Opportunities in Experiments at RHIC and the EIC

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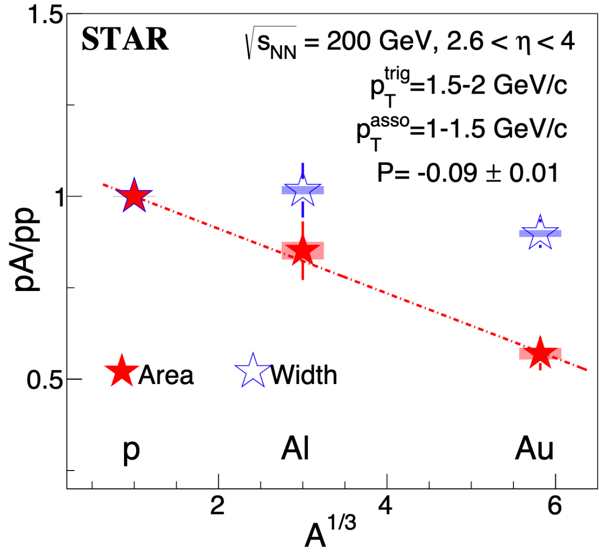
STAR, PRL 129, 092501 (2022)

STAR pp and pA data

$$x = \frac{p_{T1}\, e^{-y_1} + p_{T2} e^{-y_2}}{\sqrt{s}},\, Q \sim \frac{p_{T1} + p_{T2}}{2}$$



Area and width @ $(\Delta\phi = \pi)$
\+ pedestal

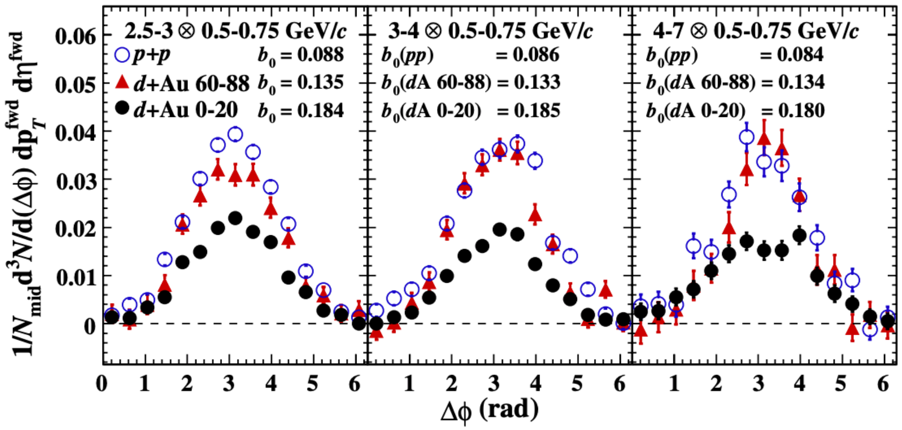
Relative area = $\frac{Area\ in\ p+A}{Area\ in\ p+p} < 1$
Suppression is observed

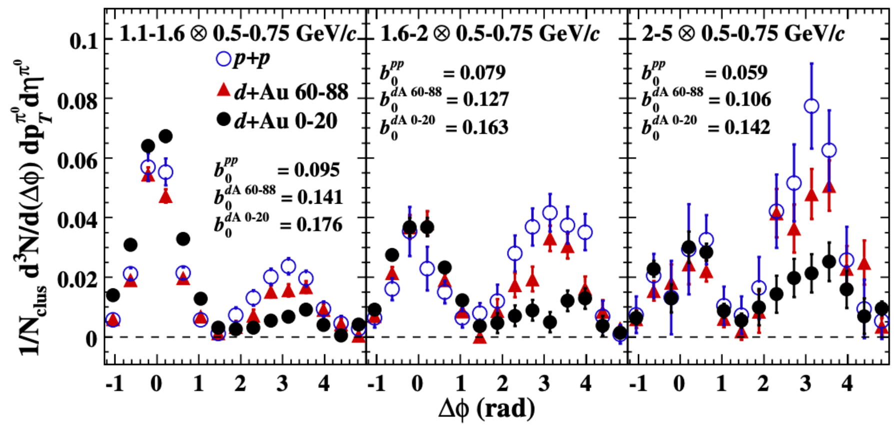
Relative width ~ 1
Broadening is not observed – why?

PHENIX pp and dA data

mid-forward, $|\eta^{trig}| < 0.35$, $3 < |\eta^{asso}| < 3.8$

forward-forward, $3 < |\eta| < 3.8$

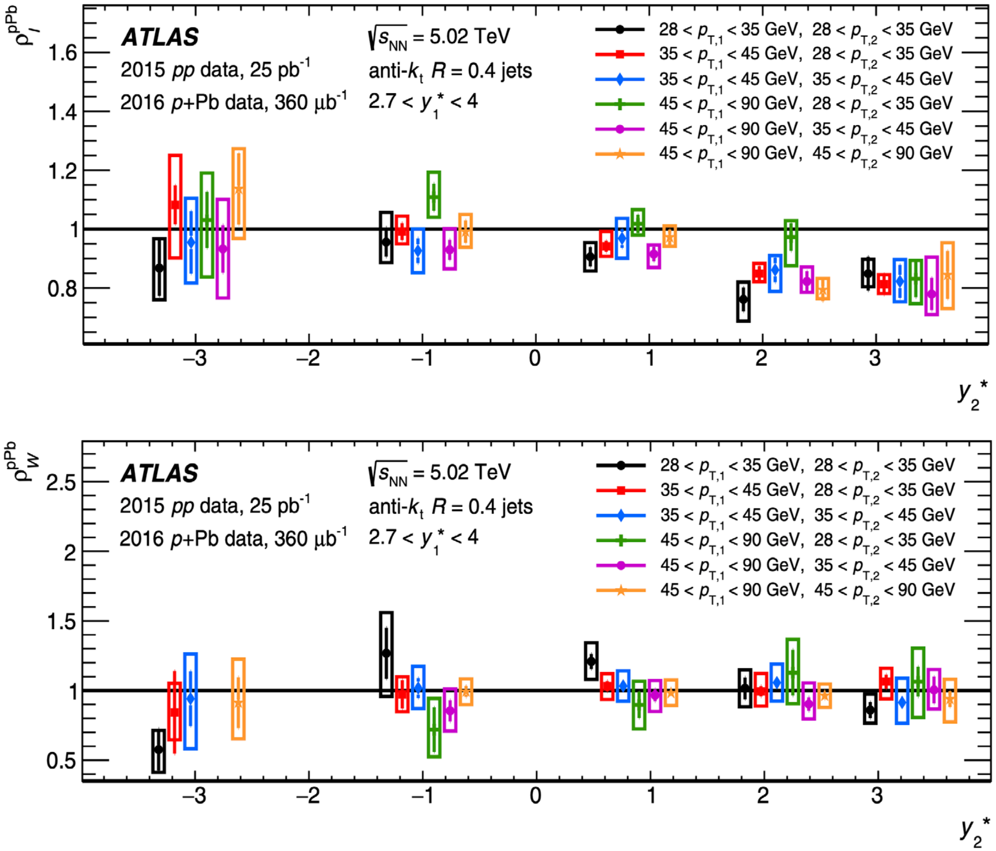




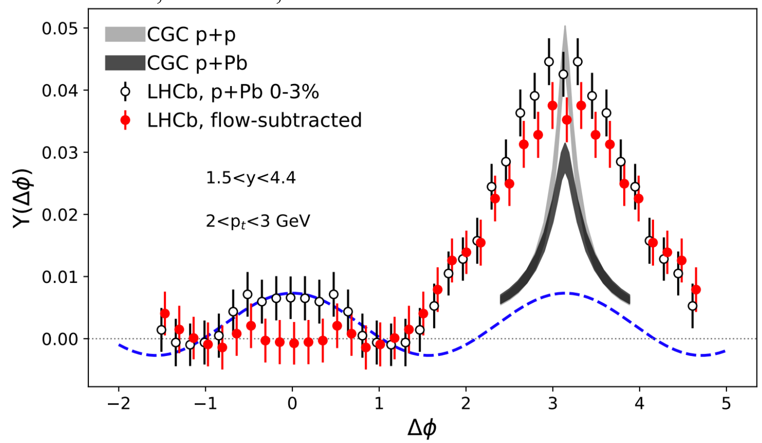
- Same method used to extract the area and width as STAR, with pedestal subtracted
- Suppression is observed in both cases
- Relative width ~ 1 for mid-forward correlation; high pedestal in dA compared to the baseline pp that possibly biases the width extraction, inconclusive for fwd-fwd correlation on broadening

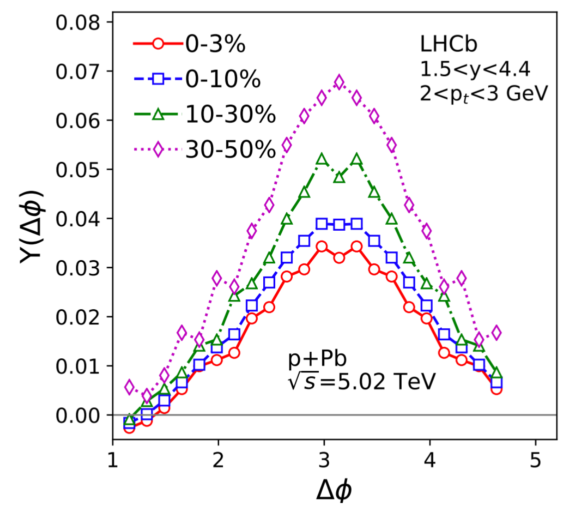
LHC pp and pPb data

ATLAS, PRC 100, 034903 (2019)



LHCb, NPA 982, 291





Less suppression compared to STAR dihadron

- $x_{Pb} \rightarrow 10^{-4}, Q^2\ > \sim 800\ GeV^2$

Width extracted as σ from the Gaussian fit:

