Probing nonlinear gluon effects by forward di-hadron correlations

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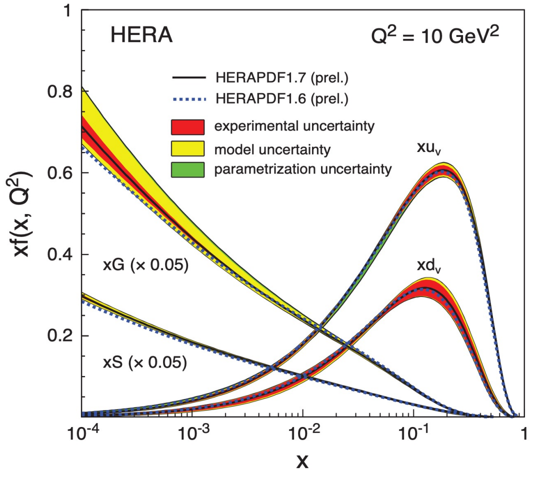
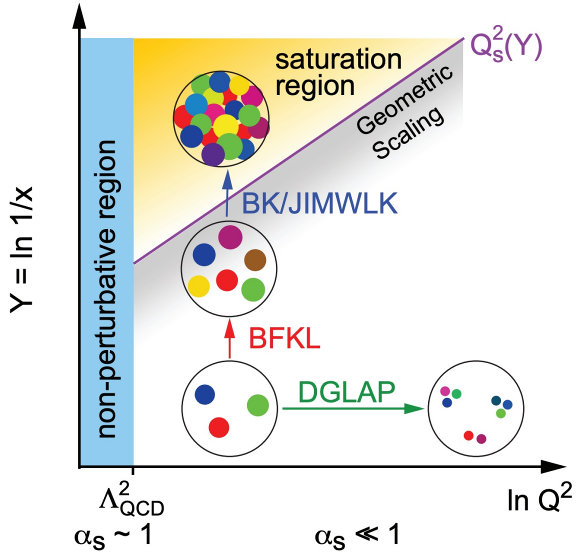
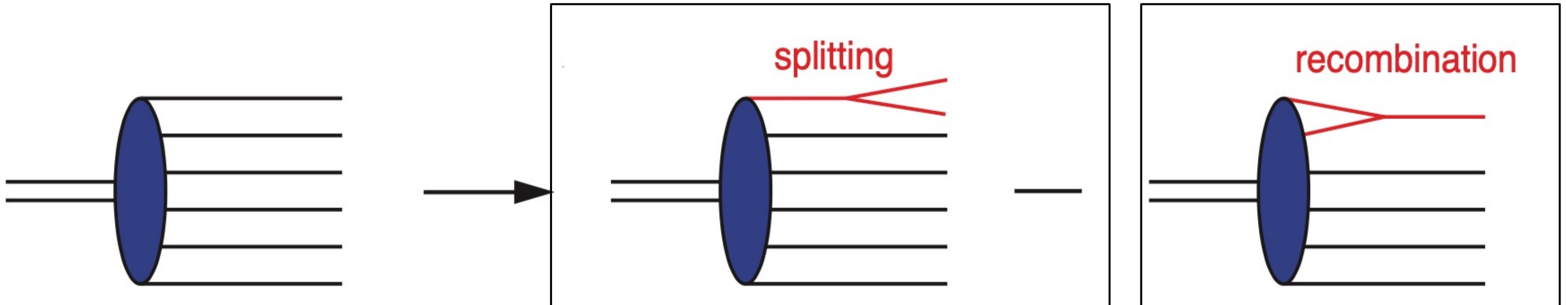
RBRC Seminar, April 28th 2022

Gluon saturation







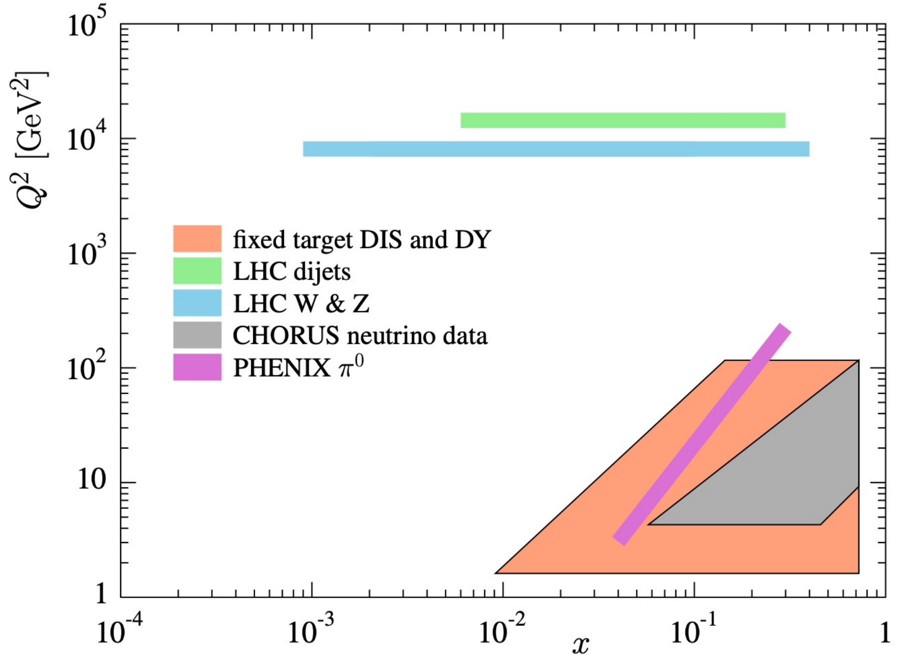
$$\frac{\partial N(x)}{\partial \ln(1/x)} = \alpha_s K_{BFKL} \otimes N(x) - \alpha_s N^2(x)$$

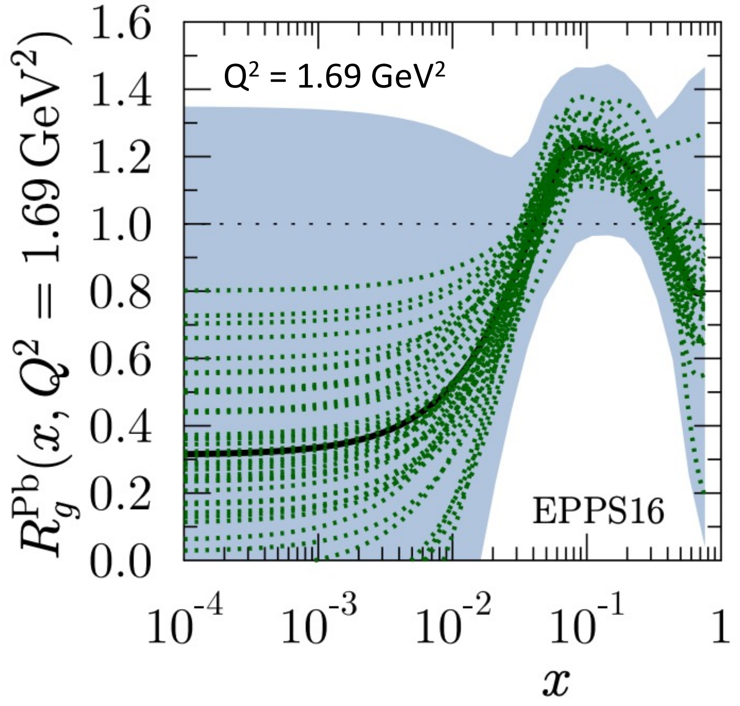
linear | nonlinear

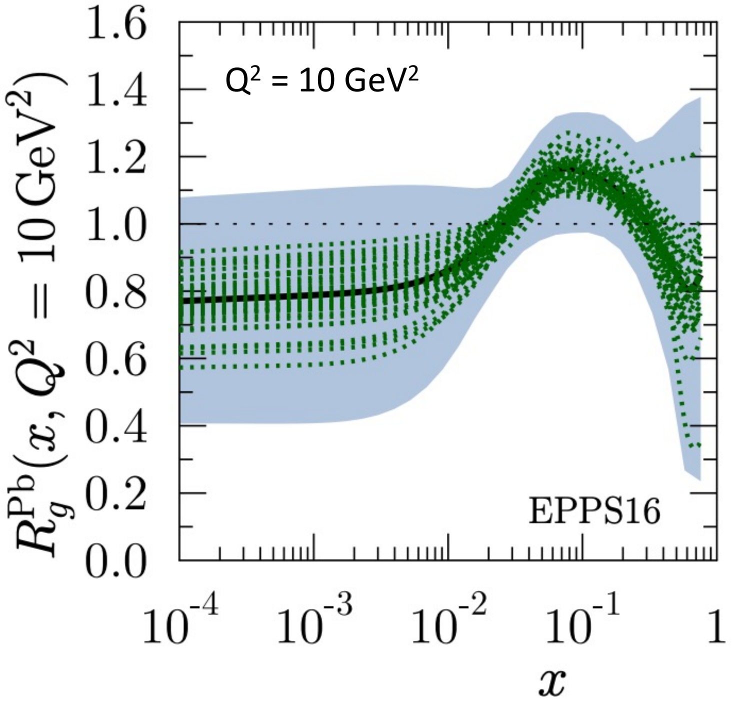
- Gluon density rapidly increases at small x: gluon splitting → BFKL → linear evolution
- Nonlinear gluon effect: gluon recombination → BK → non-linear evolution
- Gluon saturation (**$Q^2 < Q^2_s$**): gluon recombination = gluon splitting
- Nuclear gluon distributions at saturation region?

Current knowledge of nPDFs

K.J.Eskola et al.,EPJC (2017) 77:163





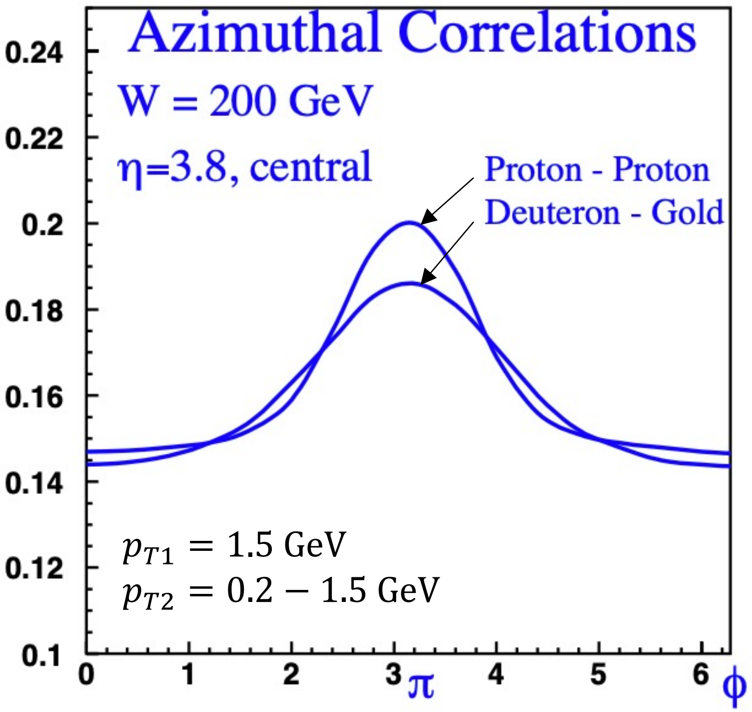


- EPPS16:
  - LHC data in p+Pb collisions → low x but high Q^2
  - DIS, DY and PHENIX π^0 data: low/moderate Q^2
  - x and Q^2 evolution behavior of suppression → cold nuclear matter (CNM) effect
- Nuclear gluon distributions have large uncertainty at small x, moderate Q^2 and low Q^2 → further inputs from RHIC data

Di-hadron measurement in d+Au

- **CGC** successfully predicted the strong **suppression of the hadron inclusive yields** in d+Au relative to p+p, by gluon saturation effects

- **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



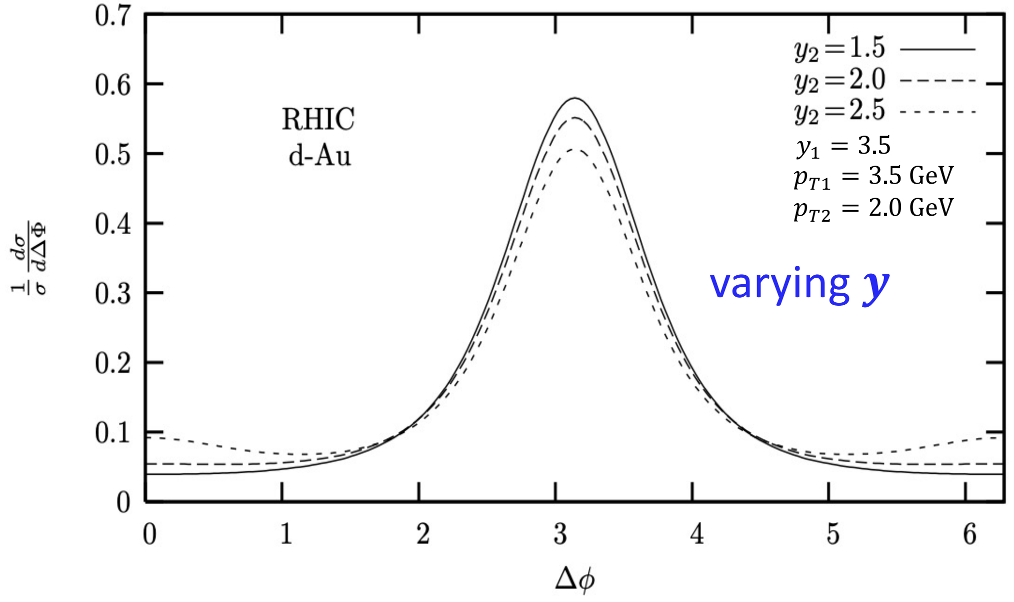
Deletion of away-side peak in d+A relative to p+p as saturation feature

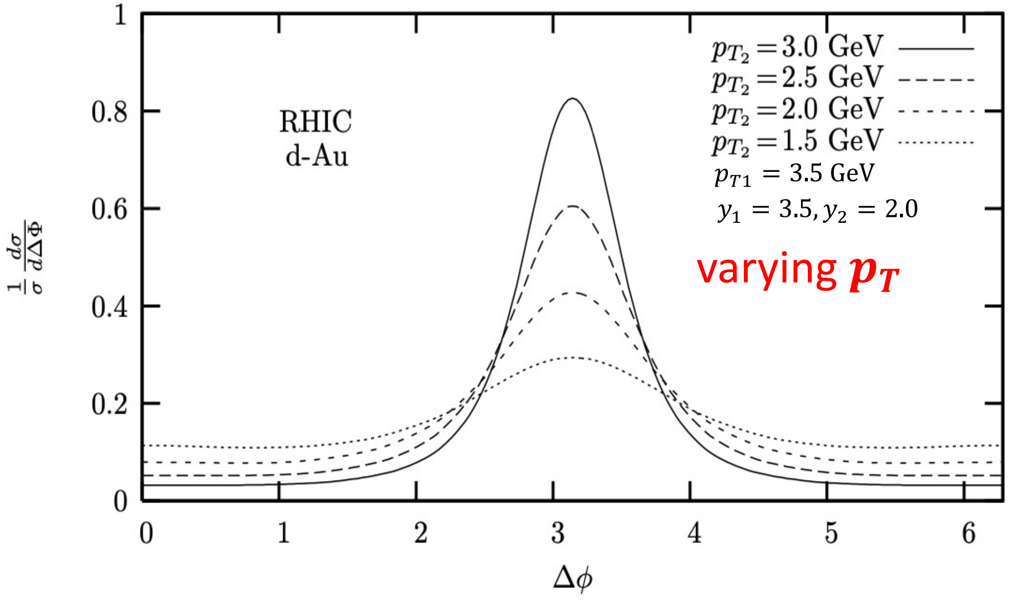
Note: self normalization ($\Delta\phi$ distribution normalized by N_{pair})

