MPI@LHC 2022

# Back-to-back di-$\pi^0$ azimuthal correlations at forward rapidities at STAR

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Brookhaven National Laboratory
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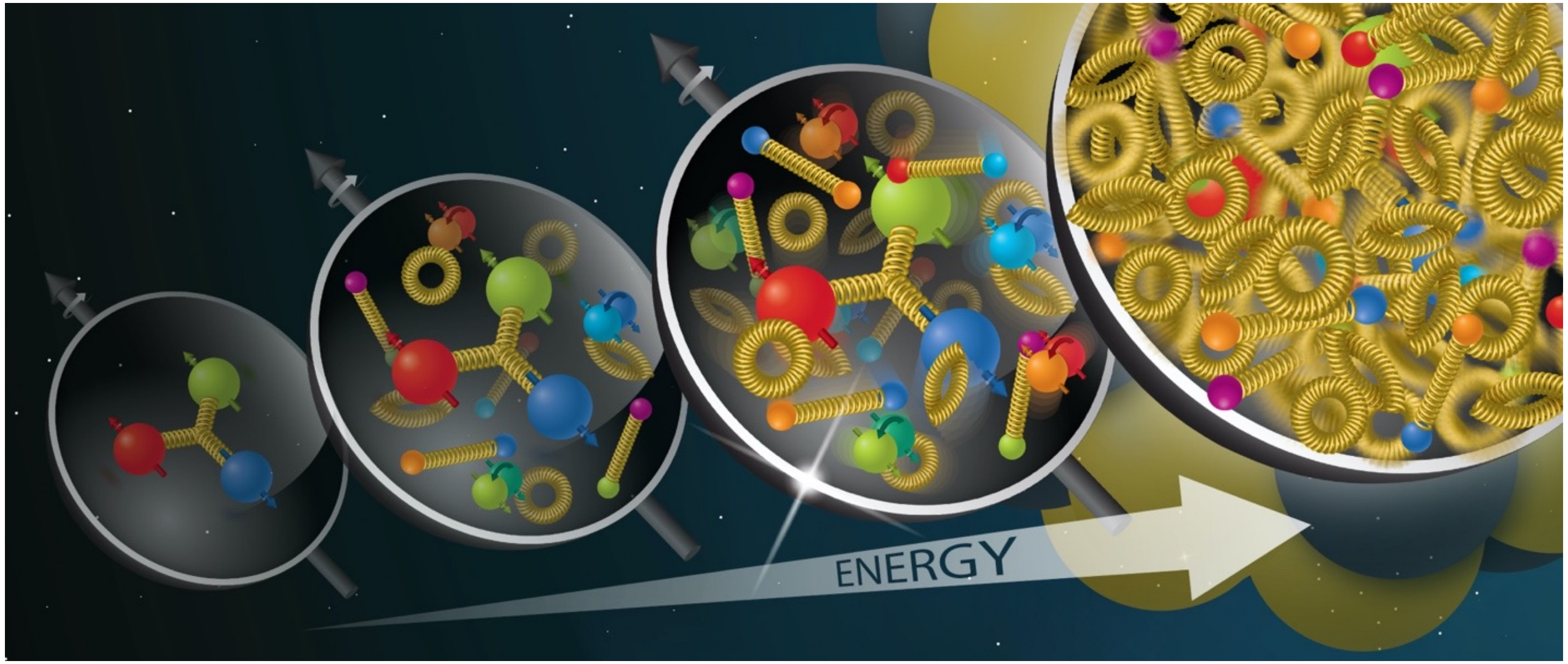
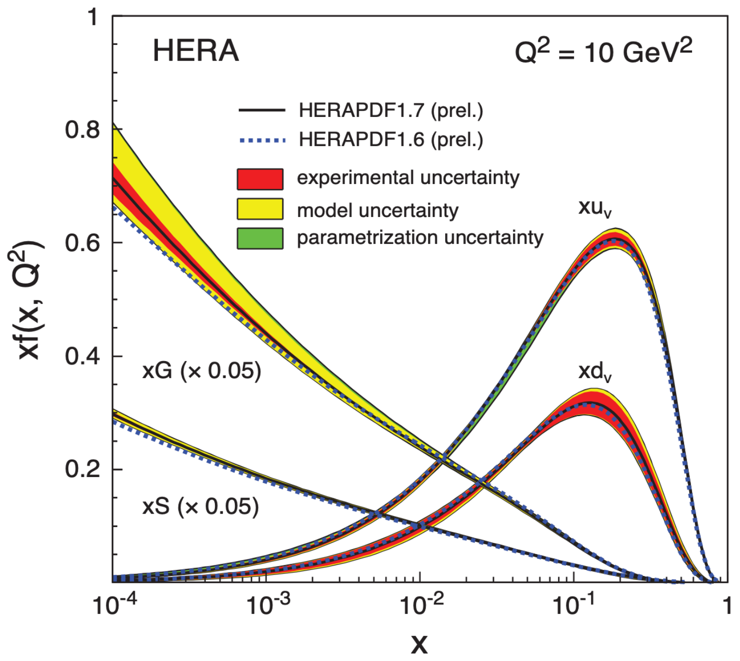
# High gluon density in nucleon

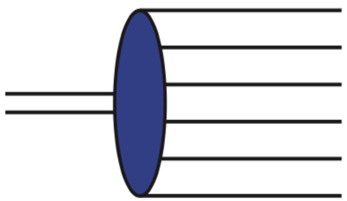



- One can “take snapshots” of partonic structure of the proton with a probe particle in high energy collisions
- Results from DIS: gluon density rapidly increases towards small $x$, which can be explained by gluon splitting

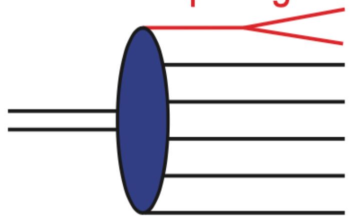
# Gluon saturation

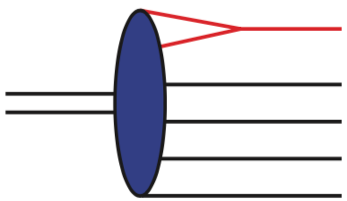
Gluon density



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

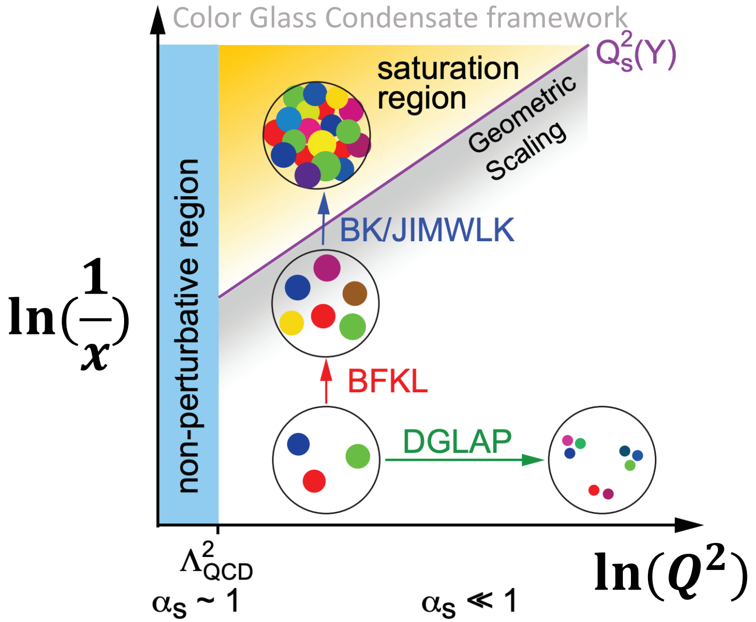
Balitsky-Kovchegov (BK) evolution equation




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

linear — nonlinear



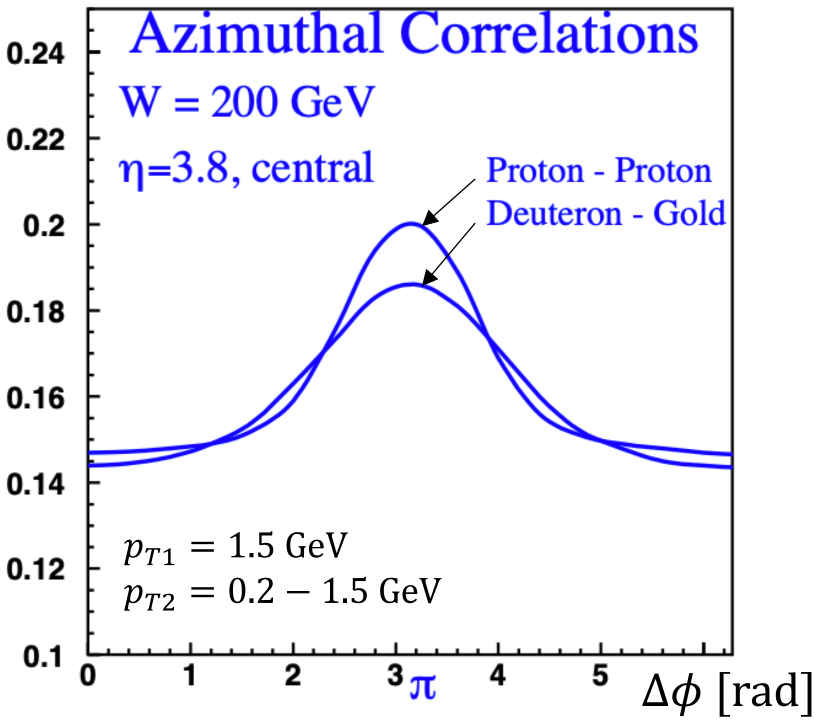

- The rapid increase of gluon density: gluon splitting → linear evolution
- Increase should be tamped at a certain point: gluon recombination → non-linear evolution
- A new regime of QCD: gluon saturation ($Q^2 < Q_s^2$) when gluon recombination = gluon splitting
- Saturation region is easier to be reached in heavier nuclei: $Q_s \propto A^{1/3}$

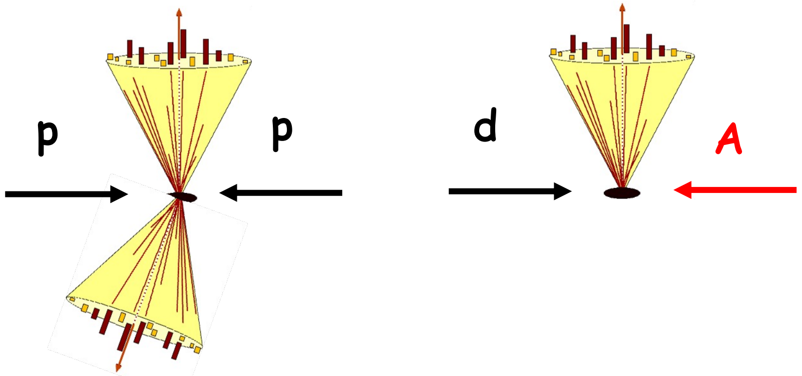
How to probe nuclear gluon distributions at saturation region?

