Gluon Saturation from RHIC and Future EIC

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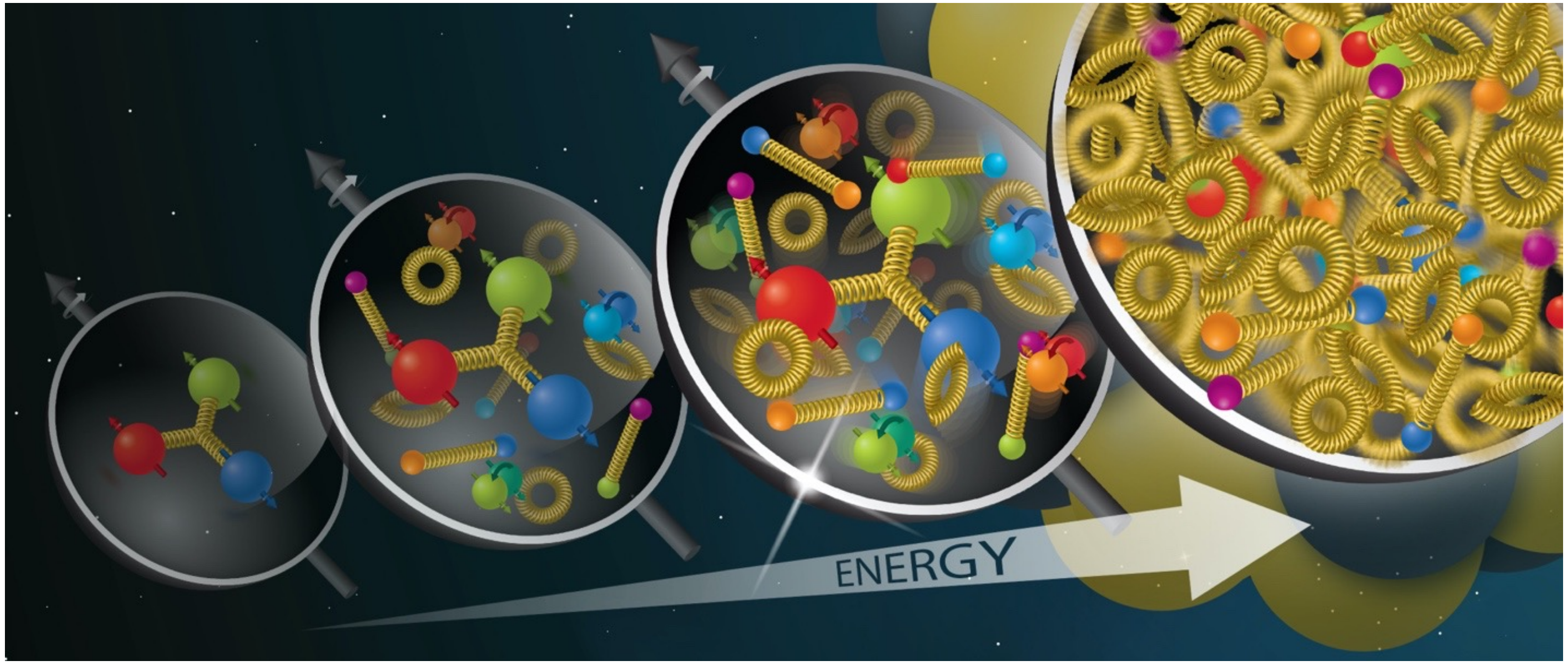
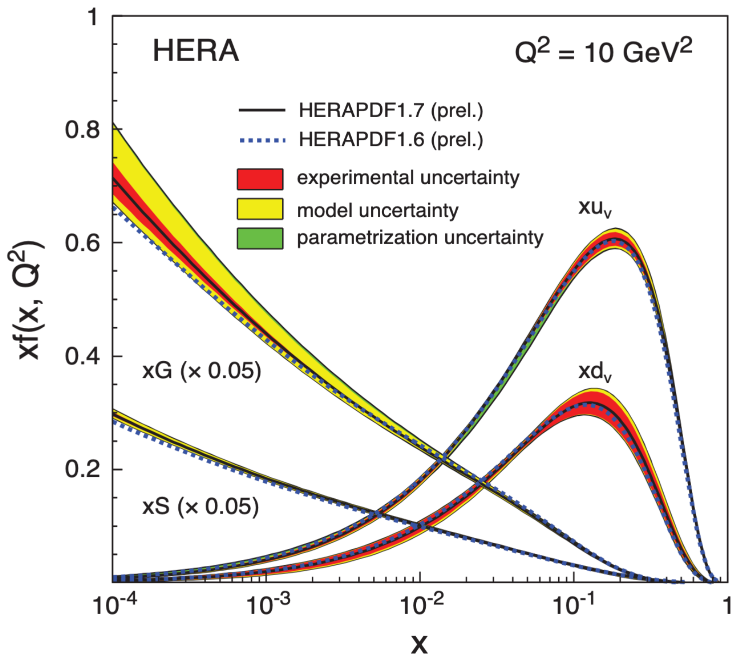
High gluon density in nucleon

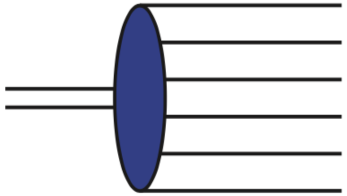




- One can "take snapshots" of partonic structure of the proton with a probe particle in high energy collisions
- Results from DIS: Gluon density rapidly increases towards small x, which can be explained by gluon splitting

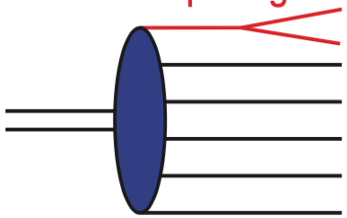
Gluon saturation

Gluon density

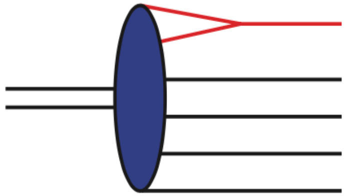


Balitsky-Fadin-Kuraev-Lipatov (BFKL) evolution equation
Balitsky-Kovchegov (BK) evolution equation

splitting



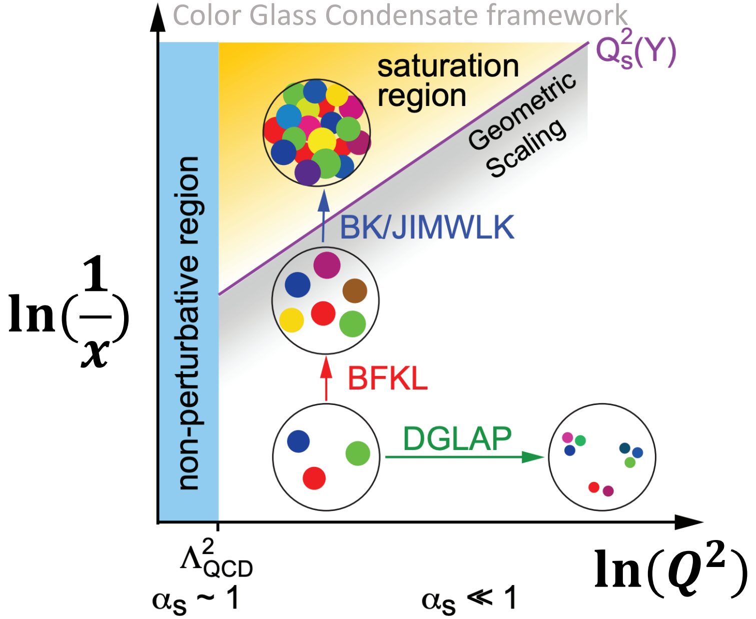
recombination



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

linear

nonlinear



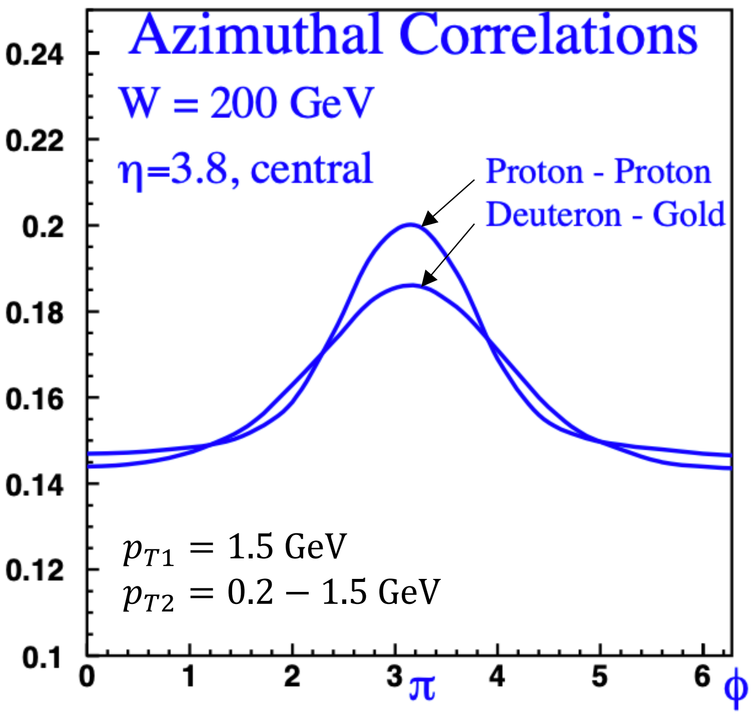
- The rapid increase of gluon density: gluon splitting → linear evolution
- Increase should be tamped at a certain point: gluon recombination → non-linear evolution
- A new regime of QCD: Gluon saturation ($Q^2 < Q_s^2$) at gluon recombination = gluon splitting
- Saturation region is easier to be reached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

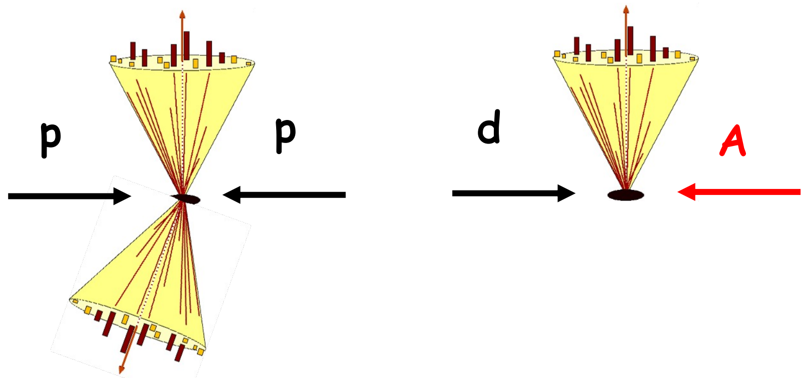
How to probe nuclear gluon distributions at saturation region?

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

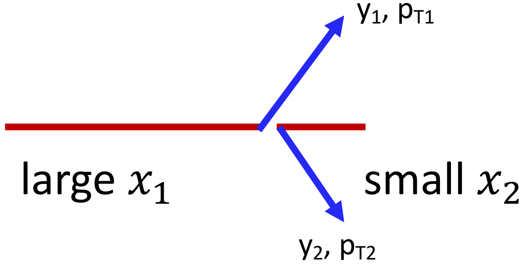
- Di-hadron in p+p as baseline: 2-to-2 process

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

- Following theoretical predictions on di-hadron:

Saturation signatures on p_T, y, b, A

Forward di-parton kinematics



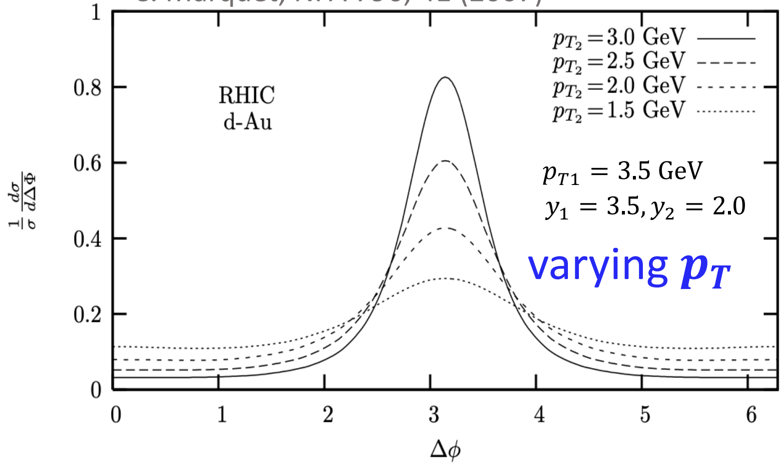
$$x_2 \sim \frac{p_{T1}e^{-y_1} + p_{T2}e^{-y_2}}{\sqrt{s}};\ Q \sim \frac{p_{T1} + p_{T2}}{2}$$

