Electroweak, jet and heavy flavor probes in proton-lead collisions at the LHC

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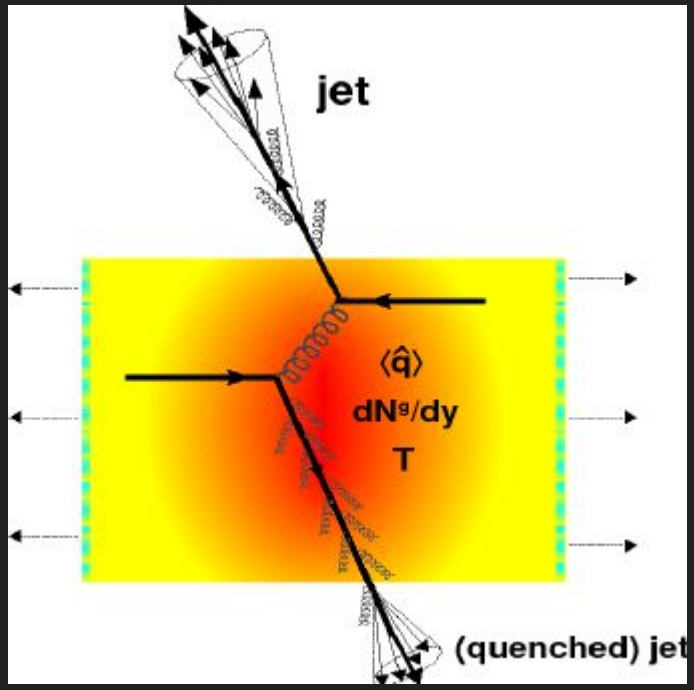
CIPANP-2018

Jets, HF and EW particles in HI collisions

- High-p_T jets produced in early stages of HI collisions
  - lose energy by radiative and collisional processes in the QGP
  - Energy loss leads to “jet quenching”
  - Measurement of jet quenching can determine transport-coefficient : $\hat{q}$



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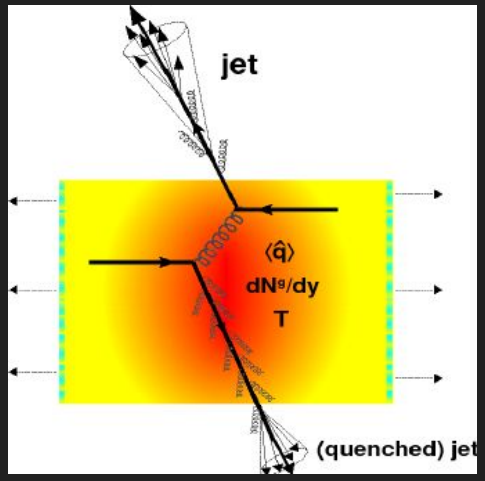
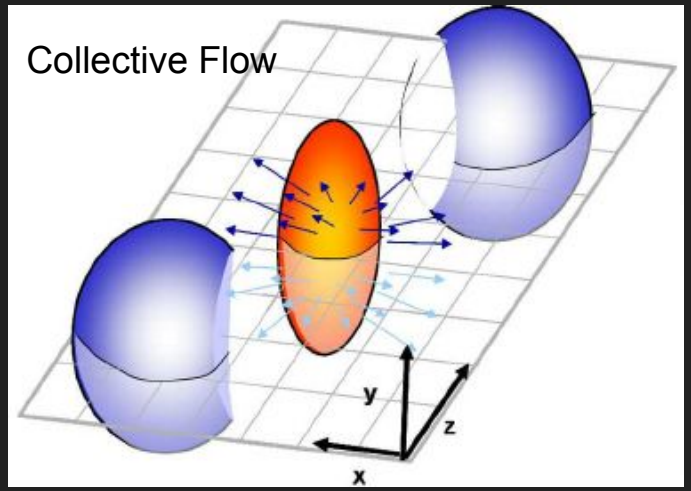
  - Low p_T heavy-quarks can partially thermalize
  - Constrain heavy-quark diffusion coefficient





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- EW particles (W,Z,γ)
  - not expected to interact with QGP
  - Measuring suppression (or lack of it) in HI collisions serves as standard candle
  - Also information on cold-nuclear effects (CNM), eg. modifications to PDFs

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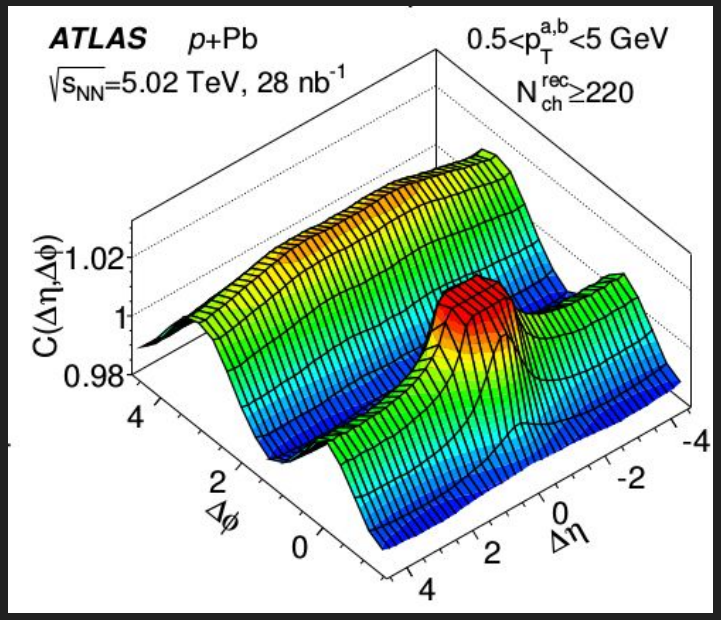
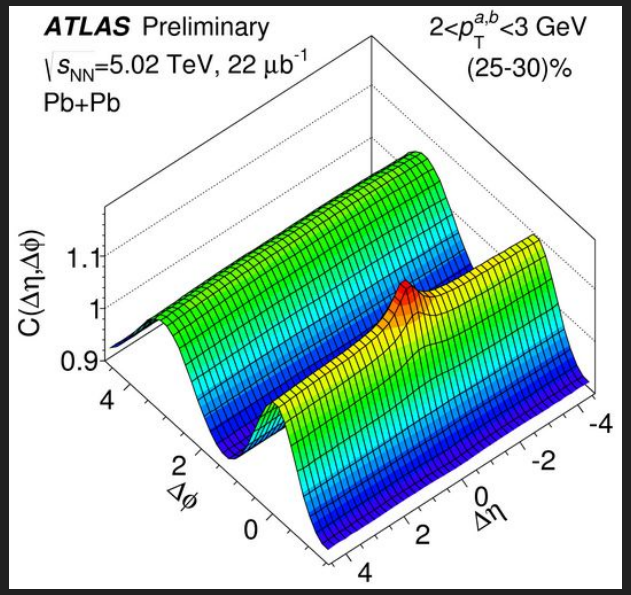
  - ATLAS: Phys. Rev. Lett. 110, 182302 (2013) (arXiv 1212.5198)
  - CMS : Phys. Lett. B 718 (2013) 795. (arXiv 1210.5482)



p+A



A+A

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- This required detailed measurements of hard- and EW-probes in p+Pb
  - Determine if the other signature of QGP -- Jet quenching -- can be observed in p+Pb collisions or not
  - Does HF “flow” in p+Pb?

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- Differential and integrated Cross-Sections (CS) for W/Z/γ/Jets.

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  - modification relative to expectation from incoherent superposition of nucleon-nucleon collisions

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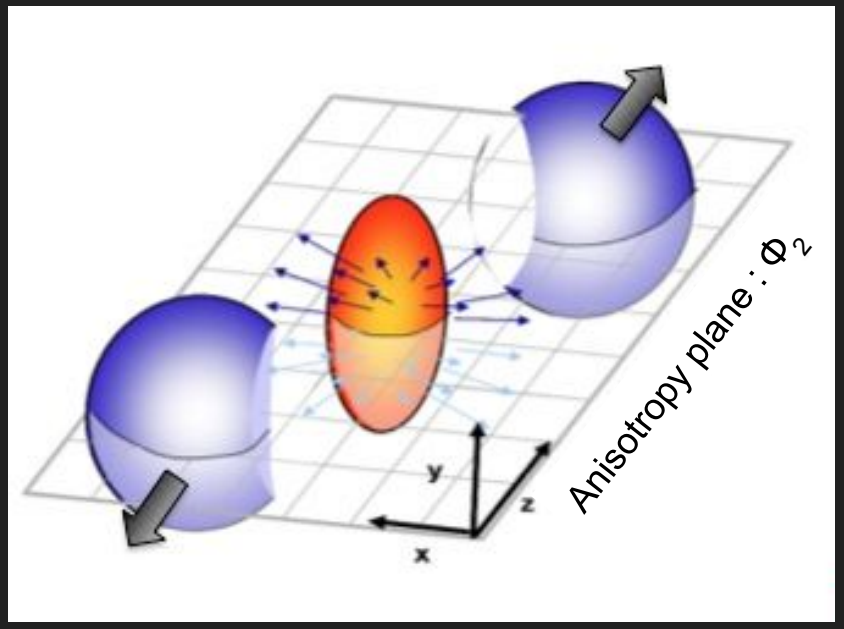
- R_{CP} : (poor-man's R_{pA})
  - Compare yields in central (high-multiplicity) and peripheral (low multiplicity) events, scaled by corresponding T_{Pb}

$$R_{\mathrm{CP}}(p_{\mathrm{T}}, \eta) = \frac{\langle T_{\mathrm{Pb,P}} \rangle}{\langle T_{\mathrm{Pb,C}} \rangle} \frac{(1/N_{\mathrm{evt,C}})\mathrm{d}^2 N_{p\mathrm{Pb,C}}/\mathrm{d}\eta \mathrm{d}p_{\mathrm{T}}}{(1/N_{\mathrm{evt,P}})\mathrm{d}^2 N_{p\mathrm{Pb,P}}/\mathrm{d}\eta \mathrm{d}p_{\mathrm{T}}}$$

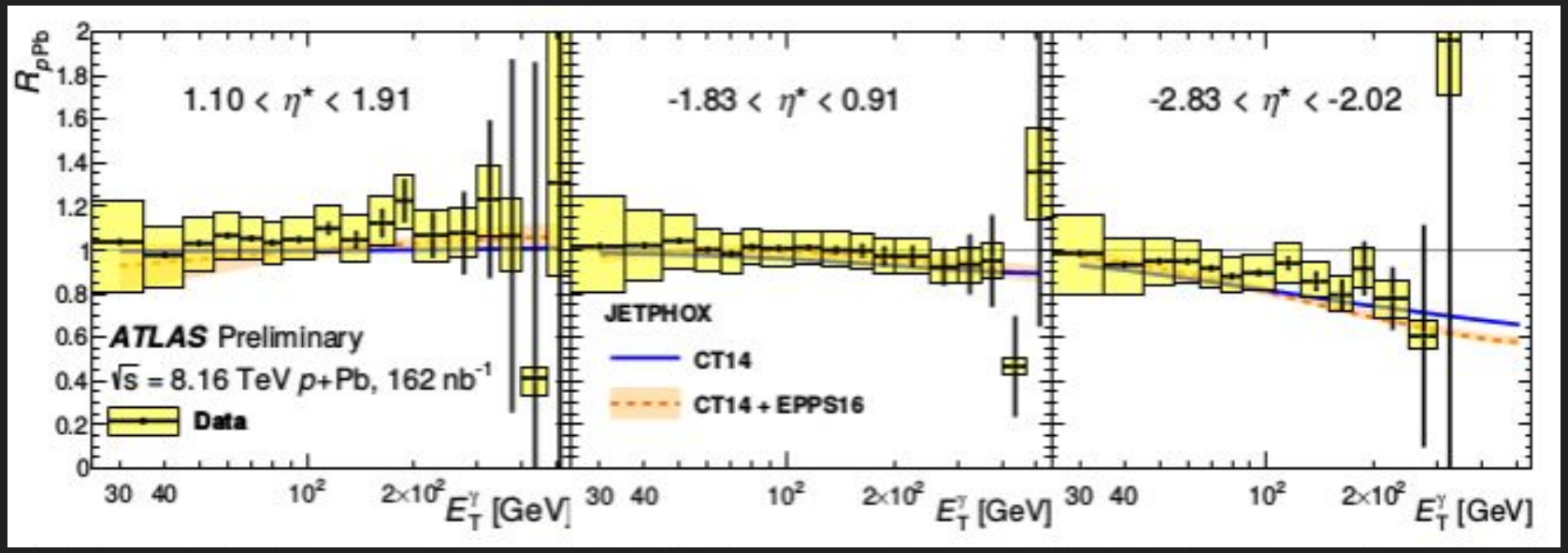
Observables

- Azimuthal anisotropy : quantifiled by Fourier coefficients v_n
- v_2 is typically the leading anisotropy

$$\frac{dN}{d\phi} = \left\langle \frac{dN}{d\phi} \right\rangle \left(1 + \sum_{n \geq 1} 2 v_n \cos\left(n\left[\phi - \Phi_n\right]\right) \right)$$



R_{pPb} for isolated prompt photons.



ATLAS-CONF-2017-072

R_{pPb}~1 at nearly everywhere

R_{pPb} <1 at higher E_T and backward-η* : Reflects difference between up and down quark composition of the Pb w.r.t. the proton.

Effect seen in JETPHOX theory calculations.