# Di-hadron measurement in d+Au

- Color Glass Condensate successfully described the strong suppression of the **inclusive hadron yields** in d+Au relative to p+p owning to gluon saturation effects → nuclear modified fragmentation serves as another interpretation?

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




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

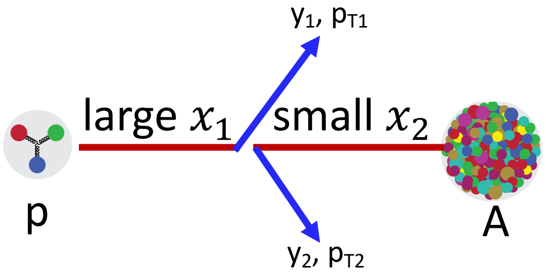
- Di-hadron in p+p as baseline: 2-to-2 process

- Suppression of away-side peak in d+A relative to p+p as a saturation signature

# Saturation signatures on $p_T, y, b, A$

**Decrease $x, Q^2$:**

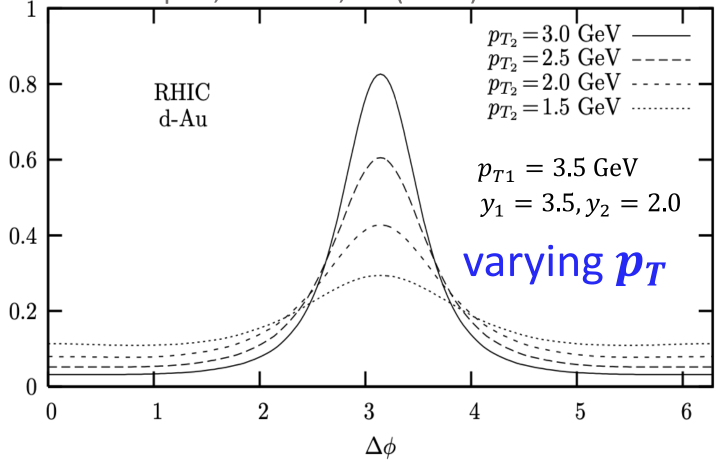
1. More forward direction
2. Lower $p_T$ hadron



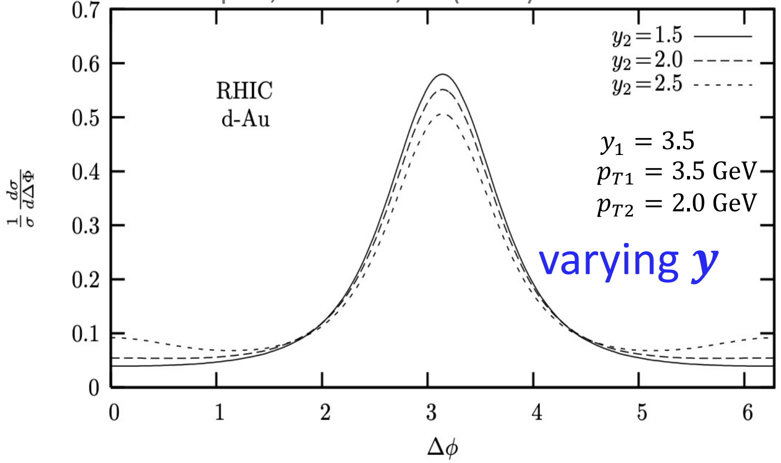

$$x_2 \sim \frac{p_{T1}e^{-y_1} + p_{T2}e^{-y_2}}{\sqrt{s}}$$

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

C. Marquet, NPA 796, 41 (2007)




C. Marquet, NPA 796, 41 (2007)



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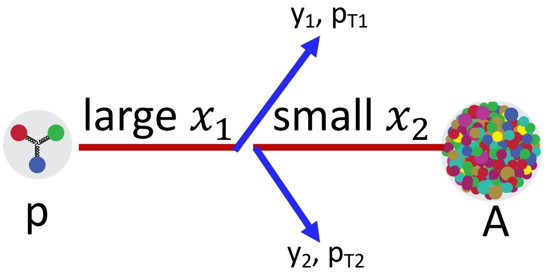


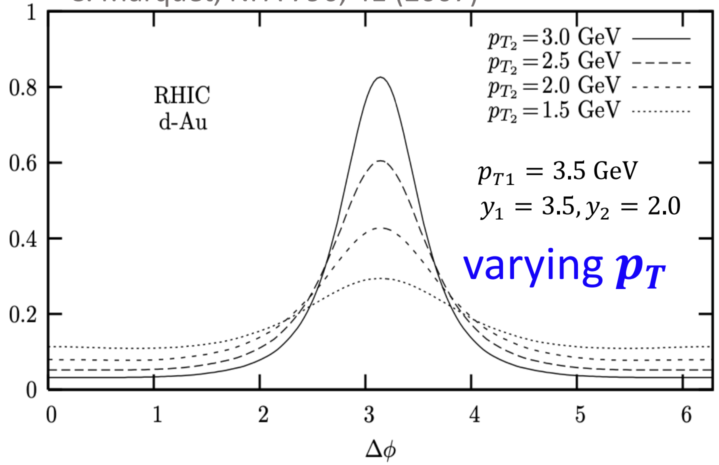

$$x_2 \sim \frac{p_{T1} e^{-y_1} + p_{T2} e^{-y_2}}{\sqrt{s}}$$

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

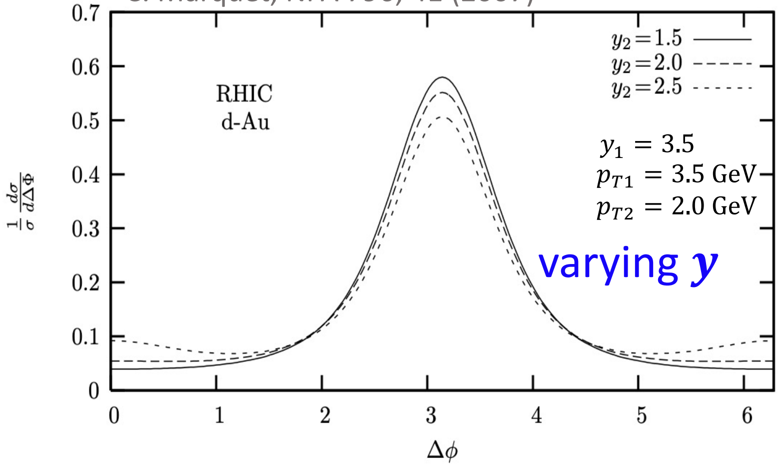
**Increase $Q_s$:**

1. More central collisions
2. Heavier nuclei

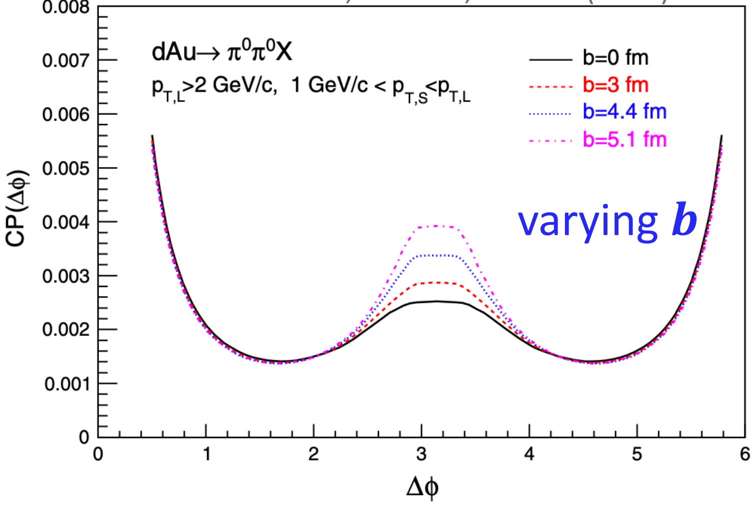
C. Marquet, NPA 796, 41 (2007)




