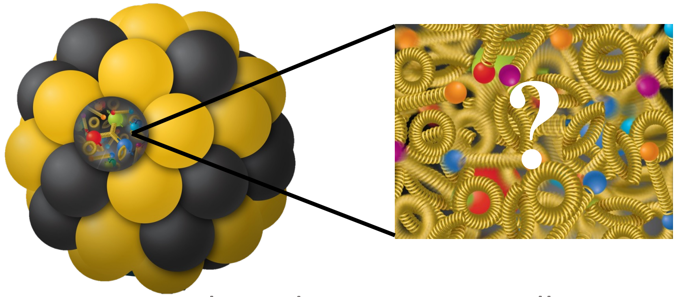
STAR ☆



gluon dynamics at small x

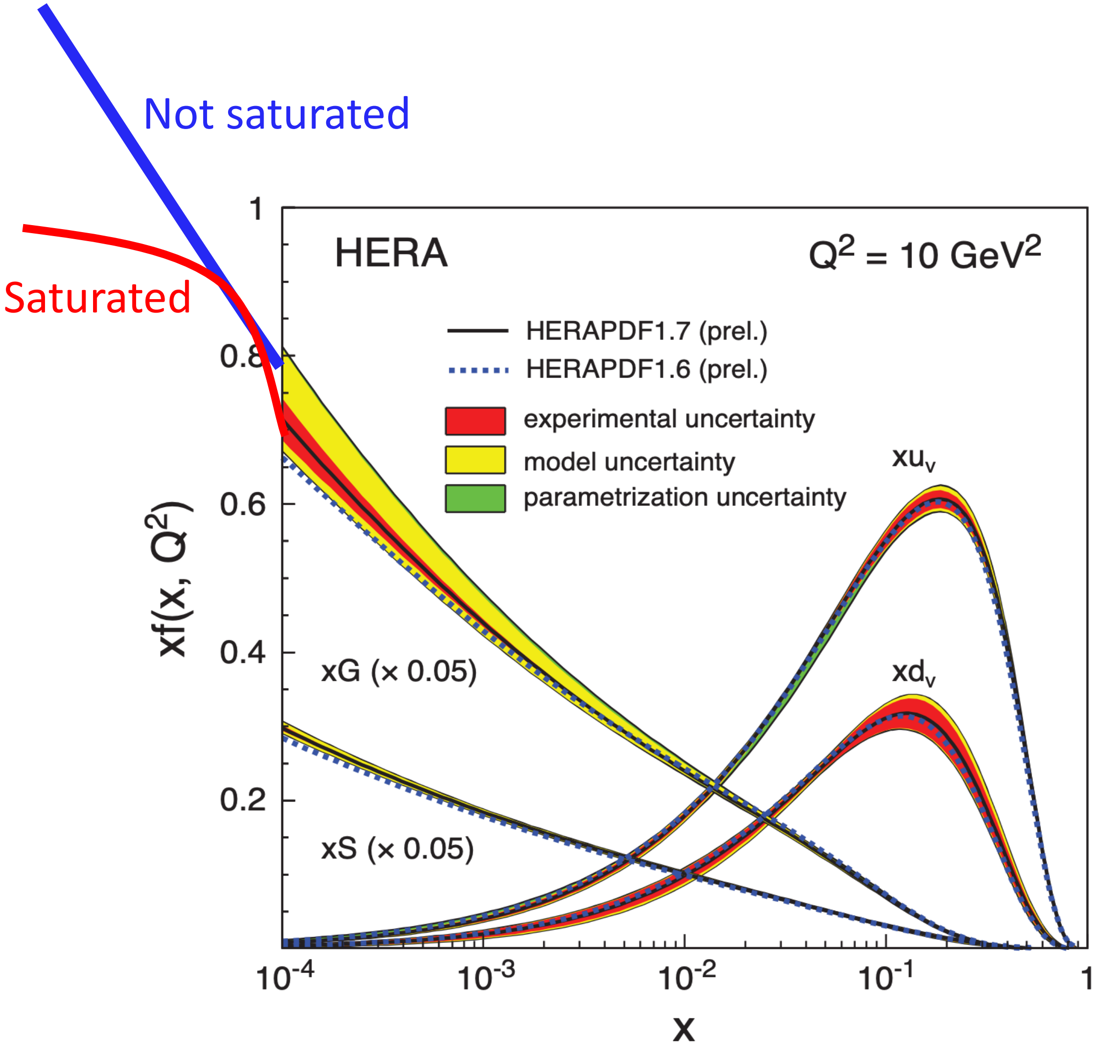
Experimental search for gluon saturation at STAR

Xiaoxuan Chu, BNL

CFNS workshop, May 16th 2024

From Quarks and Gluons to the Internal Dynamics of Hadrons, May 15 – 17, 2024
Center for Frontiers in Nuclear Science, Stony Brook University

Gluon saturation



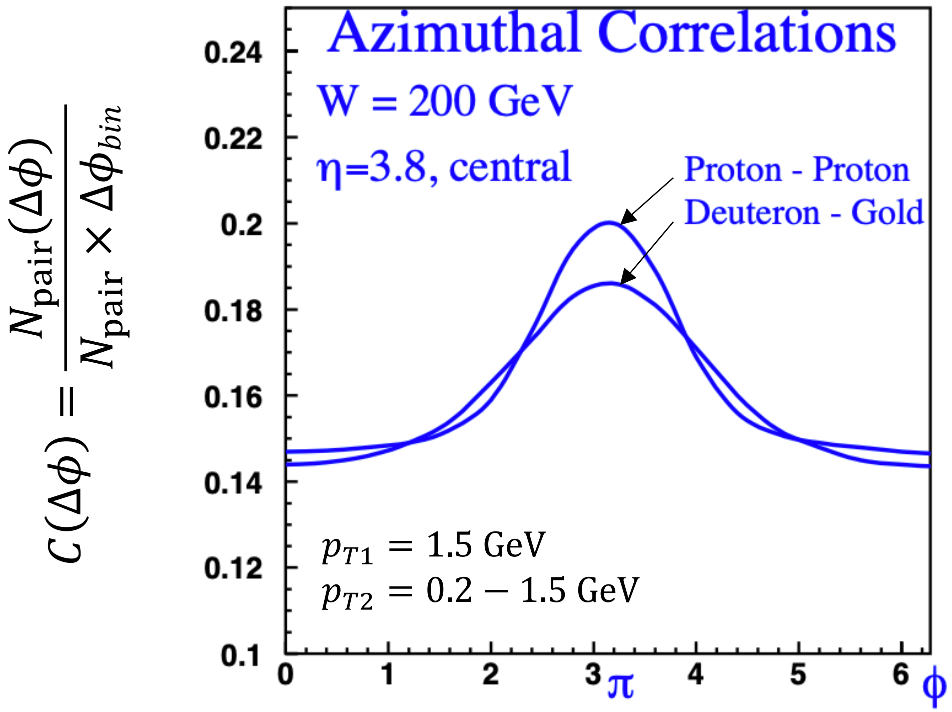
- Gluon density rapidly increases at small x: gluon splitting → linear evolution
- Nonlinear gluon effect: gluon recombination → non-linear evolution
- Gluon saturation (**$Q^2<Q^2_s$**): gluon recombination = gluon splitting
- It's easier to access saturation region in heavy nuclei than nucleon:

$$Q_s^2 \propto A^{1/3}(1/x)^{\lambda}$$

Di-hadron measurement in d+Au

- **CGC** successfully predicted the strong **suppression of the hadron inclusive yields** in d+Au relative to p+p, by gluon saturation effects

- **Di-hadron** as another observable provides further test, was first proposed by D. Kharzeev, E. Levin and L. McLerran from NPA 748 (2005) 627-640



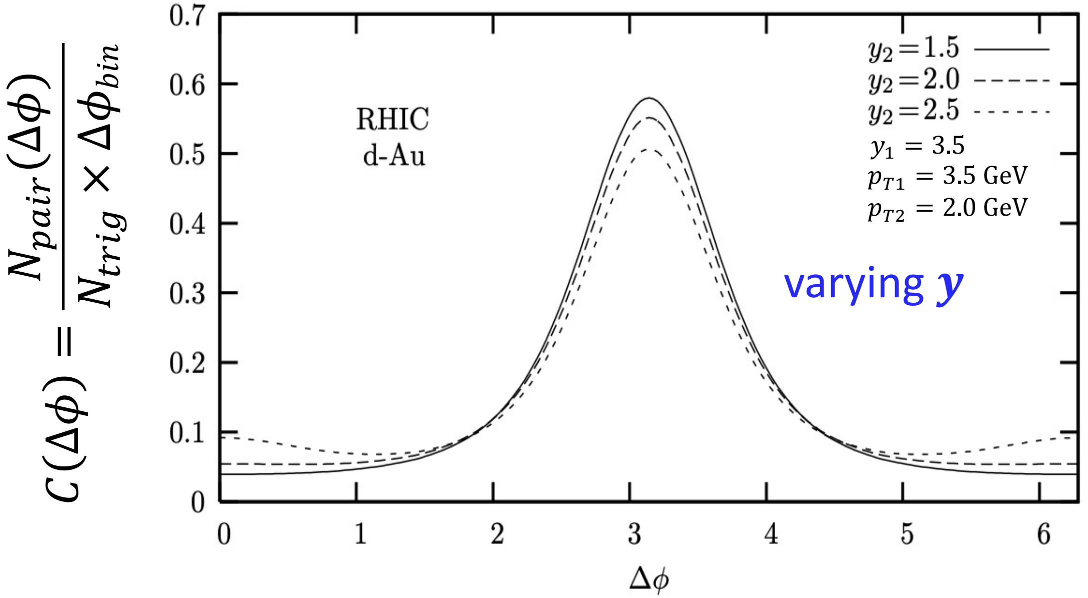
Deletion of away-side peak in d+A relative to p+p as saturation feature:

