LHC forward physics from hard probes

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IN THE CITY OF NEW YORK

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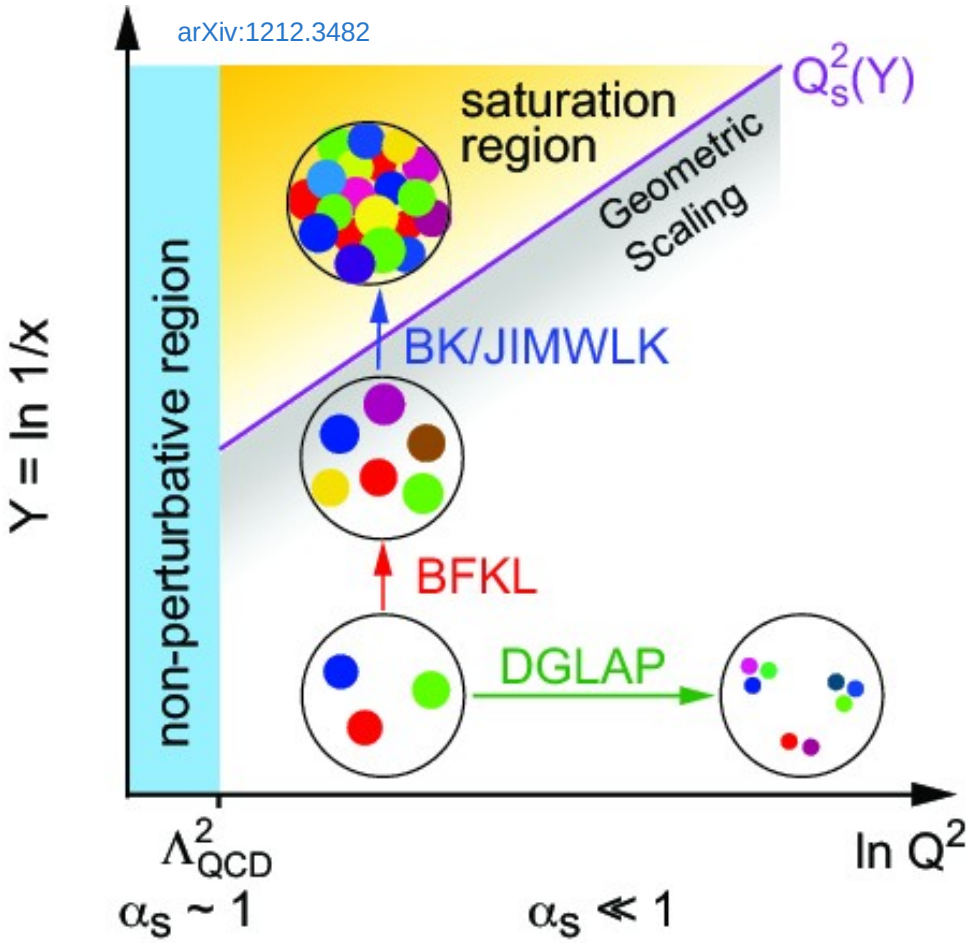
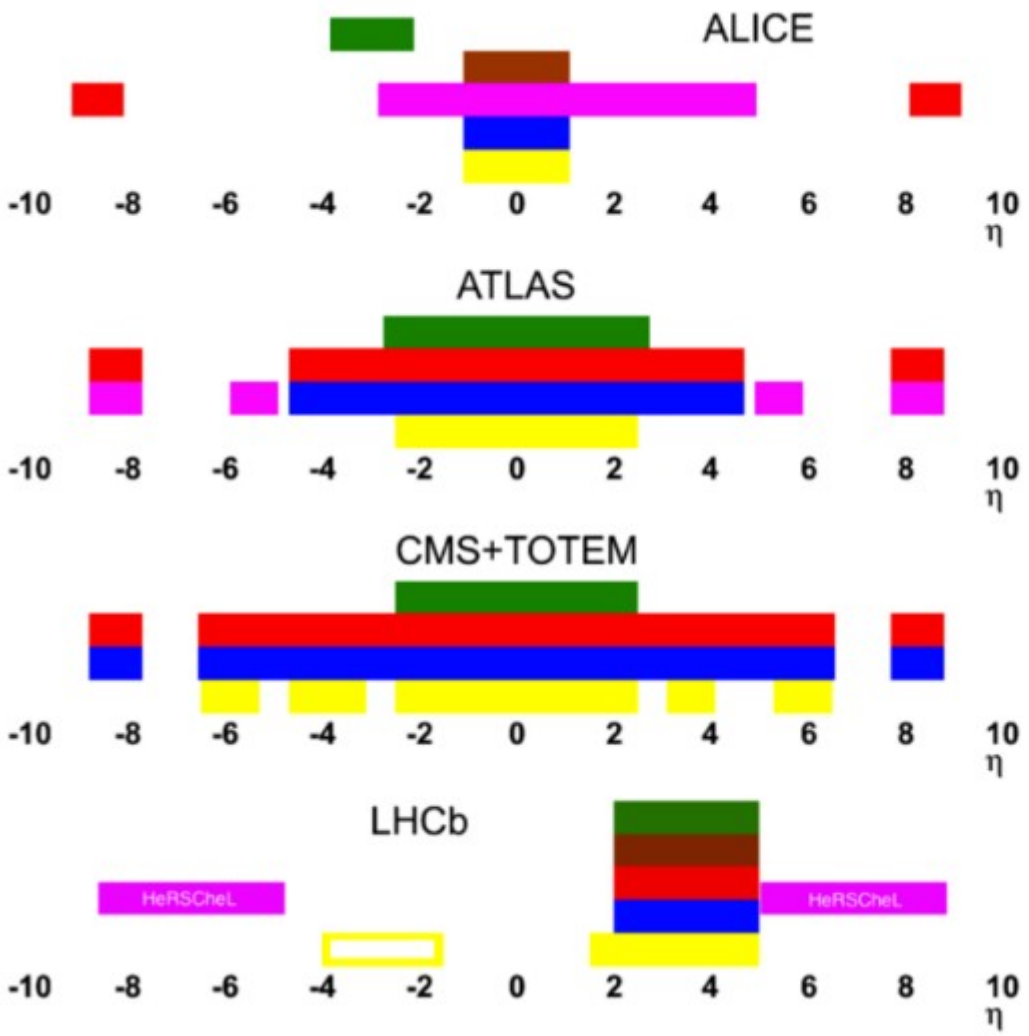
Forward Hard Probes of Initial Stages

- Do we have reliable theoretical description of this kinematic regions?
- How far do our approximations in QCD stay valid?
- Can we see onset of gluon saturation or non-linear QCD effects?
- What is the size of modification of the quark and gluon structure functions for nucleons inside nuclei?
- How cold nuclear matter (CNM) influence the production of hard processes?



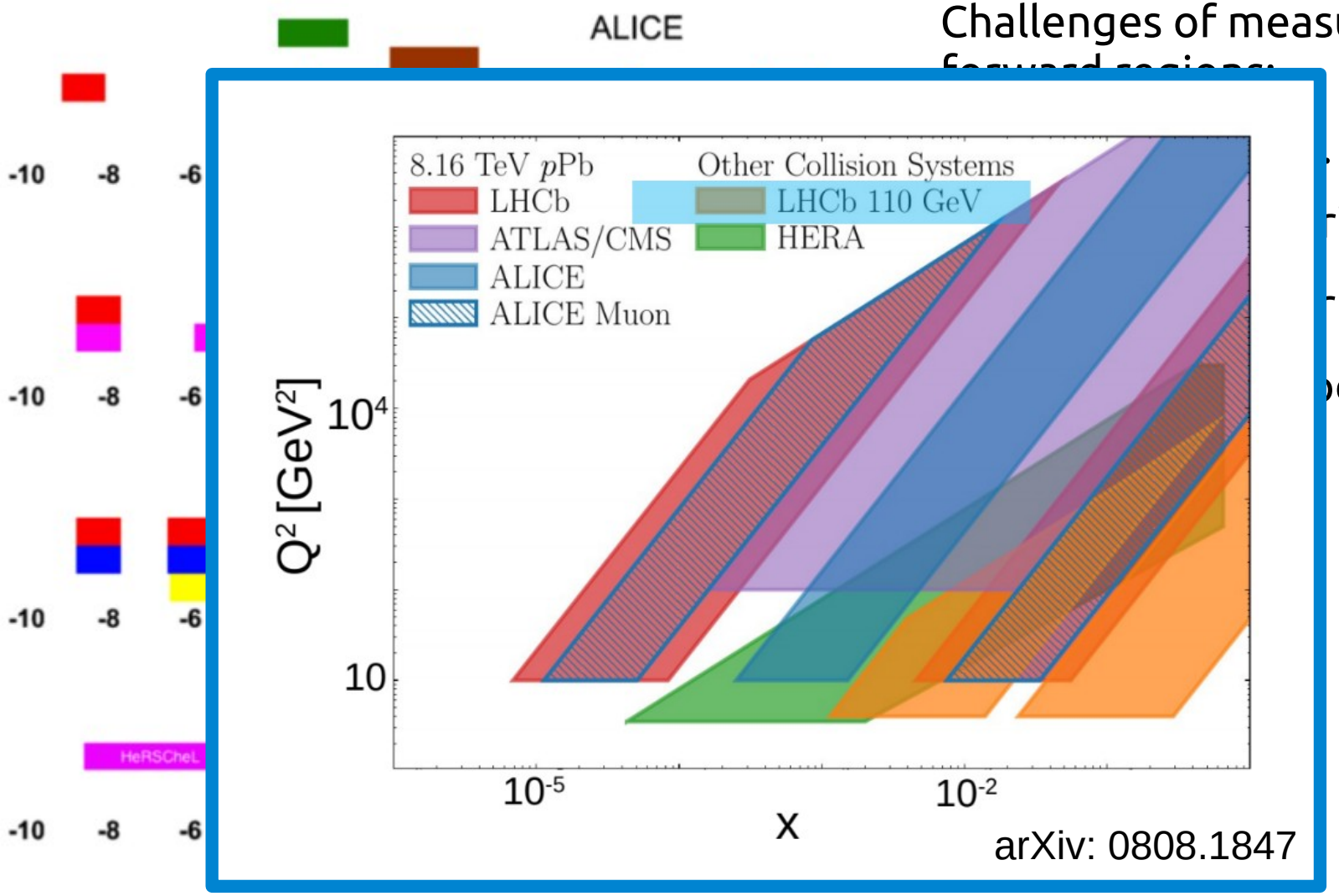
Instrumentation in forward region



Challenges of measurements in forward regions:

- Limited coverage.
- Detector granularity.
- Triggering on forward signatures.
- Uncertainty in modeling.
- Knowledge of performance.

Instrumentation in forward region



Challenges of measurements in

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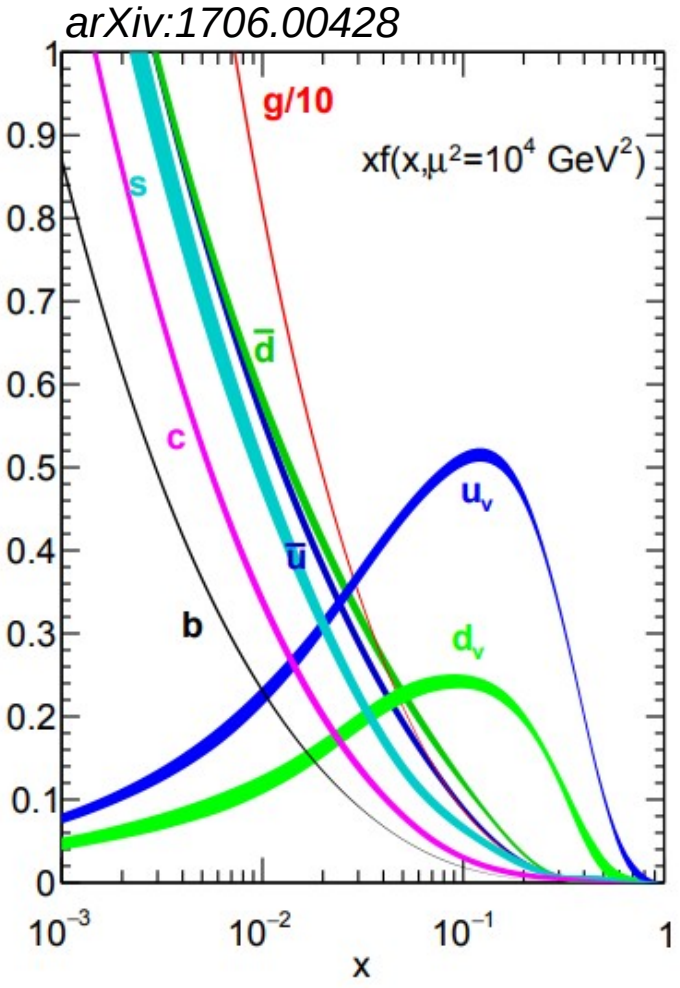
Forward jet production

- Collinear factorization and DGLAP successful in describing large-Q^2 processes and moderate x.
- Expected to fail at low-x.
- Do we need BFKL describe forward jet production?
- What is role of MPI?
- Steep rise of gluon PDFs at low-x versus unitary.
- Saturation can bring expected change of trend at low x.

➡ measurement to be performed with as low p_T and as forward direction as possible.



Forward jet production

- Collinear factorization and DGLAP successful in describing large-Q^2 processes and moderate x.
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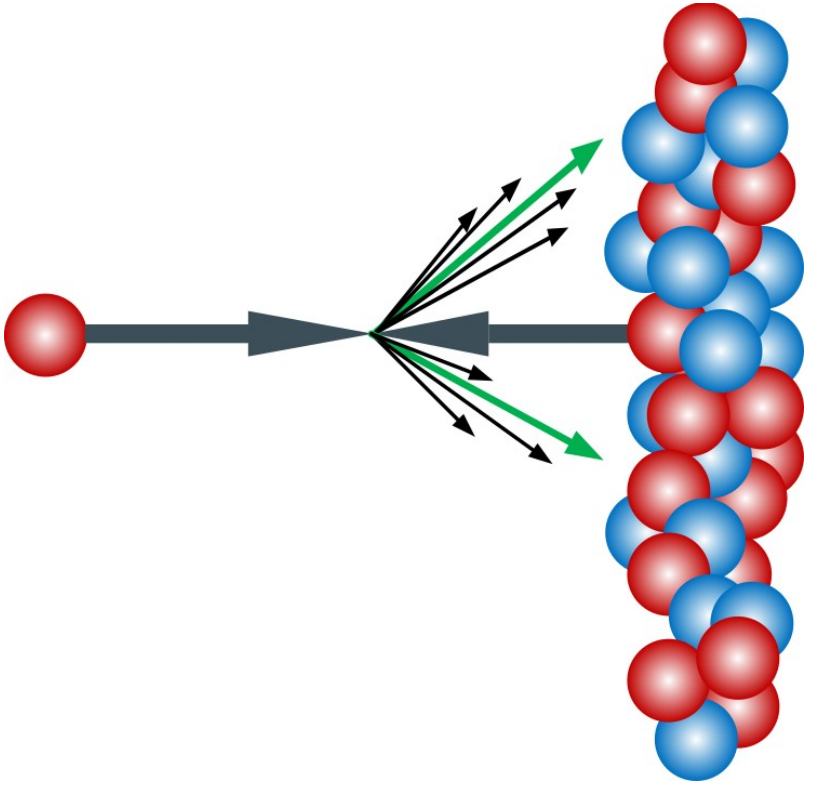
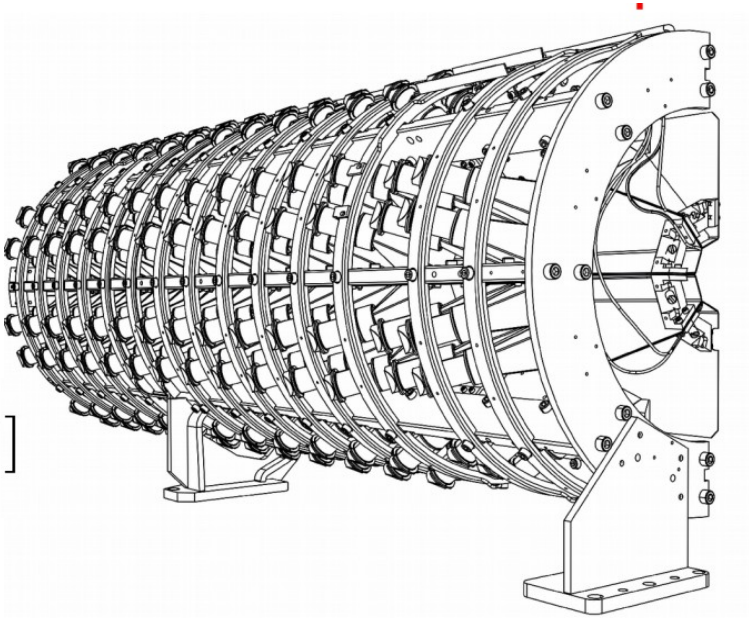
➡ measurement to be performed with as low p_T and as forward direction as possible.

