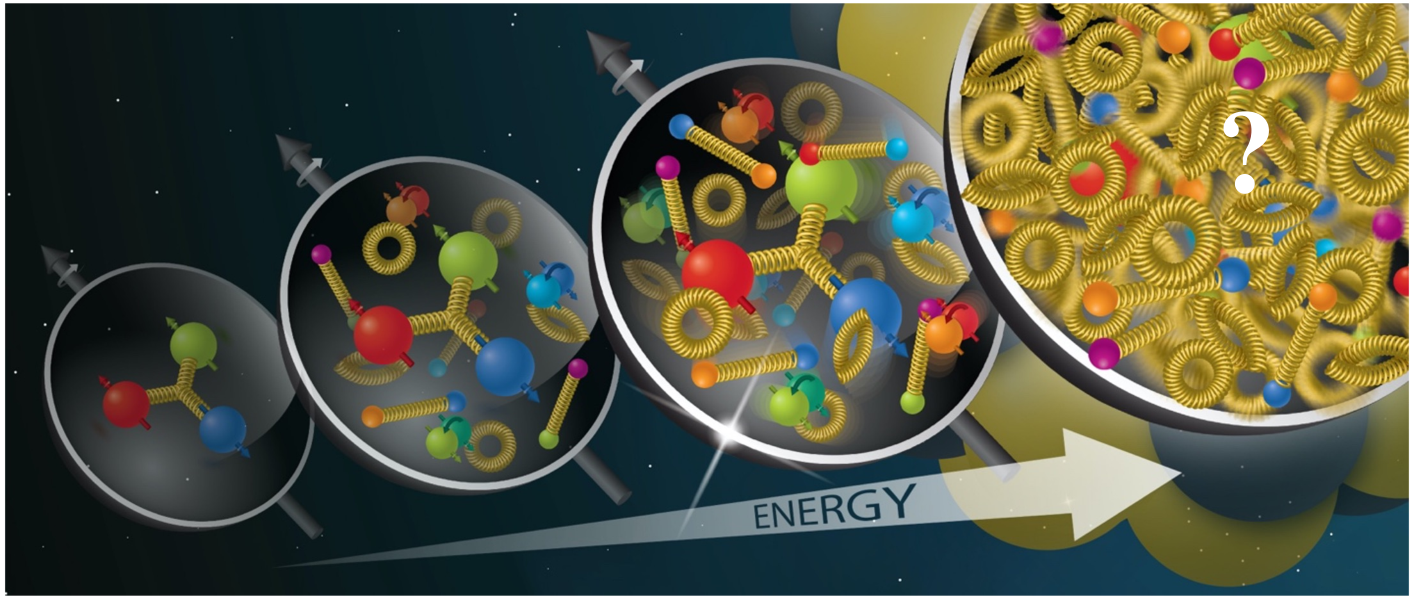
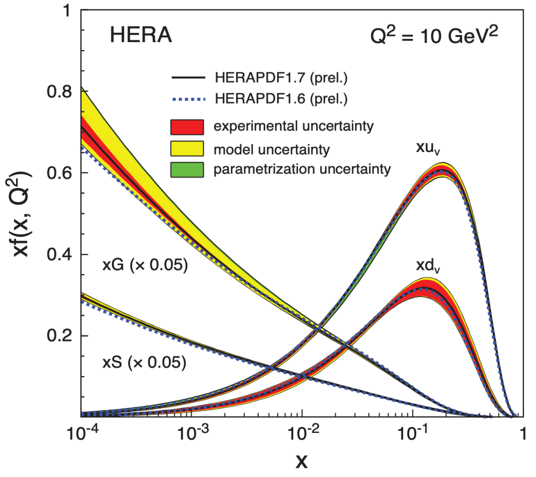
Gluon Saturation at RHIC

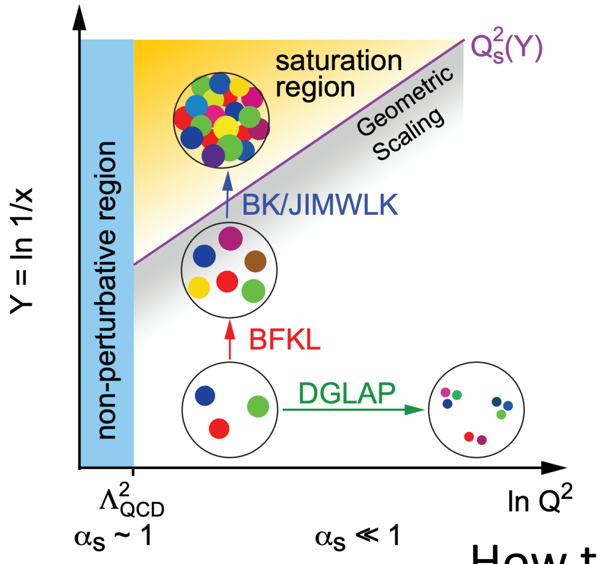
Xiaoxuan Chu, BNL



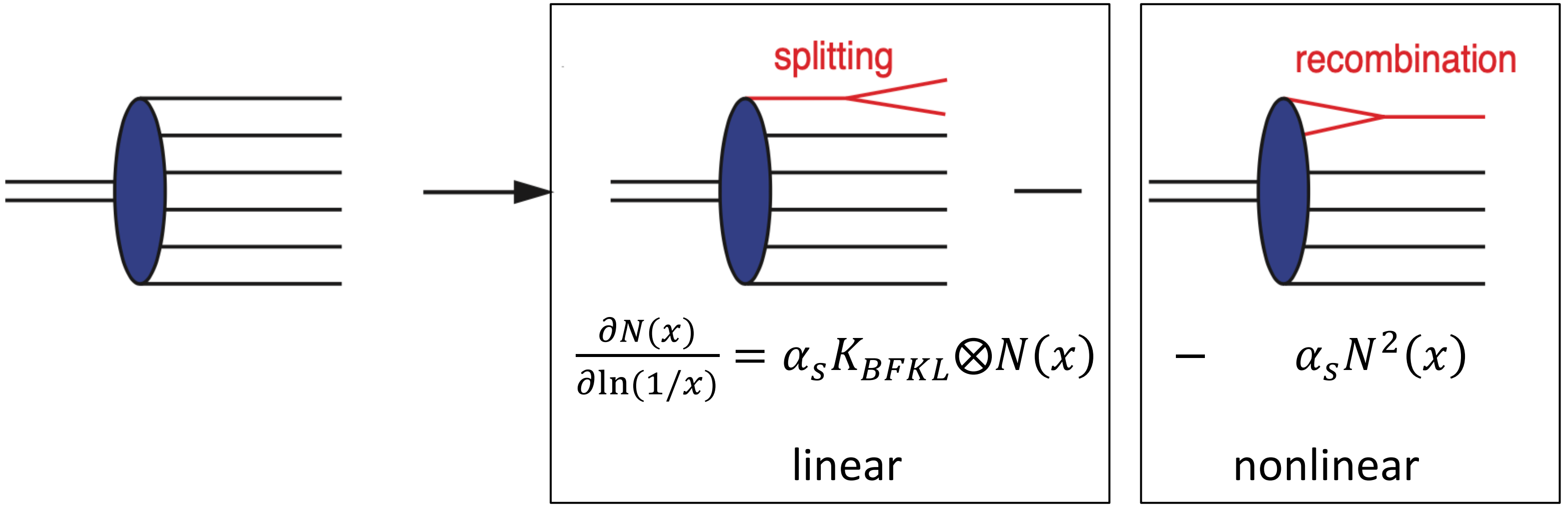
SURGE Collaboration Meeting and Workshop, June 28th – 30th 2023

Gluon saturation





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



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

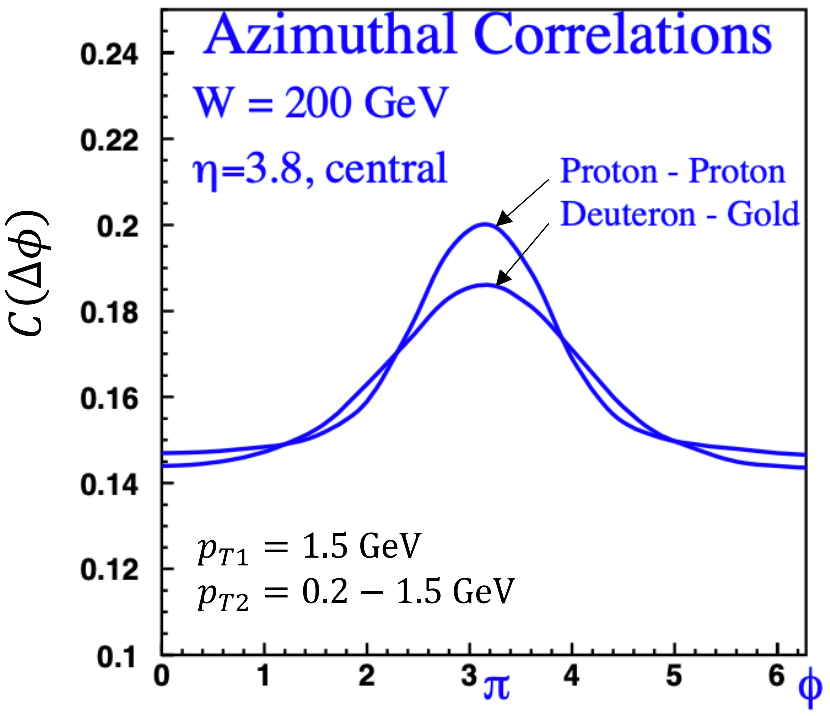
- The rapid increase of gluon density: gluon splitting → linear evolution
- Increase should be tamped at a certain point: gluon recombination → non-linear evolution
- Gluon saturation ($Q^2 < Q_s^2$) at gluon recombination = gluon splitting
- Saturation region is easier to be reached in nuclei: $Q_s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

How to probe nuclear gluon distributions at saturation region?

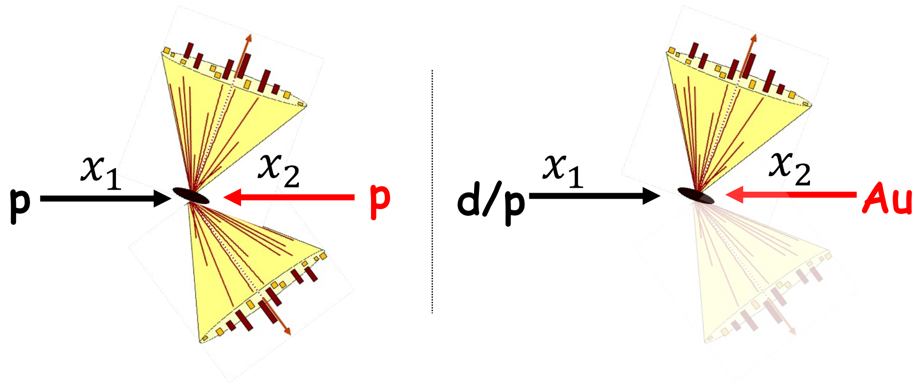
Di-hadron measurement in d+Au

- **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

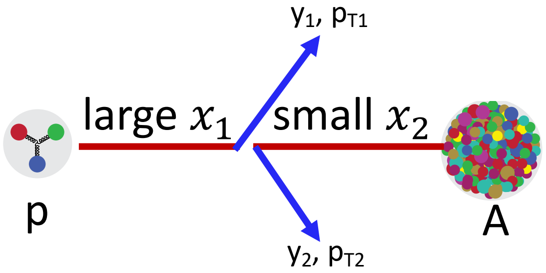
- Di-hadron in p+p as baseline: 2-to-2 process

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

Saturation signatures on p_T, y, b, A

Decrease x, Q^2:

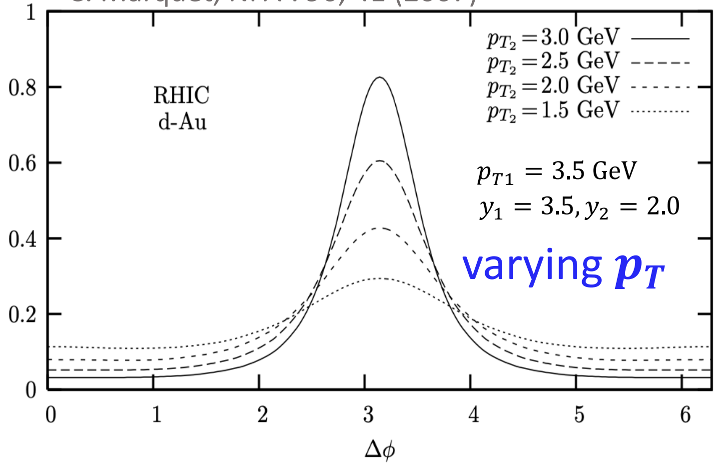
1. More forward direction
2. Lower p_T hadron: very sensitive to p_T



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

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

C. Marquet, NPA 796, 41 (2007)



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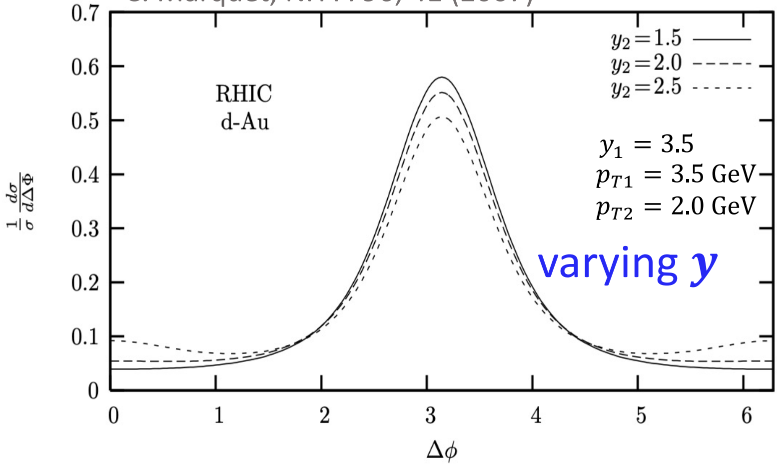

