ATLAS and CMS results from pPb collisions

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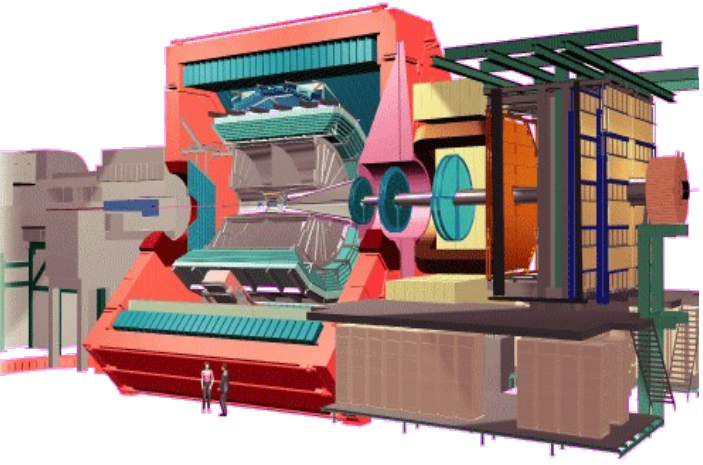
- Heavy ion physics at the LHC
- ATLAS and CMS results in pPb collisions
  - *Charged particle multiplicity and spectra*
  - *Anisotropic flow*
  - *Dihadron angular correlations*
  - *High transverse momentum hadrons*
  - *Jets (inclusive jets, photon+jet, b-jets)*
  - *B-mesons*
  - *Quarkonia*
  - *Electroweak probes (Z and W bosons)*
- Summary and outlook

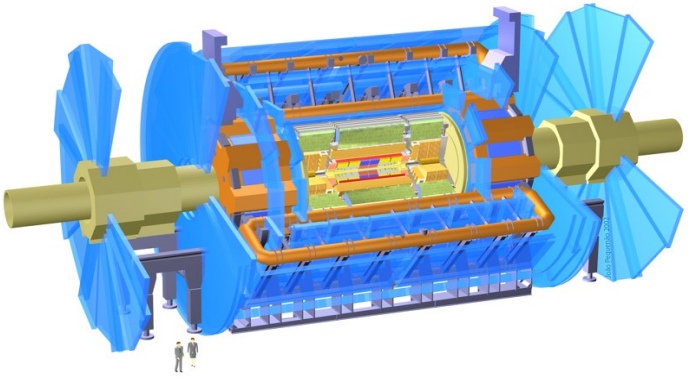
Heavy ion physics at the LHC

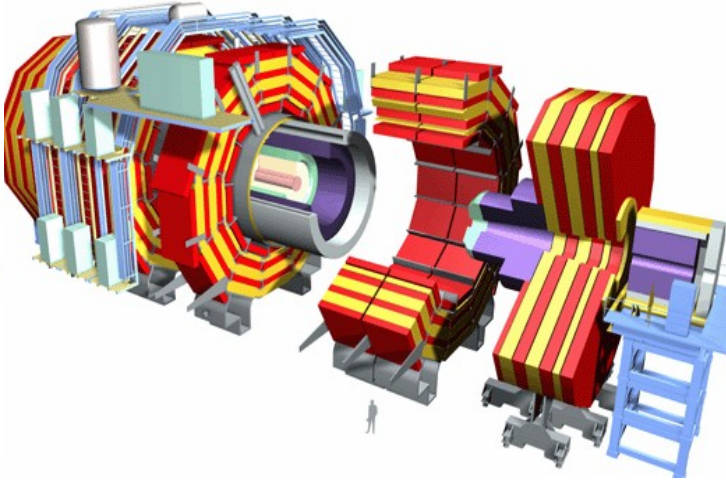
2010, 2011: PbPb ($\sqrt{s_{NN}}$ = 2.76 TeV);
2012/2013: pPb ($\sqrt{s_{NN}}$ = 5.02 TeV); *≥2015:* PbPb ($\sqrt{s_{NN}}$ = 5.1 or 5.02 TeV);...

New regime of heavy ion physics with the important role of hard probes
complementary measurements from ALICE & CMS/ATLAS
(LHCb also has taken some pPb data)

ALICE **ATLAS** **CMS**



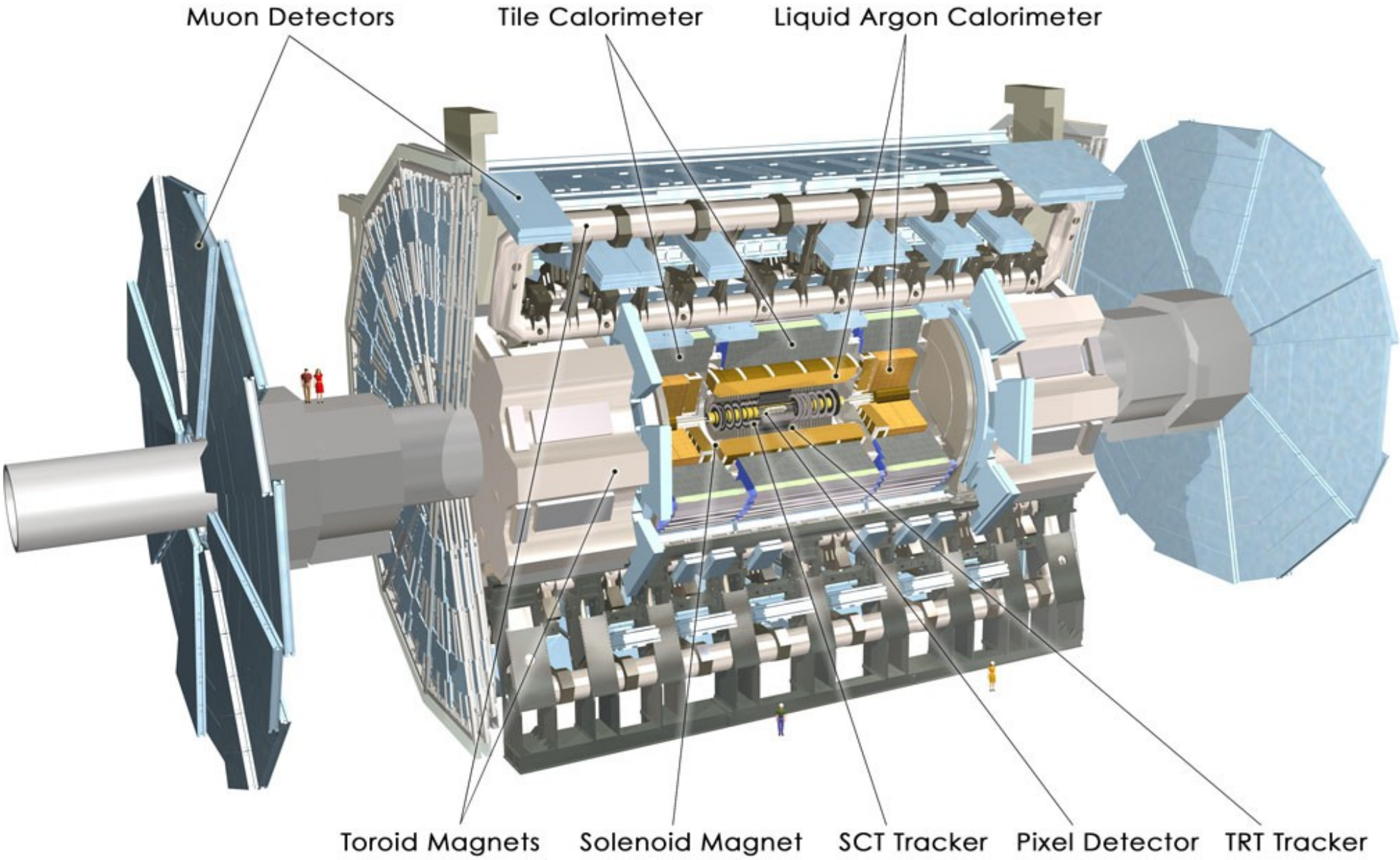




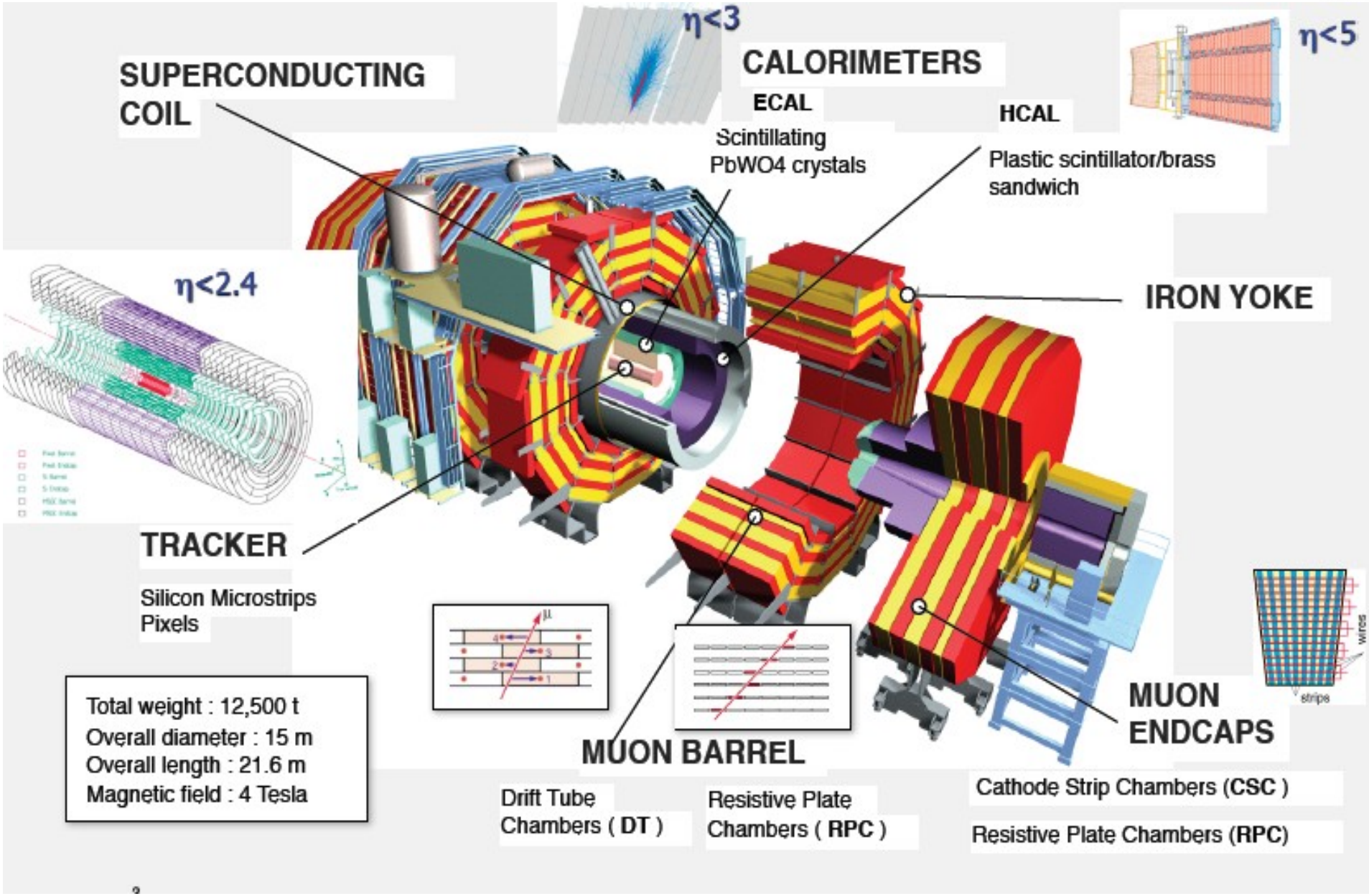
ALICE (low-p_T charged particle tracking, hadron ID, central *e*, forward μ (J/ψ, Υ), γ multiplicity,...)
soft probes + selected hard probes

CMS/ATLAS (high-p_T charged particle tracking, central μ (J/ψ, Υ, Z, W), hard γ, calorimetric jets...)
hard probes + selected soft probes

ATLAS detector



CMS Detector



ATLAS & CMS Heavy Ion Public Results

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

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIN

Messages from PbPb & motivation for pPb

PbPb collisions

Hydrodynamical (collective) properties of multi-particle system

- Anisotropic flow
- Two-particle azimuthal correlations ("ridge")

Medium-induced energy loss of hard quarks and gluons ("jet quenching")

- Transverse momentum imbalance in *jet+jet, γ+jet, Z+jet* production
- Suppression of hard hadron and jet yields
- Modification of internal jet structure

Debye screening of colour charge and thermal charmonium production

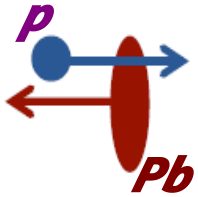
- Specific pattern of quarkonium suppression (J/ψ, Υ)
- Regeneration and anisotropic flow of J/ψ mesons

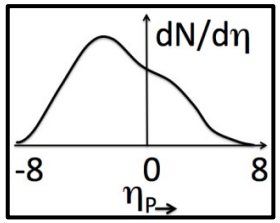
pPb collisions

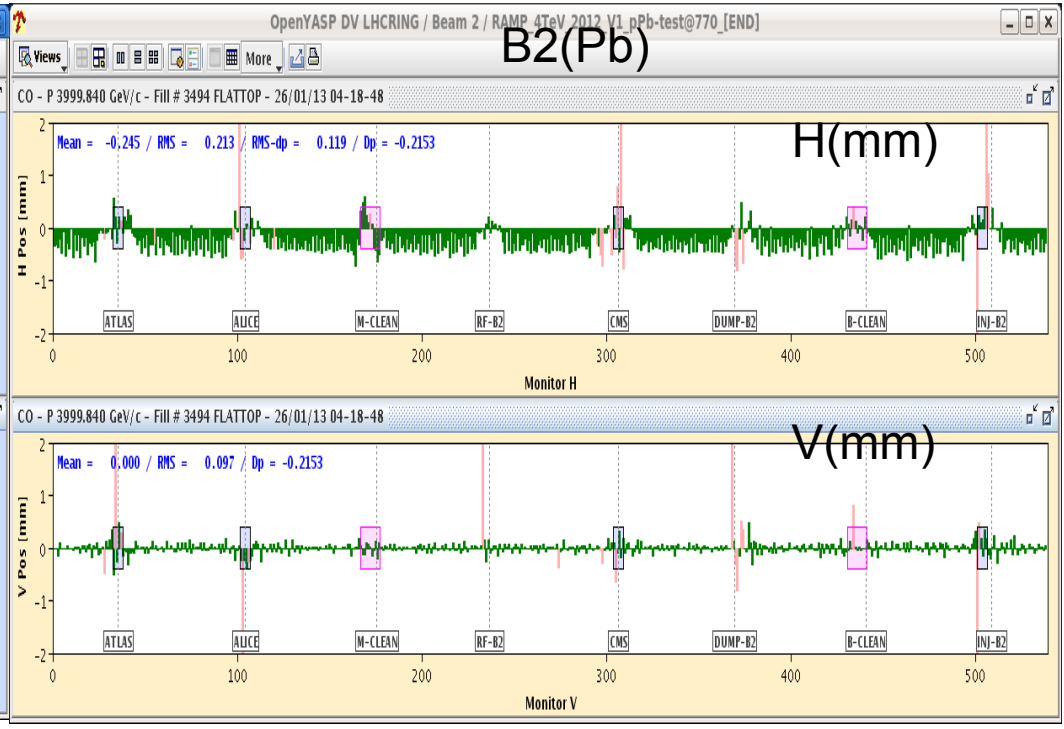
Provide baseline measurement for the PbPb program. Offer unique possibility for specific investigations in new QCD domain by getting the information about nuclear PDF's and initial/final state cold nuclear matter effects.

LHC proton-lead run 2013

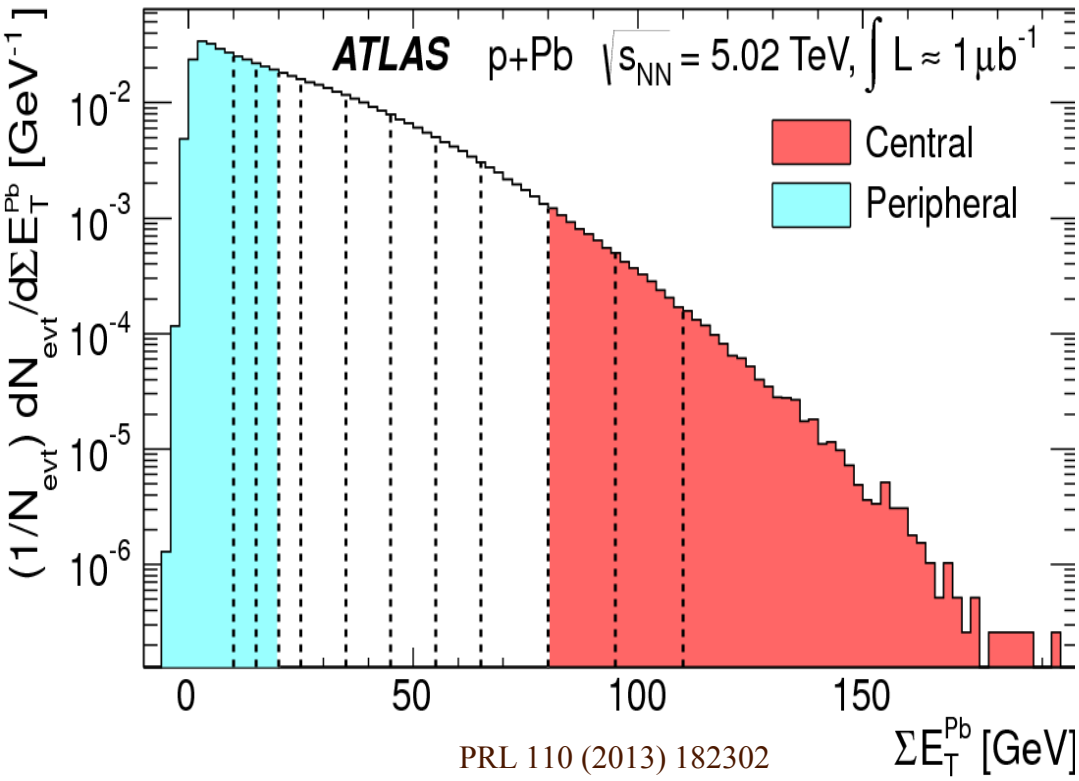
- Final integrated luminosity is 28 nb^{-1} for ATLAS and 35 nb^{-1} for CMS
- Injectors: average number of ions per bunch was ~1.4×10^8 at start of stable beams, i.e. around twice the nominal intensity



