Low-x from di-hadron correlations in ep, eA and pp, pA collisions

Xiaoxuan Chu, BNL

CFNS Workshop, Stony Brook University, July 14-17th 2026

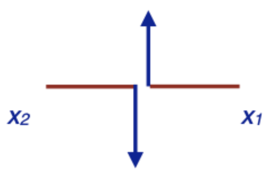
@BrookhavenLab

Date: 07/15/2026

Di-parton kinematics

Kinematics map from Marco van Leeuwen

Both outgoing partons at mid-rapidity



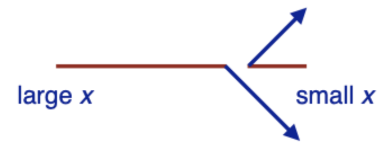
Both incoming partons at moderate x

$$\hat{s} = x_1 x_2 s \approx (2 p_T)^2$$

$$x_1 \approx x_2 \approx \frac{2 p_T}{\sqrt{s}}$$

Large x → q

Both outgoing partons at forward rapidity



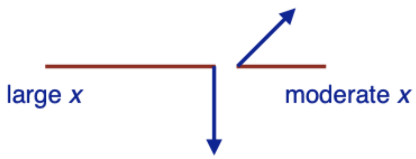
Boosted configuration:
One small-x, one large-x parton

$$\hat{s} = x_1 x_2 s \approx (2 p_T)^2$$

$$x_1 \approx \frac{p_T}{\sqrt{s}} e^{-y}$$

Smallest x → g

One parton forward, one closer to mid-rap



Large mass final state

$$Q^2 = \hat{s} > (2 p_T)^2$$

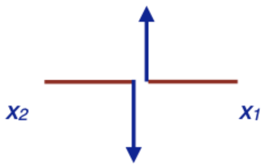
small probability

Moderate x

Di-parton kinematics

Kinematics map from Marco van Leeuwen

Both outgoing partons at mid-rapidity



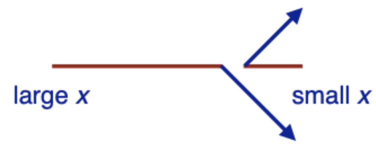
Both incoming partons at moderate x

$$\hat{s} = x_1 x_2 s \approx (2 p_{\mathrm{T}})^2$$

$$x_1 \approx x_2 \approx \frac{2 p_T}{\sqrt{s}}$$

Large x → q

Both outgoing partons at forward rapidity



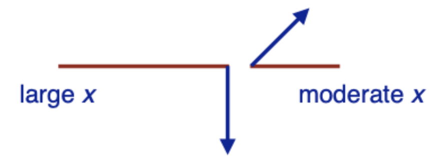
Boosted configuration:
One small-x, one large-x parton

$$\hat{s} = x_1 x_2 s \approx (2 p_{\mathrm{T}})^2$$

$$x_1 \approx \frac{p_T}{\sqrt{s}} e^{-y}$$

Smallest x → g

One parton forward, one closer to mid-rap



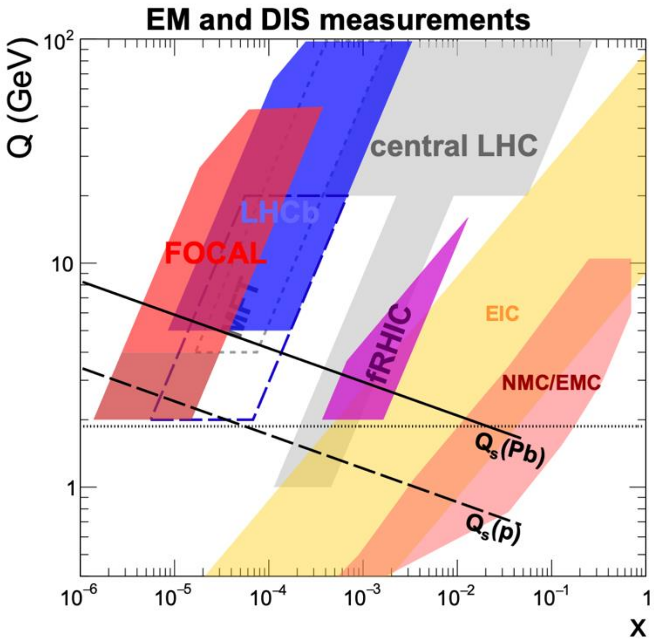
Large mass final state

$$Q^2 = \hat{s} > (2 p_{\mathrm{T}})^2$$

small probability

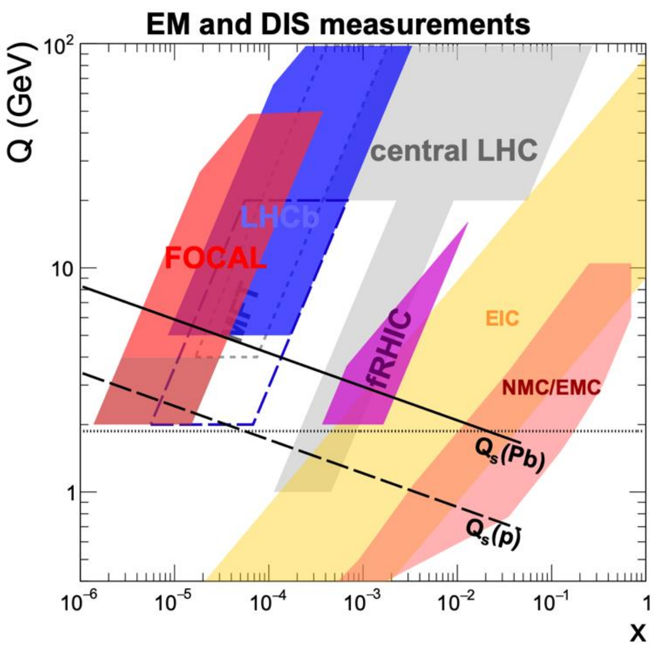
Moderate x

Saturation with di-hadron correlation

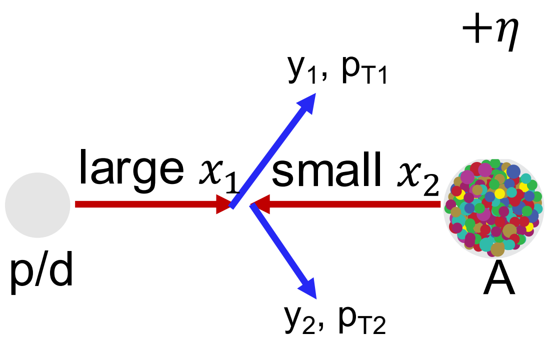


Gluon saturation: $Q^2 < Q_s^2$

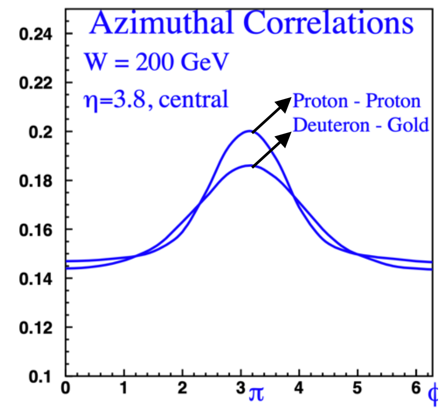
Saturation with di-hadron correlation



Gluon saturation: $Q^2 < Q_s^2$



NPA 748, 627 (2005)

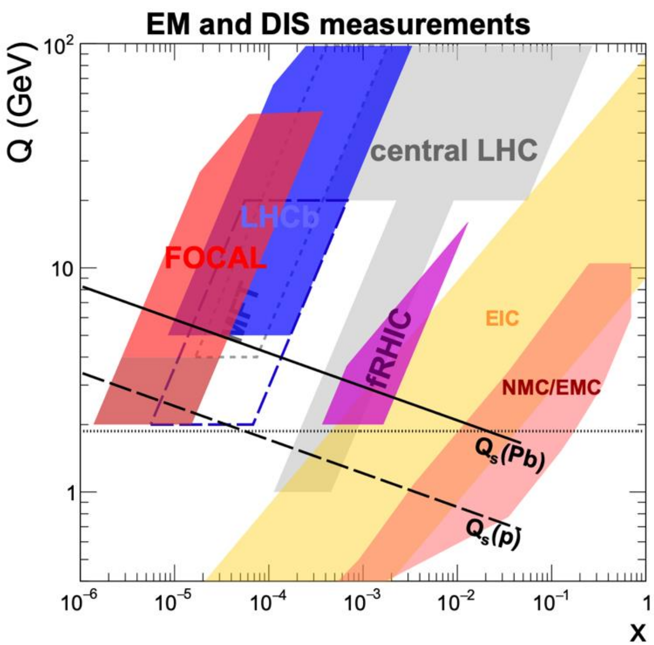


$$C(\Delta\phi) = \frac{N_{pair}(\Delta\phi)}{N_{trig} \times \phi_{bin}}$$

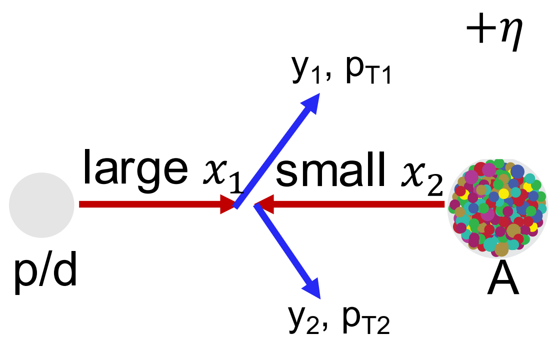
Saturation signature:

- Suppression
- Broadening

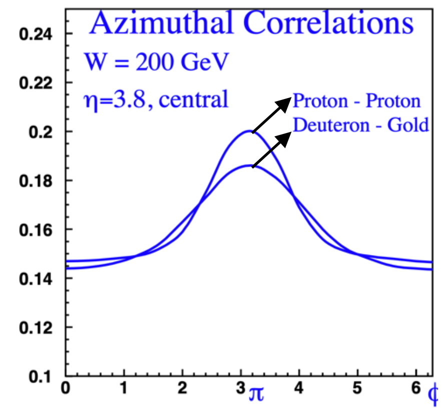
Saturation with di-hadron correlation



Gluon saturation: $\boldsymbol{Q^2} < \boldsymbol{Q_s^2}$



NPA 748, 627 (2005)

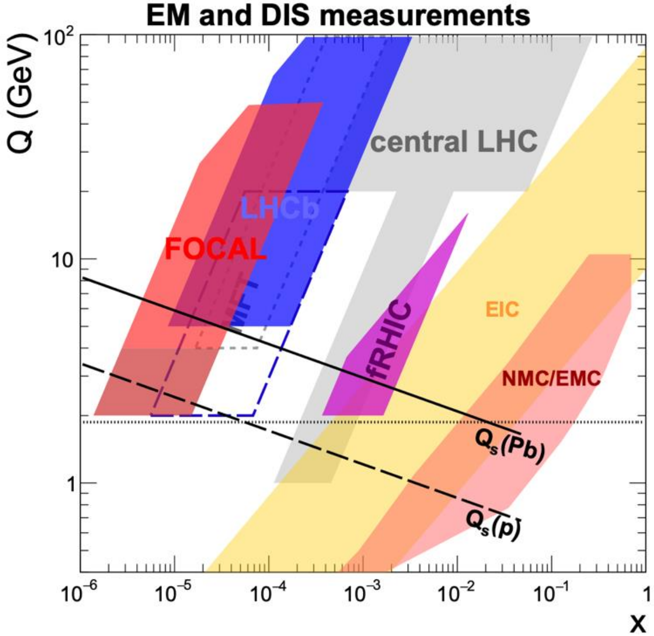


$$Q_s \propto A^{\frac{1}{3}} \cdot x^{-\lambda} \cdot \frac{1}{b}, \ x_2 \sim \frac{p_{T1}e^{-y_1} + p_{T2}e^{-y_2}}{\sqrt{s}}$$

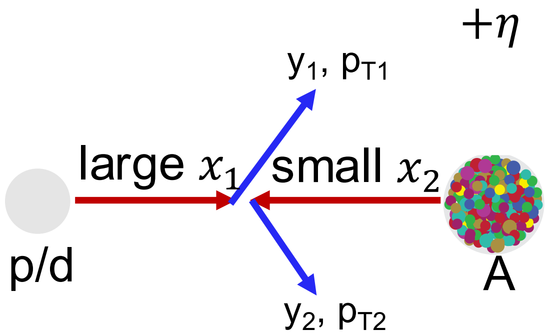
- Large A
- Small x: forward product and low p_T
- Small b: central collisions

$Q \propto \frac{p_{T1}+p_{T2}}{2}$, small Q: low p_T

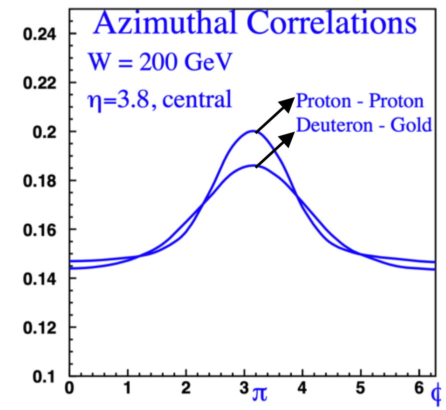
Saturation with di-hadron correlation



Gluon saturation: $\boldsymbol{Q^2} < \boldsymbol{Q_s^2}$



NPA 748, 627 (2005)



$$Q_s \propto A^{\frac{1}{3}} \cdot x^{-\lambda} \cdot \frac{1}{b}, \; x_2 \sim \frac{p_{T1}e^{-y_1} + p_{T2}e^{-y_2}}{\sqrt{s}}$$