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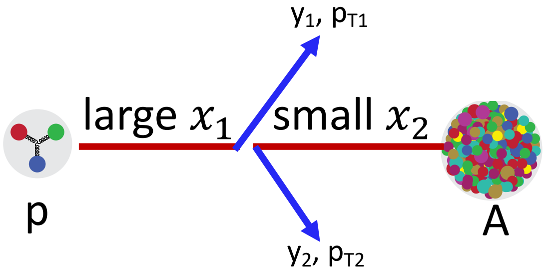

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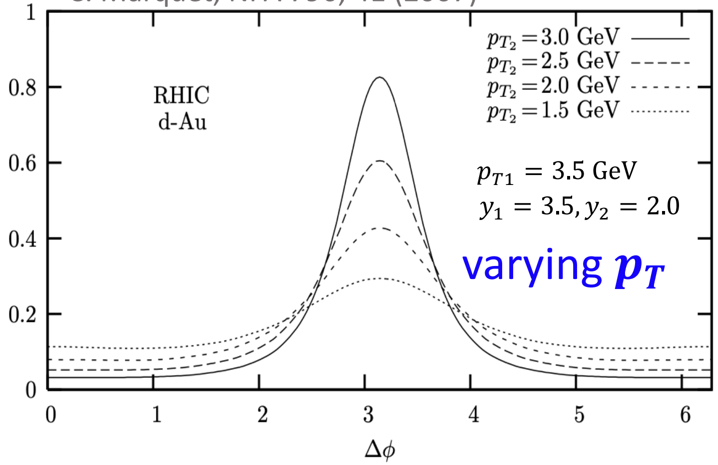
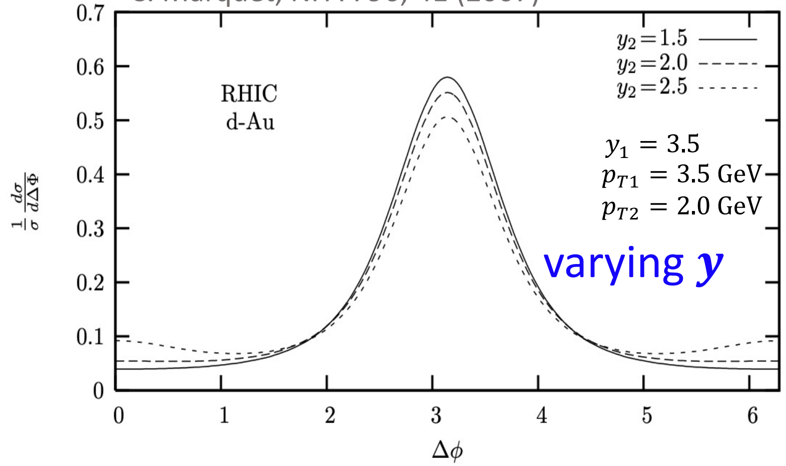


varying p_T

C. Marquet, NPA 796, 41 (2007)

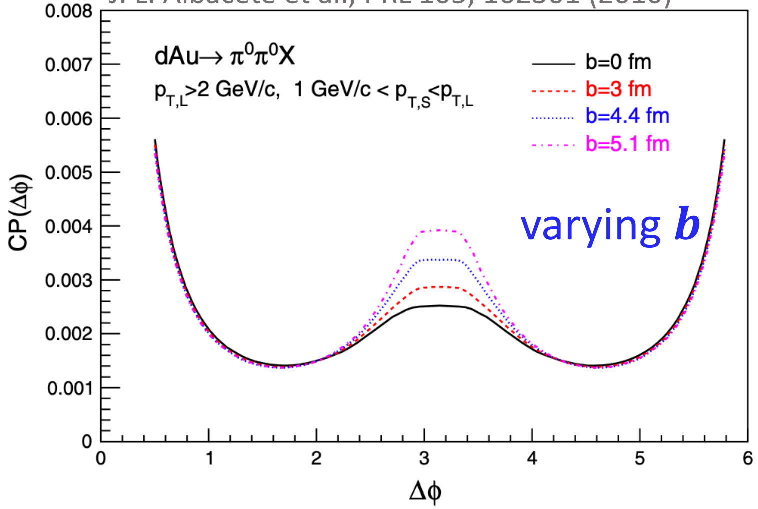


varying y

Increase Q_s:

1. More central collisions
2. Heavier nuclei

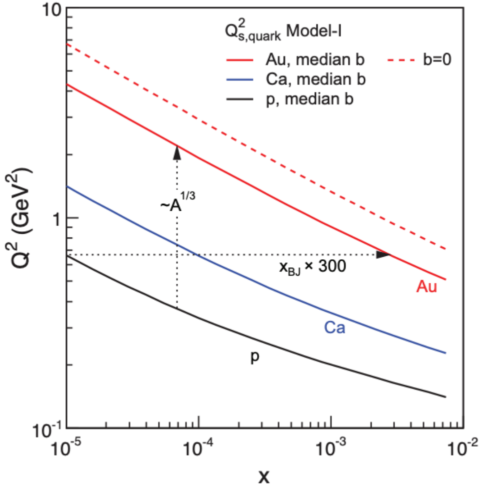
J. L. Albacete et al., PRL 105, 162301 (2010)



varying b

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

EIC white paper

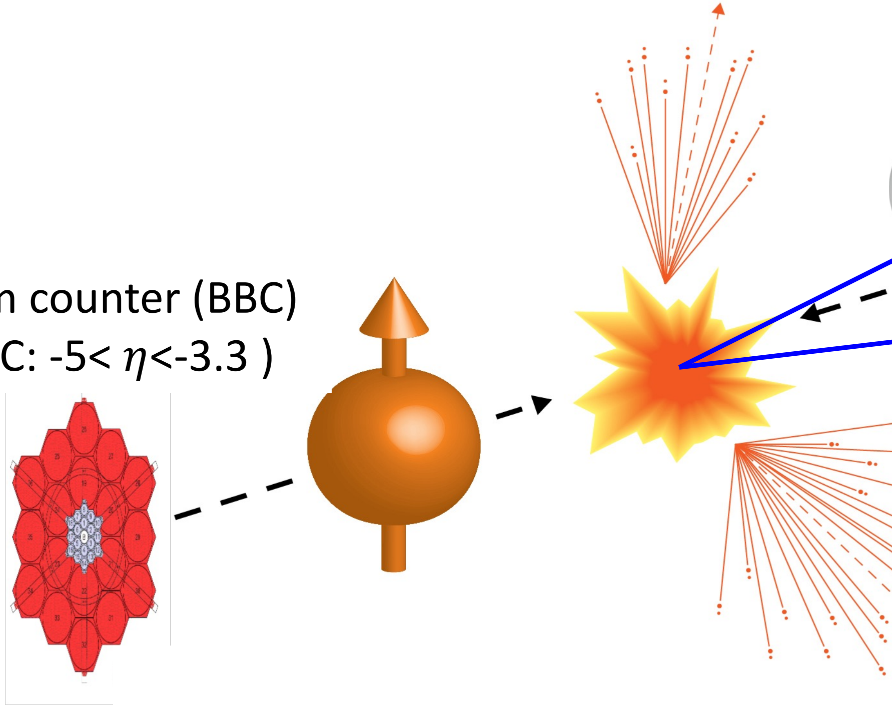


varying A

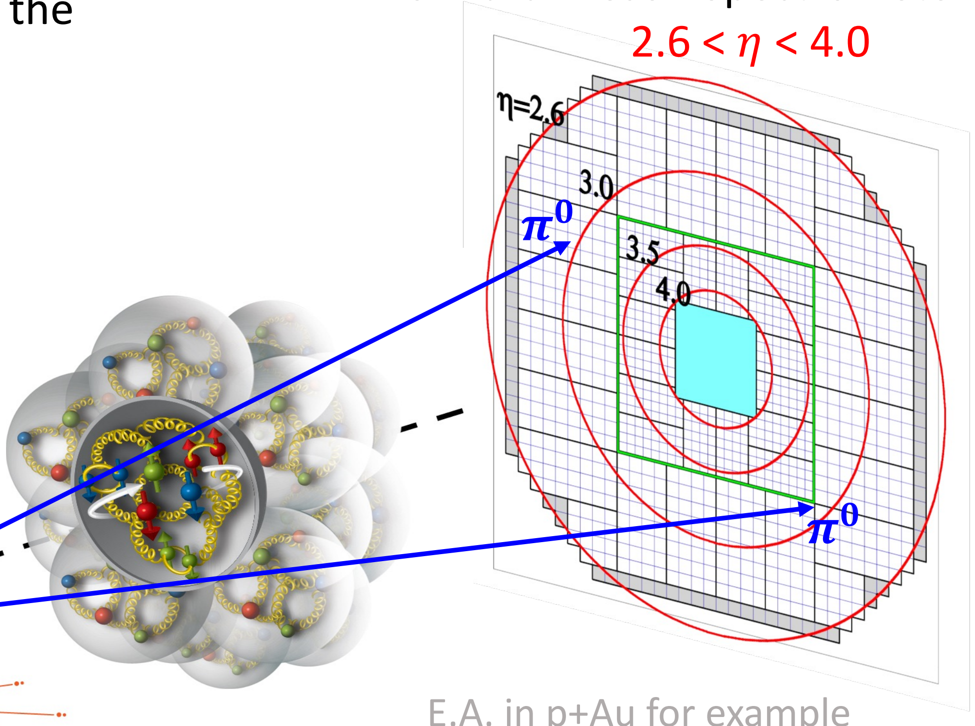
$Q_s \propto A^{1/3}$

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 FMS with $2.6 < \eta < 4.0$
- **Event activity (E.A.):** energy deposition at BBC describes the degree of the p(d)+A collisions
- **Observable:** $C(\Delta\phi) = \frac{N_{pair}(\Delta\phi)}{N_{trig} \times \Delta\phi_{bin}}$, π^0_{trig} → higher p_T π^0



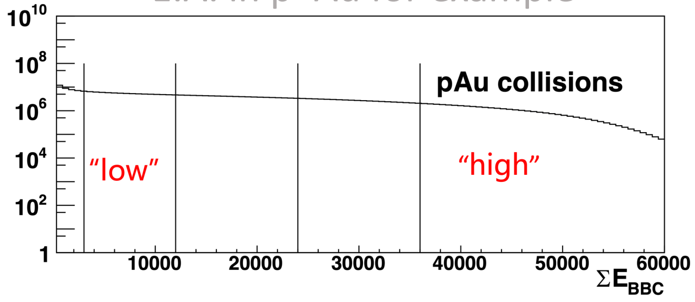
Beam beam counter (BBC)
(inner BBC: $-5< \eta<-3.3$)



Forward Meson Spectrometer (FMS)