- Gluon density increased in nuclear collisions → increased sensitivity.
- Sensitive also to the onset of non-linear QCD.

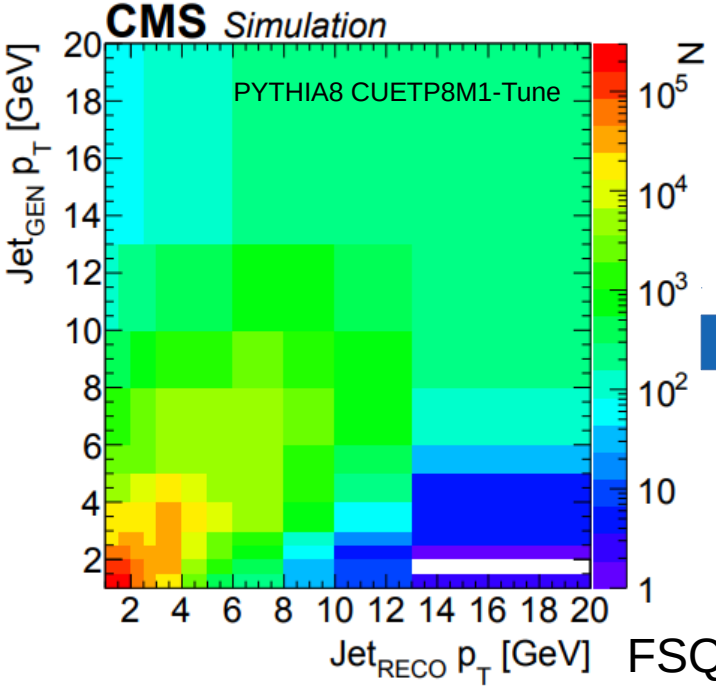


Forward jets@CMS

- Measured in CASTOR detector at -6.6 < η < -5.2
  - Longitudinal and φ segmentation; no η segmentation.
- Resolution 25% (10%) at 550 GeV (2500 GeV)



$$x \approx \frac{p_T}{\sqrt{s}} e^{\pm\eta} \approx 10^{-6} \quad [\, p_T = 10\,GeV\,;\eta = -6\,;\sqrt{s} = 13\,TeV\,]$$



Large bin migration due to the energy resolution
→ requires ~80 iteration in the unfolding!

Also significant uncertainty in modeling.

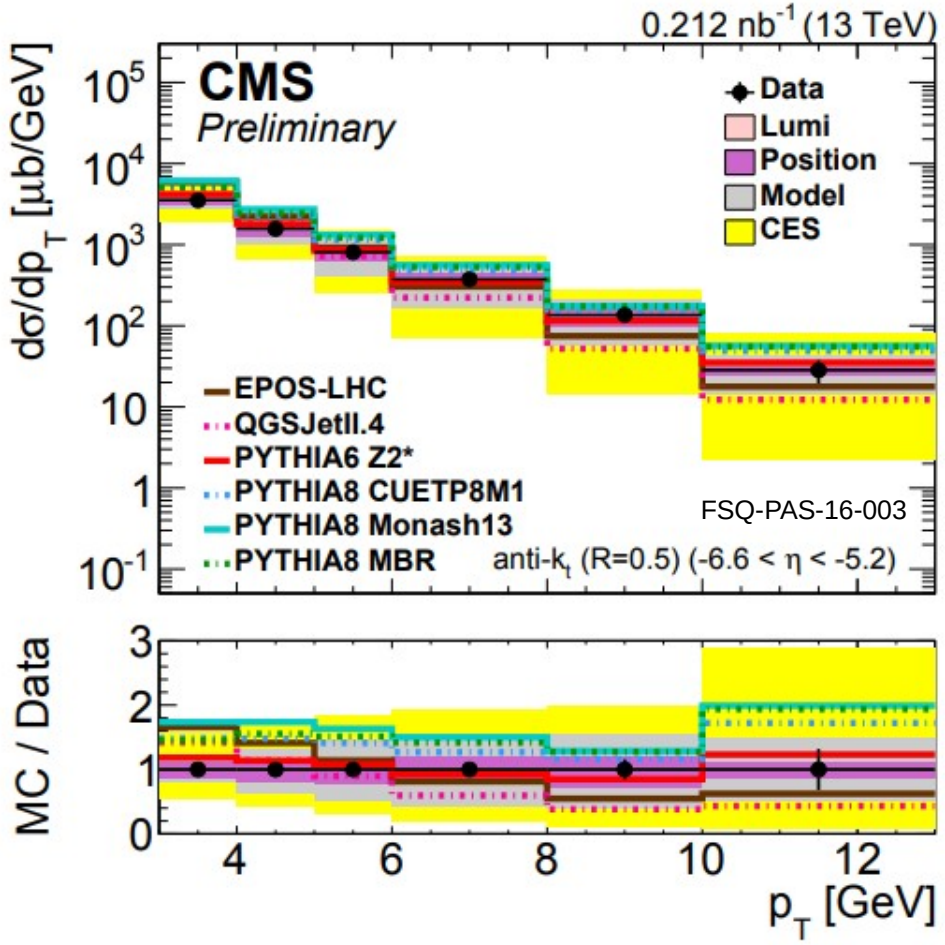
→ Large systematic uncertainties.

FSQ-16-003-PAS

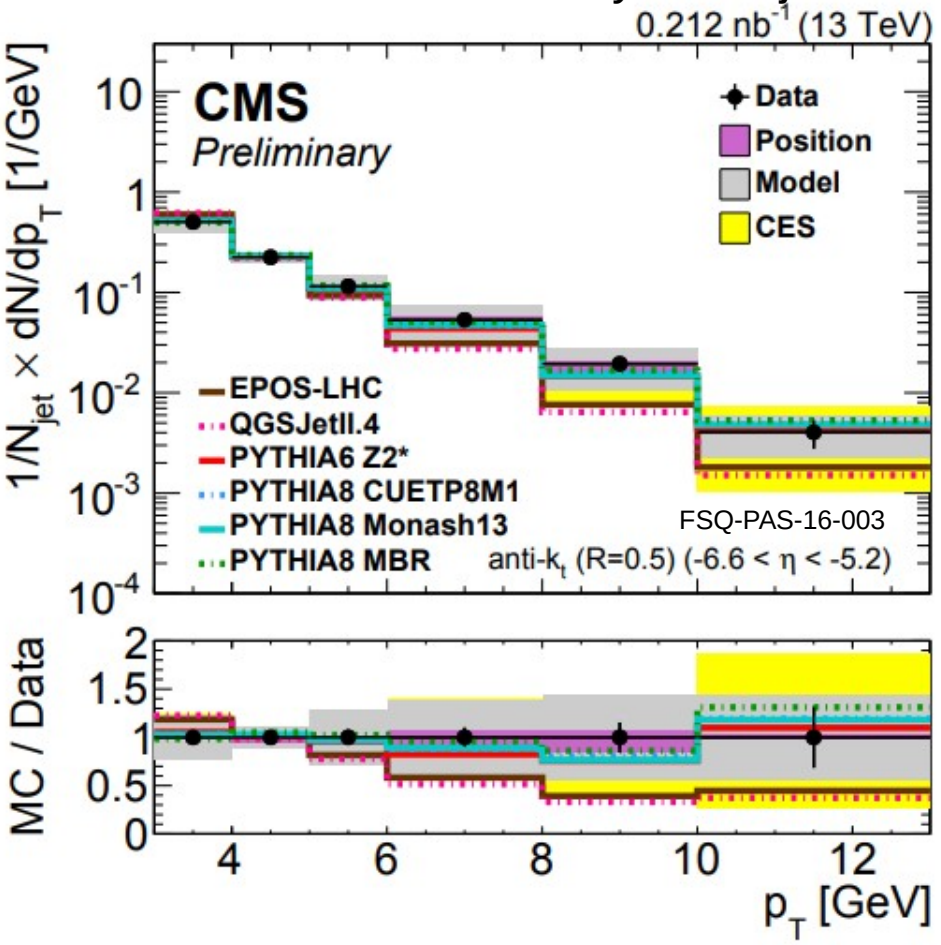
More details in talk by A. Bylinkin

Forward jets@CMS in *pp*

Cross-sections



Yields normalized by total #jets

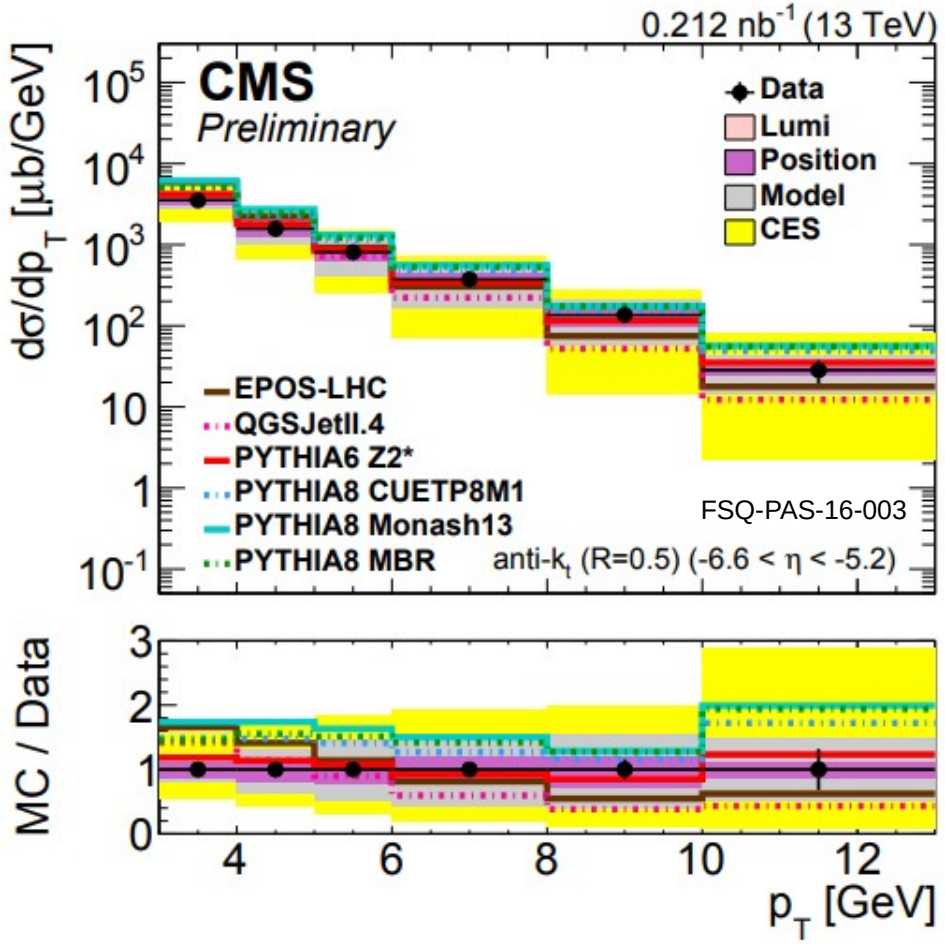


- All models consistent with the data due to the large systematic uncertainties.

More details in talk by Alexander Bylinkin

Forward jets@CMS in *pp*

Cross-sections



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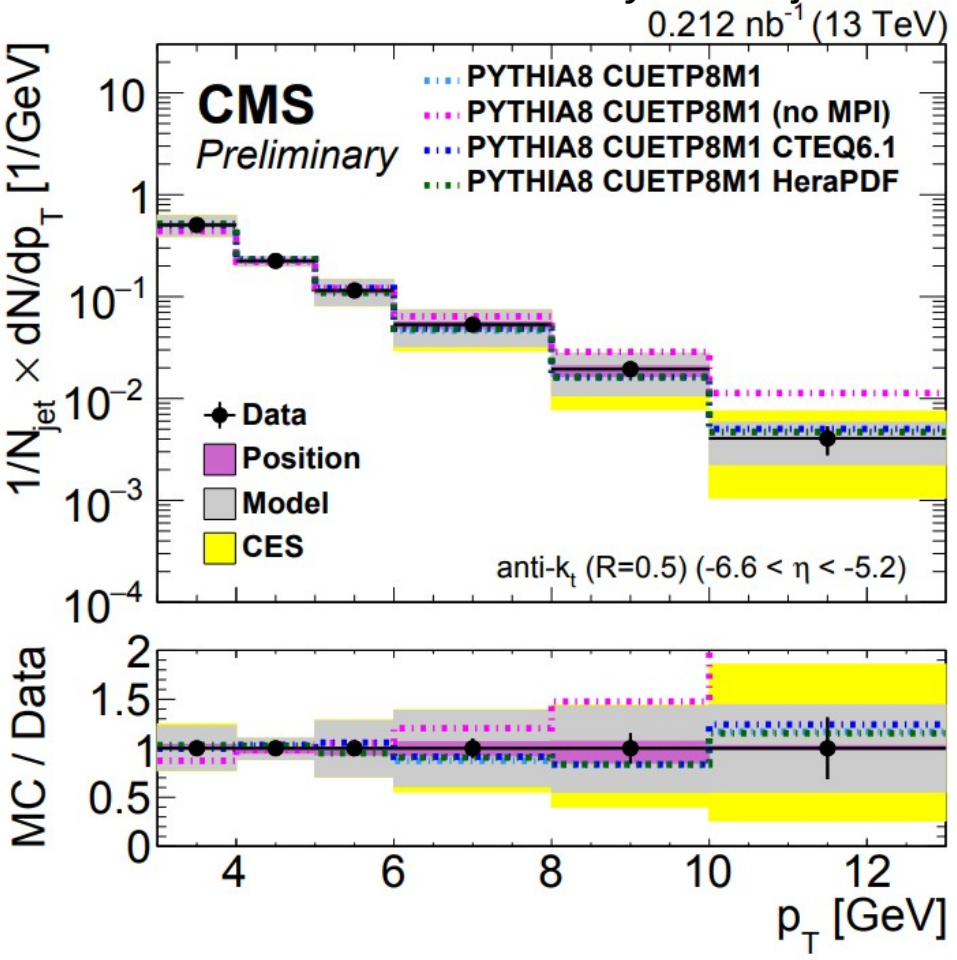
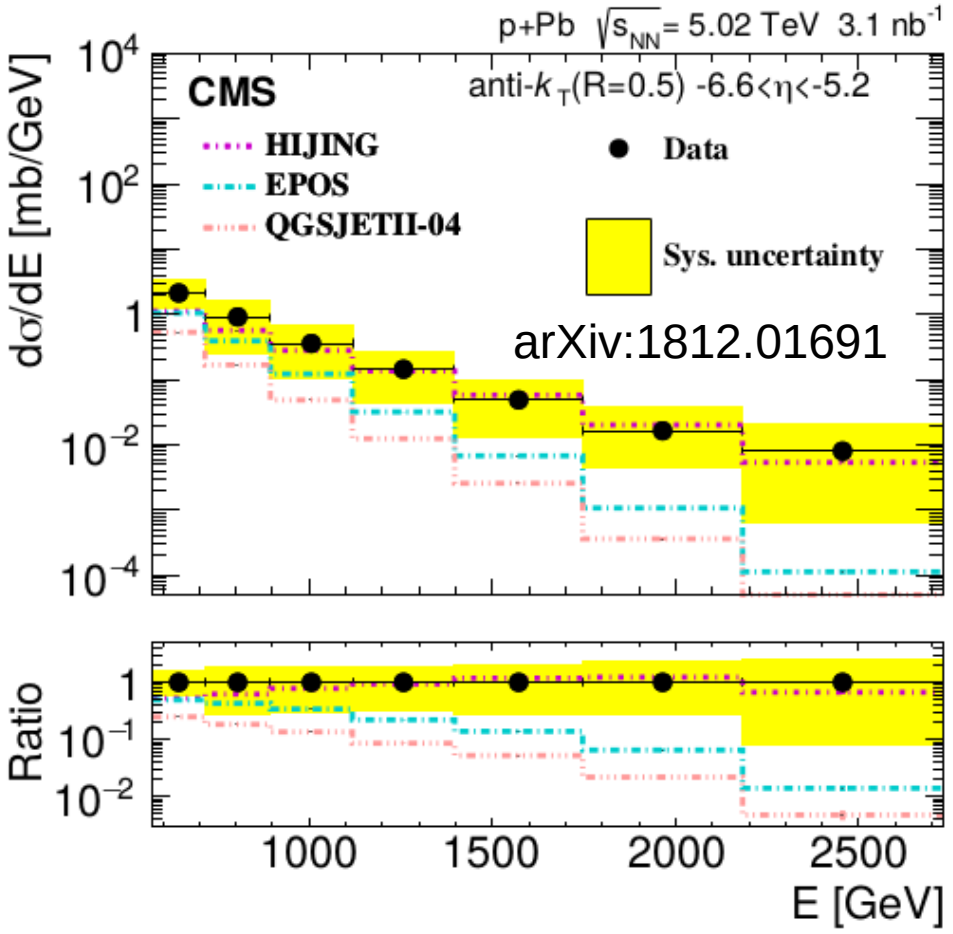