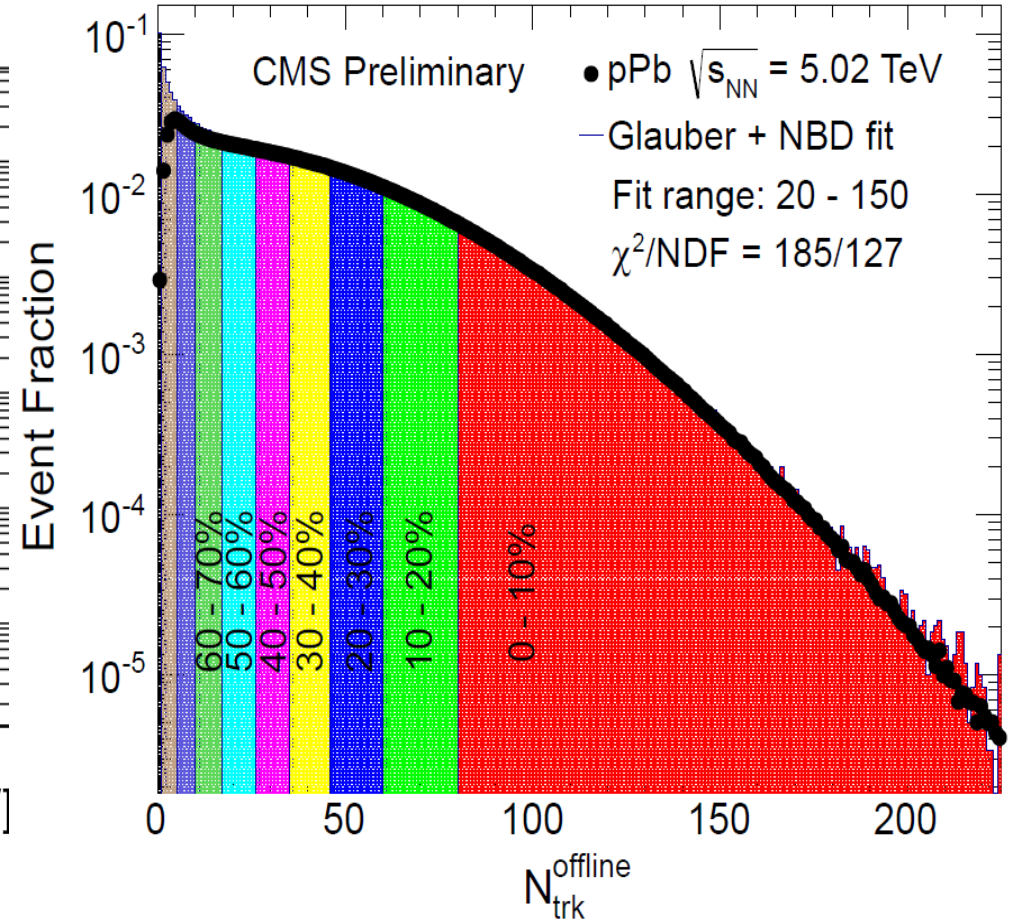




Proton-lead event centrality determination



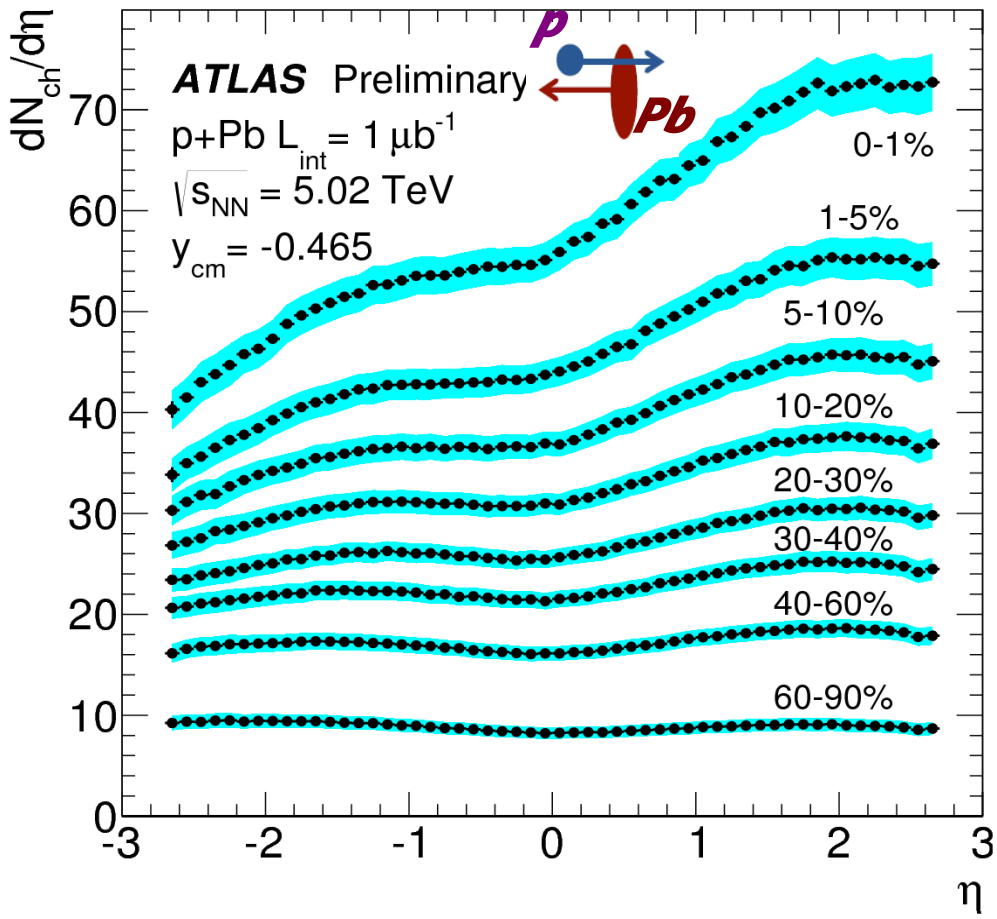
PRL 110 (2013) 182302



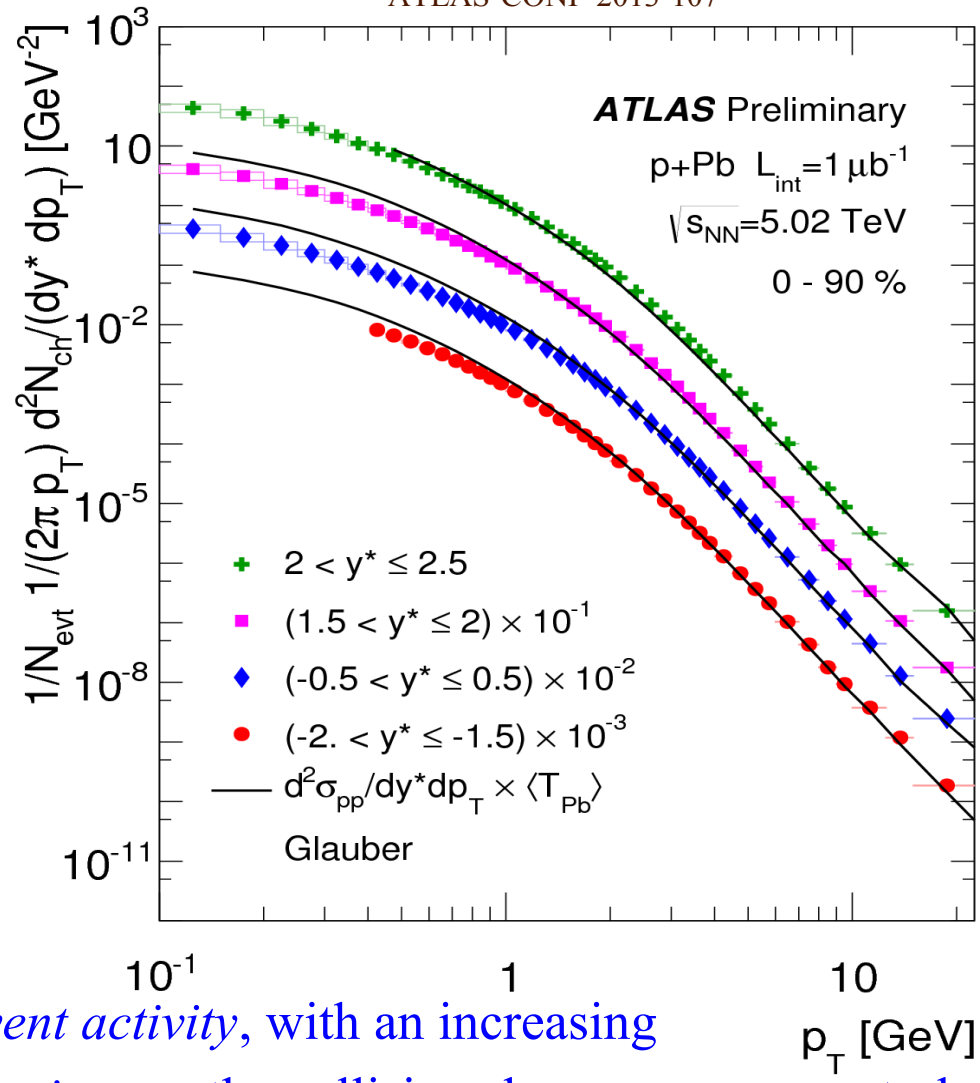
Like PbPb collisions, events are classified according to the percentile of the pPb inelastic cross section based on *total deposited energy in the forward calorimeters or charged particle multiplicity* (Pb-going side measurements are used). However correlation between event activity and event geometry in pPb is much broader than in PbPb. Moreover, it may be biased by hard production processes when hard probes vs. centrality being measured.

Charged particle multiplicity and spectra

ATLAS-CONF-2013-096

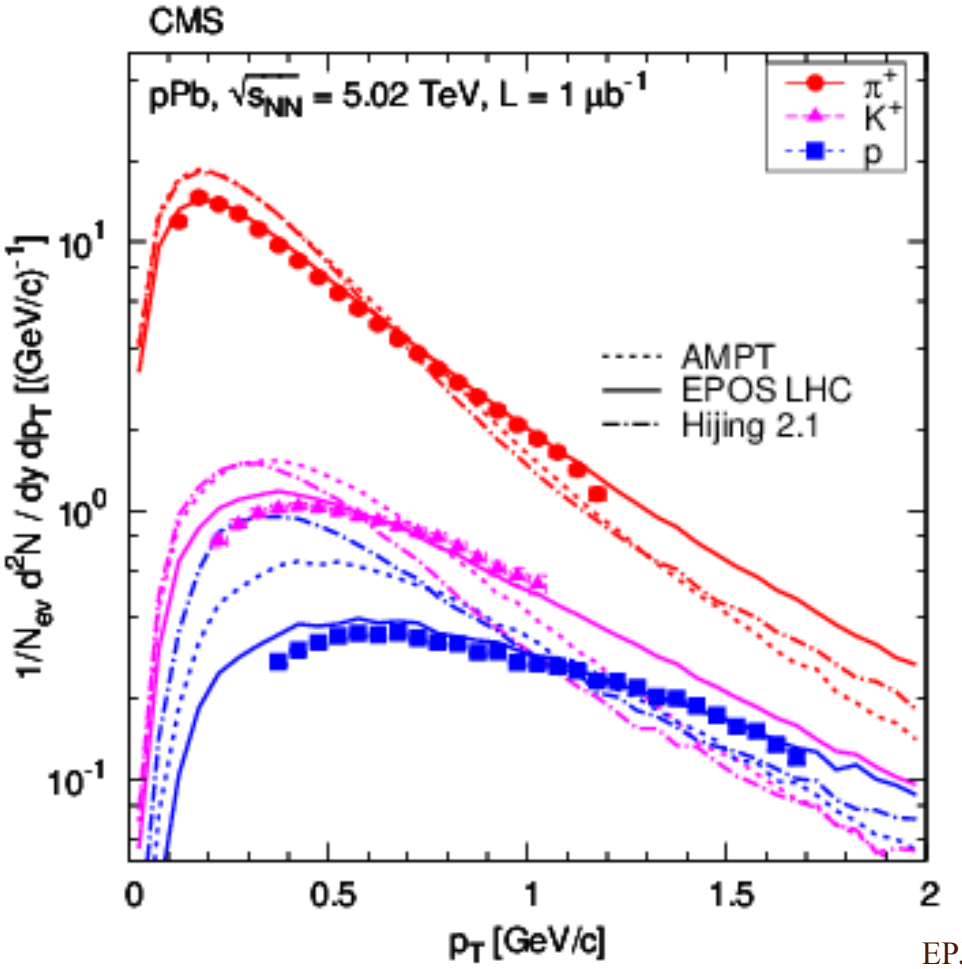


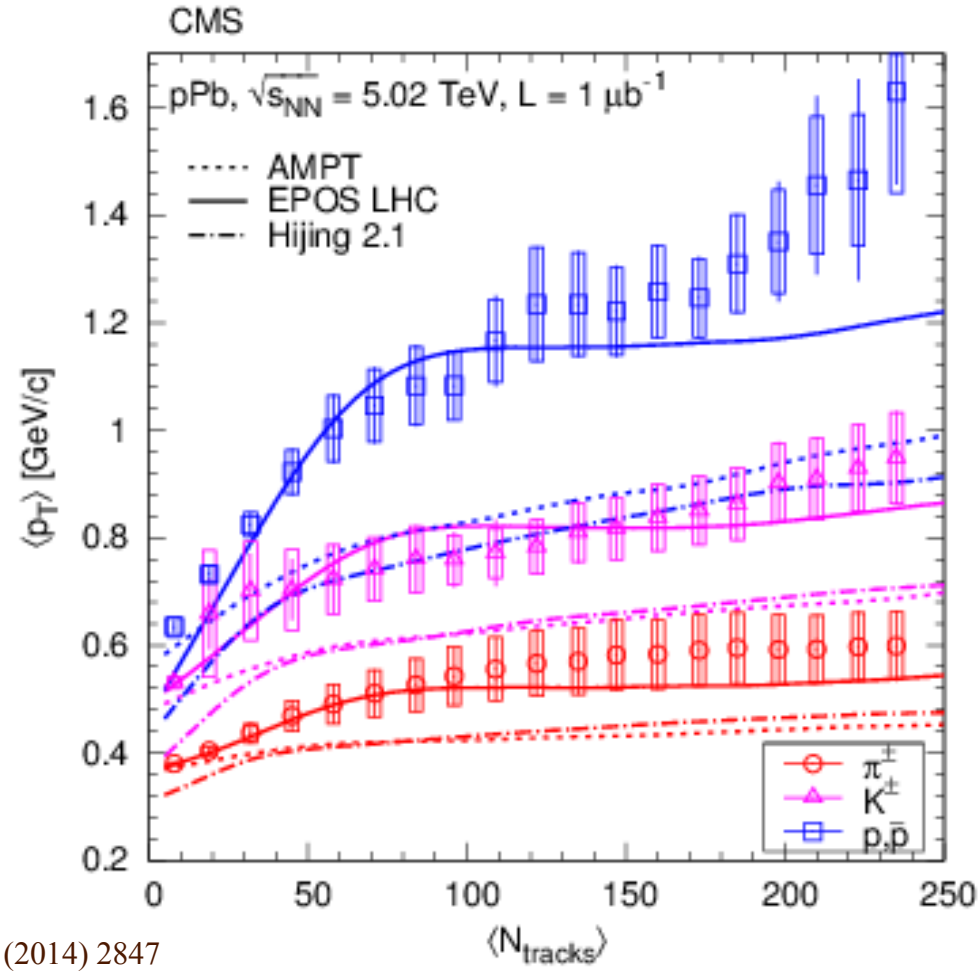
ATLAS-CONF-2013-107



- Rapidity dependence *varies strongly with event activity*, with an increasing *asymmetry between p-going & Pb-going directions* as the collisions become more central
- Transverse momentum dependence at high p_T is reproduced by *simple Glauber NN scaling*

Pion, kaon and proton spectra

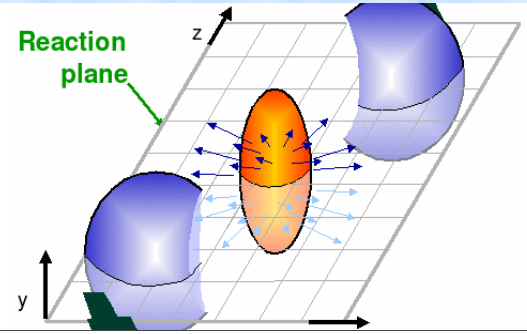




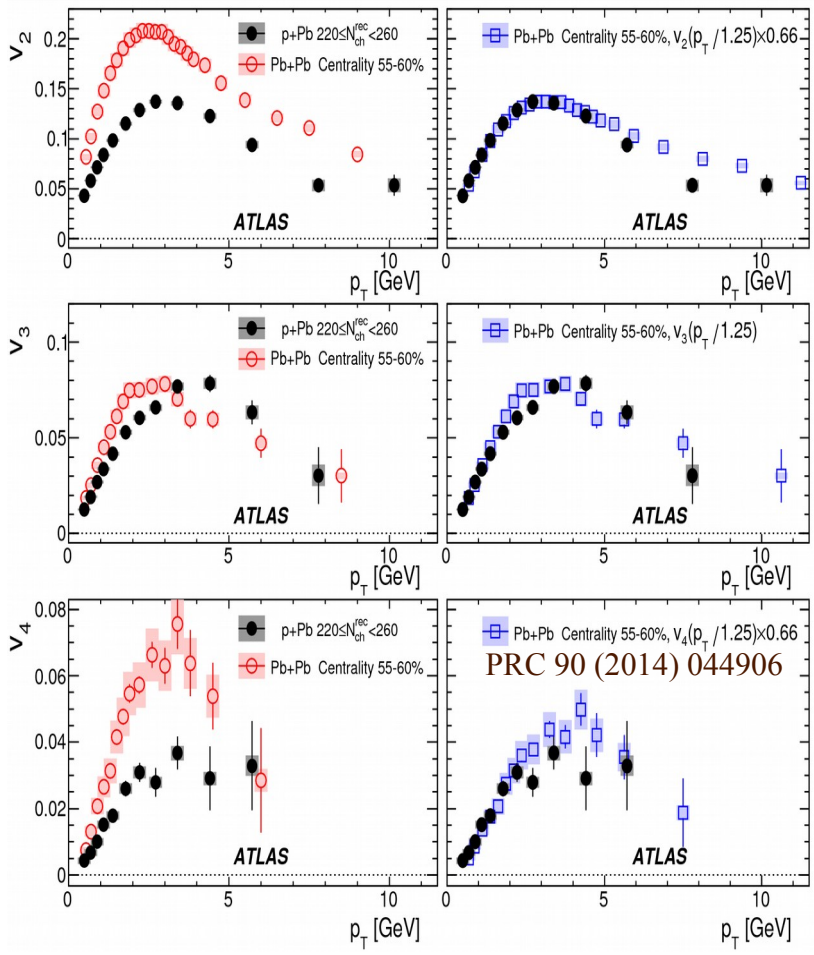
EPJC 74 (2014) 2847

- Spectra are generally *flatter than predicted by models*
- Mean transverse momentum *rises with multiplicity at low multiplicities* (harder single NN scatterings like pp) & *saturates at high multiplicities* (multiple NN scatterings like PbPb)

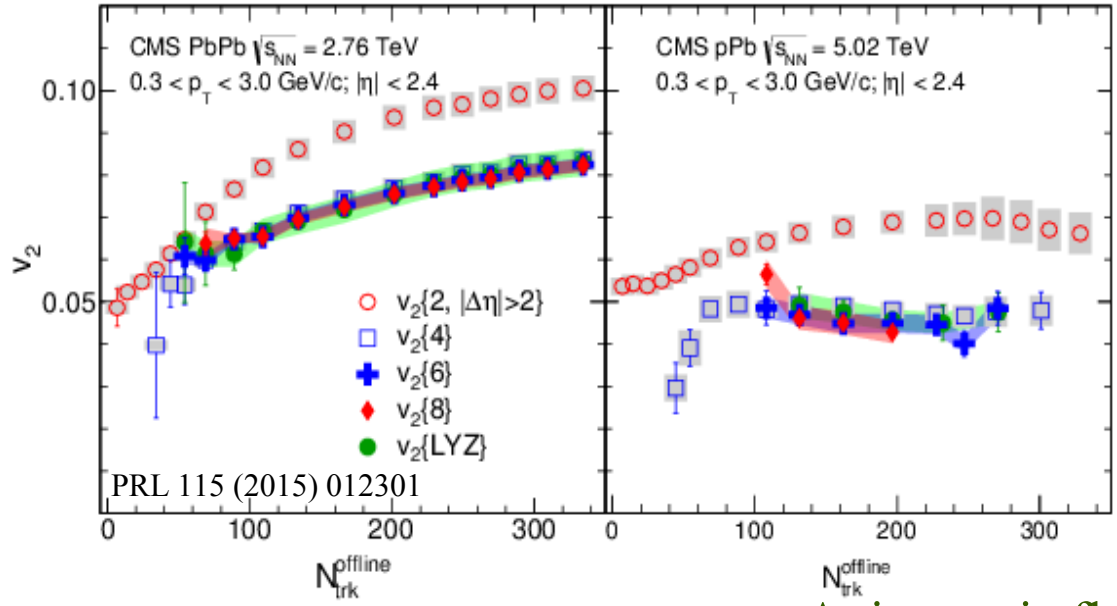
Anisotropic flow



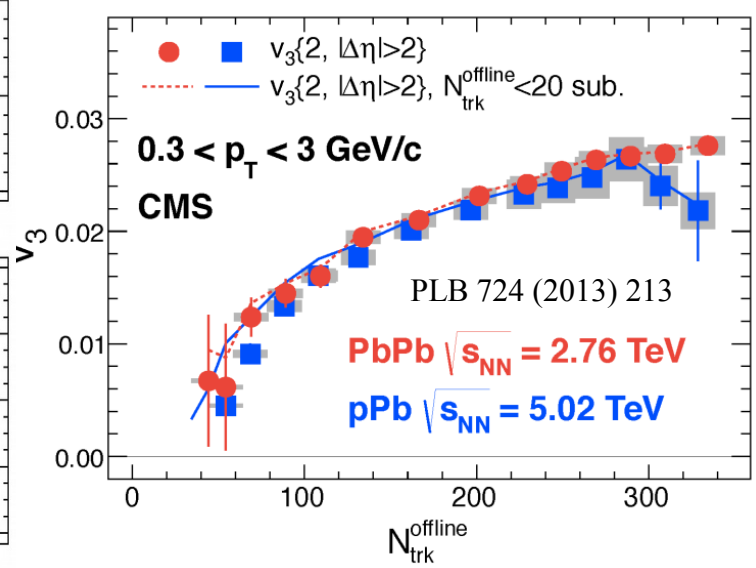
$dN/d\varphi = N\{1+ \Sigma_n 2v_n \cos(n\varphi)\}/2\pi, \qquad v_n = \langle\cos(n\varphi)\rangle$



