EW and nPDF in HIC: Experimental review

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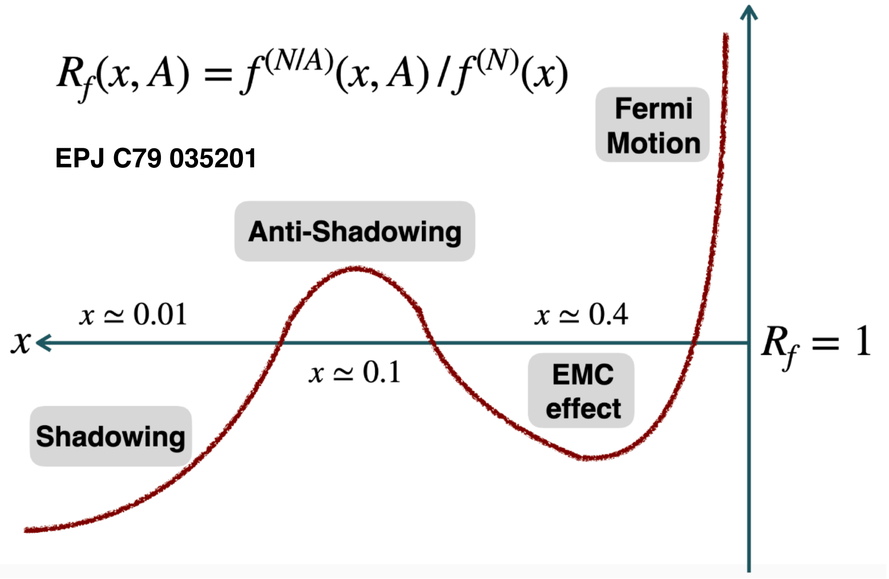
Snowmass meeting,
EF07: Electroweak and nPDF in HIC

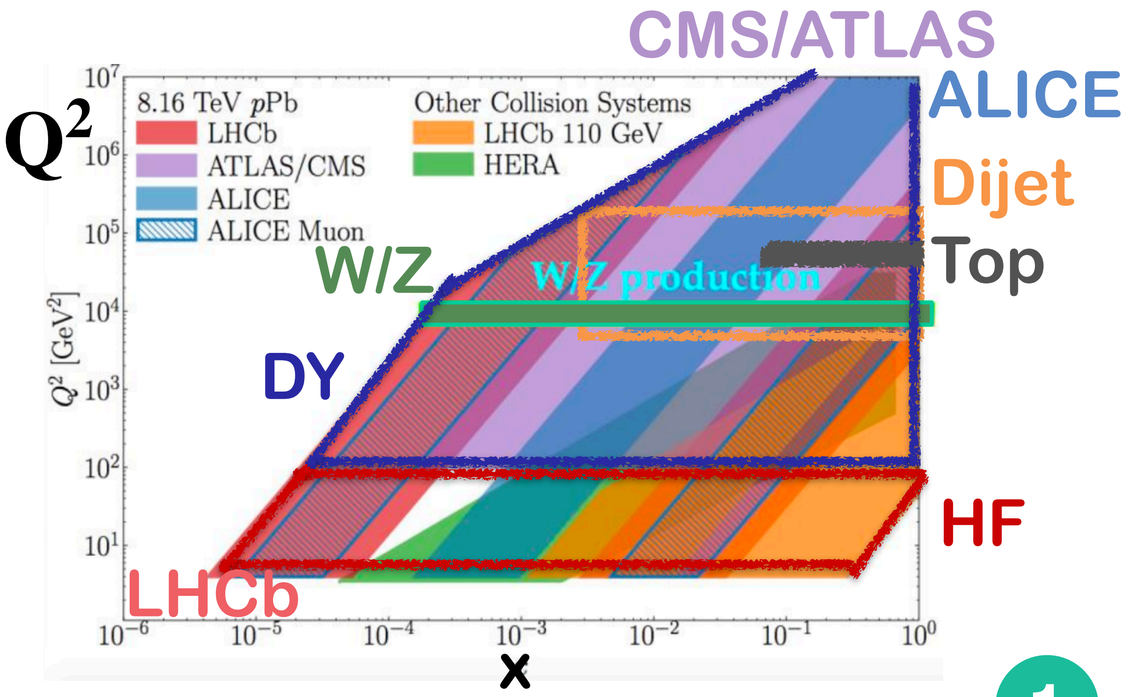
RICE

Introduction



- Parton PDFs **modified by nuclear medium.**
- Robust **understanding** of **nPDF effects** are **crucial** to interpret the **heavy-ion measurements**.
- Deviations from linear DGLAP evolution (i.e. **saturation**) should be enhanced in nuclei.

- **Variety of probes can constrain nPDFs:**
  - W and Z bosons.
  - Low mass Drell-Yan and prompt photons.
  - Top quarks.
  - Dijet.
  - Heavy-Flavour in pPb.
  - Quarkonia and dijets in UPC.
  - Among others.



Outline

- **EW boson and top quark measurements in HIC**
  - W boson
  - Z boson and Drell-Yan
  - Prompt photons
  - Top quarks

- **Future HIC facilities and nPDF prospects:**
  - CERN:
    - LHC upgrades
    - Future Circular Collider
  - China:
    - Electron Ion Collider in China
  - USA:
    - RHIC upgrades
    - Electron Ion Collider in US

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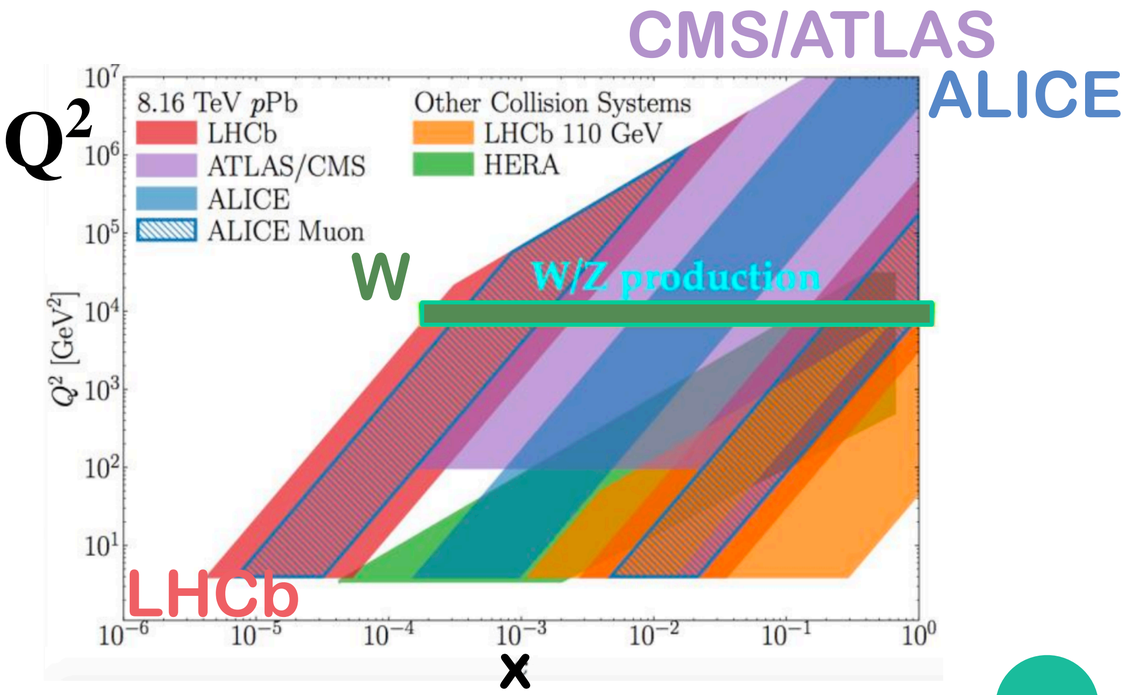
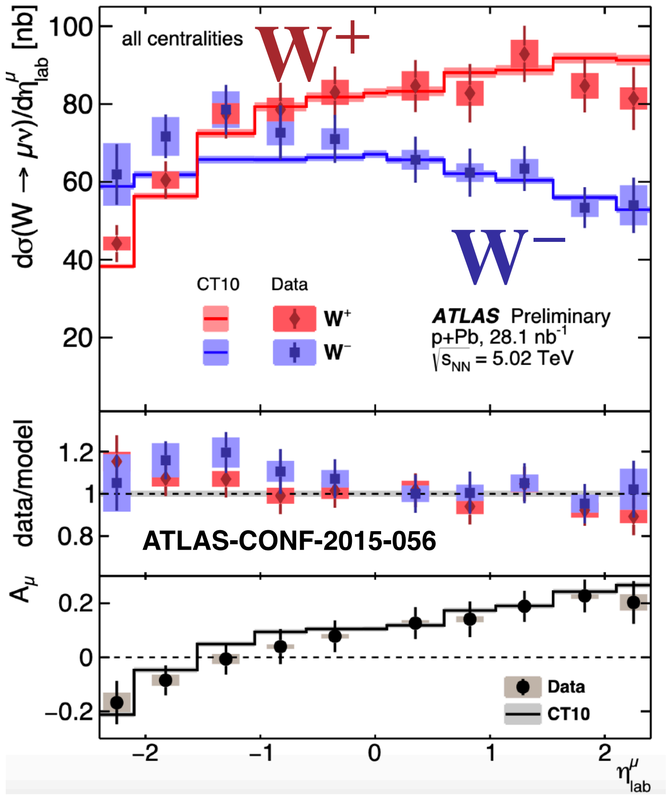
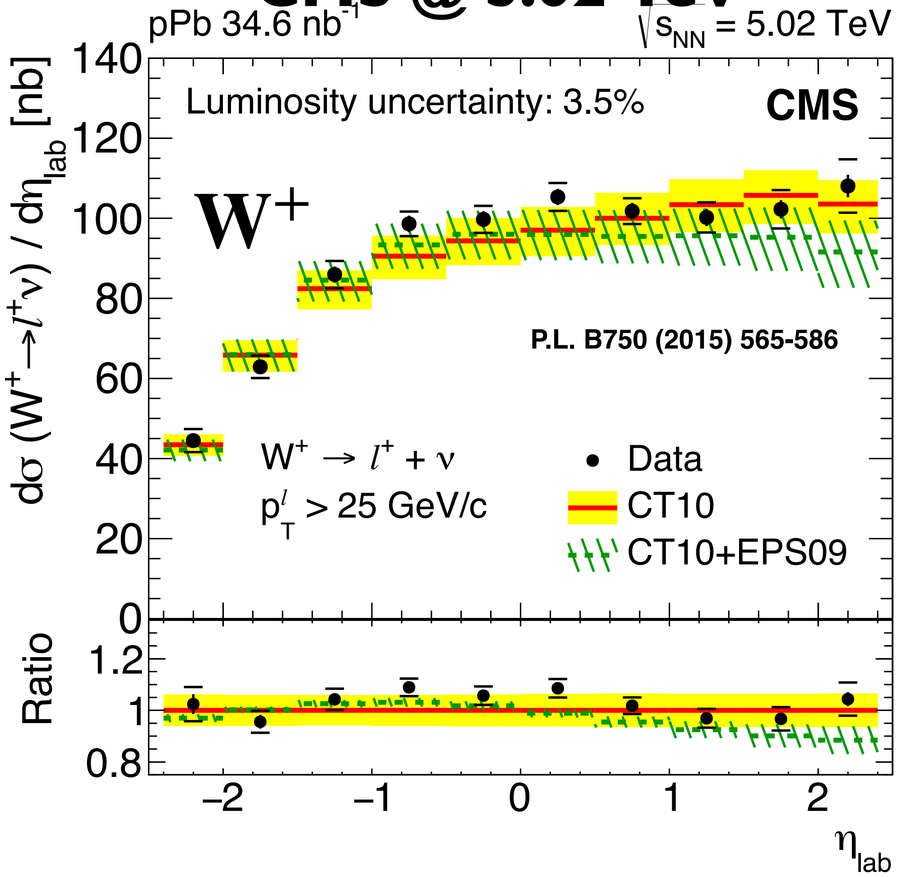


W boson in pPb at 5.02 TeV

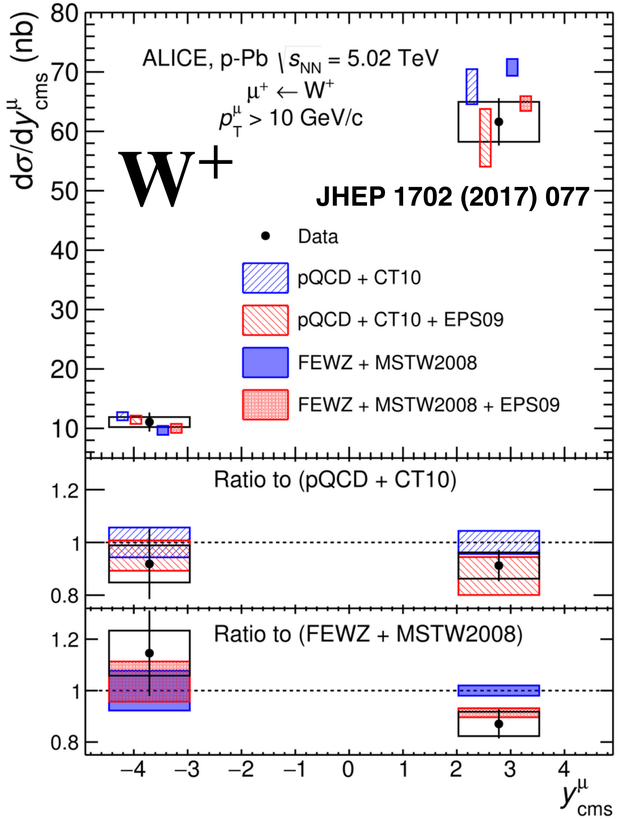
ATLAS @ 5.02 TeV



CMS @ 5.02 TeV



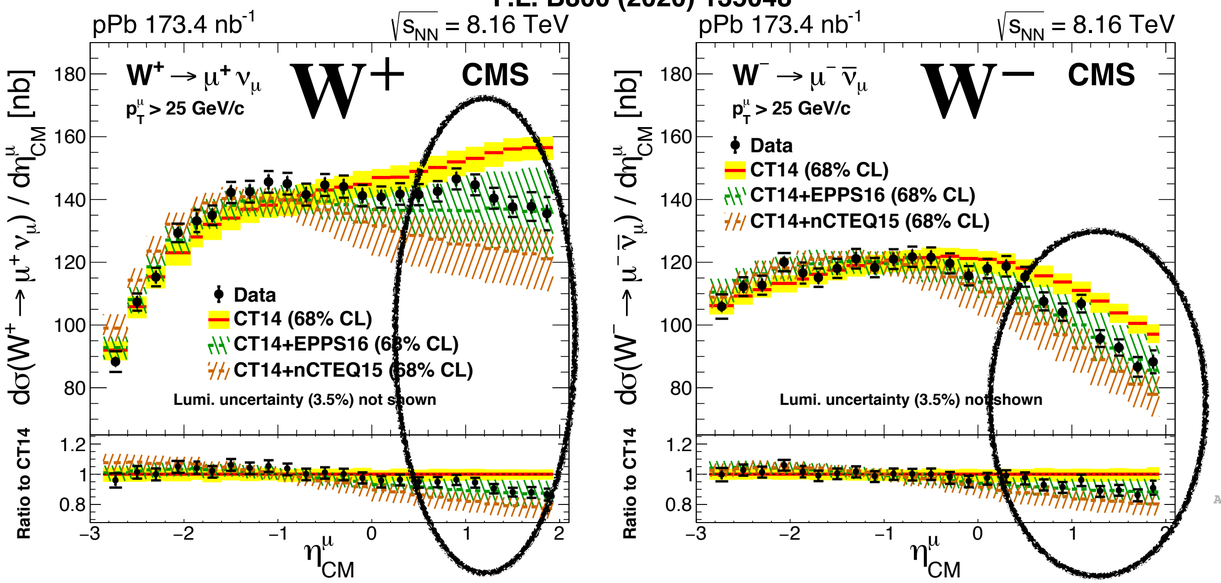
ALICE @ 5.02 TeV



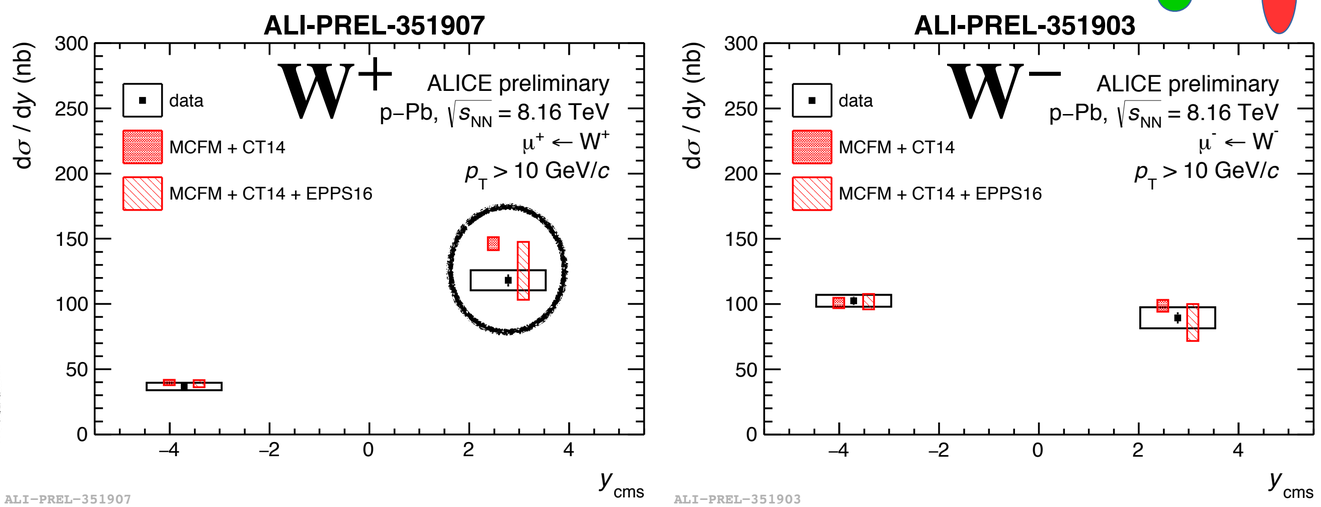
- Measurements compatible with CT10 and CT10+EPS09 calculations.
- Statistical precision of pPb data at 5.02 TeV limits sensitivity to nuclear PDF effects.

W boson in pPb at 8.16 TeV

CMS @ 8.16 TeV



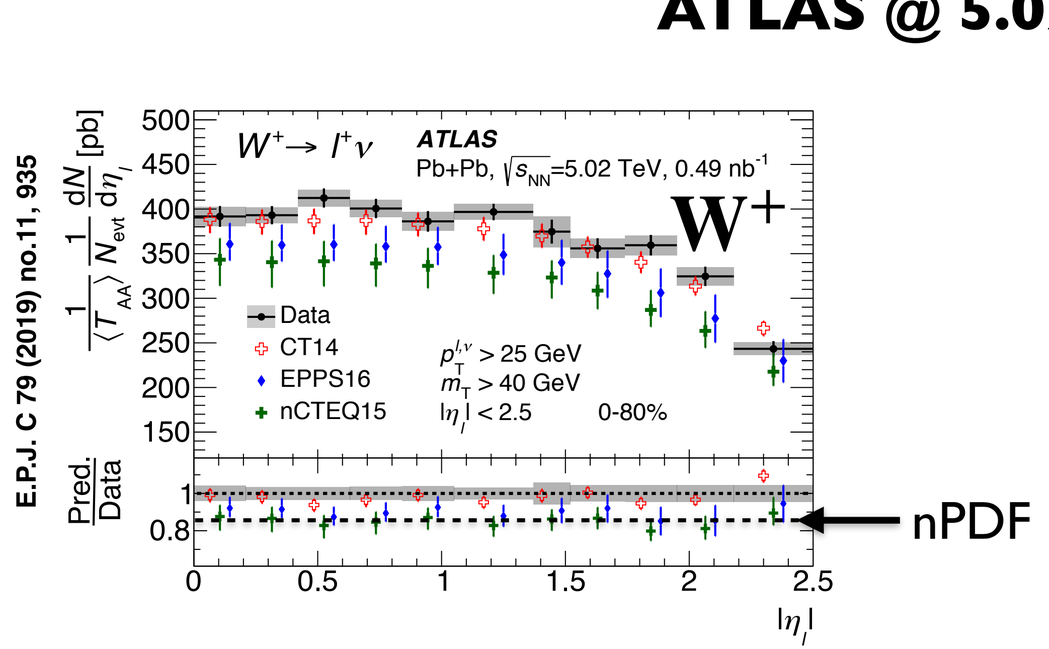
ALICE @ 8.16 TeV



- CMS results strongly deviate (>5σ) from CT14 PDF calculations in forward region.
  - Data provides clear evidence of nuclear modification of PDFs in pPb.
  - Experimental uncertainties are significantly smaller than nPDF uncertainties.
- ALICE preliminary W^+ results also deviate from CT14 by 2.7σ at forward rapidity.

W boson in PbPb

ATLAS @ 5.02 TeV

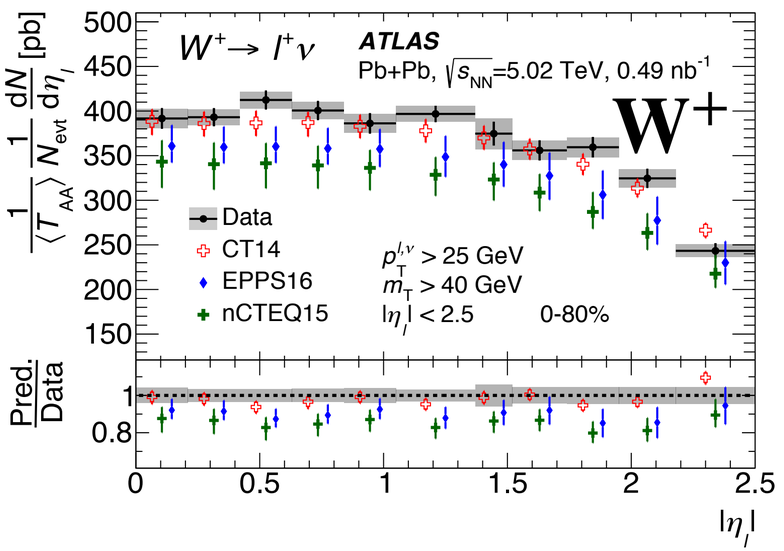


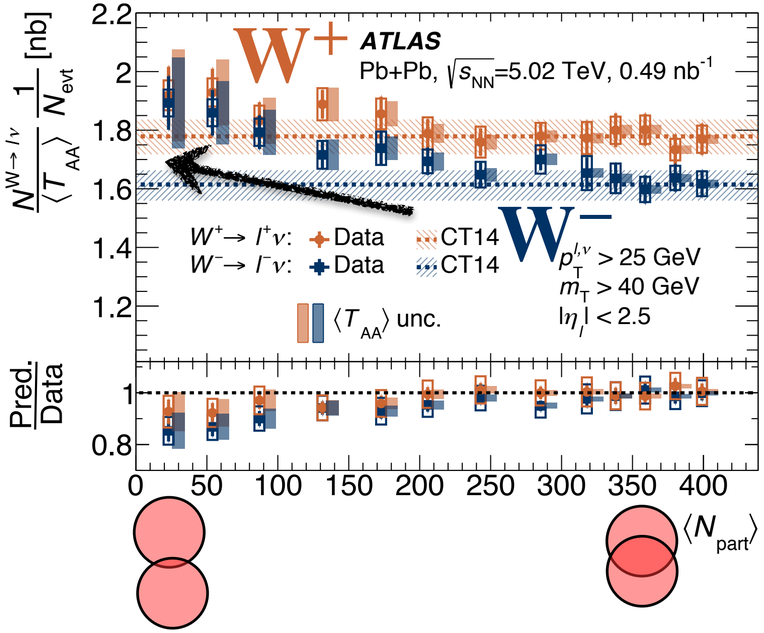
- Good agreement with CT14 while nPDF models underestimate the data by 10-20%.

W boson in PbPb

ATLAS @ 5.02 TeV

E.P.J. C 79 (2019) no.11, 935





- Good agreement with CT14 while nPDF models underestimate the data by 10-20%.
- Centrality dependence not fully described by free-proton PDF.
- Slight increasing trend for W^- towards peripheral collisions.

W boson in PbPb

ATLAS @ 5.02 TeV

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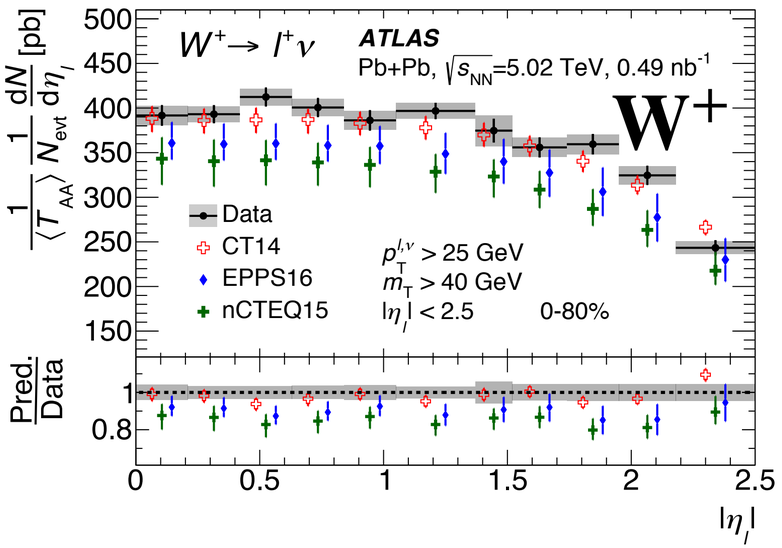
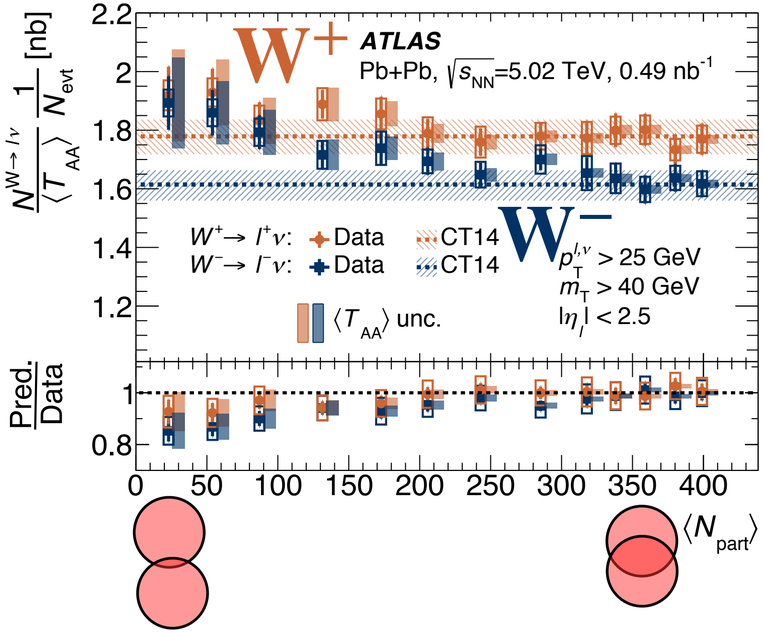
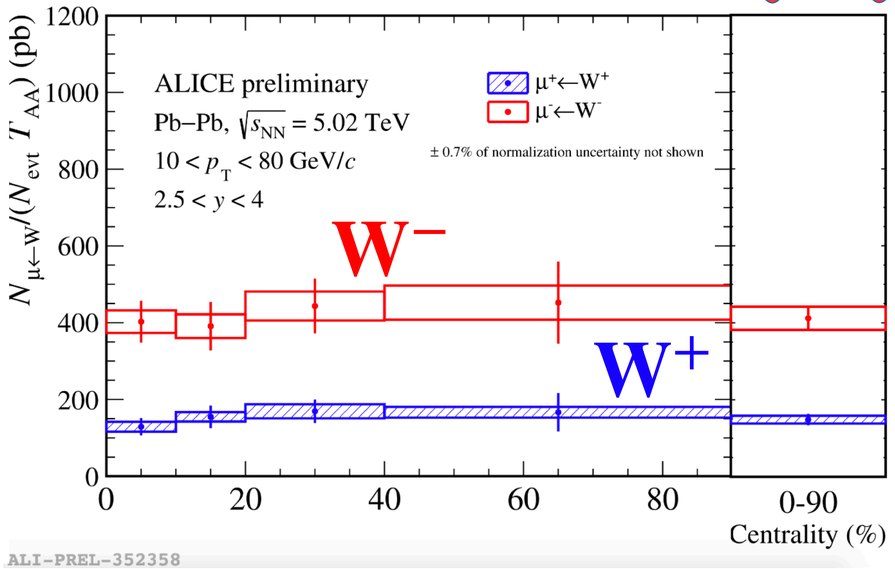




ALICE @ 5.02 TeV

arXiv:2008.07809v1



- Good agreement with CT14 while nPDF models underestimate the data by 10-20%.
- Centrality dependence not fully described by free-proton PDF.
- Slight increasing trend for W^- towards peripheral collisions.
- First PbPb preliminary measurement of W at forward rapidity.
  - ALICE planning to combine 2015 y 2018 data.