Correlation suppressed more as:

Smaller $x(Q^2)$
1. More forward direction
2. Lower p_T hadron

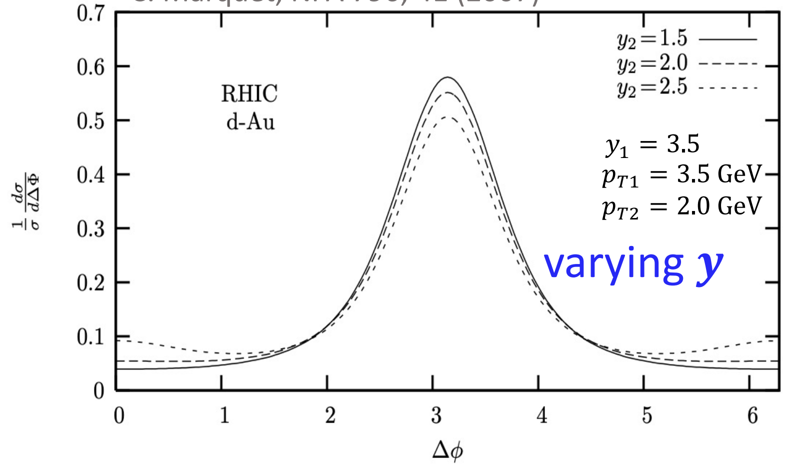
Larger Q_s
3. More central collisions
4. Heavier nuclei

C. Marquet, NPA 796, 41 (2007)



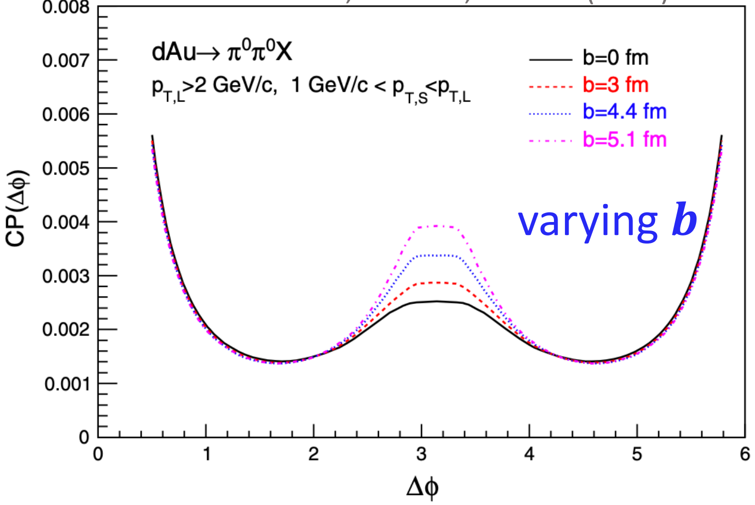
varying p_T

C. Marquet, NPA 796, 41 (2007)



varying y

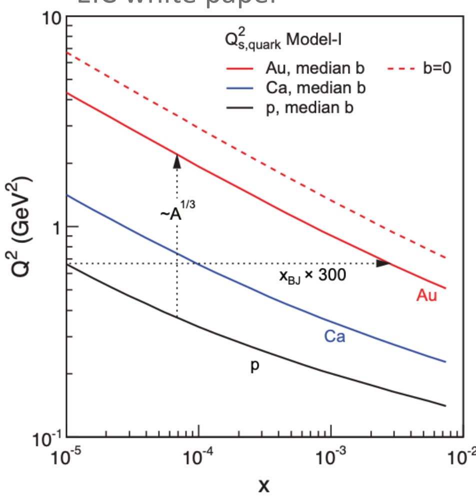
J. L. Albacete et al., PRL 105, 162301 (2010)



varying b

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

EIC white paper



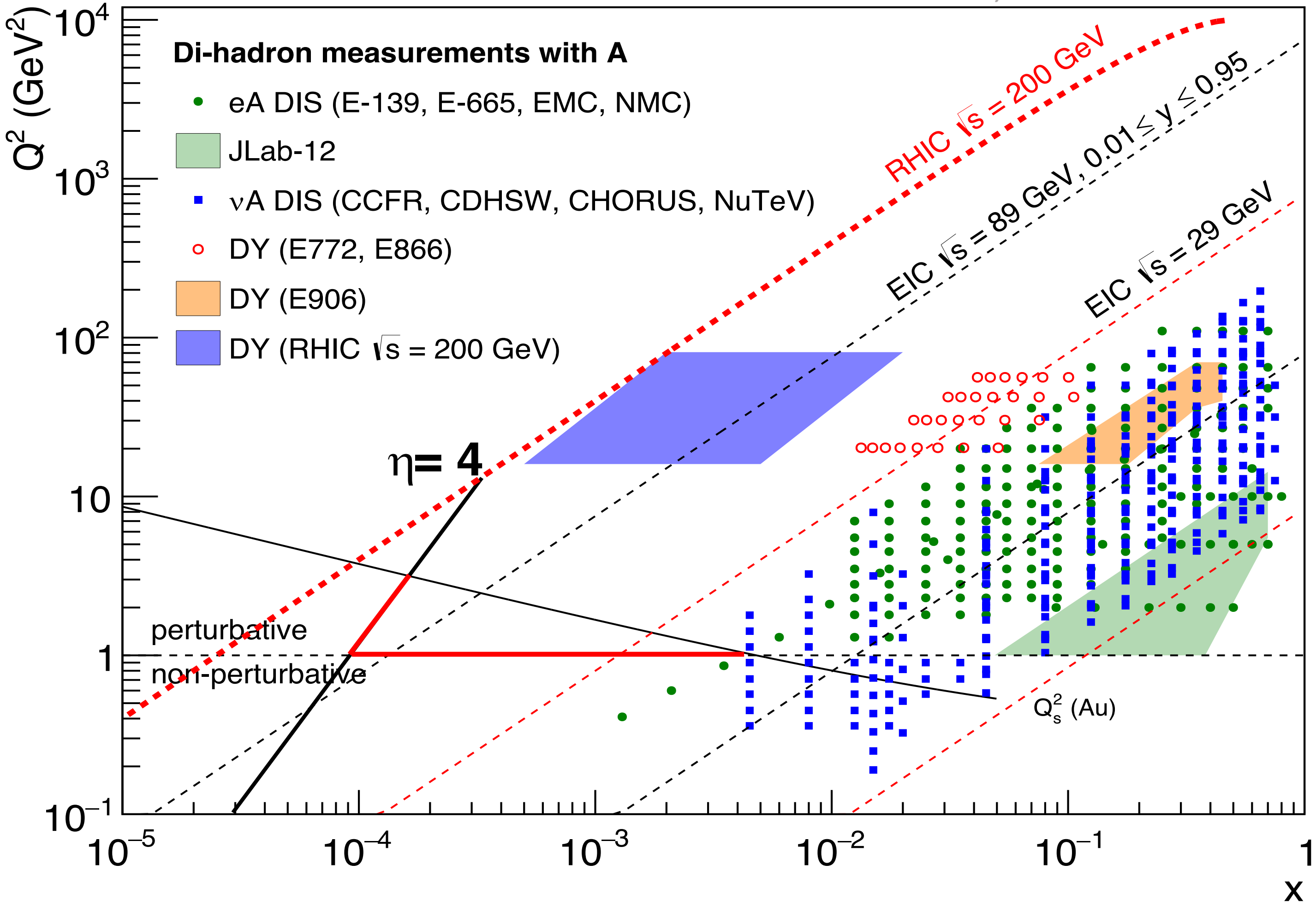
varying A

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

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

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

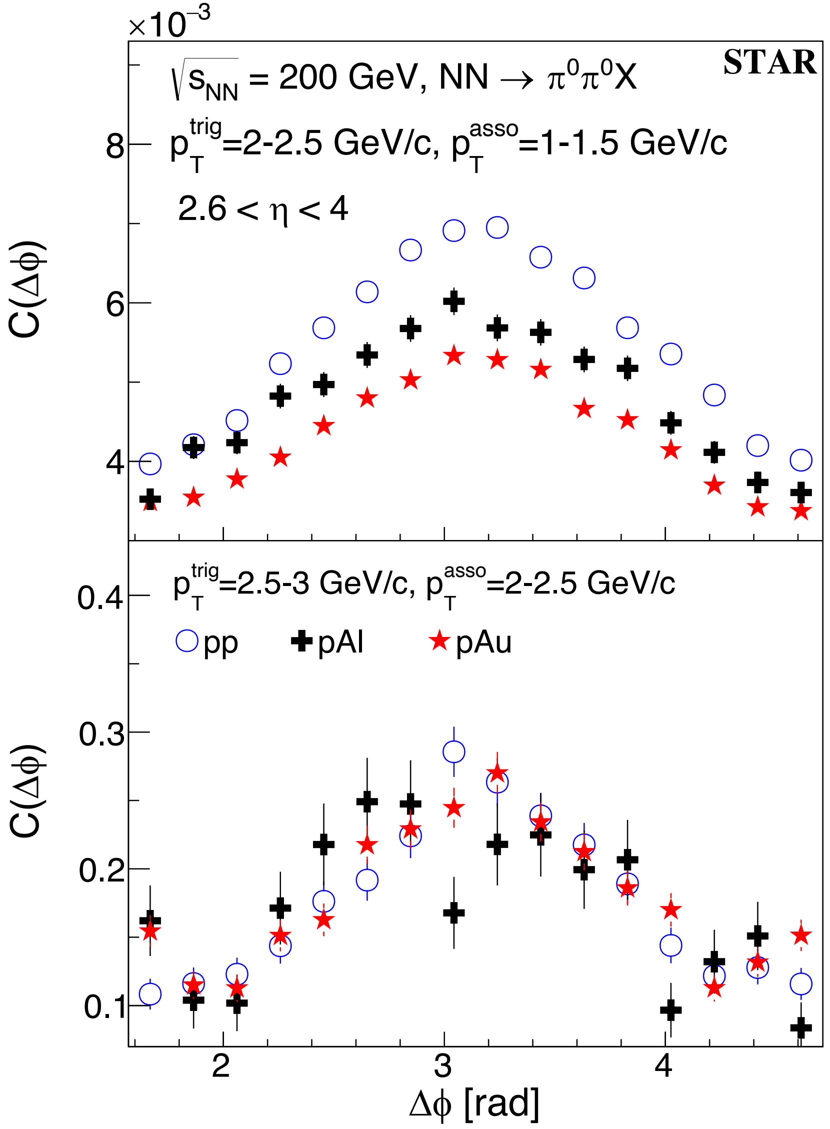
R. Abdul Khalek et al., arXiv:2103.05419



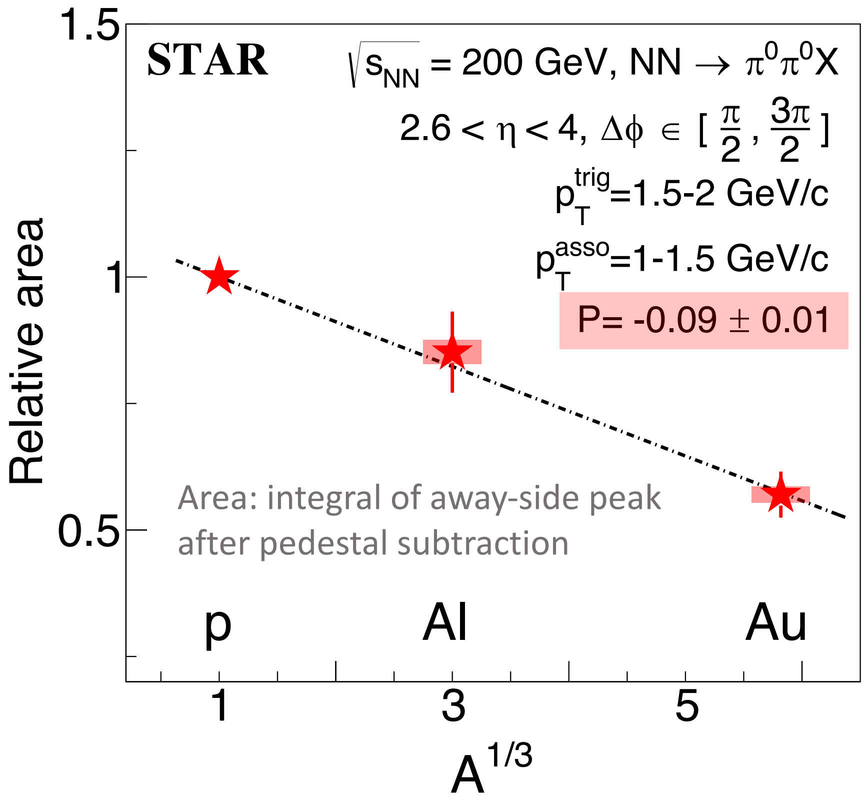
STAR data can access linear-nonlinear transition region