C. Marquet, NPA 796, 41 (2007)

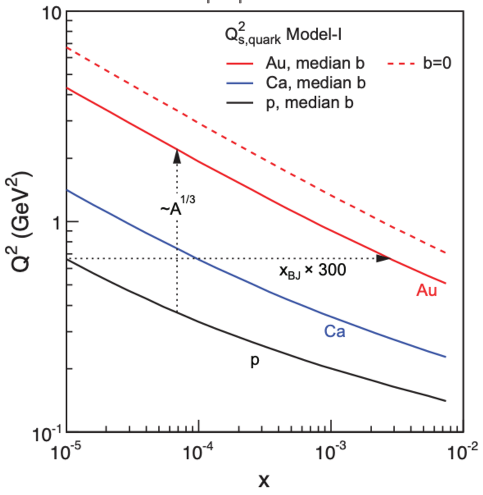



J. L. Albacete et al., PRL 105, 162301 (2010)




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

EIC white paper

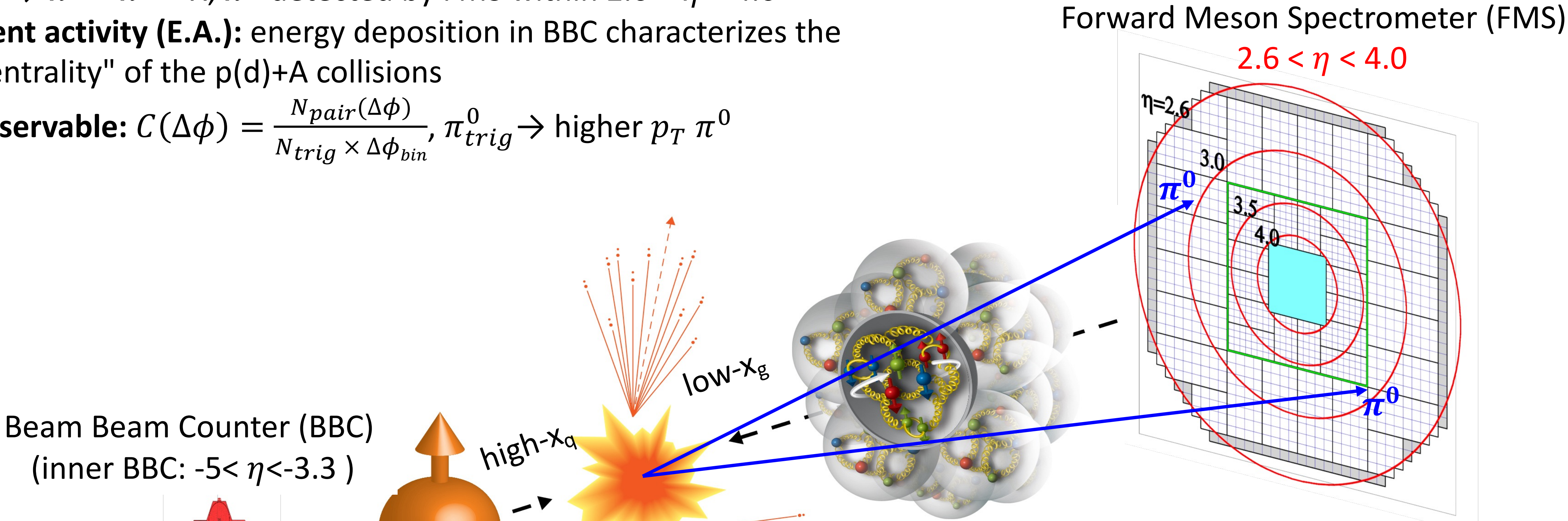


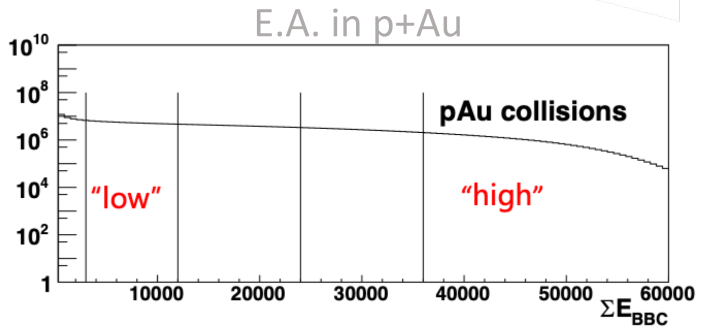

varying $A$

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

# Di-$\pi^0$ measurement at STAR

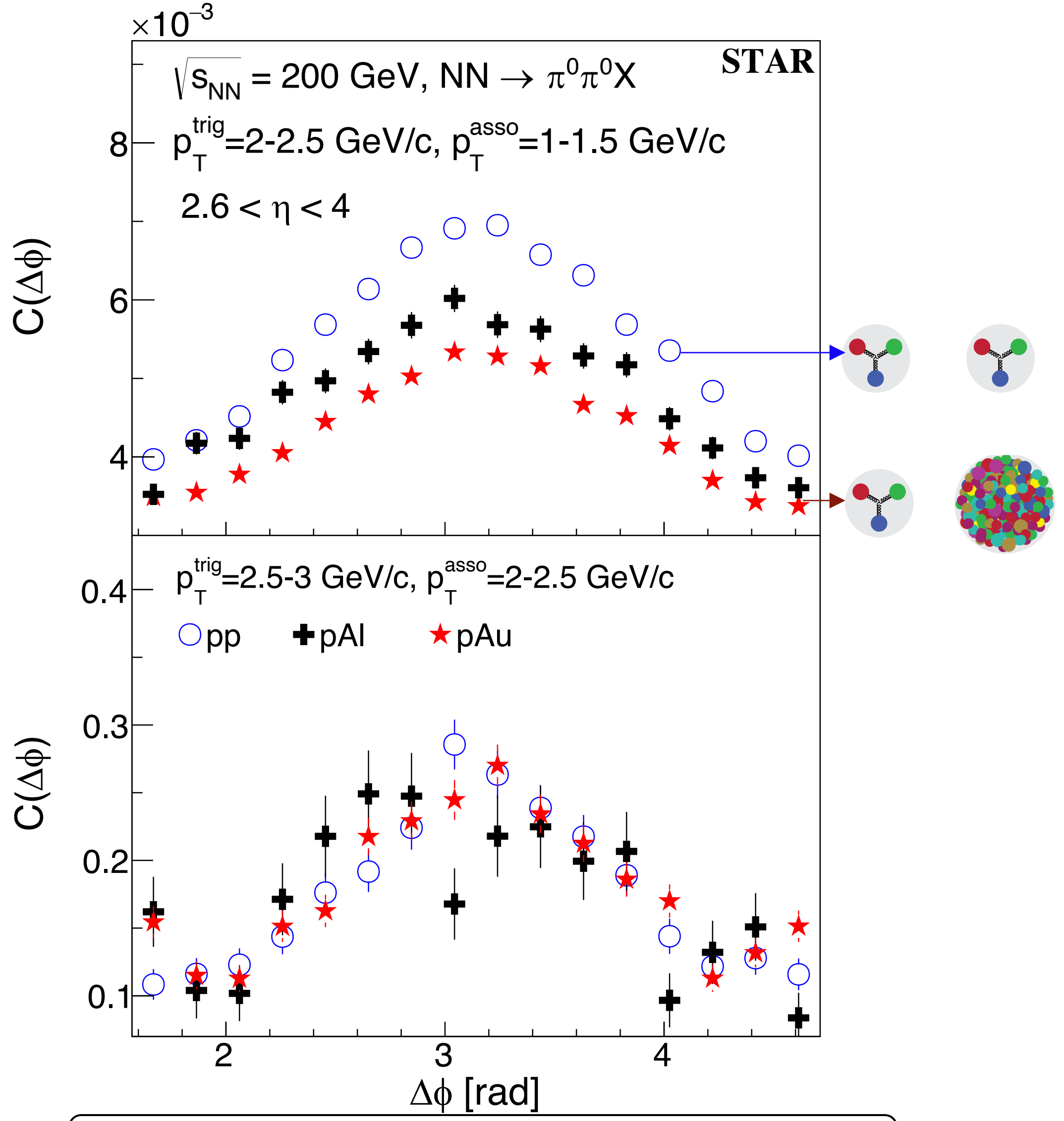
- p+p, p+Al, p+Au and d+Au collisions at $\sqrt{s_{NN}} = 200$ GeV
- NN → $\pi^0 + \pi^0$ + X, $\pi^0$ detected by FMS within 2.6 < $\eta$ < 4.0
- **Event activity (E.A.):** energy deposition in BBC characterizes the "centrality" of the p(d)+A collisions
- **Observable:** $C(\Delta\phi) = \frac{N_{pair}(\Delta\phi)}{N_{trig}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



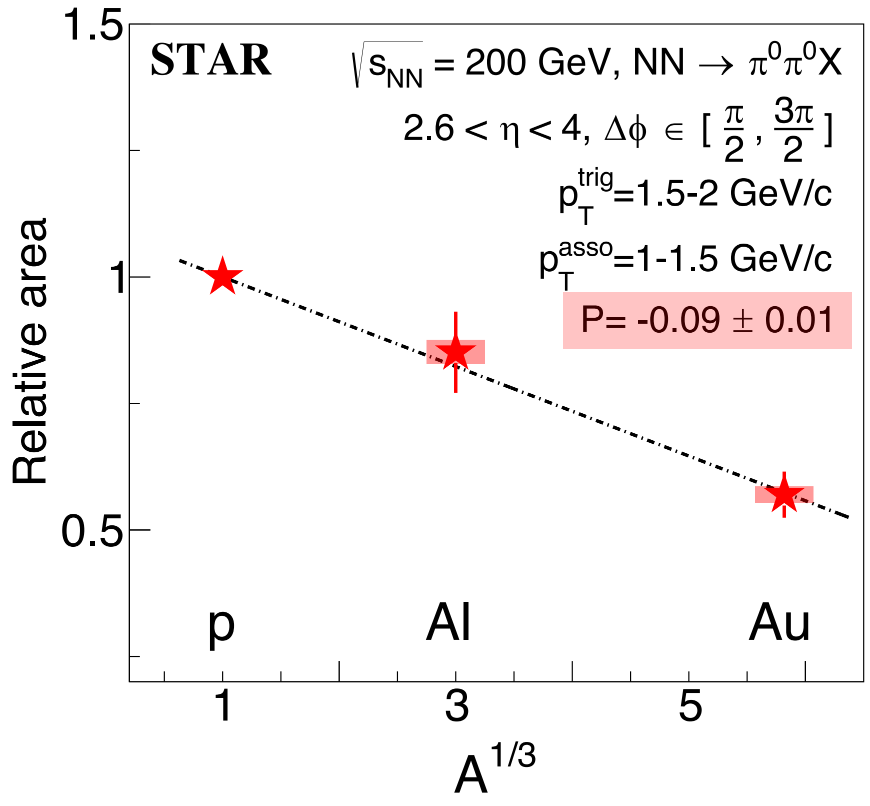



STAR, PRL 129, 092501 (2022)

