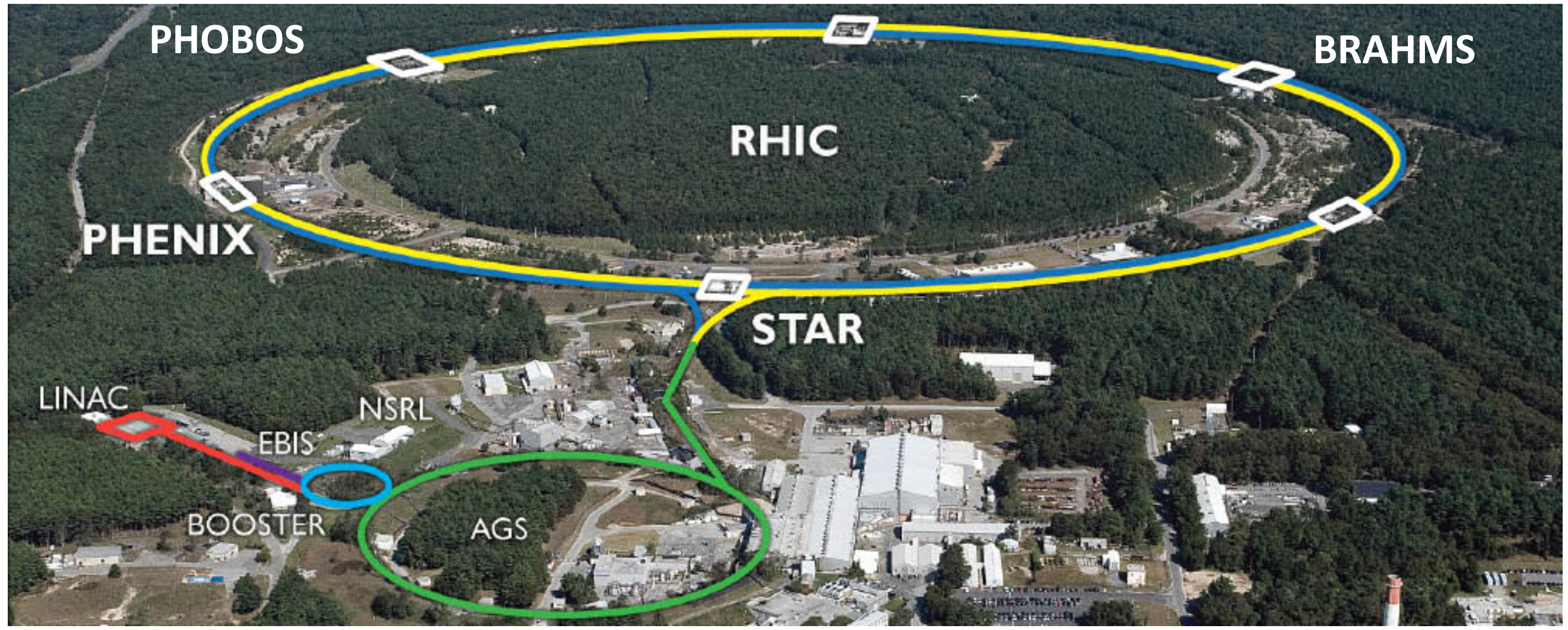
Effects of non-linear gluon dynamics at RHIC

Audrey Francisco
CEA-Saclay IRFU
17 Novembre 2022

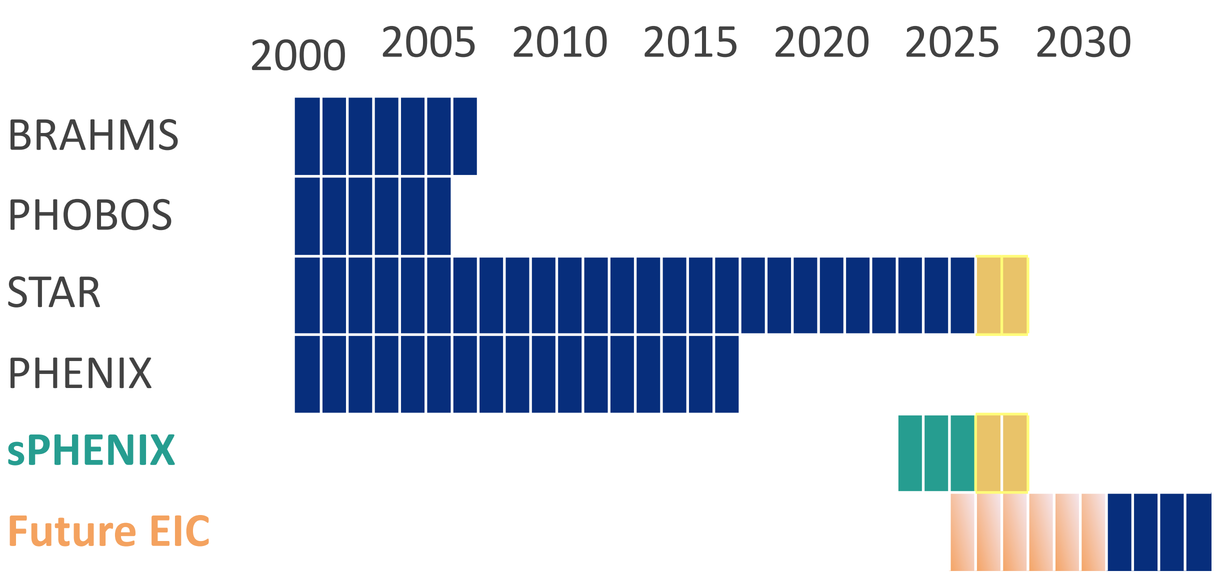
Material largely copied from Xiaoxuan Chu (BNL)

Experiments at RHIC

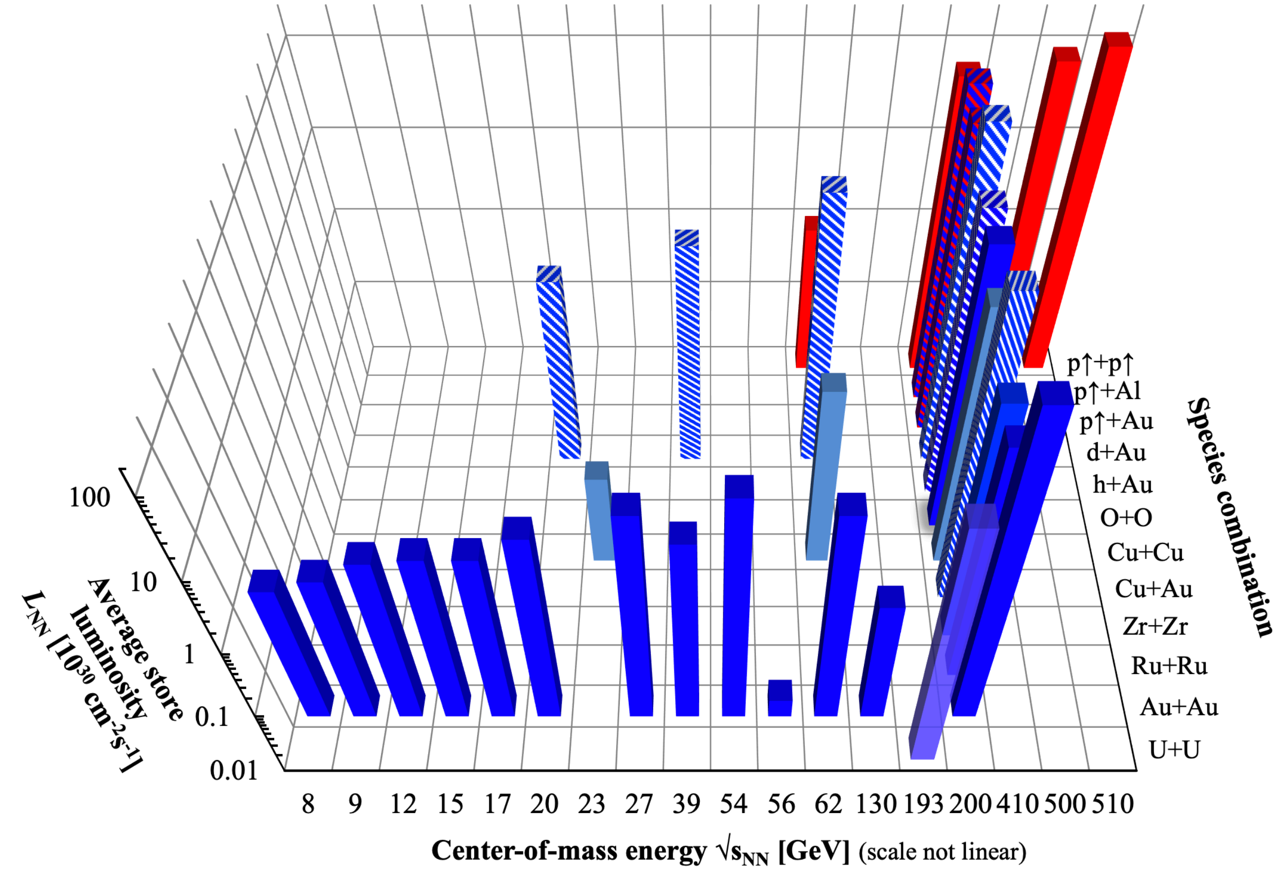
Relativistic Heavy Ion Collider



Data taking

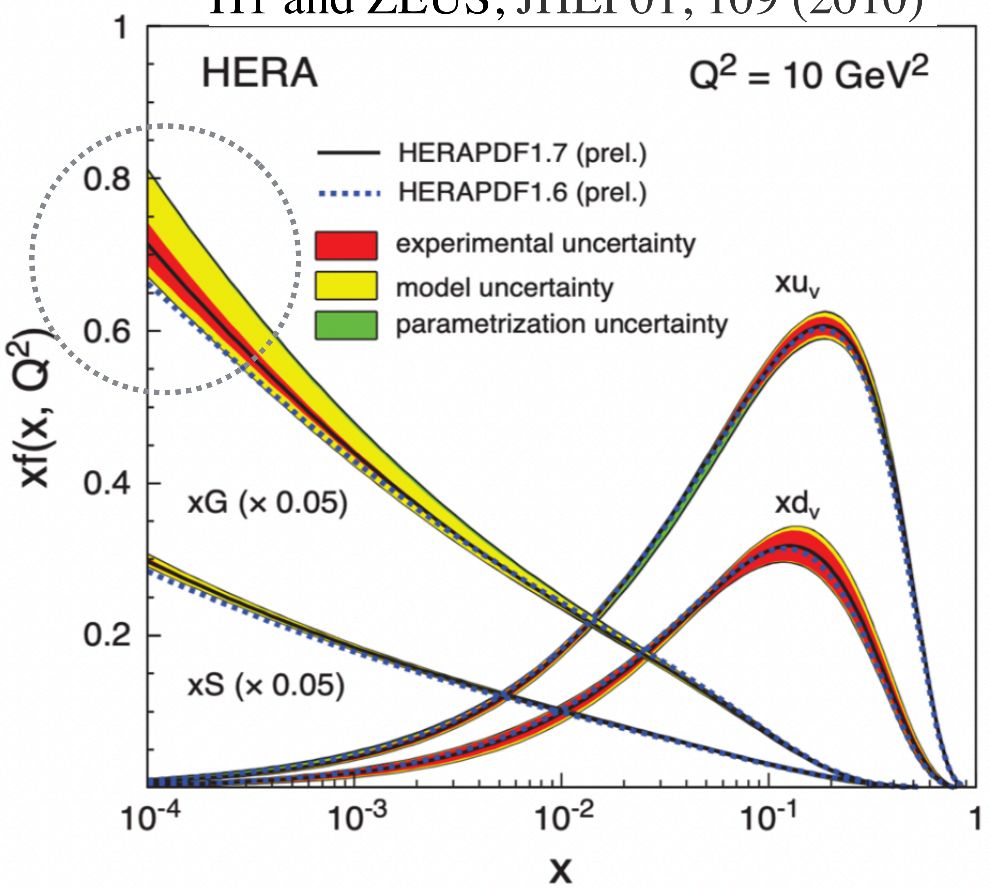


RHIC energies, species combinations and luminosities (Run-1 to 22)



Gluon saturation at low x

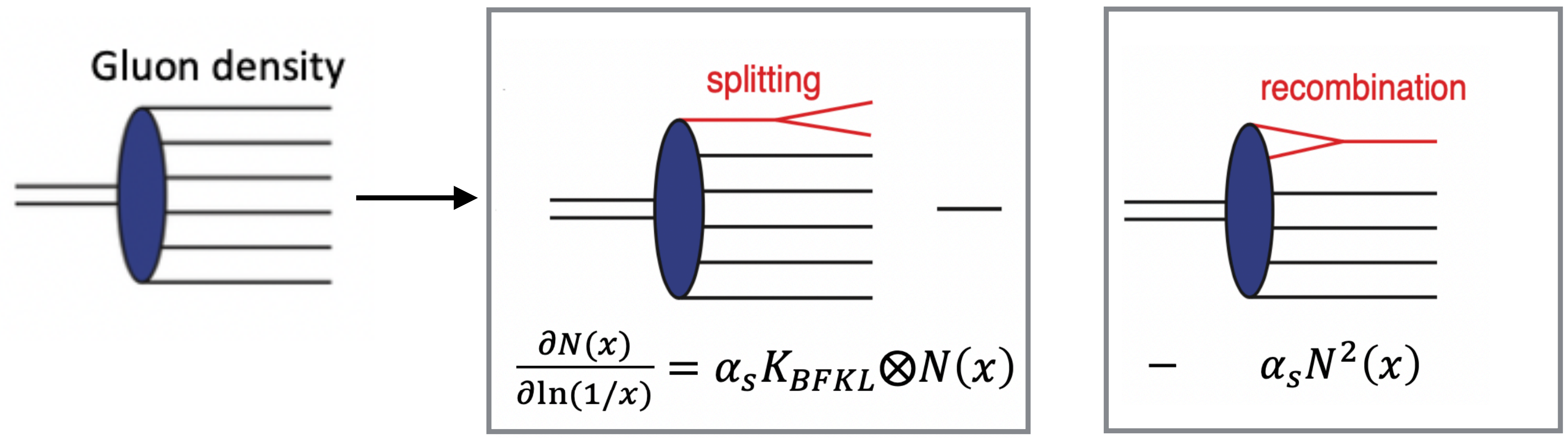
H1 and ZEUS, JHEP01, 109 (2010)



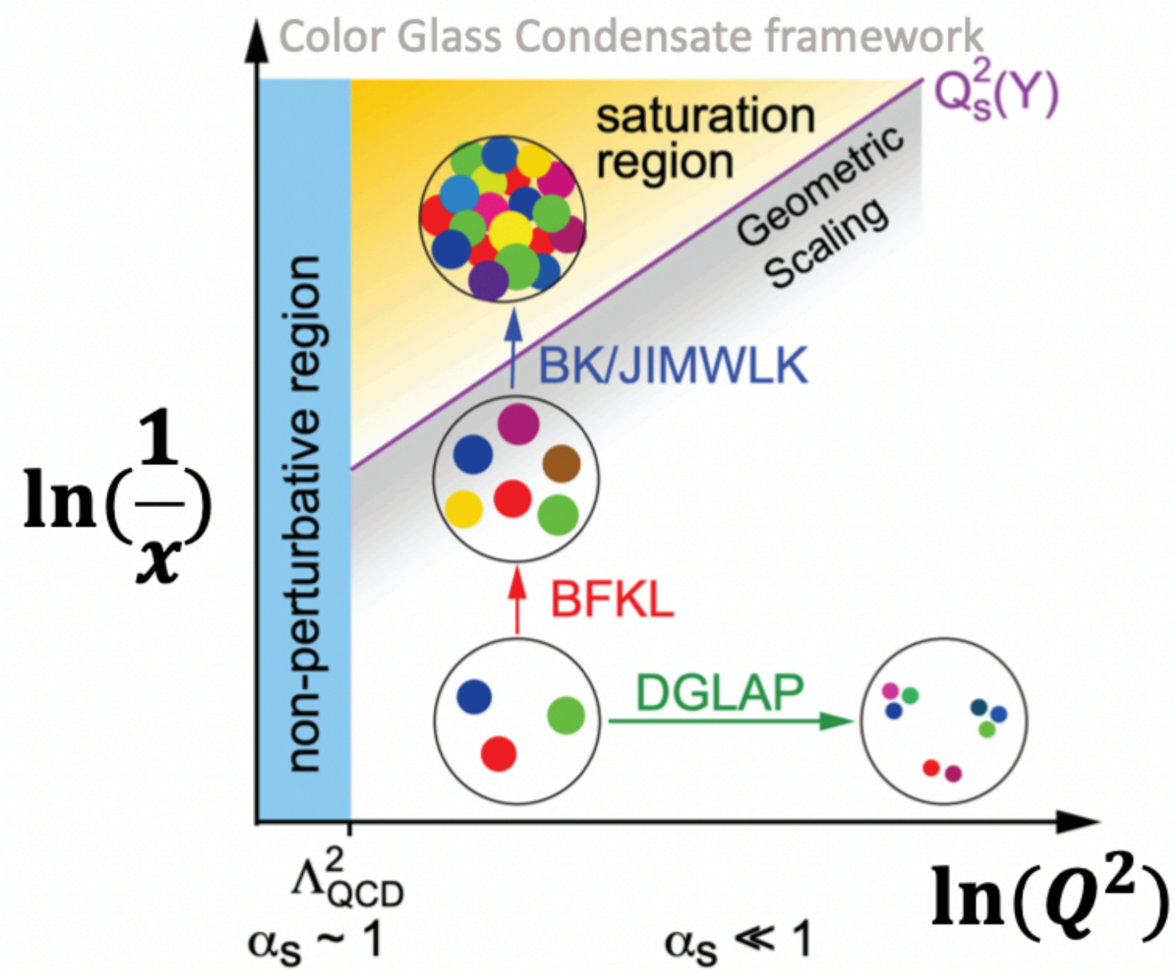
Parton **D**istribution **F**unctions:

Rapid increase of gluon density through gluon splitting…

…tamped by gluon recombination

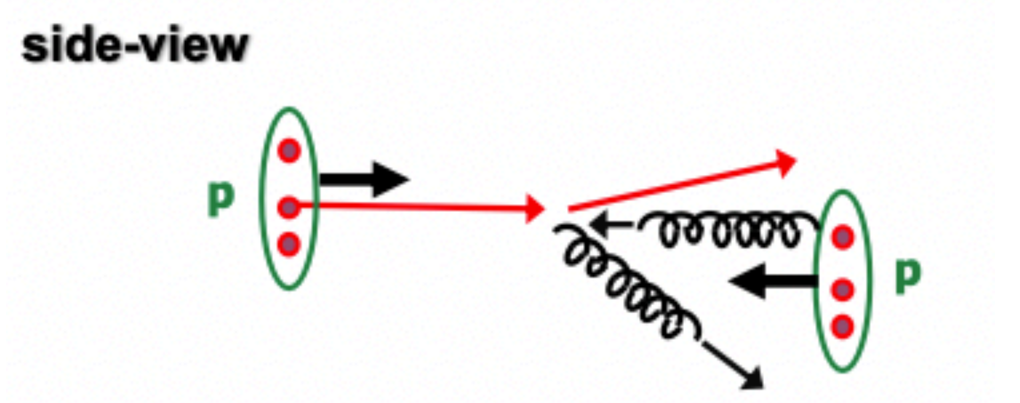


linear evolution *non-linear evolution*

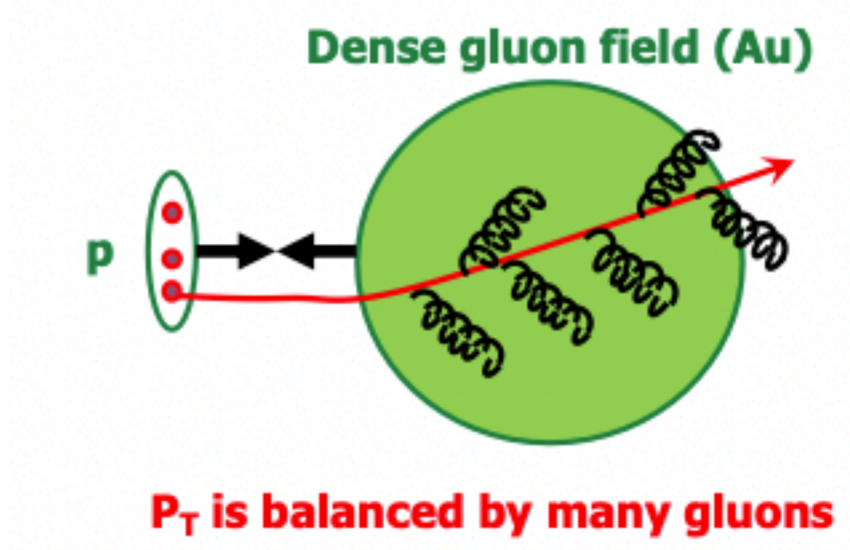


- **Saturation scale Q_s^2:** ***balance between gluon splitting and recombination ($Q^2 < Q_s^2$)***
- **Transition from linear to non-linear gluon dynamics**

Probes of saturation



$$x_A = \frac{p_{T1}\, e^{-y_1} + p_{T2} e^{-y_2}}{\sqrt{s}} \ll x_p = \frac{p_{T1}\, e^{y_1} + p_{T2} e^{y_2}}{\sqrt{s}}$$



Forward p-A collisions:
High-x quark from p interacting with a low-x gluon from A

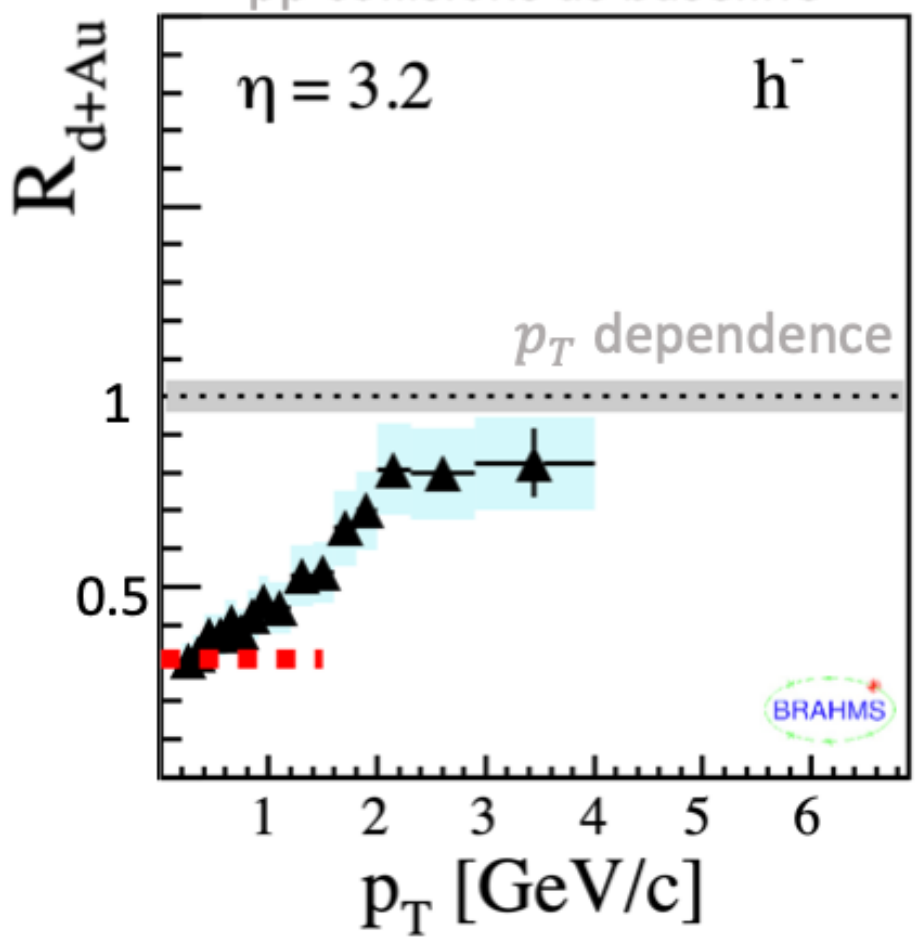
- Suppression of inclusive hadron yields in p(d)+A relative to p+p by gluon saturation effects

Probes of saturation (inclusive)

Suppression of inclusive charged hadrons with BRAHMS

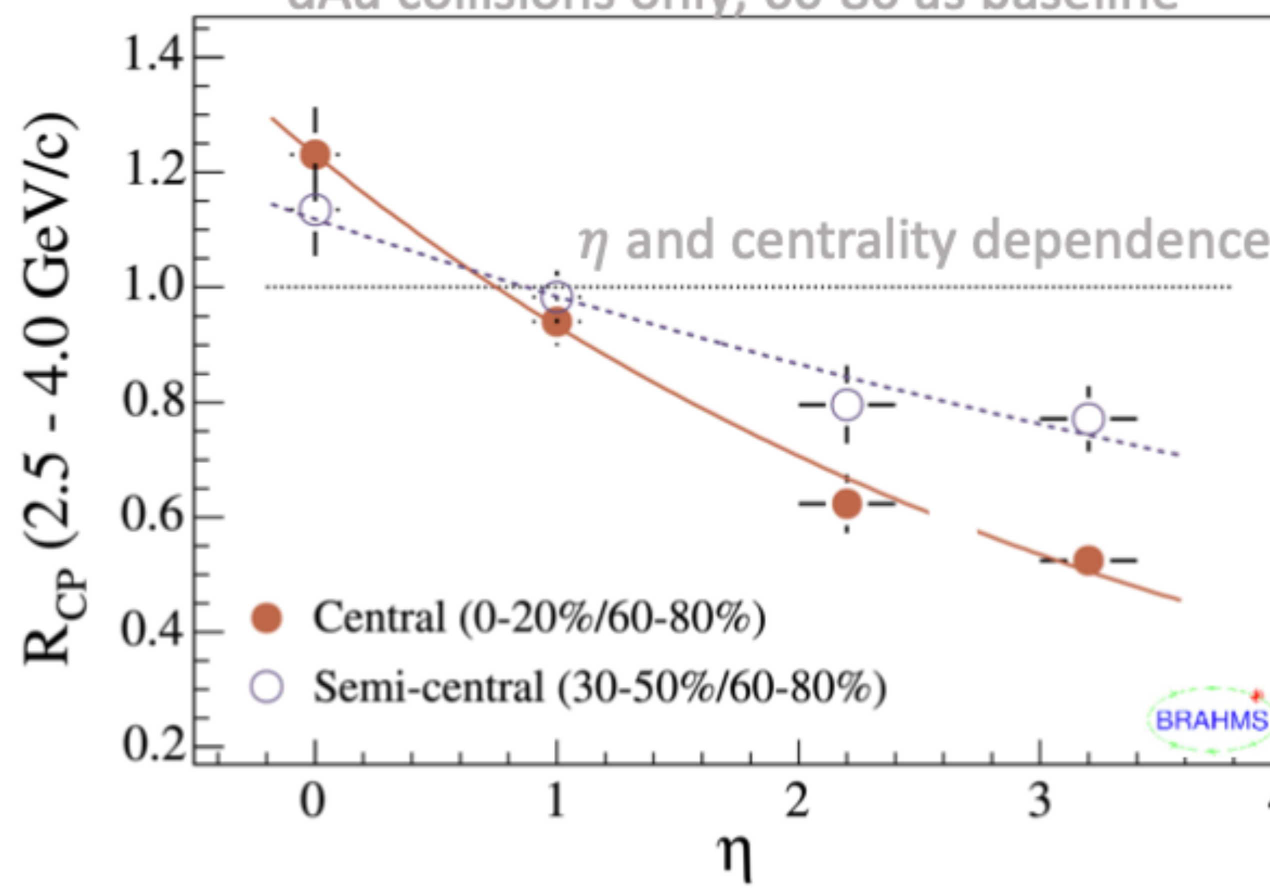
$$R_{d+Au} = \frac{d^2N^{dAu}/dp_T d\eta}{\langle N_{coll}\rangle d^2N^{pp}/dp_T d\eta}$$

pp collisions as baseline



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

dAu collisions only; 60-80 as baseline

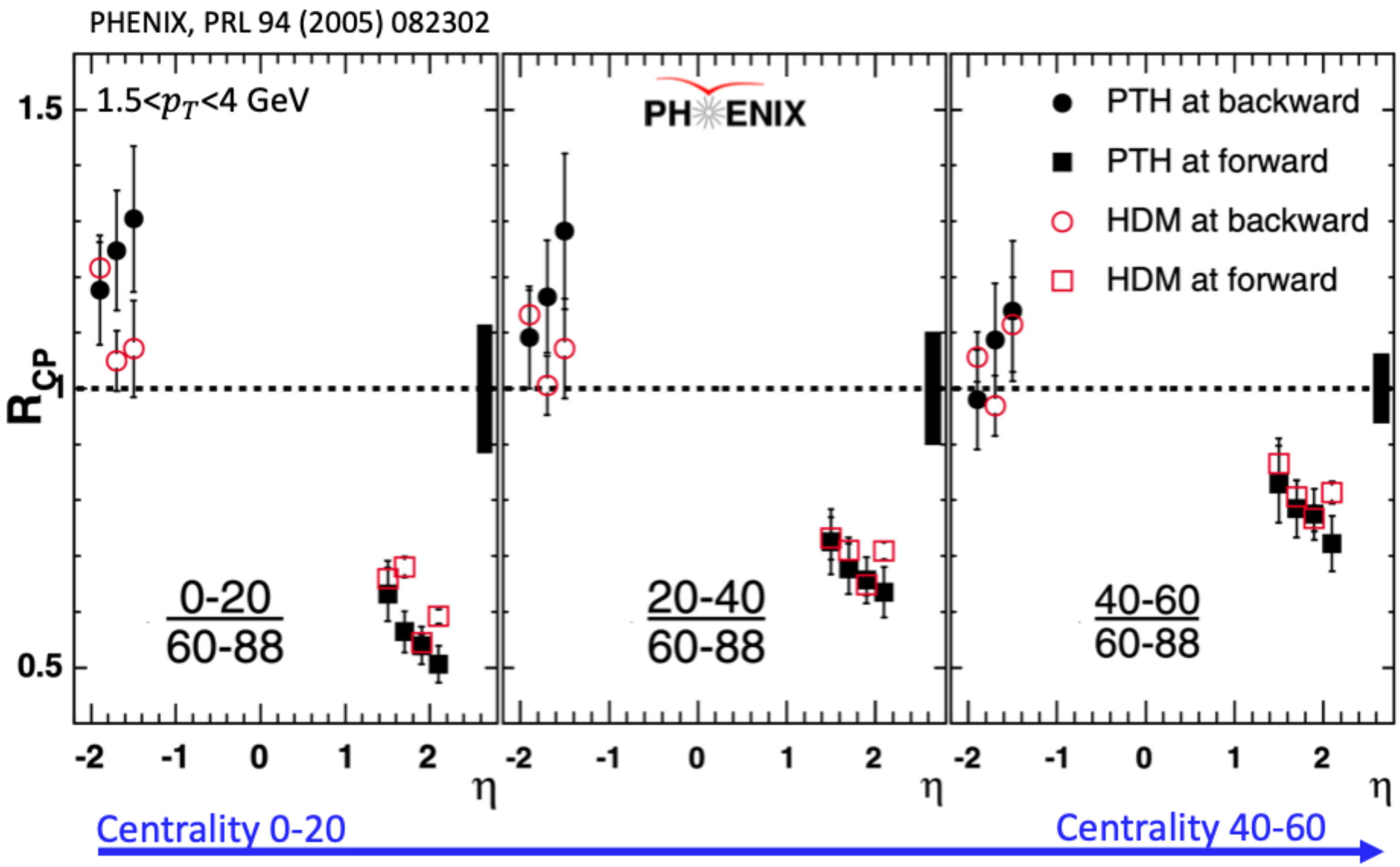


BRAHMS, PRL 93 (2004) 242303

- R_{dAu} <1 below 2GeV/*c* and decreases with η
- "Such effects are consistent with the onset of saturation in the Au nuclei gluon density at small x values which modifies the shapes and magnitudes of the R_{dAu} and R_{cp} ratios at all transverse momenta."

Probes of saturation (inclusive)

Suppression of inclusive charged hadrons with PHENIX



dAu collisions √s=200GeV

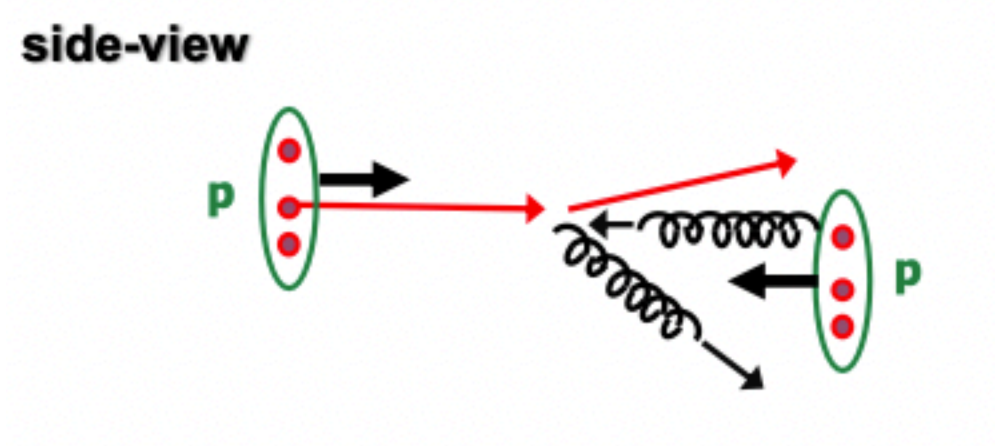
Backward → Forward

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

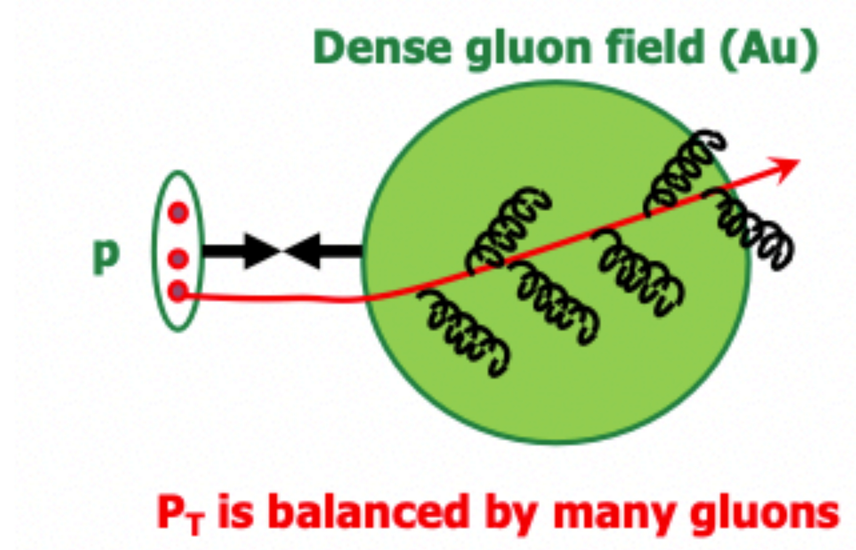
*PHT: punch through hadron
*HDM: hadron decay meson

- R_{CP} decreases with η and in central collisions
- “The forward rapidity suppression is in qualitative agreement with the expectation of shadowing and saturation effects in the small x region in the gold nucleus.”