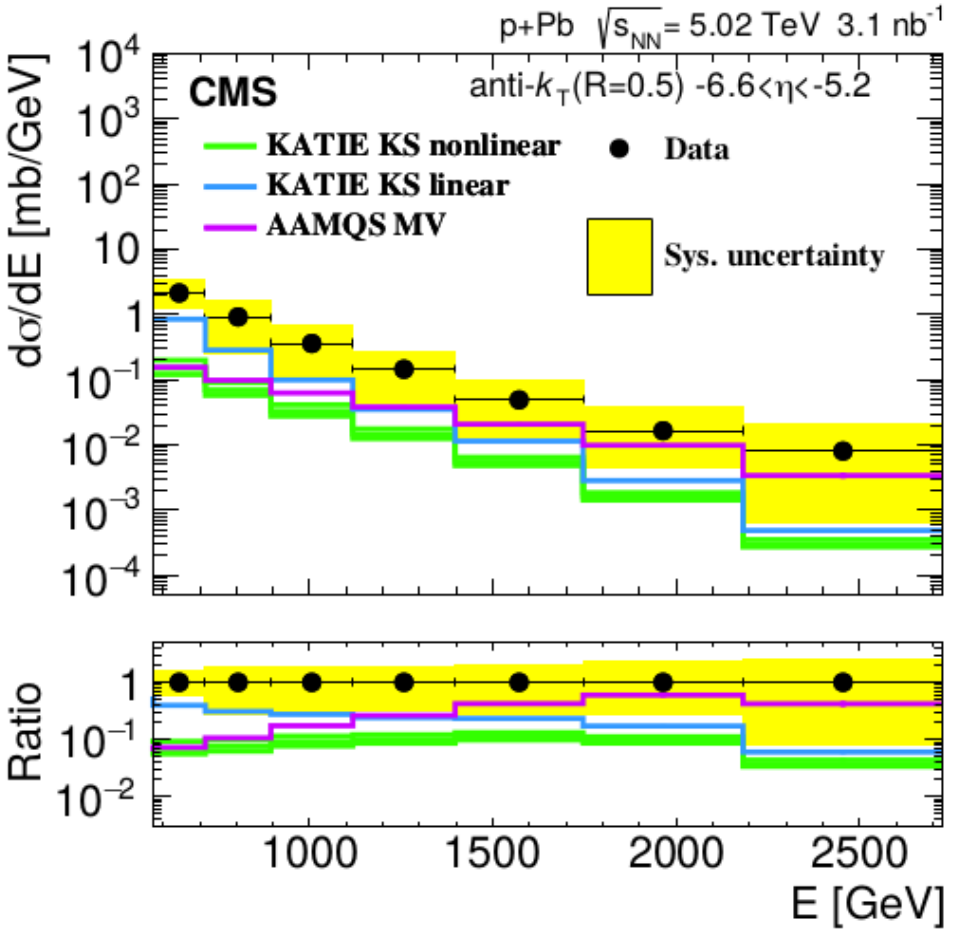
- All models consistent with the data due to the large systematic uncertainties.
- But sensitivity to MPI.

More details in talk by Alexander Bylinkin

Forward jets@CMS in *p*+Pb

- Jet cross-section in **proton** going side in 5.02 ***p*+Pb** collisions.

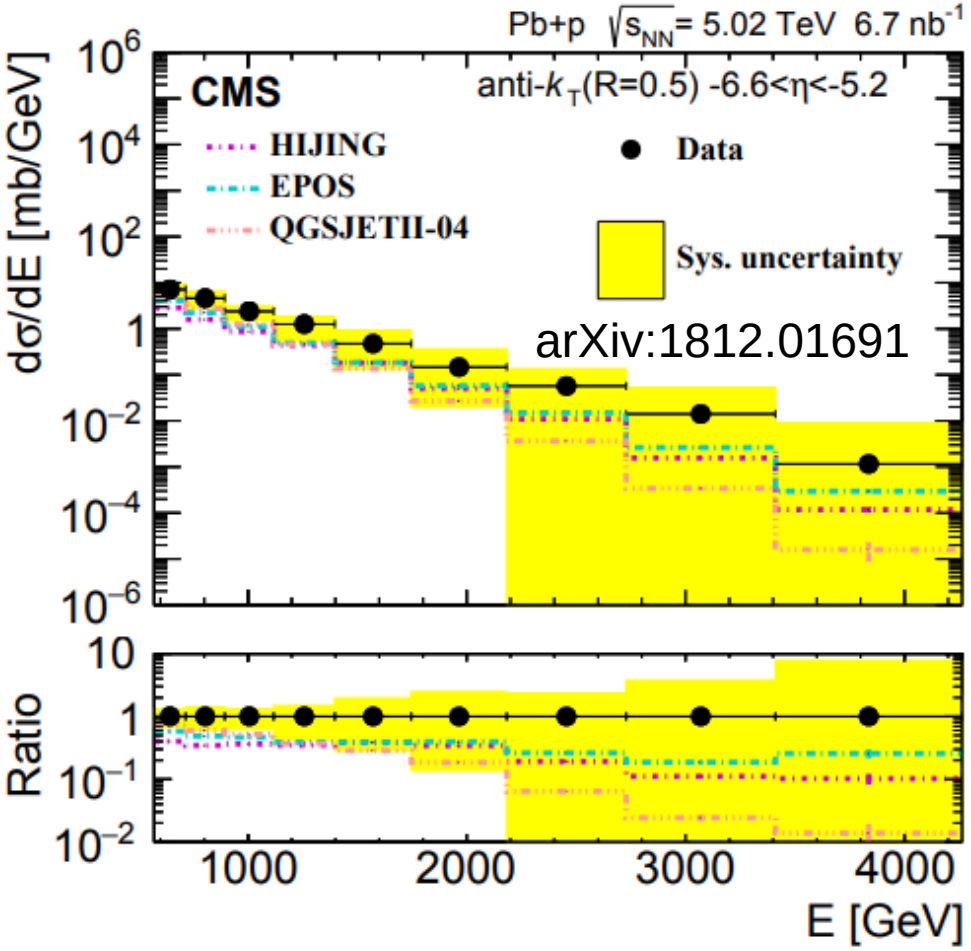


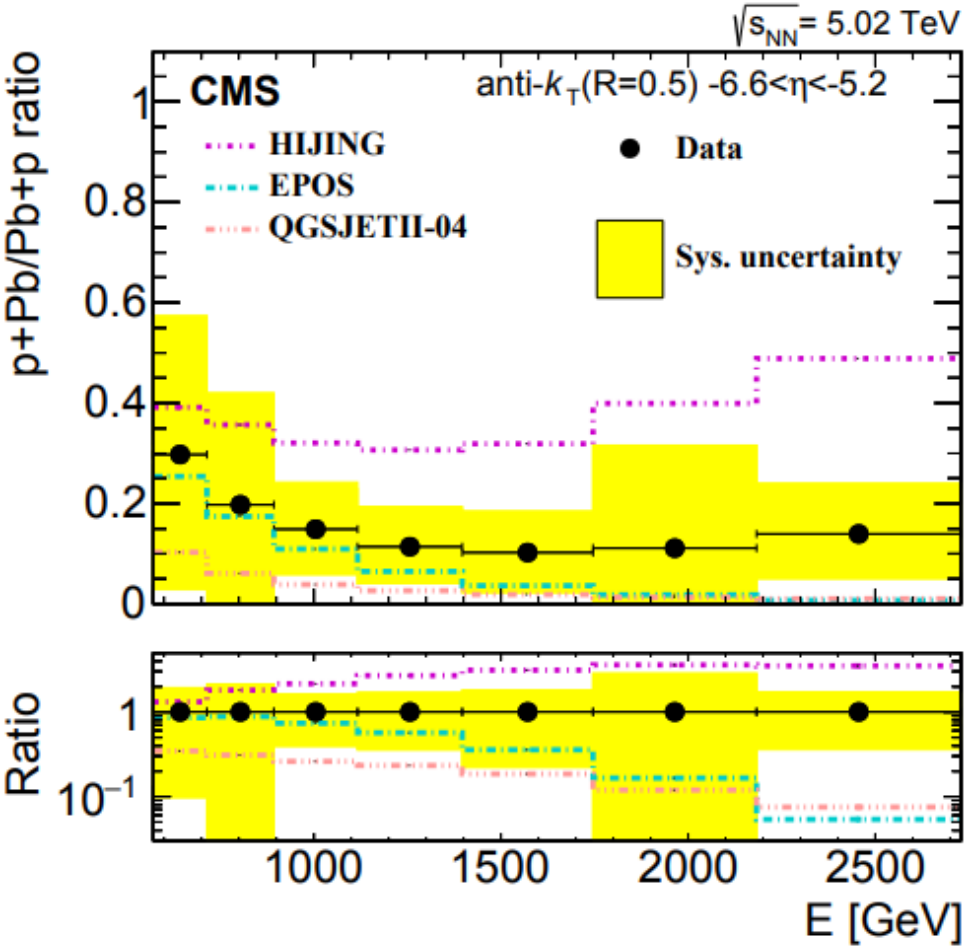


- Despite the large uncertainties data prefers HIJING MC with saturation effects through shadowing.

Forward jets@CMS in *p*+Pb

- Jet cross-section in **lead** going side in 5.02 **Pb+*p*** collisions.





- → Ratios should be directly sensitive to saturation effects + significant cancellation of systematic uncertainties.
- However the interpretation difficult due to different center-of-mass rapidity selection.

Forward dijest@ATLAS in *p*+Pb

- Measurement of forward-forward and forward-central dijet correlations.
- The forward-forward configuration at lowest p_T (28 GeV) probes x down to 1.5×10^{-4}.

More details in talk by D. Perepelitsa

Angular correlations

$$C_{12} = \frac{1}{N_1}\frac{\mathrm{d}N_{1,2}}{\mathrm{d}\Delta\phi}$$

$$W_{12} = \mathrm{RMS}(C_{12})$$

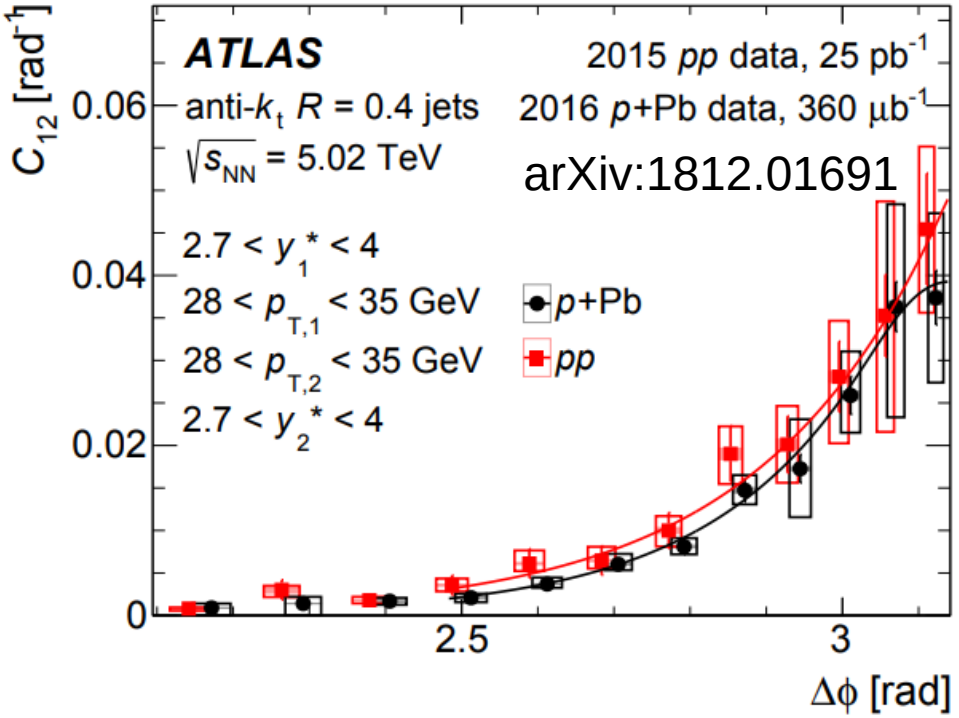
$$\rho_W^{\mathrm{pPb}} = \frac{W_{12}^{p+\mathrm{Pb}}}{W_{12}^{pp}}$$