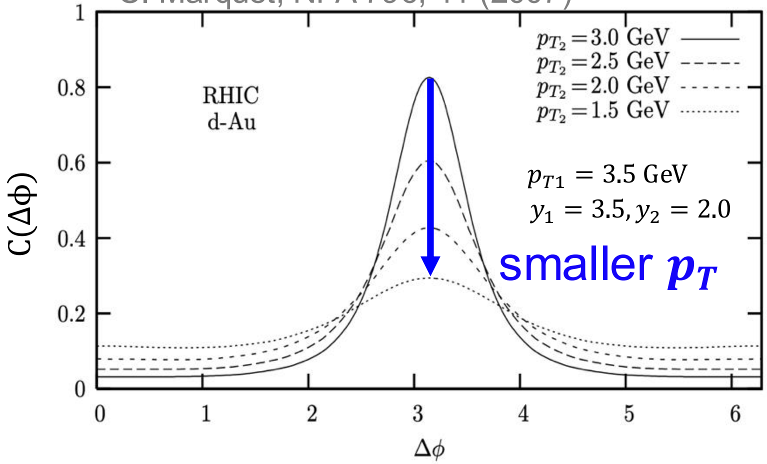
- Large A
- Small x: forward product and low p_T
- Small b: central collisions

$Q \propto \frac{p_{T1}+p_{T2}}{2}$, small Q: low p_T

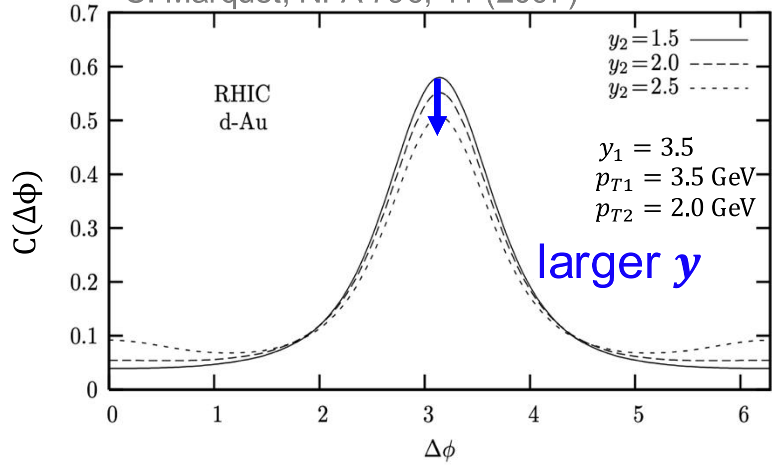
Scan Q^2, x, and Q_s by varying p_T, y, b, and A

Saturation with di-hadron correlation

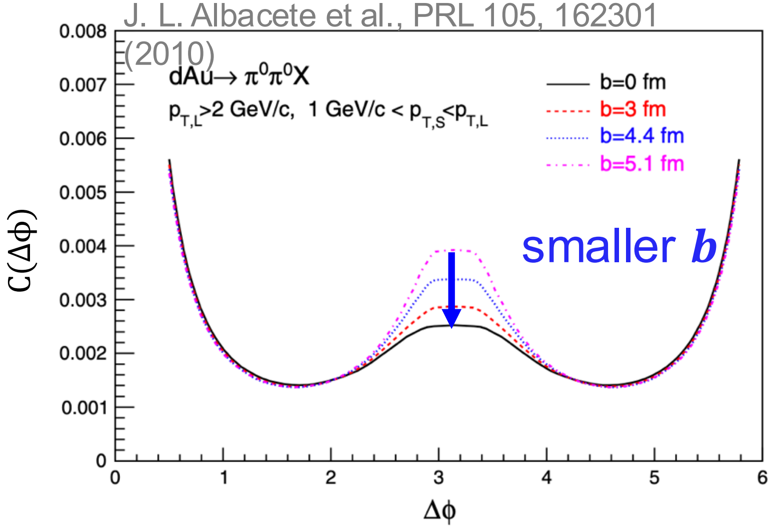
C. Marquet, NPA 796, 41 (2007)



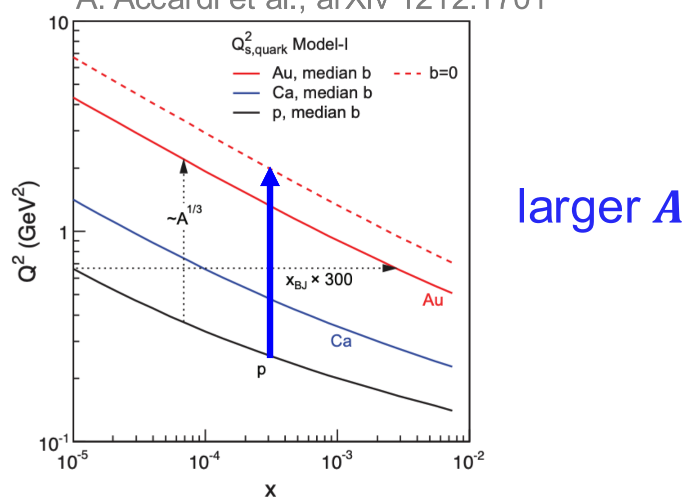
C. Marquet, NPA 796, 41 (2007)



J. L. Albacete et al., PRL 105, 162301 (2010)

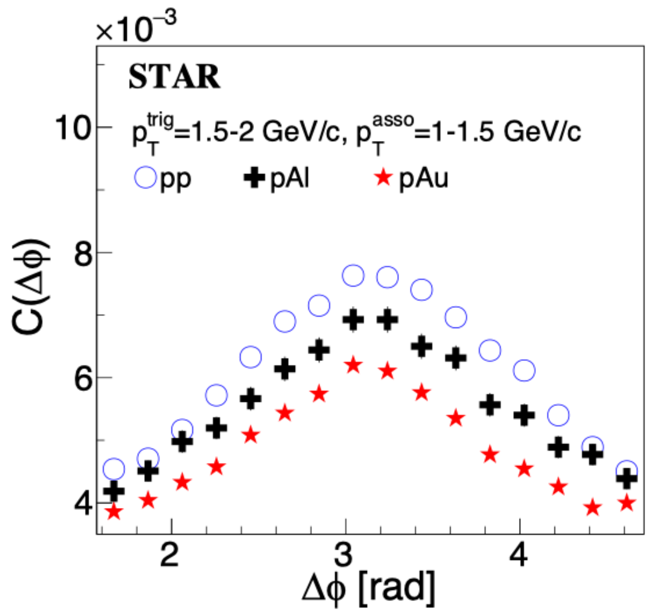


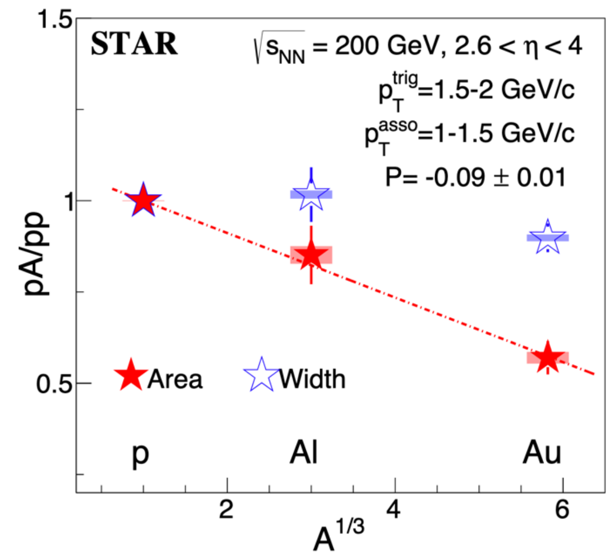
A. Accardi et al., arXiv 1212.1701



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

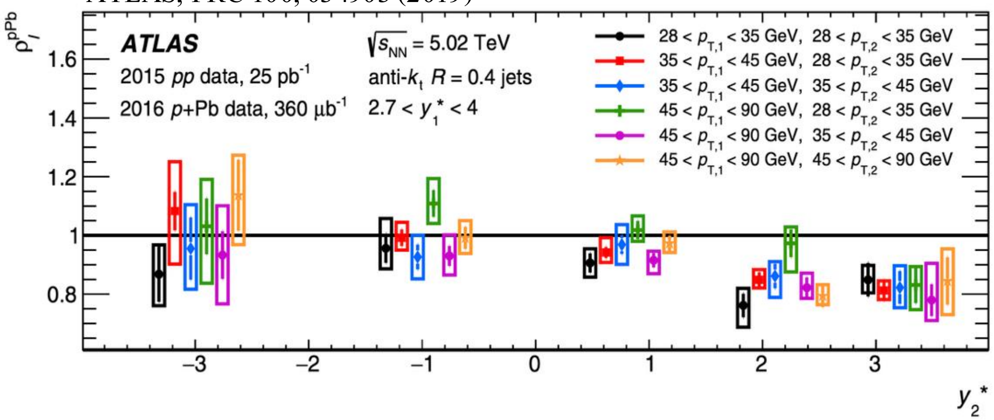
Relative area = $\frac{Area\ in\ p+A}{Area\ in\ p+p} < 1$

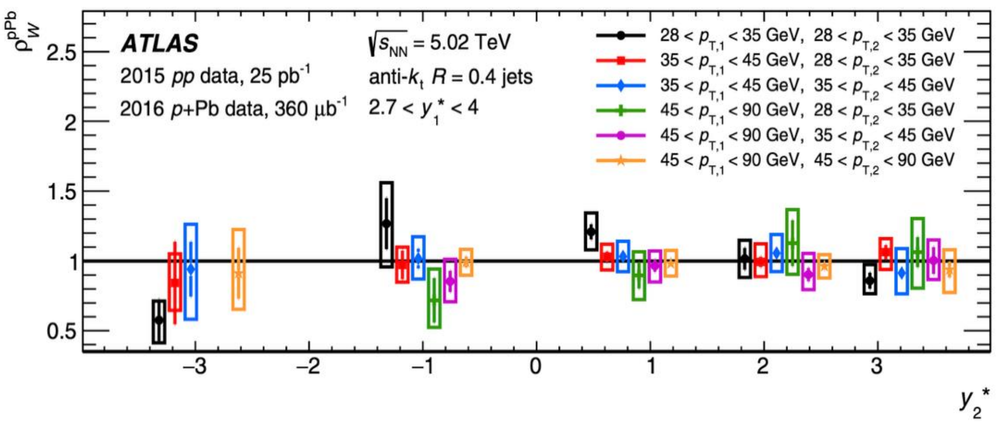
Predicted suppression is observed

Relative width ~ 1
Predicted broadening is not observed – why?

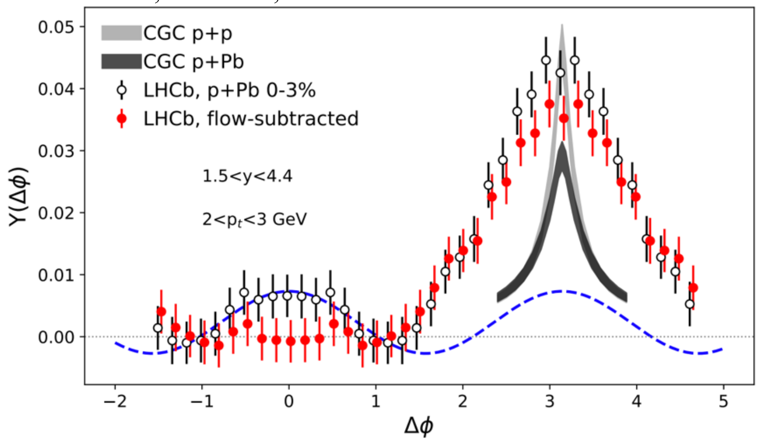
LHC pp and pPb data

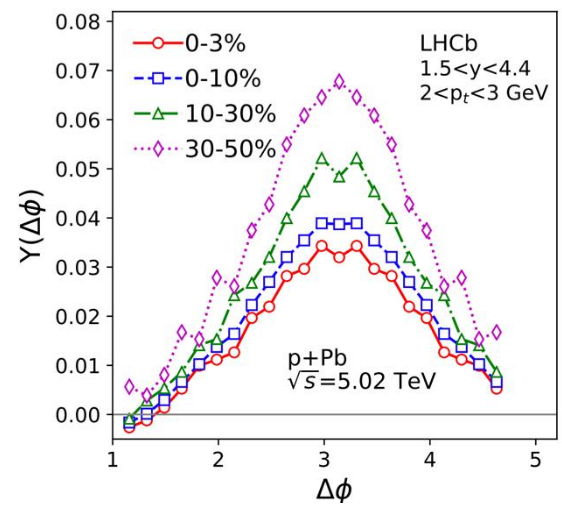
ATLAS, PRC 100, 034903 (2019)





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:

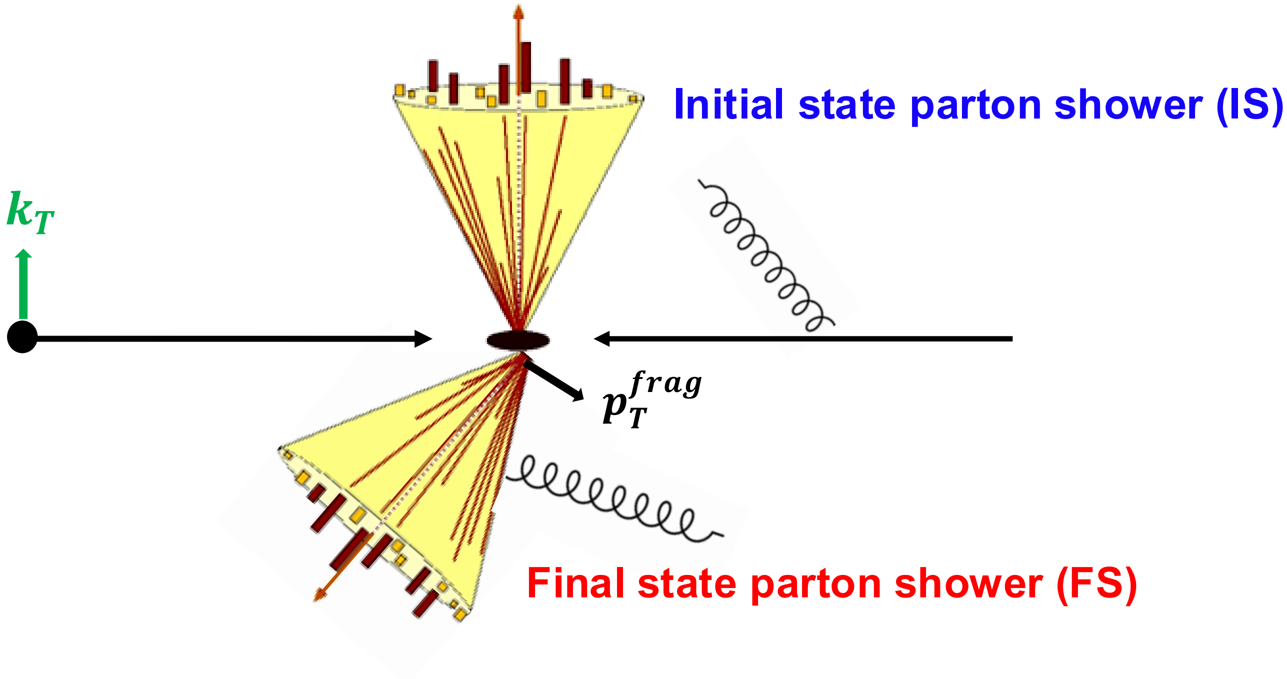
- Remains the same in p+p and p+Pb

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

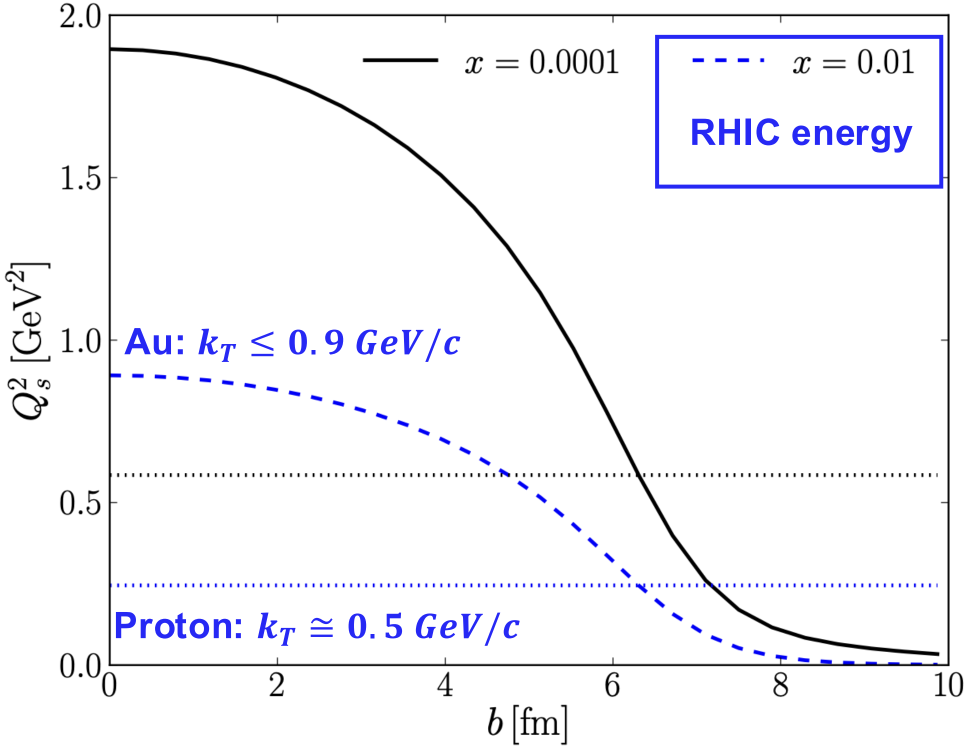
Factors can cause the broadening:



- 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

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

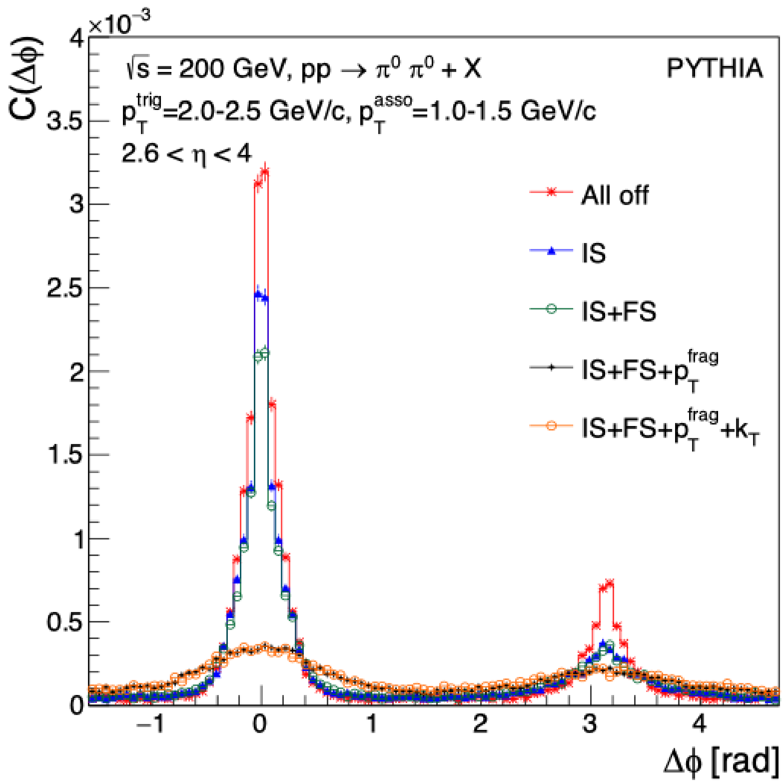


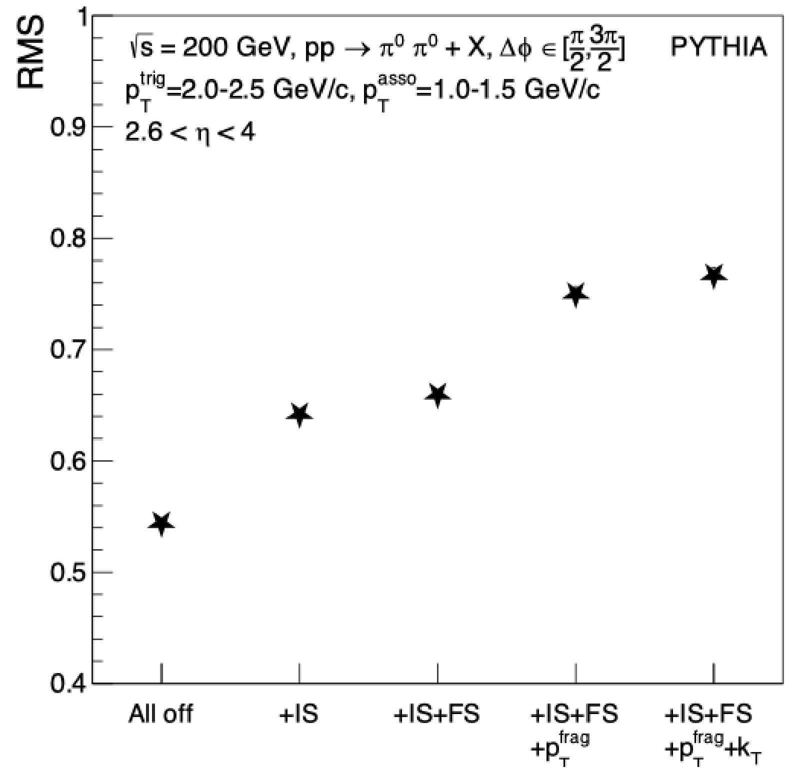
Saturation implemented in simulation by parameterizing intrinsic $Q_S \sim k_T$:

At RHIC energy,
for proton: $k_T \cong 0.5\ GeV/c$;
for Au: $k_T \sim 1\ GeV/c$

K. Cassar et al., PRD 112, 034034 (2025)

Broadening in simulation for pp, pA



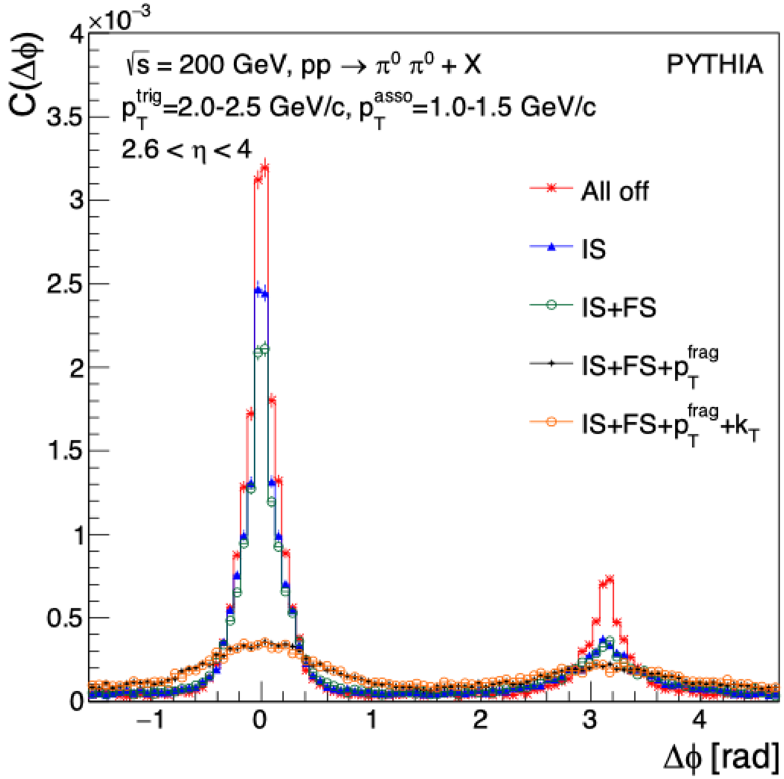


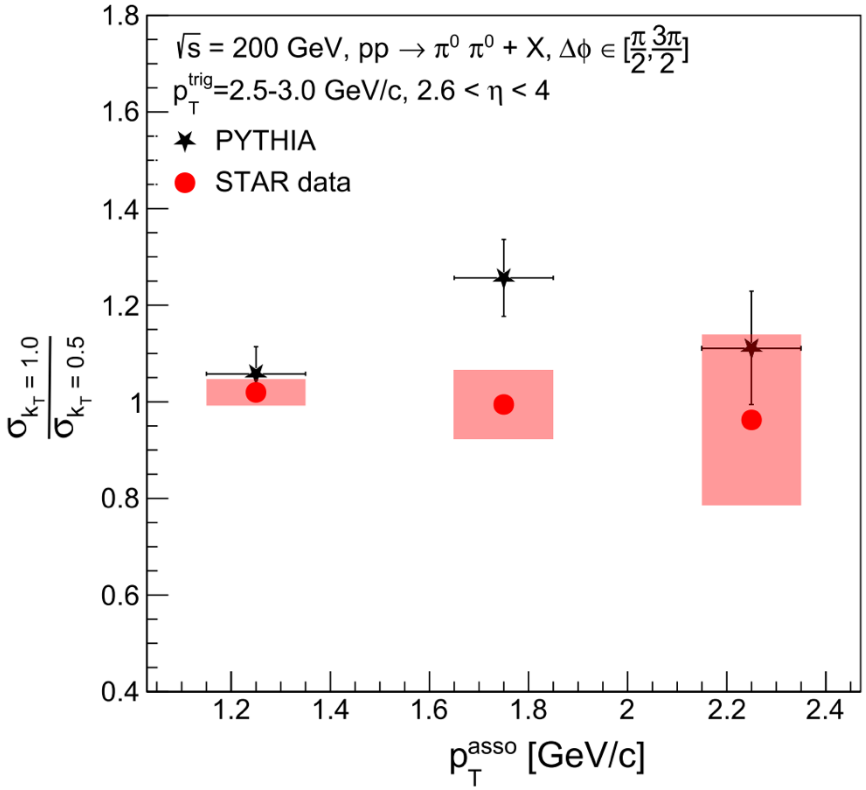
RMS @ $(\Delta\phi = \pi)$
due to sharp peak at all off

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

K. Cassar et al., PRD 112, 034034 (2025)

Broadening in simulation for pp, pA

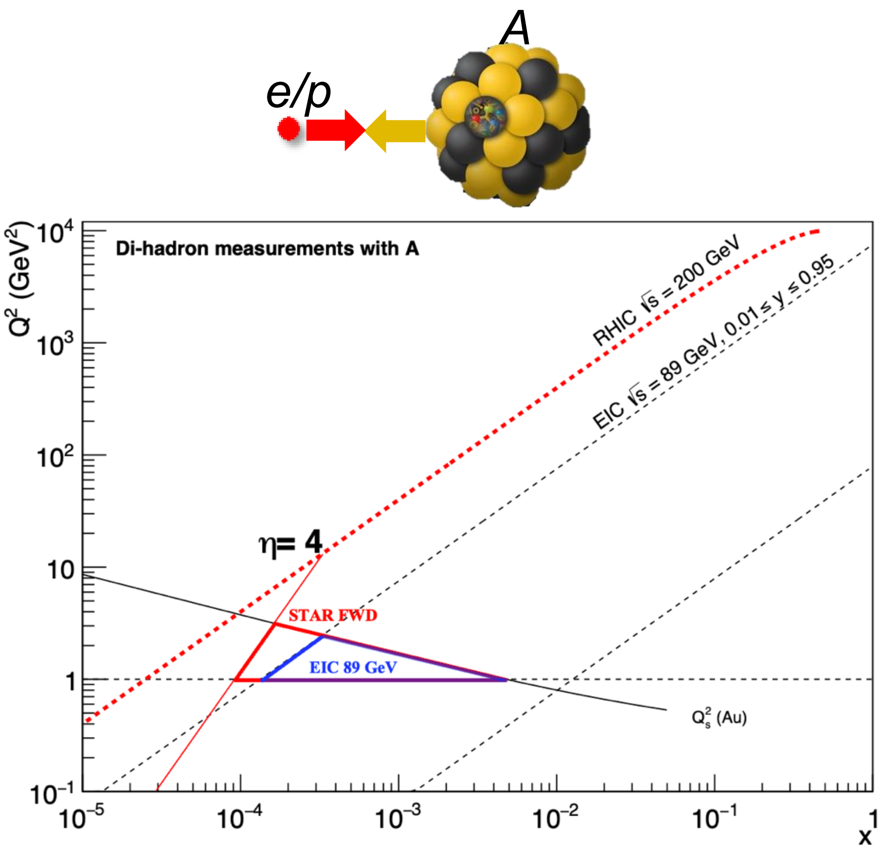




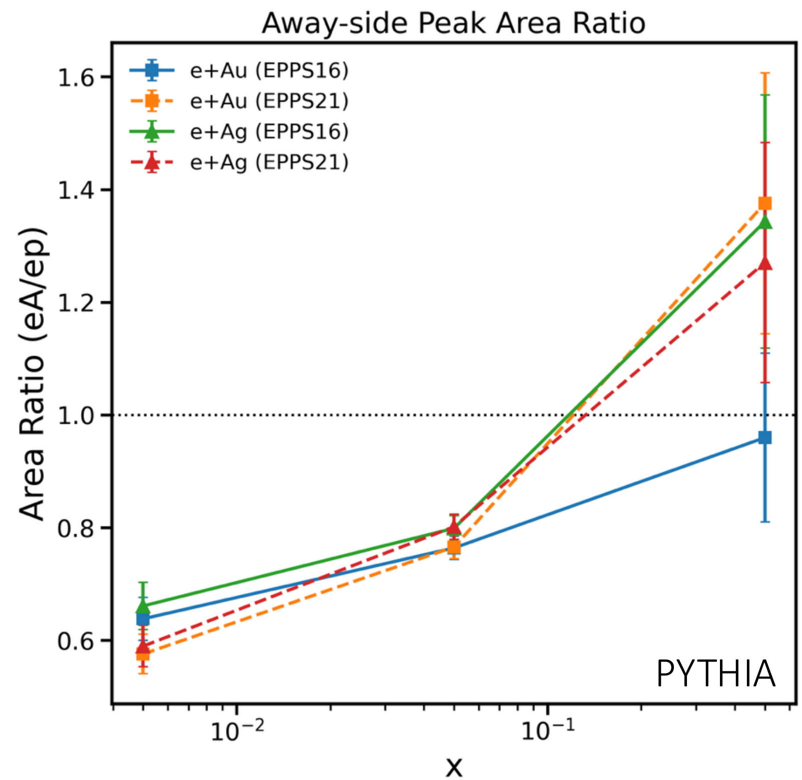
RMS @ ($\Delta\phi = \pi$)
due to sharp peak at all off

