Probing Gluon Saturation Through Two-Particle Correlations at STAR

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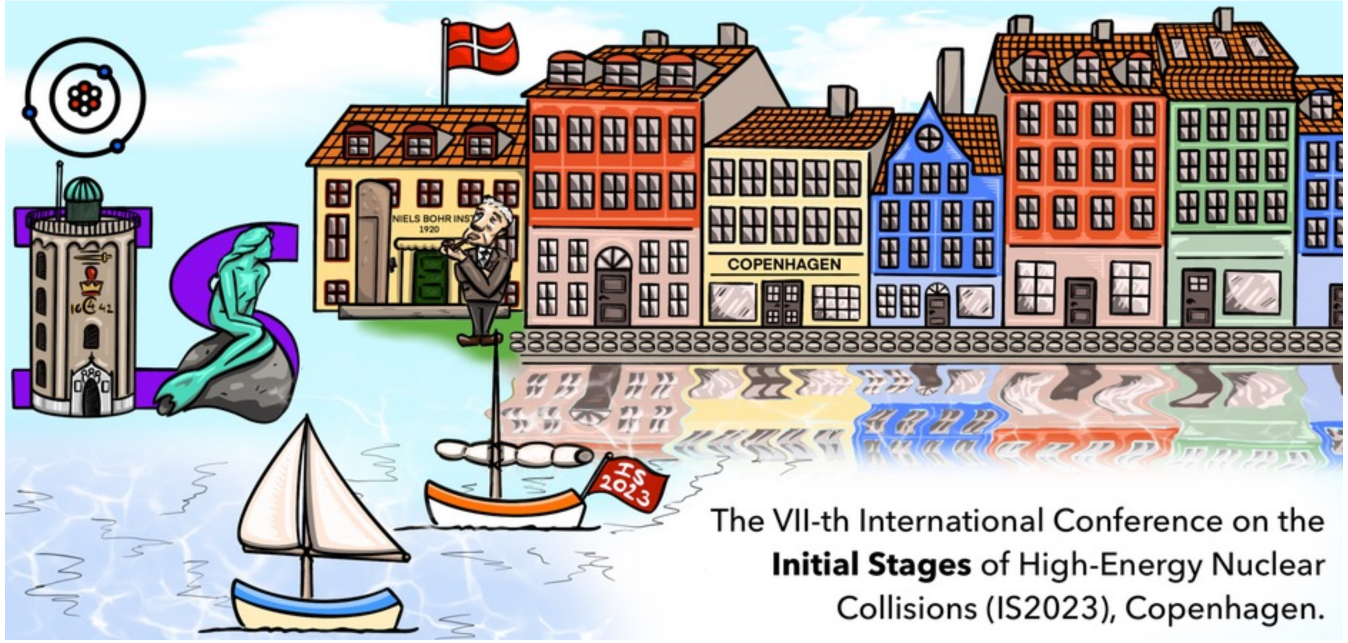
for the STAR Collaboration



TEMPLE UNIVERSITY

STAR

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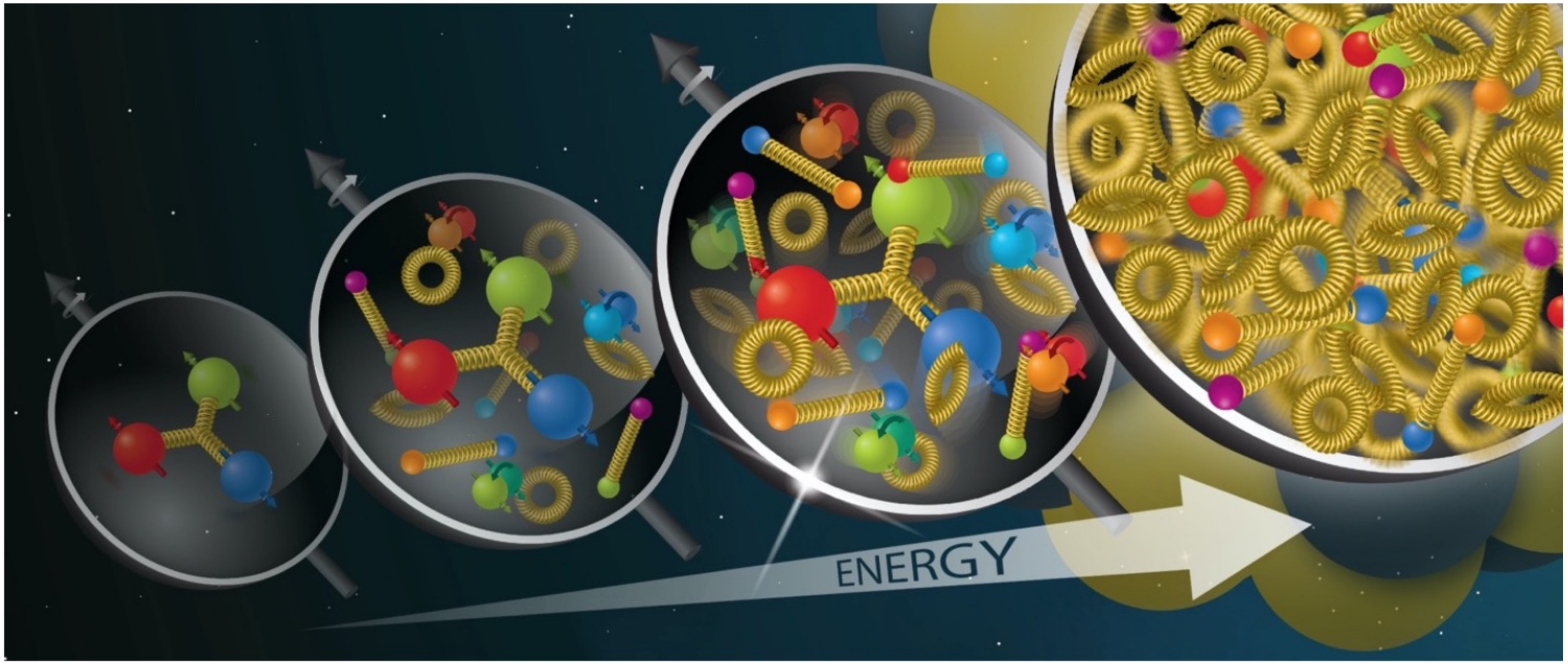
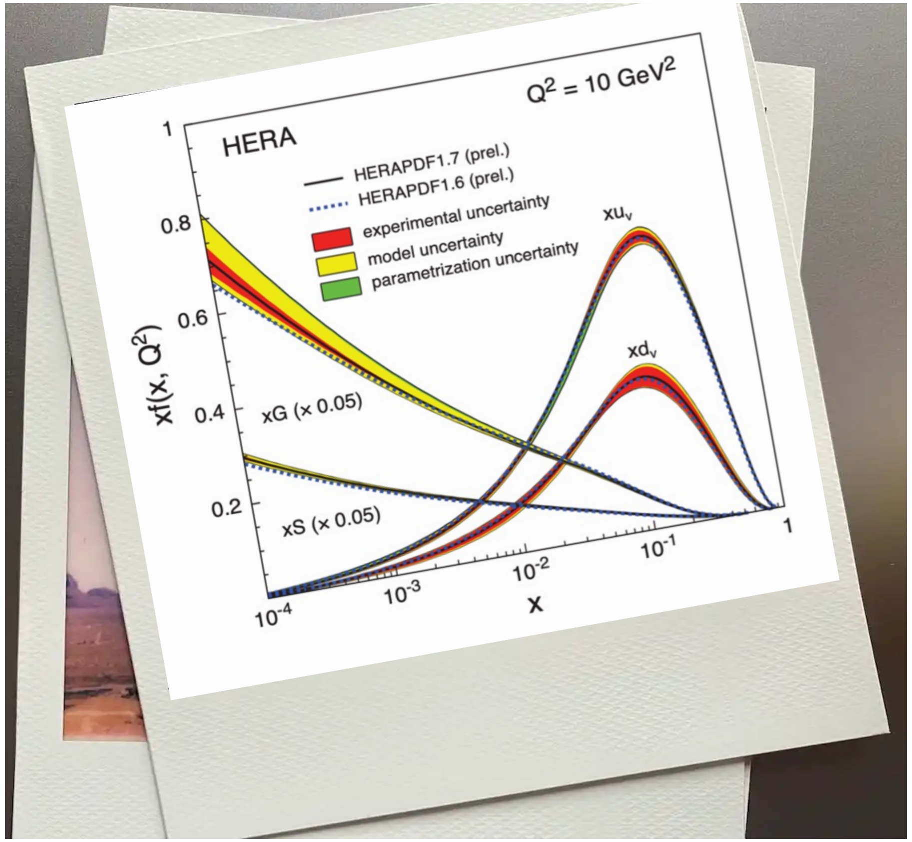
Gluon Density in the Nucleon

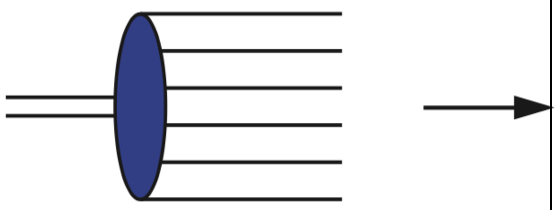




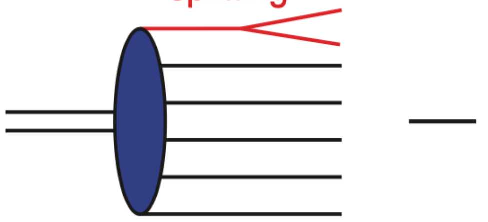
- Particles from high energy collisions can be used to probe and take "snap shots" of the partonic structure of the proton.
- Results from DIS: Gluon density rapidly increases towards small x
  - ➢ gluon splitting