Consistent with free nucleon PDFs and nuclear PDFs

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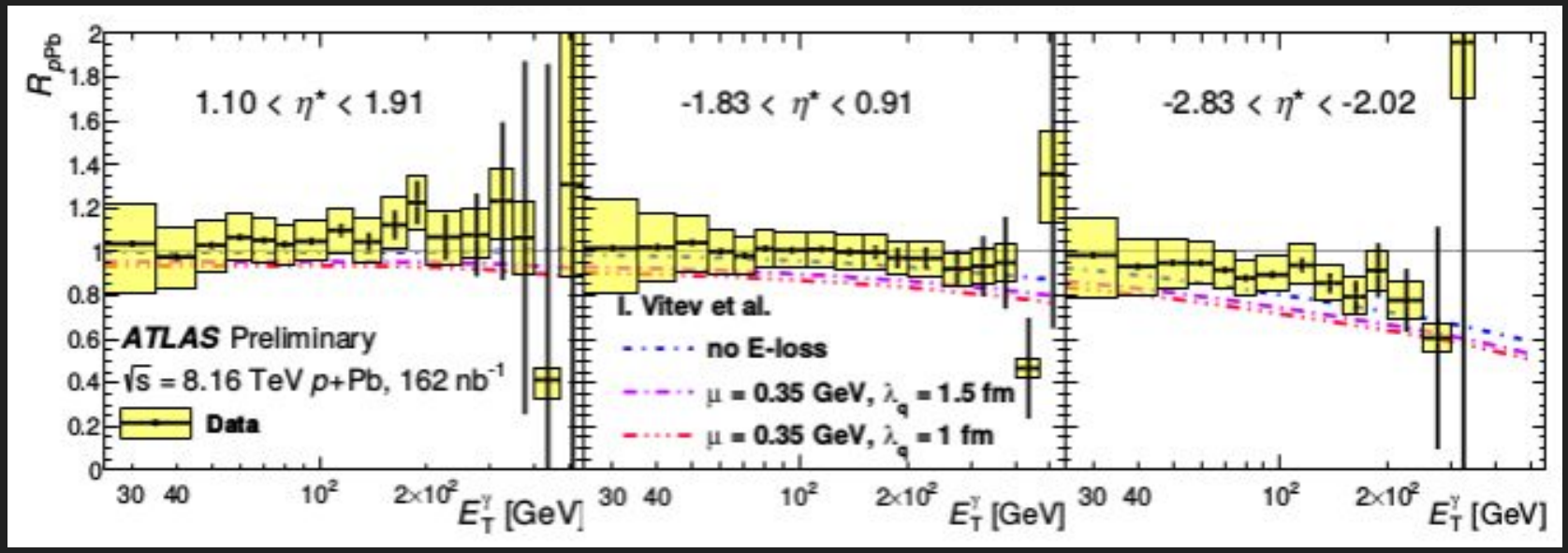

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Data disfavours suppression due to initial state Energy-loss effects

Z production in p+Pb

- In Pb+Pb collisions Z-production
  - Scales with N_{coll} (like gamma,W)
  - p_T, η distribution Reproduced by PYTHIA*T_{AA}
  - Consistent with NLO-QCD calculation without including NPDF effects
  - Though nPDF effects cannot be ruled out.

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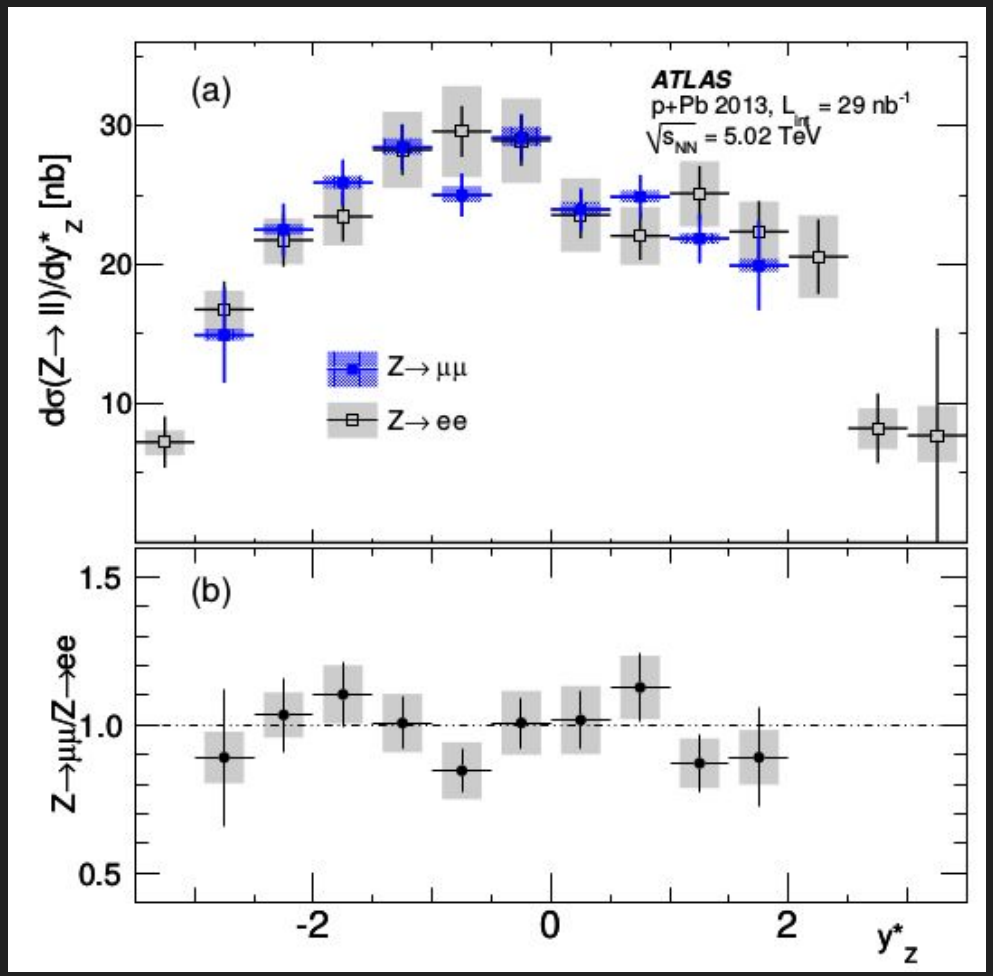
- ATLAS measures Z boson production via
  - Z->e+e- decays ; |y*|<3.5
  - Z->μ+μ- decays ; -3<y*<2
- Channels are then combined

- CS is very asymmetric about y*=0

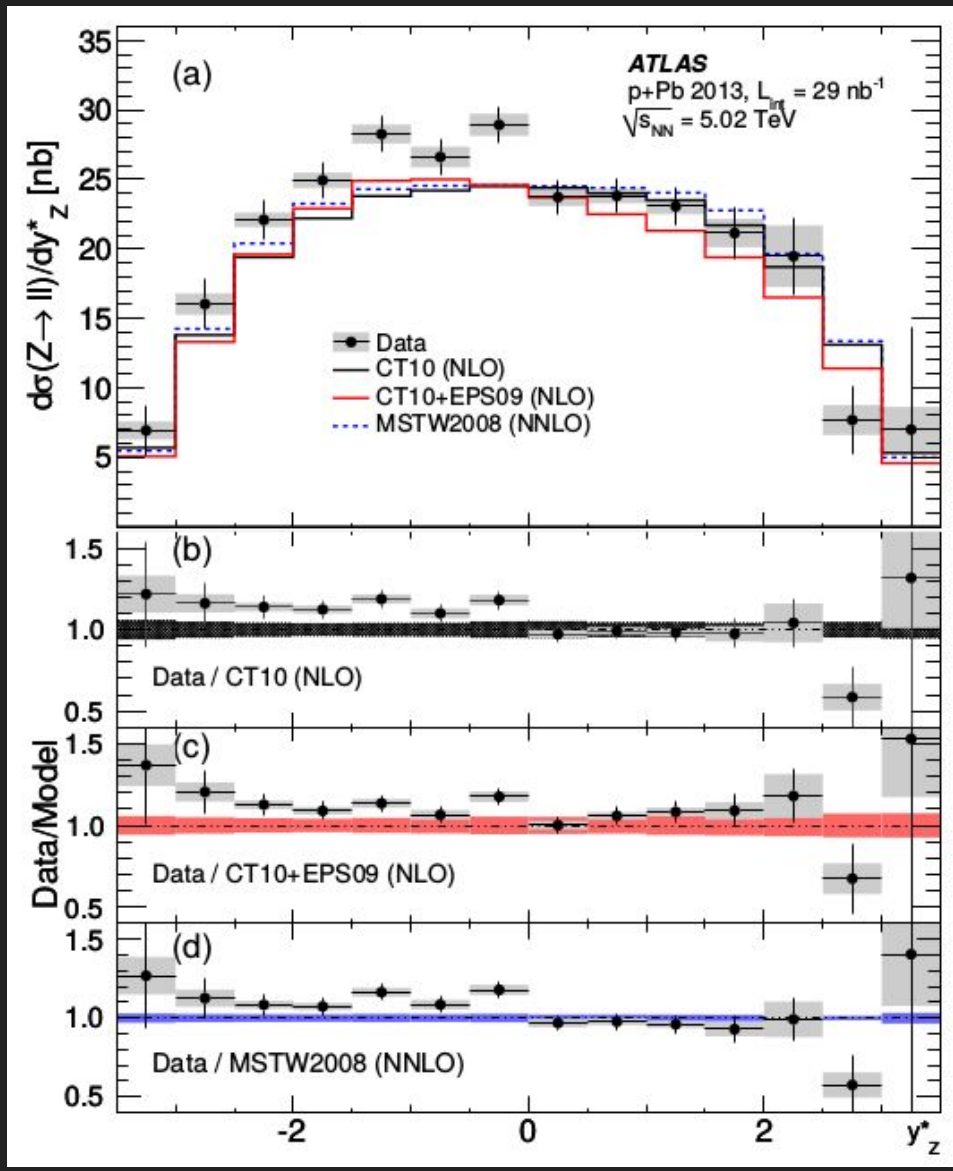


ATLAS: arXiv 1507:06232
CMS : arXiv:1512.06461

Z production

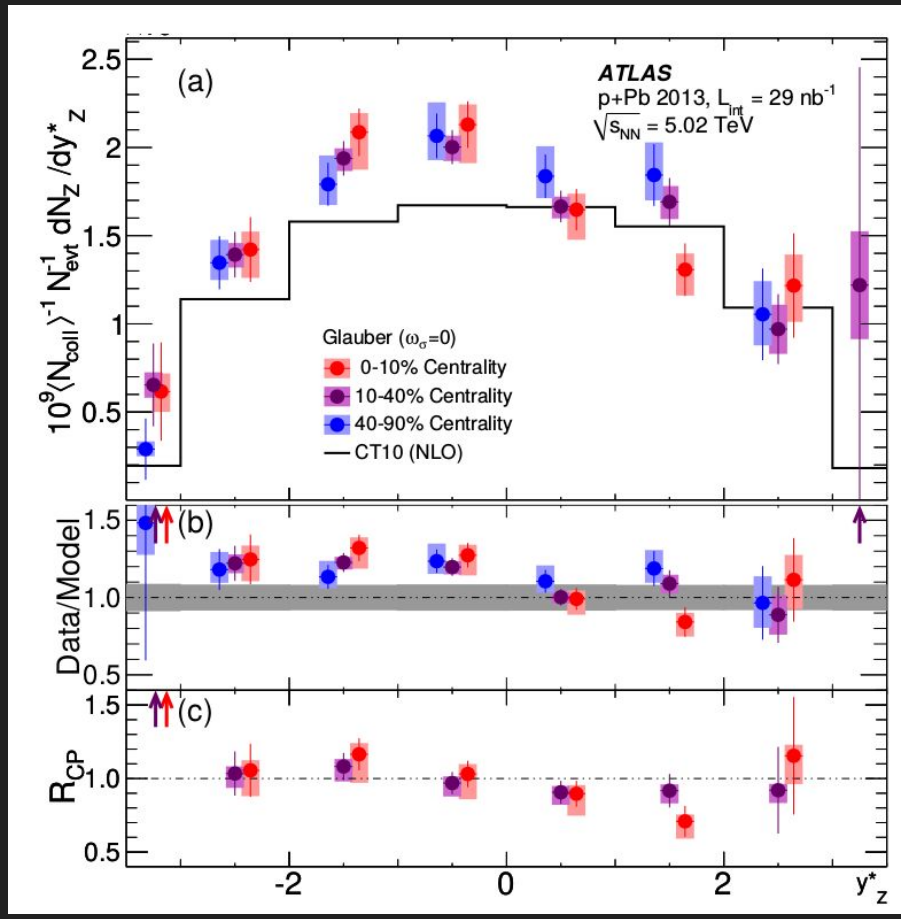
arXiv 1507:06232, 1512.06461

- CS compared to predictions composed of $82\sigma_{pp \to Z+X} + 126\sigma_{pn \to Z+X}$
- n-n CS calculated using different PDFs
  - MSTW2008 (NNLO)
  - CT10 (NLO)
  - CT10 +EPS09 (NLO) : includes nuclear modifications
- CS smaller in all cases compared to data
- If only considering shape, i.e. ignoring normalization, models give p-values of:
  - MTW2008 (NNLO) : 0.01
  - CT10 (NLO) : 0.07
  - CT10 +EPS09 (NLO) : 0.76
- Clear sign of nuclear effects.