Probes of saturation



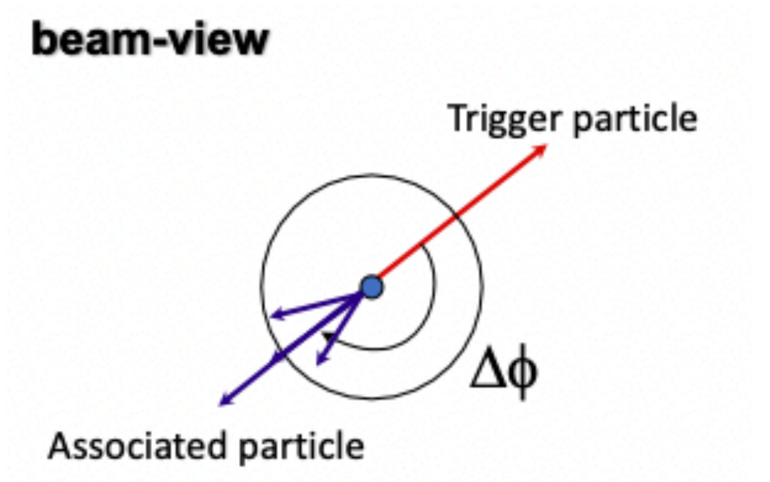
$$x_A = \frac{p_{T1}\,e^{-y_1} + p_{T2}e^{-y_2}}{\sqrt{s}} \ll x_p = \frac{p_{T1}\,e^{y_1} + p_{T2}e^{y_2}}{\sqrt{s}}$$



Forward p-A collisions:
High-x quark from p interacting with a low-x gluon from A

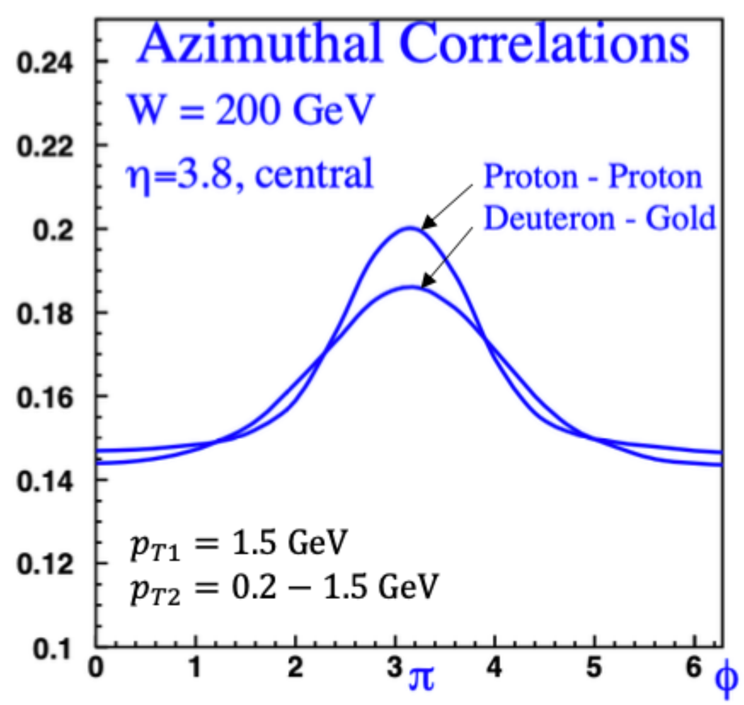
- Suppression of inclusive hadron yields in p(d)+A relative to p+p by gluon saturation effects

- Suppression of di-hadron correlations (D. Kharzeev, E. Levin and L. McLerran from NPA 748 (2005) 627-640)



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

Azimuthal correlations between 2 final hadrons in pp and pA



pp: 2 back-to-back particles

pA collisions : multiple interactions with the gluons in the nuclei

→ smearing of the away-side

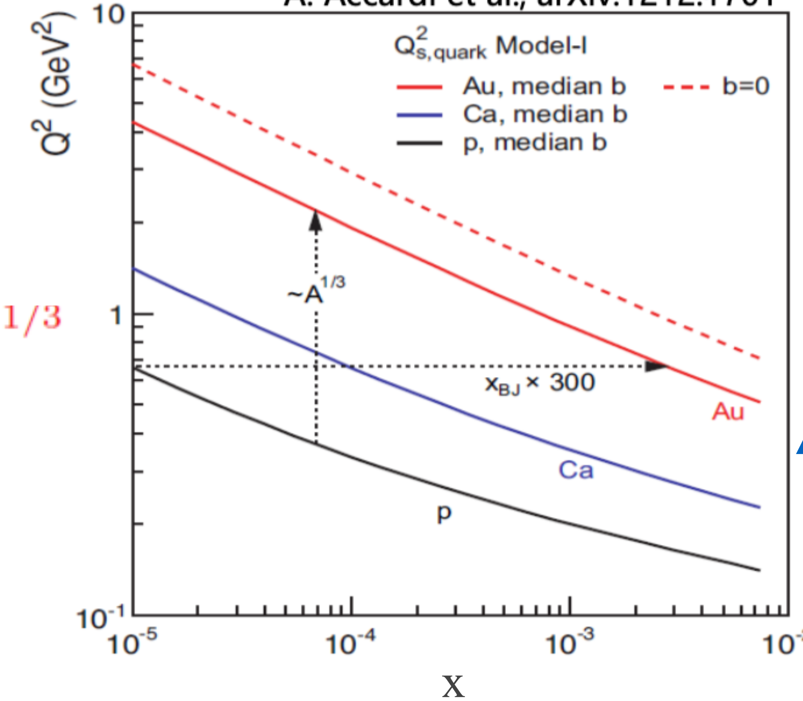
CGC predictions : suppression + broadening (not observed)

Reaching the saturation regime

- **Large Q_s^2**

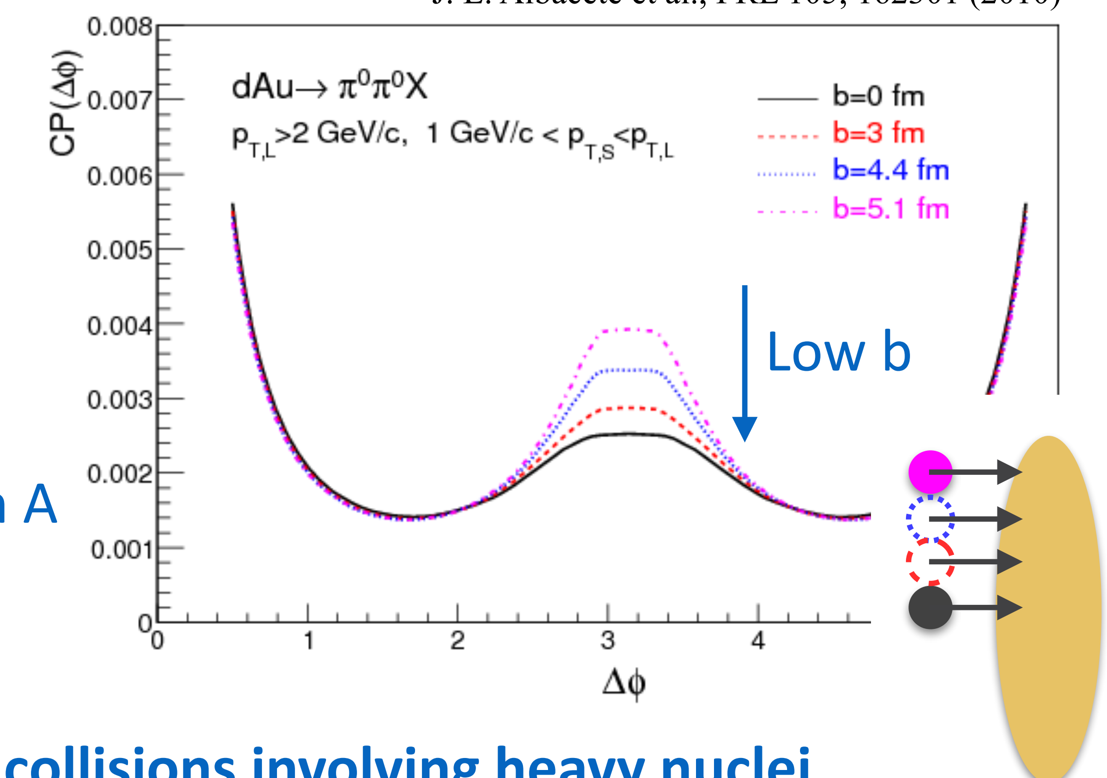
$$Q_s^2(x) \sim A^{1/3}\left(\frac{1}{x}\right)^{\lambda} \sim \left(\frac{A}{x}\right)^{1/3}$$

A. Accardi et al., arXiv:1212.1701



High A

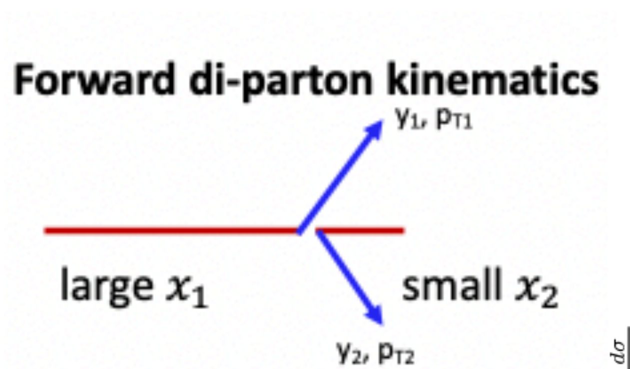
J. L. Albacete et al., PRL 105, 162301 (2010)



Low b

- **Low x**

→ **Easier to reach in central collisions involving heavy nuclei**

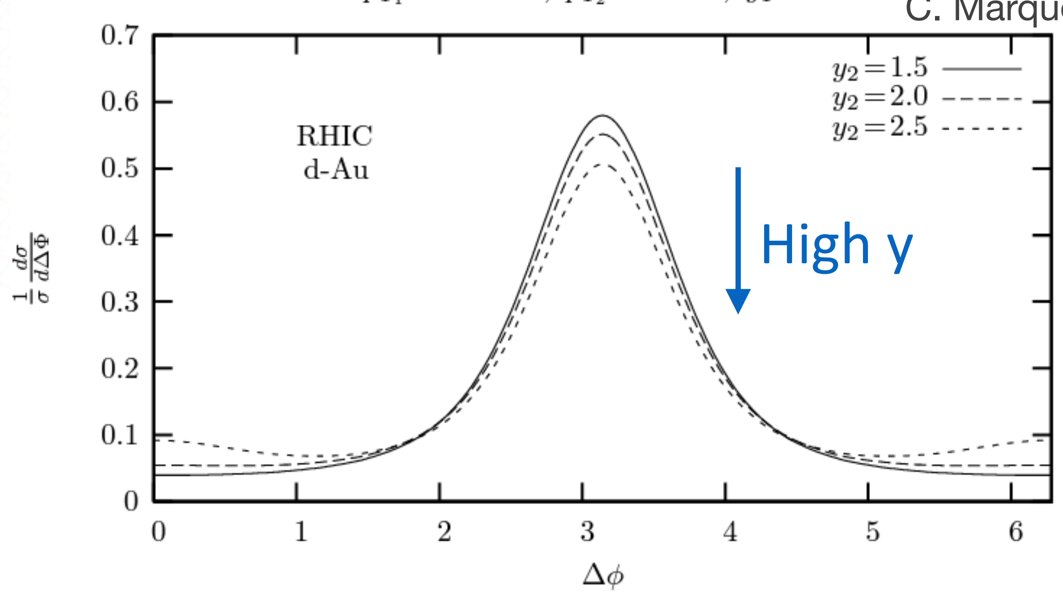


$$x_2 \sim \frac{p_{T1}e^{-y_1} + p_{T2}e^{-y_2}}{\sqrt{s}}$$

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

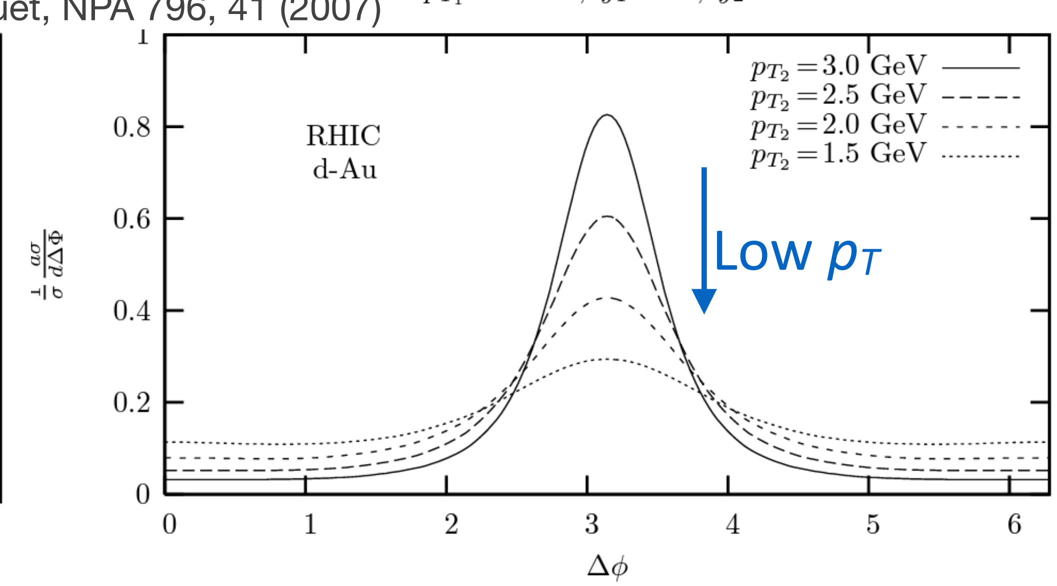
C. Marquet, NPA 796, 41 (2007)

$p_{T_1} = 3.5$ GeV, $p_{T_2} = 2$ GeV, $y_1 = 3.5$



High y

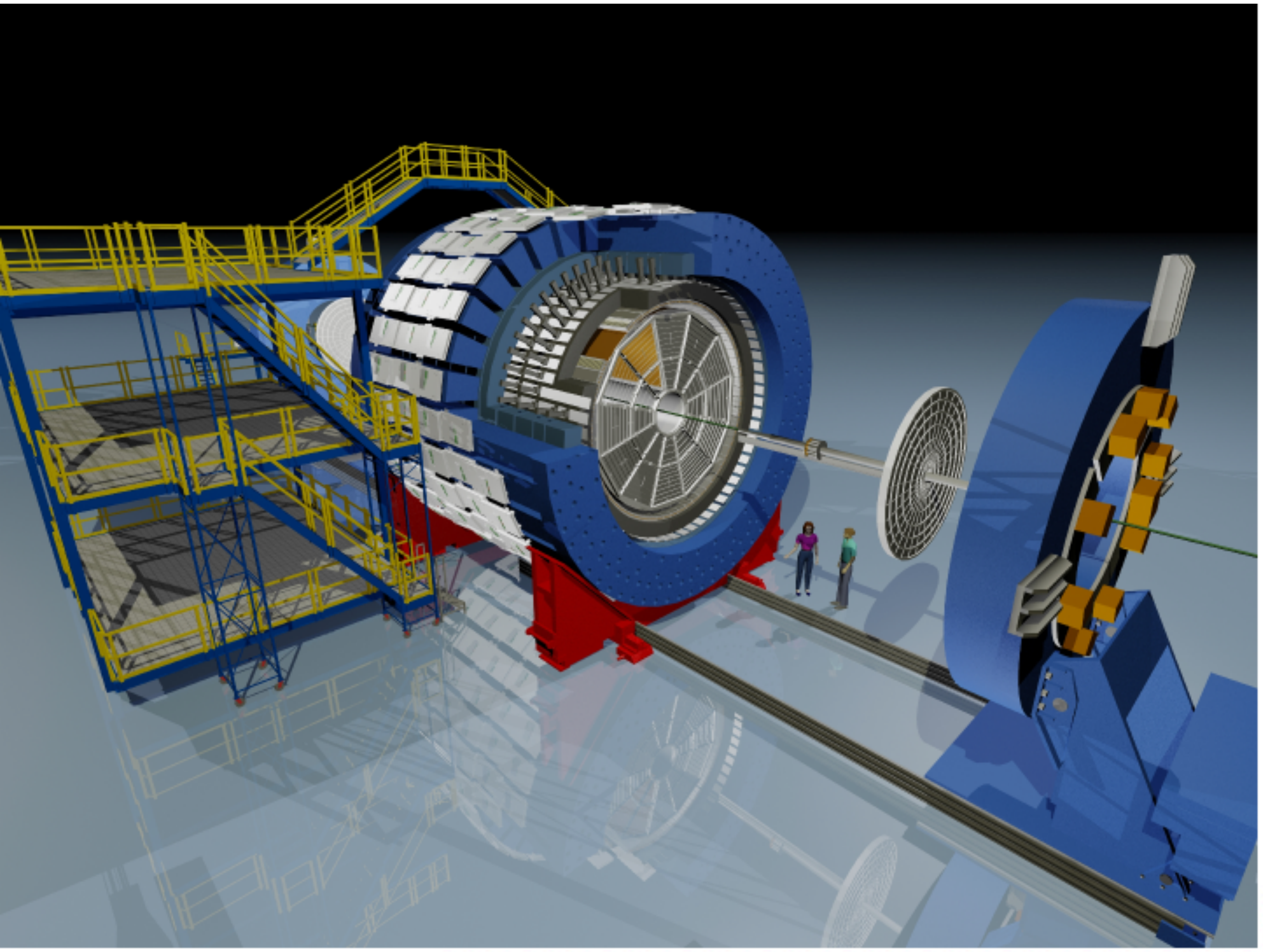
$p_{T_1} = 5$ GeV, $y_1 = 3.5$, $y_2 = 2$



Low p_T

→ **Low-p_T and forward measurements**

The Solenoid Tracker At RHIC



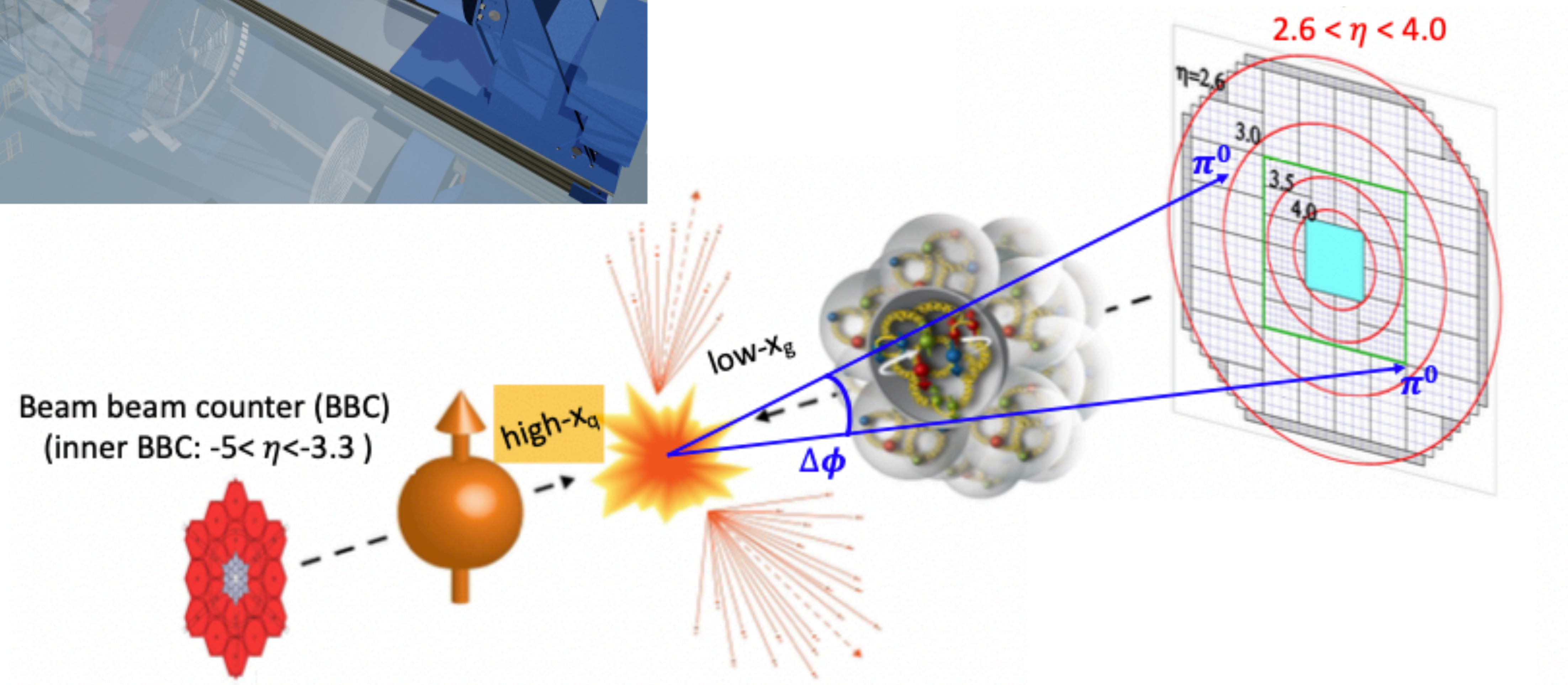
p+p, p+Al, p+Au and d+Au collisions at √sNN = 200 GeV