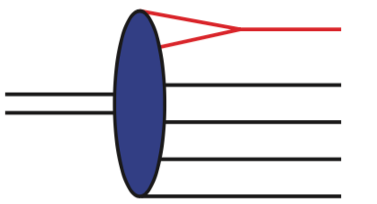
Gluon Saturation

Gluon density



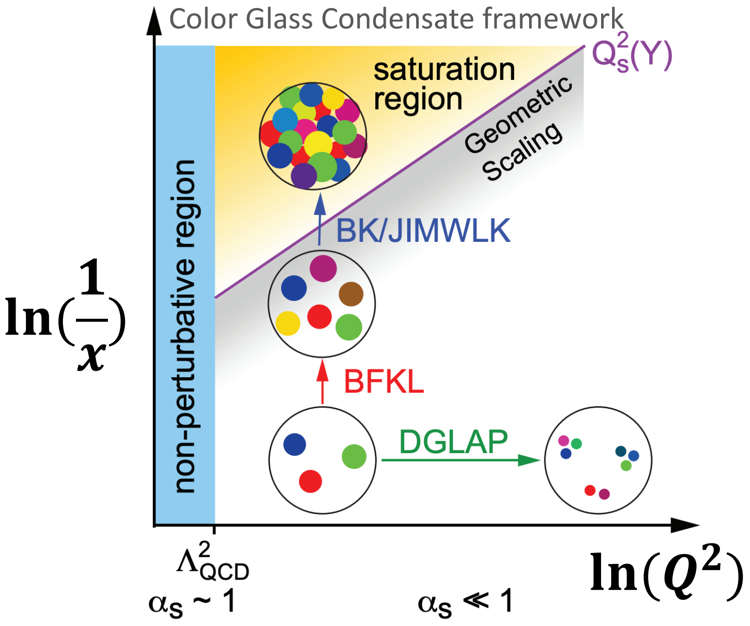
Balitsky-Fadin-Kuraev-Lipatov (BFKL) evolution equation
Balitsky-Kovchegov (BK) evolution equation





$$\frac{\partial N(x)}{\partial \ln(1/x)} = \alpha_s K_{BFKL} \otimes N(x) \quad - \quad \alpha_s N^2(x)$$

linear — nonlinear



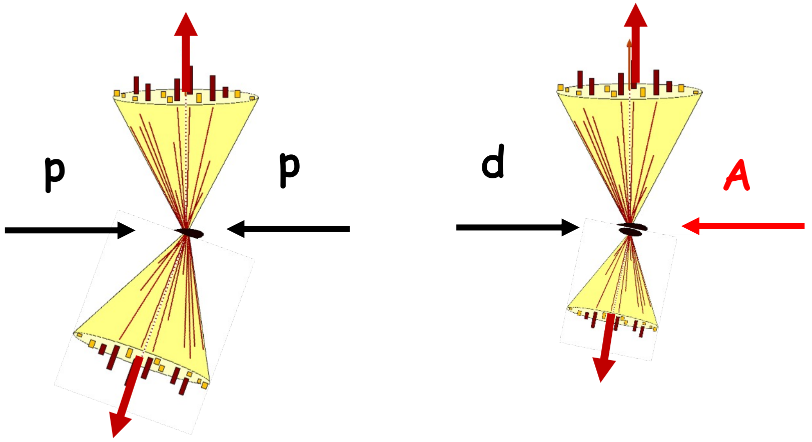
- Rapid rise of gluon density caused by gluon splitting → Linear evolution
- At a certain point the gluon increase should be tamed by gluon recombination → non-linear evolution
- New regime of QCD: Gluon saturation (**$Q^2 < Q^2_s$**) where gluon recombination = gluon splitting
- Saturation region is easier to access in nuclei: $Q_s \propto A^{1/3}$

Looking for Saturation

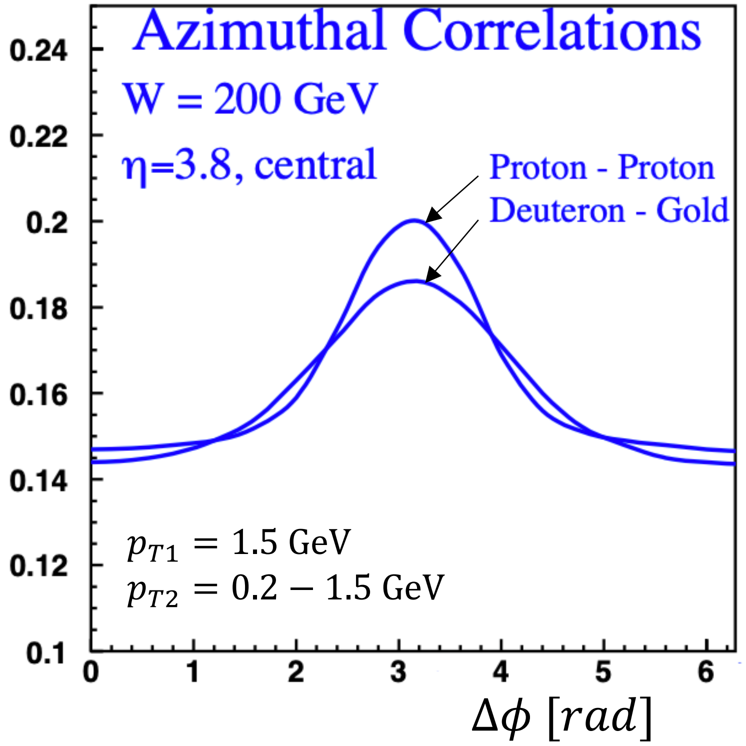
- Color Glass Condensate successfully described the strong suppression of the **inclusive hadron yields** in dAu relative to pp owing to gluon saturation effects.
  - Can be further tested in di-hadron correlation and nuclear dependent transverse single spin asymmetry measurements

Di-Hadron Correlations

- First proposed by D. Kharzeev, E. Levin and L. McLerran NPA 748 (2005) 627.



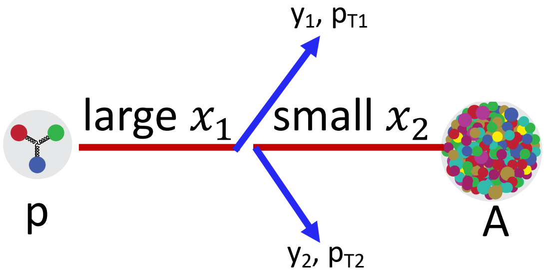
Observable: $C(\Delta\phi) = \frac{N_{pair}(\Delta\phi)}{N_{trig} \times \Delta\phi_{bin}}$



Saturation Signatures

Decrease x, Q^2:

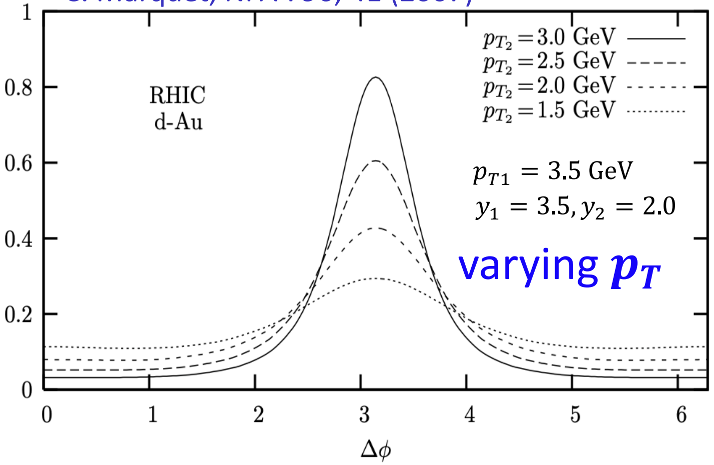
1. More forward direction
2. Lower p_T hadron: very sensitive to p_T



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

$$Q \sim \frac{p_{T1} + p_{T2}}{2}$$

C. Marquet, NPA 796, 41 (2007)



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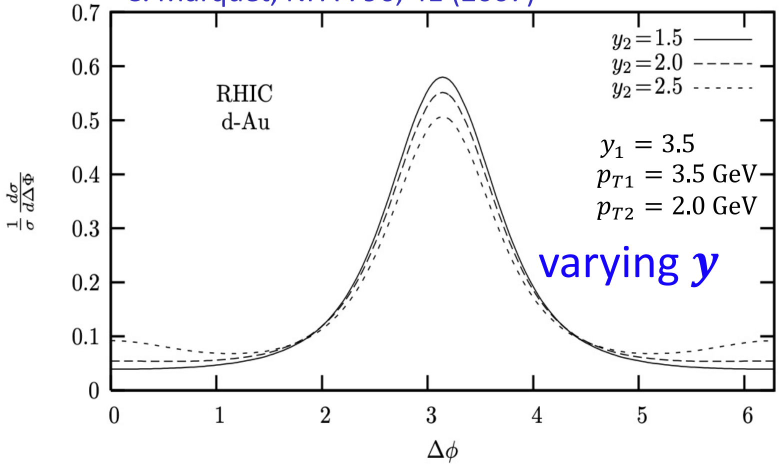

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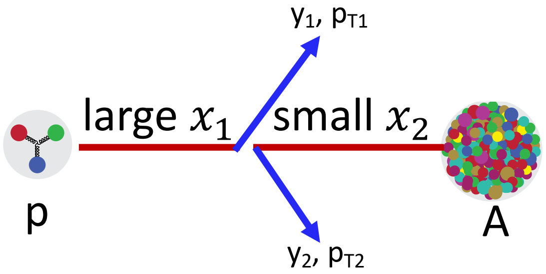

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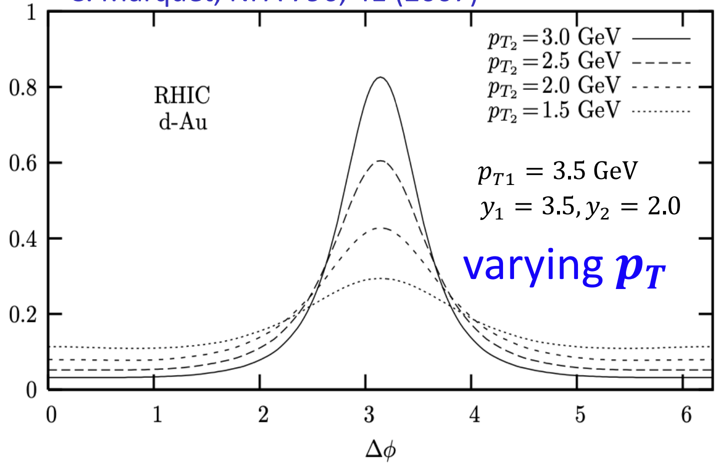

