Heavy Ion results on hard scattering and jet quenching

from ATLAS and CMS

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Motivation

- In collisions of heavy nuclei at very high energies one expects creation of hot and dense medium which may, under certain conditions, undergo transition to so called Quark Gluon Plasma phase where quarks and gluons are free to interact directly.
- In experiments at RHIC and LHC it has been observed that properties of high transverse momentum particles and particle jets are modified in such heavy nuclei collisions compared to properties in collisions of protons and this was attributed to interactions of these particles with medium created in the collision.
- Studies of hard scattering processes is the way to understand properties of the produced medium and whether it fits the properties of the QGP.

- We study these effects by measuring deviation R_{AB} of production yields from simple linear superposition of the number of nucleon-nucleon collisions, N_{coll}, proportional to T_{AB} – the mean nuclear thickness function of the incoming nucleon/parton fluxes.
- R_{AB} = 1 no medium effects

$$R_{AB} = \frac{\frac{1}{N_{evt}} \frac{d^2 N_{cent}^{jet}}{dp_T dy}}{\langle T_{AB} \rangle_{cent} \frac{d^2 \sigma_{pp}^{jet}}{dp_T dy}}$$

$$N_{coll} = T_{AB} \times \sigma_{NN}$$

Heavy Ion data at LHC

Data collected by ATLAS and CMS experiments at the LHC collider
(luminosities differ somewhat between experiments, CMS values given)

Dec. 2010	Pb+Pb	2.76 TeV	7 μb^{-1}
Dec. 2011	Pb+Pb	2.76 TeV	150 μb^{-1}
Mar. 2011	p+p	2.76 TeV	230 nb^{-1}
Sep. 2012	p+Pb	5.02 TeV	1 μb^{-1}
Jan. 2013	p+Pb	5.02 TeV	35 nb^{-1}
Feb. 2013	p+p	2.76 TeV	5.4 pb^{-1}

Latest analyses now using:
$\Rightarrow$ High statistics PbPb data from 2011
$\Rightarrow$ New pPb data from 2013
$\Rightarrow$ High statistics pp from 2013, 20 x more pp reference data

Jets in Pb+Pb collisions

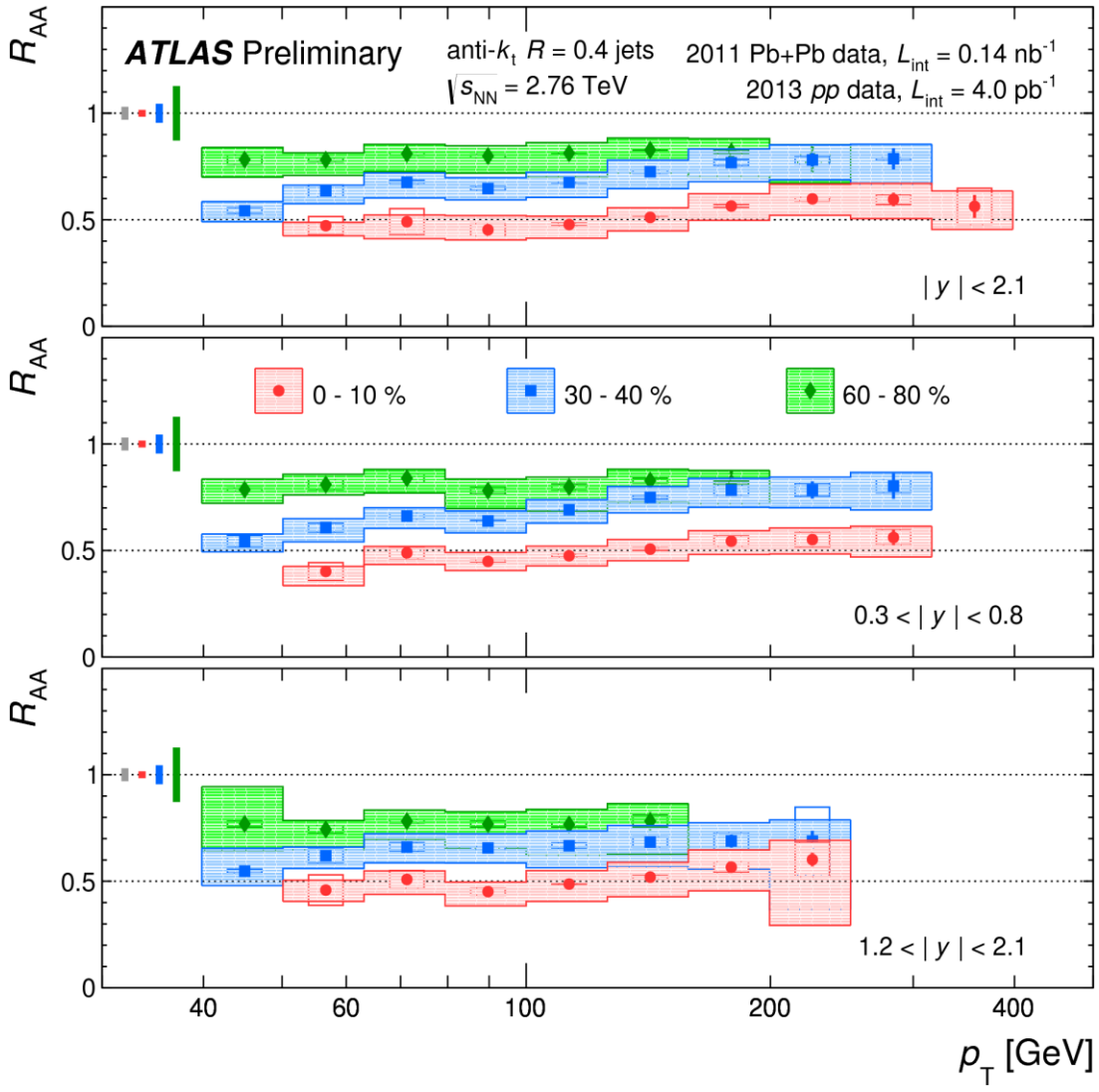
- Jets provide a powerful tool to probe the hot and dense medium created in HI collisions
- Experiments at RHIC provided first evidence of jet quenching by observation of suppression of high transverse momentum particles
- At the LHC a direct evidence of parton energy loss has been observed in significant modification of dijet and photon-jet p_T-balance and suppression of inclusive jet spectra with increasing collision centrality.

Results:

- ❑ ATLAS and CMS
  - Old: Strong imbalance of dijet transverse momenta in central PbPb collisions
  - Old: Strong imbalance and a significant decrease in the ratio p_T^{Jet}/p_T^{γ} relative to Pythia
  - Old: Jet (central-to-peripheral) R_{cp} suppressed by a factor of two in central collisions
- ❑ ATLAS
  - Old: Suppression of jet fragment yields at intermediate values of longitudinal momenta
  - New: Jet R_{AA} vs p_T and rapidity y: ATLAS-CONF-2014-025
  - New: Jet fragmentation vs p_T and z: ATLAS: arXiv:1406.2979
- ❑ CMS
  - Old: Momentum balance recovered by including low-p_T particles at large radial distance
  - New: Extended study of jet fragmentation p_T vs R, comparison with pp: PAS-HIN-14-010

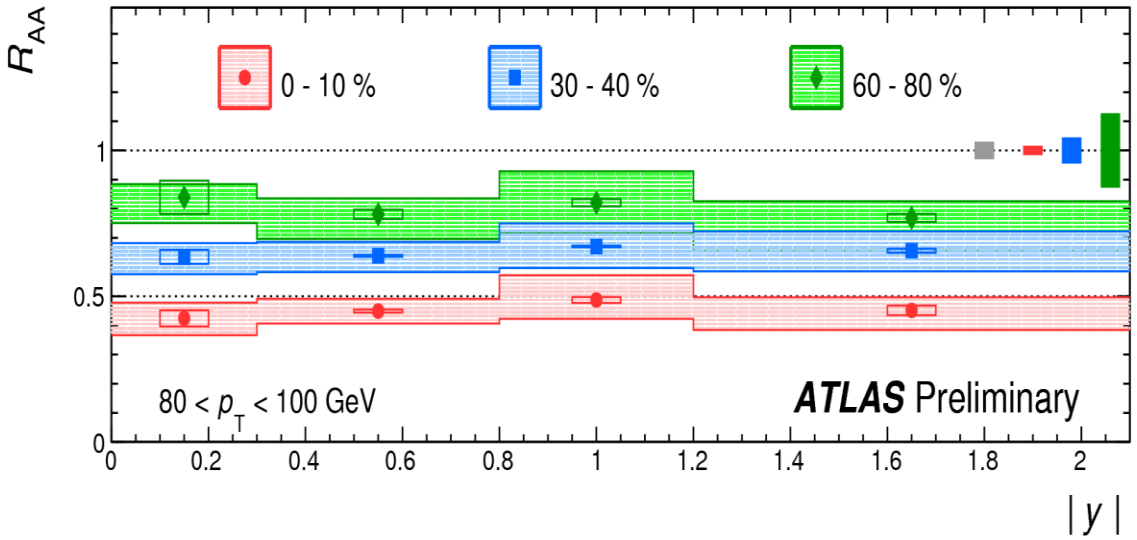
Jet R_{AA} vs p_T

- R_{AA} vs p_T
  - In three distinct centrality bins
- Observe
  - Factor of ~ 2 suppression up to jet p_T of 400 GeV
  - Slow increase with increasing jet p_T
  - Slope possibly depending on collision centrality

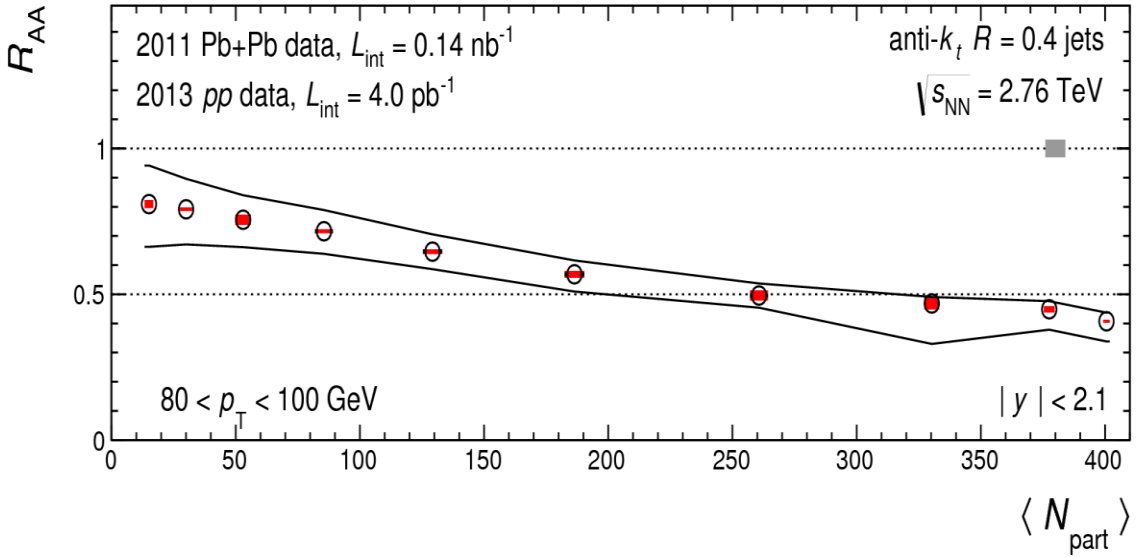


Jet R_{AA}: centrality and y dependence

- R_{AA} vs y
  - no significant dependence on rapidity observed in the measured y range