PRC 90 (2014) 044906



PRL 115 (2015) 012301

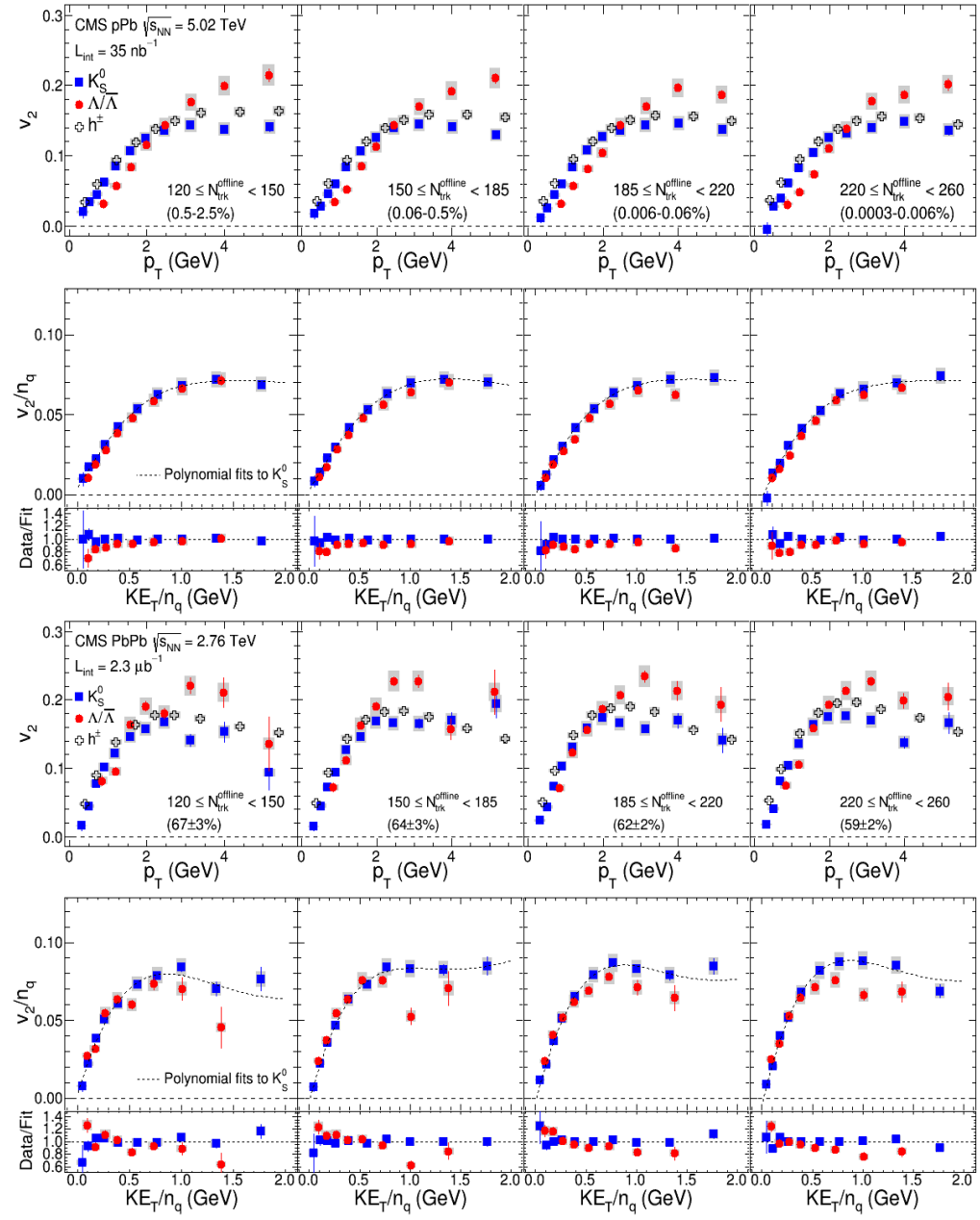


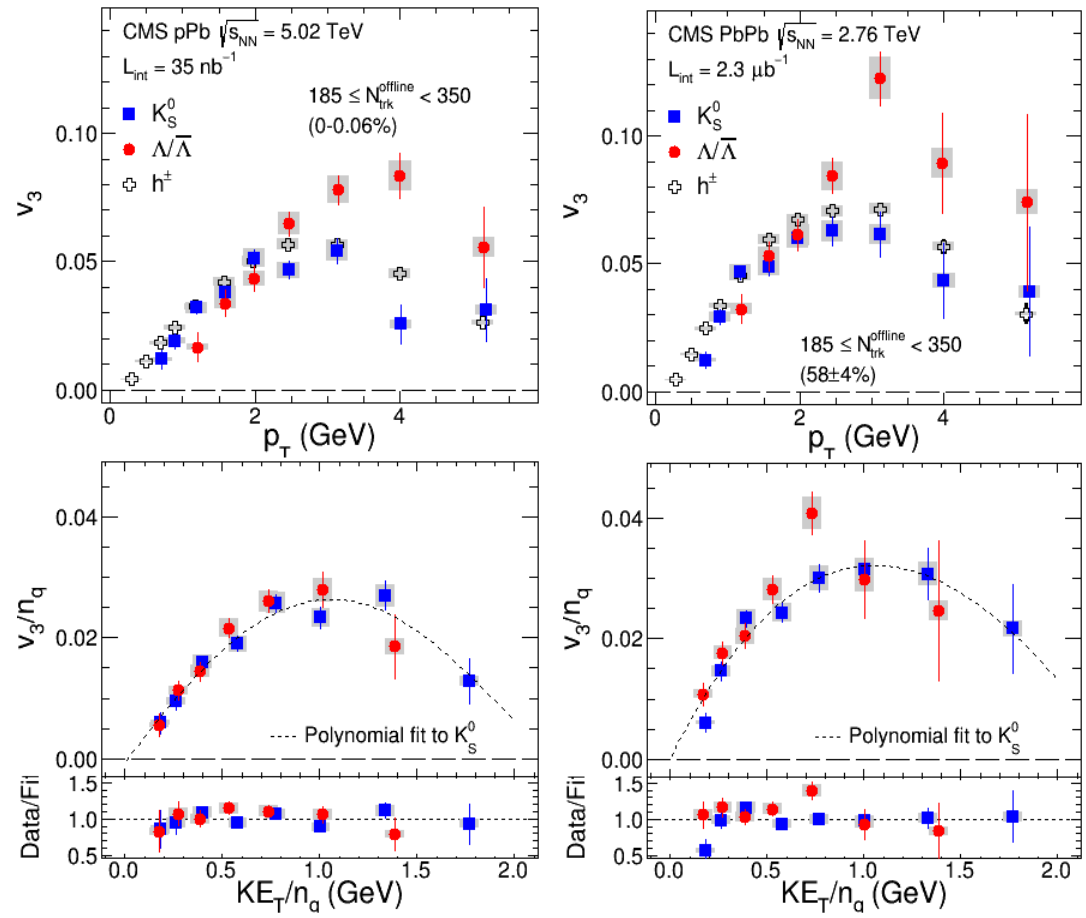
PLB 724 (2013) 213

Anisotropic flow – measure of "collectivity"

Significant v_2 and v_4, and sriking similarity of v_3 vs. multiplicity in pPb and PbPb with drastically different *collision geometry and its fluctuations*

Elliptic v_2 and triangular v_3 flows (K_s^0, Λ)





PLB 742 (2015) 200

v_2 and v_3 in pPb & PbPb show *mass ordering*(stronger in pPb) and ≈ *quark scaling* (better in pPb)

Dihadron angular correlations

p+p 7 TeV

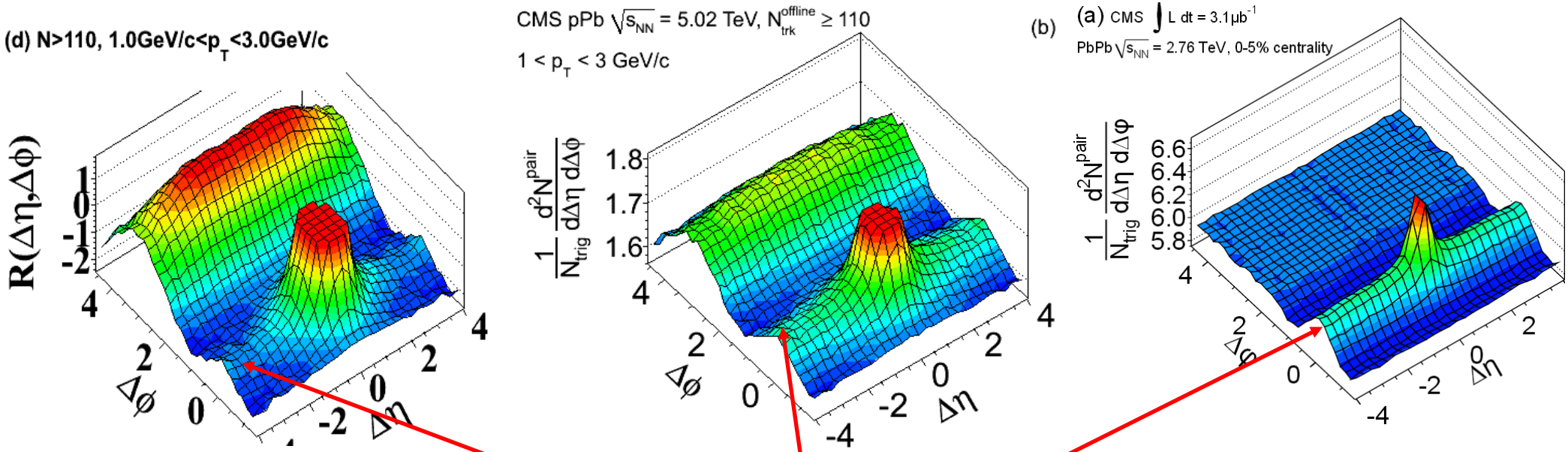
JHEP 09 (2010) 091

p+Pb 5.02 TeV

PLB 718 (2013) 795

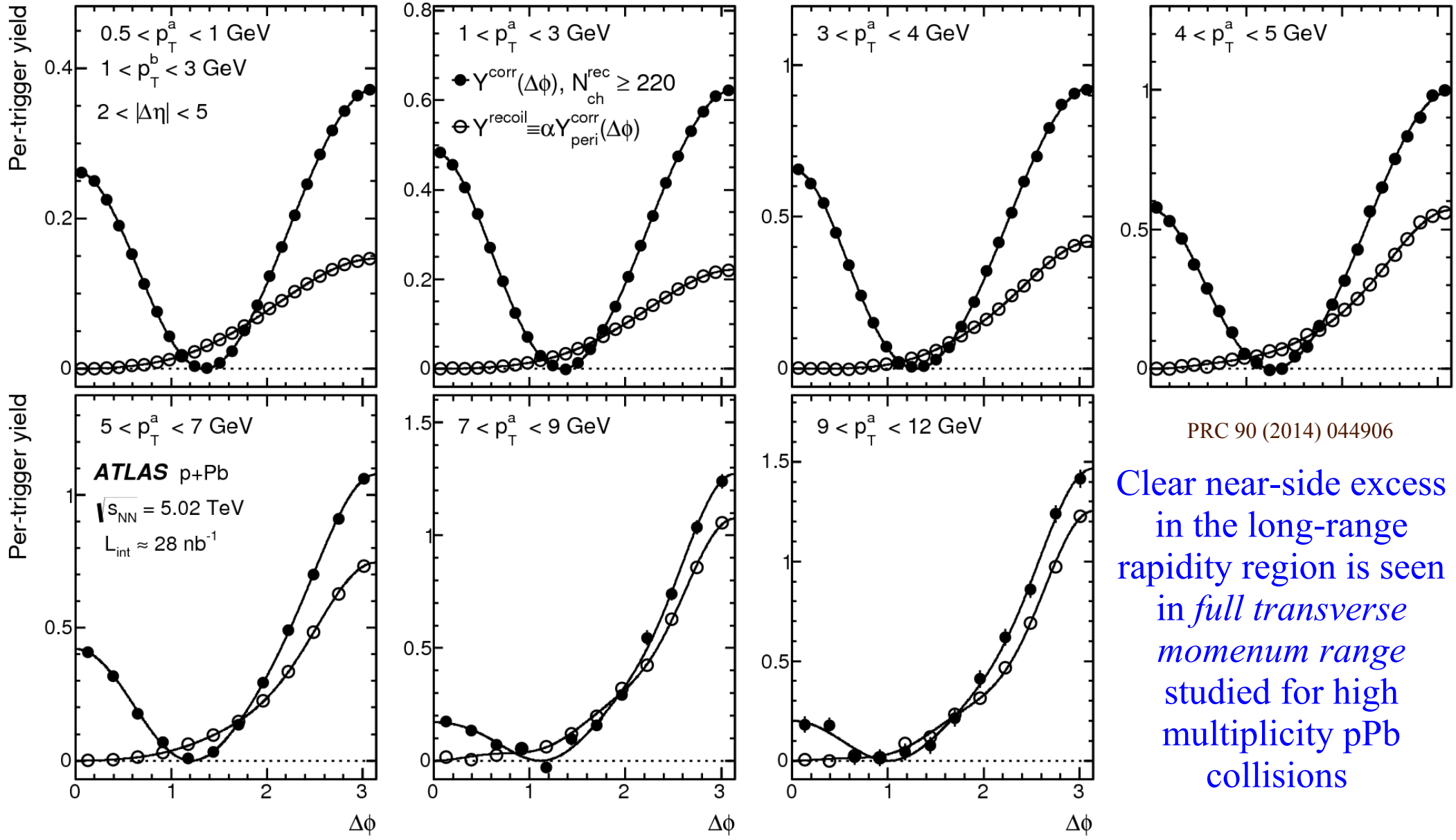
Pb+Pb 2.76 A TeV, 0-5%

JHEP 07 (2011) 076



"Ridge" *(long-range azimuthal correlations)* is observed
in high multiplicity pp and pPb as well as in central and semi-central PbPb collisions

Dihadron angular correlations



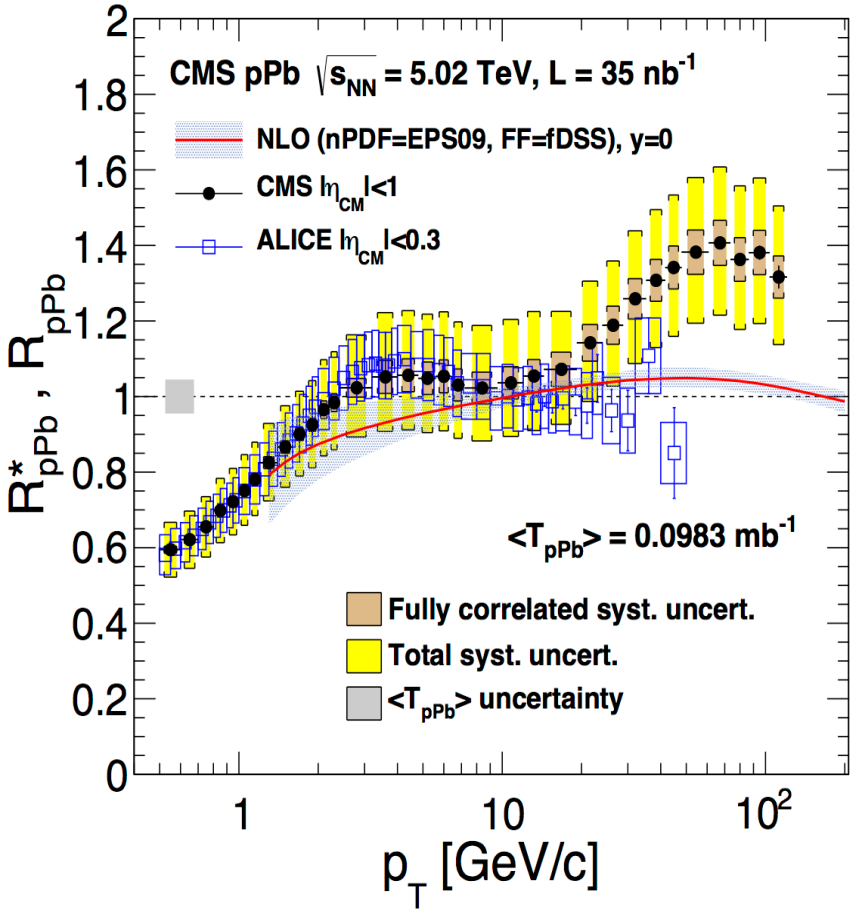
PRC 90 (2014) 044906

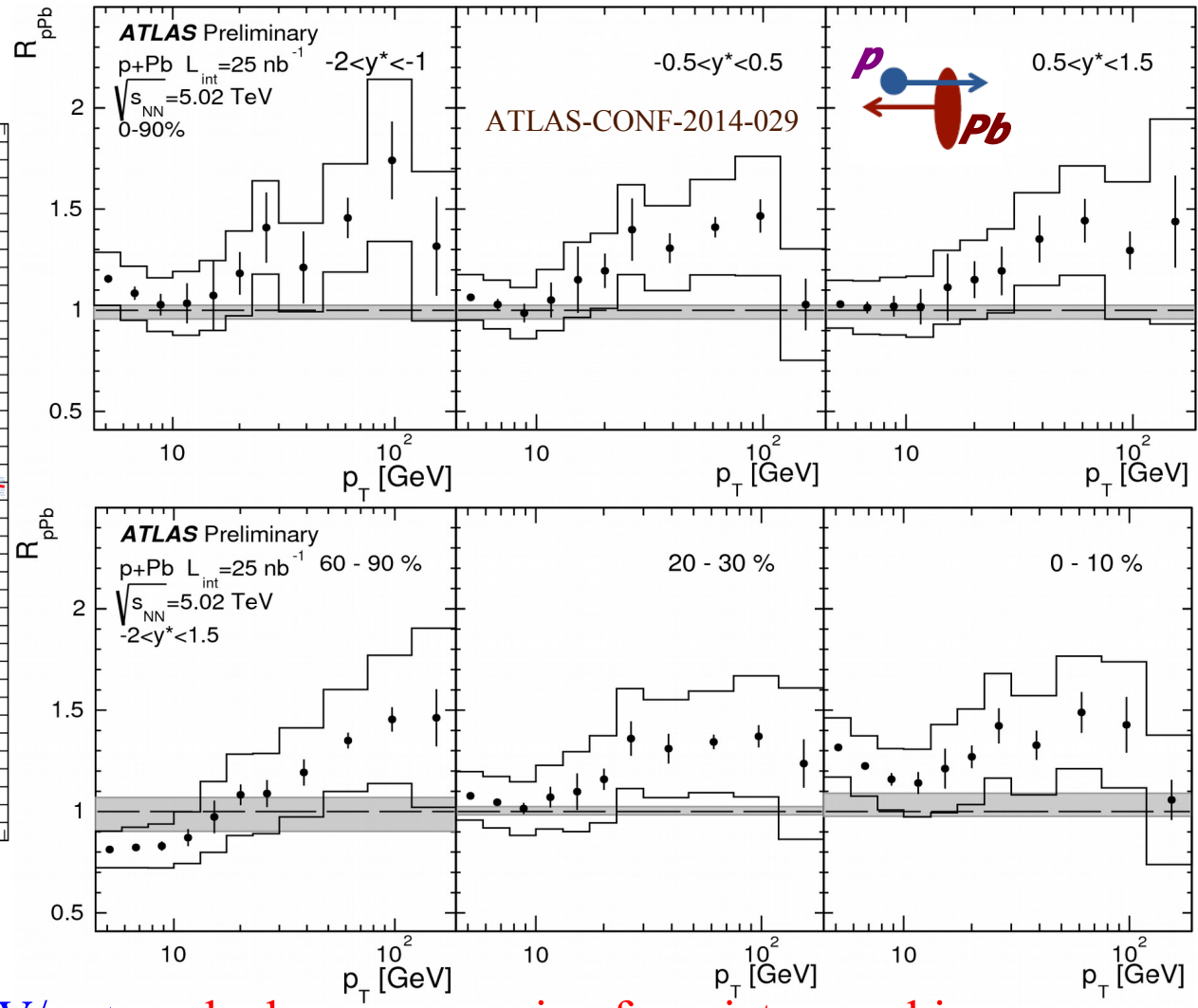
Clear near-side excess in the long-range rapidity region is seen in *full transverse momenum range* studied for high multiplicity pPb collisions

