**, where it is observed to **increase**

Centrality splitting

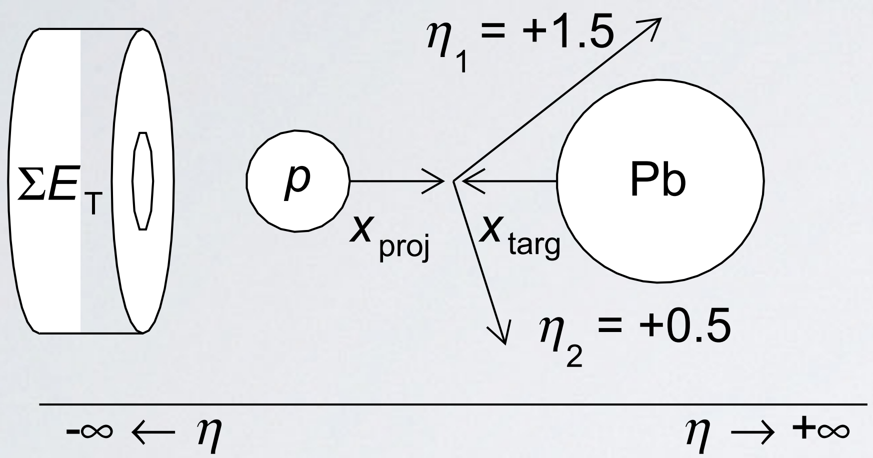
"**Centrality bias**": **central events** pick events with **higher yield**, **peripheral events** pick events with **lower yield**

ATLAS/PHENIX effect is the **opposite**:
peripheral events have a **higher yield** per nucleon,
central events have a **lower yield** per nucleon

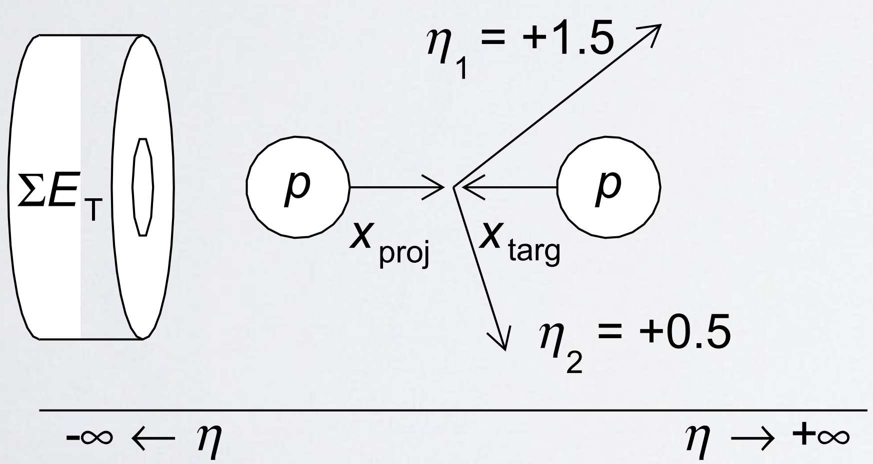
Perhaps there is a **trivial energy conservation effect**:
in pp, can a forward jet deplete the backwards ΣE_T?

