Heavy ions and small-x at CMS

Saray Arteaga Escatel

May 23, 2024

Workshop on medical and high energy physics

Sonora, Mexico

Outline

1.- Introduction

2.- Present key current measurements which probe low-x physics:

- 2.1.- Forward Jets in pPb at CMS
- 2.2.- Dijet azimuthal correlations
- 2.3.- Constraining gluon distributions in nuclei: pp + Pb dijets

3.- Summary

- Picture of the proton formed by three quarks is not that accurate.

Nuclear modifications?

etc...

1 MeV = 1.78X10^{-30} kg

Proton mass:

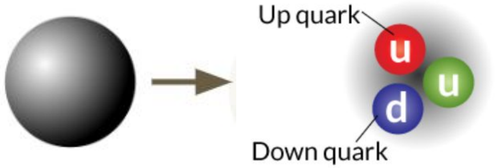
up quark mass = 2.2 MeV
down quark mass = 4.7 MeV +

6.9 MeV

proton mass = 938 MeV

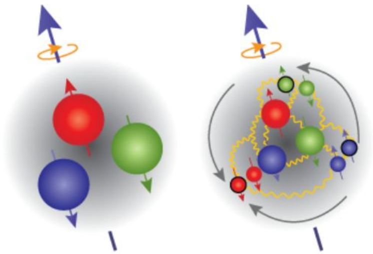
Heavy quark content?

The mass of the quarks adds up to only a fraction of a percent of the total proton mass!

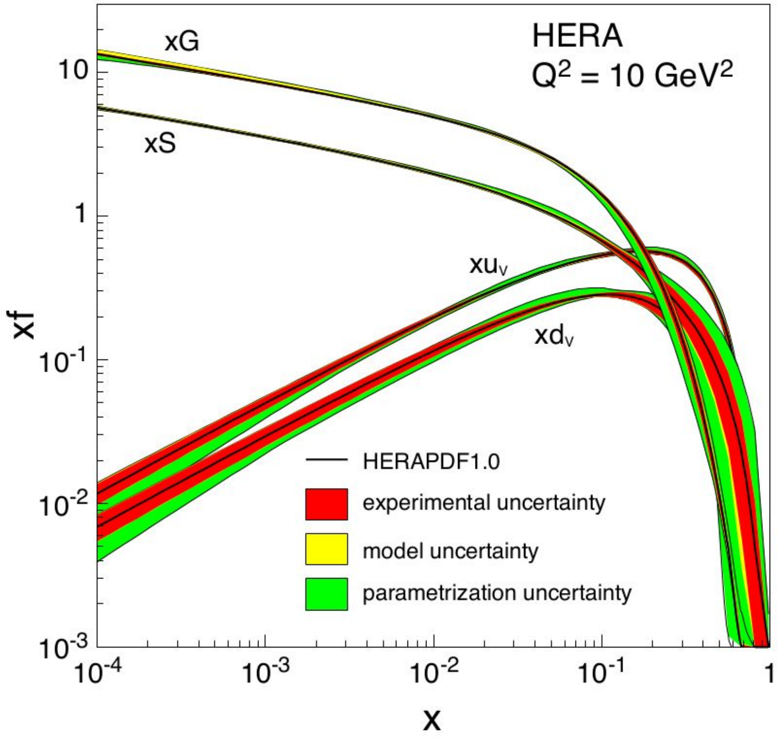


Proton spin:

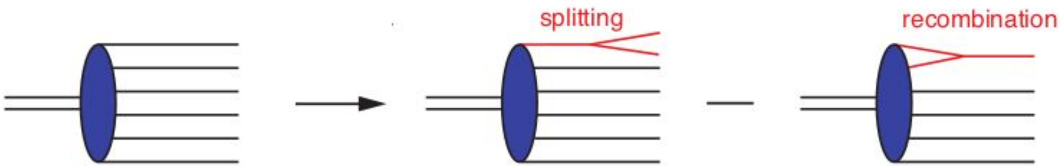
- Sum of the ½ spin from three quarks? Not that simple.
- Experiments have established that about 30% of the proton spin comes from these three quarks.