- Following theoretical predictions on di-hadron:

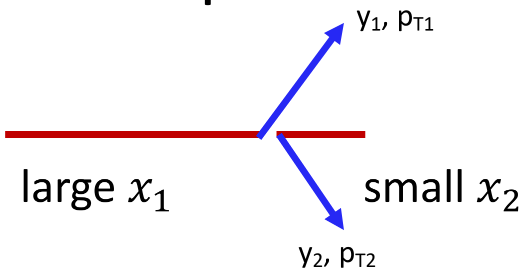
Saturation signatures on p_T and y

C. Marquet in NPA 796, 41 (2007)





Forward di-parton kinematics



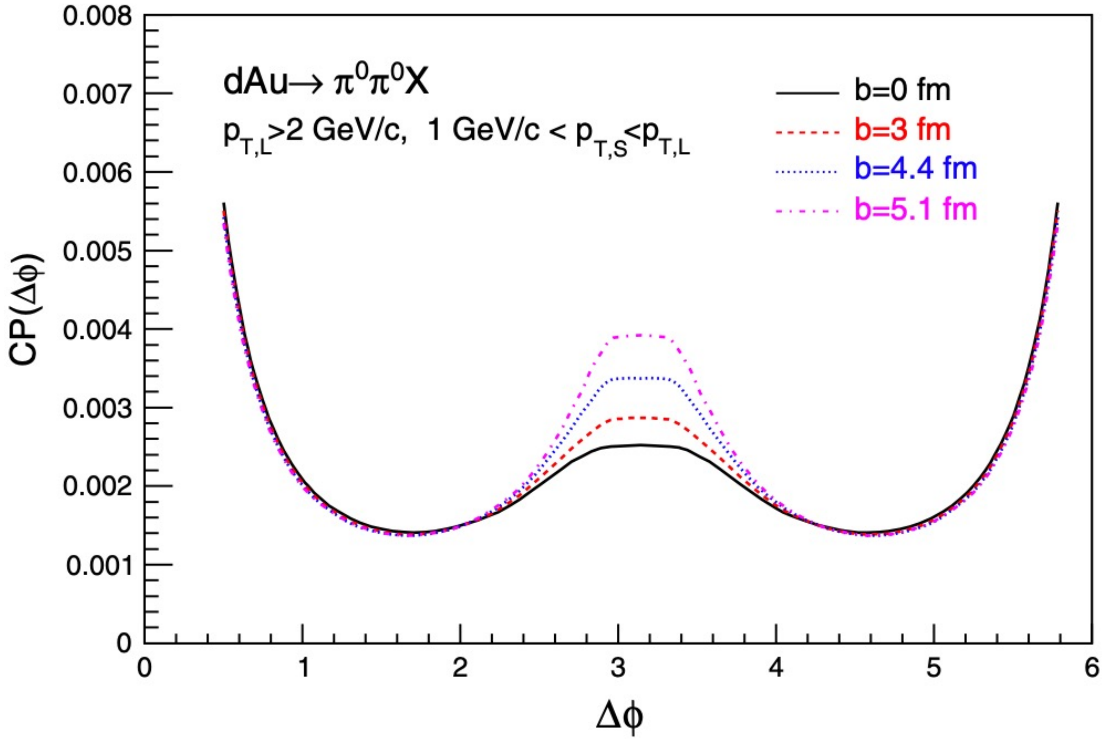
$$x_2 \sim \frac{p_{T1} e^{-y_1} + p_{T2} e^{-y_2}}{\sqrt{s}}; \; Q \sim \frac{p_{T1} + p_{T2}}{2}$$

- Correlation suppressed as x_2 decreases
- x (and Q^2) scanned by varying p_T and y

Note: $\Delta\phi$ distribution normalized by N_{trig}

Saturation signatures on b and A

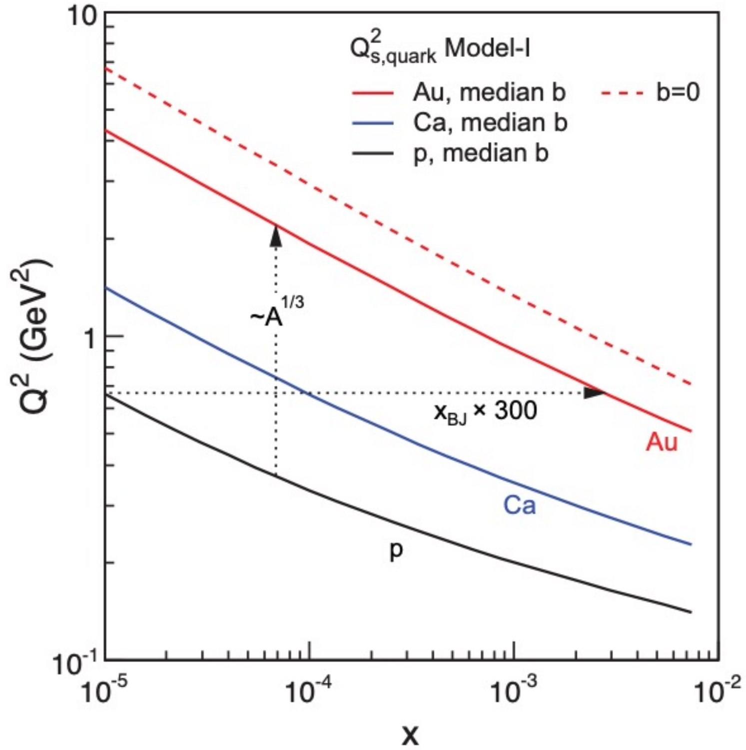
J. L. Albacete and C. Marquet, PRL 105, 162301 (2010)



$Q_s \propto T_A(b) \propto 1/b$:
smaller b, larger Q_s→ easier to reach saturation region

Woods-Saxon potential: $T_A(b)$

arXiv: 1212.1701



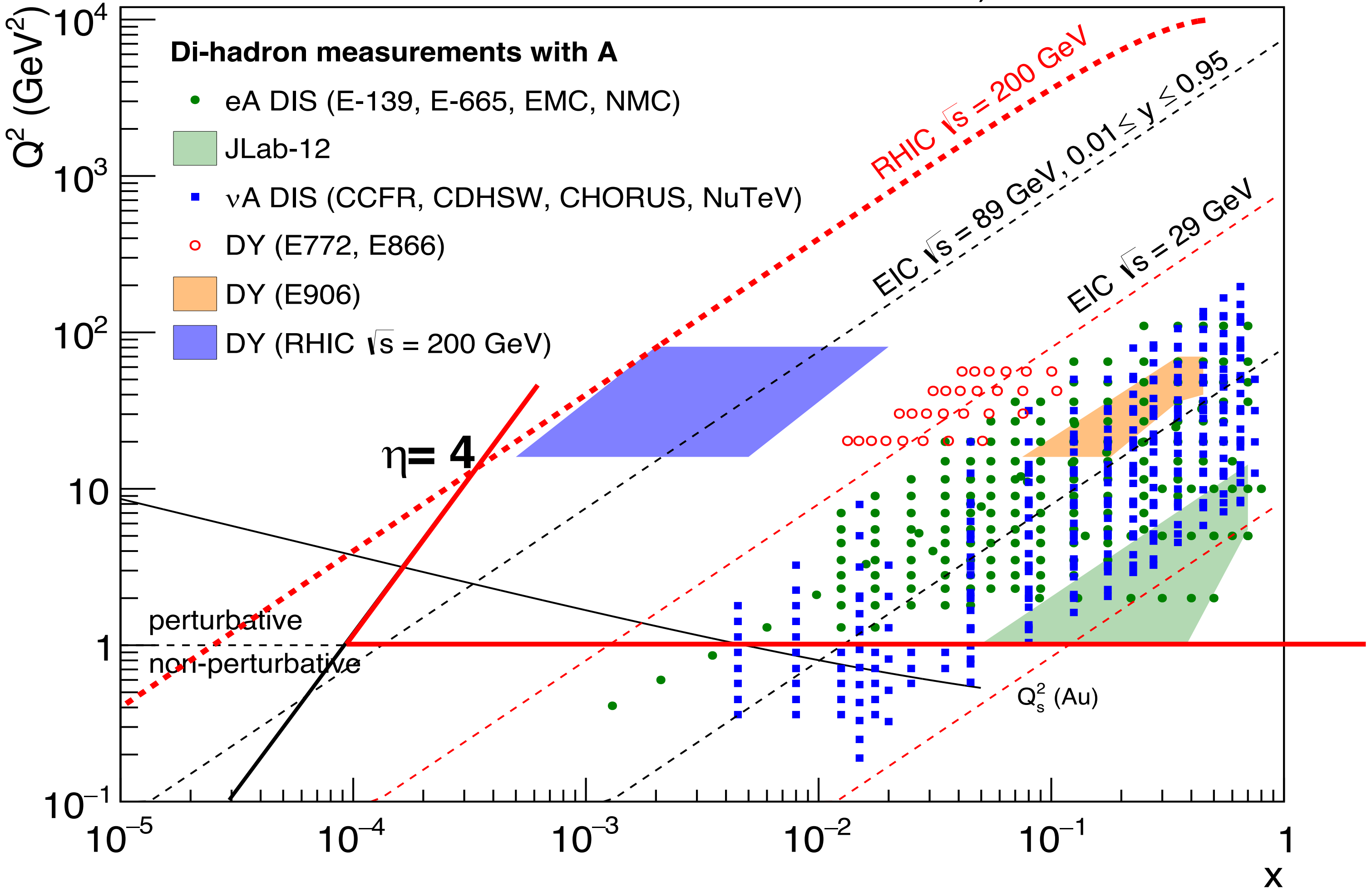
$Q_s \propto A^{1/3}$:
Larger A, larger Q_s→ easier to reach saturation region

Do we observe the nonlinear gluon dynamics signatures from recent STAR p+p, p+A, and d+A data?

- **p+p, p+Al, and p+Au collisions:** STAR, arXiv: 2111.10396
    - d+Au collisions: STAR preliminary results

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

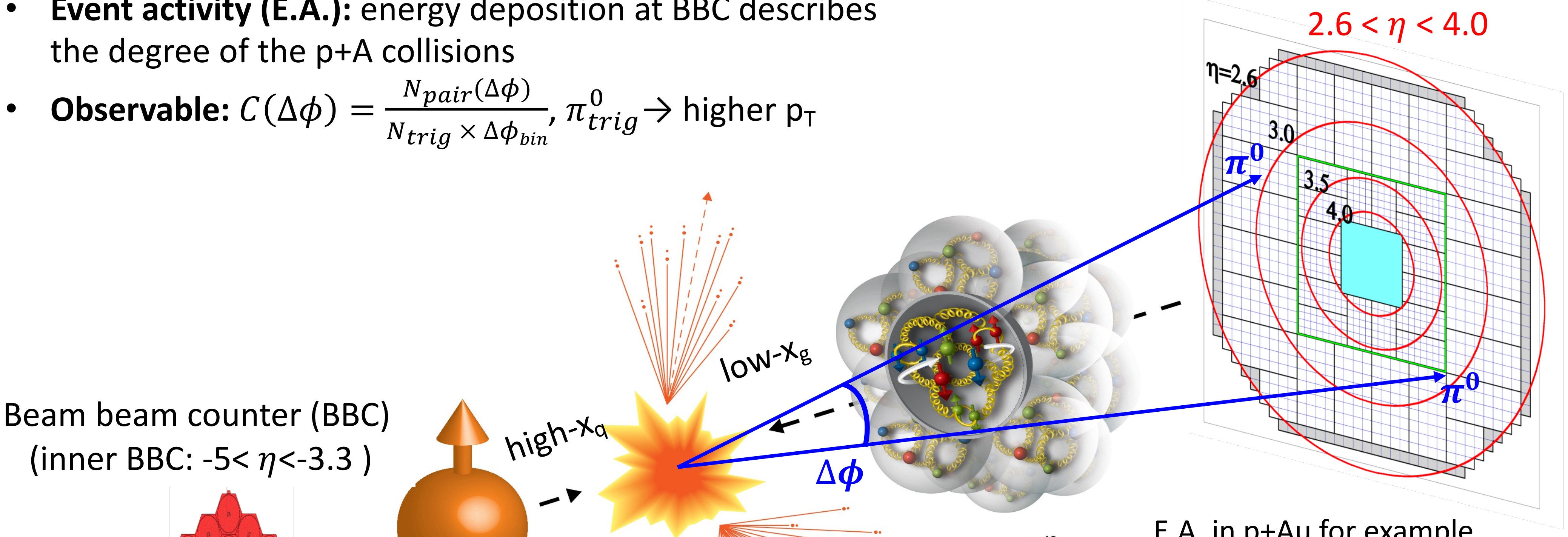
R. Abdul Khalek et al., arXiv:2103.05419

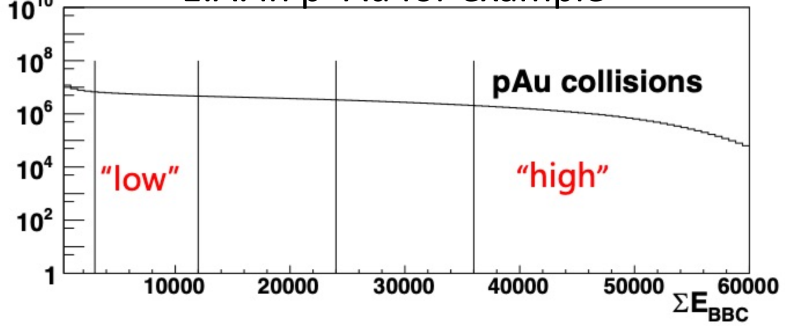


STAR data can access linear-nonlinear transition region

Di-π^0 measurement at STAR

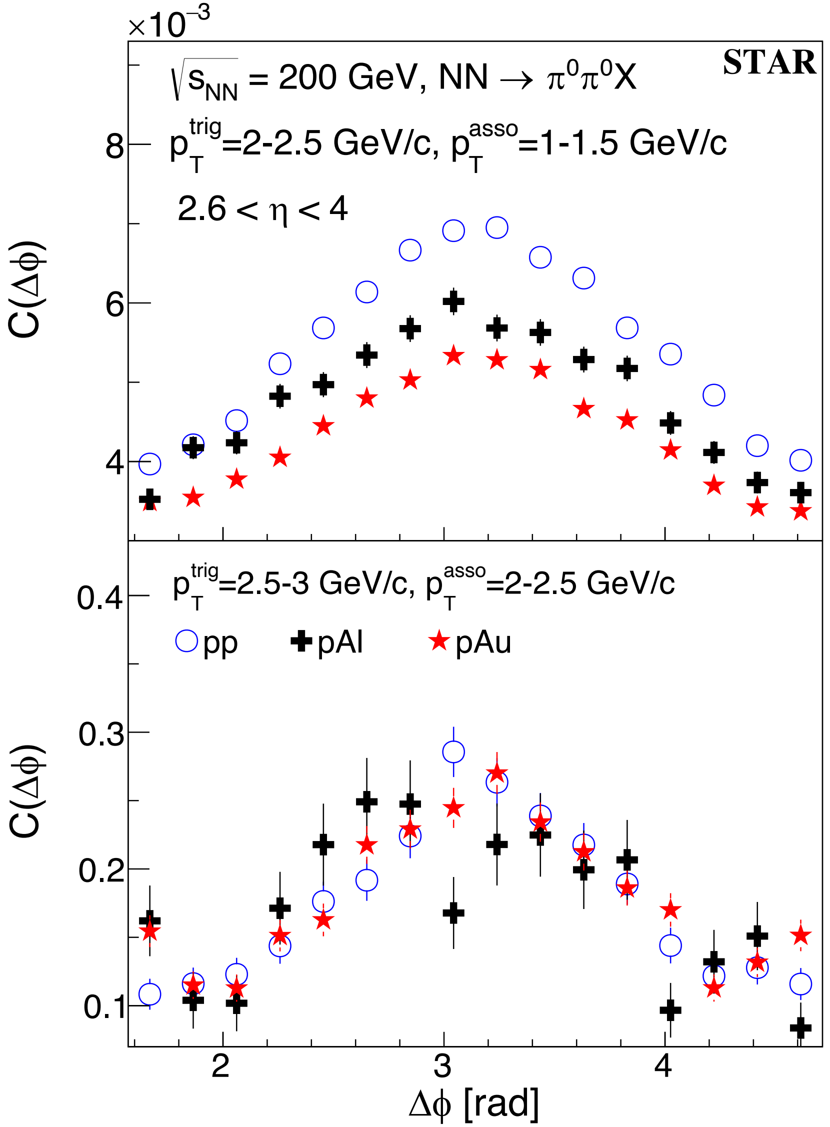
- **p+p, p+Al, p+Au** and d+Au collisions at $\sqrt{s_{NN}} = 200$ GeV
- NN → $\pi^0 + \pi^0$ + X, π^0 detected by FMS with $2.6 < \eta < 4.0$
- **Event activity (E.A.):** energy deposition at BBC describes the degree of the p+A collisions
- **Observable:** $C(\Delta\phi) = \dfrac{N_{pair}(\Delta\phi)}{N_{trig}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