STAR, PRL 129, 092501 (2022)

p_T and A dependence



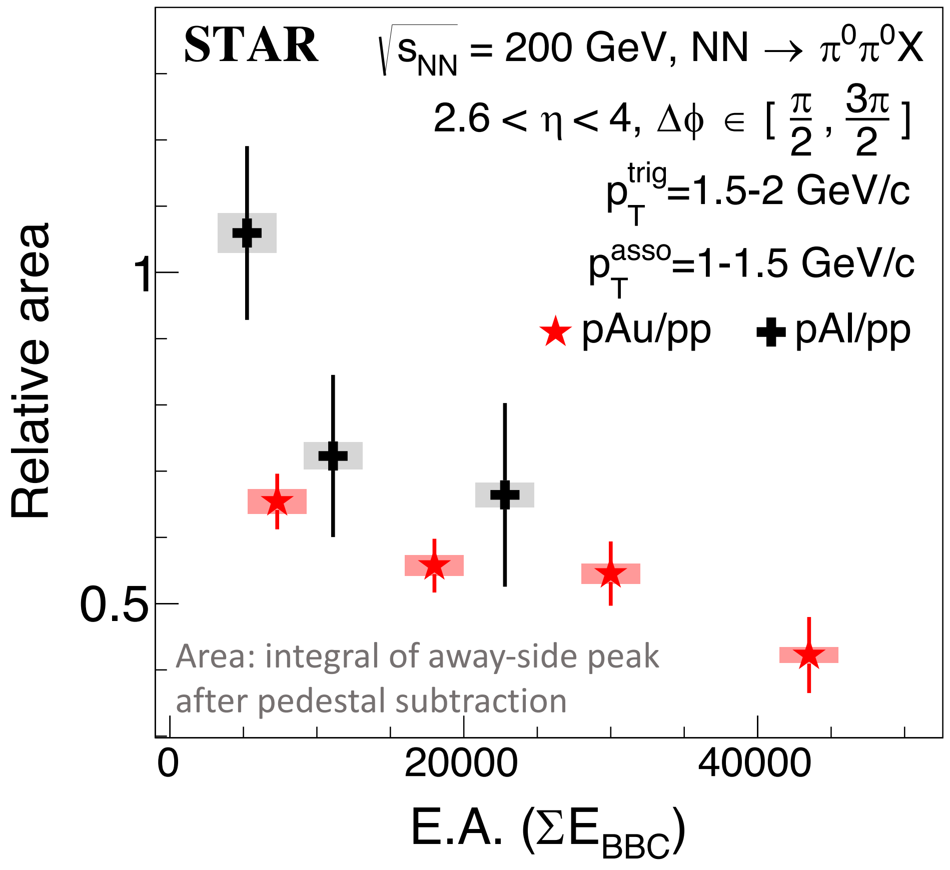
Gaussian (Area and width) at $\Delta\phi = \pi$ + pedestal



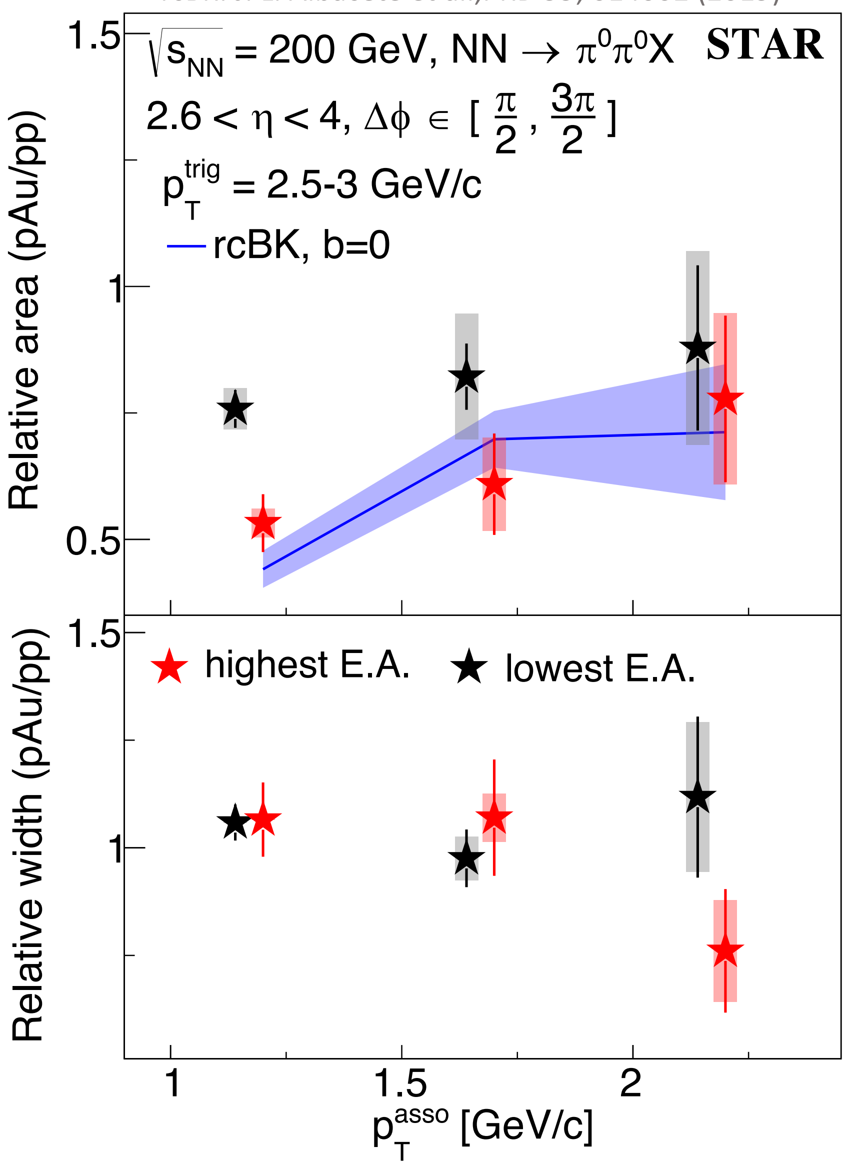
- Suppression at low p_T not high p_T
- Fixed p_T (smallest p_T) bin → $x - Q^2$ phase space is fixed, suppression is dominantly affected by various A:
  - Suppression linearly depends on $A^{1/3}$
  - Slope from the fitting = -0.09 $\pm$ 0.01

STAR, PRL 129, 092501 (2022)

E.A. dependence



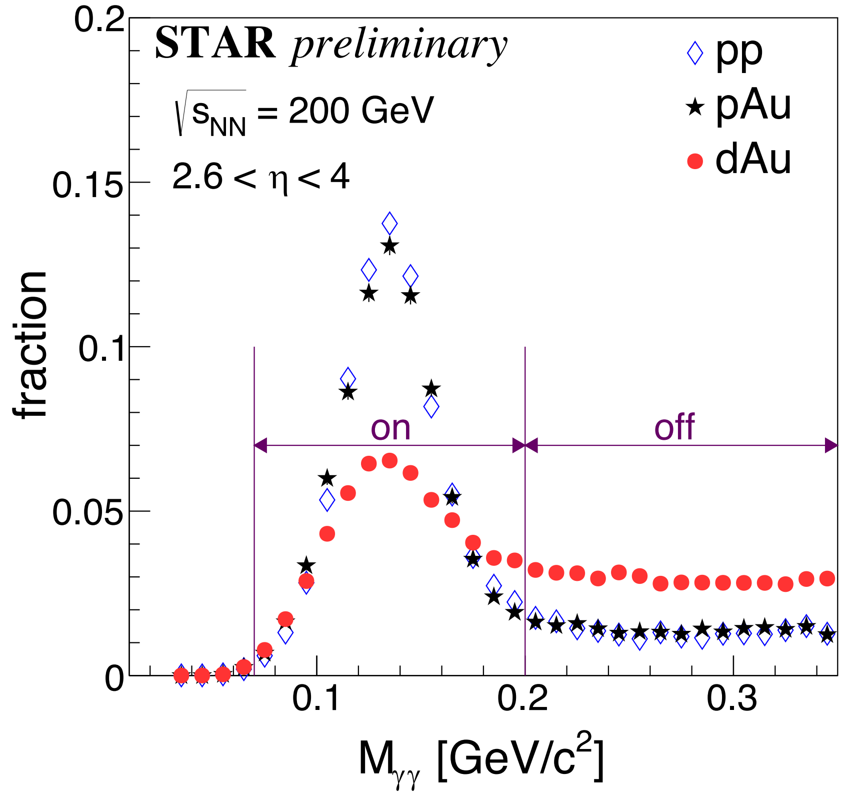
rcBK: J. L. Albacete et al.,PRD 99, 014002 (2019)

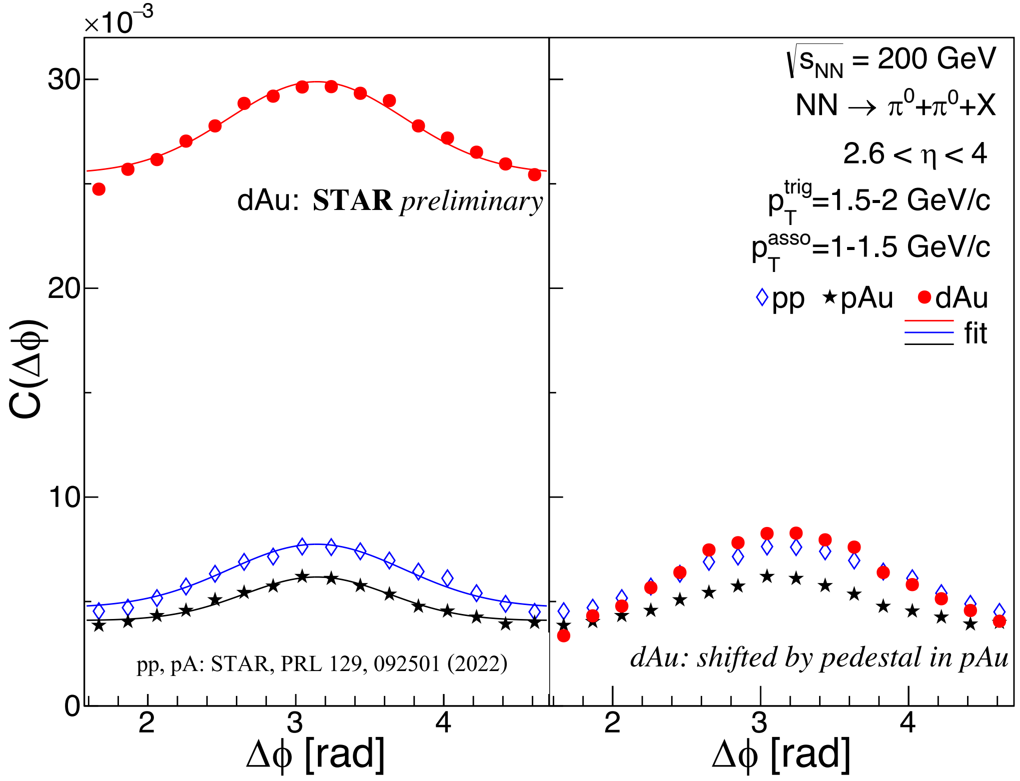


- Suppression increases with *E.A., highest E.A. data is consistent with predictions at $b = 0$; E.A. is not identical to centrality
- No broadening is observed