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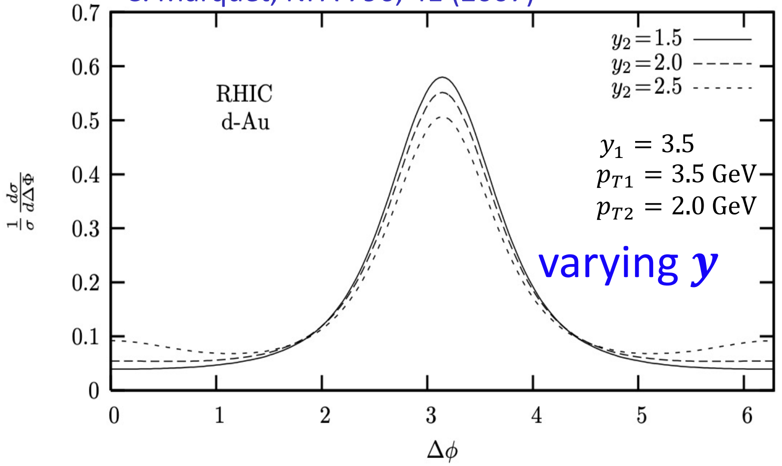
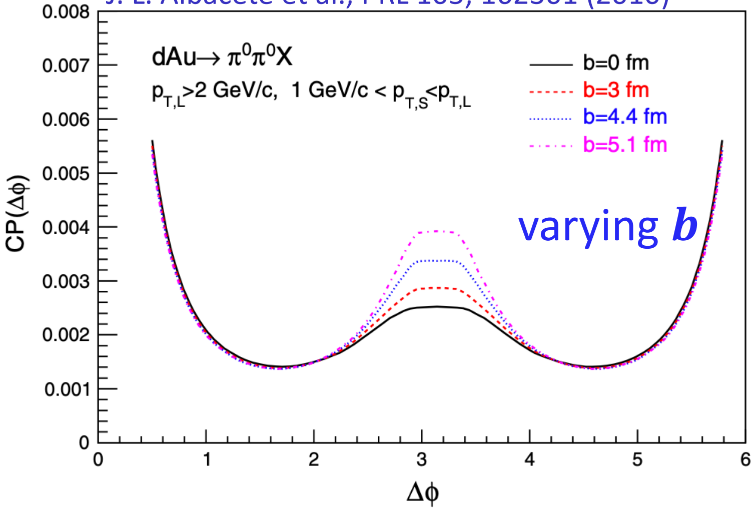


Increase Q_s:

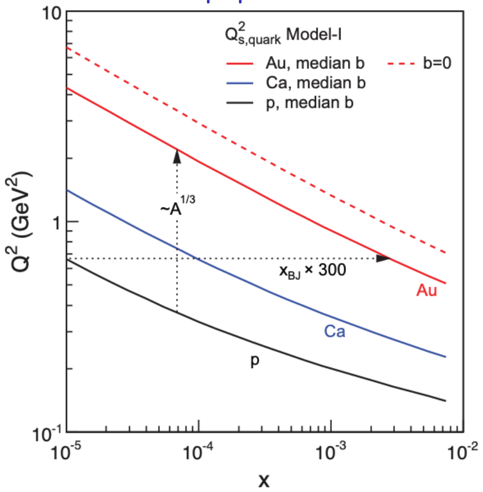
1. More central collisions
2. Heavier nuclei

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



$Q_s \propto T_A(b) \propto 1/b$

EIC white paper



varying A

$Q_s \propto A^{1/3}$

Di-π^0 Measurements at STAR

Measurement

- pp, pAl, pAu and dAu collisions at $\sqrt{s_{NN}} = 200\ GeV$
- NN $\rightarrow \pi^0\pi^0 X,$ detected by FMS ($2.6 \leq \eta \leq 4.0$)

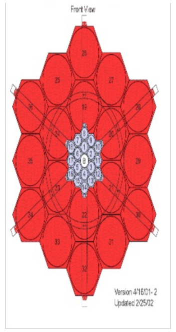
Event Activity (E.A.)

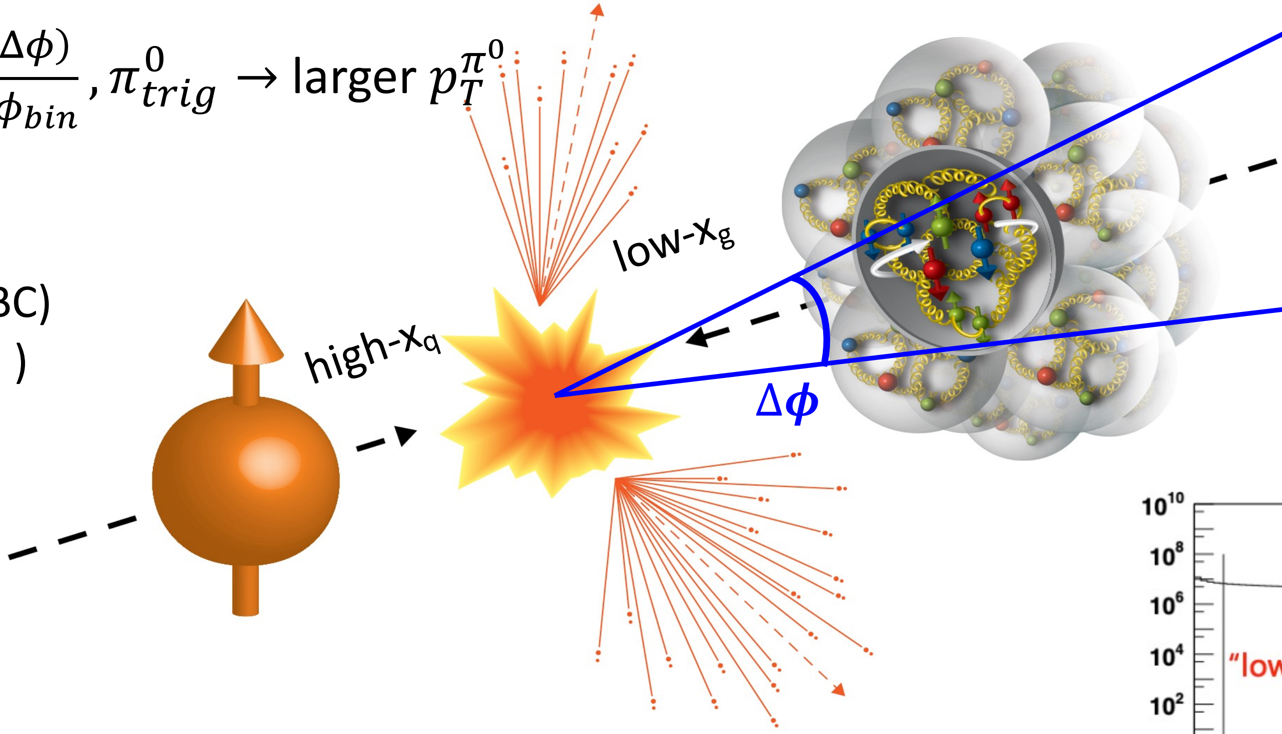
- Energy deposition in BBC characterizes the "centrality" of the collisions

Observable:

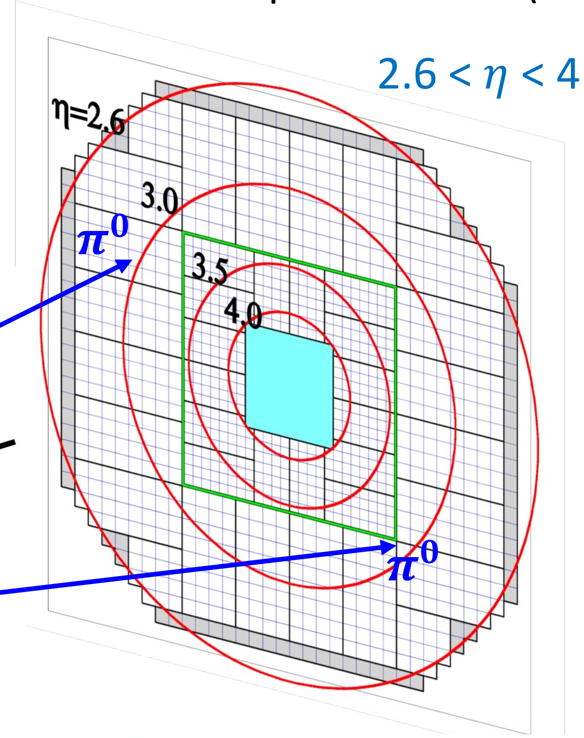
- $C(\Delta\phi) = \frac{N_{pair}(\Delta\phi)}{N_{trig}\Delta\phi_{bin}}, \pi^0_{trig} \rightarrow$ larger $p_T^{\pi^0}$

Beam beam counter (BBC)
(inner BBC: -5< η<-3.3)

