QuarkMatter 2023
The 30th International Conference on Ultrarelativistic Nucleus-Nucleus Collisions

Probing gluon saturation through two-particle correlations at STAR and the EIC

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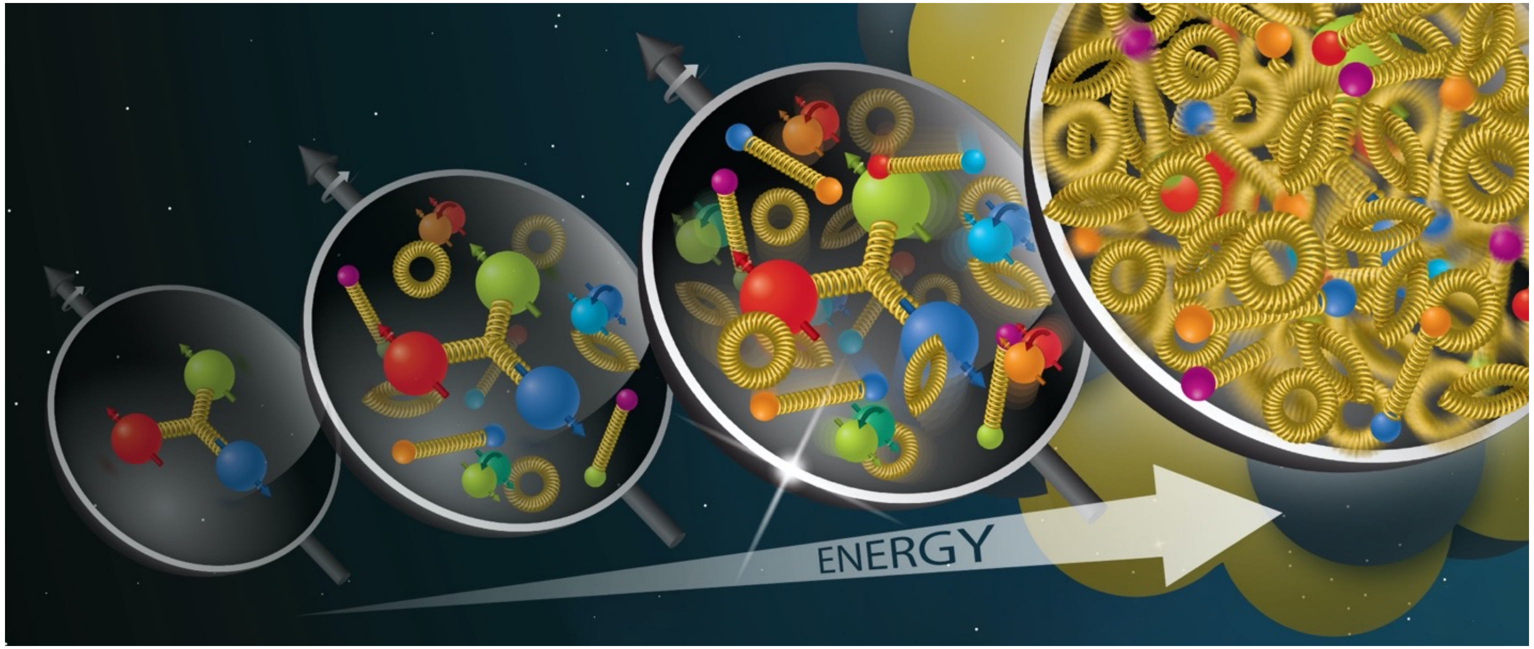
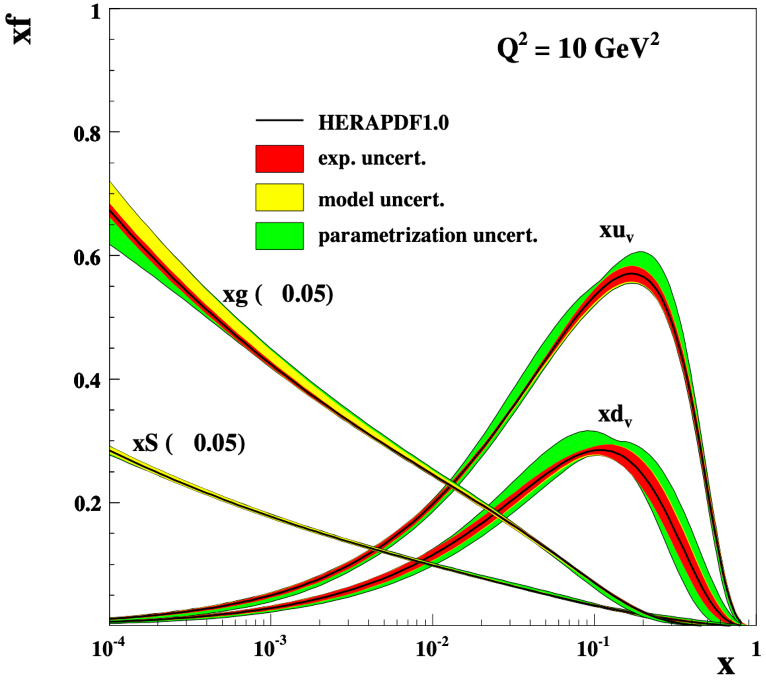
STAR ePIC

2023

High gluon density in nucleon



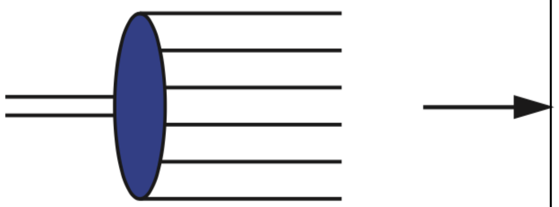
H1 and ZEUS, JHEP01 (2010) 109



- Particles from high energy collisions can be used to probe and take “snap shots” of the partonic structure of the proton.
- Results from DIS: At sufficiently small x, the wave function of the proton is dominated by gluons and the gluon density has to be saturated at some point.

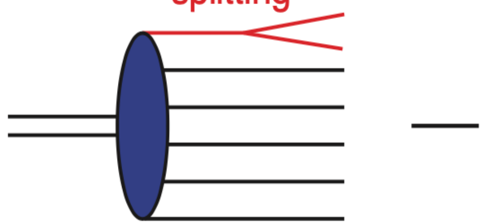
Gluon saturation

Gluon density

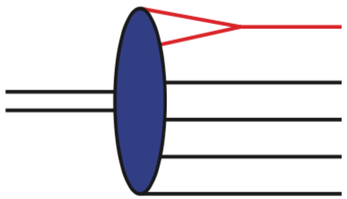


Balitsky-Fadin-Kuraev-Lipatov (BFKL) evolution equation
Balitsky-Kovchegov (BK) evolution equation