- Remains the same in p+p and p+Pb

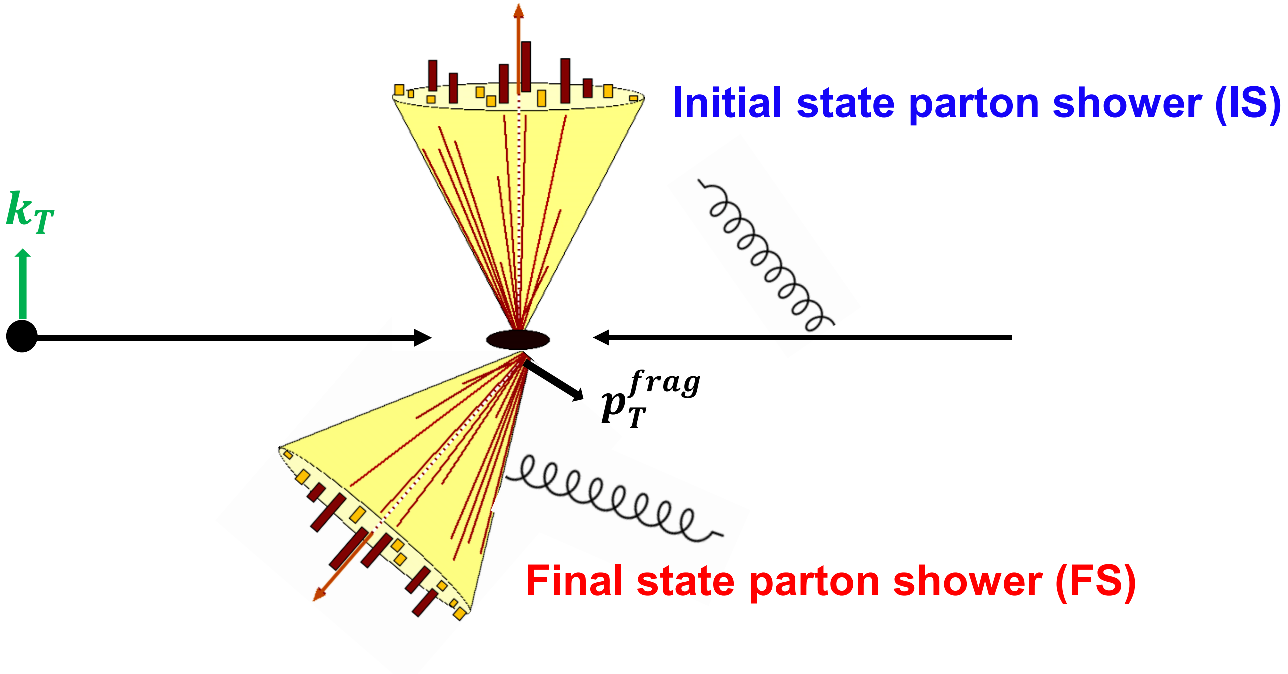
LHCb did not report forward di-hadron correlation widths

- None of the experiments has claimed the observation of the broadening phenomenon predicted by CGC to date

- Meanwhile, there are serval effects leading to a wider away-side correlation, which may overshadow the broadening from saturation

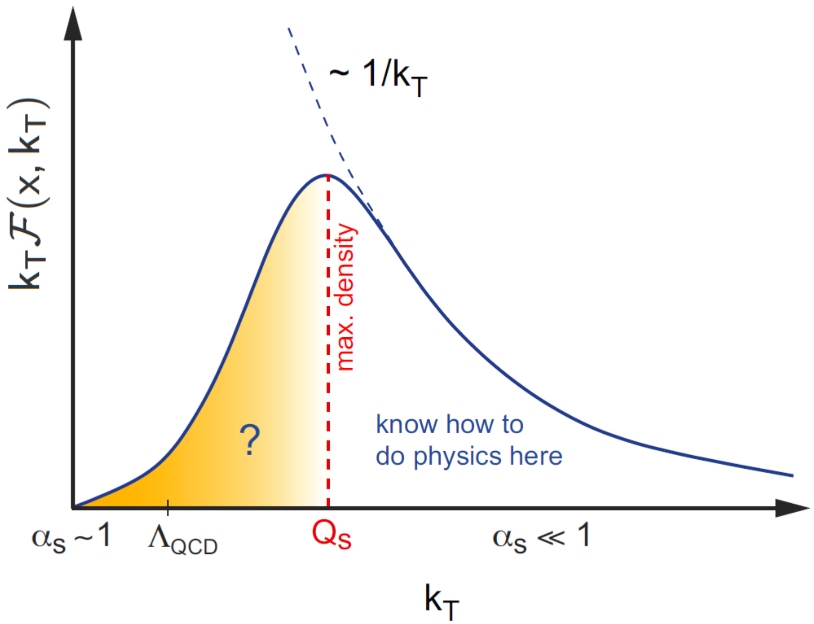
Broadening in simulation studies

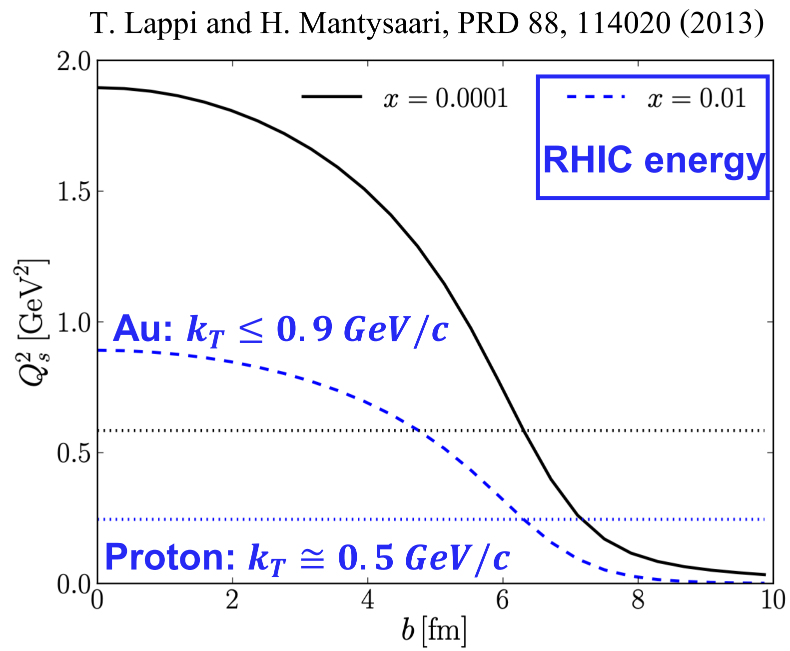
Factors can cause the broadening:



- Intrinsic k_T: saturation related factor, $k_T \approx Q_s$, it's larger in eA/pA than ep/pp
- Parton shower (Sudakov effect) and p_T^{frag}: independent of collision system
- All can lead to broad away-side peaks

Broadening induced by saturation





- $Q_s >> \Lambda_{QCD}$, $\alpha_s(Q^2s) << 1$, the majority of the gluons have transverse momenta $k_T \approx Q_s$
- Using DIS data in a CGC framework to fix the proton's saturation scale, then extend the model to nuclei to estimate their saturation scales

Saturation implemented in simulation by parameterizing intrinsic $Q_S \sim k_T$:
at RHIC energy,
for proton: $k_T \cong 0.5\ GeV/c$;
for Au: $k_T \sim 1\ GeV/c$

Broadening in simulation for pp, pA

STAR tune simulation, no detector effect:

Event selection:

- Two π^0s produced in FMS rapidity acceptance (2.6<η<4.0)
- π^0 p_T> 1 GeV/c, which is FMS threshold

Method:

- Turn on initial-state radiation, final-state radiation, and p_T^{frag} one by one, check how each factor changes the width of the away-side correlation of two π^0s
- Change k_T based on everything else is on, to see the influence induced by saturation only

Broadening in simulation for pp, pA

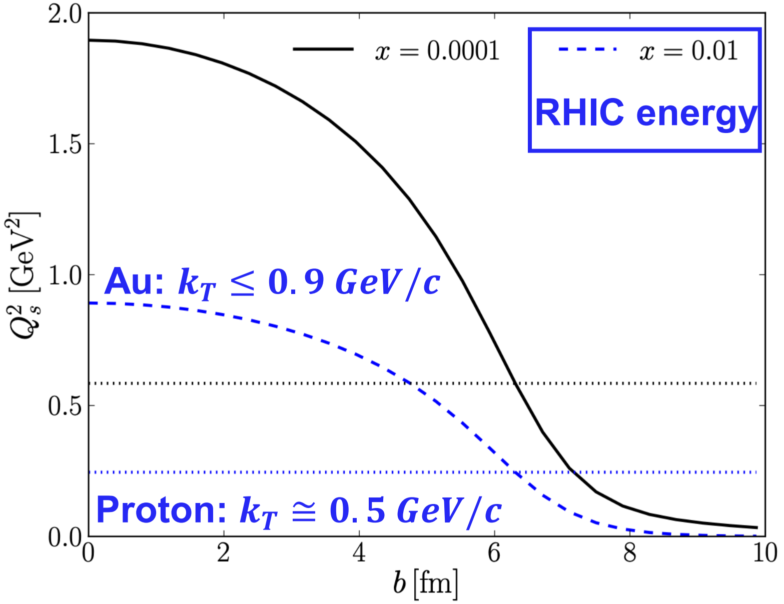
RMS @ $(\Delta\phi = \pi)$
due to sharp peak at all off

- Two major sources for broadening: IS and p_T^{frag}
- k_T (saturation) is not the dominate source