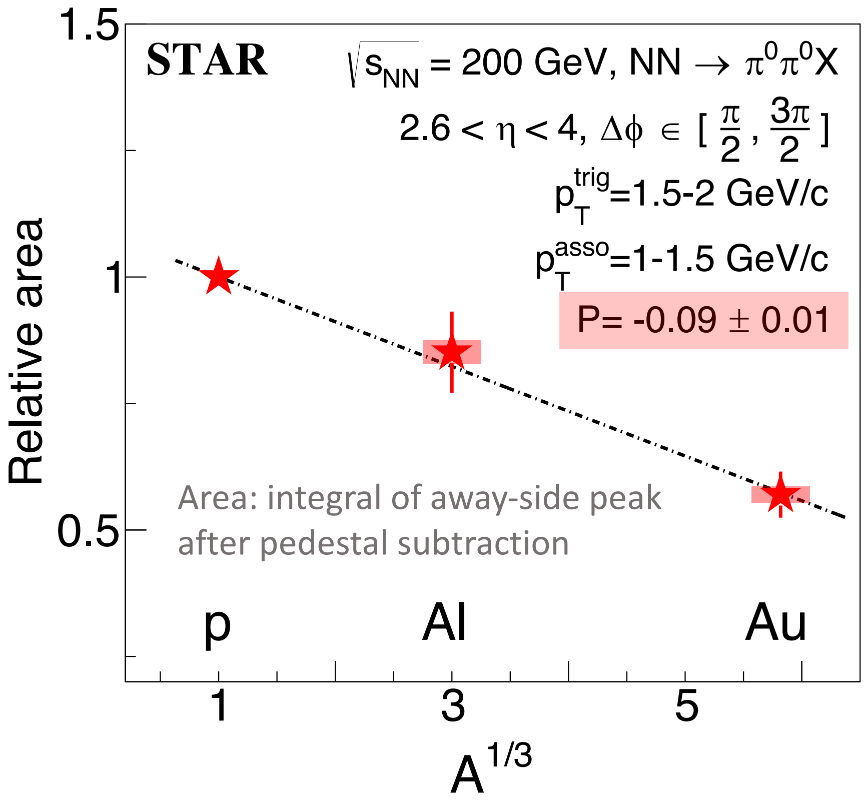




STAR, arXiv: 2111.10396

p_T and A dependence

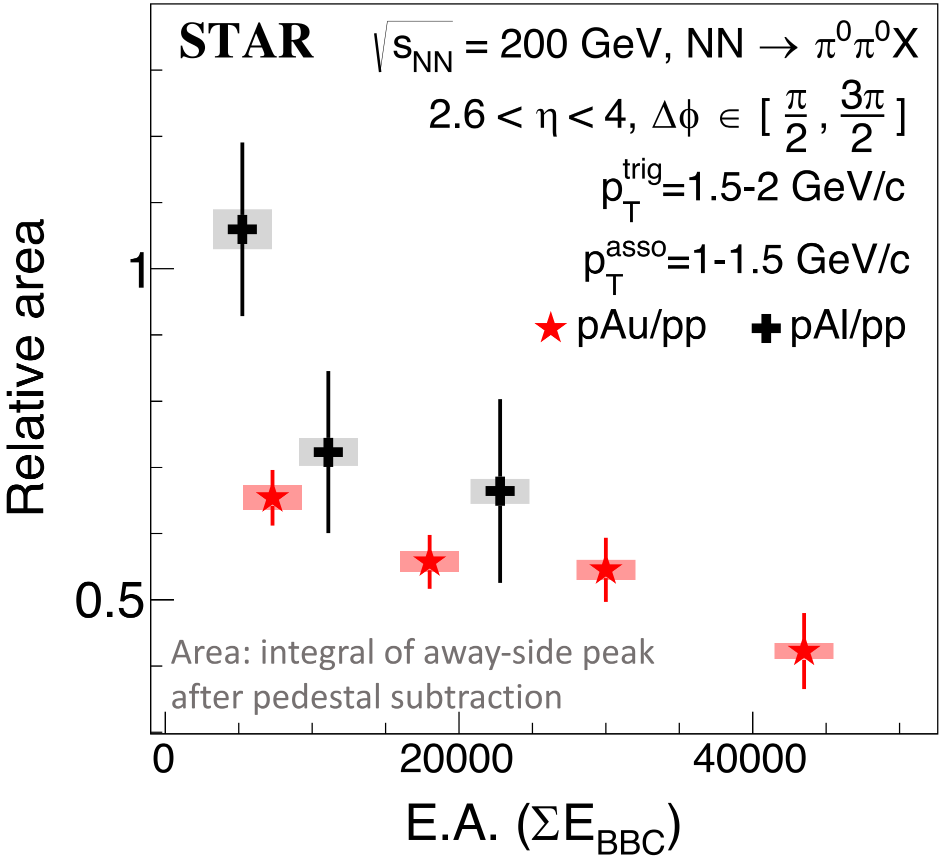


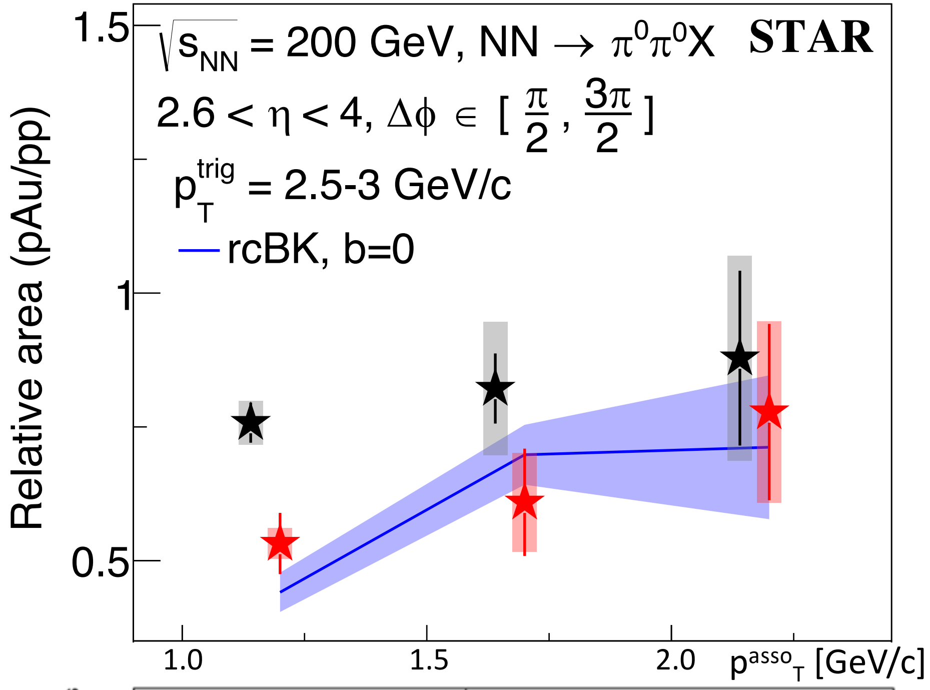


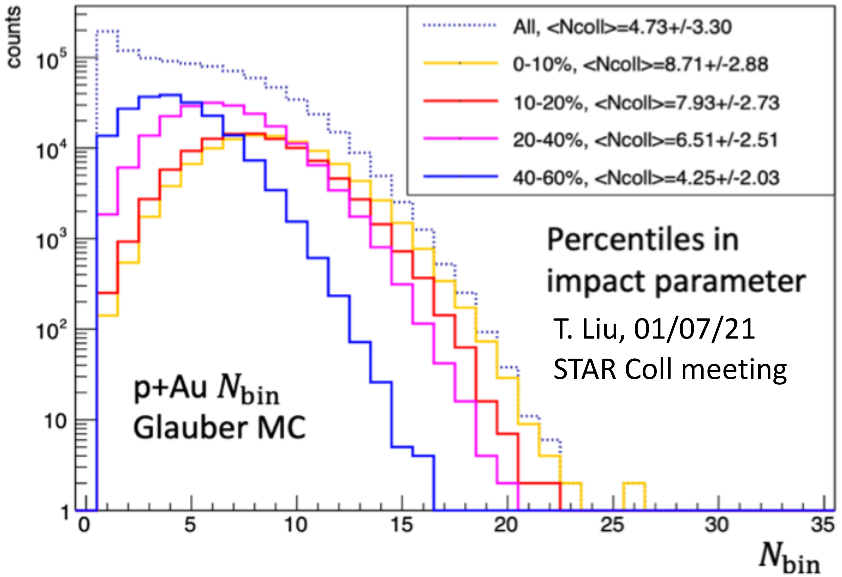
- Suppression at low p_T not high p_T
- Fixed p_T (smallest p_T) bin → $x - Q^2$ phase space is fixed, suppression is dominantly affected by various A:
  - Suppression linearly depends on $A^{1/3}$
  - Slope from the fitting = -0.09 $\pm$ 0.01

E.A. dependence

STAR, arXiv: 2111.10396



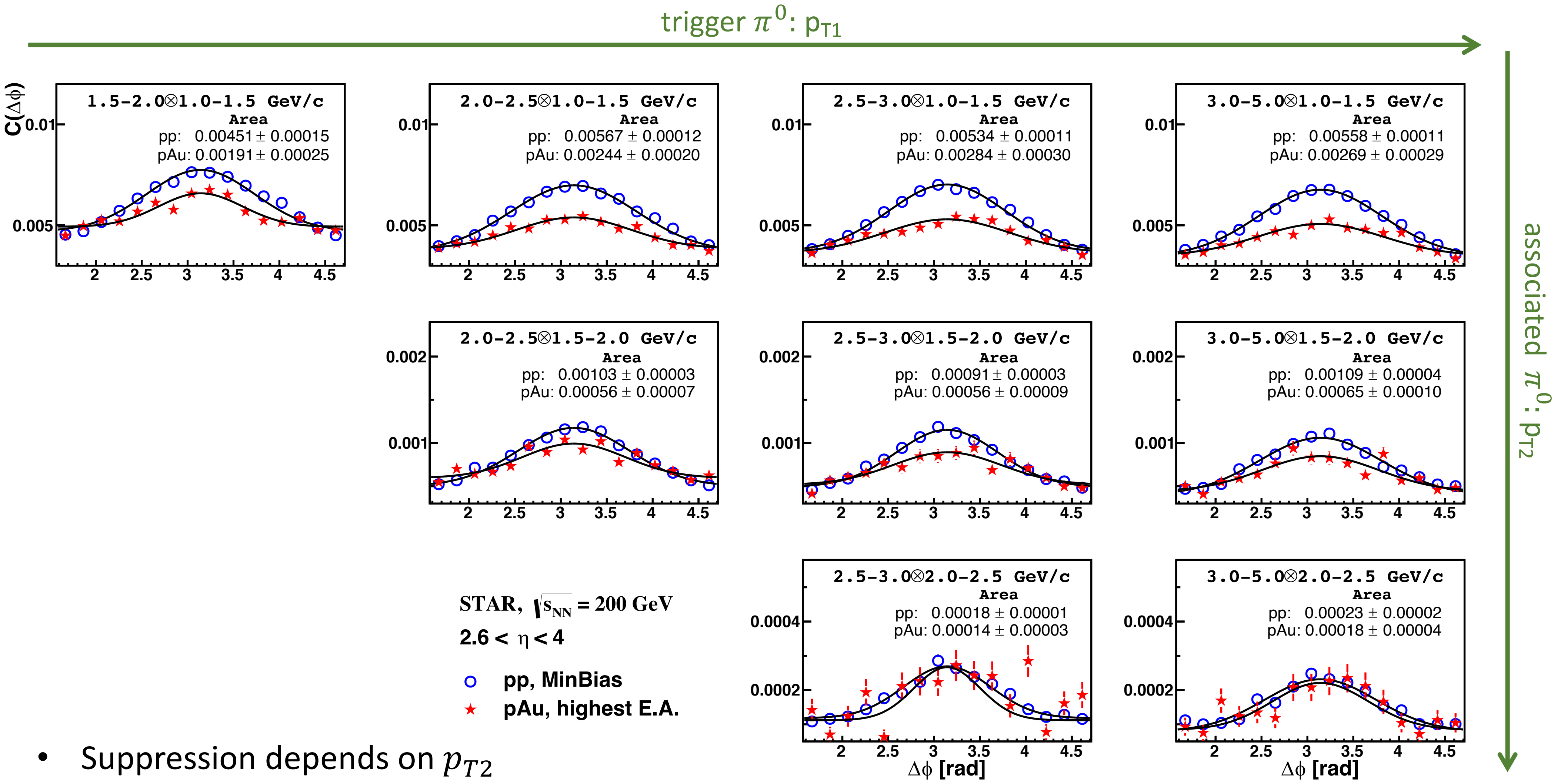




- Suppression increases with E.A., highest E.A. data is consistent with predictions at $b = 0$
- Traditional definition of centrality doesn't work well for small systems: what is the variable best corelated with b in small systems?