Outline

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  - W boson
  - **Z boson and Drell-Yan**
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  - Top quarks

- Future HIC facilities and nPDF prospects:
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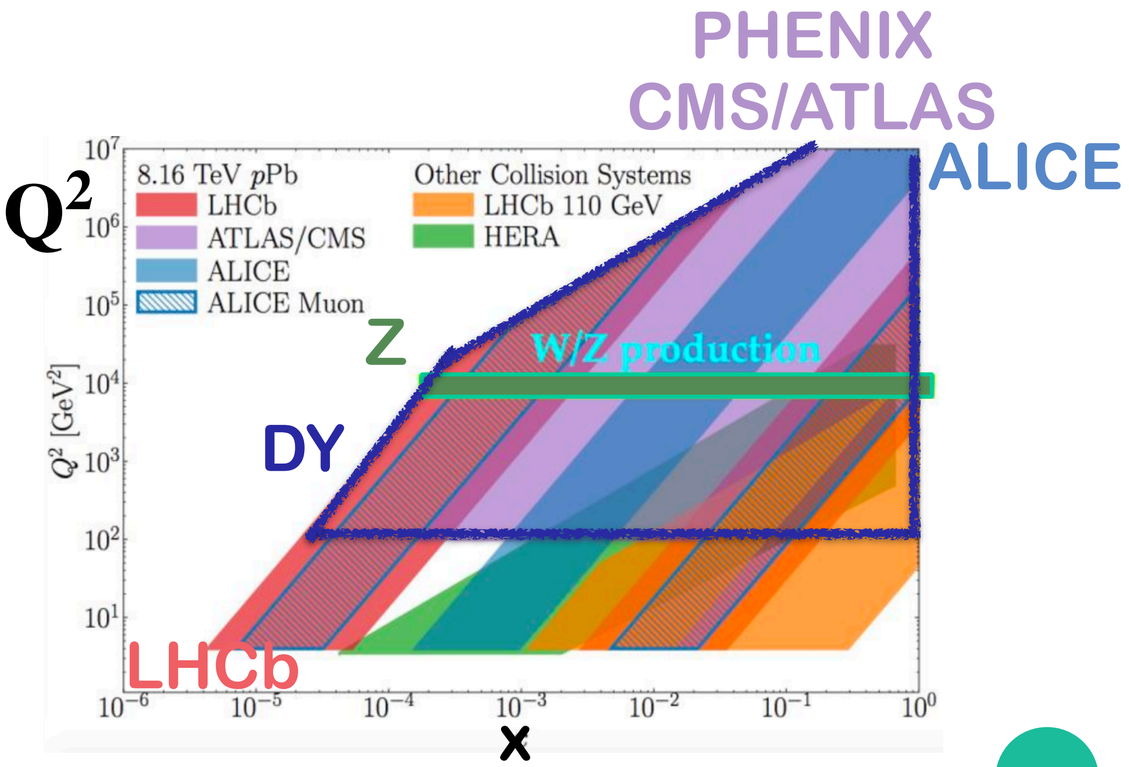
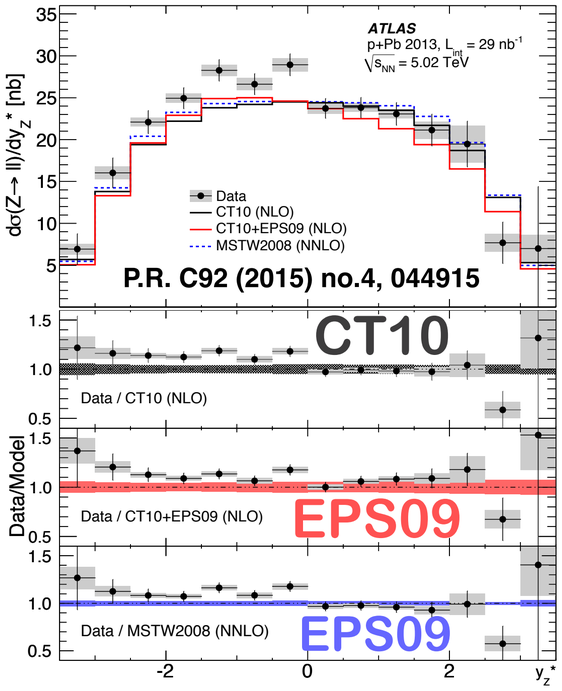
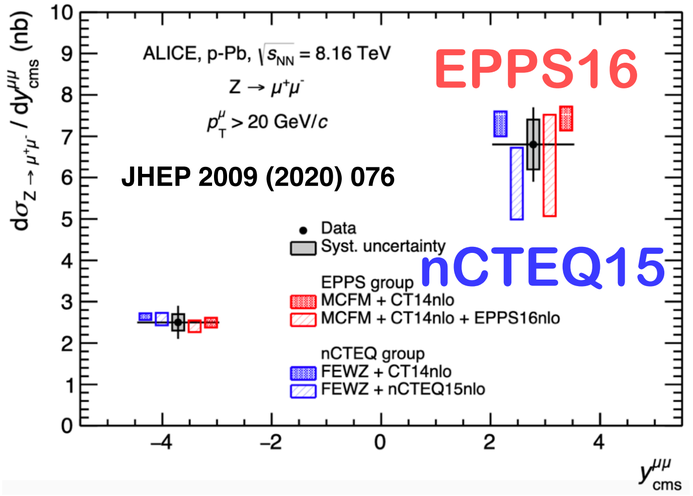


Z boson in pPb

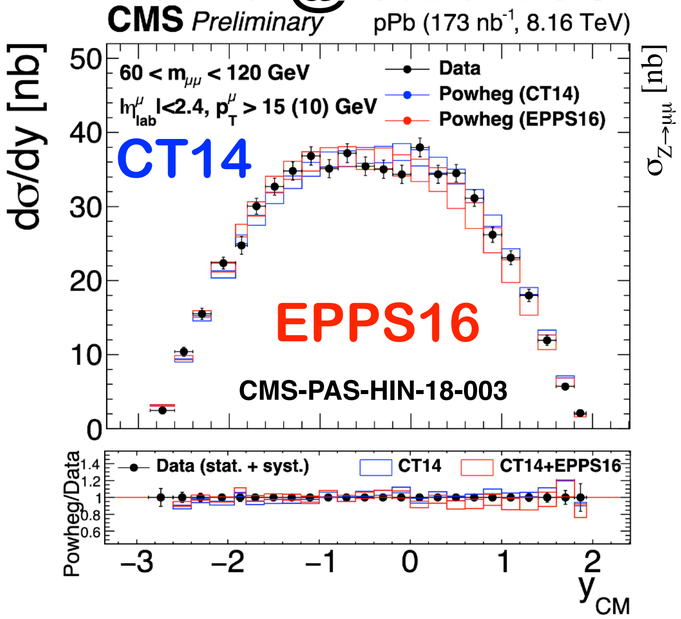
ATLAS @ 5.02 TeV



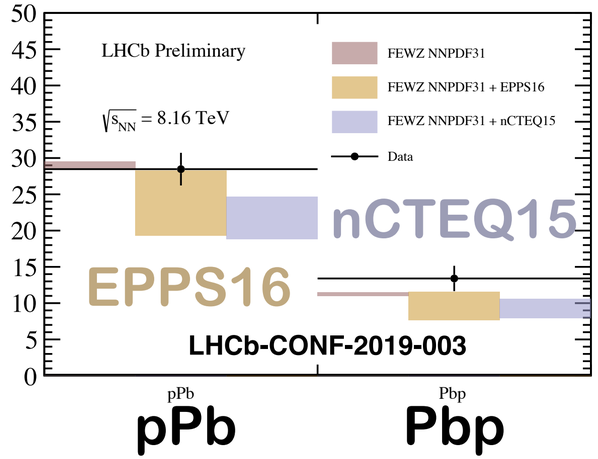
ALICE @ 8.16 TeV



CMS @ 8.16 TeV

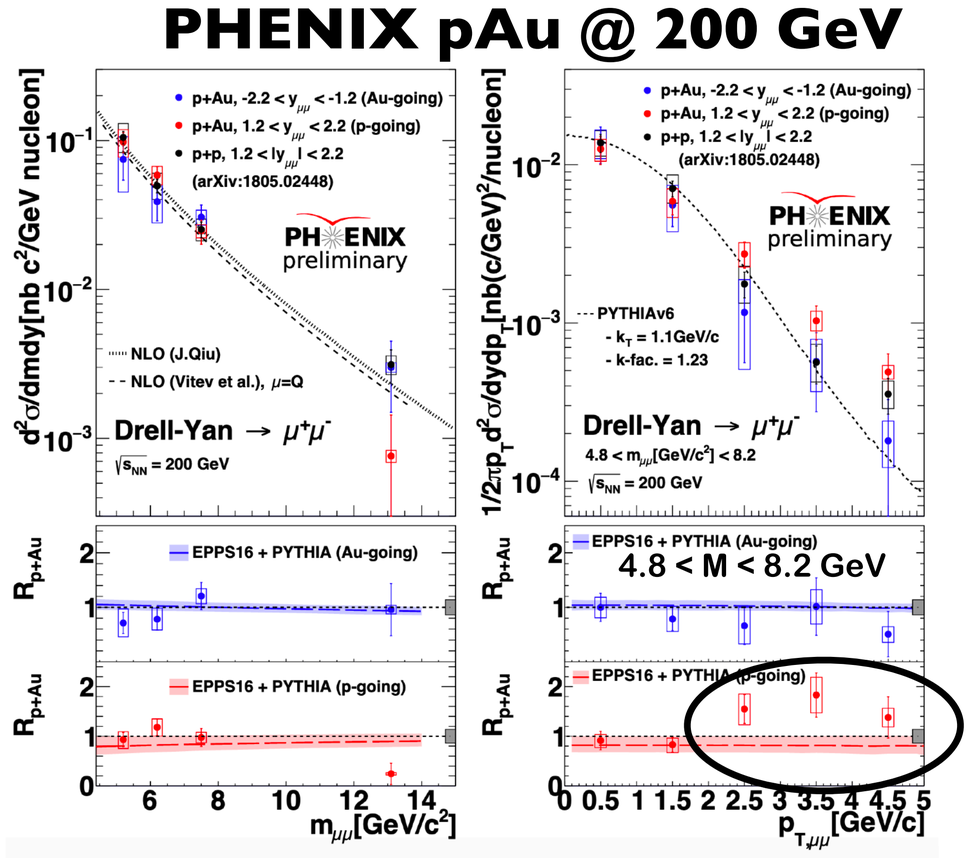


LHCb @ 8.16 TeV



- Results agree well with the (n)PDF calculations within current uncertainties.
- New results from ALICE and CMS at 8.16 TeV are also compatible with all PDF models.

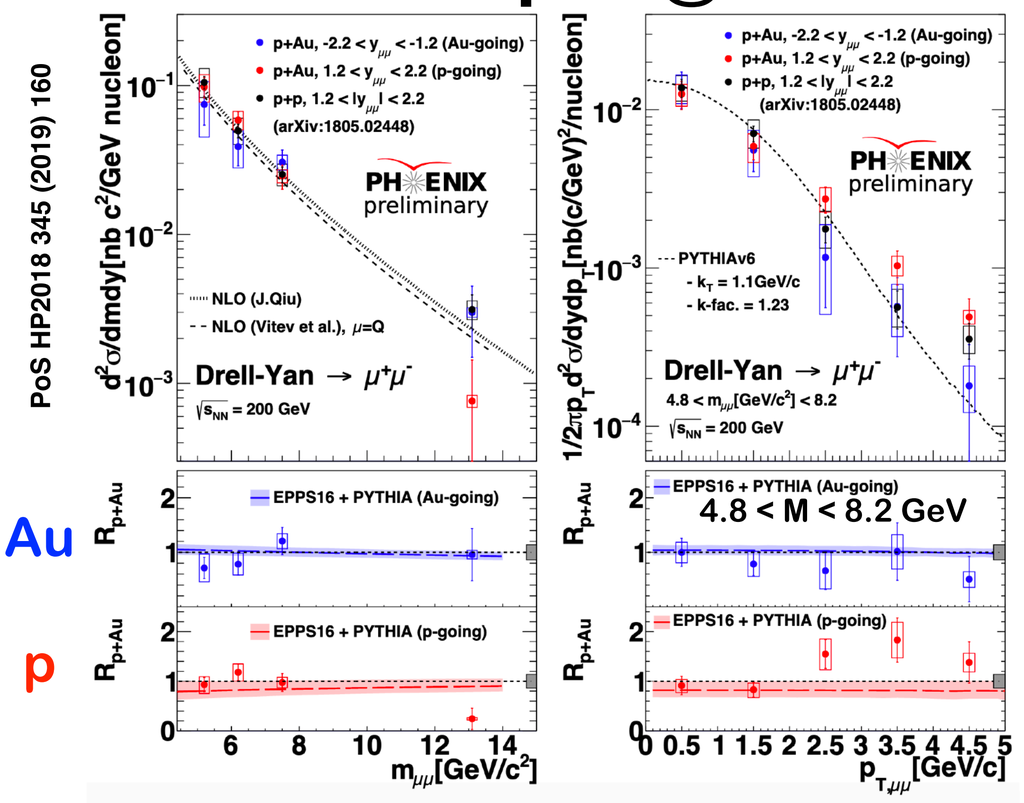
Drell-Yan in pA



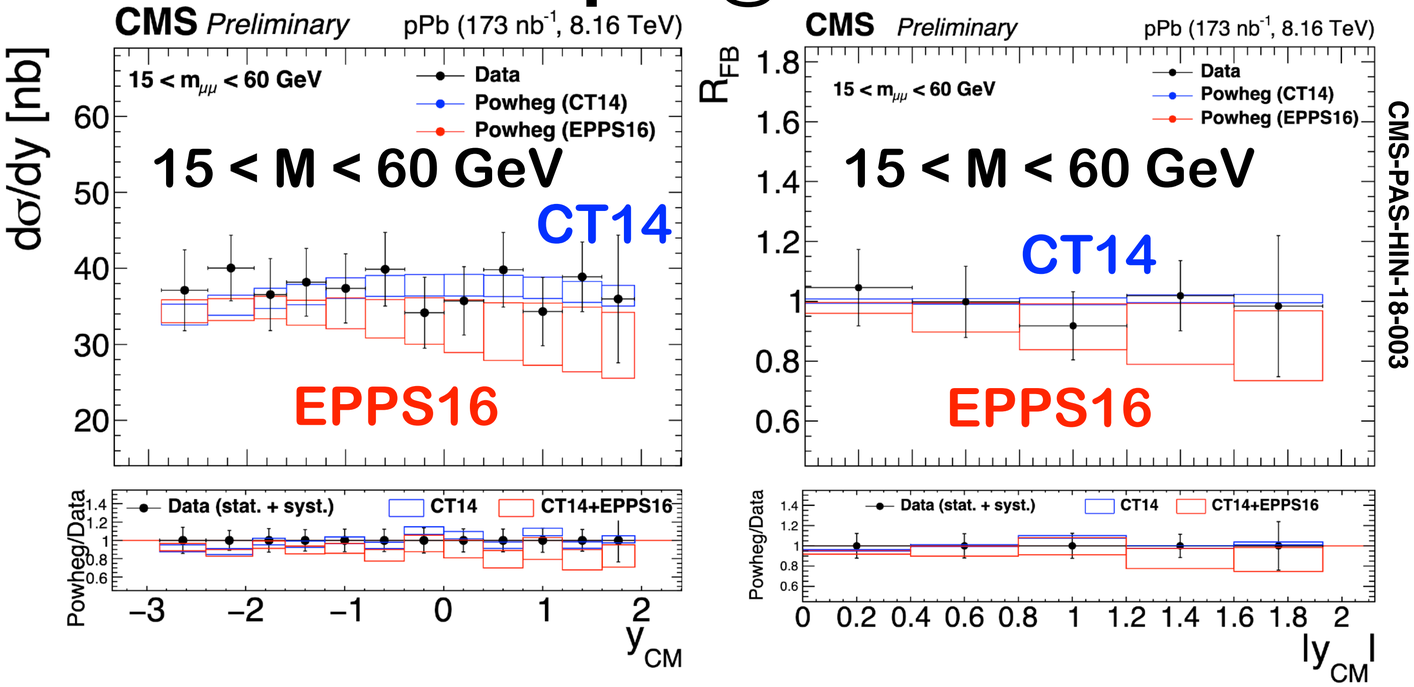
- PHENIX preliminary pAu results show hint of enhancement at pT > 2 GeV in p-going side.

Drell-Yan in pA

PHENIX pAu @ 200 GeV



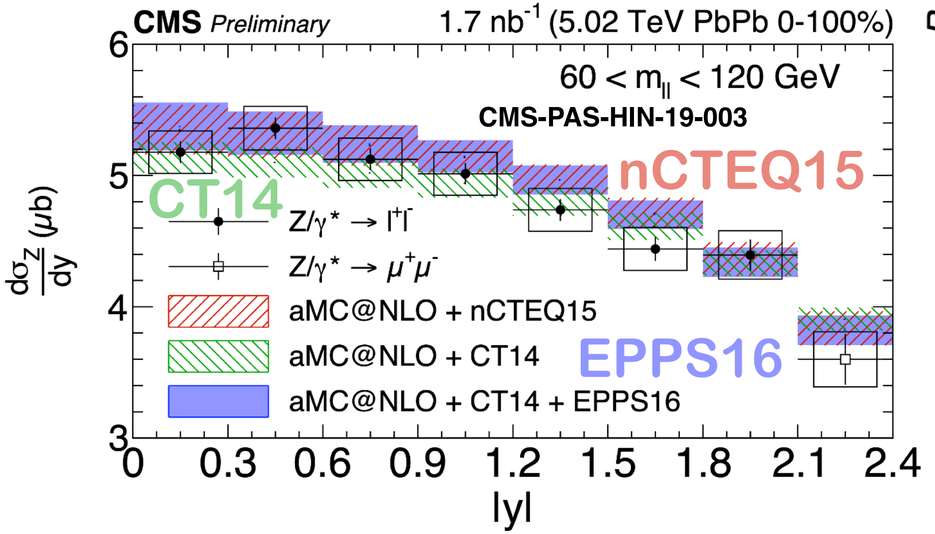
CMS pPb @ 8.16 TeV



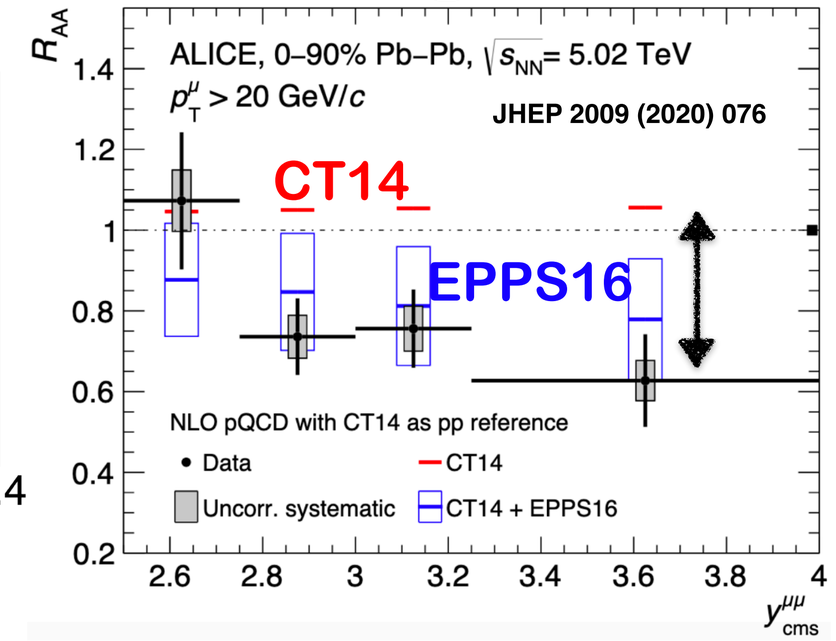
- PHENIX preliminary pAu results show hint of enhancement at pT > 2 GeV in p-going side.
- CMS preliminary pPb results are consistent with both CT14 and EPPS16 calculations.

Z boson in PbPb

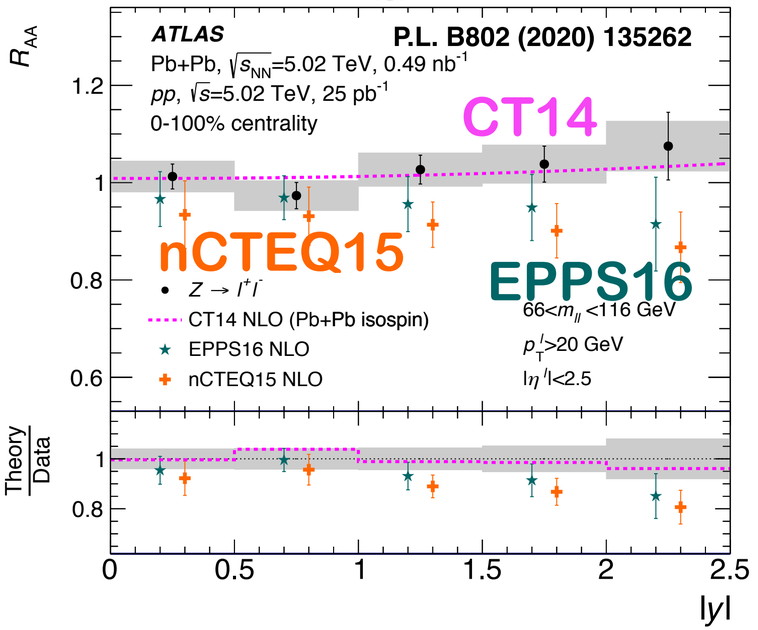
CMS @ 5.02 TeV



ALICE @ 5.02 TeV



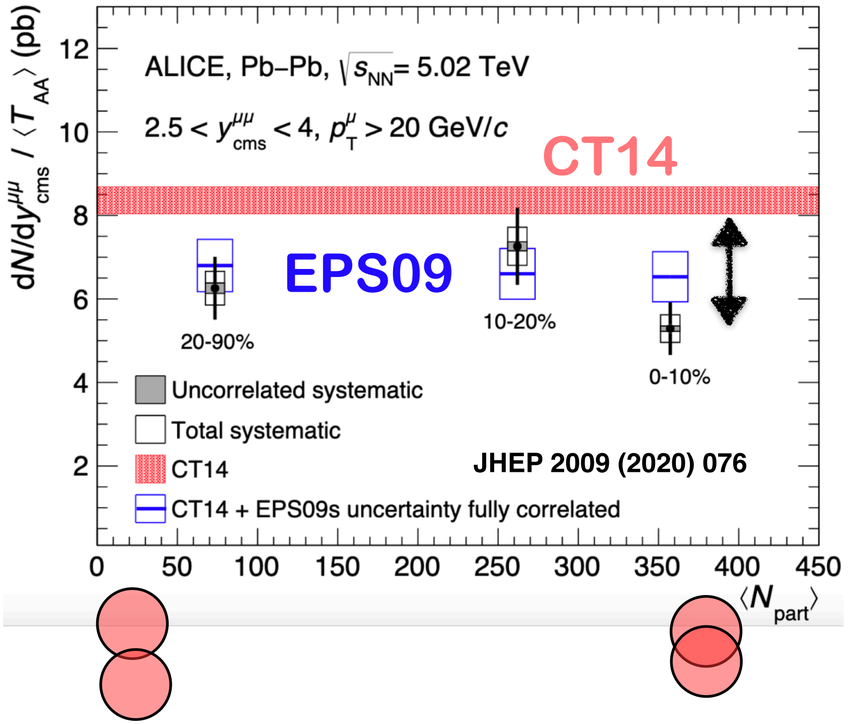
ATLAS @ 5.02 TeV



- New results from CMS, ALICE (2015+2018) and ATLAS in 2020.
- CMS cross-section measurements agree with PDF and nPDF calculations.
- ALICE R_{AA} data deviates from CT14 (int. yield ~ 3.4σ), and agrees with EPPS16 calculations.
- ATLAS R_{AA} results are compatible with CT14 while slightly underestimated by nPDF models.

EW boson centrality dependence

ALICE @ 5.02 TeV



- ALICE new Z boson results slightly favours nuclear PDFs over CT14.