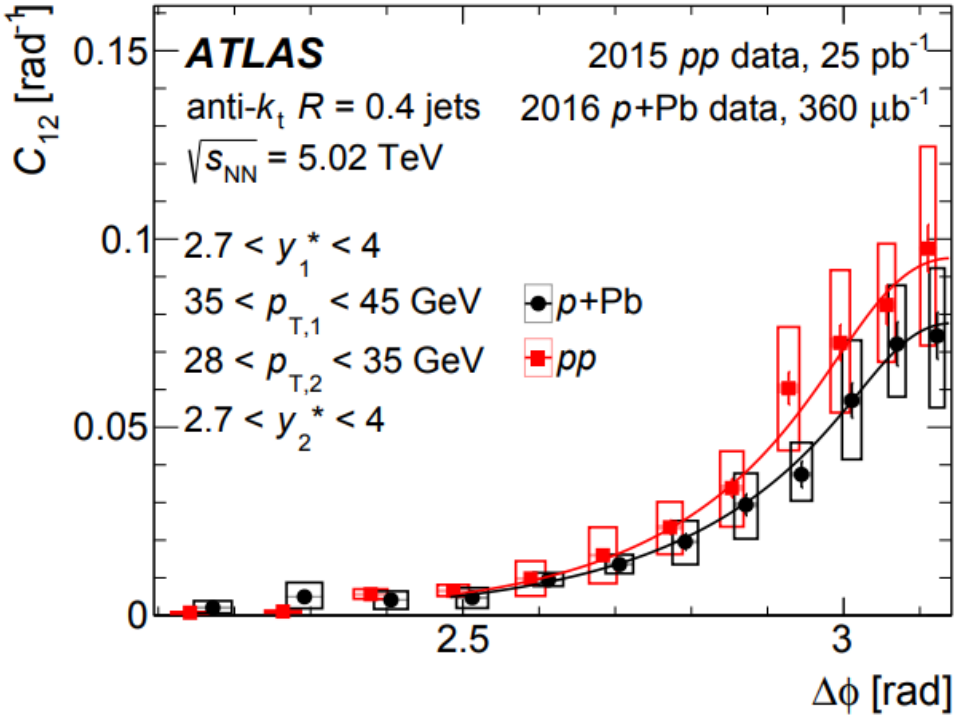
Di-jet conditional yields

$$I_{12} = \frac{1}{N_1}\frac{\mathrm{d}N_{1,2}}{\mathrm{d}y_1^*\mathrm{d}y_2^*\mathrm{d}p_{\mathrm{T},1}\mathrm{d}p_{\mathrm{T},2}}$$

$$\rho_I^{\mathrm{pPb}} = \frac{I_{12}^{p+\mathrm{Pb}}}{I_{12}^{pp}}$$

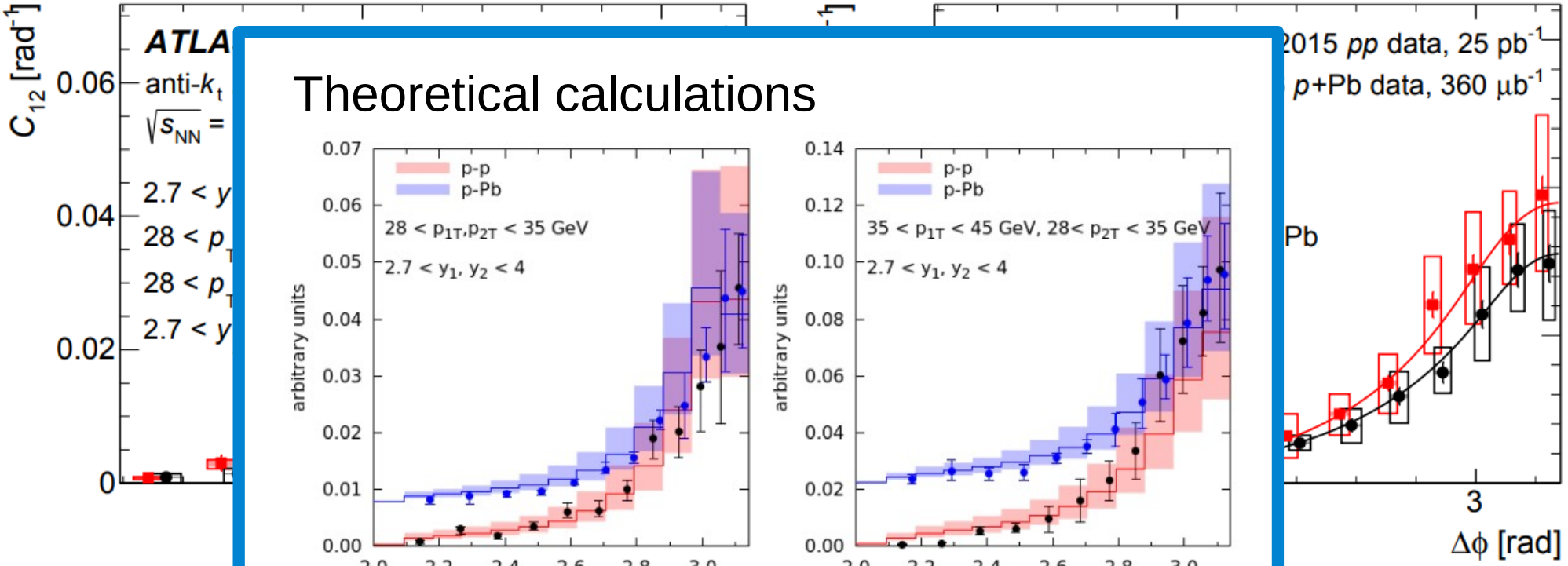
Angular correlations





- No significant changes in shapes but visible changes in integrals, i.e conditional yields

Angular correlations



Theoretical calculations

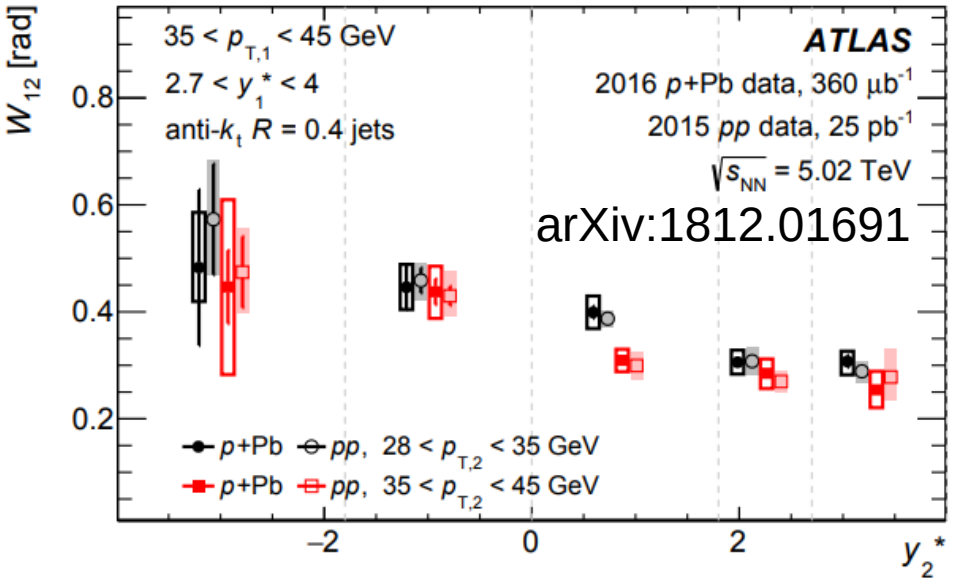
arXiv:1903.01361

Effects due to gluon saturation and the resummation of large logarithms of the hard scale included.

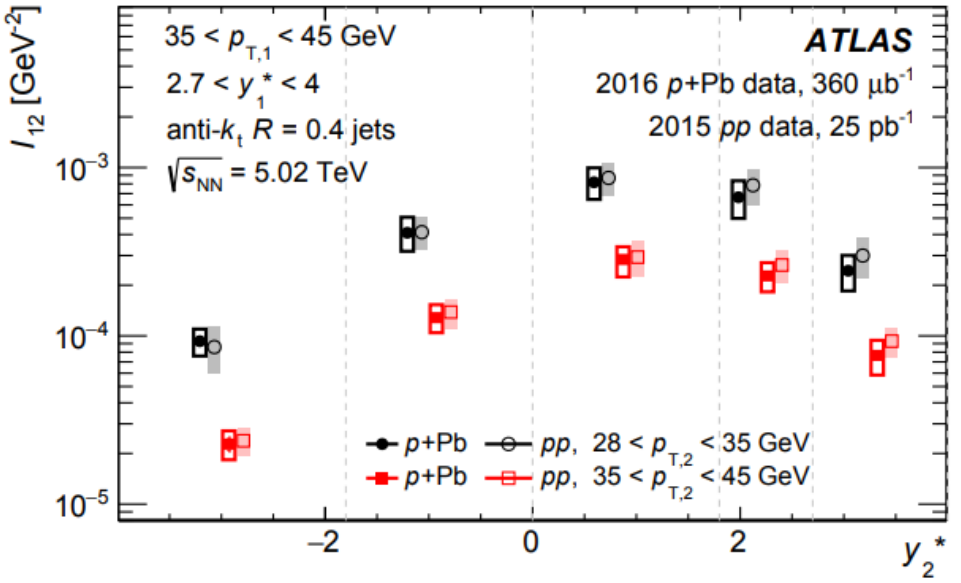
- The for *x* down to 1.5 x 1

Di-jets in *p*+Pb and *pp*

Widths of angular correlations

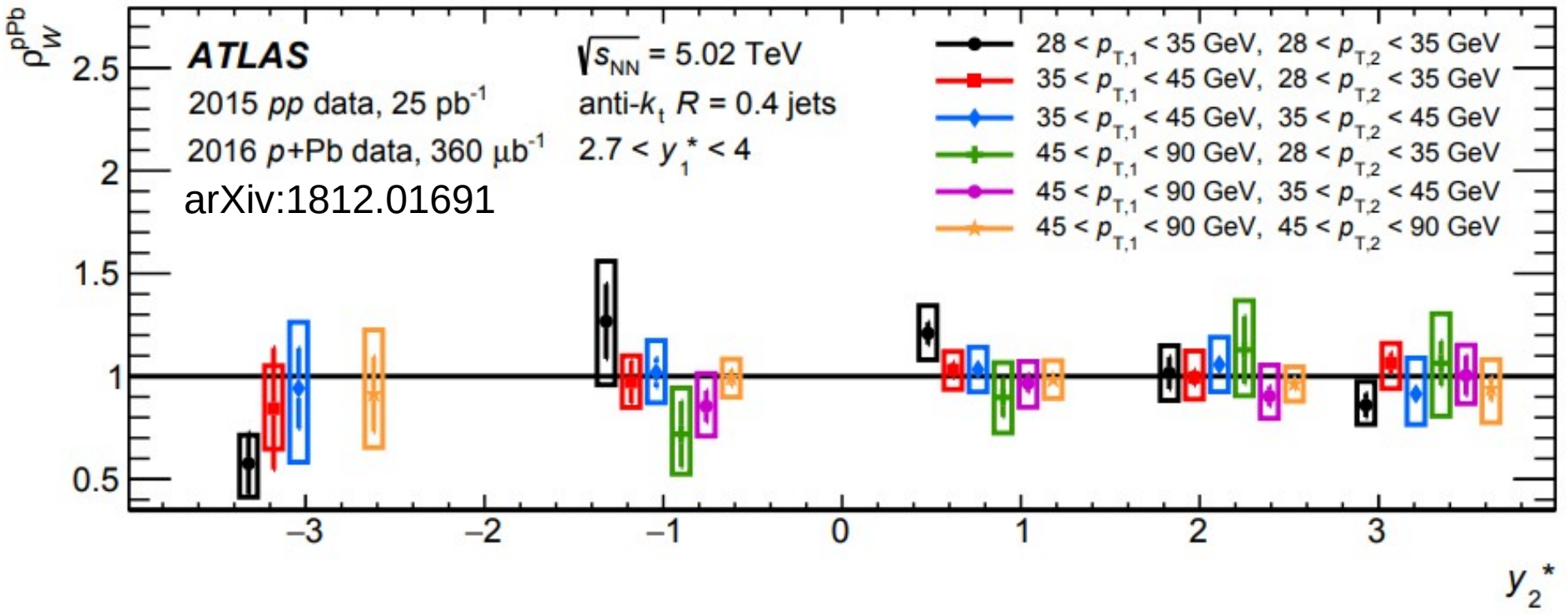


Di-jet conditional yields



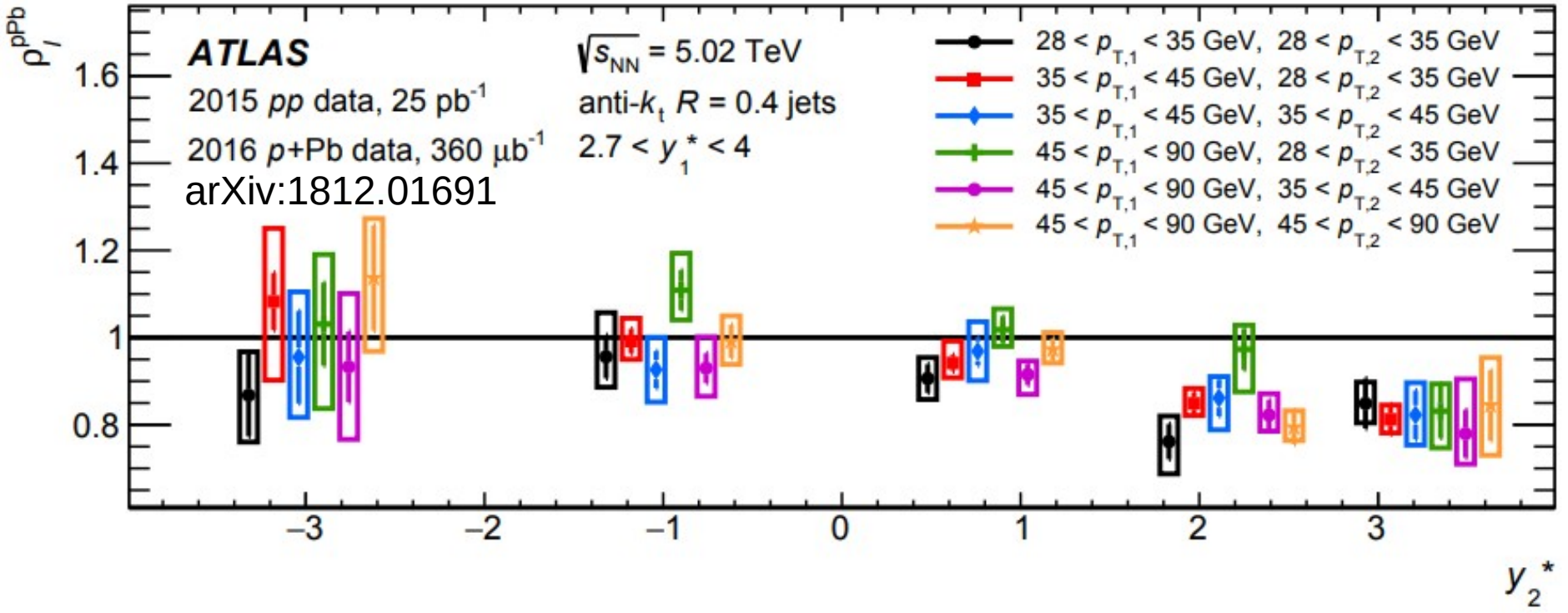
- Widths of azimuthal correlations increase with increasing rapidity separation and p_T imbalance between jets.
- Dependence of yield given by faster decrease of the di-jet cross-section at large rapidity compared to inclusive jet cross-section.

p+Pb vs *pp*: widths



- No significant broadening of azimuthal correlations in *p*+Pb compared to *pp*.