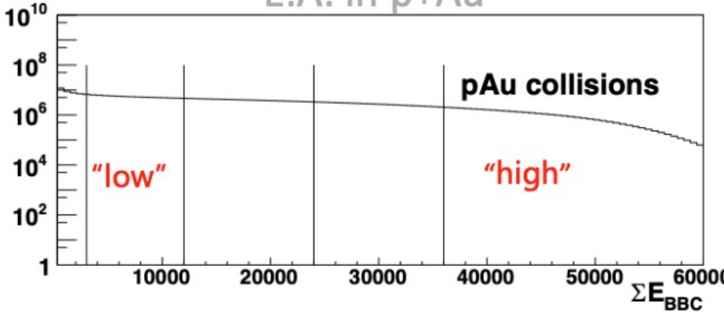




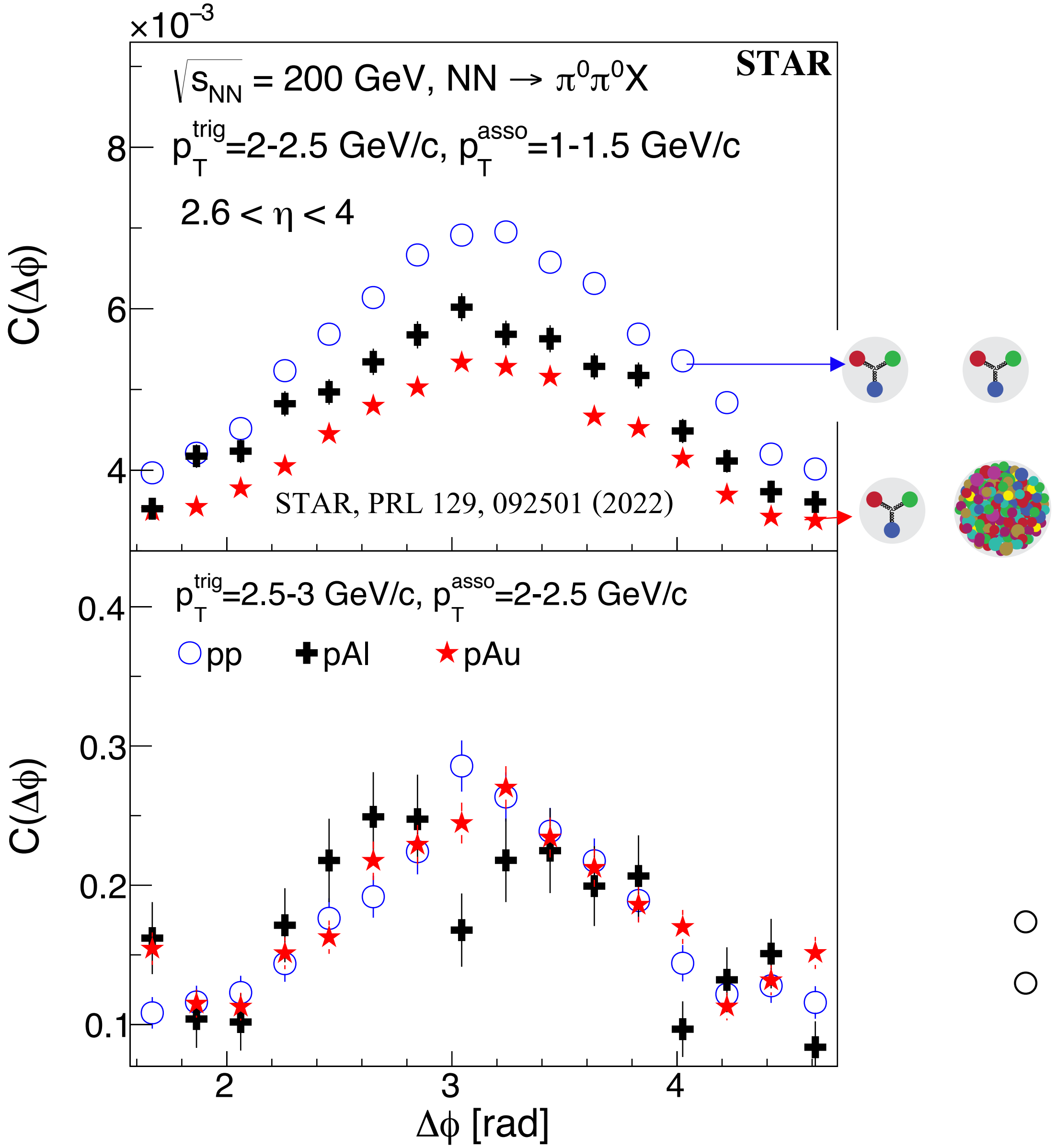
Forward Meson Spectrometer (FMS)