Z production

- Compare Z yields in different centrality bins, scaled by number of binary n-n collisions
- After binary scaling, Yields in more central events show stronger FB asymmetry.
- Data and model difference (middle panel) larger in more central events
- R_{CP} shown in lower panel has slope of:
  - -0.11 +-0.04 in 0-10% centrality
  - -0.05 +-0.03 in 10-40% centrality



arXiv 1507:06232, 1512.06461
ATLAS-CONF-2016-107

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- Compare Z yields in different centrality bins, scaled by number of binary n-n collisions
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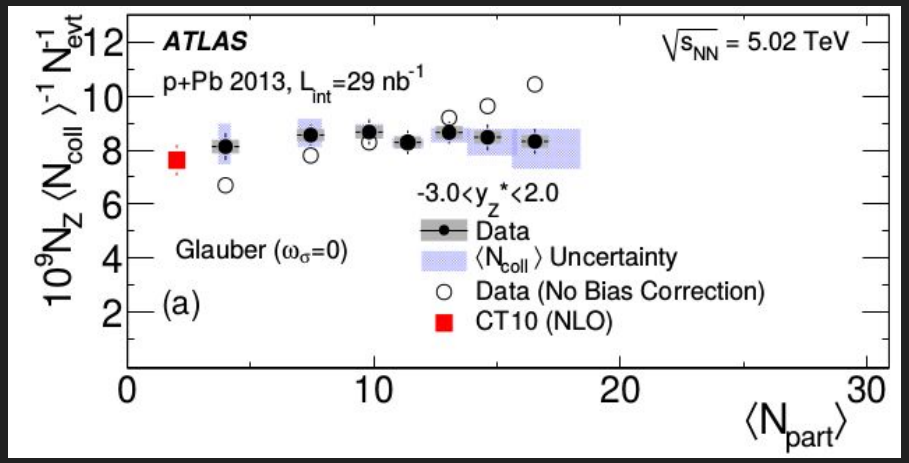
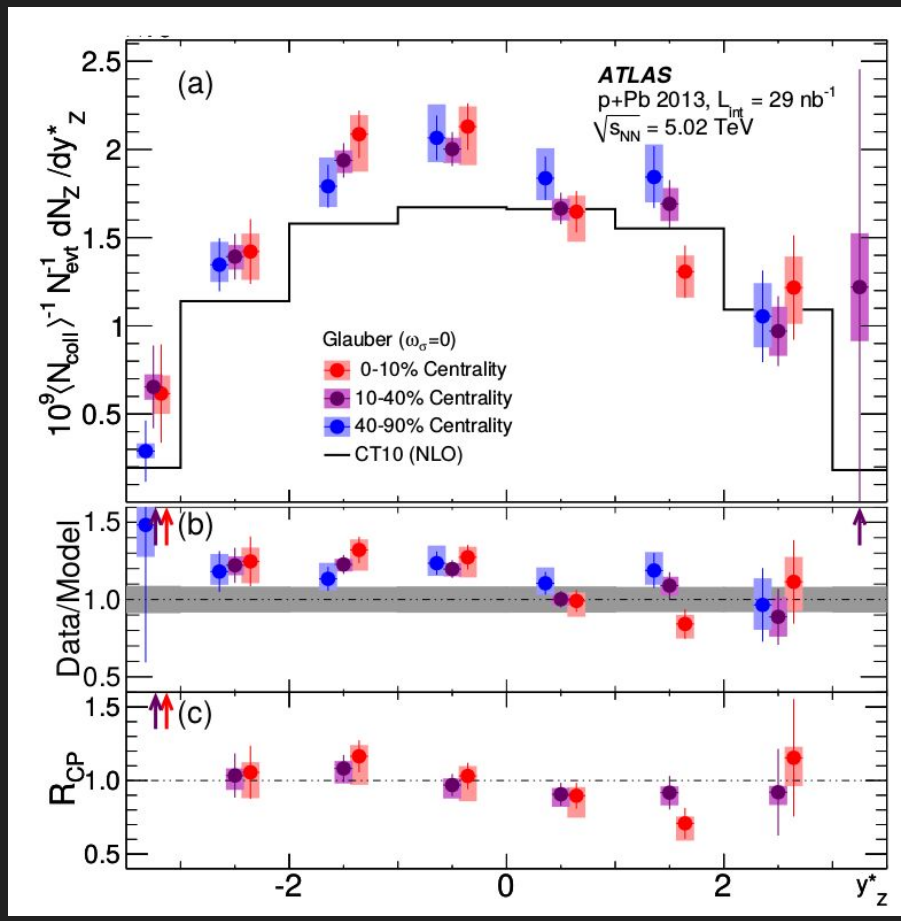
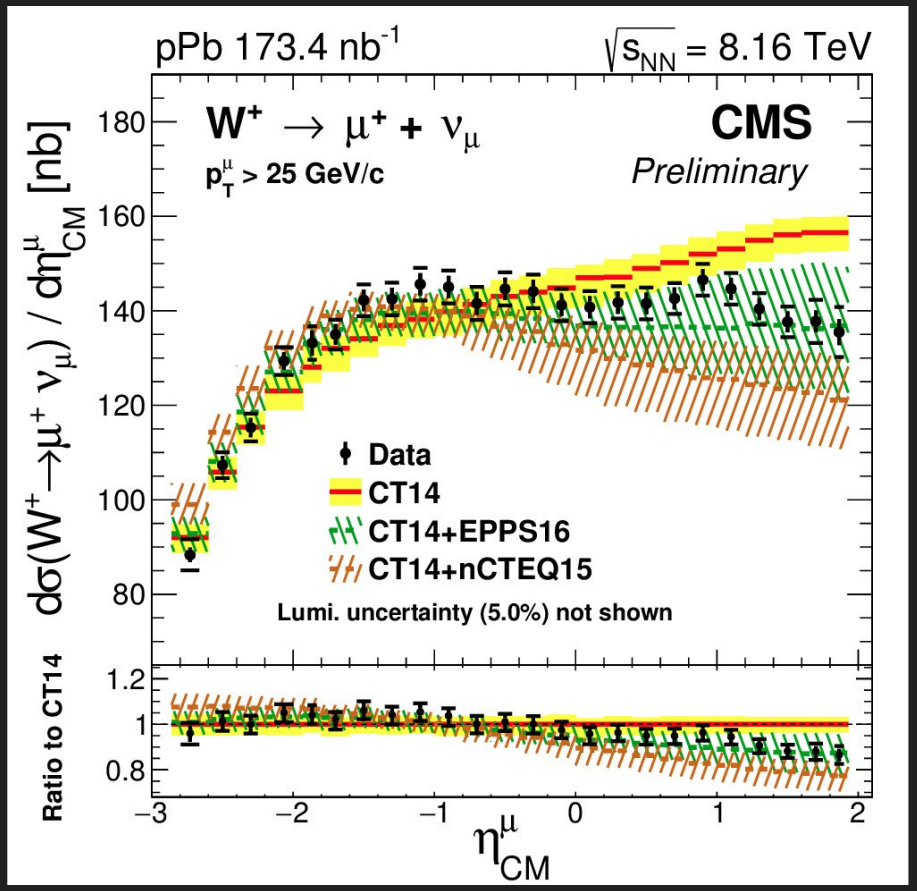
- R_{CP} shown in lower panel has slope of:
  - -0.11 +-0.04 in 0-10% centrality
  - -0.05 +-0.03 in 10-40% centrality
- Integrated over y*, yields scale with N_{coll}:
  - FB asymmetry key to observing nPDF effects

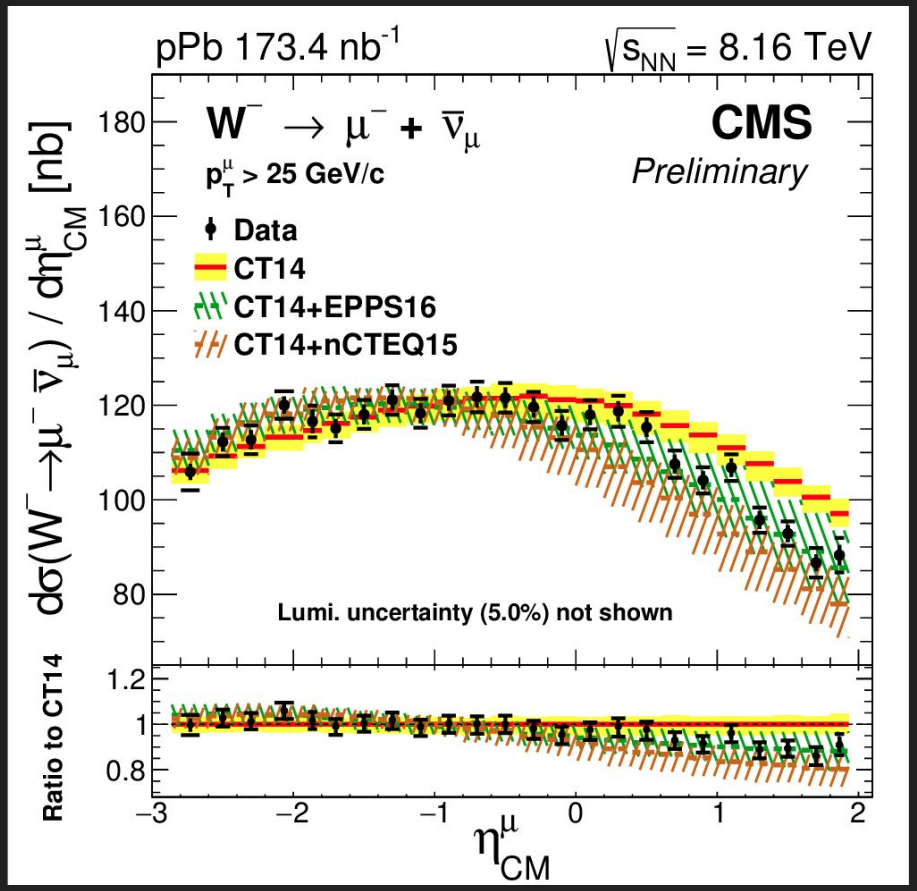




arXiv 1507:06232
ATLAS-CONF-2016-107

W production



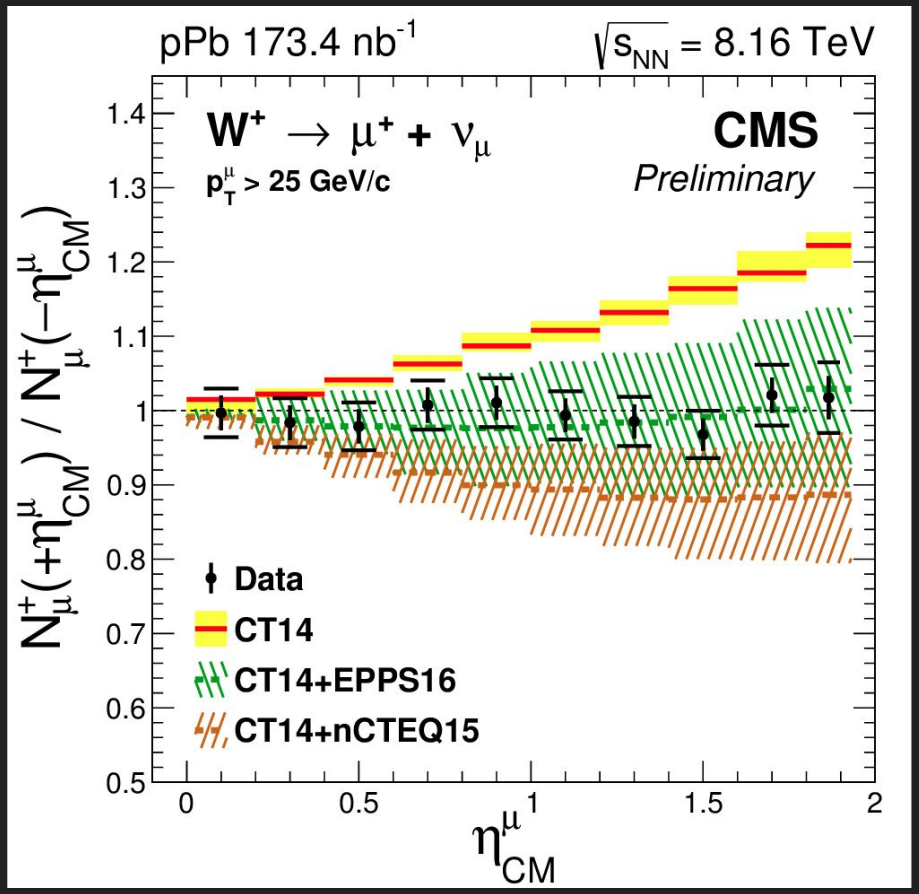


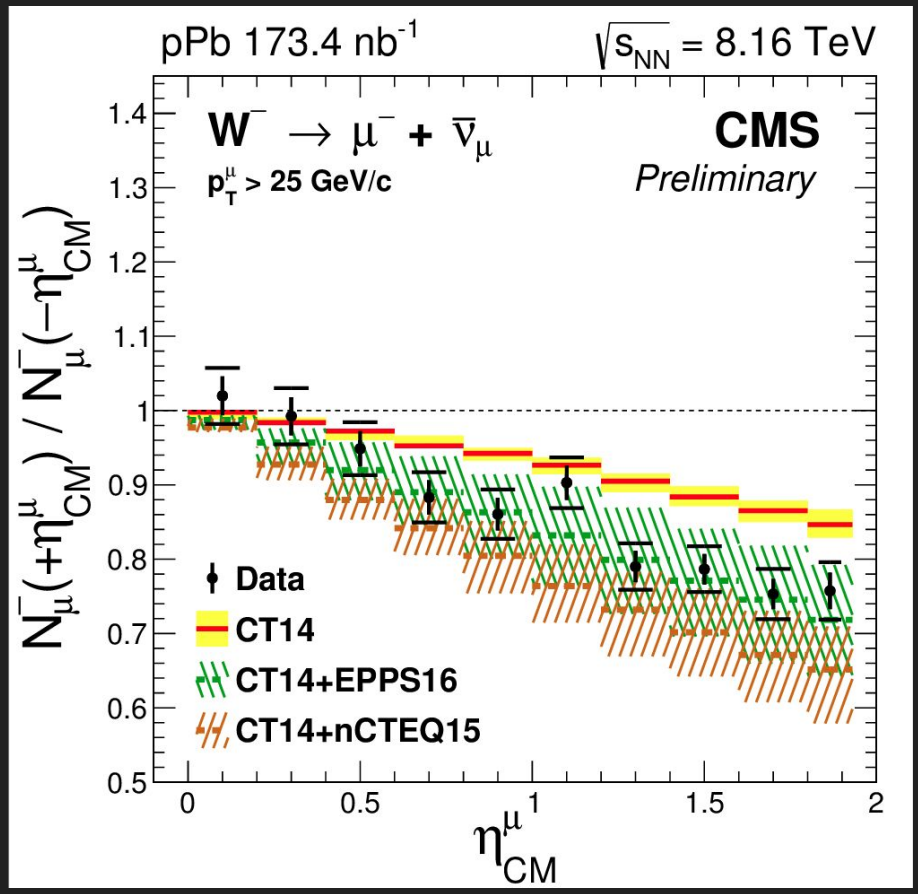
W→μν cross section as function of muon pseudorapidity