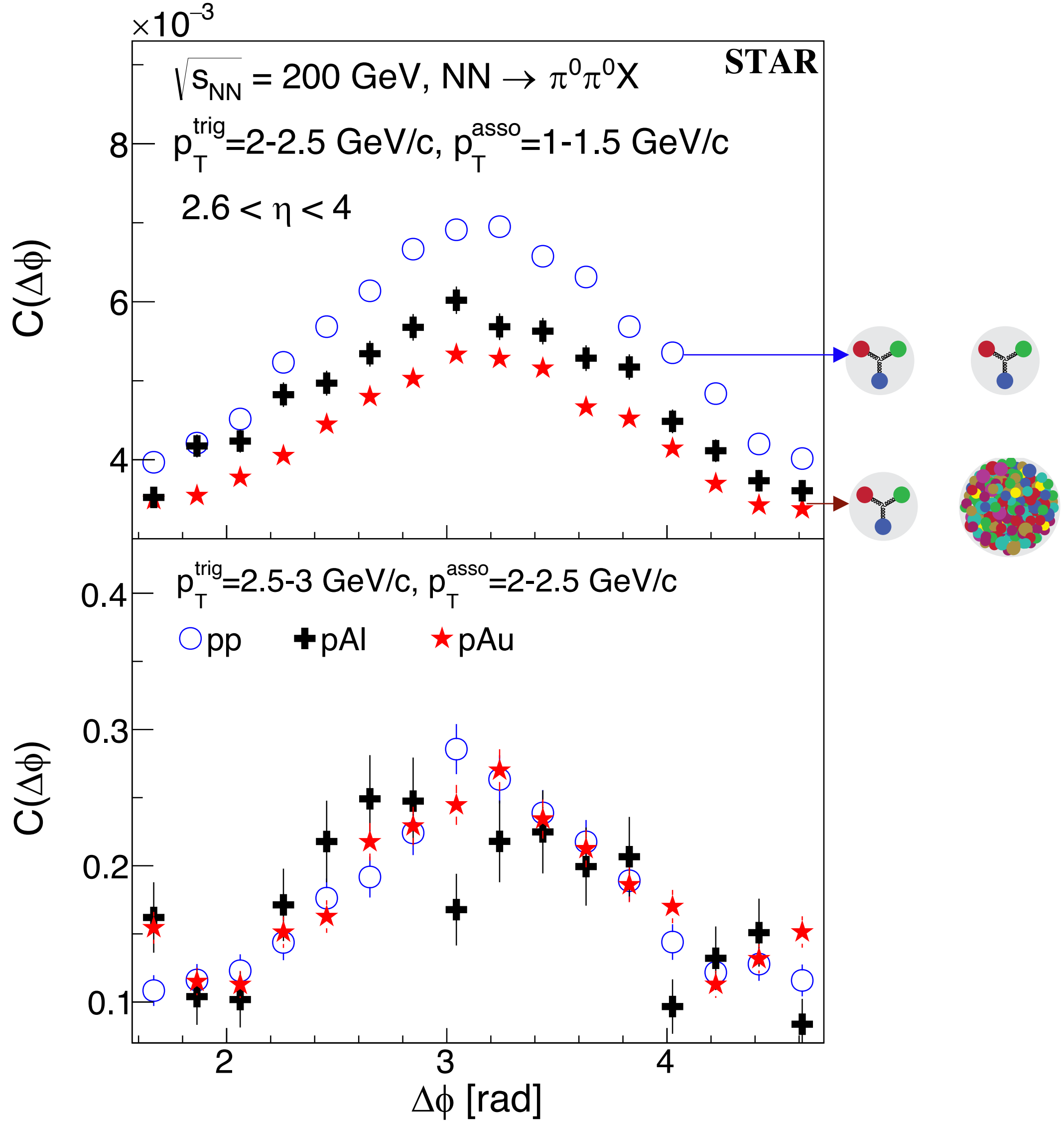
$2.6 < \eta < 4.0$

E.A. in p+Au for example

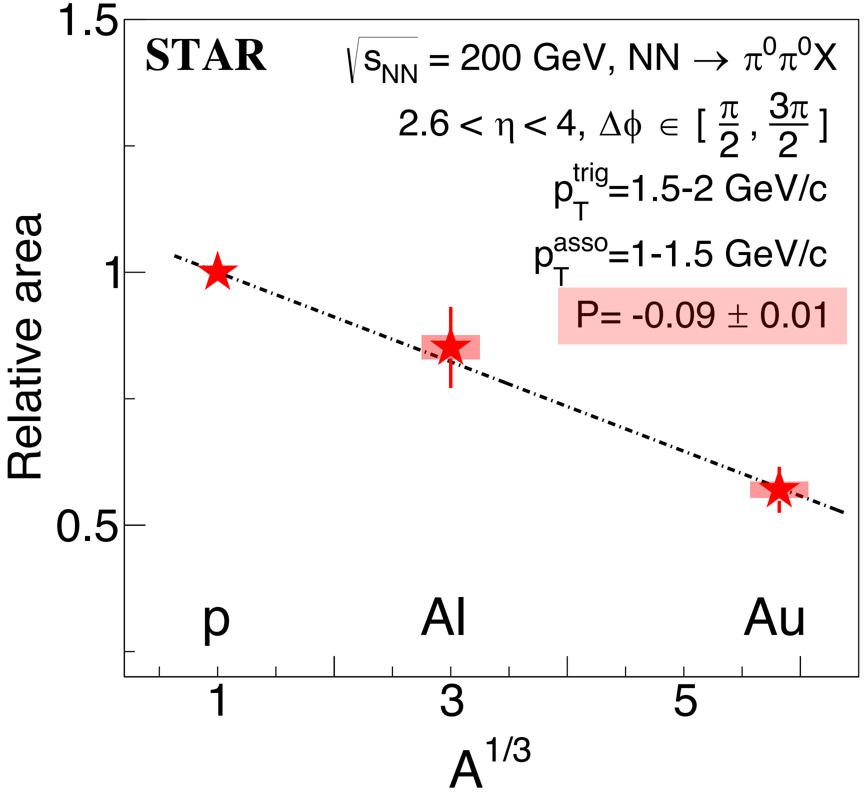


STAR, PRL 129, 092501 (2022)

p_T and A dependence



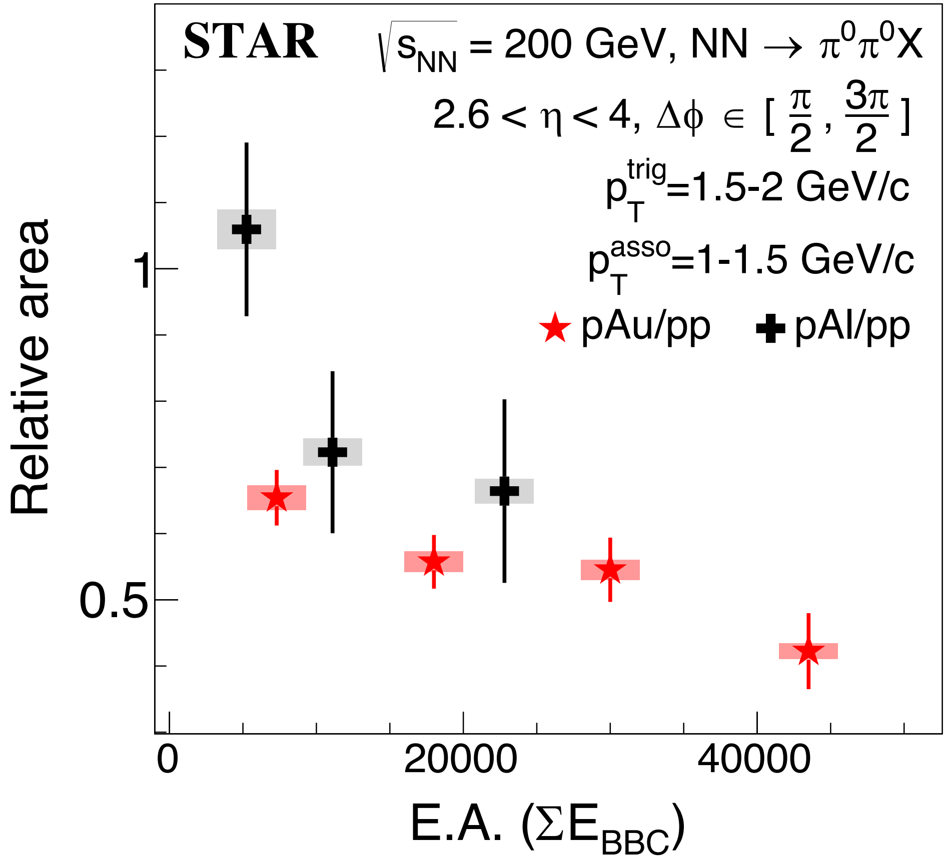
Gaussian (Area and width) at $\Delta\phi = \pi$ + pedestal



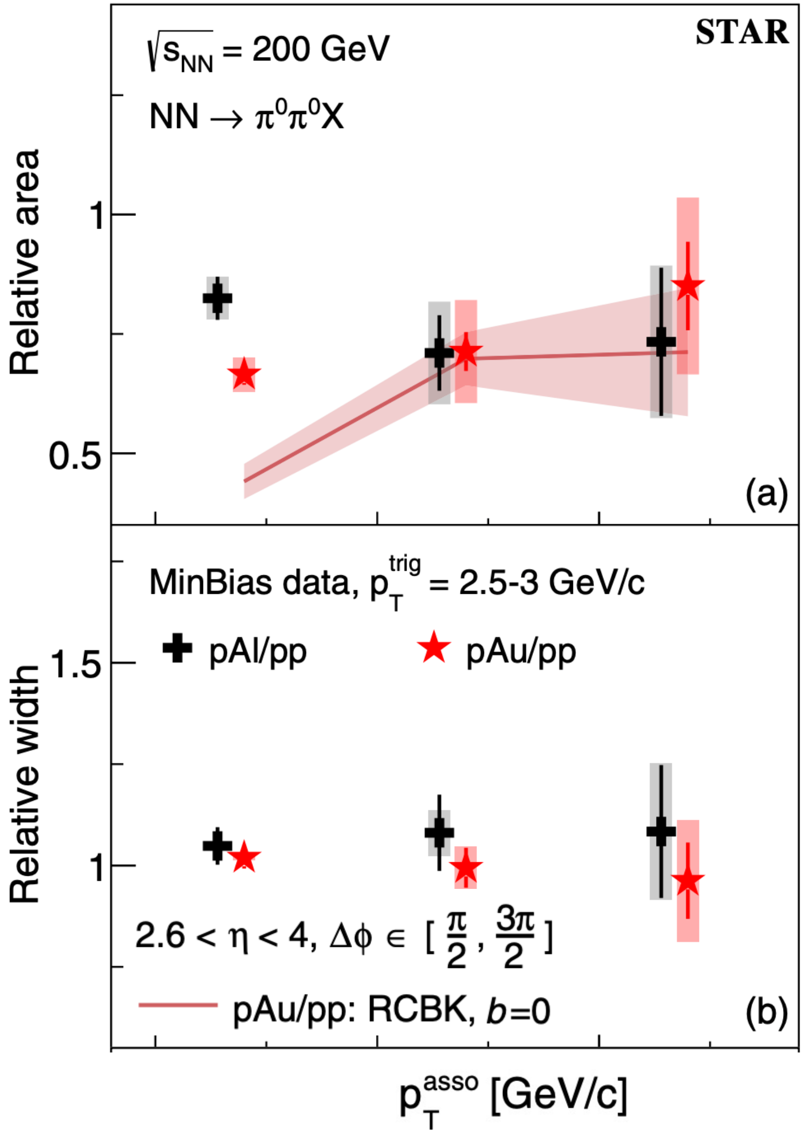
- Suppression observed at low p_T not high p_T
- In fixed $x - Q^2$ phase space, suppression is dominantly affected by various A:
  - Suppression linearly depends on $A^{1/3}$

STAR, PRL 129, 092501 (2022)

E.A. dependence



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

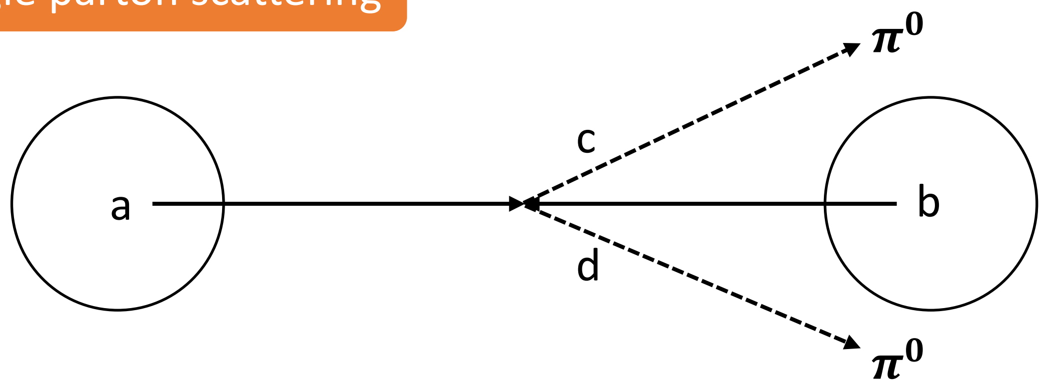


- Suppression increases with *E.A., highest E.A. data is consistent with predictions at $b = 0$;
- No broadening is observed

*E.A. (event activity): energy deposited in BBC in nuclei-going direction

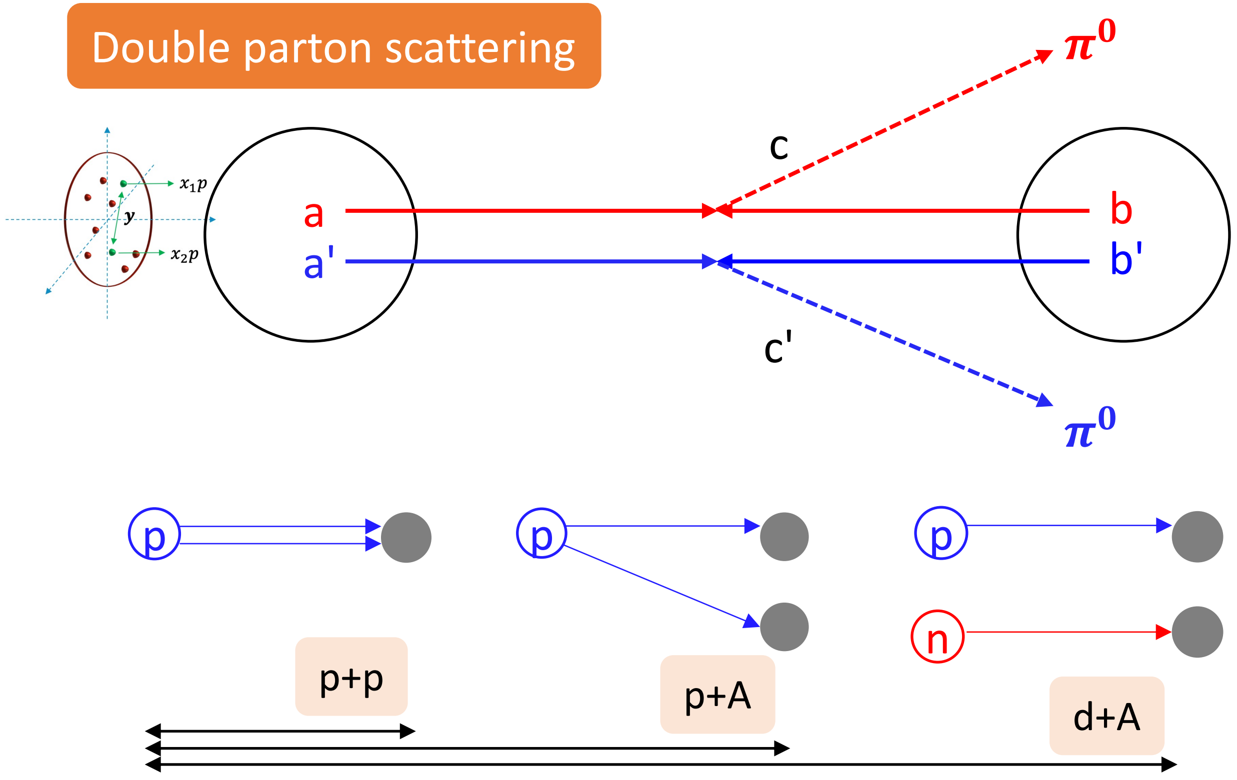
How about d+Au?