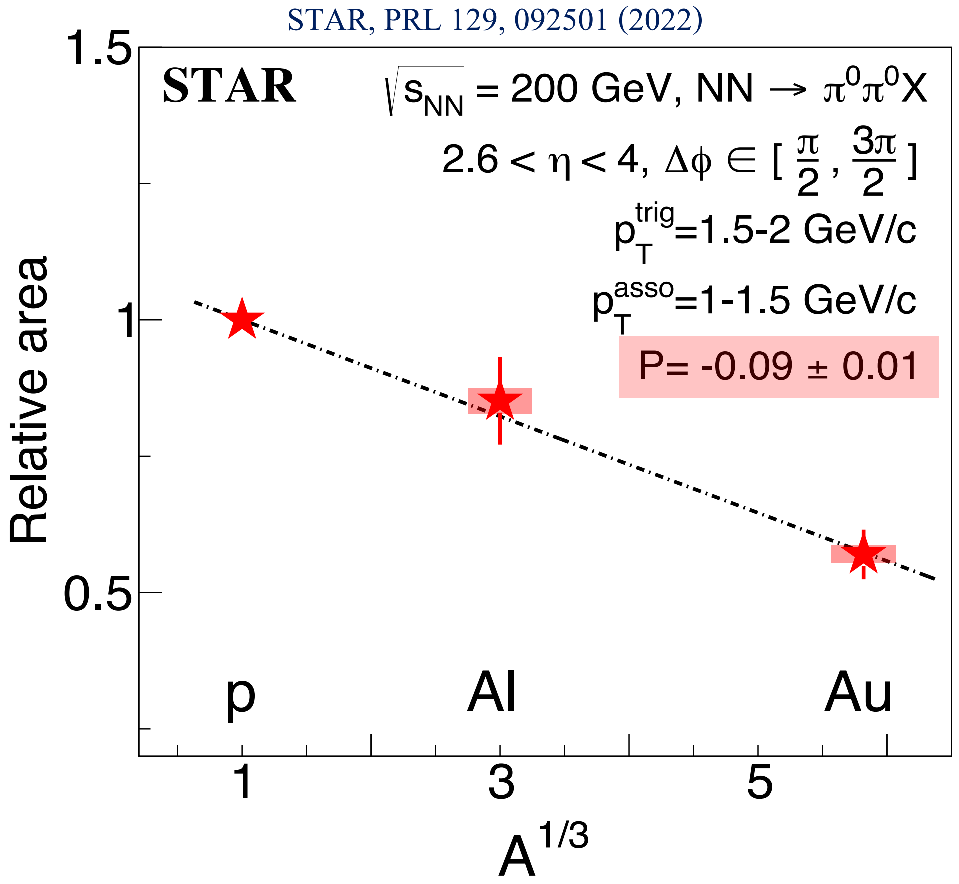


E.A. in p+Au



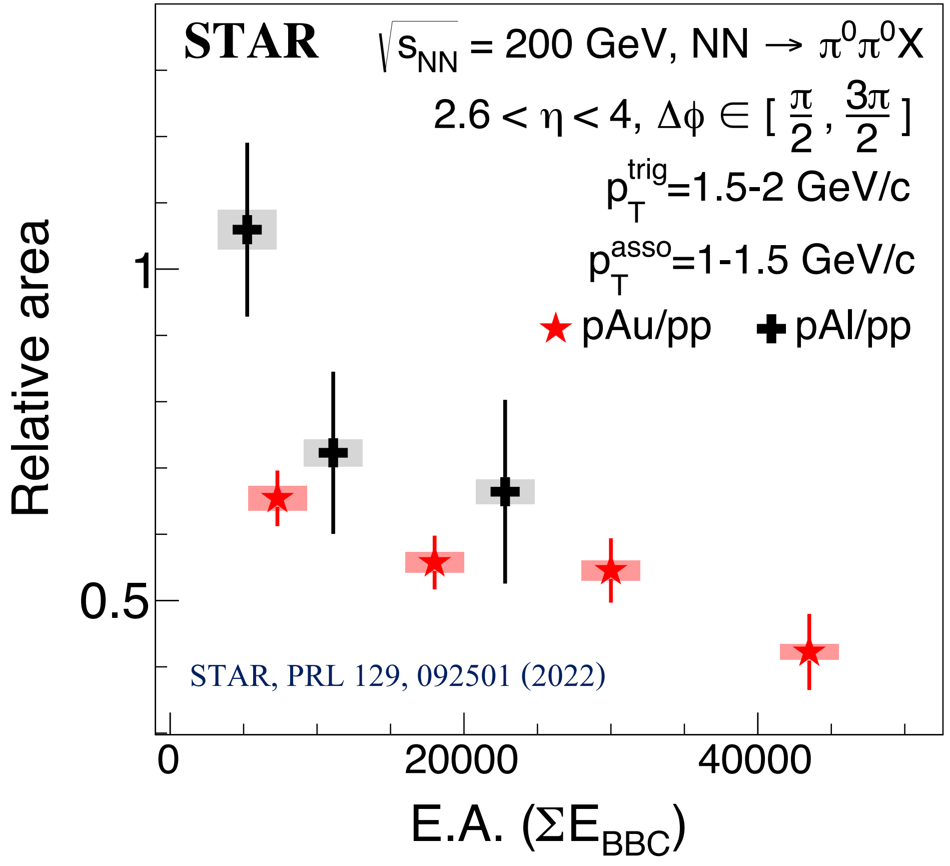
p_T and A Dependence



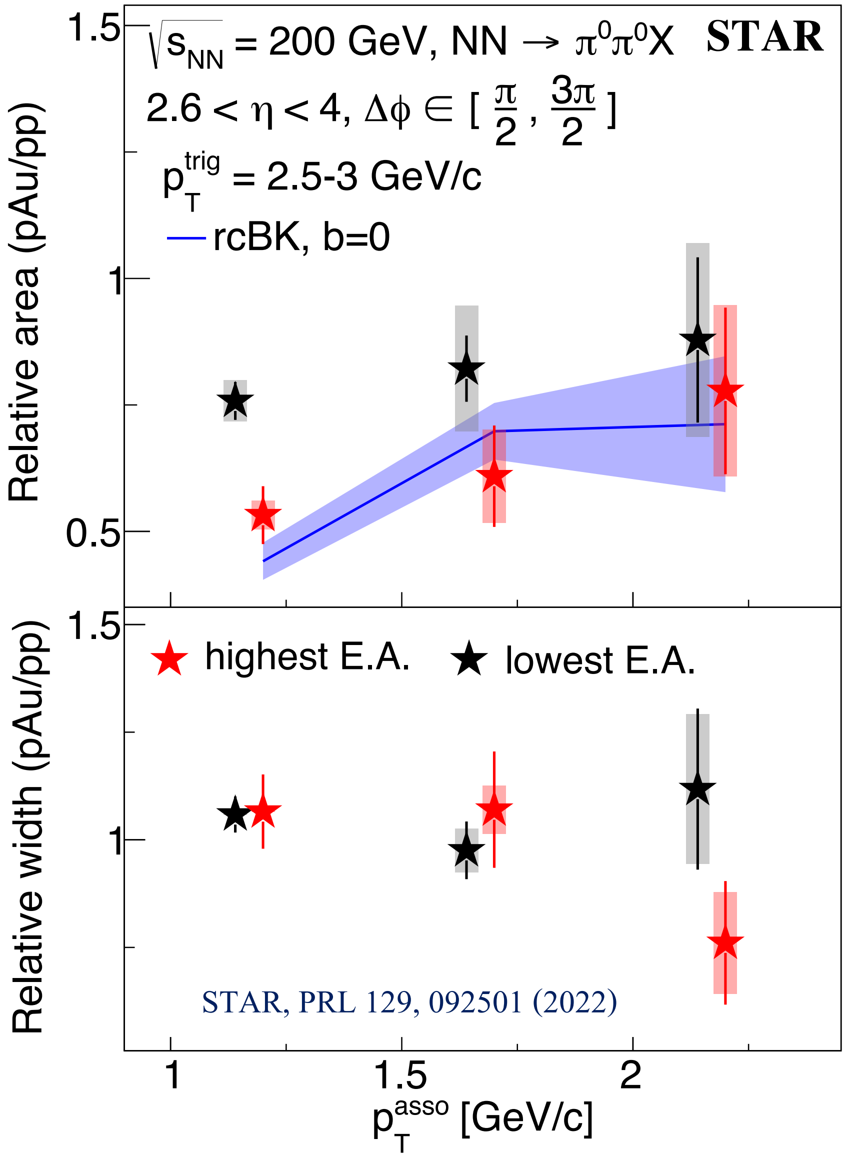


- Suppression observed at low p_T not high p_T
- In fixed $x - Q^2$ phase space, suppression is dominantly affected by various A:
  - Suppression linearly depends on $A^{1/3}$

Event Activity Dependence



rcBK: J. L. Albacete et al.,PRD 99, 014002 (2019)

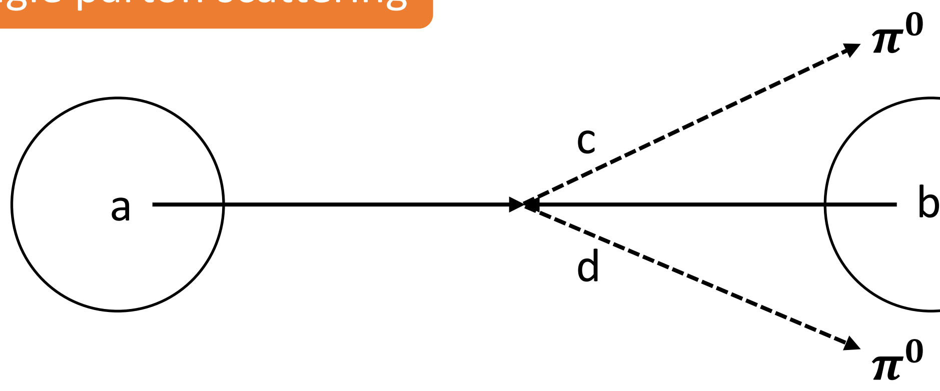


- Suppression increases with E.A., highest E.A. data is consistent with predictions at $b = 0$;
- No broadening is observed

What About dAu?

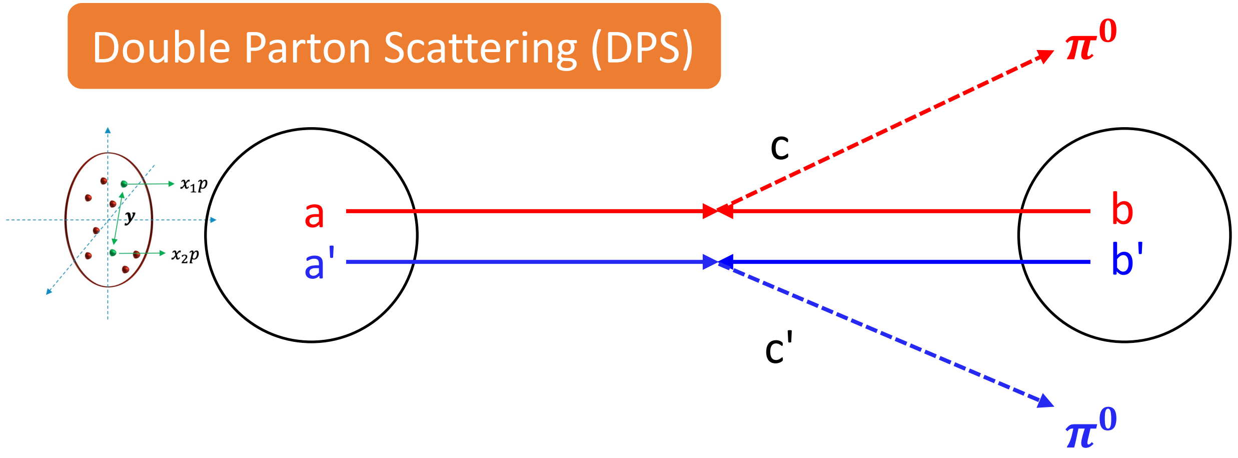
*M. Strikman et al., PRD 83, 034029 (2011)

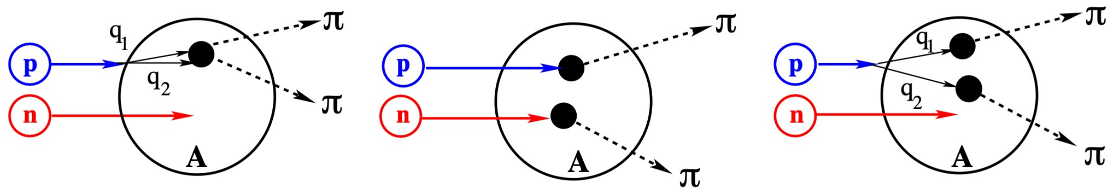
Single parton scattering



Two π^0 generated from the same hard scattering

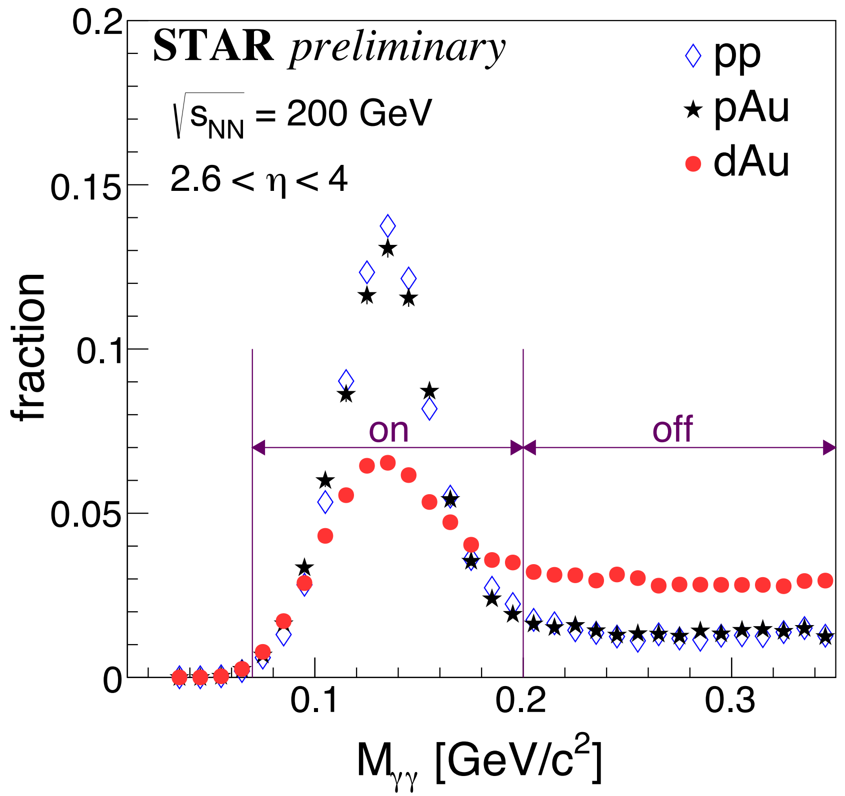
Double Parton Scattering (DPS)

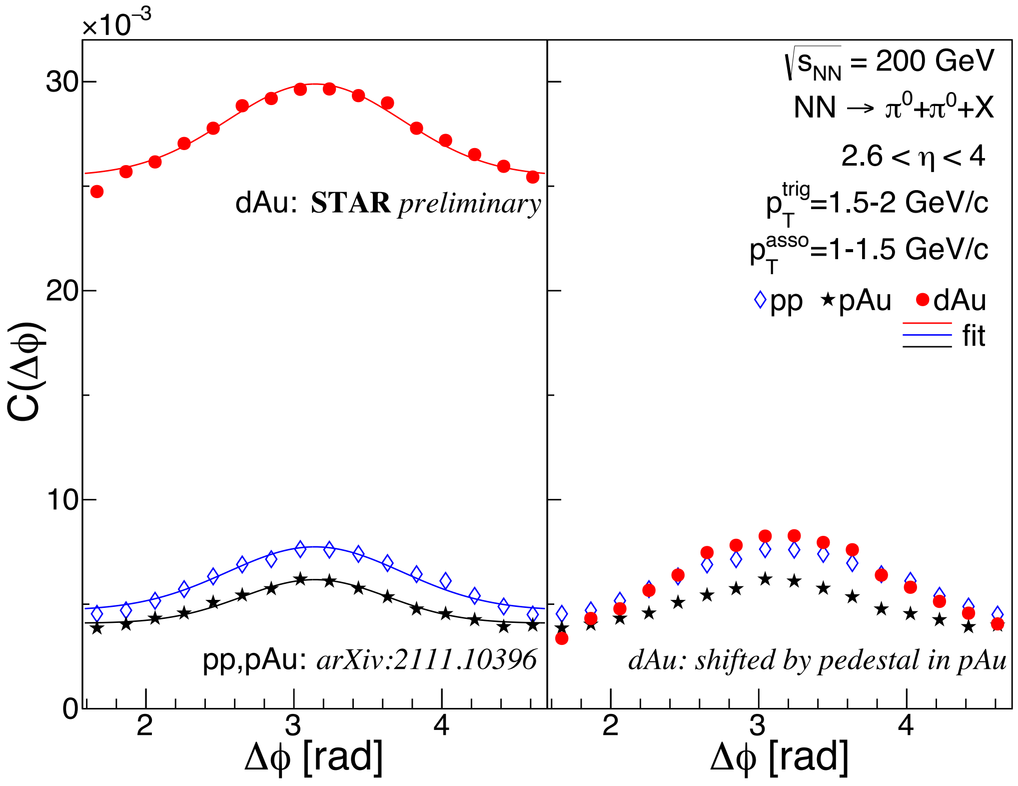




- DPS is predicted* to be enhanced and not negligible at forward rapidities; different in pp, pA and dA
- Open questions: Two π^0 generated from the same or different hard scattering? DPS affects the correlation?