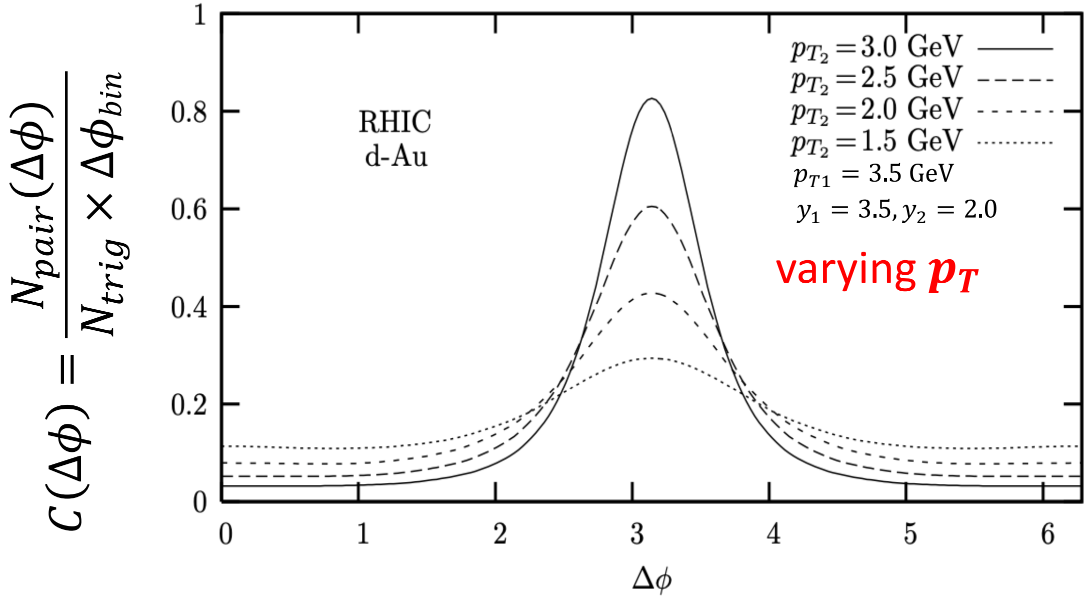
- Suppression
- Broadening

- Following theoretical predictions on di-hadron:

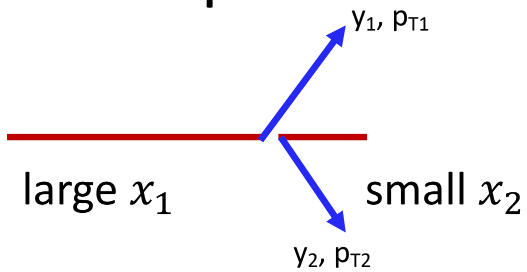
Saturation signatures on p_T and y

C. Marquet in NPA 796, 41 (2007)





Forward di-parton kinematics

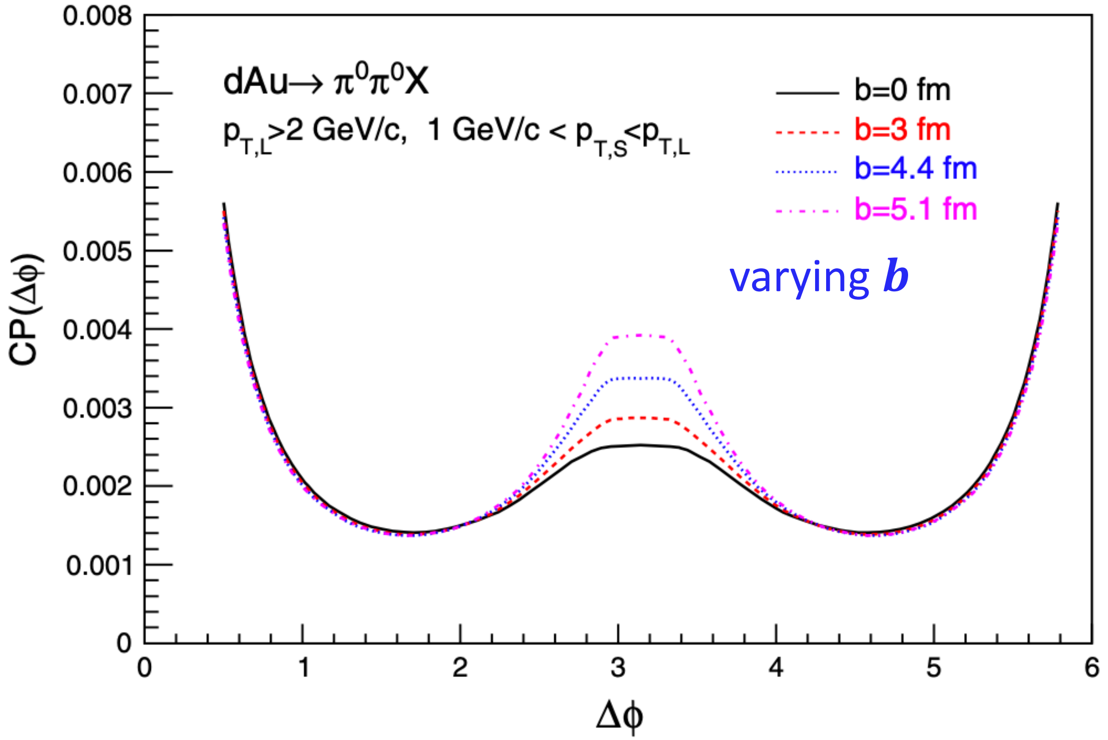


$$x_2 \sim \frac{p_{T1}e^{-y_1} + p_{T2}e^{-y_2}}{\sqrt{s}}; \; Q \sim \frac{p_{T1} + p_{T2}}{2}$$

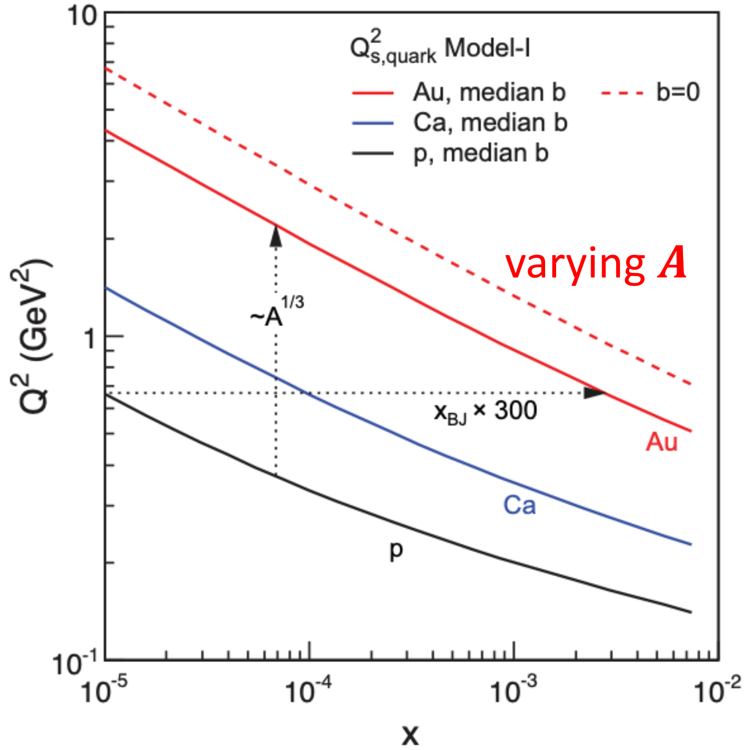
x (and Q^2) scanned by varying p_T and y

Saturation signatures on b and A

J. L. Albacete and C. Marquet, PRL 105, 162301 (2010)



arXiv: 1212.1701



$Q_s \propto T_A(b) \propto 1/b$, $T_A(b)$ is Woods-Saxon potential:
smaller b, larger Q_s→ easier to reach saturation region