Single parton scattering



Two π^0 generated from the same hard scattering

Double parton scattering



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

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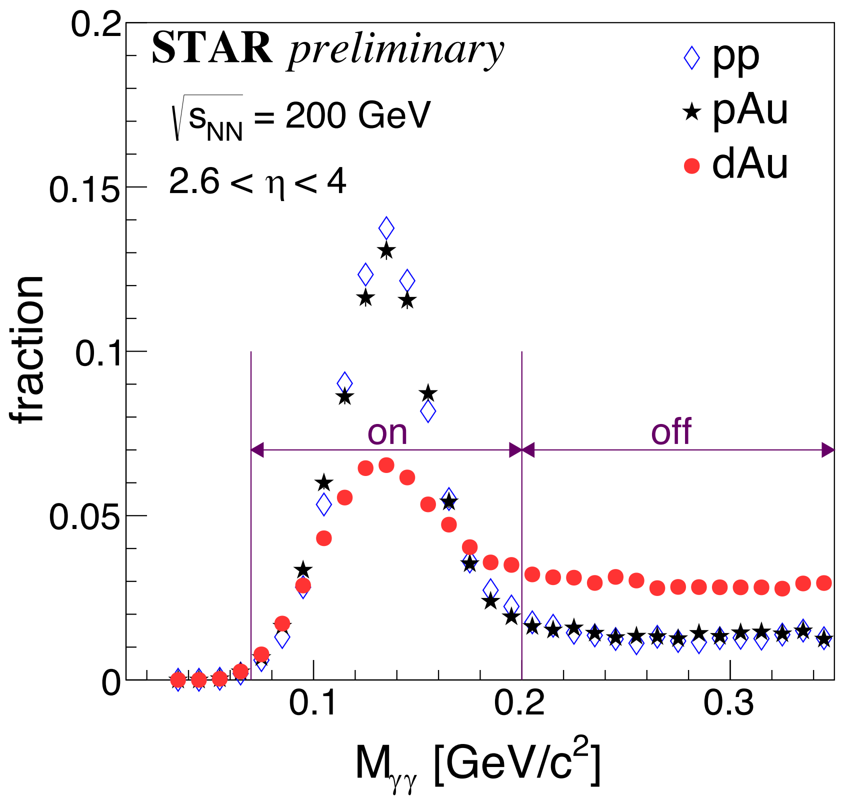
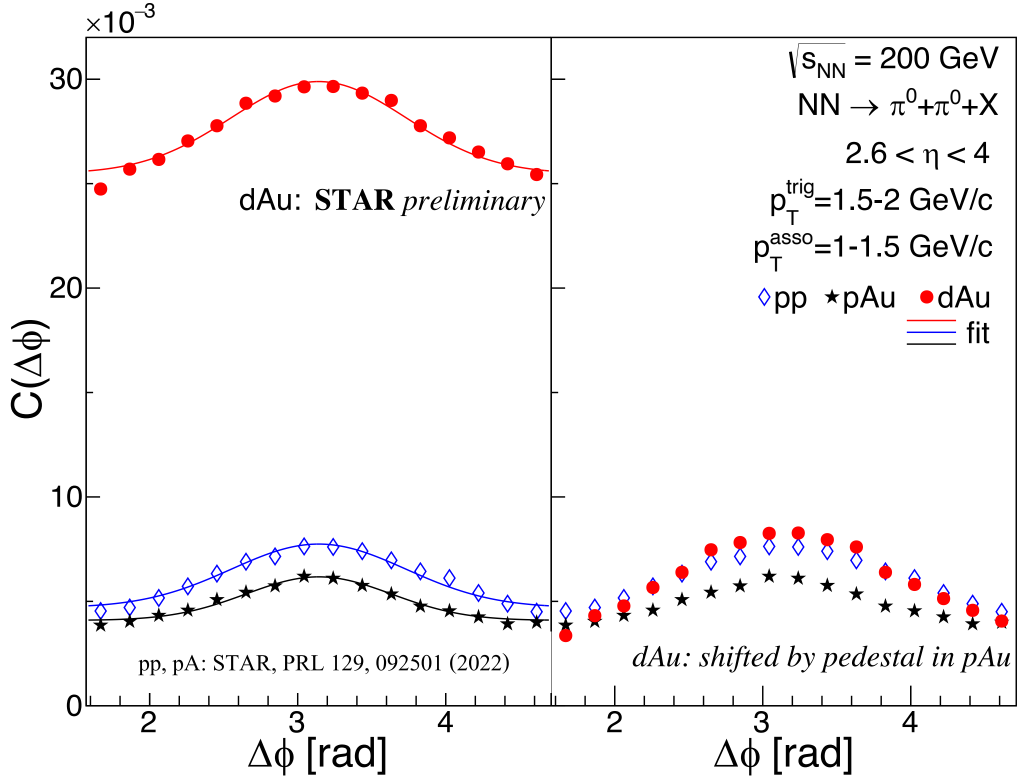
[*] M. Strikman et al., PRD 83, 034029 (2011)

Di-π^0 measurement in d+Au at STAR

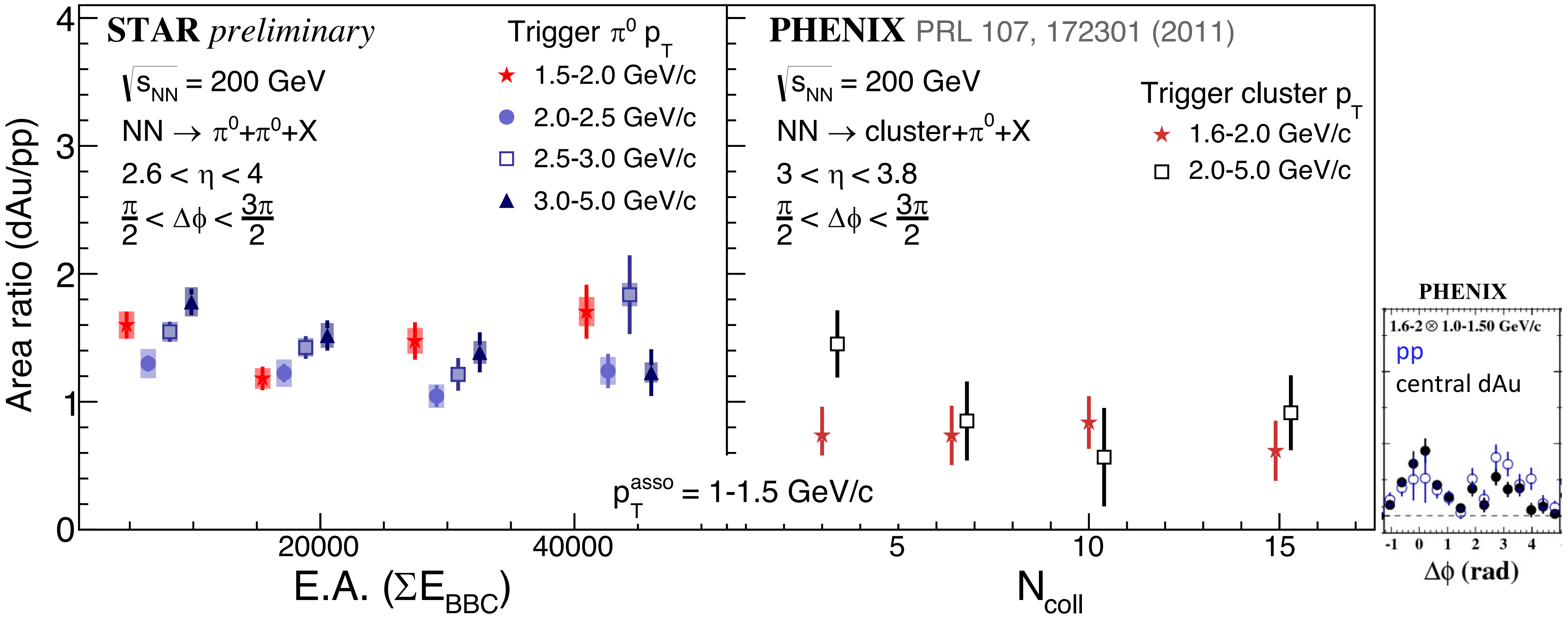




Challenging to conclude the forward di-π^0correlation measurement in d+Au

- π^0 PID: 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

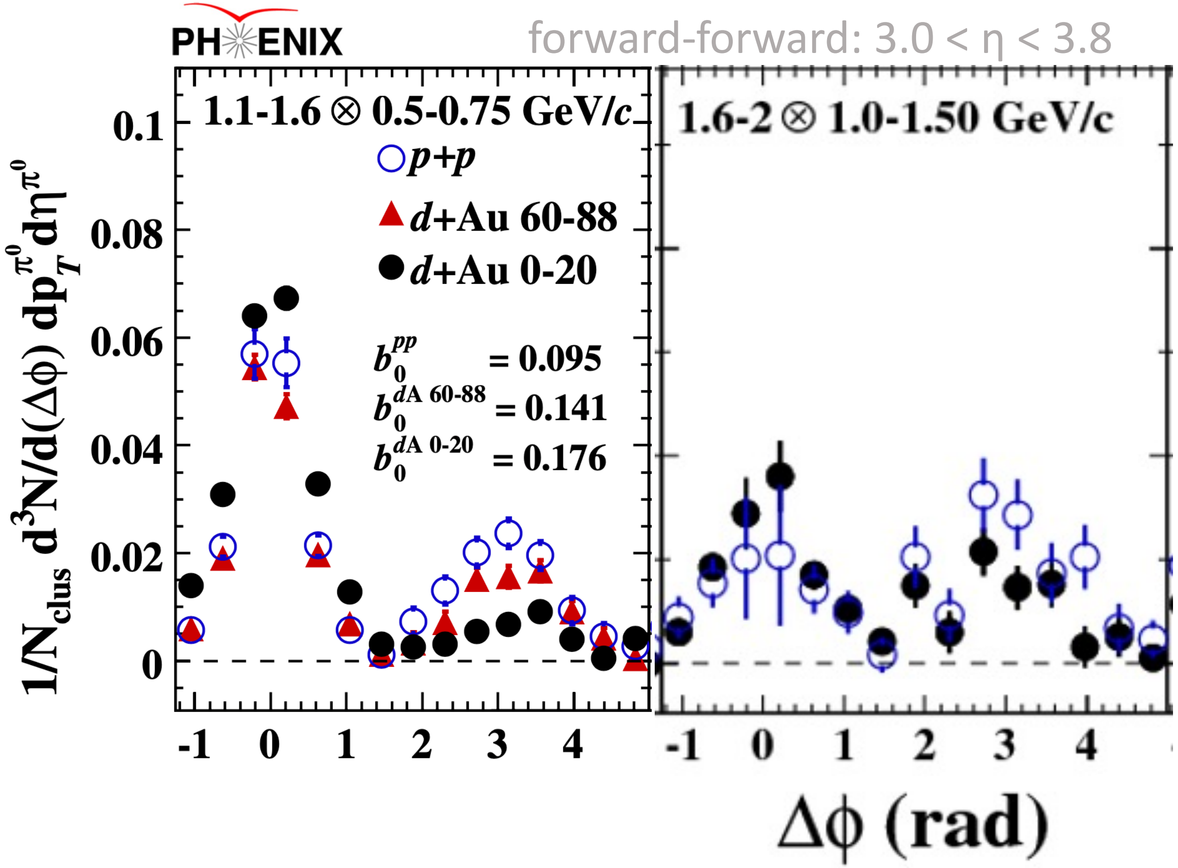
E.A./centrality dependence in d+Au?

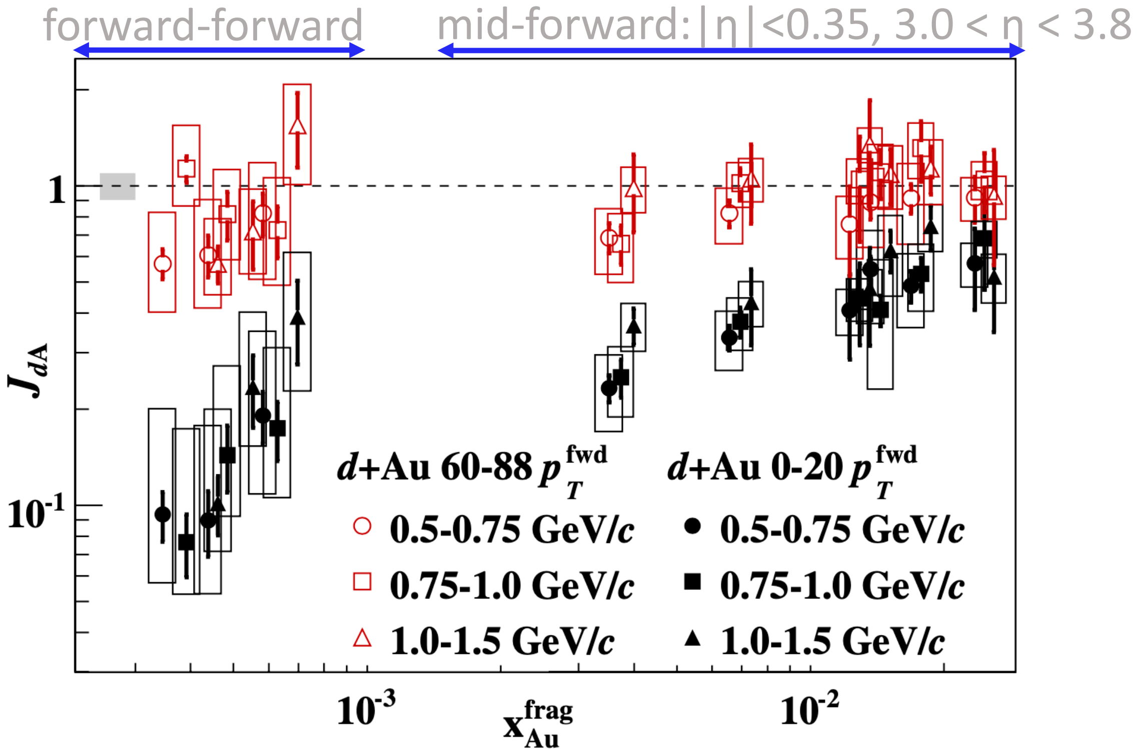


- In the overlapping p_T range of two collaborations, no suppression or E.A./centrality dependence in d+Au relative to p+p
- Suppression observed only at very low p_T $(p_T^{asso} = 0.5 - 0.75\ \text{GeV}/c)$at PHENIX, where STAR FMS cannot reach