K. Cassar et al., arXiv:2503.08447

Broadening in simulation for pp, pA

T. Lappi and H. Mantysaari, PRD 88, 114020 (2013)

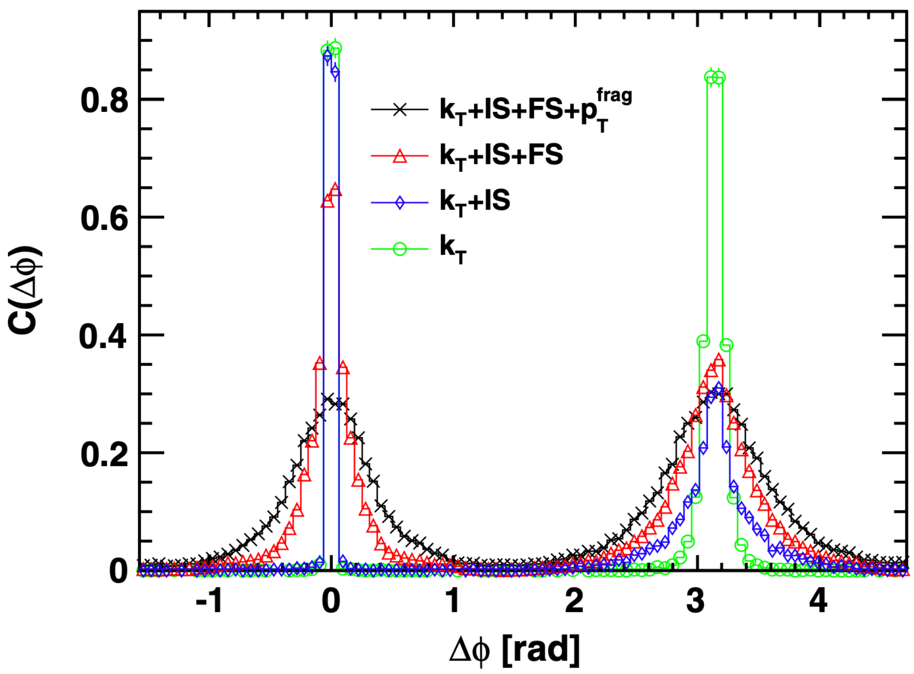


- Saturation implemented in simulation by parameterizing intrinsic $Q_S \sim k_T$: at RHIC energy, for proton: $k_T \sim 0.5\ GeV/c$; for Au: $k_T \sim 1\ GeV/c$
- With PS and p_T^{frag} turned on, away-side width stays unchanged by increasing k_T, broadening is not expected to occur in p+Au compared to p+p at RHIC; possible explanation for the experimental results

L. Zheng et al., PRD 89 (2014) 074037

Broadening in simulation at the EIC

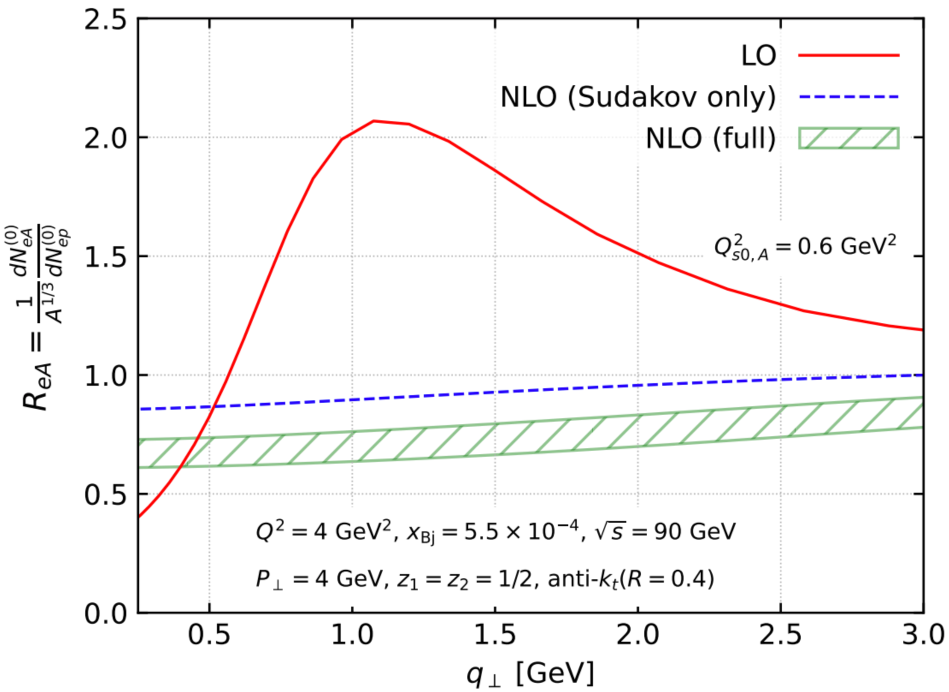
Di-charged hadron



	Near-side $\Delta\phi$ RMS	Away-side $\Delta\phi$ RMS
k_T	0.21	0.25
$k_T + \mathrm{IS}$	0.30	0.72
$k_T + \mathrm{IS} + \mathrm{FS}$	0.65	0.81
$k_T + \mathrm{IS} + \mathrm{FS} + p_T^{\mathrm{frag}}$	1.00	1.00

- Near side peak width mainly affected by final state parton shower and fragment p_T^{frag}
- Away side peak width dominated by initial state parton shower

Similar explanation from theory



LO: saturation alone, neither Sudakov nor small-x evolution, broadening and suppression at small q_T

LO+Sudakov: saturation + Sudakov (initial + final state radiation). very little broadening and small suppression

Full NLO = LO + Sudakov + small-x evolution: very weak broadening but strong suppression

Sudakov kills the broadening induced by LO saturation

Non-linear evolution suppresses the cross-section with slight broadening

What we’ve learnt so far:

- NLO contribution cannot be ignored, high precision measurement is needed

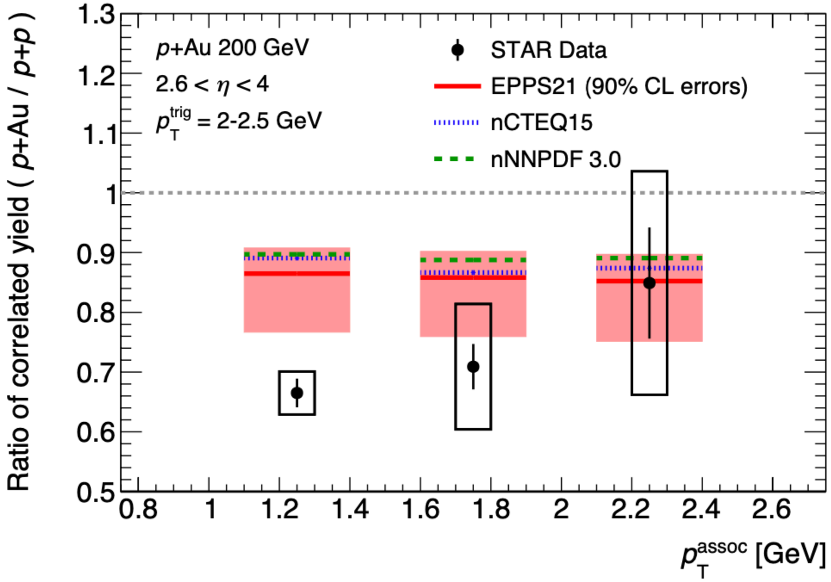
- If one wants to claim the discovery of gluon saturation, we need several observables that can only be interpreted by non-linear effects

The EIC will provide possibilities in measuring more observables

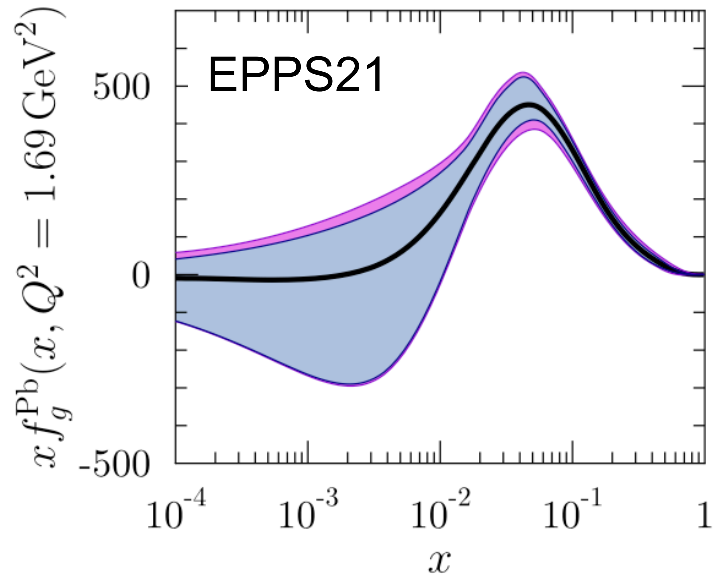
Other mechanisms: nPDFs

nPDF at small Q^2

D. Perepelitsa, PRC 111 (2025), 054901



K. Eskola et al., EPJC 82 (2022) 413



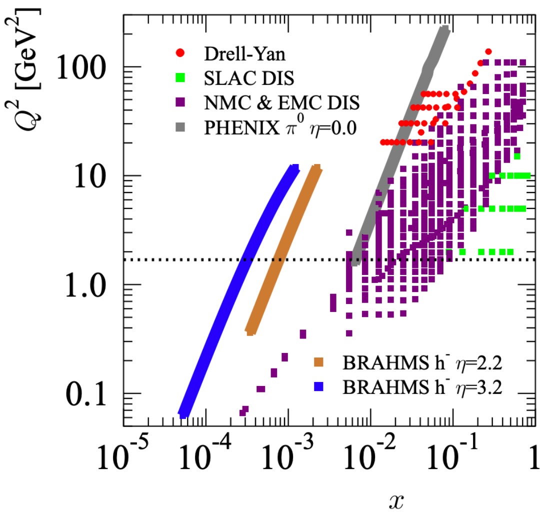
- No p_T dependence, overshoot low p_T data
- The vanishing gluon density at small Q^2 is used

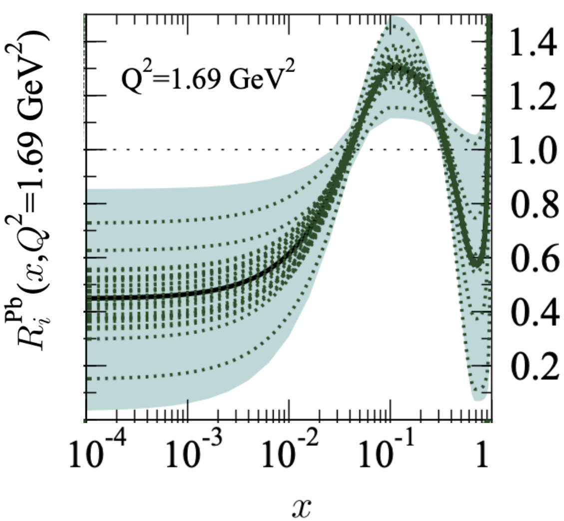
- Gluon density is 0 with largely negative error

nPDF: EPPS

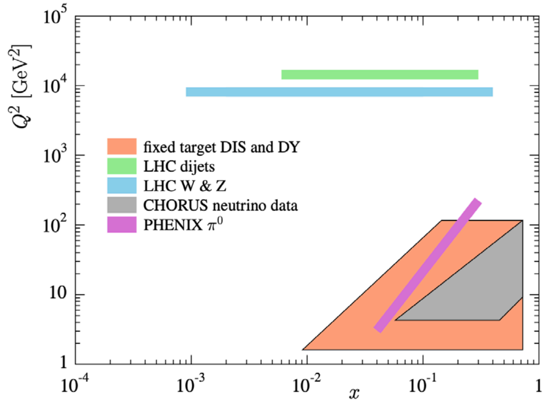
JHEP 04 (2009) 065
EPJC 77 (2017) 163
EPJC 82 (2022) 413