Full p_T picture

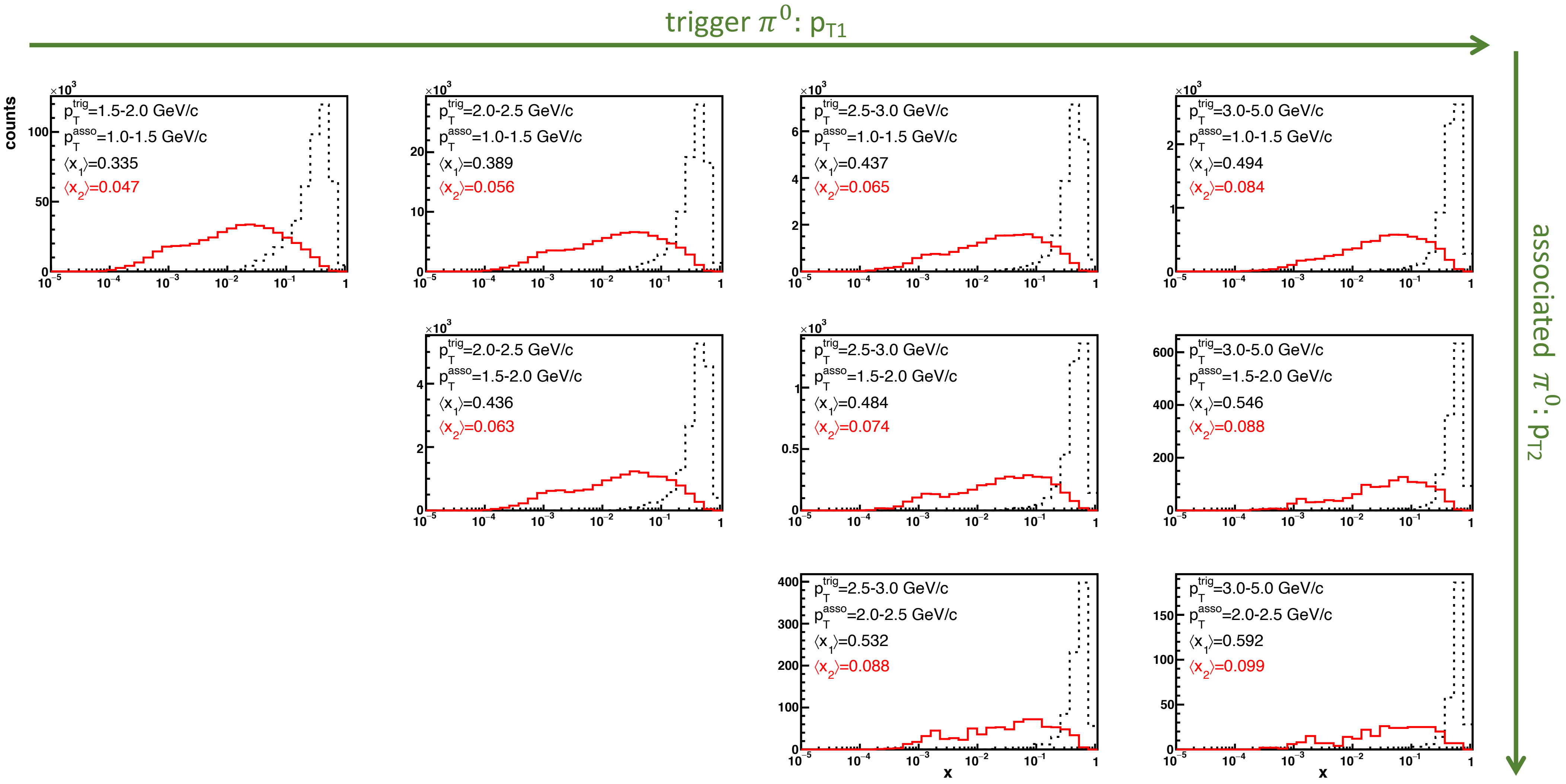
STAR, arXiv: 2111.10396



- Suppression depends on p_{T2}
- At fixed p_{T2}, suppression rarely depends p_{T1}

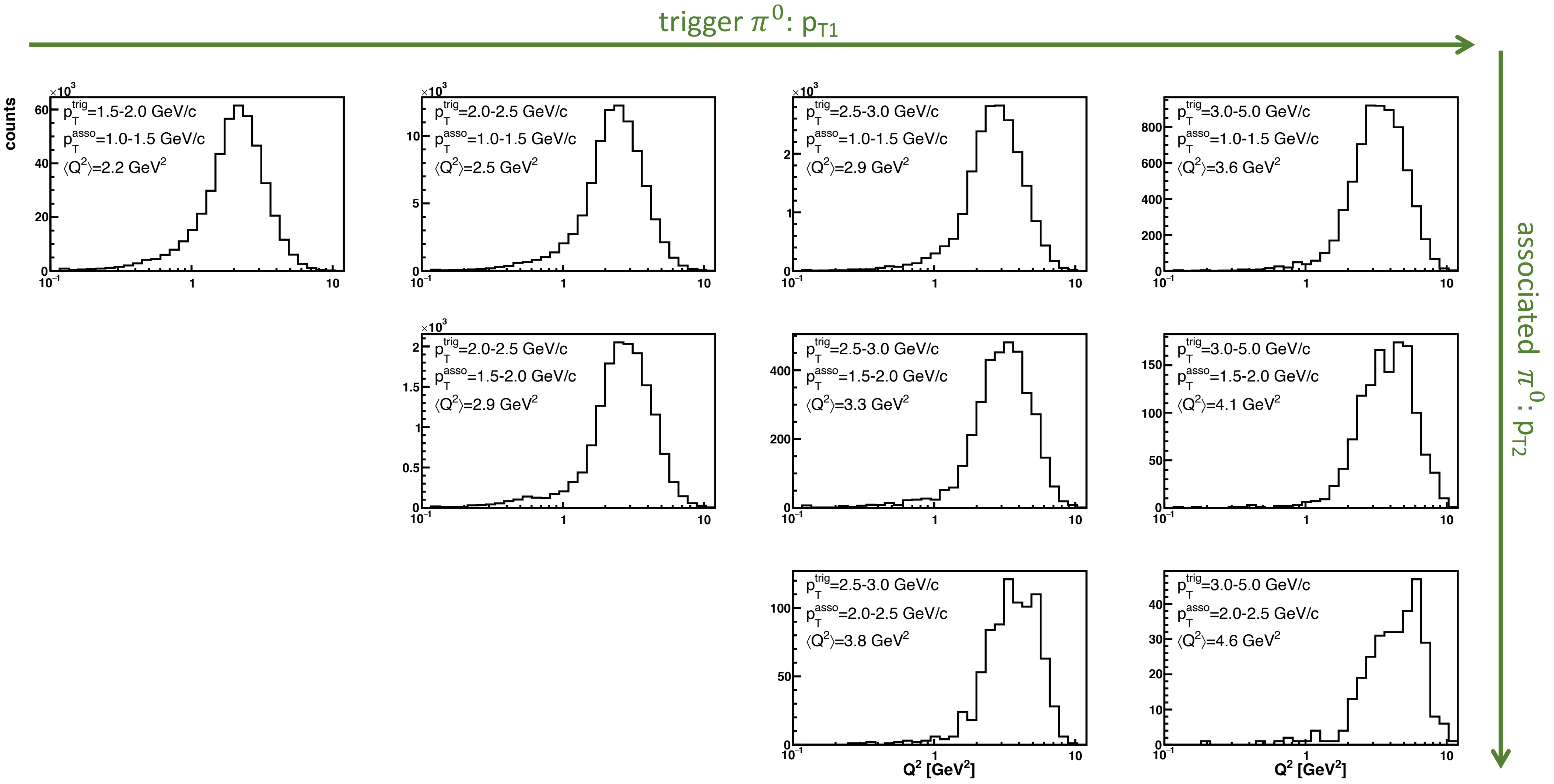
Simulated x

STAR, arXiv: 2111.10396



Simulated Q^2

STAR, arXiv: 2111.10396



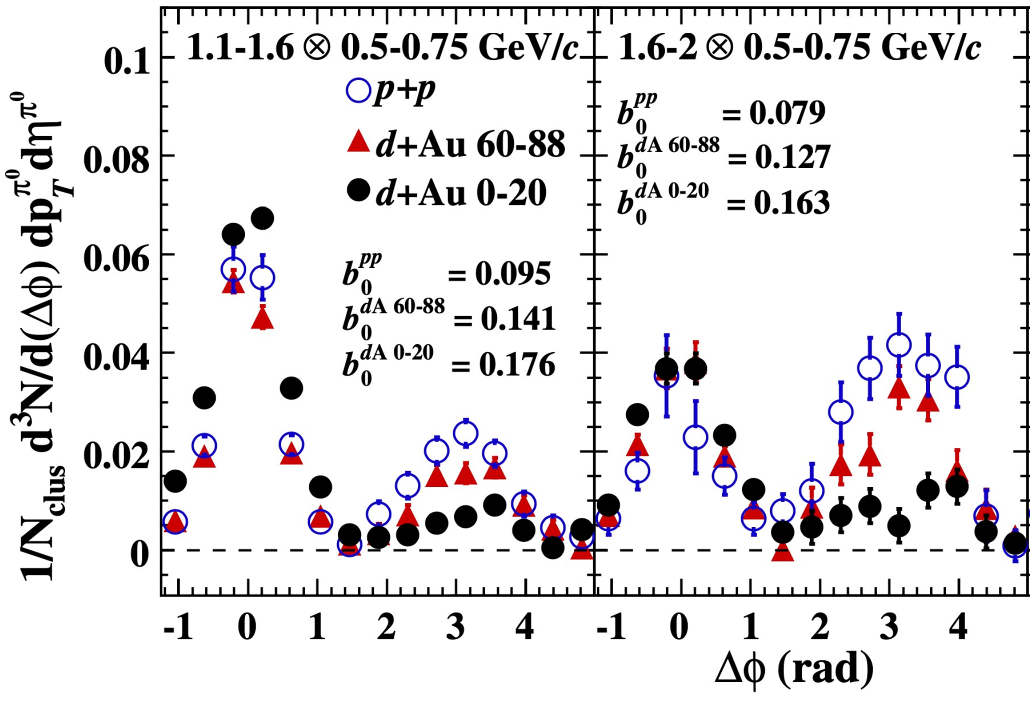
Do we observe the nonlinear gluon dynamics signatures from recent STAR p+p, p+A, and d+A data?

- **p+p**, p+Al, and **p+Au collisions**: STAR, arXiv: 2111.10396
- **d+Au collisions:** STAR preliminary results

PHENIX data

PHENIX, PRL 107, 172301 (2011)

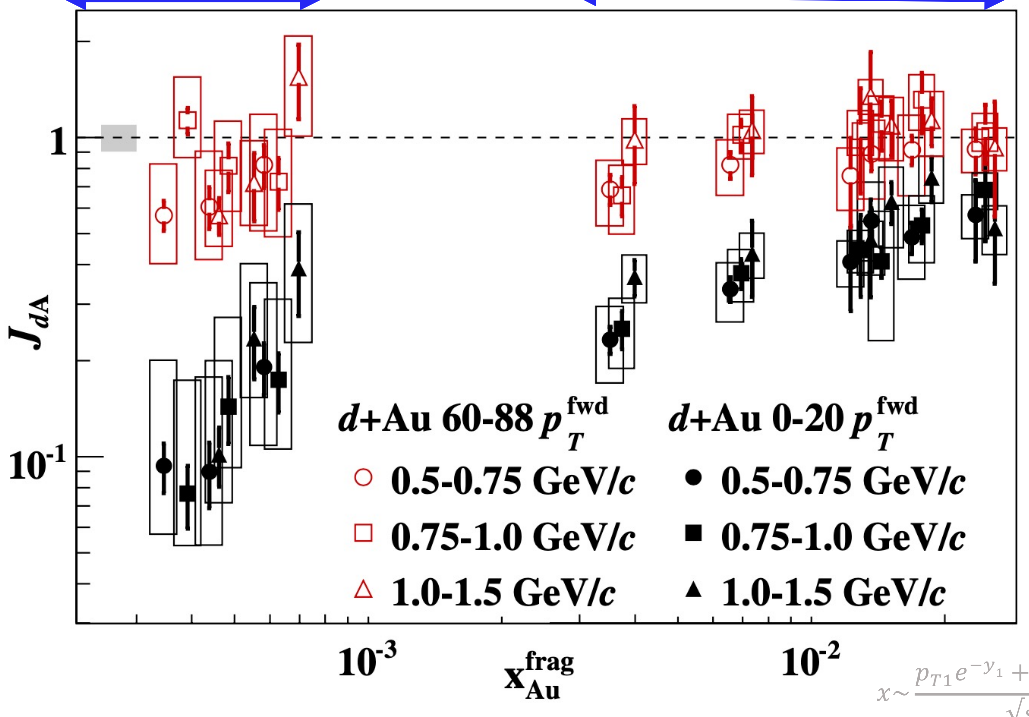
forward-forward: 3.0 < η < 3.8



Note: $\Delta\phi$ distribution normalized by N_{trig}

forward-forward

mid-forward: |η|<0.35, 3.0 < η < 3.8



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

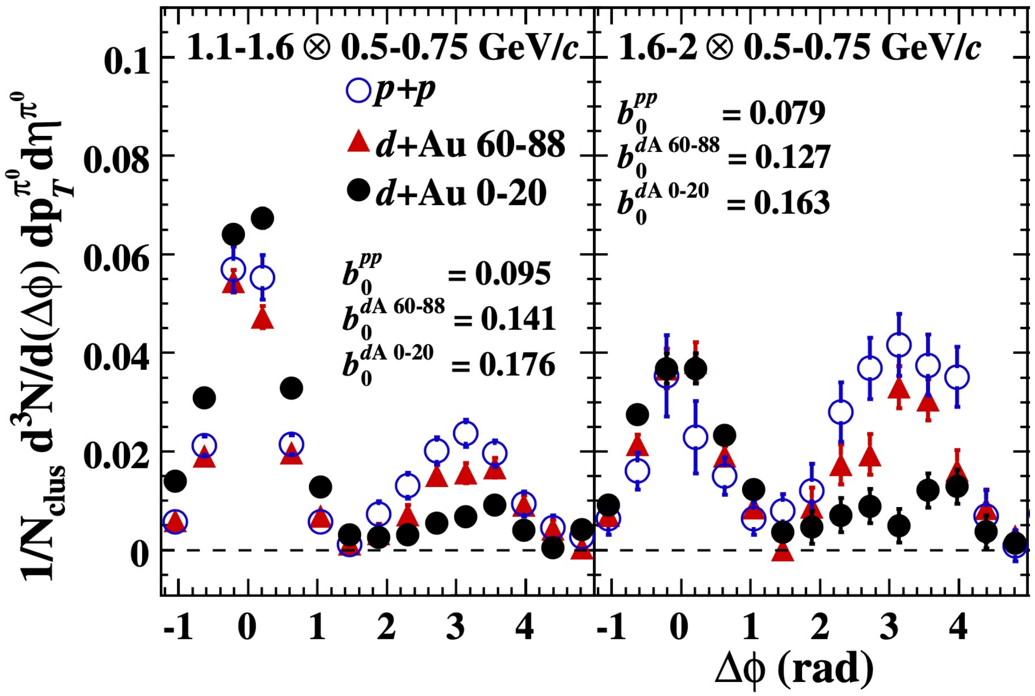
$J_{dA} = R_{dAu} \times I_{dAu}$

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

- **Away-side correlation**: suppression dependence on rapidity and centrality is studied by PHENIX