Compared to expectations from based model using free-nucleon and nuclear-modified PDFs

CMS-PAS-HIN-17-007
ATLAS-CONF-2015-56

W production





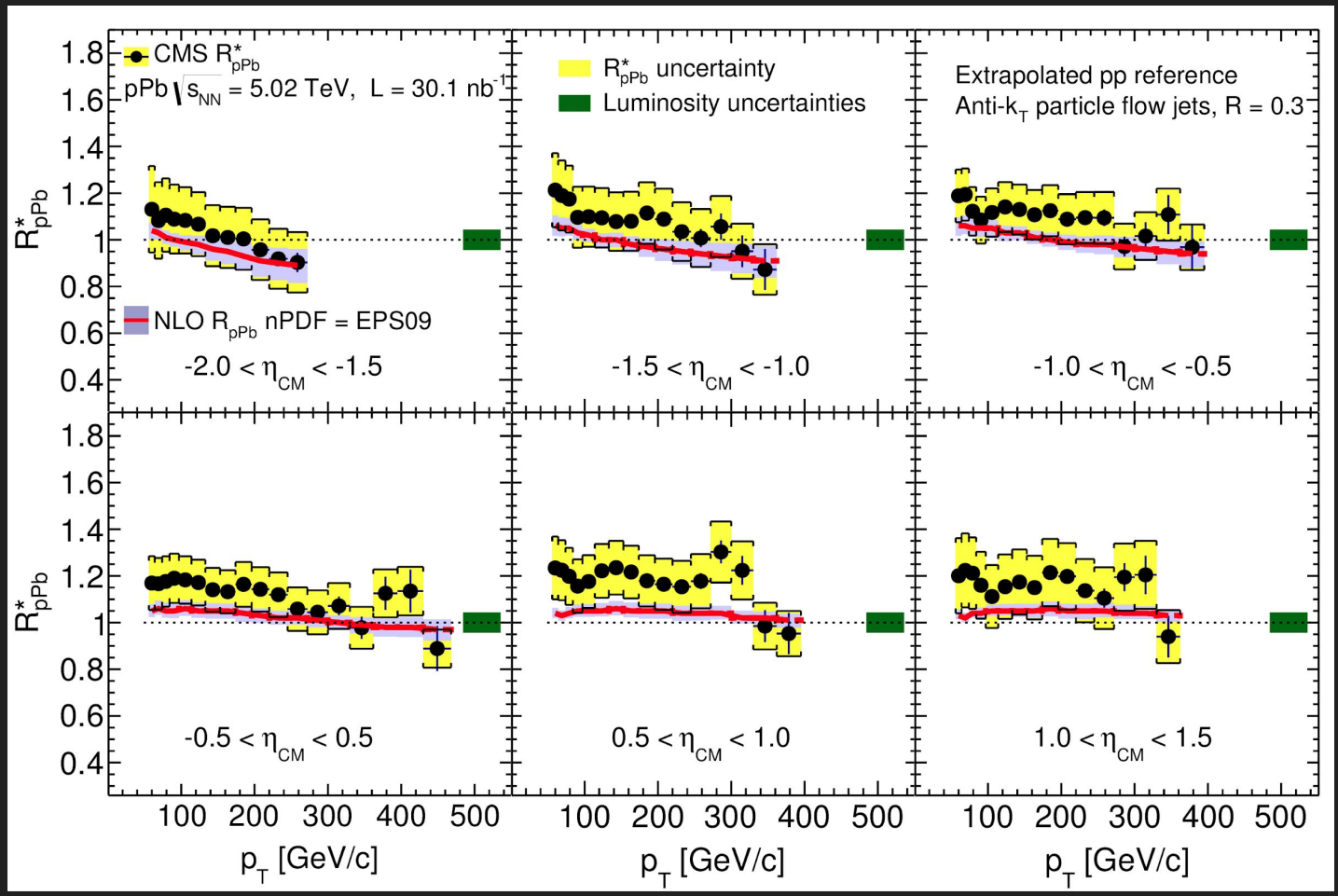
FB asymmetry for $W^+ \rightarrow \mu^+\nu$ (left) and $W^- \rightarrow \mu^-\nu$ (right)

Clear nuclear effects observed

CMS-PAS-HIN-17-007
ATLAS-CONF-2015-56

Inclusive jet R_{pPb}

CMS, arXiv:1601.02001



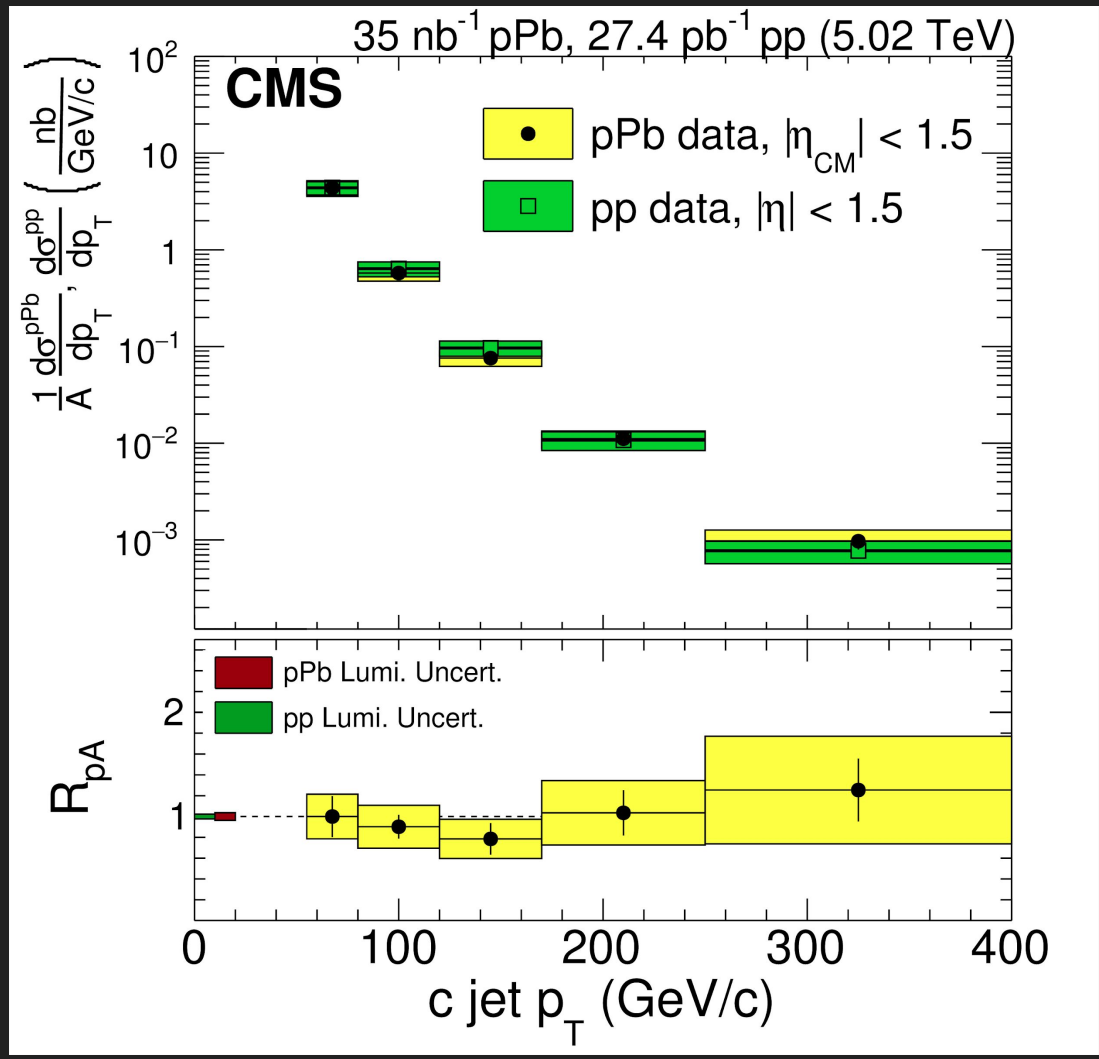
- Small enhancements observed at low jet p_T for all η.
- R_{pPb} approximately independent of p_T, except in most backward η range.
- For $|\eta| < 0.5$ and $56 < p_T < 300$ GeV, $R_{pPb} = 1.17 \pm 0.01$ (stat) $\pm$ 0.12 (syst)
- R_{pPb} compatible with NLO pQCD calculations.

HF-Jets : c-jet R_{pA}

CMS has measured spectra and R_{pA} for c-jets at 5.02 TeV

No significant jet energy modification observed for c jets with p_T> 55 GeV.

R_{pA} is p_T- independent
~0.92 ± 0.07 (stat) ± 0.11 (syst).



arXiv:1612.08972

HF-Jets : b-jet suppression

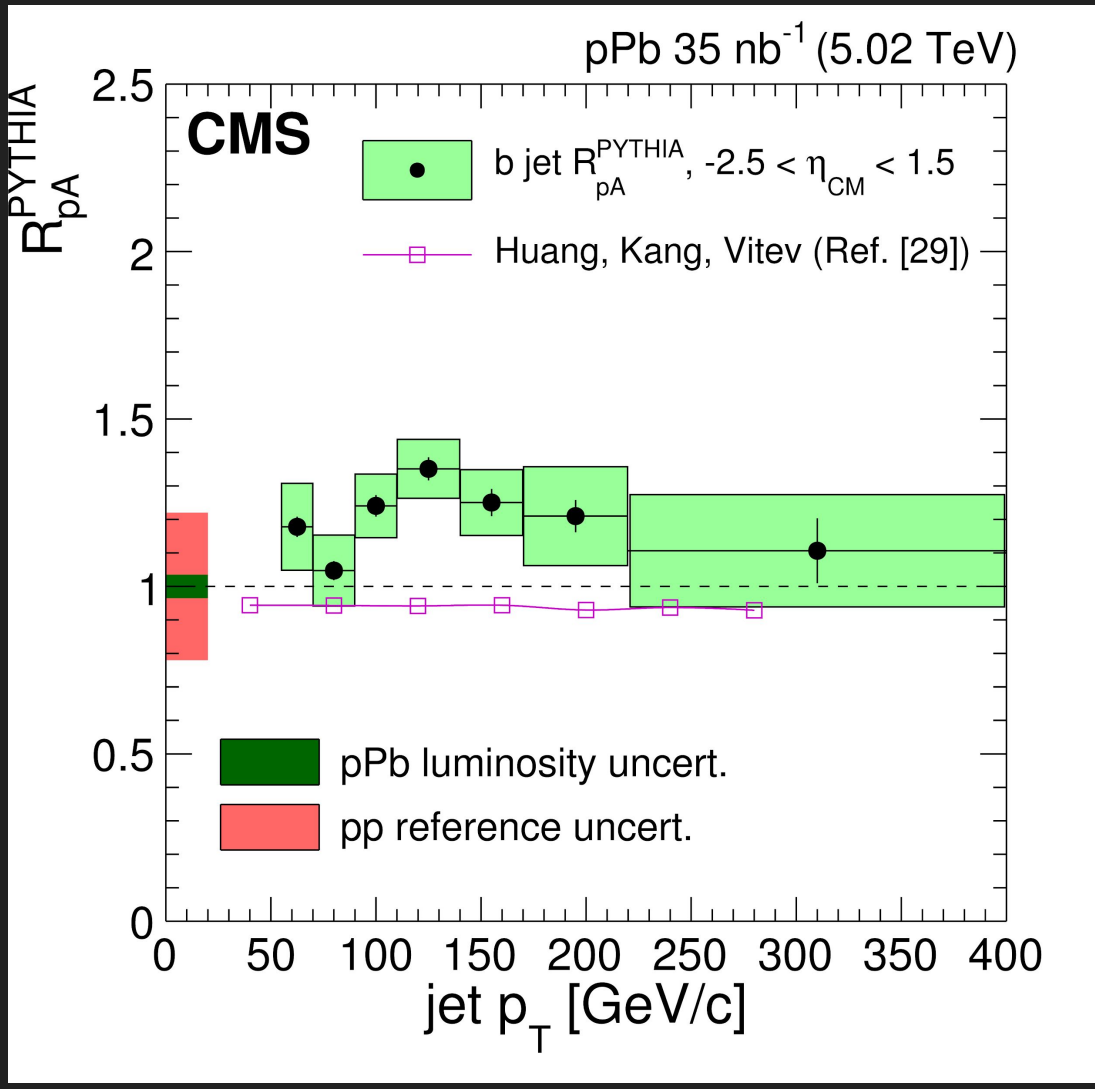
arXiv:1510.03373

b jet R_{pA}^{PYTHIA} at 5.02 TeV pPb collisions over 55-400 GeV pT range.