PHENIX, PRL 107, 172301 (2011); PhD thesis

d+Au at PHENIX





J_{dA} = Area ratio× $\mathbf{R_{dA}}$

Used at STAR

$\mathrm{R_{dA}} \sim \frac{2}{N_{coll}}$

Suppression in central dAu compared to pp:

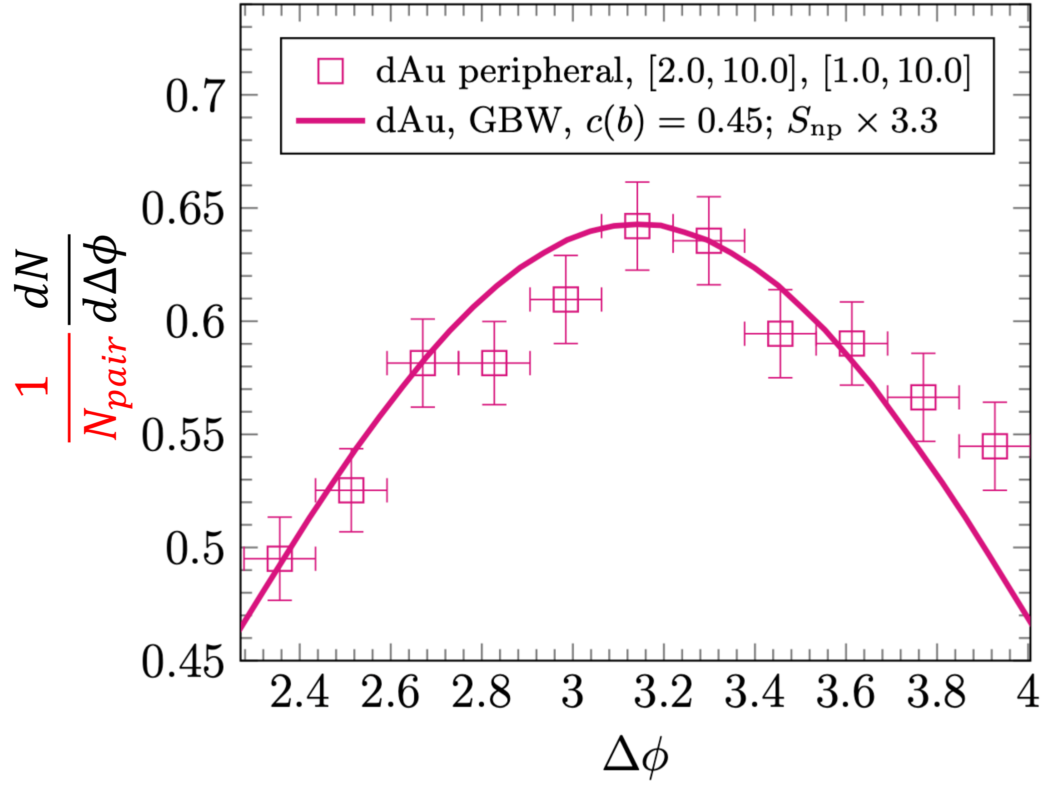
- observed only at very low p_T ($p_T^{asso} = 0.5 - 0.75$ GeV/c) at PHENIX, where STAR FMS cannot reach
- absent at high p_T ($p_T^{asso} = 1.0 - 1.5$ GeV/c)

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

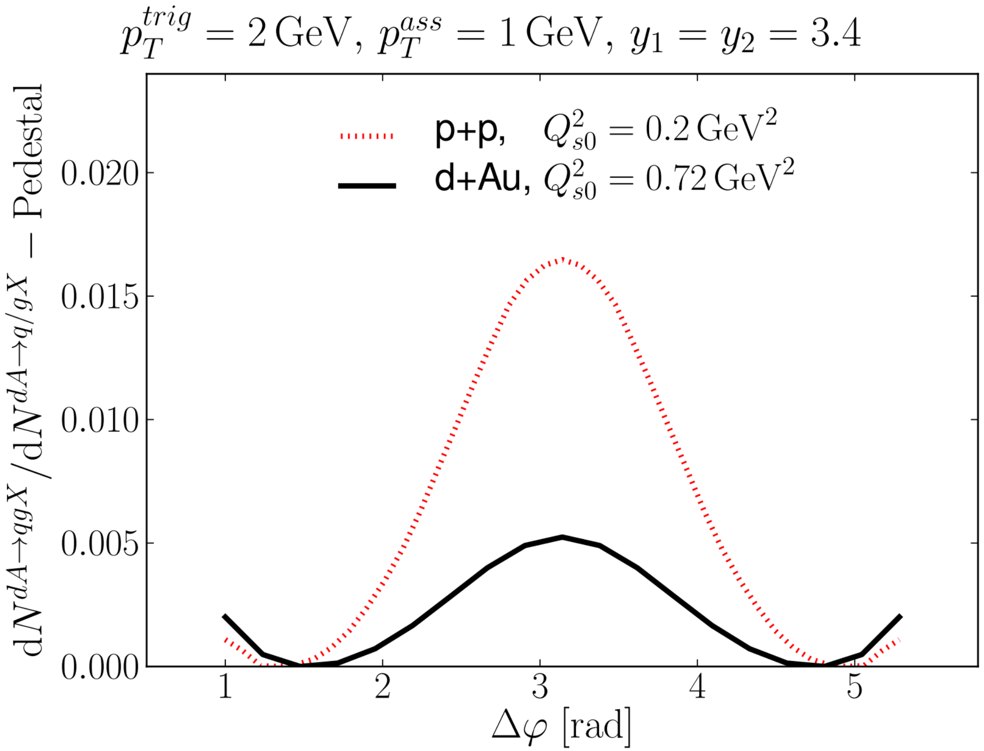
Examples of normalization

Experiment: $\frac{1}{N_{trig}}\frac{dN_{pair}}{d\Delta\phi}$

PLB 784 (2018) 301-306



NPA 908 (2013) 51-72



Various ways of normalizations, Left: $\frac{1}{N_{pair}}\frac{dN_{pair}}{d\Delta\phi}$; right: $\frac{1}{N_{trig}}\frac{dN_{pair}}{d\Delta\phi}$

Left: different normalization from the experiment method

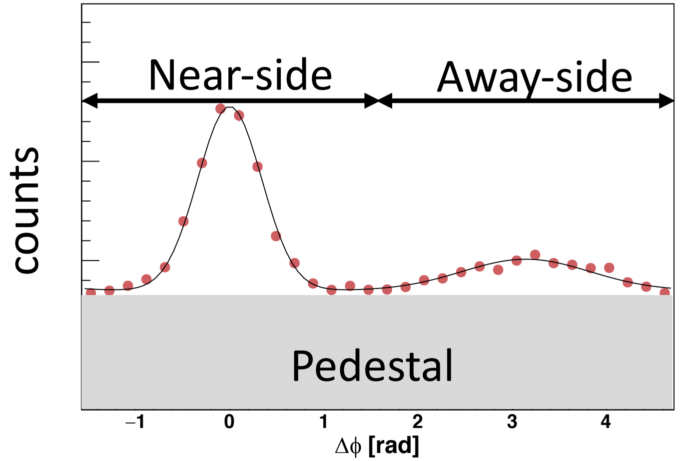
Right: same normalization from the experiment method

Normalization summary

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	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

Experiment: $\frac{1}{N_{trig}}\frac{dN_{pair}}{d\Delta\phi}$

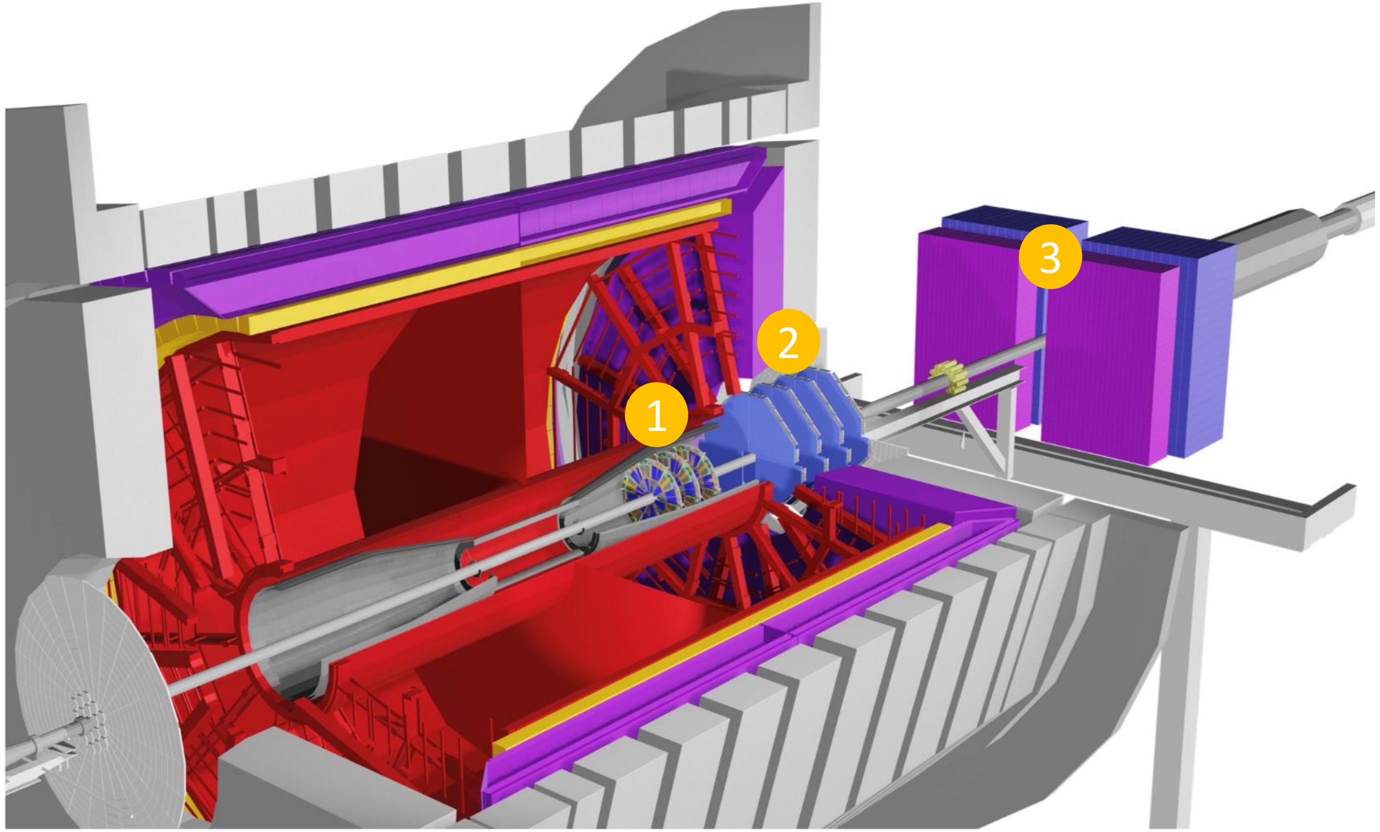


For dAu:

- Complicated normalizations
- Undetermined DPS
- Large background

Di-π^0 measurement favors cleaner p+A than d+A collisions. More p+Au data are coming in 2024!