p+Pb vs *pp*: yields

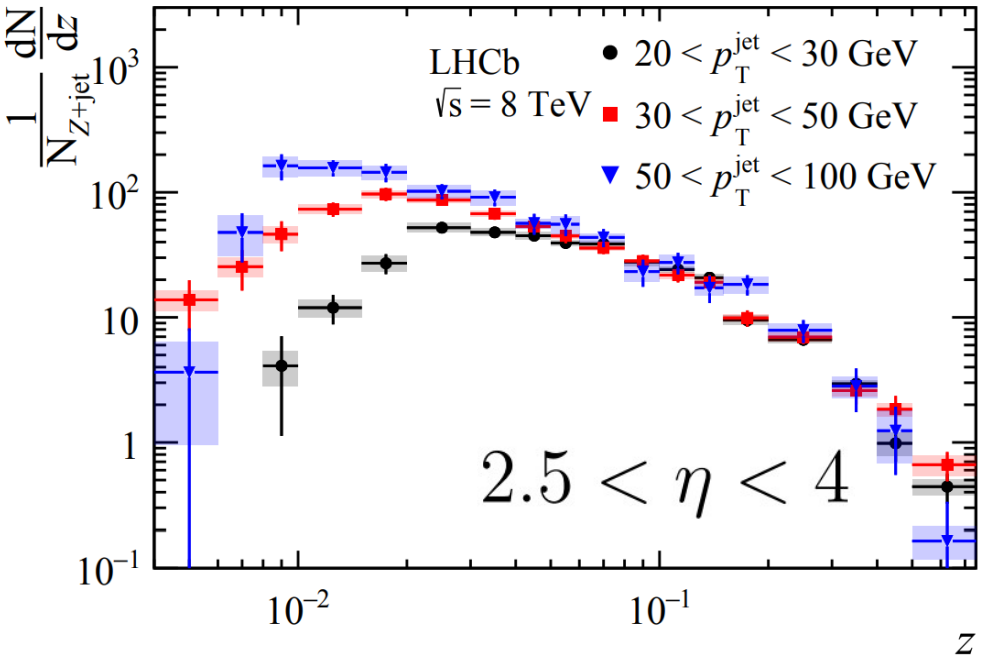


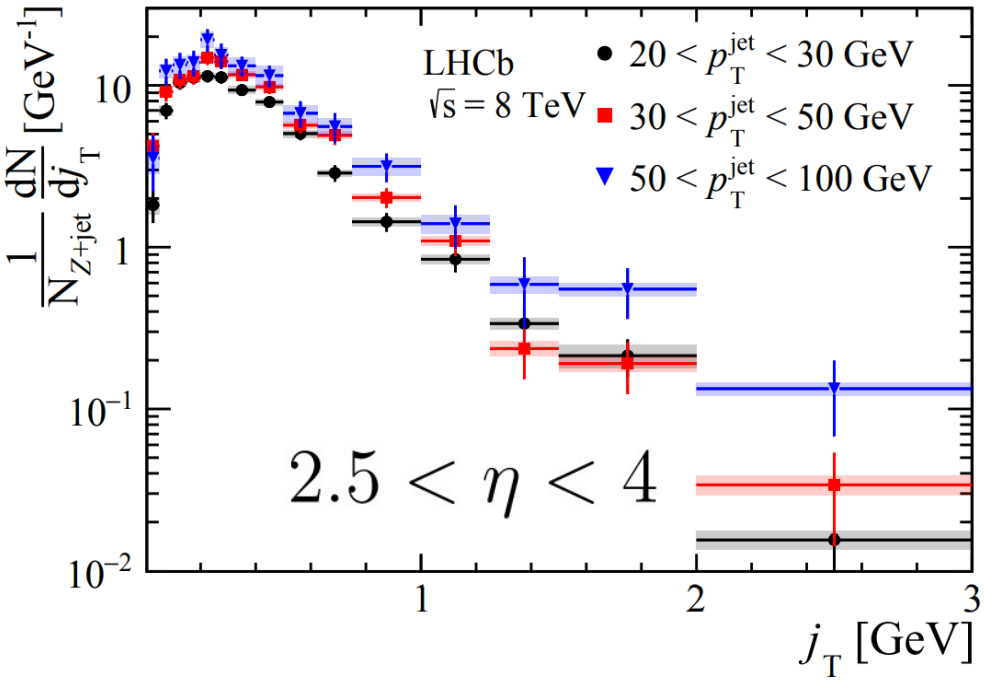
- Up to 20% suppression of conditional yields for forward-forward configuration in *p*+Pb compared to *pp*.
- Together with CMS dijet measurement (arXiv:1812.01691) will improve nPDFs.

Forward jet fragmentation functions@LHCb

- Measurement of longitudinal fragmentation functions and transverse momentum of charged hadrons in Z-tagged forward.

$$z \equiv \frac{\mathbf{p}_{\text{jet}} \cdot \mathbf{p}_{\text{hadron}}}{|\mathbf{p}_{\text{jet}}|^2} \qquad j_{\text{T}} \equiv \frac{|\mathbf{p}_{\text{jet}} \times \mathbf{p}_{\text{hadron}}|}{|\mathbf{p}_{\text{jet}}|}$$





- Dominated by light-quark jets → information about non-perturbative harmonization important also for HI physics.

arXiv:1904.08878

Forward jet fragmentation functions@LHCb

- Measurement of longitudinal fragmentation functions and transverse momentum of charged hadrons in Z-tagged forward.

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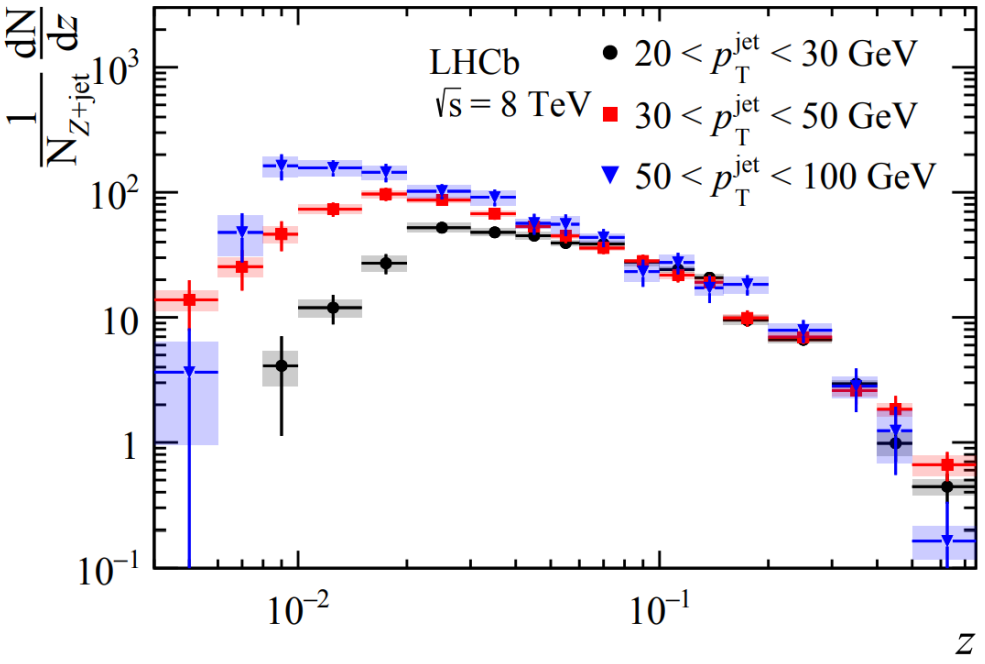
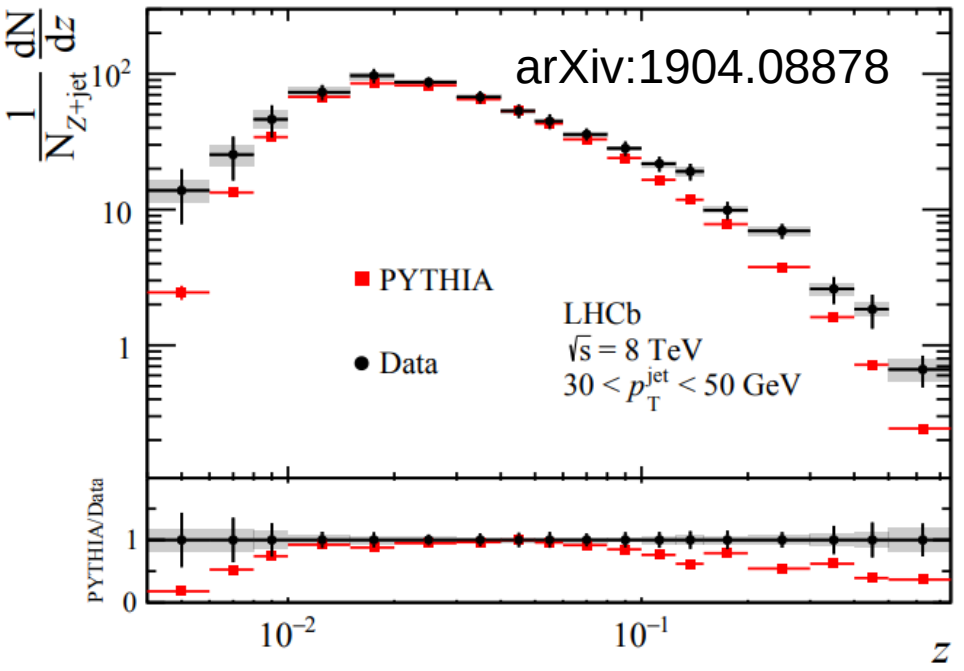




- Significant discrepancy when compared to PYTHIA8.
- Jet cross-section (arXiv1605.00951;not shown) described better .

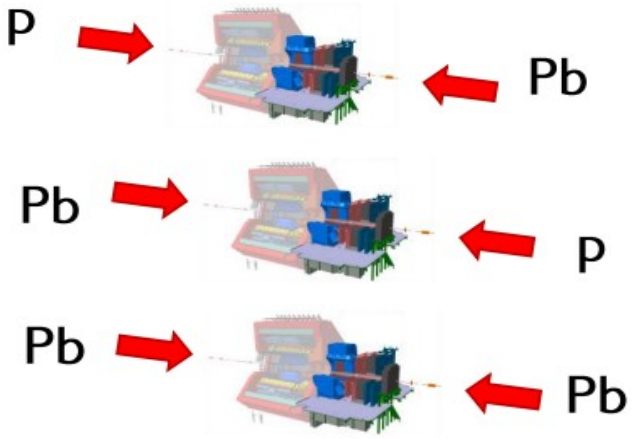
Electroweak bosons@ALICE

- Measurement of Z and W in -4<η<-2.5 in 5.02 TeV Pb+Pb and 8.16 TeV *p*+Pb.

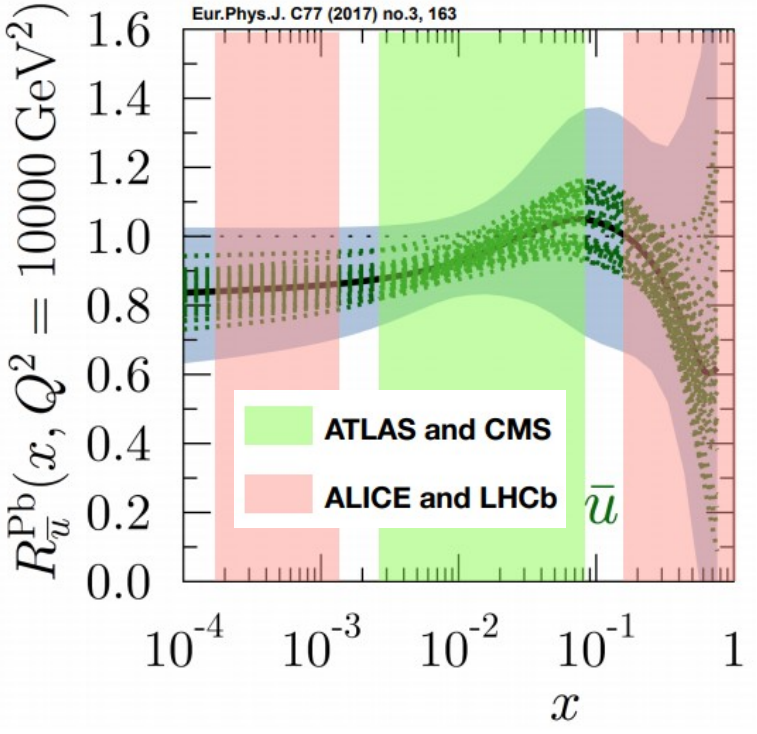
"p-going": $2.03 < y_{\mathrm{cms}} < 3.53$

"Pb-going": $-4.46 < y_{\mathrm{cms}} < -2.96$

Pb-Pb: $2.5 < y_{\mathrm{cms}} < 4$



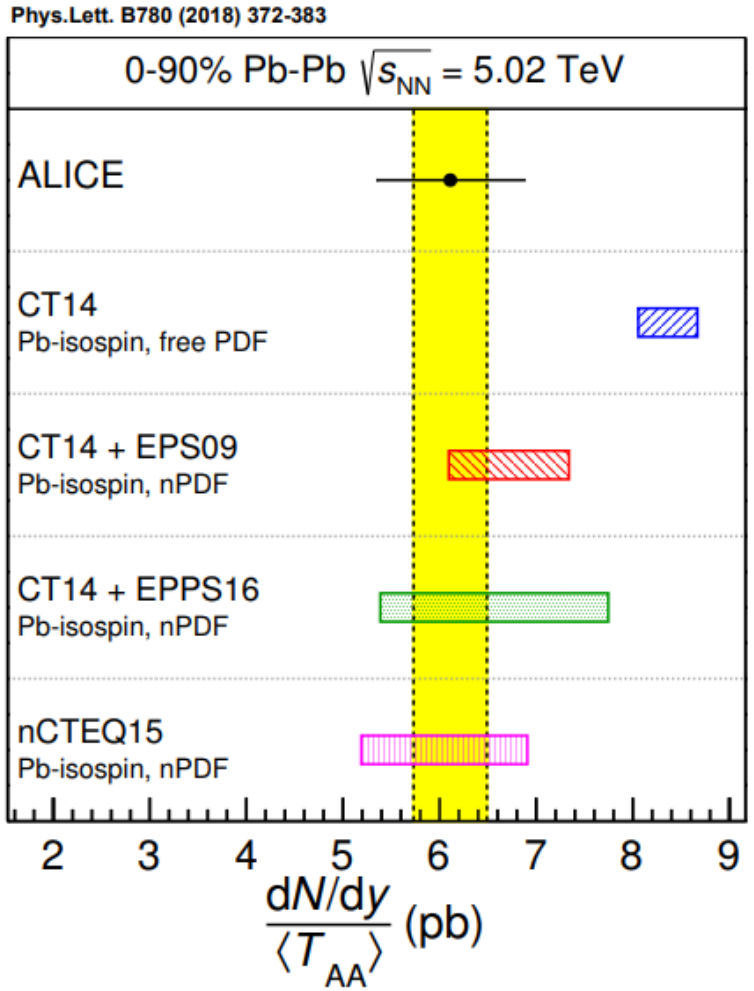
From slides by Nicolo Valle



- Accessing nPDFs in regions of large Q^2.
- Complementary to midrapidity measurements by ATLAS and CMS.

Z bosons@ALICE

Z in 5.02 TeV Pb+Pb collisions

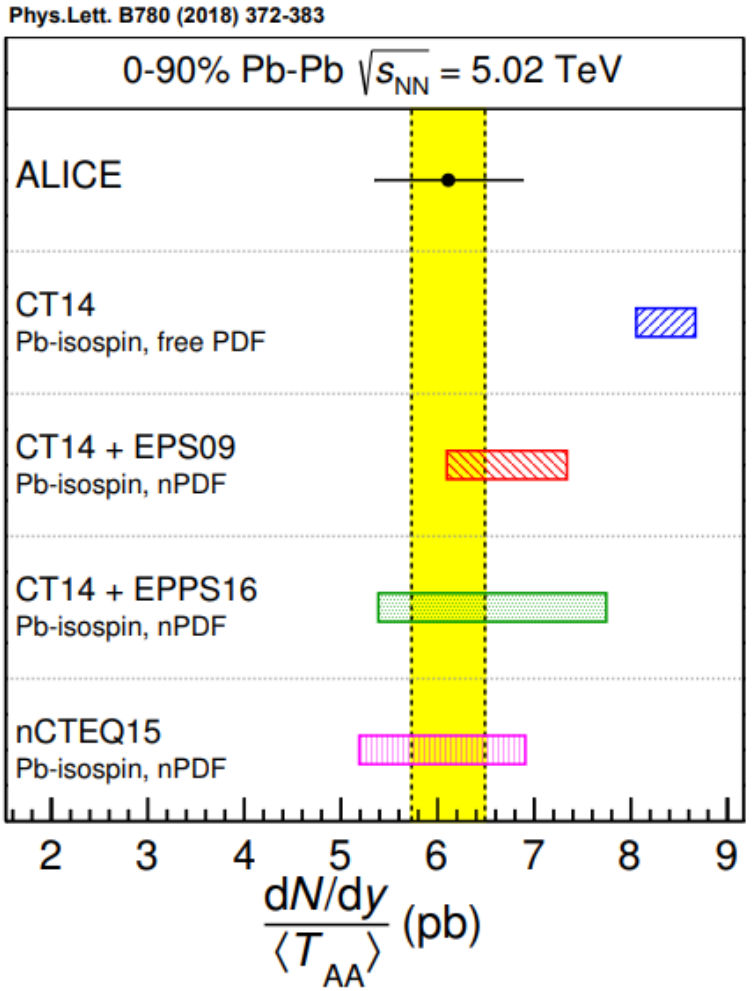


- Yields and R_{AA} (not shown) consistent with nPDF, 2.3σ from free PDF.