Testing trivial hypothesis

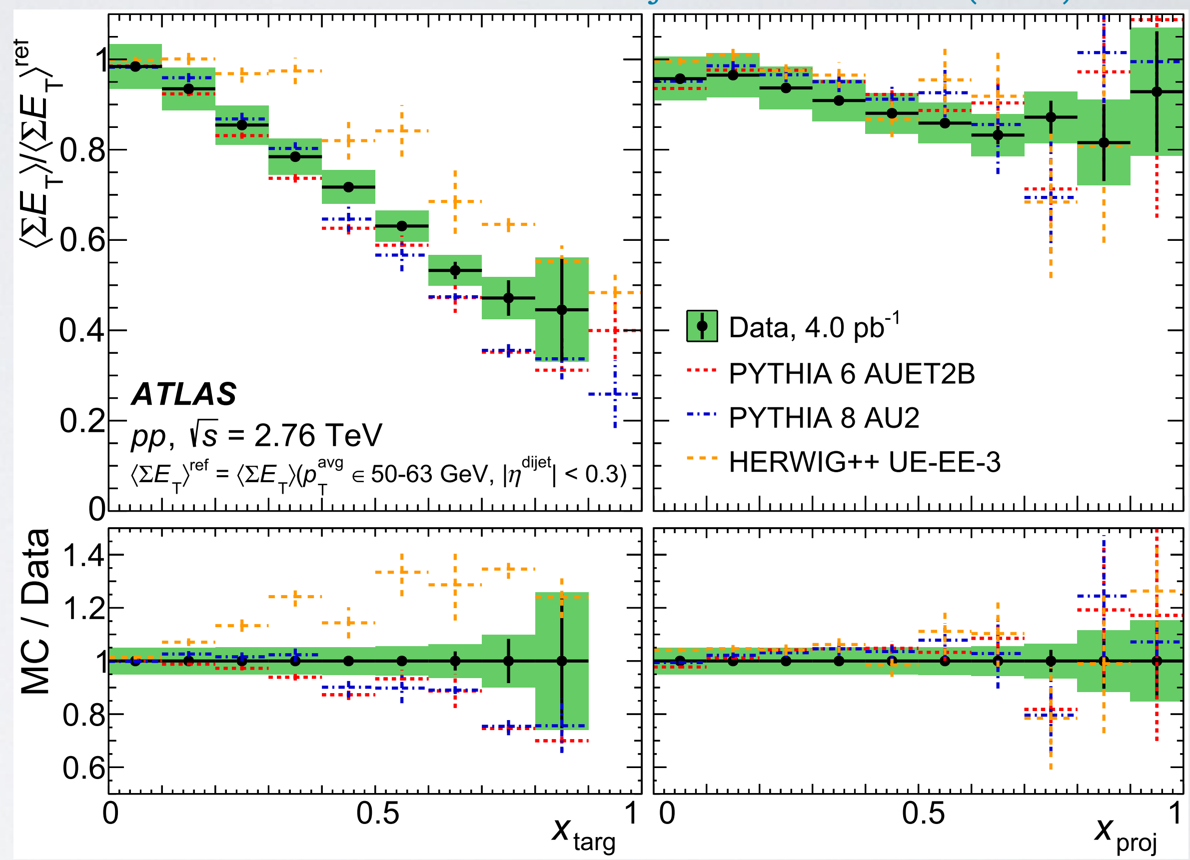
(a) *p*+Pb collision



(b) *pp* collision



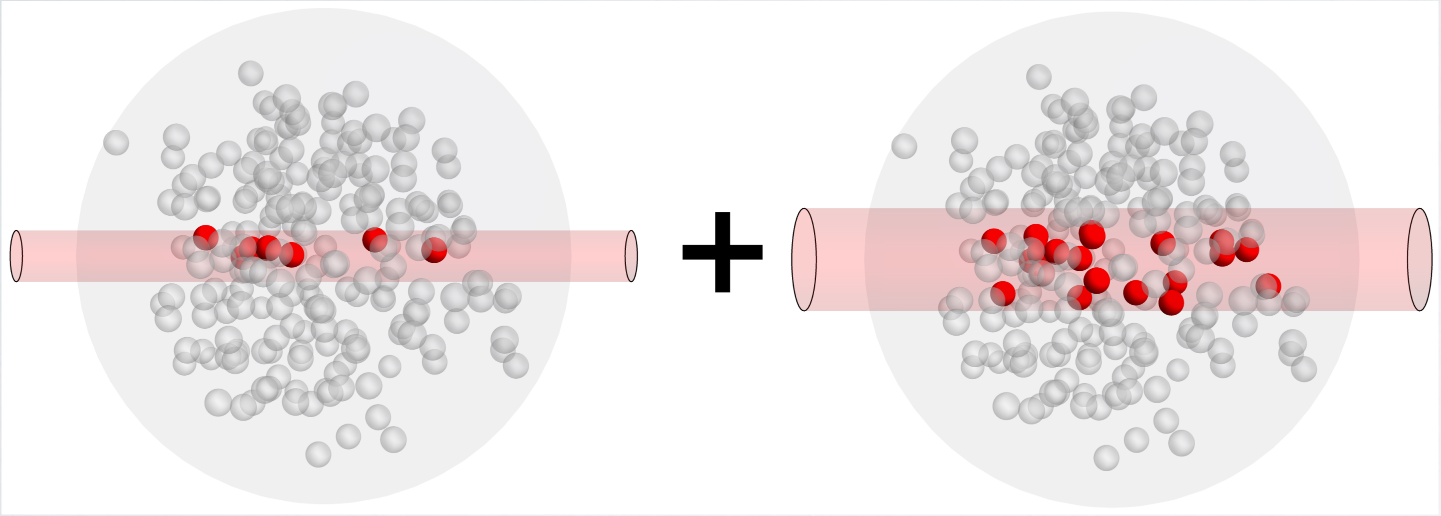
Physics Letters B 756 (2016) 10–28



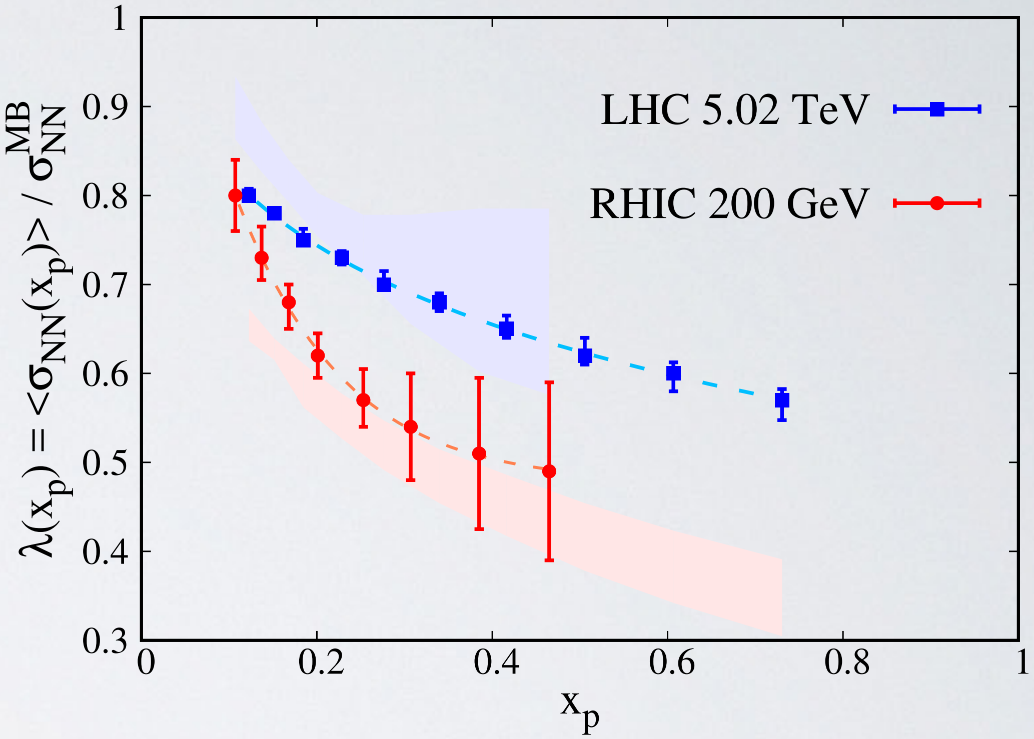
ATLAS studied ΣE_T production as function of dijet kinematic variables, **x_{proj}** (defined **away** from ATLAS FCal) & **x_{targ}** (defined **toward** ATLAS FCal)

Strong effect for x_{targ}, not x_{proj}: opposite to trivial hypothesis (& in MC)!