Other thoughts for PHENIX data

forward-forward: 3.0 < η < 3.8



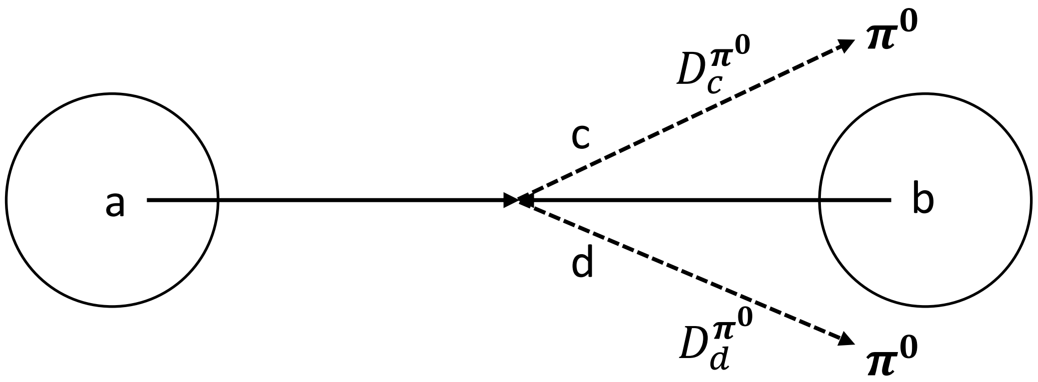
Low p_T	Pedestal ratio (central dAu/pp): 1.9
High p_T	Pedestal ratio (central dAu/pp): 2.1

- **Pedestal**: high pedestal in d+Au; ratio(d+Au/p+p) tends to increase with p_T
  PRD 83, 034029 (2011) → double parton interactions (DPS) in d+Au? → correlation is also affected by DPS?
- **Motivation of performing the similar measurement at STAR** → Impact of DPS in d+Au; complementary studies

Di-π^0 from SPS/DPS

M. Strikman and W. Vogelsang, PRD 83, 034029 (2011)

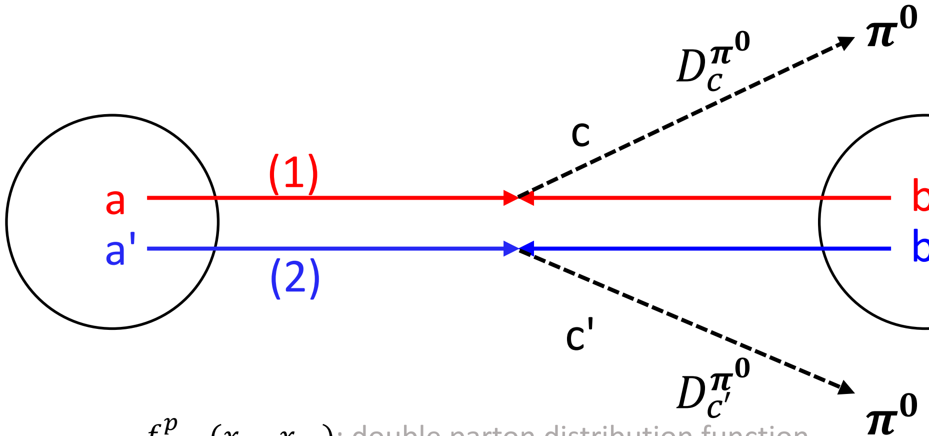
Single parton scattering (SPS) in pp: a+b→c+d+X



Leading-twist (**LT**) mechanism

$$\sigma_{LT} \propto f_a^p(x_a) \otimes f_b^p(x_b) \otimes \sigma^{ab\to cdX} \otimes D_c^{\pi^0} \otimes D_d^{\pi^0}$$

Double parton scattering (DPS) in pp: a+b→c+X and a'+b'→c'+X



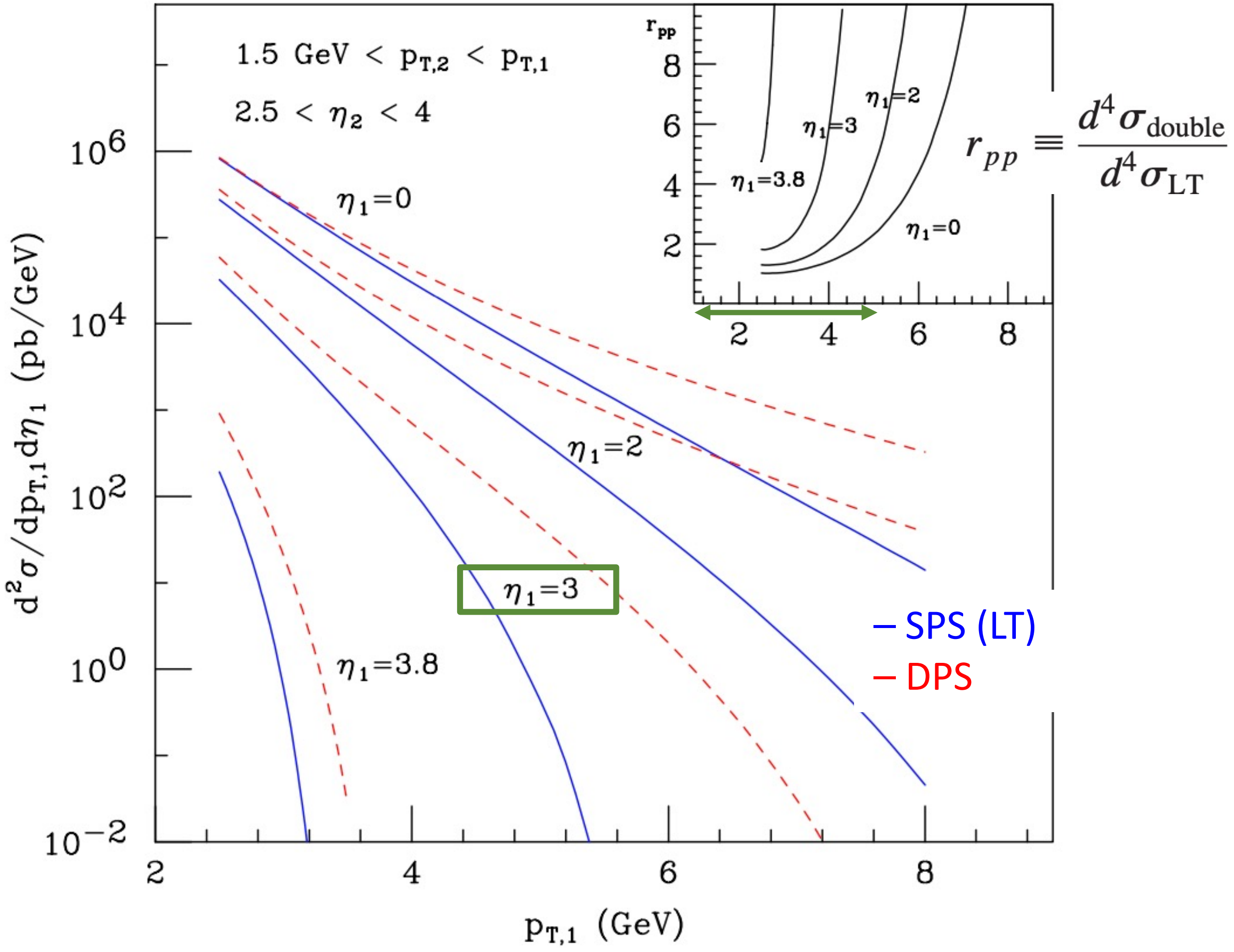
$f^p_{q_1q_2}(x_{q_1}, x_{q_2})$: double parton distribution function

$$\sigma_{double} \propto f^p_{aa'}(x_a, x_{a'}) \otimes f^p_{bb'}(x_b, x_{b'})$$
$$\otimes\ \sigma^{ab\to cX} \otimes D_c^{\pi^0} \qquad (1)$$
$$\otimes\ \sigma^{a'b'\to c'X'} \otimes D_{c'}^{\pi^0} \qquad (2)$$

If q_1,q_2 correlated: $f^p_{q_1q_2}(x_{q_1}, x_{q_2}) \neq f^p_{q_1}(x_{q_1}) f^p_{q_2}(x_{q_2})$

If q_1,q_2 uncorrelated: $f^p_{q_1q_2}(x_{q_1}, x_{q_2}) = f^p_{q_1}(x_{q_1}) f^p_{q_2}(x_{q_2})$

DPS dominates at forward rapidities

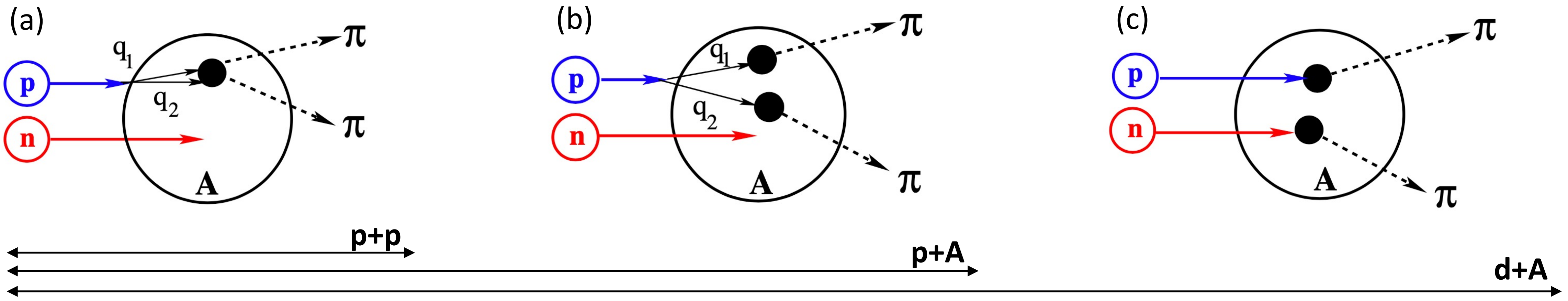


- DPS is enhanced and not negligible at high rapidities
- Green box and arrow represent the kinematics STAR data can reach

DPS in d+Au?

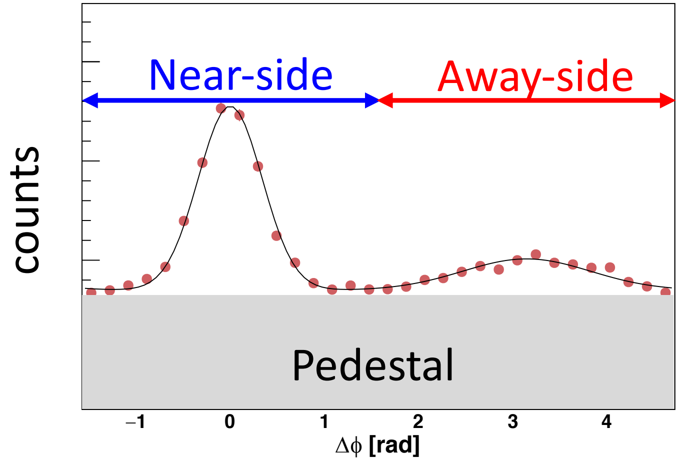
M. Strikman and W. Vogelsang, PRD 83, 034029 (2011)

Examples contribution of DPS

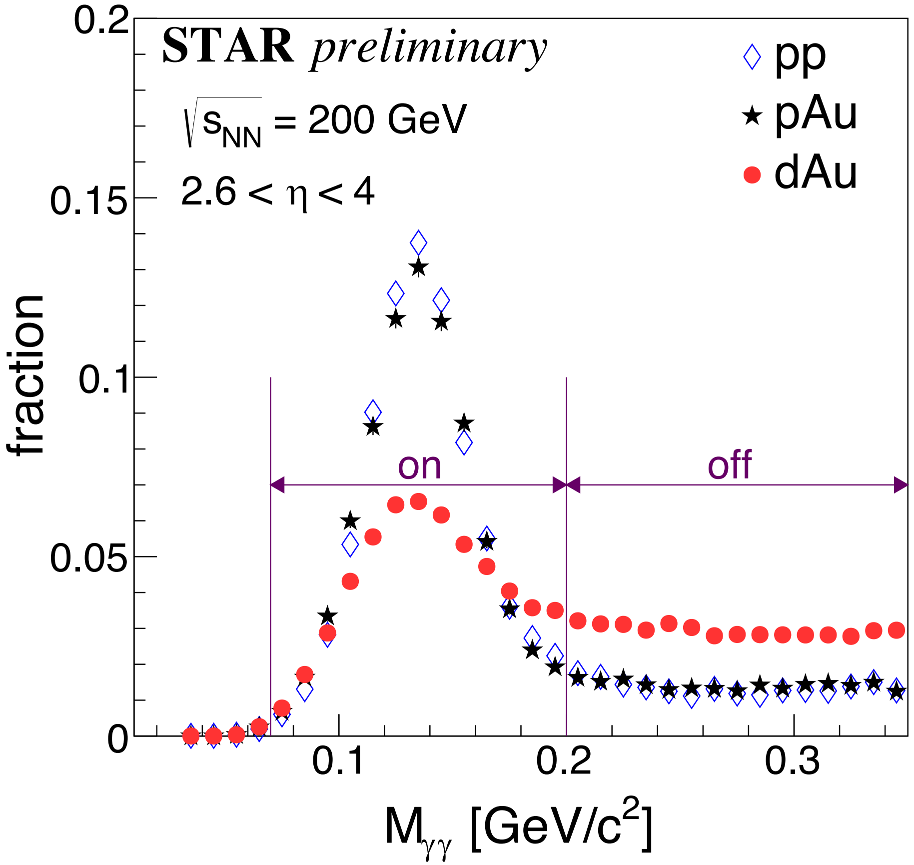


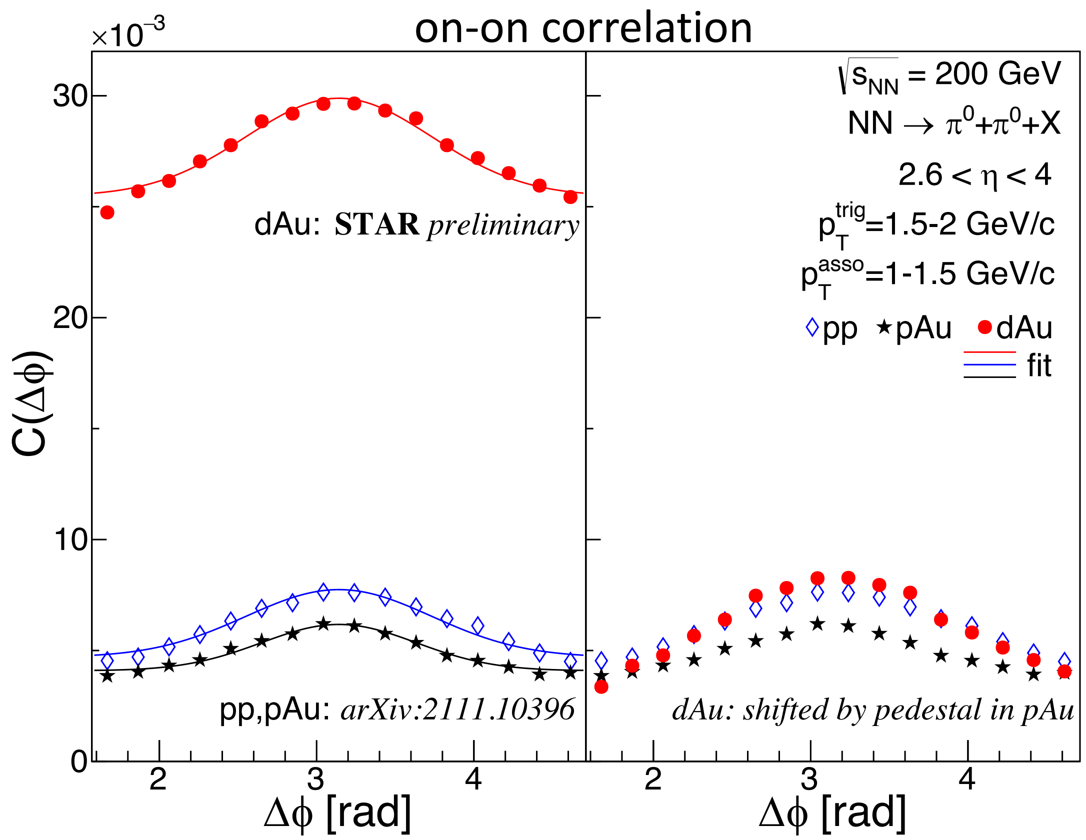
Comparison of p+p, p+Au and d+Au → study the individual source of DPS