Future measurements with STAR Forward Upgrade



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

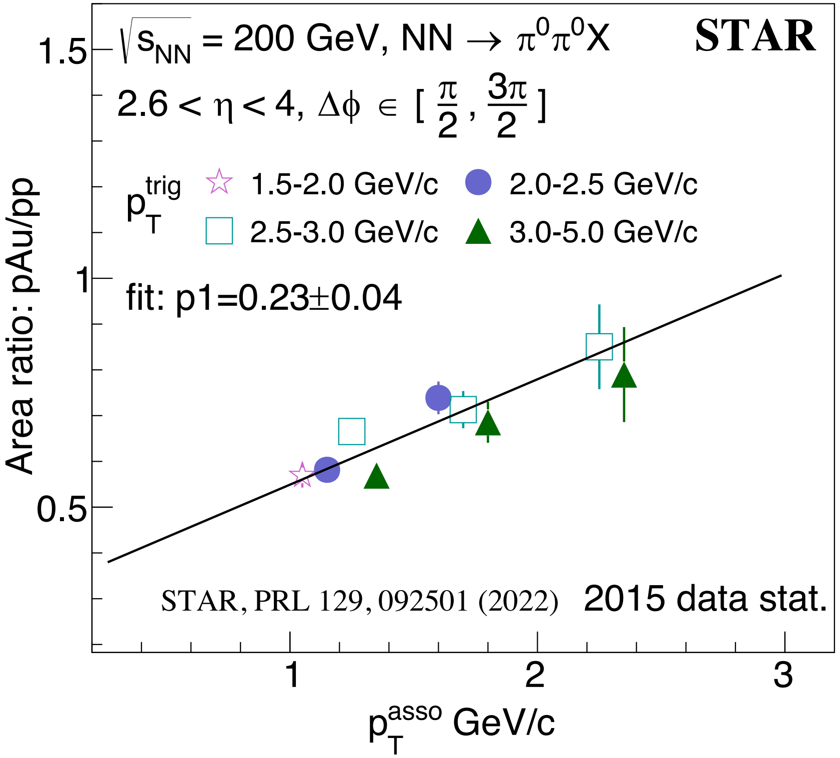
Year	System	$\sqrt{s}$ (GeV)
2023	Au+Au	200
2024	p+p, p+Au	200
2025	Au+Au	200

Detector	pp and pA	AA
ECal	~10%/$\sqrt{E}$	~20%/$\sqrt{E}$
HCal	~50%/$\sqrt{E}$+10%	---
Tracking	charge separation photon suppression	0.2<p_T<2 GeV/c with 20-30% 1/p_T

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: $p_T^{jet} > 5\ GeV/c$ → higher x and Q^2
- Direct photon: q+g→q+γ; statistic driven

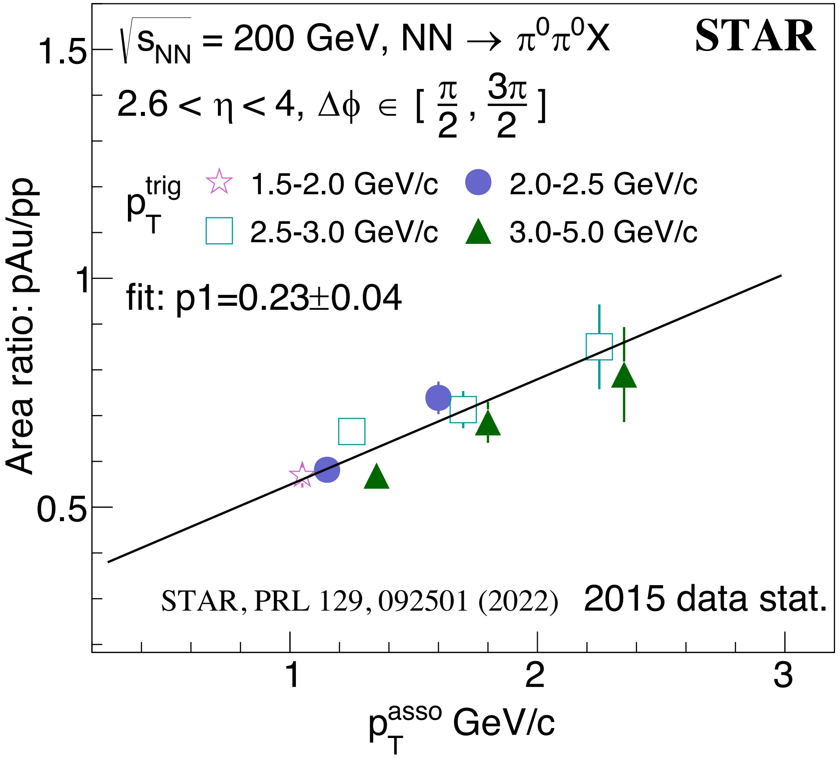
Future measurements with STAR Forward Upgrade



Expectation for run 24 pp and pA data with **di-hadron**:

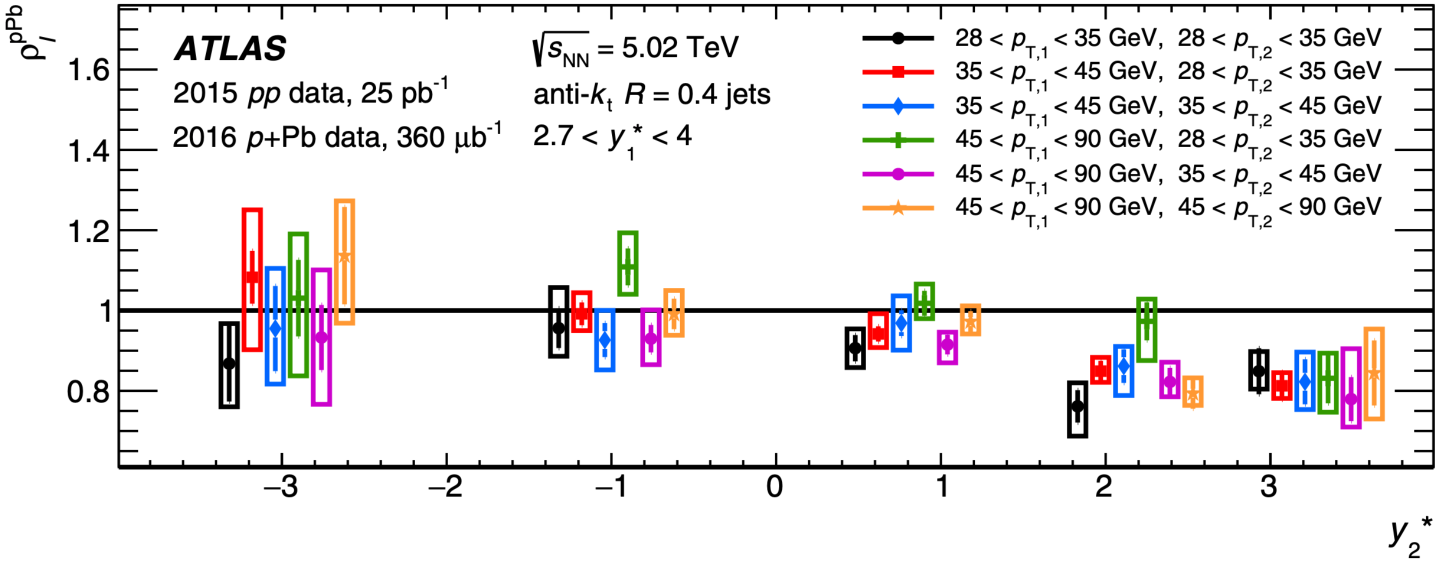
- high p_T: enough statistic for disappearing suppression
- lowest p_T: largest suppression expected to be observed

Future measurements with STAR Forward Upgrade



STAR, PRL 129, 092501 (2022)

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, less suppression compared to STAR dihadron
- x_{Pb}→10^{-4}; but $Q^2 > \sim 800\ GeV^2$, too high?

Expectation for run 24 pp and pA data with **di-hadron**:

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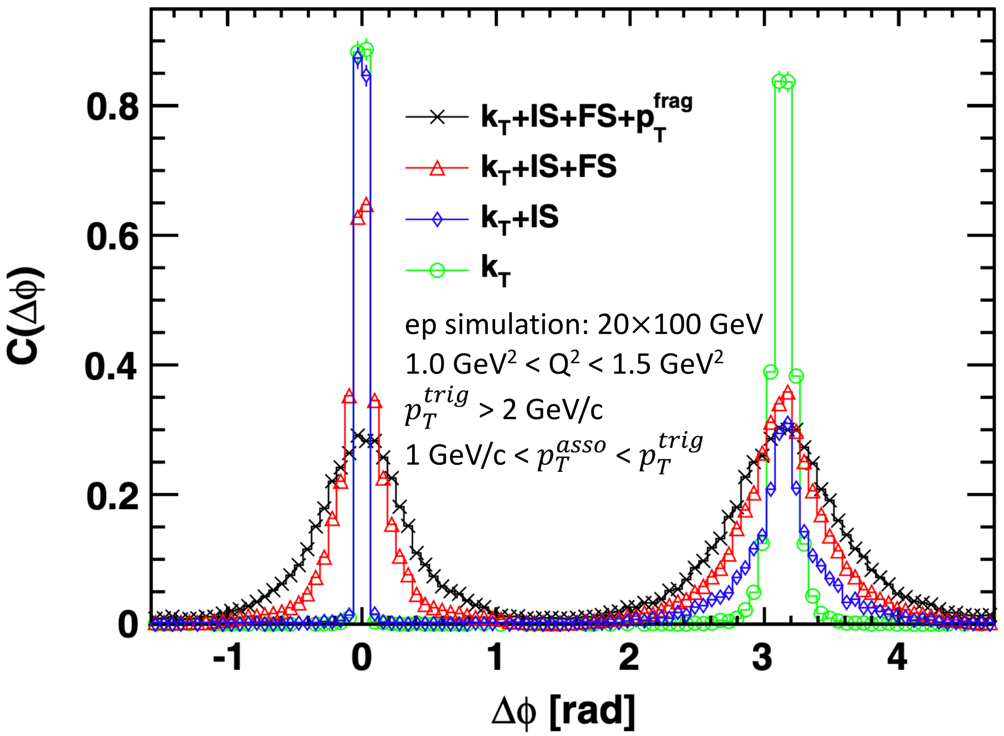
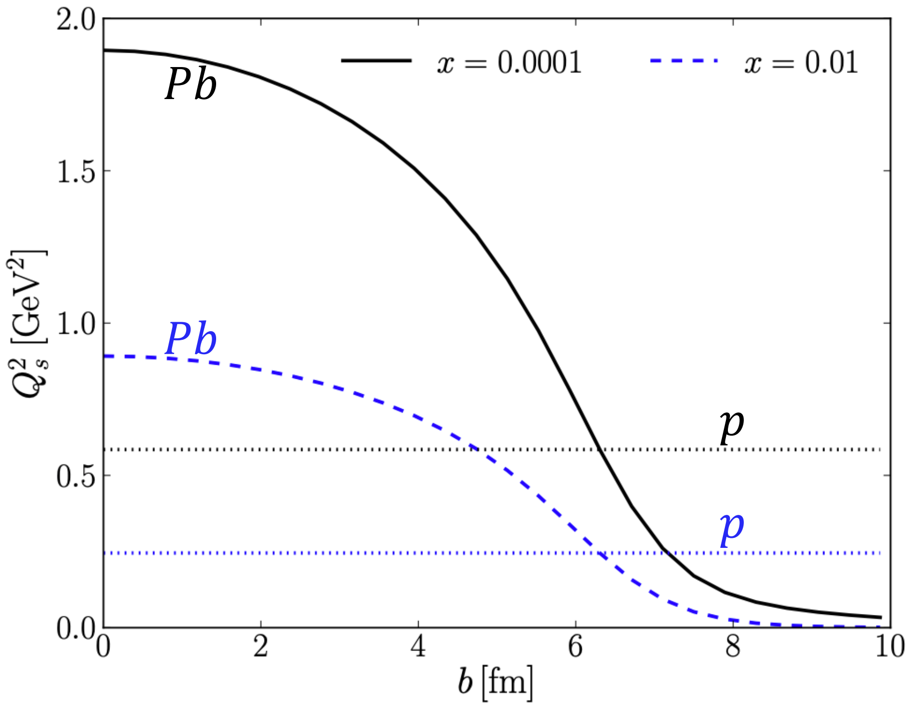
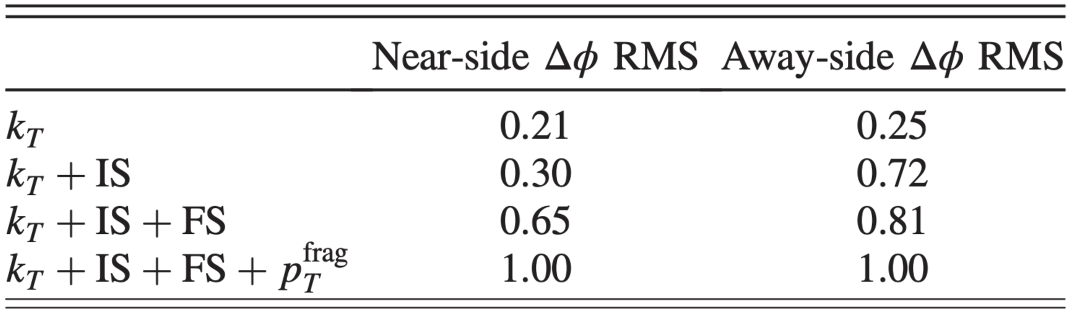
Broadening phenomena

PRD 89, 074037 (2014)



PRD 88, 114020 (2013)



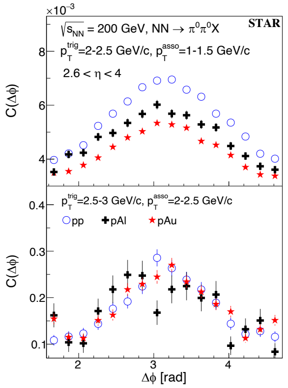


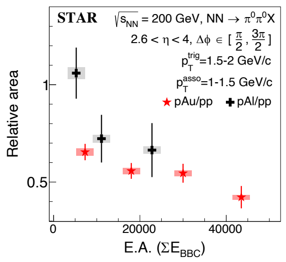
	Near-side $\Delta\phi$ RMS	Away-side $\Delta\phi$ RMS
k_T	0.21	0.25
$k_T + \mathrm{IS}$	0.30	0.72
$k_T + \mathrm{IS} + \mathrm{FS}$	0.65	0.81
$k_T + \mathrm{IS} + \mathrm{FS} + p_T^{\mathrm{frag}}$	1.00	1.00

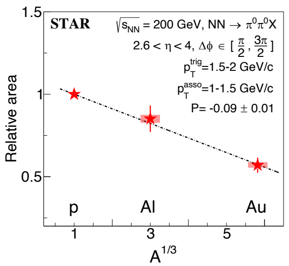
- IS: the dominate effect leading to a broad away-side peak
- Considering intrinsic k_T, PS, p_T^{frag}, and detector smearing, challenging to observe broadening phenomena
- Future measurement with di-charged hadron: near-side peak used to calibrate
- Working on the similar studies in pp collisions