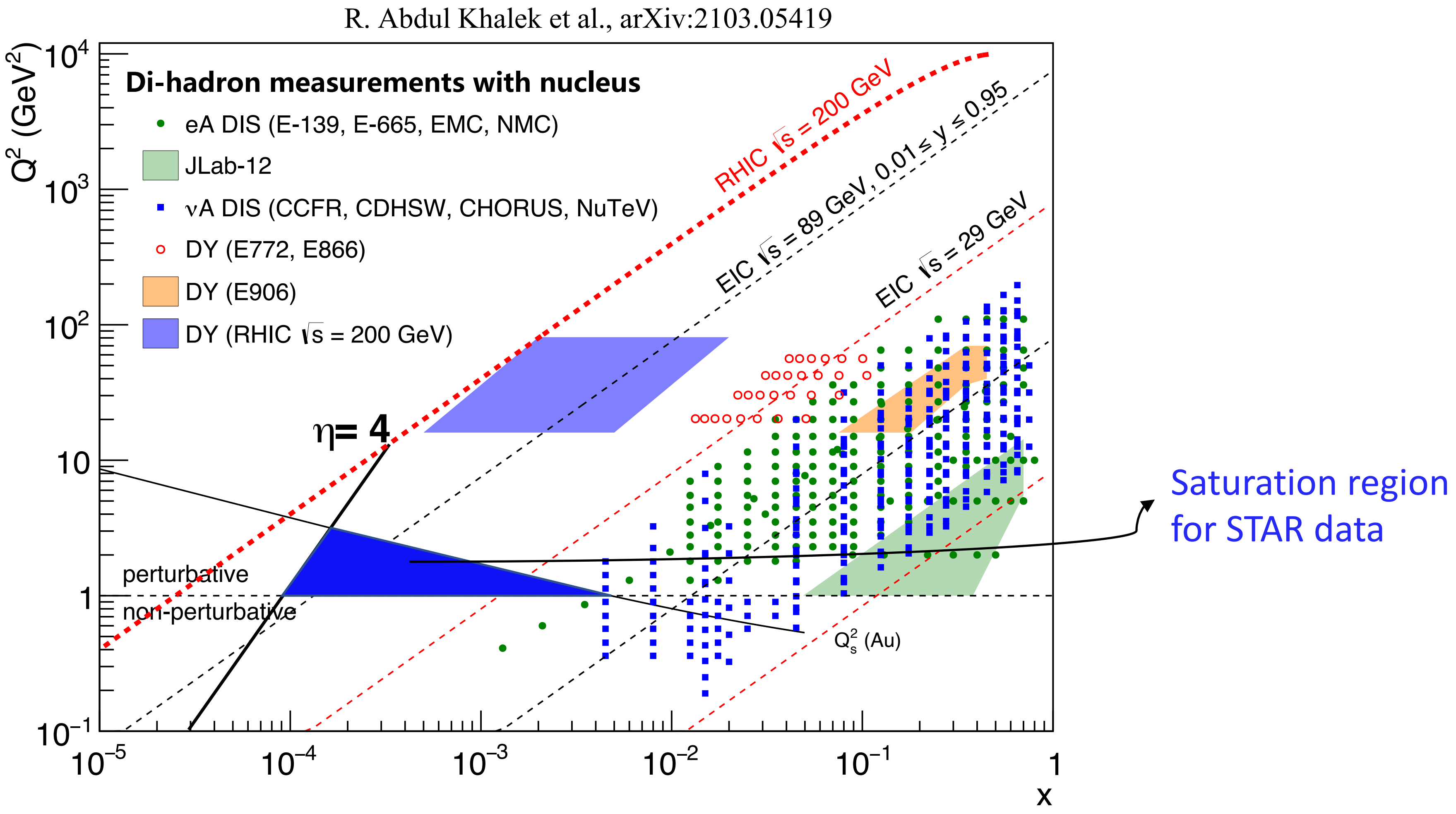
$Q_s \propto A^{1/3}$:
Larger A, larger Q_s→ easier to reach saturation region

Q_s scanned by varying b and A

Can we observe the nonlinear gluon dynamics signatures from recent STAR p+p, p+A, and d+A data?

- **p+p, p+Al, and p+Au collisions:** STAR, PRL 129, 092501 (2022)
  - d+Au collisions: STAR preliminary results