NN→$\pi 0$ +$\pi 0$ +X

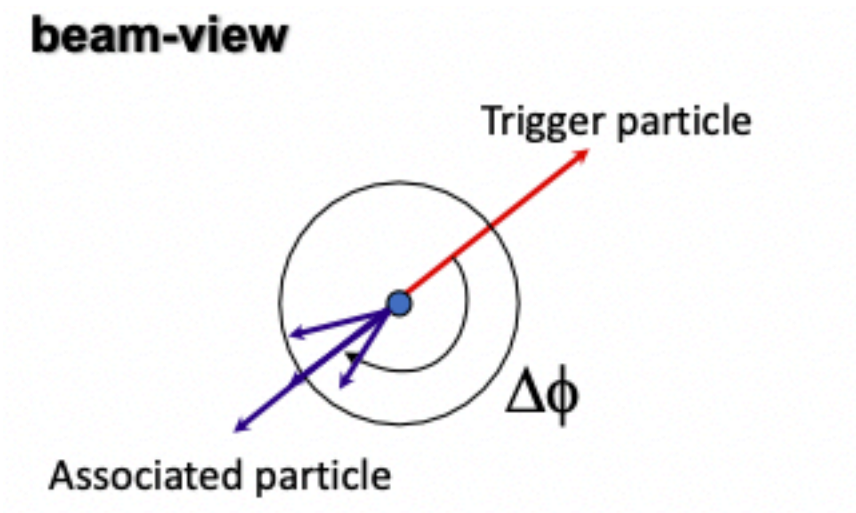
$\pi 0$ detected by FMS

Event activity measured with BBC

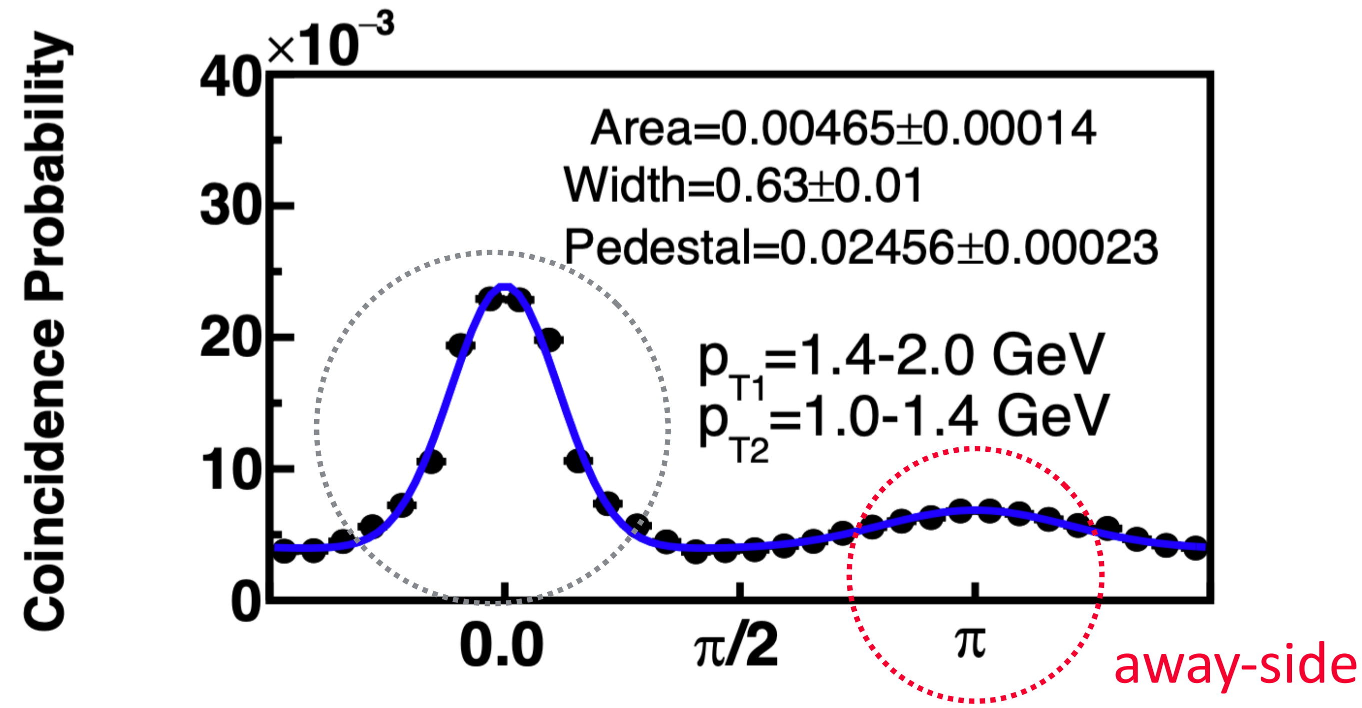
The Forward Meson Spectrometer



Di-π^0 correlations with STAR



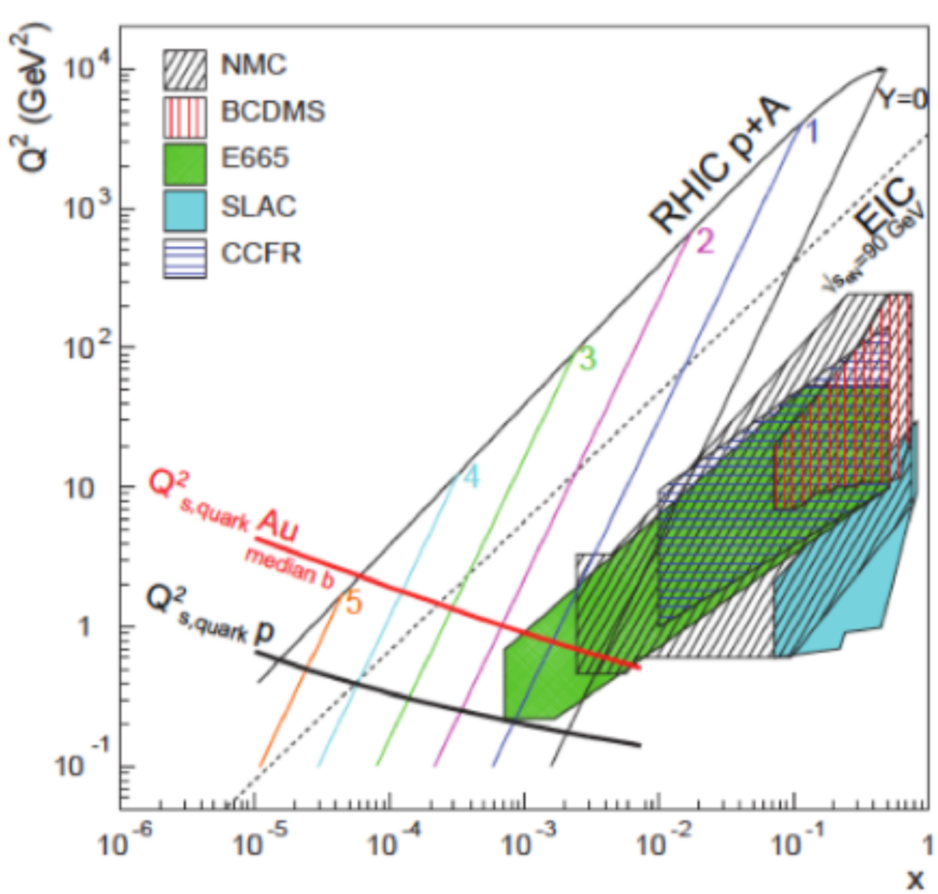
$$C(\Delta\phi) = \frac{N_{pair}(\Delta\phi)}{N_{trig} \times \Delta\phi}$$



Fit function:

$\Delta\phi = 0$ $\quad\quad$ $\Delta\phi = \pi$

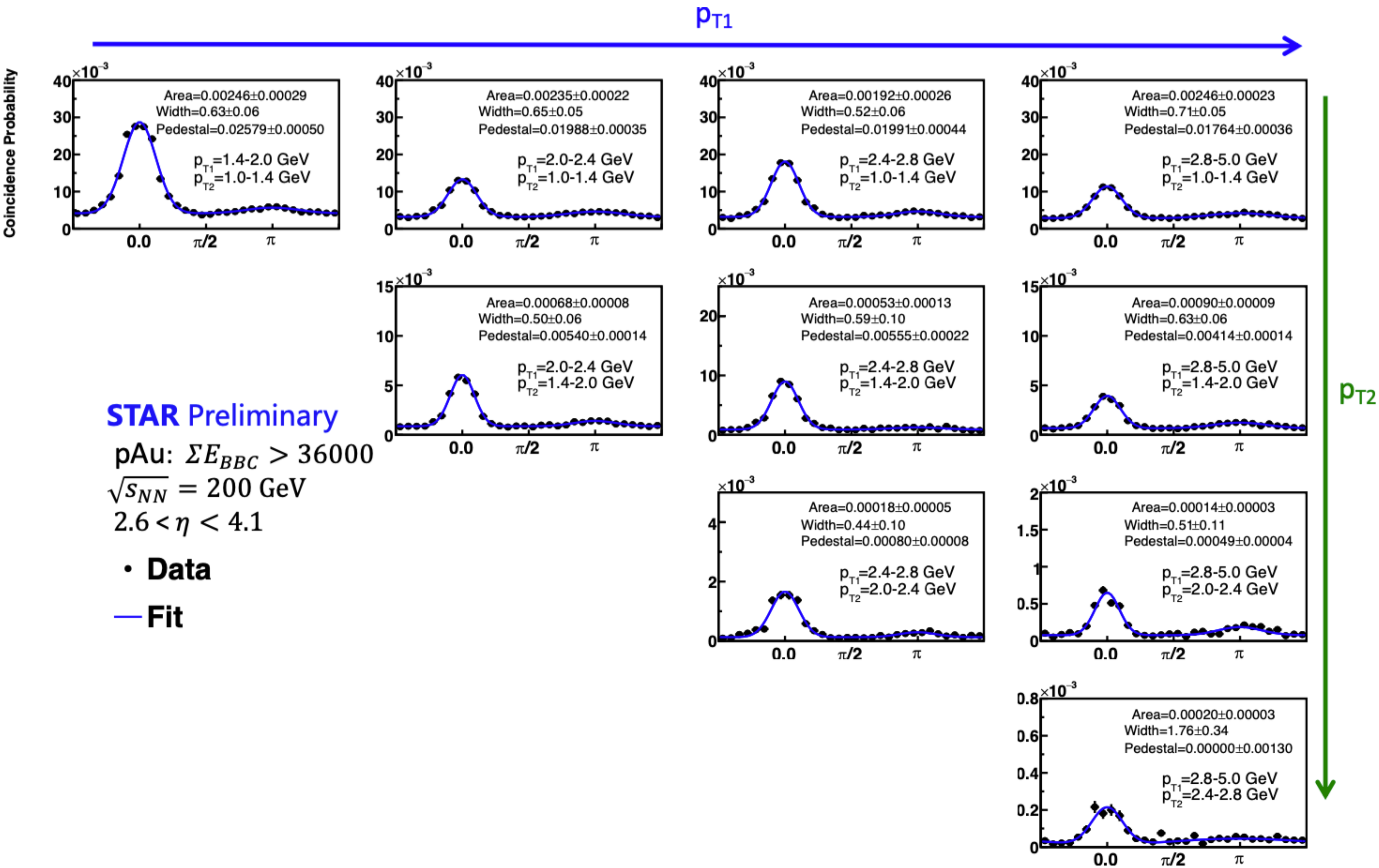
Pedestal/2π + Gaussian + Gaussian (Area and width)



Play with x and Q_S^2

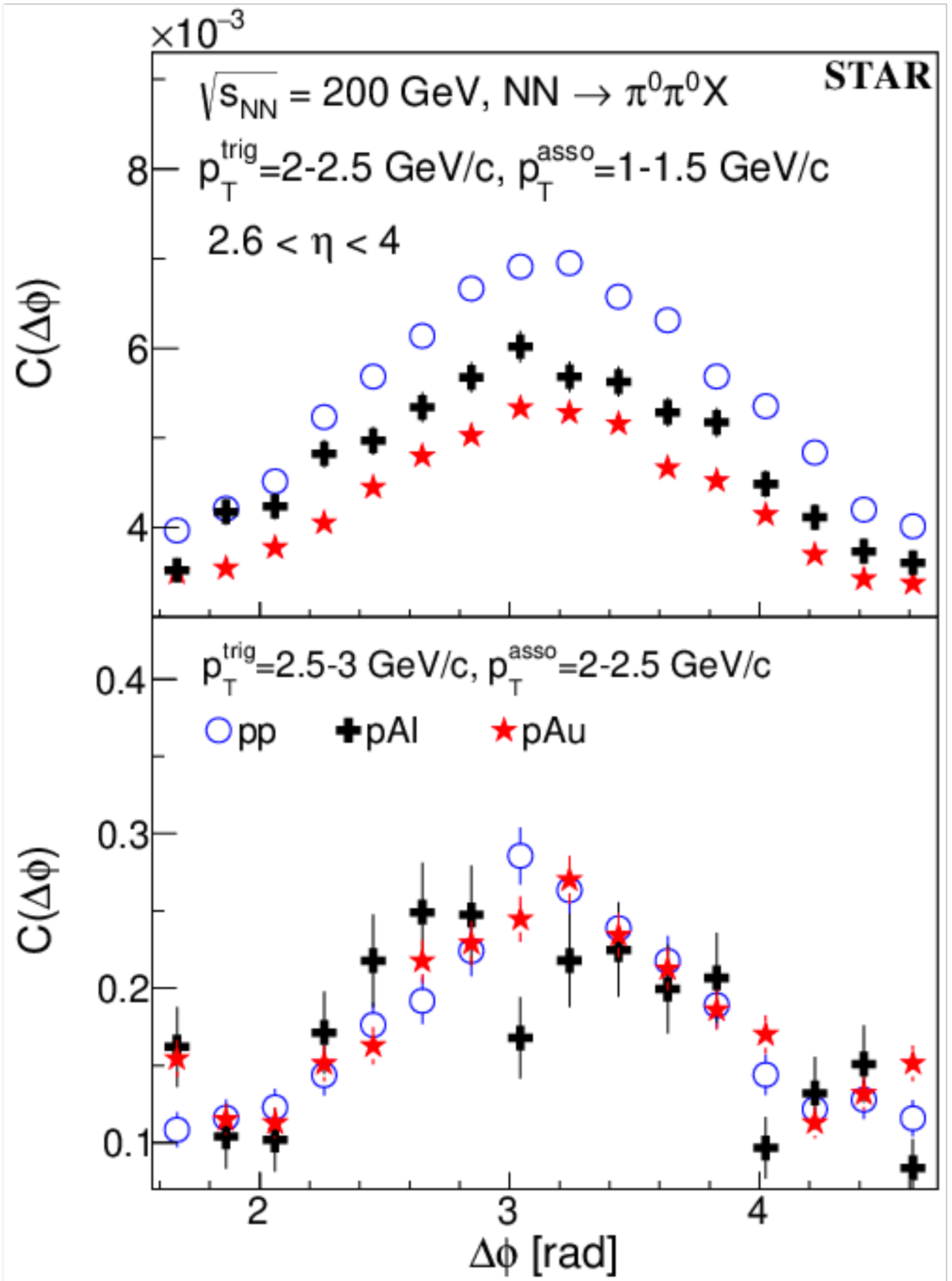
- Vary p_T of trigger π^0 and associated π^0 ➔ scan x
- Vary event activity (E.A.) ➔ scan Q_S^2
- Vary nuclei (p, Al, Au)➔ scan Q_S^2

Di-π^0 correlations in "high activity" pAu



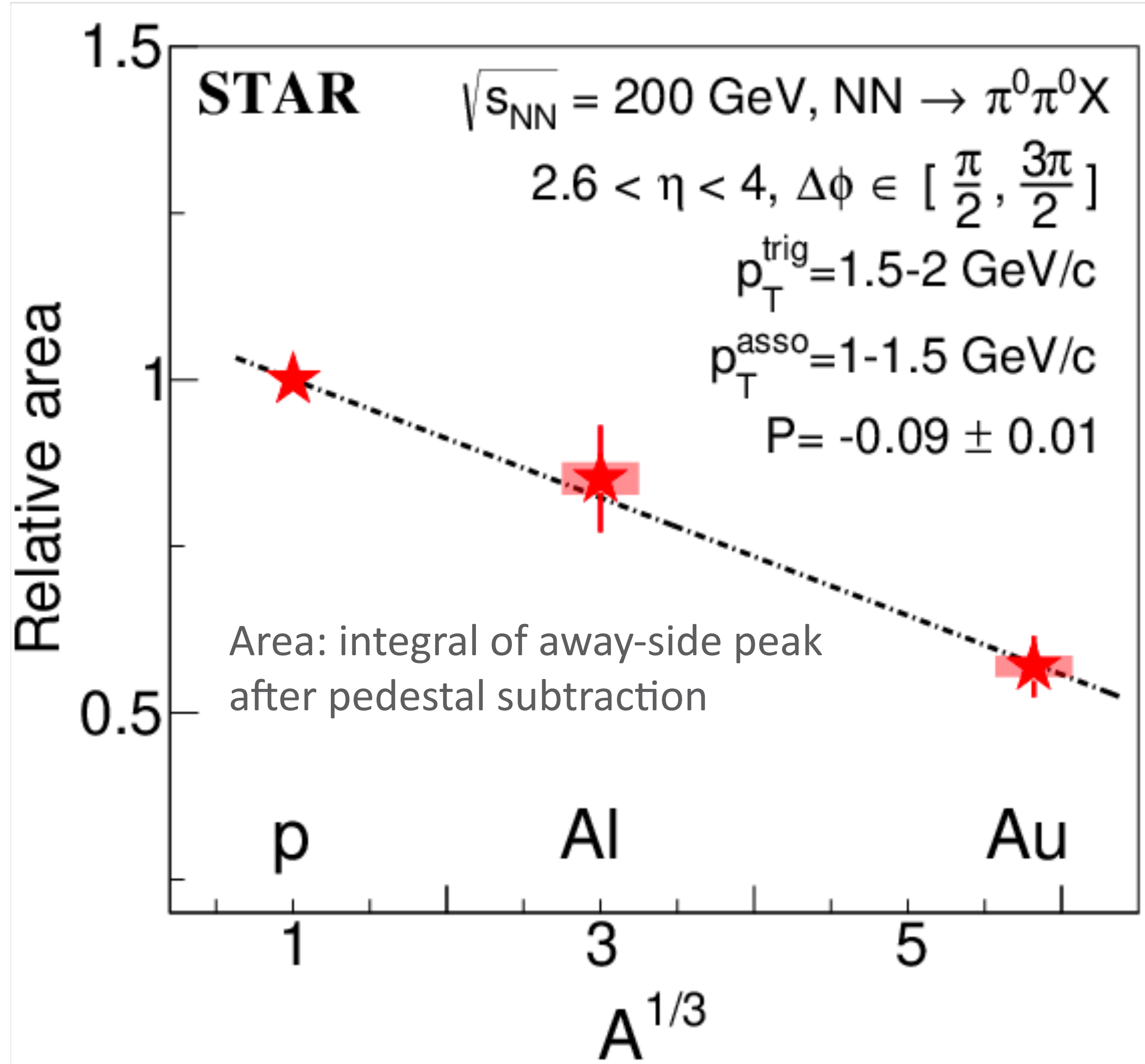
p_T and A dependence

STAR, PRL 129, 092501 (2022)



