The p+A Programs at RHIC and the LHC

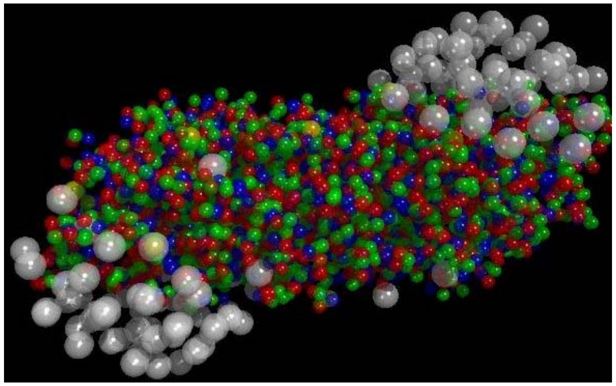
John Lajoie

Iowa State University

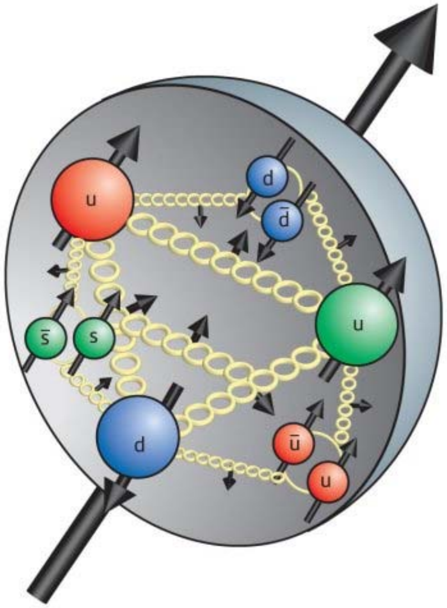
Many thanks to Ernst Sichtermann, Tony Frawley, Elke Aschenauer, Brian Cole, Hannu Paukkunen, Anne Sickles, Marco Stratmann, Julia Velkovska, …

The Big Picture At RHIC and the LHC

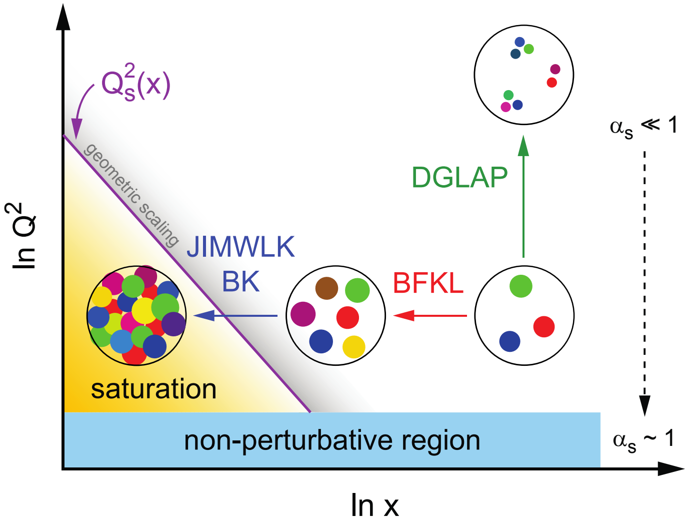
How do collective, many-body phenomena arise from first-principles QCD?



Quark-Gluon Plasma



Polarized Protons

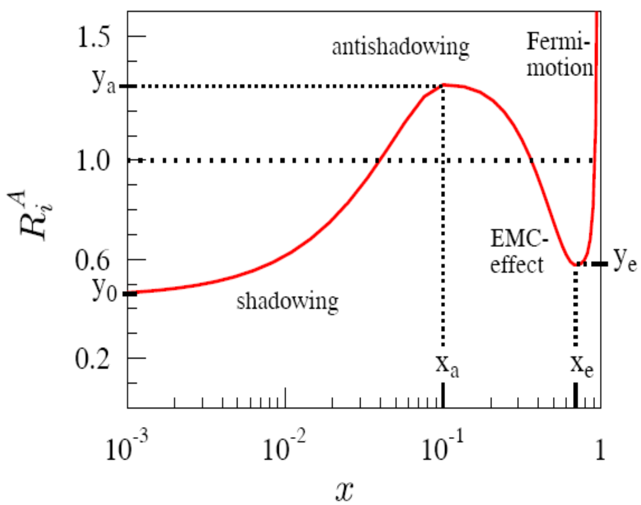


Gluons in Nuclei

Gluons in Nuclei

$$R_G^{Pb}(x,Q^2) = \frac{xG_A(x,Q^2)}{AxG_p(x,Q^2)}$$

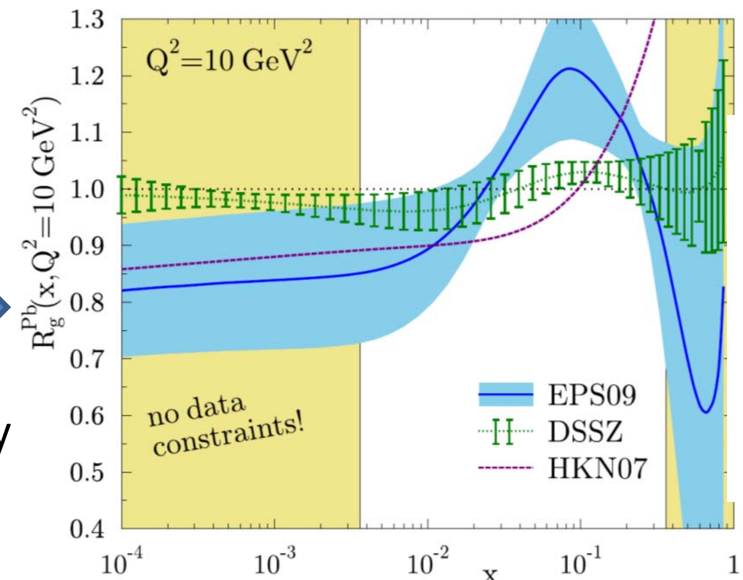
shadowing/saturation in nuclei



Fit data on nuclei:
SLAC, NMC, EMC
DIS+DY+PHENIX
midrapidty π^0

Lack of data
⇨large uncertainly
in gluon pdf
at low-x

gluons



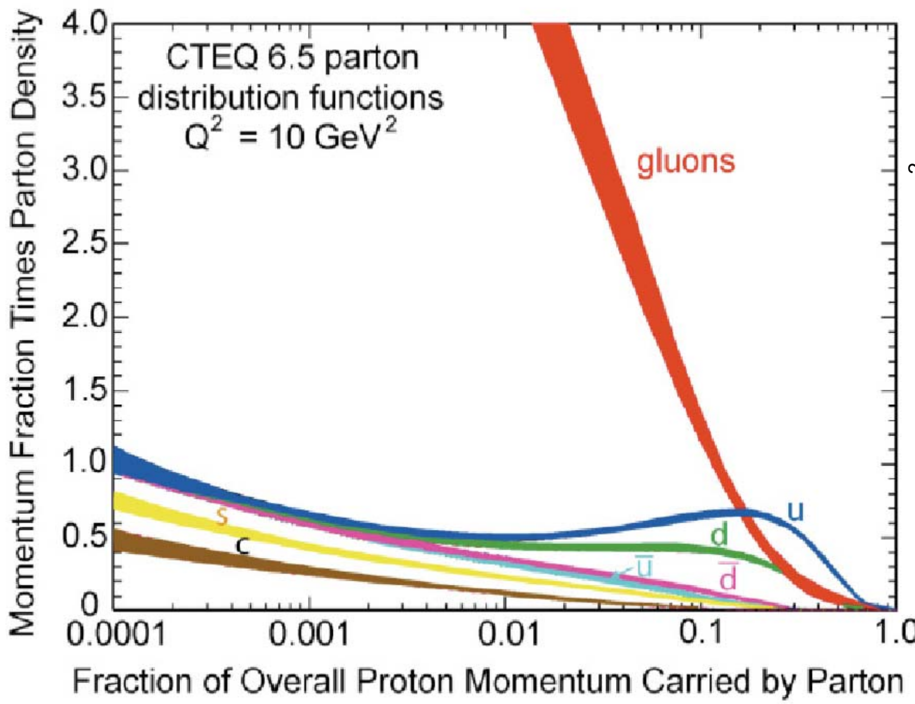
Large uncertainty at low-x

Paukkunen DIS 2014

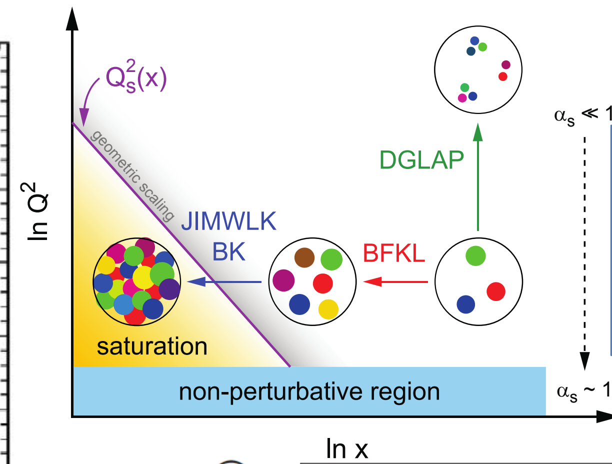
Large uncertainties in the nuclear gluon PDF at low-x: many important effects to disentangle – *shadowing, antishadowing, nonlinear QCD, saturation*, etc.

Important for fundamental understand of partonic processes in nuclei, *as well as* for the initial conditions at RHIC and the LHC.