Nuclear modifications factor (hadrons)

EPJC 75 (2015) 237

$$R_{pA} = 1/A\ N_{pA}/N_{pp}$$

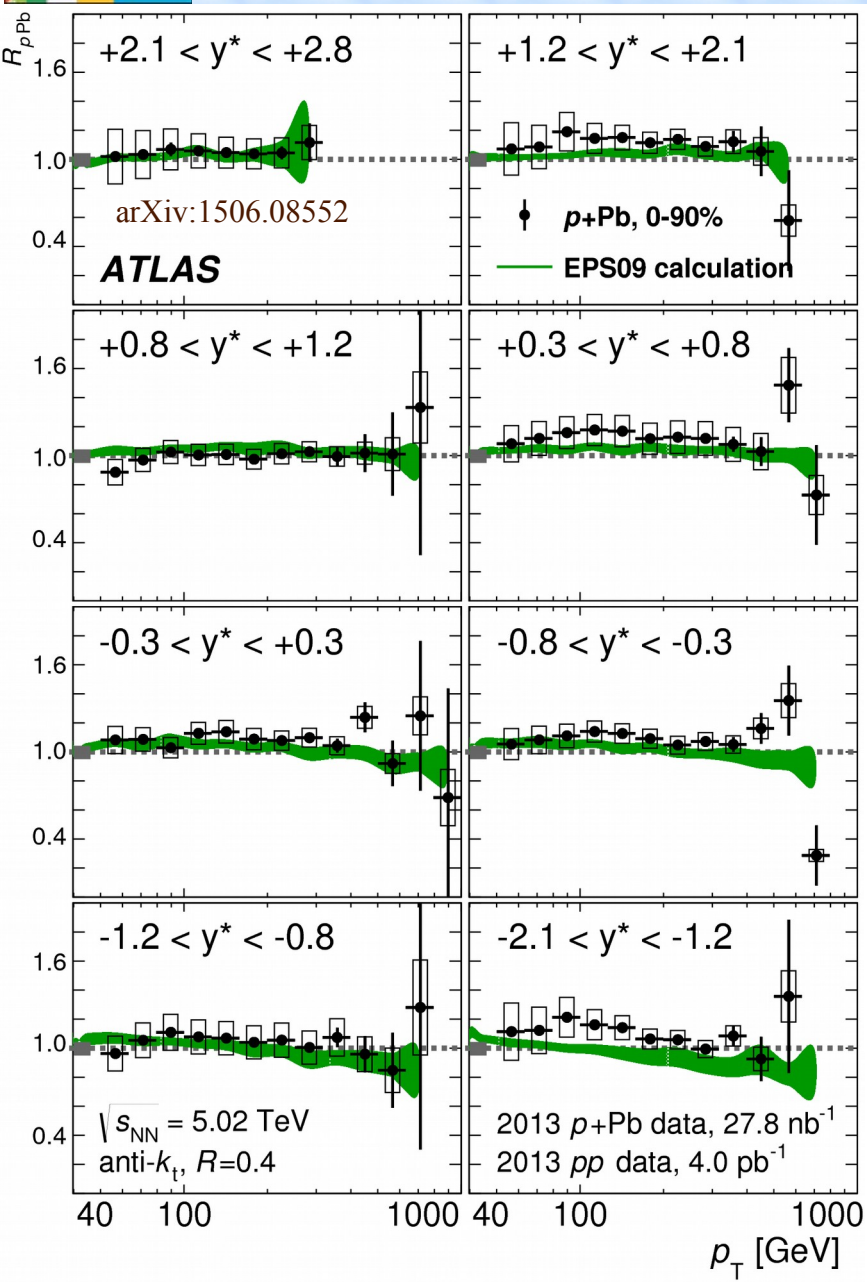




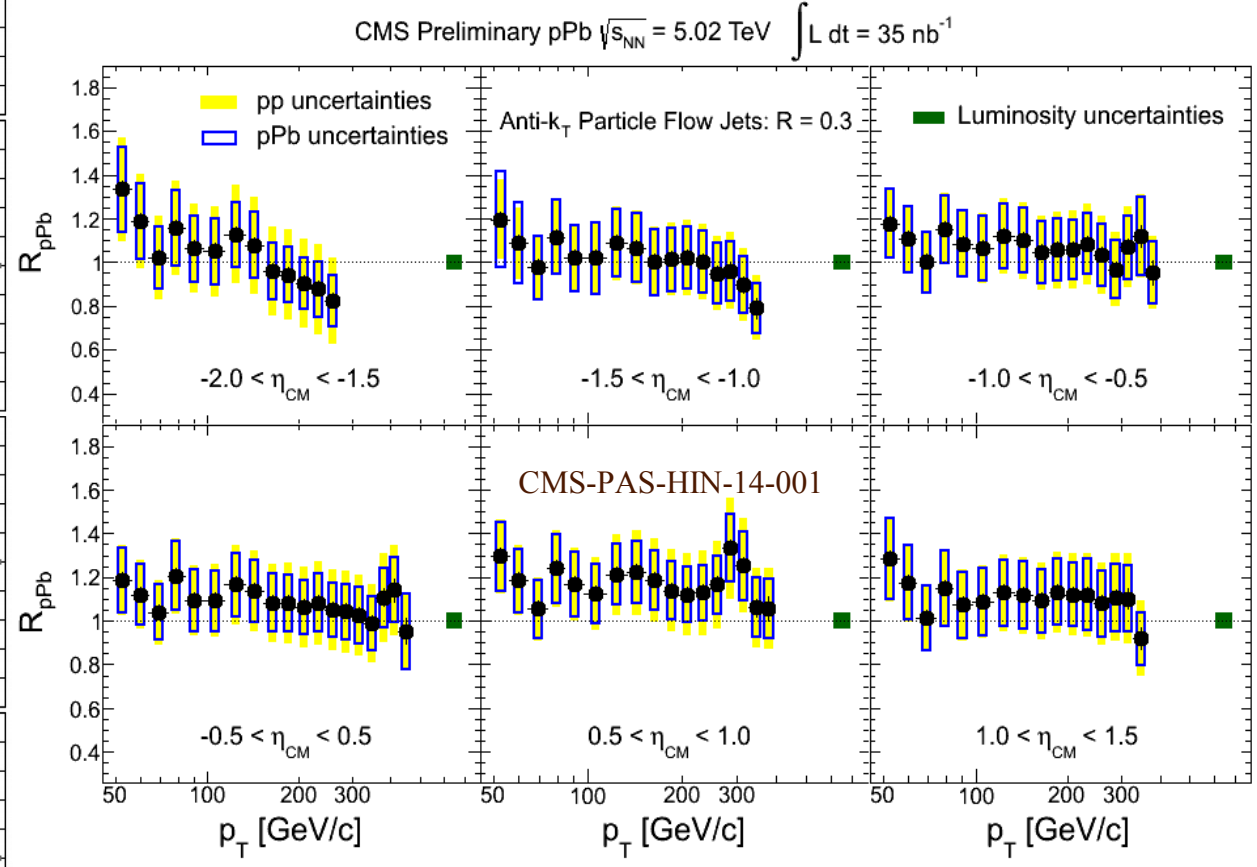
- Modification factor ~1 at p_T~2-20 GeV/c ⇨ no hadron suppression from jet quenching seen
- Enhancement at p_T>20 GeV/c ⇨ too large for anti-shadowing? due to more quark-jets in pPb?

But ALICE does not confirm! *(different pp interpolation to 5.02 TeV)* ⇨ need pp data!

Nuclear modifications factor (inclusive jets)

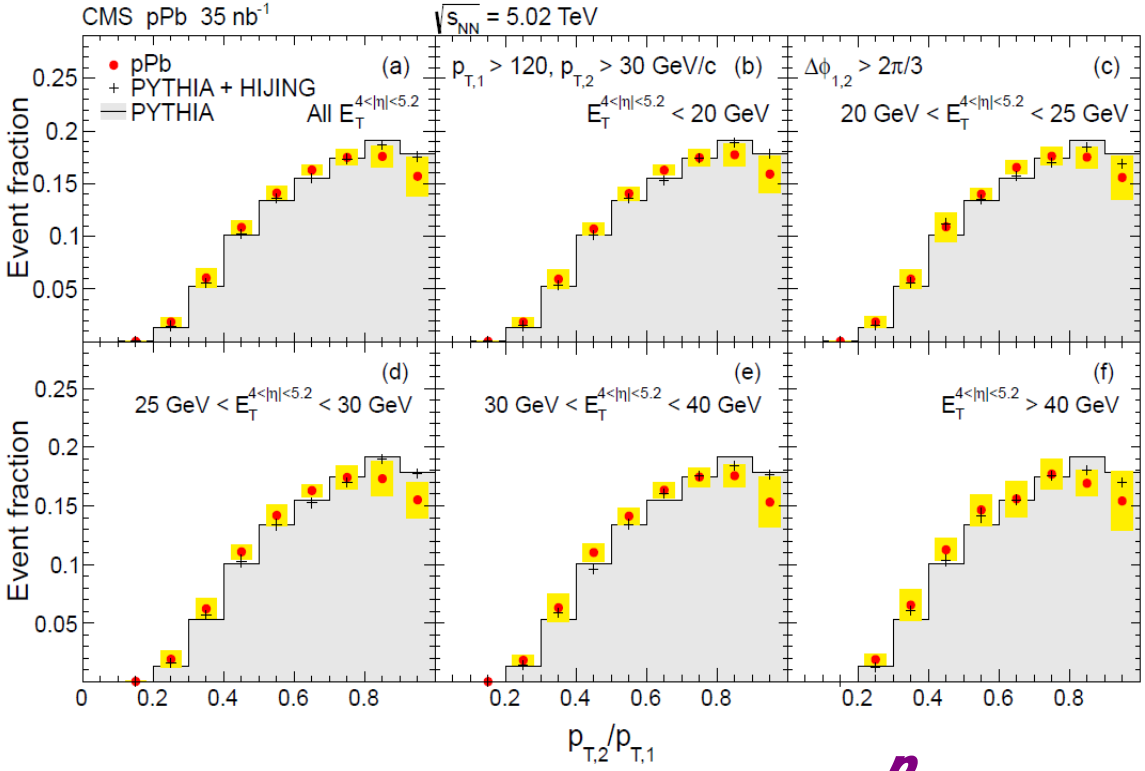


$$R_{pA} = 1/A\ N_{pA}/N_{pp}$$



Data are consistent with nPDF calculations (EPS09) ⇨ no jet quenching seen?

Asymmetry of dijet energy



EPJC 74 (2014) 2951

No centrality dependence of *dijet momentum balance*

no jet quenching seen

CMS pPb 35 nb^{-1}

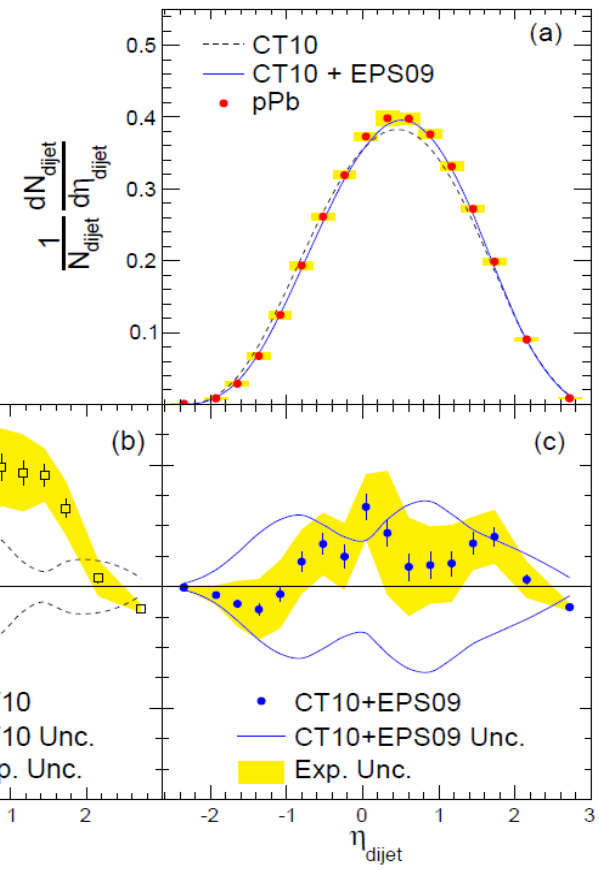
$\sqrt{s_{NN}}$ = 5.02 TeV

$p_{T,1}$ > 120 GeV/c

$p_{T,2}$ > 30 GeV/c

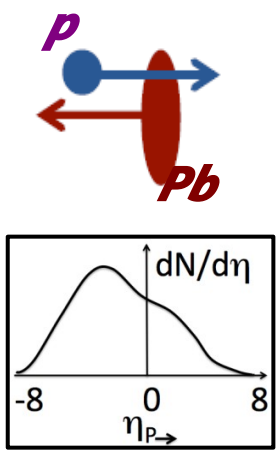
$\Delta\phi_{1,2}$ > 2π/3

All $E_T^{4<|\eta|<5.2}$

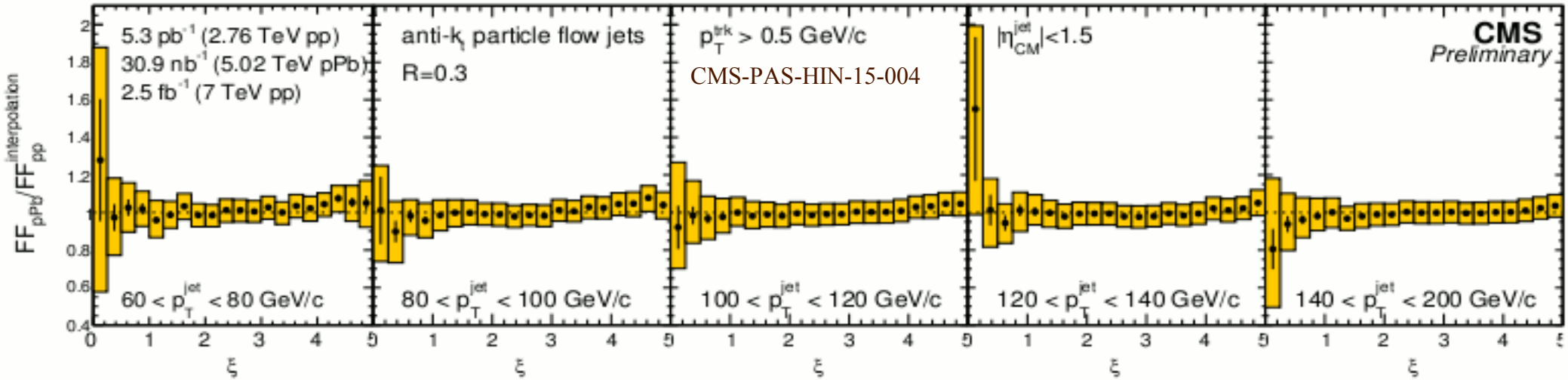


Pronounced *shift of mean dijet rapidity* in Pb-going η direction vs centrality

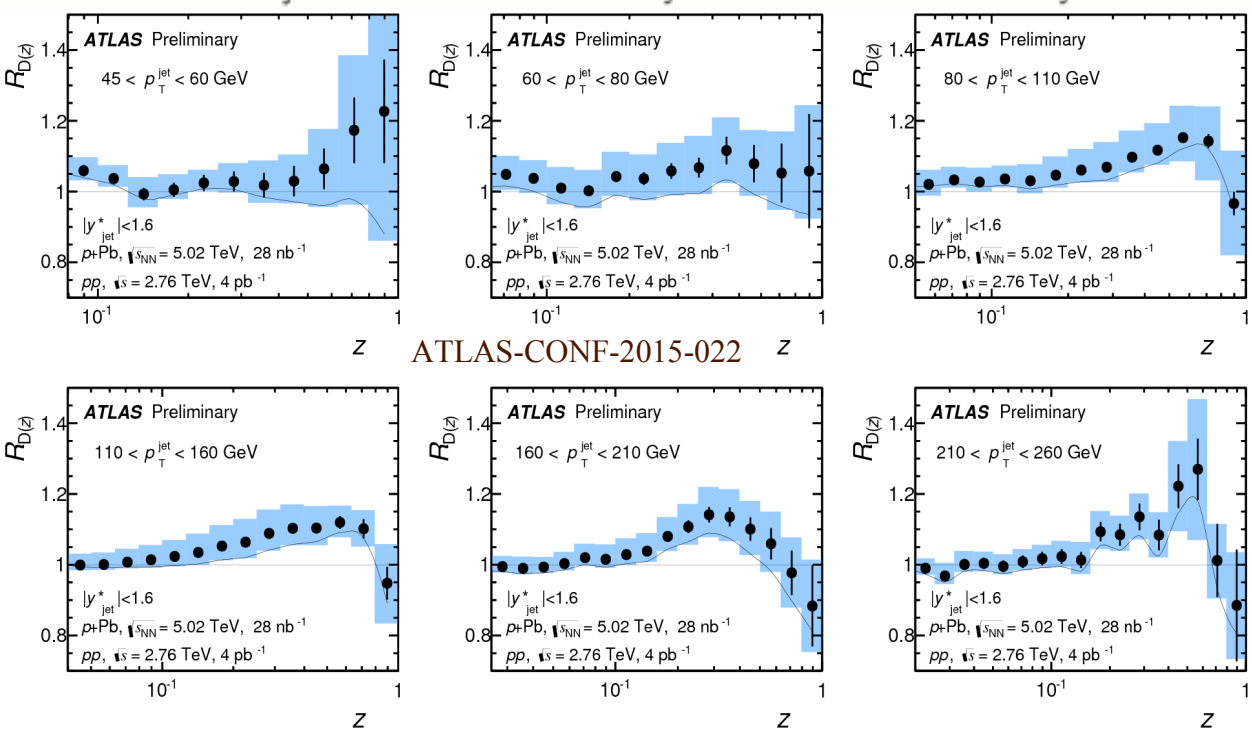
Initial state effect (nuclear shadowing)?