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

Di-π^0 measurement in d+Au at STAR





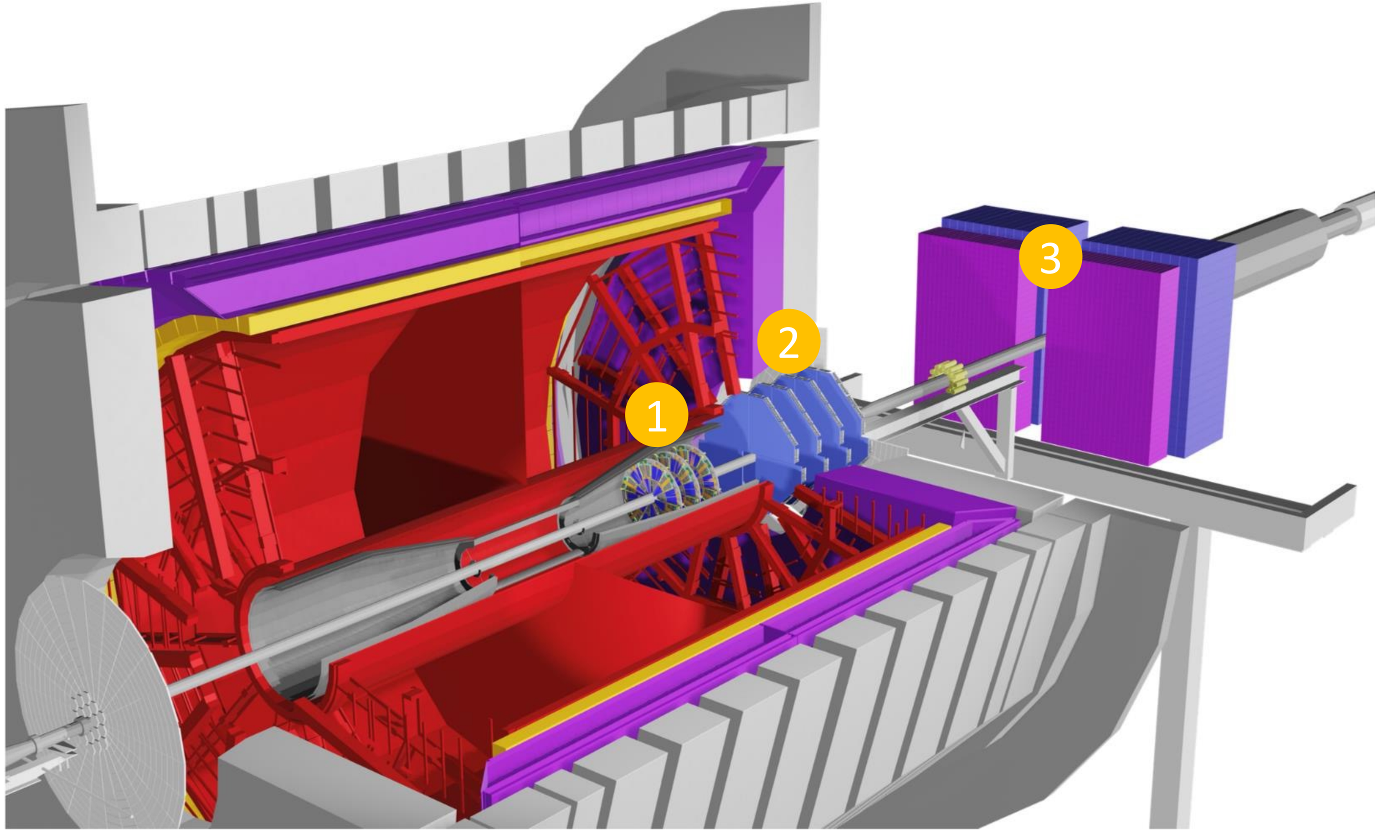
Challenging to conclude the forward di- π^0 correlation measurement in d+Au

- π^0 PID: much higher background in d+Au than p+p/Au; combinatoric contribution is large in d+Au
- Double parton interactions affect the correlation? → two π^0s separately from two hard scatterings?

Previous measurement in d+Au from PHENIX: PRL 107, 172301 (2011); DPS: M. Strikman et al., PRD 83, 034029 (2011)

Di-π^0 measurement favors for 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 photon suppression	$0.2<p_T<2$ GeV/c with 20-30% $1/p_T$

STAR Forward Upgrade: $2.5 < \eta < 4$

Three new systems:

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

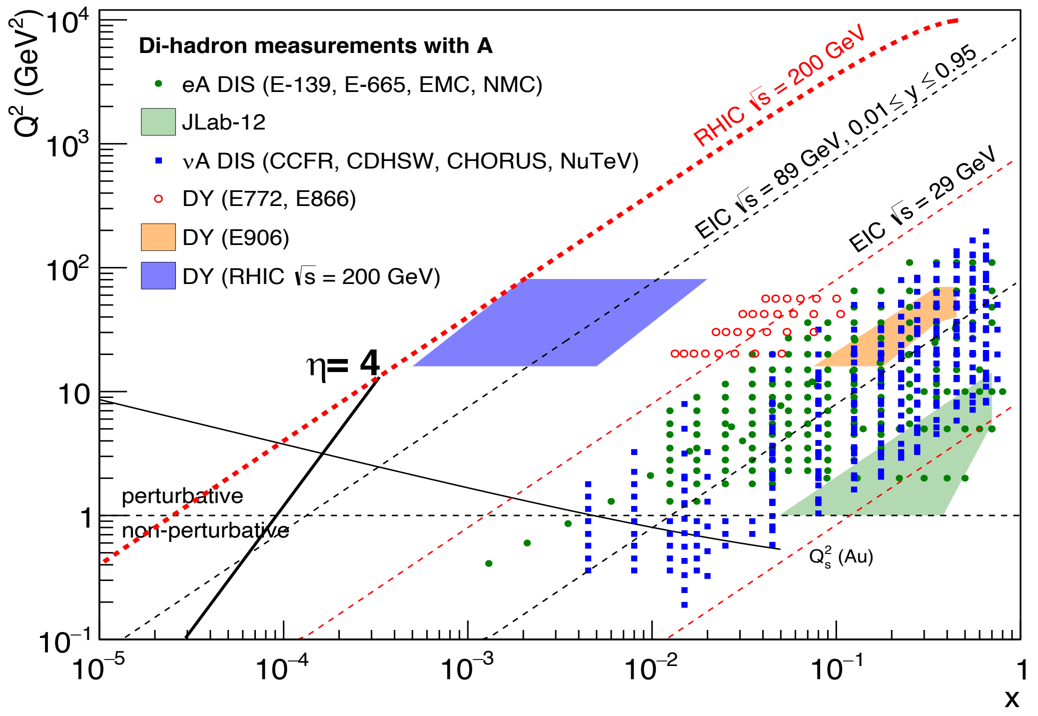
Future STAR data with forward upgrade

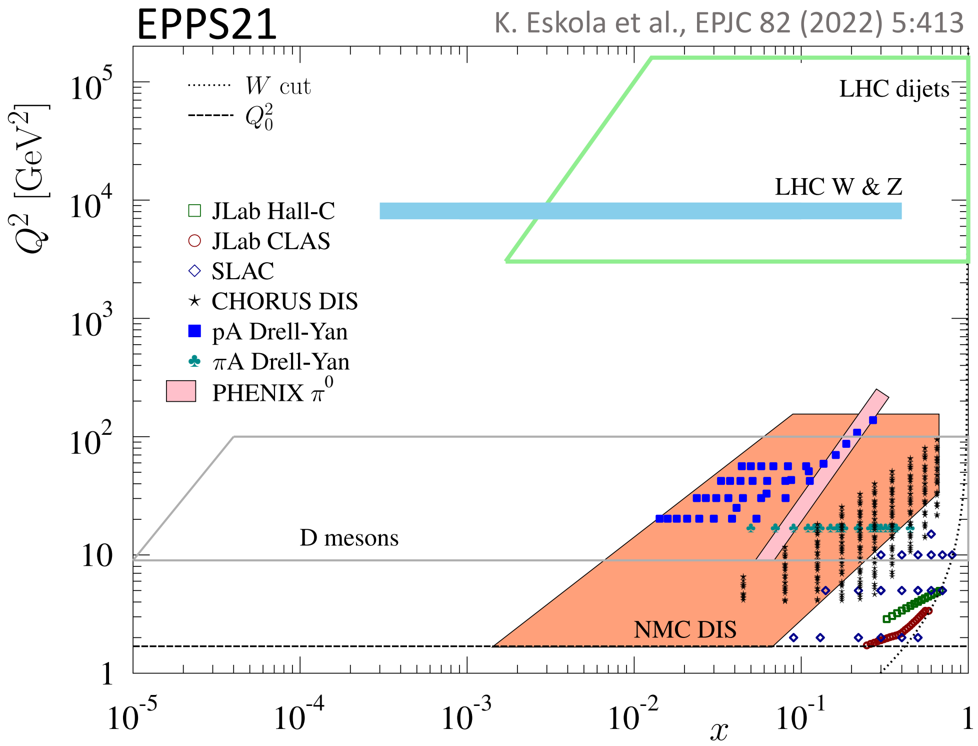
Year	System	$\sqrt{s}$ (GeV)
2023	Au+Au	200
2024	p+p, p+Au	200
2025	Au+Au	200

To explore nonlinear gluon dynamics with expanded observables:

- Di-$h^{+/-}$: access lower p_T
- di-jet: more accurate proxy to di-parton
- Direct photon (-jet): q+g→q+γ

Future measurement at EIC and the LHC



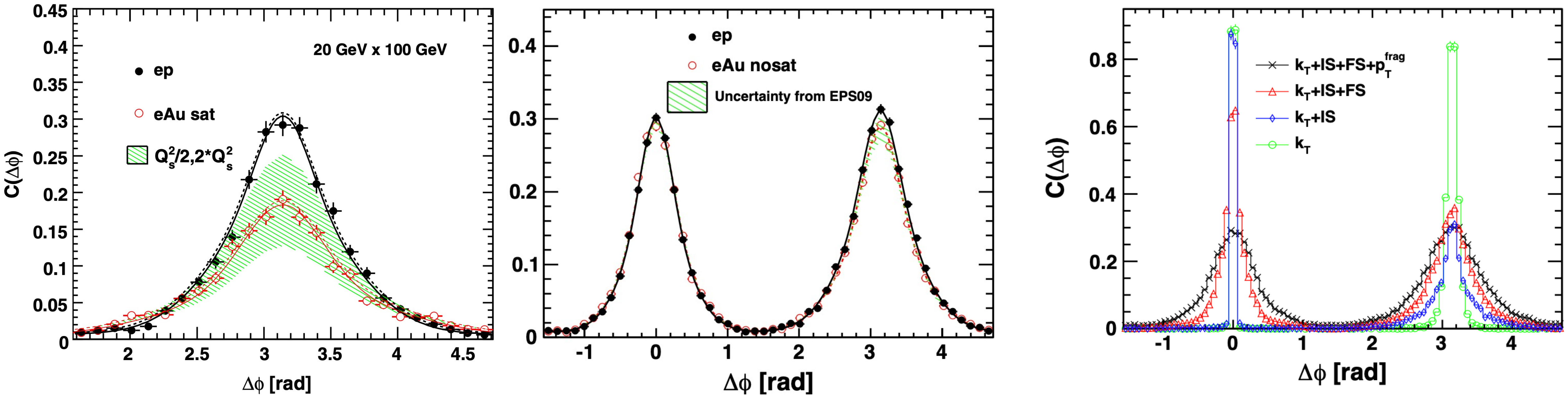


- RHIC results will be an important basis for very similar measurements at the future EIC
  - Very similar $x - Q^2$ phase space at close collision energy
  - Nonlinear effects seen with different complementary probes (eA and pA), one can claim a discovery of saturation effects and their universality
- Data from RHIC + the LHC access the full phase space: *LHC data → low x at high Q^2; RHIC data → low/moderate Q^2

*ALICE FoCal and LHCb pushing the small-x program at LHC, see backup

Di-hadron correlations at EIC

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



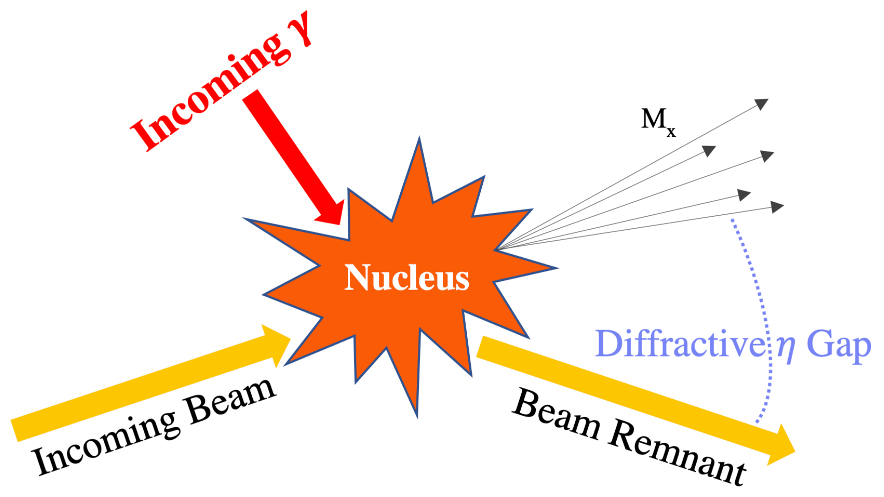
Constrain sat. and nosat. models a lot with limited statistics of 1 fb^{-1}

- Strong suppression is reproduced by sat. model not by nosat. model (EPS09 nPDF) including energy loss

Effects from intrinsic k_T, initial and finail-state radiation (Sudakov effect), fragment p_T^{frag} are investigated:

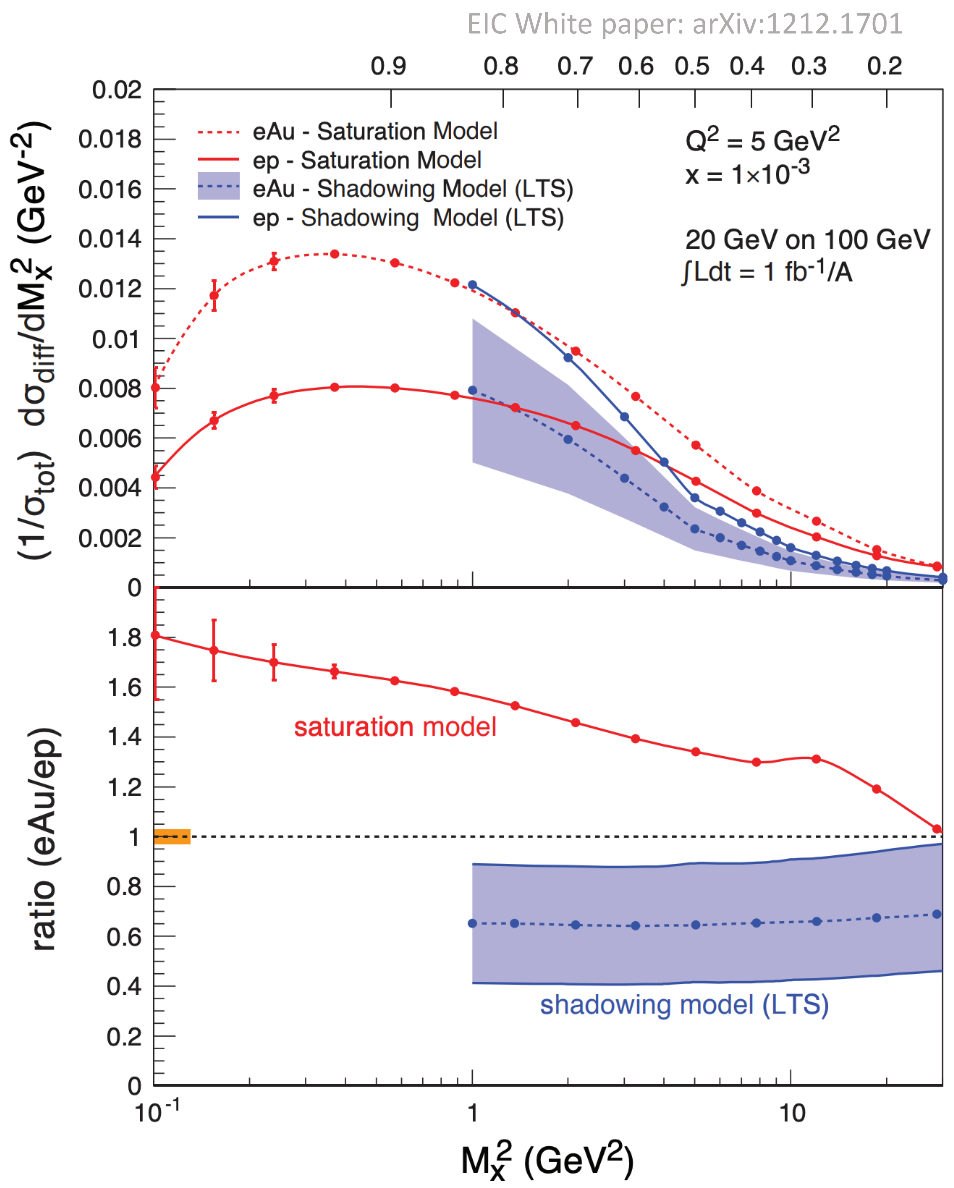
- Near side peak width mainly affected by final state parton shower and fragment p_T^{frag}
- Away side peak width dominated by initial state parton shower

Diffraction at EIC

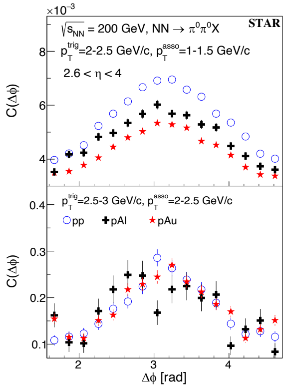


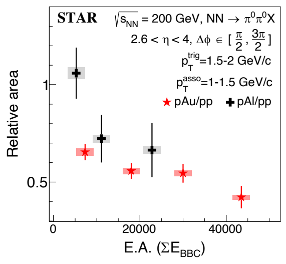
Diffraction in eA

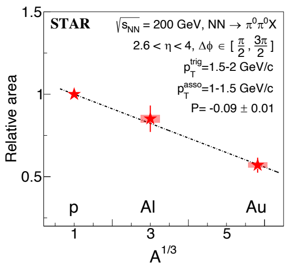
- Diffractive processes most sensitive to the underlying gluon distribution: $F^{diff} \propto k_g^2$
- Double ratio sensitive to saturation and shadowing
  - $\sigma_{diff}/\sigma_{tot}(\text{eAu} > \text{ep})$: saturation
  - $\sigma_{diff}/\sigma_{tot}(\text{ep} > \text{eAu})$: shadowing

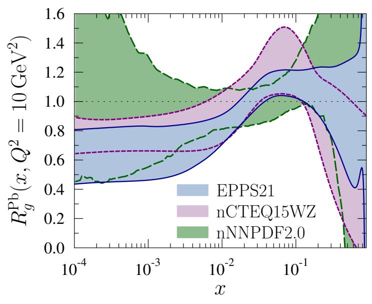


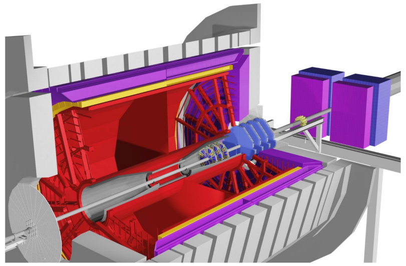
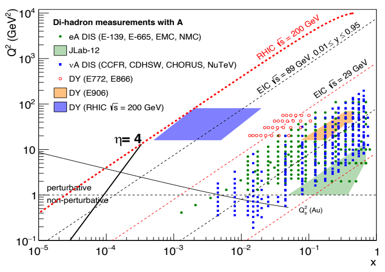
Summary and outlook









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 for 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

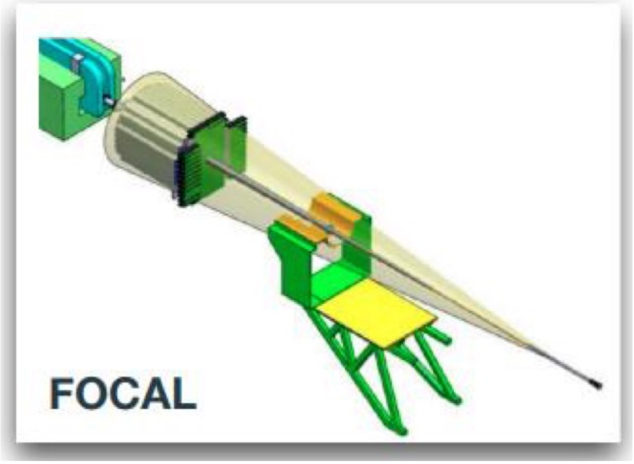
STAR forward upgrade with expanded observables in p+Au
More opportunities with diffraction measurements

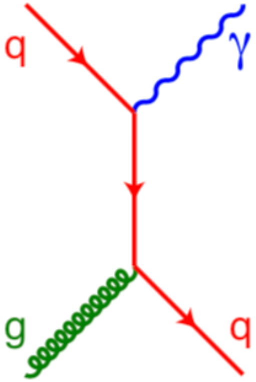
RHIC data deeply connected to EIC: close energy, similar phase space, complementary probes to test universality

Back up

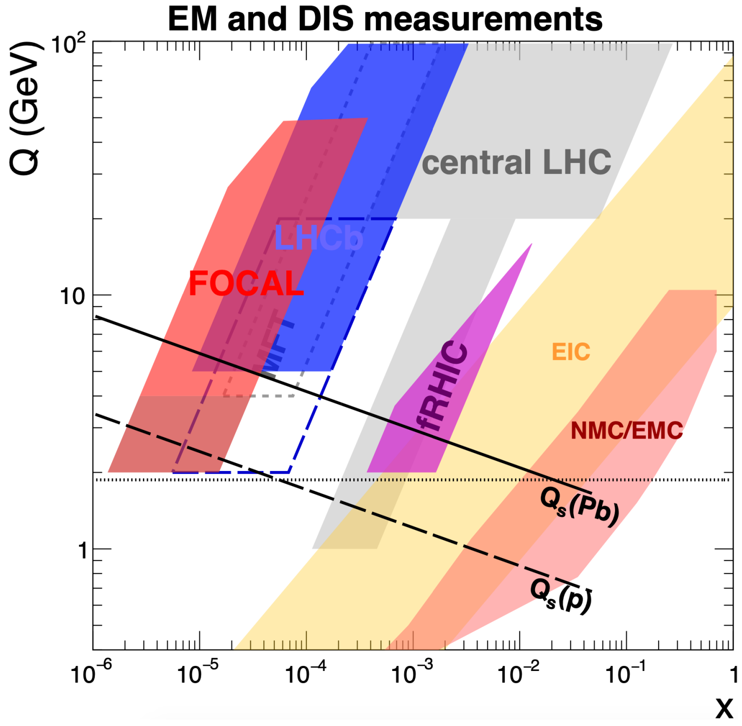
ALICE FoCal and LHCb pushing the small-x program at LHC

3.4 < η < 5.8





CERN-LHCC-2020-009



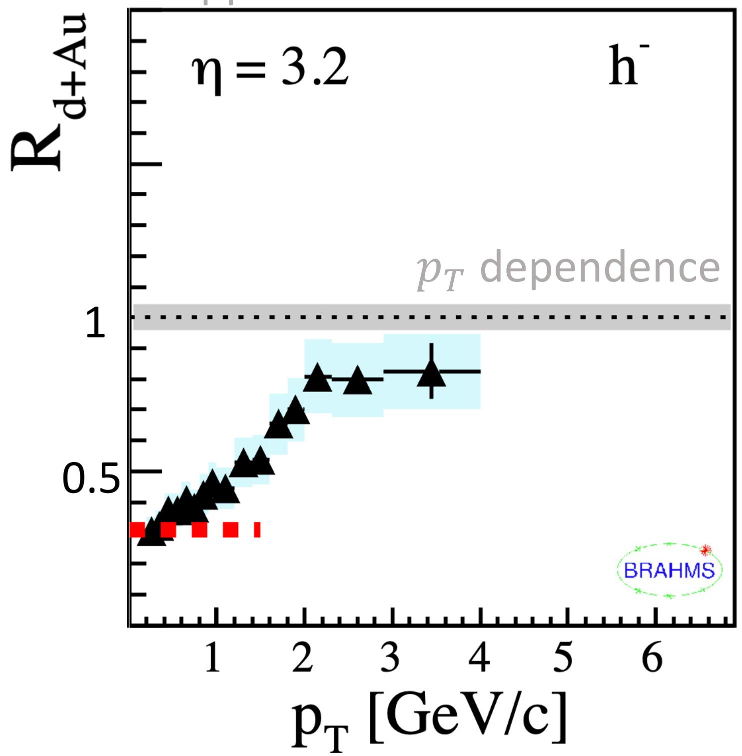
- Si-W ECAL with high effective pointing resolution: resolves direct photons from decay photos of neutral pions and eta mesons
- Cu-SciFi spaghetti HCAL: isolation and jets

- Logarithmic dep. of QCD evolution on x and Q, requires several measurements over largest possible kinematic coverage within and/or across experiments
- FoCal + LHCb at uniquely low x, where saturation scale may be large enough at small x
  - Measure isolated γ, DY, open charm, W/Z, jets and correlations as well as vector mesons in UPC
- FoCal also enables correlation measurements over extreme phase space using central ALICE and muon arm