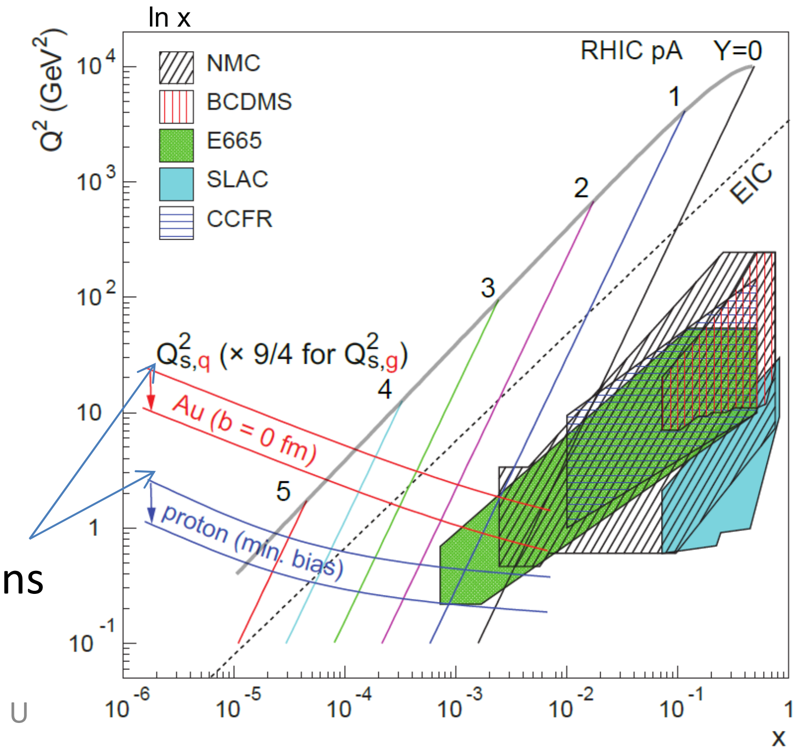
Saturation



(x)



The gluon density grows to the point where recombination tames the growth of the gluon distribution at small x.



The nucleus is an *amplifier* of high gluon densities.

$$\left(Q_S^A\right)^2 \approx c Q_0^2 \left(\frac{A}{x}\right)^{1/3}$$

gluons

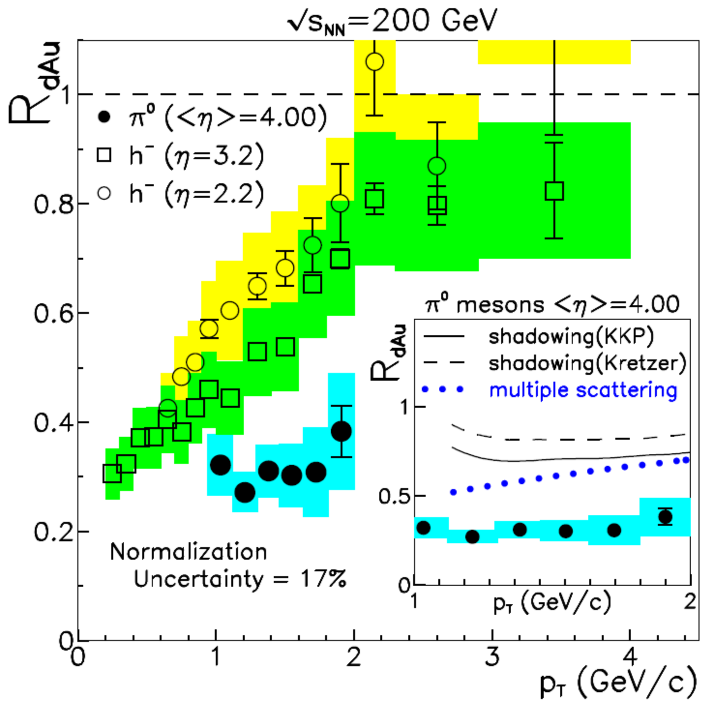
The Big Questions

- What is the gluon density in heavy nuclei? How is it modified in the nuclear environment?

- What role does saturation play in determining this gluon density?

- What is the saturation scale Q_s, and how does it depend on A and x?

What do we know from d+Au at RHIC?

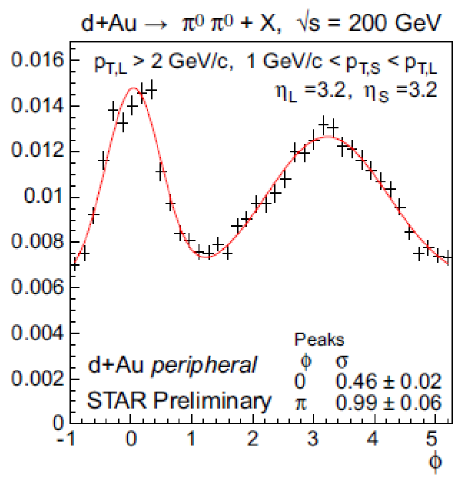


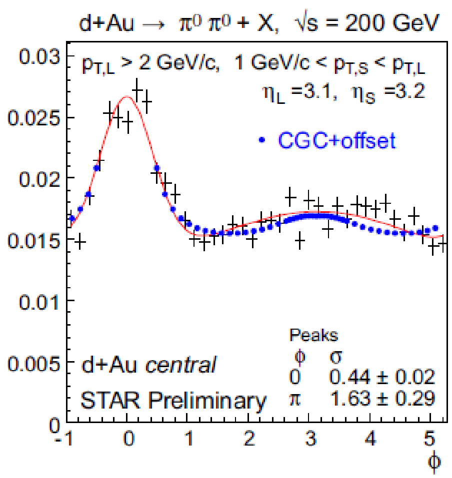
PHENIX/BRAHMS/STAR R_{dAu}

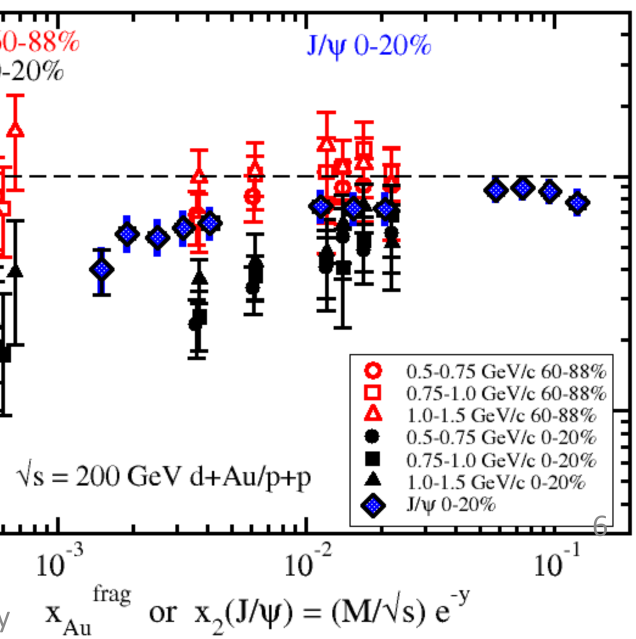
Forward R_{dAu} shows higher suppression

$$R_{dAu} = \frac{d^2\sigma/dydp_T\big|_{dAu}}{\langle N_{coll}\rangle d^2\sigma/dydp_T\big|_{pp}}$$

PHENIX/STAR forward π^0 correlations and J/Ψ suppressed

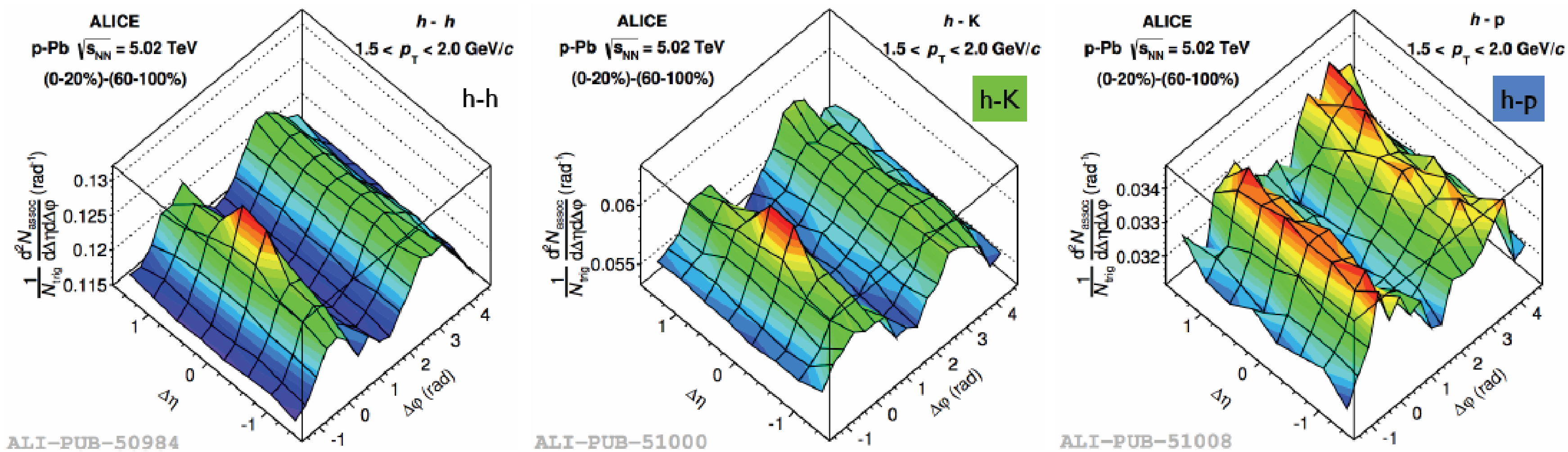






What do we know from p+Pb at the LHC?