Jet fragmentation function



CMS-PAS-HIN-15-004



ATLAS-CONF-2015-022

$$\xi = -\ln z = -\ln \frac{p_T^{track}}{p_T^{jet}}$$

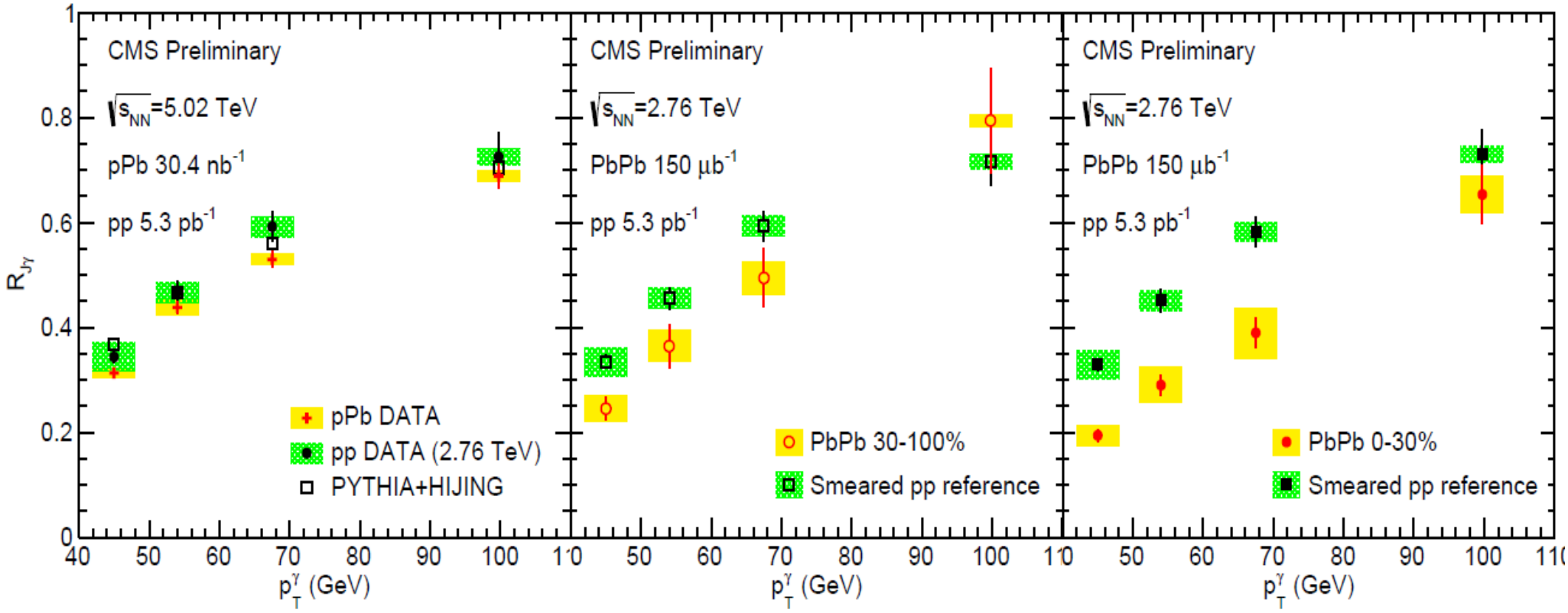
CMS does not see any modifications of *longitudinal jet profile,* while ATLAS suggests the excess for 0.2<z< 0.8 in jets with p_T>80 GeV (the same p_T range where inclusive charged particle spectrum is enhanced)

different pp interpolation to 5 TeV

need pp data!

Photon+jet correlation

CMS-PAS-HIN-13-006

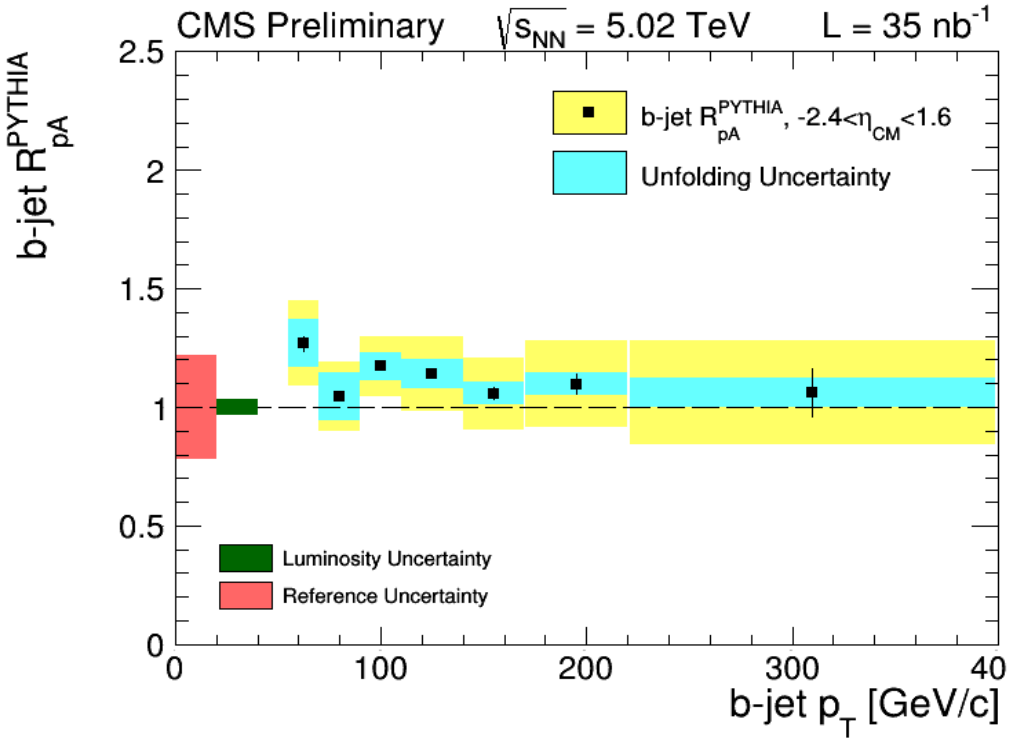


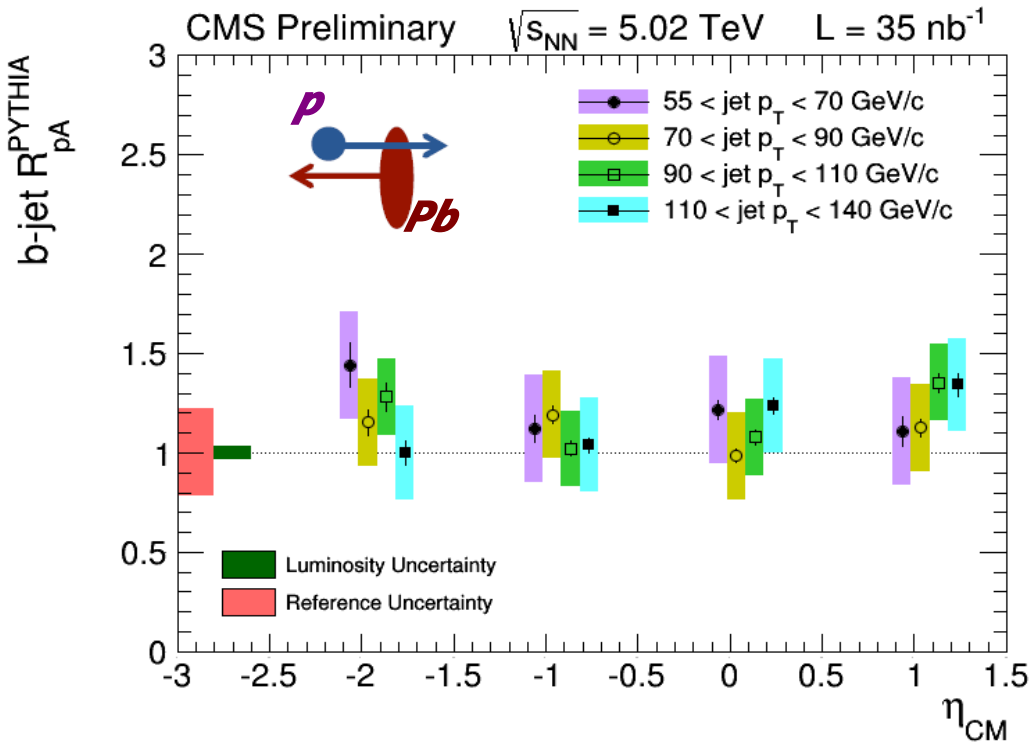
No reducing *the fraction of isolated photons with associated partner jet* in pPb collisions as compared with pp and MC simulations ⇨

jet energy seems unmodified

Nuclear modifications factor for B-jets

CMS-PAS-HIN-14-007



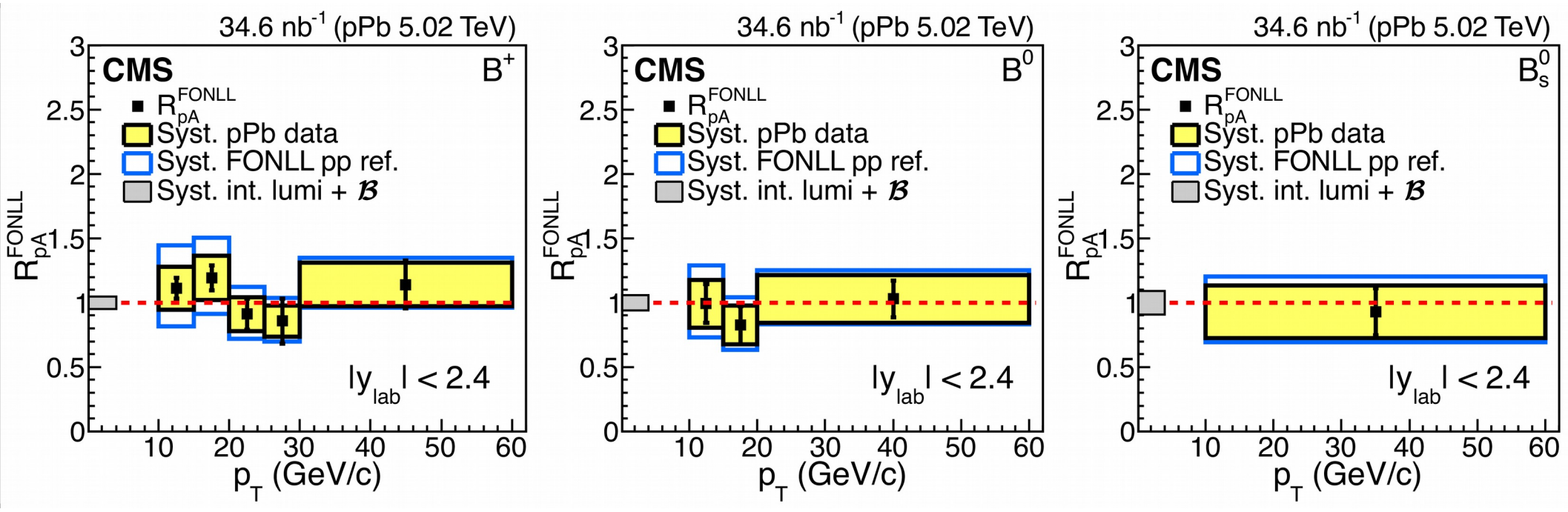


$$R_{pA} = 1/A\ N_{pA}/N_{pp}$$

B-jets show no suppression in pPb ⇨
no b-jet quenching seen

Nuclear modifications factor for B-mesons

arXiv:1508.06678

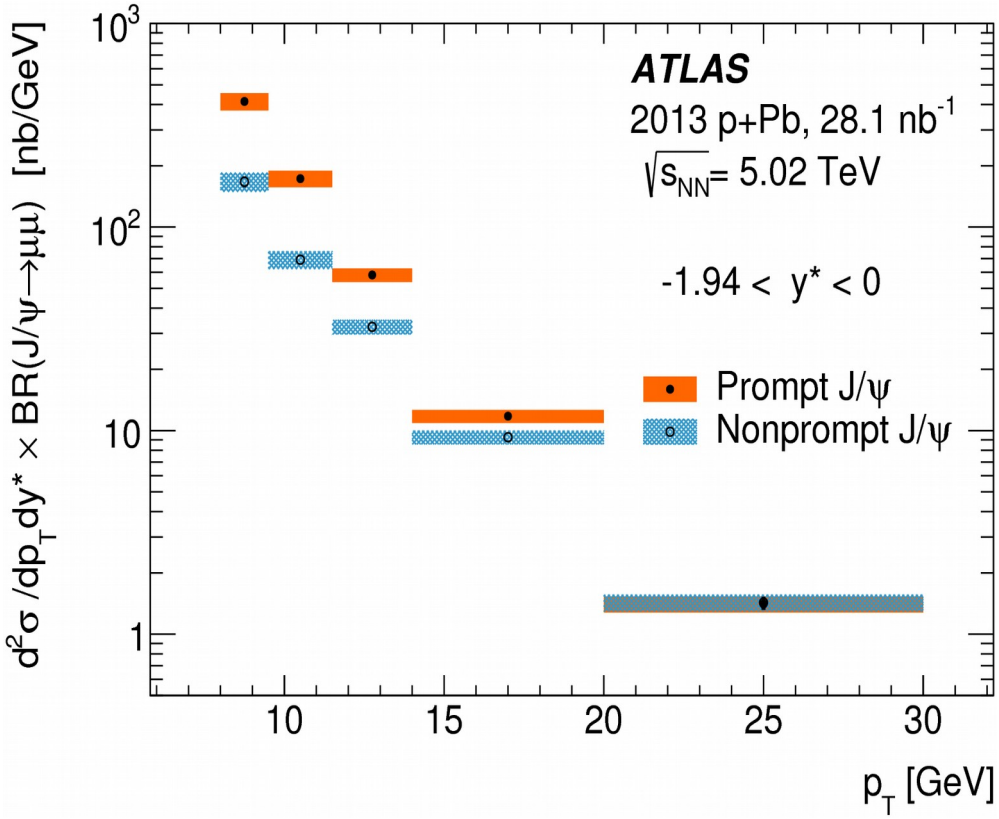


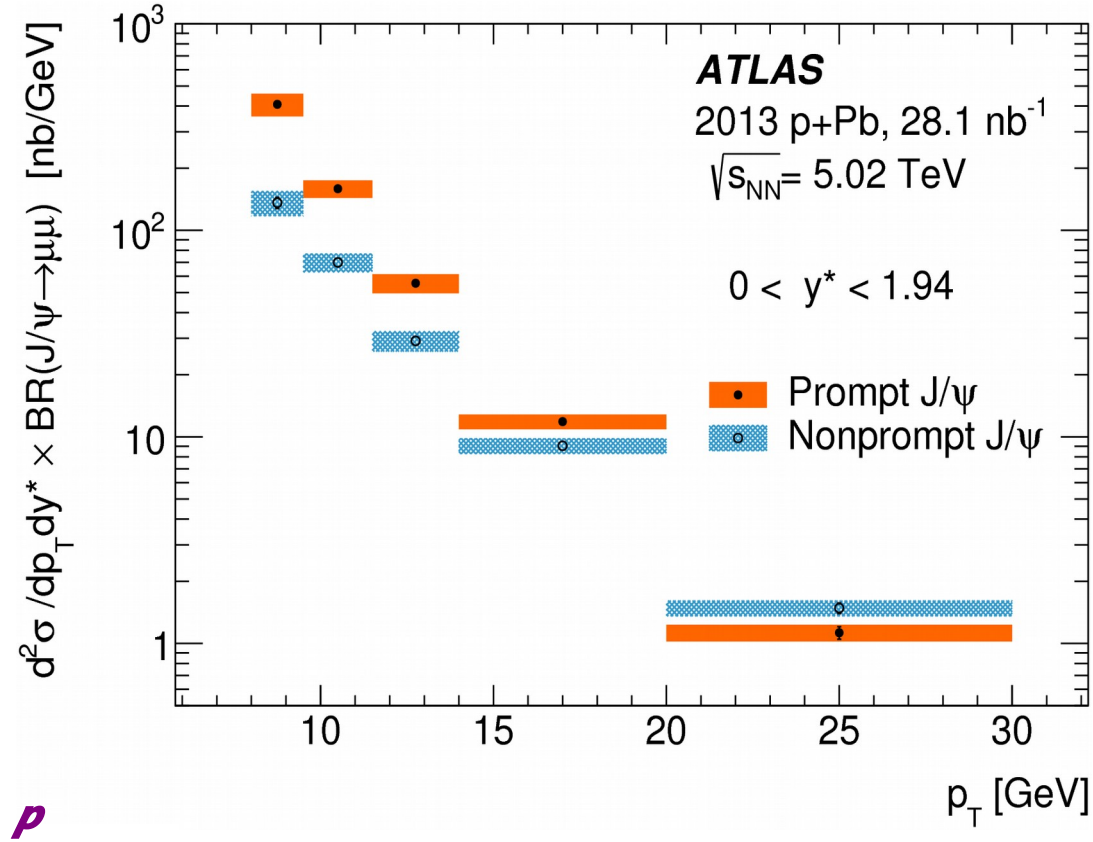
$$R_{pA} = 1/A\ N_{pA}/N_{pp}$$

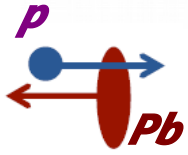
B decays show no suppression in pPb ⇨
no b-quark quenching seen

J/ψ differential cross sections

arXiv:1506.08552

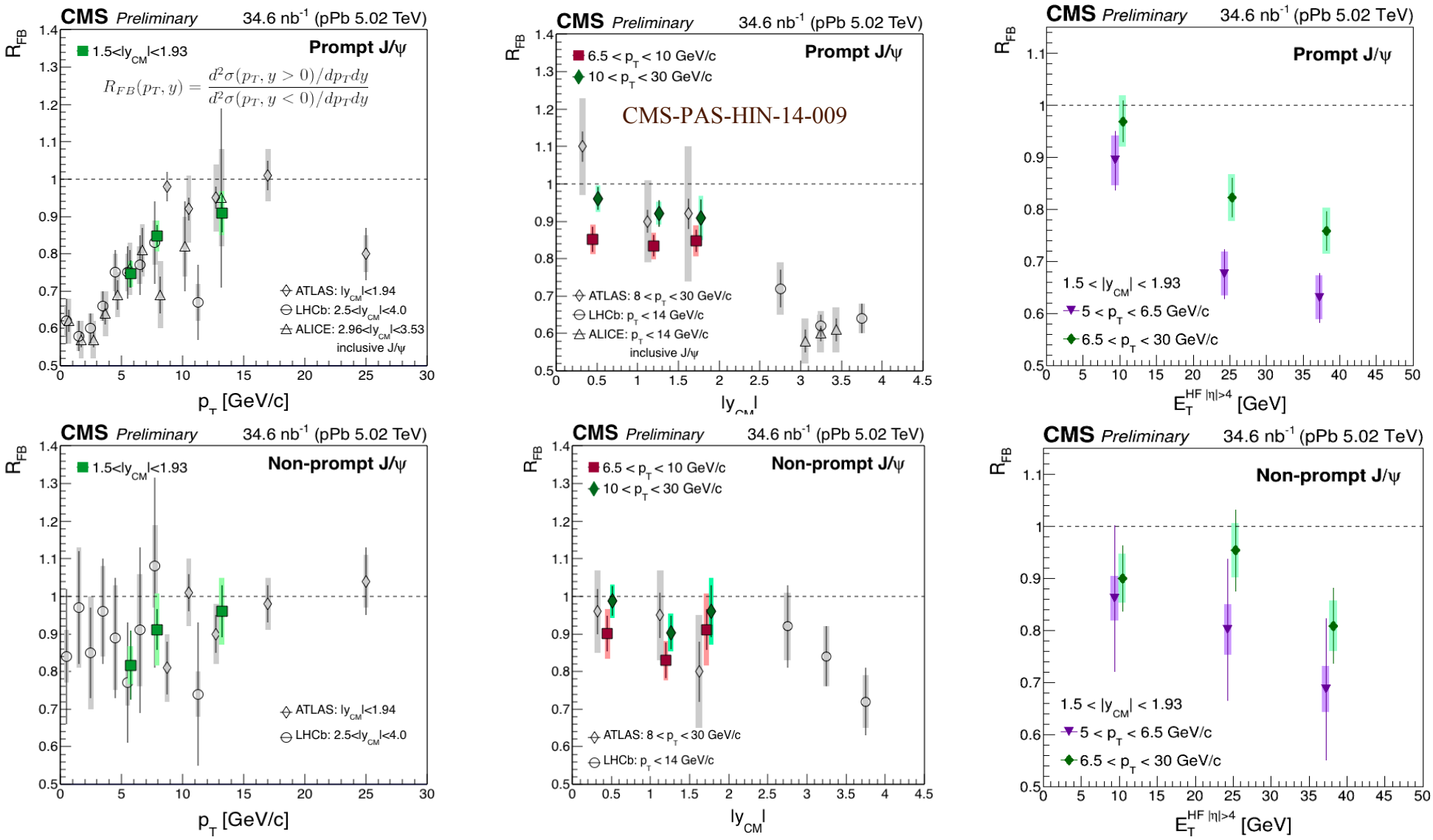






Fraction of non-prompt J/ψ to inclusive J/ψ *increases with* p_T (~50% at highest measured p_T) without significant rapidity dependence ⇨ consistent with pp data