- **Compare pedestal**: DPS provides an explanation of higher pedestal in d+Au
- **Compare away-side correlation →** window open to studies of **double parton distributions** in nucleons:
  - q_1,q_2 correlated: DPS enhances the correlation
  - $q_{1,}q_2$ uncorrelated: DPS will only enhance pedestal



p+p, p+Au and d+Au comparison

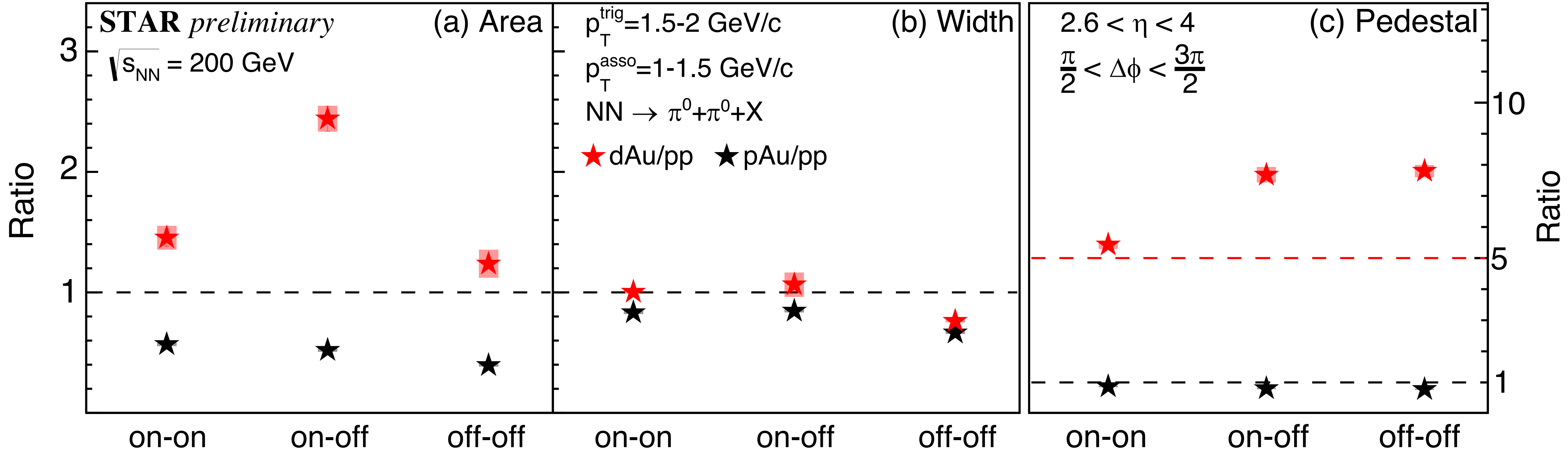




S/(S+B)	STAR	PHENIX (PhD thesis)
p+p	82%	81%
d+Au	58%	73%

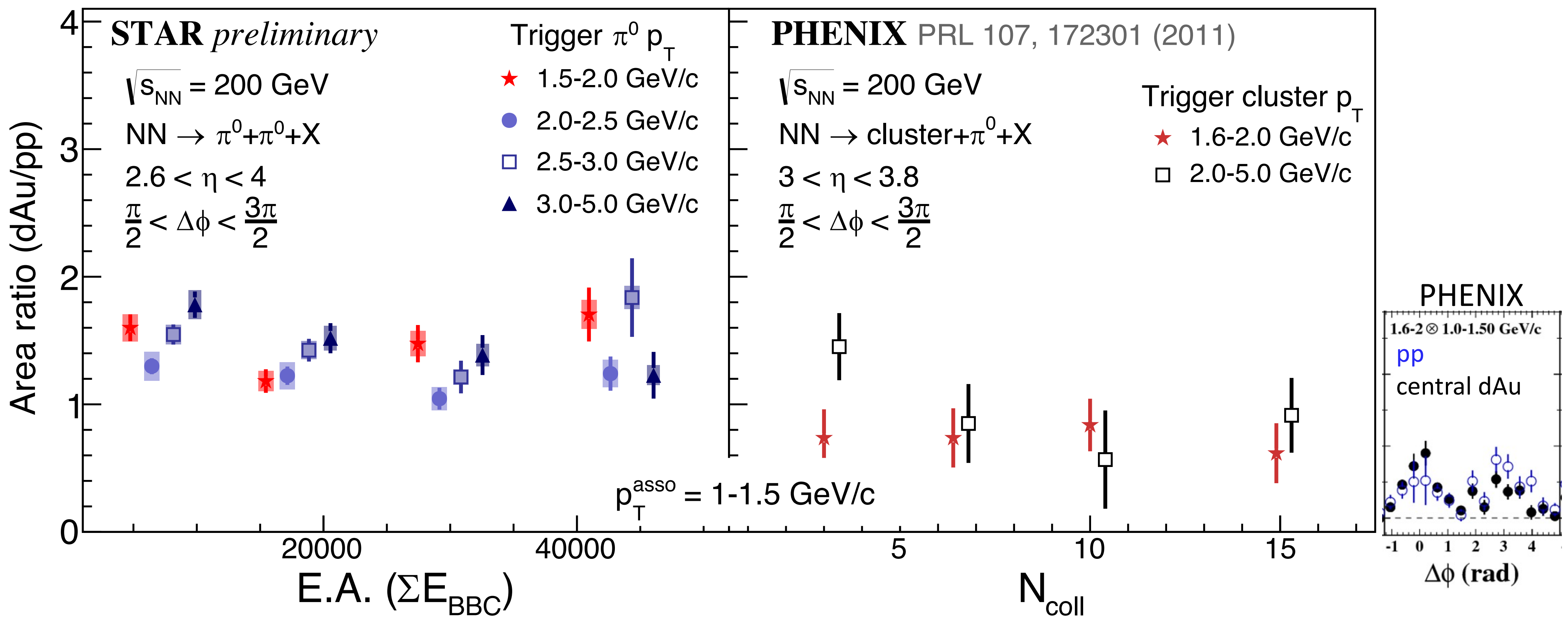
- π^0 PID: much higher background in d+Au than p+p (Au)
- Very high pedestal: d+Au > 5 times higher compared to p+p (Au)
- Away-side: enhancement in d+Au compared to p+Au

Combinatoric contributions in d+Au



- Area: contribution from off mass window is high in d+Au
  - not fair to directly compare d+Au and p+p without background subtraction, but we don't fully understand the background correlation
  - potential enhancement lead by DPS can not be determined so far…
- Width: roughly stable in three collision systems → no broadening
- Pedestal: d+Au/p+p > 5; d+Au/p+p ~ 1 → no DPS in p+Au, but is there DPS in d+Au?

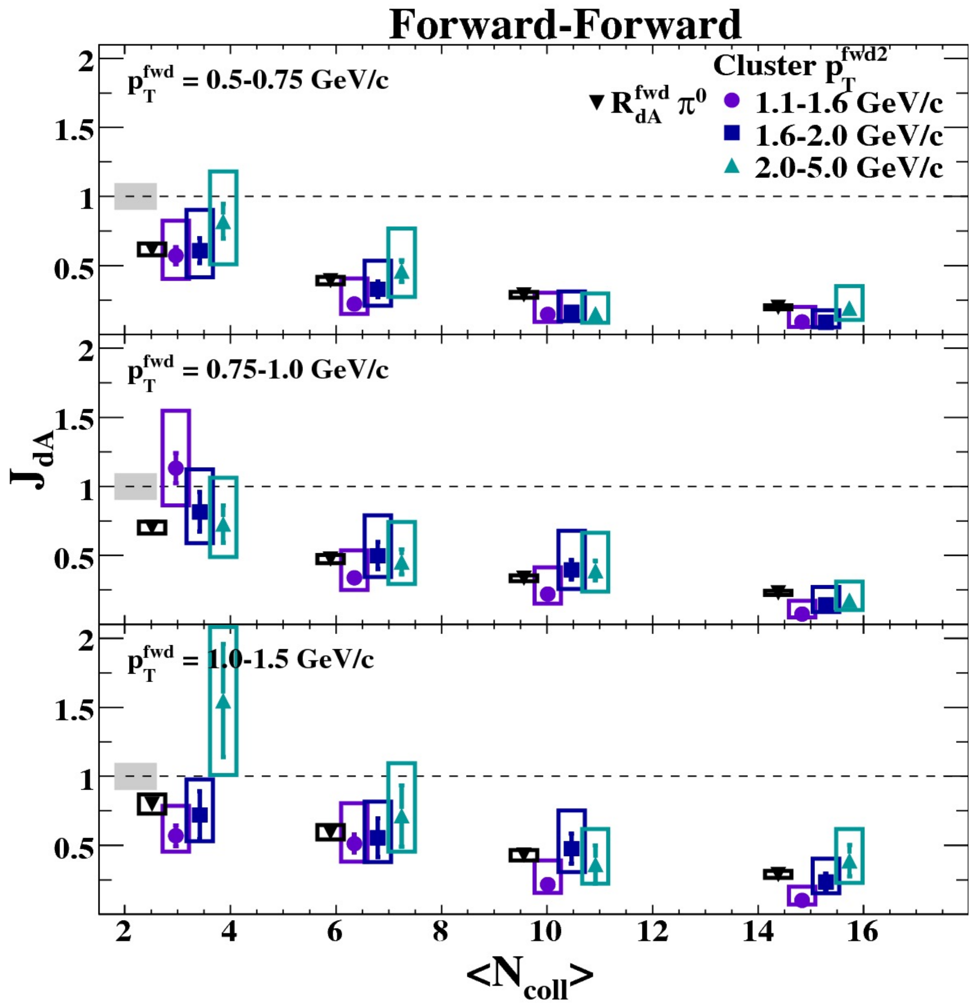
E.A. dependence in d+Au



- 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 cannot reach

How to describe suppression?