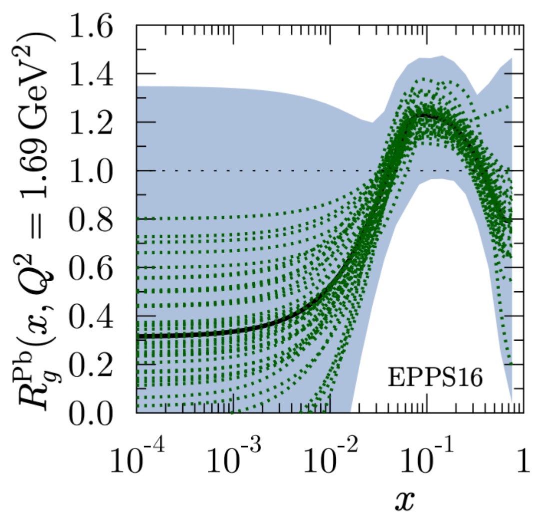
EPS09



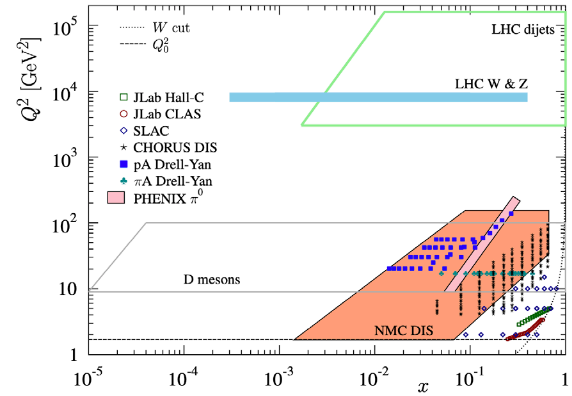


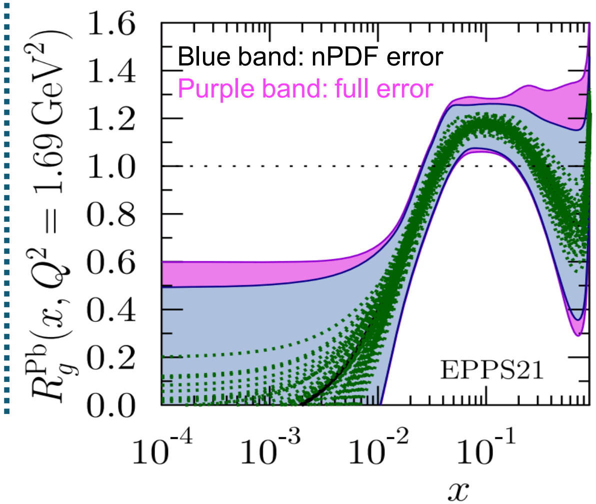
EPPS16





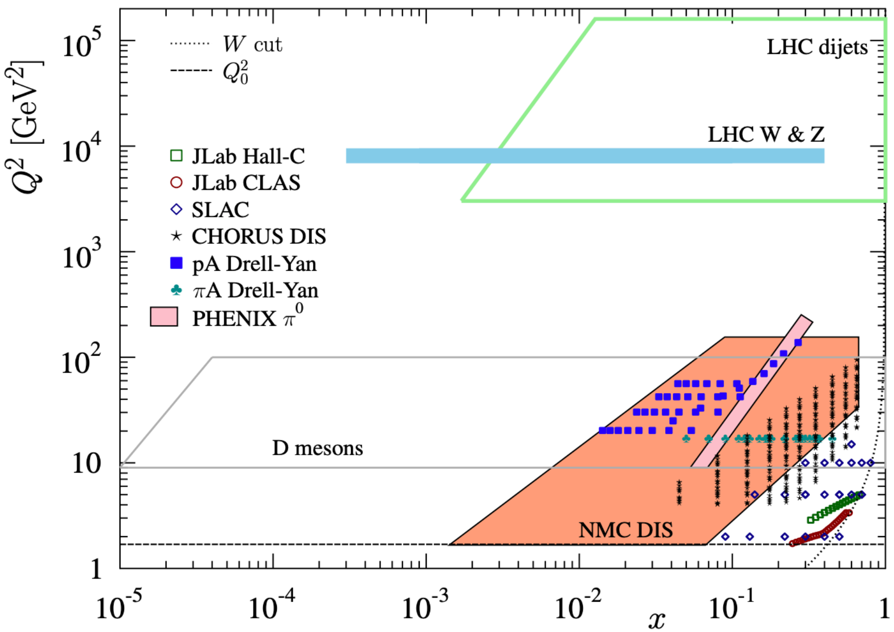
EPPS21



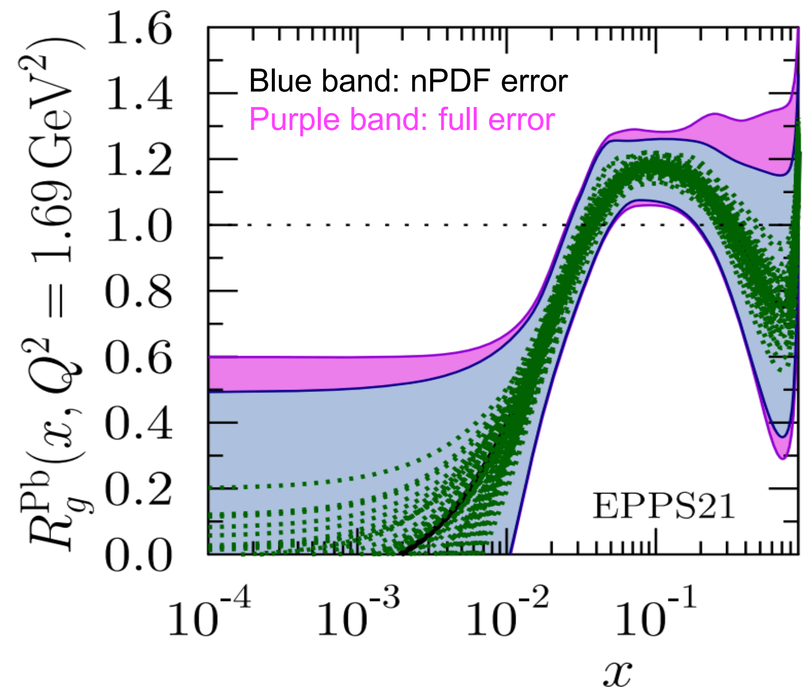


At small Q^2, gluon density eventually becomes 0, large impact from LHCb D

EPPS21



$Q^2 = 1.69$ GeV^2



- LHCb D meson data made a significant impact → gluon density becomes 0 at small Q^2? Suspect nonlinear gluon dynamics was included in initial condition for extraction? BUT they didn't use BK/BFKL. Should try to use higher p_T data to get rid of the saturation effect and use BK/BFKL
- Meanwhile, hadronization is included in the fit as EPPS used final state, but nuclear modified fragmentation is not included in the fit → needs to be improved, pp and pA can not separate initial and final state effect (except direct photon), but the EIC can

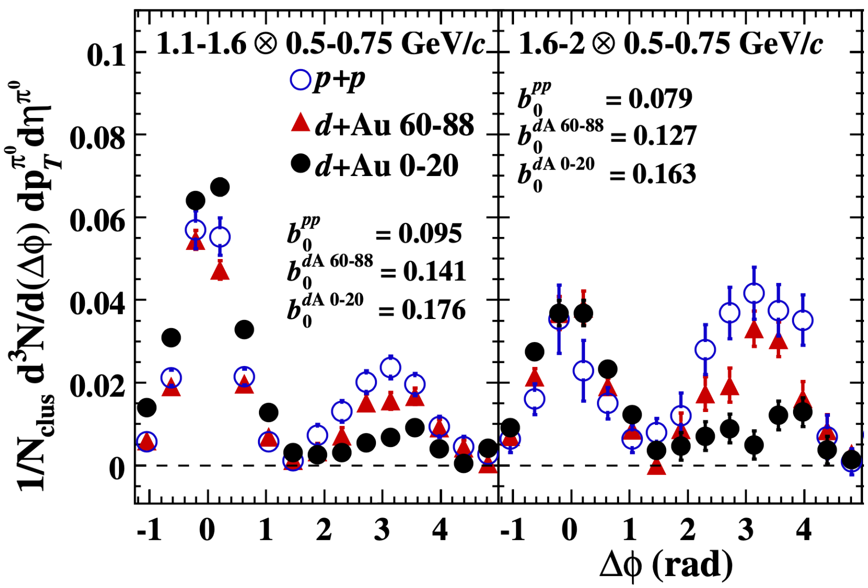
- So far, additional pA data-taking is not clear for the last RHIC Run

- What we can do at this momentum is to analyze Run16 dAu data to further investigate gluon saturation