Average R_{pA}^{PYTHIA} =1.22 ± 0.15 (stat + syst pPb) ± 0.27 (syst PYTHIA)

Indicates that jet energy loss effects are not significant for the b-jets.

R_{pA}^{PYTHIA} values consistent with unity and also with the enhancement observed by CMS for charged particles at high p_T.



Jet fragmentation in Pb+Pb

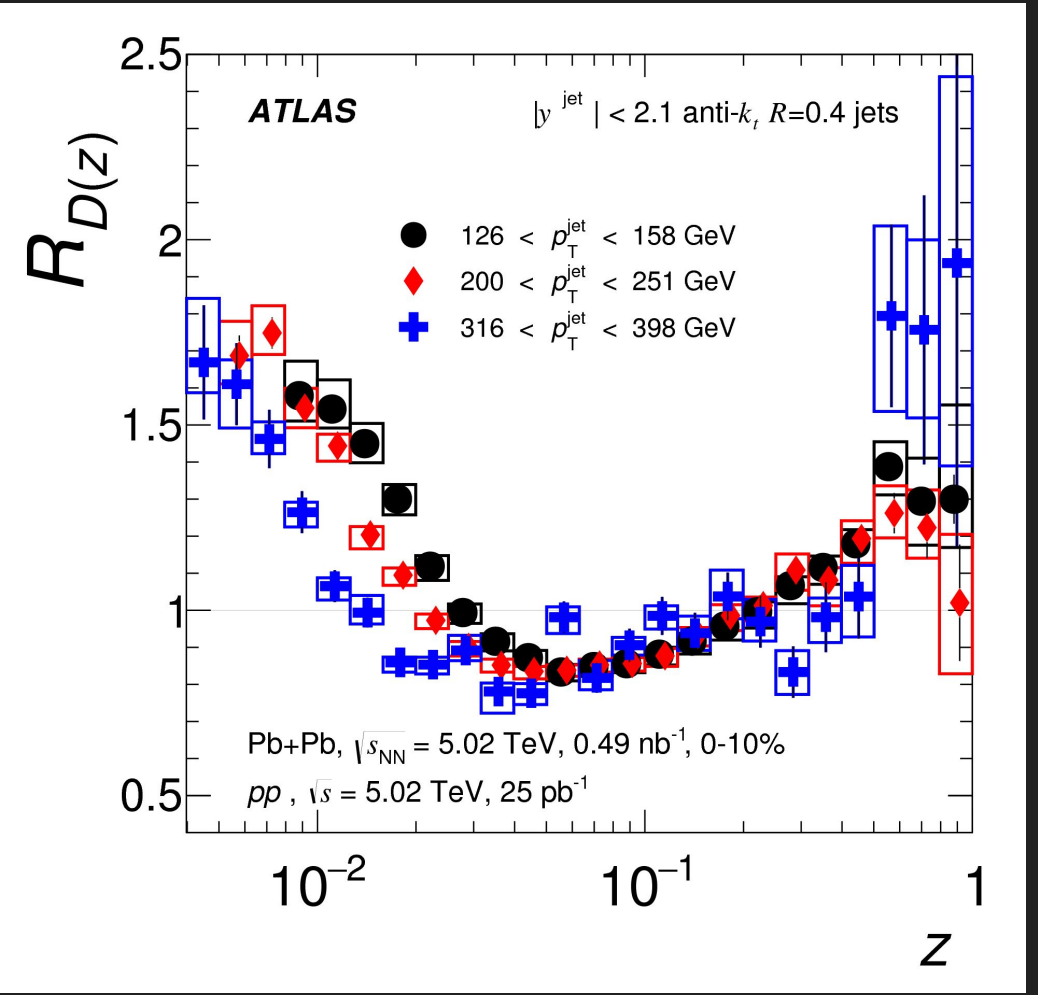
arXiv:1805.05424

Jet Fragmentation functions in Pb+Pb collisions show significant deviation from pp collisions

$$z \equiv p_{\mathrm{T}} \cos \Delta R \; / \; p_{\mathrm{T}}^{\mathrm{jet}}$$

$$D(z) \equiv \frac{1}{N_{\mathrm{jet}}} \frac{dn_{\mathrm{ch}}}{dz}$$

$$R_{D(z)} \equiv \frac{D(z)_{\mathrm{PbPb}}}{D(z)_{pp}}$$

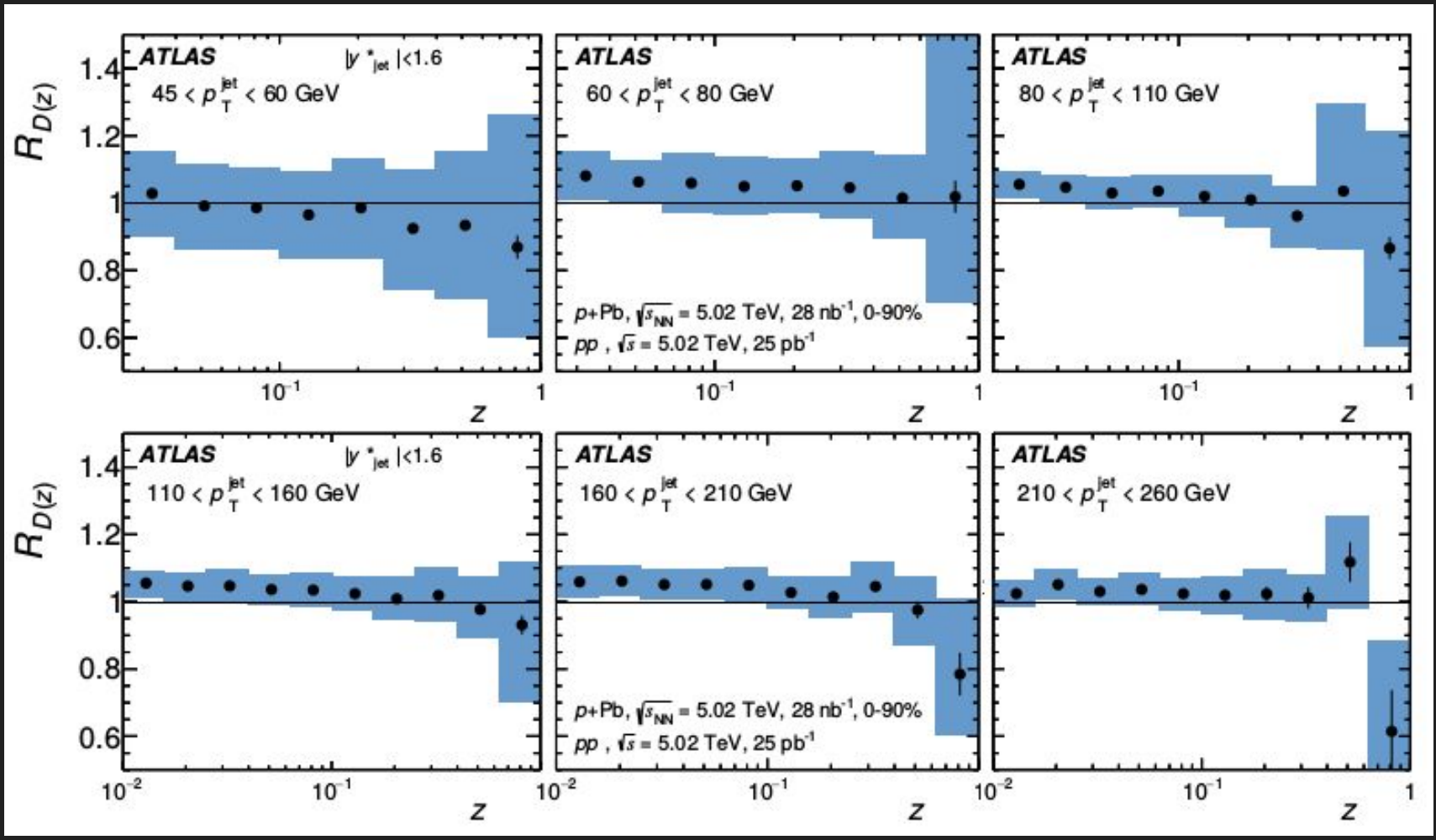


Particles yields enhanced at high and low-z and decreased at intermediate-z.

Deviation increases with increasing centrality and is only weakly dependent on jet rapidity.

Jet fragmentation in p+Pb

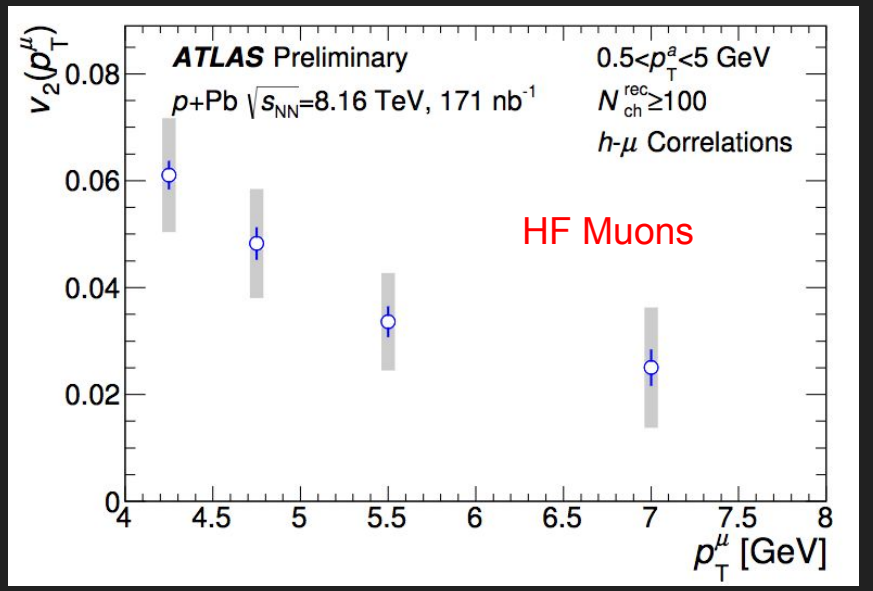
arXiv 1706:02859



On the other hand, in p+Pb collisions there is no evidence of modifications on Jet fragmentation functions (similar to peripheral Pb+Pb collisions).

Flow for open heavy flavor

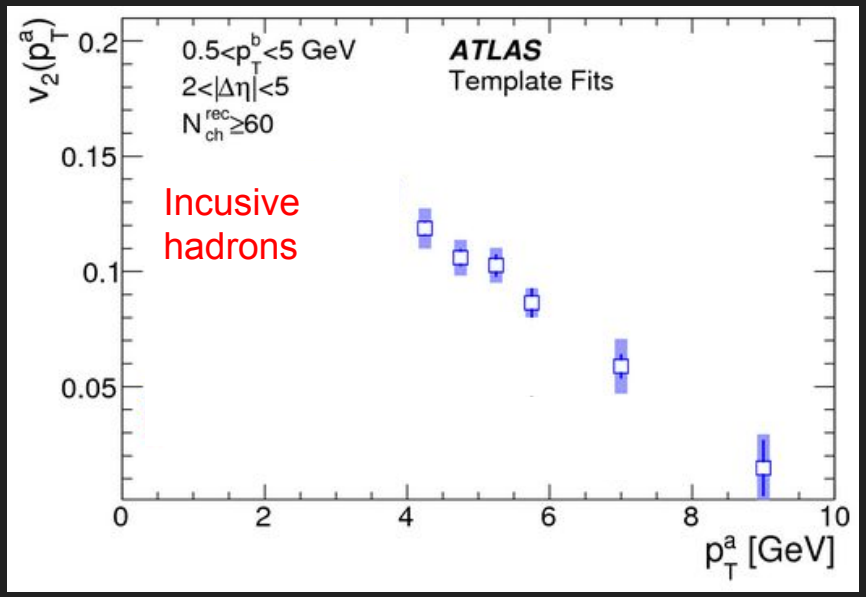
ATLAS-CONF-2017-006

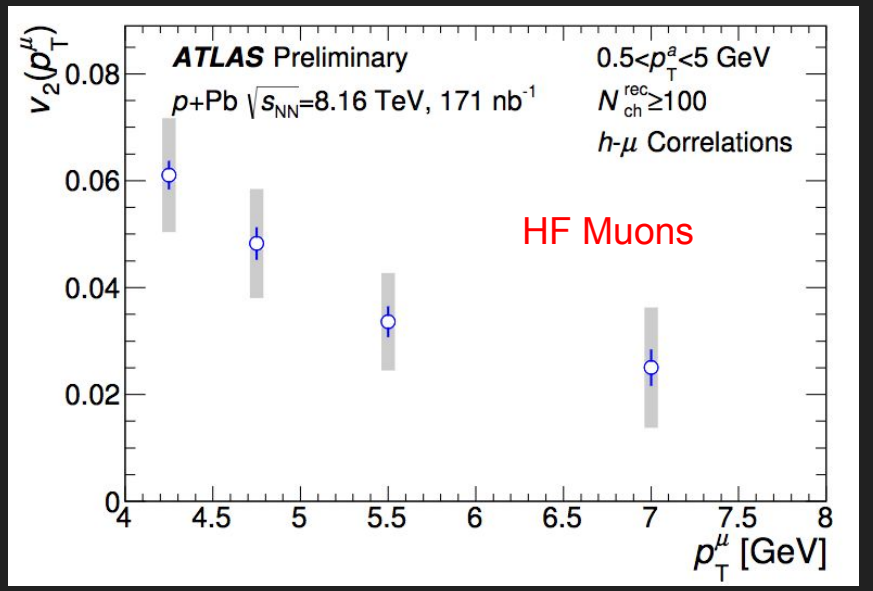


- Significant azimuthal anisotropy (v_2) observed for muons over 4-8 GeV
- Over this p_T range nearly all muons (~99%) come from decays of b and c hadrons.
- Indicates significant HF-v_2