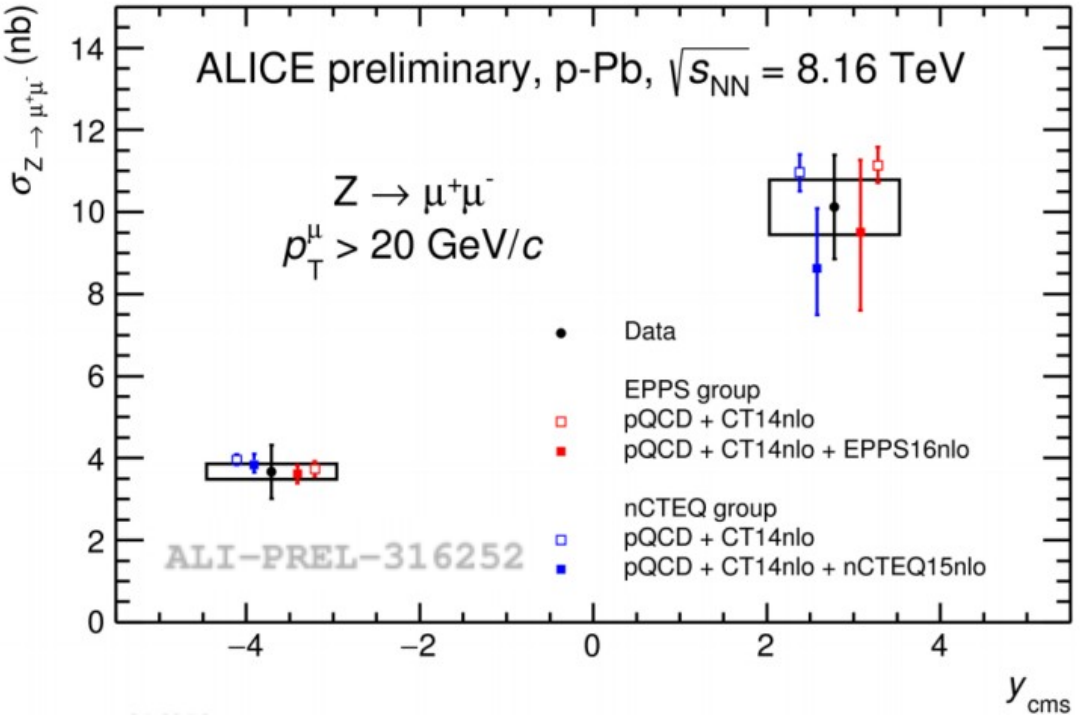
More details in talk by Nicole Valle

Z bosons@ALICE

Z in 5.02 TeV Pb+Pb collisions



Z in 8.16 TeV *p*+Pb collisions



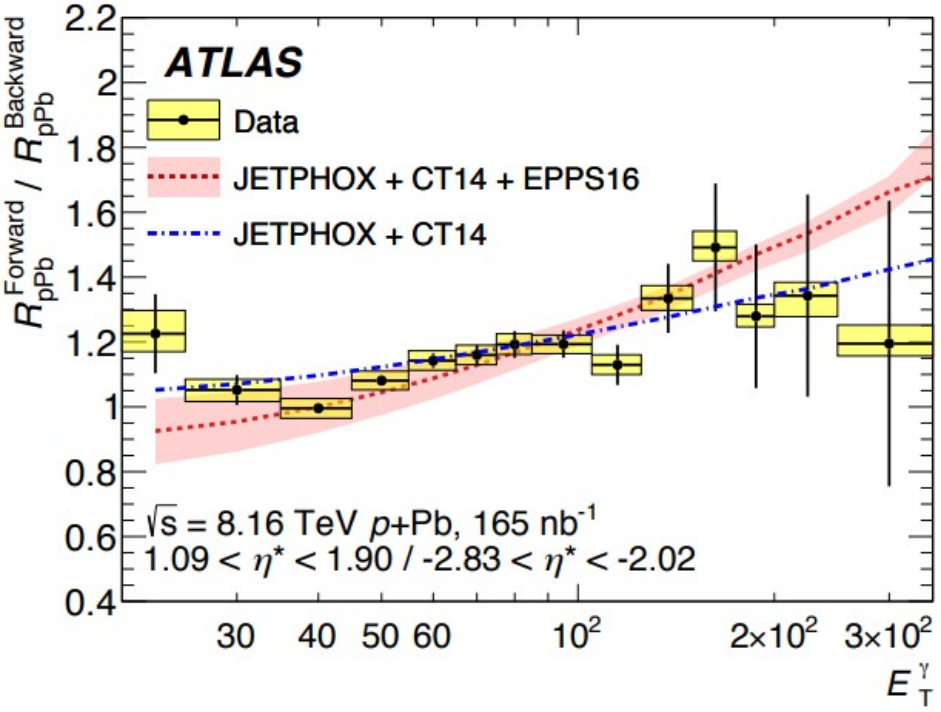
- Current precision of the p+Pb measurement not sufficient for firm conclusions.

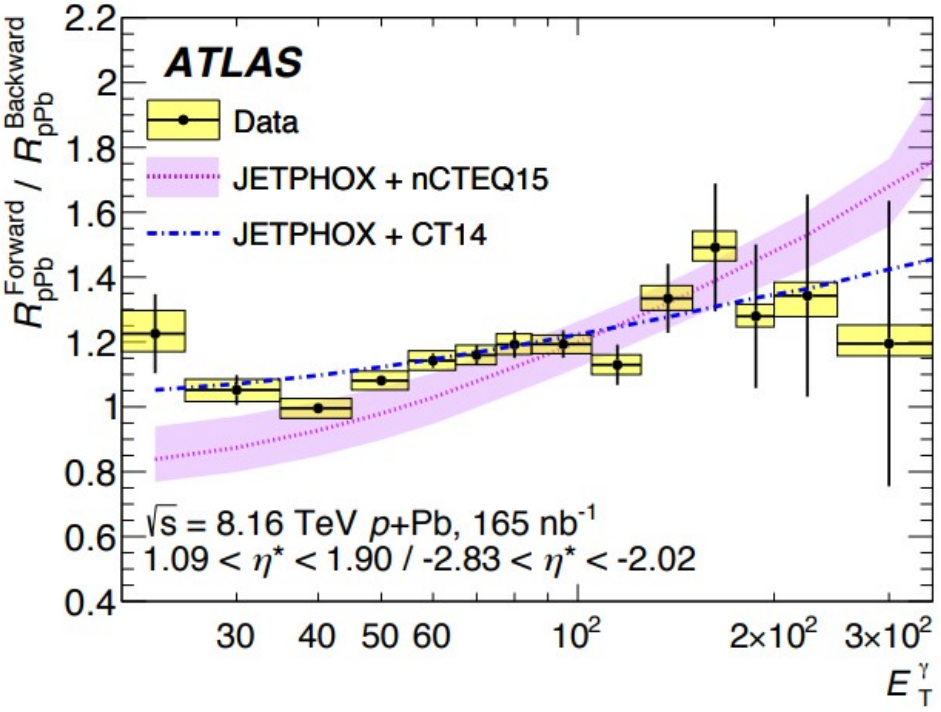
More details in talk by Nicole Valle

Photons@ATLAS

- Photon measurements limited to mid-rapidity and semi-forward regions.
- ATLAS measures of $R_{p\mathrm{Pb}}$ in center-of-mass rapidity from -2.83 up to 1.90.

Forward/backward $R_{p\mathrm{Pb}}$ ratio





- Sensitive to gluon shadowing/quark anti-shadowing at low E_{T}.
- Data seems to be more compatible with free PDFs.

More details in talk by D. Perepelitsa.

Forward Heavy-Flavours @ALICE&LHCb

- Test pQCD calculations, MPIs and CNM in *p*+Pb collisions.
- Access to different *x* and Q^2 region compared to EW bosons.
  - Low-x down to ~10^{-6} @ forward rapidity & high-x ~10^{-2} in backward rapidity

Forward Heavy-flavours @LHCb

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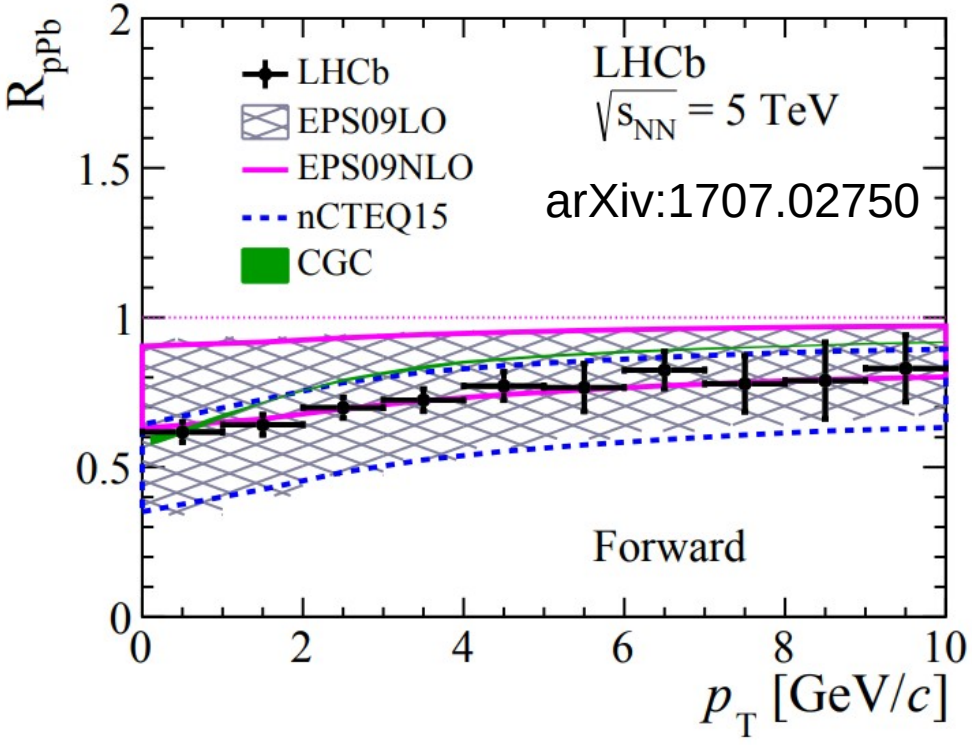
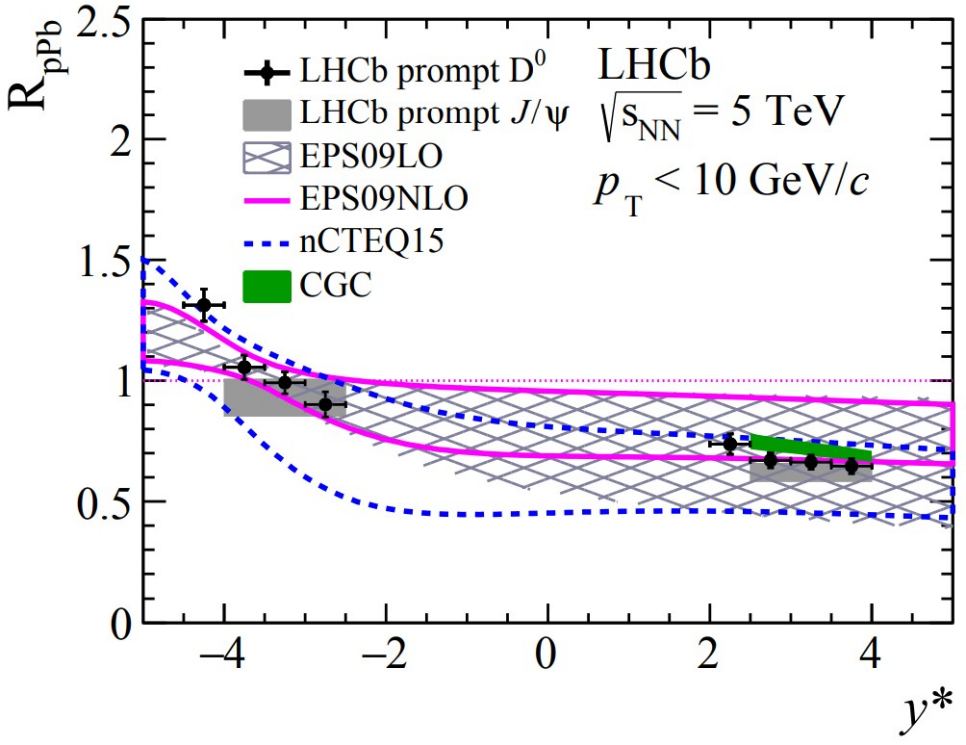
Fully reconstructed promt D^0 by LHCb





- Can provide constrain on gluons nPDFs.
- Similar measurement of forward B^+,B^0,Λ_b^0 production in 8.02 TeV *p*+Pb.

Forward Heavy-flavours @LHCb

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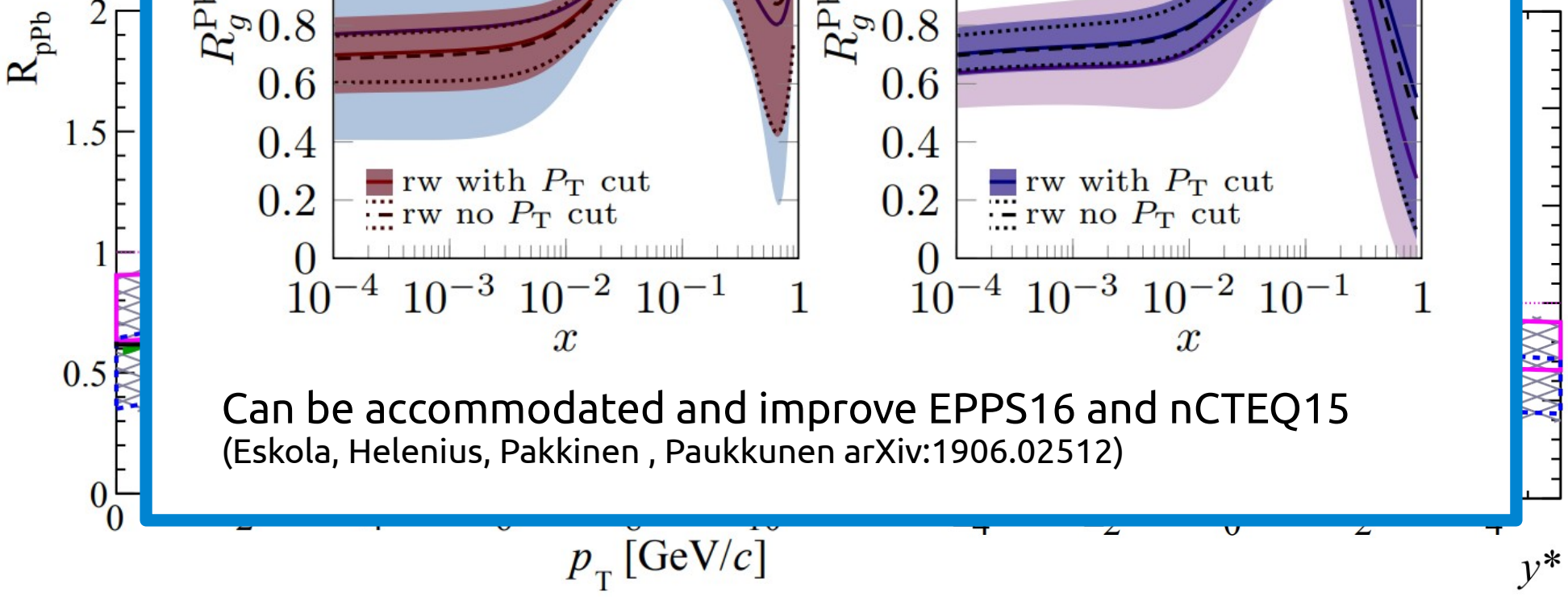