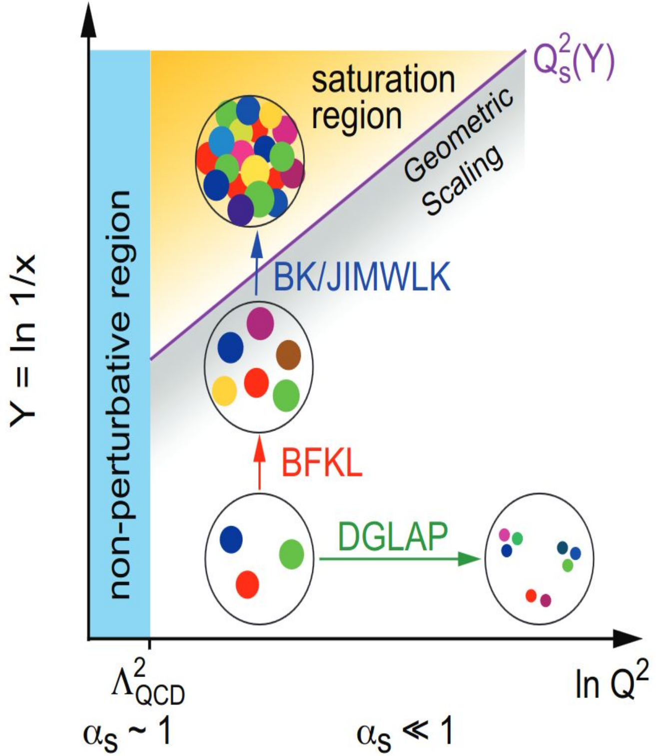


Small-x physics



- HERA results show that the proton structure is more complicated.
- Protons made up of 'sea' of quarks and gluons.
- Presented the behavior of the distribution functions, PDFs, of these quarks and gluons
- PDFs of valence quarks decrease with the decreasing of x .
- PDFs of 'sea' quarks and gluons increase at low values of x.
- Gluons distribution dominates at x< 0.1

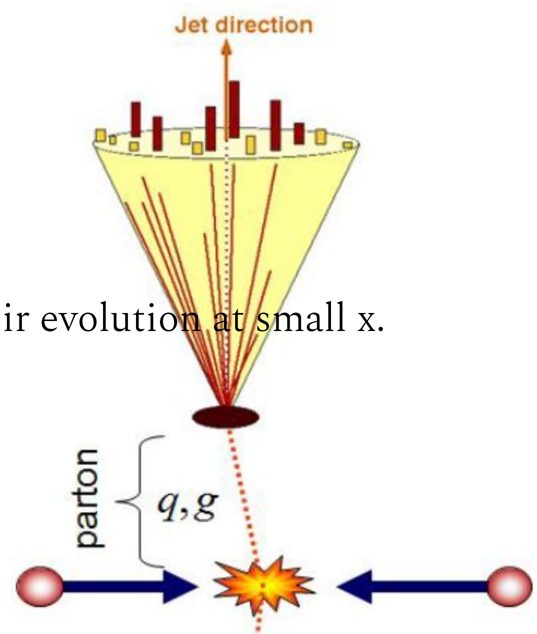




- A first approximation, the small-x evolution of the proton/nuclear wave function is dominated by gluon splitting: g-> g g . This contribution incorporated in DGLAP equations.
- At high gluon density expected to have recombination contributions. gg->g
- Energy at splitting and recombination mechanisms in balance = Saturation scale.
- Saturation effects expected to be universal.
- Saturation scale in heavy ion larger than single nucleon.

- Q^2 increases as $A^{1/3}$. For lead ~ factor 6 with respect to proton
- More accessible experimentally.

Forward Jets in pA at CMS



- Low x gluon density poorly known

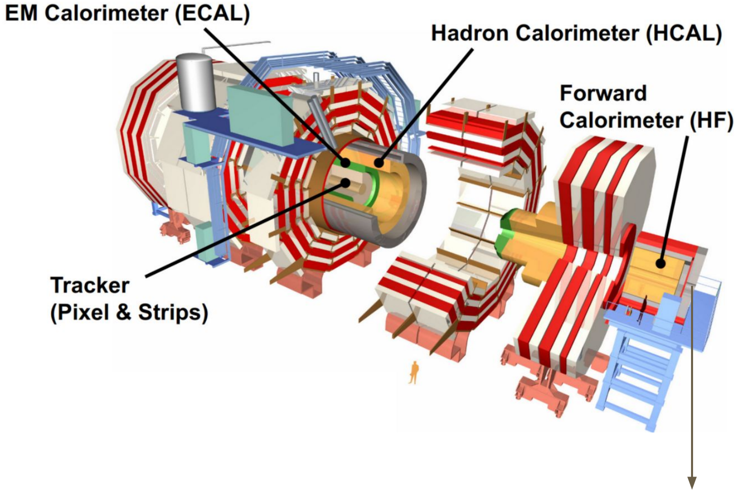
- Very forward jets allow to probe the low-x domain region $x \approx \frac{p_T}{\sqrt{s}} e^{\pm\eta}$