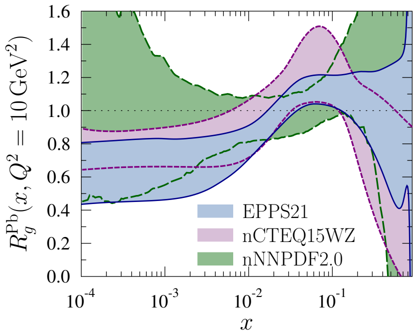
See elke's talk on Friday

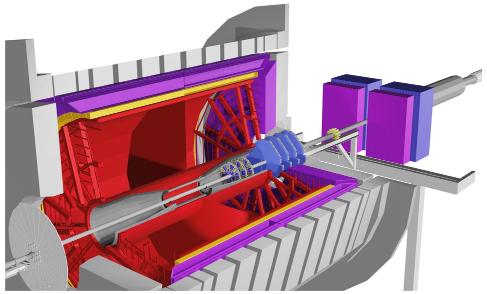
Summary and outlook











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

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

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

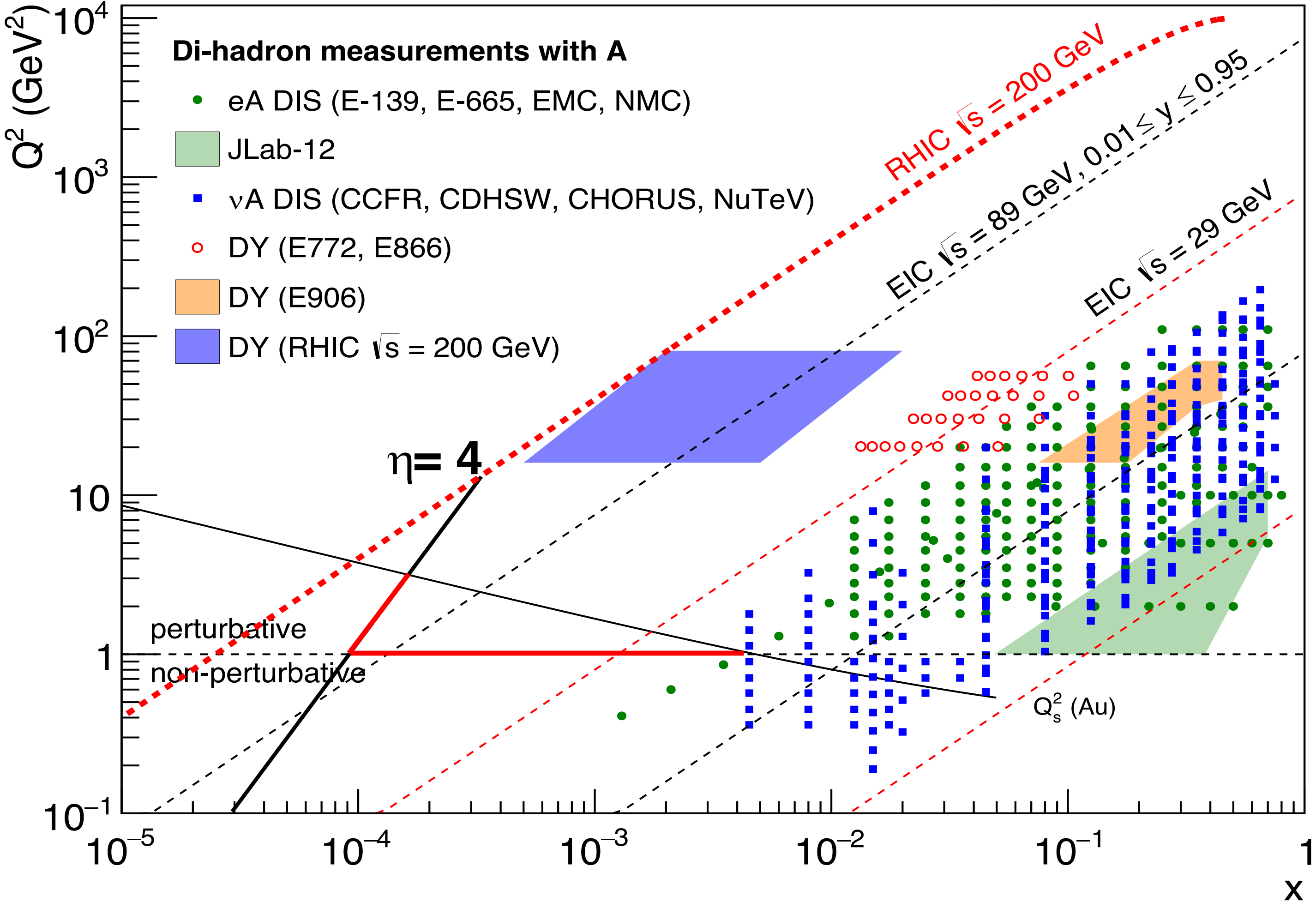
Nuclear gluon distributions remain largely unconstrained in the nonlinear regime: important input from RHIC at low and moderate Q^2

STAR forward upgrade with expanded observables in p+Au
More opportunities with diffraction measurements

Future measurement with di-charged hadron: further understanding of the broadening phenomena

Back up

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

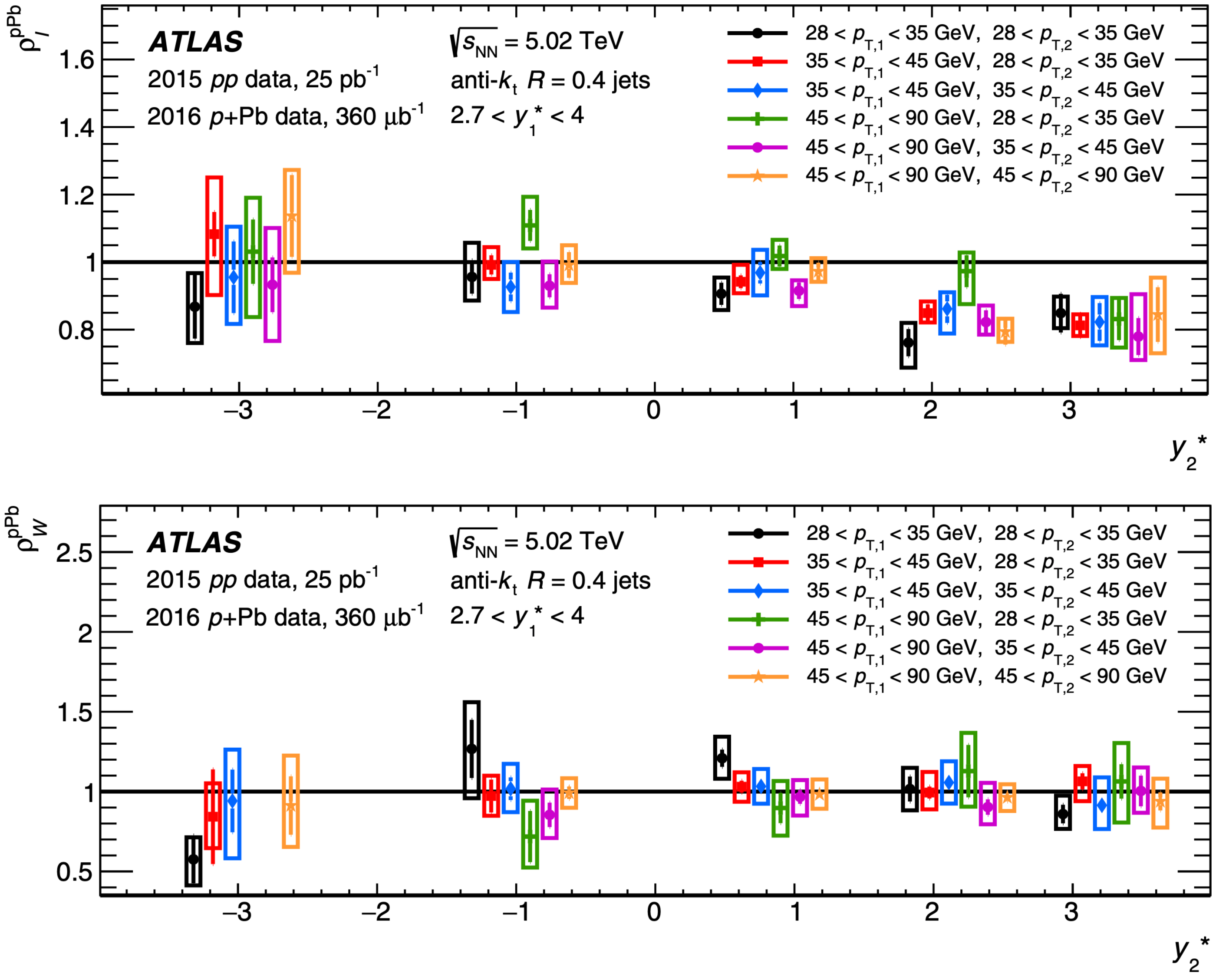


R. Abdul Khalek et al., arXiv:2103.05419

STAR data can access linear-nonlinear transition region

Dijet at ATLAS

ATLAS, PRC 100, 034903 (2019)



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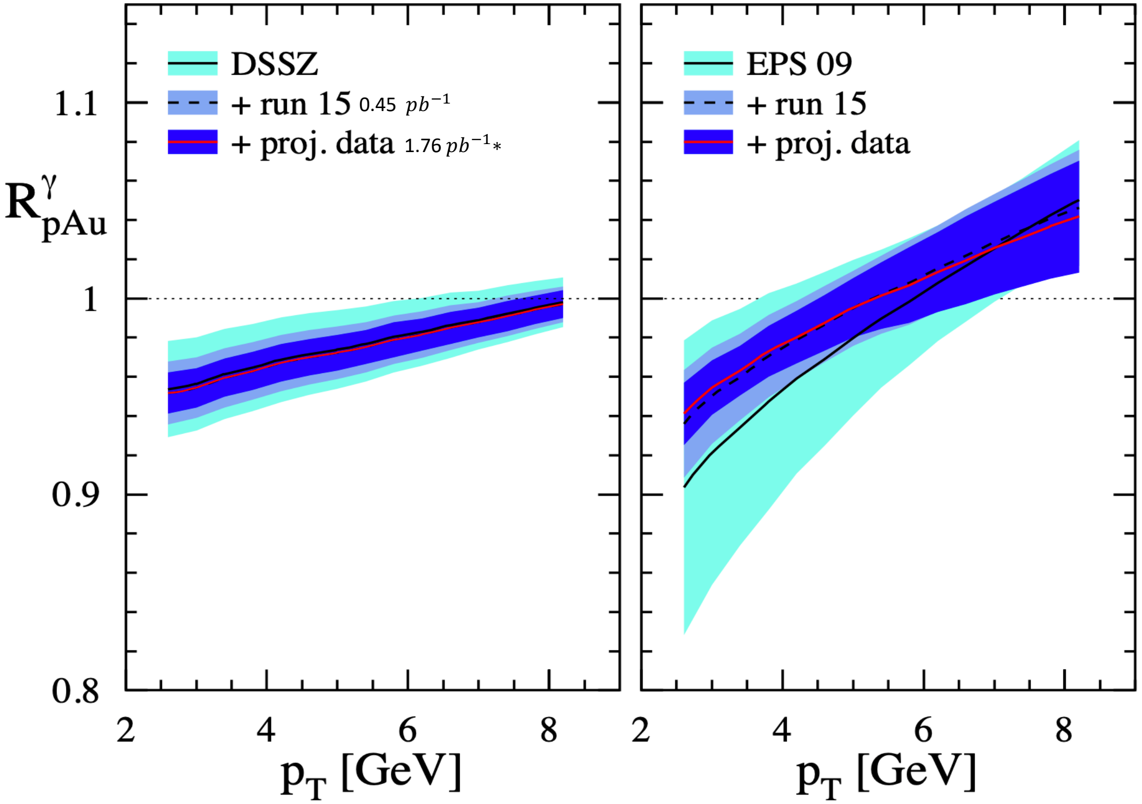
- Rapidity dependence
- $\frac{pPb}{pp}$~0.8 at most forward, less suppression compared to STAR dihadron
- x_{Pb}→10^{-4}; but $Q^2 > \sim 800\ GeV^2$, too high?