Di-π^0 Measurement in dAu at STAR



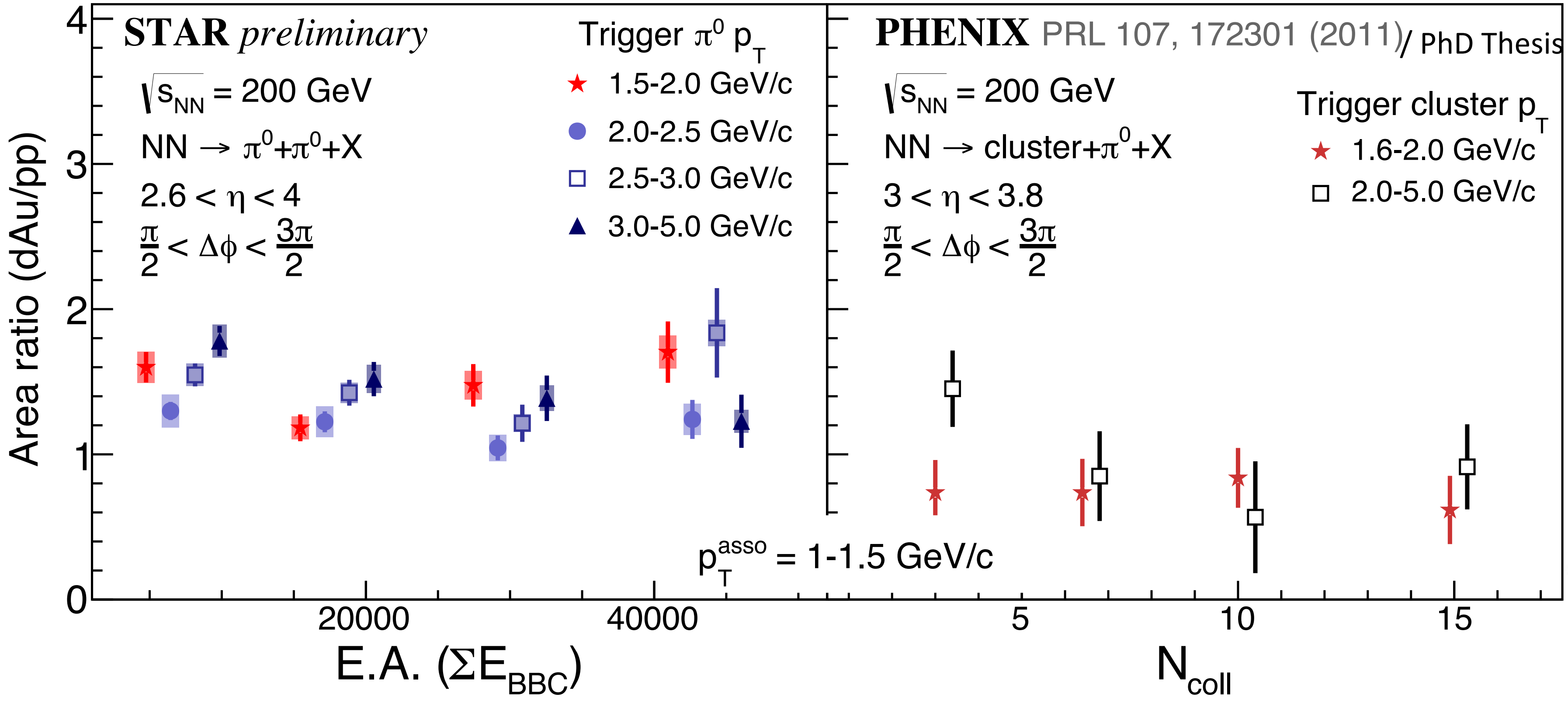


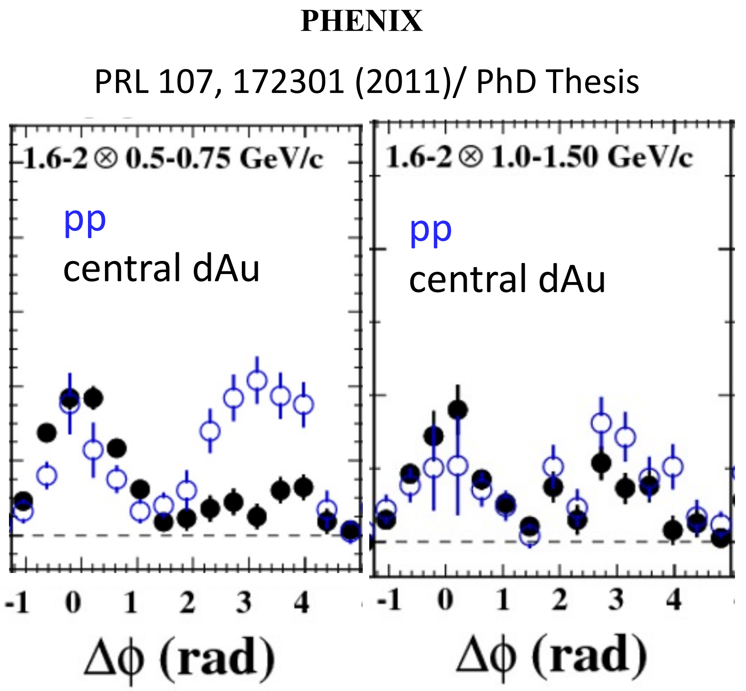
Challenging to conclude the forward di-π^0 correlation measurement in dAu

- π^0 PID: much higher background in dAu than pp and pAu
- Pedestal: much higher in dAu than pp and pAu; stable in pp and pAu

Di-π^0 measurement favors cleaner pA than dA collisions

E.A/ Centrality Dependence in dAu



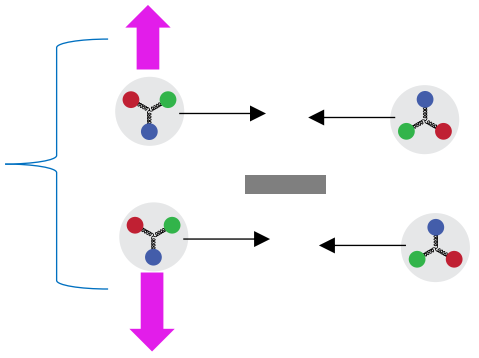


- In the overlapping p_T range (1.6– 5.0 GeV/c) of two collaborations, no clear suppression or E.A./centrality dependence in dAu relative to pp
- Suppression observed only at very low p_T ($p_T^{asso} = 0.5 - 0.75\ \mathrm{GeV}/c$) at PHENIX, where STAR FMS cannot reach

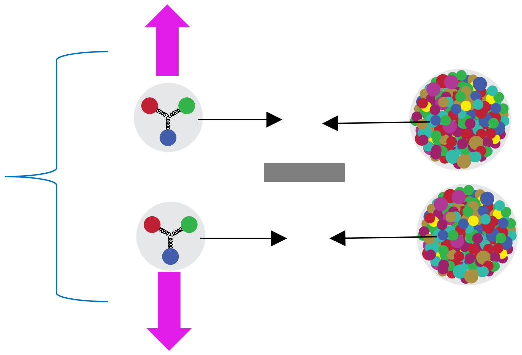
Investigate Saturation via Spin Asymmetries

- The transverse single spin asymmetry, $A_{N,}$ is sensitive to QCD fields near a struck quark, the nuclear dependence of A_N should be sensitive to phenomena that modify the local fields → gluon saturation
- There are predictions that in the saturation region that A_N would scale as $A^{-1/3}$, and scale as A^0 above the saturation region [Phys. Rev. D95 (2017) 014008]

$$A_N(p^{\uparrow}p) = \frac{d\sigma_{pp}^{\uparrow} - d\sigma_{pp}^{\downarrow}}{d\sigma_{pp}^{\uparrow} + d\sigma_{pp}^{\downarrow}}$$



$$A_N(p^{\uparrow}A) = \frac{d\sigma_{pA}^{\uparrow} - d\sigma_{pA}^{\downarrow}}{d\sigma_{pA}^{\uparrow} + d\sigma_{pA}^{\downarrow}}$$



- STAR measured π^0 A_N and its nuclear dependence in transversely polarized pp, pAl, and pAu collisions $\sqrt{s_{NN}} = 200\ GeV$ in the FMS [Phys. Rev. D103 (2021) 072005]