EW boson centrality dependence

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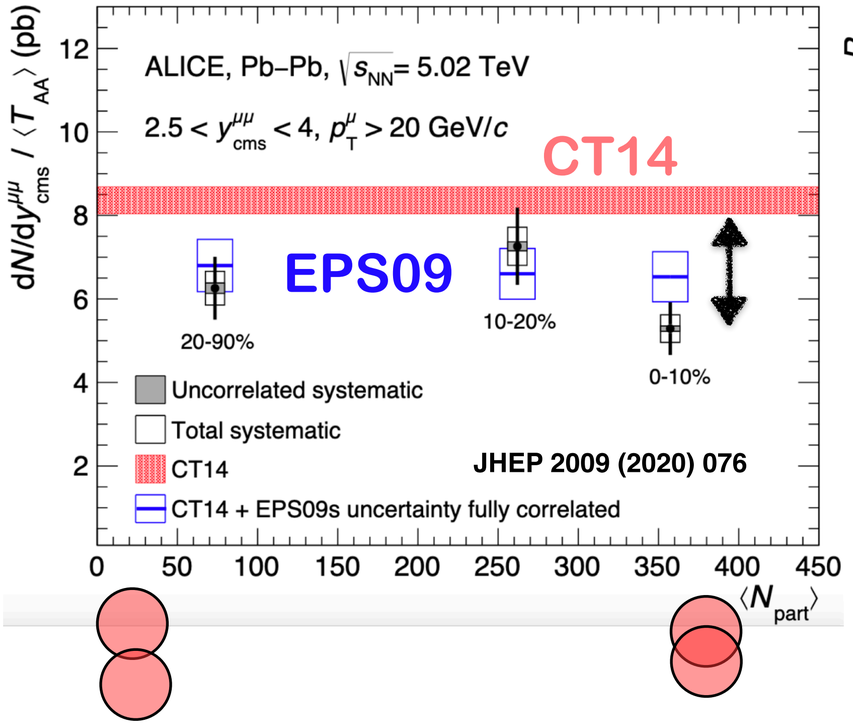

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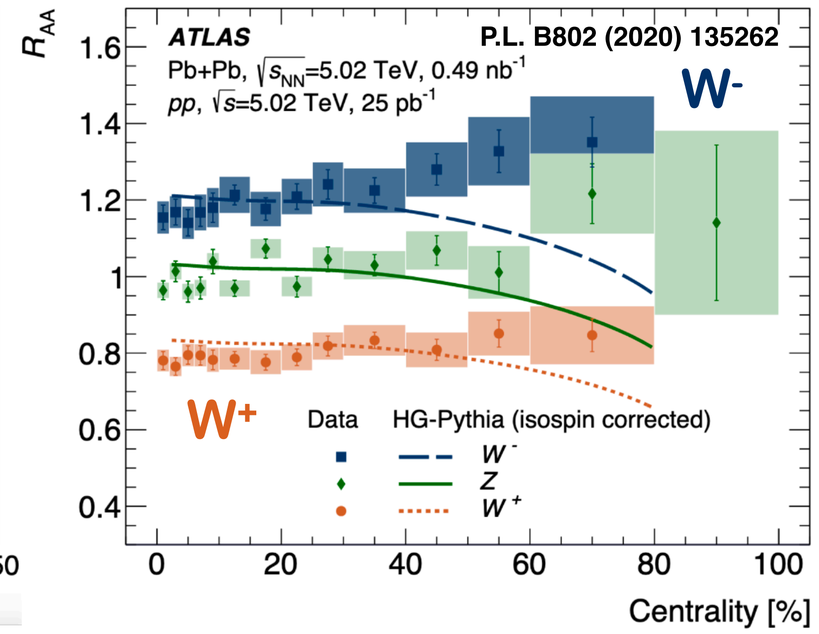

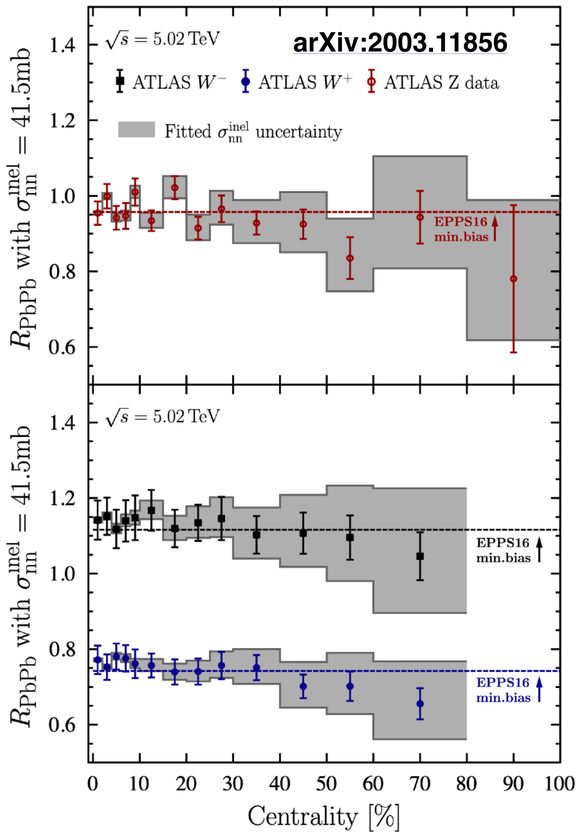

- ALICE new Z boson results slightly favours nuclear PDFs over CT14.
- Z and W boson trend vs centrality shows slight enhancement towards peripheral collisions, not described by HG-PYTHIA model calculations → favours shadowing of σ_{NN}.

EW boson centrality dependence

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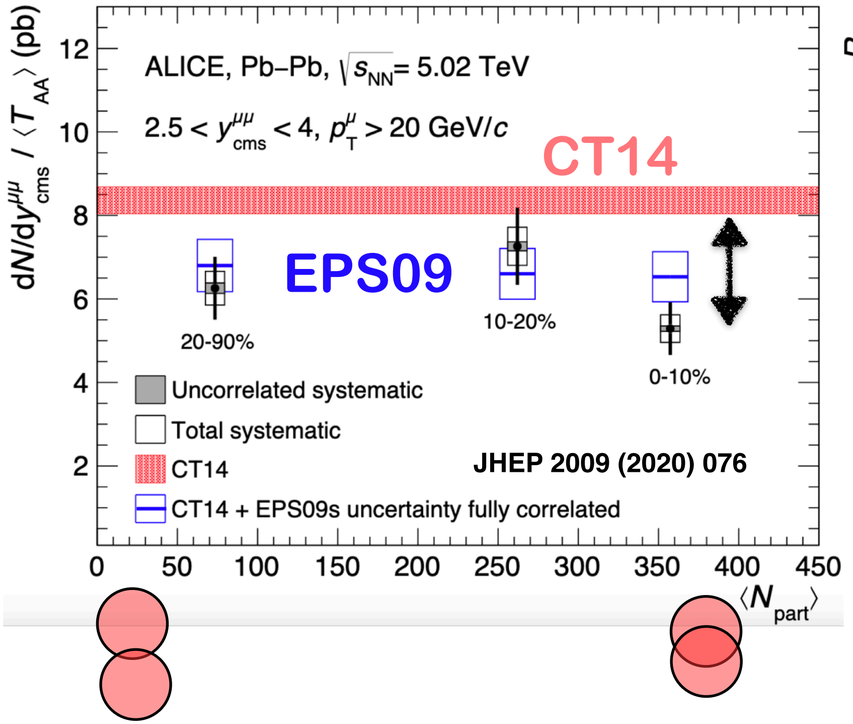

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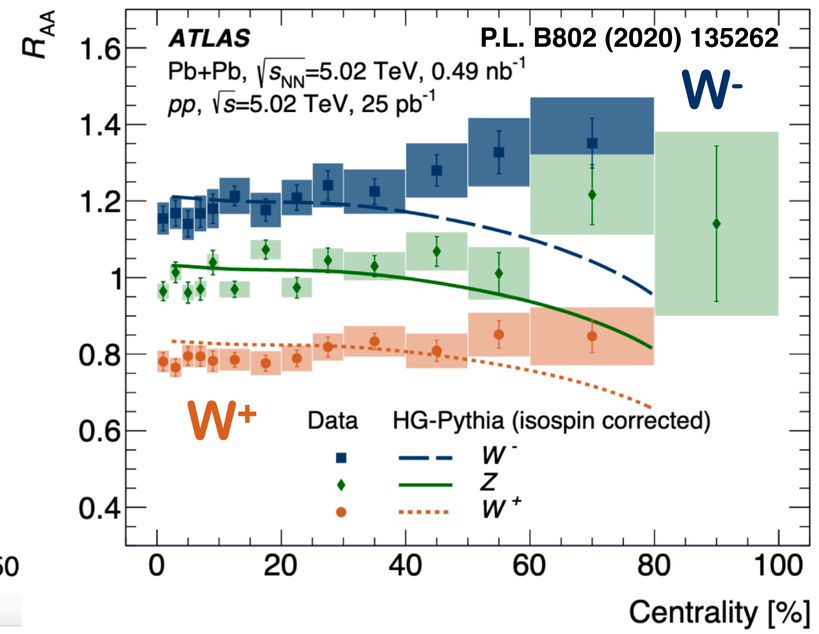
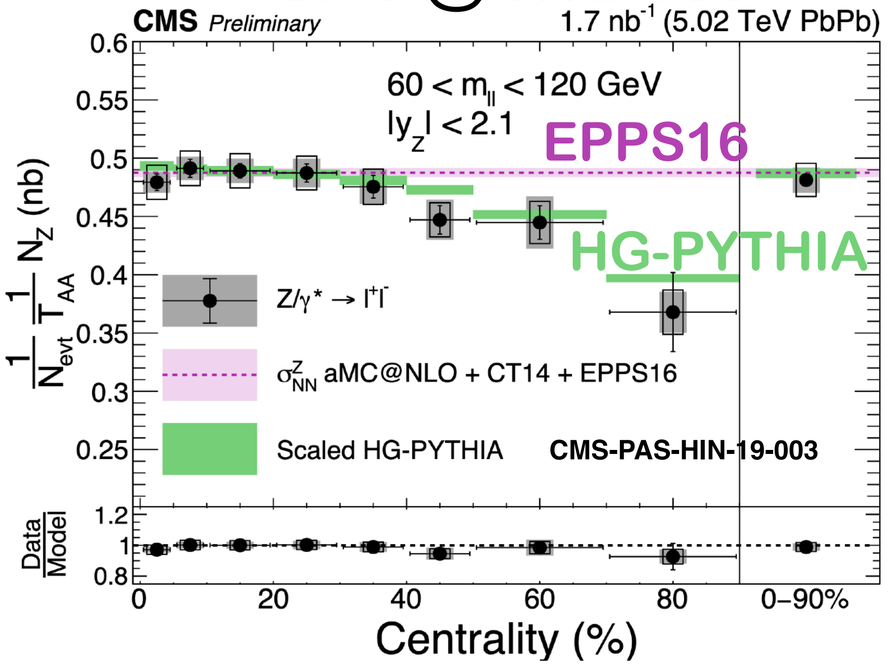


CMS @ 5.02 TeV



- ALICE new Z boson results slightly favours nuclear PDFs over CT14.
- Z and W boson trend vs centrality shows slight enhancement towards peripheral collisions, not described by HG-PYTHIA model calculations → favours shadowing of σ_{NN}.
- CMS Z boson data shows 'suppression' in peripheral events consistent with HG-Pythia.
  - Clear tension between ATLAS and CMS Z boson yields in peripheral PbPb.

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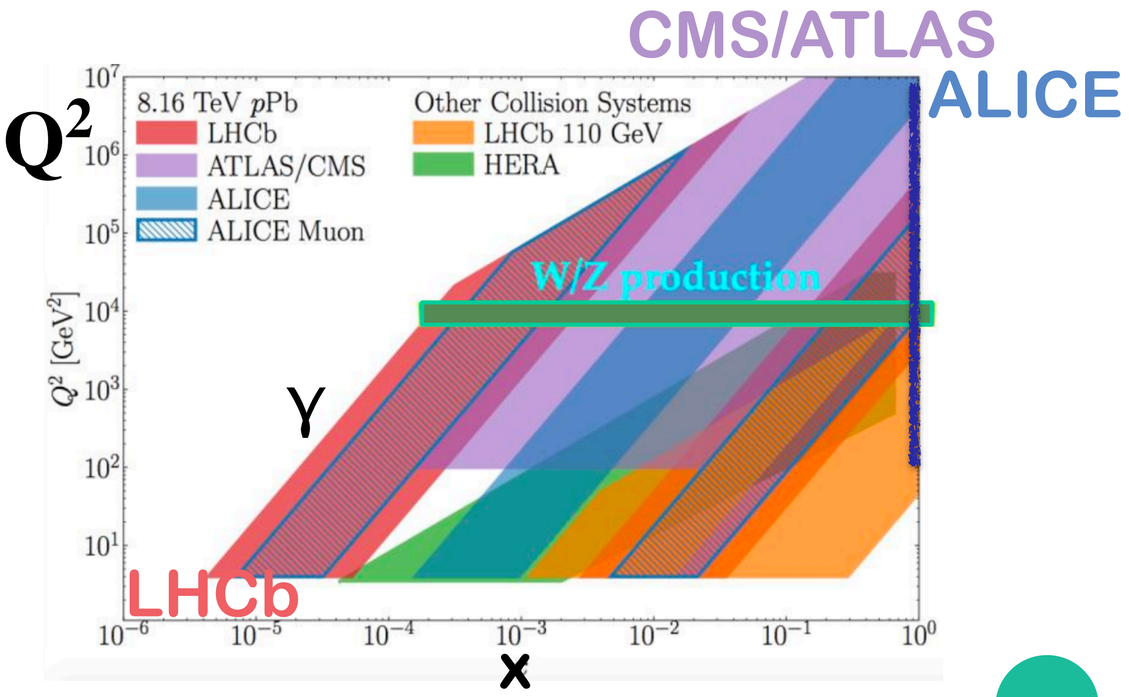
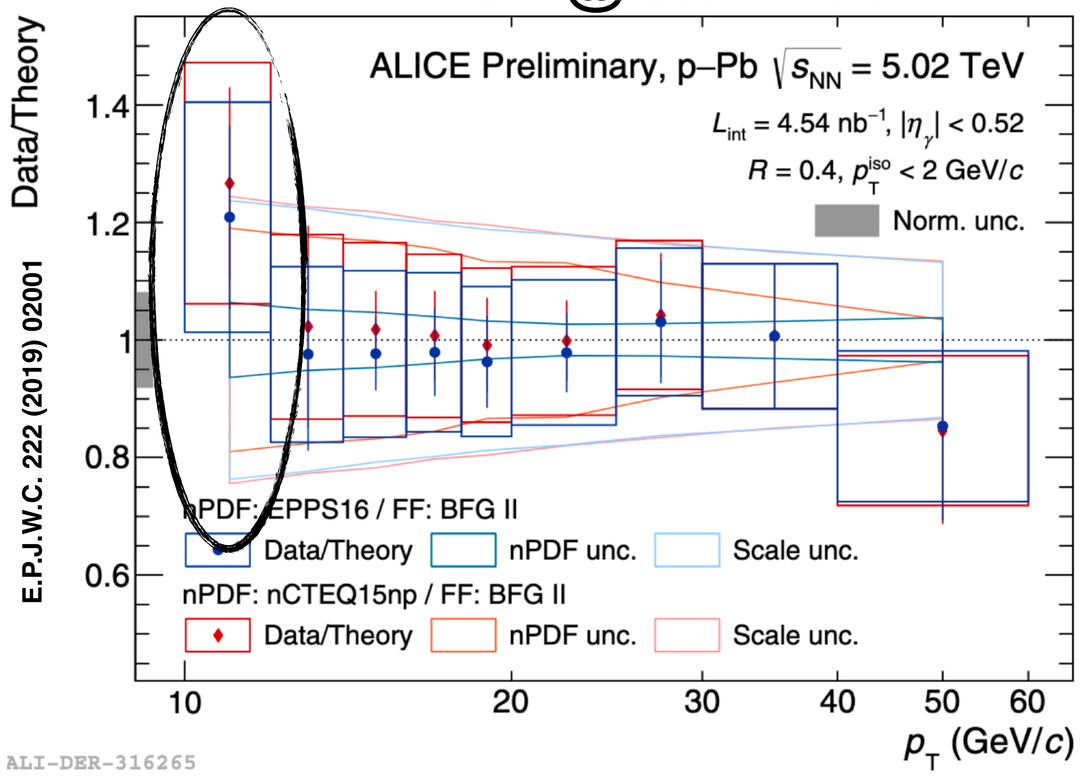
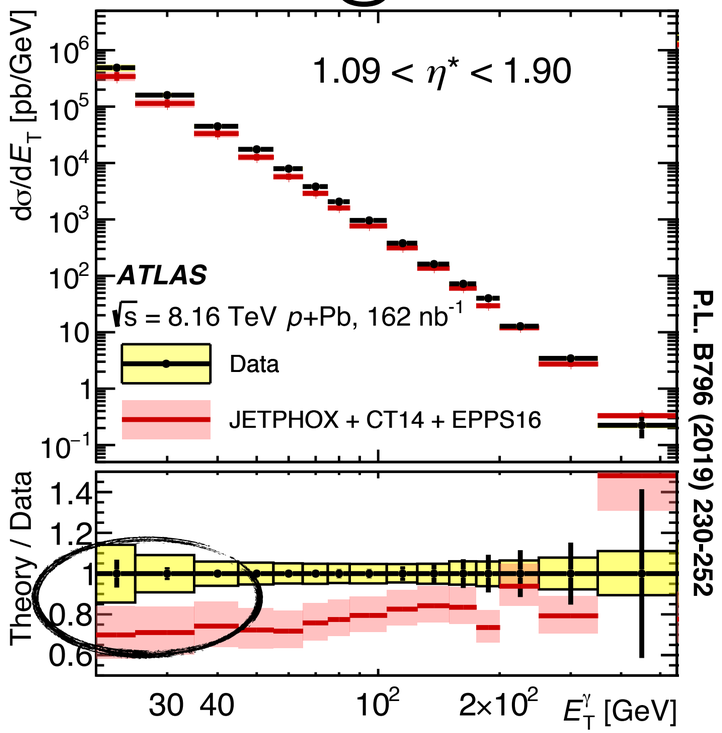


Prompt photons in pPb

ALICE @ 5.02 TeV

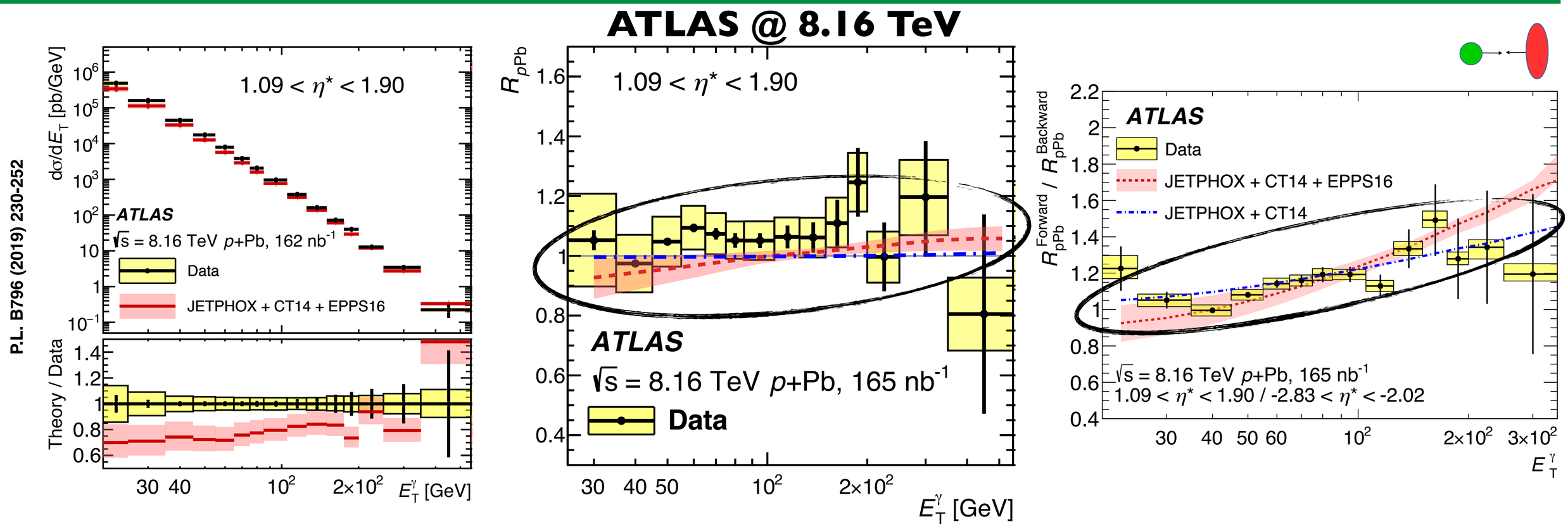


ATLAS @ 8.16 TeV



- Cross-section measurements larger than nPDF NLO calculations by ~20% at low E_T.

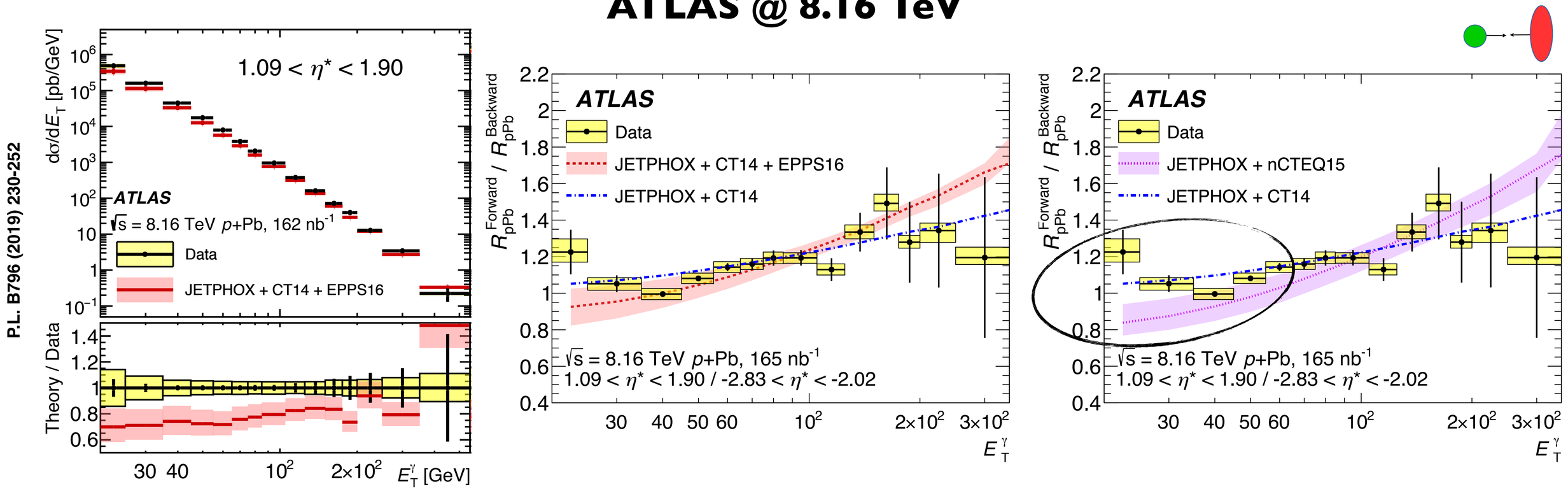
Prompt photons in pPb



- Cross-section measurements larger than nPDF NLO calculations by ~20% at low E_T.
- However, R_{pPb} and FB ratio well described by EPPS16 and CT14 calculations.

Prompt photons in pPb

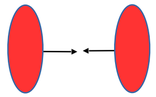
ATLAS @ 8.16 TeV



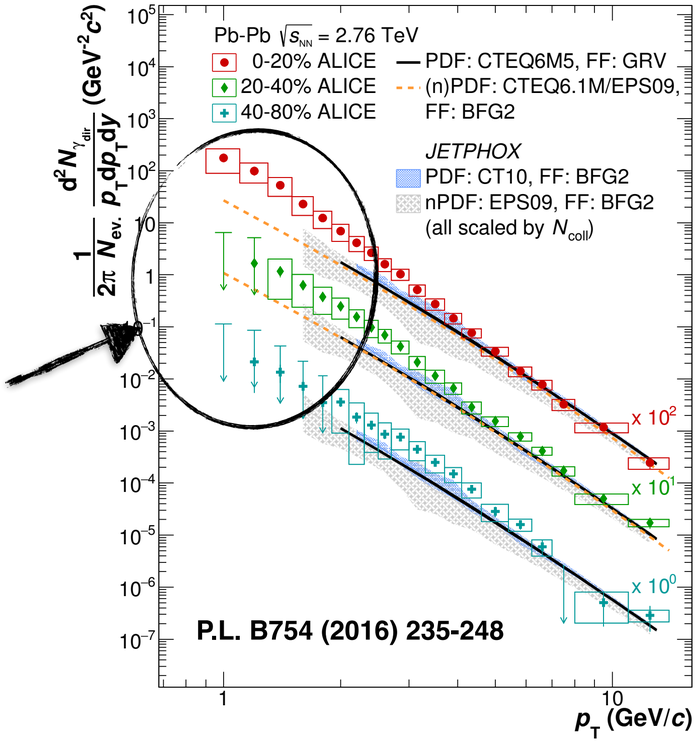
- Cross-section measurements larger than nPDF NLO calculations by ~20% at low E_T.
- However, R_{pPb} and FB ratio well described by EPPS16 and CT14 calculations.
- nCTEQ15 slightly under-predicts FB ratio at low E_T.