Simulation describes data well

Universality between pA and eA



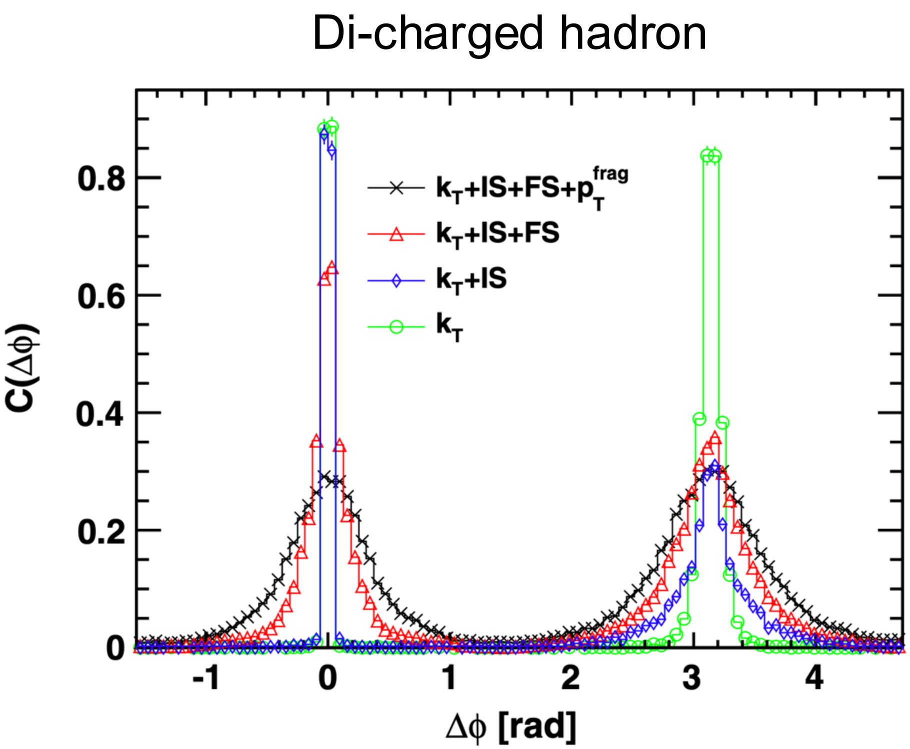
G. Garcia's talk, this morning



Test universality of gluon saturation by different probes:

- Clear away-side suppression in e+A compared to e+p; Suppression stronger for heavier nuclei
- Qualitative agreement with STAR p+A results

Broadening in simulation at the EIC

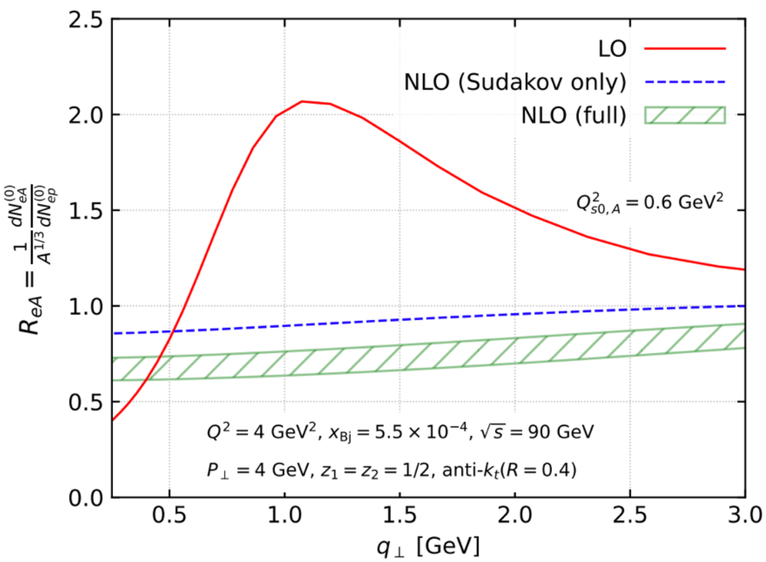


	Near-side $\Delta\phi$ RMS	Away-side $\Delta\phi$ RMS
k_T	0.21	0.25
k_T + IS	0.30	0.72
k_T + IS + FS	0.65	0.81
k_T + IS + FS + p_T^{frag}	1.00	1.00

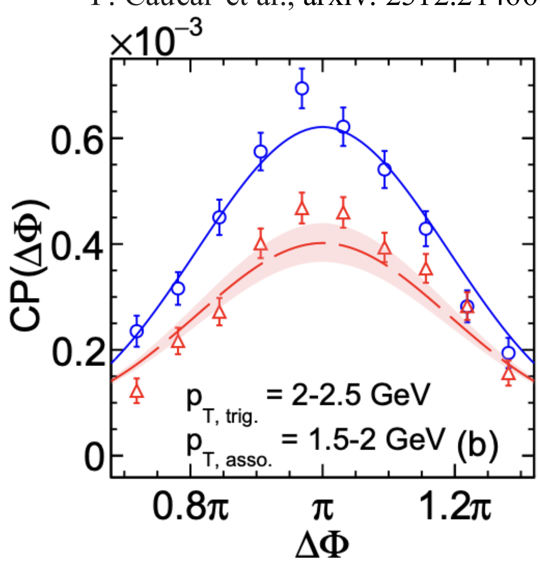
- Near side peak width mainly affected by final state parton shower and fragment p_T^{frag}
- Away side peak width dominated by initial state parton shower

Similar explanation from theory

P. Caucal et al., PRL 132, 081902 (2024)



P. Caucal et al., arxiv: 2512.21466



LO: saturation alone, broadening and suppression at small q_T

LO+Sudakov: saturation + Sudakov (initial + final state radiation), very little broadening and 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

Reasonable description of suppression

What we’ve learnt so far:

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

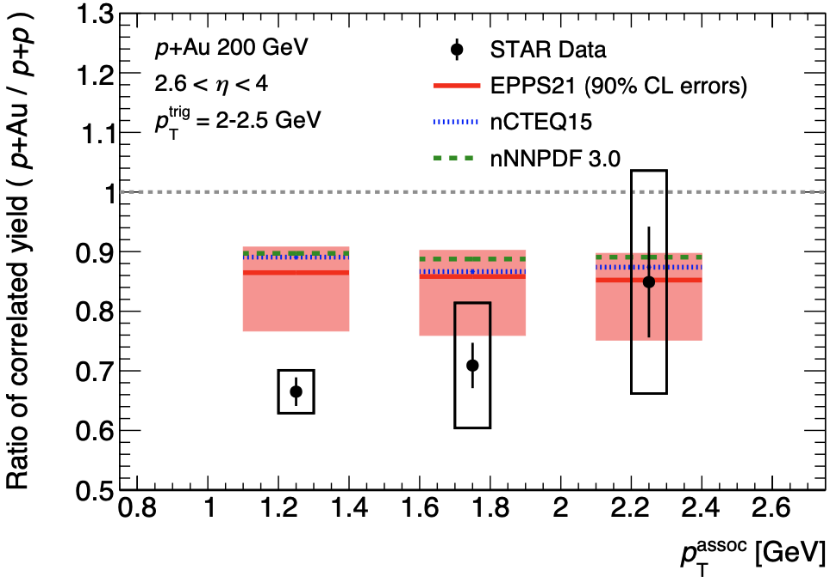
- If one wants to claim the discovery of gluon saturation, we need several observables that can only be interpreted by non-linear effects

The EIC will provide possibilities in measuring more observables

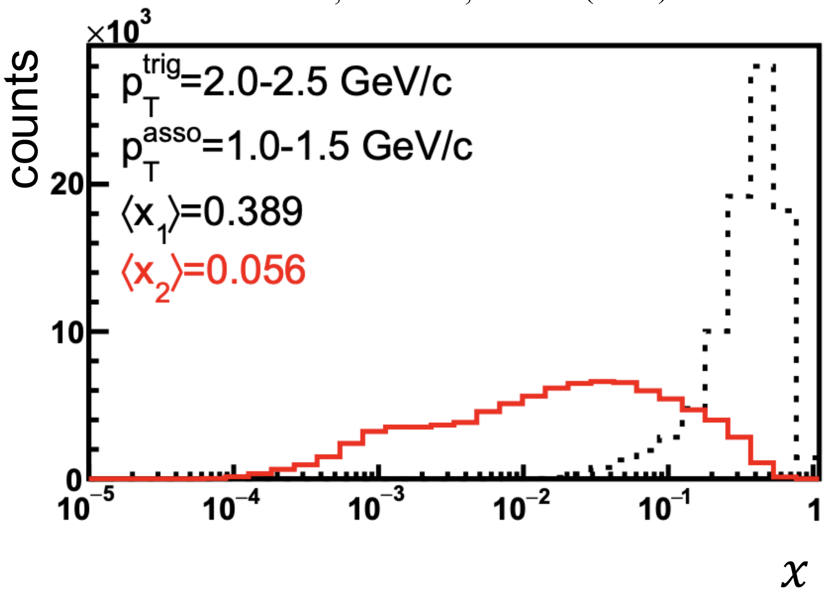
Other mechanisms: nPDFs

nPDF at small Q^2

D. Perepelitsa, PRC 111 (2025), 054901



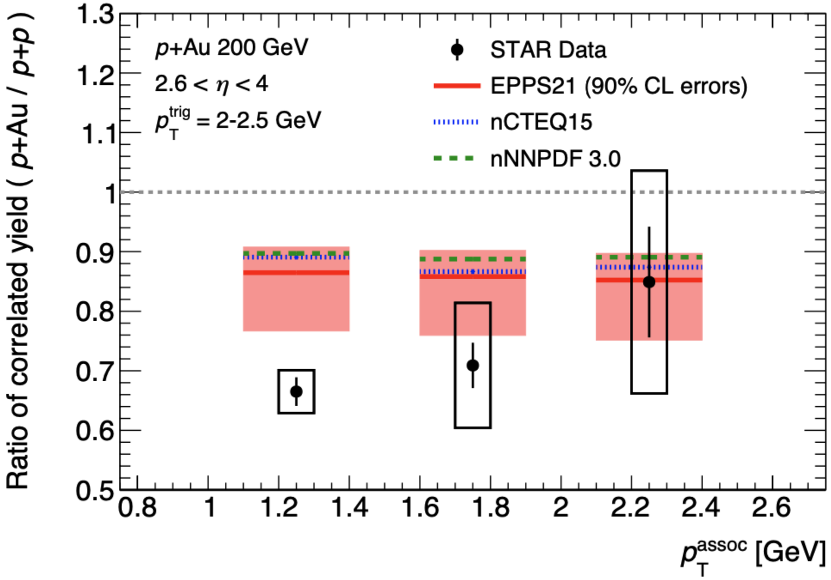
STAR, PRL 129, 092501 (2022)



- No p_T dependence, overshoot low p_T data
- For the lowest p_T bin: $\langle x_2 \rangle \sim 0.056$, $\langle Q^2 \rangle \sim 3$ GeV^2