"Collective" behavior observed in high multiplicity p+p/p+Pb collisions!

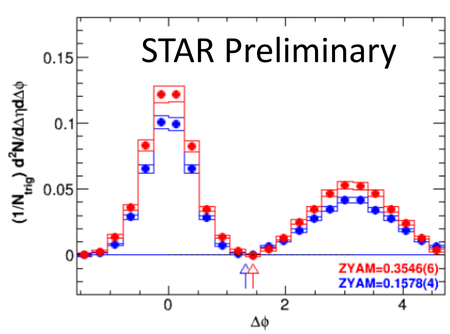


What is the origin of this behavior?

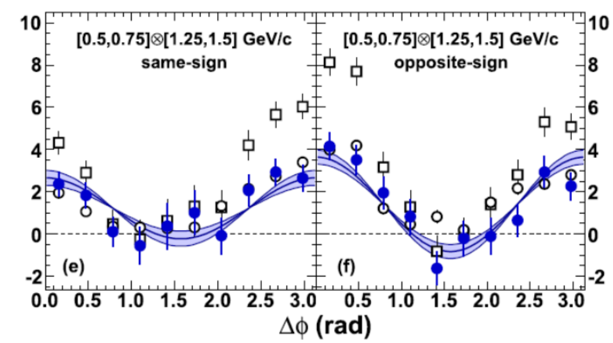
- Jet-medium/multi-parton interactions (arXiv 1203.2048)
- CGC (PRD 87 094304)
- Hydrodynamics from small dense system (arXiv 1211.0845)

CMS: Phys. Lett. B718 (2013) 795
ATLAS: Phys. Rev. Lett. 110 (2013) 182302
ALICE: Phys. Lett. B719 (2013) 29-41

Similar behavior observed in RHIC d+Au…



Y. Li QM2014

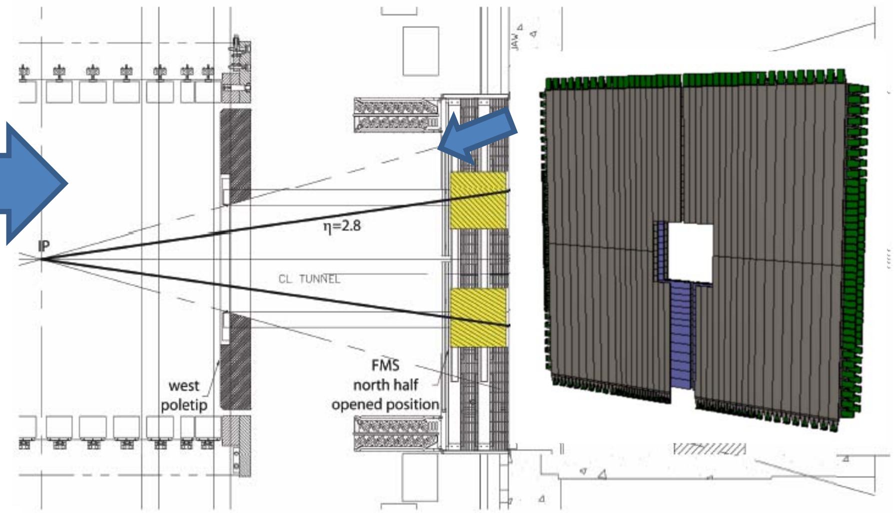


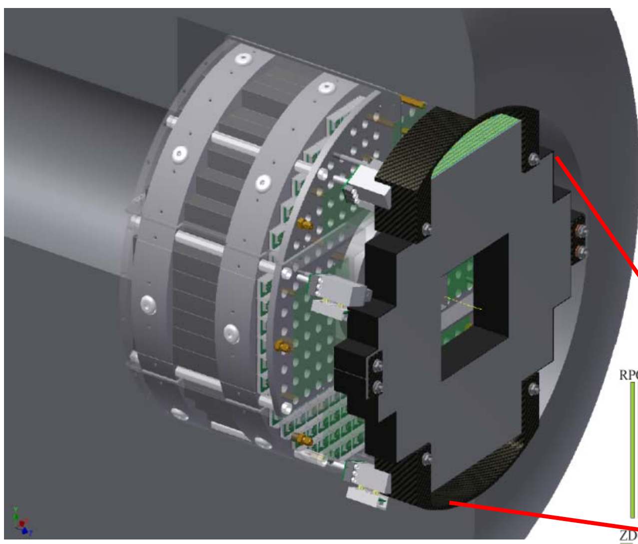
Phys. Rev. Lett. 111 (2013) 112301

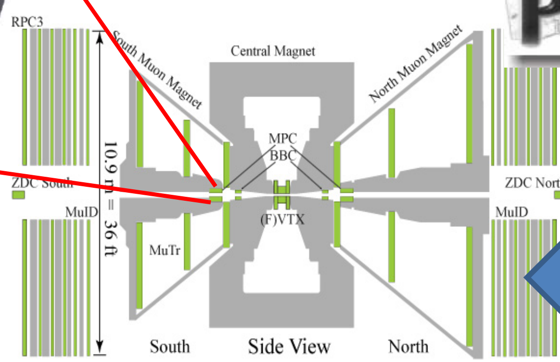
The Near Future

RHIC Near Term Upgrades

STAR FPS Preshower Array



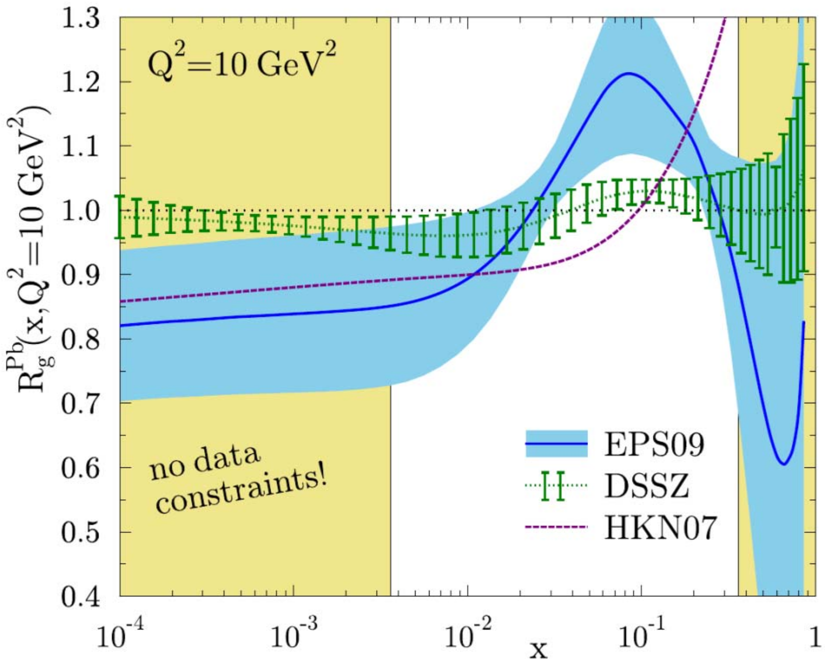


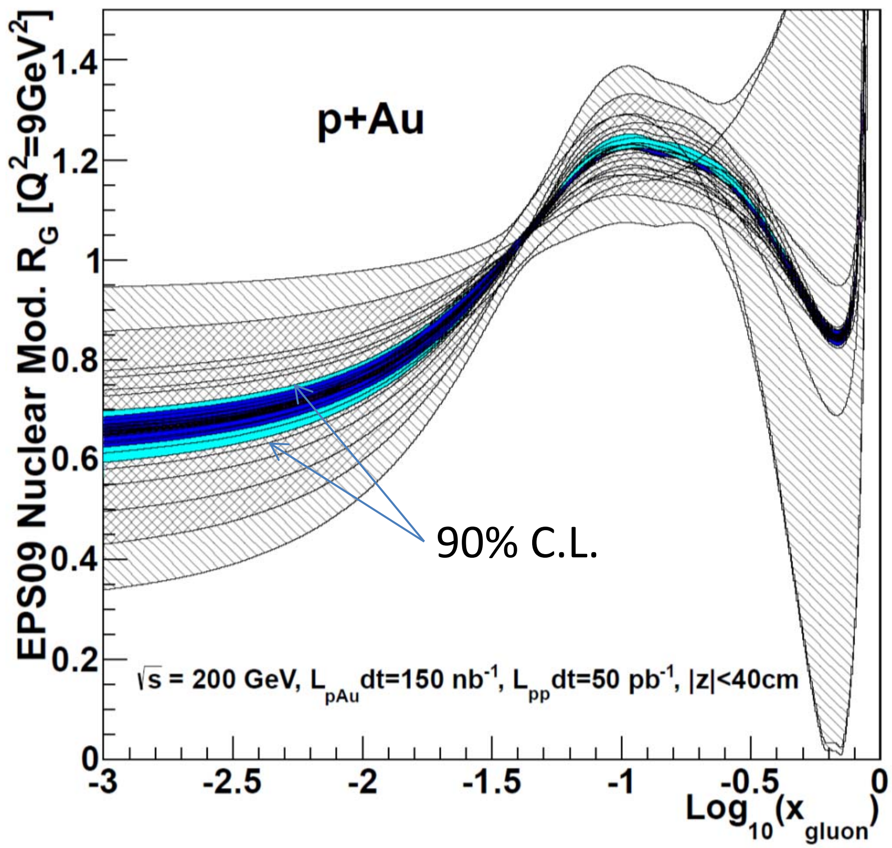


PHENIX MPC-EX Preshower

nPDF Limits from Photons @ RHIC

No CNM final state effects!