- forward jets with low p_T offer insights into the parton densities and their evolution at small x.

- sensitive to non-linear QCD effects

- Constrain low-x gluon PDFs
- Saturation scale in heavy ion larger than single nucleon.
- Q^2 increases as $A^{1/3}$ for lead ~ factor 6 with respect to proton.
- More accessible experimentally.
- Jets in the p+Pb data probe the ion parton density at low values of x → therefore sensitive to possible enhanced saturation effects in nuclei.

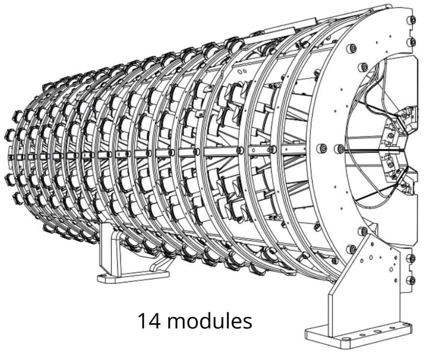
Forward Calorimeter at CMS



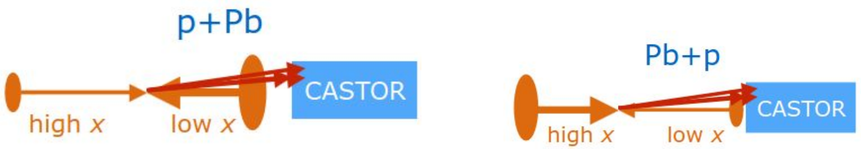
- CASTOR EM-hadronic calorimeter at CMS:
  $-6.6 \le \eta \le -5.2$
  - Forward calorimeter at 14 m from interaction point