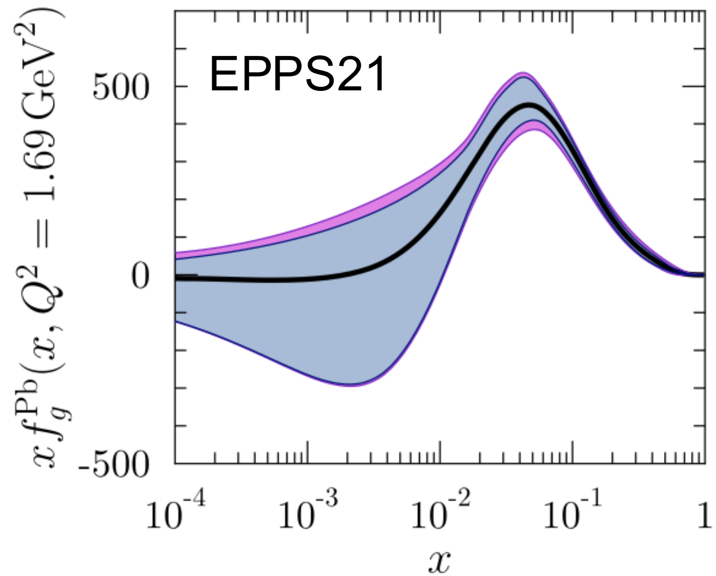
nPDF at small Q^2

D. Perepelitsa, PRC 111 (2025), 054901



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

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



- Gluon density is 0 with largely negative error

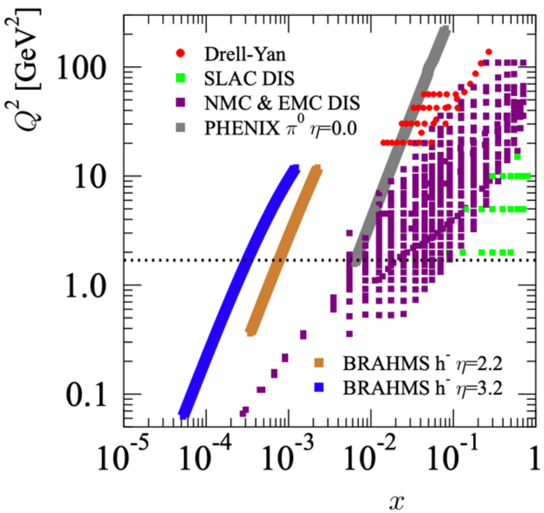
JHEP 04 (2009) 065

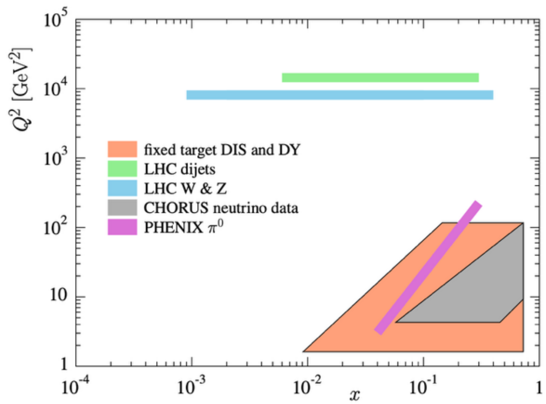
EPJC 77 (2017) 163

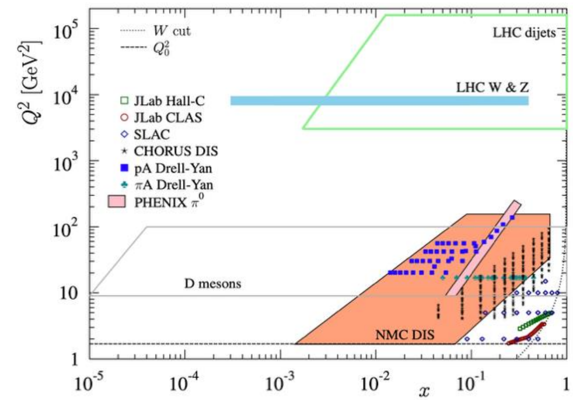
EPJC 82 (2022) 413

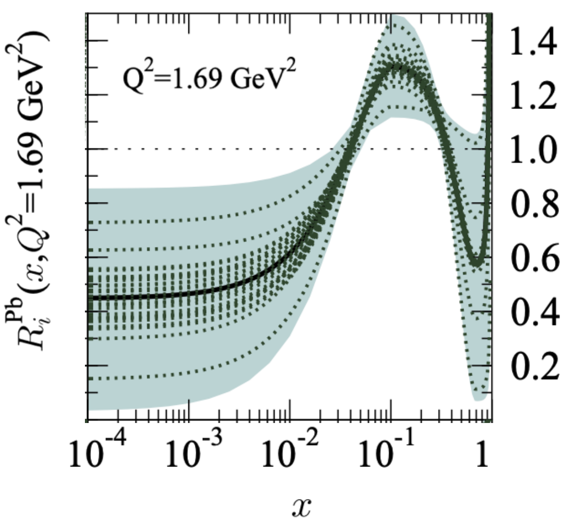
nPDF: EPPS

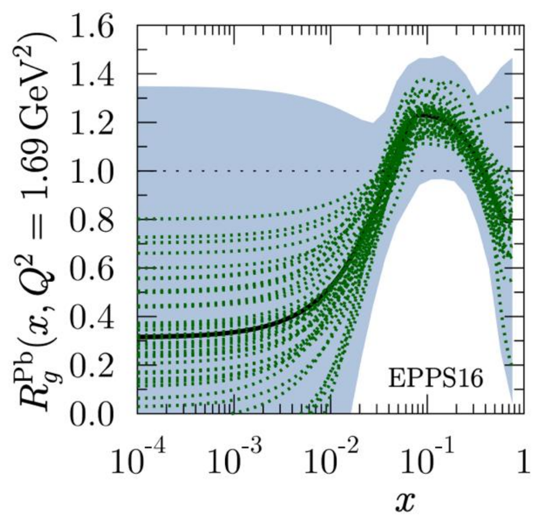
EPS09	EPPS16	EPPS21

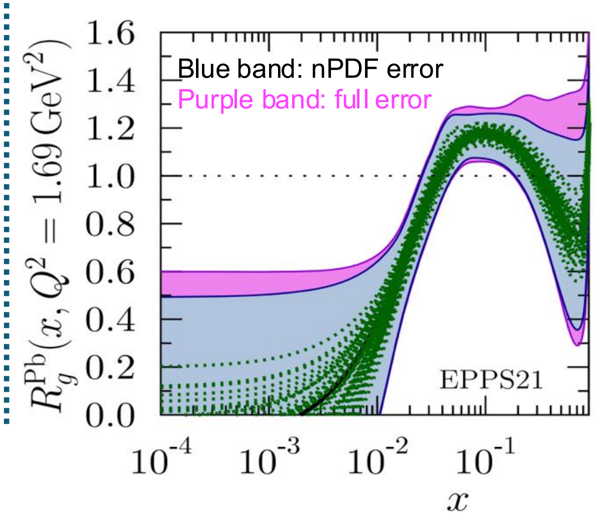






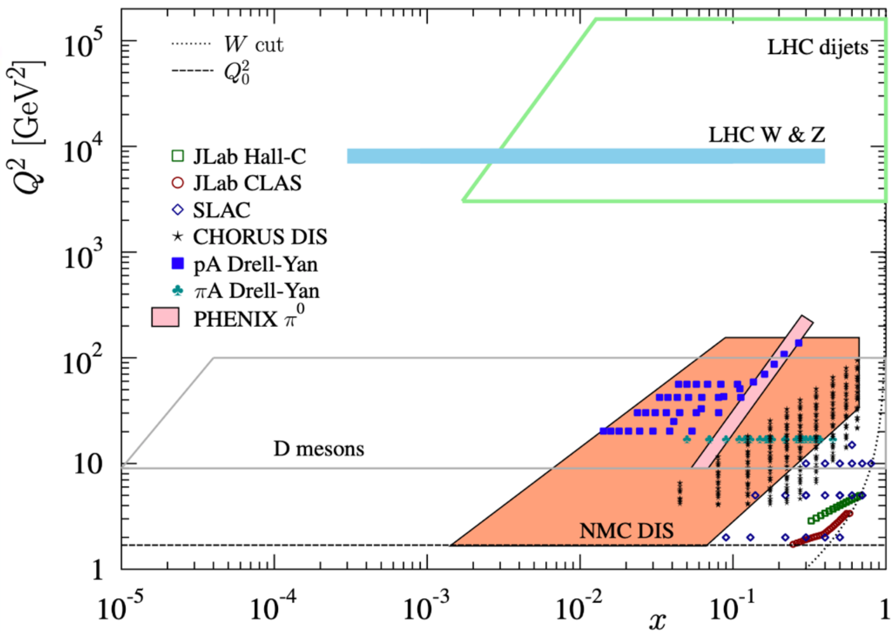




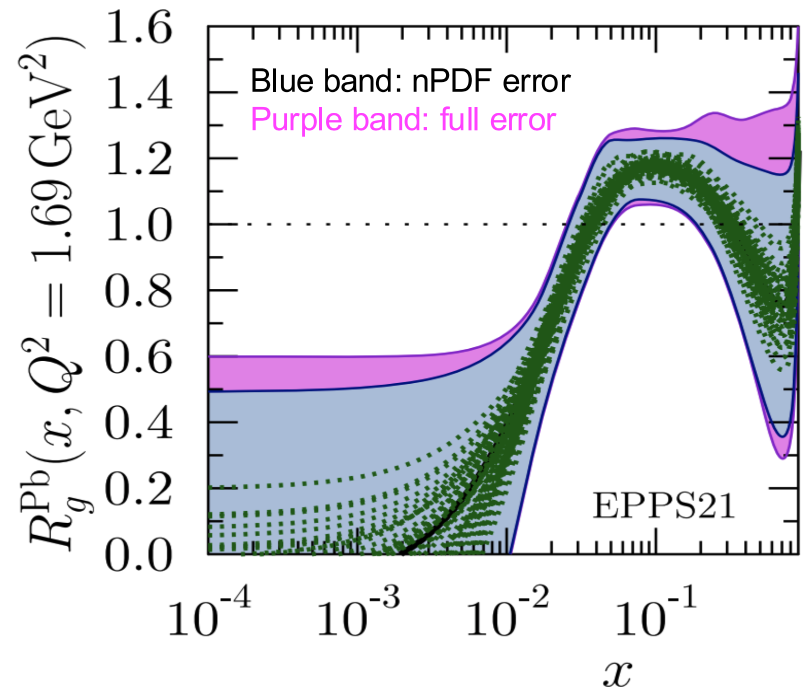


At small Q^2, gluon density eventually becomes 0, large impact from LHCb D

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

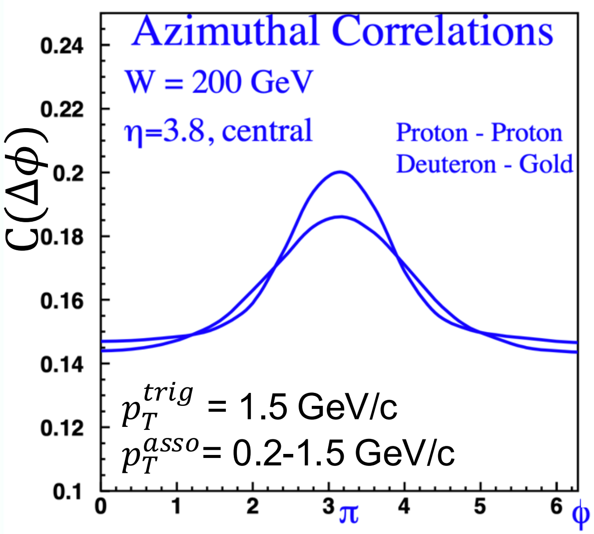
- Normalization: both experimentally and theoretically

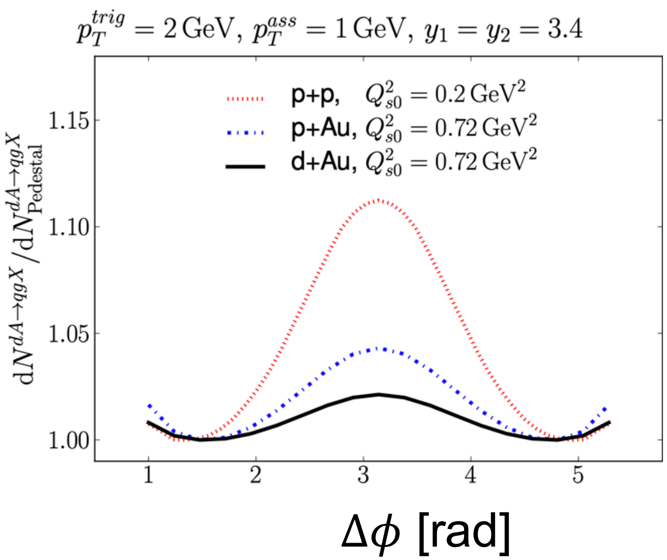
Examples of normalization

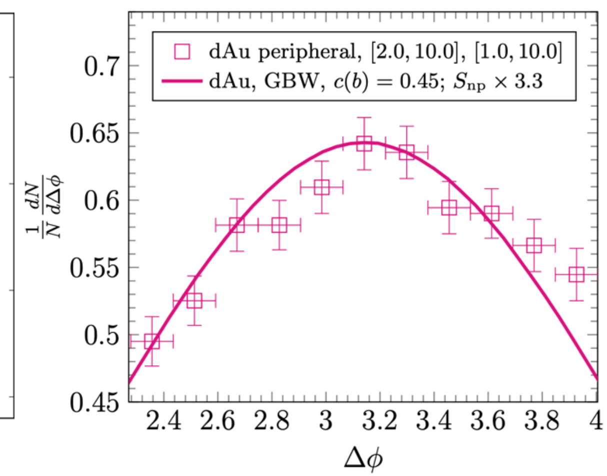
NPA 748, 627 (2005)

NPA 908 (2013) 51-72

PLB 784 (2018) 301-306







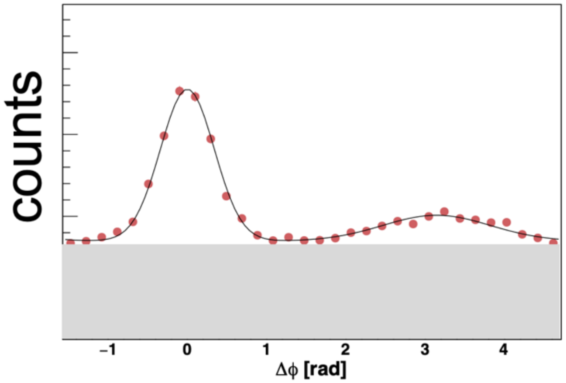
$$C(\Delta\phi) = \frac{N_{pair}(\Delta\phi)}{N_{trig} \times \phi_{bin}}$$

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

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

Summary in normalization

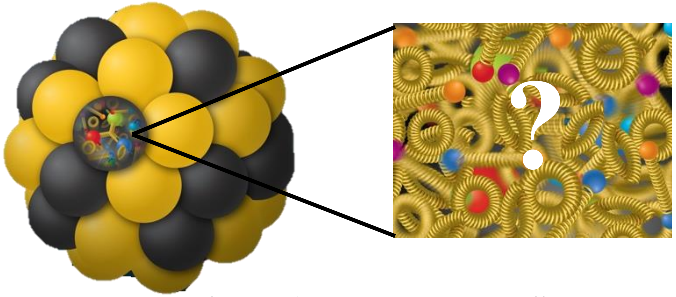
Experimental papers	Normalized by	Systems	Details
STAR	N_{trig}	p+p, p+Al, p+Au, d+Au	Compare area ratio
PHENIX	N_{trig}	p+p, d+Au	Compare area ratio×R_{dAu}
ATLAS and LHCb	N_{trig}	p+p, p+pb	Compare area ratio



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

Summary and outlook

Precision measurements are needed as CGC has entered NLO era.



gluon dynamics at small x

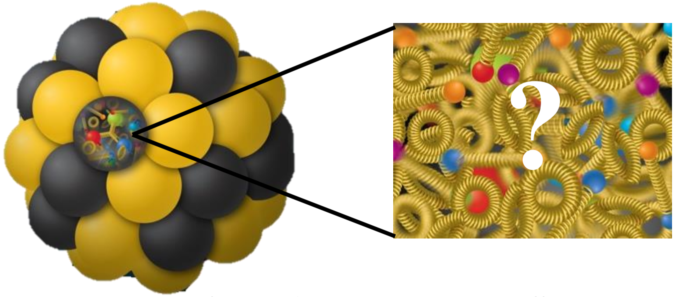
Efforts from our group:

PRD 89, 074037 (2014), First EIC simulation paper on saturation
PRD 96, 074035 (2017), Photoproduction channel at the EIC
PRD 101, 072003 (2020), Jets at the EIC
PRL 129, 092501 (2022), di-π^0 correlation on A dependence at STAR
PRD 112, 034034 (2025), di-π^0 correlation with NLO in pp simulation
Hard Probes (2026), R_{pA} for forward production at STAR
ePIC ESR (2026), di-$h^{\pm}$ correlation with NLO and charm for the EIC

In progress, Inclusive and jet measurements with NLO at the EIC

Summary and outlook

Precision measurements are needed as CGC has entered NLO era.