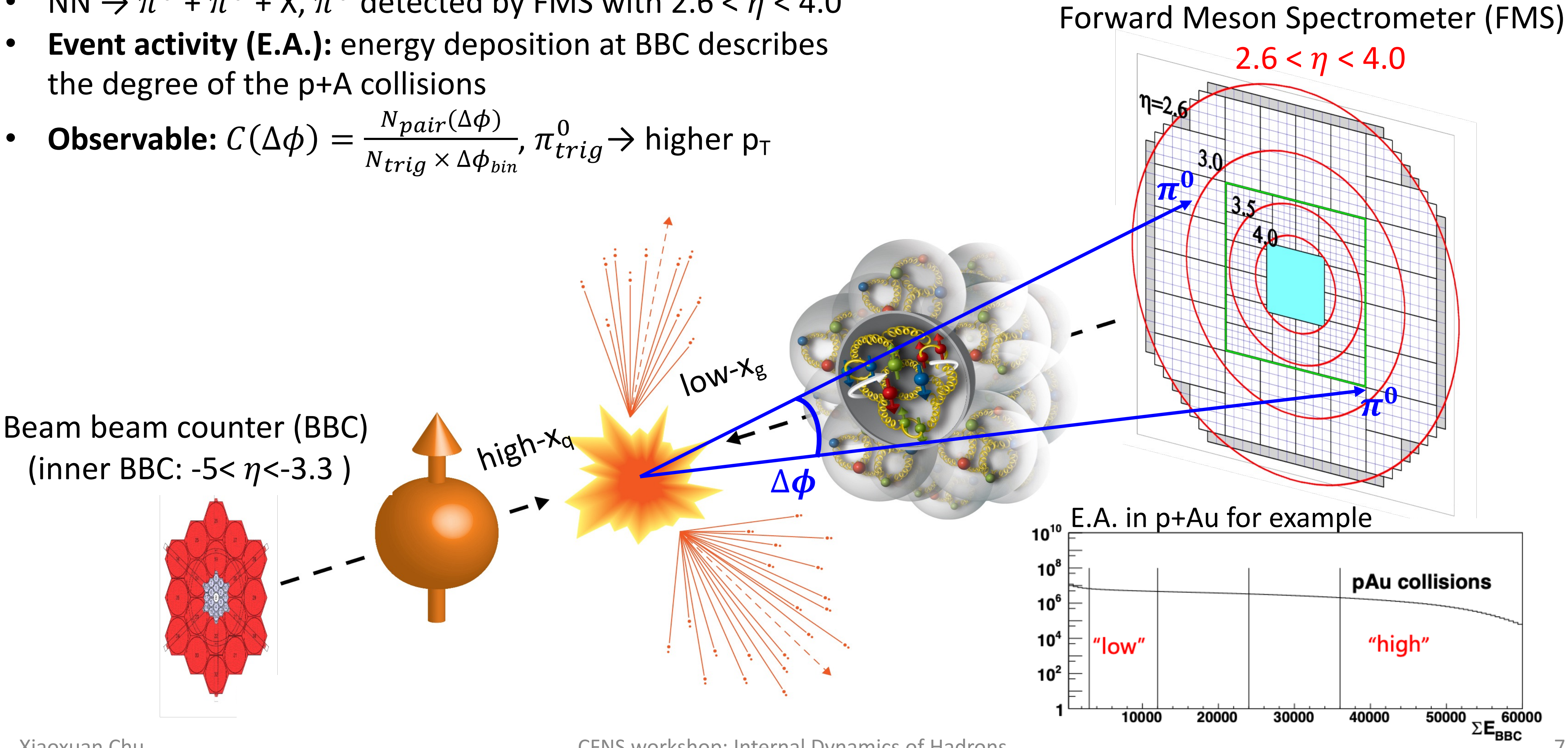
STAR data in $x - Q^2$ phase space



STAR data can access linear-nonlinear transition region

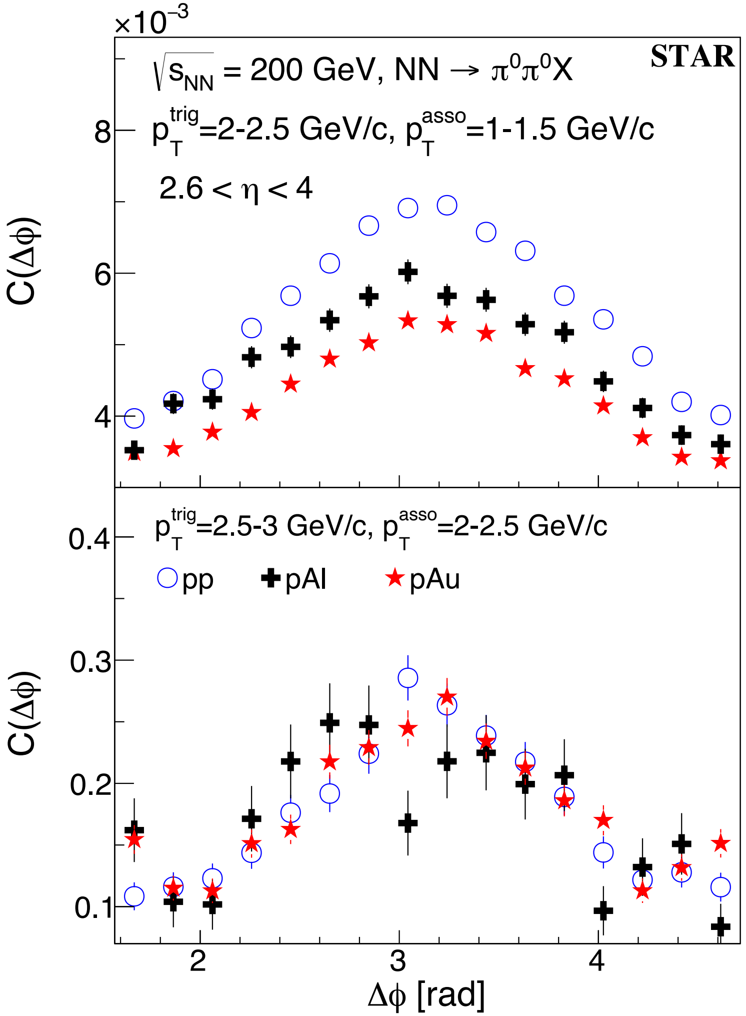
Di-π^0 measurement at STAR

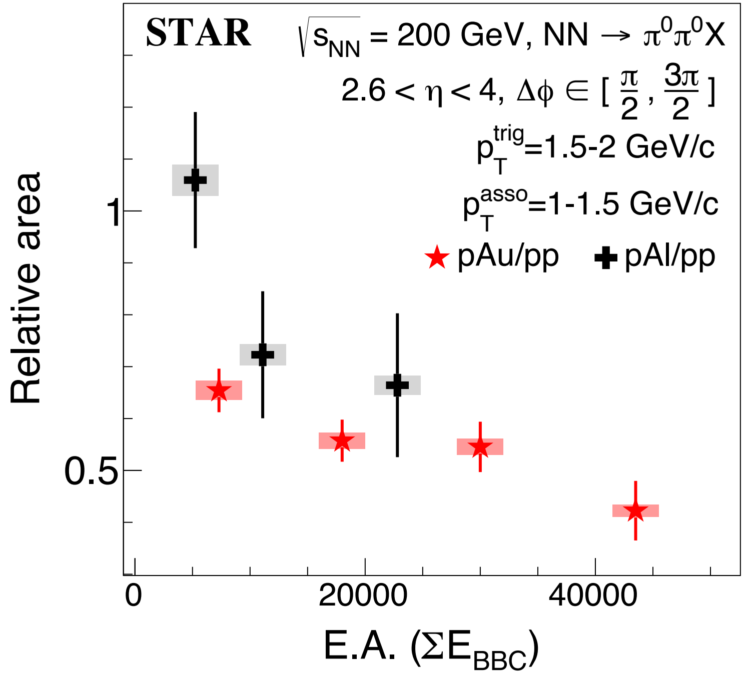
- **p+p, p+Al, p+Au** and d+Au collisions at $\sqrt{s_{NN}} = 200$ GeV
- NN → $\pi^0 + \pi^0$ + X, π^0 detected by FMS with 2.6 < η < 4.0
- **Event activity (E.A.):** energy deposition at BBC describes the degree of the p+A collisions
- **Observable:** $C(\Delta\phi) = \frac{N_{pair}(\Delta\phi)}{N_{trig} \times \Delta\phi_{bin}}$, π^0_{trig}→ higher p_T

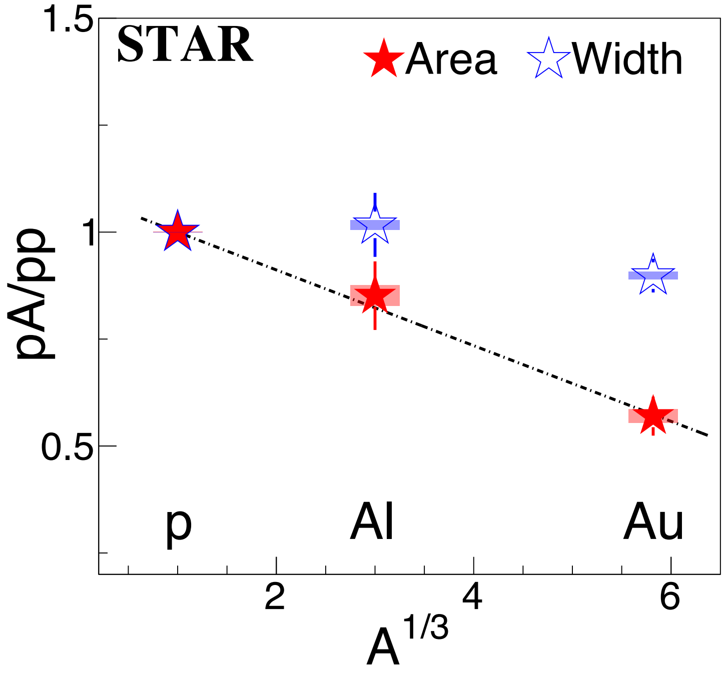


p_T, E.A. and A dependence

STAR, PRL 129, 092501 (2022)







- p_T dependence: suppression at low p_T not high p_T
- A dependence: suppression linearly depends on $A^{1/3}$
- E.A. dependence: larger suppression at higher E.A.

All good, but the predicted broadening was not observed, why?

→ theory, simulation, experiment improvements?

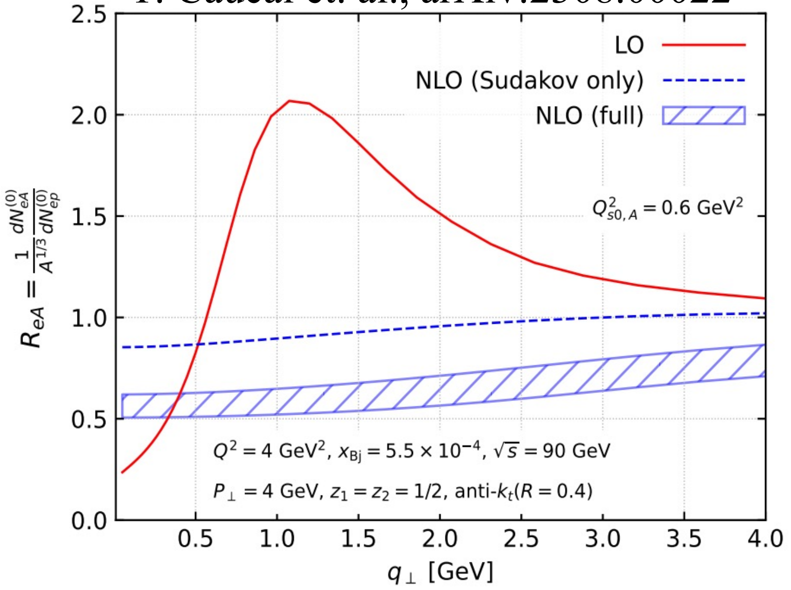
Precision calculation needed for saturation

Quark Matter 2023, talk by H. Mantysaari

Color Glass Condensate at precision level

CGC calculations are now entering the NLO era ($\alpha_s \ln 1/x \sim \mathcal{O}(1)$, NLO $= \alpha_s^2 \ln 1/x$)

P. Caucal et. al., arXiv:2308.00022



- Heavy quark production (Hanninen et al, 2022)
- Exclusive J/ψ, ρ, ϕ, Υ (Penttala, H.M, 2022)
- Hadron production in pA (Shi et al, 2021; H.M, Tawabutr, 2023)
- Dihadron correlations in DIS (Caucal et al 2023)

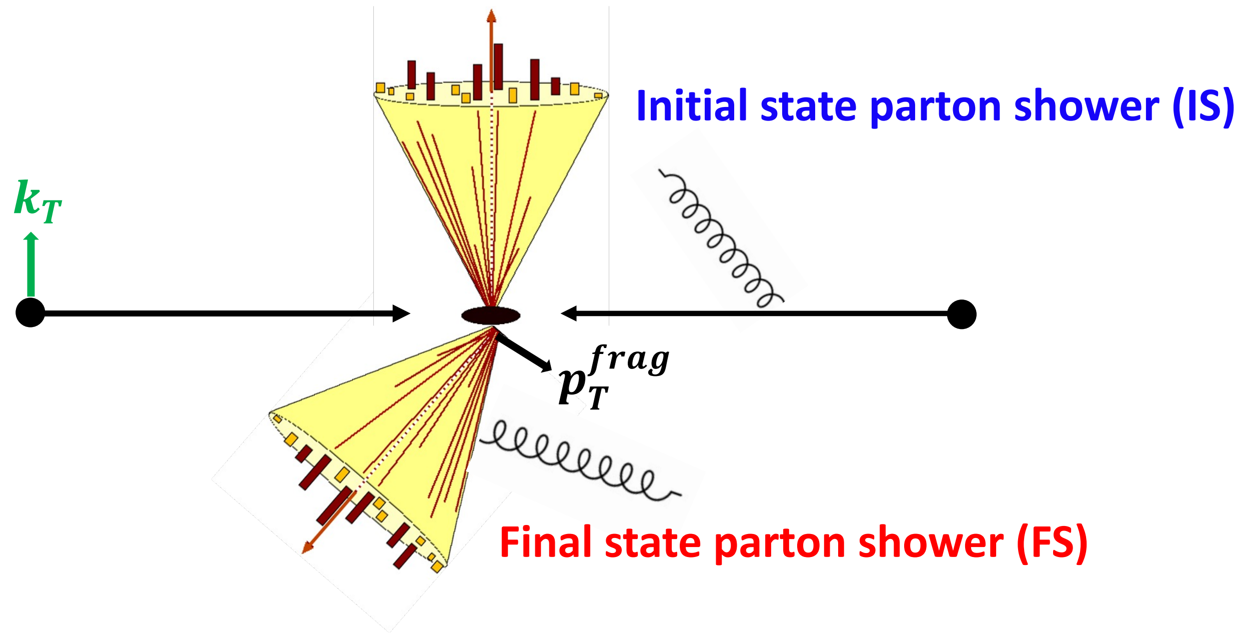
Not the full lists

- STAR observed A dependence but not the predicted angular broadening phenomena, why?
- High precision calculation from the saturation model is needed for the puzzle of broadening: LO → NLO

Potential modifications to the current-predicted correlation function with precision calculation

How about broadening in simulation?