Shrinking protons



Alvioli et al, arxiv:1709.04993



Hypothesis of Alvioli et al: cross section of proton depends on x_p of emitted hard parton:

high x_p: **smaller configuration** of beam remnant → **lower ΣE_T**

low x_p: **larger configuration** of beam remnant → **higher ΣE_T**

Higher x_p configuration have smaller cross section,
→ migrates central events to more peripheral bins

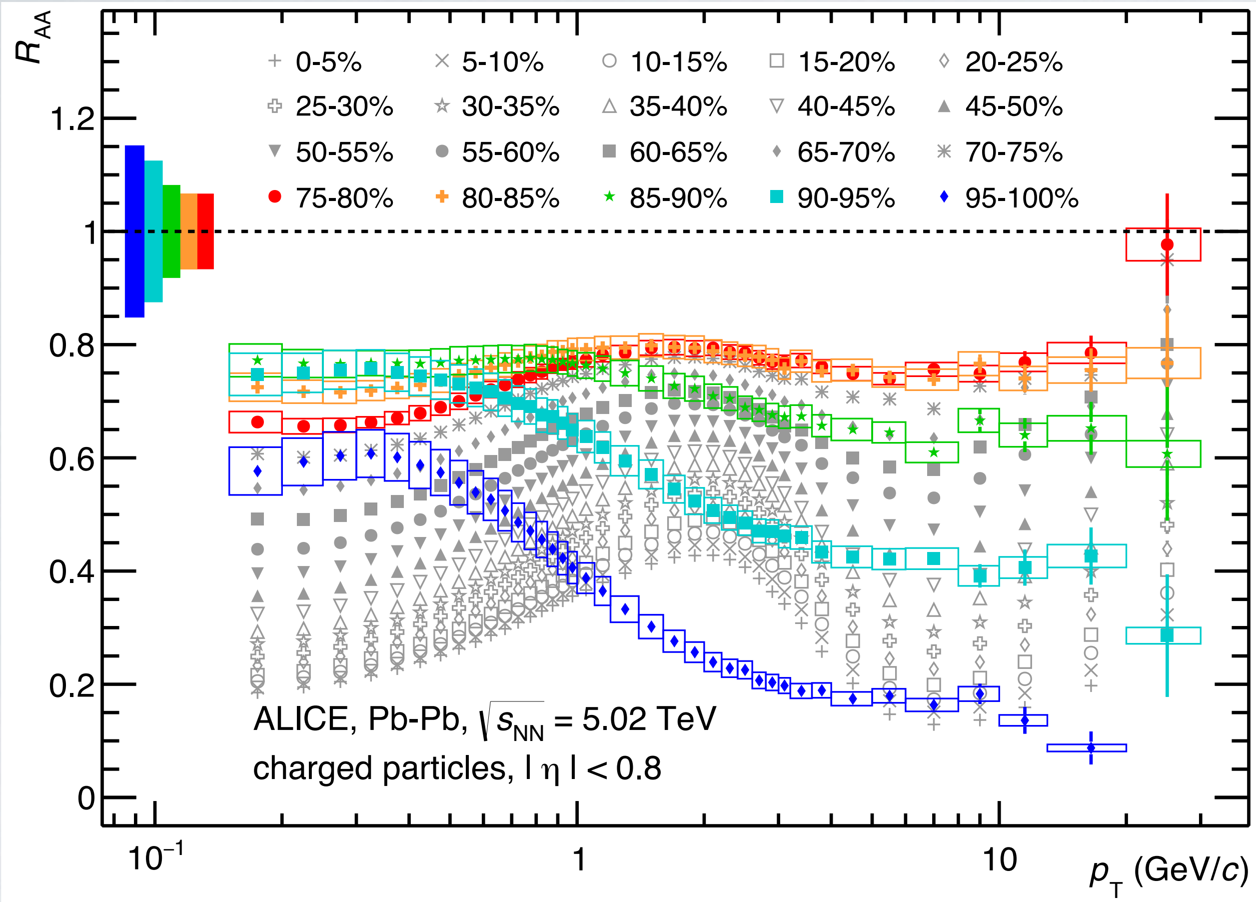
Conclusions

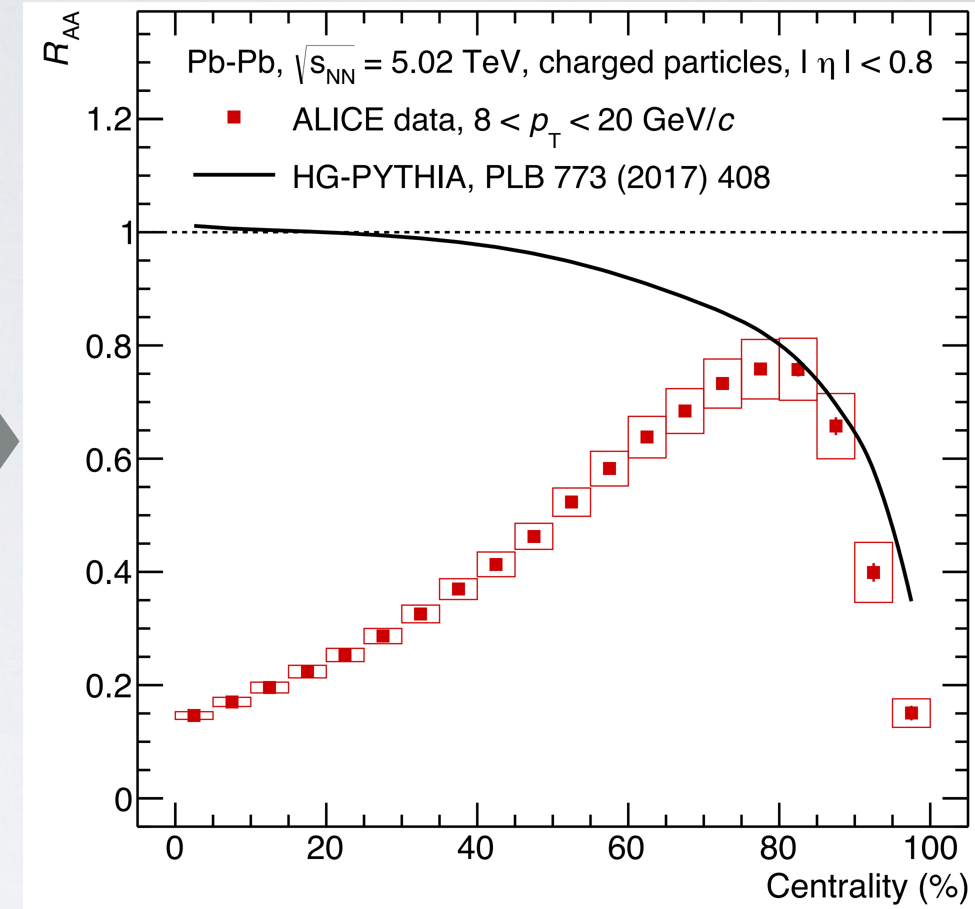
Lessons from hard processes in p+Pb

Increasing knowledge of nPDFs from W/Z/γ/jets…
…but impact parameter dependence still in early stages

Correlation of hard process yield with multiplicity in pp complicates extraction of yields/collision.
Self normalized quantities can be studied vs. event activity
…but no reason to give up. Different techniques to correct for it.

Spatial fluctuations of proton wave-function seem to be an irreducible part of our understanding of pp and p+Pb: influences flow physics and even centrality at high enough x_p.