Width extracted as σ from the Gaussian fit:

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

Future measurements with STAR Forward Upgrade

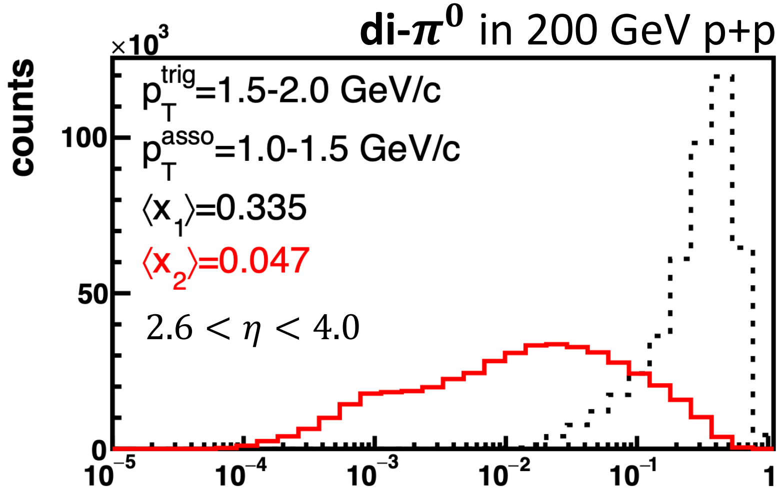
arXiv:1602.03922



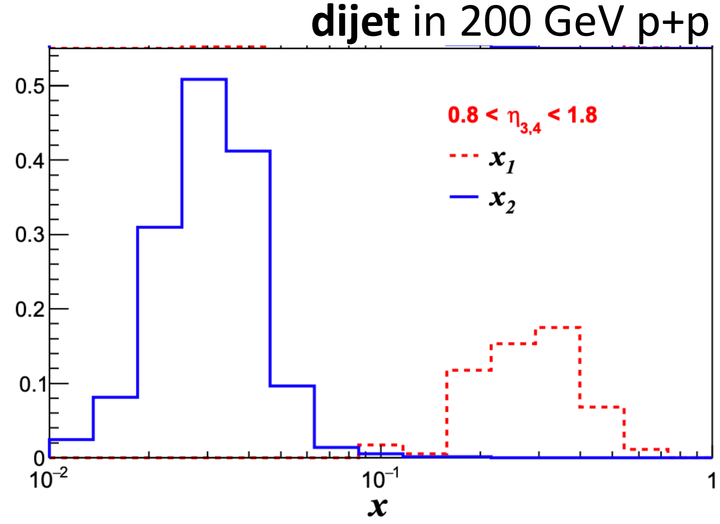
Direct photon (-jet):

- q+g→q+γ, sensitive to gluon
- remove finial state effect
- small cross section and background γ

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



STAR, PRL 129, 092501 (2022)

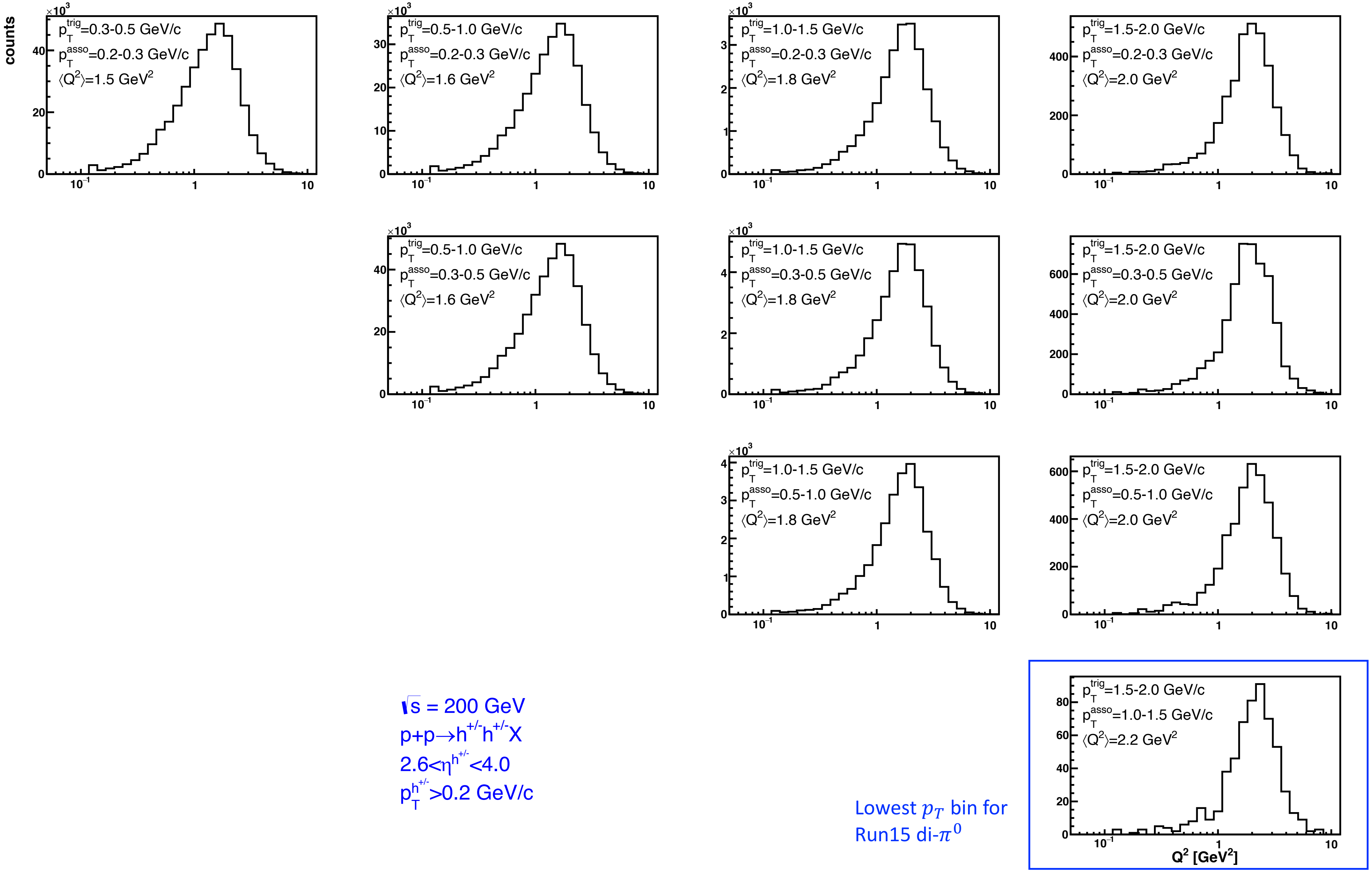


STAR, PRD 98 (2018) 32011

Dijet, compared to dihadron:

- helps to select cleaner small x_2 channels
- more accurate proxy to di-parton
- can not probe small p_T: $p_T^{jet} > 5\ GeV/c$

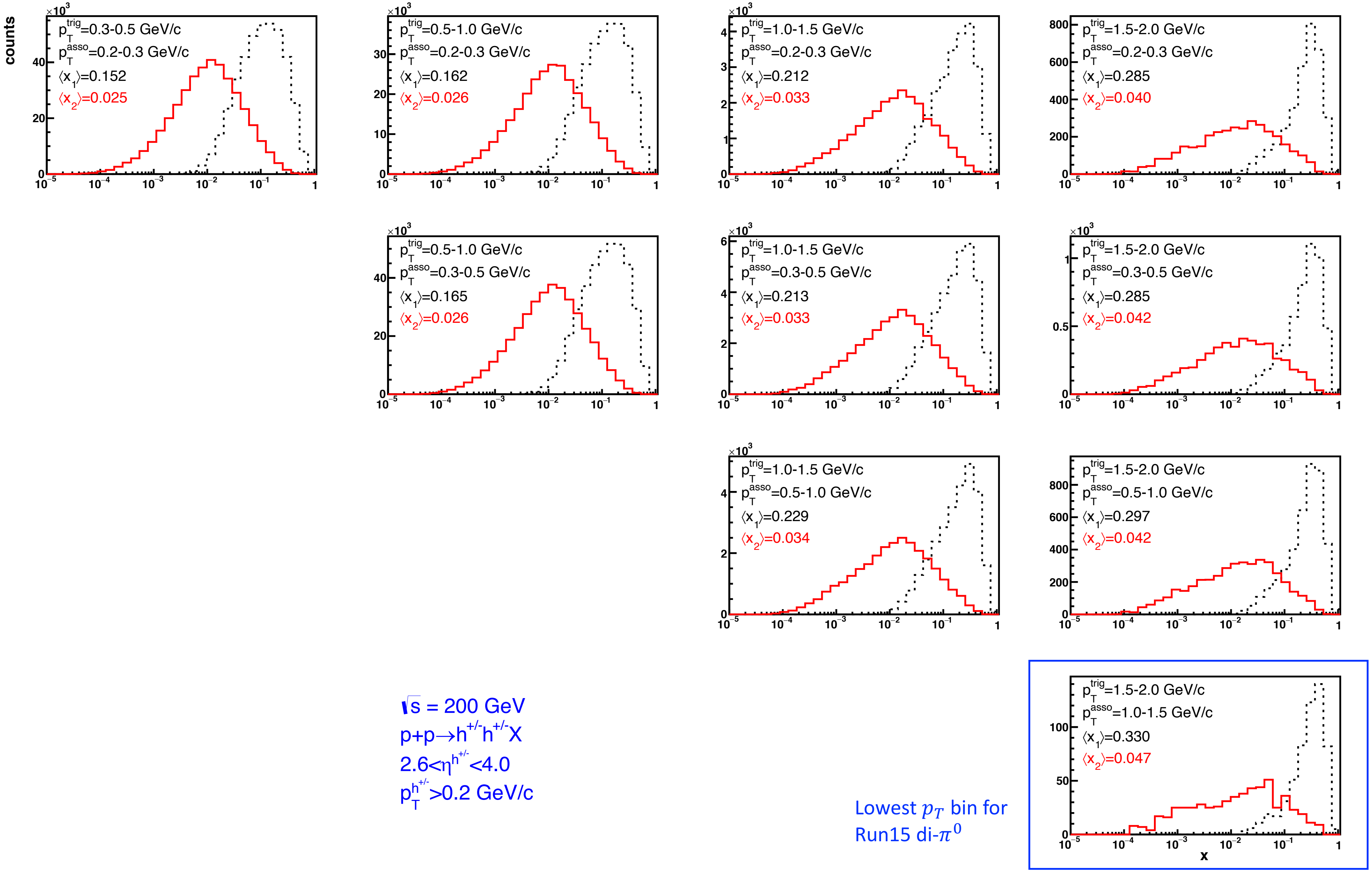
Di-$h^{+/-}$ simulation: Q^2



$\sqrt{s}$ = 200 GeV
p+p→$h^{+/-}h^{+/-}$X
2.6<$\eta^{h^{+/-}}$<4.0
$p_T^{h^{+/-}}$>0.2 GeV/c

Lowest p_T bin for Run15 di-π^0

Di-$h^{+/-}$ simulation: x



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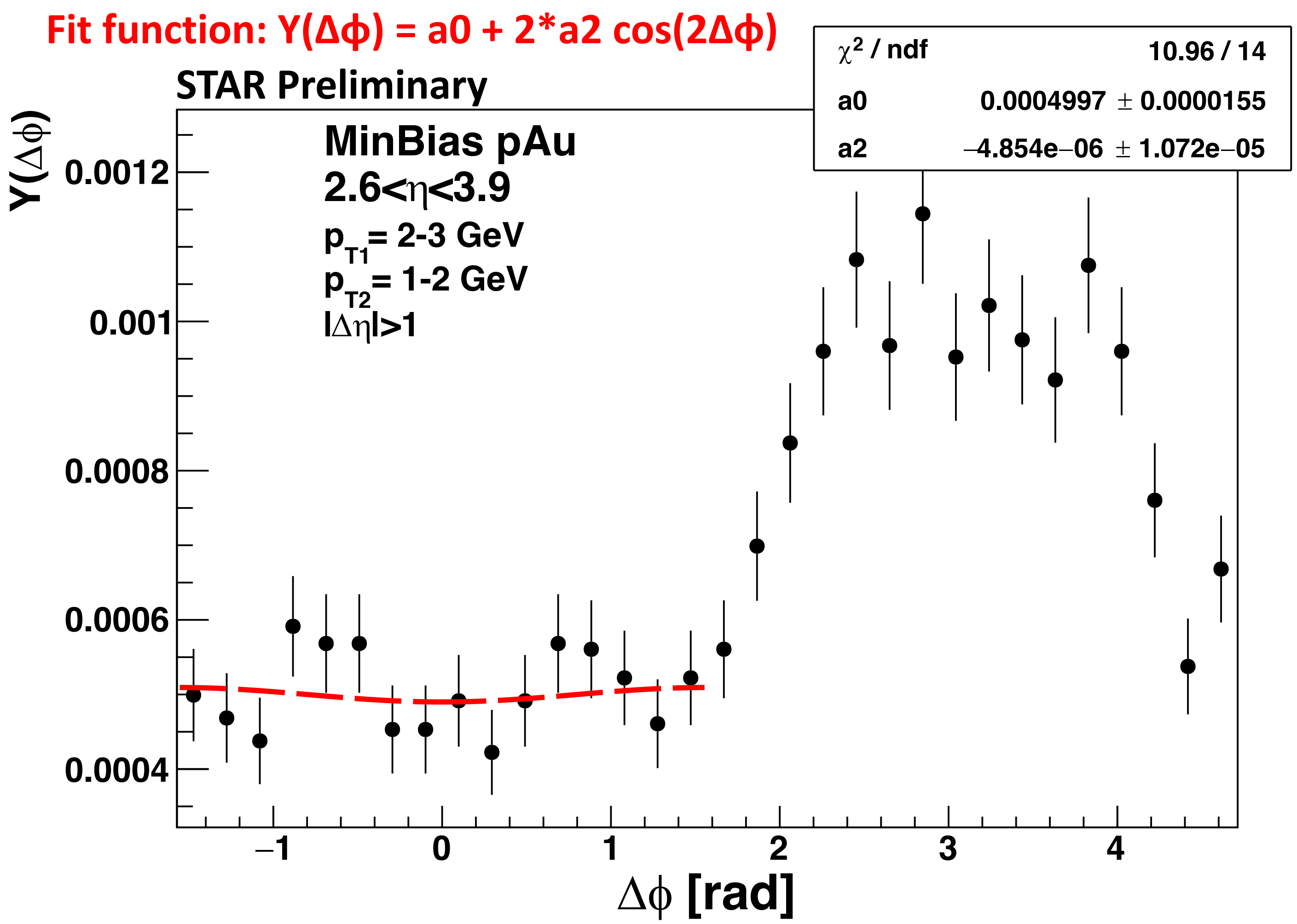
Lowest p_T bin for Run15 di-π^0

Flow-like correlation for FMS di-π^0



Fit function: $Y(\Delta\phi) = a0 + 2*a2 \cos(2\Delta\phi)$

STAR Preliminary

- Flow signal from near side is not very strong for the current measurement
- π^0s at FMS have very high energy; hard to require those two π^0s to be from different jets at near side.
- Due to limited rapidity coverage of FMS, it's harder to accurately estimate long range correlation. Even if there is flow, centrality dependence is opposite, → makes suppression stronger.