- R_{AA} vs N_{part}
  - monotonically decreases vs centrality ($\langle N_{part} \rangle$)
    - ⇒ 0.8 in peripheral (60-80%)
    - ⇒ 0.4 in central (0-1%)

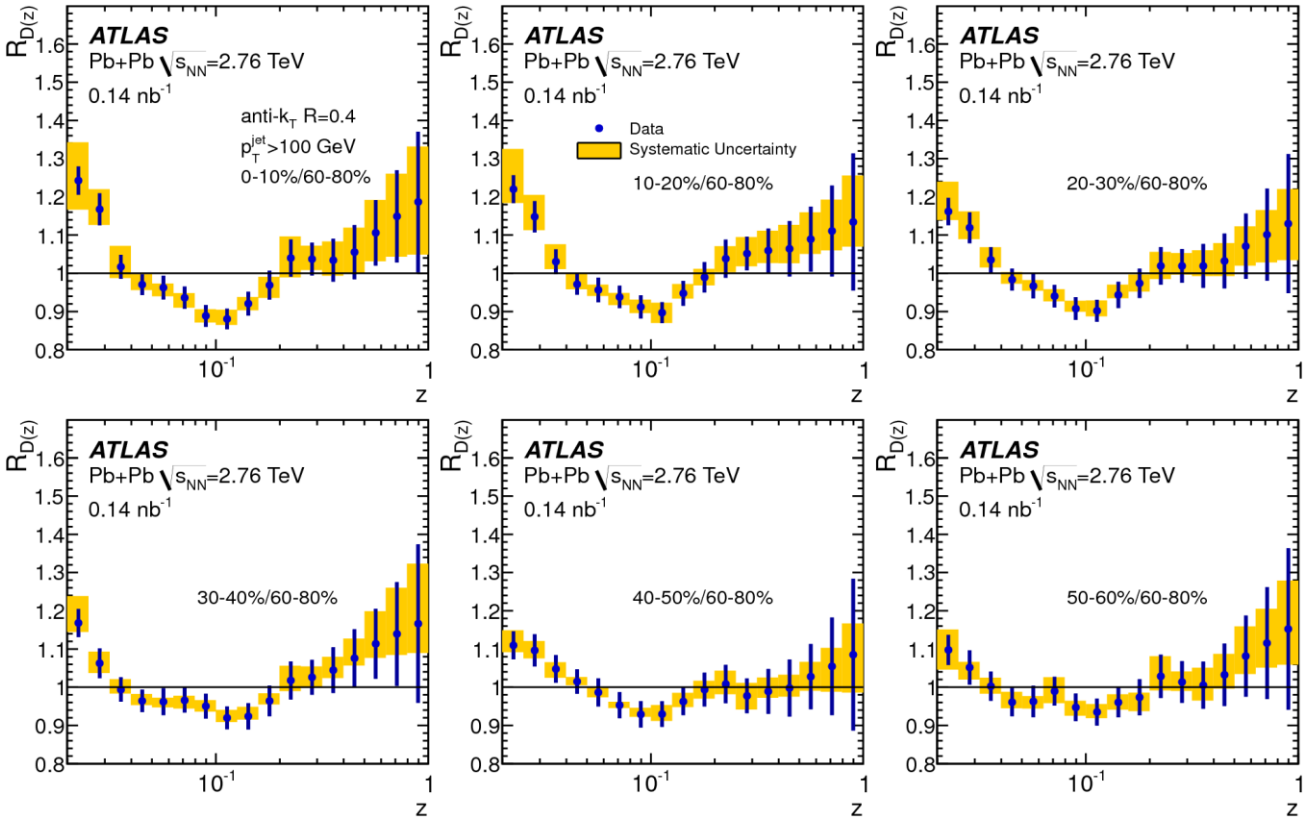


Pb+Pb modified jet fragmentation

- Ratios of D(z), $R_{D(z)}$ for R=0.4 jets are shown vs centrality to 60-80% bin

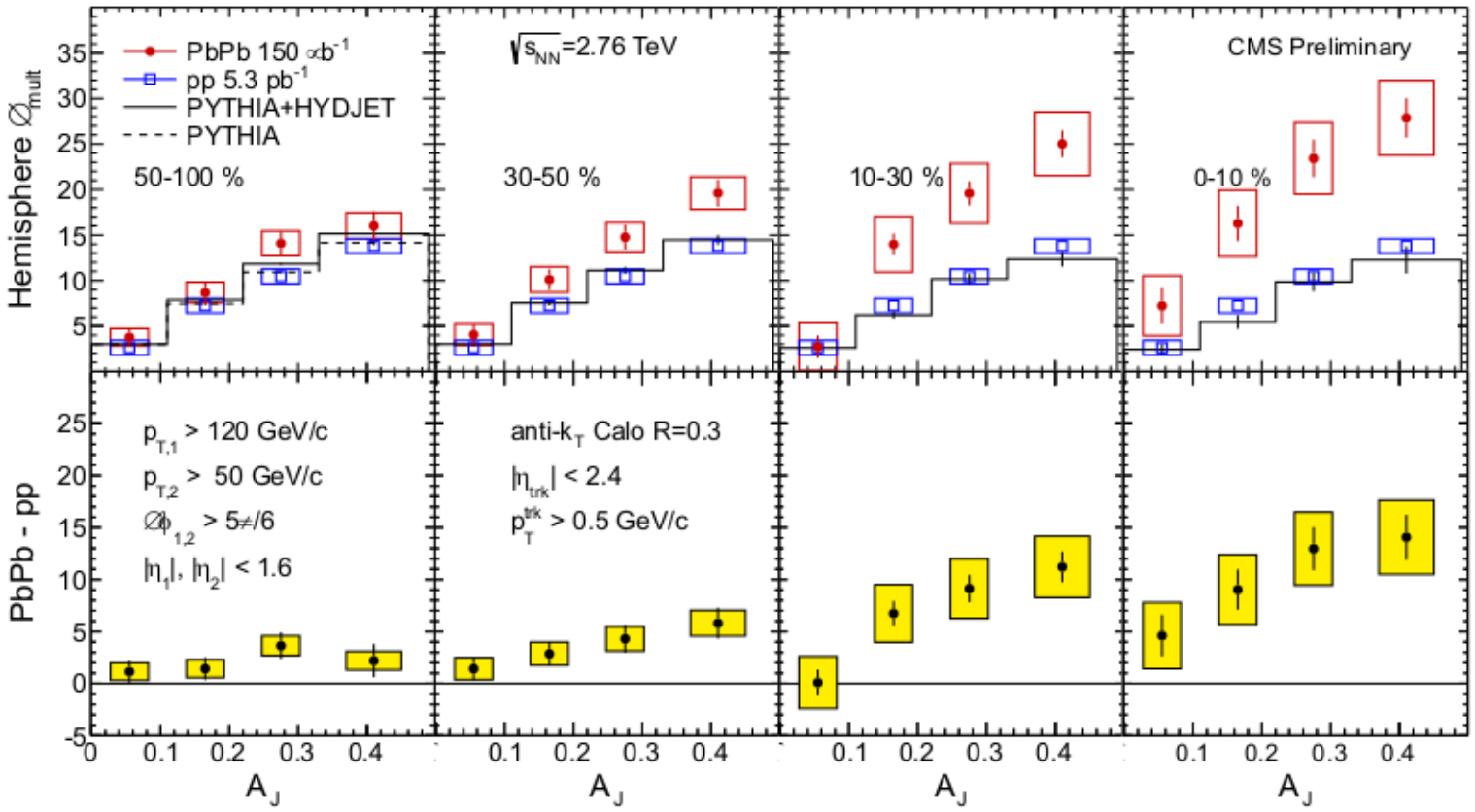
$$z = p_T^{had}/p_T^{jet}\cos\Delta R$$

$$R_{D(z)} = D(z)^{cent} / D(z)^{periph}$$



- A significant modification of fragmentation seen in central collisions:
  - $\Rightarrow$ enhancement in fragment yields for $z < 0.04$
  - $\Rightarrow$ reduction for $0.04 < z < 0.25$
  - $\Rightarrow$ enhancement for $z > 0.25$
- Similar modification seen by CMS (see arXiv:1406.0932 [nucl-ex])

Track multiplicity in jets

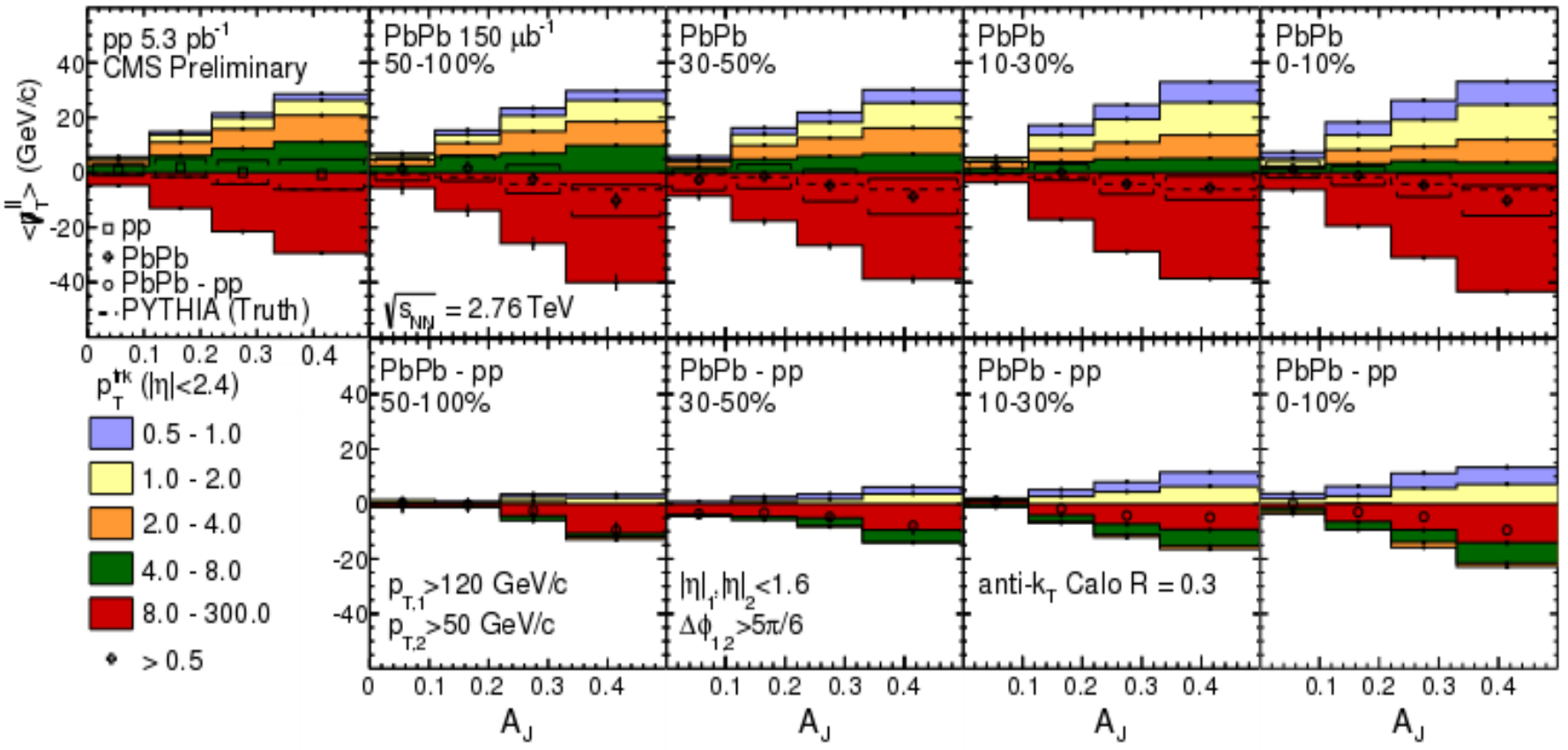


Compared to pp as a function of dijet asymmetry: $A_J = (p_{T1} - p_{T2}) / (p_{T1} + p_{T2})$