splitting



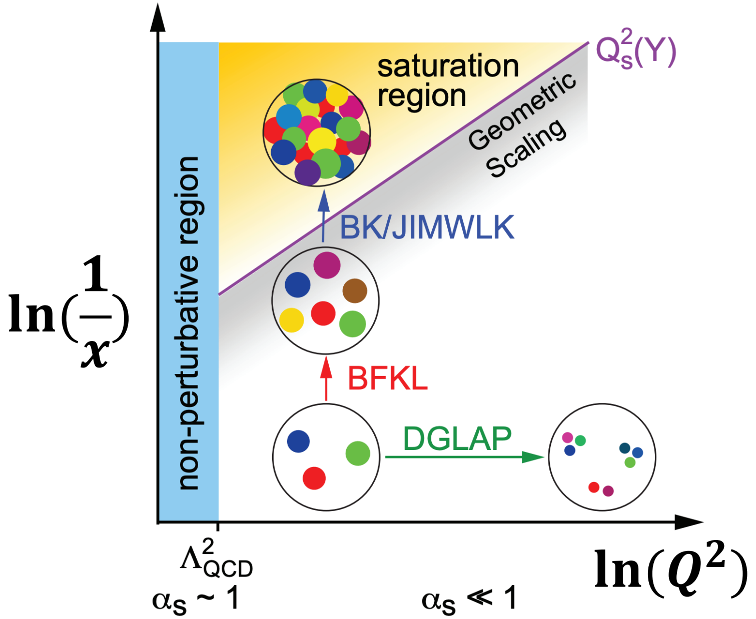
recombination



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

linear | nonlinear

Color Glass Condensate (CGC) framework



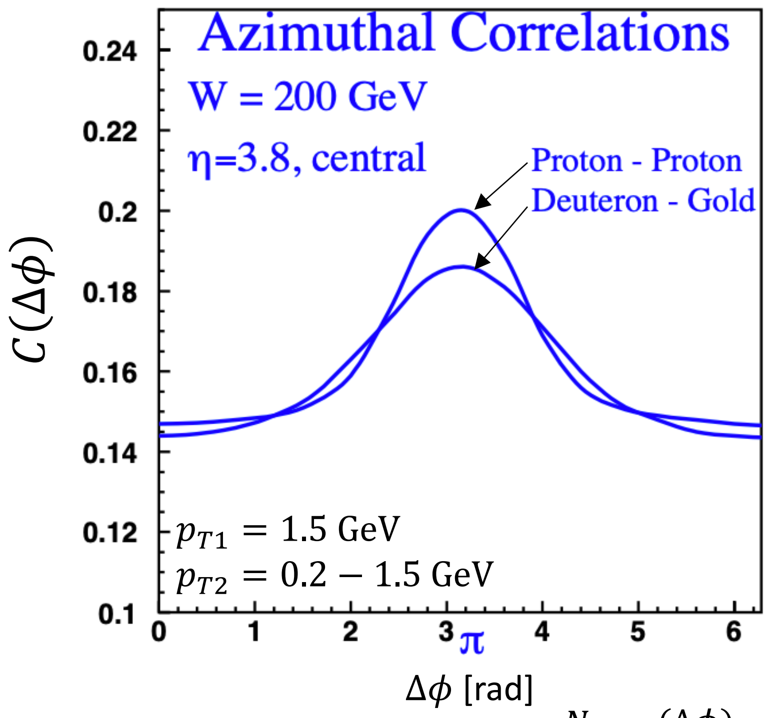
- The rapid increase of gluon density: gluon splitting → linear evolution
- Increase should be tamped at a certain point: gluon recombination → non-linear evolution
- A new regime of QCD: Gluon saturation ($Q^2 < Q_s^2$) at gluon recombination = gluon splitting
- Saturation region is easier to be reached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

How to probe nuclear gluon distributions at saturation region?

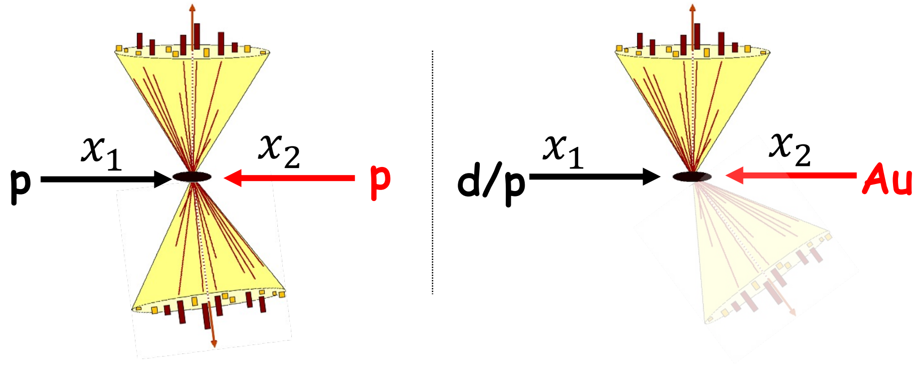
Di-hadron measurement

- **CGC** successfully predicted the strong **suppression of the inclusive hadron yields** in d+Au relative to p+p by gluon saturation effects → nuclear modified fragmentation serves as another interpretation?

- **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.



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



p: non-saturated

Au: saturated

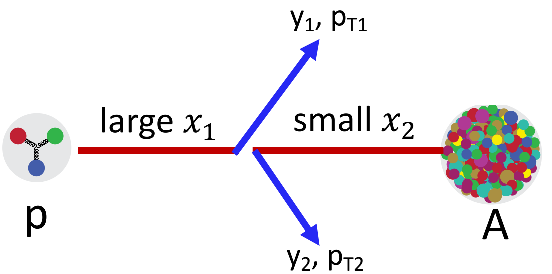
- Di-hadron in p+p serves as a baseline: 2-to-2 process.

- CGC predicts a back-to-back suppression and a broadening phenomena when gluon saturation appears.

Saturation signatures on p_T, y, b, A

Decrease x, Q^2:

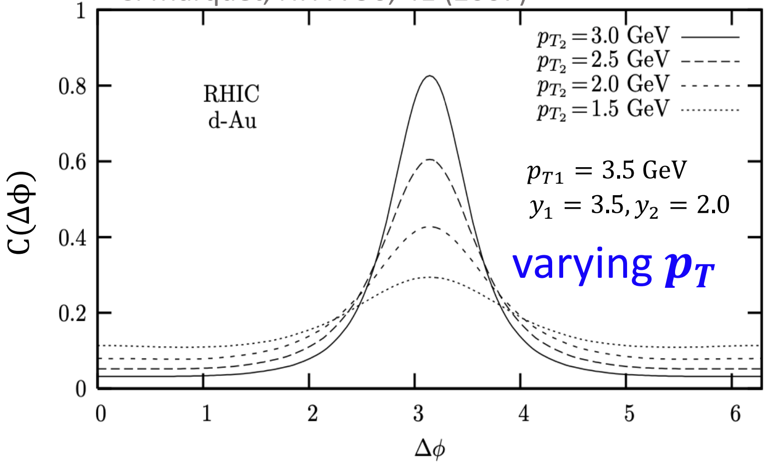
1. More forward direction
2. Lower p_T hadron → very sensitive to p_T



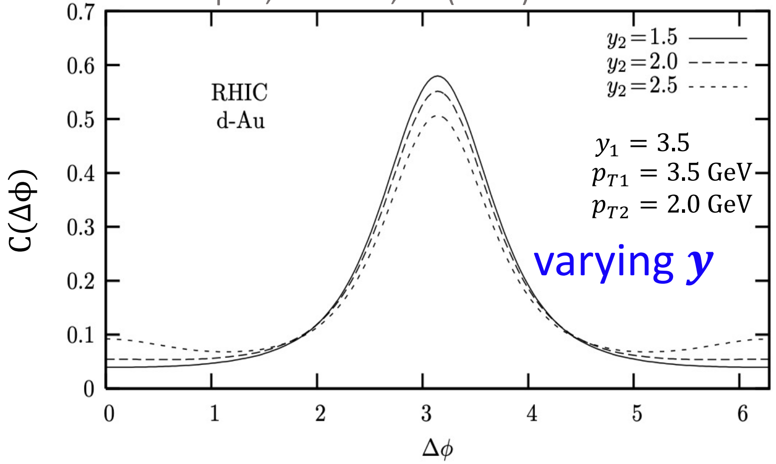
$$x_2 \sim \frac{p_{T1}e^{-y_1} + p_{T2}e^{-y_2}}{\sqrt{s}}$$

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

C. Marquet, NPA 796, 41 (2007)



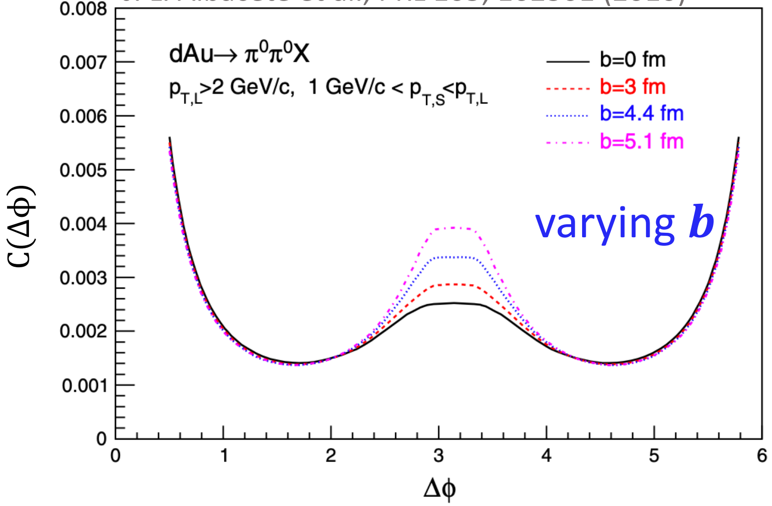
C. Marquet, NPA 796, 41 (2007)



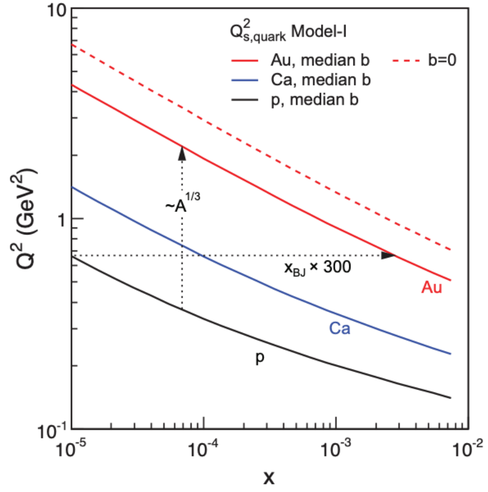
Increase Q_s:

3. More central collisions
   - $Q_s^2 \propto T_A(b) \propto 1/b$
4. Heavier nuclei
   - $Q_s^2 \propto A^{1/3}$

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



A. Accardi et al., arXiv 1212.1701

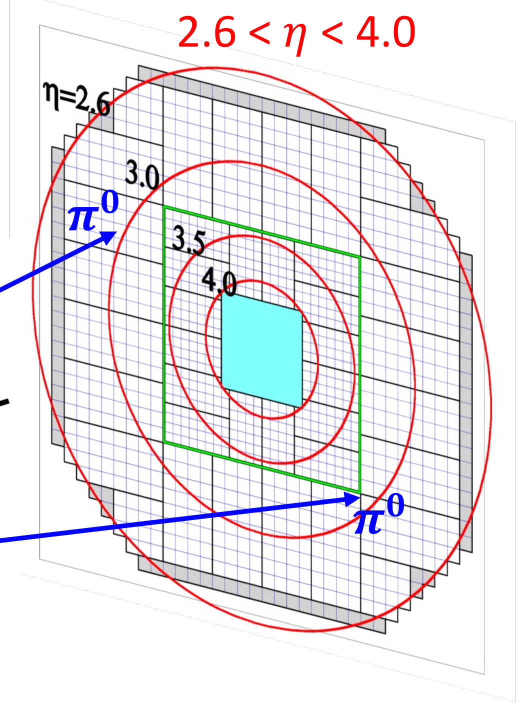


varying A

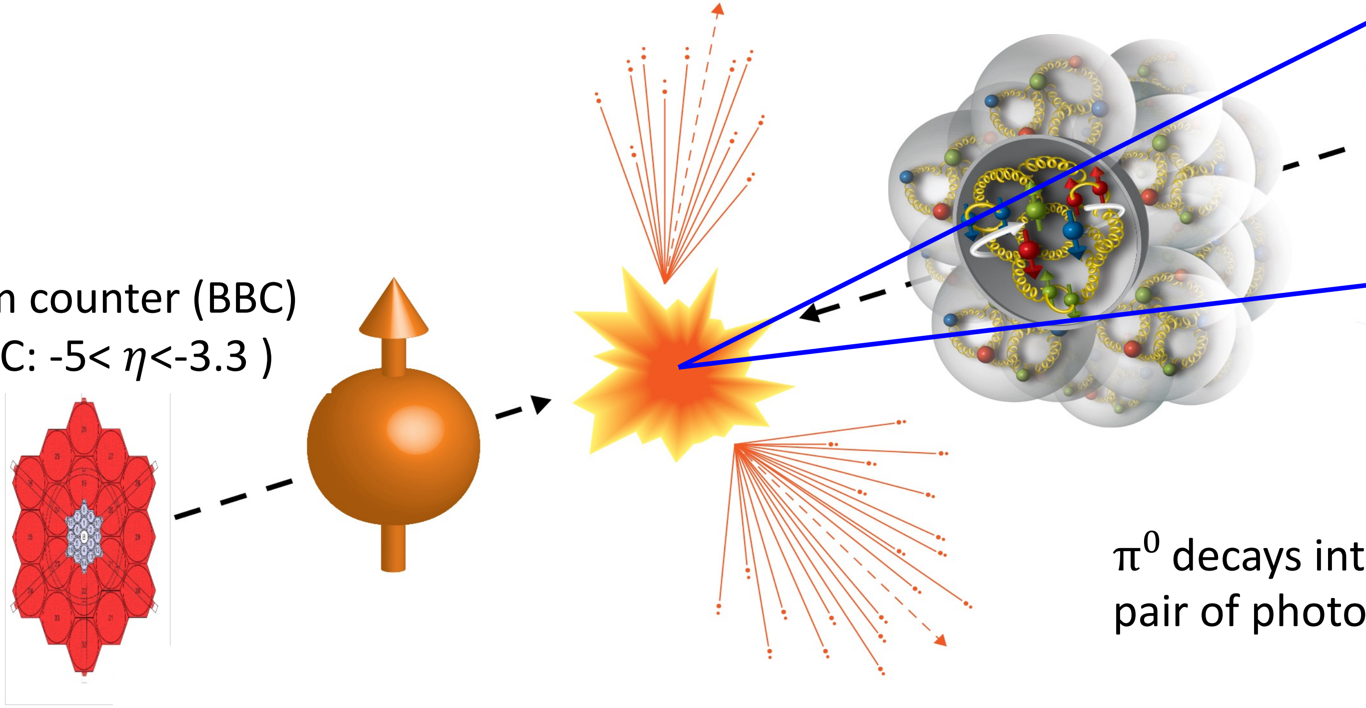
Di-π^0 measurement at STAR

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

Forward Meson Spectrometer (FMS)



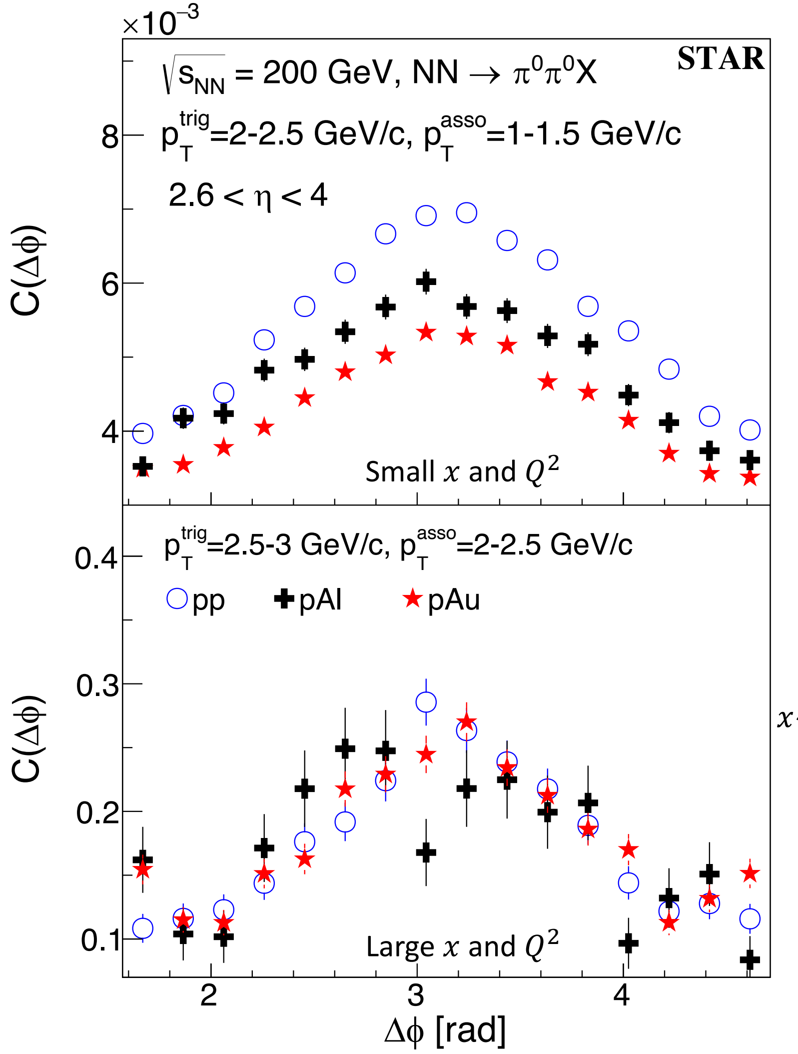
Beam beam counter (BBC)
(inner BBC: -5< η<-3.3)



π^0 decays into two photons, is constructed from a pair of photon candidates with the FMS.

Di-π^0 results at STAR

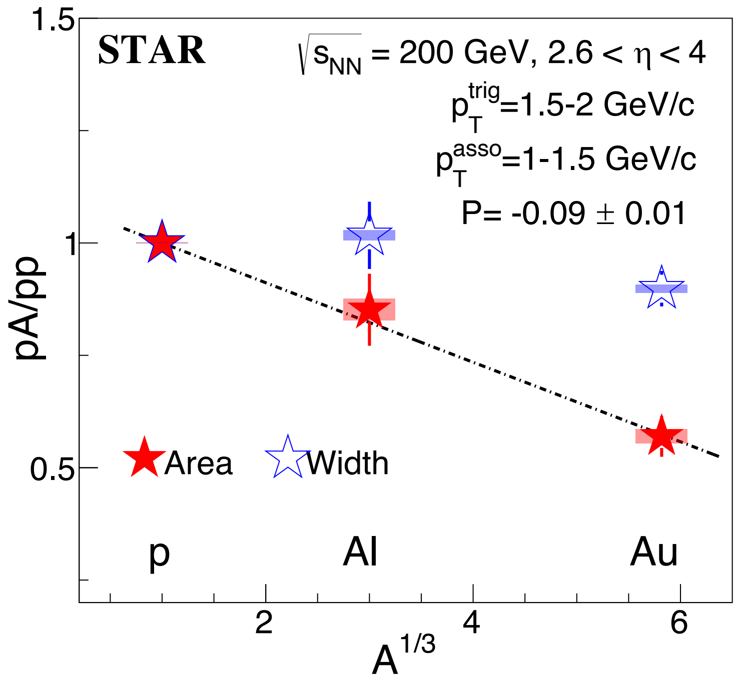
STAR, PRL 129, 092501 (2022)