Inclusive charged hadron at BRAHMAS

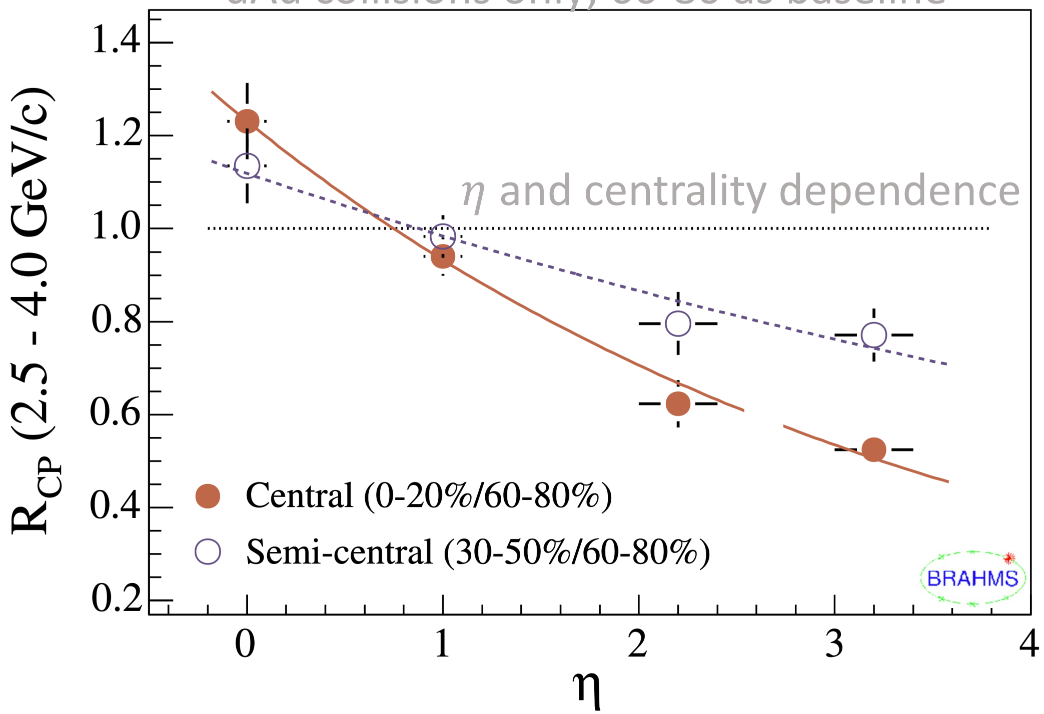
$$R_{d+Au} = \frac{d^2N^{dAu}/dp_T d\eta}{\langle N_{coll}\rangle d^2N^{pp}/dp_T d\eta}$$

pp collisions as baseline



$$R_{cp} = \frac{\frac{d^2N^{0-20/30-50}}{dp_T d\eta} / \left\langle N_{coll}^{0-20/30-50}\right\rangle}{\frac{d^2N^{60-80}}{dp_T d\eta} / \left\langle N_{coll}^{60-80}\right\rangle}$$

dAu collisions only; 60-80 as baseline

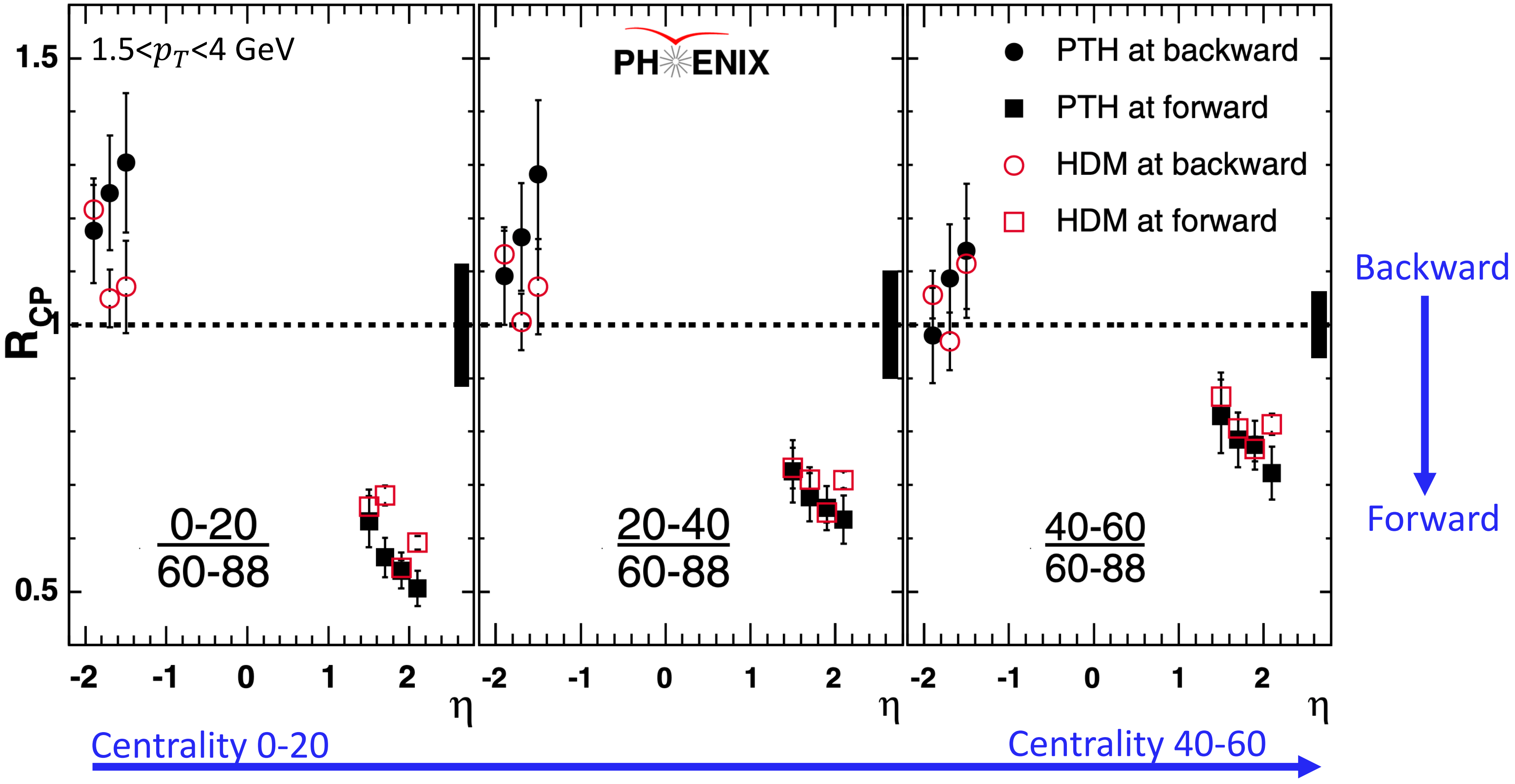


BRAHMS, PRL 93 (2004) 242303

- Yields suppression R_{dAu} < 1 at p_T < 2 GeV; first hint of gluon saturation at small x?
- R_{cp} is more pronounced in central dAu collisions
- R_{cp} decreases with increasing rapidities: scan x by varying rapidities

Inclusive charged hadron at PHENIX

PHENIX, PRL 94 (2005) 082302



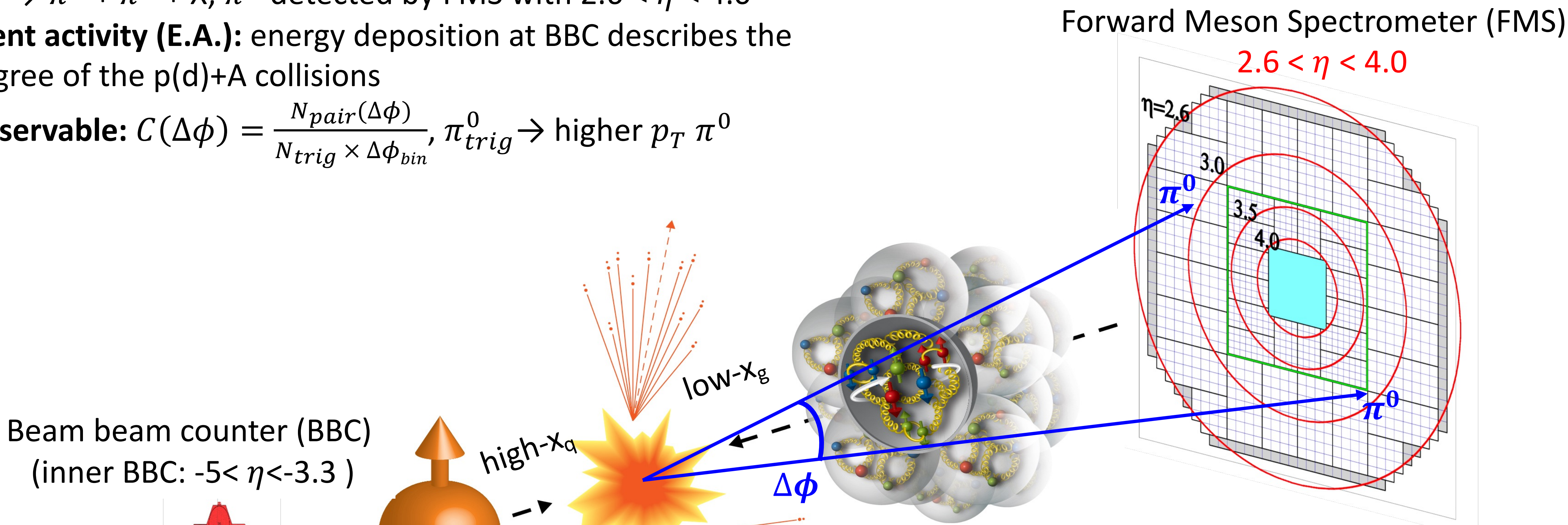
$$R_{cp} = \frac{\frac{d^2N^{0-60}}{dp_T d\eta} / \langle N_{coll}^{0-60} \rangle}{\frac{d^2N^{60-80}}{dp_T d\eta} / \langle N_{coll}^{60-80} \rangle}$$

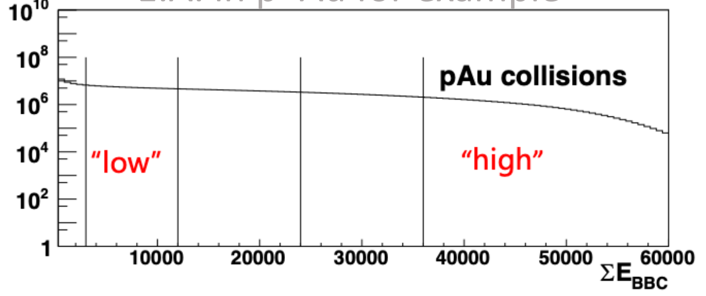
*PHT: punch through hadron
*HDM: hadron decay meson

- η dependence revisited
- Enhancement in backward direction

Di-π^0 measurement at STAR

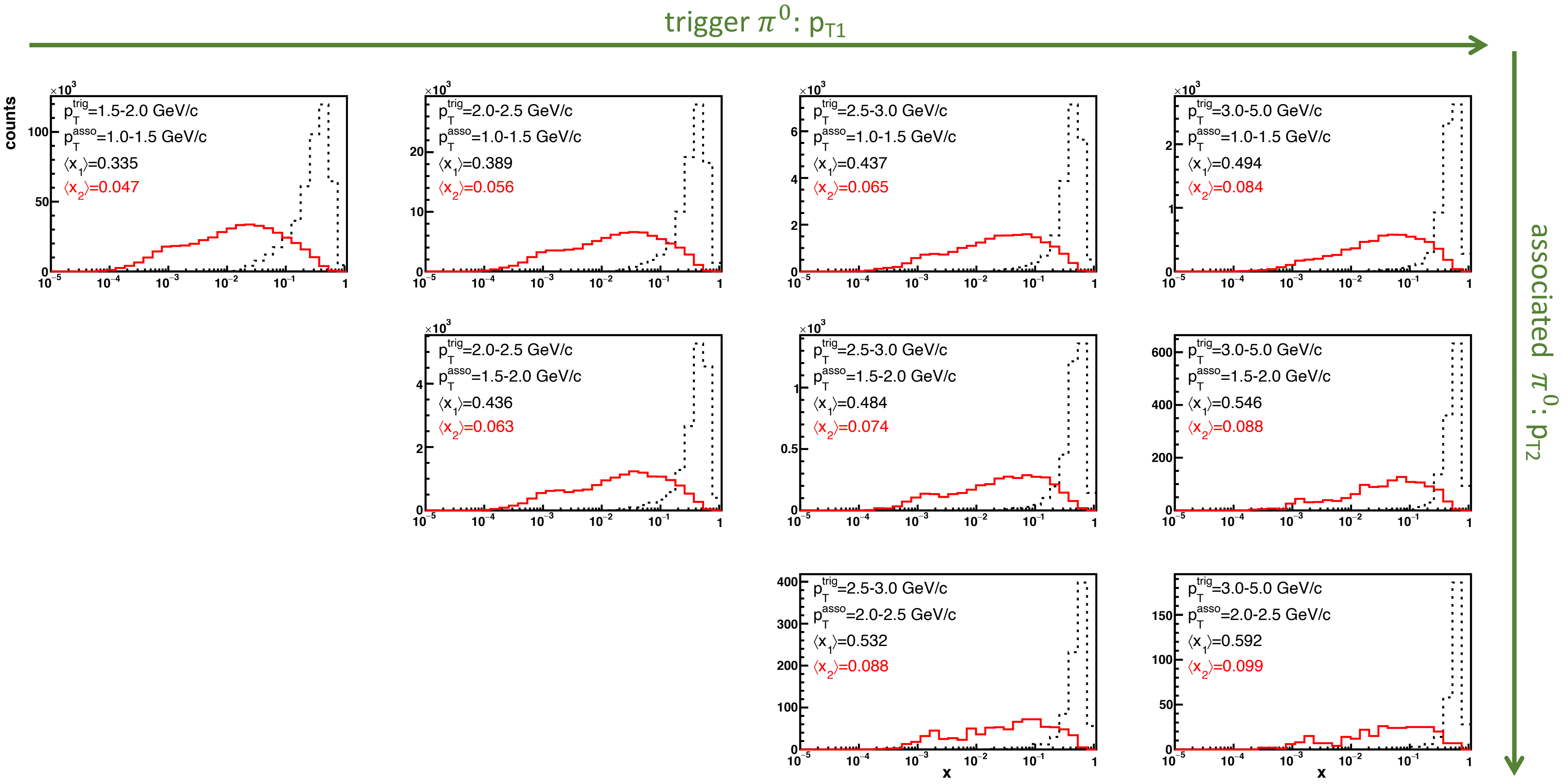
- p+p, p+Al, p+Au and d+Au (backup) collisions at $\sqrt{s_{NN}} = 200$ GeV
- NN → $\pi^0 + \pi^0$ + X, π^0 detected by FMS with $2.6 < \eta < 4.0$
- **Event activity (E.A.):** energy deposition at BBC describes the degree of the p(d)+A collisions
- **Observable:** $C(\Delta\phi) = \frac{N_{pair}(\Delta\phi)}{N_{trig}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