- Multiplicity increases as a function of A_J
- The increase is larger in PbPb and increases with centrality

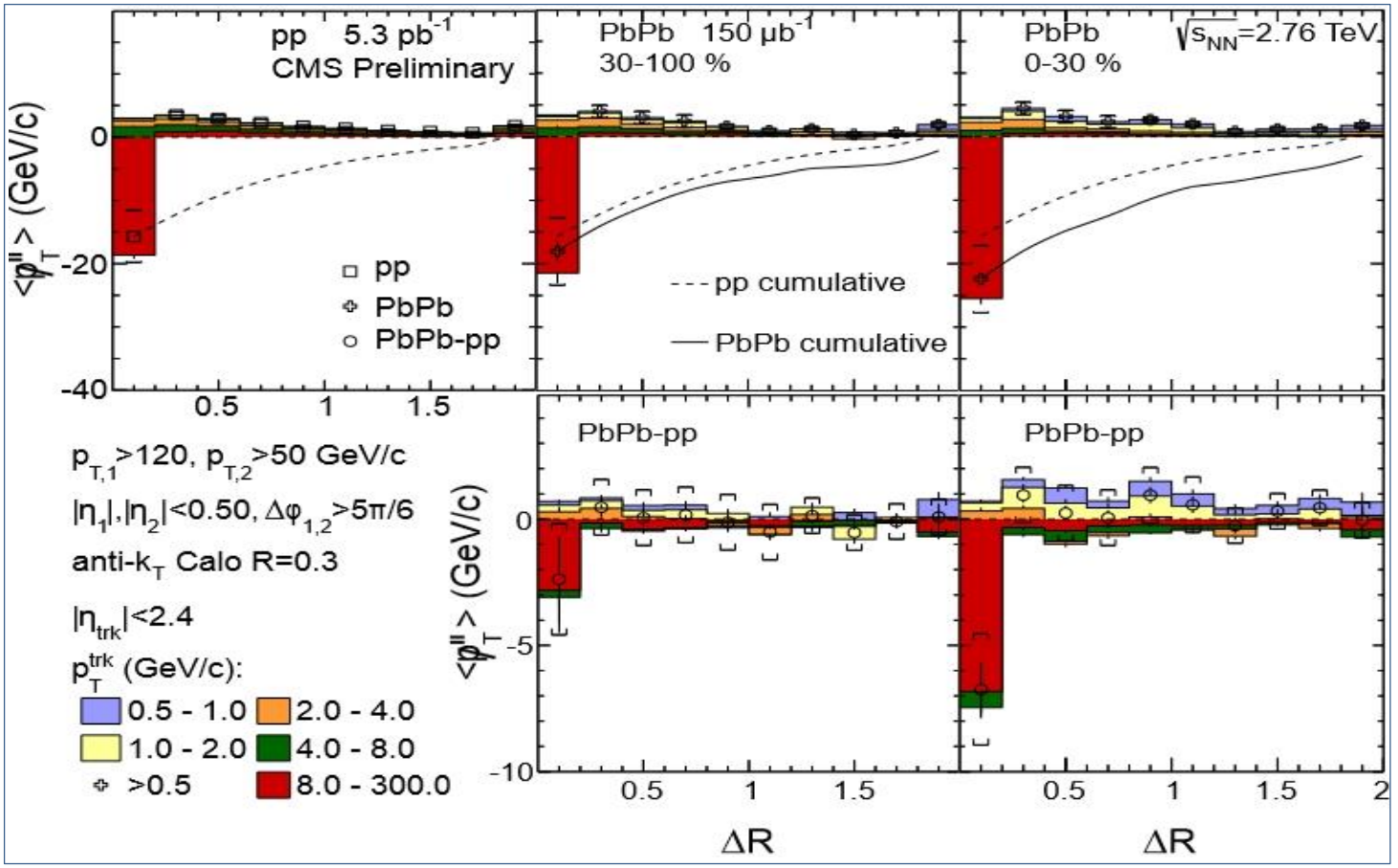
  $\Rightarrow$ Large A_J, 0-10% centrality, 15 extra particles

Energy distribution in jets



- Contributions from high p_T particles increase with increasing asymmetry A_J
  - ⇒ in pp balanced mostly by 2-8 GeV/c particles
  - ⇒ In PbPb balanced mostly by particles with p_T < 2 GeV/c

Energy distribution in jets



- High p_T imbalance at small ΔR balanced by low p_T particles in sub-leading jet extending up to large ΔR (for jet shapes see also arXiv:1310.0878 [nucl-ex])
- Subtracting pp results shows a different p_T mix in PbPb collisions
  $\Rightarrow$ but a similar p_T-integrated ΔR distribution

Jets in p+Pb collisions

- Studies of dijet properties in p+Pb collisions are of great importance to establish a QCD baseline for hadronic interactions with cold nuclear matter.
  $\Rightarrow$ this is crucial for the interpretation of the PbPb results, which could include the effects of both cold nuclear matter and a hot partonic medium.
- The dijet production rates as a function of jet pseudorapidity have also been proposed as a tool to probe the nuclear modifications of the parton distribution functions (PDFs)

Results:

❑ ATLAS:
New: Centrality and rapidity dependence of jet production (ATLAS-CONF-2014-024)

❑ CMS:
New: Jet nuclear modification factor in pPb collisions (CMS-PAS-HIN-14-001)
New: Photon jet correlation in PbPb, pPb and pp collisions (CMS-PAS-HIN-13-006)
New: Nuclear modification factor R_{pA} of b jets in pPb collisions (CMS-PAS-HIN-14-007)
New: B meson production in pPb Collisions (CMS-HIN-14-004)

Inclusive jet R_{pPb}

- Jets measured over a wide kinematic range:
  $50 < p_T < 1000$ GeV
  $-2.1 < y^* < 2.8$, y^* (nn center-of-mass)

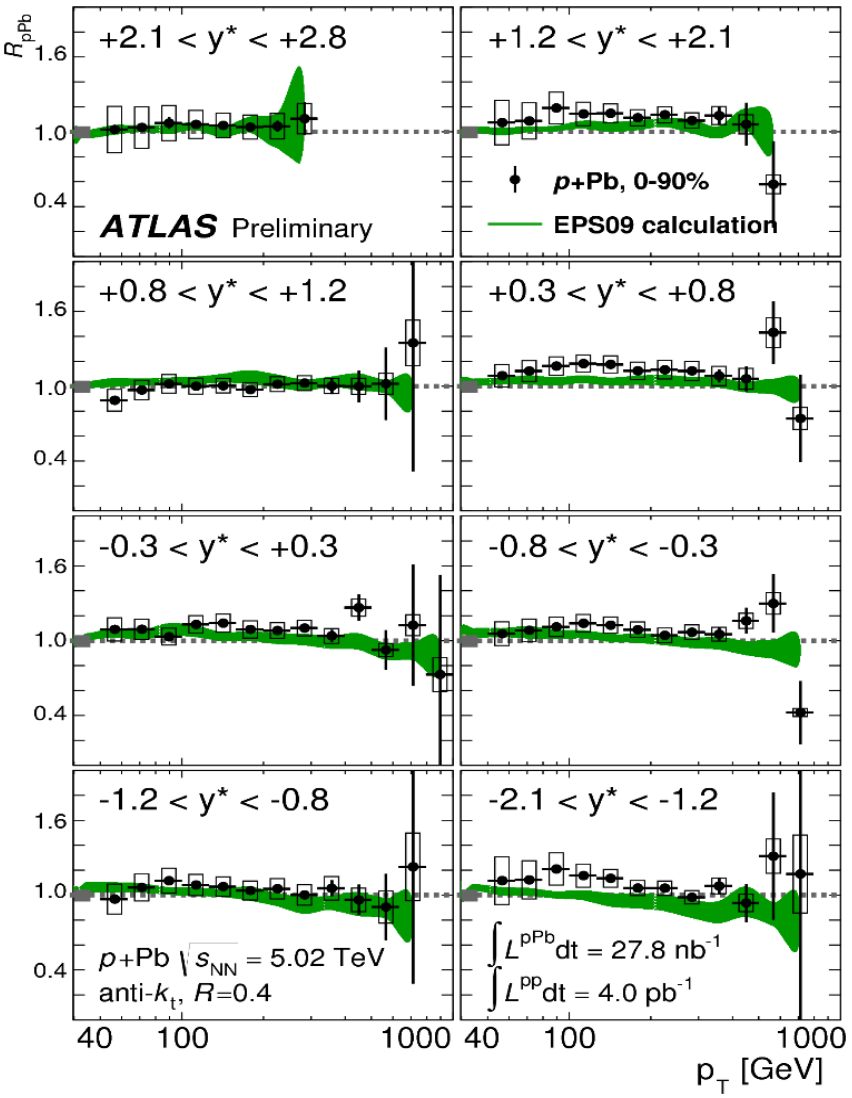
p@4TeV ⟹ ⟸ Pb@1.58TeV

$y^*<0$	$y^*>0$

- Inclusive R_{pPb} vs p_T
  - Using 2013 p-p data interpolated to 5.02 TeV reference

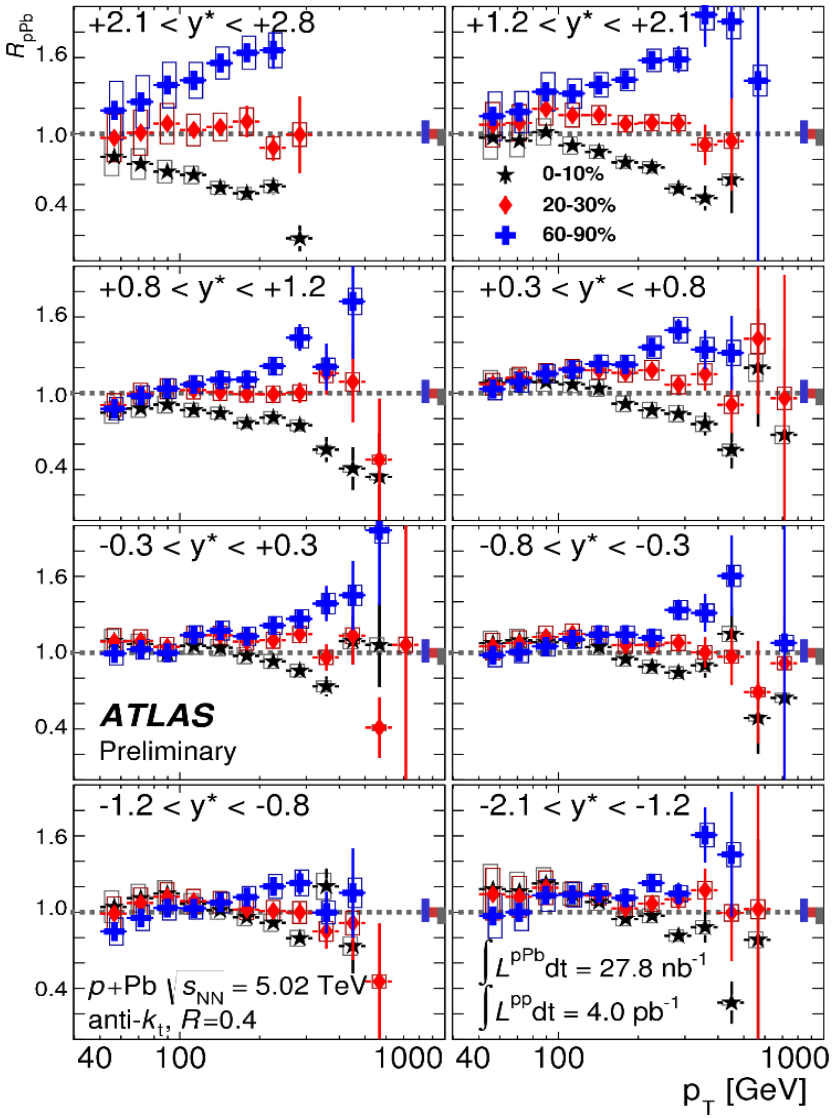
  ⇒ No suppression is seen at all rapidities; 5-10% enhancement over scaled pp