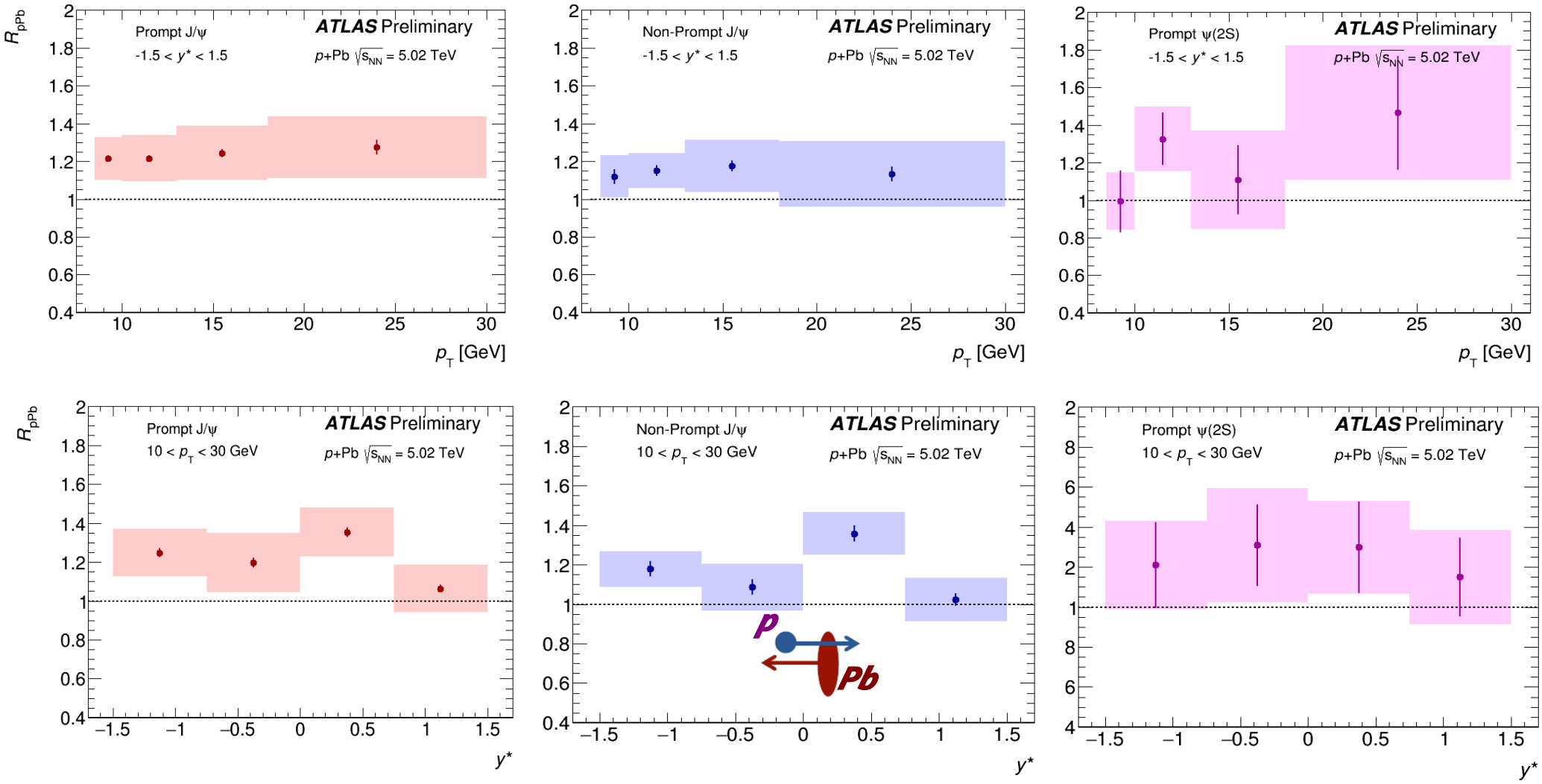
J/ψ forward-backward asymmetry



Clear *forward-backward asymmetry* for prompt & non-prompt J/ψ (more pronounced at lower p_T, larger |y|, and in higher event activity) ⇨ hint of cold nuclear matter effects?

Nuclear modification factor for J/ψ & ψ(2S)

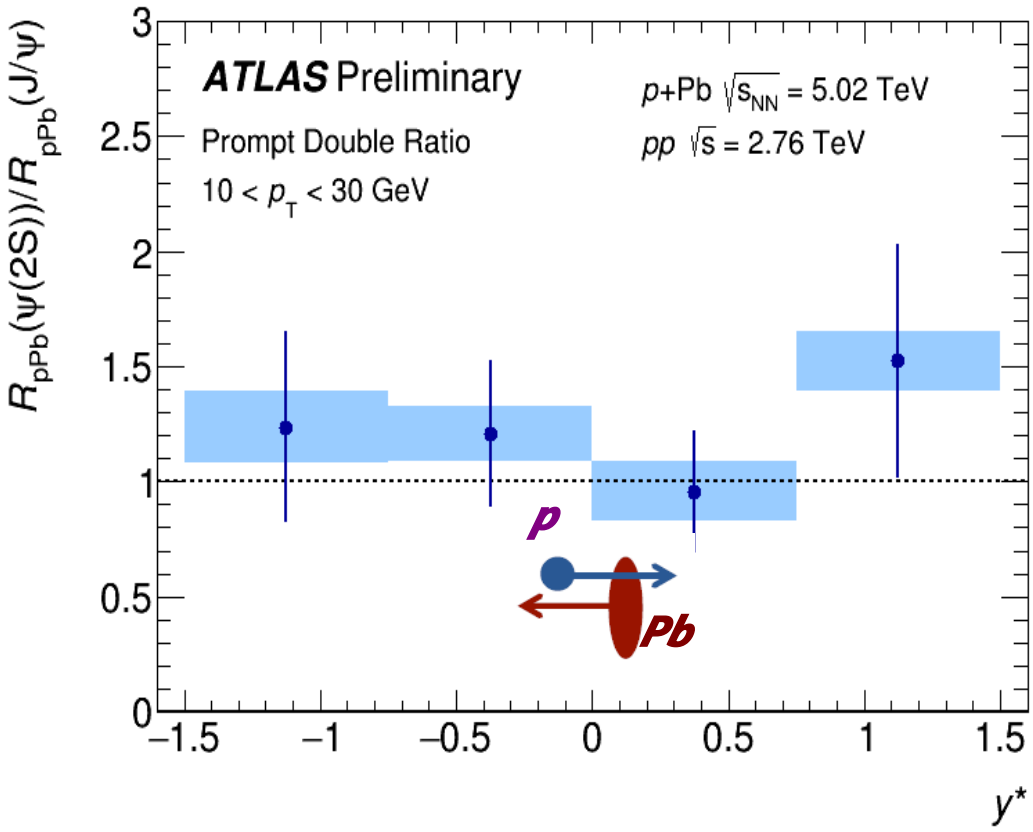
ATLAS-CONF-2015-023

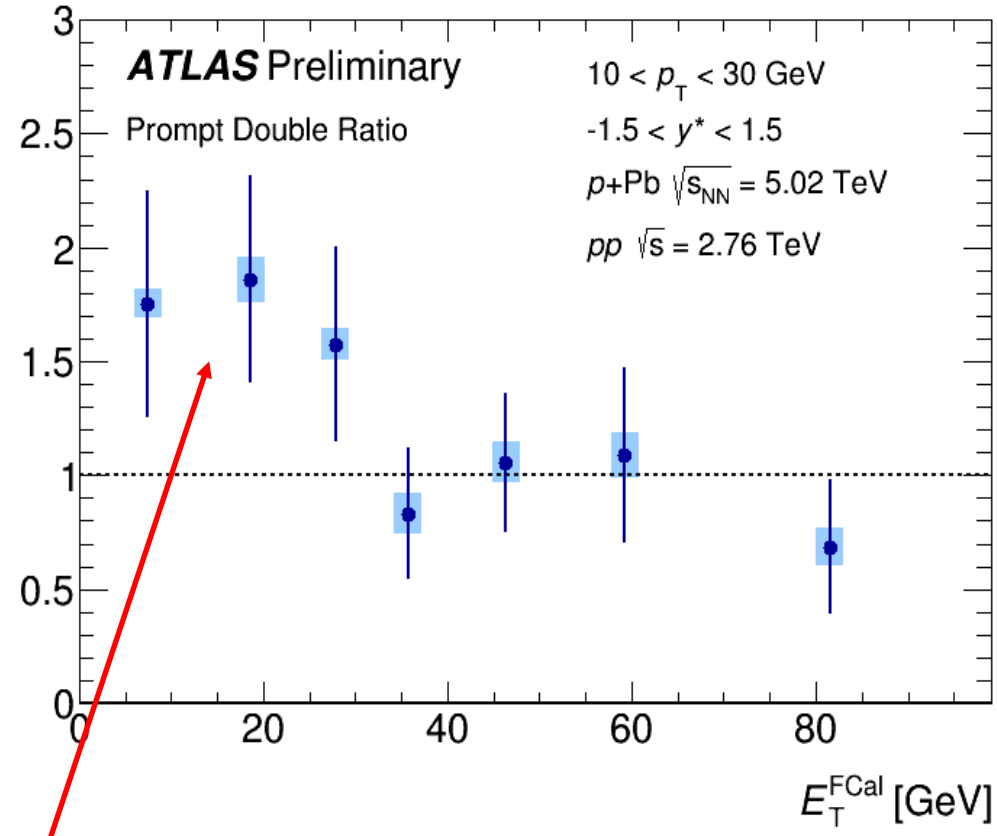


Enhancement for prompt J/ψ, non-prompt J/ψ and ψ(2S) *for all measured kinematics* ⇨ hint of cold nuclear matter effects?

Double ψ(2S)/J/ψ ratio

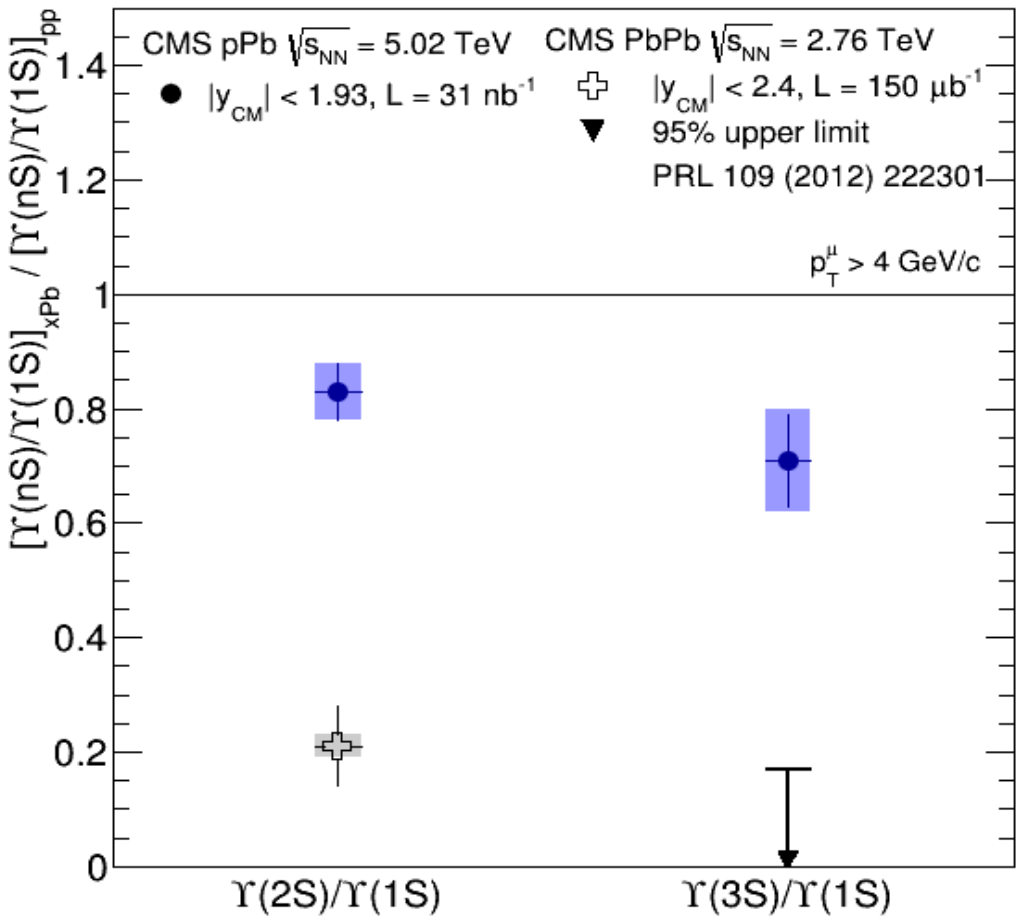
ATLAS-CONF-2015-023

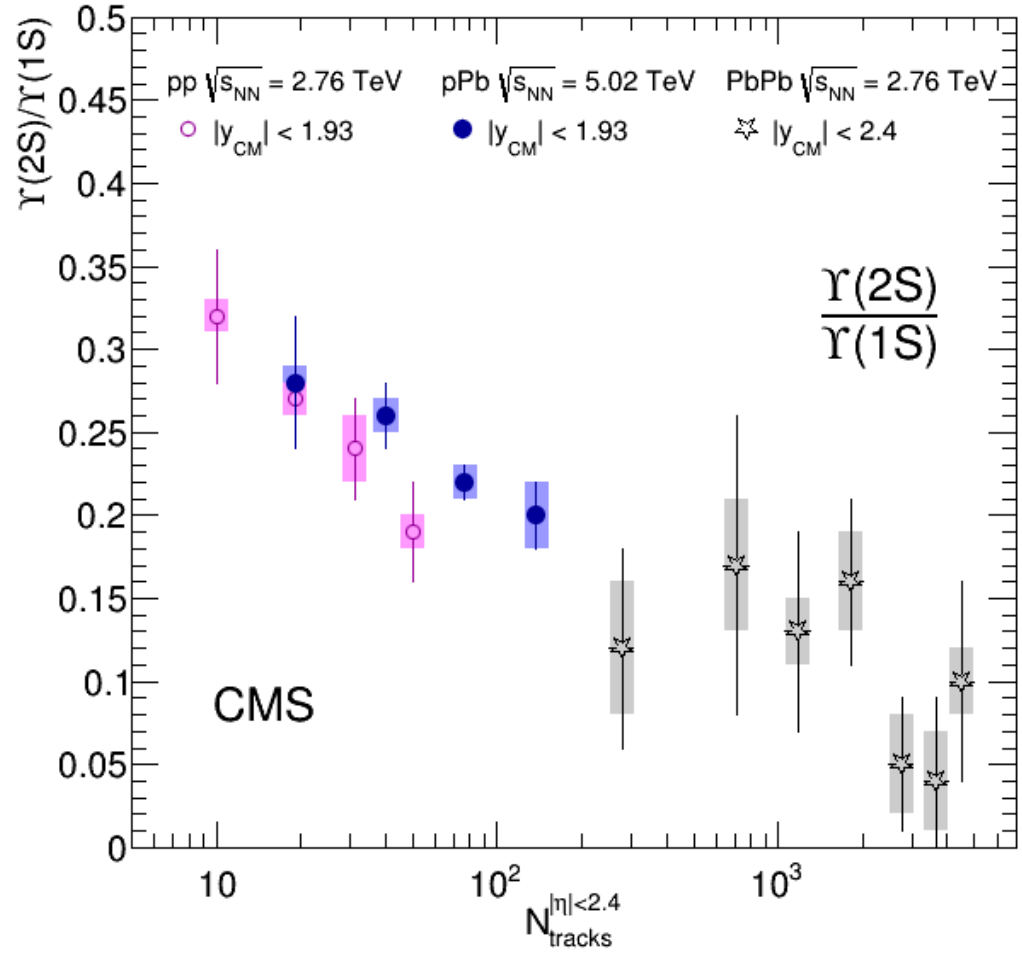




Double ratio of prompt ψ(2S)/J/ψ enhanced *at low centrality* ⇨
initial or final state effect? (ALICE sees the suppression but at low p_T)

ϒ(2S,3S)/ϒ(1S) suppression

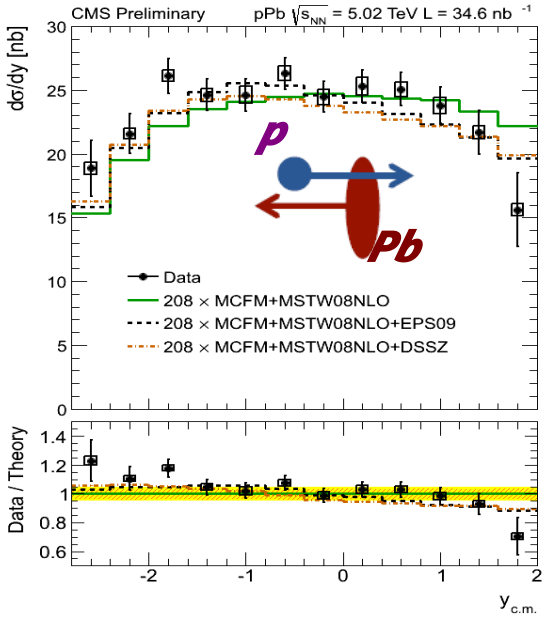




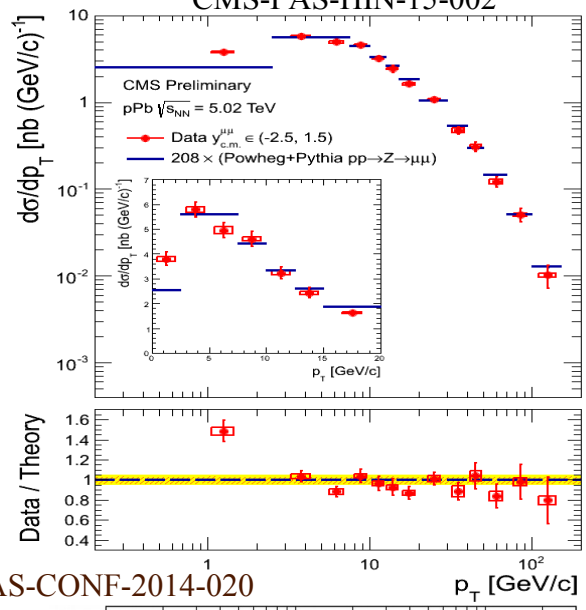
JHEP 04 (2014) 103

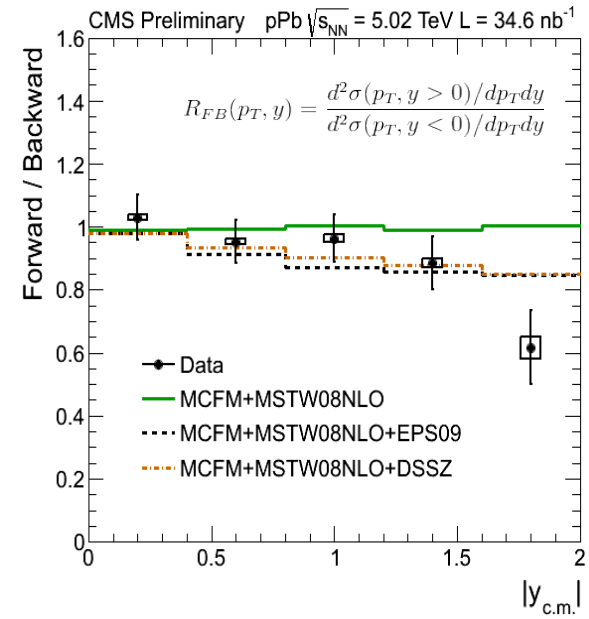
- Moderate Y(nS)/Y(1S) *suppression (much lesser than in PbPb)* ⇨ final state effect?
- Y(nS)/Y(1S) decreases with event multiplicity *for all systems:* pp, pPb, PbPb