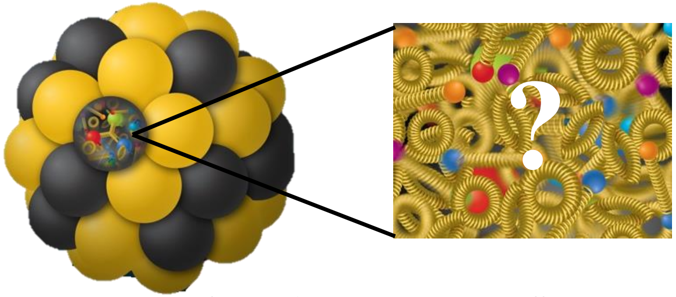
gluon dynamics at small x

What do we know about low-x in di-hadron correlations in ep, eA and pp, pA?

- Broader correlation in p+A predicted by CGC was not observed experimentally yet
  - NLO contributions are not negligible – they dilute the signal
  - nPDF interpretation needs to be verified – extraction touches sat. already?

Summary and outlook

Precision measurements are needed as CGC has entered NLO era.



gluon dynamics at small x

What do we know about low-x in di-hadron correlations in ep, eA and pp, pA?

- Broader correlation in p+A predicted by CGC was not observed experimentally yet
  - NLO contributions are not negligible – they dilute the signal
  - nPDF interpretation needs to be verified – extraction touches sat. already?
- Saturation shares the universal signatures in e+A compared to p+A in terms of suppression and (non)broadening
- Uniform normalization needed for clear interpretation between data and theory

Back up

Broadening in simulation for pp, pA

STAR tune simulation, no detector effect:

Event selection:

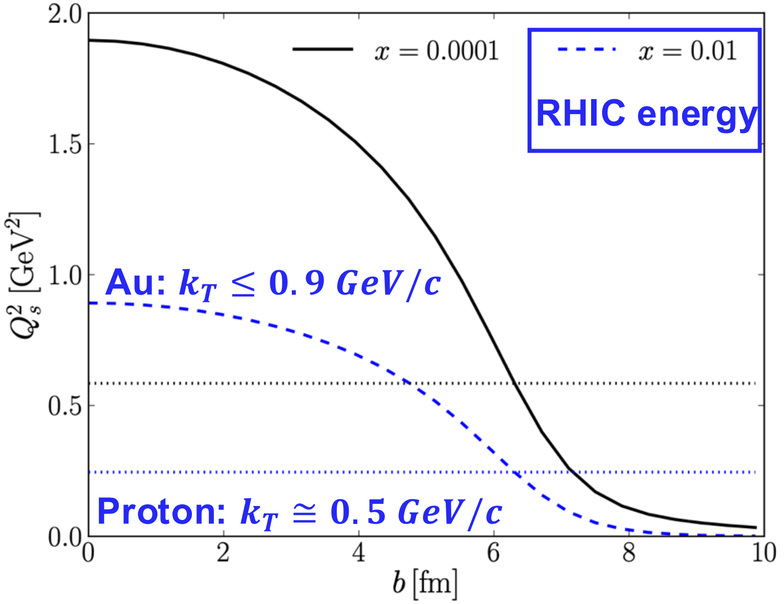
- Two π^0s produced in FMS rapidity acceptance (2.6<η<4.0)
- π^0 p_T> 1 GeV/c, which is FMS threshold

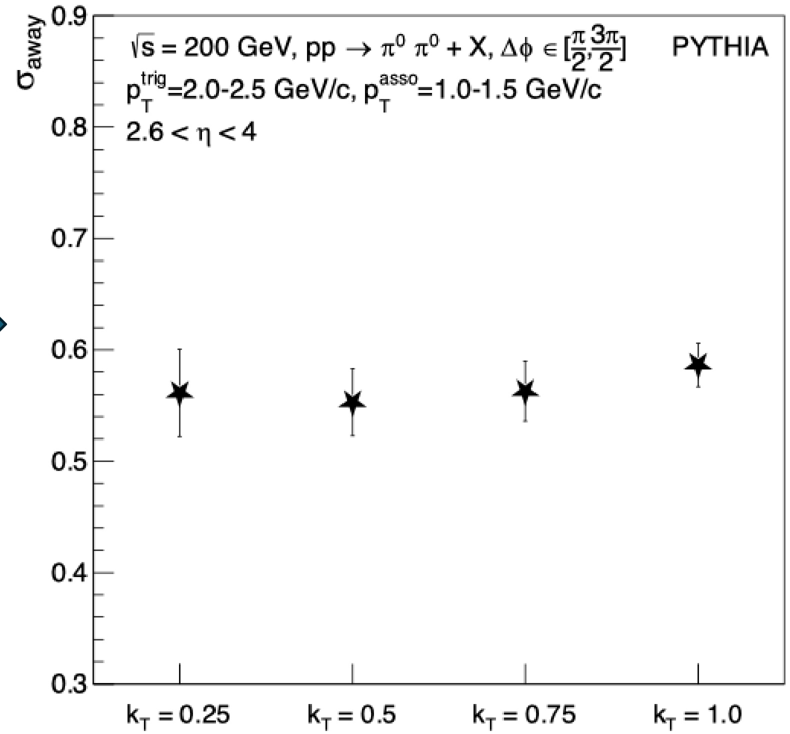
Method:

- 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

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

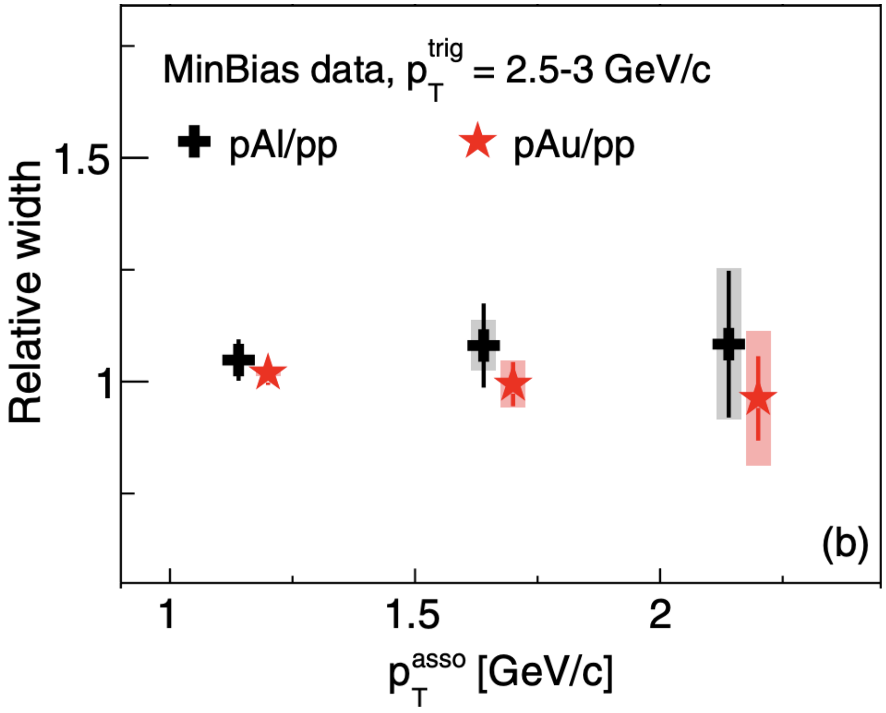




- Saturation implemented in simulation by parameterizing intrinsic $Q_S \sim k_T$: at RHIC energy, for proton: $k_T \sim 0.5\ GeV/c$; for Au: $k_T \sim 1\ GeV/c$
- With PS and p_T^{frag} turned on, away-side width stays unchanged by increasing k_T, broadening is not expected to occur in p+Au compared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

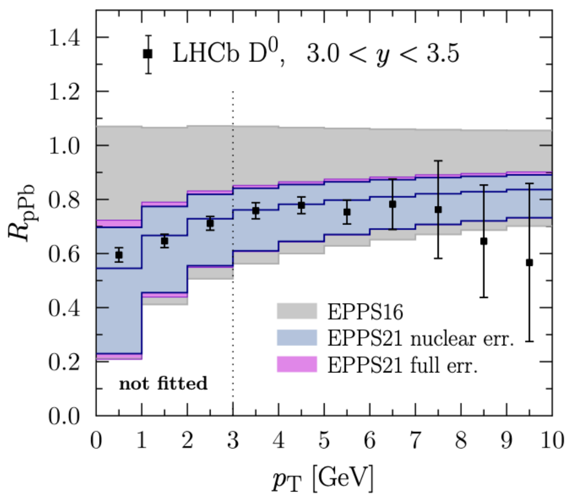
STAR pp and pA

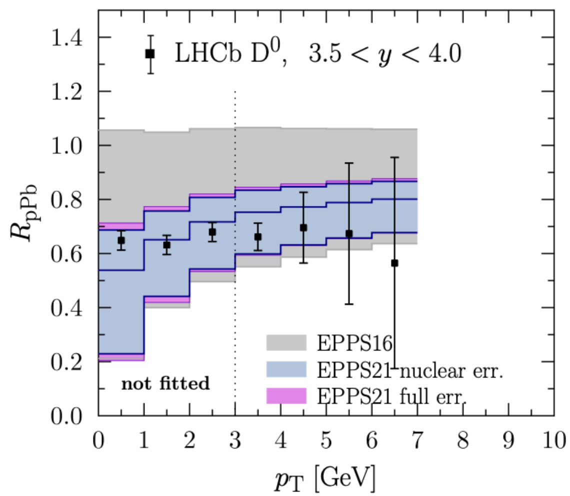
STAR, PRL 129, 092501 (2022)

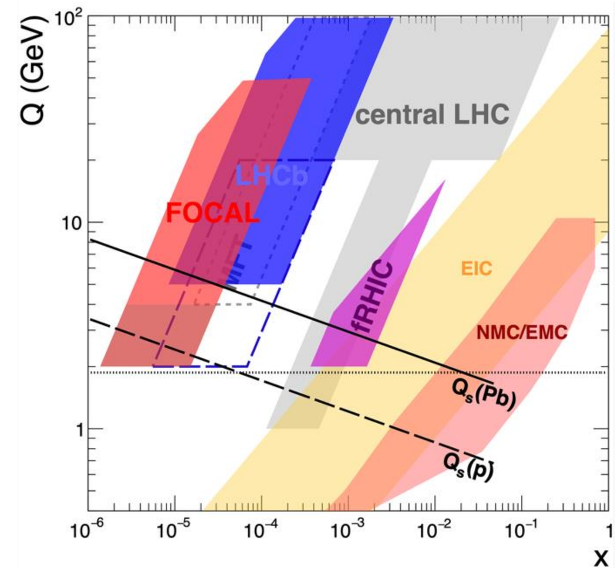


Width doesn’t change

EPPS21: LHCb data

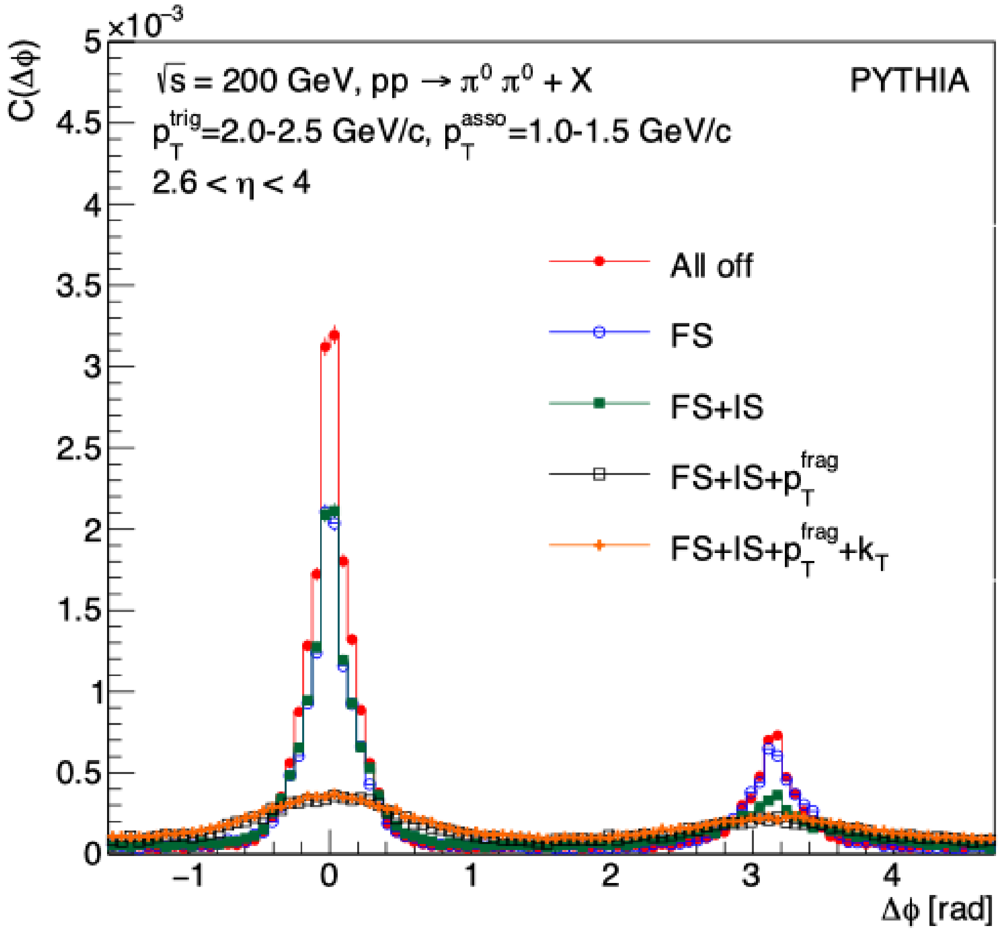






EPPS 21 used LHCb D meson data with $p_T > 3$ GeV, the region where saturation is not completely excluded.