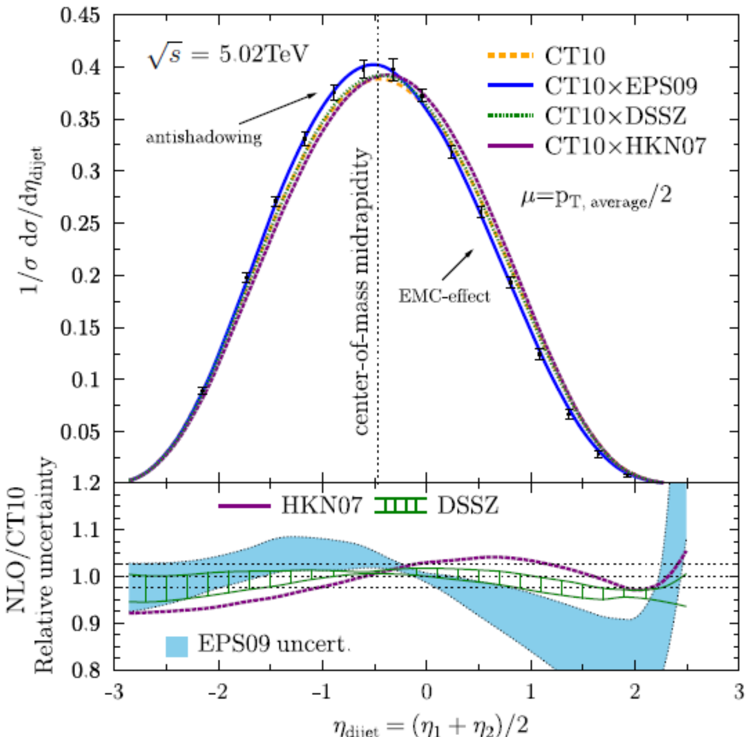
Example using MPC-EX pseudodata to constrain EPS09 family of curves.

Prompt photons in p+Au -> Precise Measurement of Gluons at Low-x

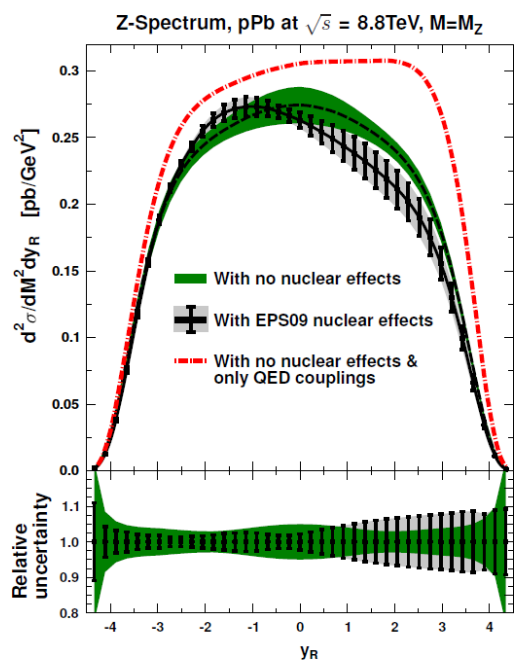
Constraints on nPDFs from the LHC

Existing CMS p+Pb dijet measurements can discriminate between different nPDFs.

Future results for photons, $W^{+/-}$, and Z bosons in p+Pb collisions will constrain nPDFs at a large scale.

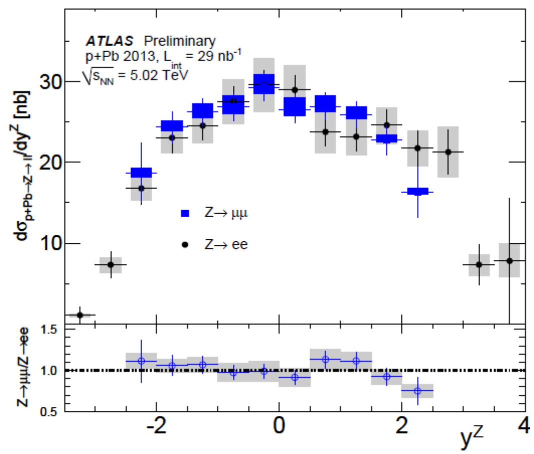


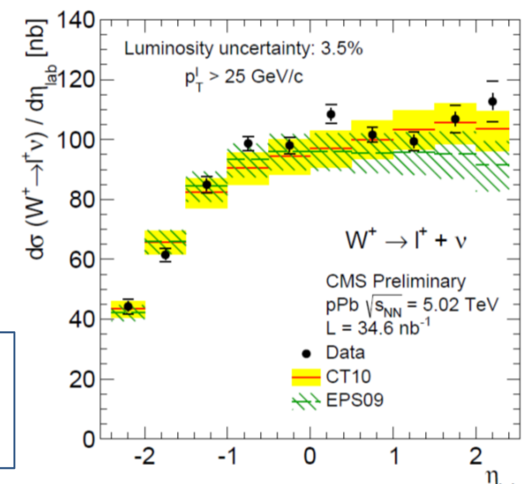
JHEP 1310 (2013) 213



JHEP 1103 (2011) 071

ATLAS-CONF-2014-20



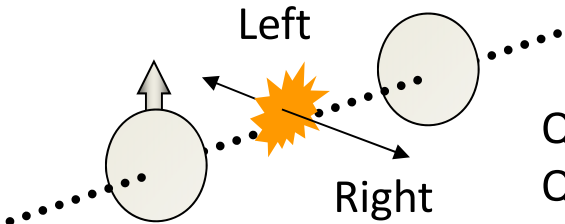


CMS PAS HIN-13-007

A combination of the RHIC and LHC data will provide significant new constraints on nPDFs.

Polarized p+A Collisions at RHIC

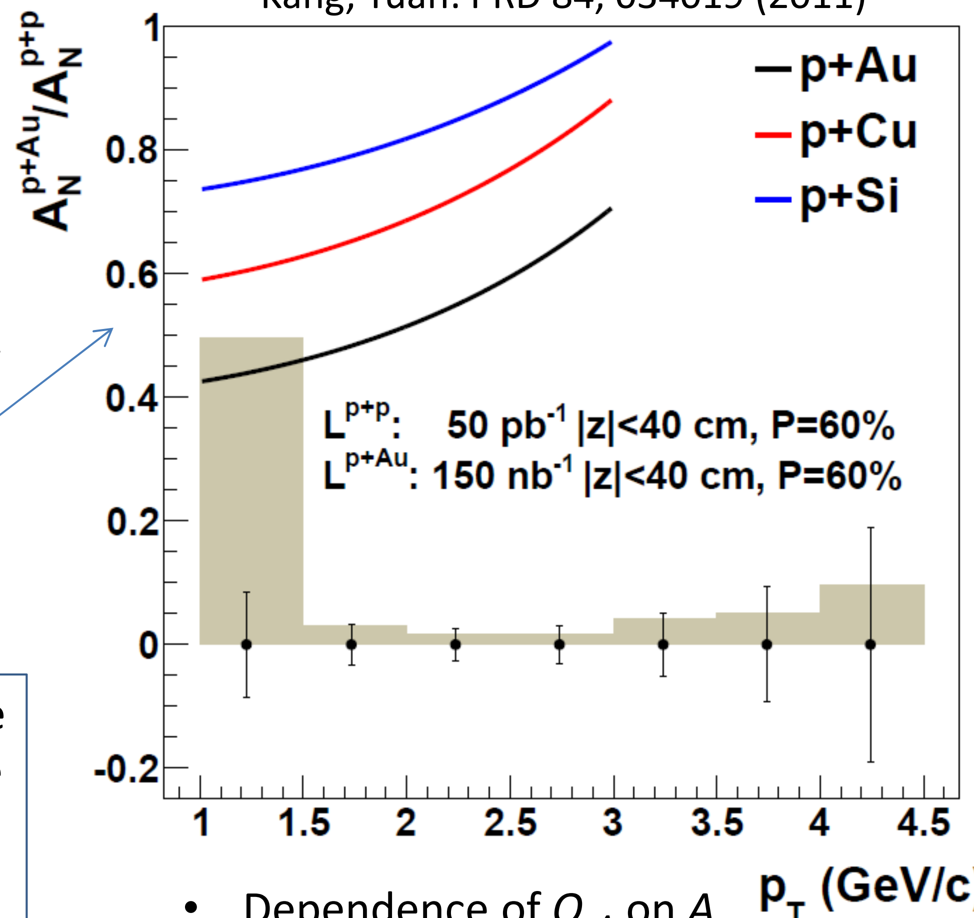
$$A_N = \frac{1}{P}\frac{\sigma_L^\pi - \sigma_R^\pi}{\sigma_L^\pi + \sigma_R^\pi}$$



$Q_{sp}{}^2 = (1.0\ \text{GeV})^2$
$Q_{sA}{}^2 = (2.5\ \text{GeV})^2$
$\delta = 0.16$ GeV

$$\left.\frac{A_N^{pA\to h}}{A_N^{pp\to h}}\right|_{P_{h\perp}^2 << Q_{sA}^2} \approx \frac{Q_{sp}^2}{Q_{sA}^2} e^{P_{h\perp}^2\delta^2/Q_{sp}^2}$$

Y. Kovchegov & M.D. Sievert: PRD 86, 034028 (2012)
Kang, Yuan: PRD 84, 034019 (2011)



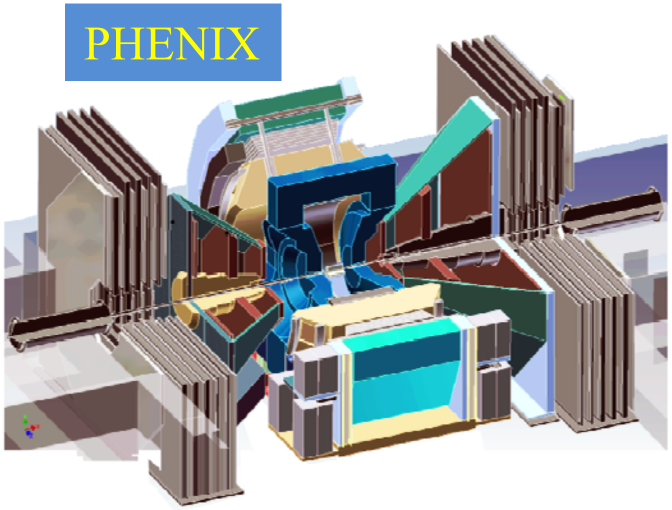
Single spin asymmetries can act as a probe of the saturation scale – the p+p reference will also be better understood with new instruments.