# $p_T$ and A dependence



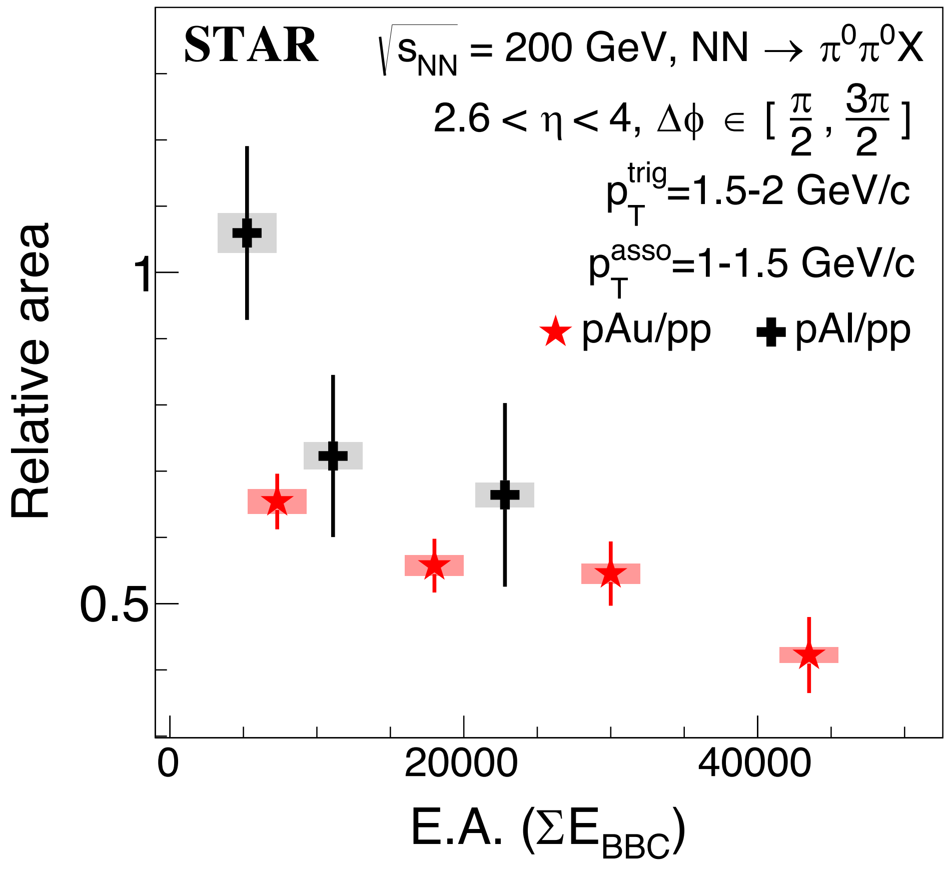

Gaussian (area and width) at $\Delta\phi = \pi$ + pedestal



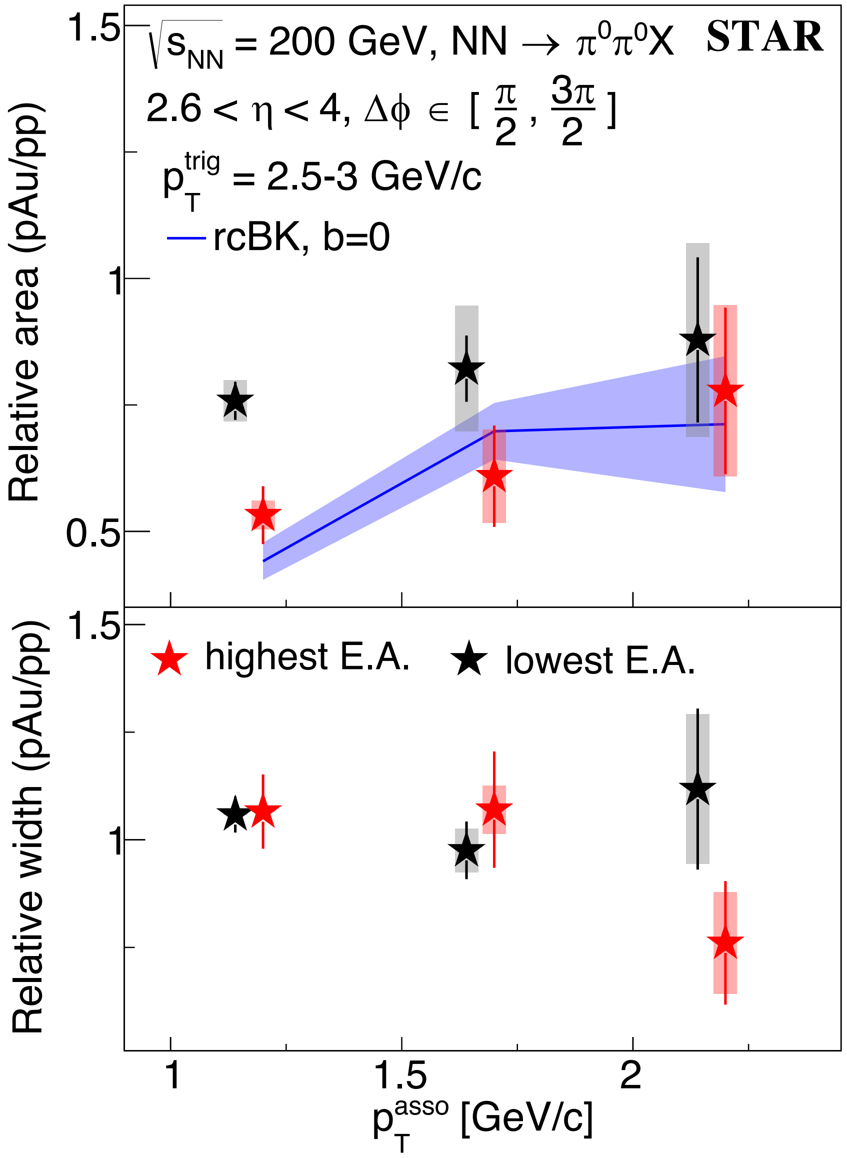

- Suppression observed at low $p_T$ not high $p_T$
- In fixed $x - Q^2$ phase space, suppression is dominantly affected by $A$:
  - Suppression linearly depends on $A^{1/3}$

STAR, PRL 129, 092501 (2022)

# E.A. dependence




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

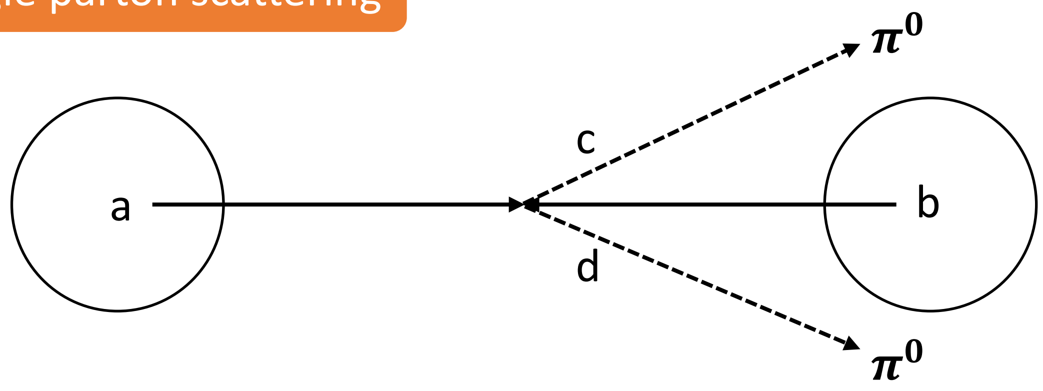



- Suppression increases with E.A.
  - Highest E.A. data is consistent with predictions at $b = 0$
  - E.A. is not identical to centrality
- No broadening is observed

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

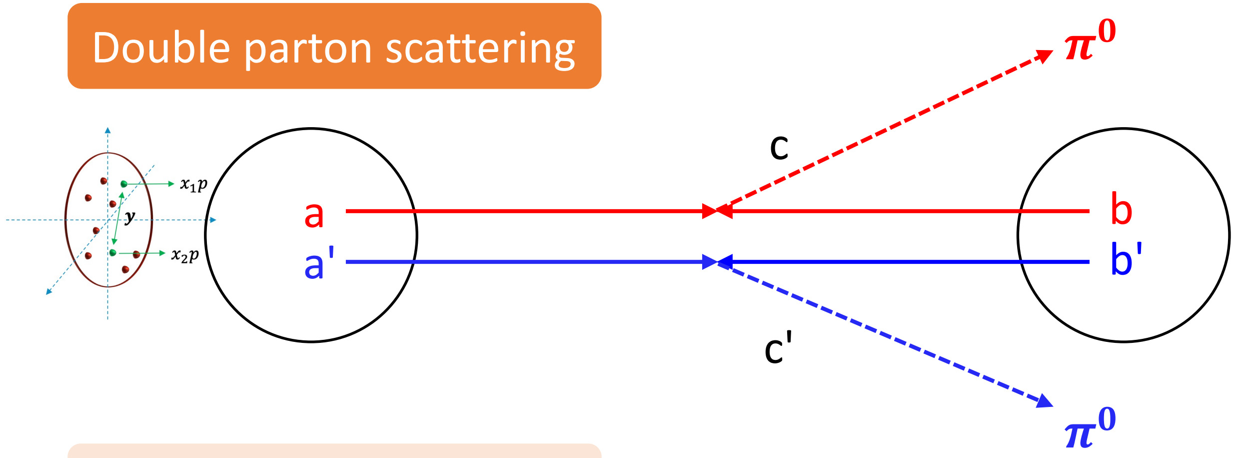
# How about d+Au?