Low p_T

Higher p_T

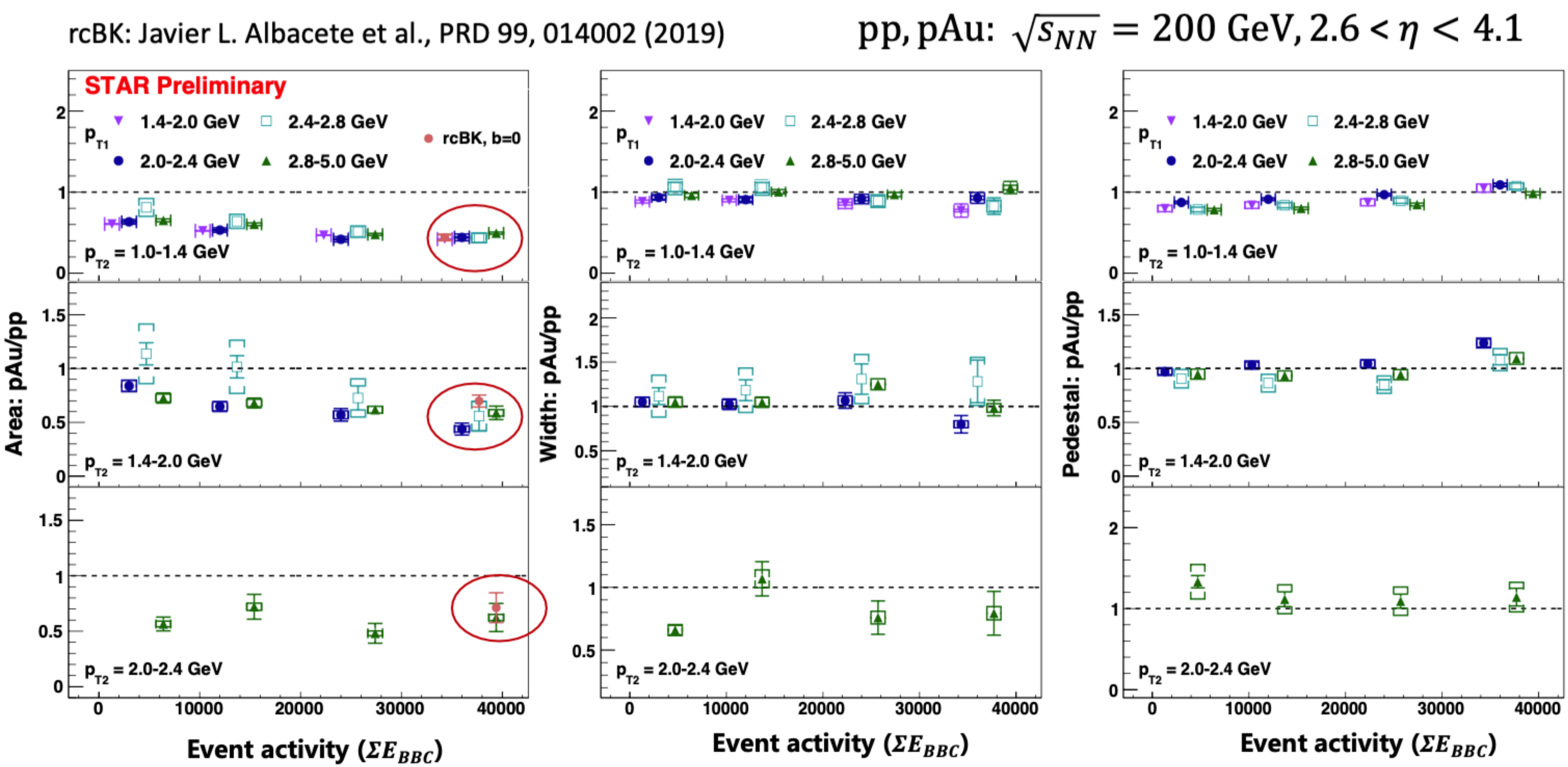


For a given p_T (x - Q^2 phase is fixed): vary A

→ **Suppression at low p_T**

- **linear suppression with $A^{1/3}$**
- **Slope from the fit: -0.09 ± 0.01**

Event activity dependence in pAu

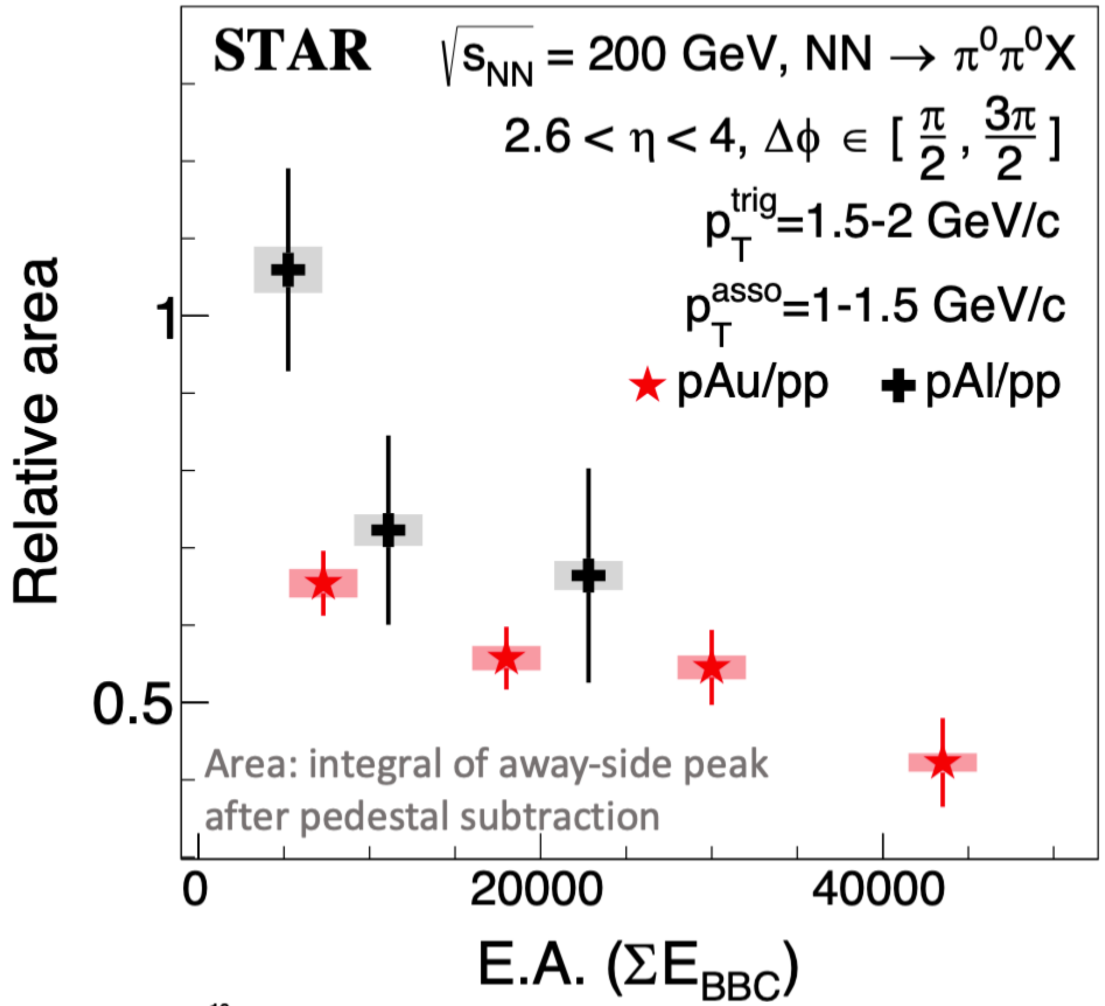


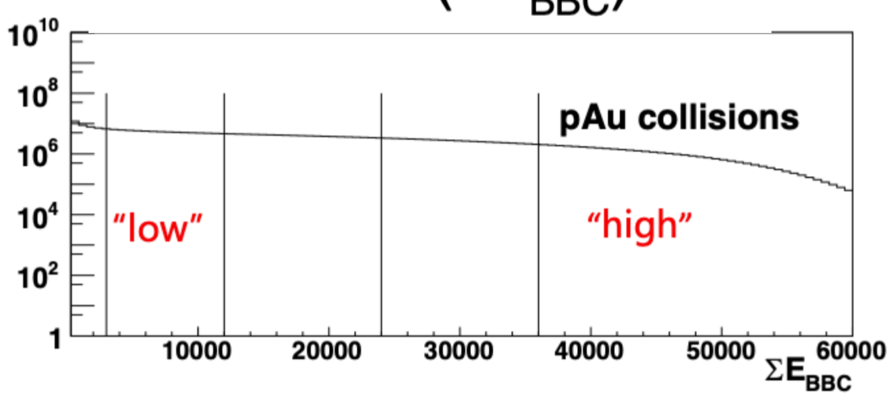
- Suppression depends on event activity → enhanced in high activity events
- Suppression at highest activity events is consistent with predictions based on gluon saturation model: rcBK at b=0
- Width and pedestal are stable in pp and pAu

Event Activity (E.A.) dependence

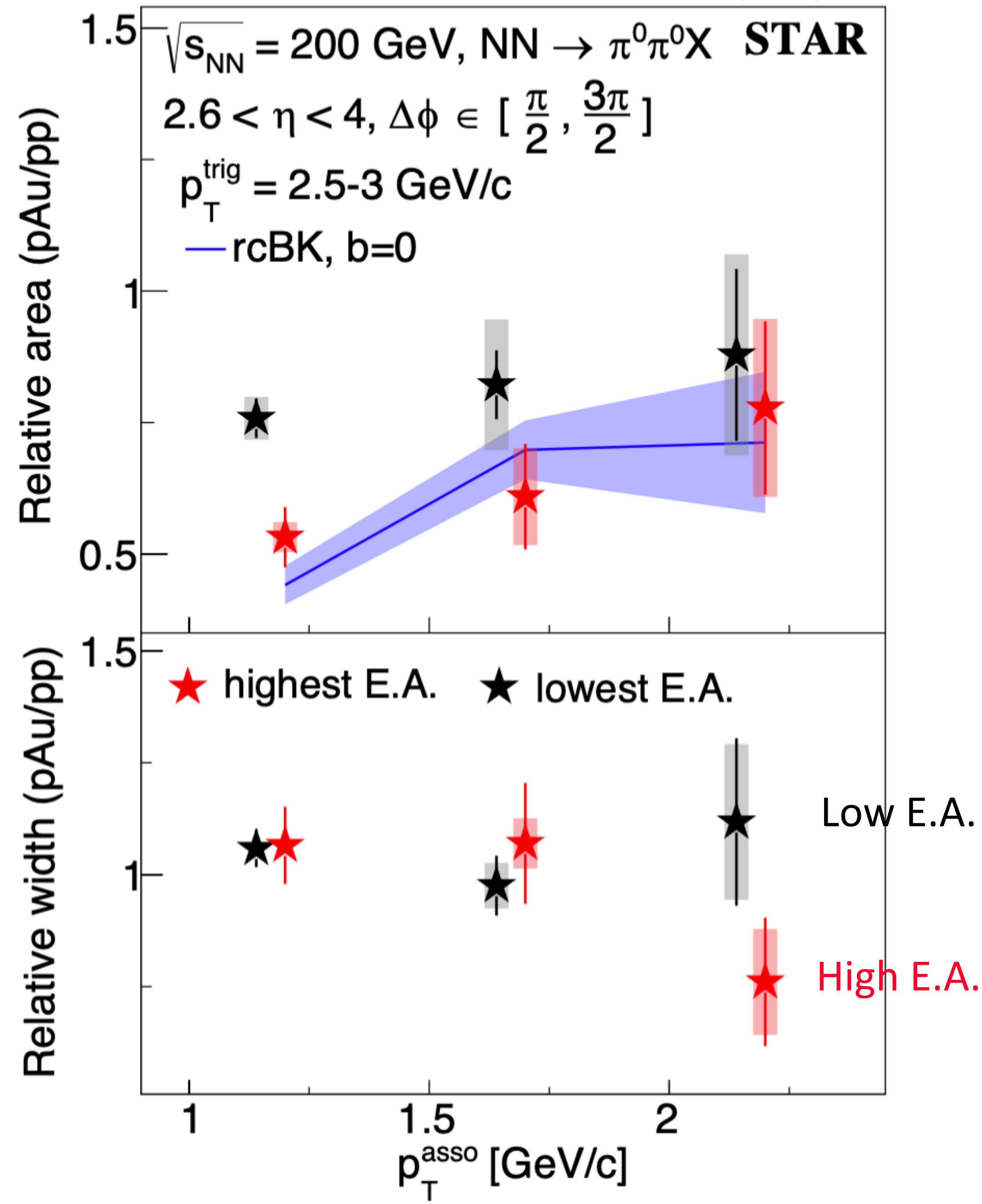
STAR, PRL 129, 092501 (2022)

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





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

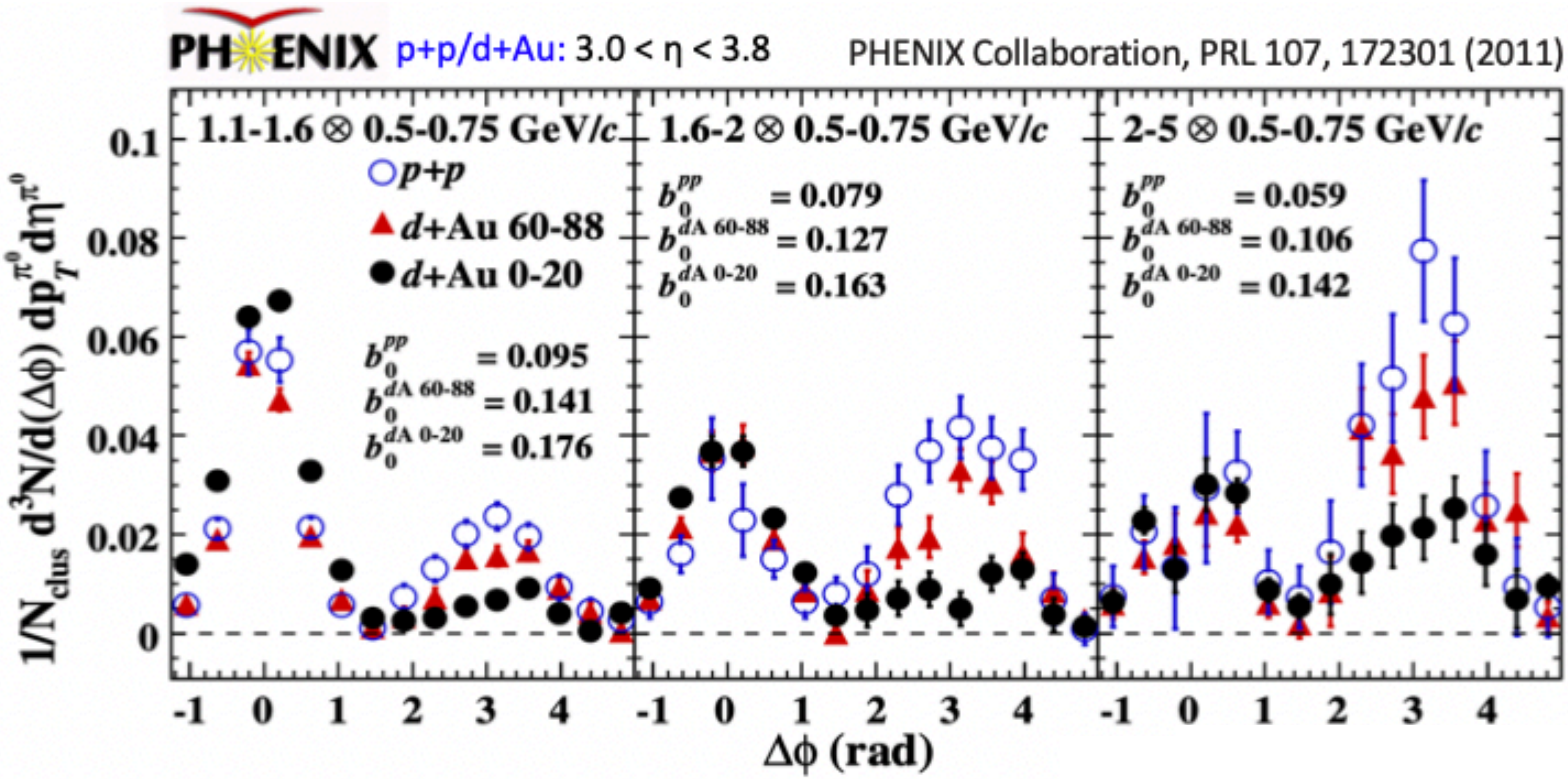


➜ **Suppression increases with E.A.** for both pAl and pAu

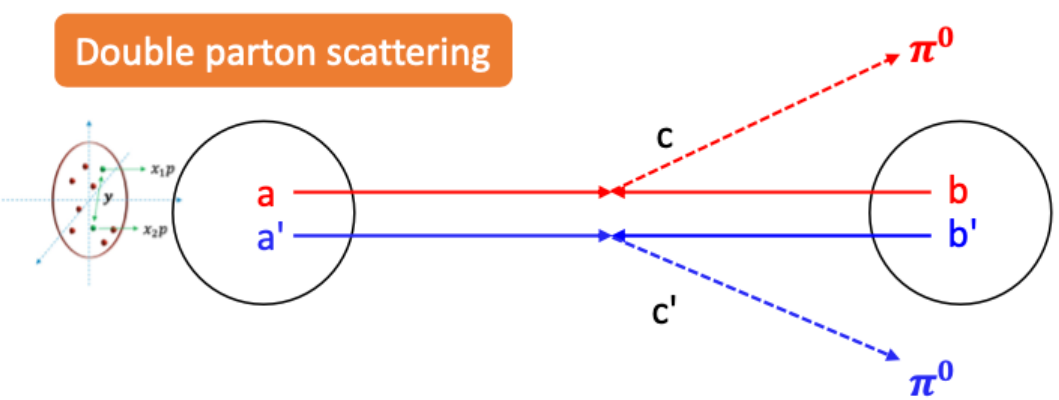
➜ Data at high E.A. **consistent with predictions at b=0**