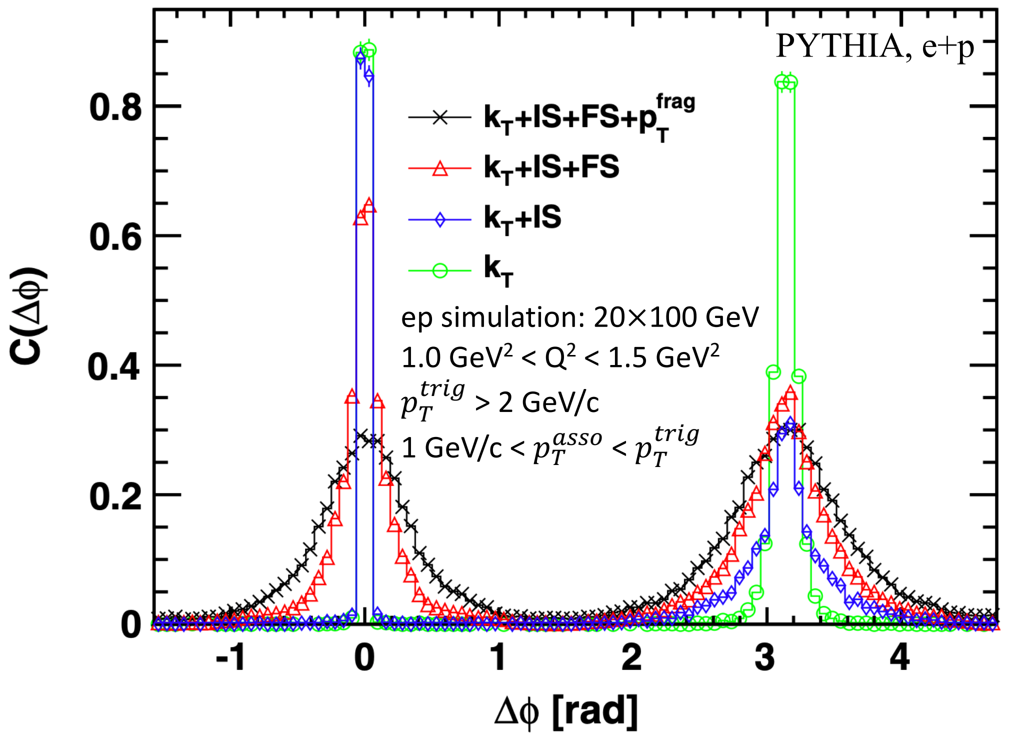
Factors can cause the broadening:



- Intrinsic k_T, parton shower, and p_T^{frag} can lead to broad near- and away-side peaks.

- Different dominate effects lead to a broad away/near-side peak; use near-side peak to calibrate

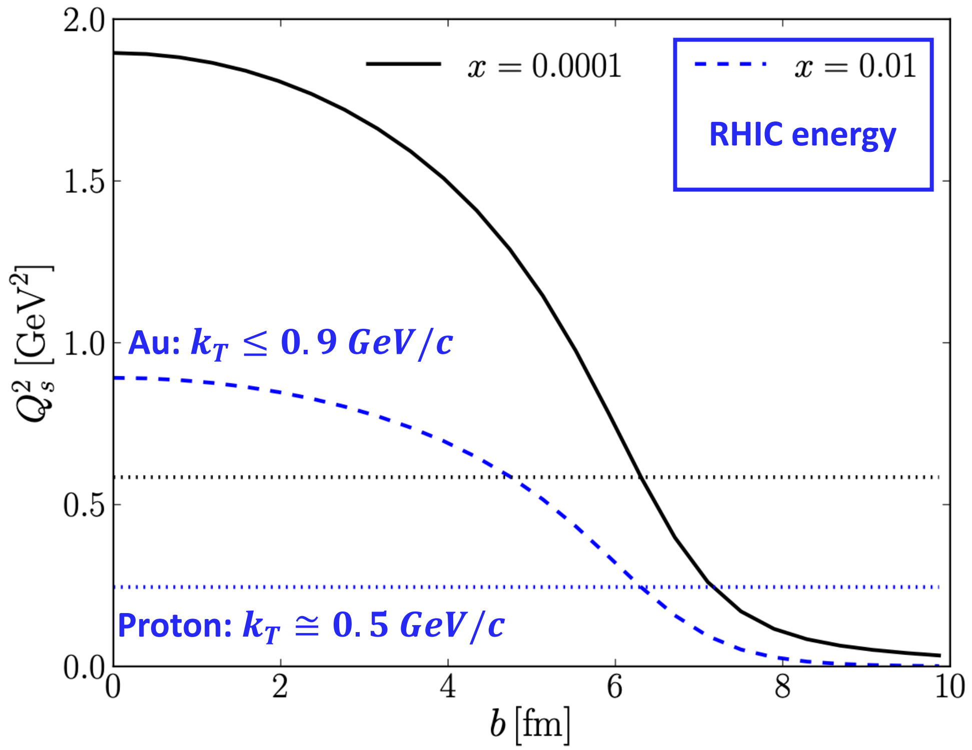
L. Zheng et al., PRD 89 (2014) 074037



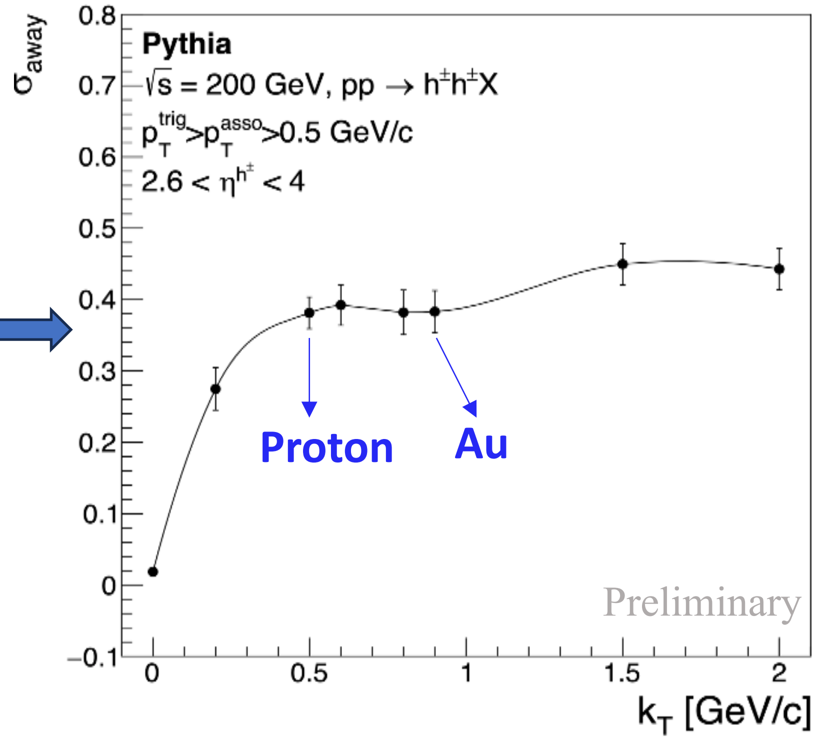
	Near-side $\Delta\phi$ RMS	Away-side $\Delta\phi$ RMS
k_T	0.21	0.25
$k_T + \mathrm{IS}$	0.30	0.72
$k_T + \mathrm{IS} + \mathrm{FS}$	0.65	0.81
$k_T + \mathrm{IS} + \mathrm{FS} + p_T^{\mathrm{frag}}$	1.00	1.00

How about the simulations at RHIC?