Direct photons in PbPb

ALICE @ 2.76 TeV



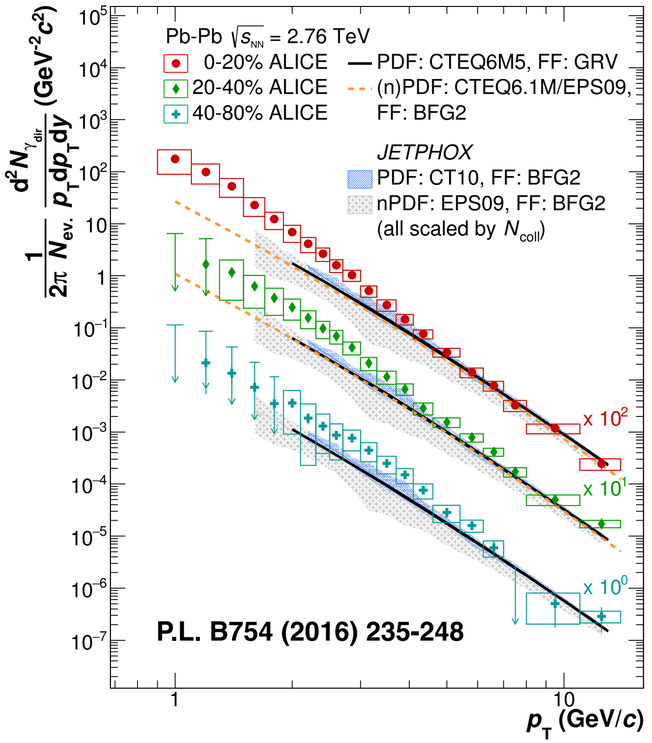
Thermal photons



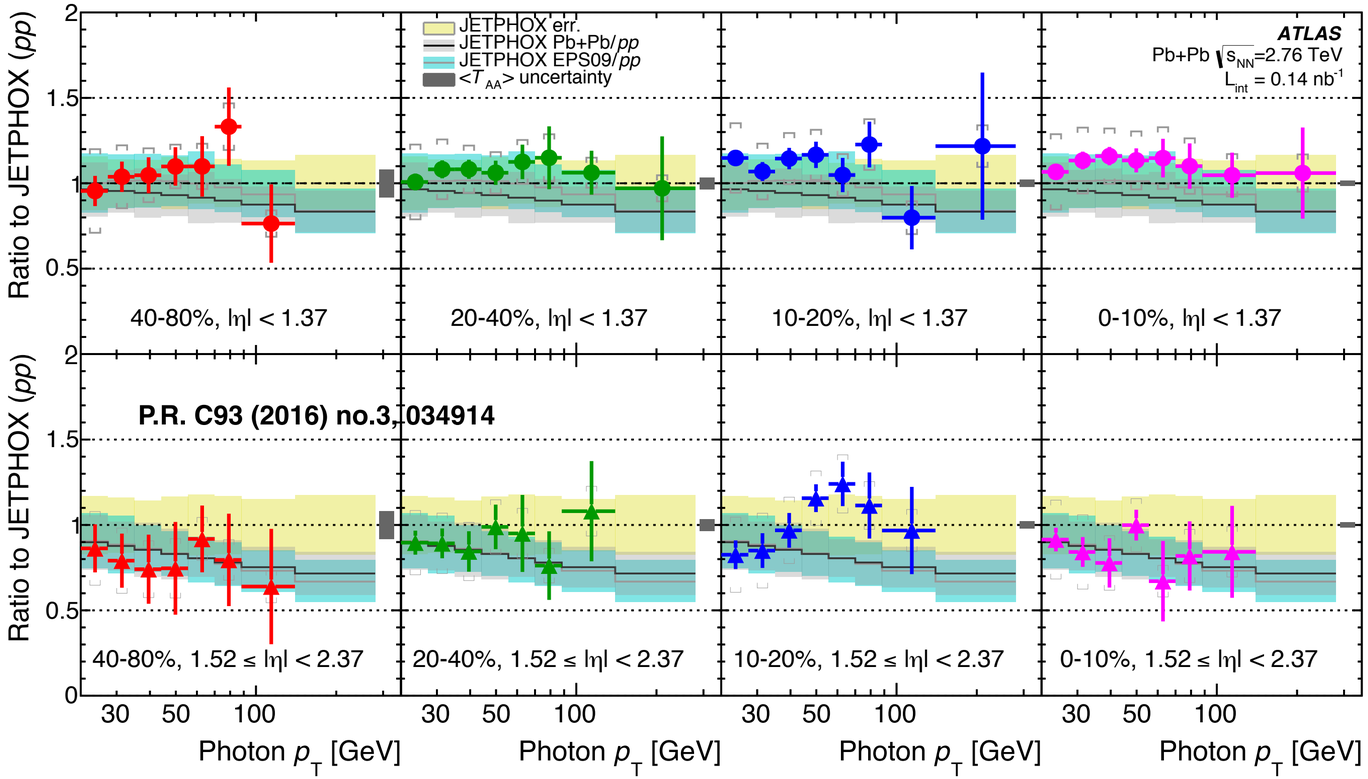
- Excess observed by ALICE at low p_T compared to pQCD calculations.

Prompt photons in PbPb

ALICE @ 2.76 TeV



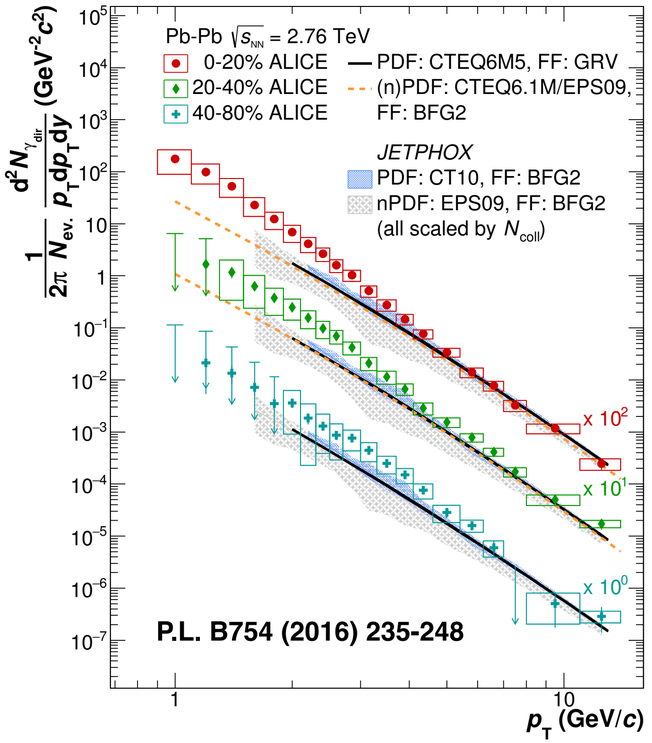
ATLAS @ 2.76 TeV



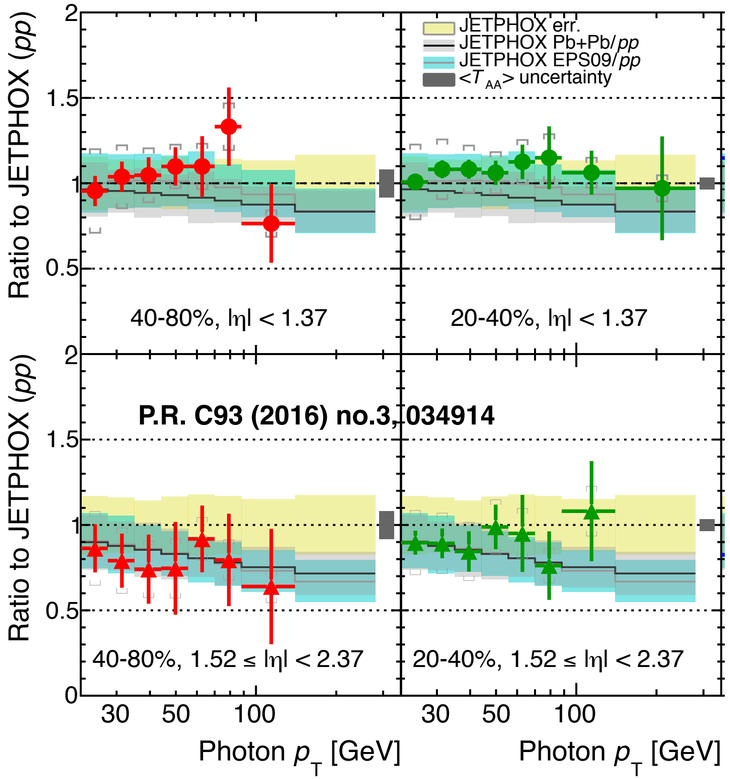
- Excess observed by ALICE at low p_T compared to pQCD calculations.
- Good agreement between ATLAS data and (n)PDF calculations across all bins.

Prompt photons in PbPb

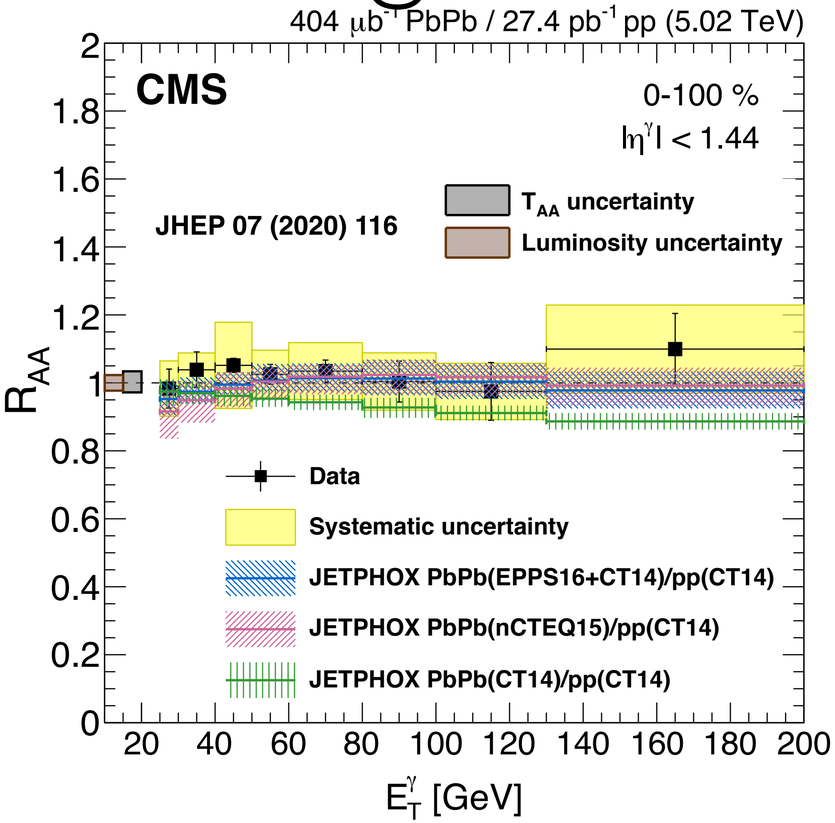
ALICE @ 2.76 TeV



ATLAS @ 2.76 TeV



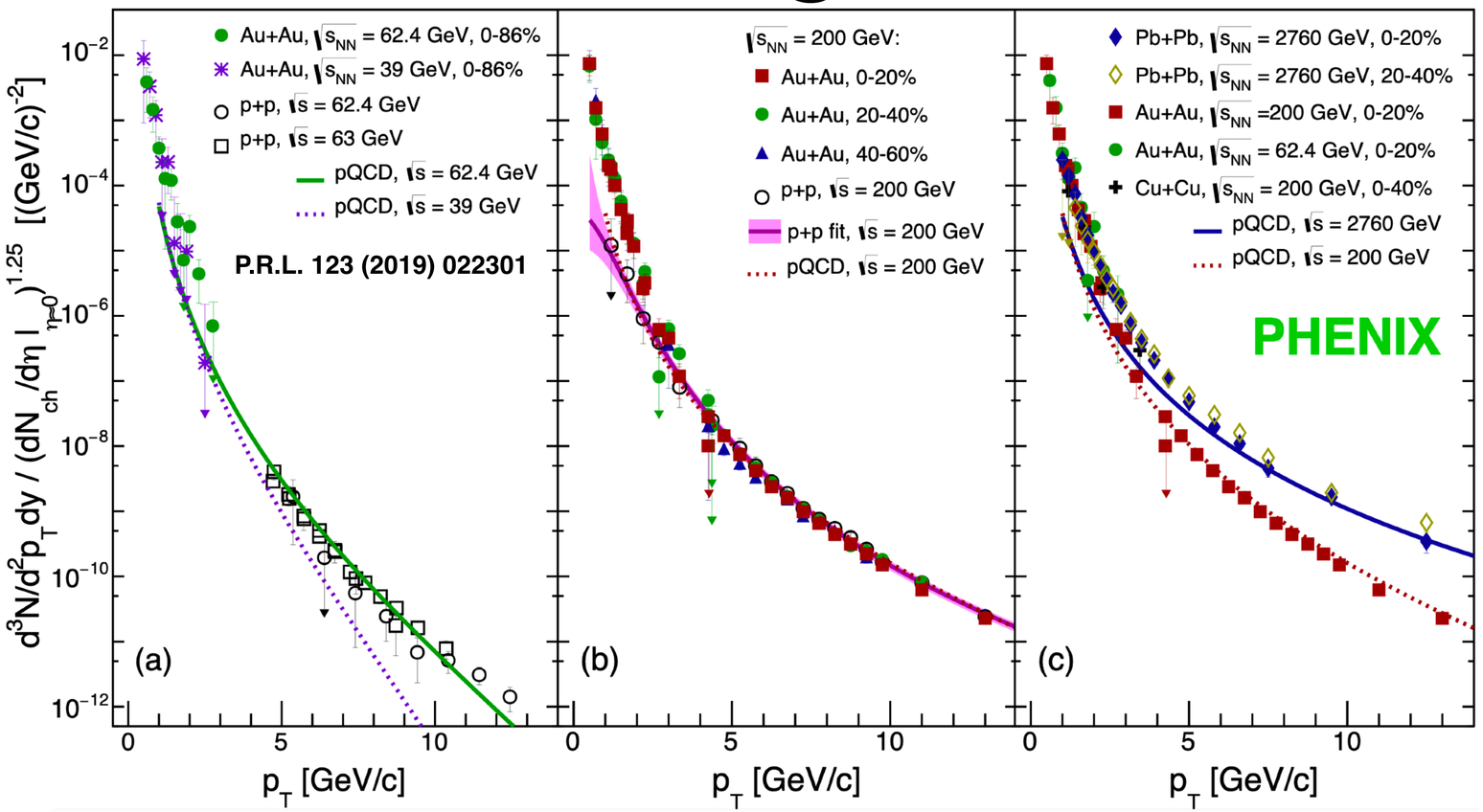
CMS @ 5.02 TeV



- Excess observed by ALICE at low p_T compared to pQCD calculations.
- Good agreement between ATLAS high p_T data and (n)PDF calculations.
- CMS R_{AA} at high E_T compatible with unity: photons not significantly modified.

Direct photons at RHIC

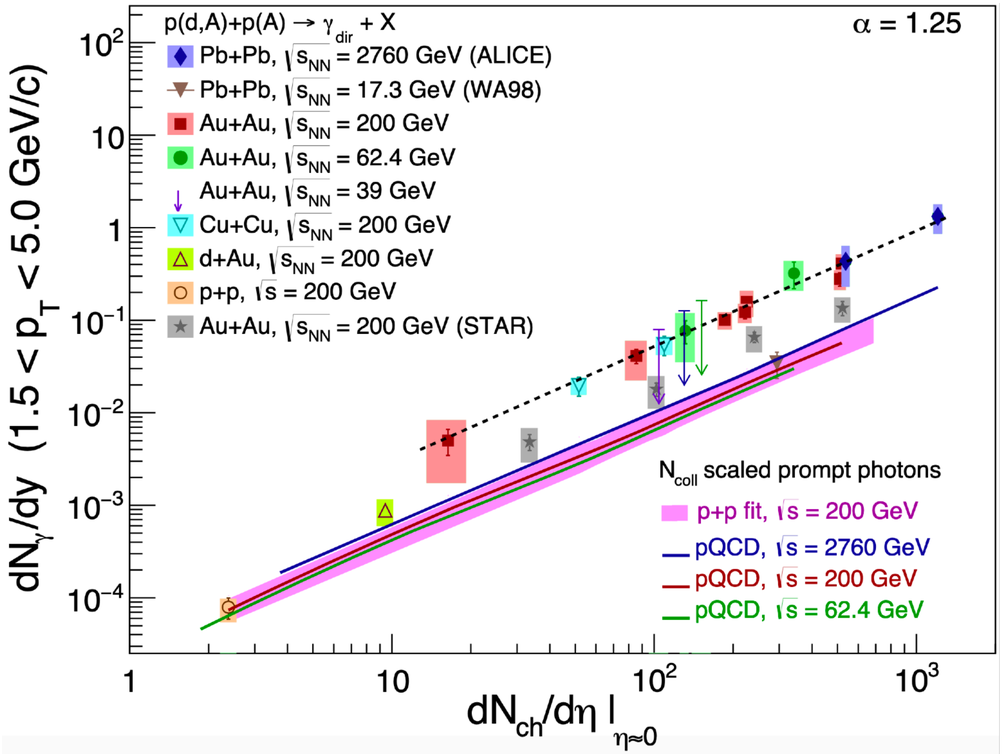
PHENIX @ 200 GeV

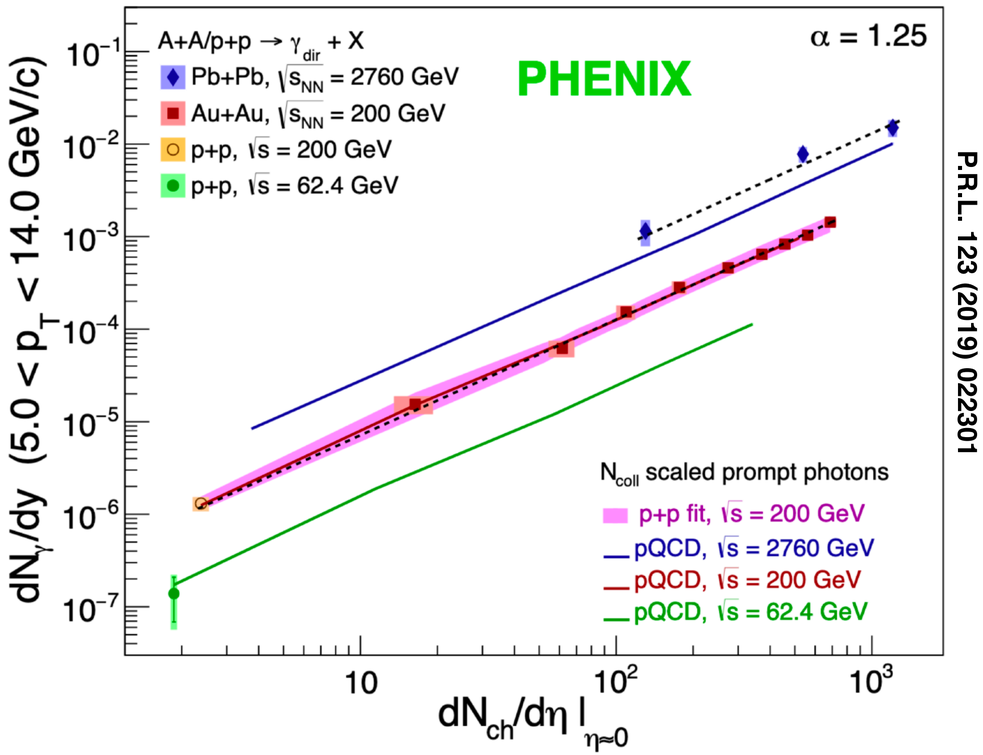


- Low p_T photon yield shows scaling with $(dN_{ch}/d\eta)^{1.25}$ regardless of collision system or energy.

Direct photons at RHIC

RHIC @ 200 GeV





- Low p_T photon yield shows scaling with $(dN_{ch}/d\eta)^{1.25}$ regardless of collision system or energy.
- STAR results also show scaling but at much lower magnitude → STAR / PHENIX tension.
- Intermediate p_T results also show scaling for same collision energy, in agreement with pQCD.

Outline

- **EW boson and top quark measurements in HIC**
  - W boson
  - Z boson and Drell-Yan
  - Prompt photons
  - **Top quarks**

- Future HIC facilities and nPDF prospects:
  - CERN:
    - LHC upgrades
    - Future Circular Collider
  - China:
    - Electron Ion Collider in China
  - USA:
    - RHIC upgrades
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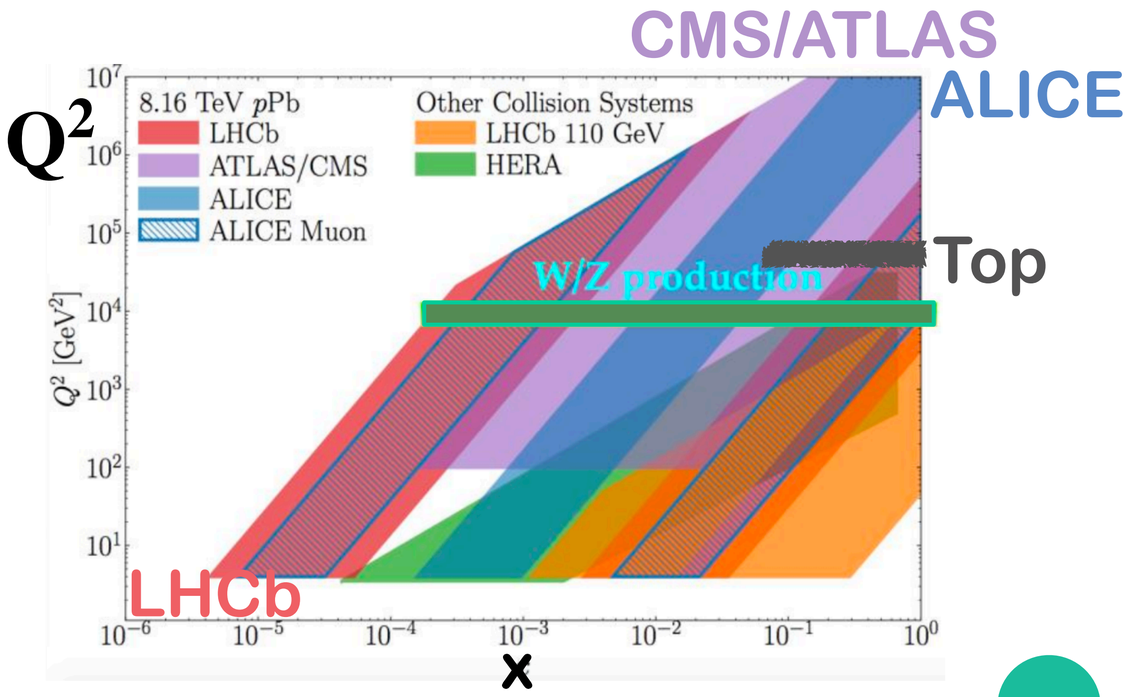
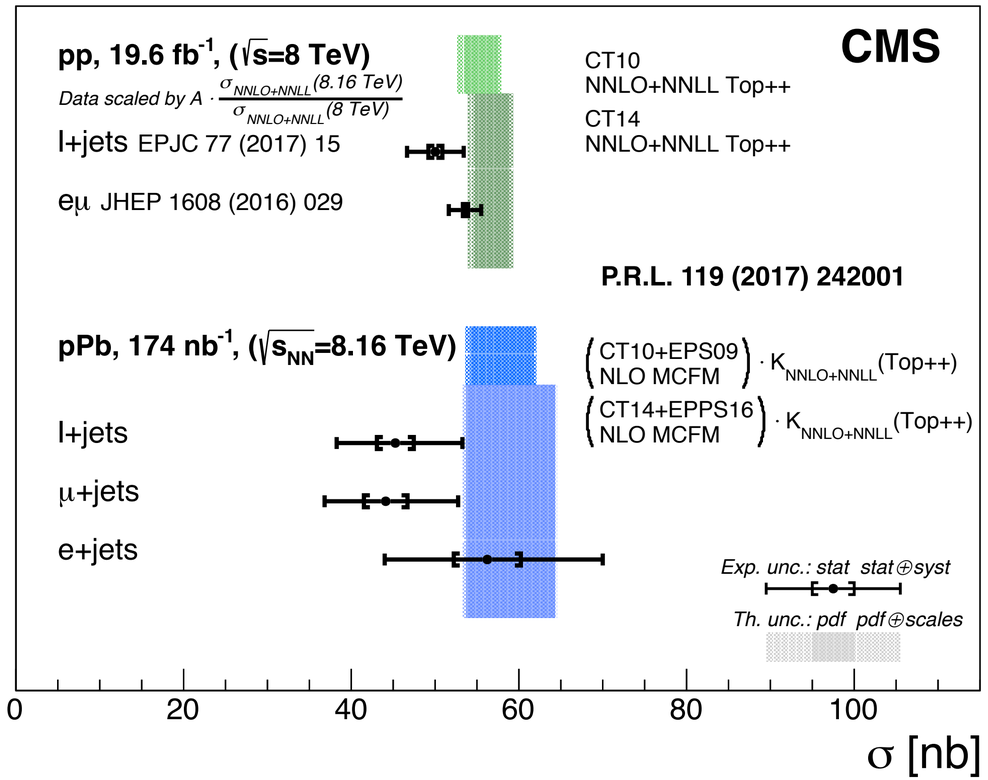
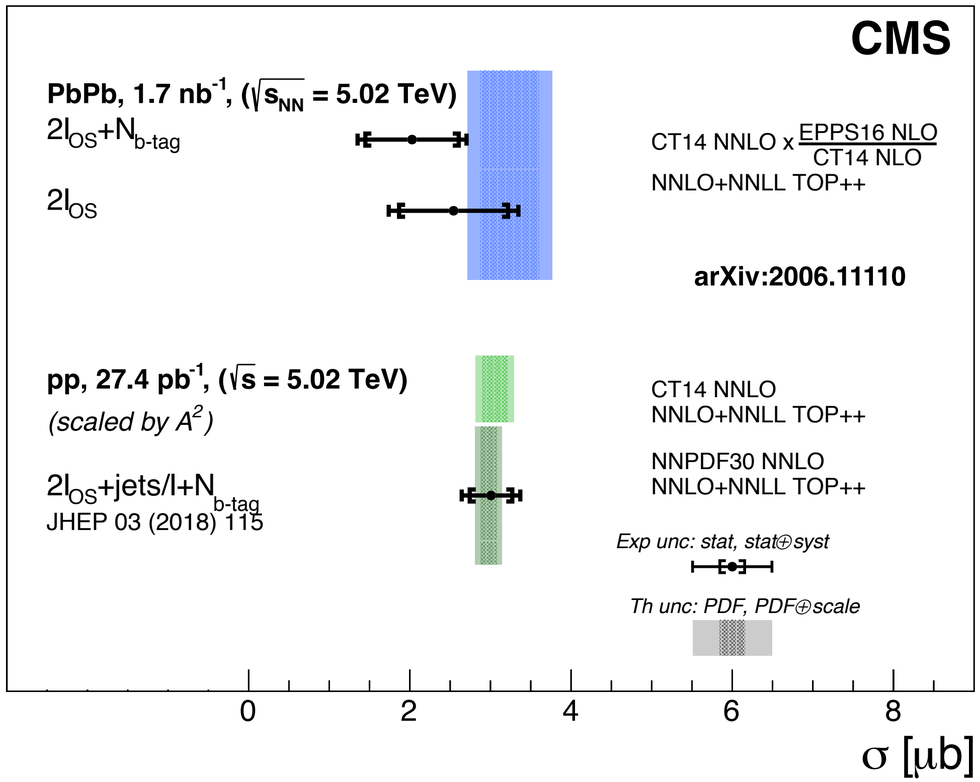


Top quarks in HI

CMS pPb @ 8.16 TeV



CMS PbPb @ 5.02 TeV



- First measurements of top quarks in HIC.
- Current results in agreement with both PDF and nPDF models.
- Large uncertainties due to lack of statistics.
  - Will be significantly improved with future high luminosity LHC and FCC.