Single parton scattering

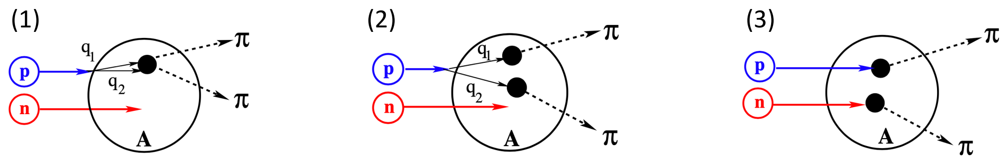



Two $\pi^0$ generated from the same hard scattering

Double parton scattering

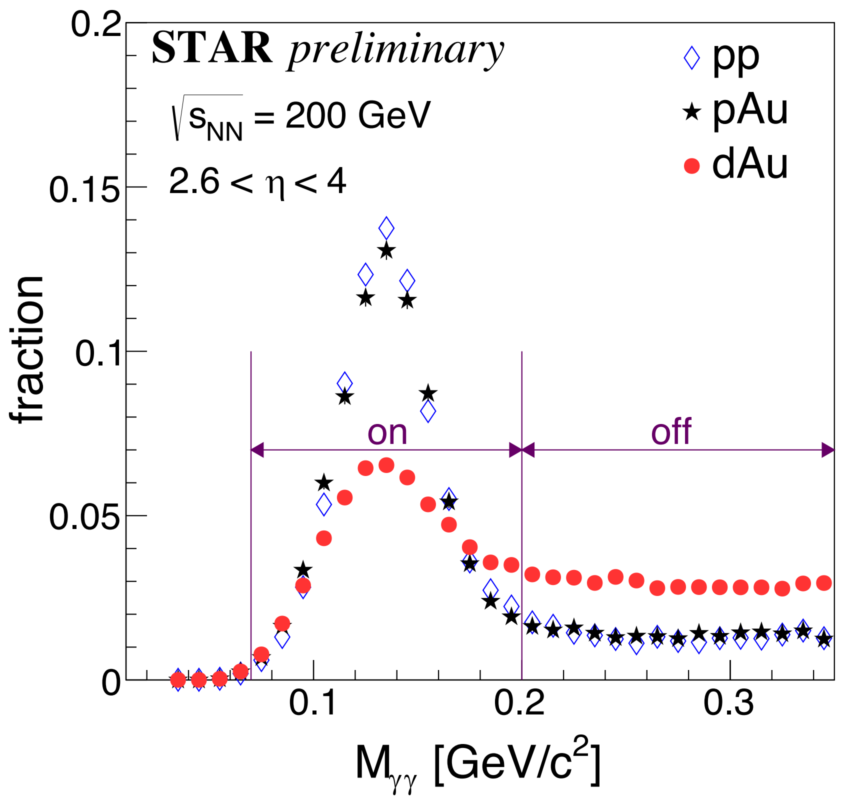


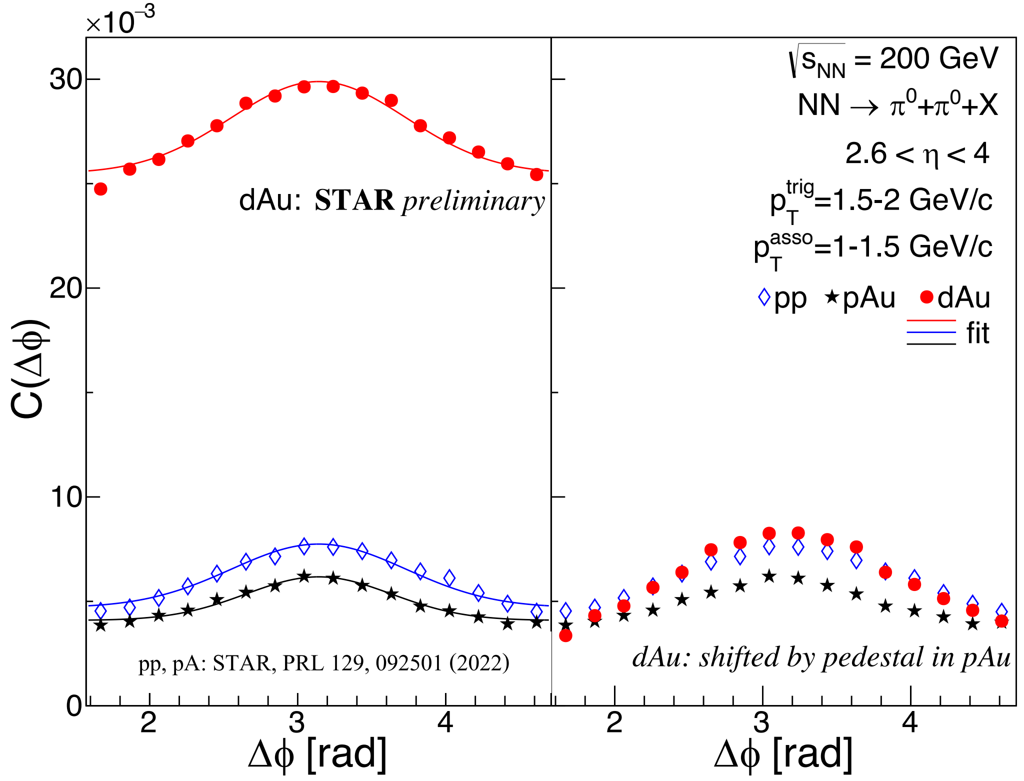

Subprocesses of DPS in d+A




- DPS is predicted* to be enhanced and not negligible at forward rapidities; different in p+p, p+A and d+A
- Open questions: two $\pi^0$ are generated from the same or different hard scattering? DPS affects the correlation?

# Di-$\pi^0$ measurement in d+Au at STAR

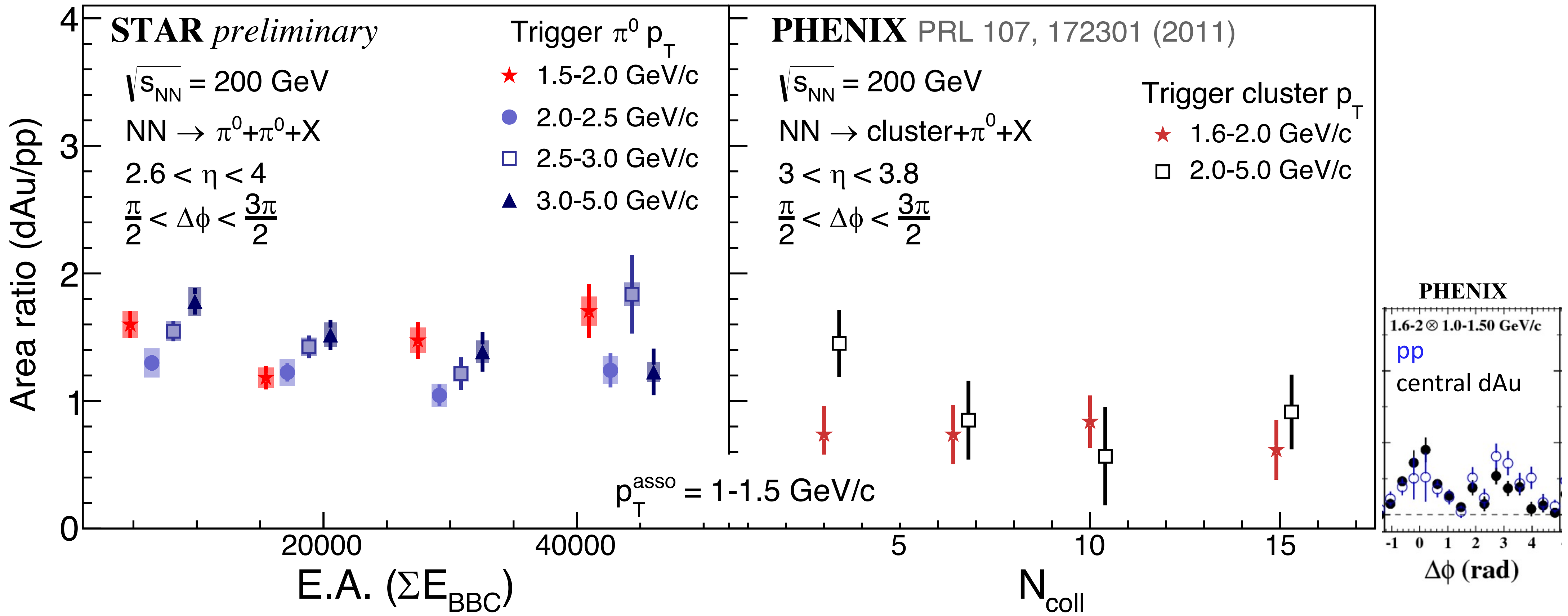



Challenging to draw conclusions based on the forward di-$\pi^0$correlation measurement in d+Au

- $\pi^0$ indentification: much higher background in d+Au than p+p/Au; combinatoric contribution is large in d+Au
- Pedestal: much higher in d+Au than p+p/Au; stable in p+p and p+Au