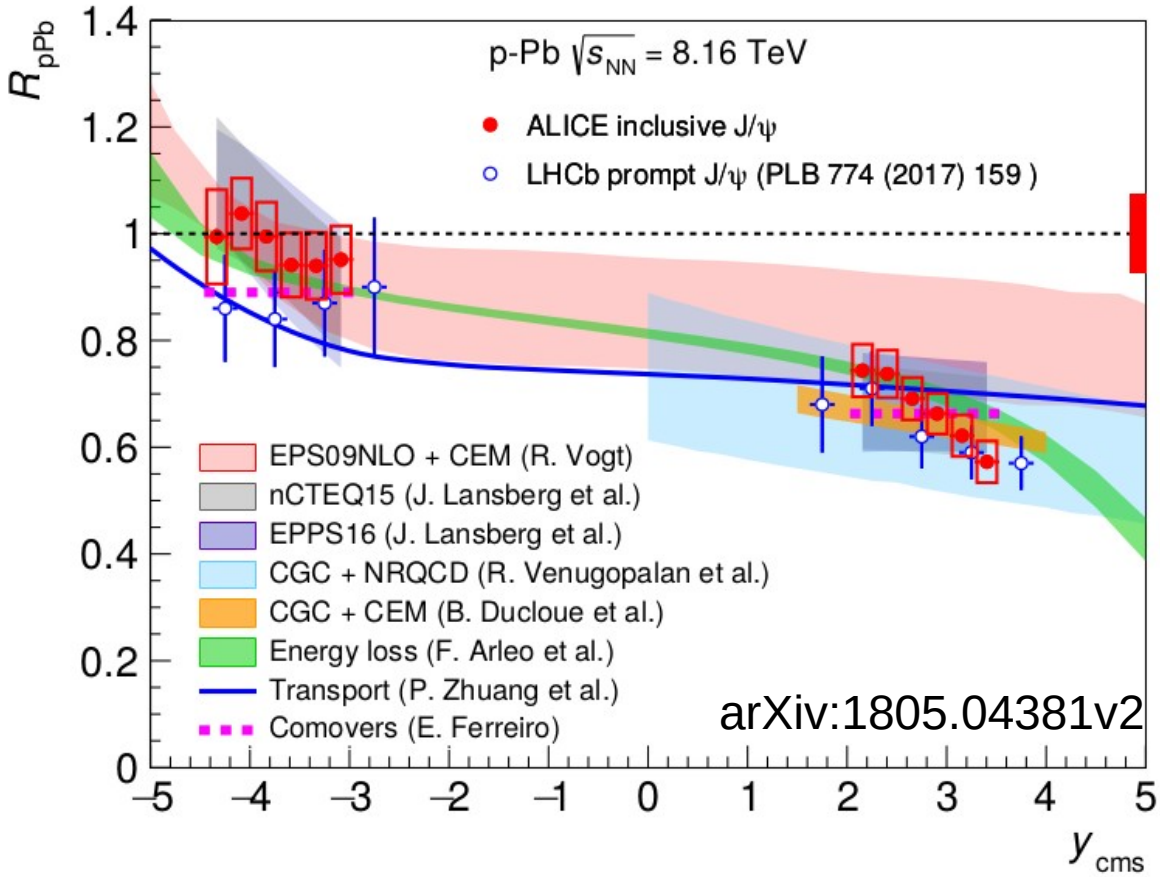
Can be accommodated and improve EPPS16 and nCTEQ15
(Eskola, Helenius, Pakkinen , Paukkunen arXiv:1906.02512)

- Can provide constrain on gluons in (anti)shadowing regions.

Quarkonia@ALICE&LHCb

- Sensitive to gluon PDFs.
- Production mechanism not fully understood.
  - In HI collisions affected also by MPIs, breakup with co-moving particles, energy loss.

J/Ψ measurements:



- Suppression in forward rapidity well described by various models.
- LHCb (promt) and ALICE (inclusive) results in good agreement.

Quarkonia@ALICE&LHCb

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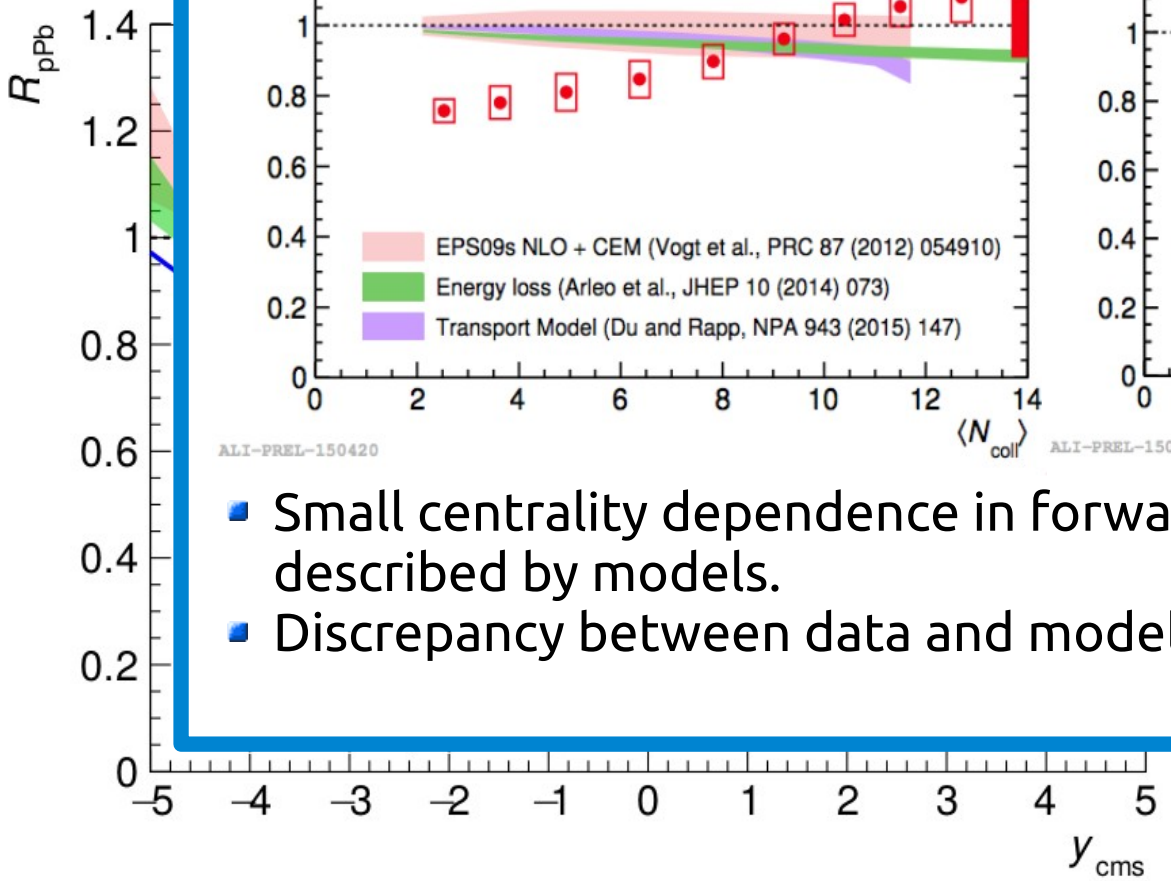
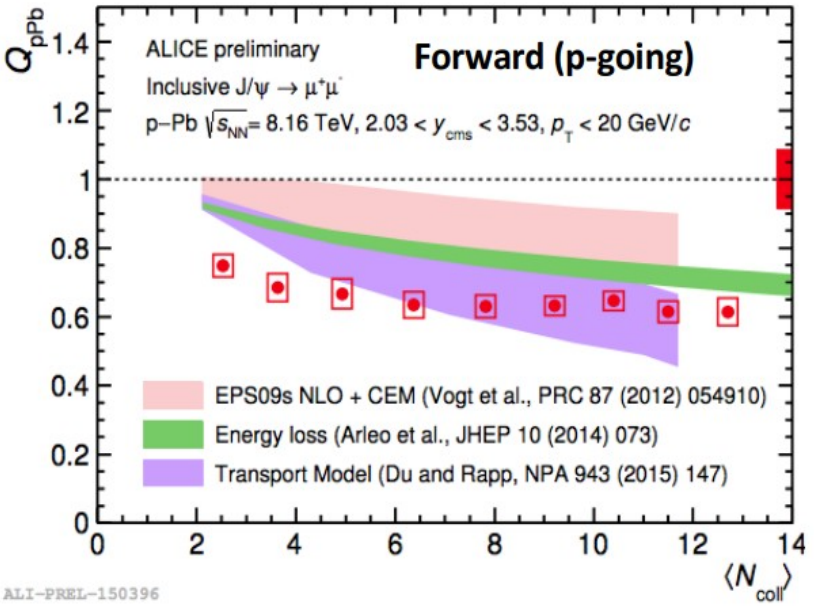


Centrality dependence

More details in talk by S. Hayashi



- Small centrality dependence in forward region qualitatively described by models.
- Discrepancy between data and model in Pb-going side.

Quarkonia@ALICE&LHCb

- Sensitive to gluon PDFs.
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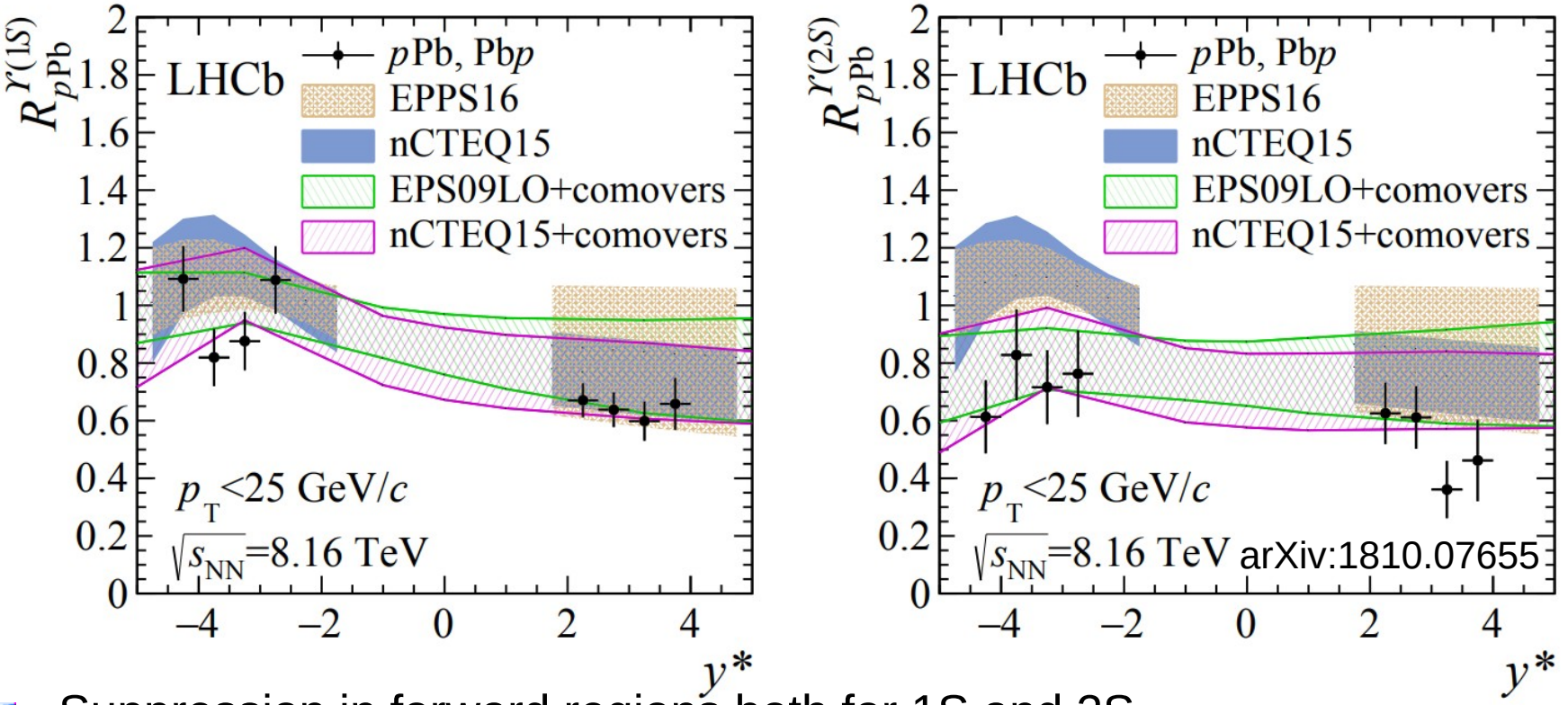
  - In HI collisions affected also by MPIs, breakup with co-moving particles, energy loss.

Y measurements in 8.16 TeV *p*+Pb (LHCb):



- Suppression in forward regions both for 1S and 2S.
- R_{pPb} (1S) > R_{pPb} (2S) and well modeled with comovers models.

Quarkonia@ALICE&LHCb

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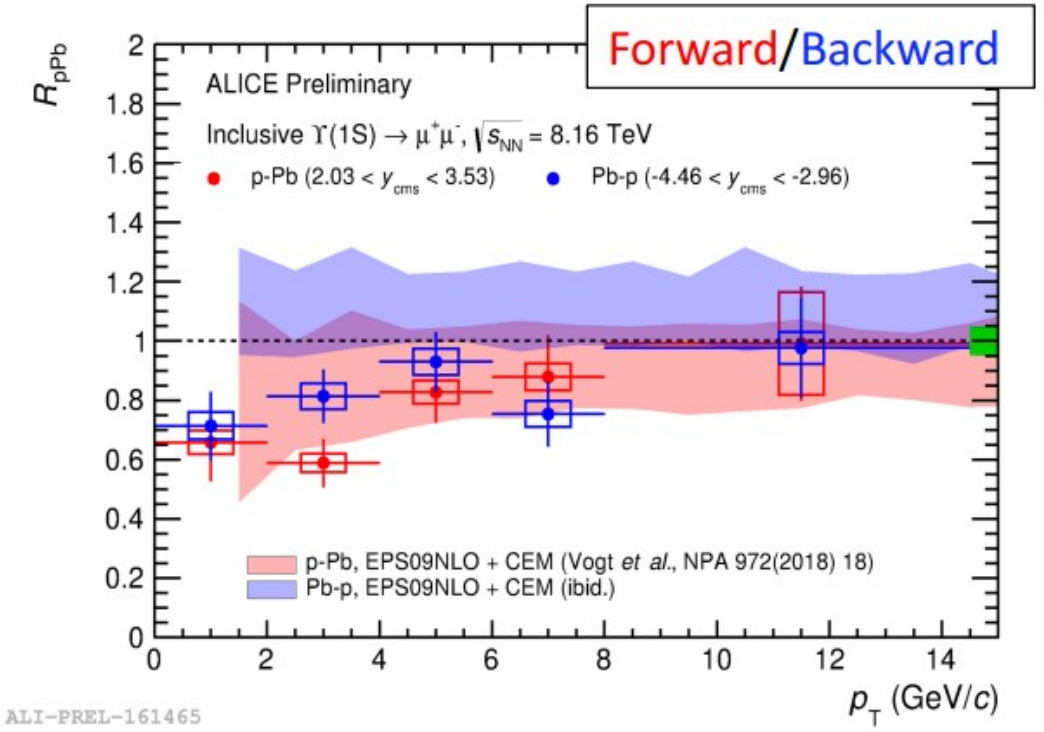
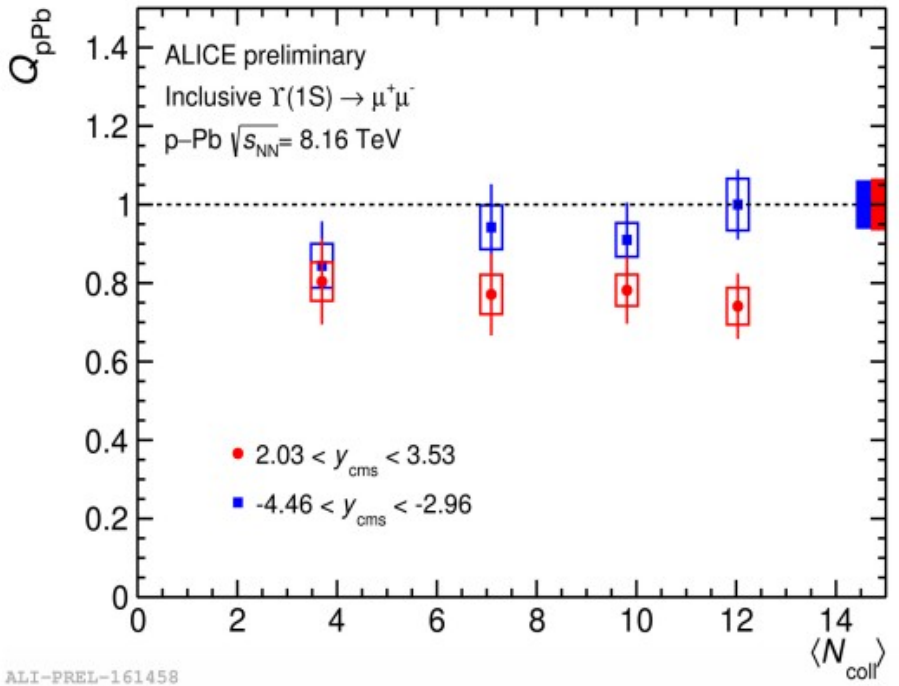
  - In HI collisions affected also by MPIs, breakup with co-moving particles, energy loss.