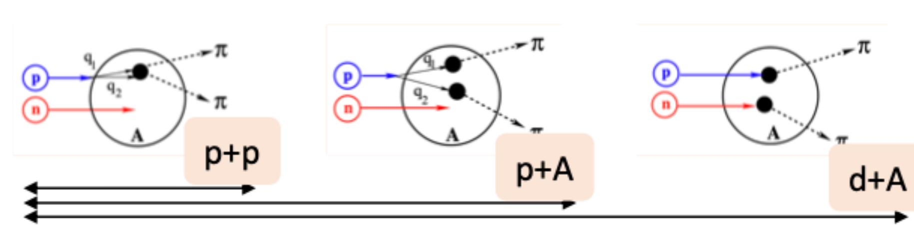
➜ No observation of broadening

Results in d+Au



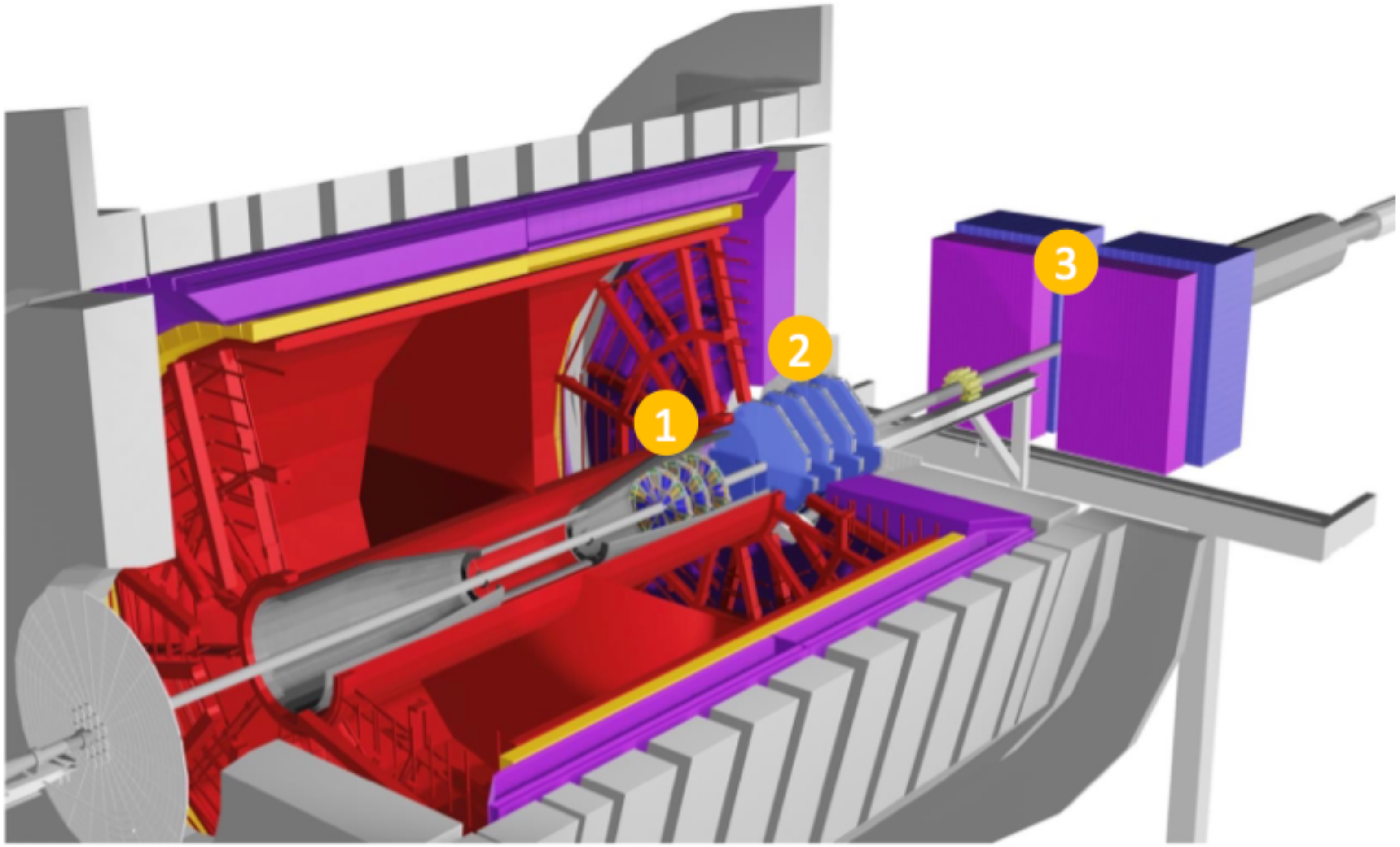
- Away-side correlation: **suppression dependence on p_T, rapidity and centrality**
- π^0 PID: much **higher background** in d+Au than p+p/Au combinatoric contribution is large in d+Au
- Contribution from **DPS**?





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

Plans for STAR measurements



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

Four new systems:

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

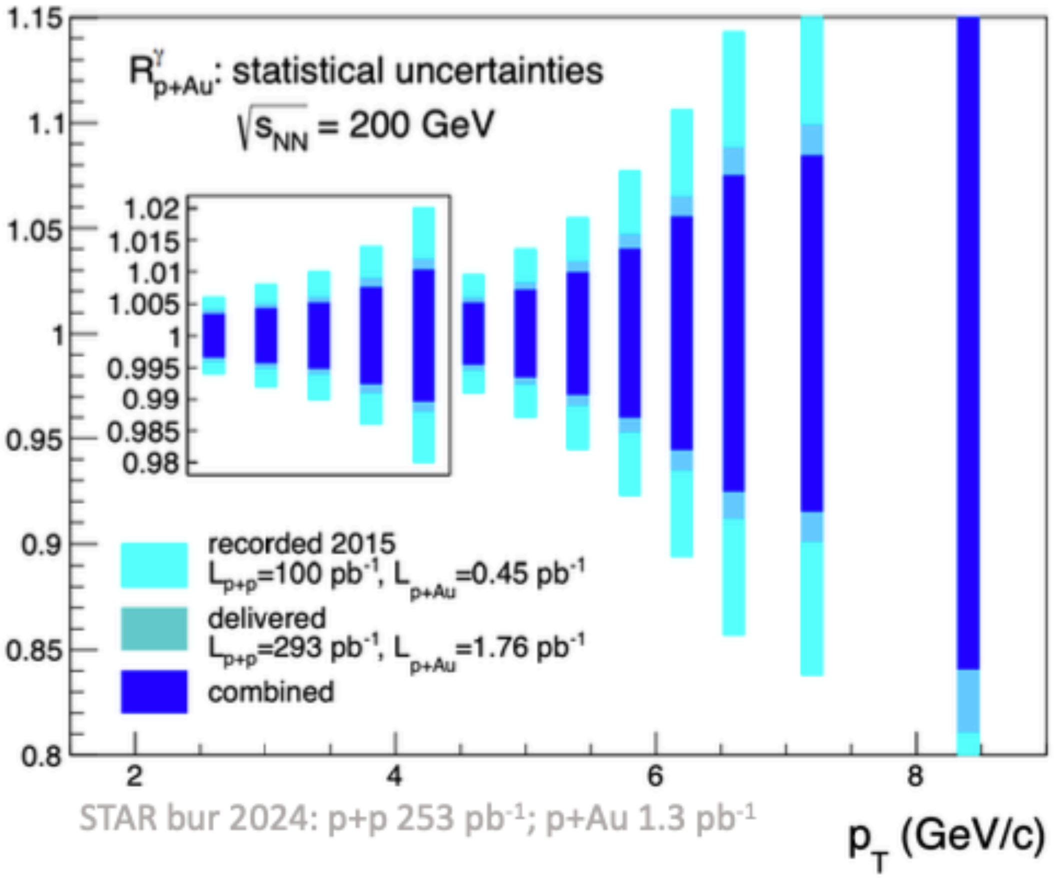
Future STAR data with forward upgrade

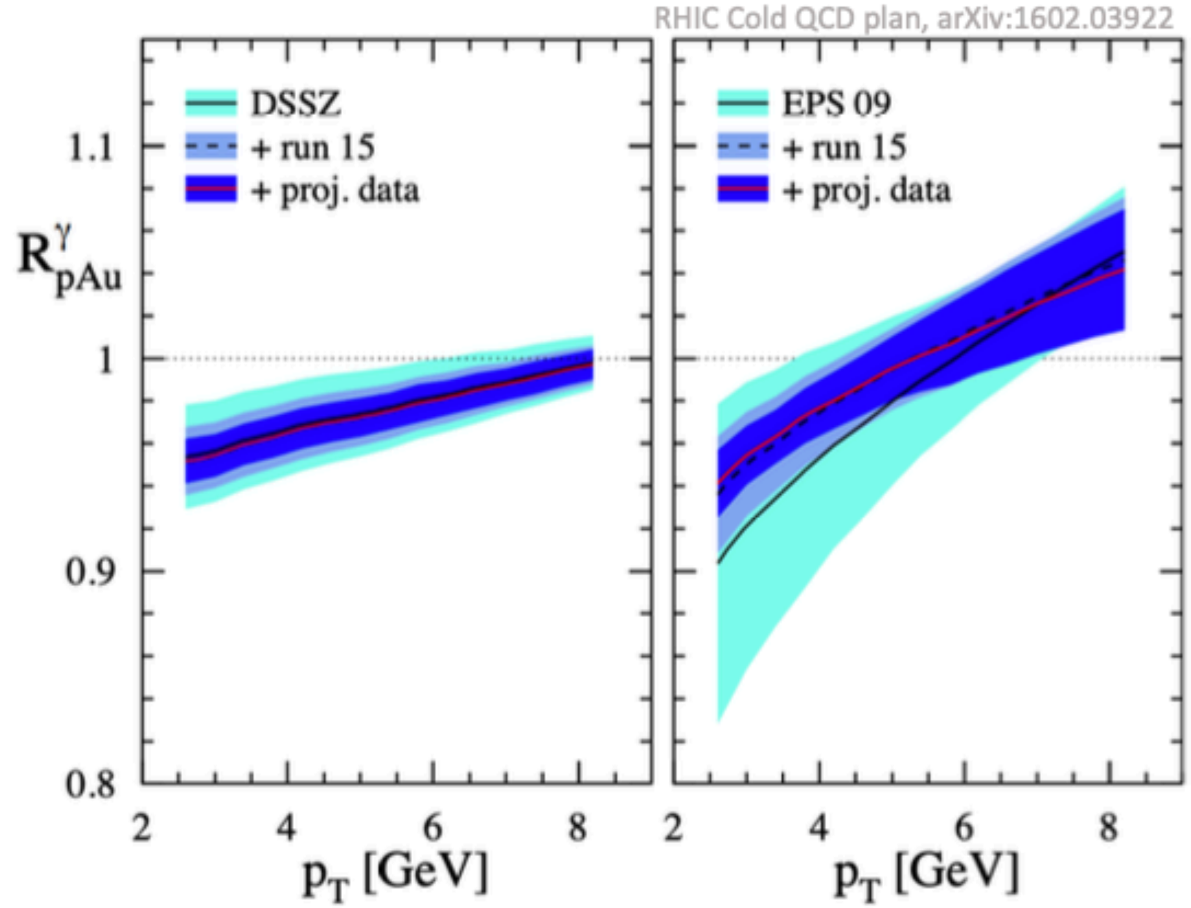
Year	System	$\sqrt{s}$ (GeV)
2023	Au+Au	200
2024	p+p, p+Au	200
2025	Au+Au	200

To explore nonlinear gluon dynamics with expanded observables:

- Di-$h^{+/-}$: access lower p_T (x, Q^2)
- di-jet: more accurate proxy to di-parton in x, Q^2 reconstruction
- Direct photon (-jet)

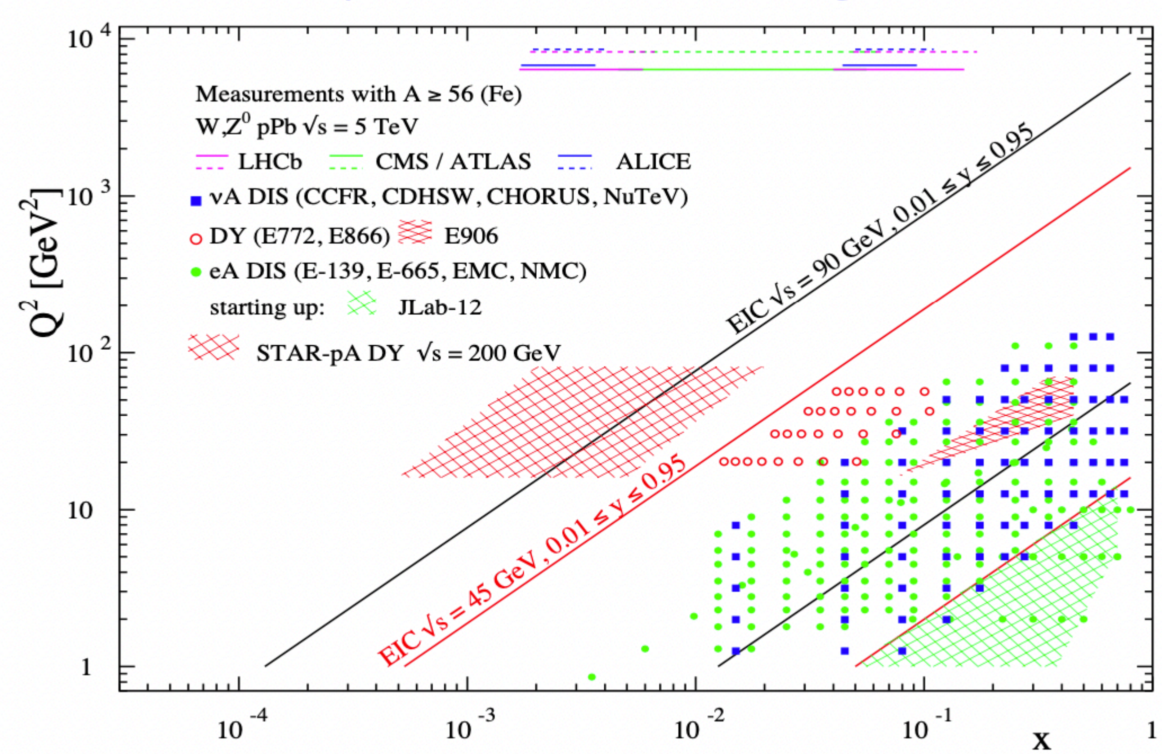
Inclusive direct photon measurements at STAR





E.C. Aschenauer et al., arXiv:1602.03922

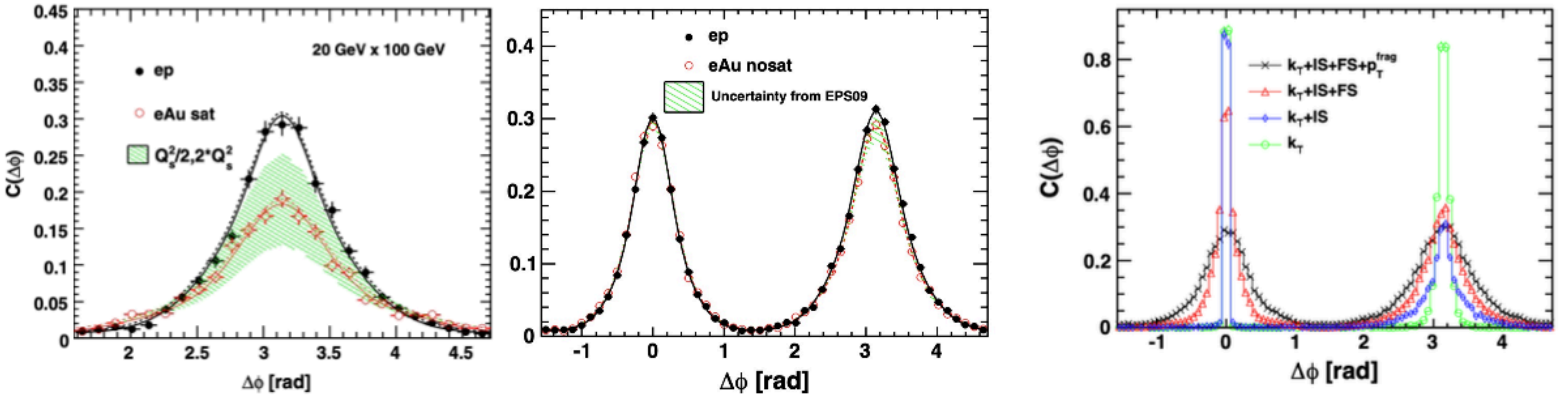
pA@RHIC kinematics range



- **Direct photon measurements:** g+q→γ+q, probes not subject to the strong interaction from the final state
- **STAR forward upgrade**: better constraint on **gluon distributions** with higher delivered integrated luminosity in pA

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 (charged hadron Vs neutral pions) width mainly affected by final state parton shower and fragment p_T^{frag}
- **Away side peak width dominated by initial state parton shower**

Summary

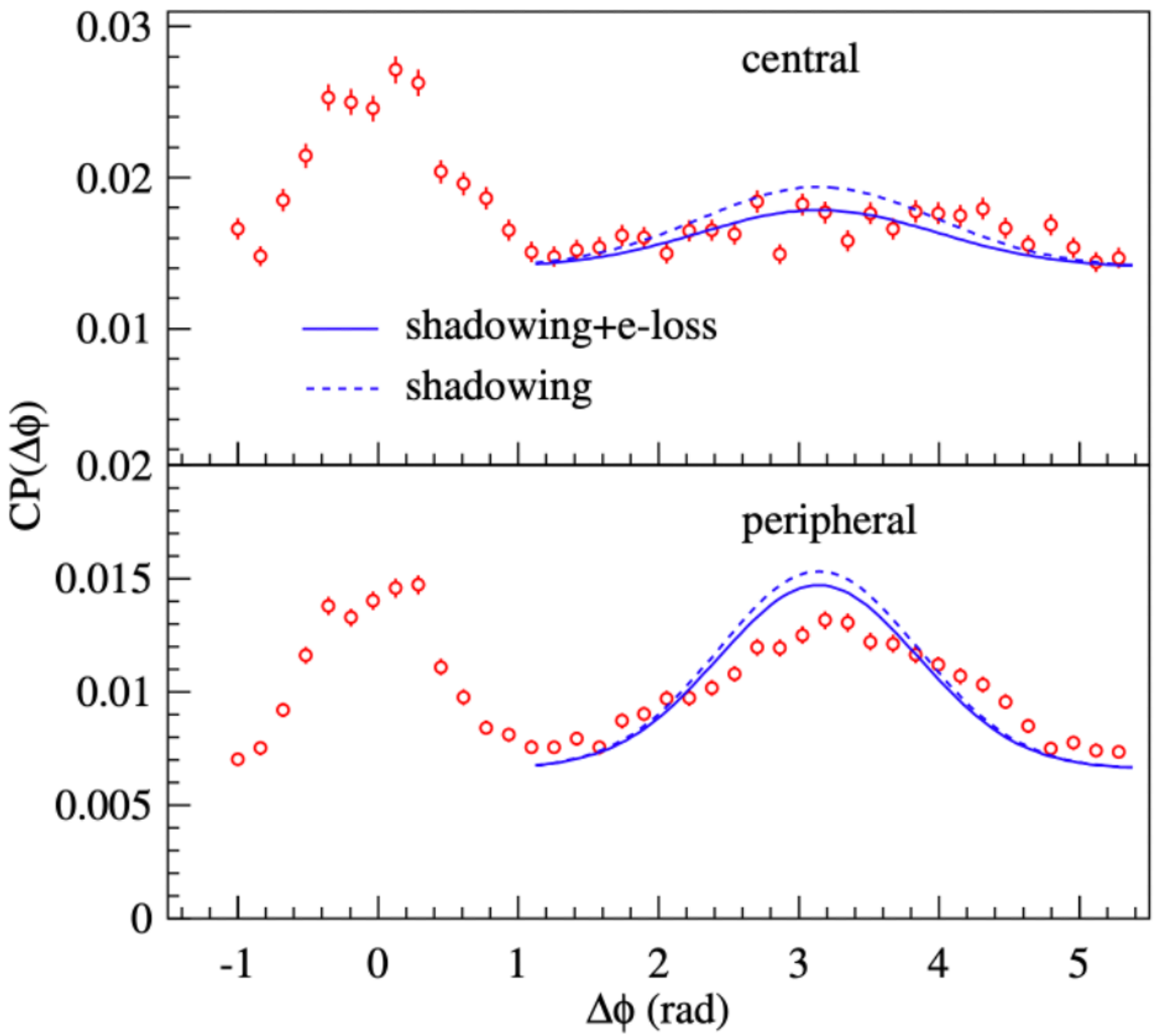
- **Access saturation regime -> forward correlations in p+A**
  - **Understand collective dynamics of gluons**
  - **Investigate inner landscape of nuclei: initial state input to eA/pA/AA**
- **Comparison of pp to pA: suppression from multiple gluon interactions**
- Ideal measurement: low pt, high sqrt(s), forward, central collision, heavy nucleus
- **Scan in x - Q^2**:
  - pt for both trigger and associated particles: scan in x ->vary gluon density
  - event activity
  - Comparison of pAu and pAl : A dependance of Qs
- Cleaner measurement in pAu than dAu
- **Future measurements with STAR forward upgrade and EIC**: expanded observables in pAu and complementary probes