A unique capability of RHIC!

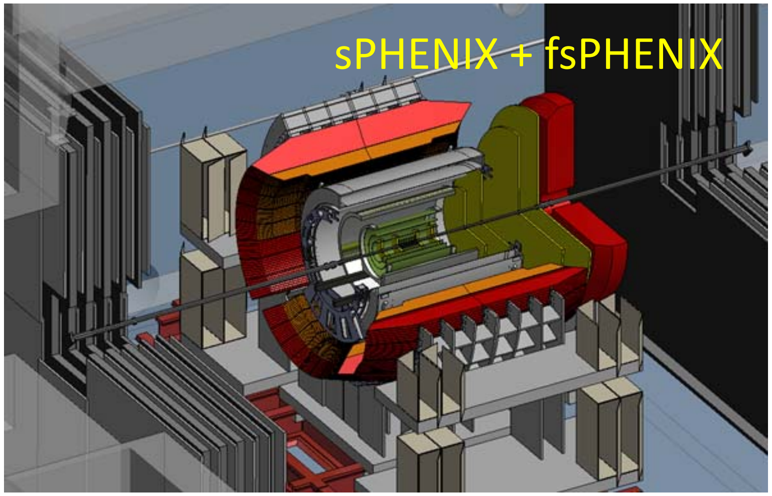
- Dependence of Q_{sA} on A
- Combined with other measurements this can estimate Q_{sp}

The Future p+A Program

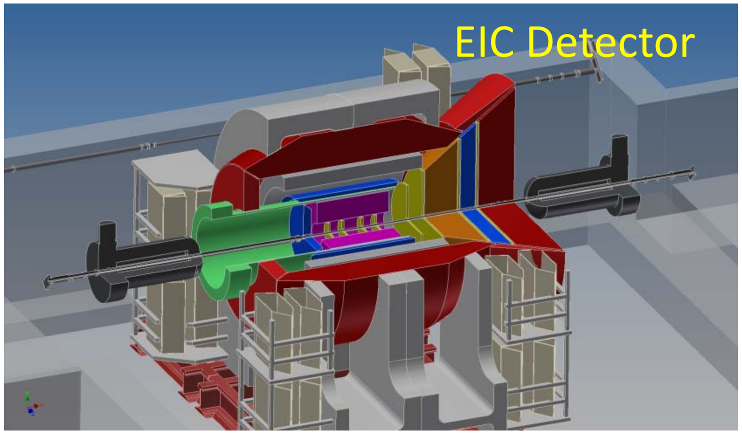
The PHENIX Detector Evolution



2021-22



~2025

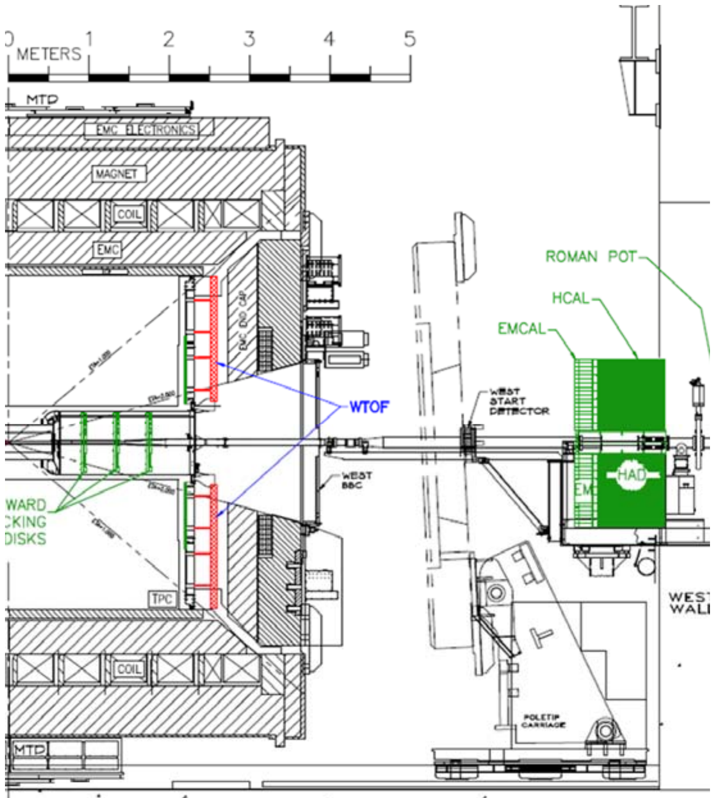


Evolve sPHENIX (HI detector) with forward instrumentation for p+p/p+A physics:

- GEM tracking chambers
- Hadronic Calorimetry
- Reconfigure existing FVTX and MuID

fsPHENIX forward instrumentation in common with evolution of sPHENIX into an EIC (eRHIC) detector.

STAR Forward Upgrades for 2021+



Forward Upgrades:

ECal:

Tungsten-Powder-Scintillating-fiber
2.3 cm Moliere Radius, Tower-size: 2.5x2.5x17 cm^3, 23 X_o

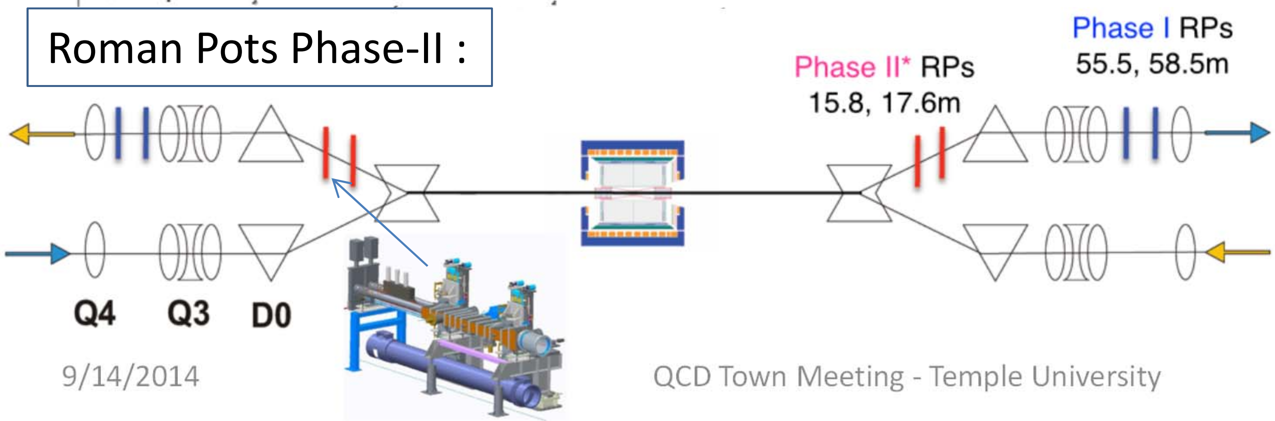
HCal:

Lead and Scintillator tiles, Tower size of 10x10x81 cm^3
4 interaction length

Tracking:

Silicon mini-strip detector 3-4 disks at z ~70 to 140 cm
Each disk has wedges covering full 2π range in ϕ
and 2.5-4 in η (other options still under study)

Roman Pots Phase-II :



STAR is also pursuing a coordinated upgrade path that can lead to an EIC detector.