- CASTOR has no η segmentation. Present energy spectra instead of pt

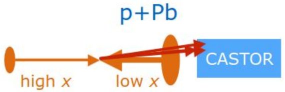
CASTOR



14 modules

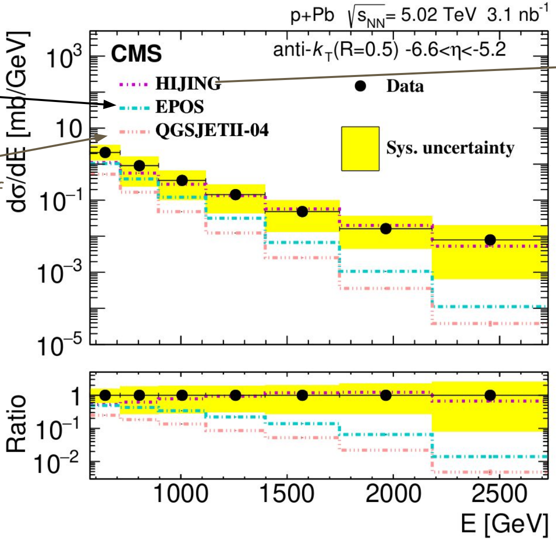


p+Pb differential jet cross section as a function of jet energy

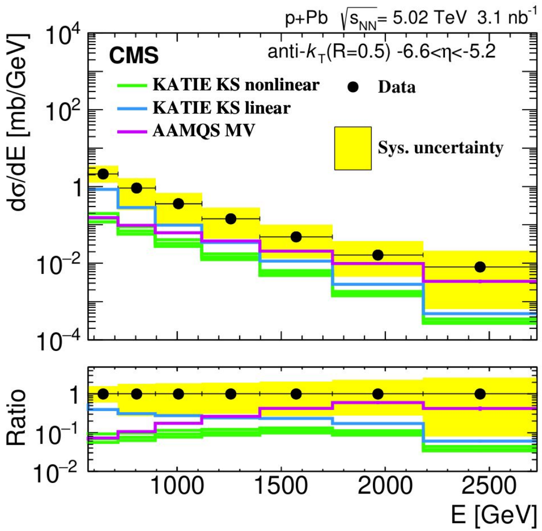


DGLAP+ pom. exchange

~EPOS but pom self interactions = saturation

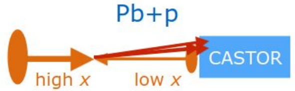


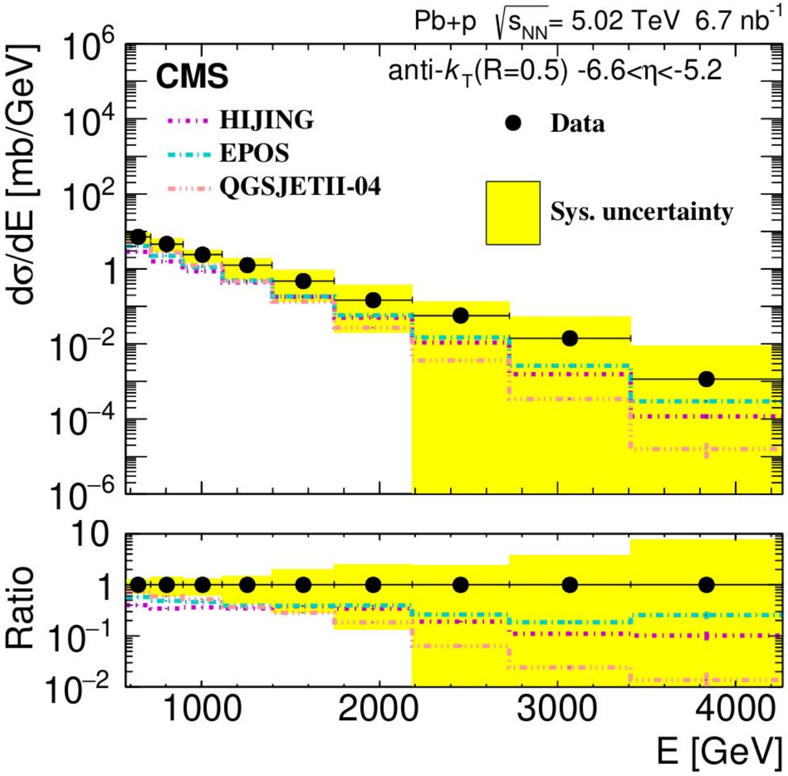
DGLAP + shadowing



- The predictions of the EPOS-LHC and QGSJETII-04 model differ by more than two orders of magnitude at E = 2.5 TeV.
  - both yield an energy spectrum that is too soft and underestimate the data at high energy.
- HIJING model describes the measured distributions best.
- KATIE-KS predictions differ by an order of magnitude in the low energy region, while converging for the high energies.
- The AAMQS model underestimates the data also in the region most affected by saturation.

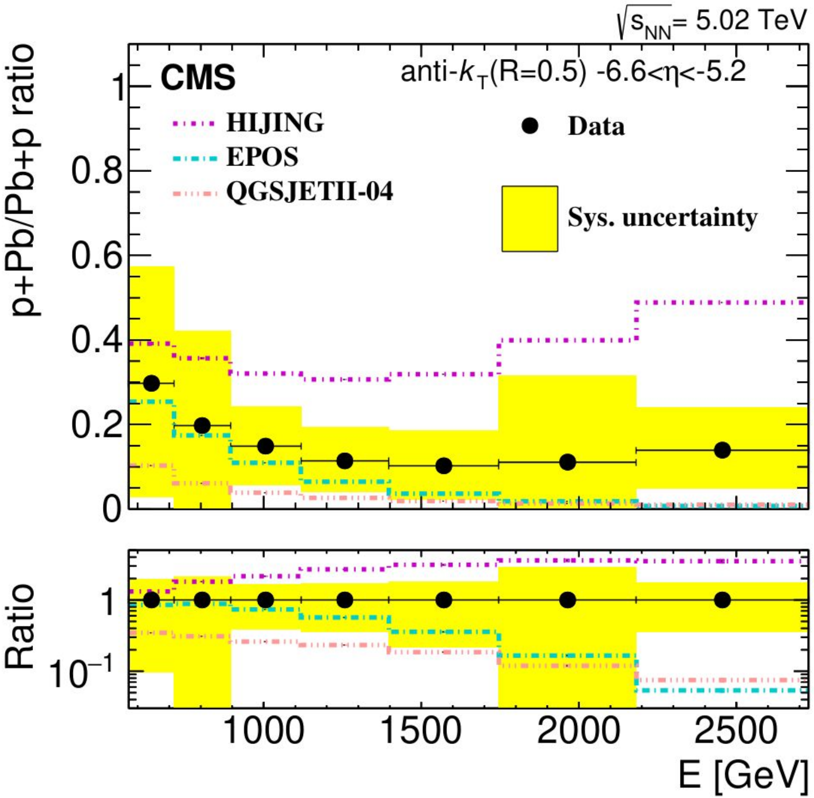
Pb+p differential jet cross section as a function of jet energy