Flow for open heavy flavor

ATLAS-CONF-2017-006

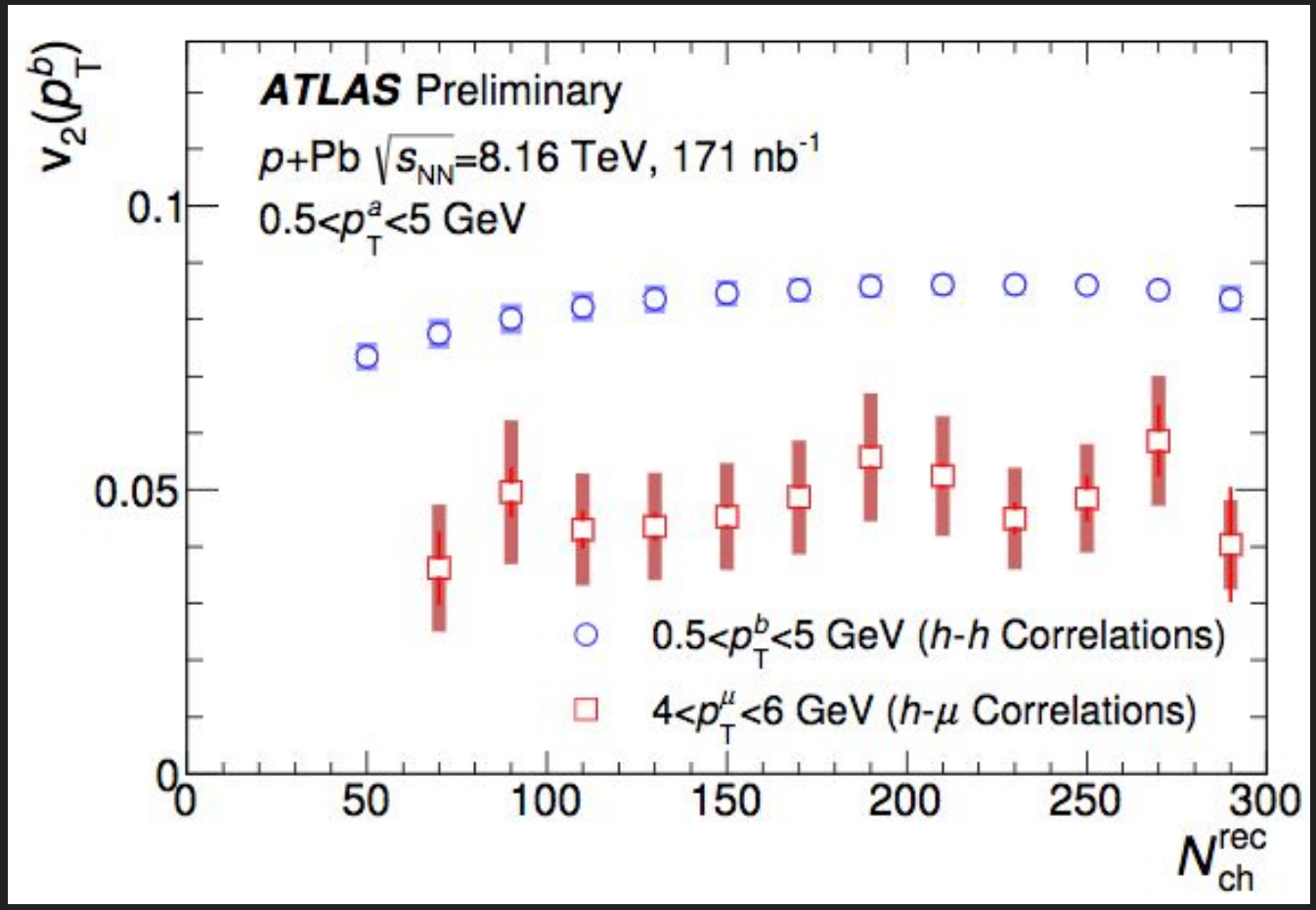




- Significant azimuthal anisotropy (v_2) observed for muons over 4-8 GeV
- Over this p_T range nearly all muons (~99%) come from decays of b and c hadrons.
- Indicates significant HF-v_2
  - Though smaller than that of inclusive hadrons.

Flow for open heavy flavor

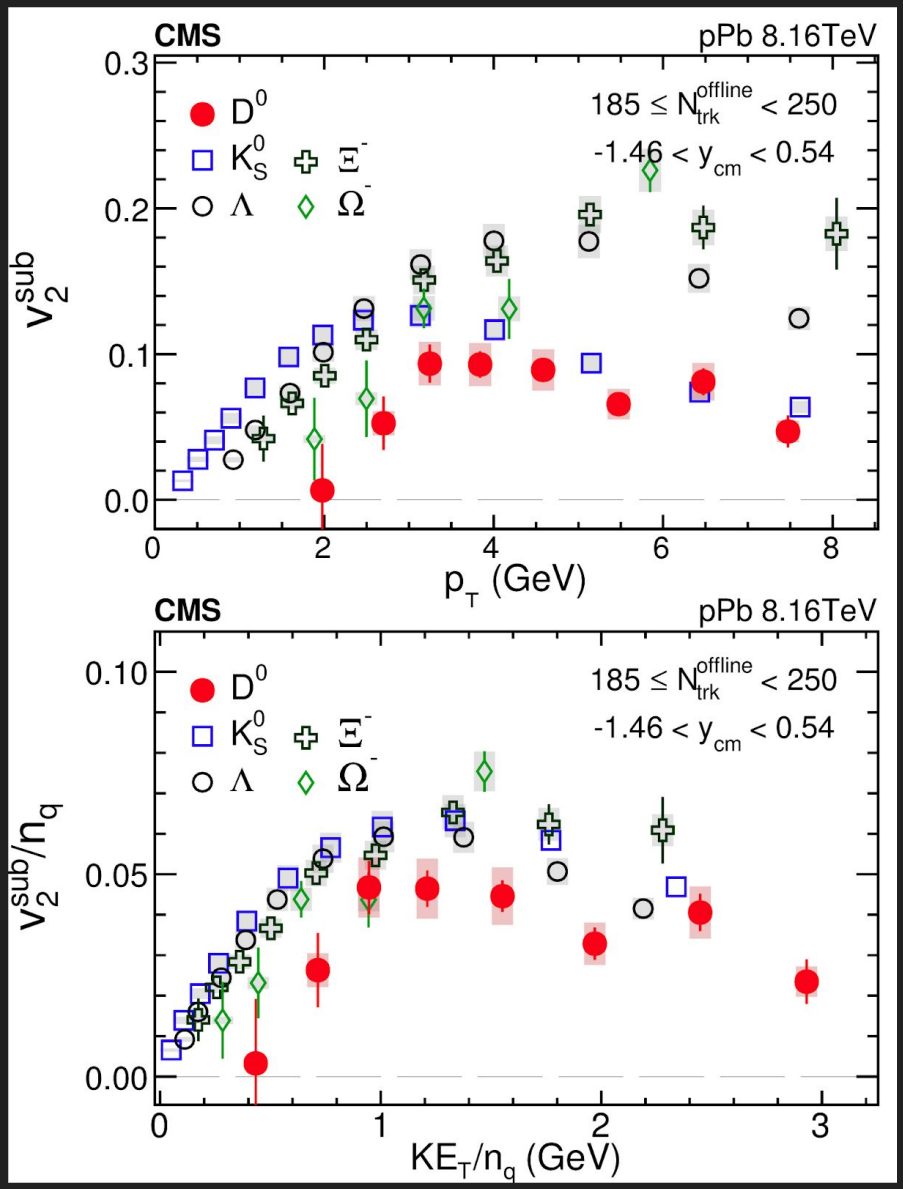
ATLAS-CONF-2017-006



- v_2 present across all event multiplicities

Flow for open heavy flavor

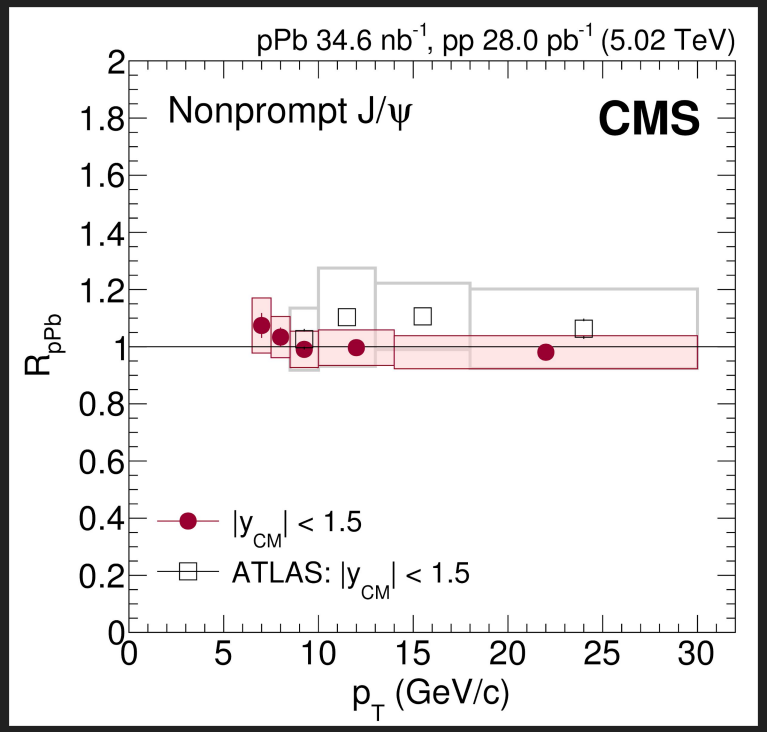
- Significant v_2 values are observed for D^0 mesons with p_T> 2 GeV in 8.16 TeV p+Pb collisions.
- Constituent quark scaled D^0 v_2 values are compared to light hadrons
- Such an effect is not observed in Pb+Pb collisions.
- Implies that in p+Pb collisions the collective behavior of charm quarks is weaker than that of the light-flavor quarks.