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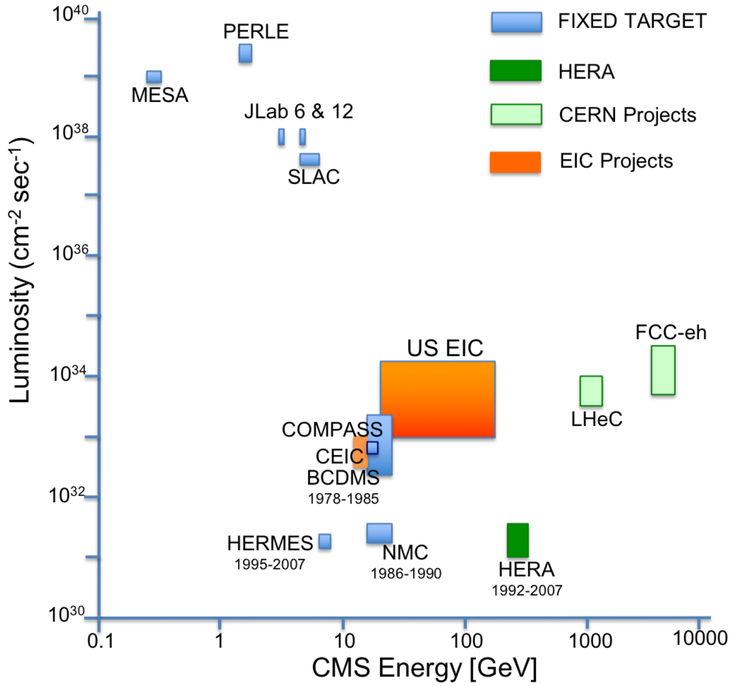

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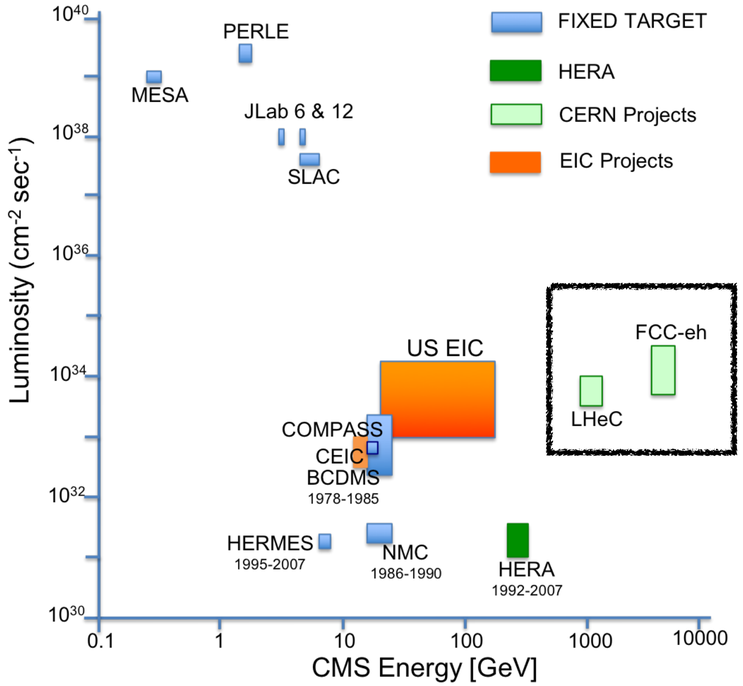
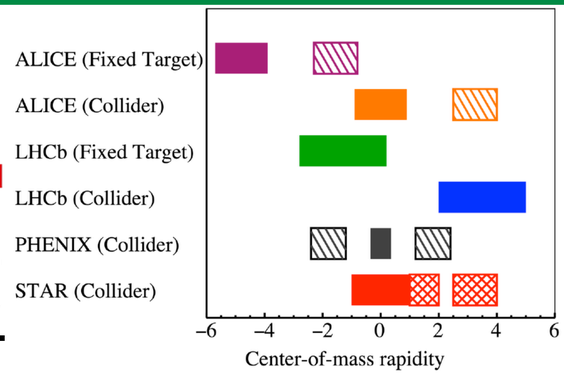
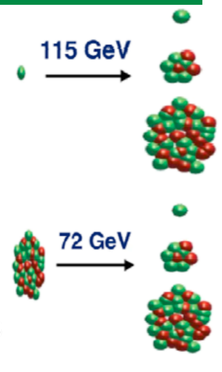


Future plans: LHC

- **A Fixed Target Experiment (AFTER) at LHC: arXiv:1807.00603**
  - Build joint programme between LHCb and ALICE collaborations.
  - LHCb currently use gas targets injected in LHC beam pipe through SMOG.
  - Goal to collide p (Pb) beams against polarised gas targets at 115 (72) GeV.





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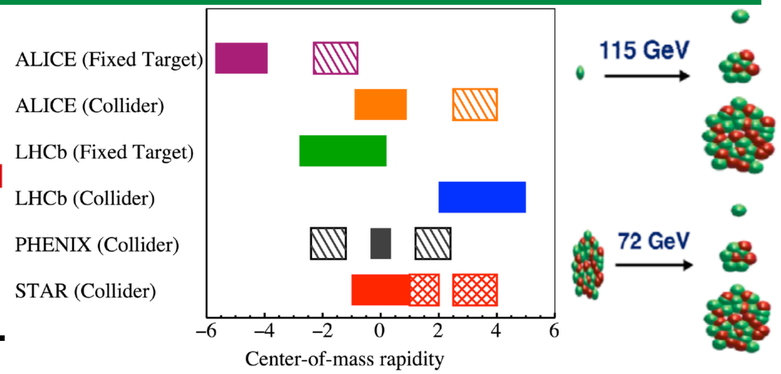

- **High Luminosity LHC (2028+): CERN-2017-007-M**
  - Major LHC upgrade to increase pp luminosity by ~x10 beyond design value.
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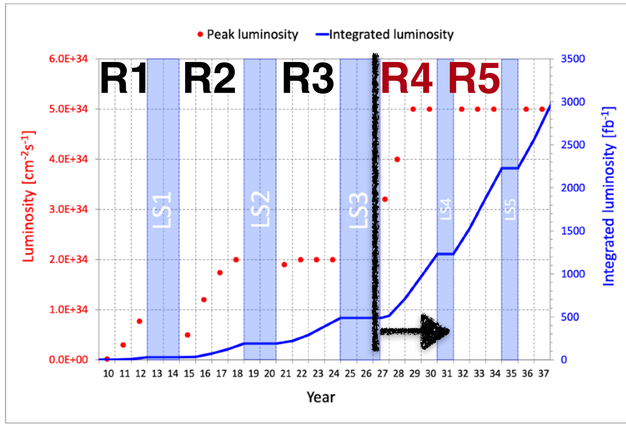

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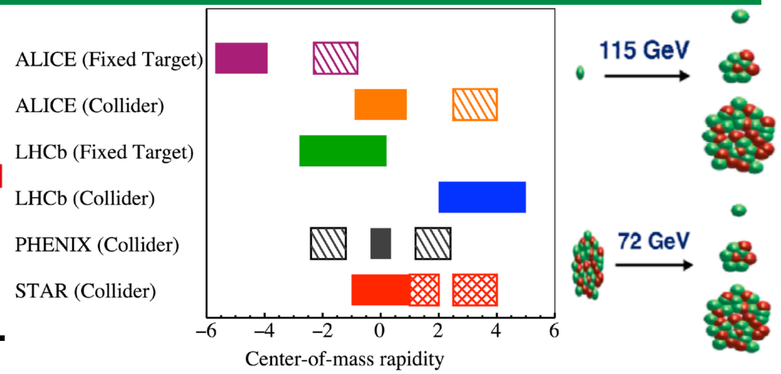

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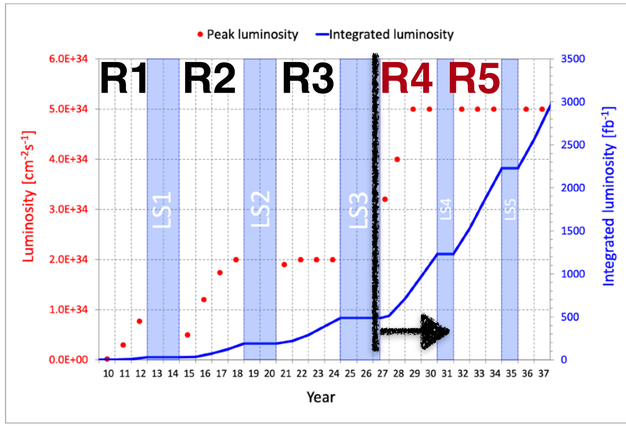

- **Large Hadron electron Collider (LHeC, 2031+): CERN-ACC-2020-2**
  - Add a 60 GeV electron beam to LHC using an Energy Recovery Linac.
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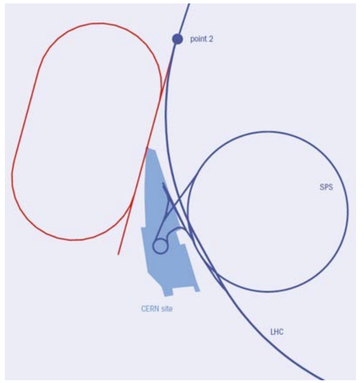

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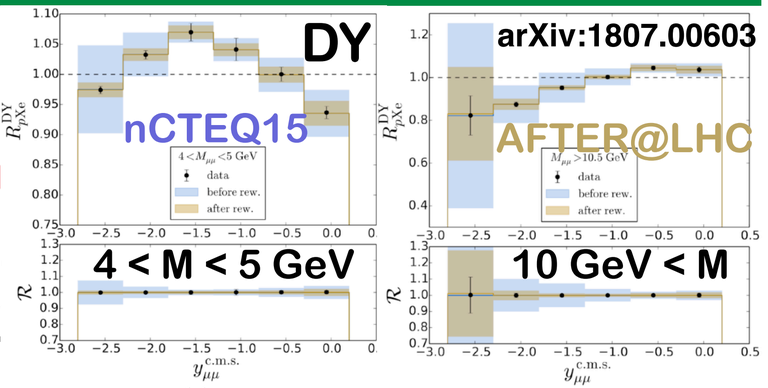

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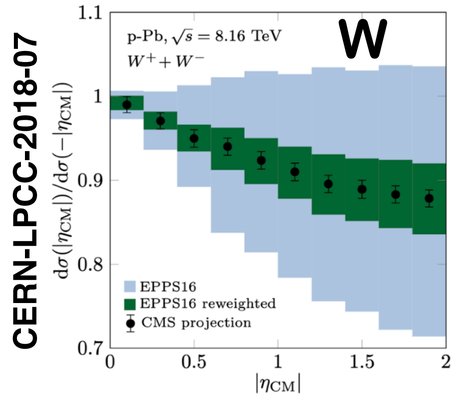

EPPS16

CMS Run 3+4

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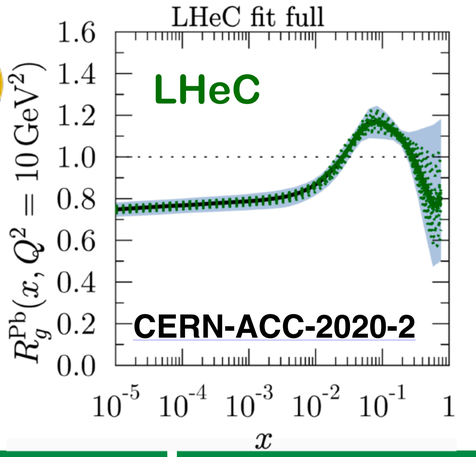

Future Circular Collider (FCC)

- **Several options been studied:**
  - FCC-ee (2040-2060): E.P.J.S.T. 228 (2019), 261-623
  - FCC-hh (pp and ions, 2060+): E.P.J.S.T. 228 (2019), 755–1107
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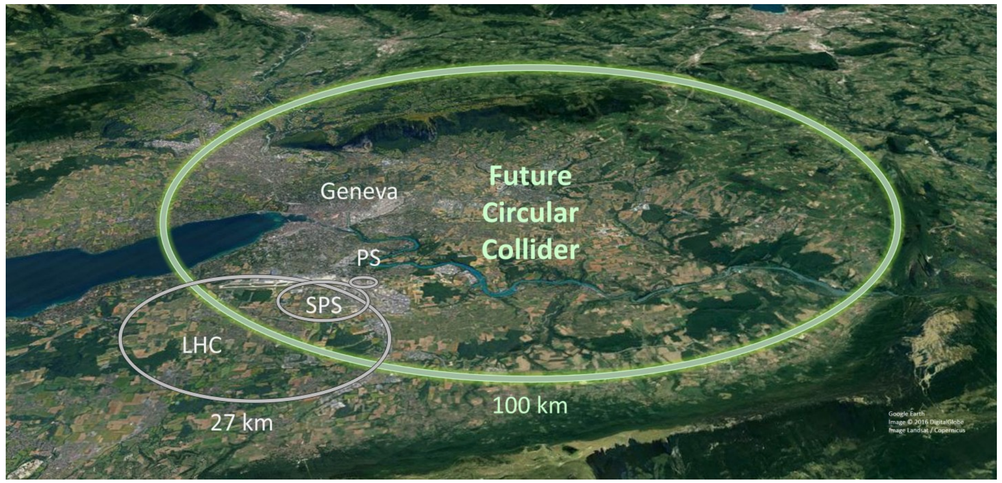
- **FCC design:**
  - 100 km circular collider linked to CERN.
  - Require magnets of 16 T for pp @ 100 TeV / pPb @ 63 TeV / PbPb @ 39 TeV
  - PbPb luminosity (35 nb^{-1}) per month up to ~3x full LHC PbPb programme.



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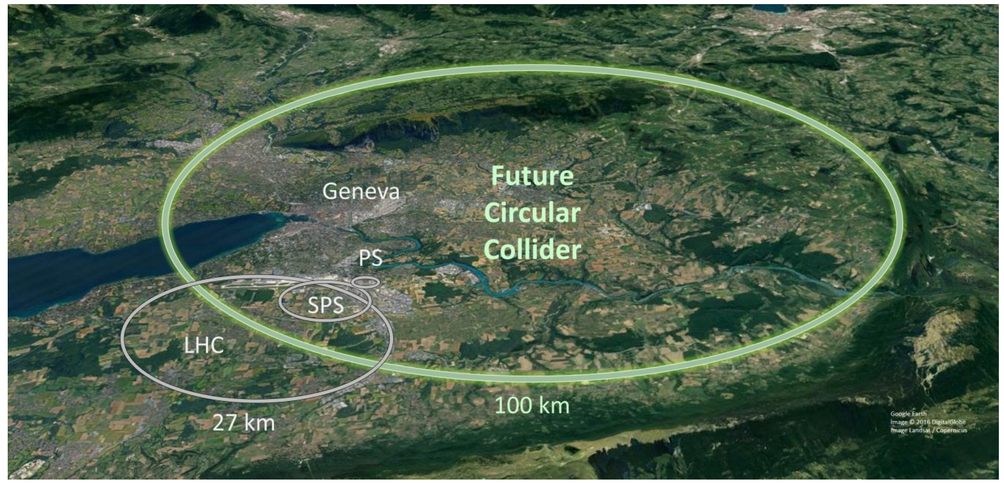
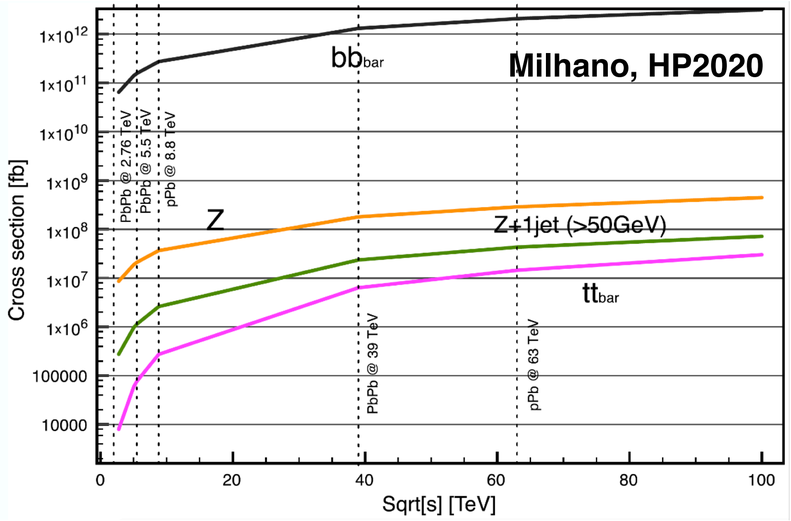
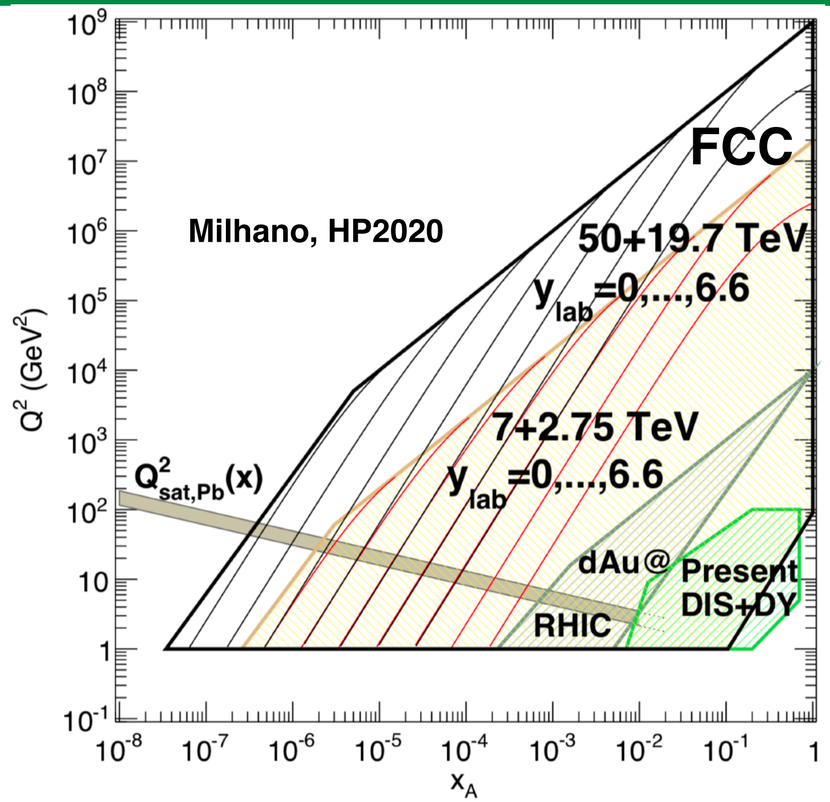




- **Large increase of all pQCD cross-sections vs LHC:**
  - Beauty increase by 6-fold
  - W/Z increases by 7-fold
  - top increases by 80-fold

Future Circular Collider (FCC)



- Substantial increase of kinematic coverage in x-Q^2 plane.
- Reach small x region probing saturation at perturbative scales.

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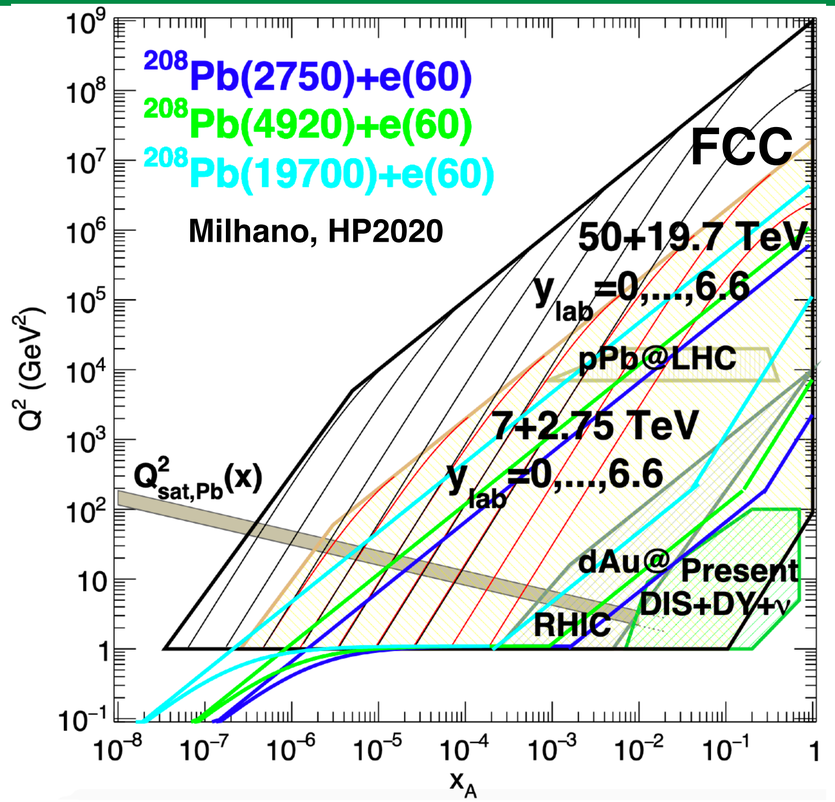

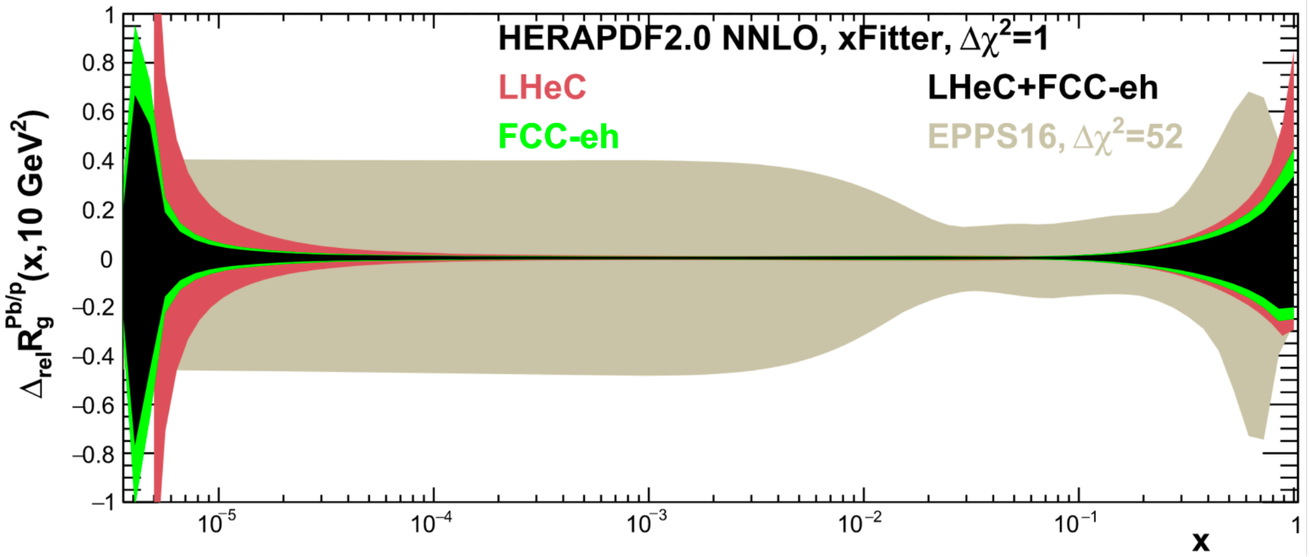

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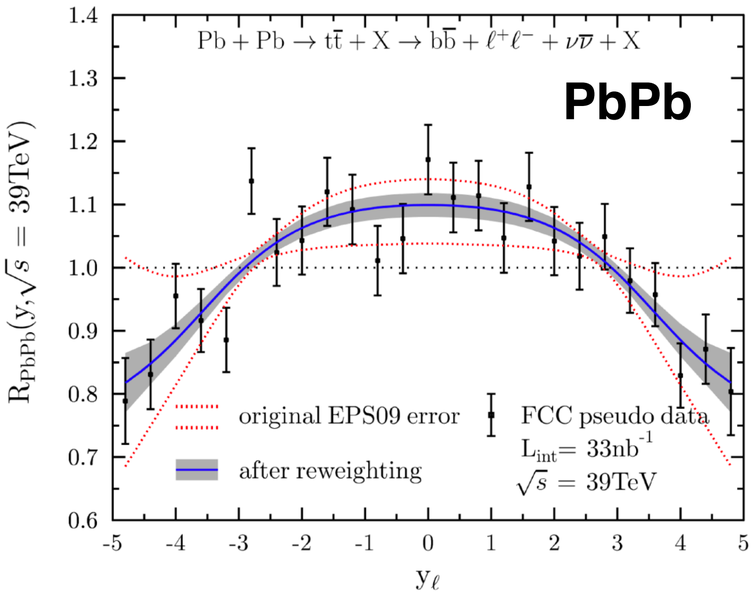
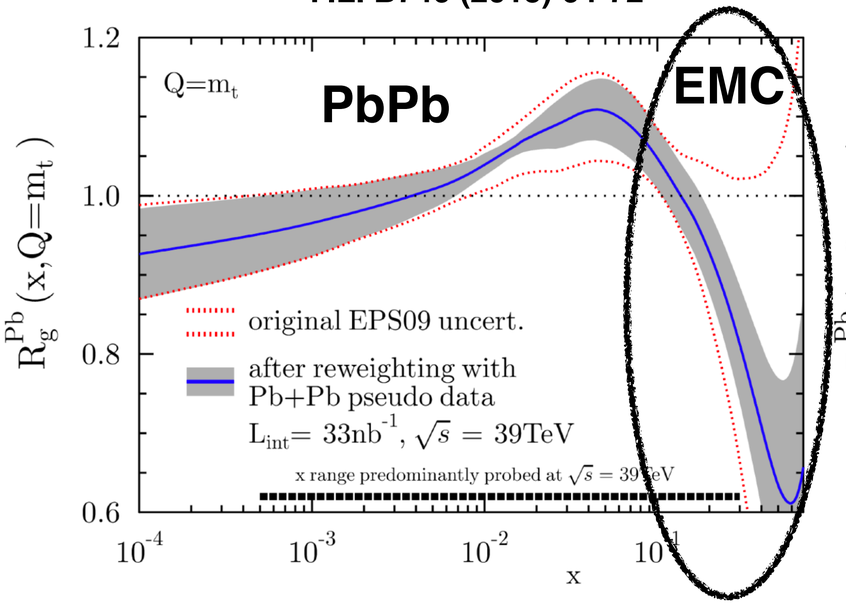
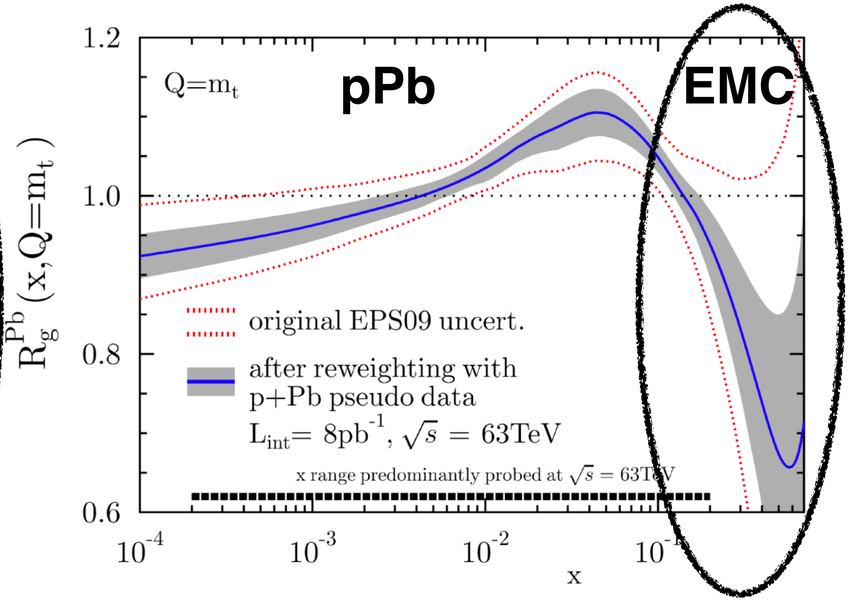


P.L. B746 (2015) 64-72





- Substantial increase of kinematic coverage in x-Q^2 plane.
- Reach small x region probing saturation at perturbative scales.
- Complementarity with LHeC providing full constraints to nPDFs.
- Top quarks in HI provide strong constraints to gluon nPDF at $Q=m_{top}$.