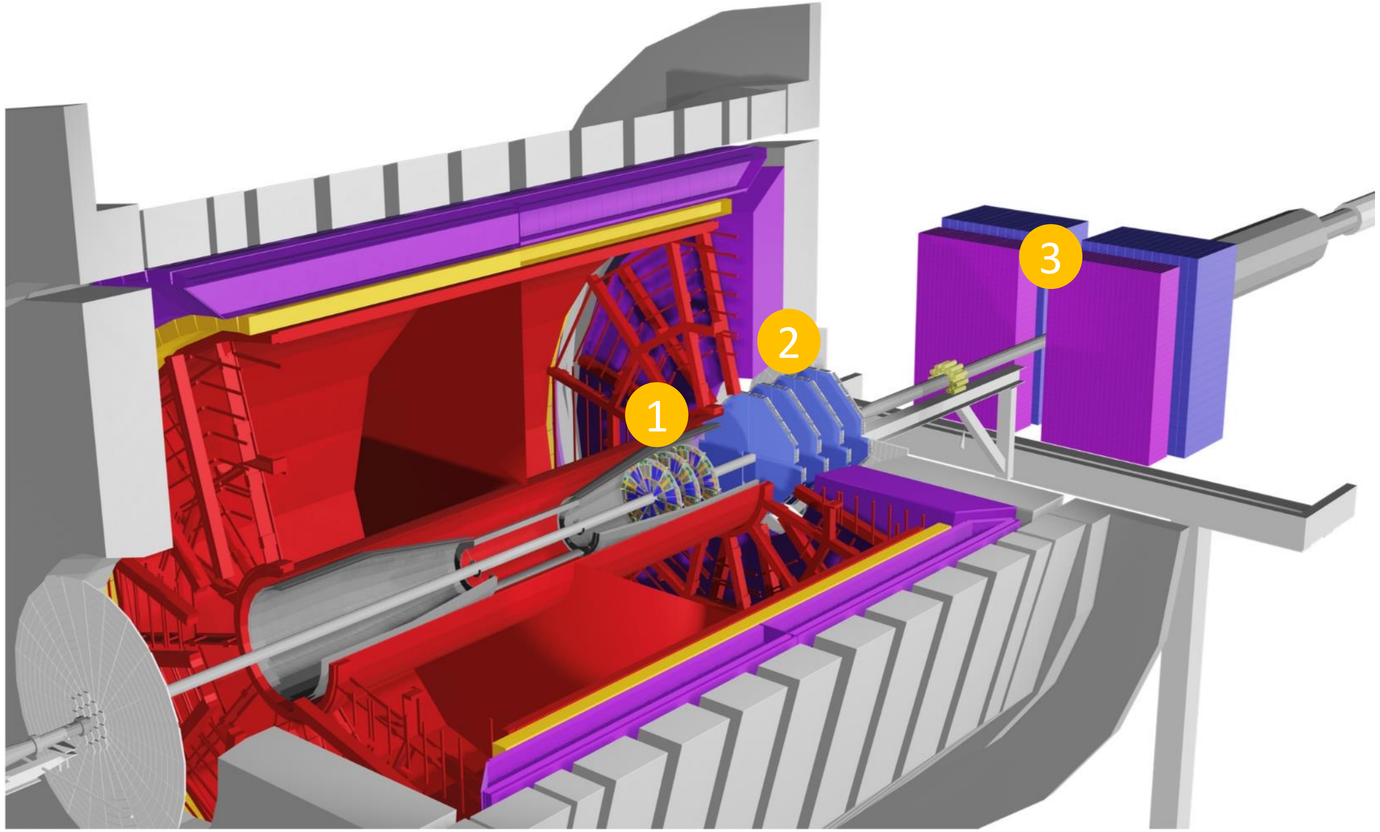
# E.A./centrality dependence in d+Au?




- In the overlapping $p_T$ range of two collaborations, no obvious E.A./centrality dependence in d+Au relative to p+p
- Significant suppression observed only at very low $p_T$ ($p_T^{asso} = 0.5 - 0.75$ GeV$/c$) at PHENIX, where STAR FMS cannot reach

**Di-$\pi^0$ measurement favors cleaner p+A than d+A collisions**

# Future measurements with STAR Forward Upgrade




| Detector | pp and pA | AA |
|---|---|---|
| ECal | ~10%/√E | ~20%/√E |
| HCal | ~50%/√E+10% | --- |
| Tracking | charge separation<br>photon suppression | **0.2**< $p_T$ <2 GeV/c<br>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)

Future STAR data with forward upgrade

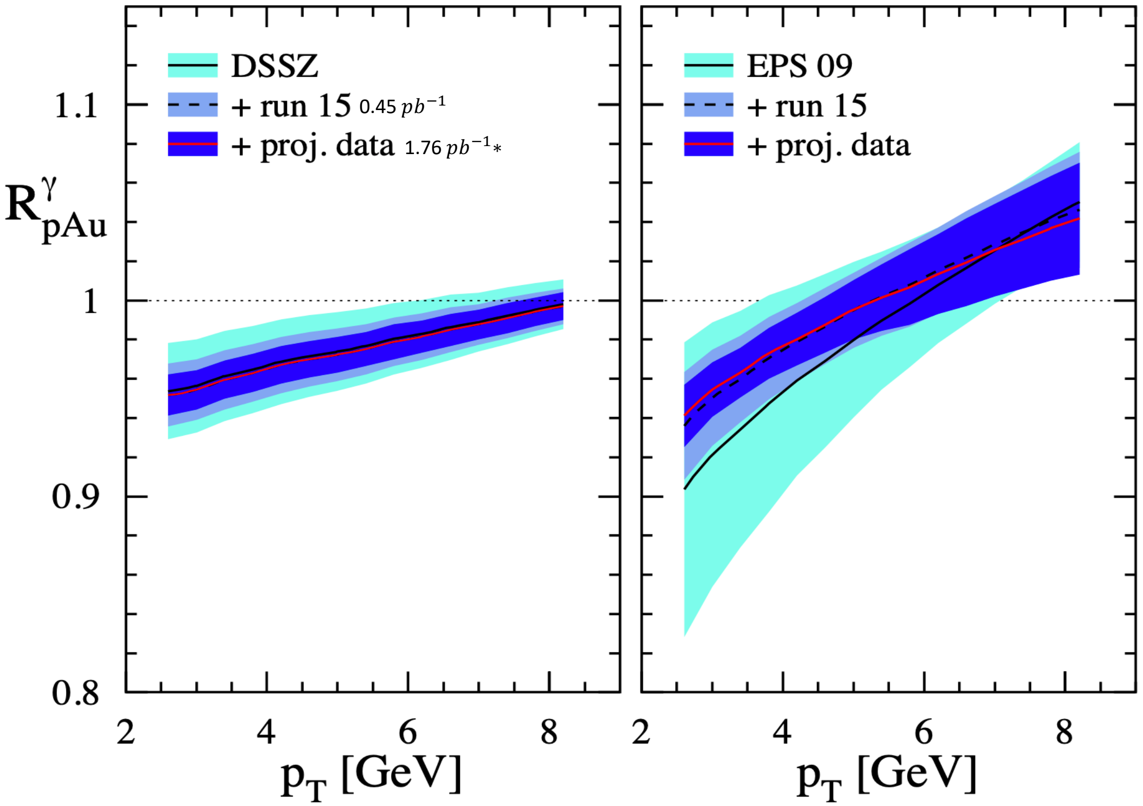
| Year | System | $\sqrt{s}$ (GeV) |
|---|---|---|
| 2023 | Au+Au | 200 |
| 2024 | $p$+$p$, $p$+Au | 200 |
| 2025 | Au+Au | 200 |