  ⇒ Results compatible with pQCD/EPS09 calculations

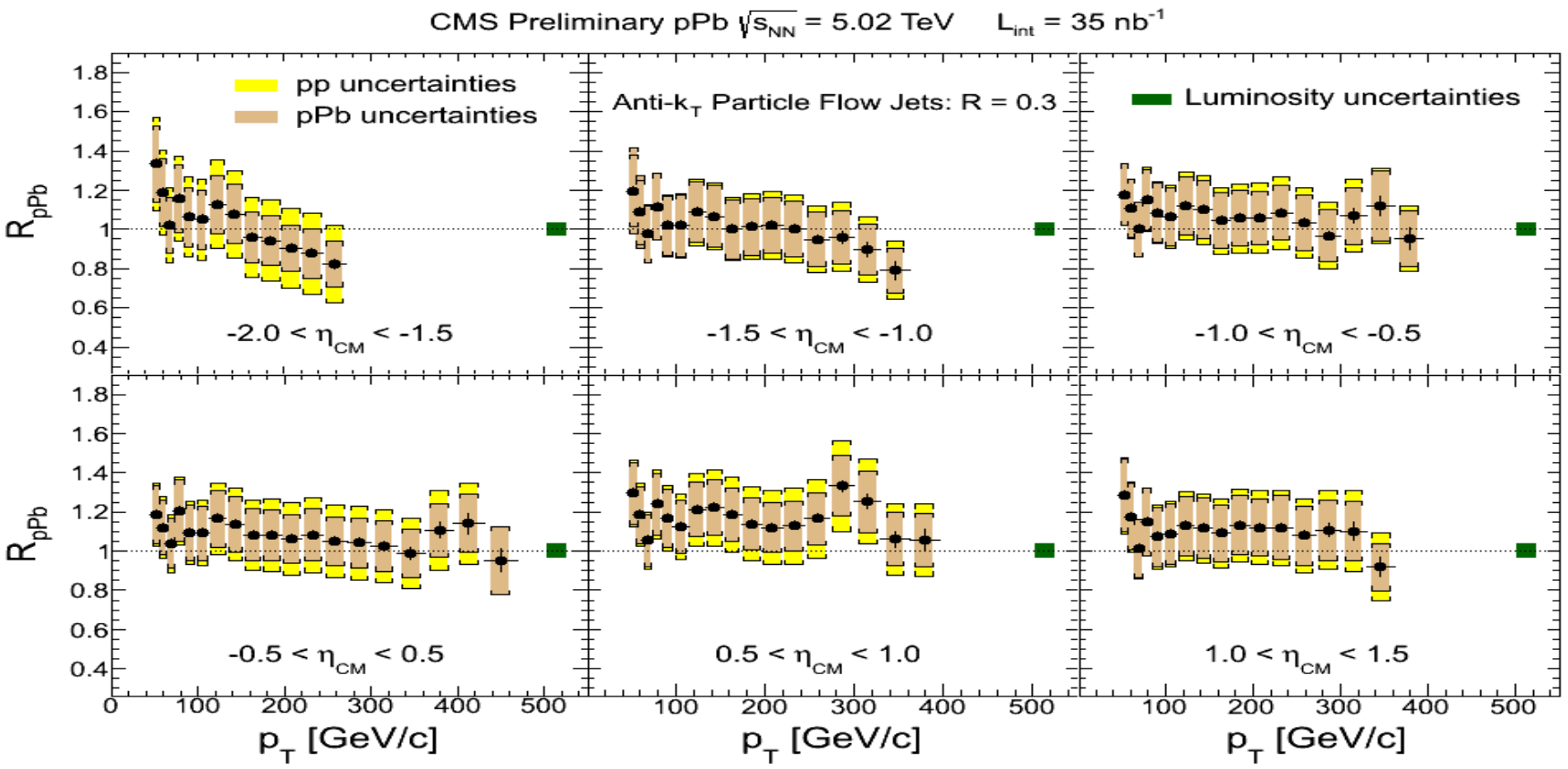


Centrality dependence of R_{pPb}

- R_{pPb} shown in three distinct centrality ranges: 0-10%, 20-30%, 60-90%
- Jets are enhanced in peripheral collisions and suppressed in central collisions at forward rapidities
- At low p_T and $y^* < 0$, $R_{pPb} \approx 1$

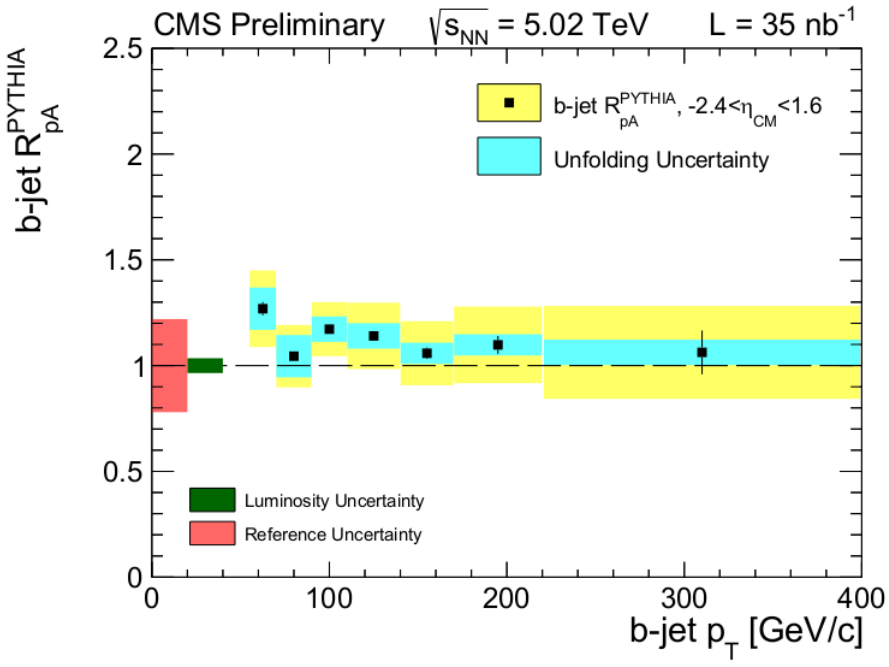


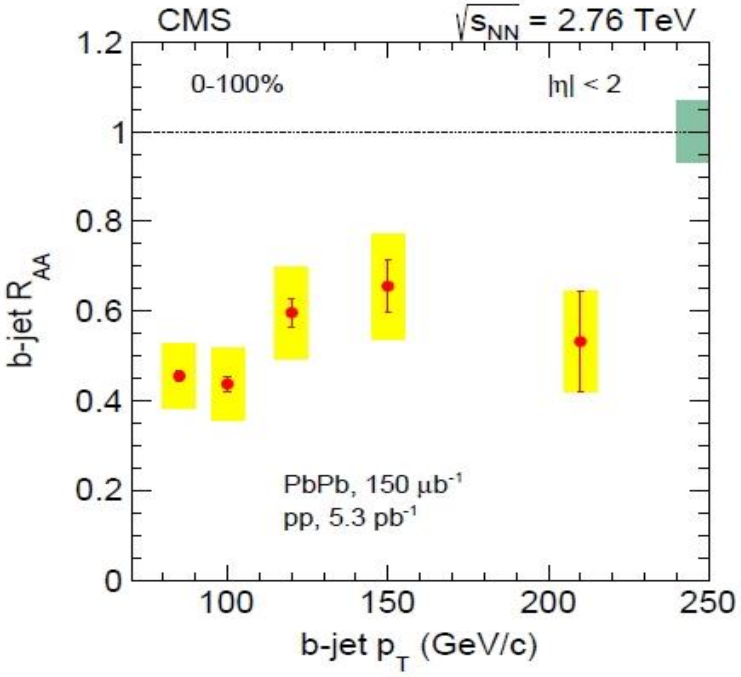
Inclusive jet R_{pPb}



- R_{pPb} measured vs interpolated to 5.02 TeV pp data reference
  - $\Rightarrow$ Relatively independent of p_T except in the most backward range, where a decrease with jet p_T is observed
  - $\Rightarrow$ Enhanced compared to scaled pp at small jet p_T in all η_{CM} ranges

R_{pPb} for b-jets



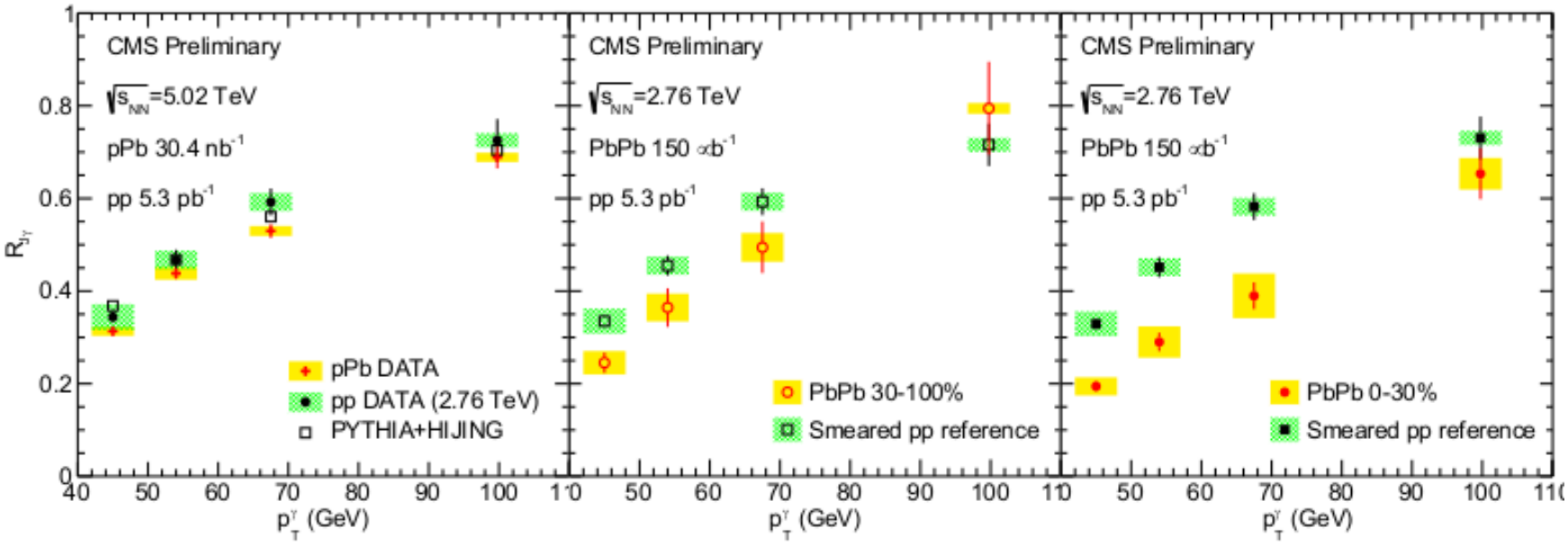


- R_{pPb}
  - ⇒ rate not suppressed
  - ⇒ small Cronin like enhancement at lower p_T