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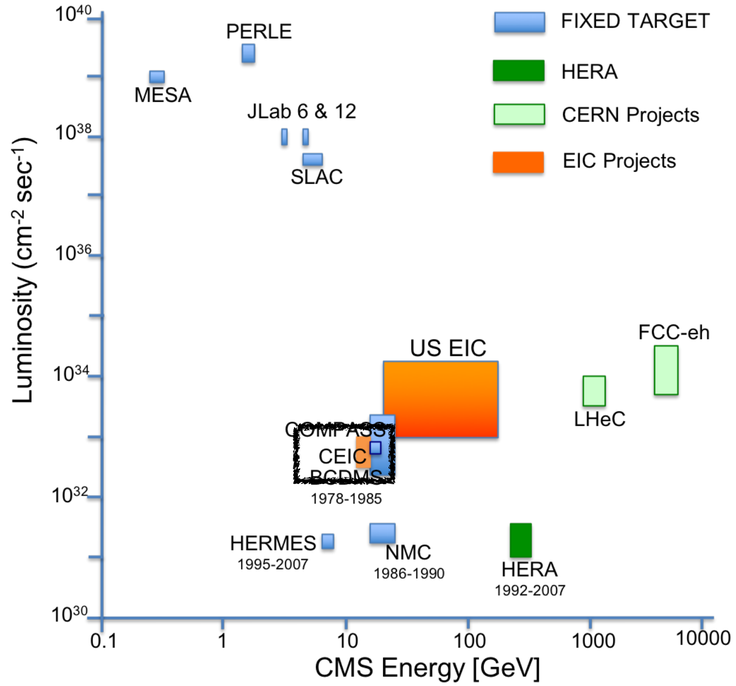
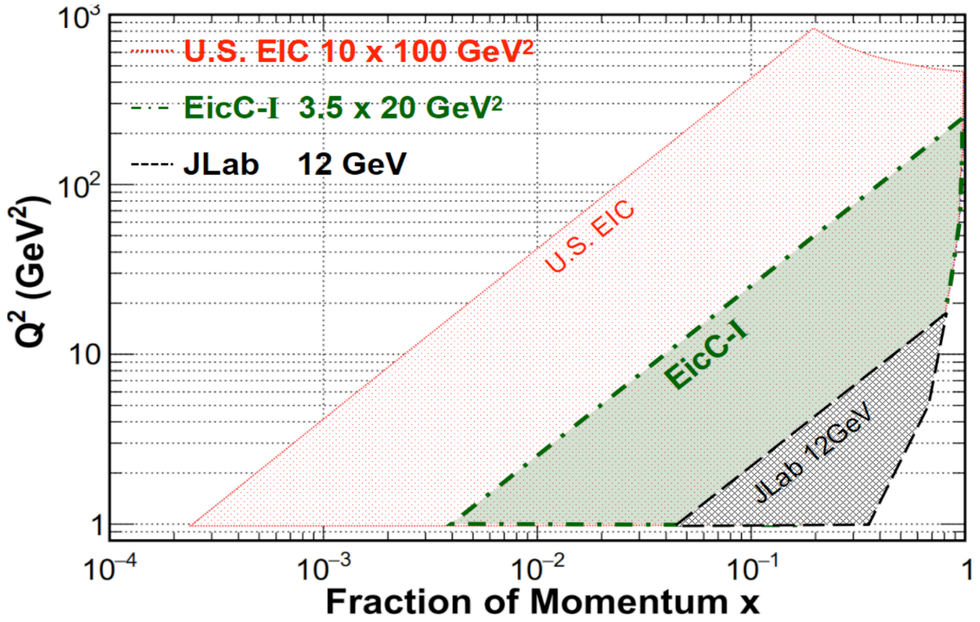
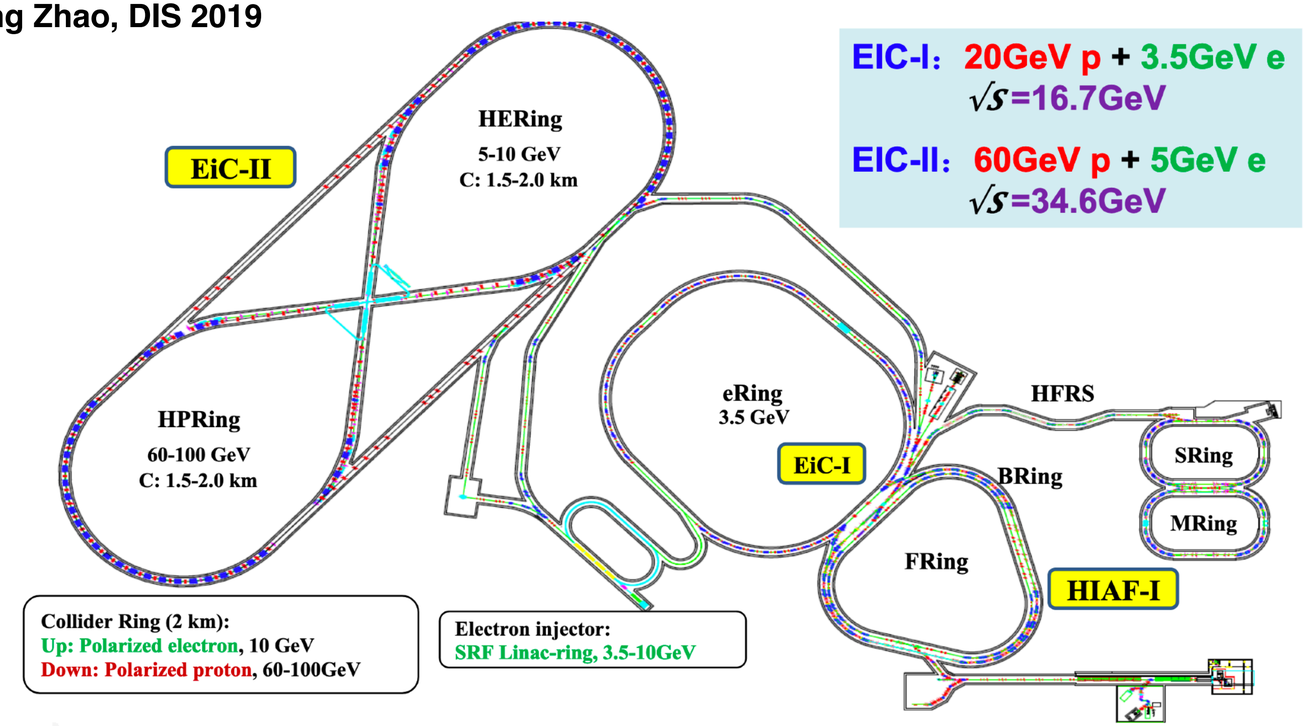


Electron Ion Collider in China (EicC)



Yuxiang Zhao, DIS 2019



- To be installed in the High Intensity Heavy-Ion Accelerator Facility in Huizhou city.
- Use polarised beams of e (3.5 GeV) and p (ions) (20 GeV/u).
- Precise measurements for nucleon spin structure with flavour separations.
- Complimentary to the US EIC with higher CM energies.
- Plan to start data taking in 2032.

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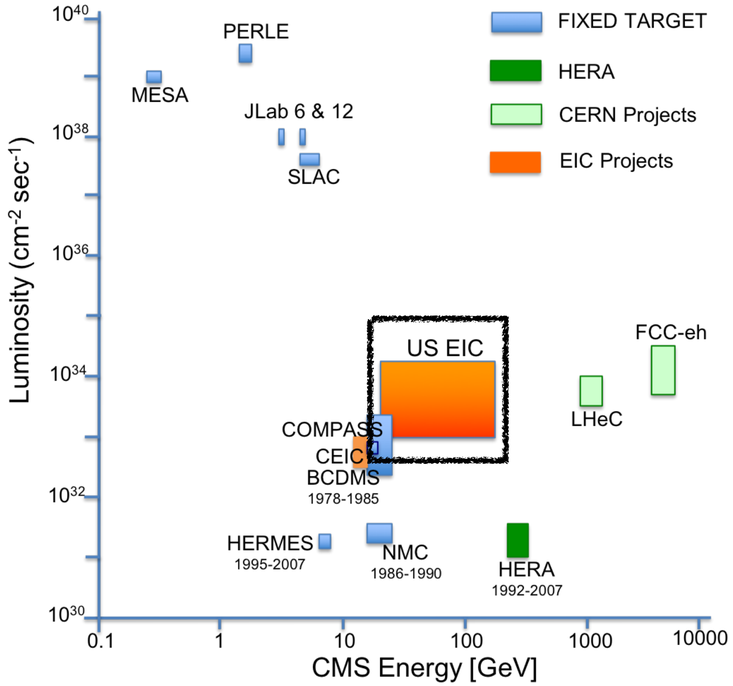

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- **sPHENIX (2023+): arXiv:1501.06197**
  - Includes a Si tracker, Ecal, Hcal, TPC, vertex detectors and 1.5T B field.
  - Plan to start data taking in early 2023: p+p, p+Au and Au+Au.
  - Goal to collect 145B minbias Au+Au events → ~30x more than current data.
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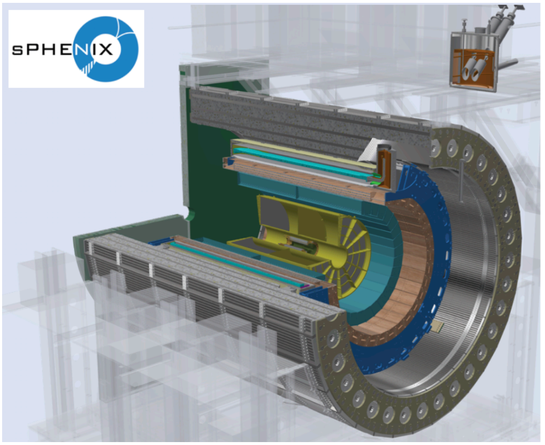

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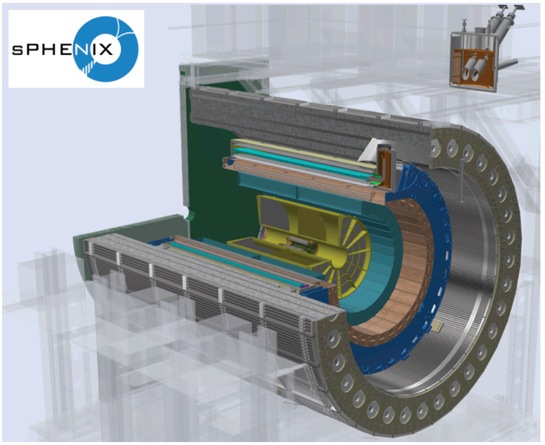
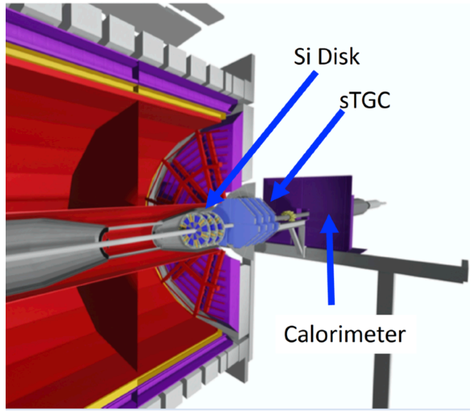


- **STAR Forward Upgrade programme (2021+): SN0648**
  - Extend tracking system to forward region ($2.5 < \eta < 4$).
  - Reuse PHENIX Ecal and add new forward hadronic calorimeter.
  - Plan to start data taking in 2021 and run in parallel with sPHENIX.
  - Focus on forward jet ($|\eta|>1$), direct photon and Drell-Yan measurements.



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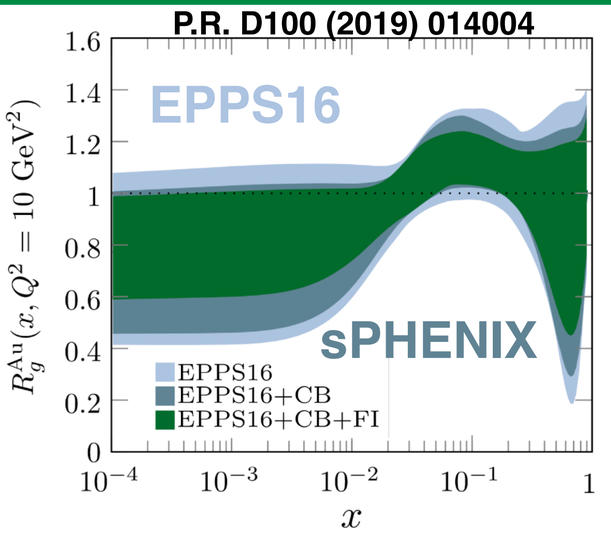

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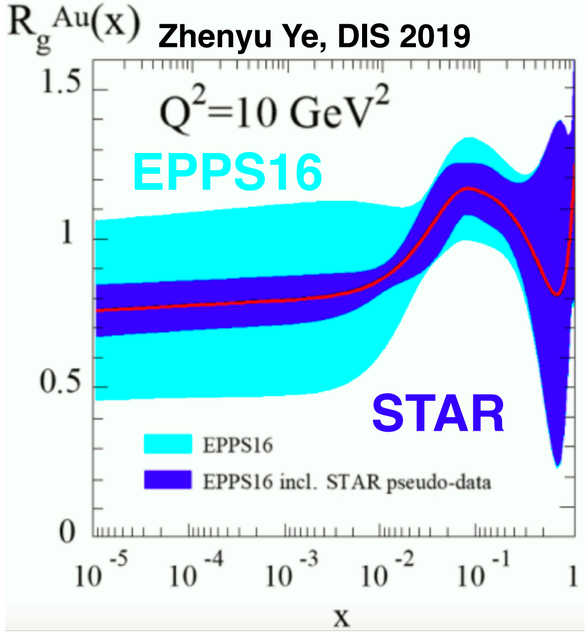
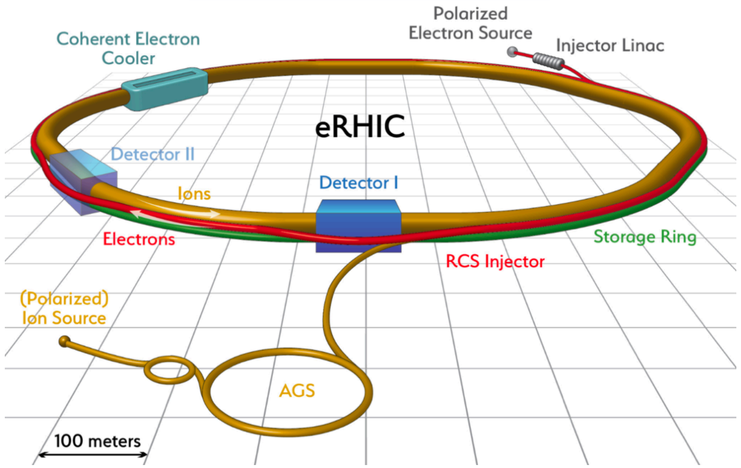


  - Both STAR and sPHENIX data will constrain the gluon nPDFs for Au.

US Electron Ion Collider (EIC)

- **EIC project (2030+): arXiv:1212.1701**
  - Accelerate polarised beams of: electrons using 400 MeV Linac and ions using AGS.
  - Collide e-A beams at ~20-140 GeV CME and ~$10^{33\text{-}34}$ $cm^{-2}s^{-2}$ luminosity.
  - Ion species ranging from proton to Uranium.
  - Consider 2 IPs with general-purpose hermetic detectors.

arXiv:1212.1701



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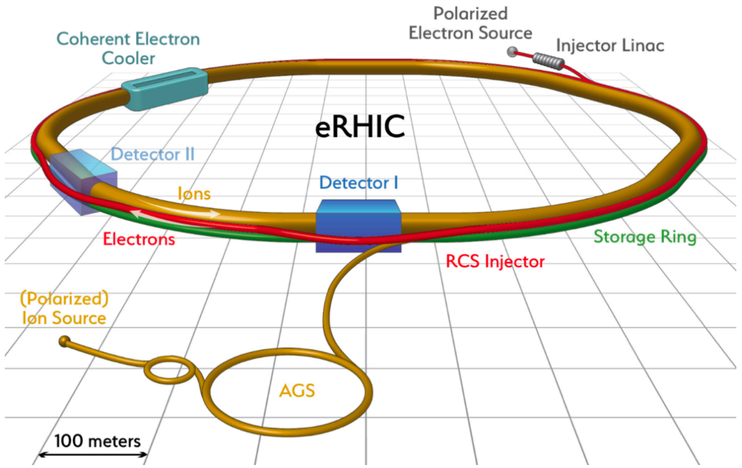
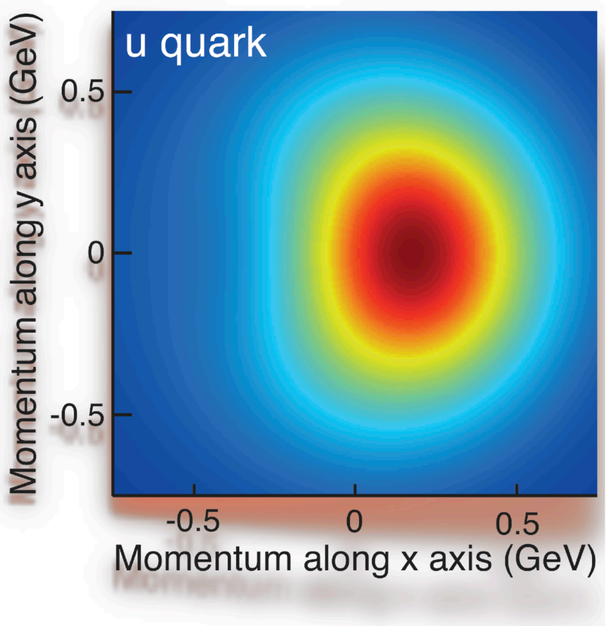


- **Main physics programme:**
  - Hadron and nuclear matter tomography: TMD and spatial imaging.



US Electron Ion Collider (EIC)

- **EIC project (2030+): arXiv:1212.1701**
  - Accelerate polarised beams of: electrons using 400 MeV Linac and ions using AGS.
  - Collide e-A beams at ~20-140 GeV CME and ~$10^{33\text{-}34}$ $cm^{-2}s^{-2}$ luminosity.
  - Ion species ranging from proton to Uranium.
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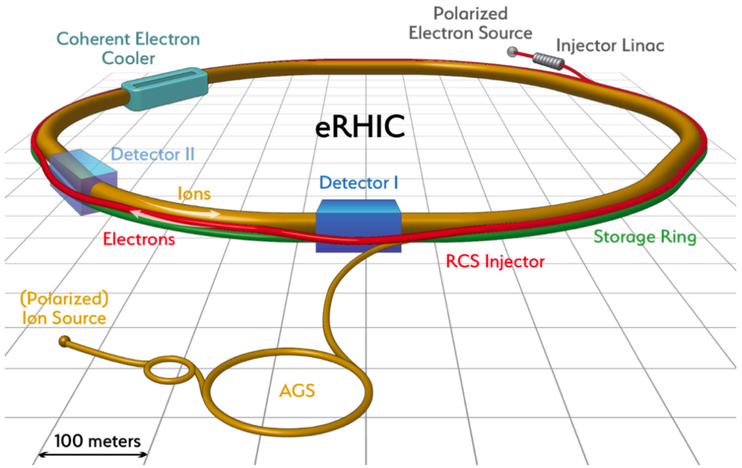

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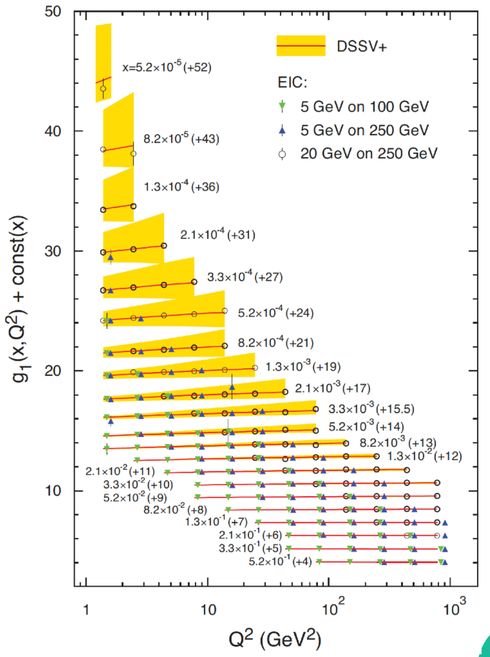

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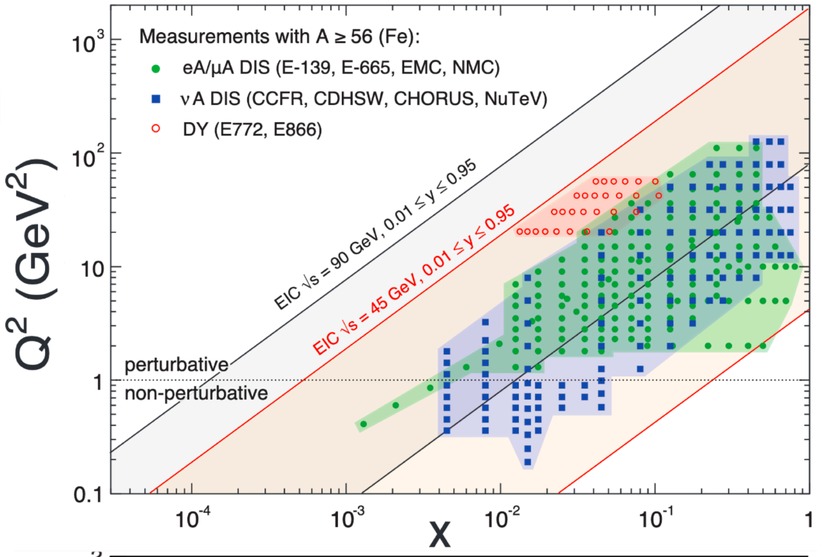
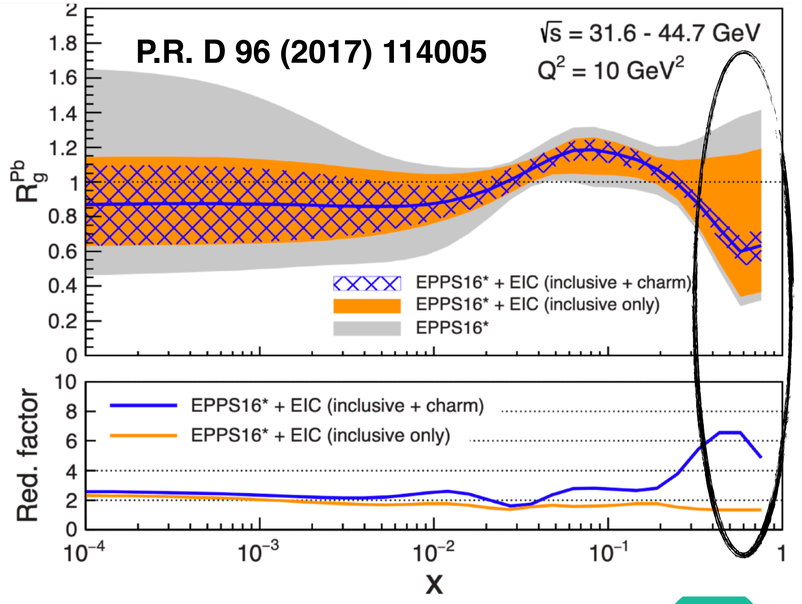


- **Main physics programme:**
  - Hadron and nuclear matter tomography: TMD and spatial imaging.
  - Spin and flavour structure of nucleon.
  - Parton distributions in nuclei covering a wide range of x and Q^2.
  - QCD at extreme parton densities: saturation.



SUMMARY

- **Electroweak and nPDF measurements:**
  - Observation of nuclear PDF effects in W boson production.
    - LHC pPb data provide constrains to current nPDF models.
  - First measurements of top quarks and Drell-Yan in HIC open new opportunities.
  - High p_T photon yields consistent with pQCD while low pT follow scales with charged particle multiplicity (tension between PHENIX and STAR).
  - Z/W bosons in PbPb sensitive to collision geometry (tension between ATLAS and CMS).

- **Long-term of QCD global analysis:**
  - Exploit data from future HIC facilities (HL-LHC, LHeC, FCC, EicC, EIC).
  - Several collision modes proposed: e-A, p-A, A-A and fixed target.
  - Scan over multiple dimensions: nPDFs, TMDs, flavour, spin, …
  - Extension to forward physics and low x-regime, probing gluon saturation.

Thank you for your attention!