Back-up

Energy loss effects

dAu collisions at 200GeV

Z. Kang et al., PRD 85, 054024 (2012)



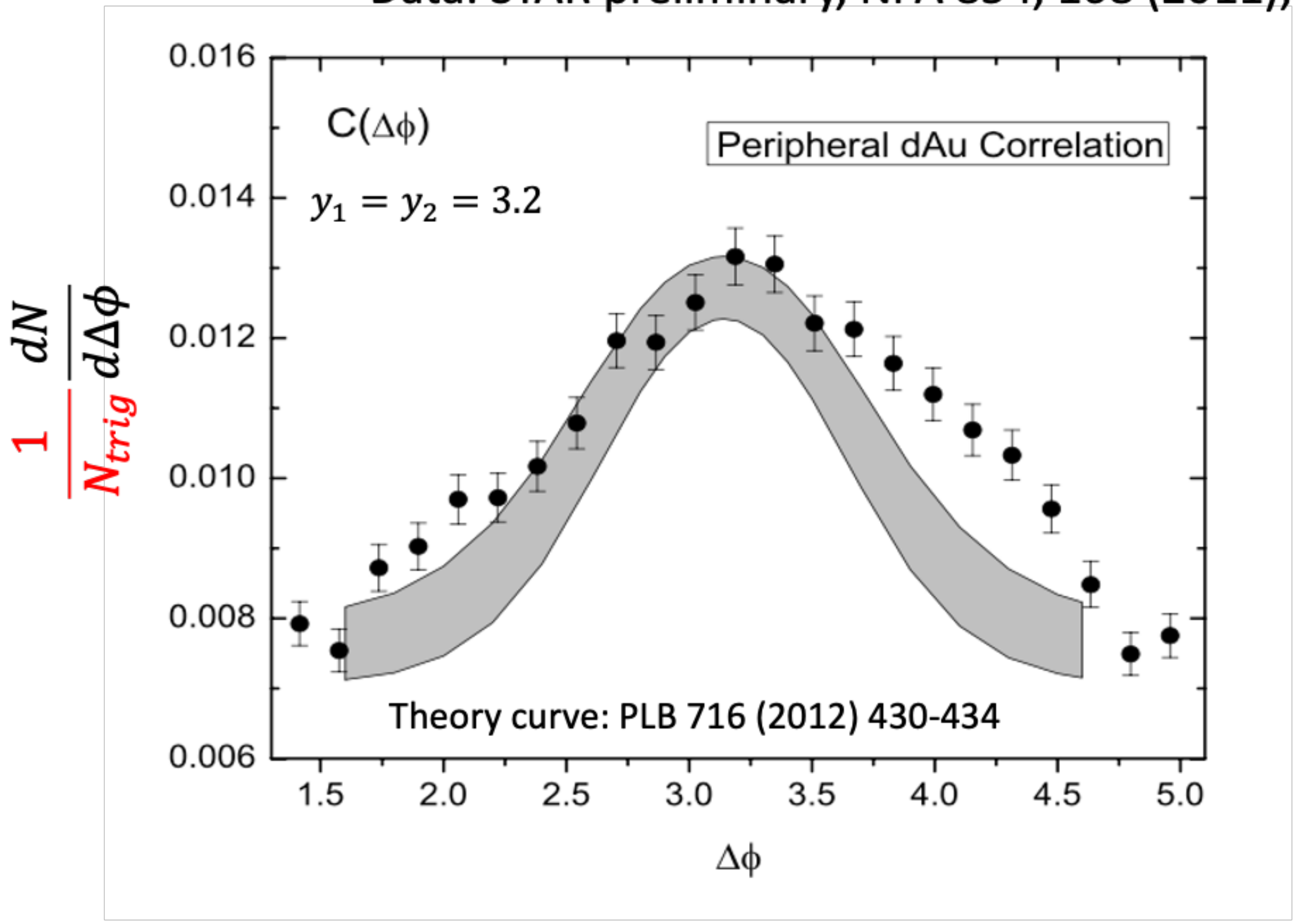
Shadowing effects:

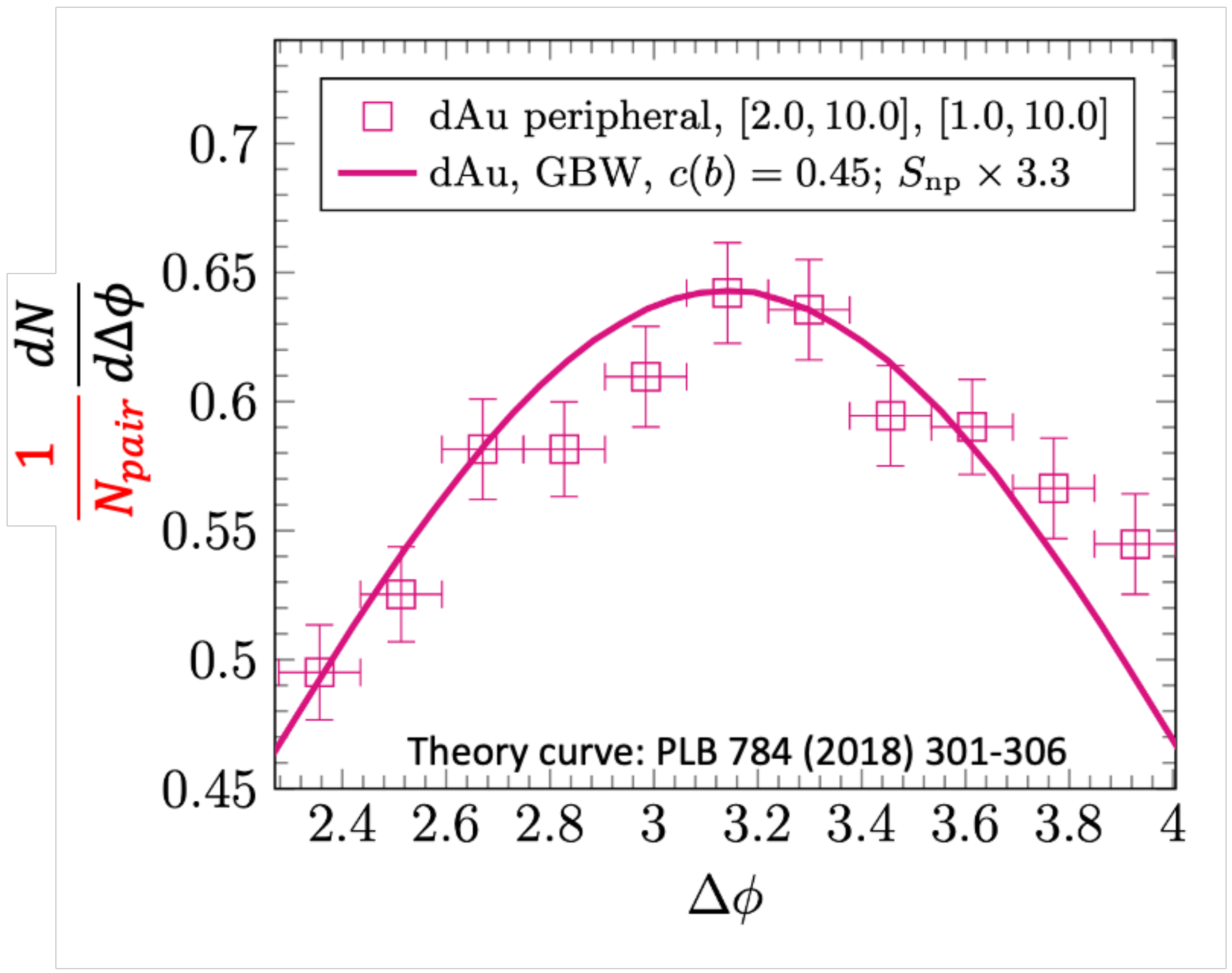
- contribute to the cross section at the power corrections level
- enhanced by large nuclear-size ($A^{1/3}$) for a given partonic channel

Energy loss effects = difference between solid bule and dashed blue, are not large enough to explain the suppression from the data

Example of different normalizations (1)

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

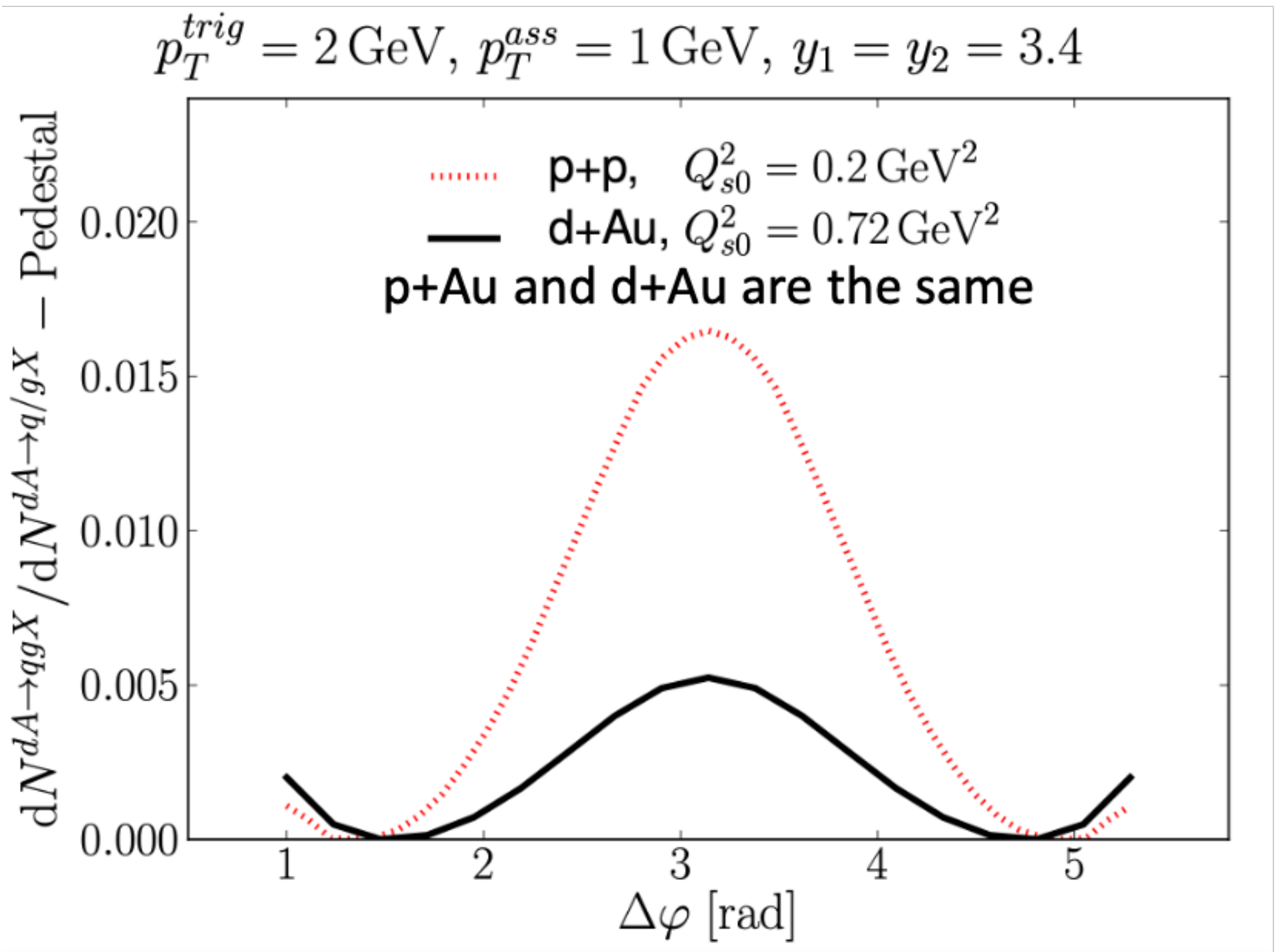


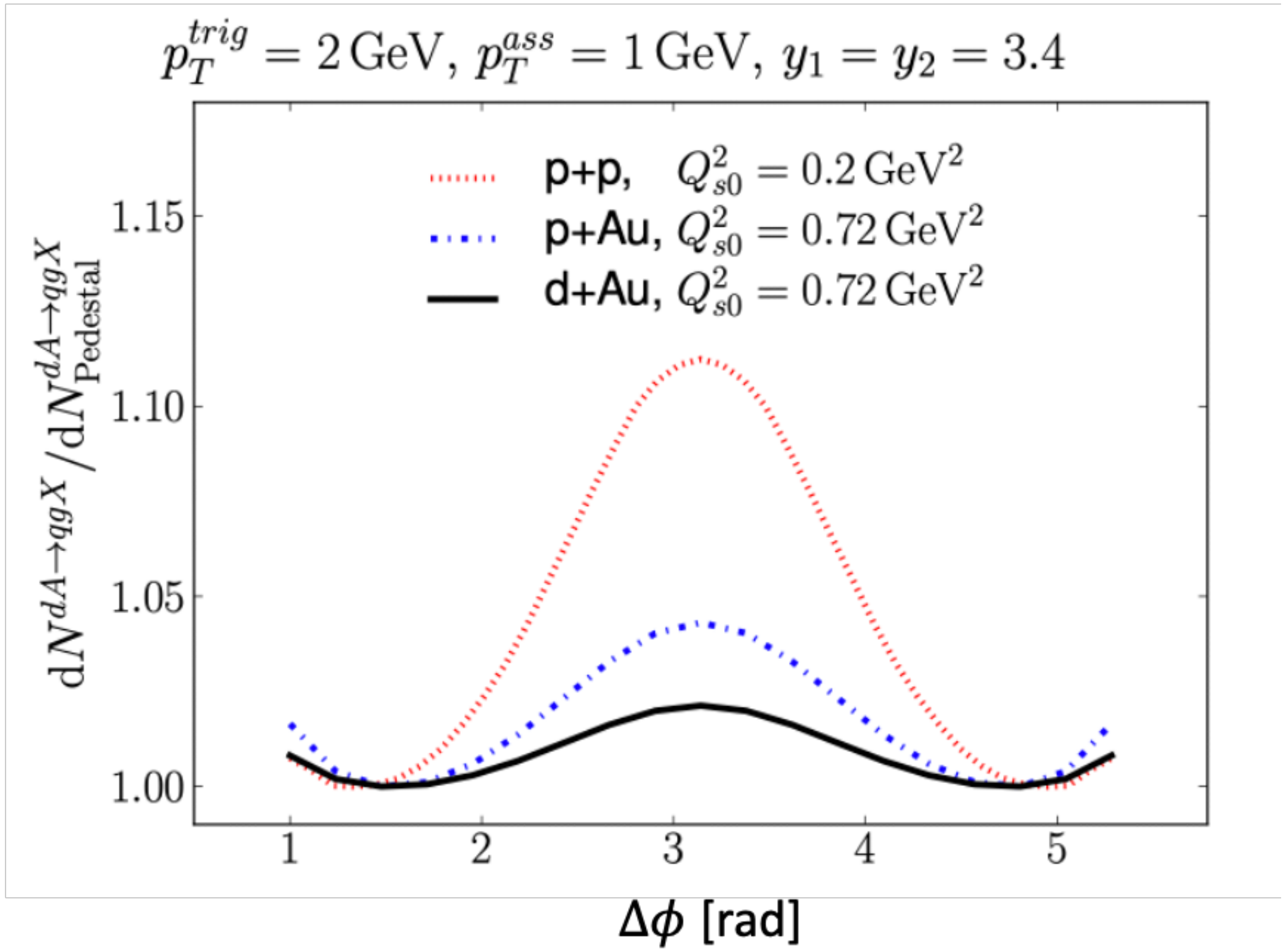


- CGC predictions based on GBW model with Sudakov effects included agrees with data better
- Two ways of normalization used: correlation function normalized by N_{trig} not N_{pair}
  - PLB 716 (2012) 430-434: normalized by N_{trig}, but issues found with p+p normalization
  - PLB 784 (2018) 301-306: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

Example of different normalizations (2)

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: $\frac{N_{pair}(\Delta\phi)}{N_{pair}\ from\ pedestal}$