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

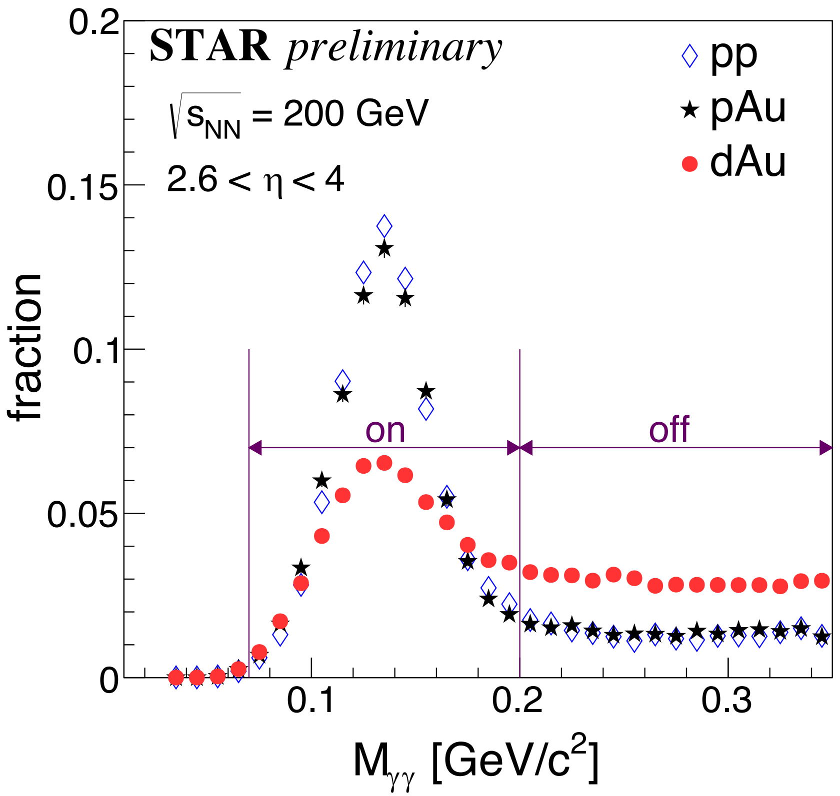
$$Q \sim \frac{p_{T1} + p_{T2}}{2}$$

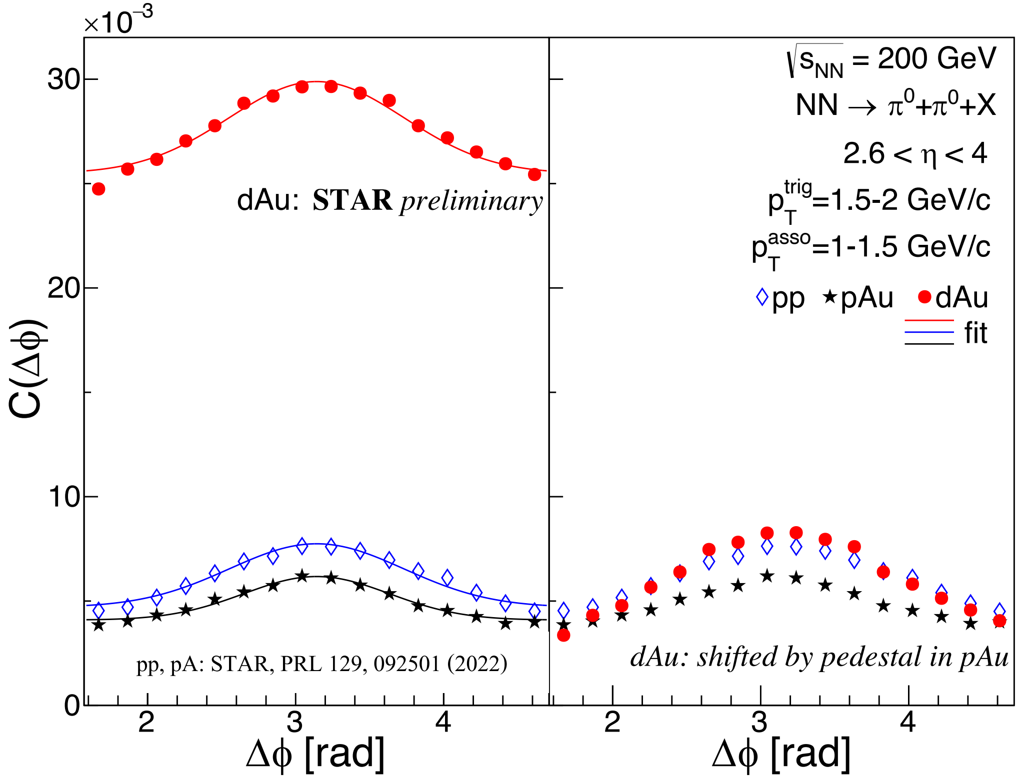
Gaussian (Area and width) at $\Delta\phi = \pi$ + pedestal



- Suppression exists at low p_T not high p_T.
- In a fixed $x - Q^2$ region, suppression is dominantly affected by various A:
  - Suppression depends linearly on $A^{1/3}$.
- No broadening is observed.

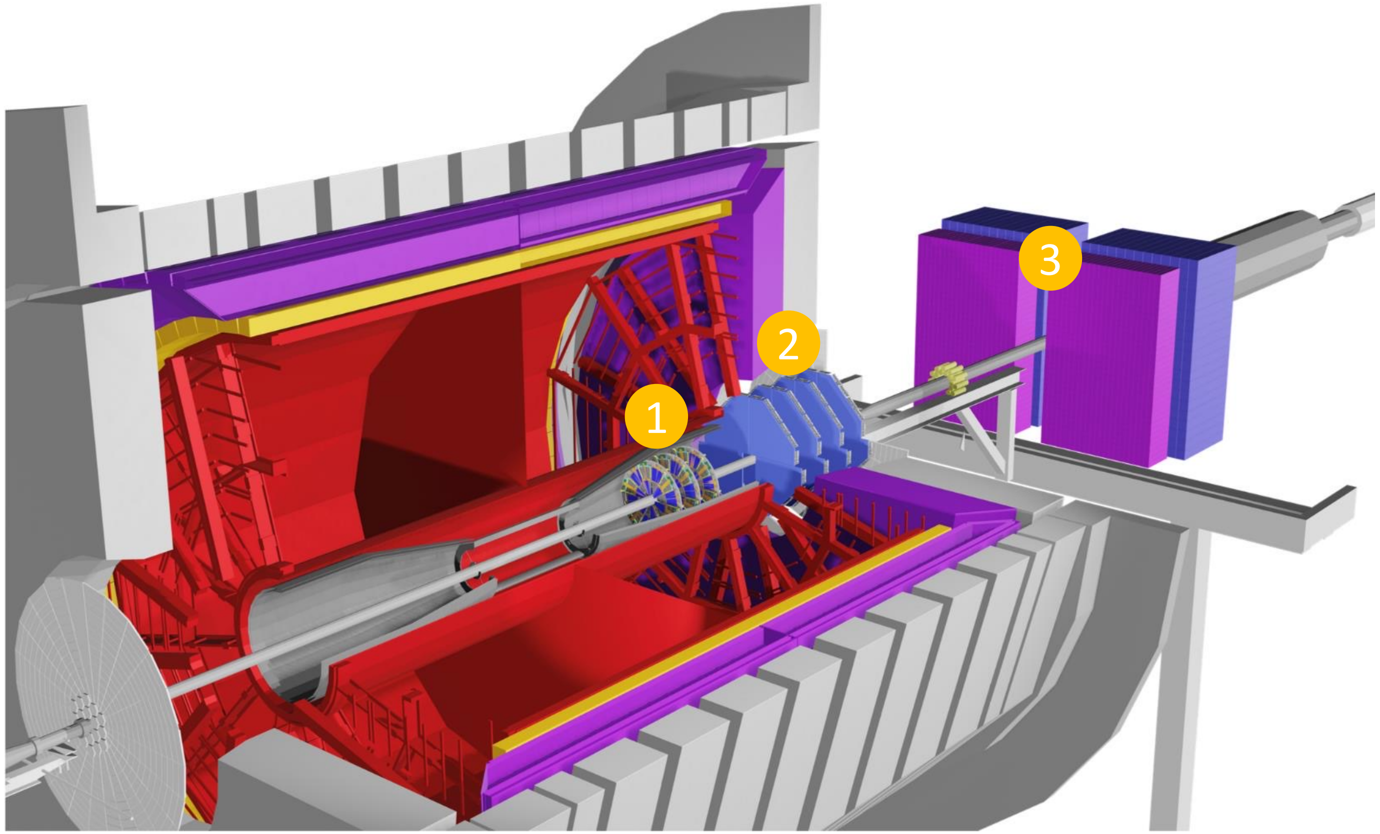
Di-π^0 results in d+Au at STAR





- Challenging to conclude the forward di-π^0 correlation measurement in d+Au, because:
  - π^0 PID: much higher background in d+Au than p+p(Au); combinatoric contribution is large in d+Au;
  - undetermined contribution from the double parton interactions.
- Di-π^0 measurement favors cleaner p+A than d+A collisions. More p+Au data are requested in 2024!