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

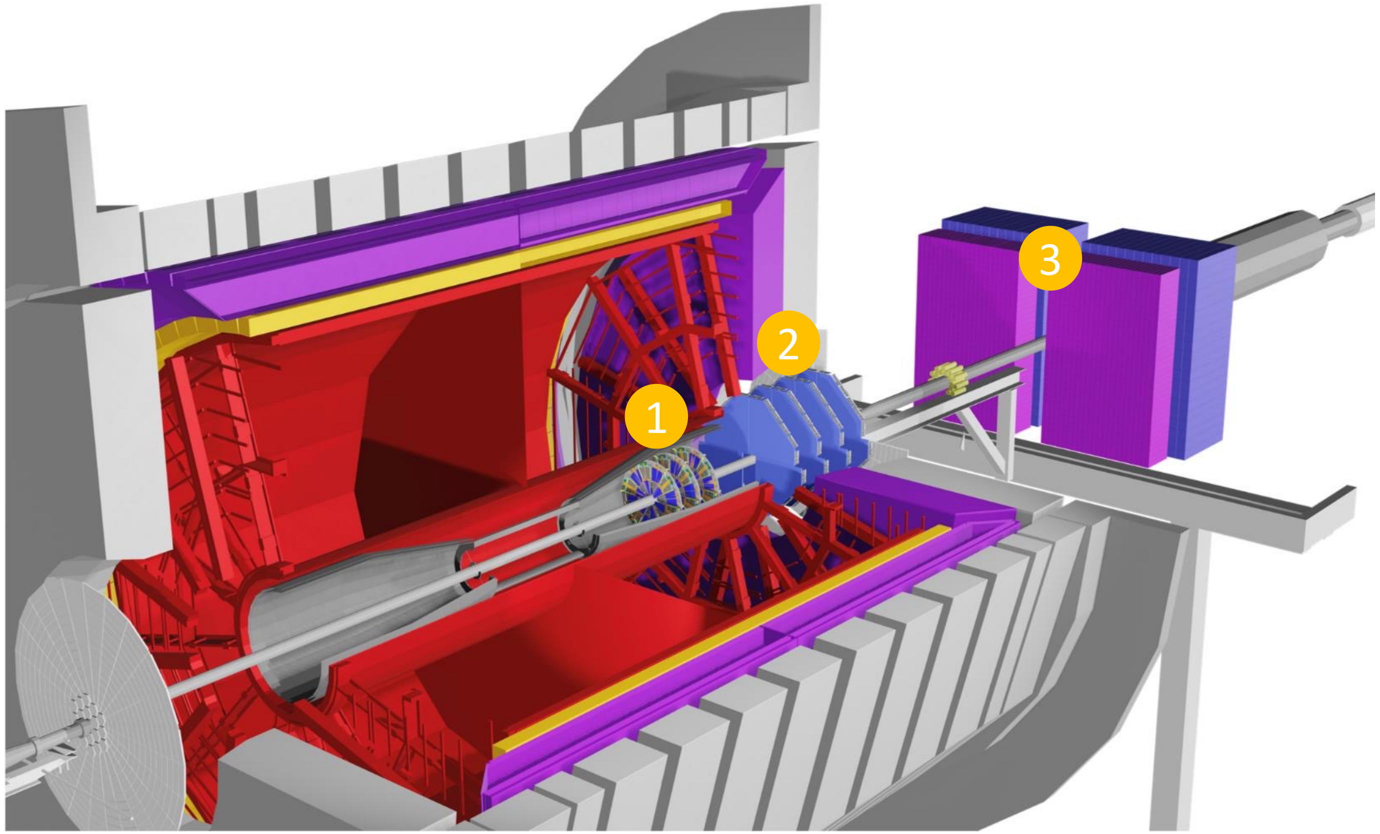


Preliminary studies by K. Cassar, undergraduate internship



- Saturation implemented in simulation by parameterizing intrinsic $\boldsymbol{Q_S \sim k_T}$: at RHIC energy, for proton: $\boldsymbol{k_T \cong 0.5\ GeV/c}$; for Au: $\boldsymbol{k_T \leq 0.9\ GeV/c}$
- Preliminary simulation studies: with intrinsic k_T, PS, and p_T^{frag} turned on, away-side width stays unchanged at $\boldsymbol{k_T > 0.5\ GeV/c}$, broadening is not expected to occur in p+Au compared to p+p; explanation for the experimental results?

Future measurements with STAR Forward Upgrade



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 (FST)
2. Forward sTGC Tracker (FTT)
3. Forward Calorimeter System (FCS)

STAR data with forward upgrade

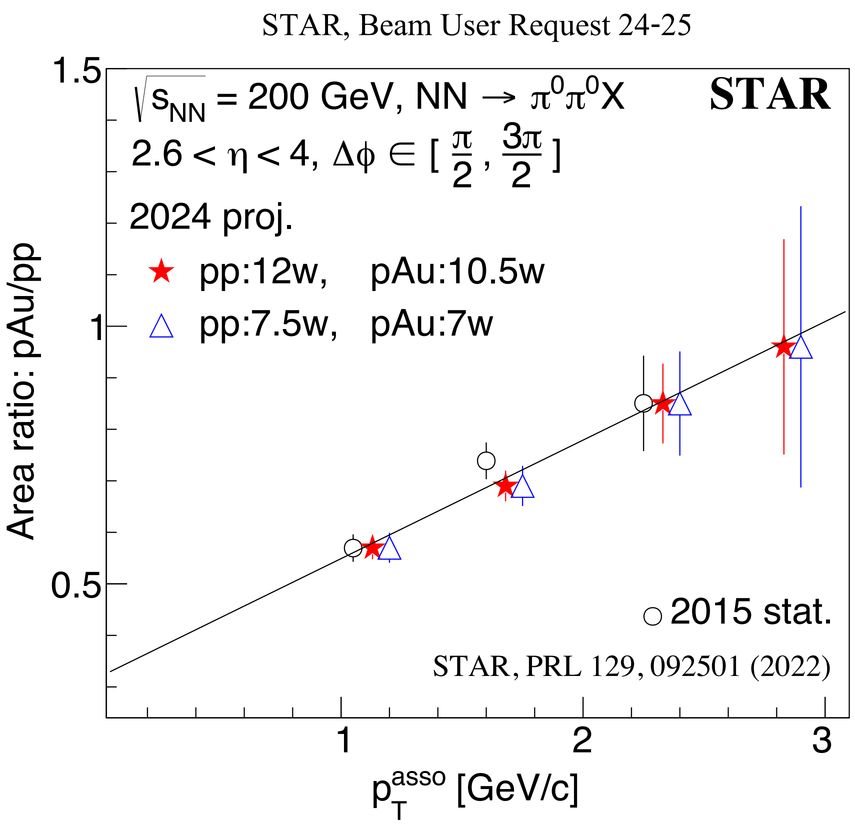
$\sqrt{s_{NN}}$ [GeV]	Species	Year
508	p+p	2022
200	p+p	2024
200	Au+Au	2023 and 2025

It's possible to take **pAu** in the last 2 years of RHIC Run!

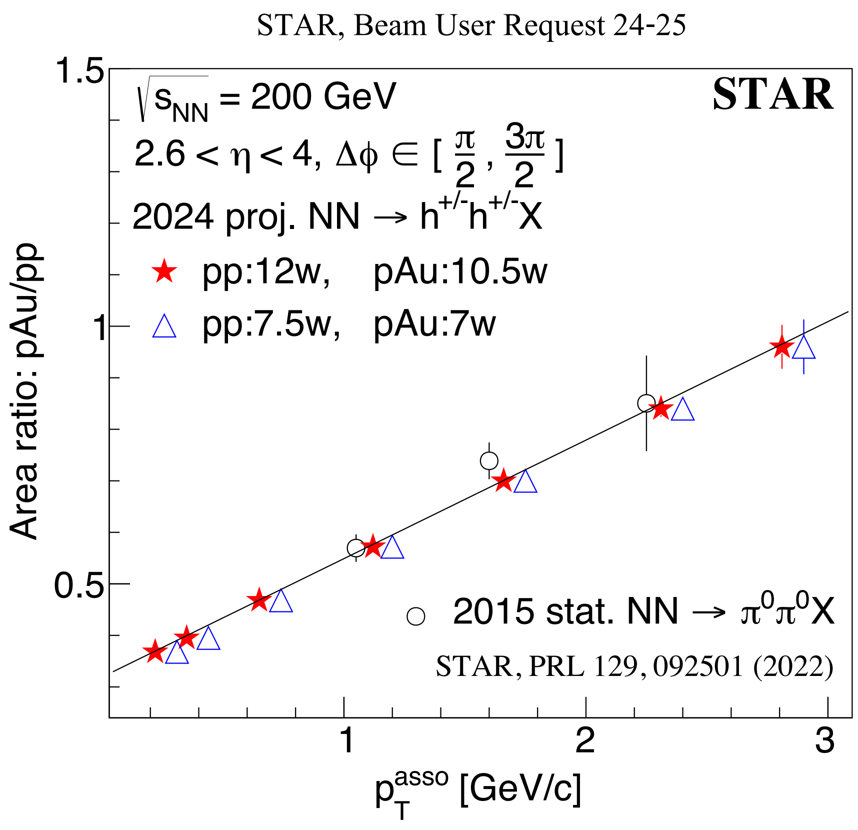
To explore nonlinear gluon dynamics with expanded observables beyond π^0s:

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

Di-h correlation projections with 2024/2025 data



Run24 di-π^0



Run24 di-$h^{\pm}$

- **Run24/25 di-π^0 projection**: Best statistic of 2024 (28 Cryo weeks) indicates ~35% reduction of the statistical error compared to 2015 data.
- **Run24/25 di-$h^{\pm}$ projection**: Higher statistic than di-π^0; ≥ 80% reduction of the statistical error compared to 2015 data; the strongest suppression expected at the lowest p_T where forward upgraded detectors can probe.