- R_{AA} in PbPb
  - ⇒ suppression observed
  - ⇒ no strong p_T dependence
  - ⇒ R_{AA} decreasing with centrality

arXiv:1312.4198 [nucl-ex]

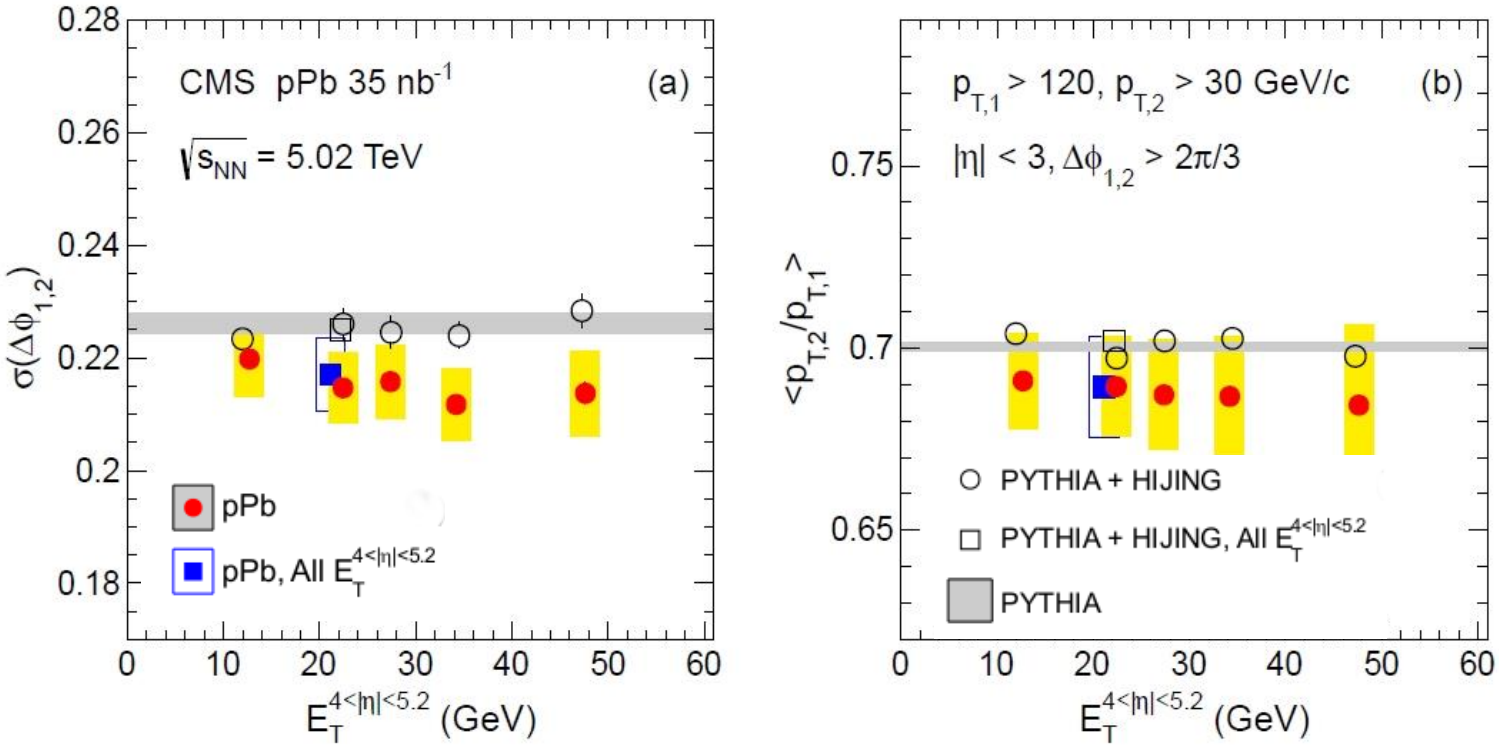
Photon – Jet fraction



- Dijets are a particularly useful tool for studying jet quenching
  – both jets should have similar momenta if not quenched
- $R_{J\gamma}$ = fraction of photons with a jet partner, $p_T^{jet} > 30$ GeV

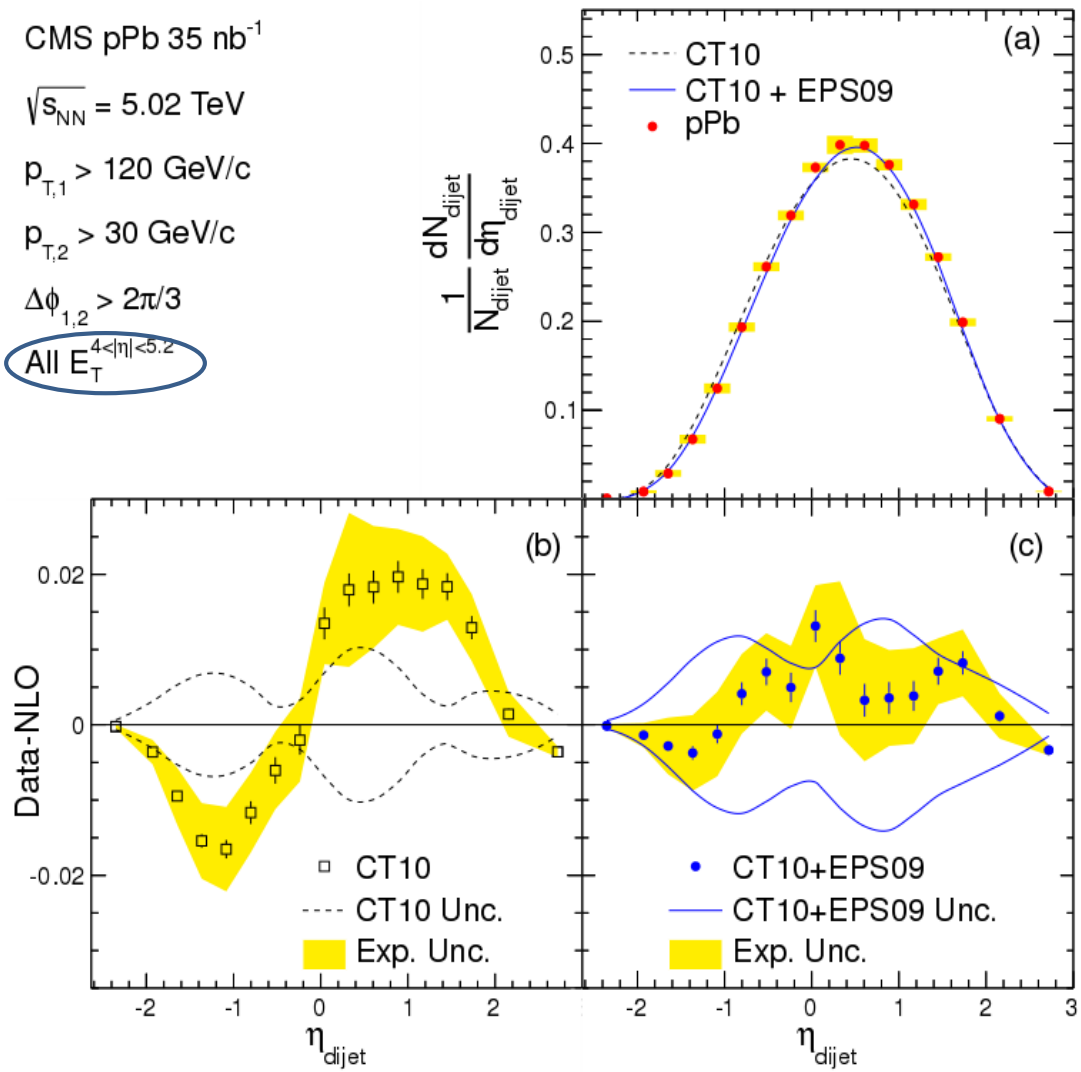
$\Rightarrow$ Fraction of photons with existing jet partner not changed in pPb vs pp while suppressed in PbPb collisions

Dijet momentum balance



- Modification of jet directions and momenta of the leading and second jet studied as a function of centrality (energy in forward directions)
  - ⇒ Jets not deflected in pPb (similar to PbPb)
  - ⇒ Jet energy is essentially unmodified in pPb
    while in PbPb second jets were pushed to lower p_T values
    arXiv:1205.0206 [nucl-ex]

Dijet rapidity shift



- $\eta_{dijet} = (\eta_1+\eta_2)/2$ dijet rapidity sensitive to nuclear PDF modifications in p+Pb hard scattering
- Data shifted vs Pythia CT10 model
- Consistent with predictions based on CT10+EPS09 nPDF