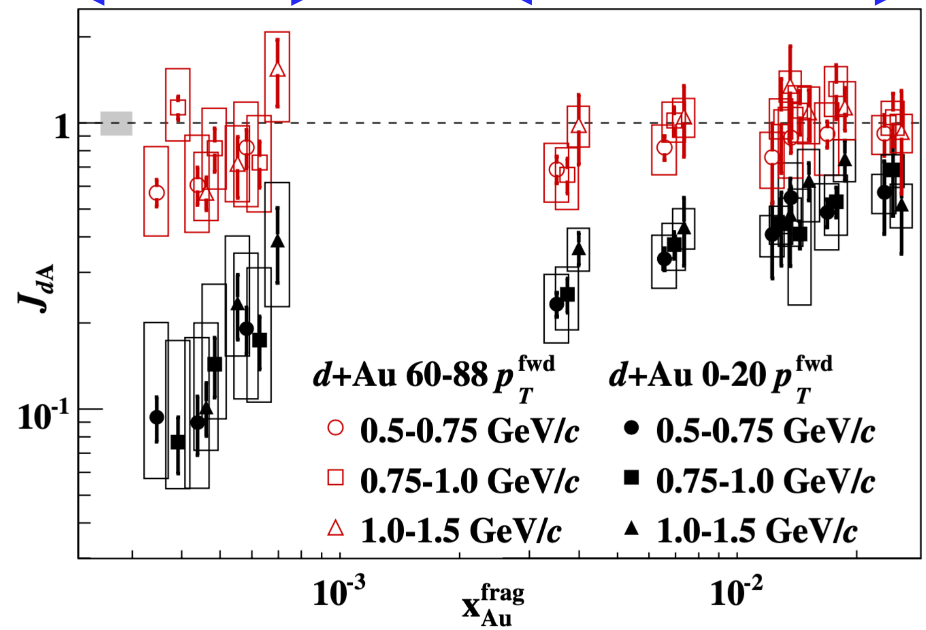
PHENIX, PRL 107, 172301 (2011)

PHENIX dAu data

forward-forward: 3.0 < η < 3.8



forward-forward mid-forward



$$J_{dA} = R_{dAu} \times I_{dAu}$$

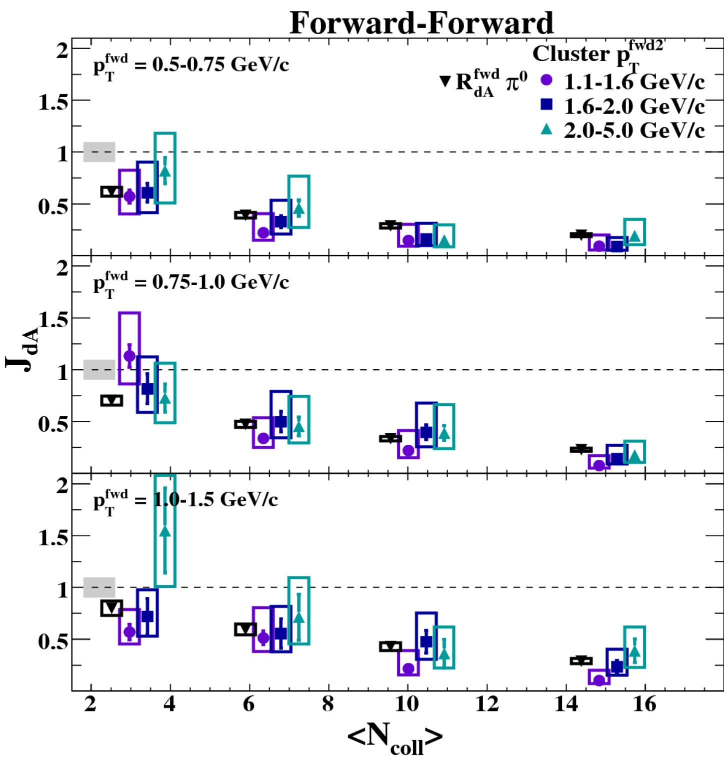
Low p_T	Pedestal ratio (central dAu/pp): 1.9
High p_T	Pedestal ratio (central dAu/pp): 2.1

I_{dAu}: area ratio dAu/pp → STAR measured

How to describe suppression?

PHENIX, PRL 107, 172301

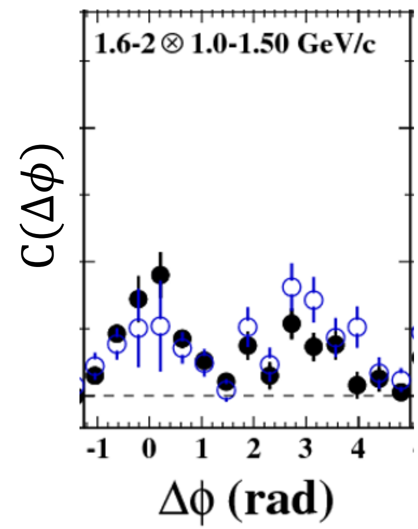
From the analysis note



$J_{dA} = I_{dA} * R_{dAu}$

I_{dA} = area ratio

$R_{dAu} \sim 2/N_{coll}$



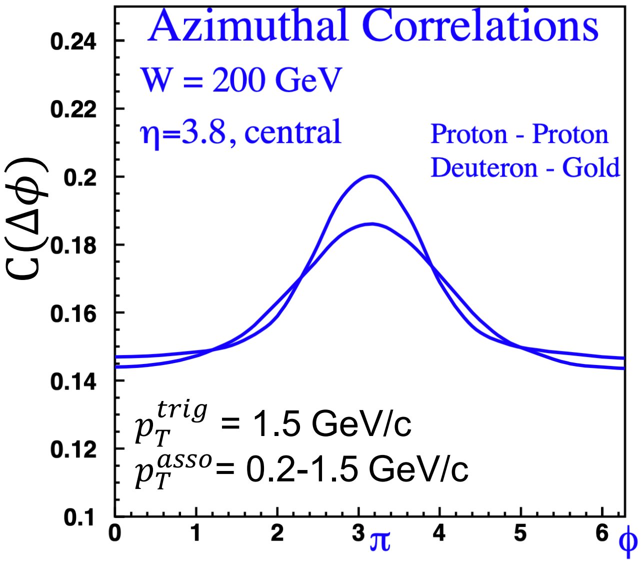
“$J_{dAu} \rightarrow 0.1$ that “10 times suppression observed in central dAu” should be clarified

In the highest associated p_T bin (red box), overlapping with STAR kinematics, no suppression is observed

Normalization from theory (1)

In the experiment:
$$C(\Delta\phi) = \frac{N_{pair}(\Delta\phi)}{N_{trig} \times \phi_{bin}}$$

Kharzeev, Levin, McLerran, NPA 748, 627 (2005)



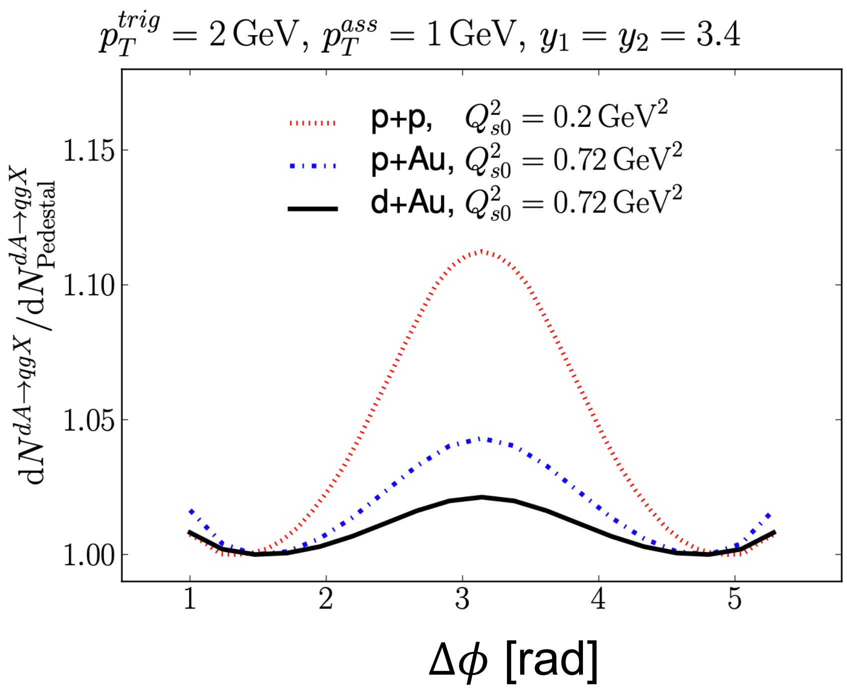
- Paper says: $\Delta\phi$ distributions normalized in a such way that the integral over azimuthal angle is equal to 1
- Normalized by N_{pair} for entire $\Delta\phi$ range → self normalization

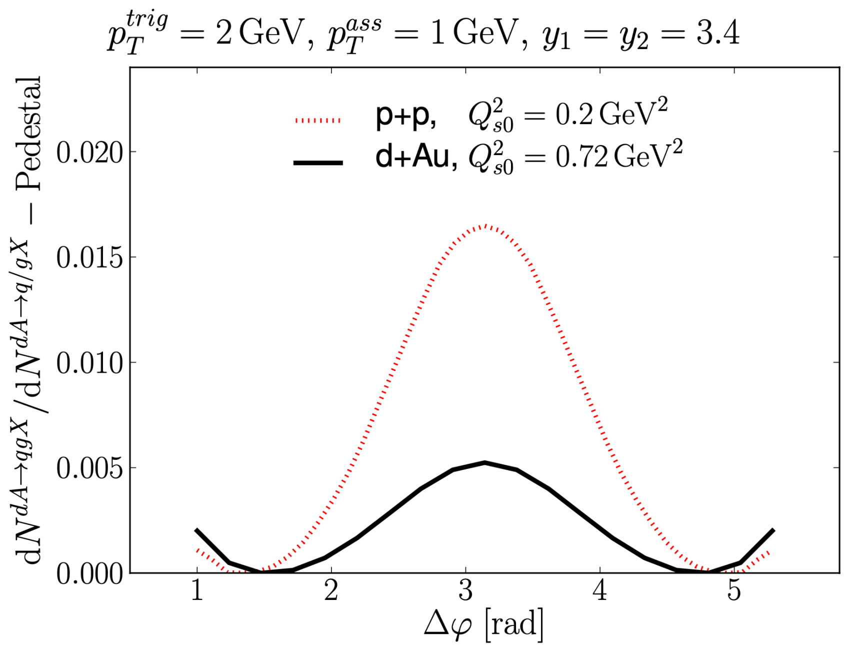
Normalization from theory (2)