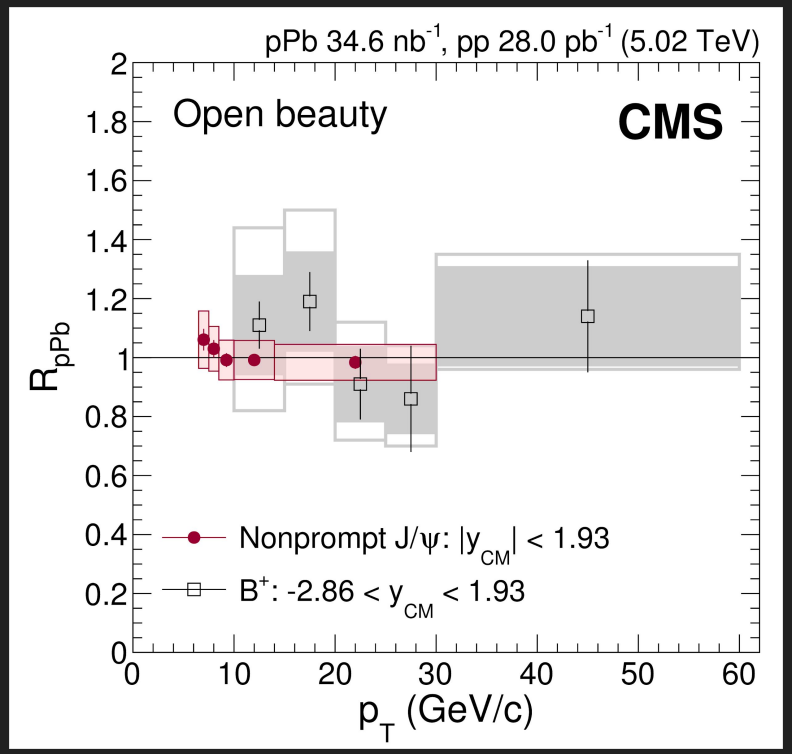


See talk by Zhenyu Chen in QMHI parallel-7

CMS: HIN-17-003

Suppression of open heavy flavor

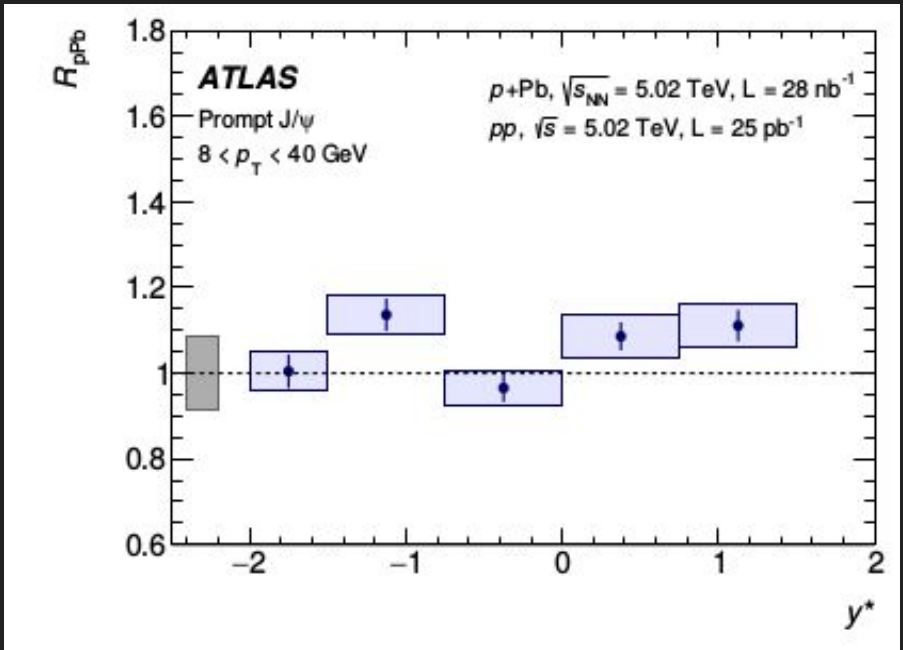


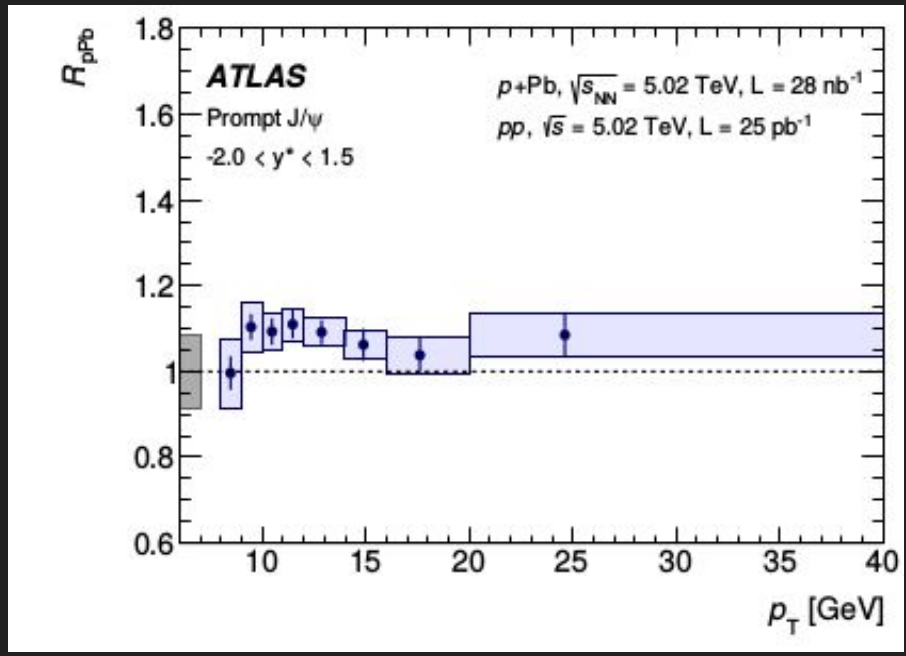


- Non-prompt j/psi (from b-decays) and B-meson R_{pPb} are consistent with unity.
- p_T as well as rapidity dependence of R_{pPb} for both is observed to be weak.
- Indicate no suppression of b-quark in p+Pb collisions

CMS: arXiv:1702.01462
ATLAS: arXiv:1709.03089

Suppression of heavy flavor





- Prompt j/psi R_{pPb} also consistent with unity.
- p_T as well as rapidity dependence of R_{pPb} weak.
- Indicate no suppression of bound c-cbar quark states in p+Pb collisions

CMS: arXiv:1702.01462
ATLAS: arXiv:1709.03089

Summary-I

- Some trends seen in R_{pPb} of EW probes --eg. lower yield for photons at backward rapidity-- attributable to modified quark content of Pb compared to p.
- Theory calculations agree better with measurements when using nPDFs instead of nucleon PDFs (W, Z).
- Data disfavours initial state energy loss

- Presence of significant HF azimuthal v_2 is observed
  - identified D^0 and HF-decay muons.
- Measured HF-v_n is significantly smaller than light hadrons,
  - and does not exhibit constituent quark scaling.
- Indicates lesser collectivity for HF

- Open HF (B-meson and non-prompt j/ψ) R_{pPb} is consistent with unity.
  - B-hadron production unmodified w.r.t. pp
- Same is true for prompt j/ψ.

Summary-II

- R_{pPb} for inclusive jets is approximately independent of p_T except at very backward rapidity
  - For $|\eta_{CM}| < 0.5$ and $56 < p_T < 300$ GeV, $R_{pPb} = 1.17 \pm 0.01$ (stat) ± 0.12 (syst)
  - Indicating slight enhancement of jet production compared to pp.

- R_{pPb} for HF-jets are approximately independent of p_T
  - c-Jets: $R_{pPb} = 0.92 \pm 0.07$ (stat) ± 0.11 (syst).
  - b-Jets : $R_{pA}^{PYTHIA} = 1.22 \pm 0.15$ (stat + syst pPb) ± 0.27 (syst PYTHIA)
  - Both are consistent with unity (though somewhat large nominal value for b-jets)

- Jet fragmentation functions in p+Pb are consistent with those in pp collisions
  - Unlike central Pb+Pb collisions where significant deviation is observed

- While there is “flow” like behavior in p+A collisions, the other signature of QGP --jet quenching-- seems to be absent.
  - Not necessarily inconsistent : also seen in peripheral A+A

Backups

HF-Jets : b-jet suppression

arXiv:1510.03373

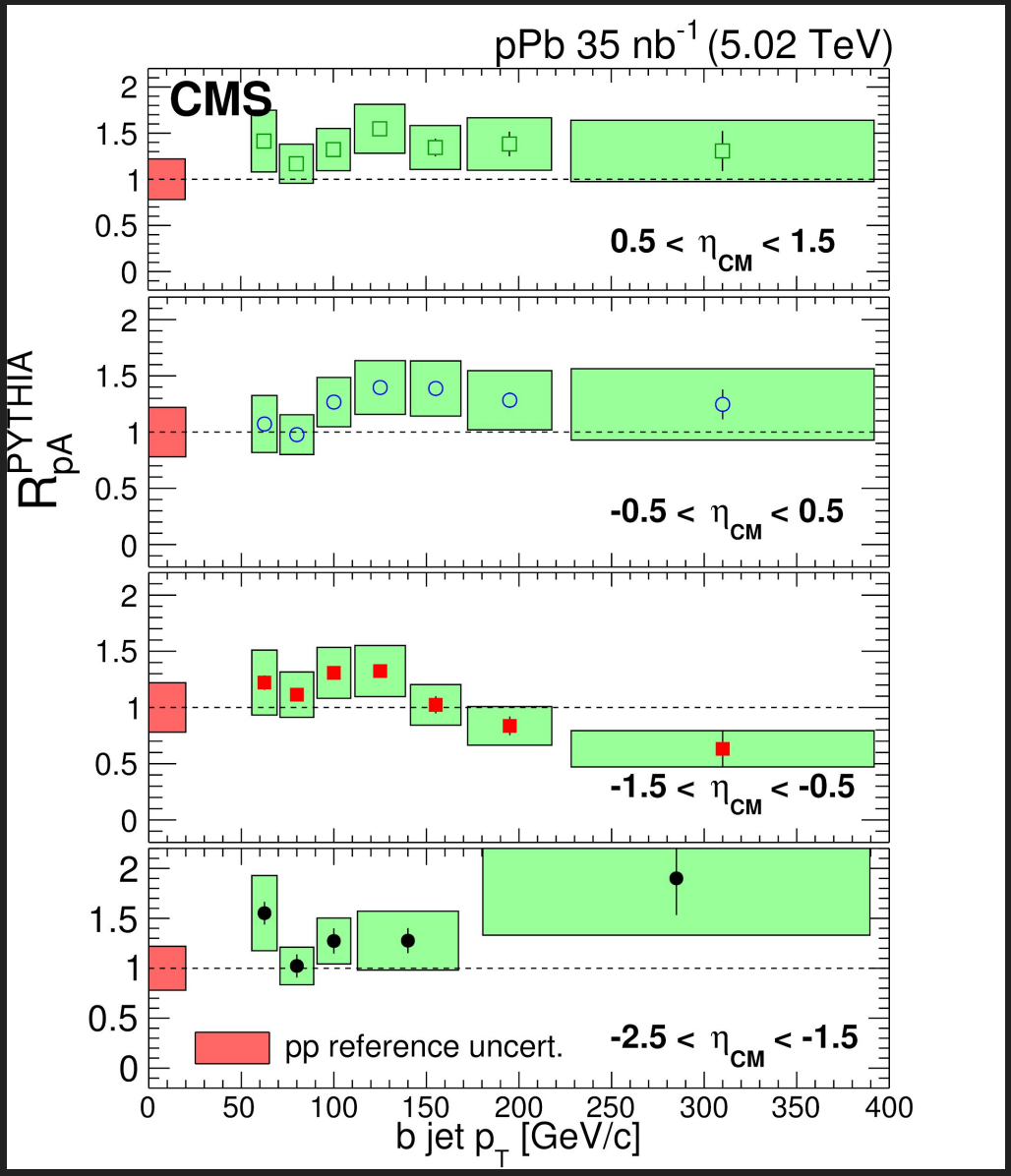
b jet R_{pA}^{PYTHIA} at 5.02 TeV pPb collisions over 55-400 GeV pT range.

Average R_{pA}^{PYTHIA} =1.22 ± 0.15 (stat + syst pPb) ± 0.27 (syst PYTHIA)

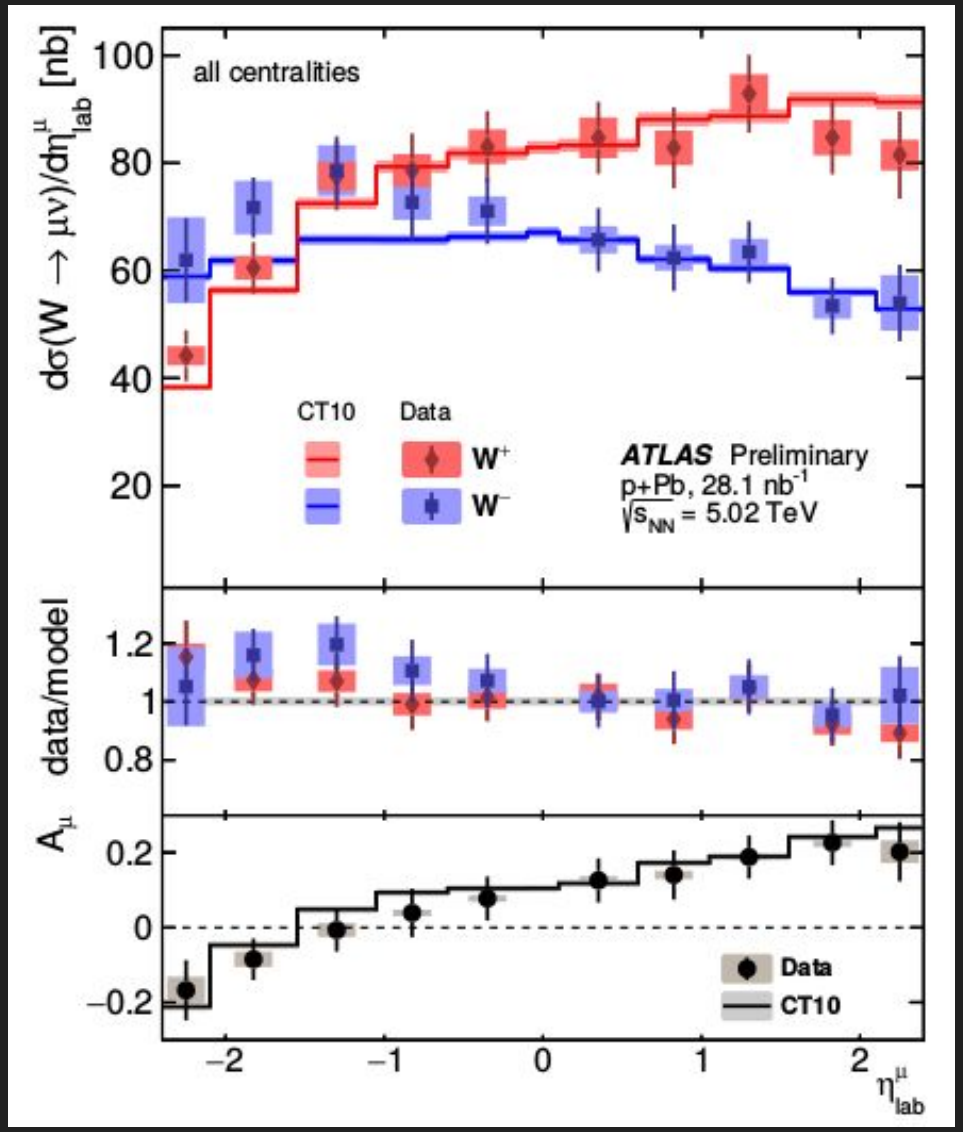
Indicates that jet energy loss effects are not significant for the b-jets.

R_{pA}^{PYTHIA} values consistent with unity and also with the enhancement observed by CMS for charged particles at high p_T.

The η-dependence of R_{pA}^{PYTHIA} is very small, indicating that nPDF effects are smaller than the uncertainties.