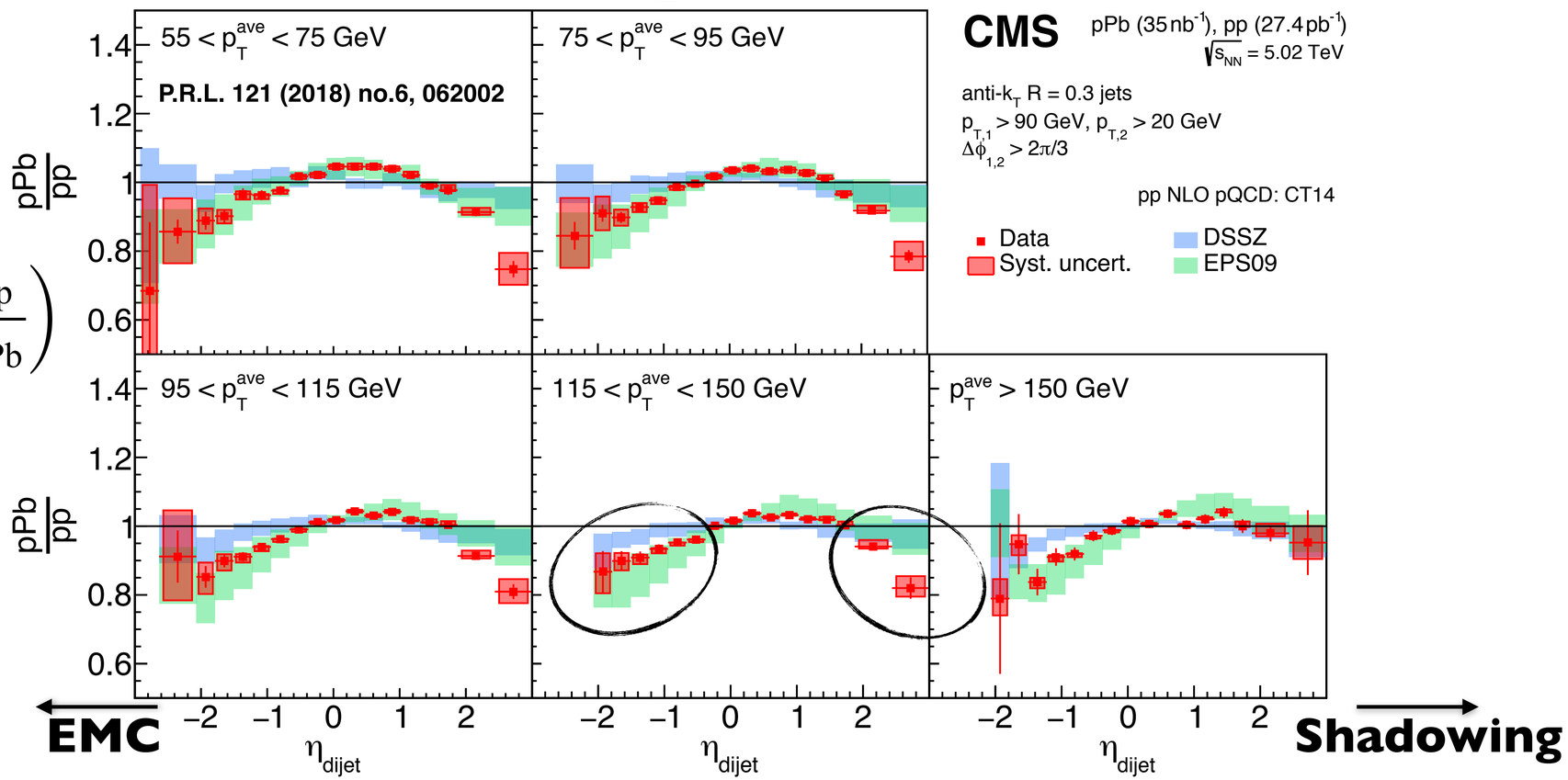
BACKUP

Dijet in pPb

CMS @ 5.02 TeV

$$\eta_{\text{dijet}} = \frac{(\eta_{j1} + \eta_{j2})}{2} \sim \frac{1}{2} \ln\left(\frac{x_{\text{p}}}{x_{\text{Pb}}}\right)$$

$$p_{\text{T}}^{\text{ave}} = \frac{(p_{\text{T},j1} + p_{\text{T},j2})}{2} \sim Q$$



- pPb/pp ratio deviate from unity in the small and large η_{dijet} regions.

Dijet in pPb

CMS @ 5.02 TeV

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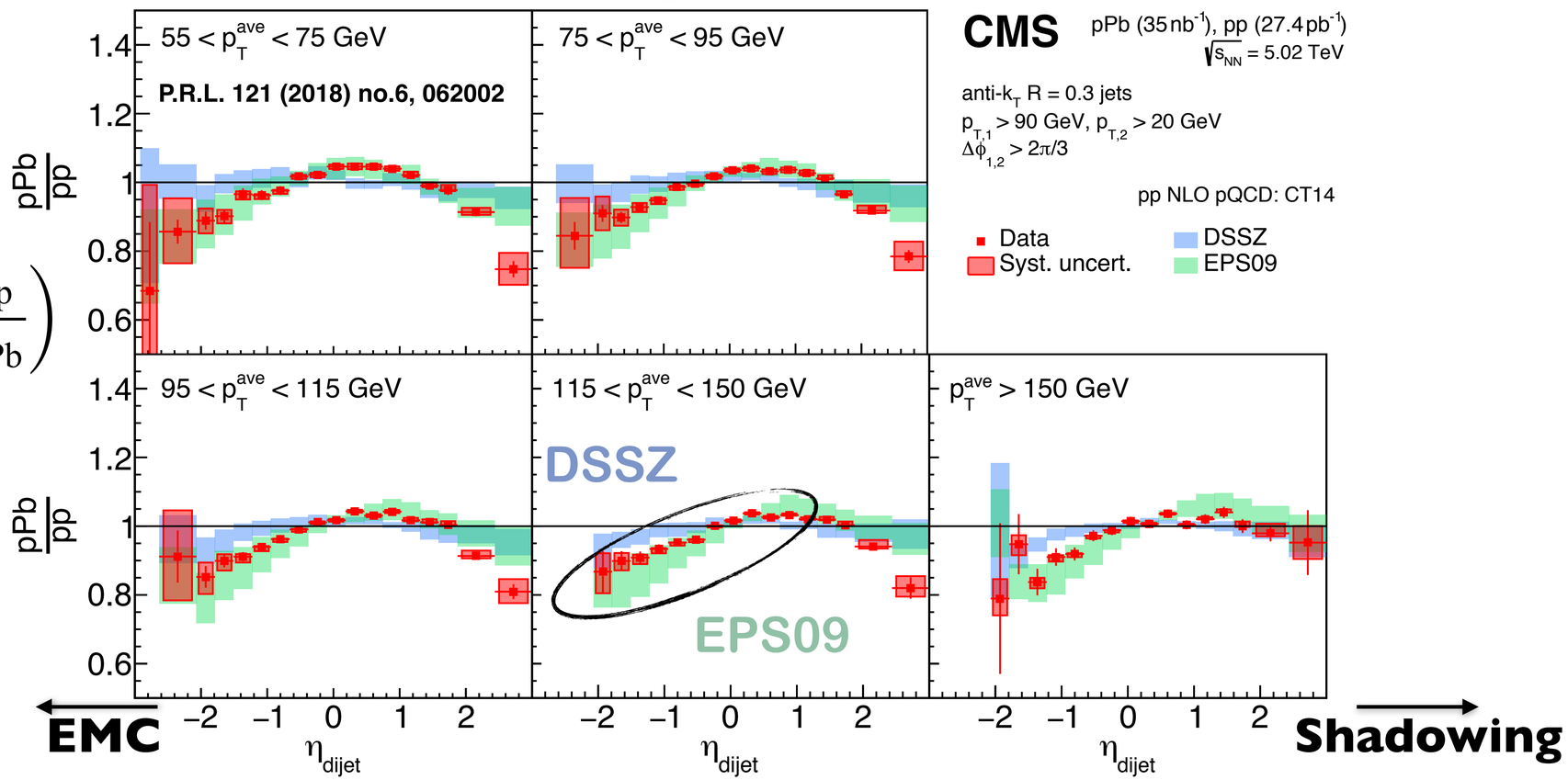

- pPb/pp ratio deviate from unity in the small and large η_{dijet} regions.
- EPS09 calculations match data at $\eta_{\text{dijet}} < 1$, while DSSZ overpredict the results.

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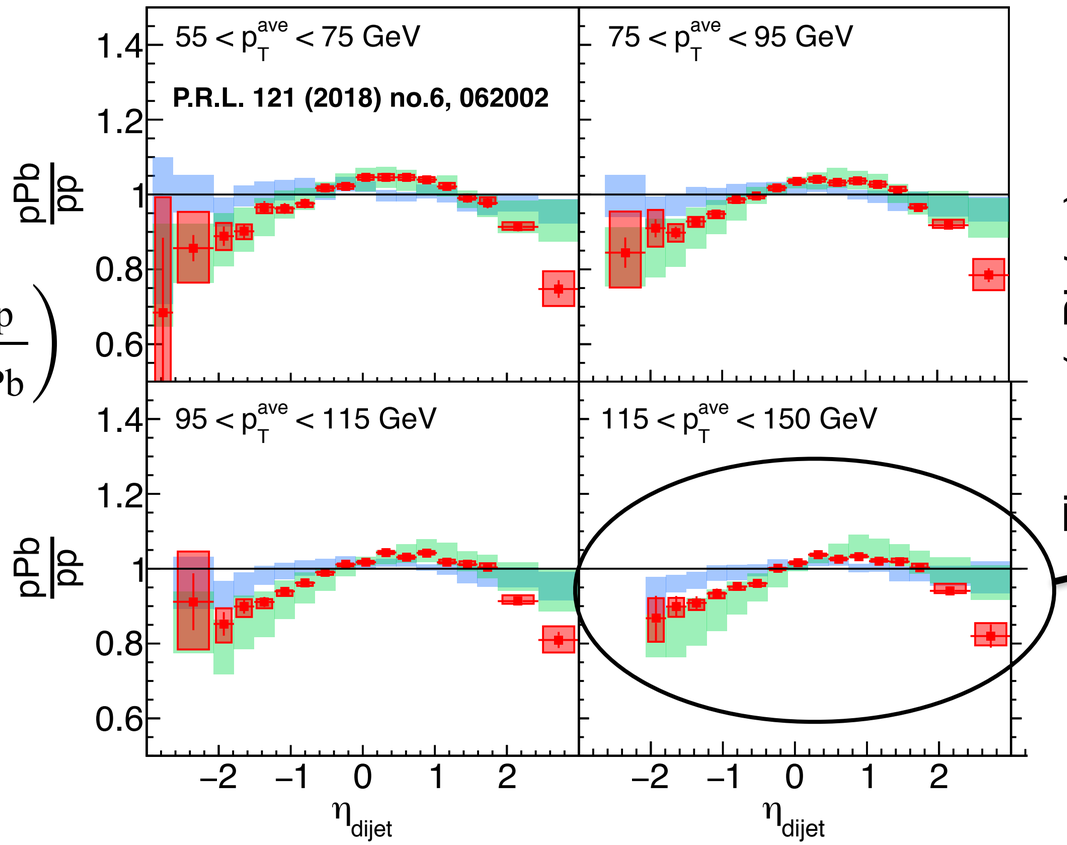
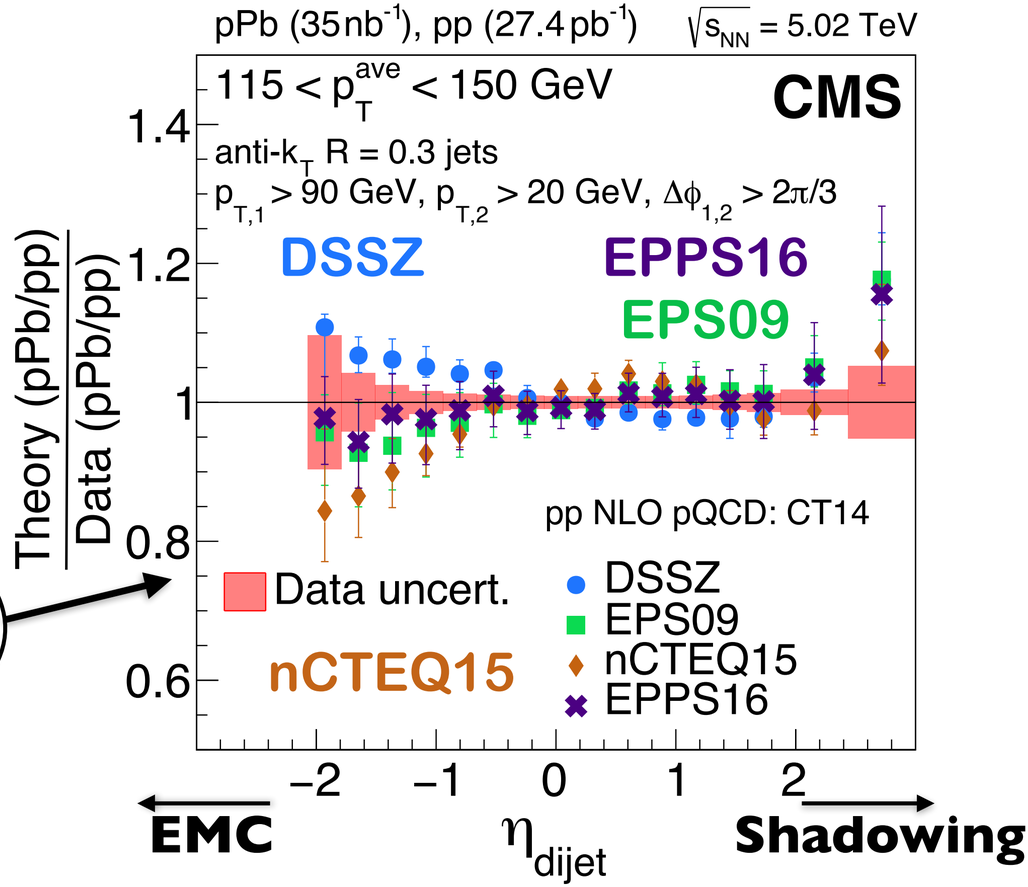
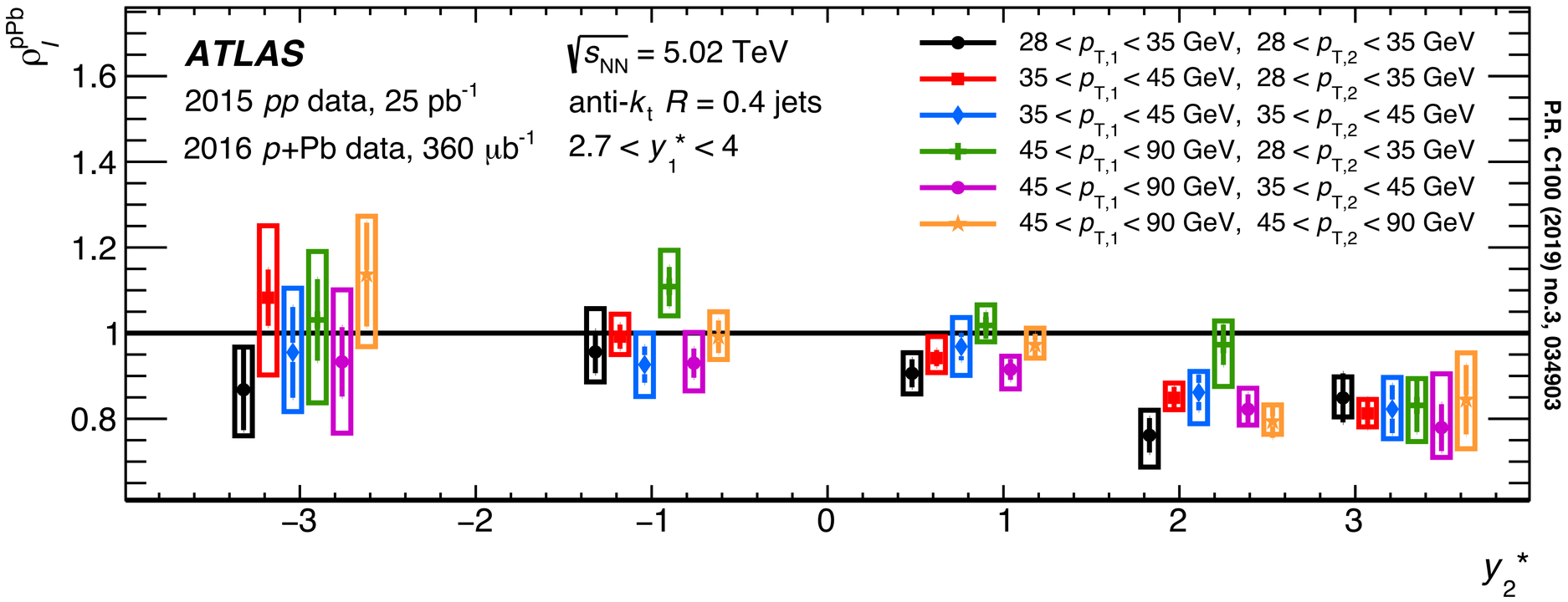




- pPb/pp ratio deviate from unity in the small and large η_{dijet} regions.
- EPS09 calculations match data at $\eta_{\text{dijet}} < 1$, while DSSZ overpredicts the results.
- Data incompatible with DSSZ and nCTEQ15, while agrees with EPS09 and EPPS16.

Dijet in pPb

ATLAS @ 5.02 TeV



- pPb/pp ratio of jet pair yields is suppressed by 20% when sub-leading jet $y_2 > 0$.

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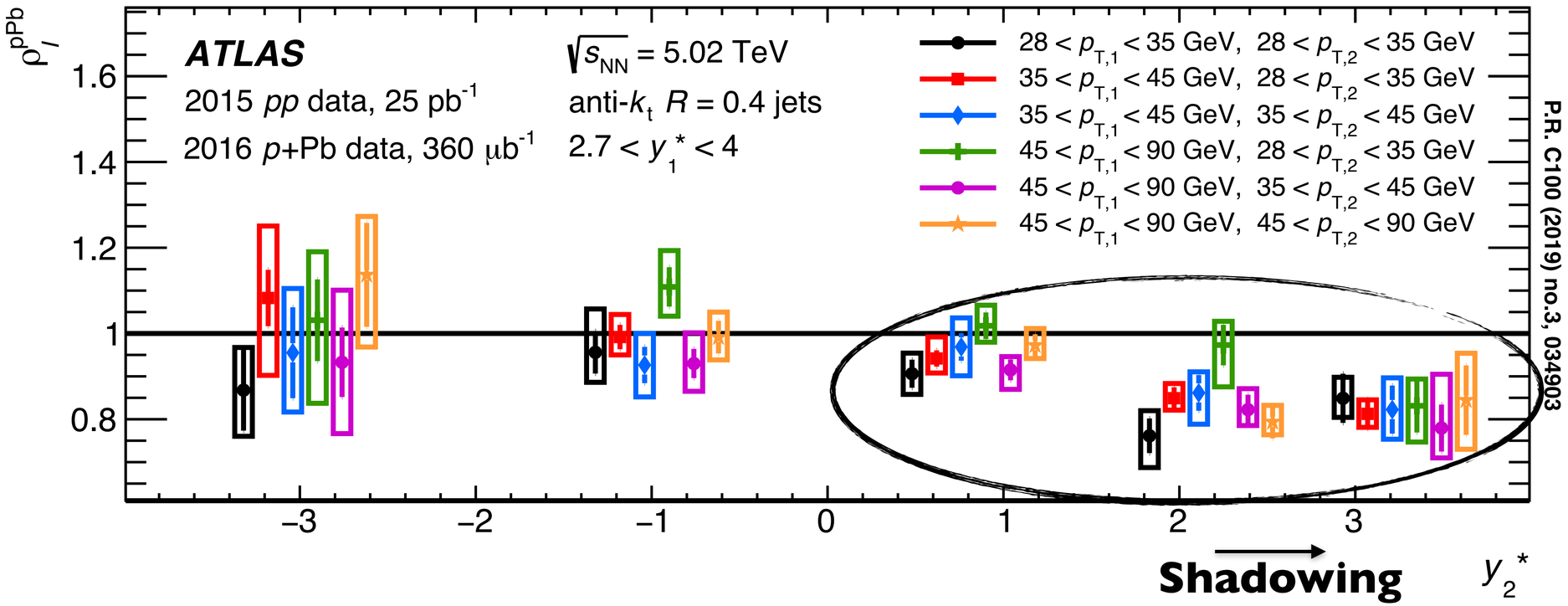
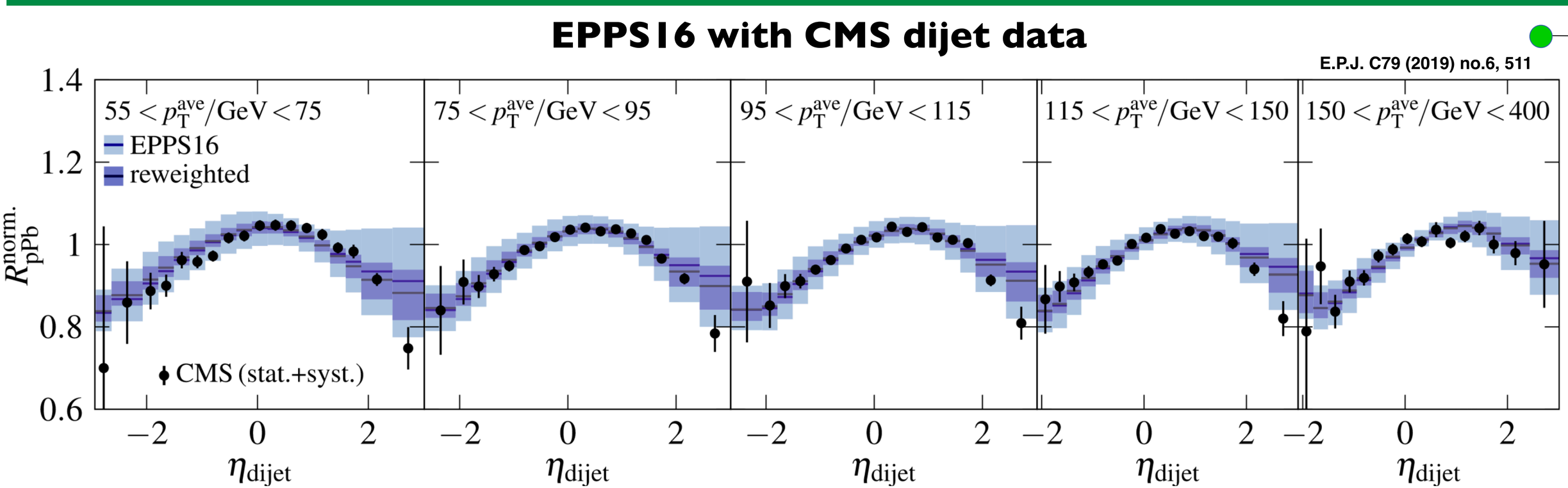
ATLAS @ 5.02 TeV



- pPb/pp ratio of jet pair yields is suppressed by 20% when sub-leading jet $y_2 > 0$.
- Suppression observed in a rapidity region where nuclear shadowing is predicted.

Impact of dijet pPb data on nPDFs

EPPS16 with CMS dijet data



- Significant reduction of EPPS16 uncertainties, specially in the forward region.

Impact of dijet pPb data on nPDFs

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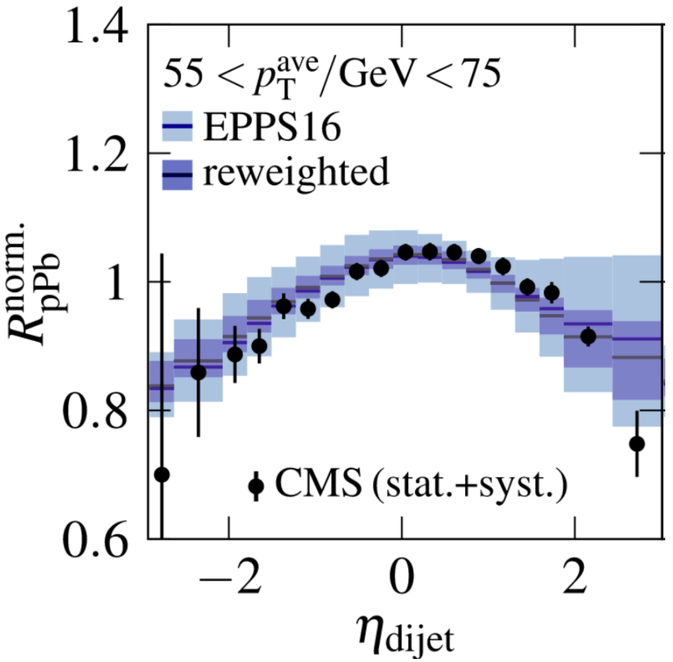