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)

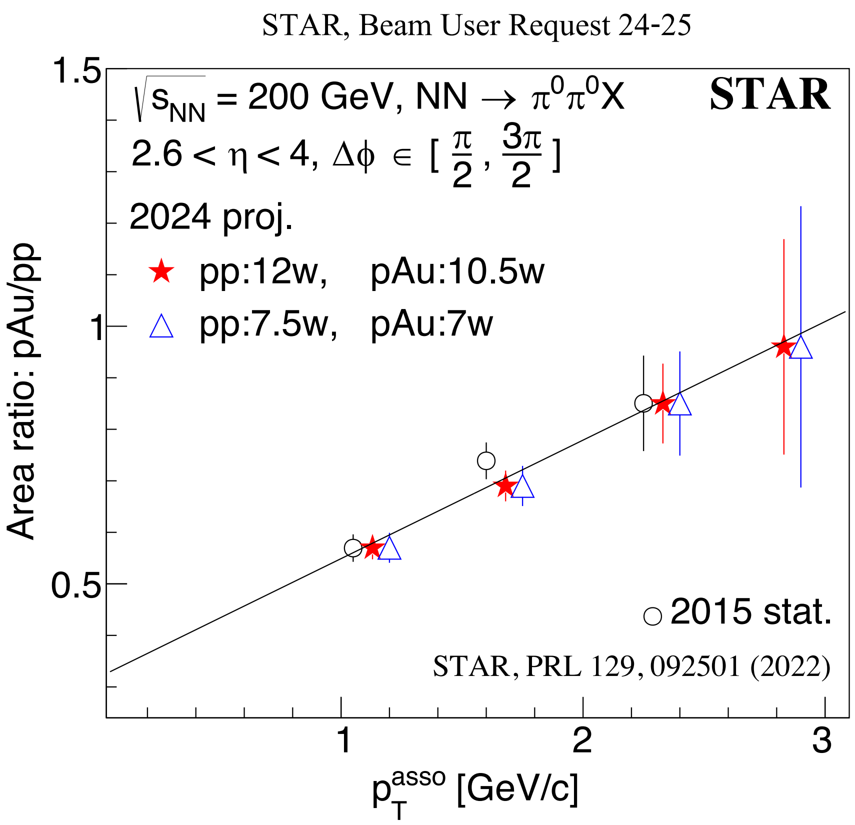
Future STAR data with forward upgrade

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

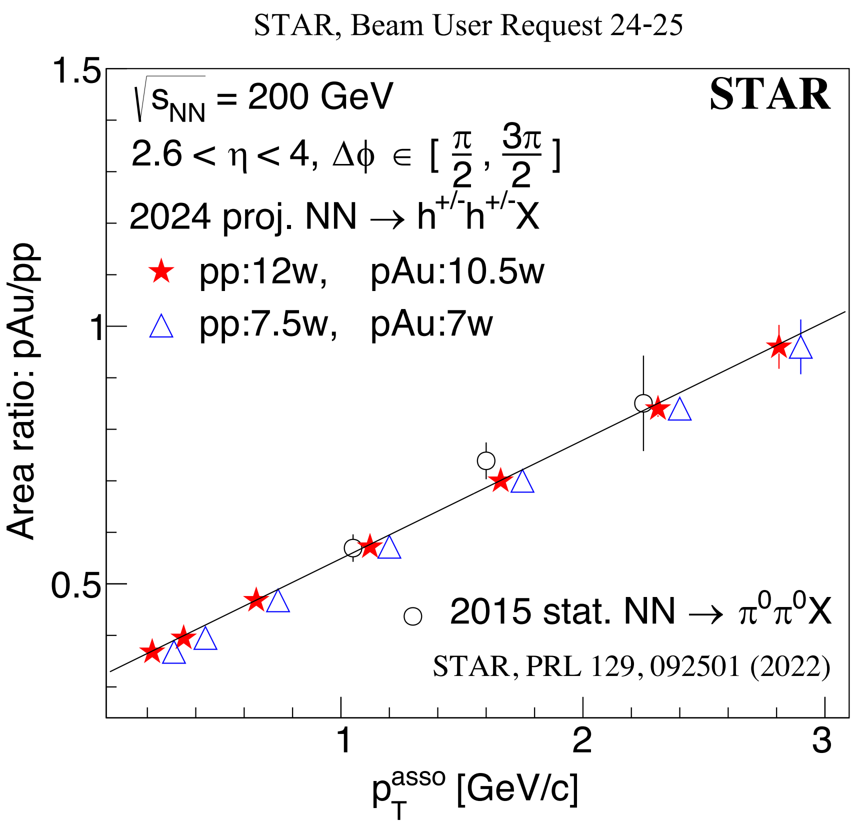
To explore nonlinear gluon dynamics with expanded observables beyond π^0s:

- 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 data



Run24 di-π^0

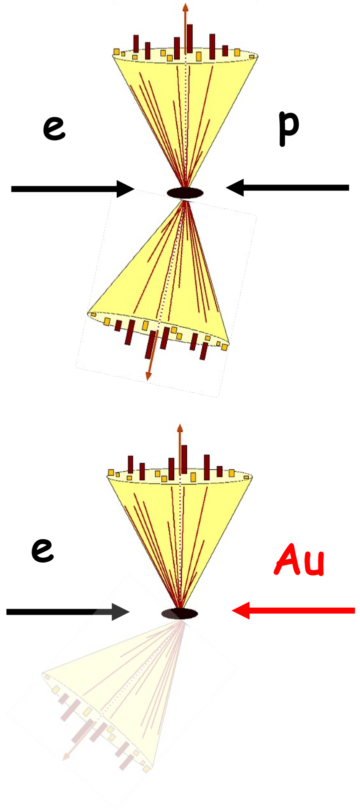


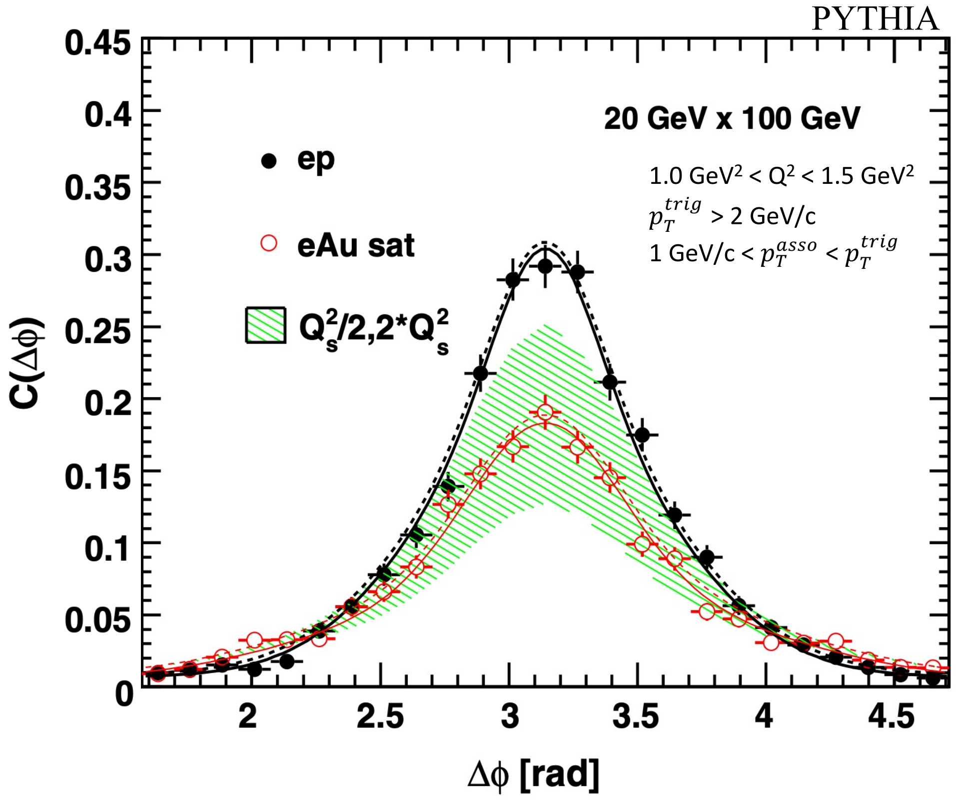
Run24 di-$h^\pm$

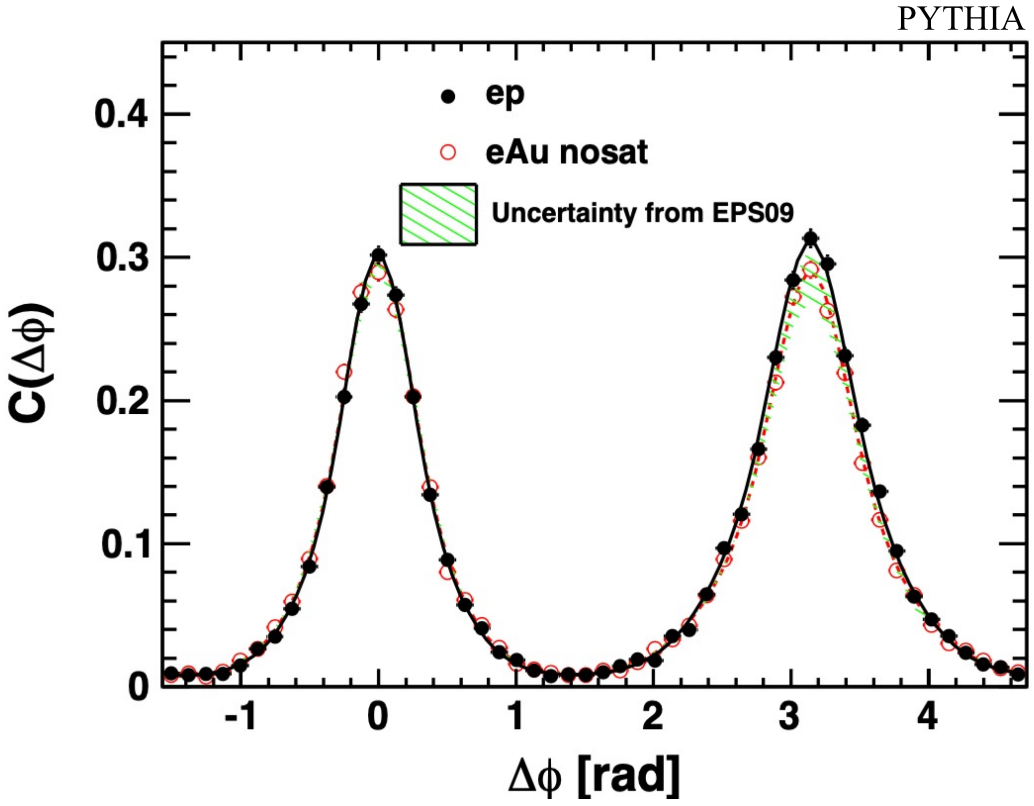
- **Run24 di-π^0 projection**: Best statistic of 2024 (28 Cryo weeks) indicates $\sim$35% reduction of the statistical error compared to 2015 data.
- **Run24 di-$h^\pm$ projection**: Higher statistic than di-π^0; $\geq$ 80% reduction of the statistical error compared to 2015 data; the strongest suppression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

Gluon saturation at the EIC

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



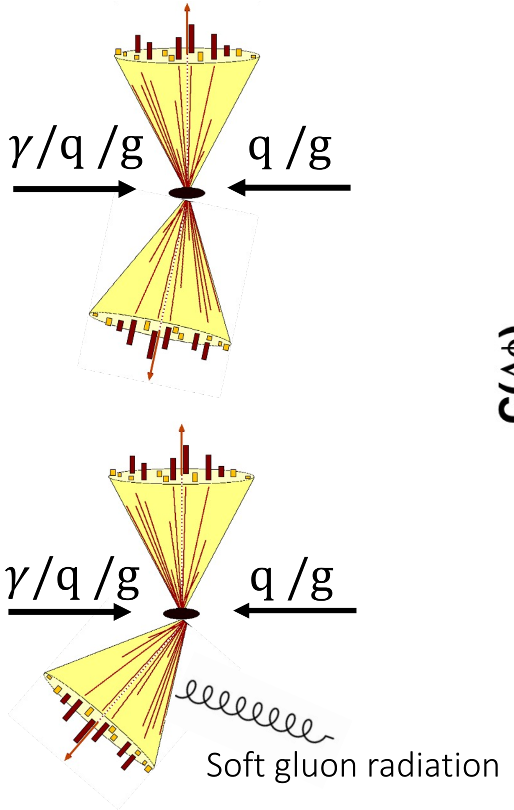


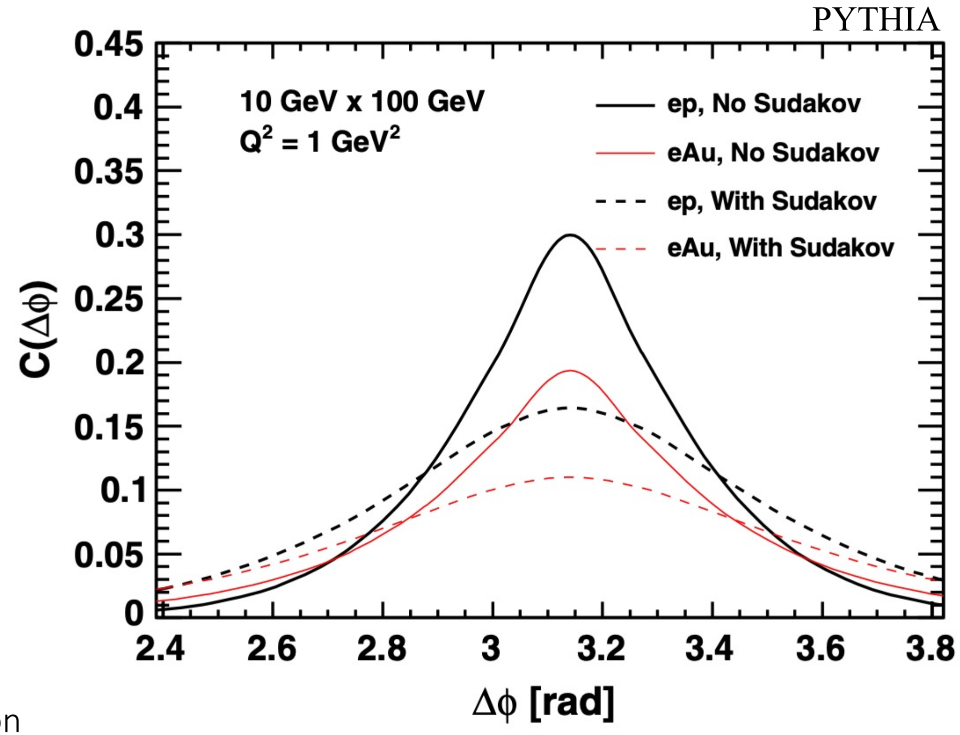


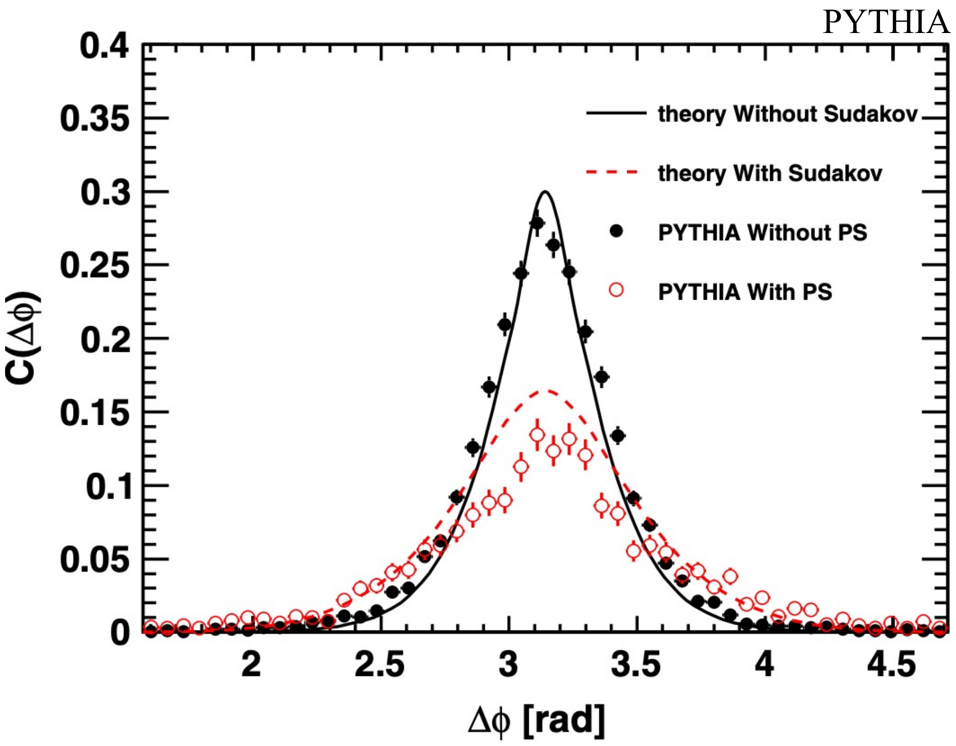
- CGC predicts the back-to-back suppression and a broadening phenomena from gluon saturation in e+A collisions.
- EIC simulation: constrain sat. and nosat. models with limited statistics of 1 fb^{-1}.
  - Suppression is reproduced by sat. model, not by nosat. model (EPS09 nPDF) including energy loss.