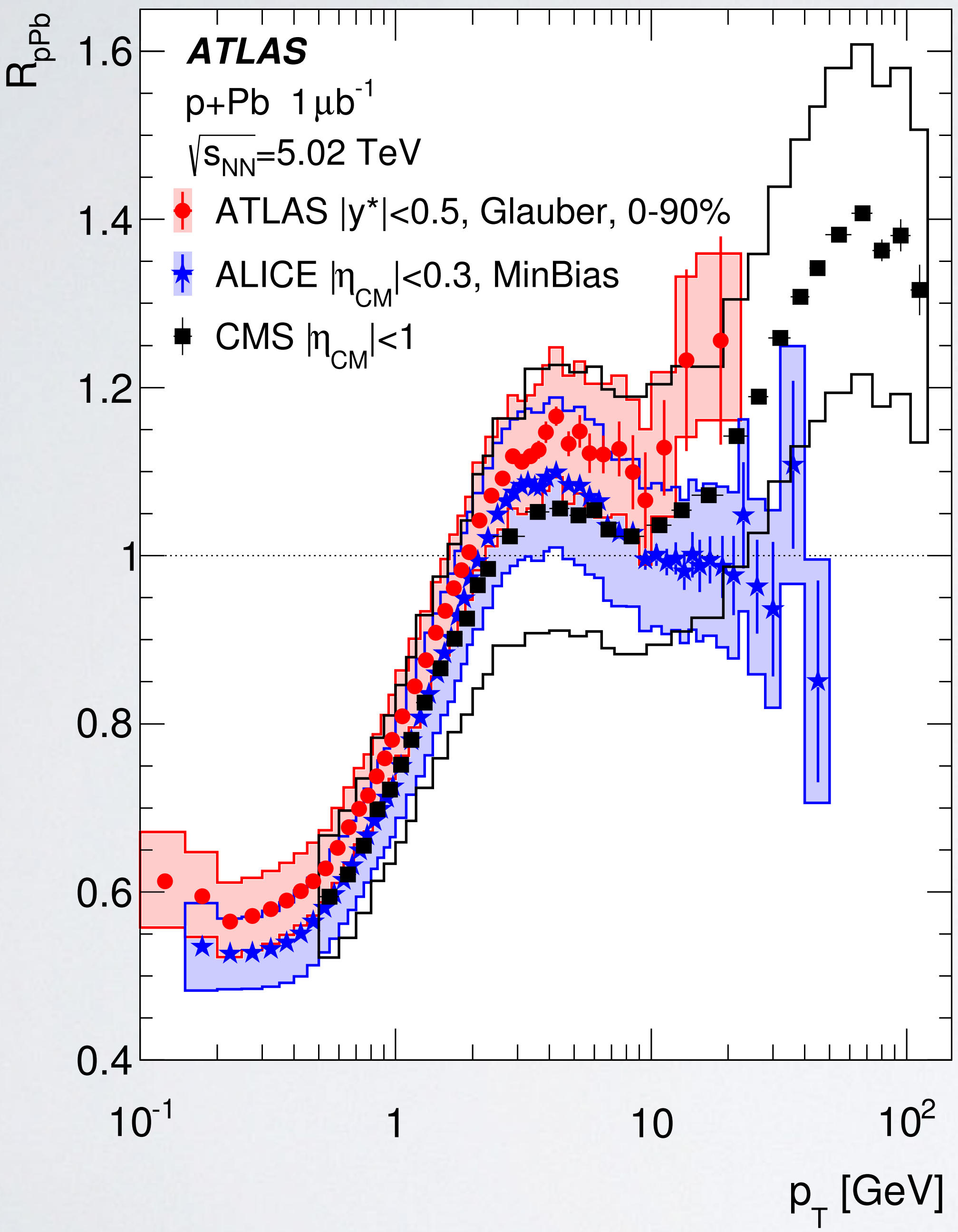
ALICE study of R_{AA} in very interesting (if a little schematic for now).
Would be very interesting to study different systems at N_{part}~20