PHENIX, PRL 107, 172301

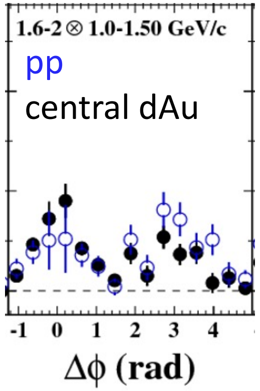


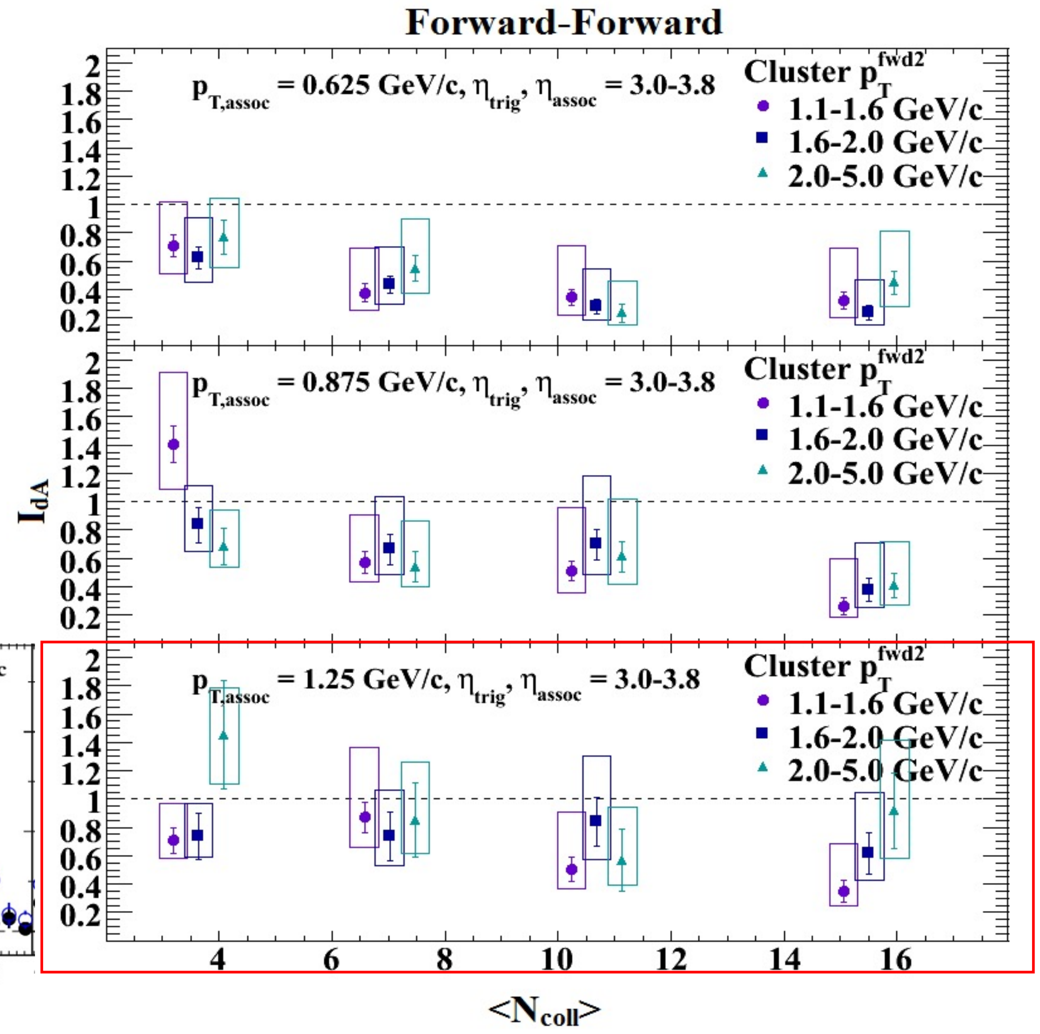
PhD thesis

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

I_{dA} = area ratio

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



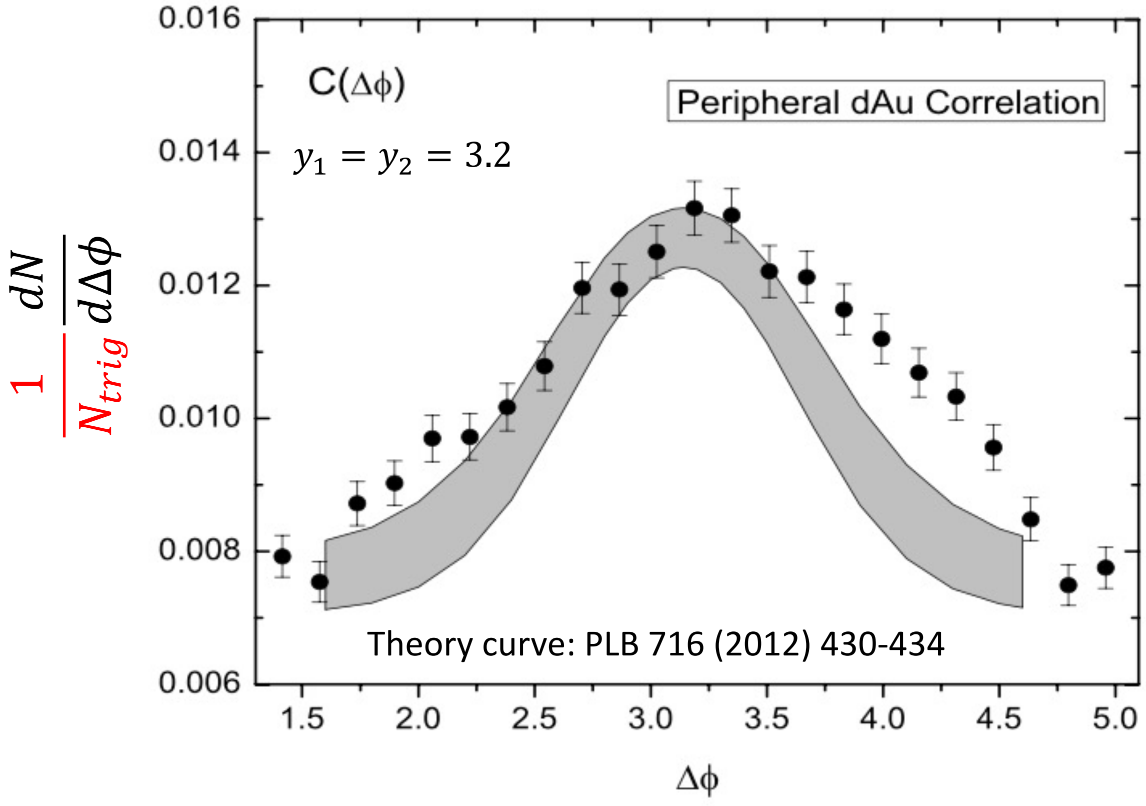


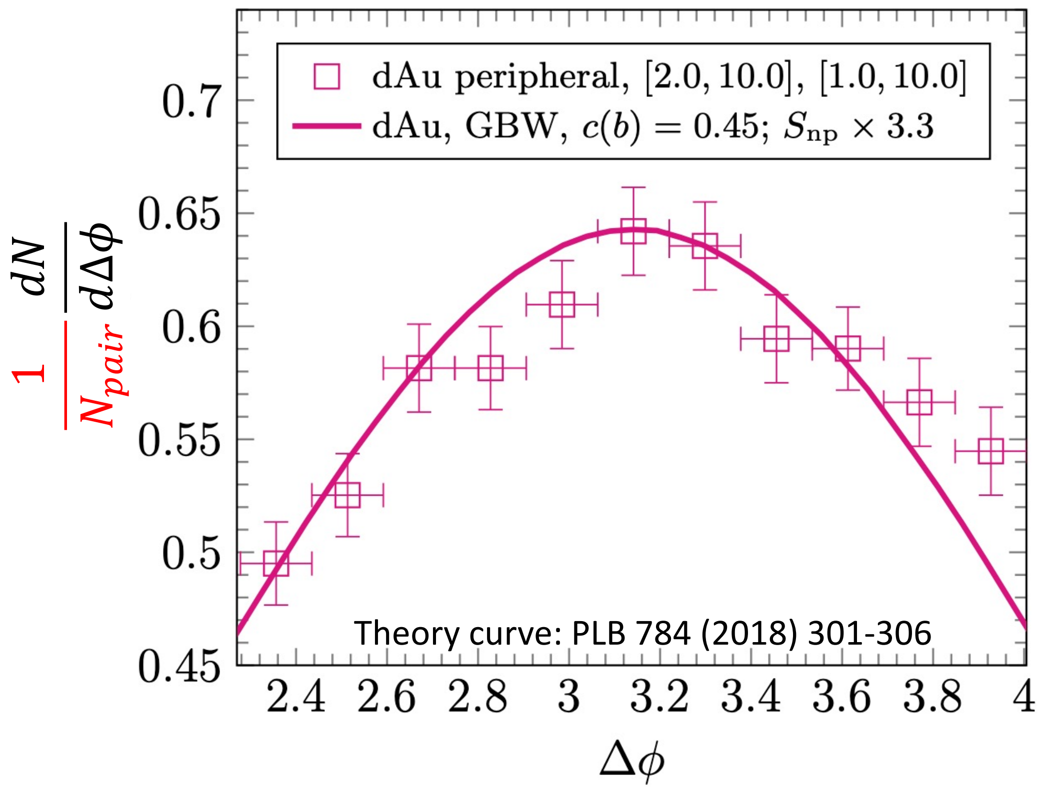
"J_{dAu} → 0.1 that "10 times suppression observed in central dAu" should be clarified

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

How to normalize?

Data: STAR preliminary, NPA 854, 168 (2011); Theory: A. Stasto et al., GBW model for CGC

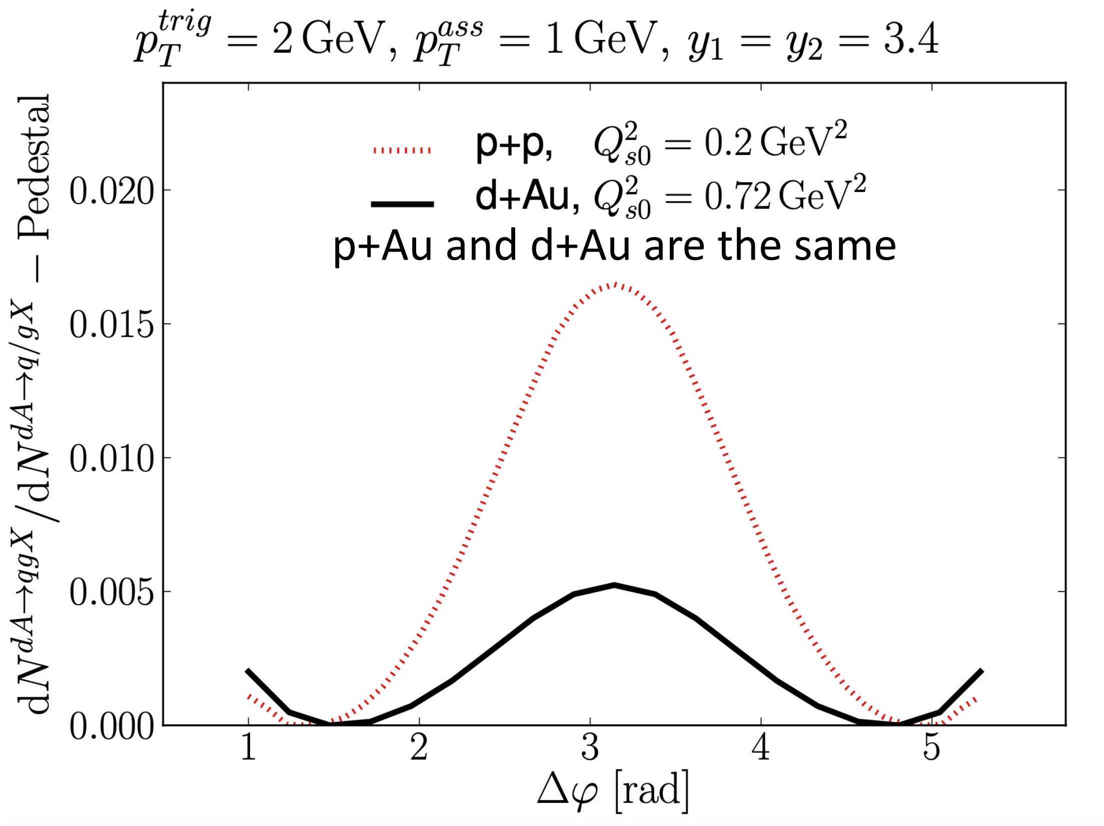


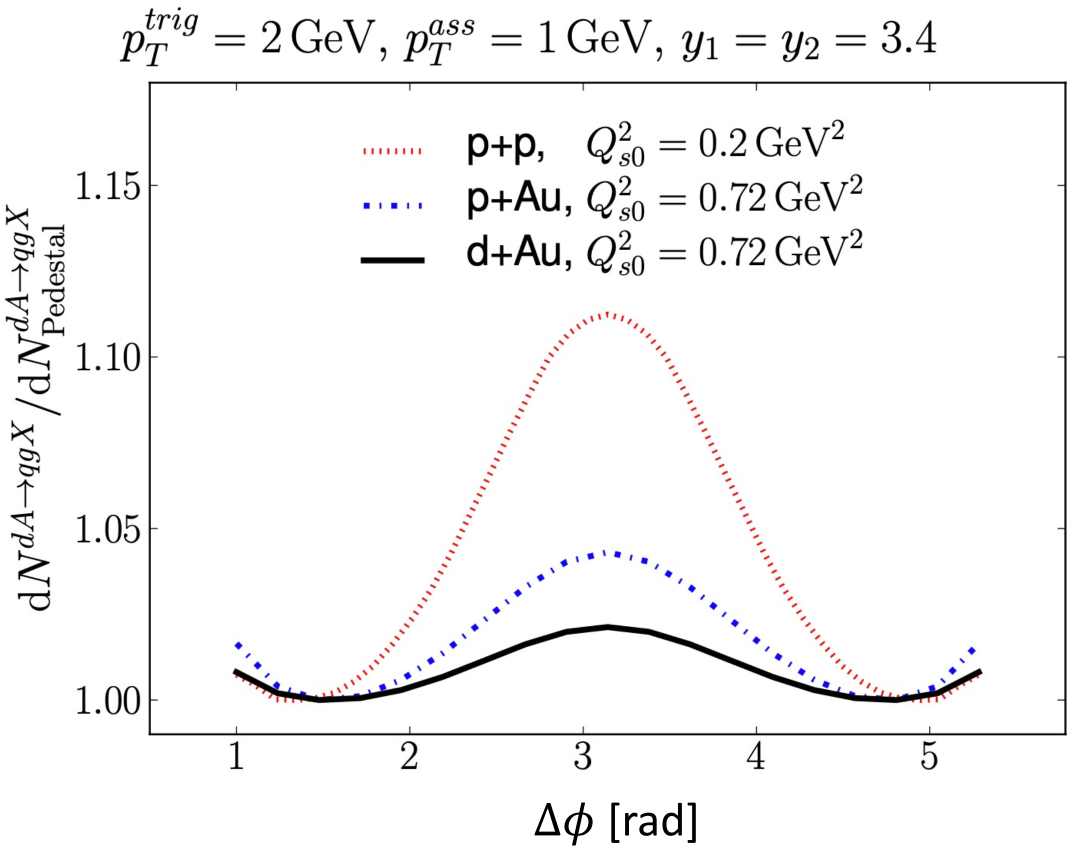


- CGC predictions based on GBW model with Sudakov effects included agrees with data better
- Two ways of normalization used: correlation function normalized by N_{trig} not N_{pair}
  - PLB 716 (2012) 430-434: normalized by N_{trig}, but issues found with p+p normalization
  - PLB 784 (2018) 301-306: normalized by N_{pair}, issues with p+p normalization fixed

How to normalize?

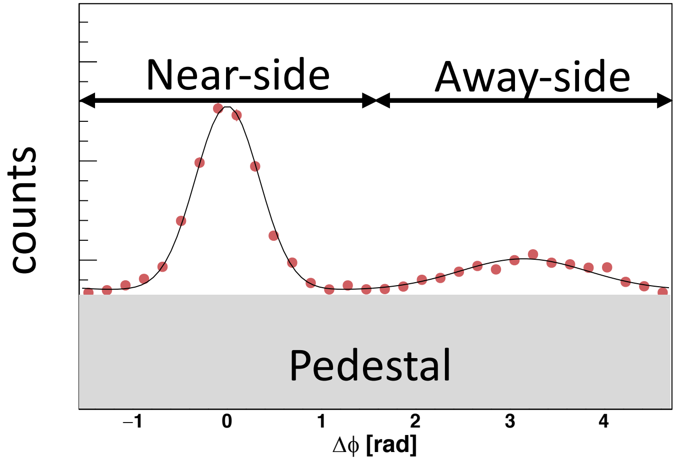
T. Lappi and H. Mantysaari, NPA 908 (2013) 51-72





- For the first time, the pedestal is predicted
- Independent scattering of two partons from the probe: $f^p_{q_1 q_2}(x_{q_1}, x_{q_2}) = f^p_{q_1}(x_{q_1})\, f^p_{q_2}(x_{q_2})$
- Two ways of normalizations : Left: $\frac{N_{pair}(\Delta\phi)}{N_{trig}}$ − pedestal; right: $\frac{N_{pair}(\Delta\phi)}{N_{pair\ from\ pedestal}}$

Normalize summary

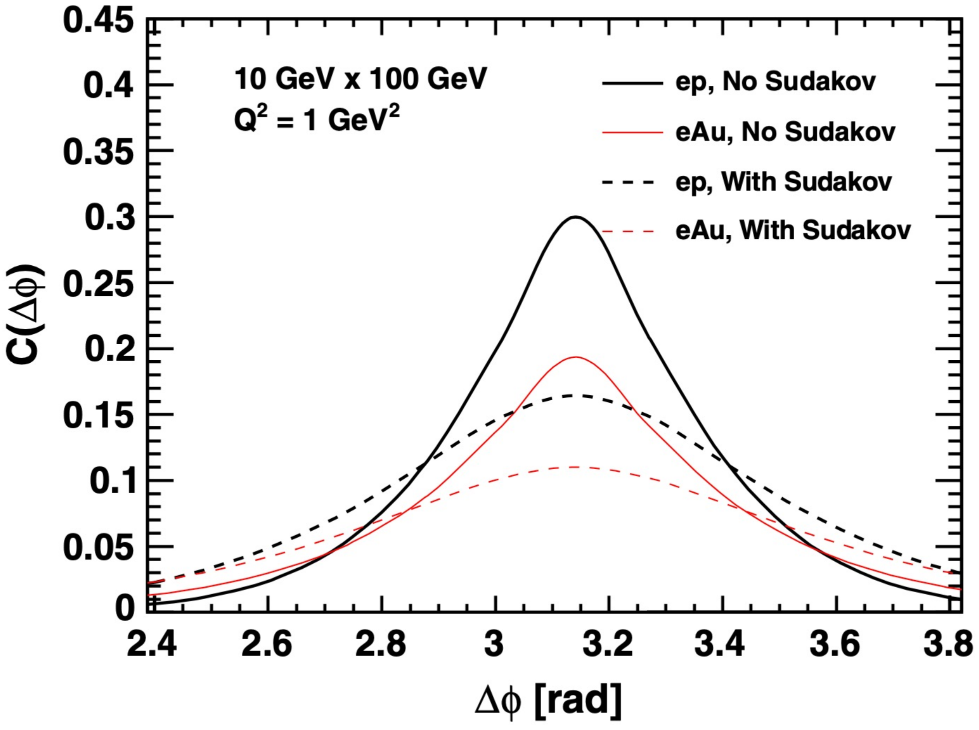


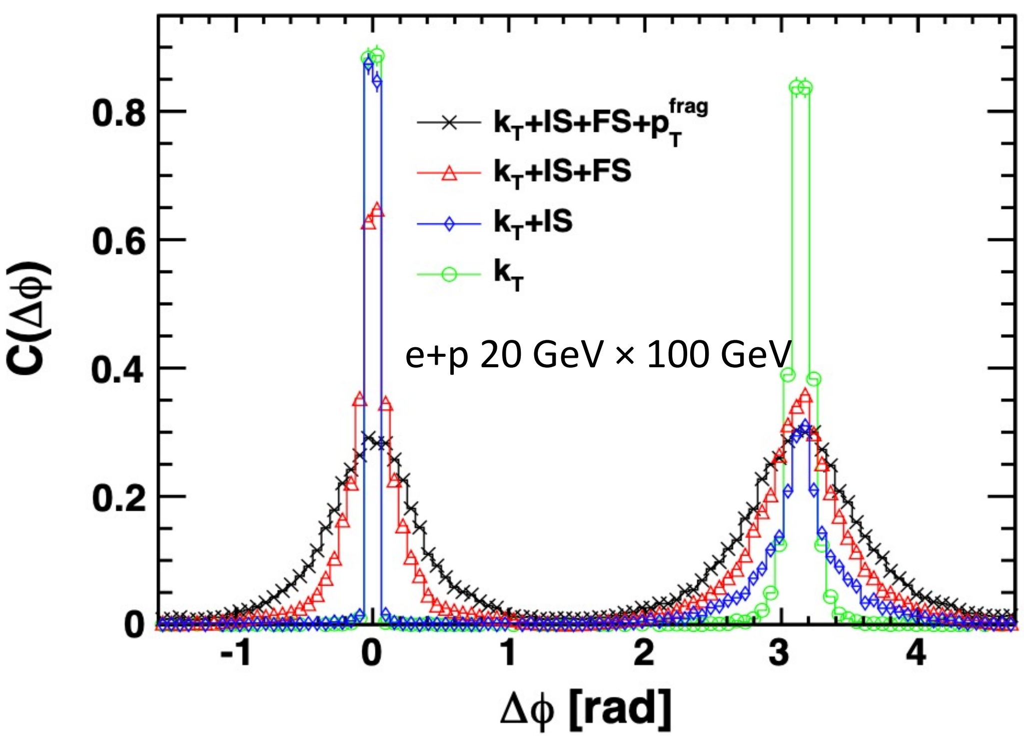
Experimental papers	Normalized by	Systems	Details
STAR	N_{trig}	p+p, p+Al, p+Au, d+Au	Compare area ratio
PHENIX	N_{trig}	p+p, d+Au	Compare area ratio×R_{dAu}