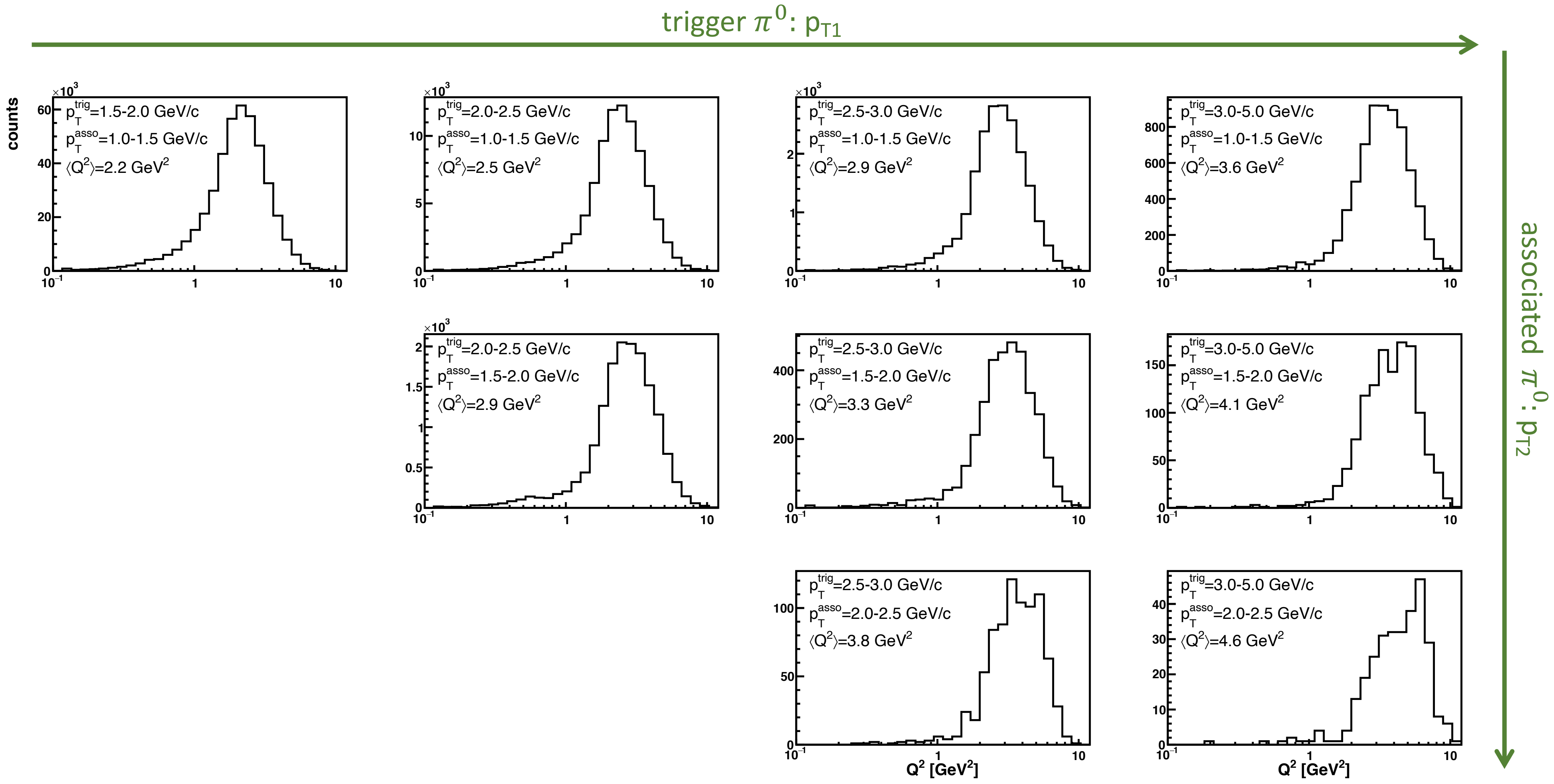
Simulated x

STAR, arXiv: 2111.10396



Simulated Q^2

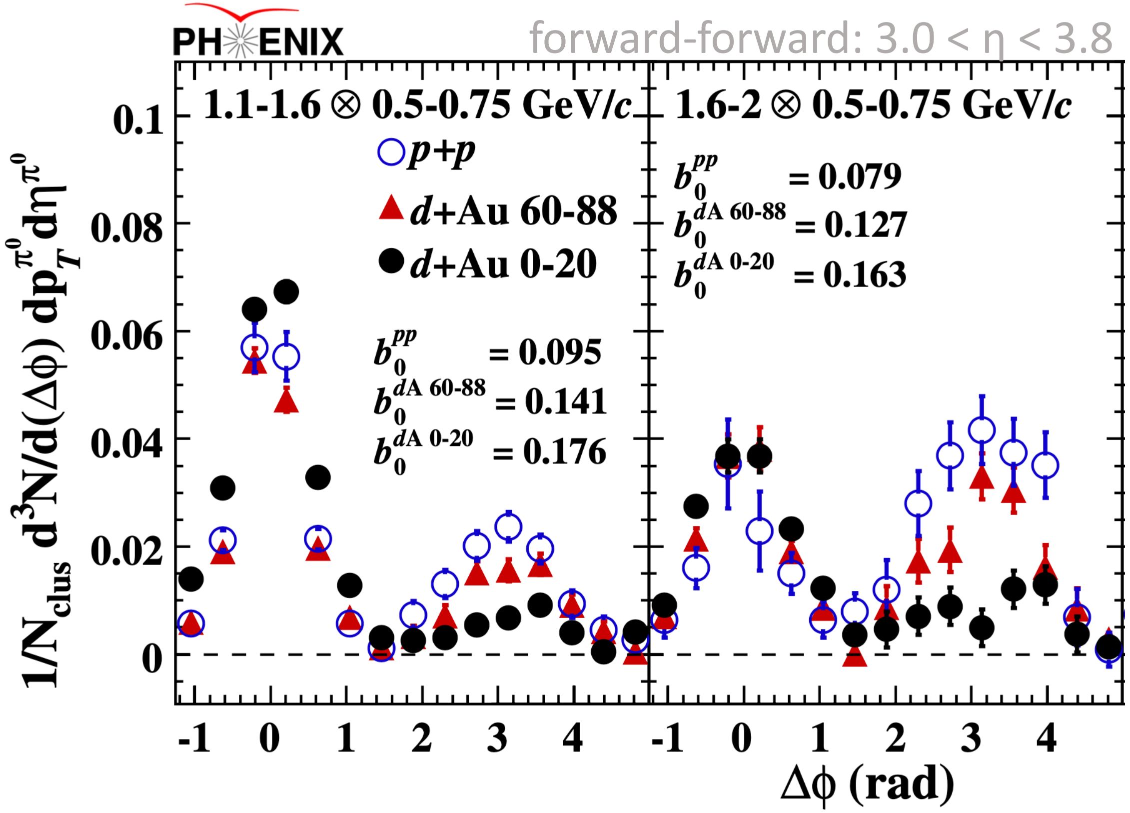
STAR, arXiv: 2111.10396

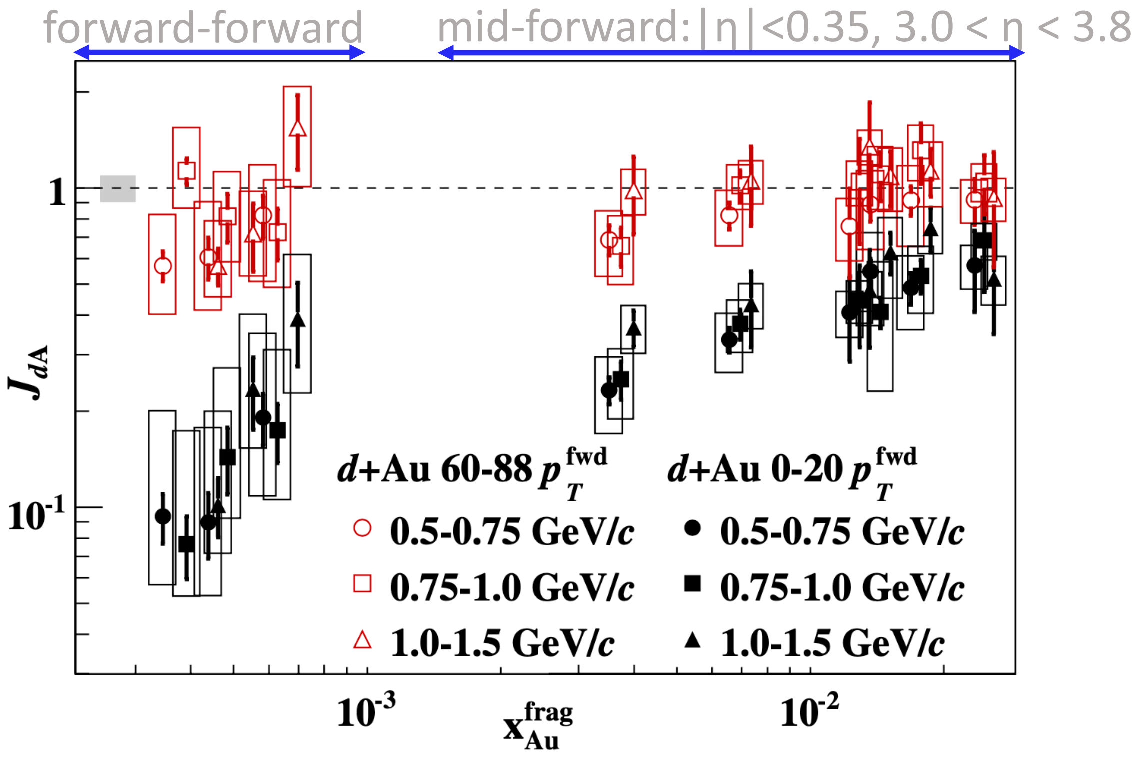


How about d+Au?

PHENIX, PRL 107, 172301 (2011)

*DPS: PRD 83, 034029 (2011)





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

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

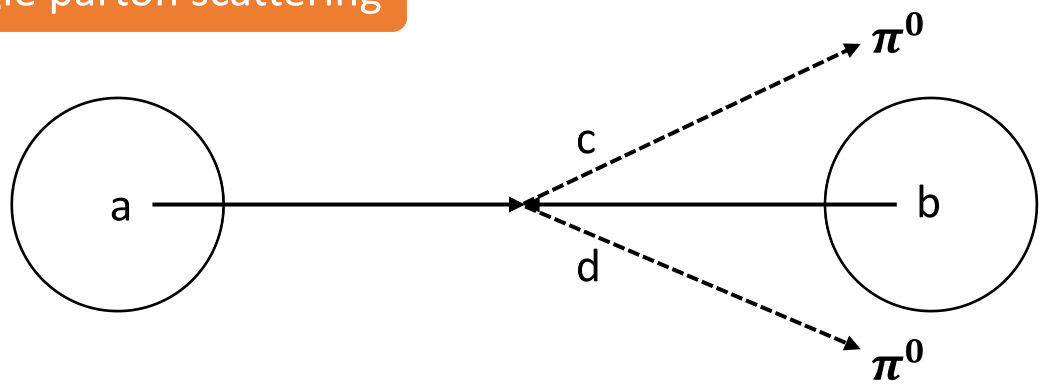
- Away-side correlation: suppression dependence on rapidity and centrality is studied by PHENIX
- Open questions: *DPS affects the correlation in d+Au? Background correlation not fully understood?