Z and W production

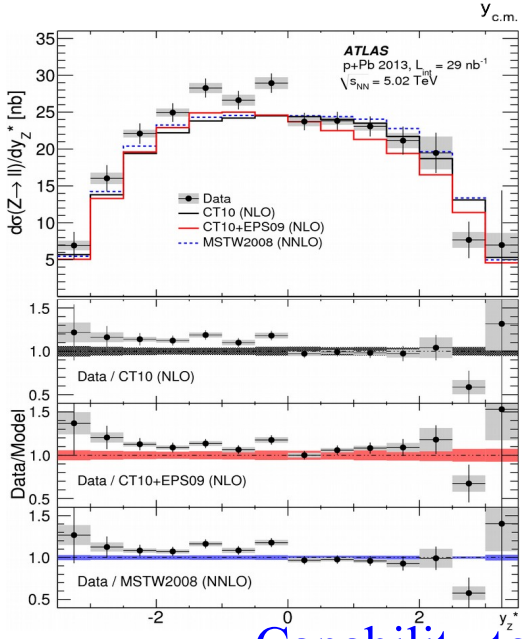


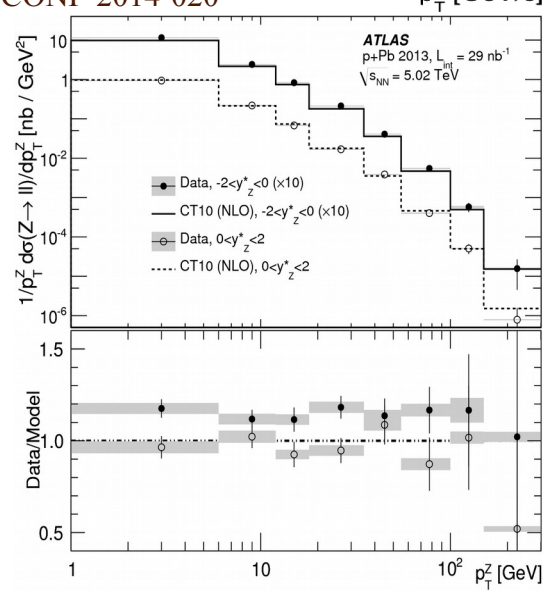
CMS-PAS-HIN-15-002

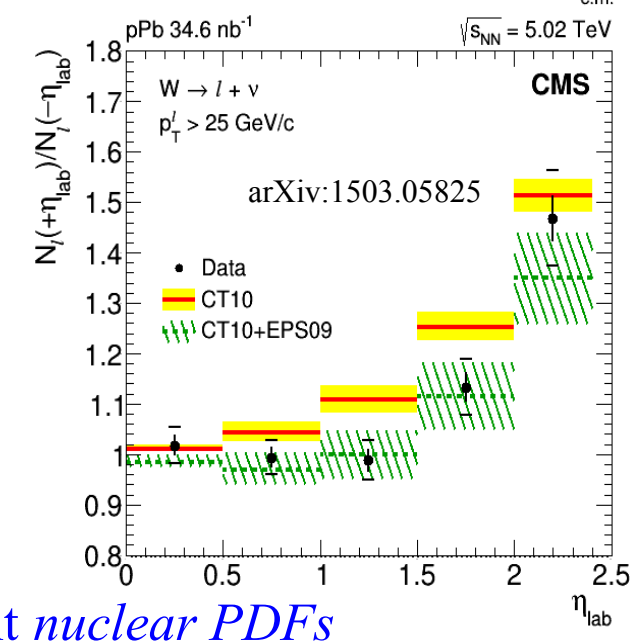




ATLAS-CONF-2014-020







Capability to test the models including different *nuclear PDFs*

Summary on ATLAS/CMS results from pPb

- *Global observables:*
  anisotropic flow and ridge in high multiplicity events
  ⇨ some collectivity?

- *High tranverse momentum hadrons:*
  no suppression from jet quenching, but indication on the enhancement at high momenta
  (ATLAS & CMS are consistent, ALICE does not confirm)
  ⇨ modified PDF? different quark/gluon jet ratio in pPb vs. pp? need pp data @ 5 TeV!

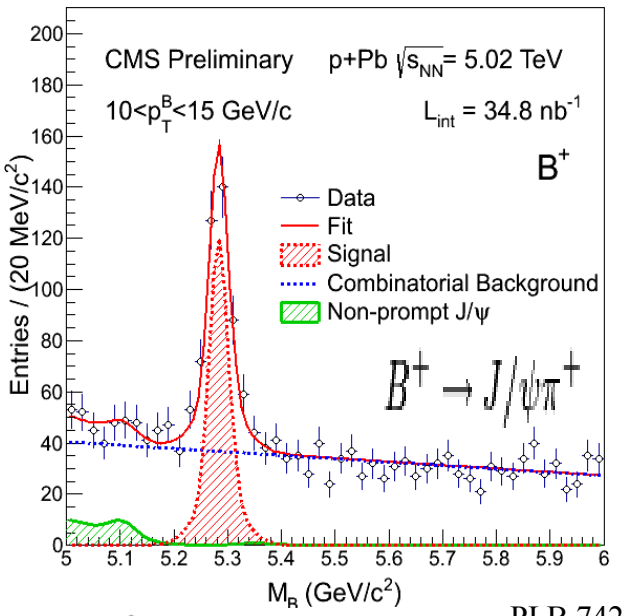
- *Jets:*
  no inclusive and b-jet suppression, no dijet and γ-jet energy asymmetry
  ⇨ no jet quenching!
  but is jet fragmentation modified? No (CMS) / Yes (ATLAS) (?) Need pp data again!

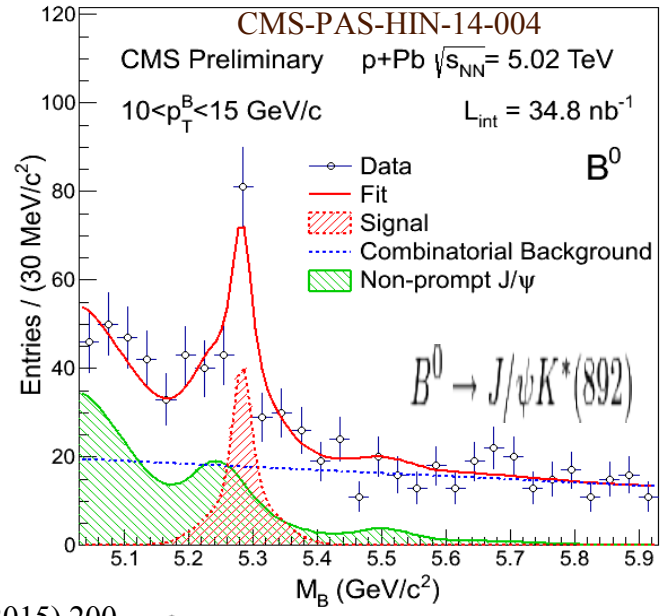
- *Quarkonia:*
  Forward-backward asymmetry and some enhancement for prompt & non-prompt J/ψ
  ⇨ cold nuclear matter effect? But ψ(2S)/J/ψ excess (ATLAS) looks puzzling.
  Moderate Υ(2S, 3S)/Υ(1S) suppression, stronger at higher multiplicities (CMS)
  ⇨ Υ's are affected by high multiplicity environment or vise versa?

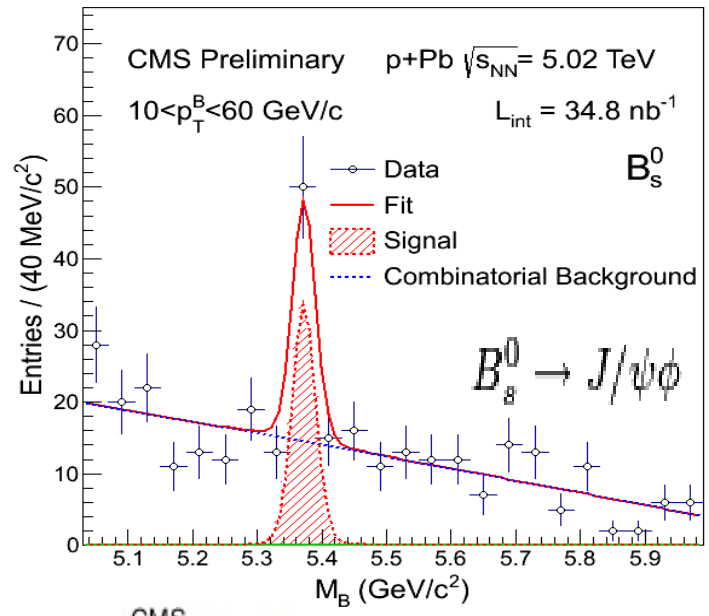
- *Electroweak probes (Z^0 and $W^{\pm}$ bosons)*
  Differential cross sections & forward-backward asymmetries are measured
  ⇨ testing nuclear PDFs

BACKUP SLIDES

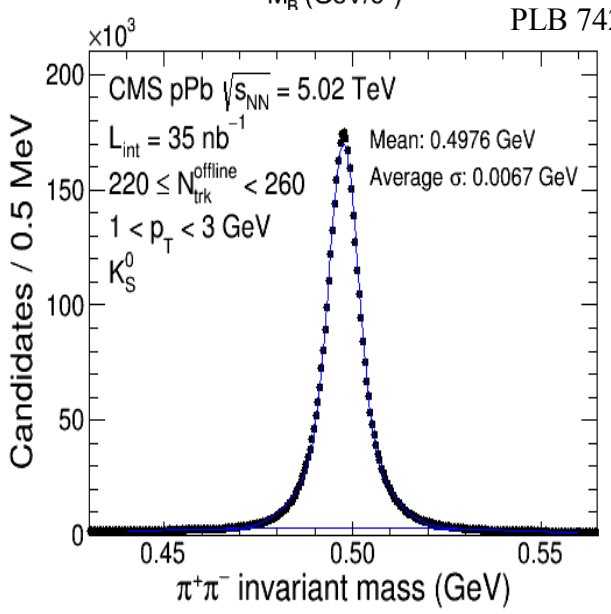
CMS particle indentification in pPb

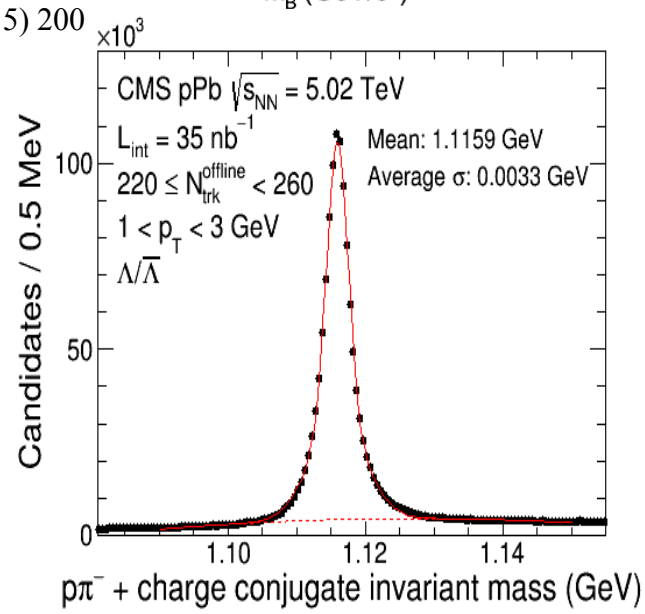


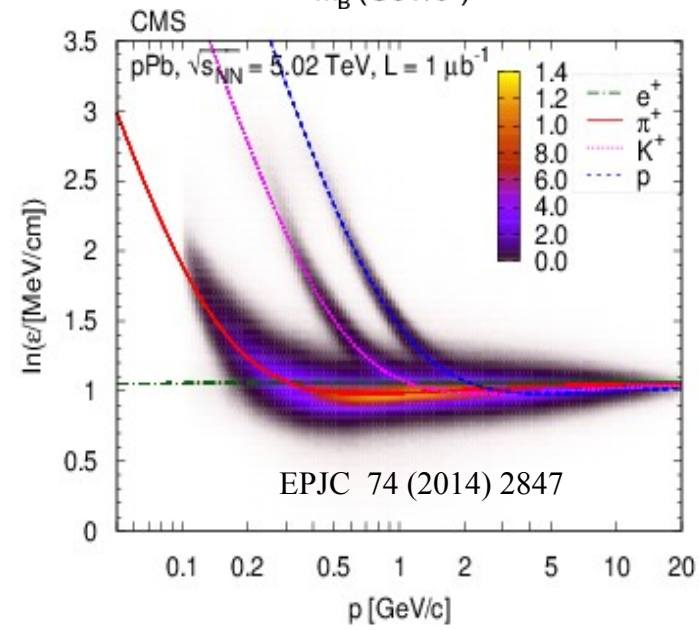




PLB 742 (2015) 200



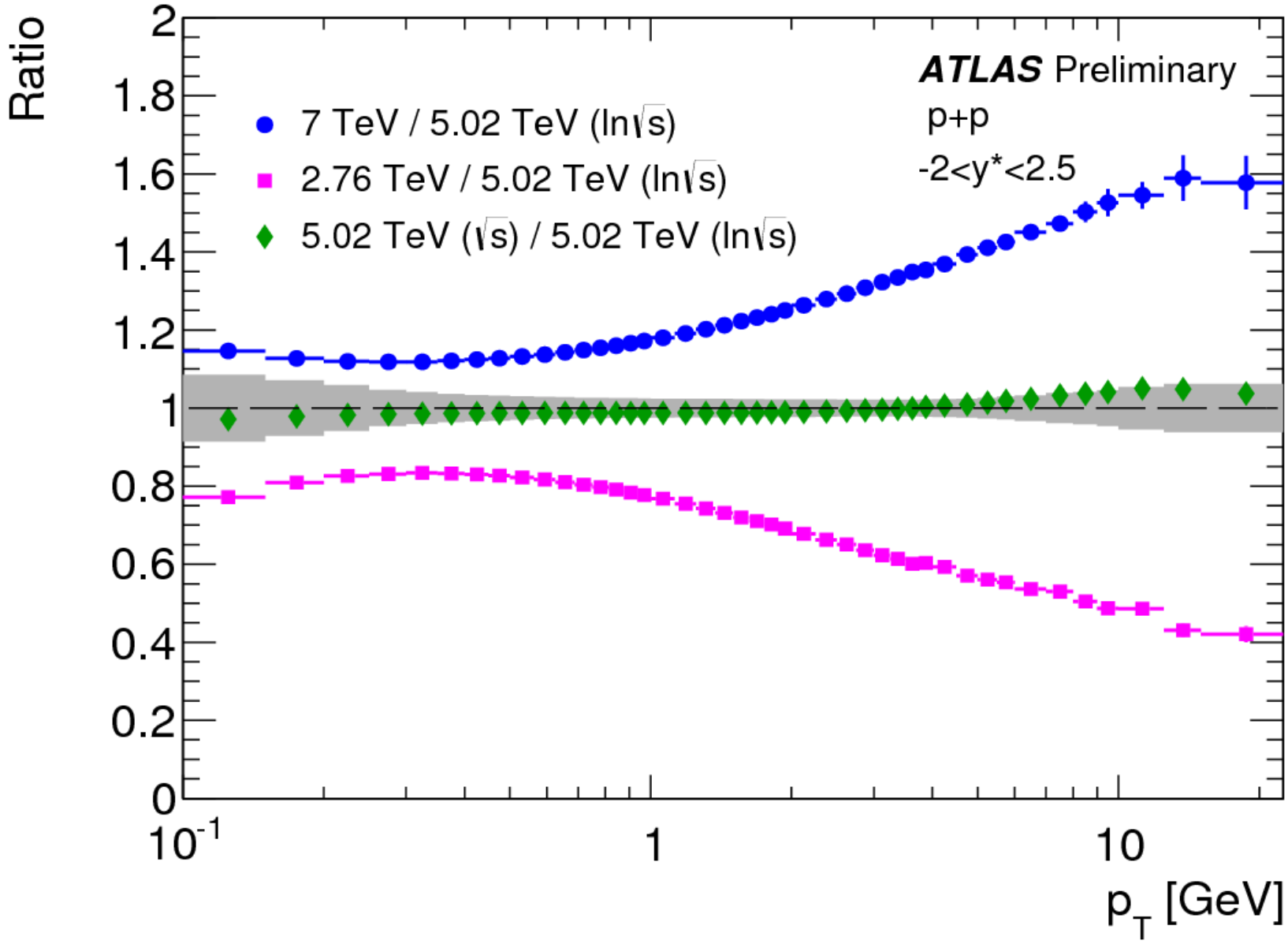




EPJC 74 (2014) 2847

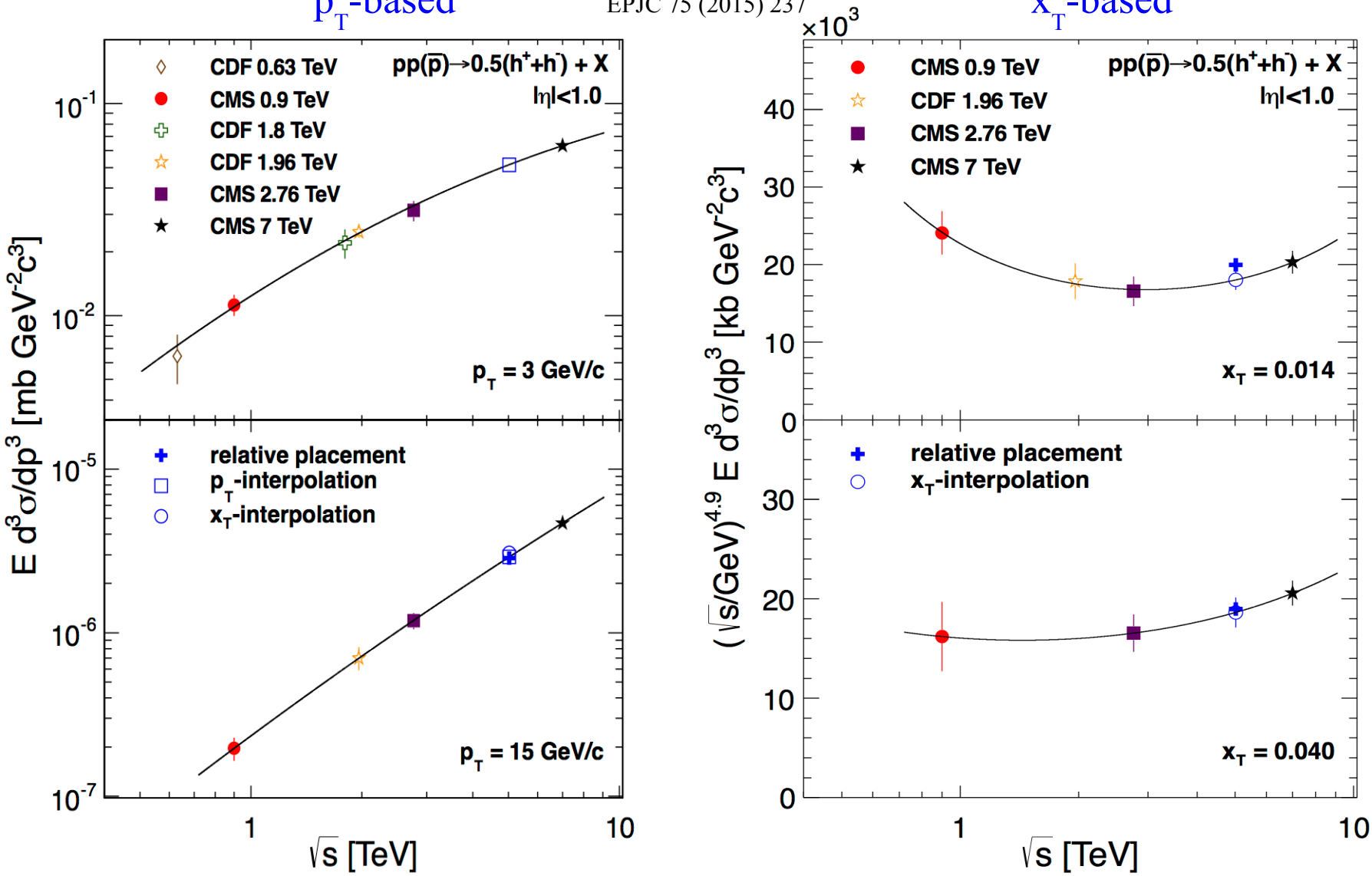
ATLAS pp @ 5.02 TeV reference
(charged hadrons)