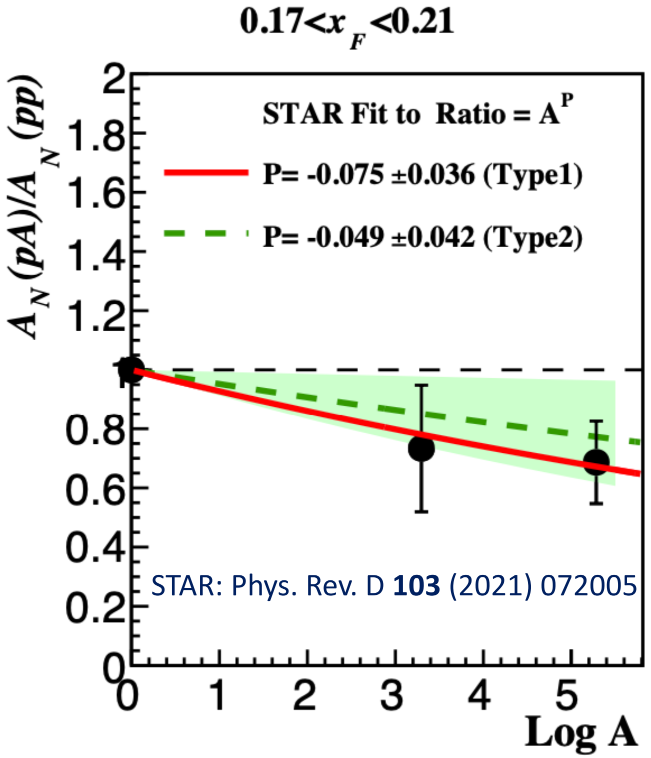
A_N Nuclear Dependance

STAR Summary

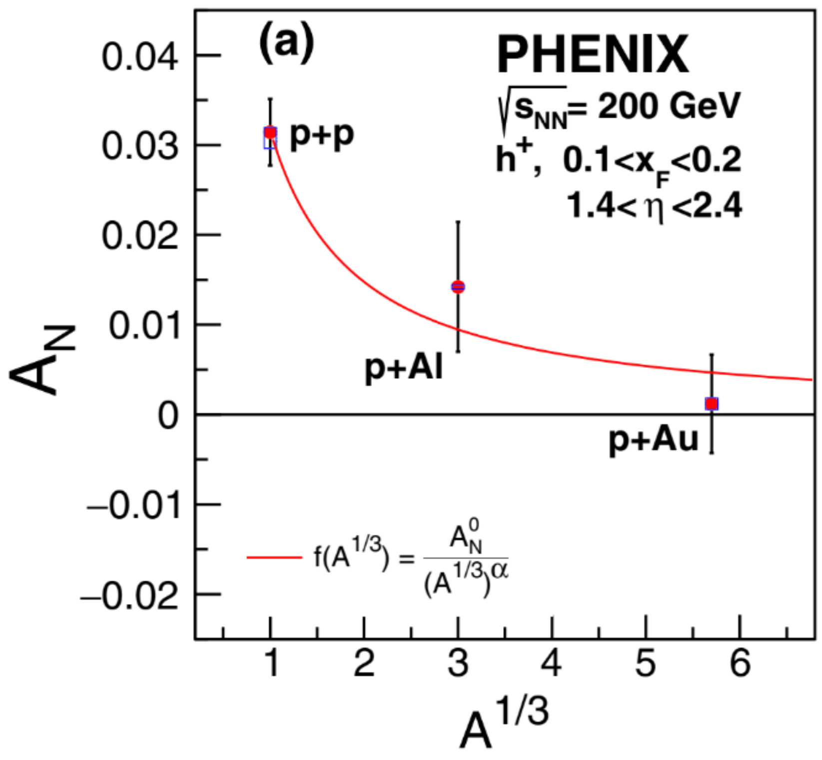
- Measured A_N for π^0
- $2.6 \leq \eta \leq 4.0$
- $0.17 \leq x_F \left(= 2\frac{p_L^h}{\sqrt{s}}\right) \leq 0.81$
- $1.5\,\frac{GeV}{c} \leq p_T \leq 7.0\,\frac{GeV}{c}$
- <P> $= -0.06 \pm 0.04$

PHENIX Summary

- Measured A_N for positively charged hadrons
- $1.4 \leq \eta \leq 2.4$
- $0.1 \leq x_F \left(= 2\frac{p_L^h}{\sqrt{s}}\right) \leq 0.2$
- $1.8\ GeV/c \leq p_T \leq 7.0\ GeV/c$
- Fits from PHENIX measurements favor exponent P = $-0.37^{+0.12}_{-0.23}$

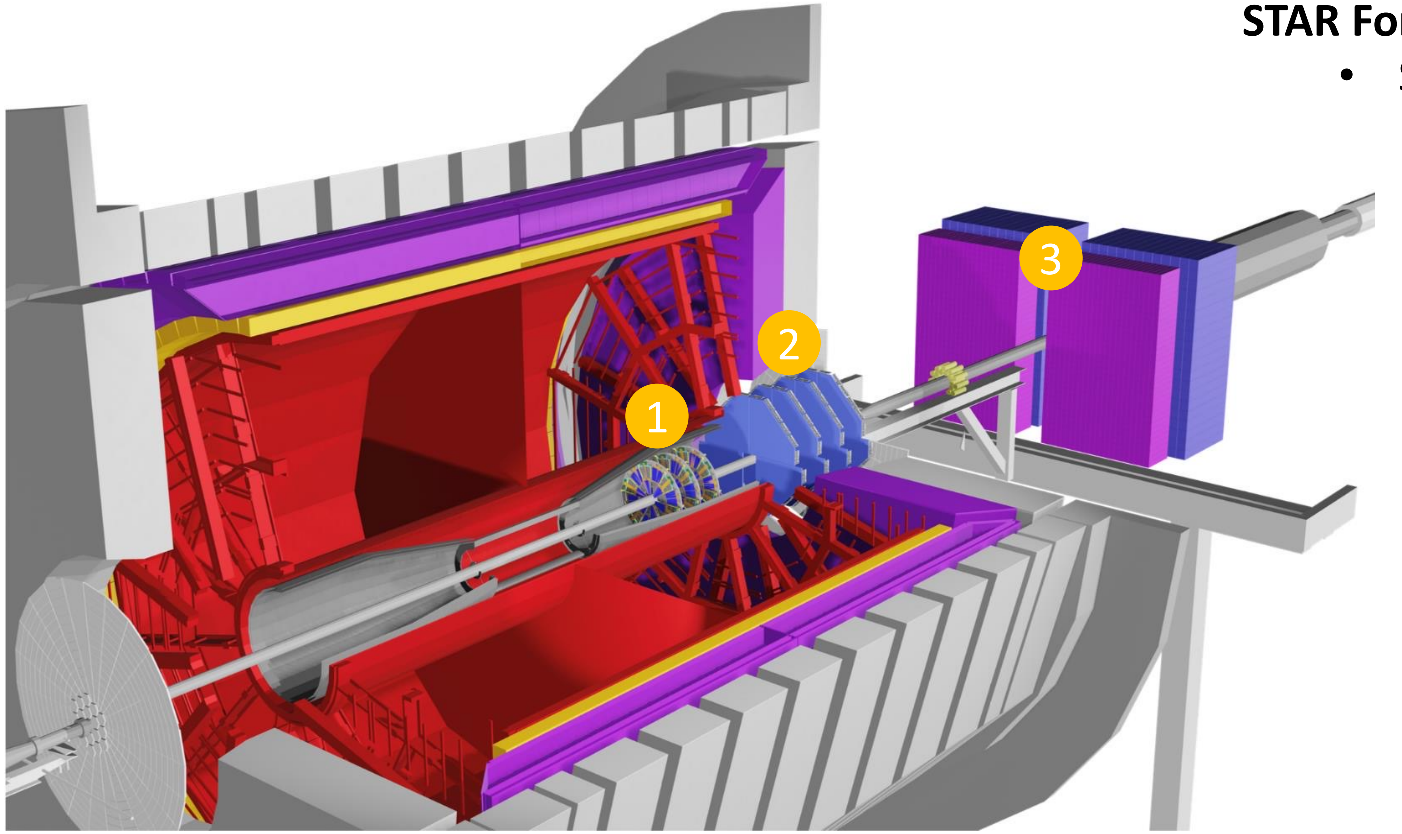


PHENIX: PRL 123 (2019) 122001



- STAR observes weaker nuclear dependence than PHENIX
- More **pp and pA** data is **critical** to understanding observed behavior

Future Measurements with STAR Forward Detector



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 Detector: 2.5 < η < 4

- Successfully completed its commissioning run in 2022

Three new systems:

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

Future STAR data with forward detector

Year	System	$\sqrt{s}$ (GeV)
2023	Au+Au	200
2024	p+p, p+Au	200
2025	Au+Au	200

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

- Di-$h^{+/-}$: access lower p_T down to 0.2 GeV/c
- Di-jet
- Direct photon (-jet)
- Forward $h^{+/-}$ A_N