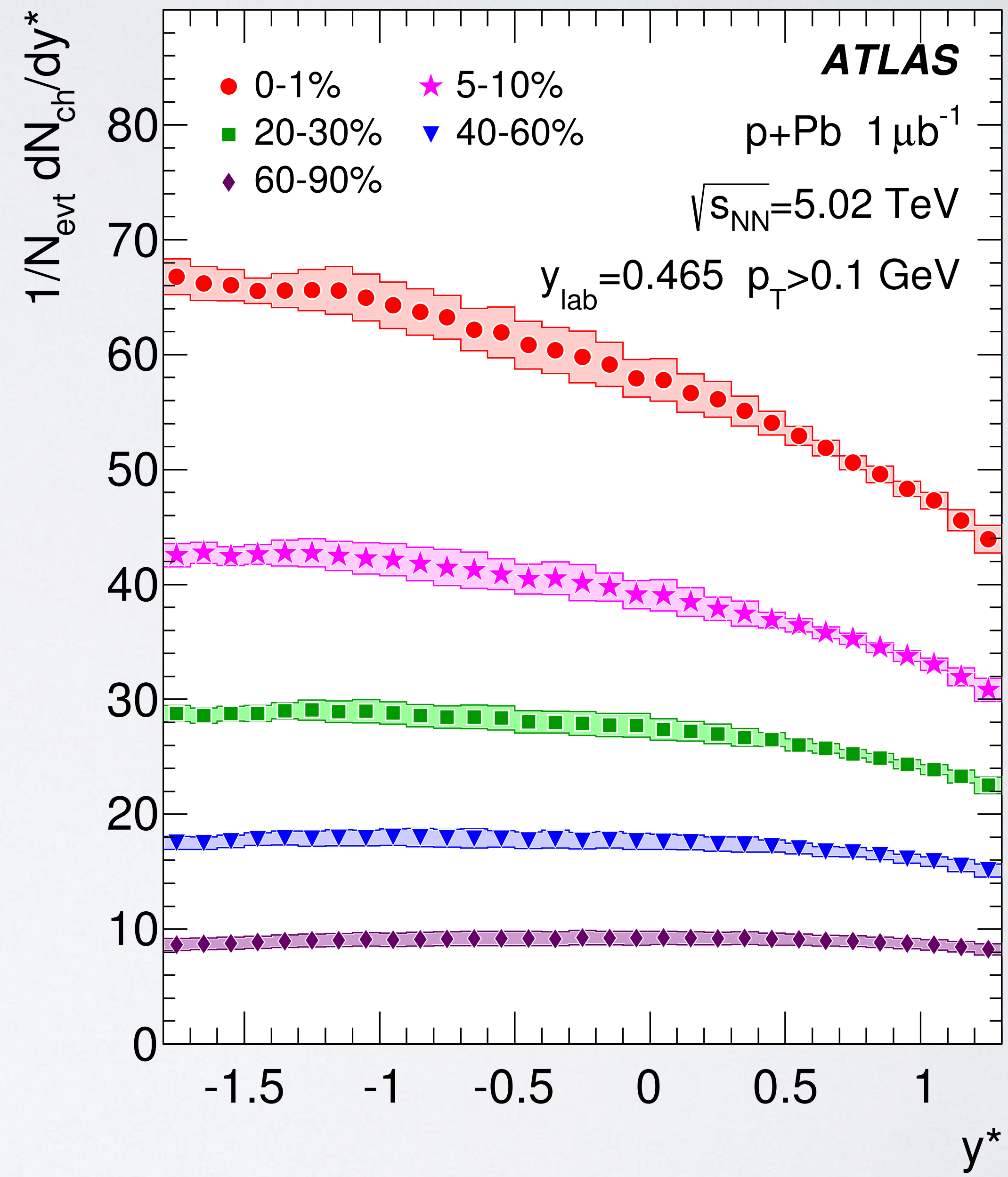
Peripheral	**Central**	**Mid-peripheral**	**Mid-central**
Au+Au (2015)	**p+Pb (2016)**	**Xe+Xe (2017)**	**O+O(201~~8~~21?)**

Each of these would have different biases:
a great opportunity to clarify these important questions for our field