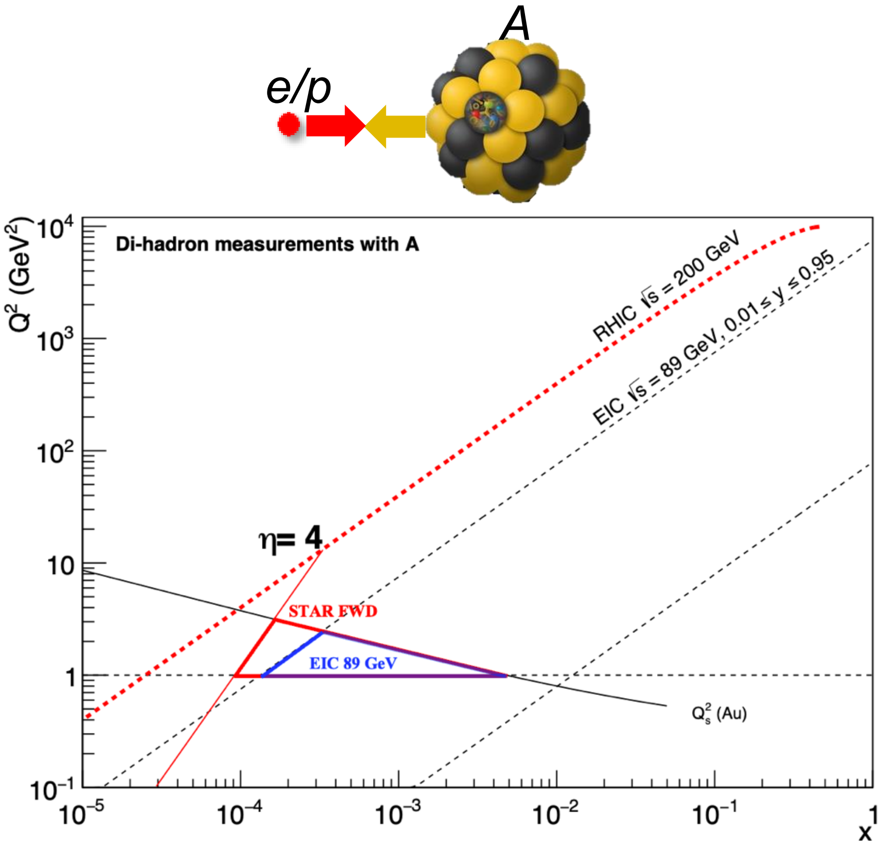
IS vs FS shower



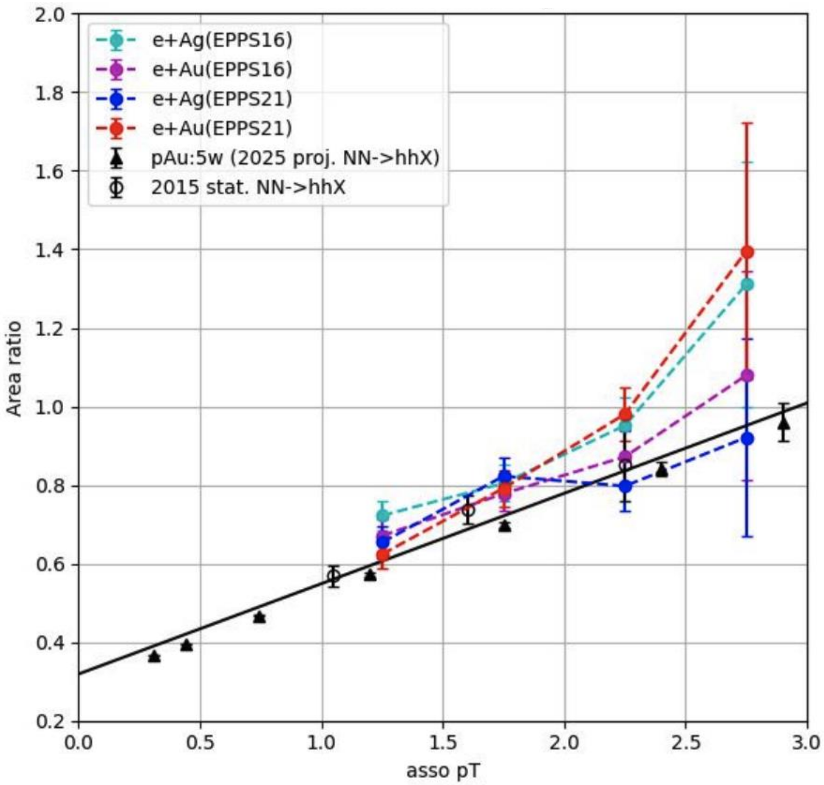
Very small change at the the away-side peak by turning on FS.

The effect from IS is much stronger than FS.

Universality between pA and eA



G. Gacia, 2nd EIC Readiness Workshop 2026



Test universality of gluon saturation by different probes:

- Clear away-side suppression in e+A compared to e+p; Suppression stronger for heavier nuclei
- Qualitative agreement with STAR p+A results

Normalization issue

Experimental result:

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

- 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

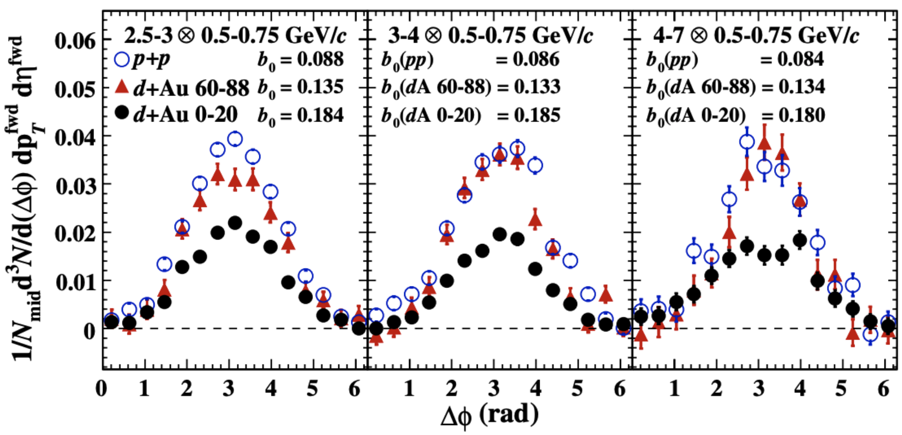
But

- 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.

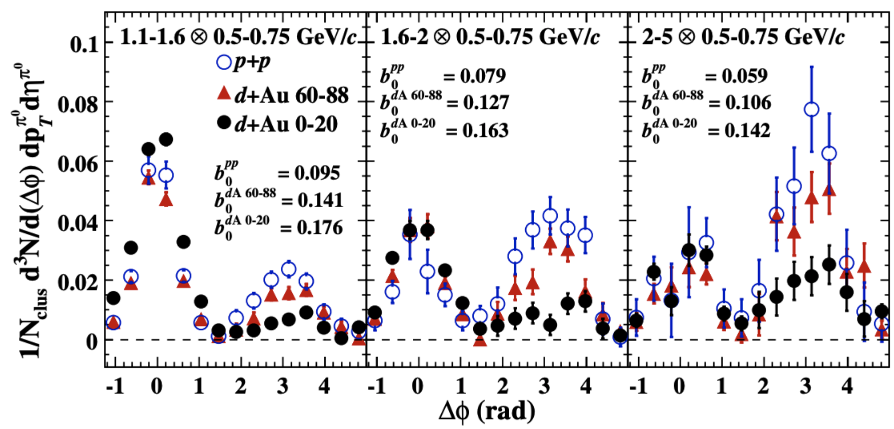
PHENIX, PRL 107, 172301 (2011)

PHENIX pp and dA data

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



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

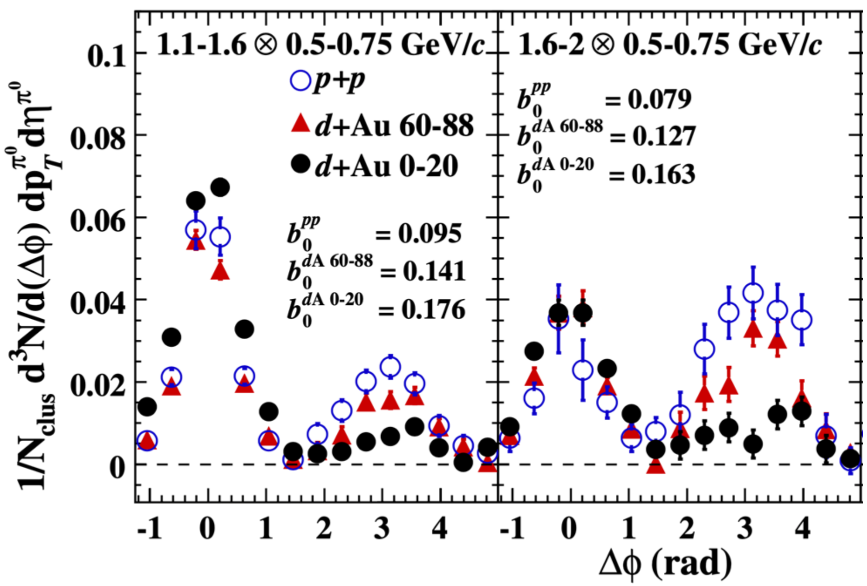


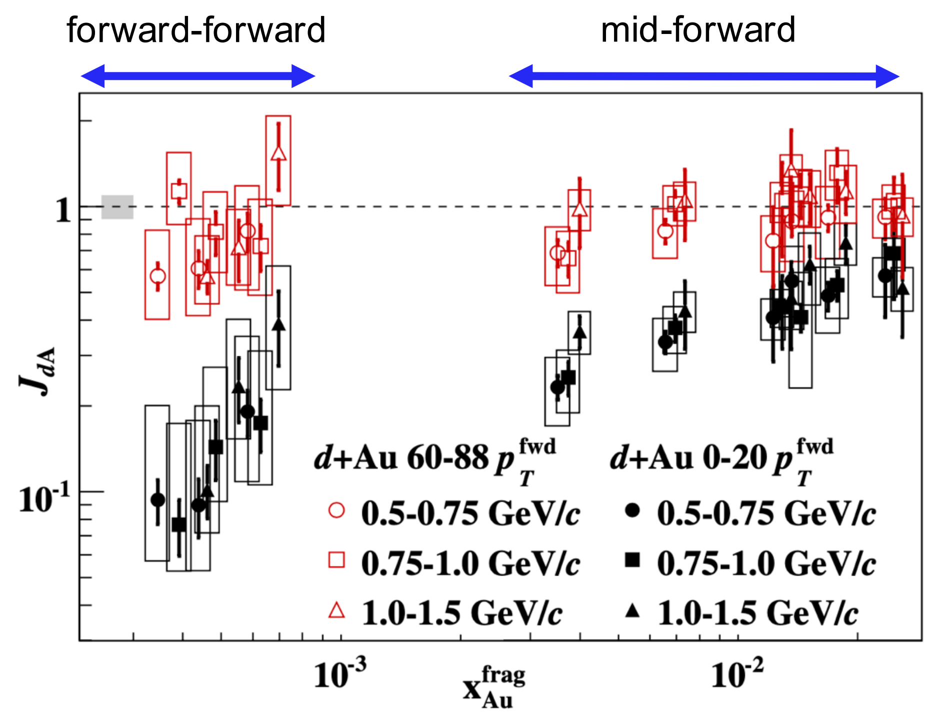
- Same method used to extract the area and width as STAR, with pedestal subtracted
- Suppression is observed in both cases
- Relative width ~ 1 for mid-forward correlation; high pedestal in dA compared to the baseline pp that possibly biases the width extraction, inconclusive for fwd-fwd correlation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

PHENIX, PRL 107, 172301 (2011)

PHENIX pp and dAu data

forward-forward: 3.0 < η < 3.8





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

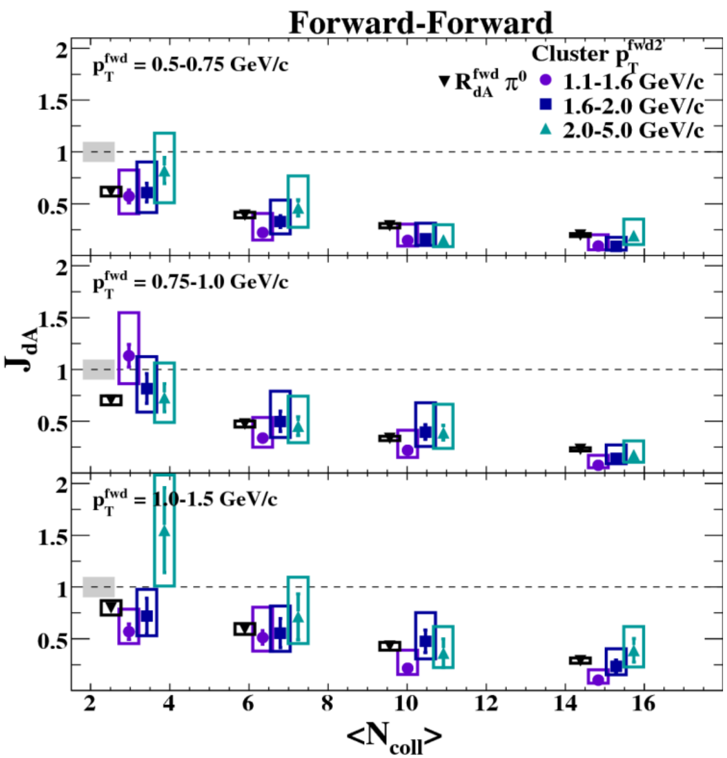
$$J_{dA} = R_{dAu} \times I_{dAu}$$

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

How to describe suppression?