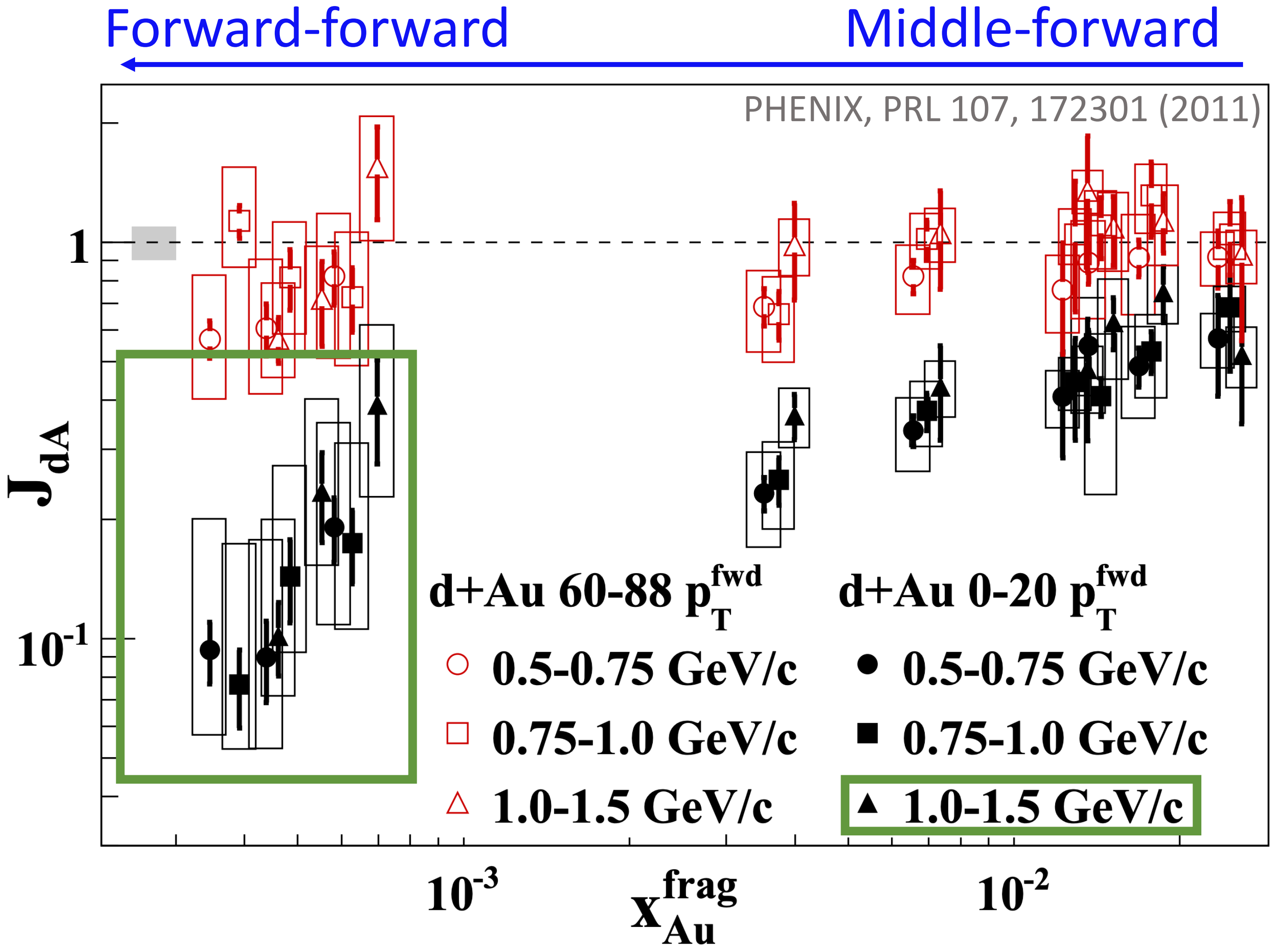
Summary

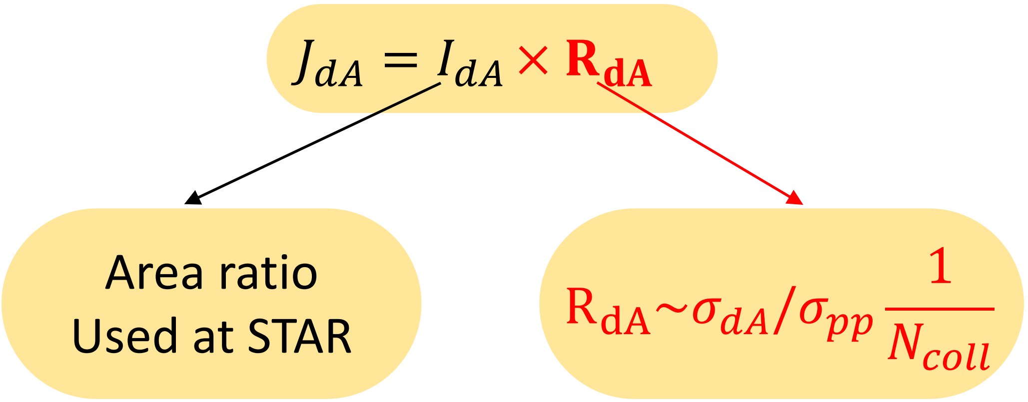
- Di-hadron measurements at RHIC provide insights into the understanding of nonlinear gluon dynamics in nuclei
- Di-hadron measurements favors ”cleaner” pAu collisions rather than dAu collisions
- A_N measurements at RHIC provide additional observables to study gluon dynamics in nuclei
- New STAR Forward detector allows for nonlinear gluon dynamics to be investigated beyond π^0 observables.

Additional pp/pA running at RHIC is critical to understanding physics

Backup

Normalization in d+Au from PHENIX



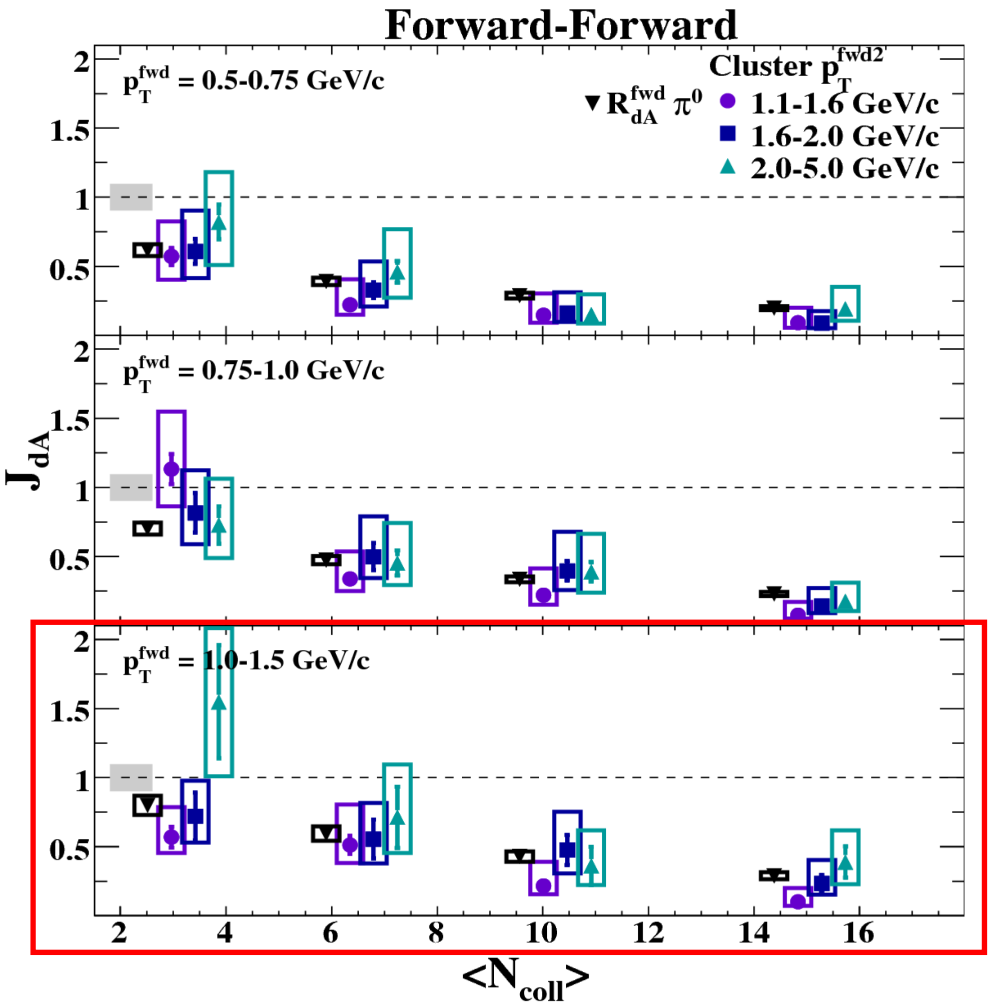


$R_{dA} \sim \frac{2}{N_{coll}}$, $N_{coll} = 15.1$ for central collisions

How to describe suppression?

[From PhD Thesis]

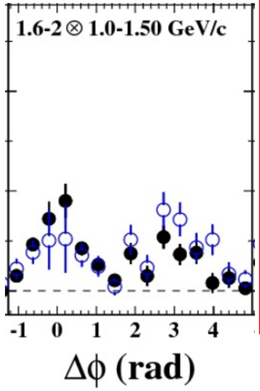
PHENIX, PRL 107, 172301

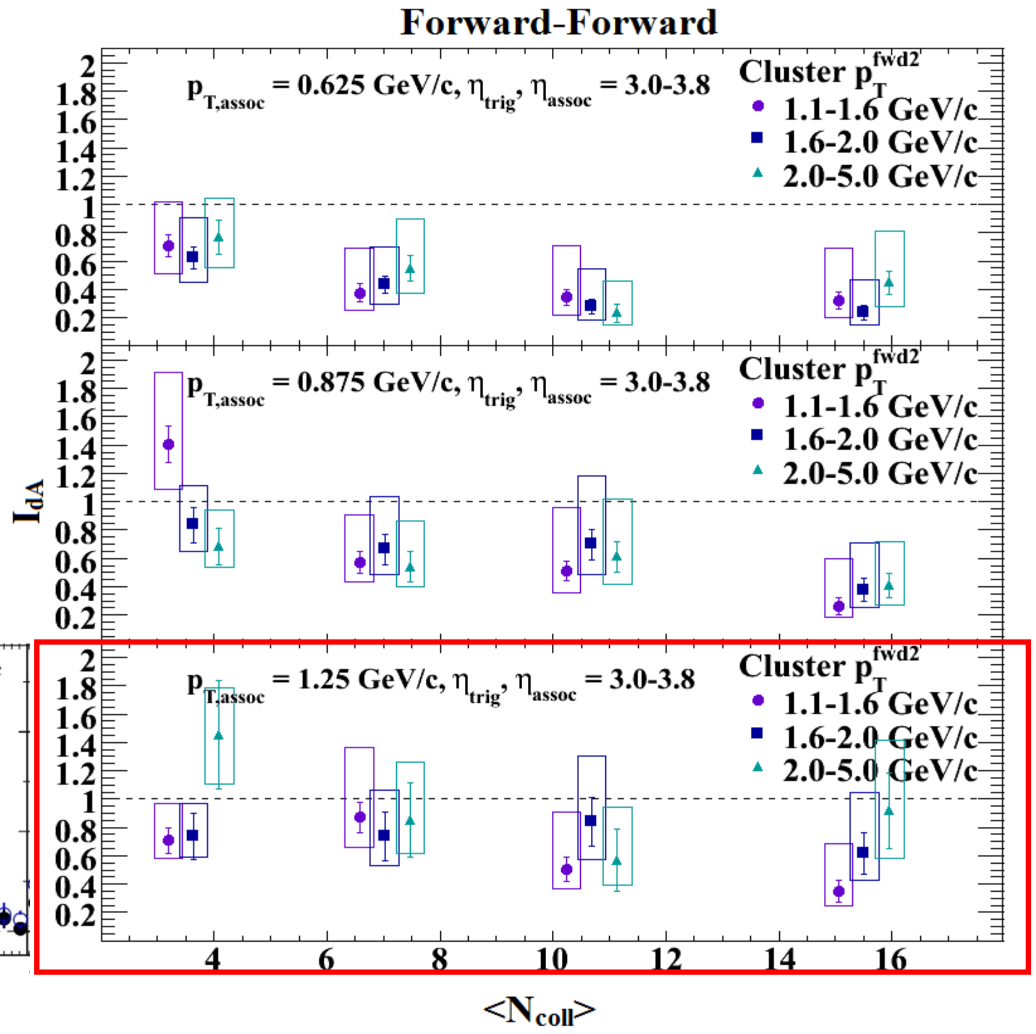


$J_{dA} = I_{dA} * R_{dAu}$

I_{dA} = area ratio

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





- In the highest associated p_T bin (red box), no clear suppression or centrality dependence is observed