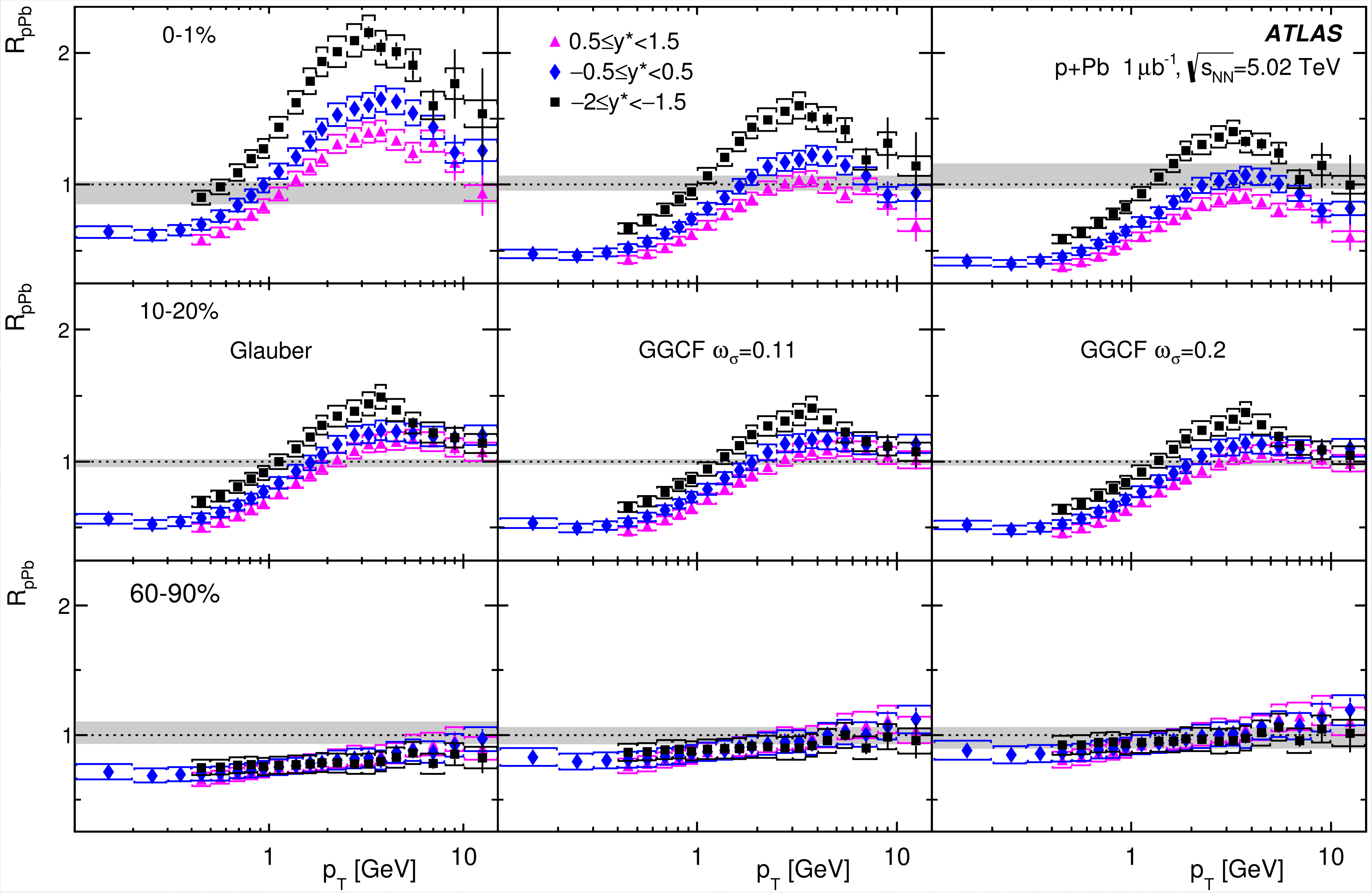
Inclusive: ATLAS charged R_{pPb}

Physics Letters B 763 (2016) 313–336





4D: ATLAS charged R_{pPb}



"Cronin" effect clearly depends on charged density:
IMO not enough discussion on how it relates to collectivity