In the experiment:

$$C(\Delta\phi) = \frac{N_{pair}(\Delta\phi)}{N_{trig} \times \phi_{bin}}$$

Lappi, Mäntysaari, NPA 908 (2013) 51-72



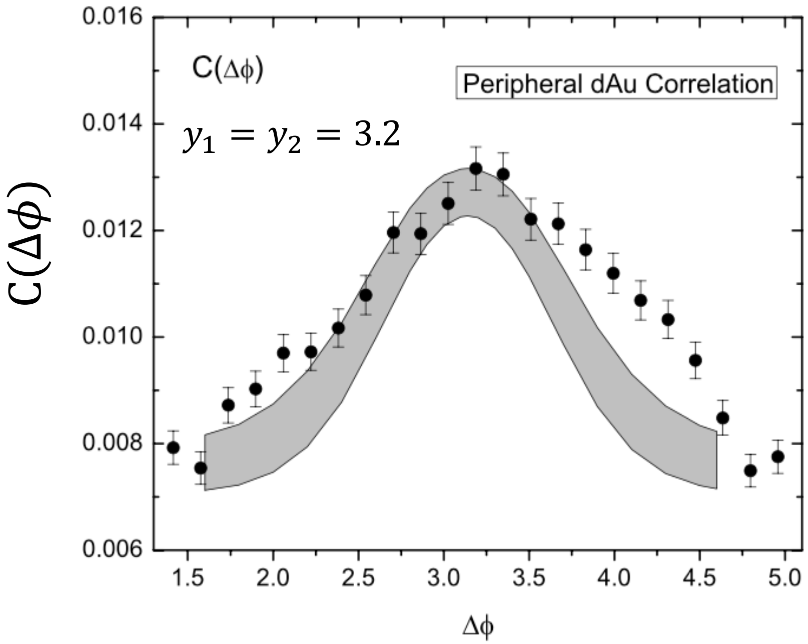


- For the first time, the pedestal is predicted, independent scattering of two partons from the probe: $f^p_{q_1 q_2}(x_{q_1}, x_{q_2}) = f^p_{q_1}(x_{q_1})\ f^p_{q_2}(x_{q_2})$
- Two ways of normalizations : Left: $\frac{N_{pair}(\Delta\phi)}{N_{pair\ from\ pedestal}}$; right: $\frac{N_{pair}(\Delta\phi)}{N_{trig}} - \mathrm{pedestal}$

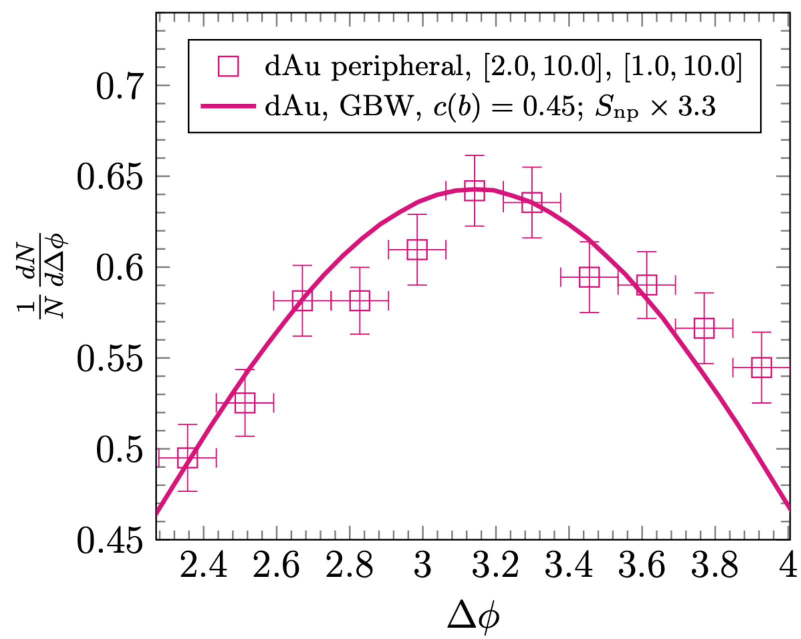
In the experiment:
$$C(\Delta\phi) = \frac{N_{pair}(\Delta\phi)}{N_{trig} \times \phi_{bin}}$$

Normalization from theory (3)

Stasto, Xiao, Yuan



Stasto, Wei, Xiao, Yuan

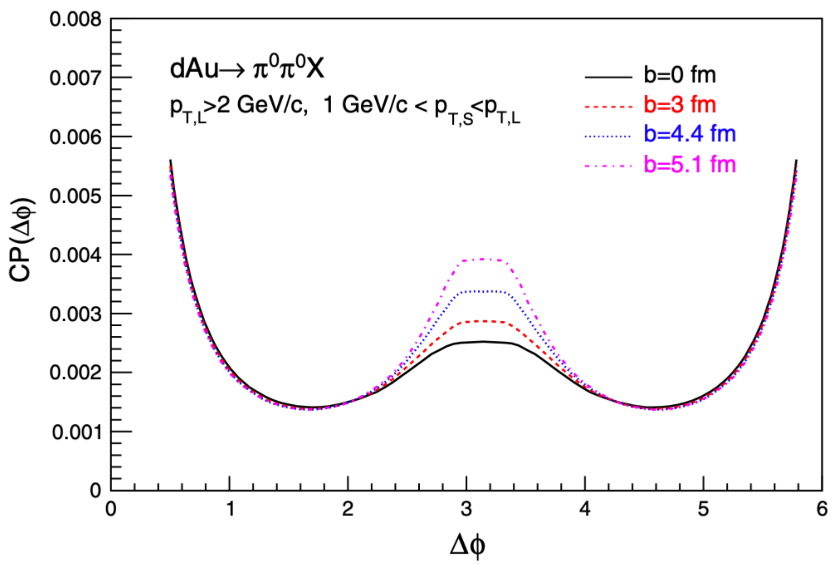


- Later paper used CGC predictions based on GBW model with Sudakov effects included
- Two ways of normalization used: correlation function normalized by N_{trig} not N_{pair}
  - PLB 716 (2012) 430-434: normalized by N_{trig}, issue with p+p normalization
  - PLB 784 (2018) 301-306: normalized by N_{pair}, issue with p+p normalization fixed

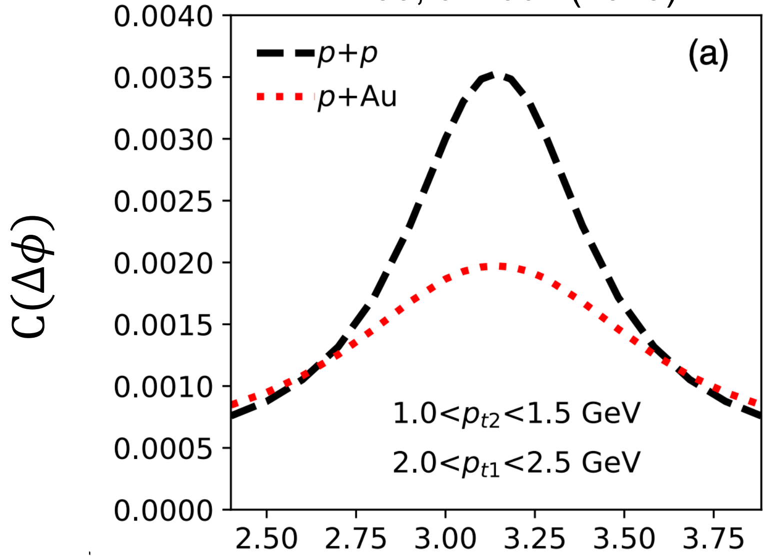
Normalization from theory (4)

In the experiment:
$$C(\Delta\phi) = \frac{N_{pair}(\Delta\phi)}{N_{trig} \times \phi_{bin}}$$

Albacete, Marquet, PRL 105, 162301 (2010)



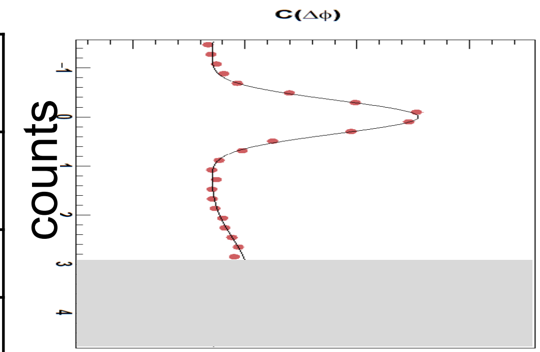
Albacete, Giacalone, Marquet, Matas, PRD 99, 014002 (2019)



Normalized by trigger particles yields → same as experiential measurement
Used in comparison with STAR data

Summary

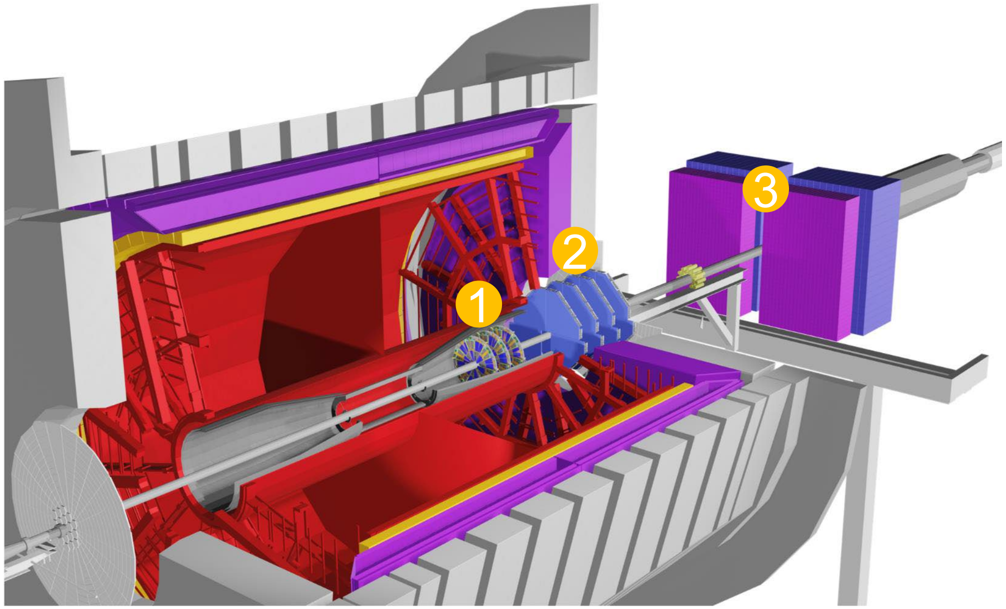
Experimental papers	Normalized by	Systems	Details
STAR	N_{trig}	p+p, p+Al, p+Au, d+Au	Compare area ratio
PHENIX	N_{trig}	p+p, d+Au	Compare area ratio×R_{dAu}
ATLAS and LHCb	N_{trig}	p+p, p+pb	Compare area ratio