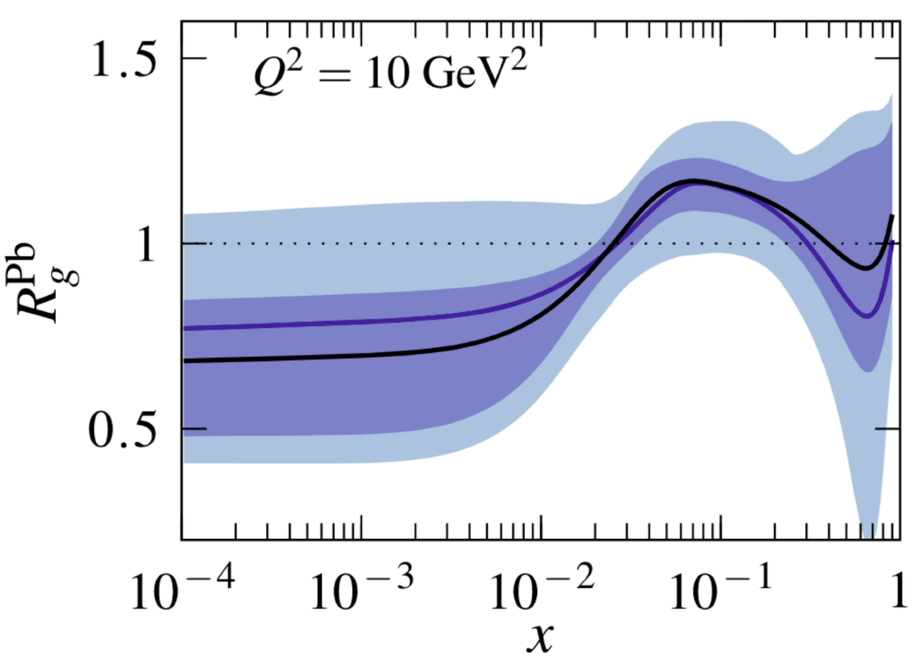

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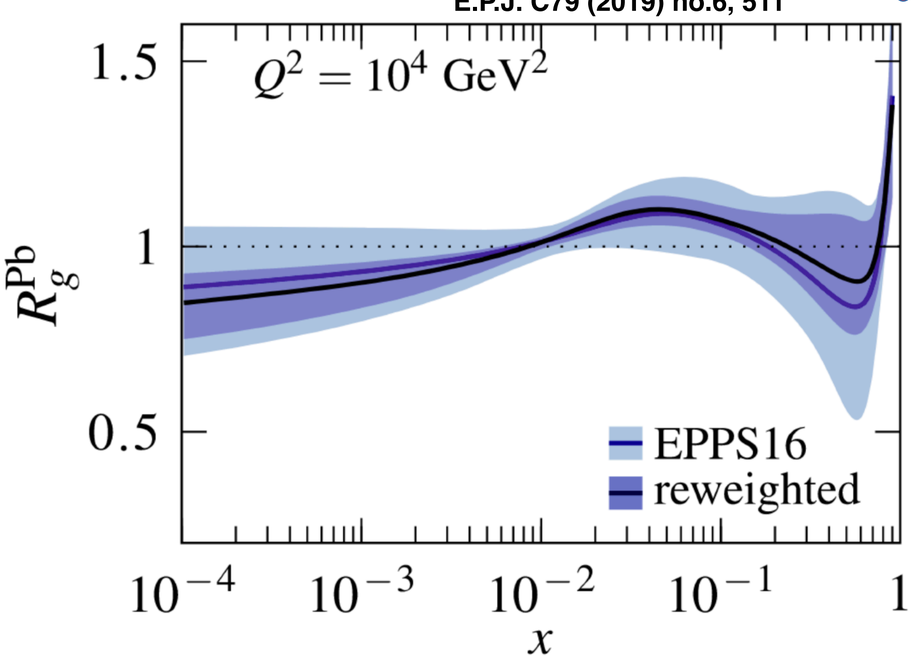
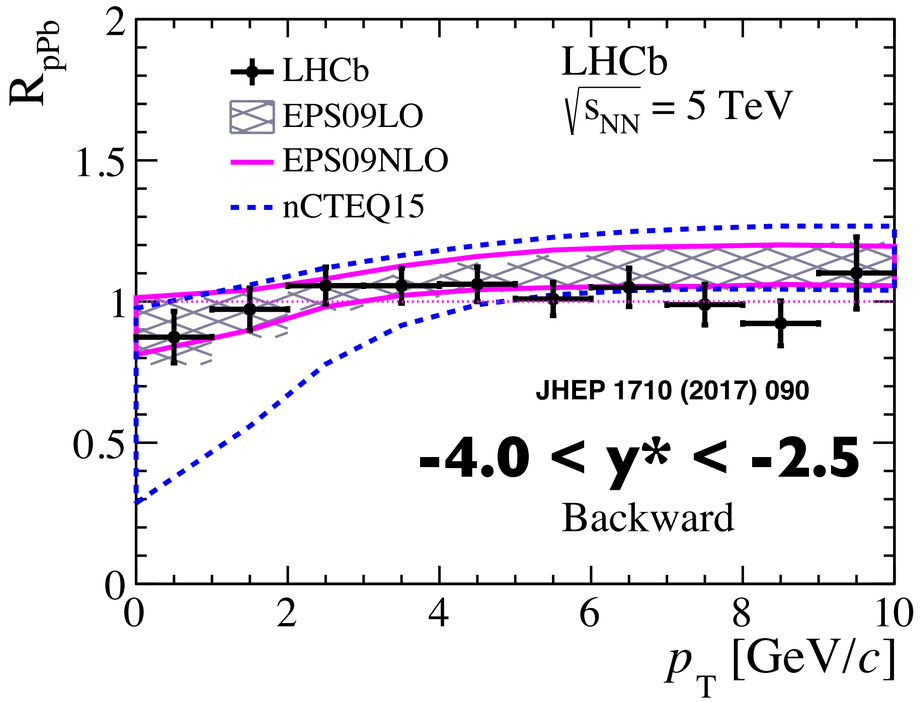
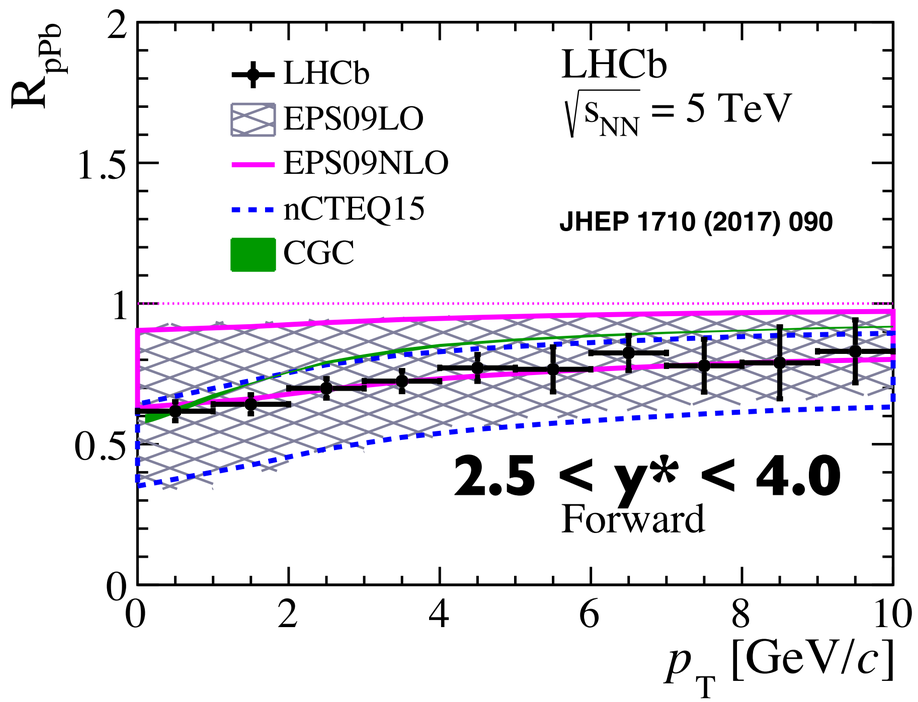


- Significant reduction of EPPS16 uncertainties, specially in the forward region.
- Mainly impact the gluon nPDF, adding strong constrains across a large x range.

Prompt D in pPb

LHCb @ 5.02 TeV

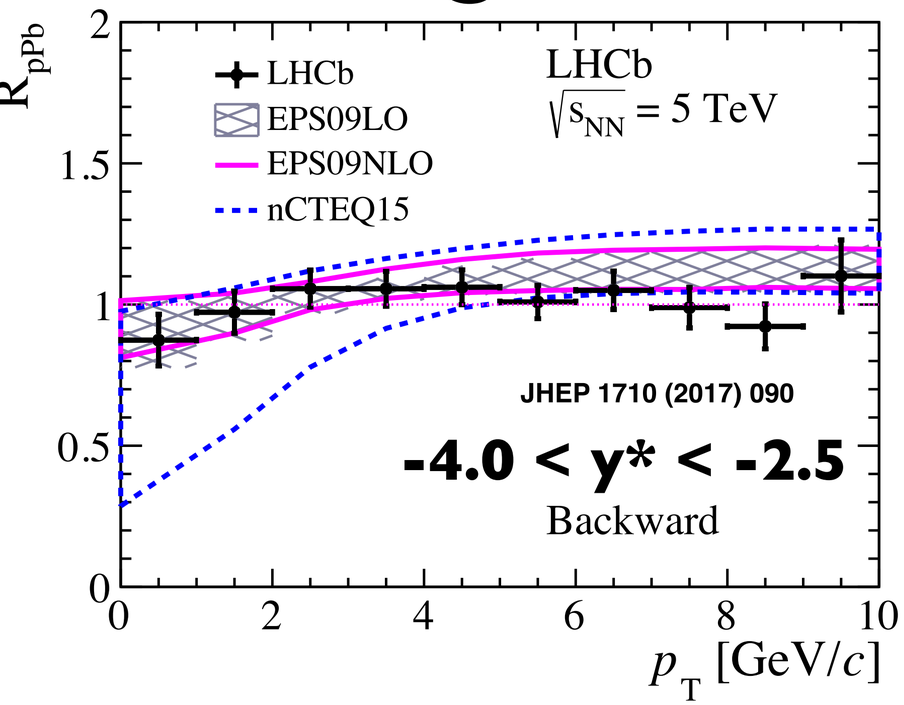




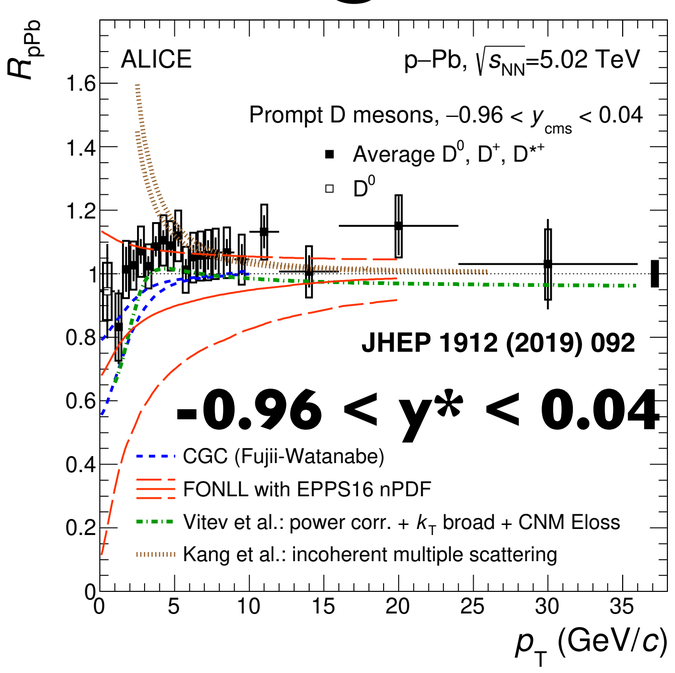
- LHCb data compatible with nPDF calculations both in forward and backward rapidities.

Prompt D in pPb

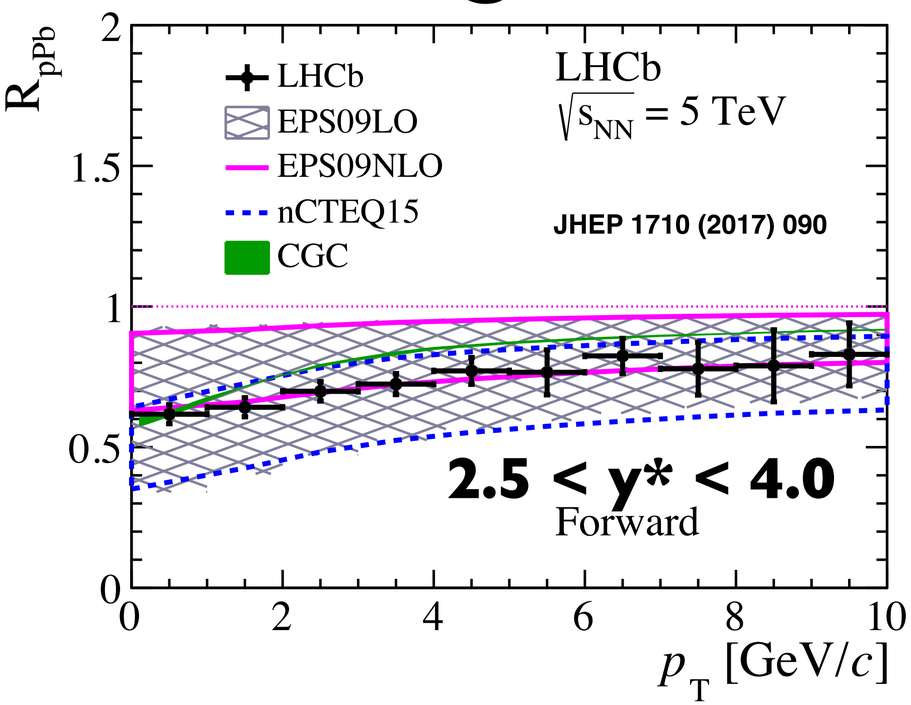
LHCb @ 5.02 TeV



ALICE @ 5.02 TeV



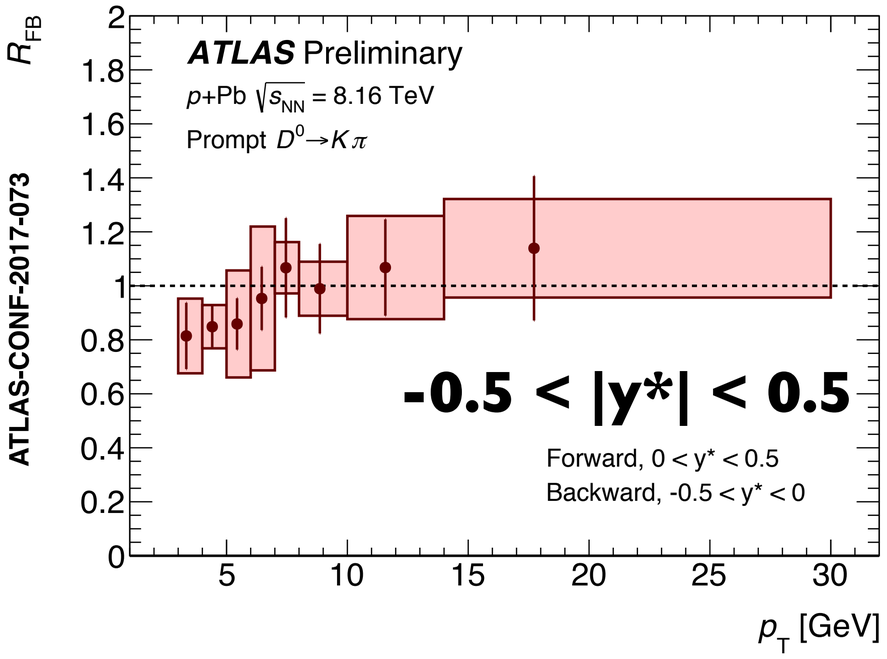
LHCb @ 5.02 TeV



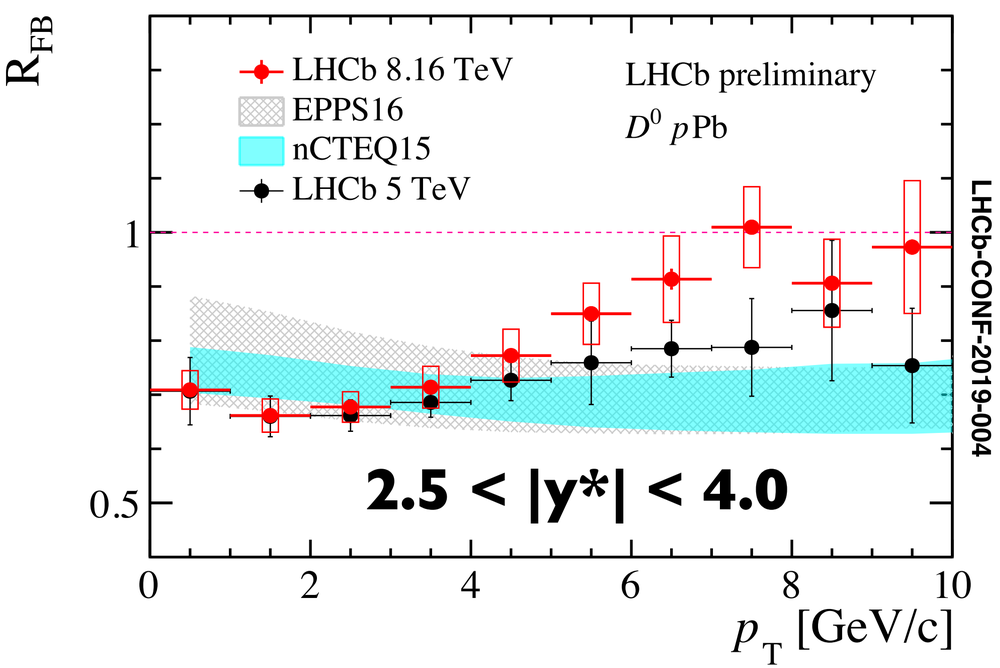
- LHCb data compatible with nPDF calculations both in forward and backward rapidities.
- ALICE mid-rapidity measurements described EPPS16 nPDF results.
- Significant deviation of R_{pPb} from unity at low p_T and at forward rapidity.

Prompt D^0 in pPb

ATLAS @ 8.16 TeV



LHCb @ 8.16 TeV



- ATLAS R_{FB} at mid-rapidity shows no significant deviations from unity.

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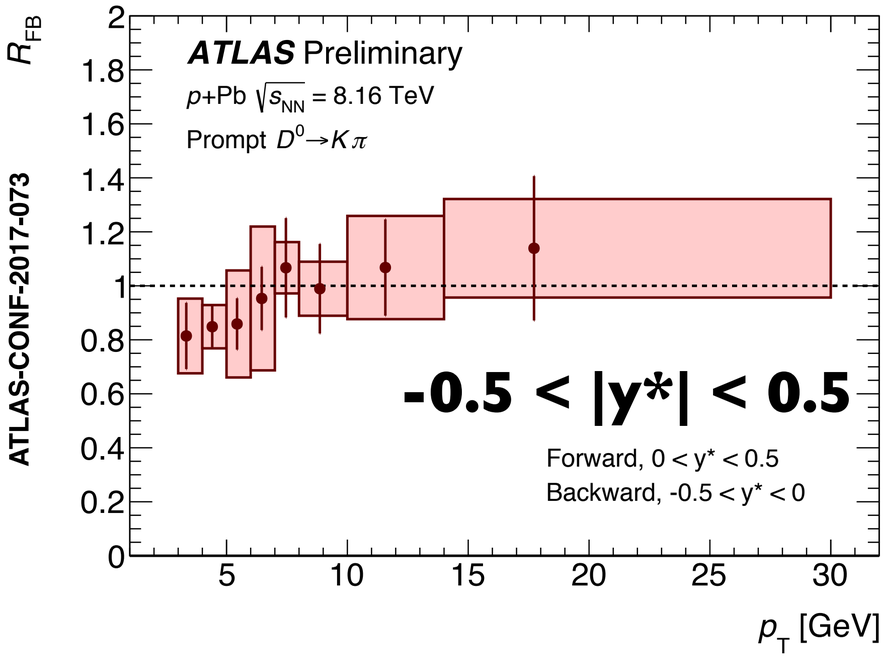

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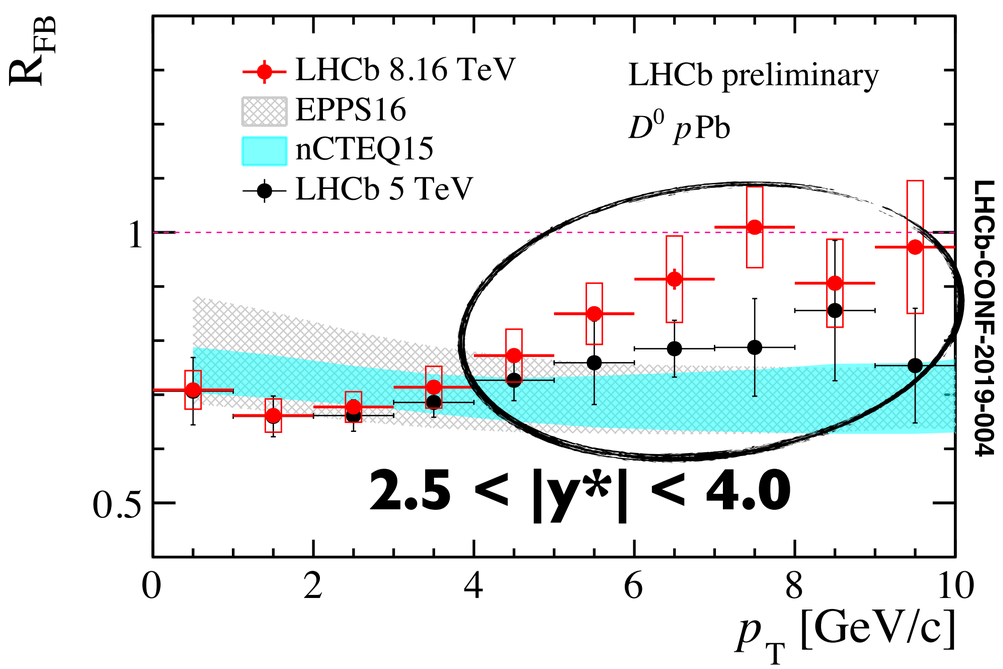
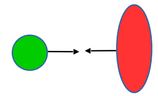


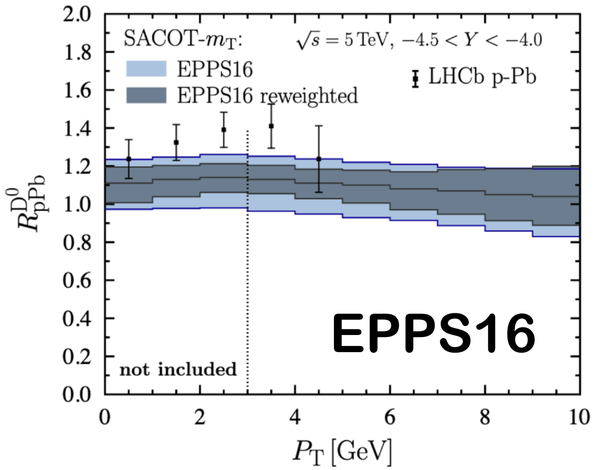
- ATLAS R_{FB} at mid-rapidity shows no significant deviations from unity.
- R_{FB} from LHCb show a rising trend with p_T, deviating from nPDF results at high p_T.

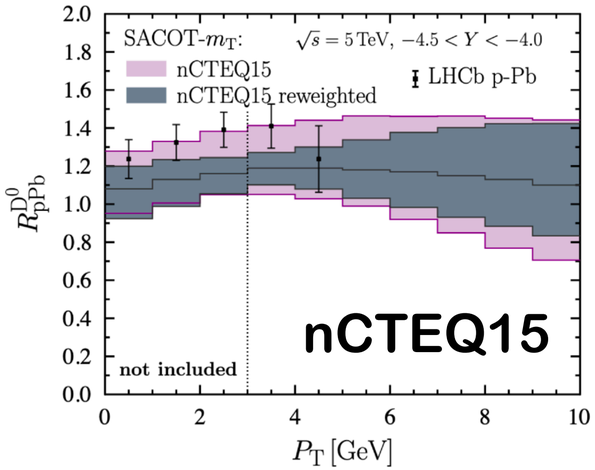
Impact of D meson pPb data on nPDFs

nPDF with LHCb D meson data

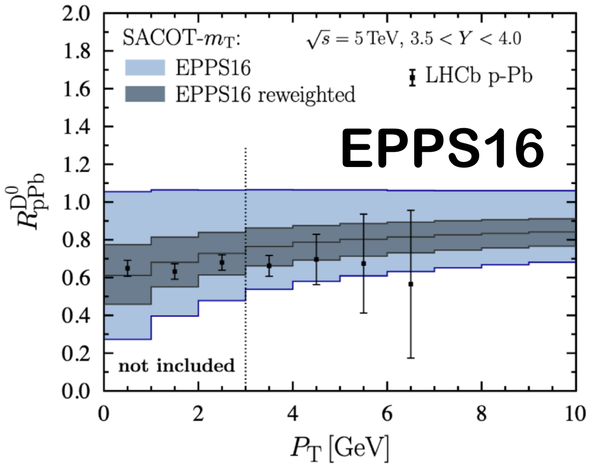


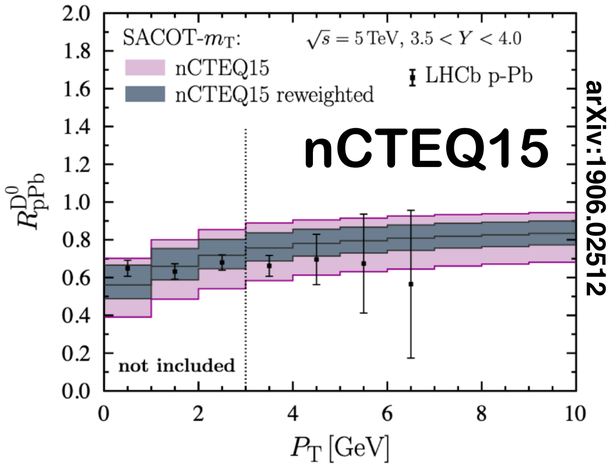
-4.5 < y* < -4.0





3.5 < y* < 4.0



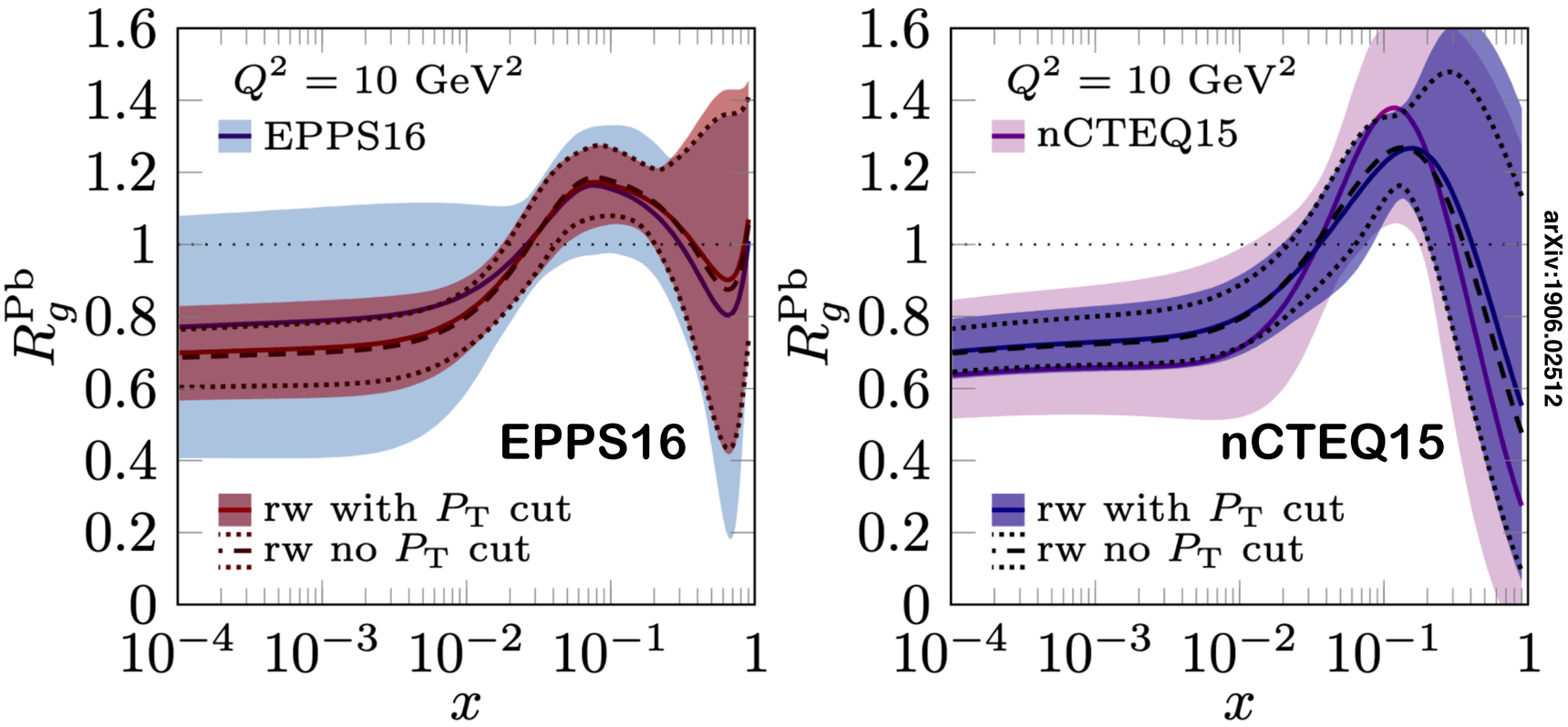


arXiv:1906.02512

- Reduction of EPPS16 and nCTEQ15 uncertainties at forward and backward rapidities.

Impact of D meson pPb data on nPDFs

nPDF with LHCb D meson data



- Reduction of EPPS16 and nCTEQ15 uncertainties at forward and backward rapidities.
- Impose tight constrains on the gluon densities, mainly at low x.