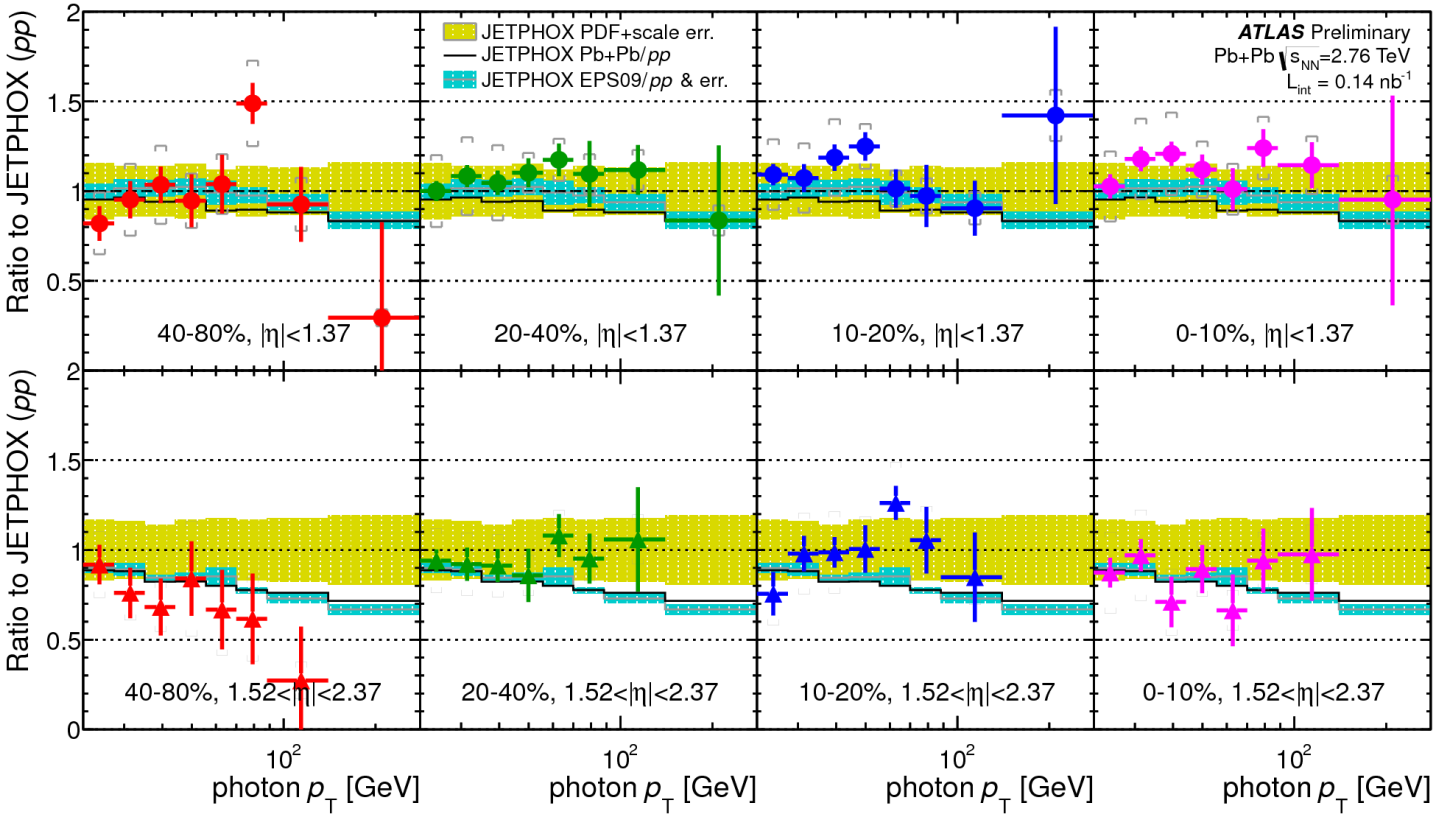
EW bosons in Pb+Pb collisions

- Electroweak (EW) bosons are colorless particles which are supposed not to interact with hot and dense medium created in heavy ion collisions. Measured together with jets they may be used as calibration tool in studies of jet quenching.
- In addition, the EW boson production mechanism (e.g. via qq-bar annihilation) makes them sensitive to parton distribution functions (PDF) which makes them suitable for studying nuclear modifications to PDFs (nPDFs).

Results:

- ATLAS:
  Old: Observed binary scaling of Z boson production in PbPb collisions
  New: Photon production in PbPb collisions (ATLAS-CONF-2014-026)
  New: W production in PbPb collisions (arXiv:1408.4674 [hep-ex])
- CMS:
  Old: Observed binary scaling of EW boson production in PbPb collisions
  Old: Photon yields also scale linearly with $\langle N_{coll} \rangle$, no interaction with QGP

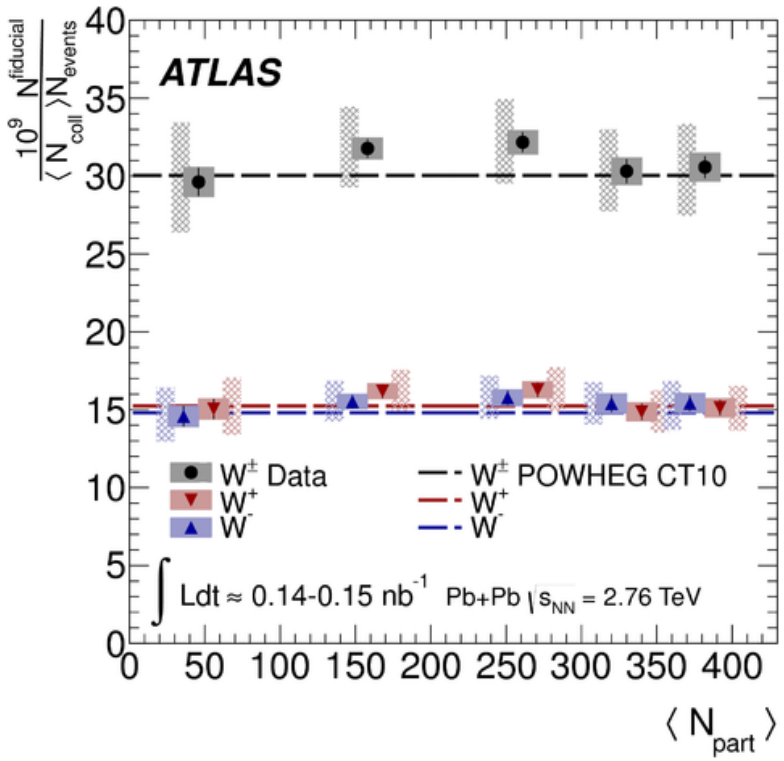
Photon yields

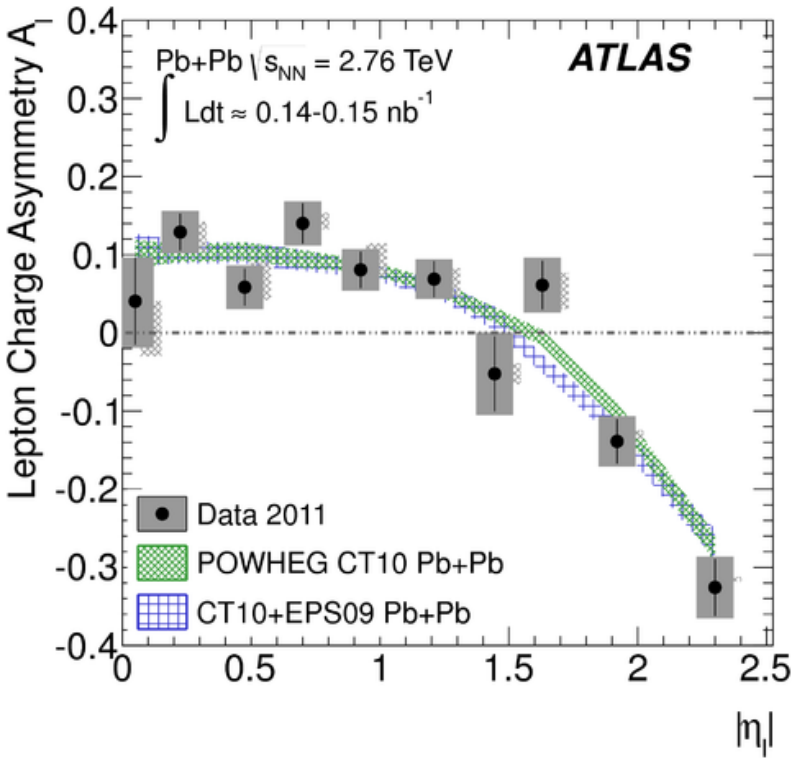


- R_{AA} ratios of isolated, direct photon yields/T_{AA}
  - to p-p (JETPHOX1.3) NLO pQCD calculation
  - for PbPb Data; also for JETPHOX Pb+Pb simulation: isospin only, EPS09
  - for 4 centrality bins and 2 (central, forward) pseudorapidity ranges

$\Rightarrow$ Ratios show scaling but data not yet able to discriminate between specific models

W± production yields





- W± yield/$\langle N_{coll}\rangle$ vs $\langle N_{par}\rangle$
  $\Rightarrow$ Yields increase proportional to N_{coll}
- W charge asymmetry (inclusive).
  $\Rightarrow$ Charge asymmetry determined by isospin
- Compatible with unmodified W production in PbPb collisions

EW bosons in p+Pb collisions

- Studies of nuclear modifications to PDFs in production of EW bosons are even more clean in proton-lead collisions where final state effects are expected to be small or none
- Used also to understand better particle production scaling properties and their Glauber geometry description

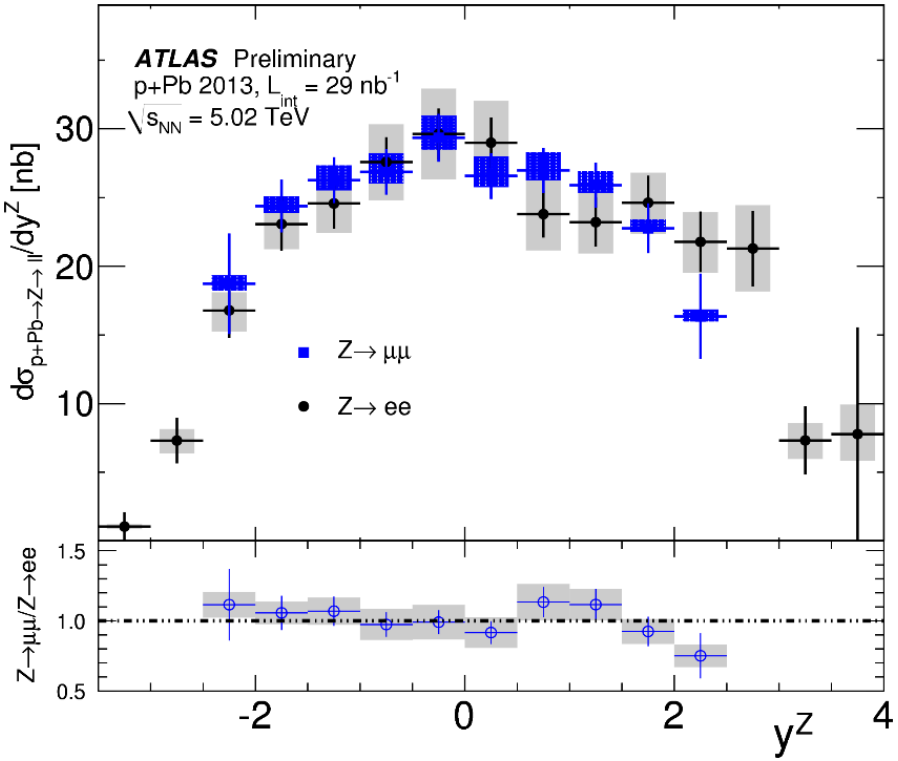
Results:

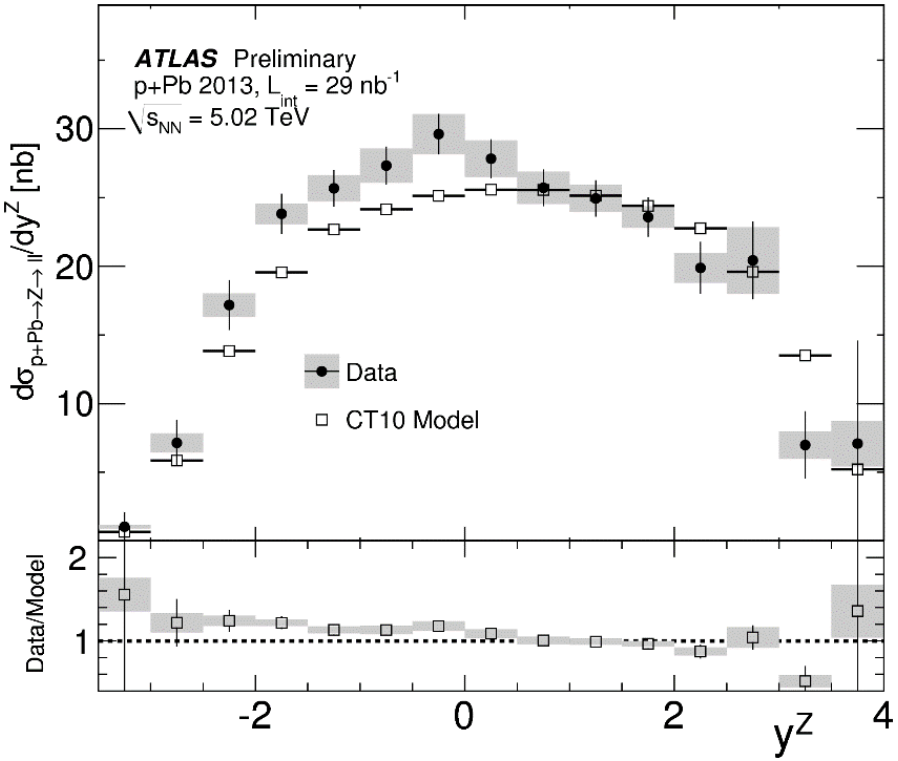
❑ ATLAS:
New: Z production in pPb collisions (ATLAS-CONF-2014-020)