Sudakov effects in e+p and e+A

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



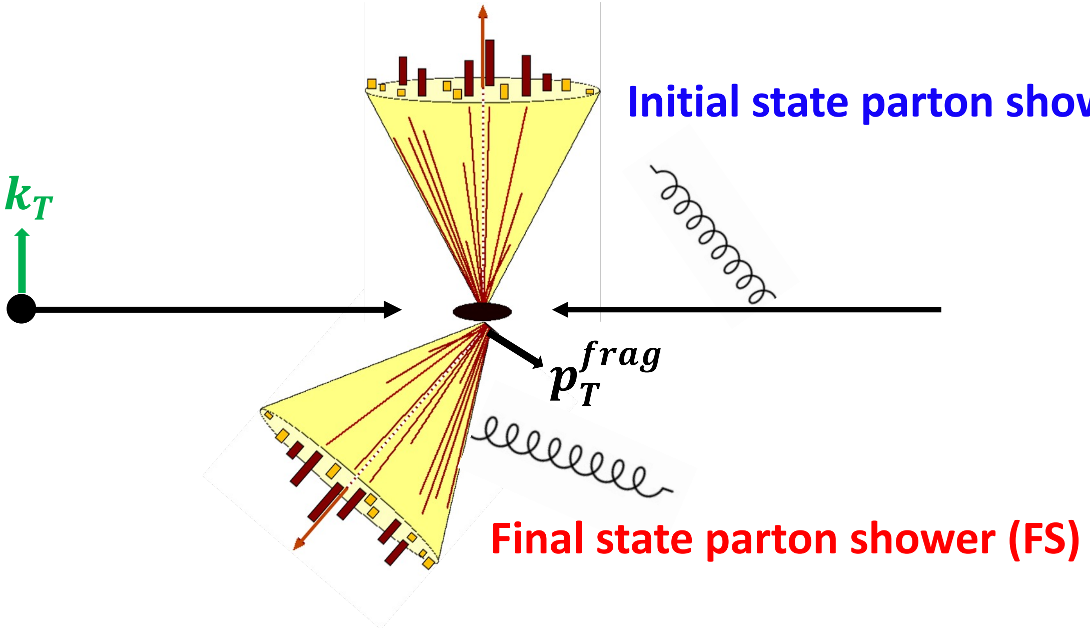


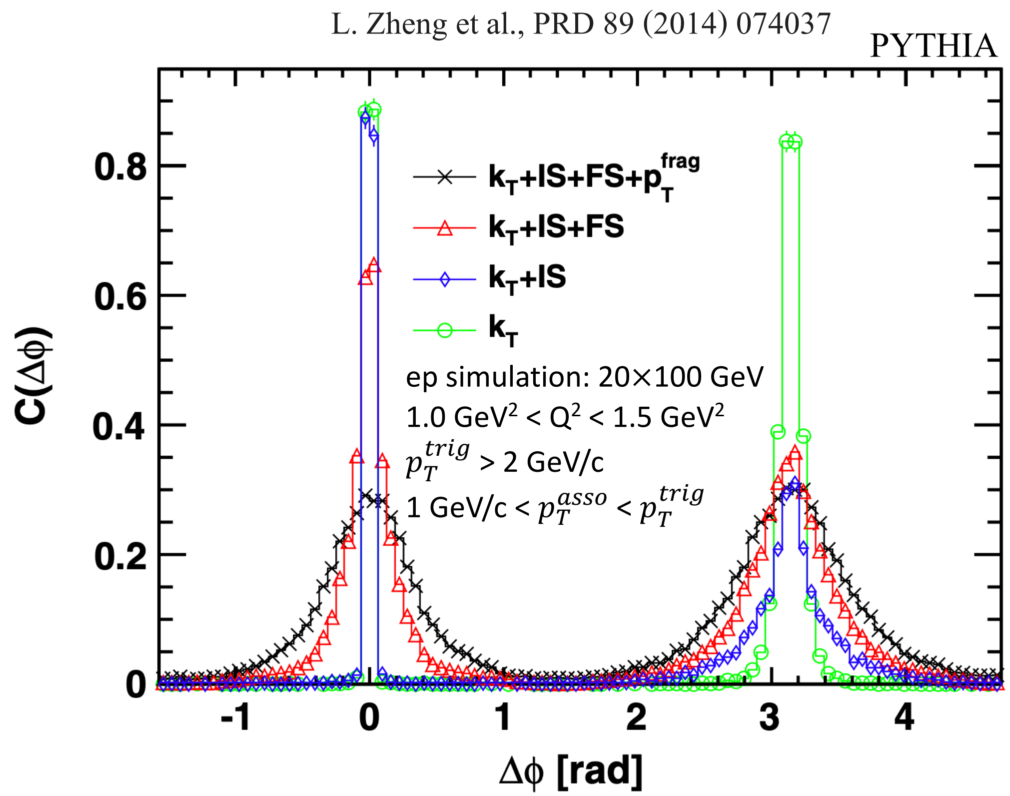


- Sudakov effect widens the back-to-back correlation functions, it exits in both e+p and e+A collisions.
- Sudakov effect is in agreement with the effect from parton shower in e+p collisions.

How about broadening?

Factors can cause the broadening:



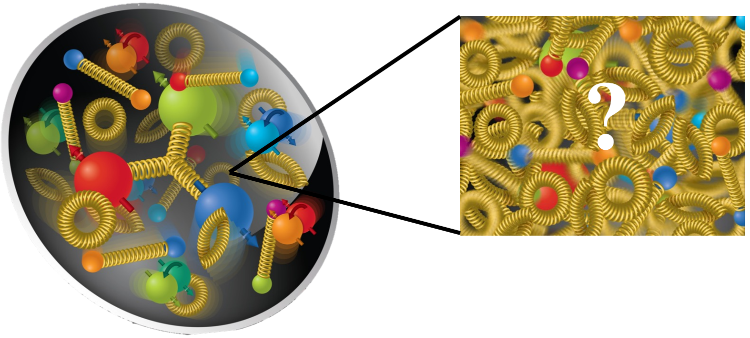


- Intrinsic k_T, parton shower, and p_T^{frag} can lead to broad near- and away-side peaks.
- IS: the dominate effect leading to a broad away-side peak.
- Precise measurement of both near- and away-side peaks with di-$h^{\pm}$ at the EIC: better understanding of each source for the broadening.

	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

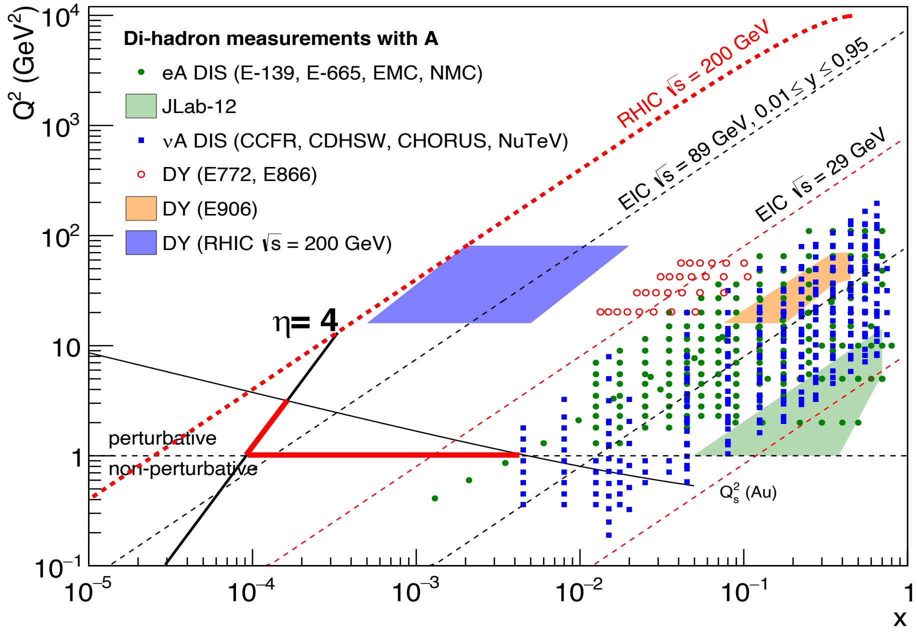
Summary and outlook

- Signatures of gluon saturation with correlation measurement from CGC: broadening and suppression dependence on A, centrality, p_T, and rapidity predicted.
- Experiments: suppression dependence on A and p_T observed at STAR; broadening not observed
  - Di-hadron in p+p, p+Al and p+Au at STAR;
  - d+Au results revisited at STAR: challenging to conclude.