Future p+A Measurements @ RHIC

- **Correlations:**
  - h-h and π^0-π^0 are straightforward experimentally
  - γ-h and γ-π^0 are easier to interpret
  - jet-jet, γ-jet gives access to complete kinematics at LO
- **Ultra-Peripheral Collisions:**
  - Access to $g(x,Q^2,b)$
- **Drell-Yan:**
  - Access $q_{bar}(x,Q_2)$
  - Complete kinematics: x_1, x_2, Q^2
  - True 2->1 process yields access to x<0.001

A p+A Timeline for the LHC and RHIC

Future ion running at LHC to be split between p+Pb and Pb+Pb…

ATLAS:
- Trigger Upgrades
- Inner Tracker

CMS:
- L1 Trigger
- HCAL Upgrade

ALICE:
- ITS Upgrade
- Trigger and DAQ

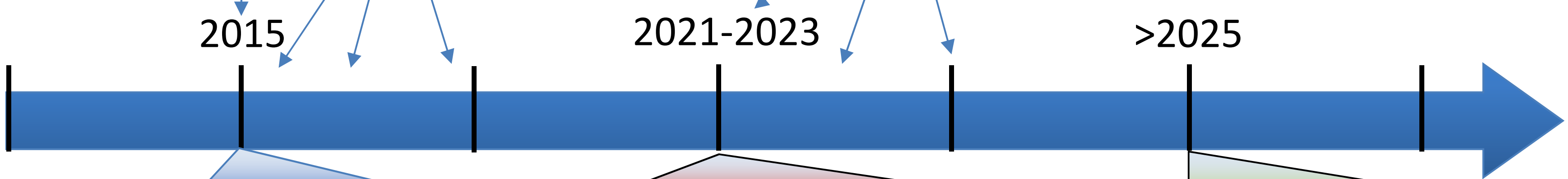
LHC

End of LS1

1 Month Ion Running 11/2015, 11/2016, 6/2018

LS2 7/18-12/19

1 Month Ion Running 11/2020, 11/2021, 12/2022



RHIC

STAR Upgrades:
- FMS-Preshower, Roman Pots-II*

PHENIX Upgrade:
- MPC-EX Preshower

Run:
- p+p 200 GeV
- p↑+Au 200 GeV transverse

Goals:
- nPDF: $g(x,Q^2)$
- Saturation
- Energy loss in CNM

STAR Upgrades:
- Forward tracker, Ecal+Hcal, Roman Pots-II

PHENIX Upgrades:
- f/sPHENIX barrel + forward

Run:
- p+p 200 GeV
- p↑+A (Au, Cu, C…) 200 GeV transverse

Goals:
- nPDF: $g(x,Q^2)$, $q(x,Q^2)$
- Saturation
- Energy loss in CNM

Electron-Ion Collider

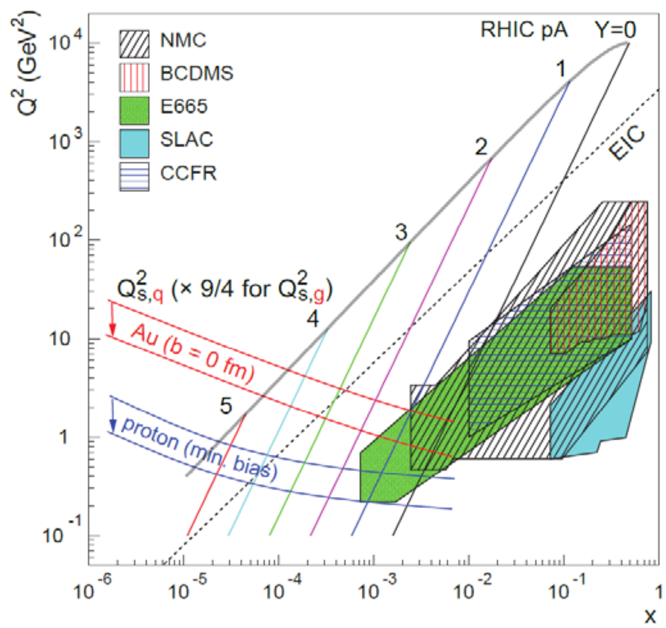
Why RHIC <u>and</u> the LHC?

- **RHIC:**
  - **RHIC "straddles" Q_{sA}**
    - RHIC can make measurements both above and below the saturation scale (rapidity and centrality)
  - **RHIC can explore the dependence of the saturation scale on nuclear size**
    - Flexibility of RHIC collider to run p+A with multiple *A* species
  - **Polarized p↑+A collisions offer a unique, fundamentally new observable**
- **LHC:**
  - **The LHC measurements provide a large lever arm in Q^2.**
  - **Higher energy at the LHC makes available new probes ($W^{+/-}$, Z)**

- **Measurements at RHIC and the LHC and *complementary!***

Why p+A and e+A?

- **p+A:**
  - Initial kinematics undetermined – a given measurement averages over a range in *x*
  - *Essential for comparison with e+A to separate universal physics from process dependence.*



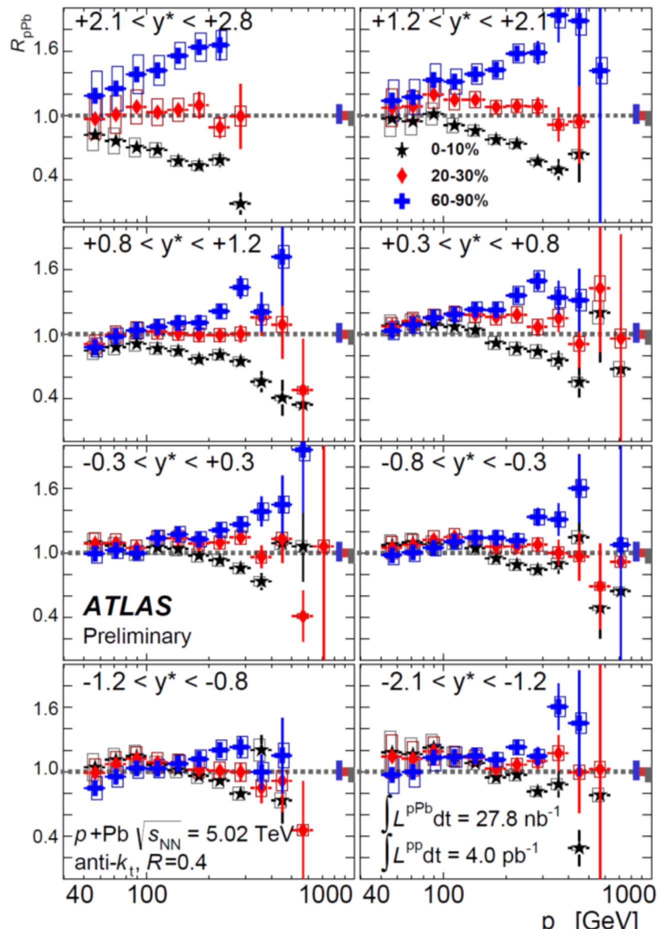
- **e+A:**
  - Initial kinematics determined event-by-event
  - Large range in x,Q^2

Summary

- **The study of p+A collisions offers a window into the structure of matter:**
  - Important to understand partonic processes on nuclei
  - Sets the initial conditions for HI collisions
  - Tantalizing hints of saturation in current RHIC data
  - Exciting evidence of collective behavior
- **Near-term detector upgrades at RHIC and analysis of existing LHC data will continue the success and open new approaches:**
  - Prompt photons in the PHENIX MPC-EX and STAR FMS
  - New nPDF constraints from RHIC + LHC data
  - Polarized p+A collisions a unique scientific opportunity!
- **PHENIX/STAR forward upgrades will enable critical new observables on the road to the EIC**
  - Extend observables to include jets, DY
- **Measurements in e+A at the EIC will enable a complete, systematic study of the behavior of low-x gluons in nuclei.**

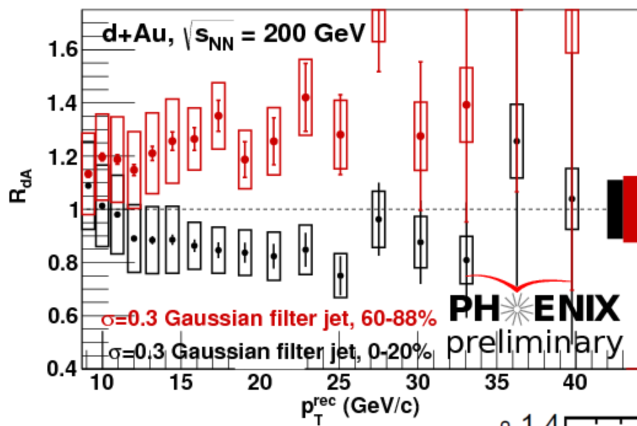
BACKUP

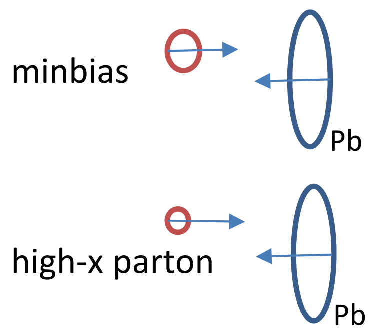
An Intriguing Idea…



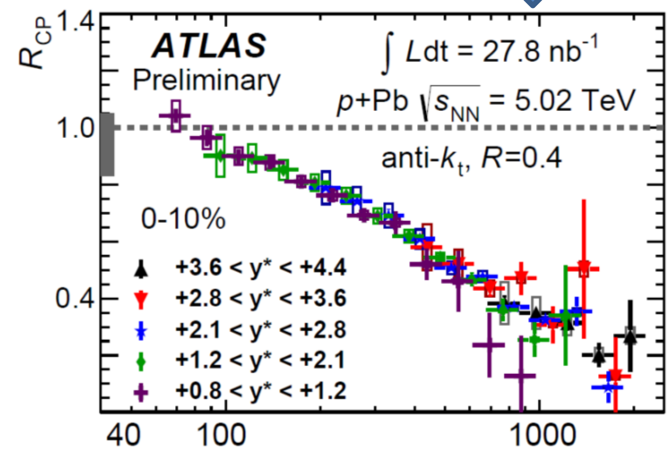
ATLAS-CONF-2014-24

Jet R_{pPb} at LHC and R_{dAu} at RHIC show a surprising pattern – suppression in central events, *enhancement* for peripheral!





Seems to be an initial state effect associated with the *x* of the parton from the proton!