❑ CMS:
New: W production in pPb collisions (CMS-PAS-HIN-13-007)
New: Z production in pPb collisions (CMS-PAS-HIN-14-003)

Z yields vs rapidity

- Z boson cross-sections measured via decays to electrons and muons
- Compared to Pythia CT10 model

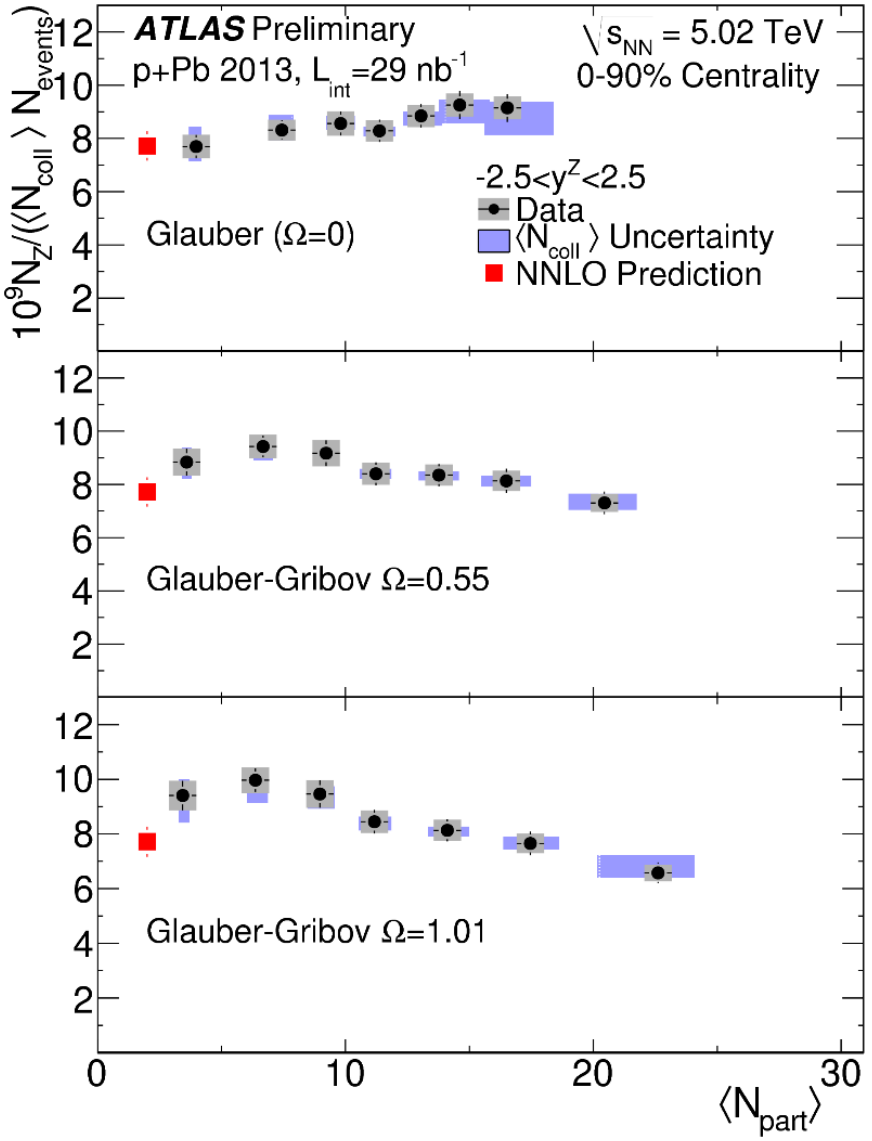




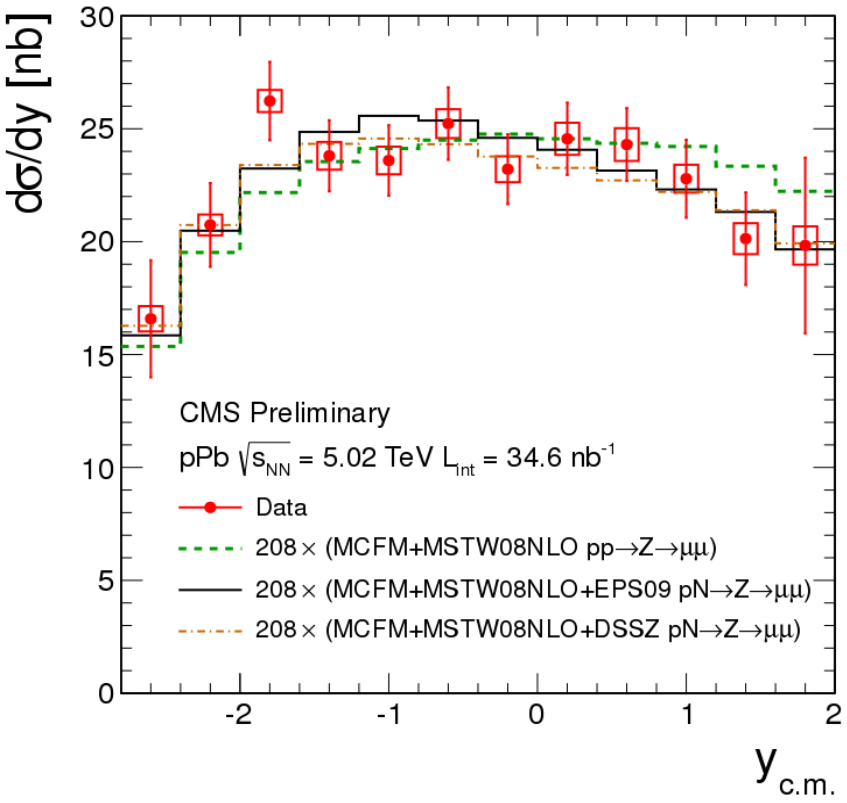
- Excellent agreement between (ee,μμ) channels
- y_Z asymmetry observed in the data, significant excess at backward (Pb going) rapidity

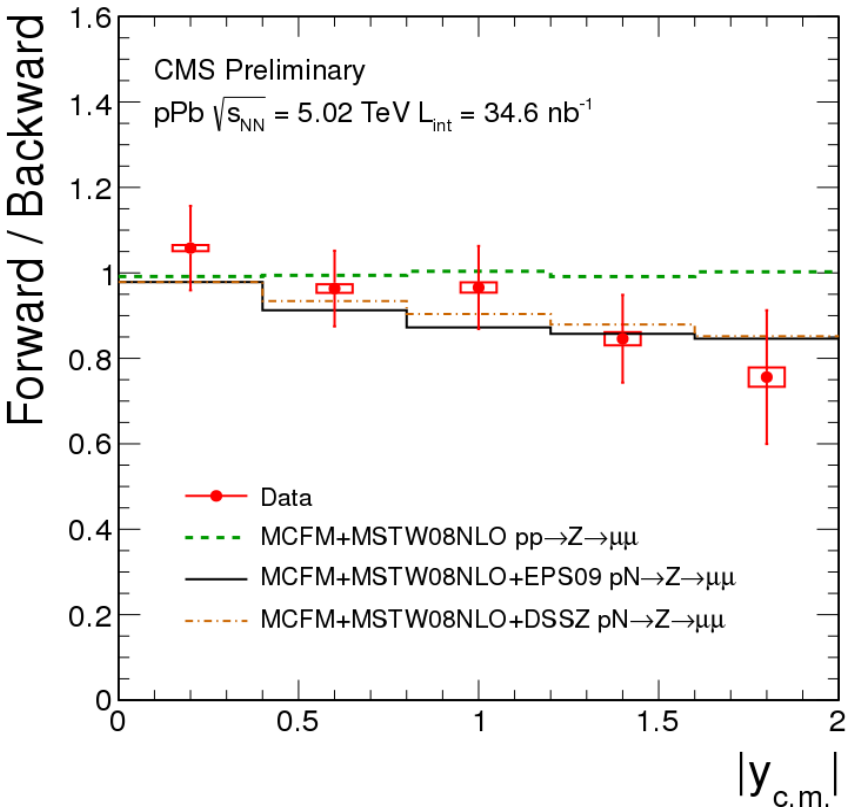
Z yields vs centrality

- Z yields/$\langle N_{coll} \rangle$ vs centrality (N_{part})
- Assume Z yields scale with pp, flat dependence expected
- Weakest centrality dependence found in Glauber-Gribov Ω = 0.55