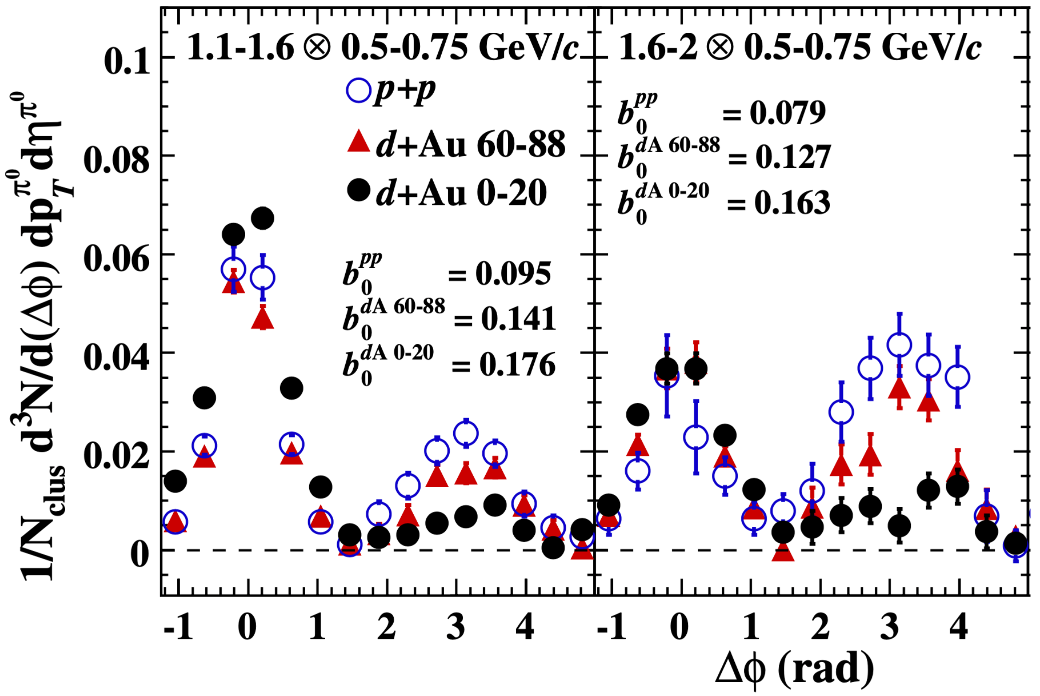
Do we observe the nonlinear gluon dynamics signatures from recent STAR p+p, p+A, and d+A data?

- **p+p**, p+Al, and **p+Au collisions**: STAR, PRL 129, 092501 (2022)
- **d+Au collisions:** STAR preliminary results

PHENIX d+Au data

PHENIX, PRL 107, 172301 (2011)

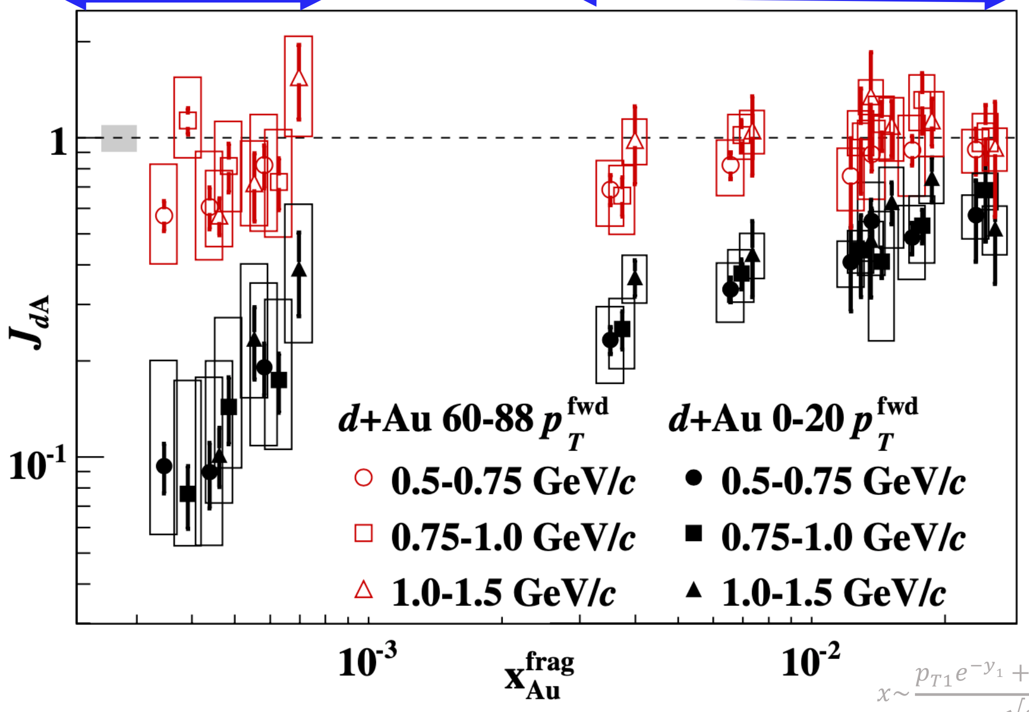
forward-forward: 3.0 < η < 3.8



Note: $\Delta\phi$ distribution normalized by N_{trig}

forward-forward

mid-forward: |η|<0.35, 3.0 < η < 3.8



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

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

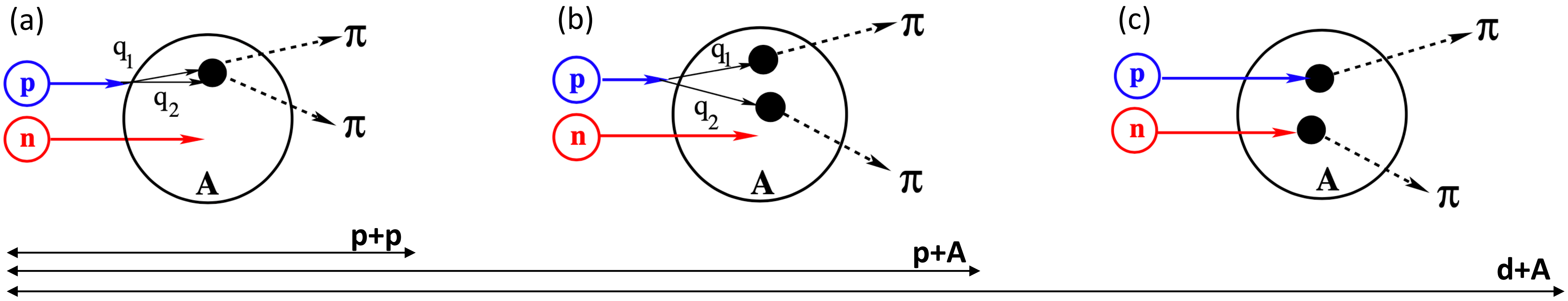
I_{dAu}: area ratio dAu/pp → what STAR measured

- **Away-side correlation**: suppression dependence on rapidity and centrality was observed by PHENIX
- **Pedestal**: high pedestal in d+Au, PRD 83, 034029 (2011) → double parton interactions (DPS) in d+Au, can affect the correlation?
- **Motivation of performing the similar measurement at STAR** → Impact of DPS in d+Au; complementary studies

DPS in d+Au?

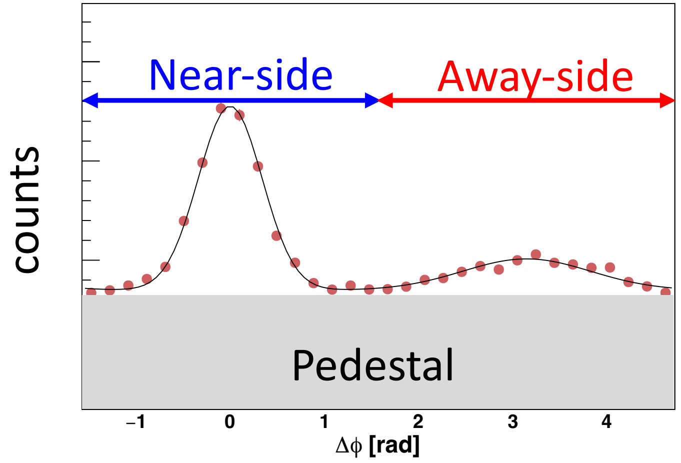
M. Strikman and W. Vogelsang,
PRD 83, 034029 (2011)