Di-π^0 measurement favors for cleaner p+A collisions

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

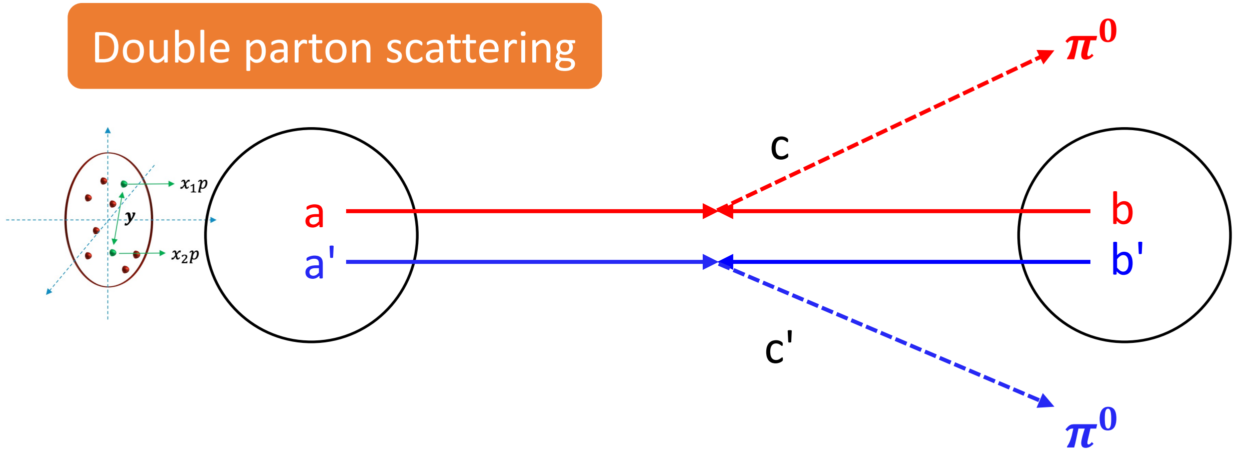
DPS in d+Au?

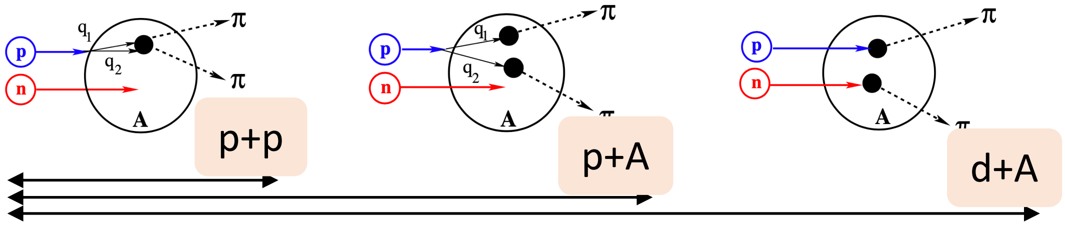
Single parton scattering



Two π^0 generated from the same hard scattering

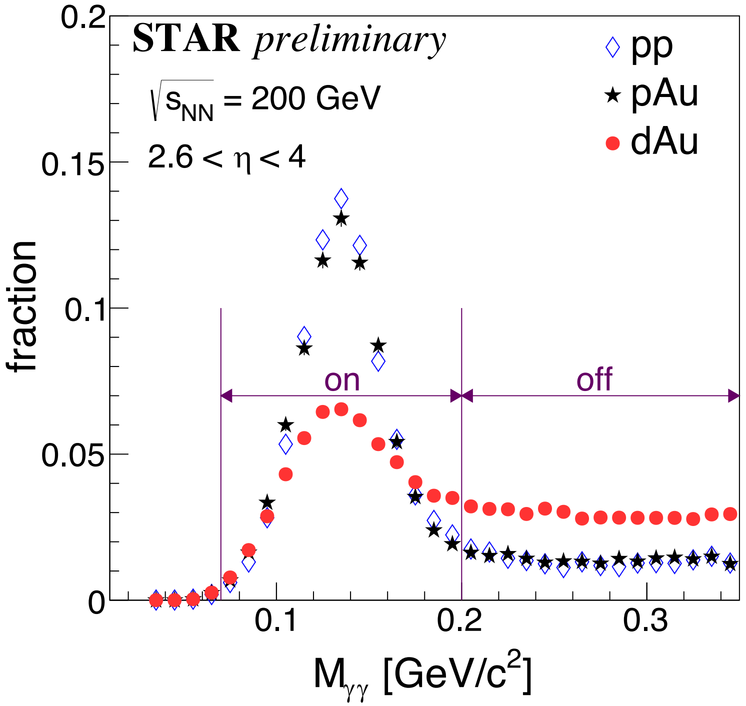
Double parton scattering

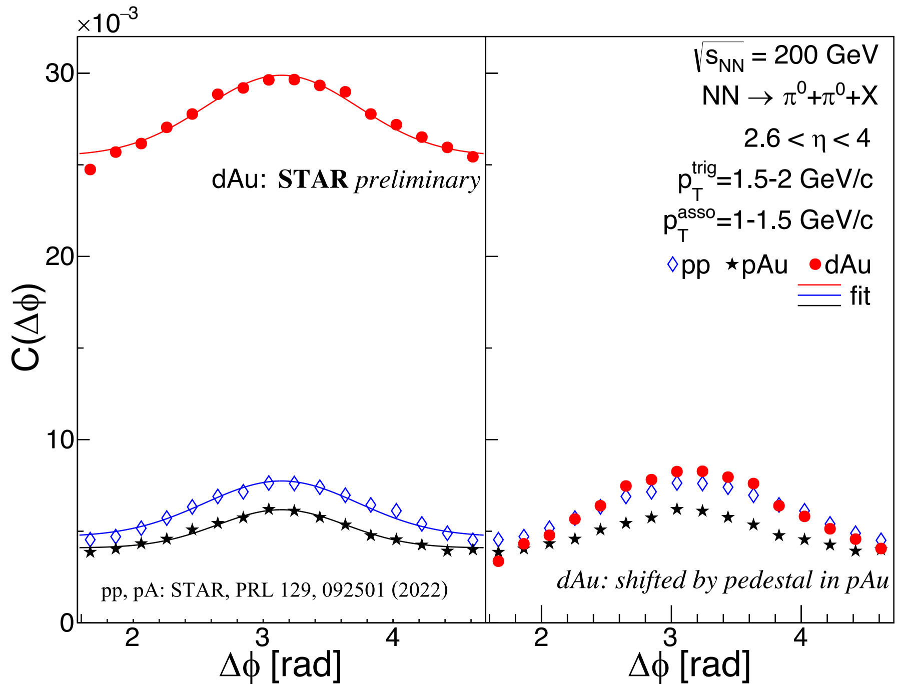


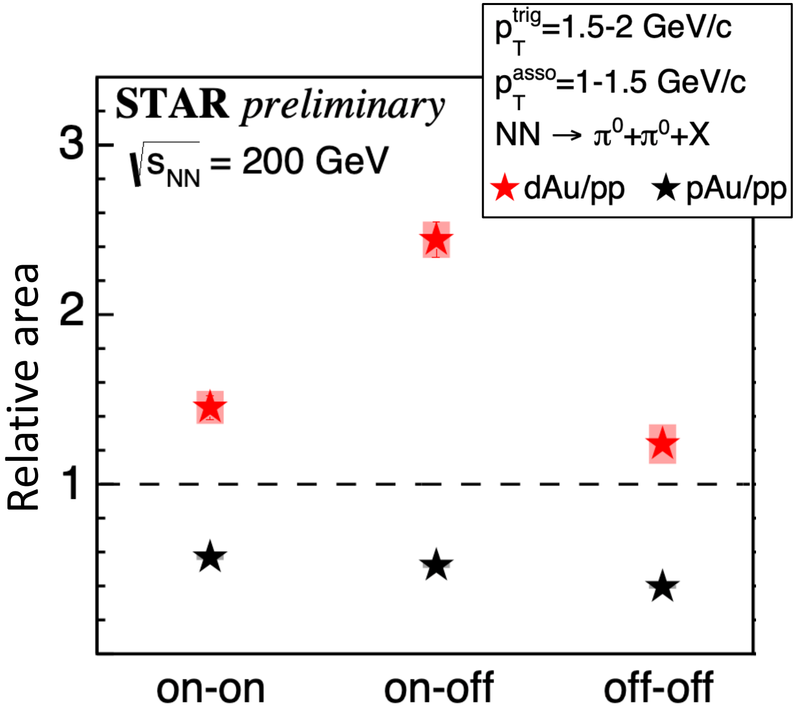


- DPS is predicted to be enhanced and not negligible at high rapidities; different in p+p, p+A and d+A
- Open questions: Two π^0 generated from the same or different hard scattering? DPS affects the correlation?

Di-π^0 measurement in d+Au at STAR



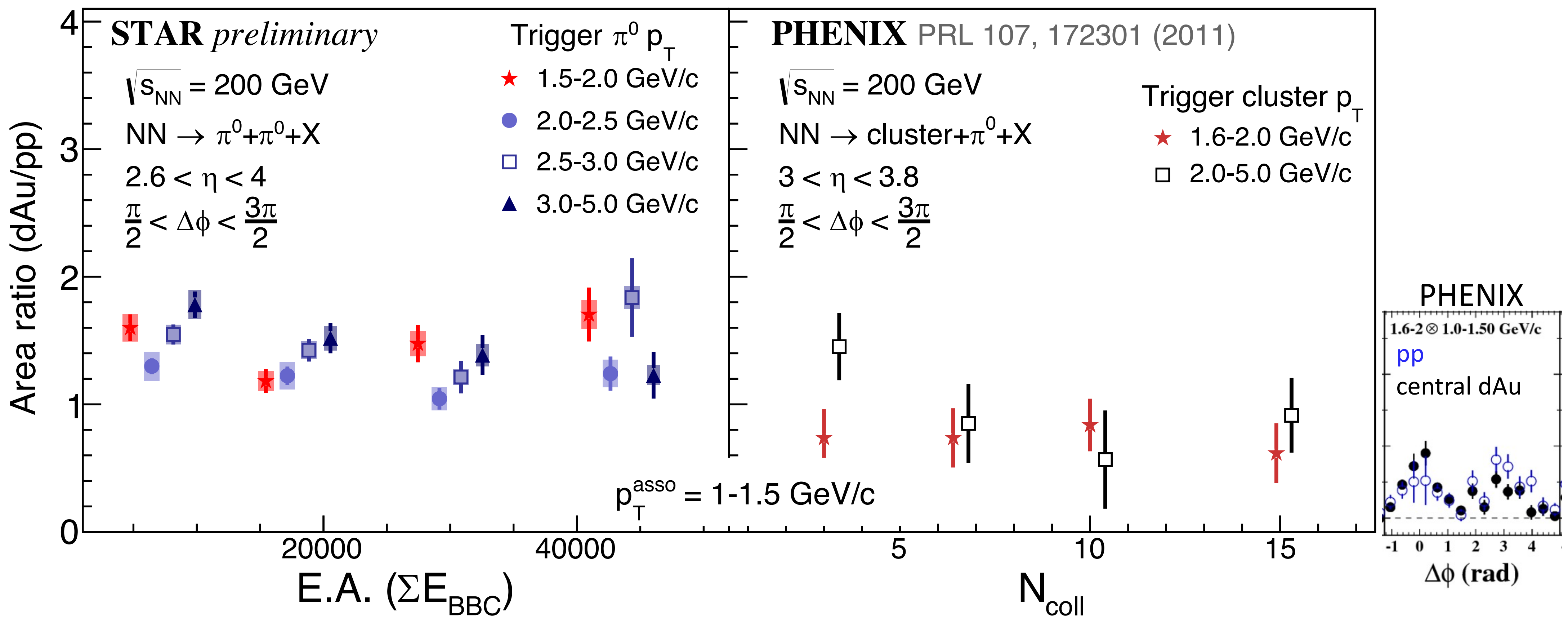




- π^0 PID: much higher background in d+Au than p+p/Au
- Combinatoric contributions are different in d+Au and p+p/Au: much higher in d+Au than p+p/Au
- Challenging to perform the forward π^0- π^0correlation measurement in d+Au: Favors for cleaner p+Au collisions

Di-π^0 measurement favors for cleaner p+A than d+A collisions

E.A. dependence in d+Au



- In the overlapping p_T range of two collaborations, no suppression or E.A. dependence in d+Au relative to p+p
- Suppression exits at very low p_T at PHENIX, where STAR FMS cannot reach