Y(1s) measurements in 8.16 TeV *p*+Pb (ALICE):

More details in talk by Shinichi Hayashi





- Models describes forward region but overestimate backward.
- No significant centrality dependence.

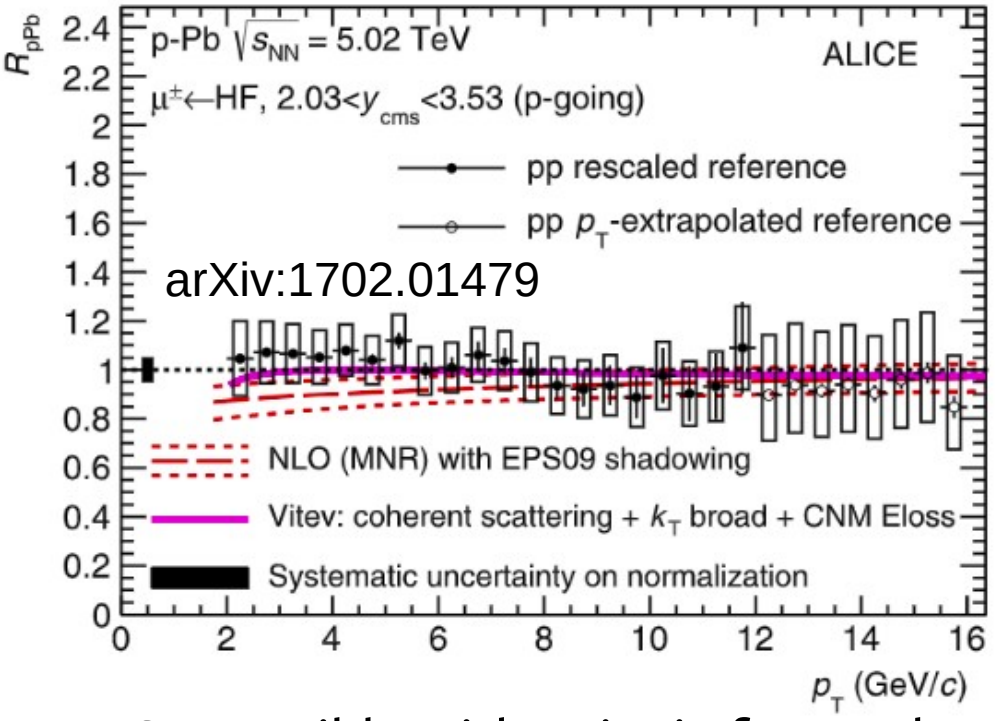
Summary

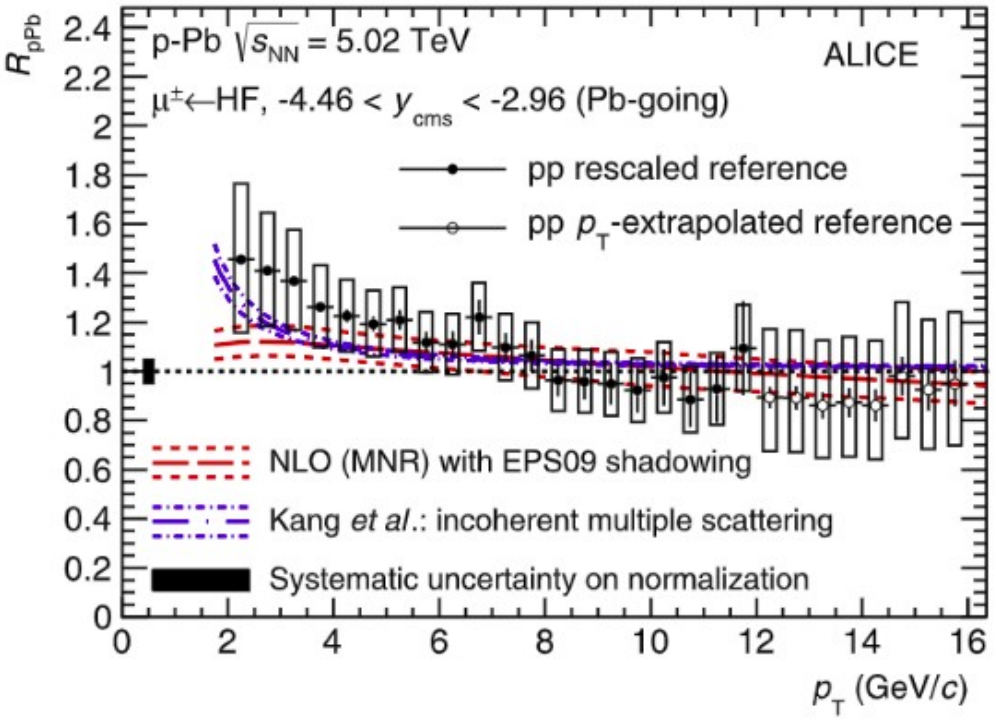
- Every LHC experiment has has unique capabilities for various forward hard probes measurements.
- We are gaining understanding of the structure of the nuclei by exploiting asymmetric *p*+Pb collisions.
- Forward jet measurements:
  - Very important benchmarks for the understanding and improvement of the soft/small-x modeling of the hadron collision interaction.
  - Further improvement in precision and kinematic reach will put stronger constrain on models.
  - New information about hadronization & fragmentation.
- Heavy flavours, EW bosons, and quarkonia measurements:
  - Test different suppression mechanisms.
  - Provide significant improvement on nPDFs.
- Lack of calorimetric forward measurements in large systems.

Forward Heavy-flavours @ALICE

- Test pQCD calculations, MPIs and CNM in *p*+Pb collisions.
- Access to different *x* and Q^2 region compared to EW bosons.
  - Low-x down to ~10^{-6} @ forward rapidity & high-x ~10^{-2} in backward rapidity

Muons from HF decays@ALICE





- Compatible with unity in forward region; deviation from binary scaling at low-p_T in backward.

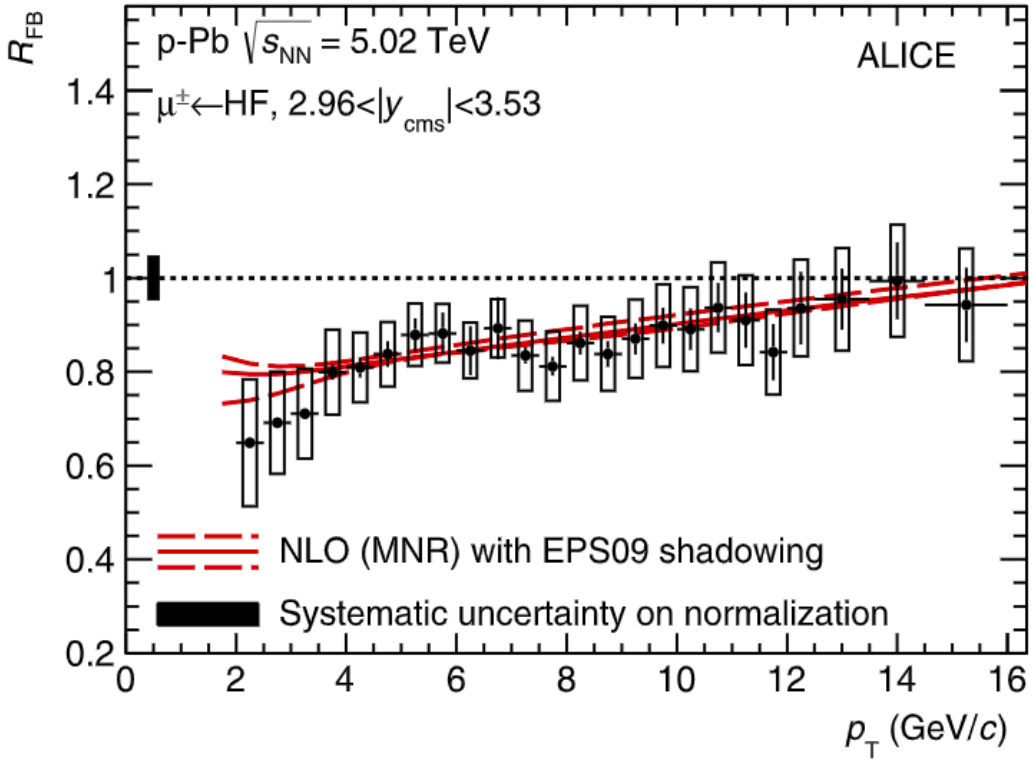
Forward Heavy-flavours @ALICE

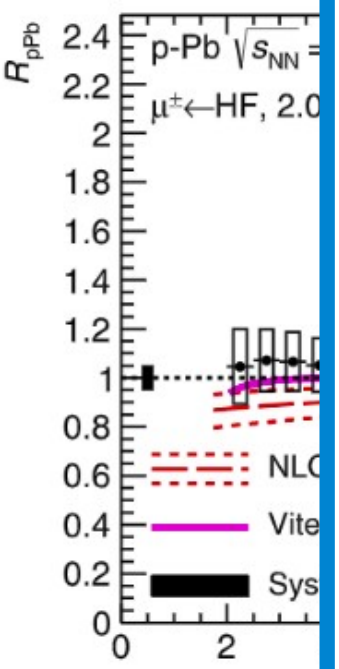
- Test pQCD calculations, MPIs and CNM in *p*+Pb collisions.
- Access to different *x* and Q^2 region compared to EW bosons
  - Low- … ckward rapi…

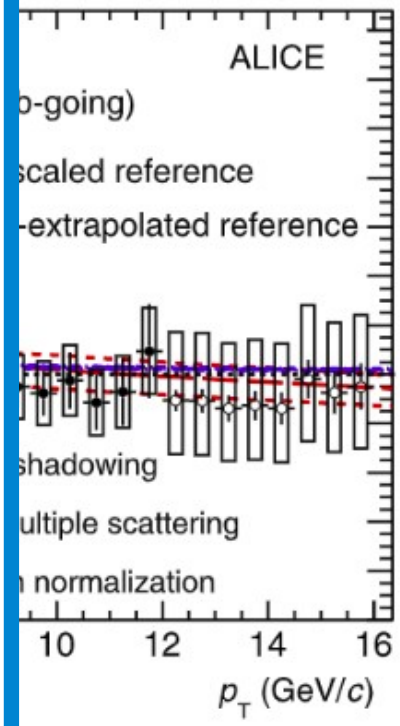
Muons from …

Forward-backward ratio

arXiv:1702.01479







Forward dijest@ATLAS in *p*+Pb

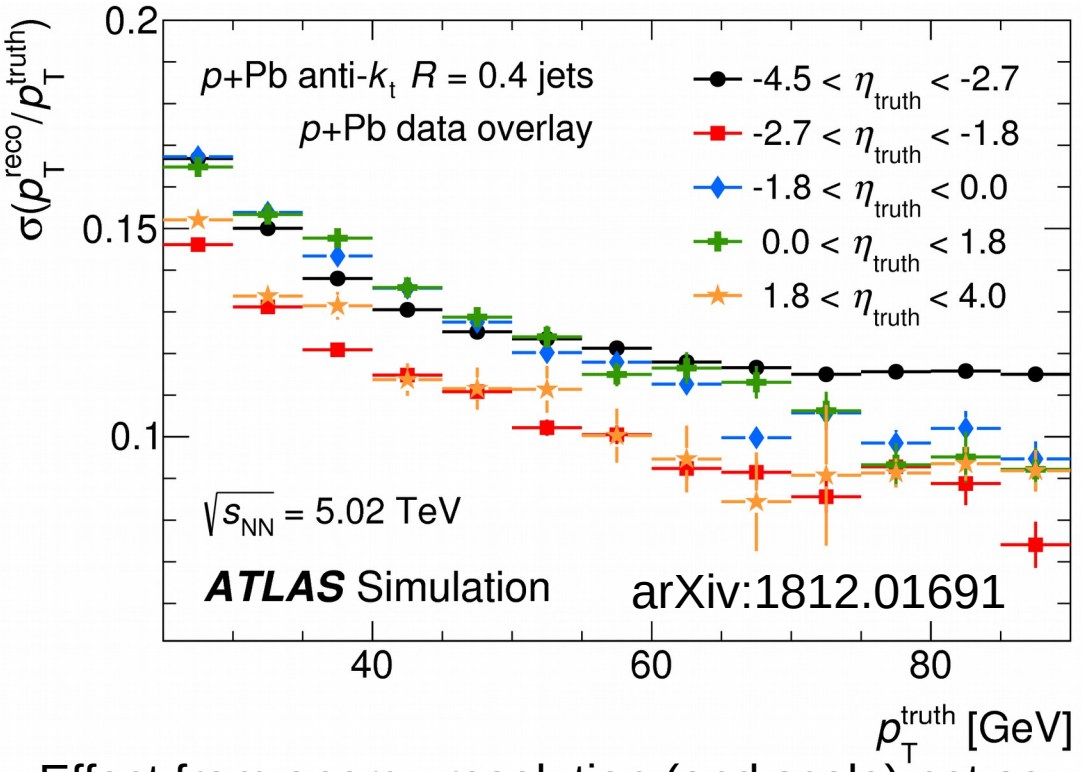
- Measurement of forward-forward and forward-central dijet correlations
- The for… …V) probes *x* down t…

Ang… …ds

$$C$$ … $$\mathrm{d}p_{\mathrm{T},1}\mathrm{d}p_{\mathrm{T},2}$$

$$W$$

$$\rho_W^{\mathrm{p}} = \frac{}{W_{12}^{pp}} \qquad \rho_I^{\prime} = \frac{}{I_{12}^{pp}}$$



Effect from energy resolution (and scale) not so dramatic as in the very forward region.
→ able to use simply bin-by-bin unfolding.