ATLAS-CONF-2013-107



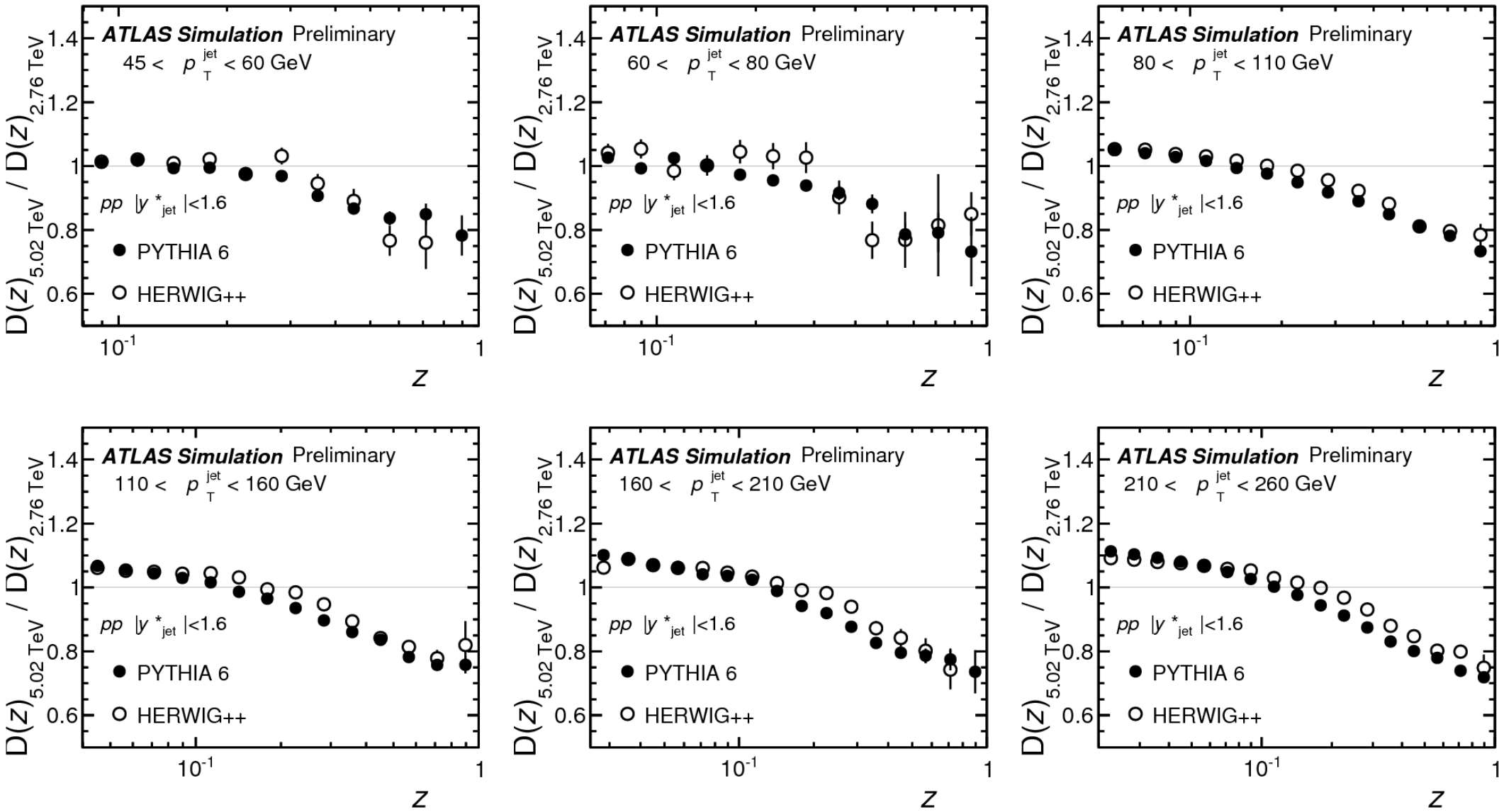
CMS pp @ 5.02 TeV reference
(charged hadrons)

p_T-based EPJC 75 (2015) 237 x_T-based



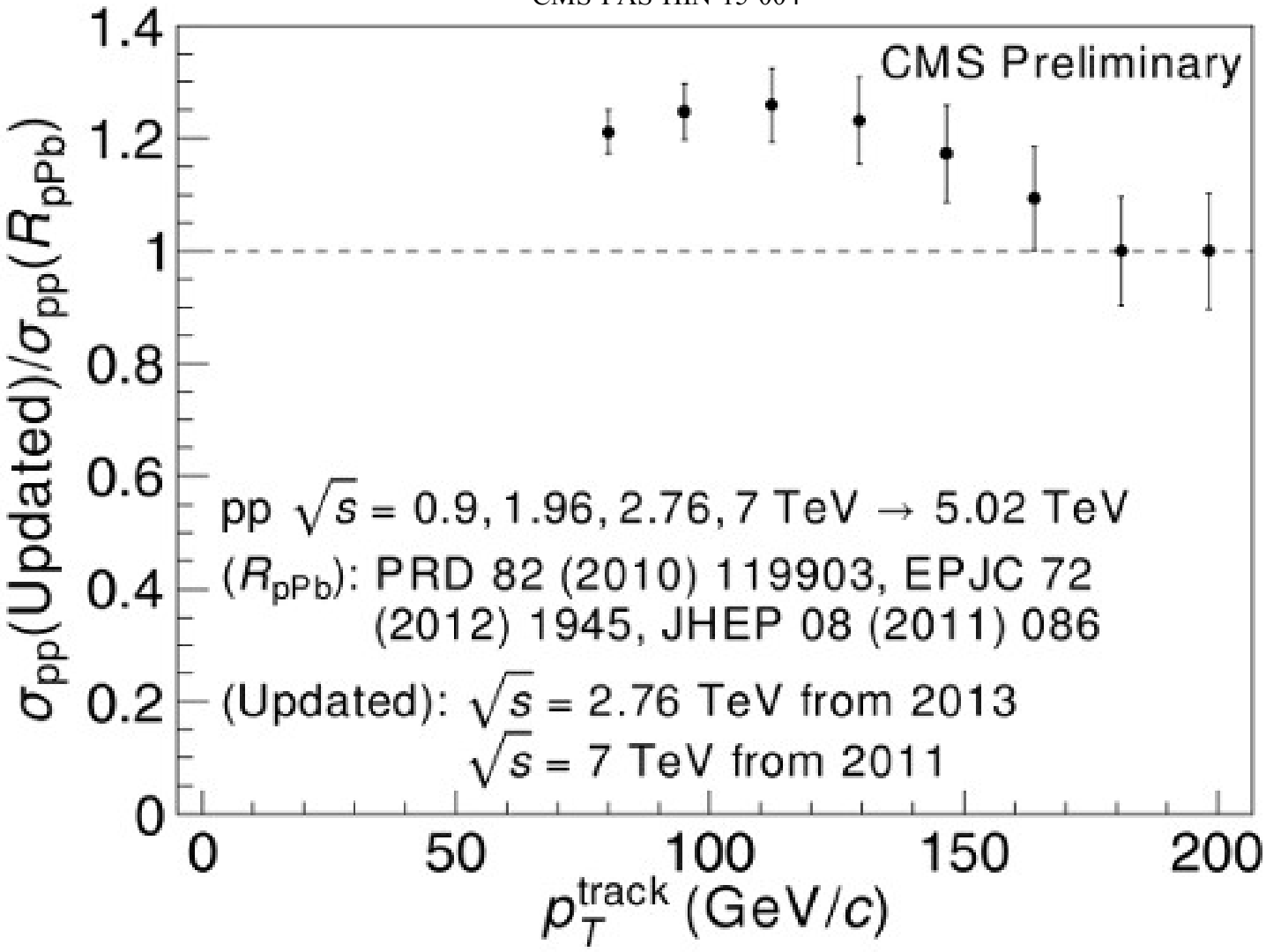
ATLAS pp @ 5.02 TeV reference
(jet fragmentation function)

ATLAS-CONF-2015-022



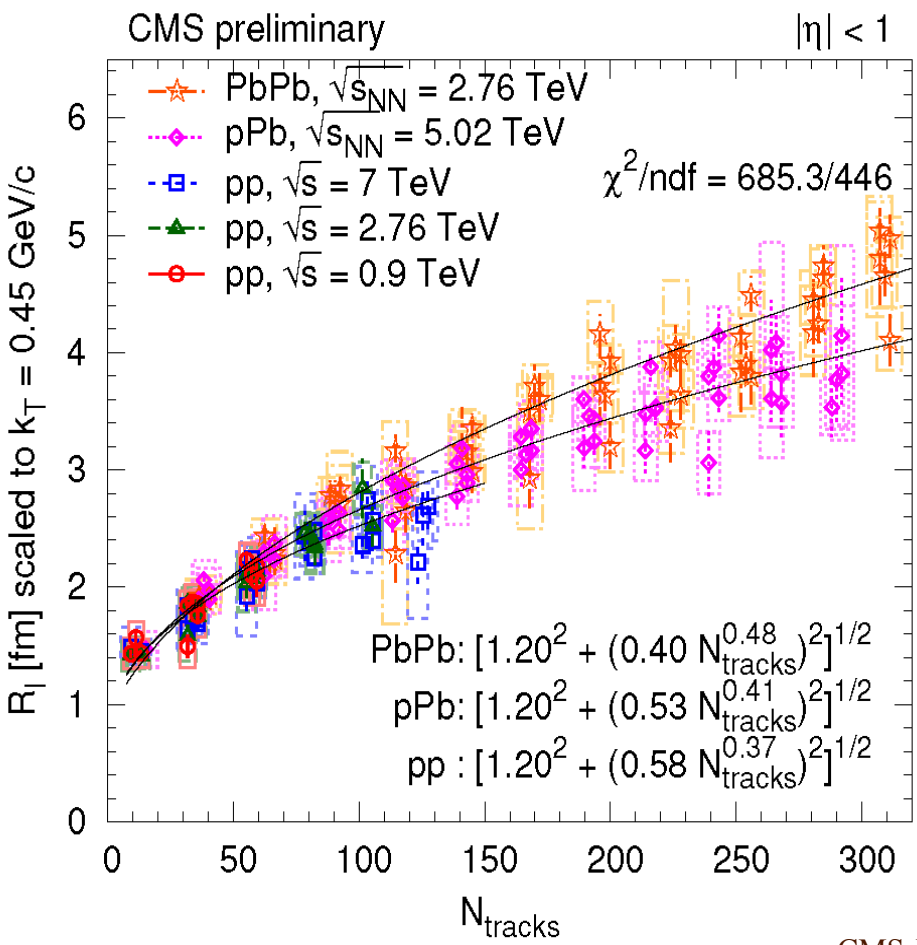
CMS pp @ 5.02 TeV reference
(jet fragmentation function)

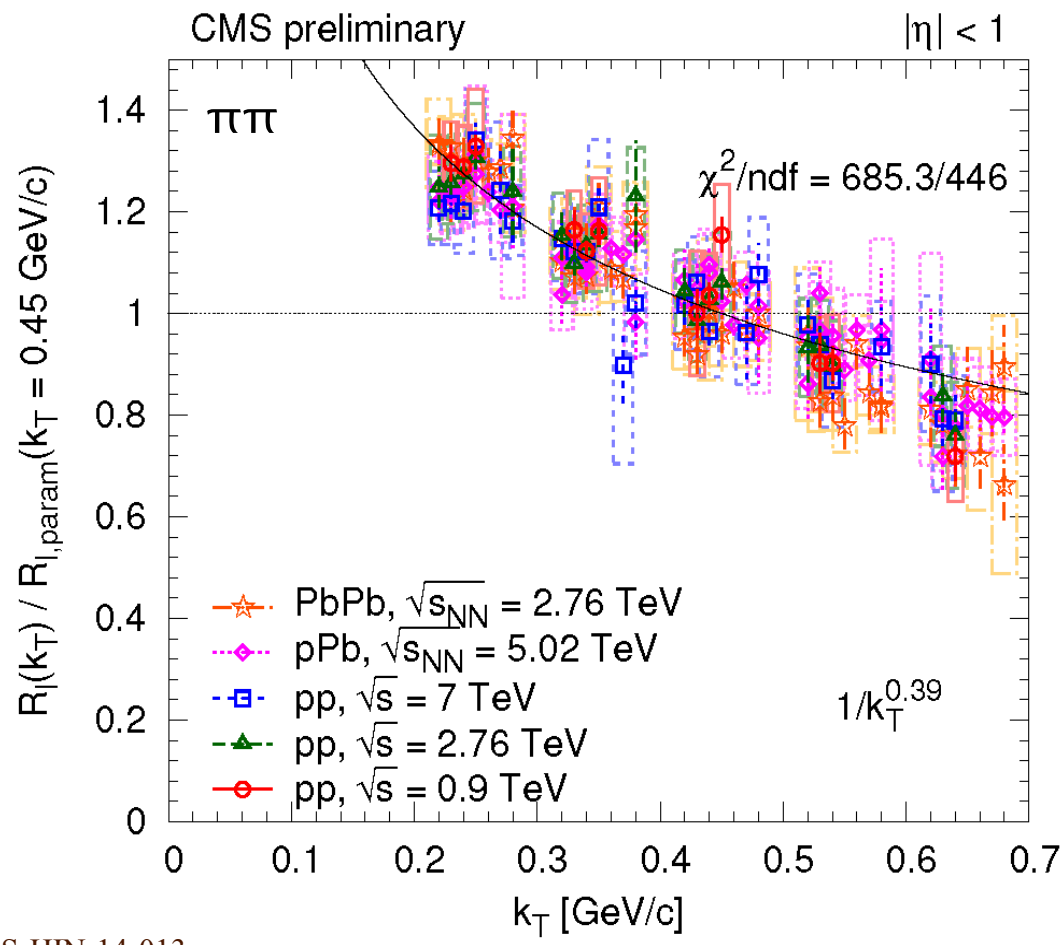
CMS-PAS-HIN-15-004



New x_T-based interpolation taking into account energy dependence of *quark-gluon fraction* (obtained from MC between 2.76 & 7 TeV pp data)

Bose-Einstein correlations (ππ, KK)



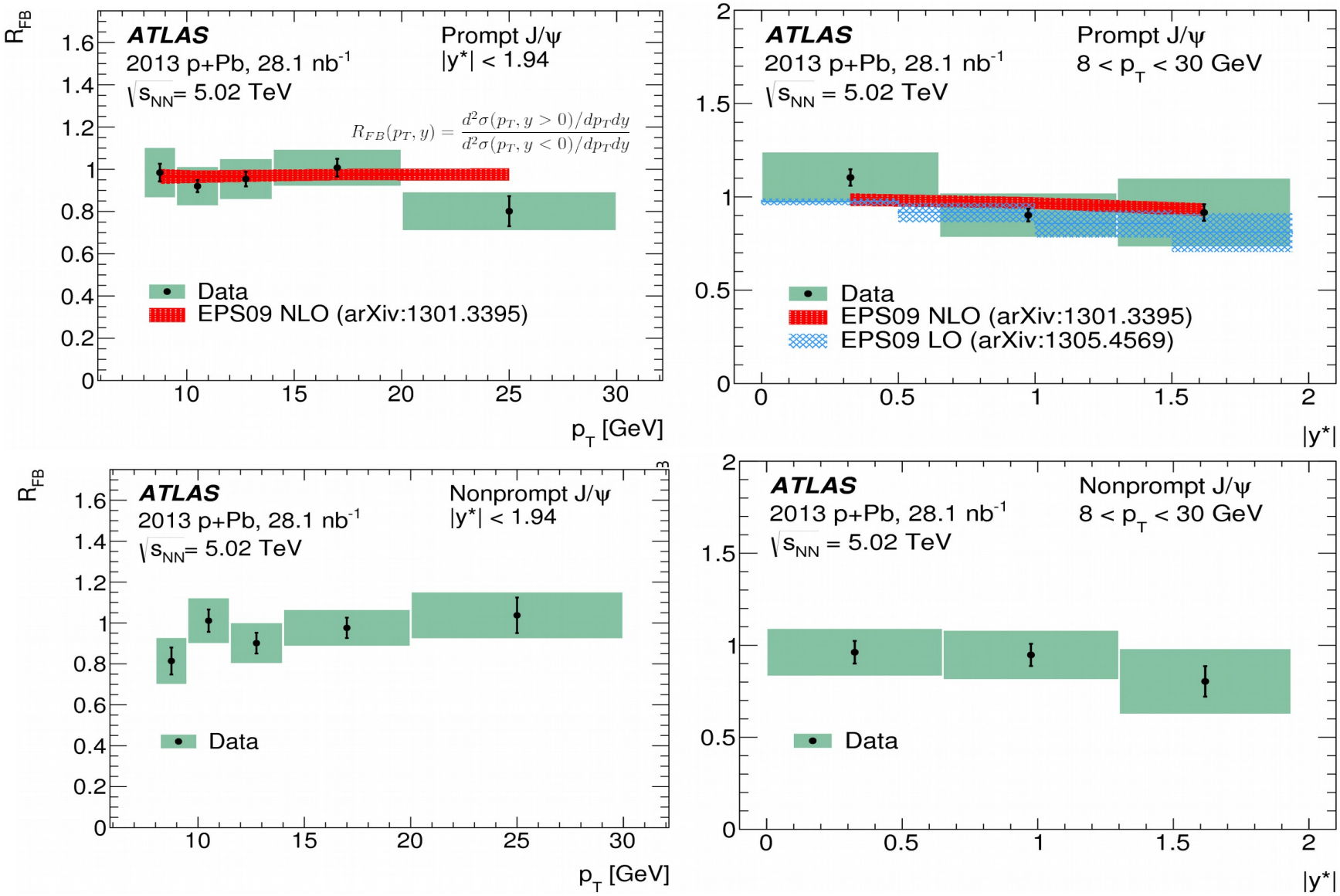


CMS-PAS-HIN-14-013

- Similar extracted radii (in the range 1-5 fm) in pPb and peripheral PbPb
- Scaling with event multiplicity and k_T

J/ψ forward-backward asymmetry

arXiv:1506.08552



ATLAS data on prompt J/ψ are consistent with nPDF calculations (EPS09)