Prediction papers	Normalized by	Systems	Details
1. 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
2. PLB 716 (2012) 430-434	N_{trig}	p+p, d+Au	same as experiment, issue with p+p
3. PLB 784 (2018) 301-306	N_{pair}	p+p, p+Au, d+Au	N_{pair} for back-to-back region: $\frac{1}{2}\pi < \Delta\phi < \frac{3}{2}\pi$
4. 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
5. PRL 105, 162301 (2010)	N_{trig}	p+p, d+Au	same as experiment
6. PRD 99, 014002 (2019)	N_{trig}	p+p, p+Au, d+Au	same as experiment, used to compare with STAR data

Future measurement at EIC

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





- Away side suppression is a combination of Sudakov (no nuclear dependence) and saturation effects?
- Sudakov effect can be estimated from the suppression at non-saturated region
- Away-side peak mainly affected by initial state parton shower (IS)
- Near-side peak mainly affected by final state parton shower (FS) and fragmentation p_T

Conclusion for theory

- Detailed signatures with back-to-back di-hadron correlation measurement from theory:
  - Suppression can be a consequence of both initial- and final-state effects
  - Initial effect → CGC: A, E.A./centrality, p_T, and rapidity dependence predicted
  - Efforts needed to determine an observable correlated best with b for small systems
  - DPS in d+Au: both pedestal and correlation affected?

Conclusion for STAR

- Detailed signatures with back-to-back di-hadron correlation measurement from theory:
  - Suppression can be a consequence of both initial- and final-state effects
  - Initial effect → CGC: A, E.A./centrality, p_T, and rapidity dependence predicted
  - Efforts needed to determine an observable correlated best with b for small systems
  - DPS in d+Au: both pedestal and correlation affected?

- p+p, p+Al, and p+Au results from STAR: A, E.A./centrality, p_T, and rapidity dependence observed
- d+Au results from STAR: Challenging to conclude
  - For nonlinear gluon dynamics: high background correlation not fully understood; favors for cleaner p+Au collisions
  - For DPS physics: favors for di-charged hadron correlation in p+p, p+A, and d+A

Clarifications

- Detailed signatures with back-to-back di-hadron correlation measurement from theory:
  - Suppression can be a consequence of both initial- and final-state effects
  - Initial effect → CGC: A, E.A./centrality, p_T, and rapidity dependence predicted
  - Efforts needed to determine an observable correlated best with b for small systems
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- Uniform normalization needed
- Background contribution cannot be ignored from the data, be careful with predictions based on the results in d+Au collisions

Outlook

- Detailed signatures with back-to-back di-hadron correlation measurement from theory:
  - Suppression can be a consequence of both initial- and final-state effects
  - Initial effect → CGC: A, E.A./centrality, p_T, and rapidity dependence predicted
  - Efforts needed to determine an observable correlated best with b for small systems
  - DPS in d+Au: both pedestal and correlation affected?

- p+p, p+Al, and p+Au results from STAR: A, E.A./centrality, p_T, and rapidity dependence observed
- d+Au results from STAR: Challenging to conclude
  - For nonlinear gluon dynamics: high background correlation not fully understood; favors for cleaner p+Au collisions
  - For DPS physics: favors for di-charged hadron correlation in p+p, p+A, and d+A

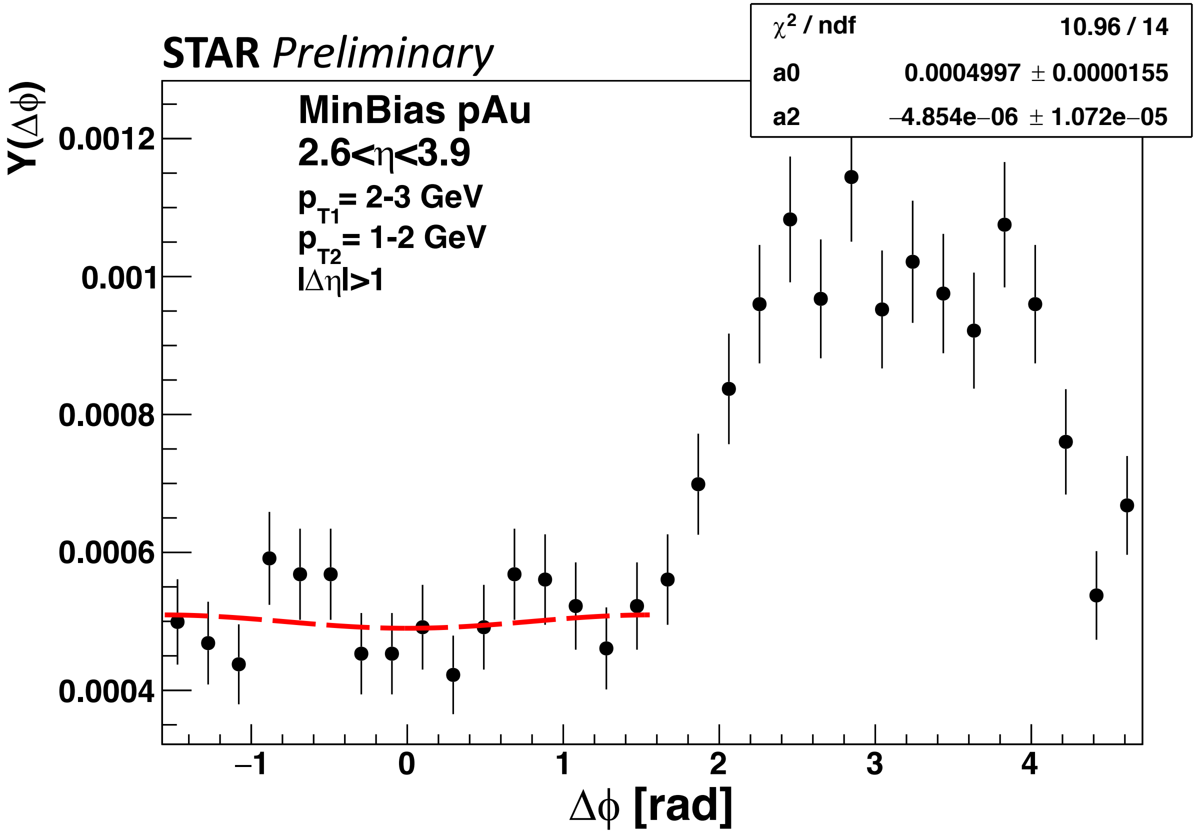
- Uniform normalization needed
- Background contribution cannot be ignored from the data, be careful with predictions based on the results in d+Au collisions

- Di-charged hadron correlation with STAR Froward Upgrade and EIC:
  - Away-side peak: background correlation controllable → probe DPS physics?
  - Near-side peak can be studied: separation of IS, FS and fragmentation p_T?

Back up

Flow-like correlation

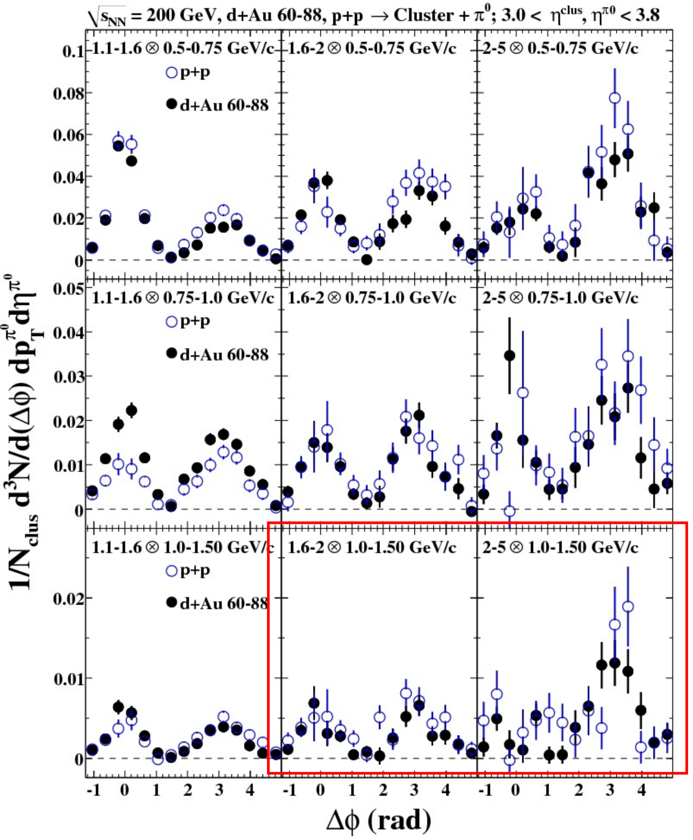
Fit function: Y(Δϕ) = a0 + 2*a2 cos(2Δϕ)



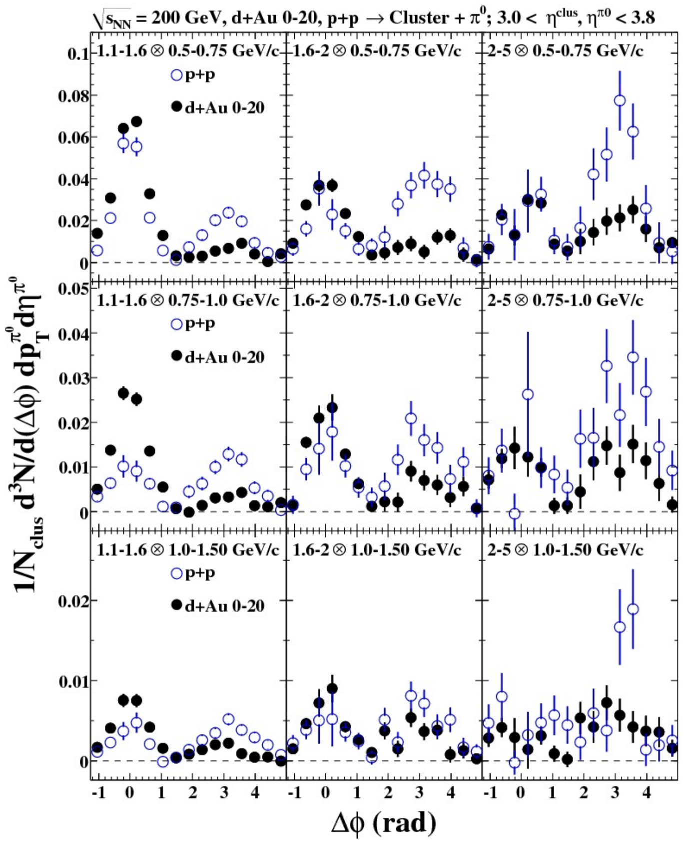
- Flow signal from near side is negligible for the current measurement
- π^0s at FMS have very high energy; hard to require those two π^0s not come from the same jet
- Due to limited rapidity coverage of FMS, it's challenging to accurately estimate long range correlation. Even if there is flow,
  → makes suppression stronger
- Saturation stays after flow-like correlation subtraction in pPt at LHCb (Nuclear Physics A 00 (2018) 1–4)

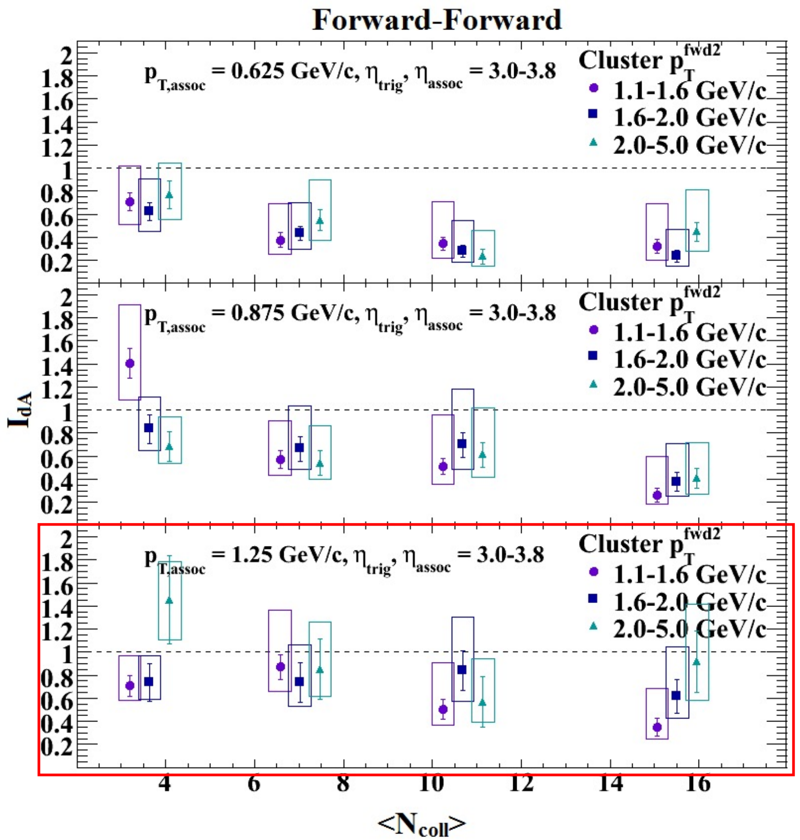
PHENIX data

dAu peripheral



dAu central





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PhD thesis for the paper

- PHENIX MPC (Muon Piston Cal) data: forward cluster-pi0 correlation, 3.0<eta<3.8, the highest pt bin is the lowest pt bin at STAR
- I_{dA} is the area ratio of the away side correlation in dAu over pp, the same observable as STAR
- In the highest pt bin: dAu = pp, no suppression is observed, no centrality dependence either