Z yields vs rapidity

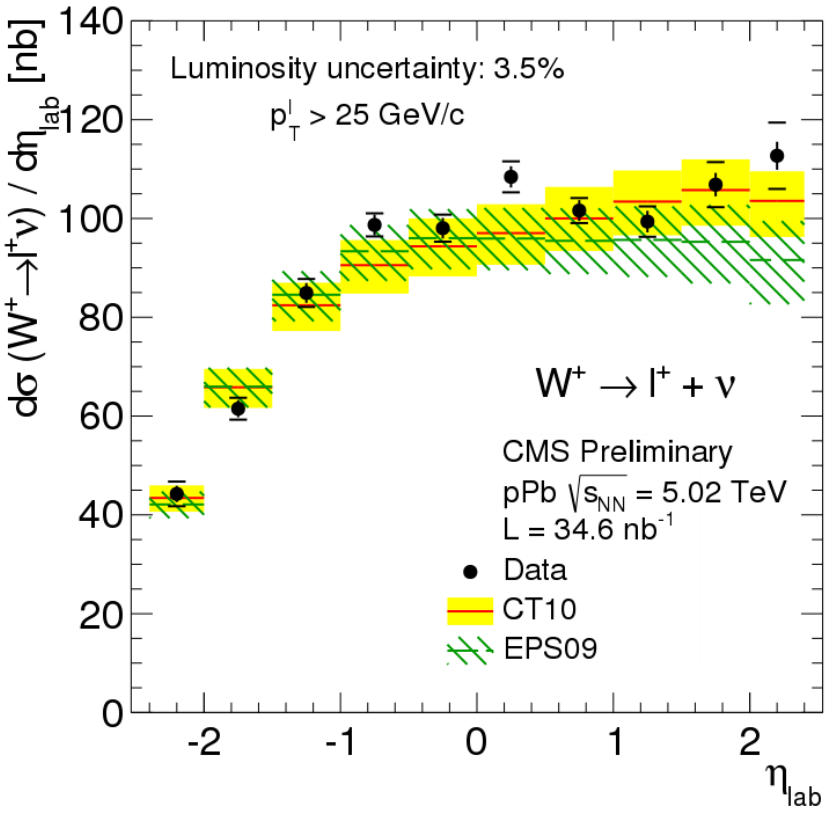


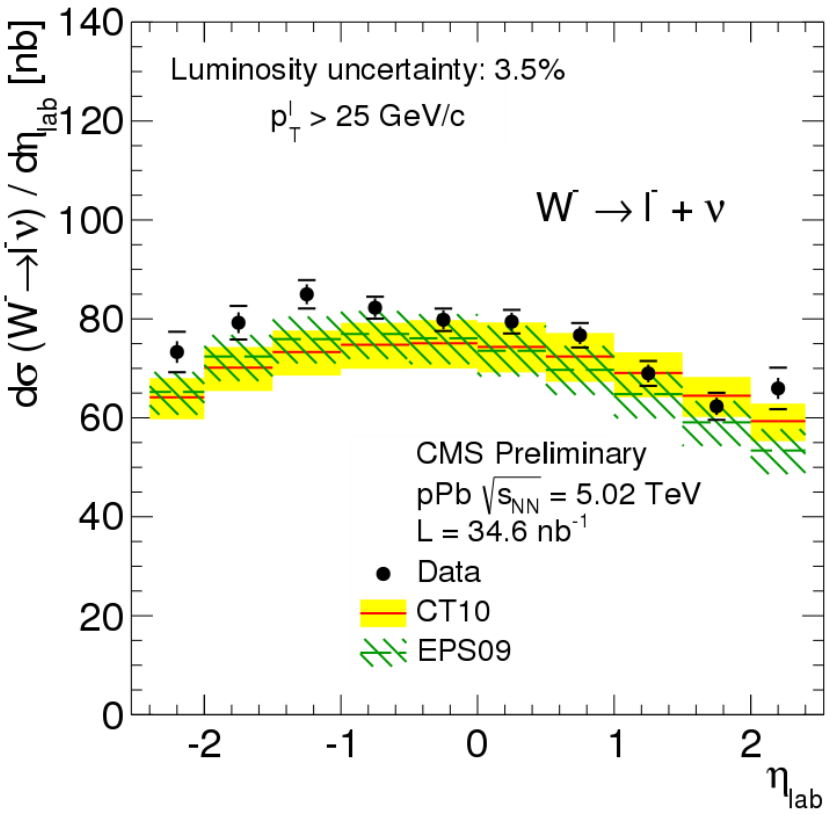


- Inclusive production cross section compared to NLO POWHEG scaled by A=208
  ⇒ Results consistent with pp linear scaling
- Forward / Backward ratio expected more sensitive to nuclear effects
  - Compared with NLO and EPS09, DSSZ model predictions

  ⇒ Hint of nuclear effects visible

W± yields

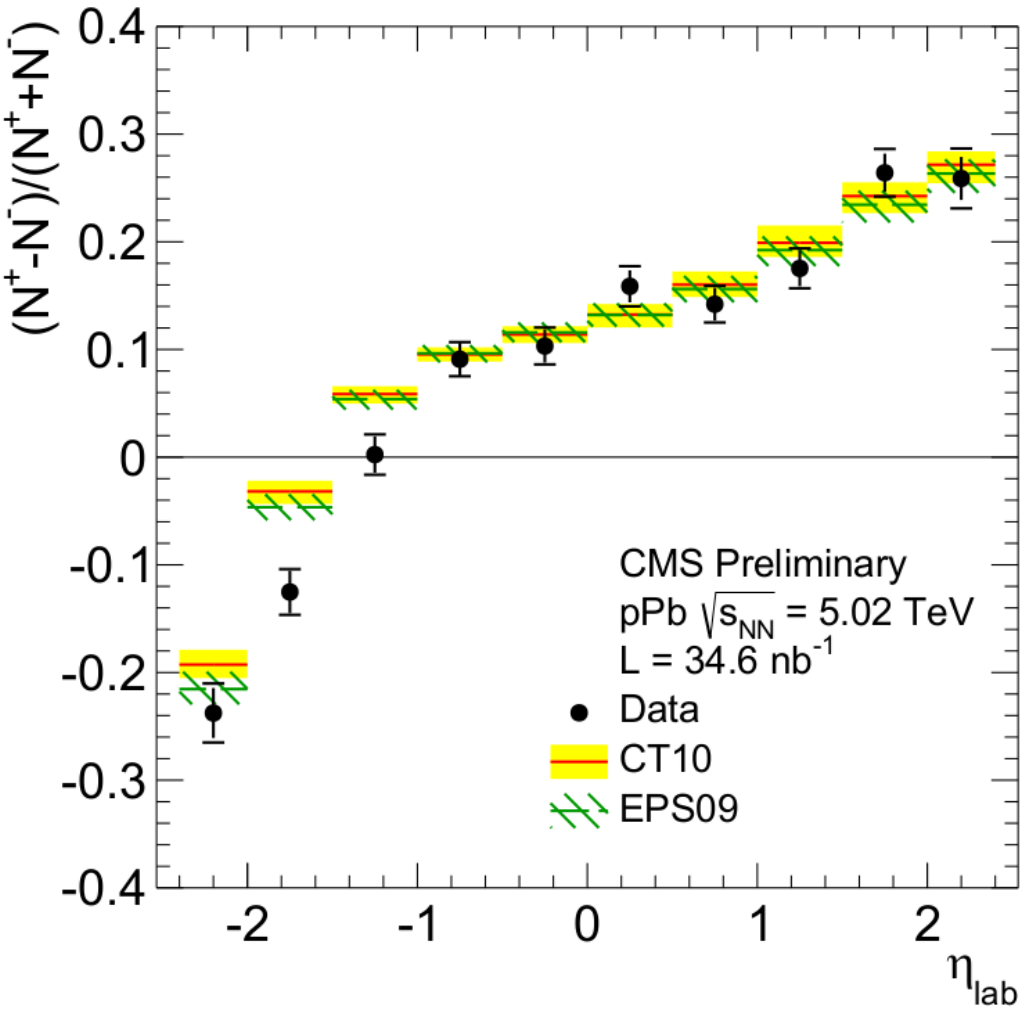




- Combined (ee,μμ) channels cross section compared to NLO theory predictions, with and without nuclear effects from EPS09
  - ⇒ Agreement is reasonable within uncertainties
  - ⇒ Small deviations from unmodified PDFs, especially for W^- at negative η

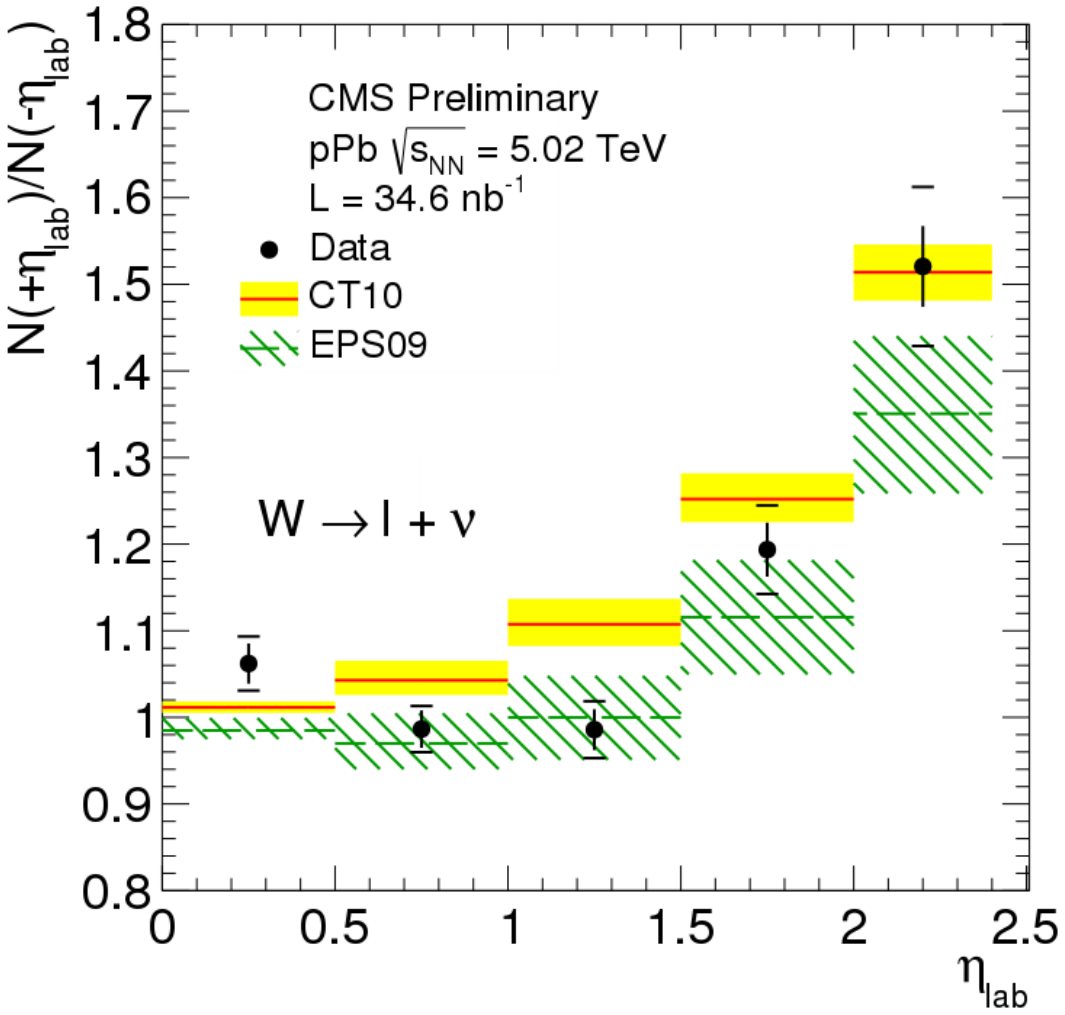
W^{+}/W^{-} charge asymmetry

- Luminosity (experimental) and scale (theory) uncertainties cancel in asymmetries.
- Charge asymmetry is a sensitive probe of the up to down quark PDF ratio
- Isospin symmetry of the quark content modification in nucleus vs proton ($R_u = R_d$) is assumed in nPDF fits
- Assuming $R_d < R_u$ would decrease the charge asymmetry in negative η and explain the difference



W forward/backward asymmetry

- Forward-backward asymmetry more sensitive to nuclear modifications
- Probes quark modifications in the shadowing over anti-shadowing/EMC effect regions
- χ2 probabilities of 10% with CT10 and 27% with including EPS09



Summary

- Jets are heavily quenched in PbPb
  - $\Rightarrow$ Suppression increases with centrality (down to R_{AA}~0.5), continues to p_T~400 GeV.
  - $\Rightarrow$ No strong flavor dependence (b-jets) of suppression at high p_T.
- Jet fragmentation in PbPb
  - $\Rightarrow$ ATLAS&CMS observe enhancements at low and high z, p_T, suppression at mid values.
  - $\Rightarrow$ CMS finds that energy goes to extra particles at large angles and lower p_T.
- Electroweak boson production in PbPb
  - $\Rightarrow$ ATLAS observes scaling with nuclear thickness, but not sensitive to confirm nuclear modifications to PDFs
- Jets are not strongly quenched in pPb
  - $\Rightarrow$ ATLAS observes non-scaling variation of yields with centrality in forward rapidities.
  - $\Rightarrow$ CMS inclusive measurement of dijet pseudorapidity shift prefers EPS09 nPDF.
- Electroweak boson production in pPb scaling with nuclear thickness
  - $\Rightarrow$ ATLAS: Z excess at backward rapidity (real effect)?
  - $\Rightarrow$ CMS: Jet, Z and W production, description with nuclear PDF preferred