**To explore nonlinear gluon dynamics with expanded observables beyond $\pi^0$s:**

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

# Future measurements with STAR Forward Upgrade

arXiv:1602.03922

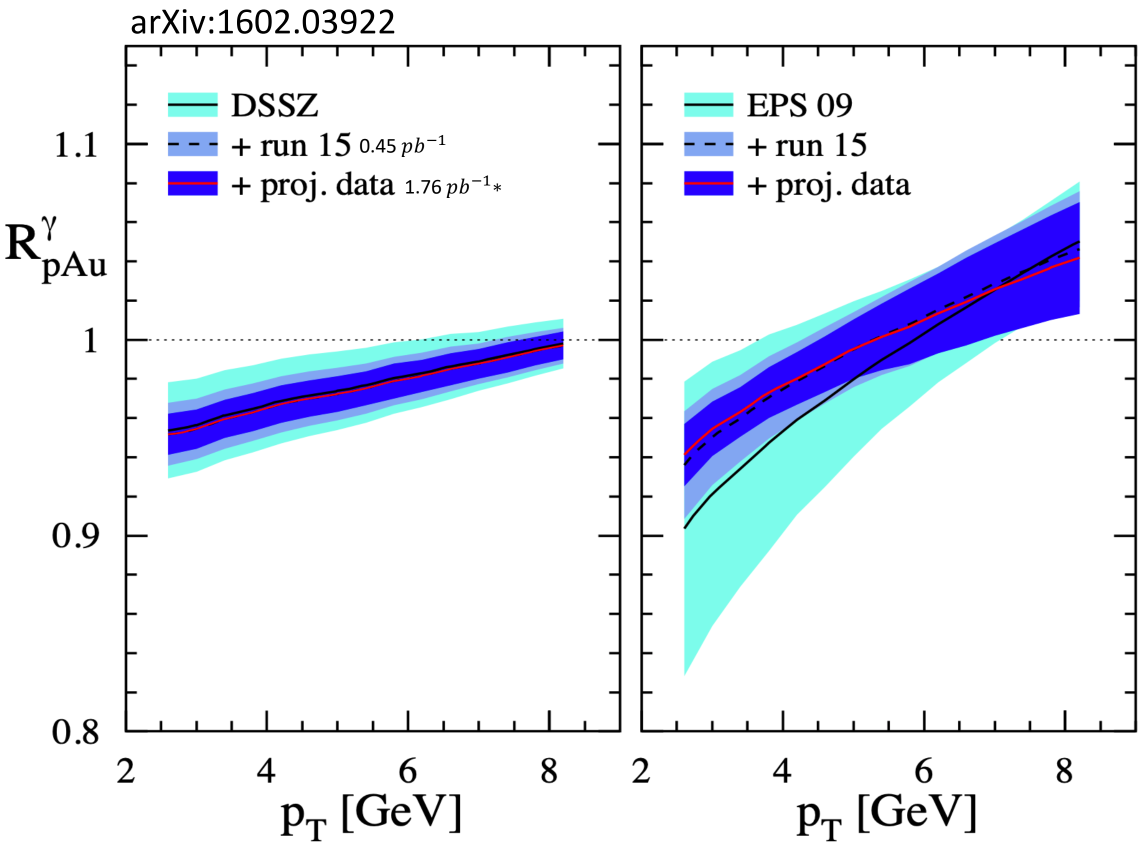


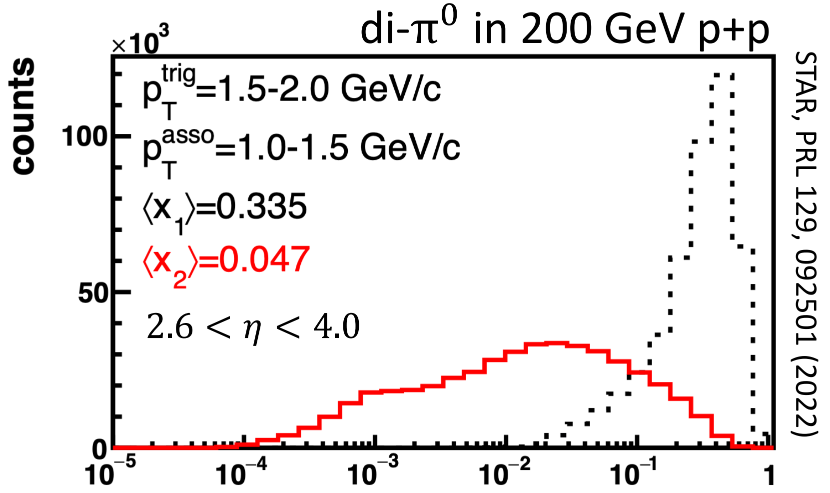

Direct photon:

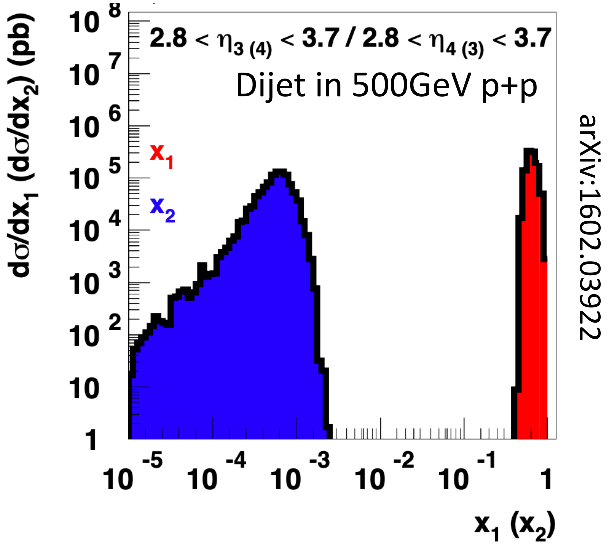
- q+g→q+$\gamma$, sensitive to gluon
- finial state effects suppressed
- small cross section and background $\gamma$

*STAR 2024 p+Au from BUR: 1.3 $pb^{-1}$

# Future measurements with STAR Forward Upgrade

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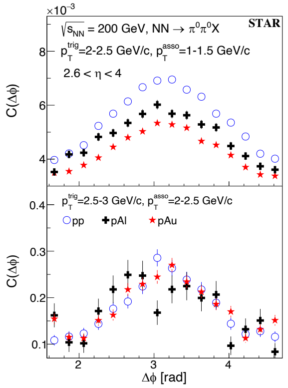
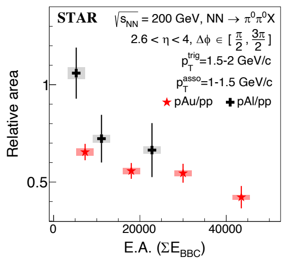
*STAR 2024 p+Au from BUR: 1.3 $pb^{-1}$

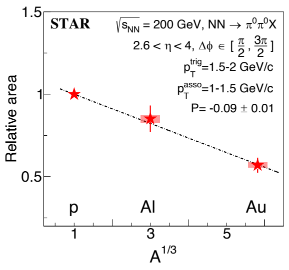
Dijet compared to dihadron:

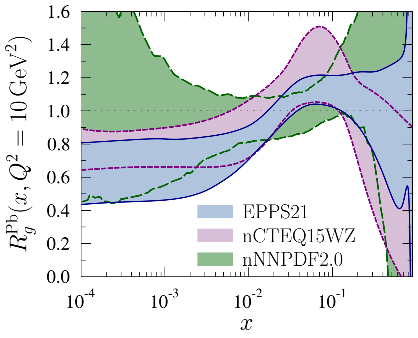
- helps to select narrower small $x_2$ range
- better proxy to diparton
- can not probe small $p_T$: $p_T^{jet} > 5\ GeV/c$

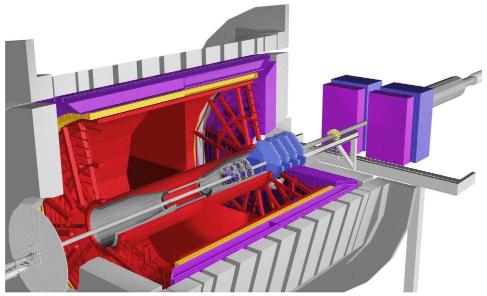
# Summary and outlook



Di-hadron measurements at RHIC provide insights into the understanding of nonlinear gluon dynamics in nuclei

Nuclear gluon distributions remain largely unconstrained in the nonlinear regime: important input from RHIC at low to moderate $Q^2$

p+p, p+A results: $A$, E.A., $p_T$ dependence

Opportunities with STAR forward upgrade: expanded observables, high precision

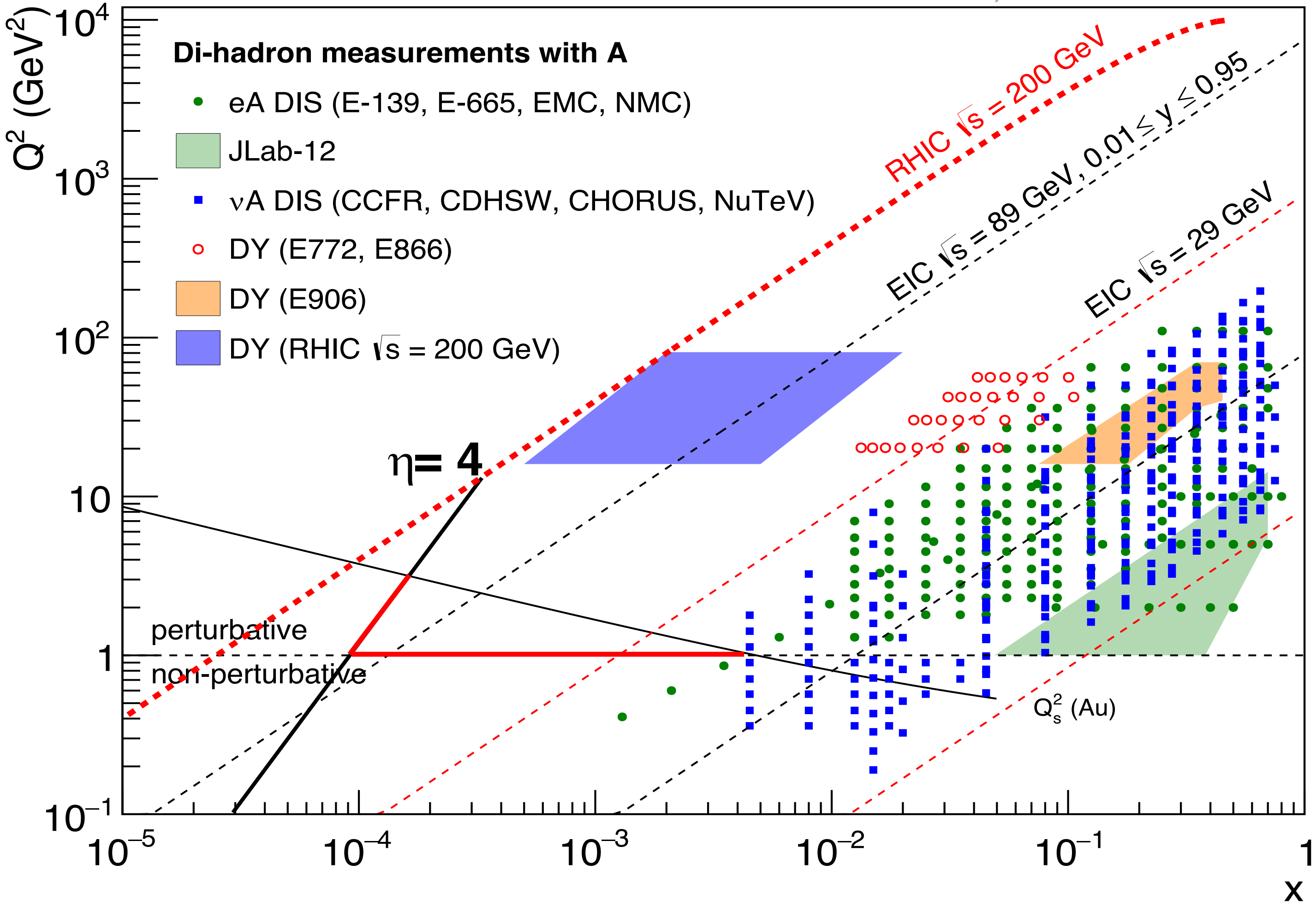
Di-hadron measurement favors cleaner p+Au collisions than d+Au collisions