Examples contribution of DPS

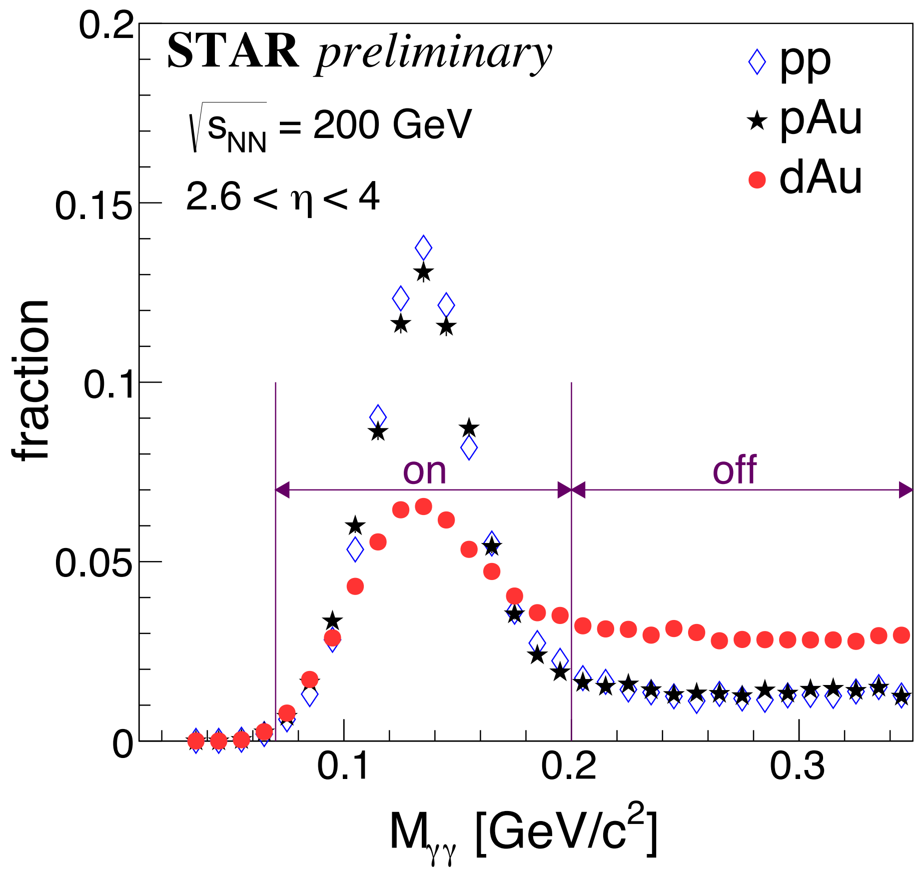


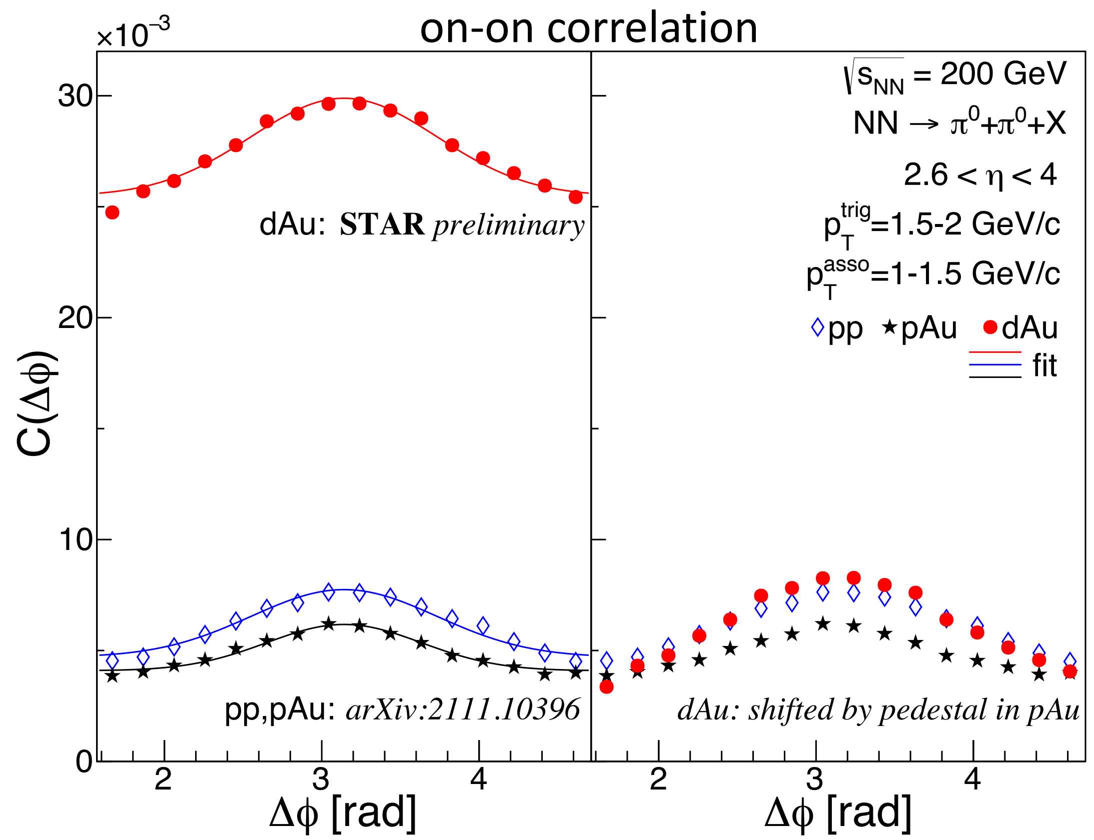
Comparison of p+p, p+Au and d+Au → study the individual source of DPS

- **Compare pedestal**: DPS provides an explanation of higher pedestal in d+Au
- **Compare away-side correlation → window open to studies of double parton distributions** in nucleons:
  - q_1,q_2 correlated: DPS enhances the correlation
  - $q_{1,}q_2$ uncorrelated: DPS will only enhance pedestal



p+p, p+Au and d+Au comparison

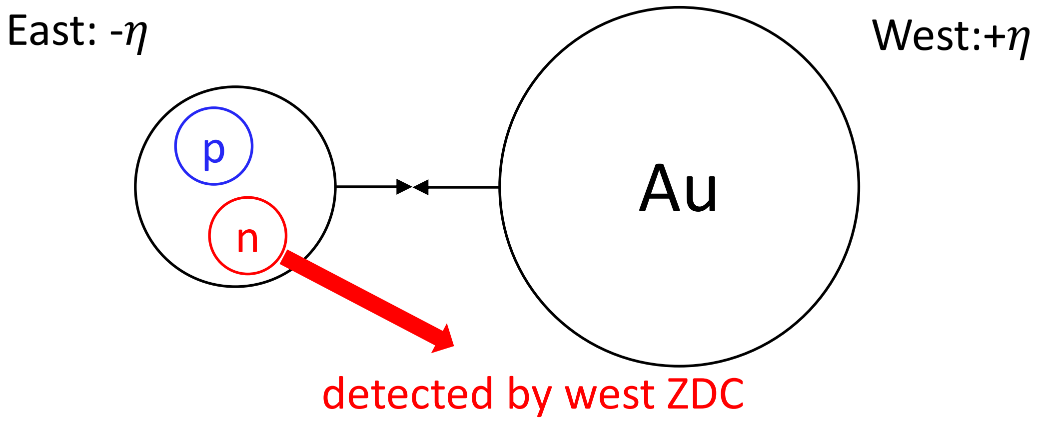




S/(S+B)	STAR	PHENIX (PhD thesis)
p+p	82%	81%
d+Au	58%	73%

- π^0 PID: much higher background in d+Au than p+p (Au)
- Very high pedestal: d+Au > 5 times higher than p+p (Au)
- Much larger combinatorial background in d+Au than p+p (Au)

What's next for d+Au?



Neutron-tagging with STAR ZDC:

Zero Degree Calorimeter (ZDC)

ZDC in the forward direction: $\eta > 6.3$

Correlation measured in two channels:

1. Inclusive channel
   - Either proton or neutron enters, or both enter the hard scattering

   – completed

2. Neutron-tagged in the forward direction
   - Proton enters the hard scattering

   – ongoing

Aim at understanding the contribution from DPS to the pedestal and correlations

Conclusion for theory

- Detailed signatures with back-to-back di-hadron correlation measurement from theory:
  - CGC: A, E.A./centrality, p_T, and rapidity dependence predicted
  - DPS in d+Au: both pedestal and correlation affected?
  - LO→NLO predictions needed

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- p+p, p+Al, and p+Au results from STAR: A, E.A./centrality, p_T, and rapidity dependence observed
- d+Au results from STAR: Challenging to conclude
  - Large background correlation not fully understood – ongoing efforts, stay tuned; favors cleaner p+Au collisions
  - For DPS physics: favors di-charged hadron correlation in p+p, p+A, and d+A

Clarifications

- Detailed signatures with back-to-back di-hadron correlation measurement from theory:
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- Background contribution cannot be ignored from the data, be careful with predictions and experimental results based on the results in d+Au collisions

Outlook

- Detailed signatures with back-to-back di-hadron correlation measurement from theory:
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- Di-charged hadron correlation with STAR Froward Upgrade and EIC:
  - Cleaner PID than π^0; lower p_T acceptance – stronger signal expected
  - Near-side peak can be studied: used to calibrate effects from IS, FS and fragmentation p_T?
  - pp, pA and ep, eA – complementarity and universality