- All models underestimate the data for a few lower energy bins.
- From ~ 1.2 TeV onwards, all models are in agreement with the data within the systematic uncertainty.

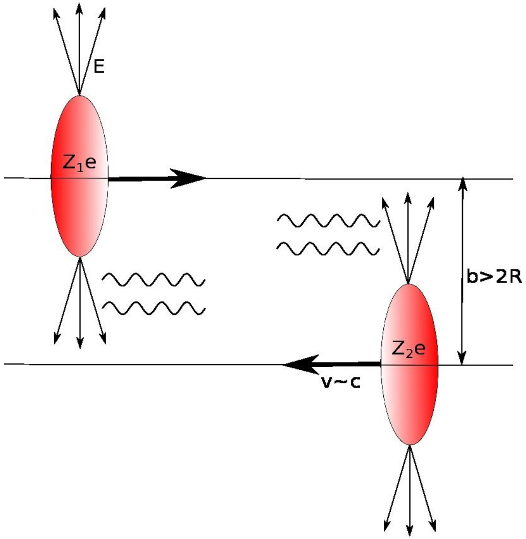
Ratio of the p+Pb to Pb+p cross sections



- p+Pb cross section order of magnitude smaller than Pb+p.
- Ratio is quite flat, substantial uncertainty cancelation occurs.
  → Ratio opportune observable
- HIJING describes shape well but an overall factor ≈ 2 off, due to poor Pb+p description.
- EPOS-LHC model describes the lower energy part of the ratio spectrum well, but fails to describe the shape at high energies.
- QGSJETII-04 underestimates both the shape and normalization of the ratio, which can also be attributed to the poor description of the p+Pb spectrum.

-No clear sign for saturation yet

With UPC's ...

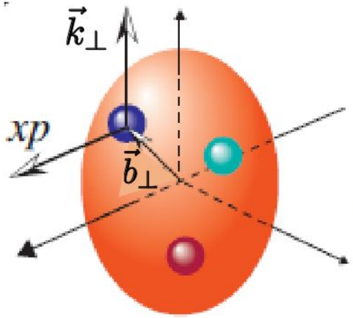


- Impact parameter is a bit bigger than the sum of the radii.
- Strong interaction effects are suppressed.

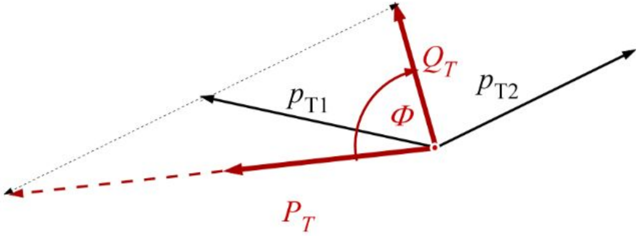
CMS dijet azimuthal correlations PbPb

Sensitive to the Wigner gluon distribution. Phys. Rev. Lett. 116, 202301 (2016)

How?



Partons also have transverse momentum $\vec{k}_\perp$ and are spread in impact parameter space $\vec{b}_\perp$



predicted non-trivial angular correlations of the gluon Wigner distributions.

Depend on impact parameter and gluon transverse momentum.