- STAR Forward Upgrade provides opportunities to further explore the nonlinear gluon dynamics with various observables.
- RHIC result is an important basis for the similar measurements at the future EIC.
- Data from the EIC and RHIC: overlapping phase space; complementary probes (e+A and p+A) → test universality.

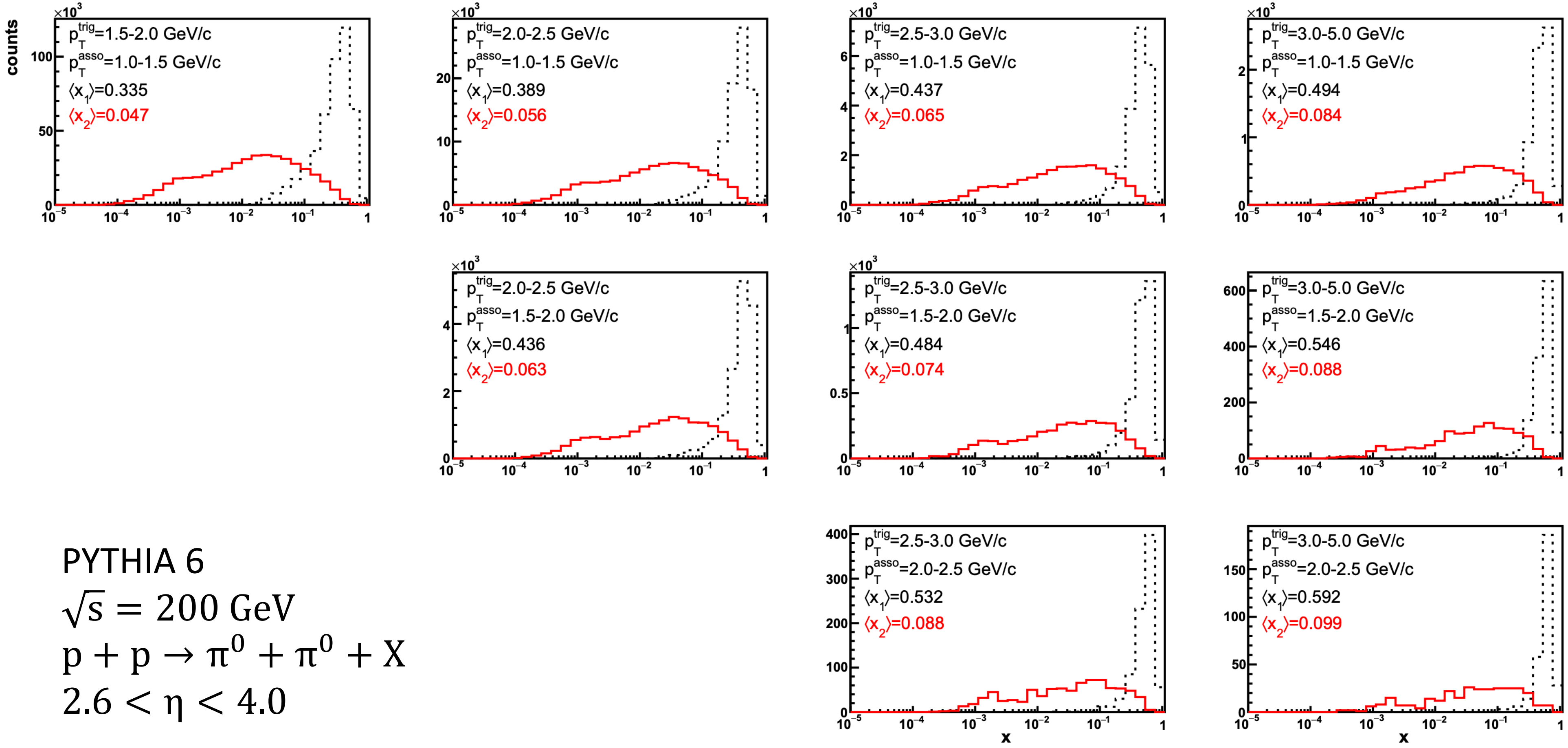
EIC Yellow Report, arXiv:2103.05419



Back up

x distribution from simulation

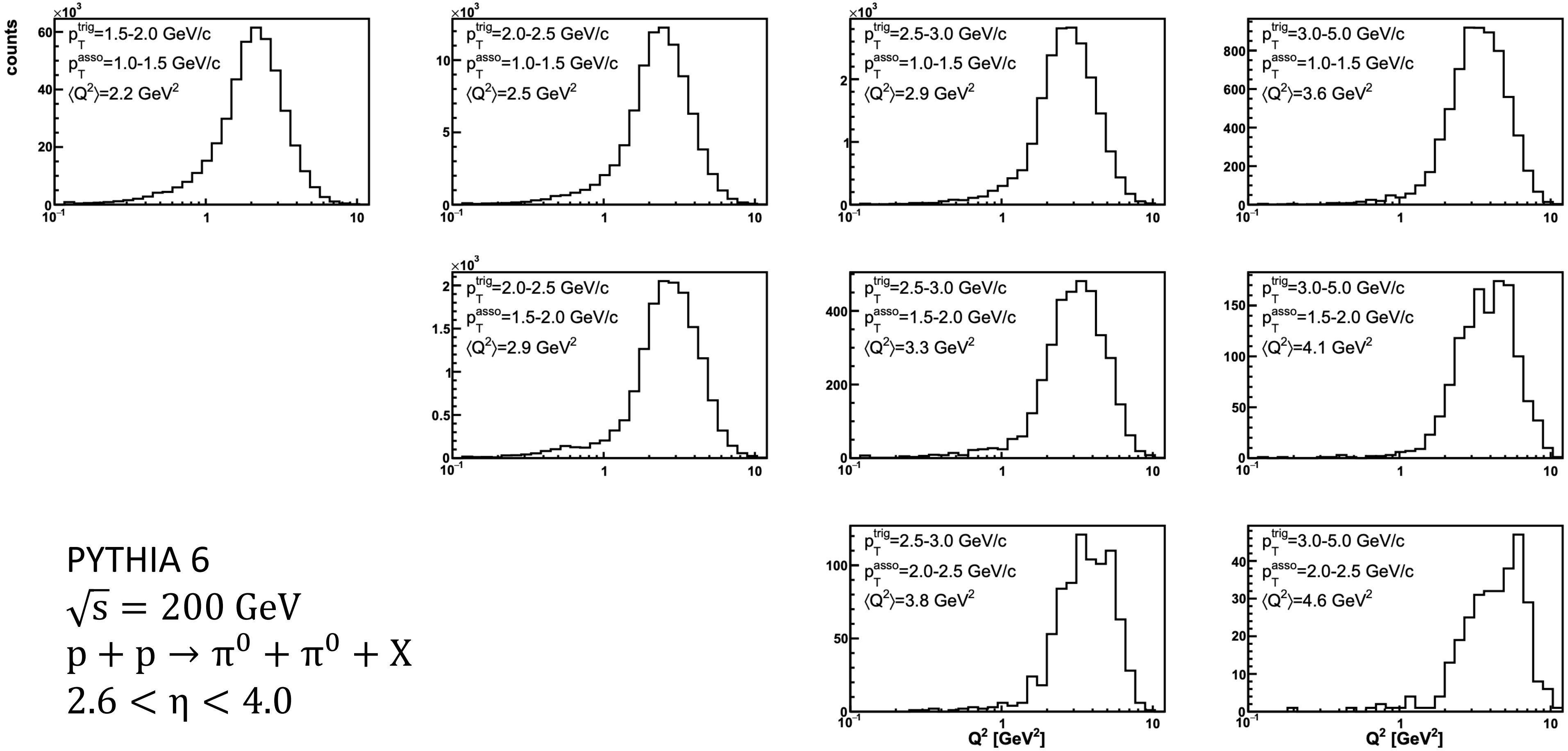
STAR, PRL 129, 092501 (2022) supplemental material



PYTHIA 6
$\sqrt{s} = 200$ GeV
$p + p \rightarrow \pi^0 + \pi^0 + X$
$2.6 < \eta < 4.0$

Q^2 distribution from simulation

STAR, PRL 129, 092501 (2022)
supplemental material



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