Theoretical papers	Normalized by	Systems	Details
NPA 748 (2005) 627-640	N_{pair}	p+p, d+Au	N_{pair} for entire $-\frac{1}{2}\pi < \Delta\phi < \frac{3}{2}\pi$ range
PLB 716 (2012) 430-434	N_{trig}	p+p, d+Au	same as experiment, issue with p+p
PLB 784 (2018) 301-306	N_{pair}	p+p, p+Au, d+Au	N_{pair} for back-to-back region: $\frac{1}{2}\pi < \Delta\phi < \frac{3}{2}\pi$
NPA 908 (2013) 51-72	N_{trig}	p+p, p+Au, d+Au	same as experiment
	N_{pair}	p+p, p+Au, d+Au	N_{pair} for pedestal
PRL 105, 162301 (2010)	N_{trig}	p+p, d+Au	same as experiment
PRD 99, 014002 (2019)	N_{trig}	p+p, p+Au, d+Au	same as experiment, compared with STAR data

- For dAu: Complicated normalizations; undetermined DPS; large background
- Di-π^0 measurement favors cleaner p+A than d+A collisions

If pAu is possible for last RHIC Run



Detector	pp and pA	AA
ECal	~10%/√E	~20%/√E
HCal	~50%/√E+10%	---
Tracking	charge separation photon suppression	0.2<p_T<2 GeV/c with 20-30% $1/p_T$

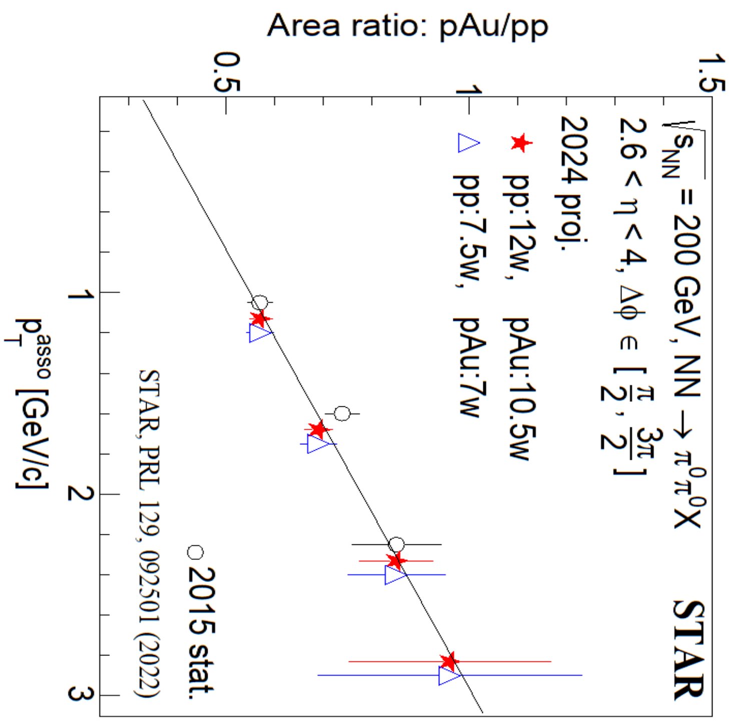
STAR Forward Upgrade:
2.5 < η < 4

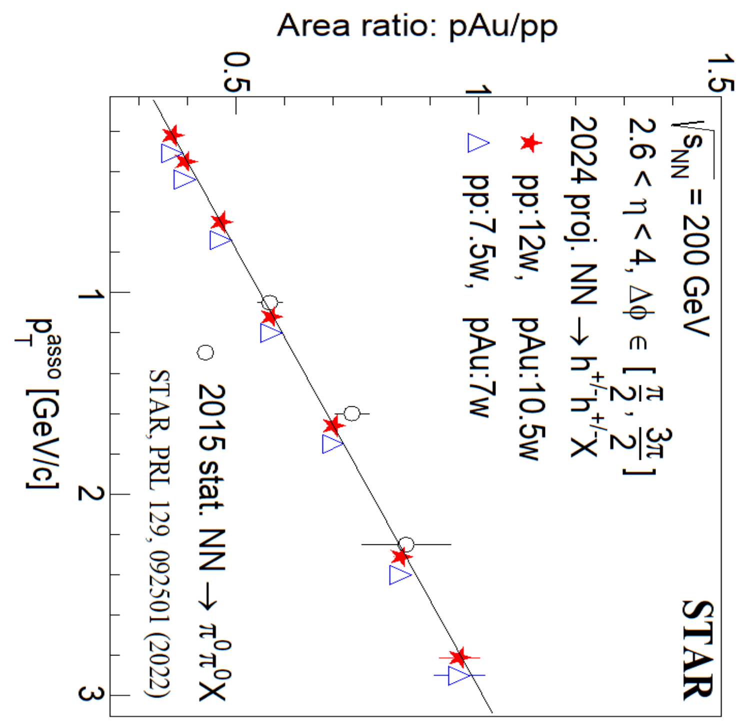
Three new systems:
1 Forward Silicon Tracker
2 Forward sTGC Tracker
3 Forward Calorimeter System

To explore nonlinear gluon dynamics with expanded observables beyond π^0s:

- Di-$h^{\pm}$: access lower p_T down to 0.2 GeV/c
- Di-jet: $p_T^{jet} > 5\ \mathrm{GeV}/c \rightarrow$ higher x and Q^2
- Direct photon: q+g→q+γ; statistic driven

Di-h correlation projections



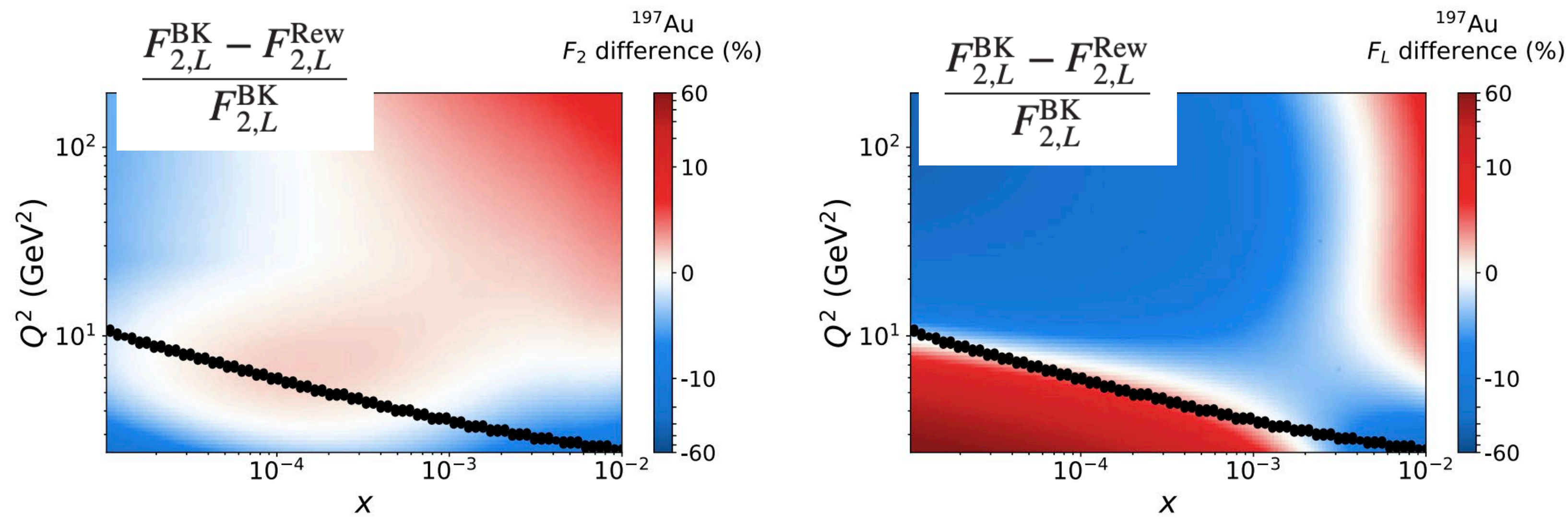


- **Run25 di- π^0 projection**: Best statistic of 2024 (28 Cryo weeks) indicates $\sim 35\%$ reduction of the statistical error

- **Run25 di-$h^\pm$ projection**: Higher statistic than di-π^0; $\geq 80\%$ reduction of the statistical error; the strongest suppression expected at the lowest p_T where forward upgraded detectors can probe

Prediction for the EIC: F_2 and F_L

Armesto, Lappi, Mantysaari, Paukkunenm, Tevio, PRD 105, 114017 (2022)



- Heavy nucleus: difference between DGLAP and nonlinear are few % for F_2 and up to 20% for F_L
- For nPDFs: the EIC can measure F_2 and F_L directly for eA, as for the proton, so we don't need to do a ratio between eA and ep and we can avoid the normalization issue