The magnitude of the spatial momentum anisotropy is measured by the second Fourier harmonic of the azimuthal distribution $v_2 = \langle \cos(2\phi) \rangle,$

$$P_T = \frac{(p_{T1} - p_{T2})}{2}$$

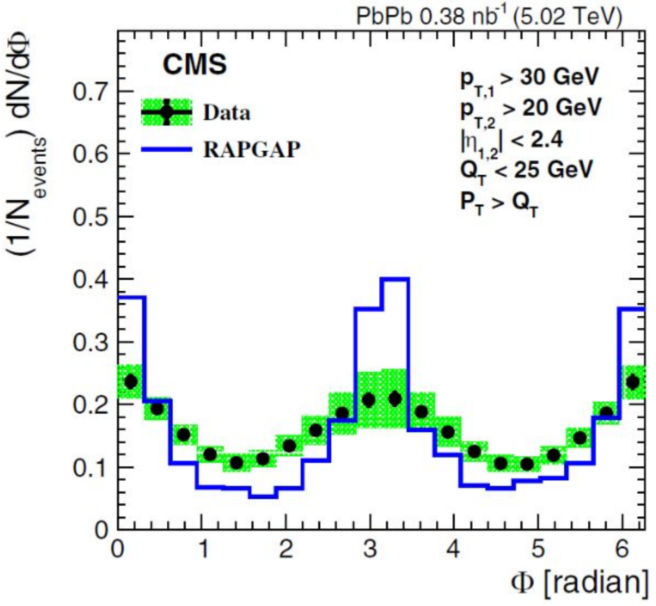
$$Q_T = (p_{T1} + p_{T2})$$

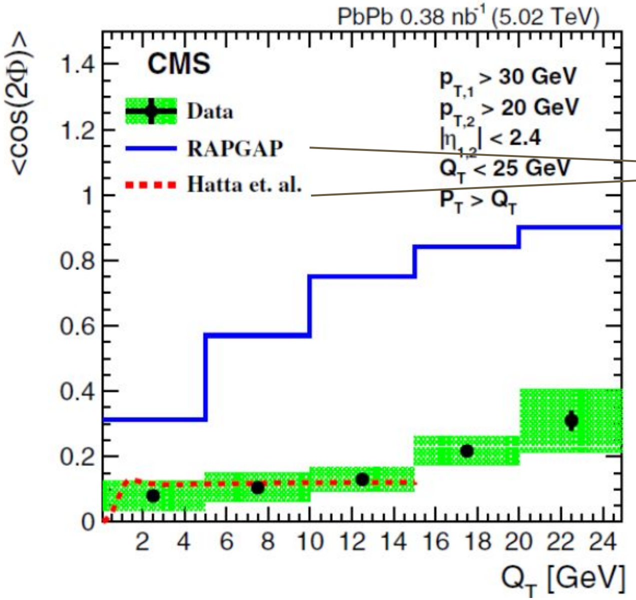
$$P_T . Q_T = |P_T||Q_T| \cos\Phi$$

Φ distribution

CMS-PAS-HIN-18-011

Phys. Rev. Lett. 131 (2023) 051901





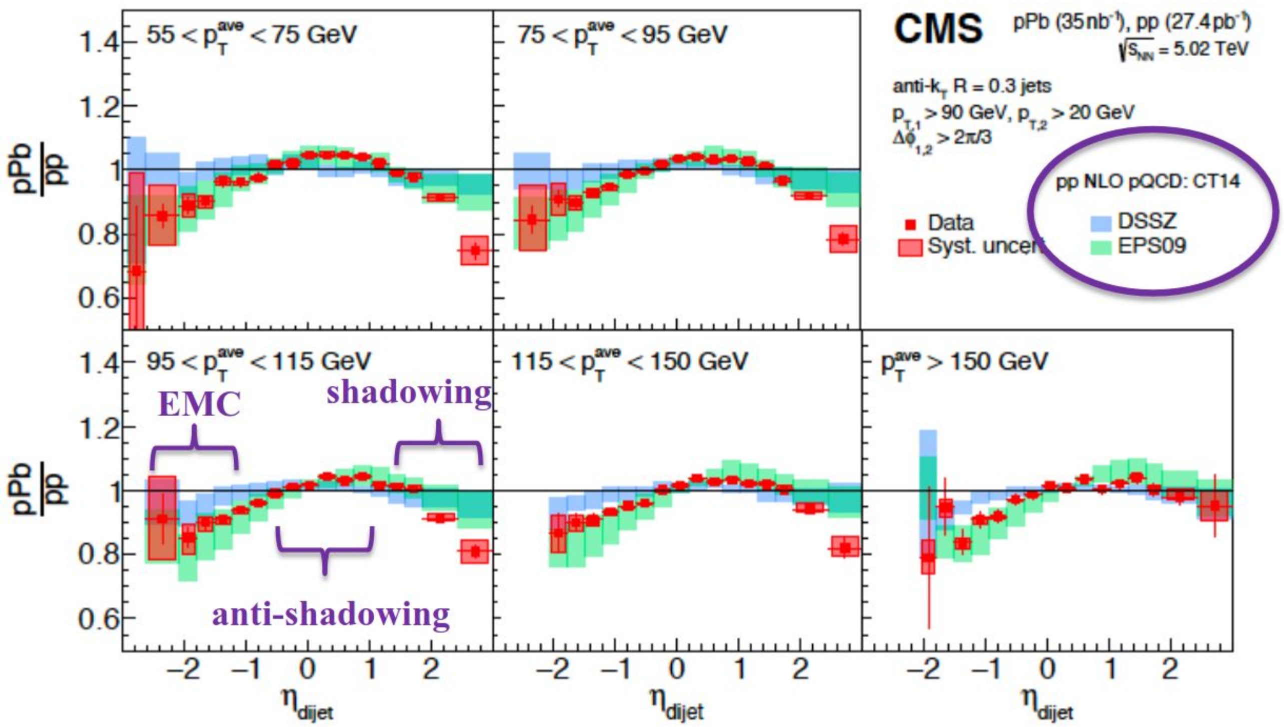
ignore the effect of elliptically polarized gluons

- Similar trend between data and RAPGAP

-<cos(2Φ)> rises with Q_T and effect is overestimated by RAPGAP.

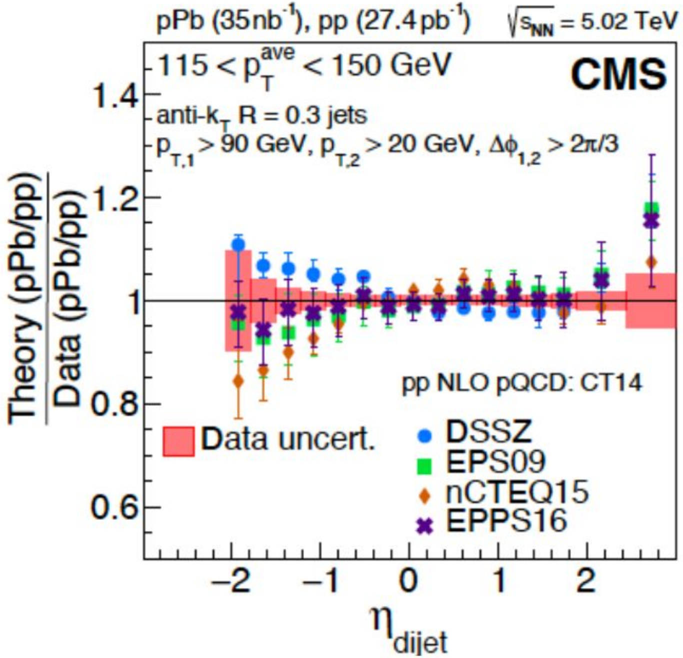
- This increase in azimuthal asymmetry has been associated with gluon saturation. **Phys. Rev. Lett. 126, 142001**

Constraining gluon distributions in nuclei: pp + PbPb dijets



- EPS09: gluon EMC effect based on PHENIX data → gluon EMC effect in good agreement
- DSSZ: does not incorporate gluon EMC effect

Phys. Rev. Lett. 121, 062002 (2018)



Good study to constraint nPDFs

DSSZ without gluon EMC effect: disfavored

EPS09: EMC implementation compatible with data

nCTEQ15: overshoots EMC and anti-shadowing effects

EPPS16 similar to EPS09 w/ relaxed constraints; larger nPDF uncertainties

Summary

- Saturation effects expected at small-x.
- Saturation scale in heavy ion larger than single nucleon
- Measurements of the differential inclusive forward jet cross sections in proton-lead collisions at 5.02 TeV have been discussed .
  - Major challenge: energy scale uncertainty
  - No clear sign for saturation yet
- Jets in UPCs are a promising new probe for low-x studies.
- Jet studies good tool to constraint nPDFs.

Thank you!