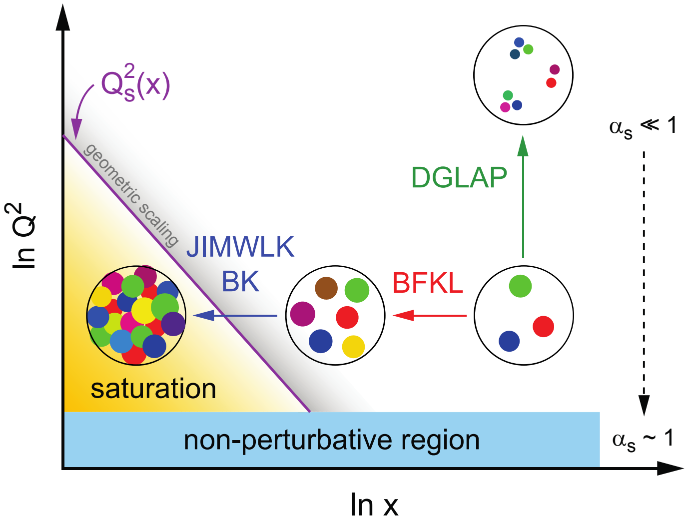


ATLAS-CONF-2014-24

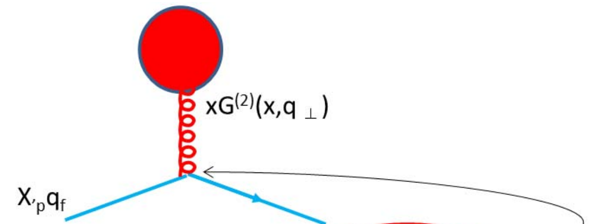
Fluctuations in proton size correlate with centrality!?

hep-ph/1307.5911

Connection to EIC : TMD Gluon PDFs



Dominguez, Marquet, Xiao, Yuan: Phys Rev. D 83: 105005 (2011)

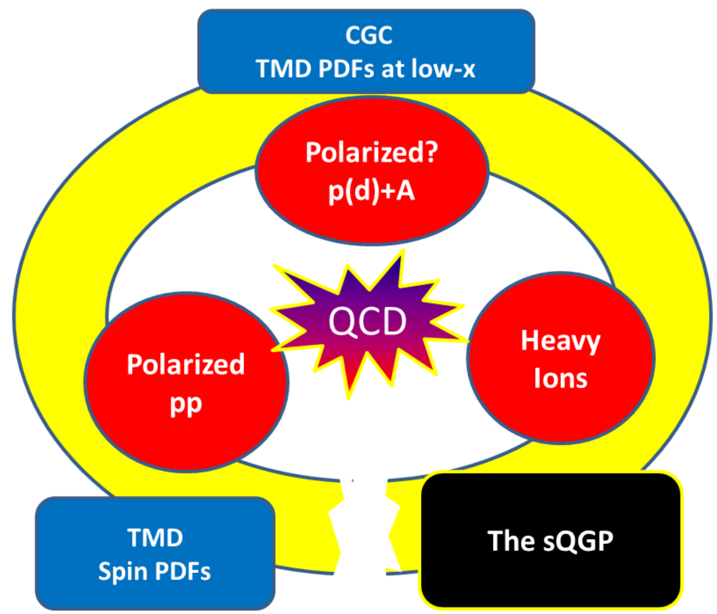


$$\frac{d\sigma^{(pA\to\gamma q+X)}}{dy_1 dy_2 d^2P_\perp d^2q_\perp} = \sum_f x_p q_f(x_p) x_g G^{(2)}(x_g, q_\perp) H_{qg\to\gamma q}$$

Transverse Momentum Dependent (TMD) factorization is ***recovered*** in low-x limit in p+A, consequence is <u>two</u> gluon distributions!

TMD PDF's at low-x are equivalent to those obtained in the Color Glass Condensate framework!

The TMD framework is important in attempts to understand single-spin asymmetries!

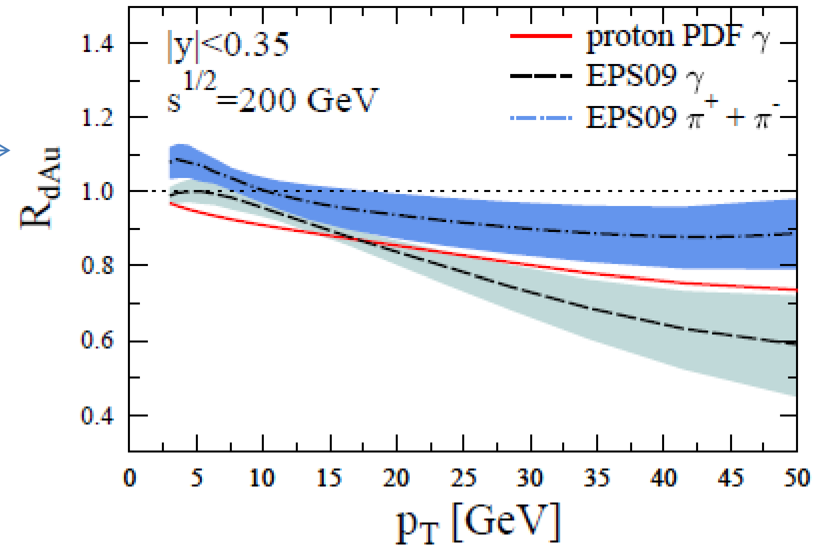


Strong synergies between RHIC programs!

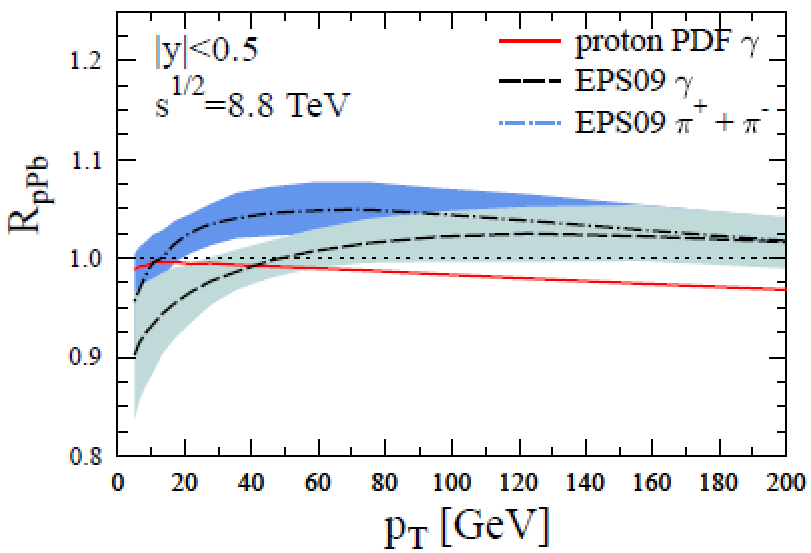
Prompt Photon Predictions

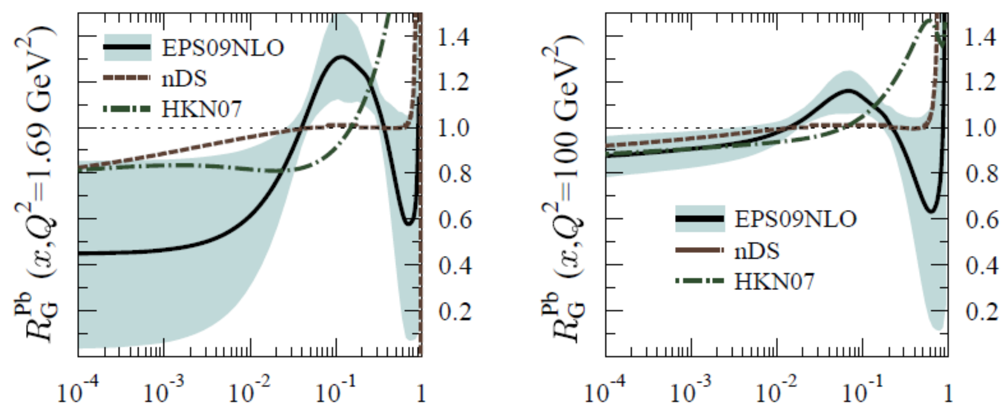
[arXiv:1103.1471v2]