PHENIX, PRL 107, 172301

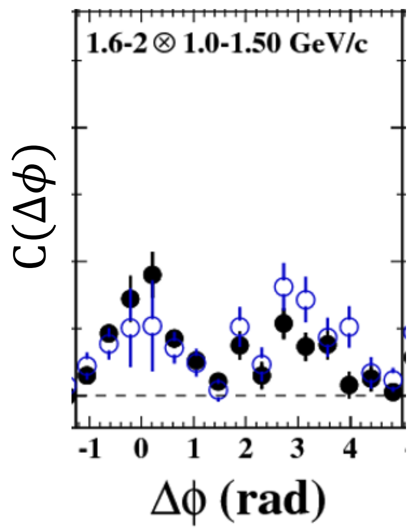
From the analysis note



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

I_{dA} = area ratio

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



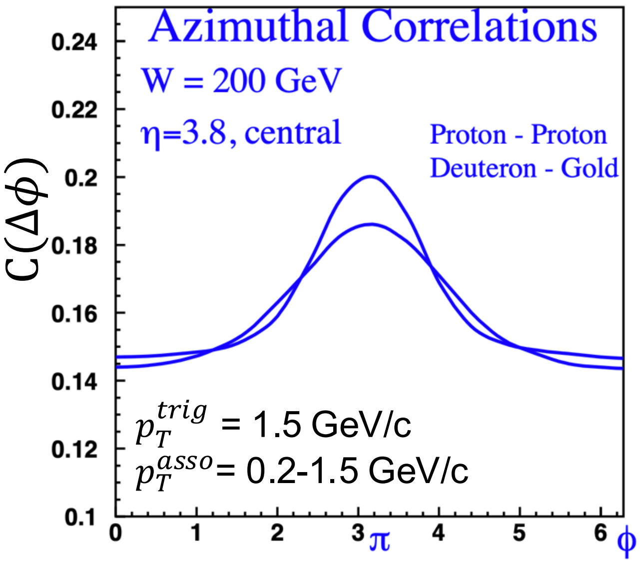
"$J_{dAu} \rightarrow 0.1$ that "10 times suppression observed in central dAu" should be clarified

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)

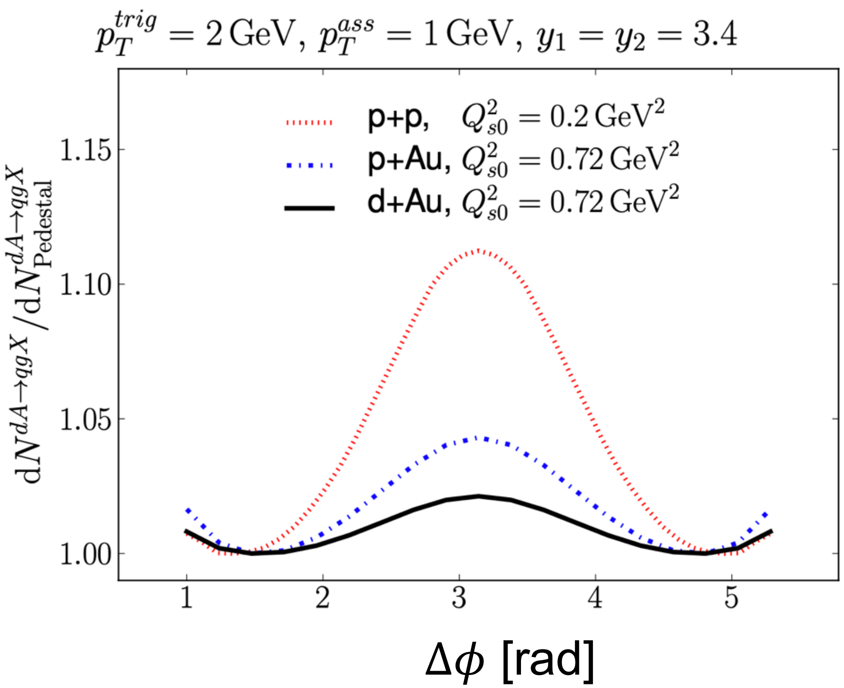


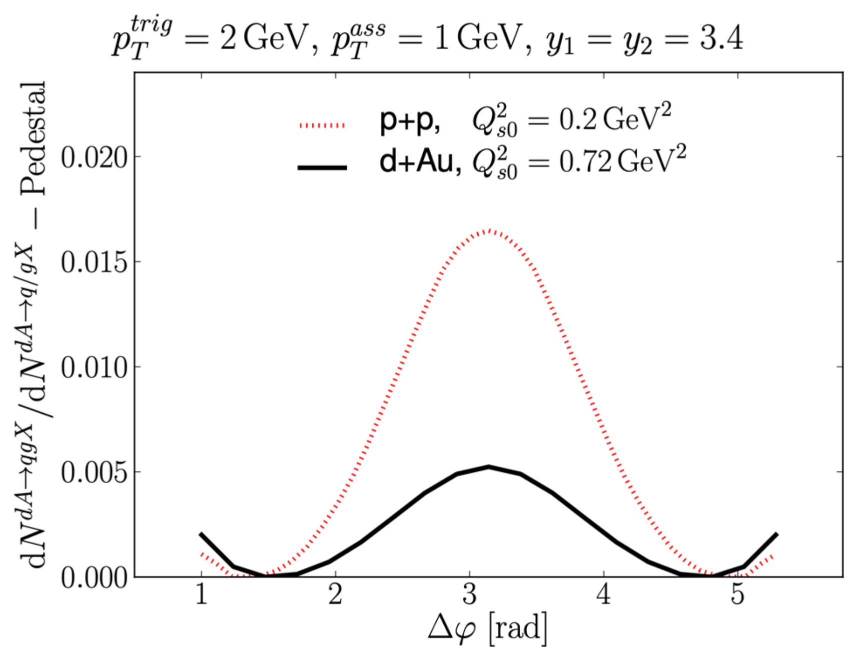
- Paper says: $\Delta\phi$ distributions normalized in a such way that the integral over azimuthal angle is equal to 1
- Normalized by N_{pair} for entire $\Delta\phi$ range → self normalization

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





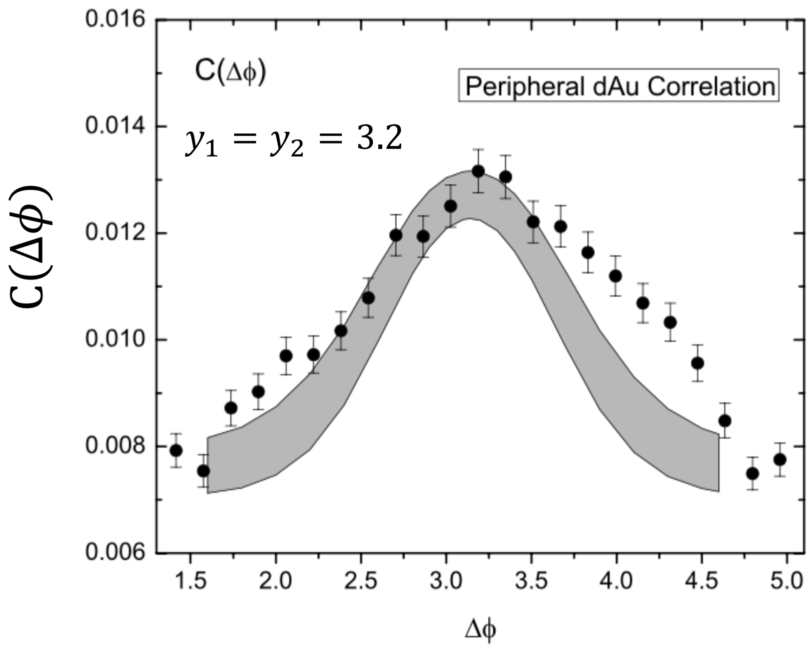
- For the first time, the pedestal is predicted, independent scattering of two partons from the probe: $f^p_{q_1q_2}(x_{q_1}, x_{q_2}) = f^p_{q_1}(x_{q_1})\, f^p_{q_2}(x_{q_2})$

- Two ways of normalizations : Left: $\frac{N_{pair}(\Delta\phi)}{N_{pair\ from\ pedestal}}$; right: $\frac{N_{pair}(\Delta\phi)}{N_{trig}} - \mathrm{pedestal}$

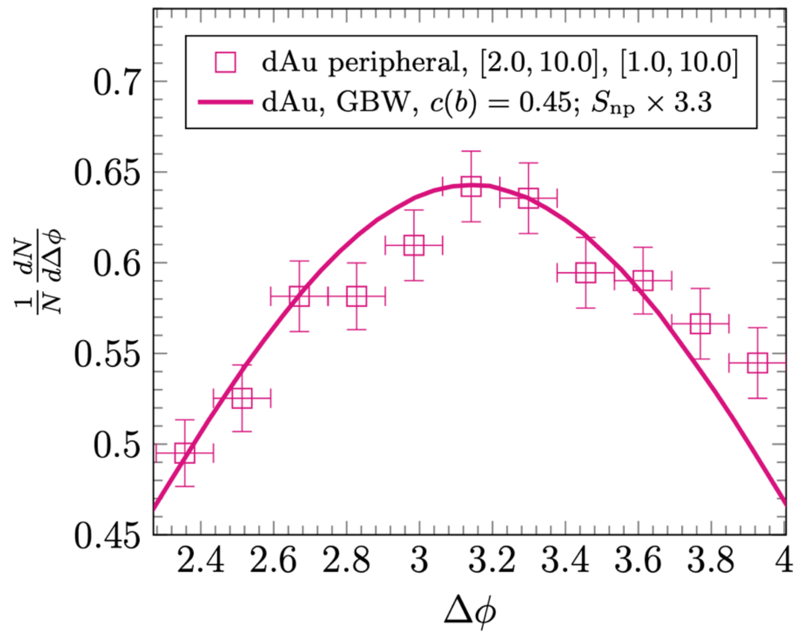
Normalization from theory (3)

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

Stasto, Xiao, Yuan



Stasto, Wei, Xiao, Yuan



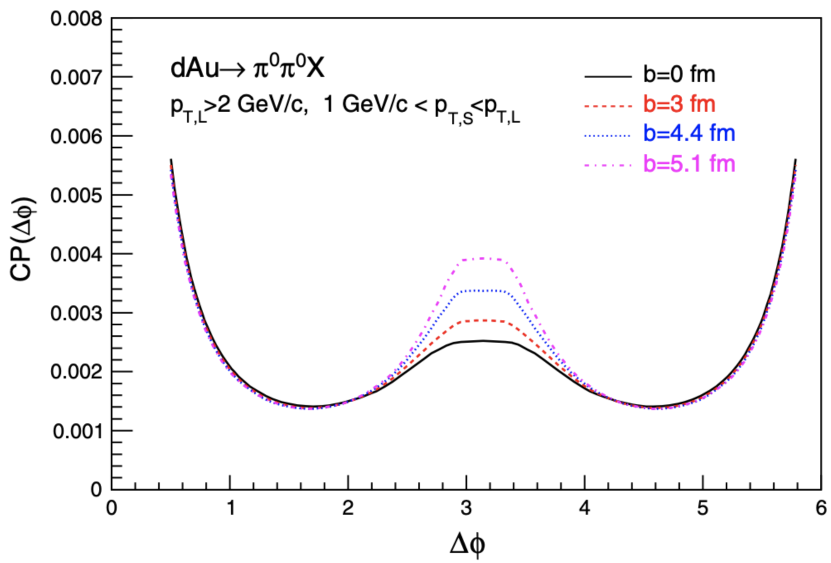
- Later paper used CGC predictions based on GBW model with Sudakov effects included
- Two ways of normalization used: correlation function normalized by N_{trig} not N_{pair}
  - PLB 716 (2012) 430-434: normalized by N_{trig}, issue with p+p normalization
  - PLB 784 (2018) 301-306: normalized by N_{pair},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

Normalization from theory (4)

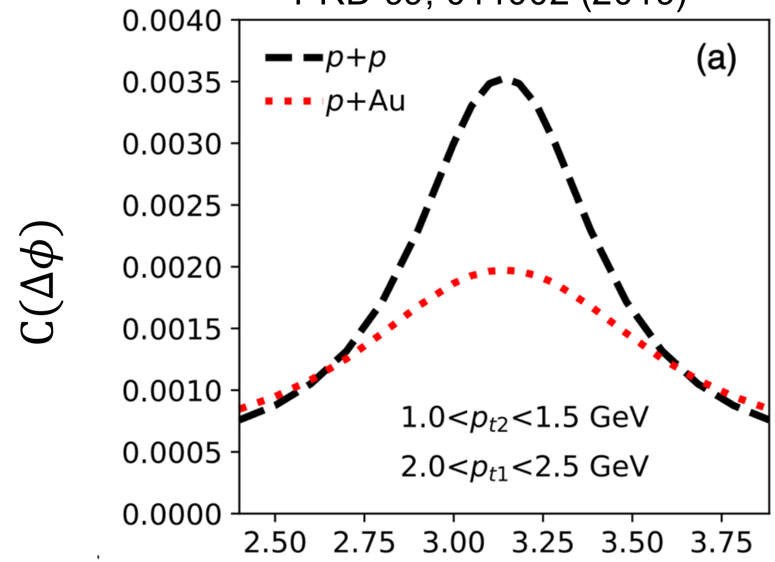
In the experiment:

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

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