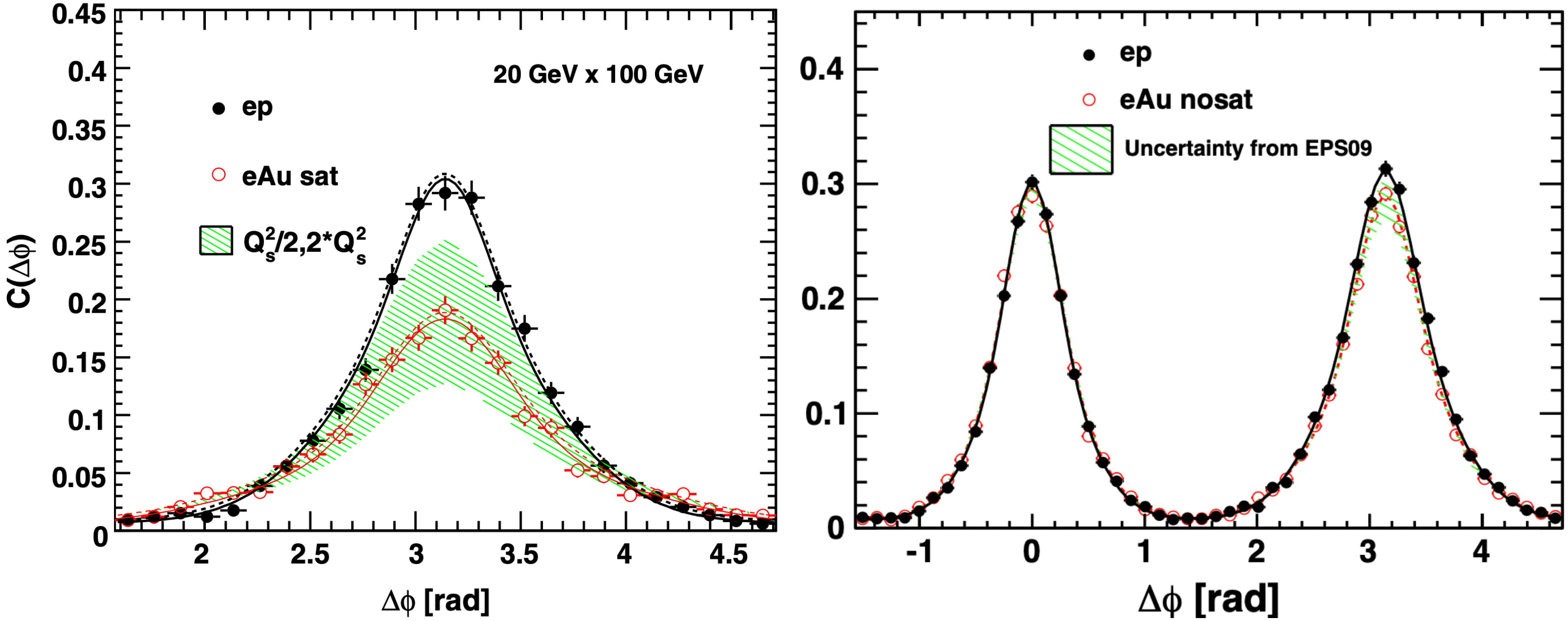
From experiment

$$R_{pA} = \frac{1}{\langle N_{\mathrm{coll}} \rangle} \cdot \frac{d^2 N_{pA}/dp_T dy}{d^2 N_{pp}/dp_T dy}$$

Rarely provided: σ_{pA}^{tot}

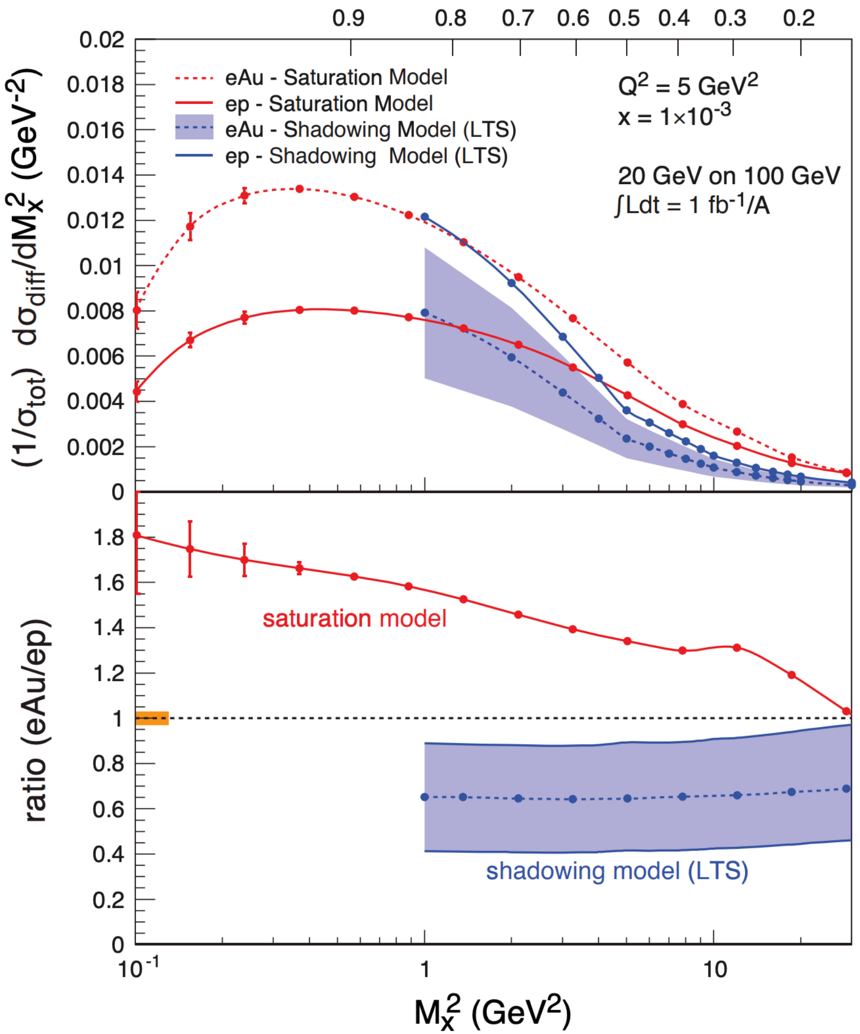
Prediction for the EIC: correlation

L. Zheng et al., PRD 89 (2014) 074037



- Constrain sat. and nosat. models a lot with limited statistics of 1 fb^{-1}: Strong suppression is reproduced by sat. model not by nosat. model (EPS09 nPDF) including energy loss
- Simulations in ep and eAg implementing the modern nPDFs is on-going, propose data-taking for early science at the EIC

Prediction for the EIC: diffraction

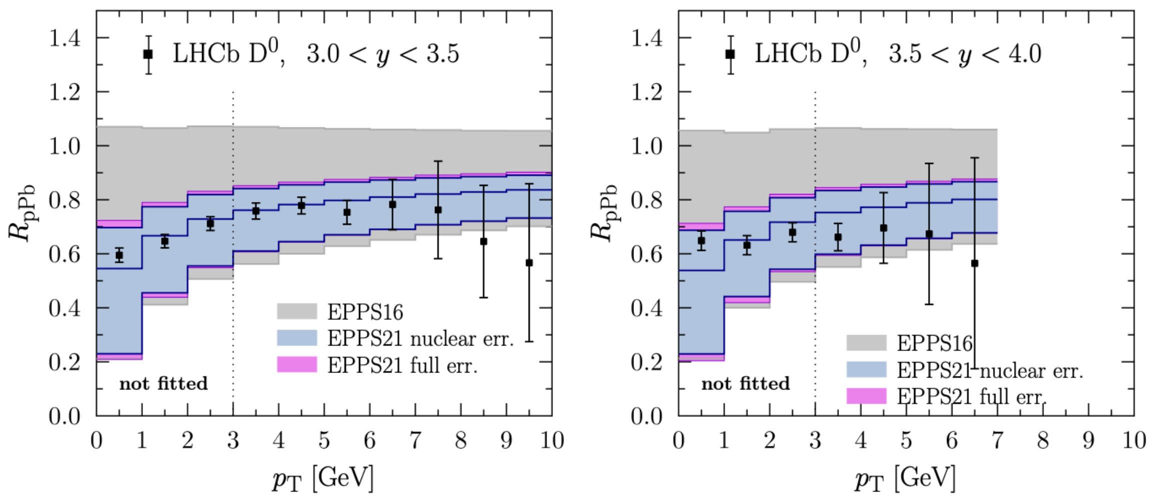


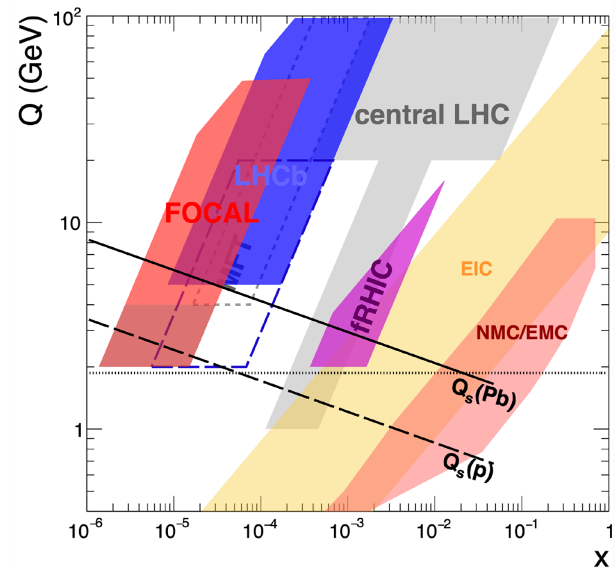
- Diffractive processes most sensitive to the underlying gluon distribution: $F^{diff} \propto k_{T,g}^2$

- Double ratio sensitive to saturation and LTS
  - $\sigma_{diff}/\sigma_{tot}(\mathrm{eAu} > \mathrm{ep})$: saturation
  - $\sigma_{diff}/\sigma_{tot}(\mathrm{ep} > \mathrm{eAu})$: LTS

Back up

EPPS21: LHCb data





EPPS 21 used LHCb D meson data with $p_T > 3$ GeV, the region where saturation is not completely excluded.

IS vs FS shower

Very small change at the the away-side peak by turning on FS.

The effect from IS is much stronger than FS.

Normalization issue

Experimental result:

$$R_{pA} = \frac{1}{\langle N_{\text{coll}} \rangle} \cdot \frac{d^2 N_{pA}/dp_T dy}{d^2 N_{pp}/dp_T dy}$$

- It is not the differential cross section ratio but the yields ratio.
- Experimental perspective: easy to deal with the systematics, e.g., detector effects, triggers, acceptance, etc. can be cancelled

But

- There is no total cross section provided for pA, the yields per event cannot be compared with theoretical calculations.
- Global analysis uses theoretical heavy-ion model instead of carefully simulating it with MC.