RHIC

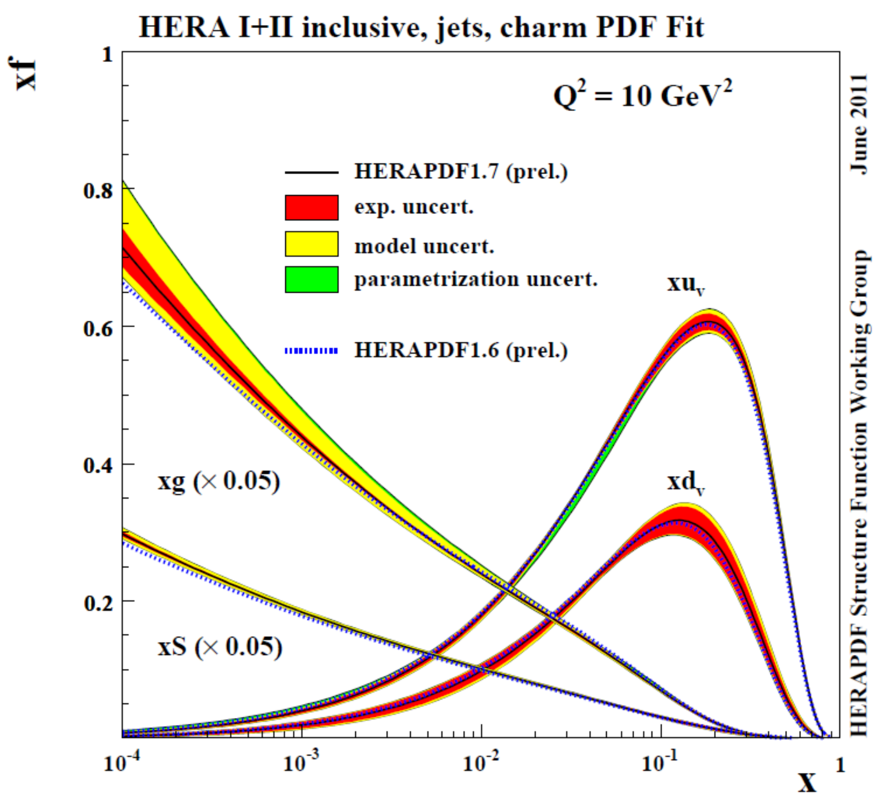


LHC

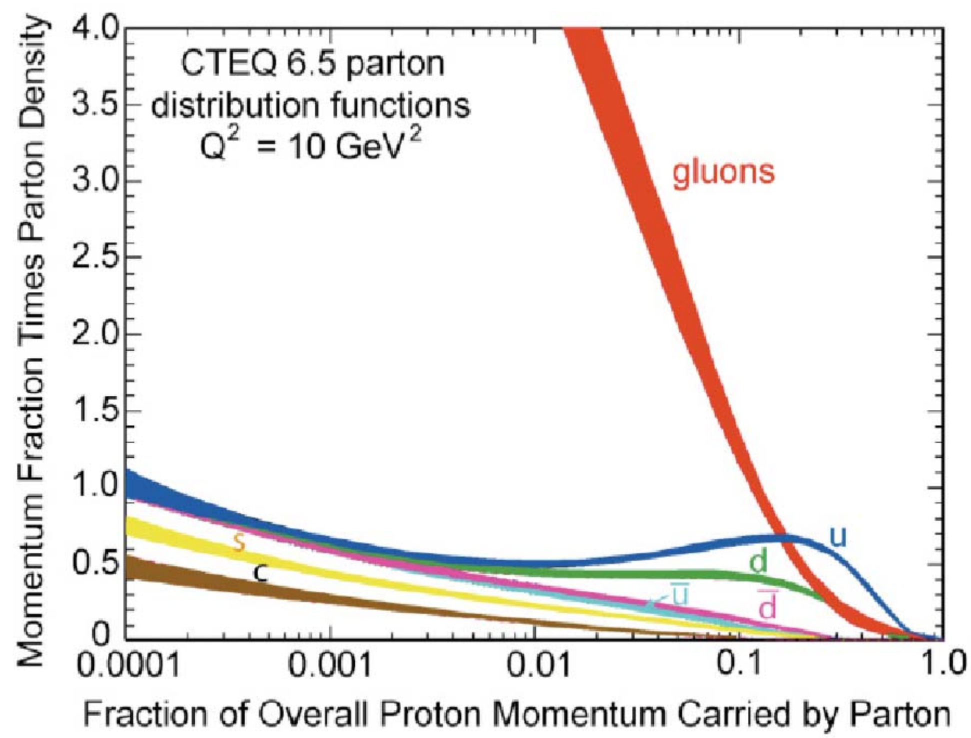




PDF's



HERA I+II inclusive, jets, charm PDF Fit
xf
$Q^2 = 10$ GeV^2
HERAPDF1.7 (prel.)
exp. uncert.
model uncert.
parametrization uncert.
HERAPDF1.6 (prel.)
xu_v
xd_v
xg (× 0.05)
xS (× 0.05)
June 2011
HERAPDF Structure Function Working Group
x



CTEQ 6.5 parton distribution functions
$Q^2 = 10$ GeV^2
gluons
u
d
s
c
$\bar{u}$
$\bar{d}$
Momentum Fraction Times Parton Density
Fraction of Overall Proton Momentum Carried by Parton

nPDF Constraints from the LHC

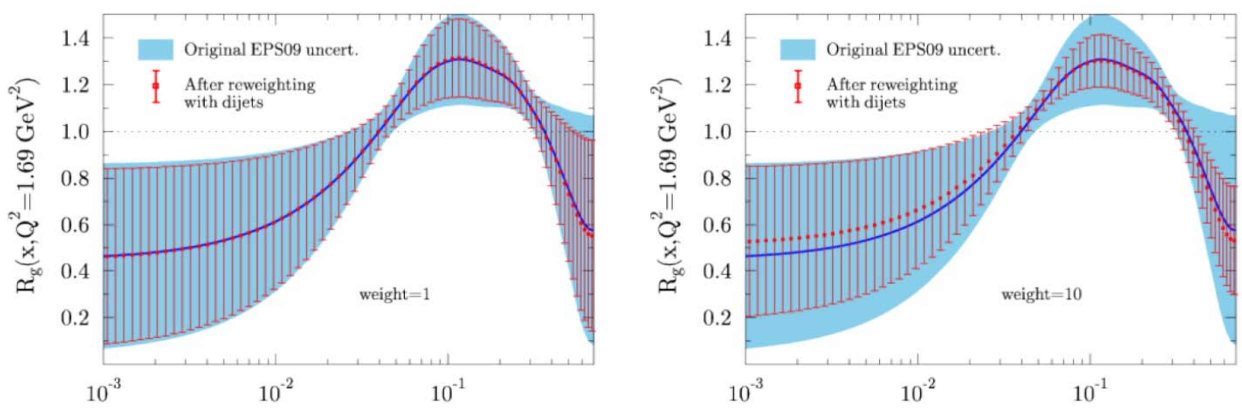
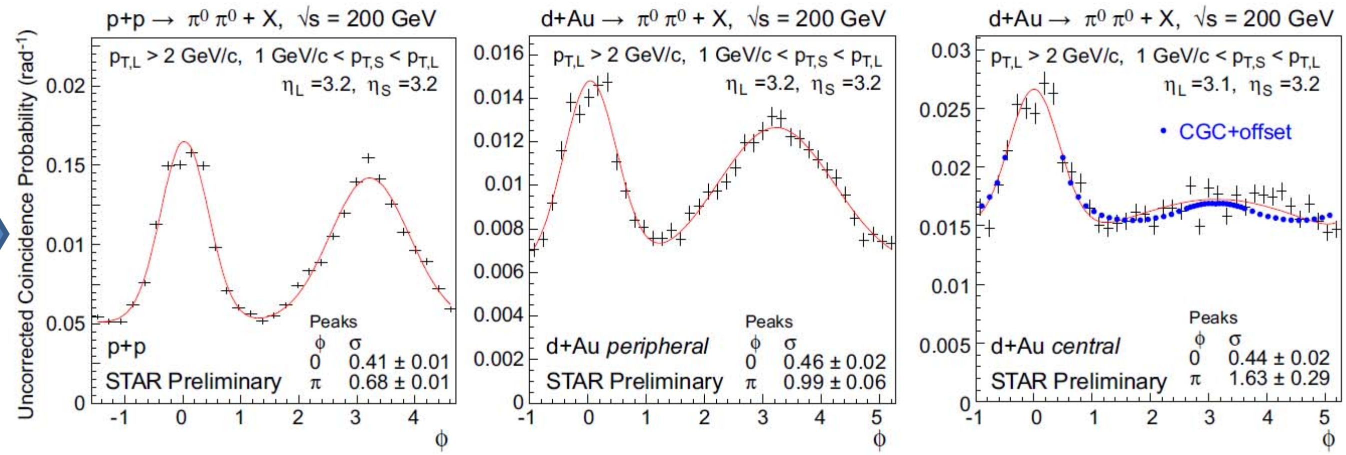


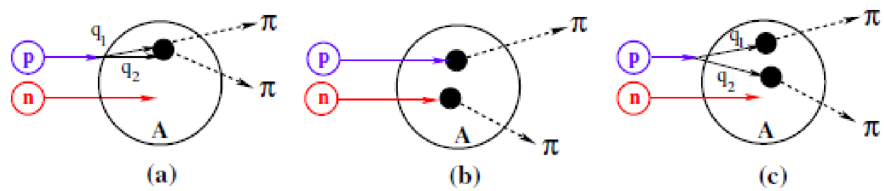
Figure 4. **Left-hand panel:** The EPS09 nuclear modification $R_G(x, Q^2 = 1.69\,\mathrm{GeV}^2)$ before and after the reweighting with CMS p+Pb dijet data. **Right-hand panel:** As the left-hand panel but giving the dijet data an extra weight of 10.

arXiv:1408.4563v1

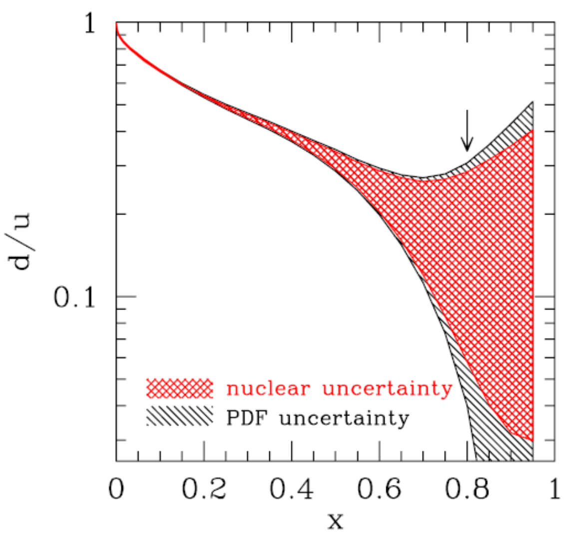
Why p+A instead of d+A?

Multi-parton interactions can contribute to the suppression of the away-side correlation strength.





Phys. Rev. D 84 014008 (2011)



Forward rapidity corresponds to *high-x* in the projectile nucleon (d or p). Nuclear corrections at high-x are large for the deuteron, which may necessitate d+p running for proper comparison.

…and you can't polarize the deuteron at RHIC…