W production



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W→μν cross section as function of muon pseudorapidity

Shown separately for W+ and W-

Compared to expectations from POWHEG based model using CT10 PDFs

Model reproduces data well except for W^{--} for $\eta<0$, most clearly seen in the middle panel

Lower panel shows the charge asymmetry:

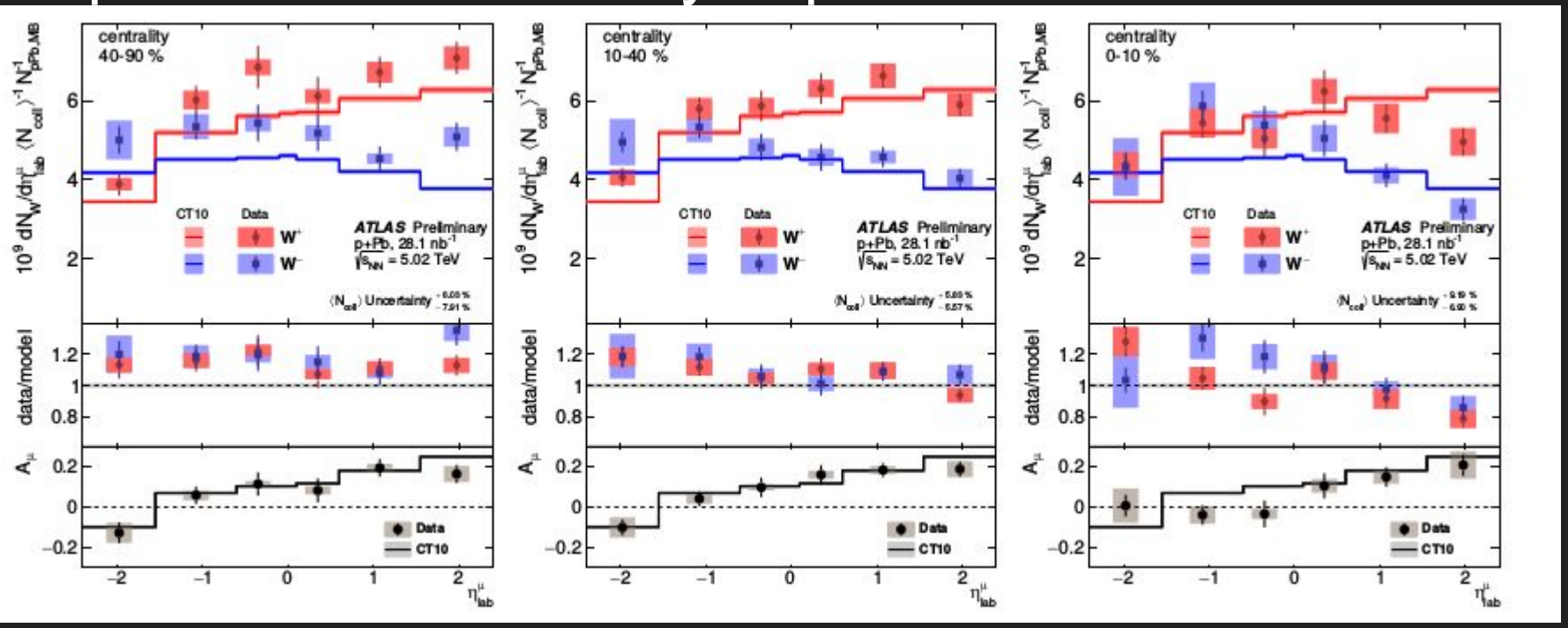
η dependence due to valence u-quarks : produce W^+ bosons having on average a higher fraction of the proton momentum

Also partially due to CM shift of $\eta=0.465$

Good agreement with model for $\eta>0$ but data below model for $\eta<0$

Same effect also observed by CMS arXiv:1503.05825

W production : centrality dependence



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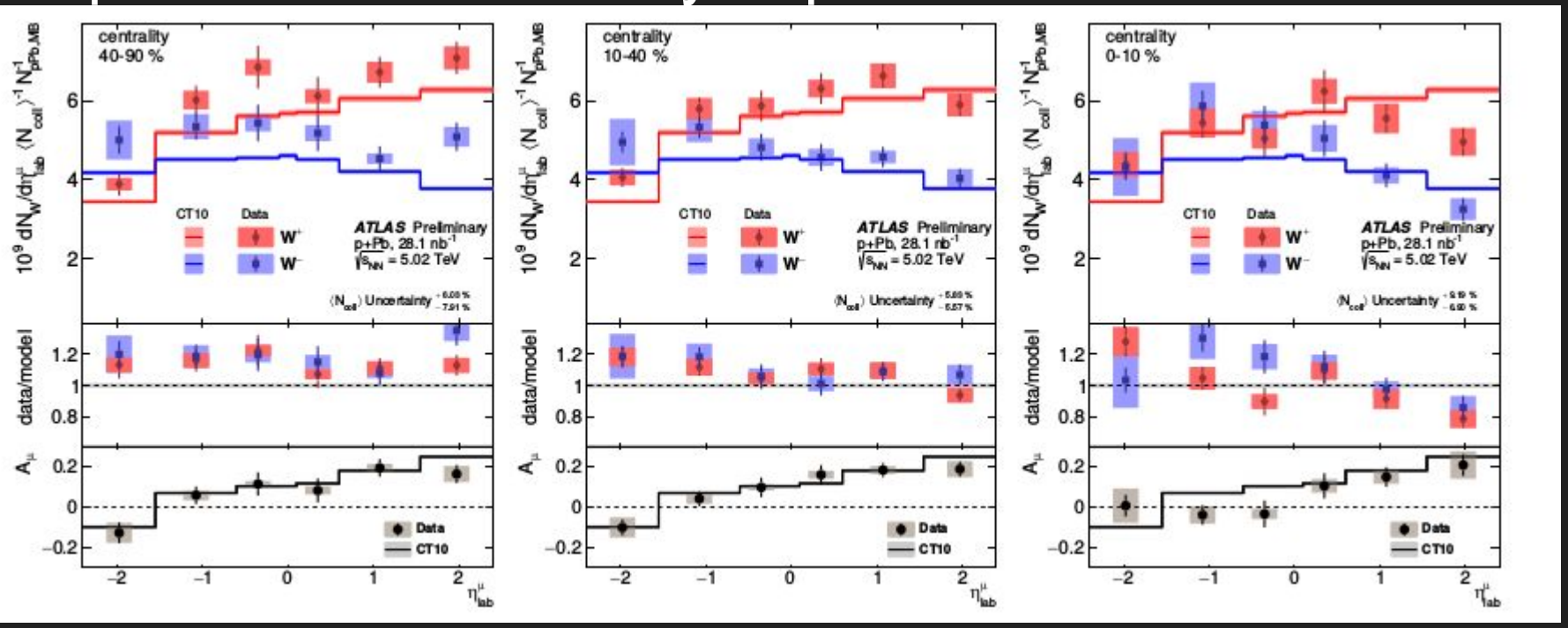
- In peripheral collisions the model calculations lower are than the data for all η.
  - may be due to the difficulty in definitively determining N_{coll} for a given centrality
- Shape of the pseudorapidity distributions for both W+ and W- bosons depends on centrality.
- data/model shows presence of a slope in the most central collisions, but not in peripheral collisions.
- The shape modification of the pseudorapidity distribution with centrality present in the W boson data is similar to the trend observed in the Z-boson data.
- The asymmetries shown in the lower panel agree between the data and model, except in the Pb-going direction (η<0) in the most central collisions.

W production : centrality dependence



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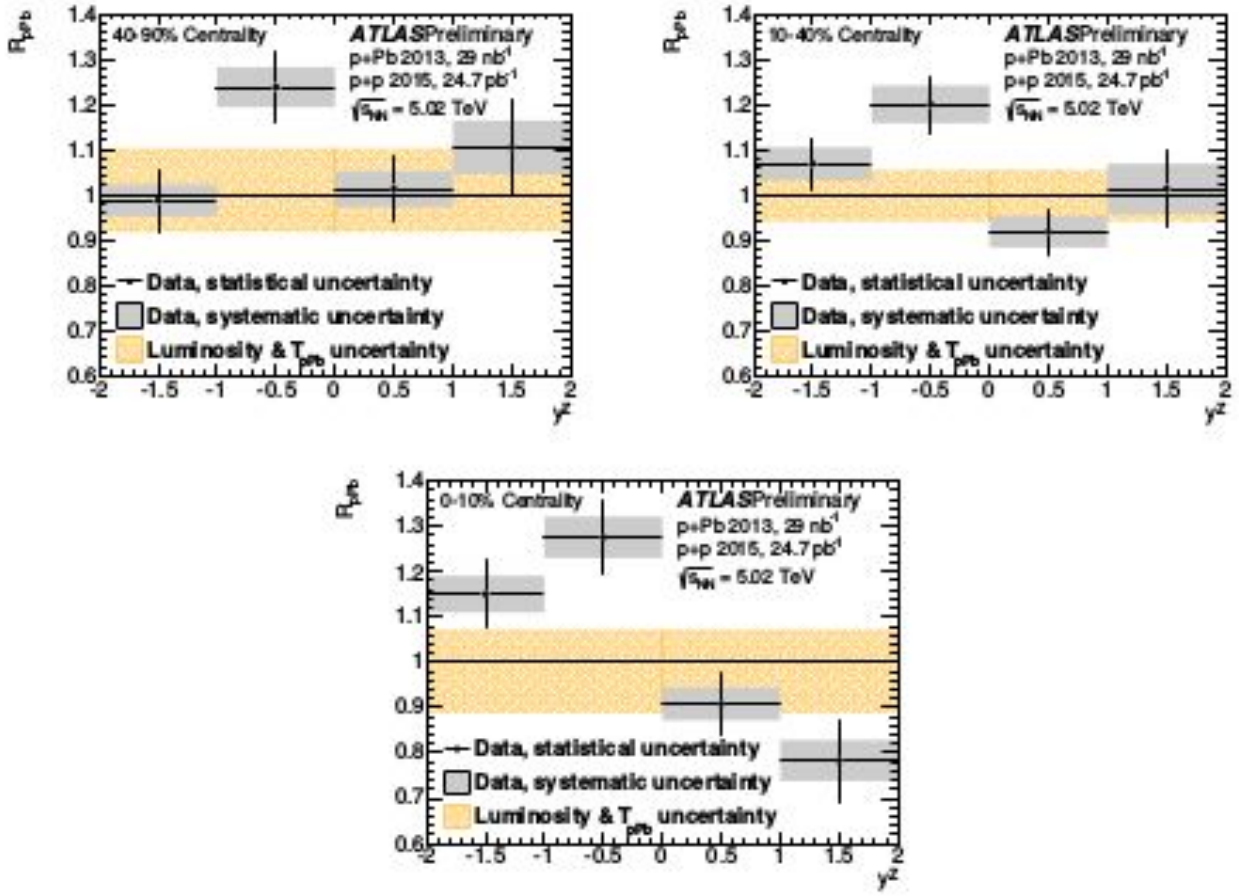
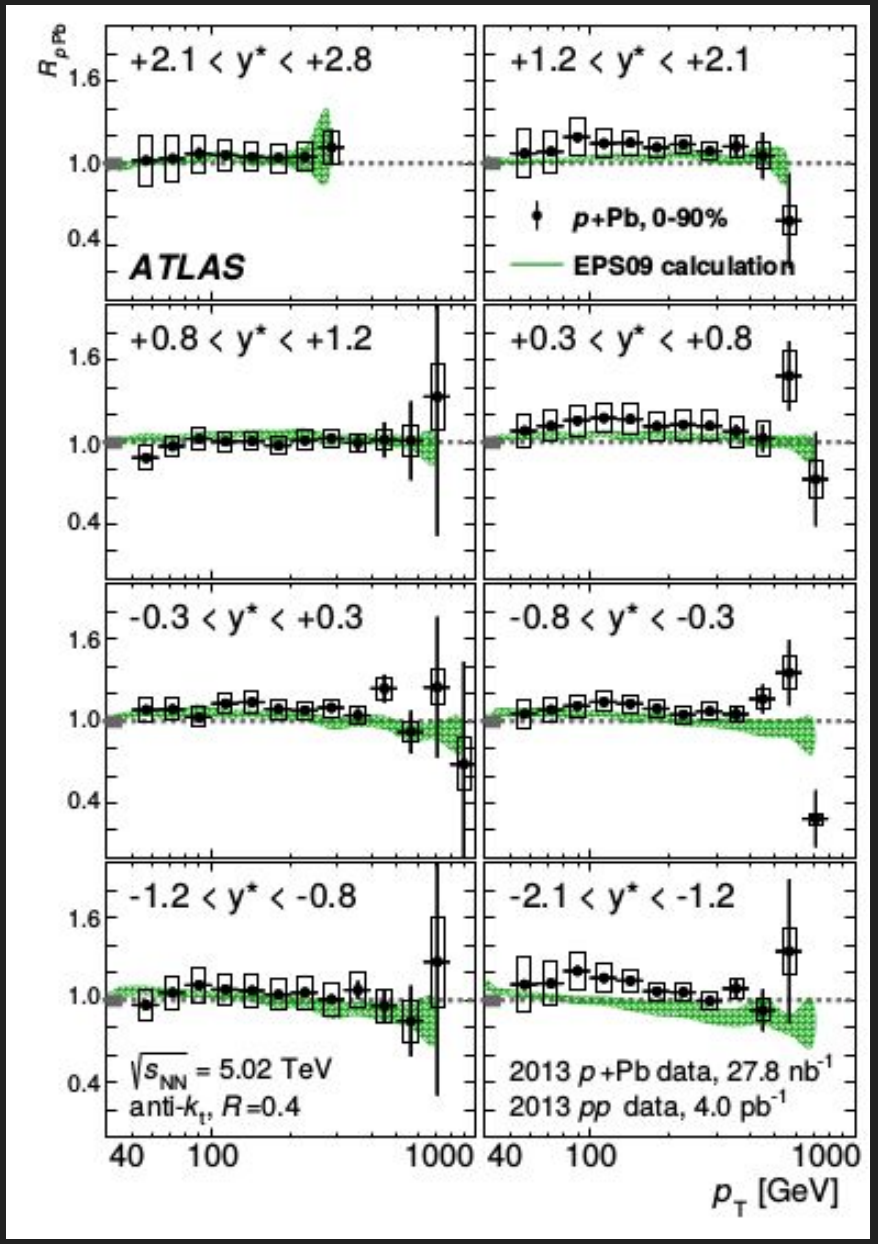
W&Z production

ATLAS-CONF-2016-107



Jet quenching in pA collisions



arXiv 1412:4092

Jet quenching in pA collisions