**Thank you for your attention!**

# Back up

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

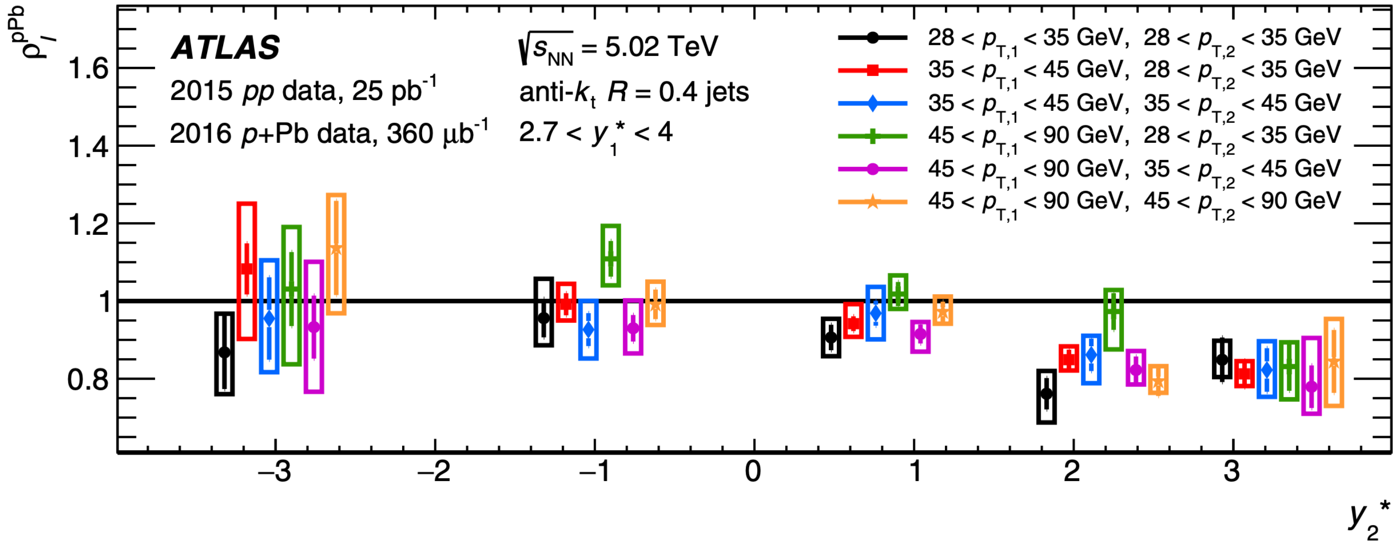
R. Abdul Khalek et al., arXiv:2103.05419

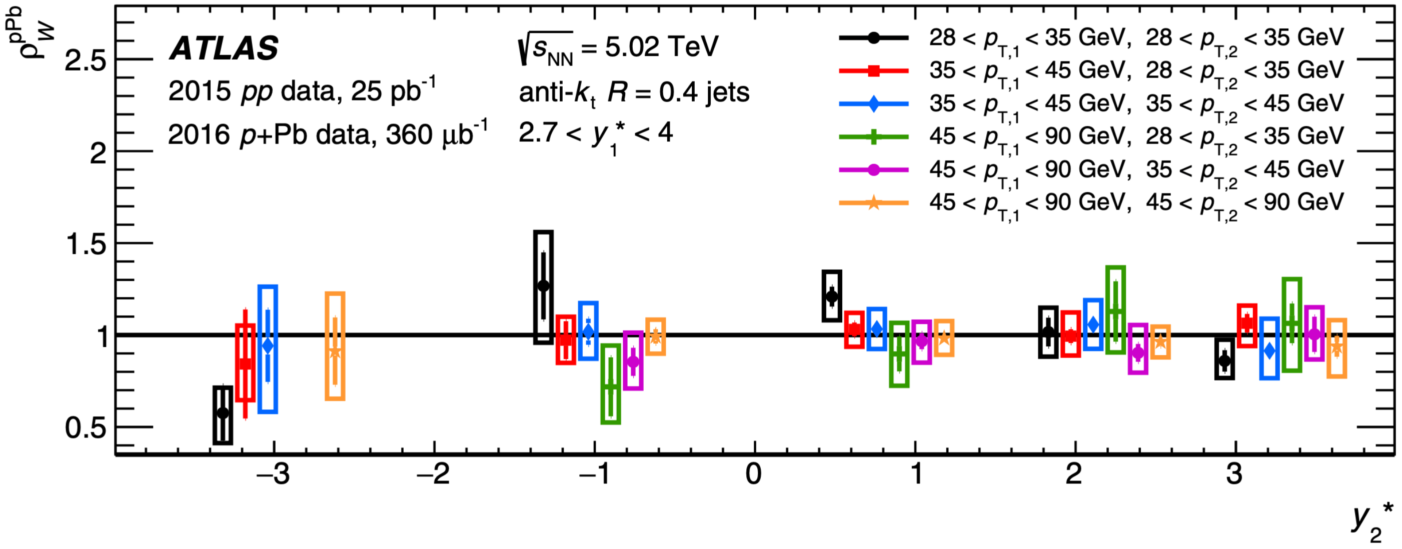



STAR data can access linear-nonlinear transition region

# Dijet at ATLAS

ATLAS, PRC 100, 034903 (2019)




Conditional dijet yields ratio of $\frac{pPb}{pp}$ is measured:

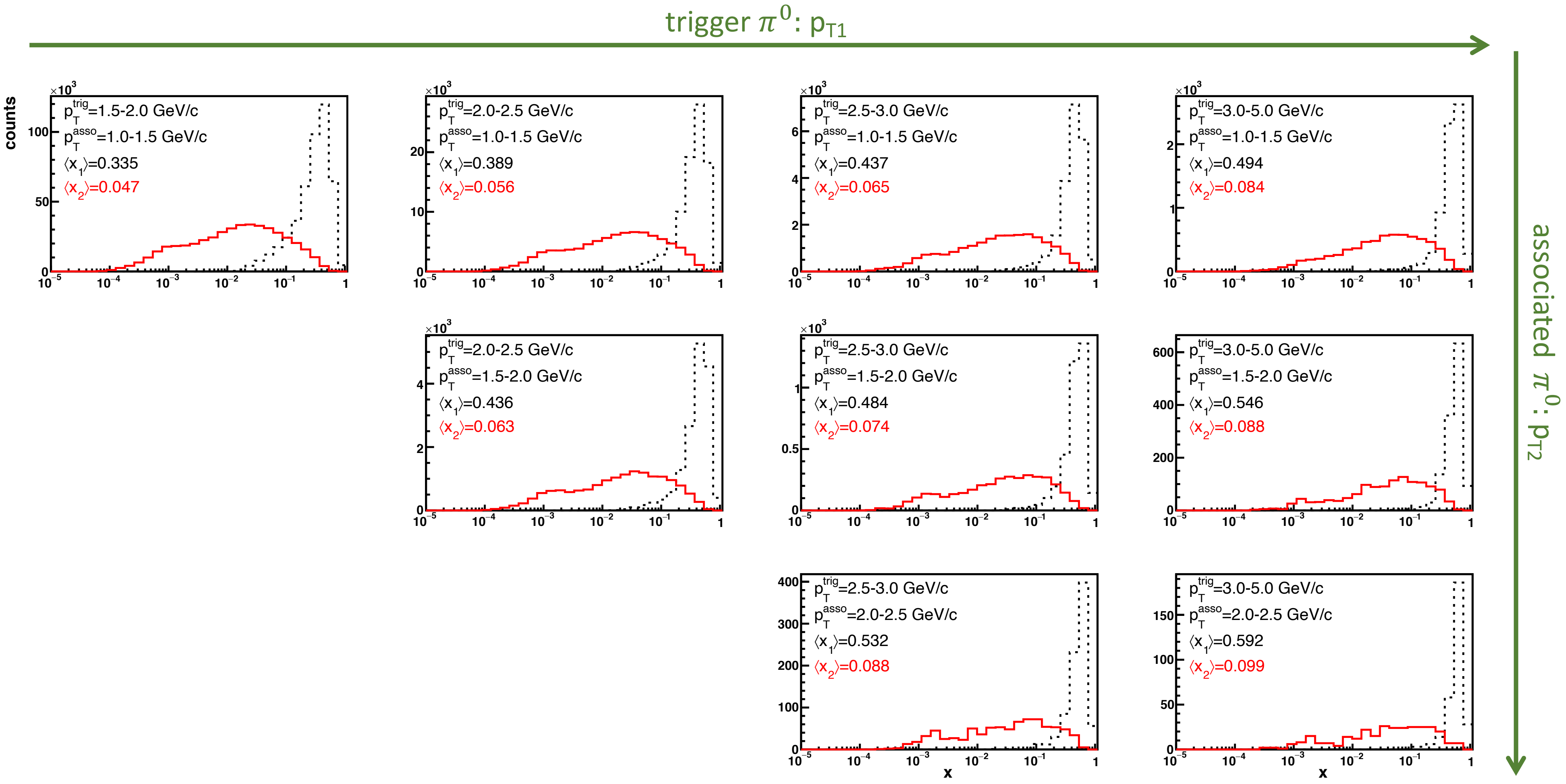
- Rapidity dependence
- $\frac{pPb}{pp}\sim 0.8$ at most forward direction, less suppression compared to STAR dihadron
- $x_{Pb} \rightarrow 10^{-4}$; but $Q^2 >\sim 800\ GeV^2$, too high?

Width extracted as $\sigma$ from the Gaussian fit:

- Remains the same in p+p and p+Pb
- Same conclusion with RHIC dihadron

STAR, PRL 129, 092501 (2022)

# Simulated $x$



STAR, PRL 129, 092501 (2022)

# Simulated $Q^2$