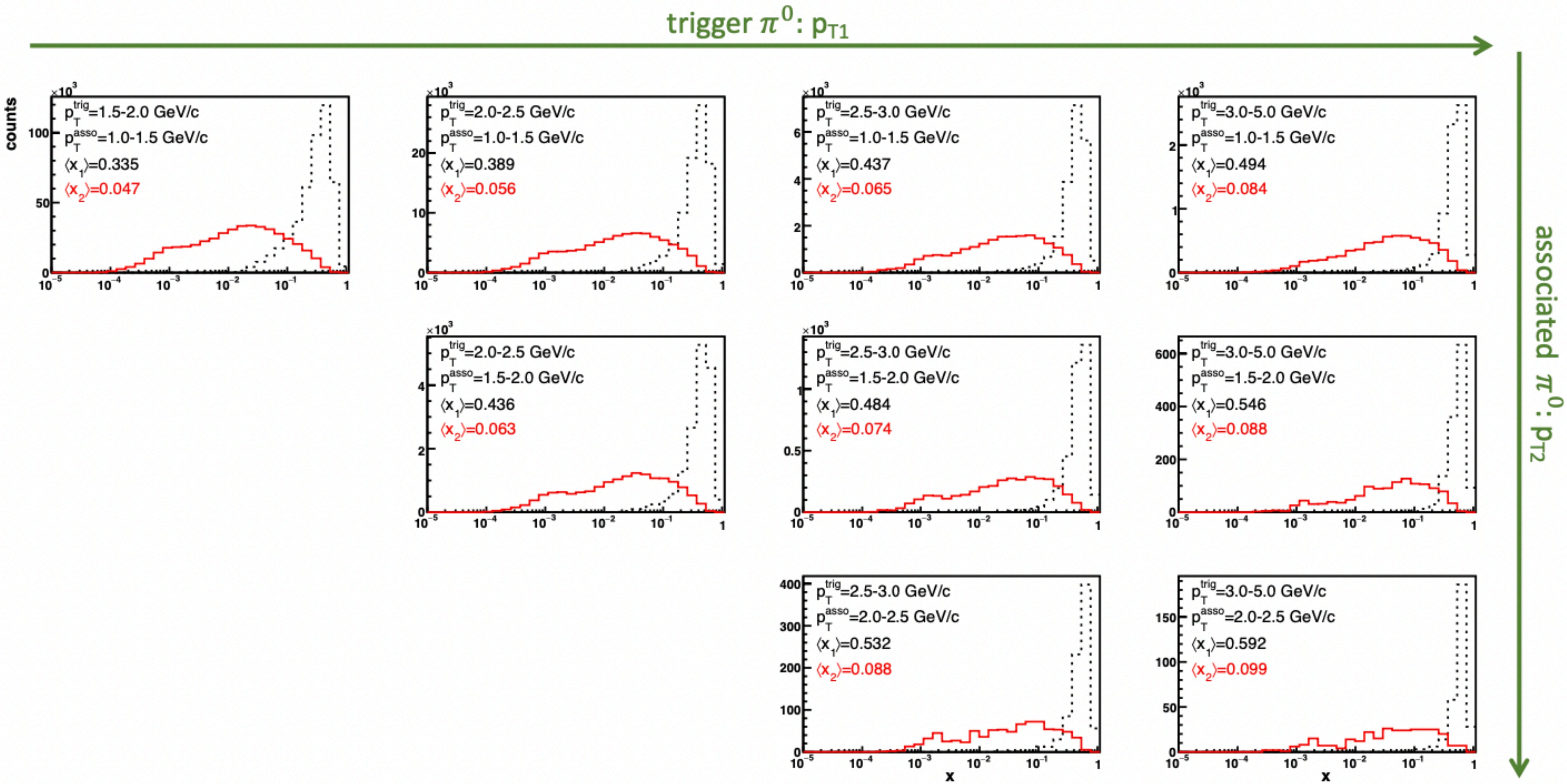
Normalization summary

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$\times R_{dAu}$

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

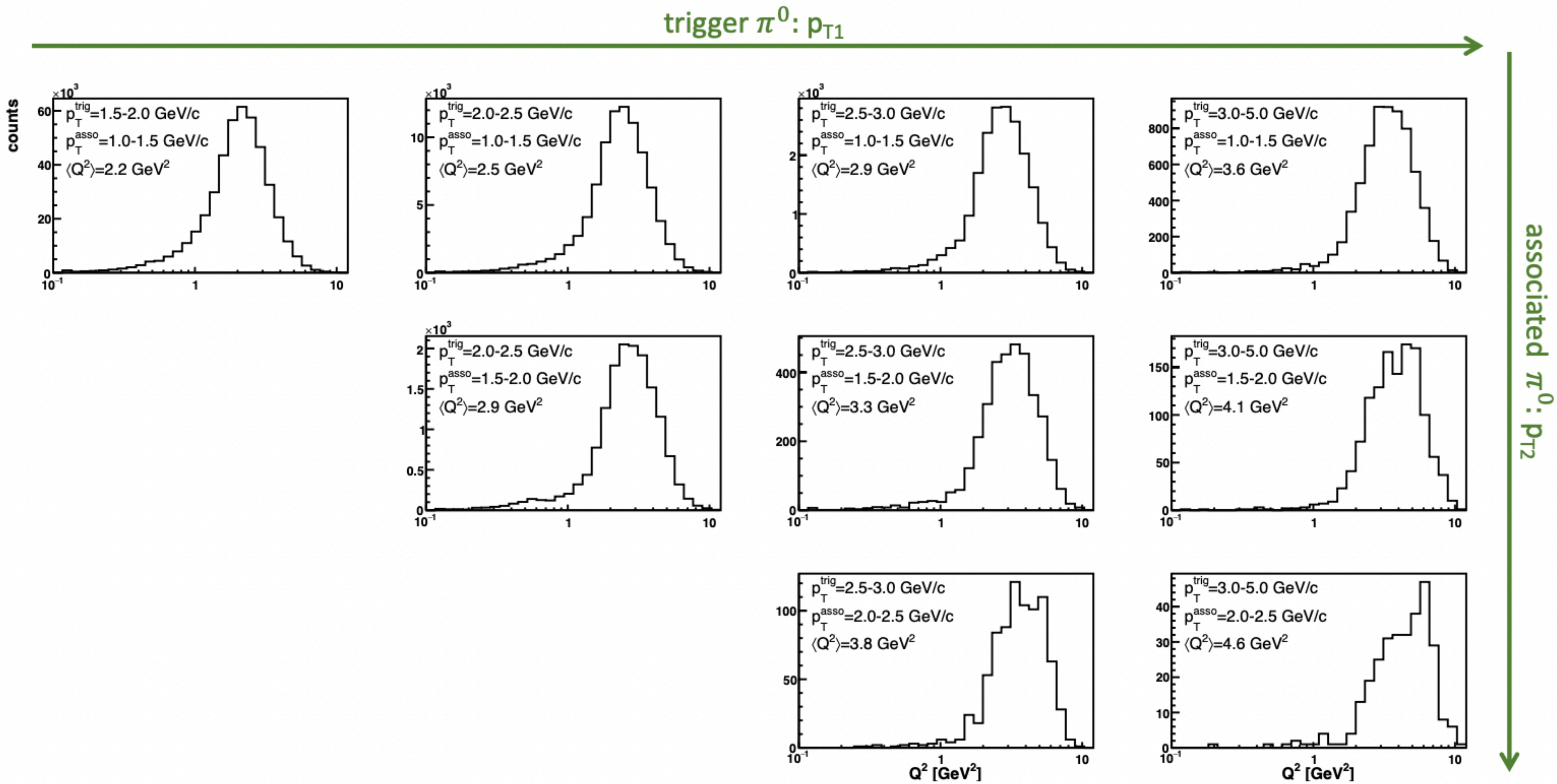
Need uniformed normalization from theory!

Simulated x



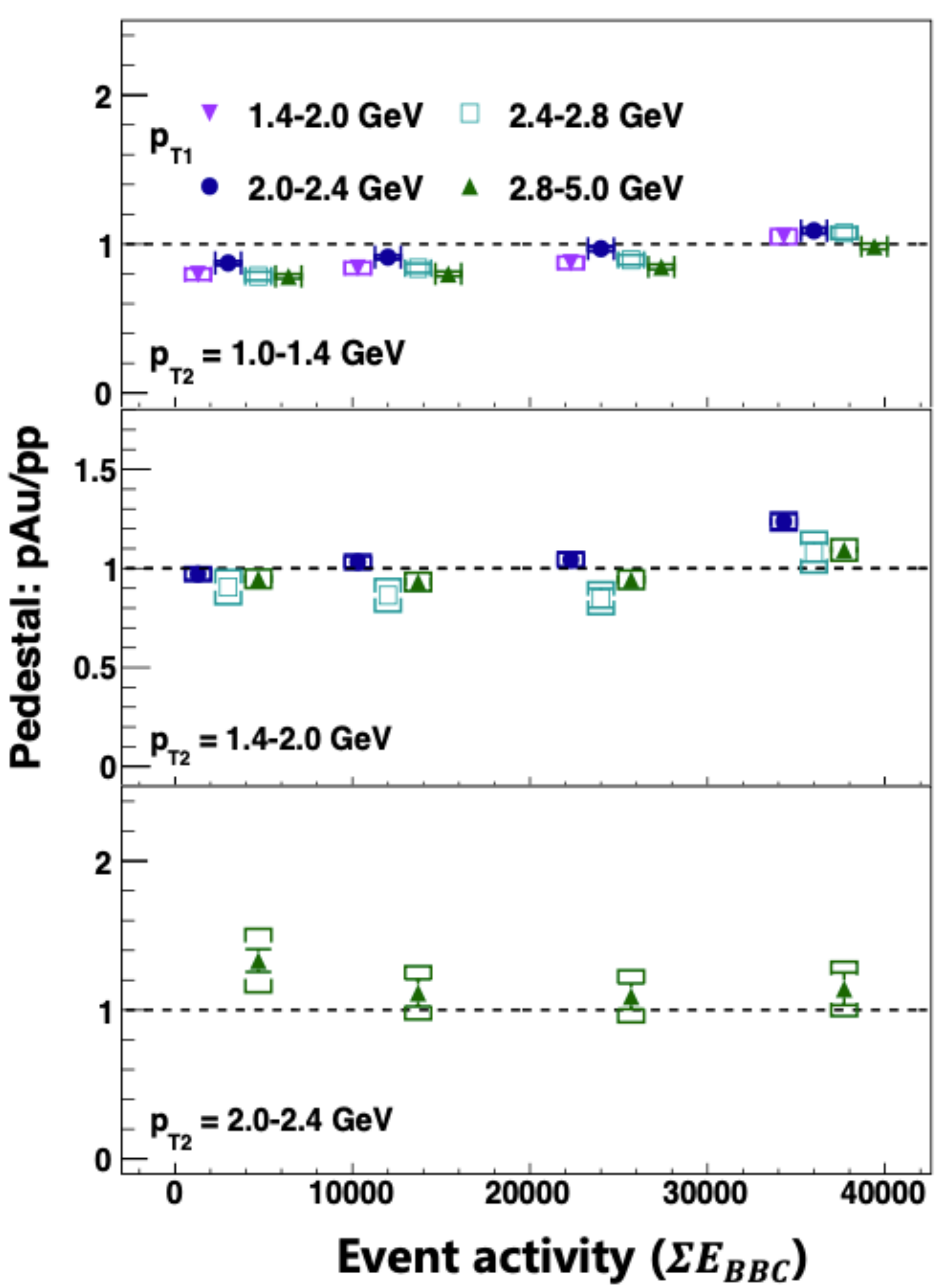
trigger π^0: p_{T1}
associated π^0: p_{T2}
counts
p_T^{trig}=1.5-2.0 GeV/c
p_T^{asso}=1.0-1.5 GeV/c
⟨x_1⟩=0.335
⟨x_2⟩=0.047
p_T^{trig}=2.0-2.5 GeV/c
p_T^{asso}=1.0-1.5 GeV/c
⟨x_1⟩=0.389
⟨x_2⟩=0.056
p_T^{trig}=2.5-3.0 GeV/c
p_T^{asso}=1.0-1.5 GeV/c
⟨x_1⟩=0.437
⟨x_2⟩=0.065
p_T^{trig}=3.0-5.0 GeV/c
p_T^{asso}=1.0-1.5 GeV/c
⟨x_1⟩=0.494
⟨x_2⟩=0.084
p_T^{trig}=2.0-2.5 GeV/c
p_T^{asso}=1.5-2.0 GeV/c
⟨x_1⟩=0.436
⟨x_2⟩=0.063
p_T^{trig}=2.5-3.0 GeV/c
p_T^{asso}=1.5-2.0 GeV/c
⟨x_1⟩=0.484
⟨x_2⟩=0.074
p_T^{trig}=3.0-5.0 GeV/c
p_T^{asso}=1.5-2.0 GeV/c
⟨x_1⟩=0.546
⟨x_2⟩=0.088
p_T^{trig}=2.5-3.0 GeV/c
p_T^{asso}=2.0-2.5 GeV/c
⟨x_1⟩=0.532
⟨x_2⟩=0.088
p_T^{trig}=3.0-5.0 GeV/c
p_T^{asso}=2.0-2.5 GeV/c
⟨x_1⟩=0.592
⟨x_2⟩=0.099
x

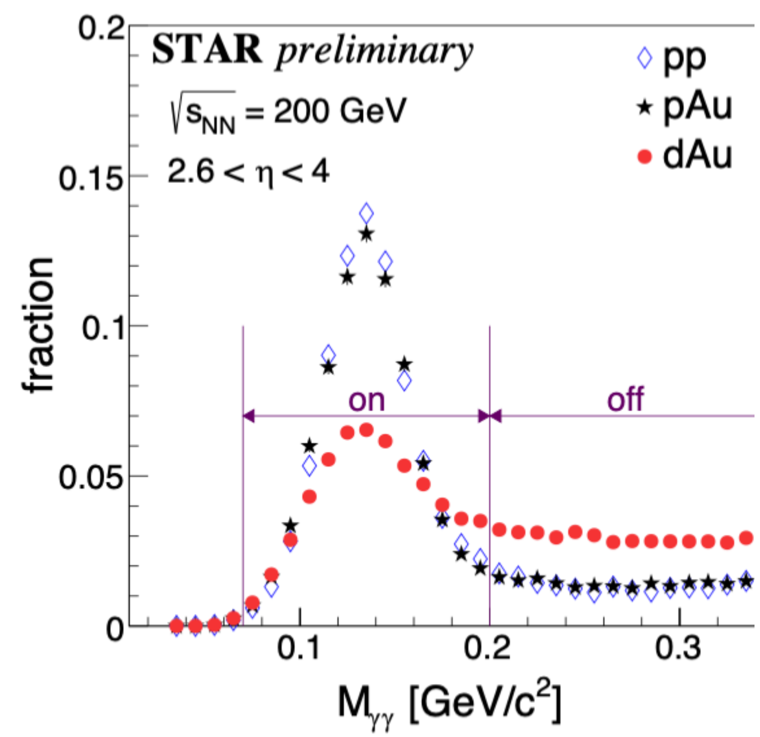
Simulated Q^2

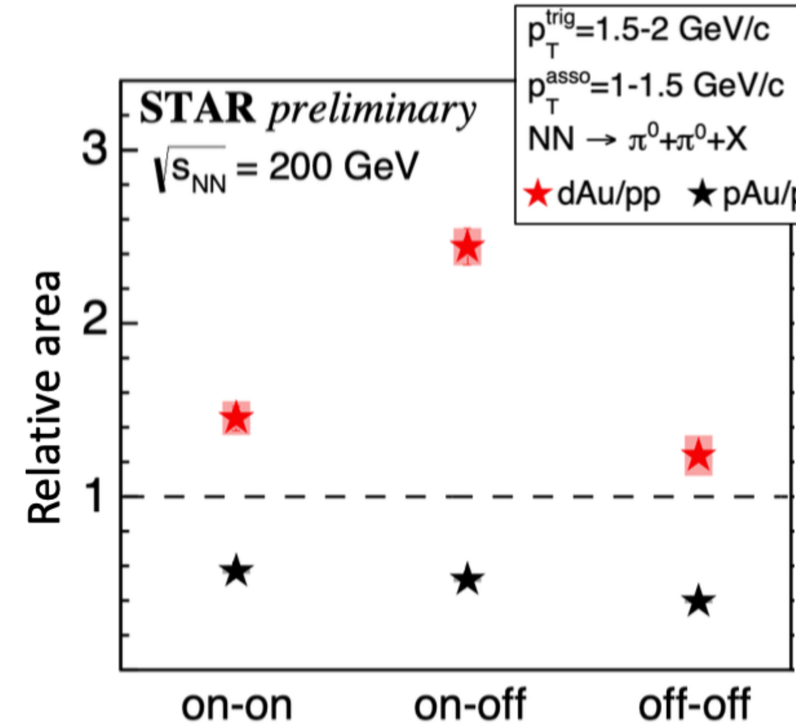


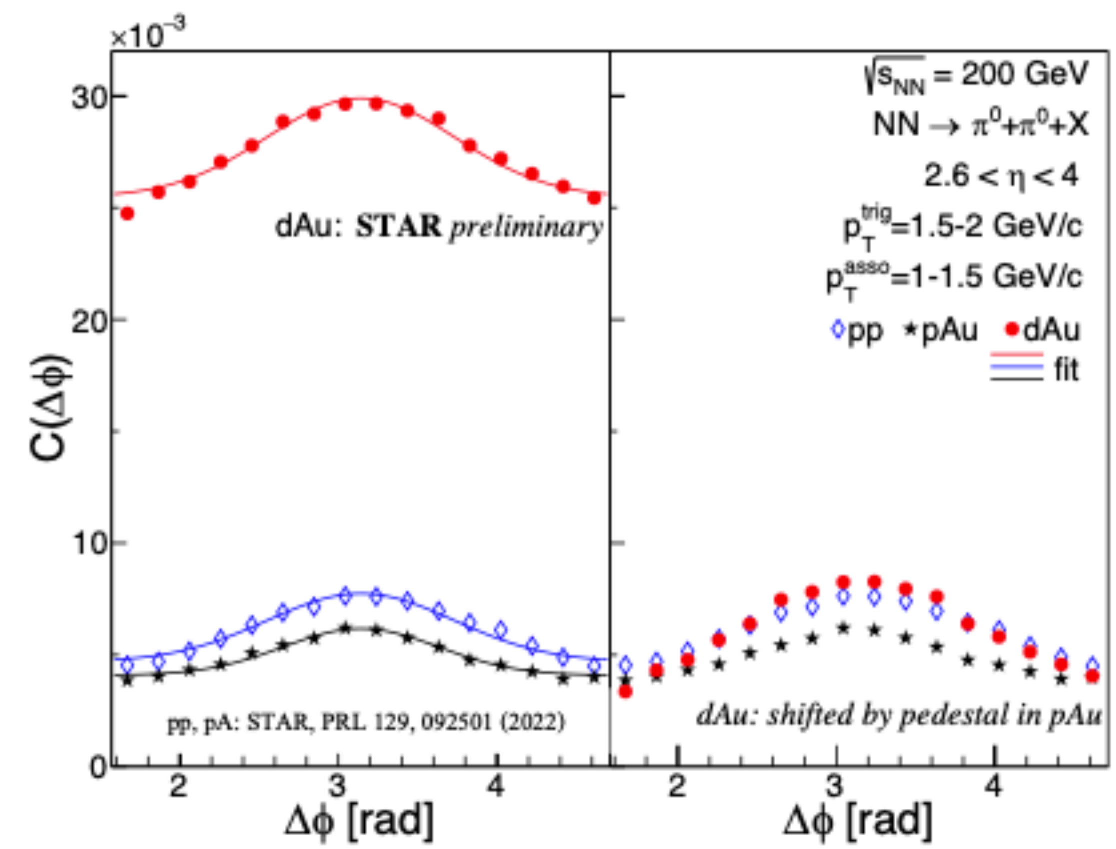
Pedestals

pp, pAu: $\sqrt{s_{NN}} = 200$ GeV, $2.6 < \eta < 4.1$



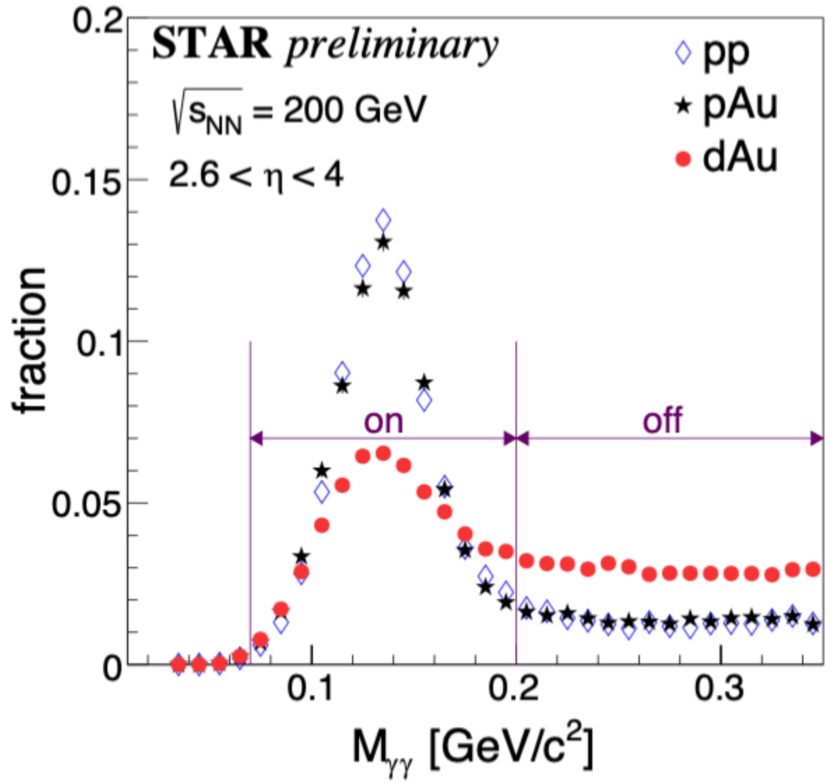


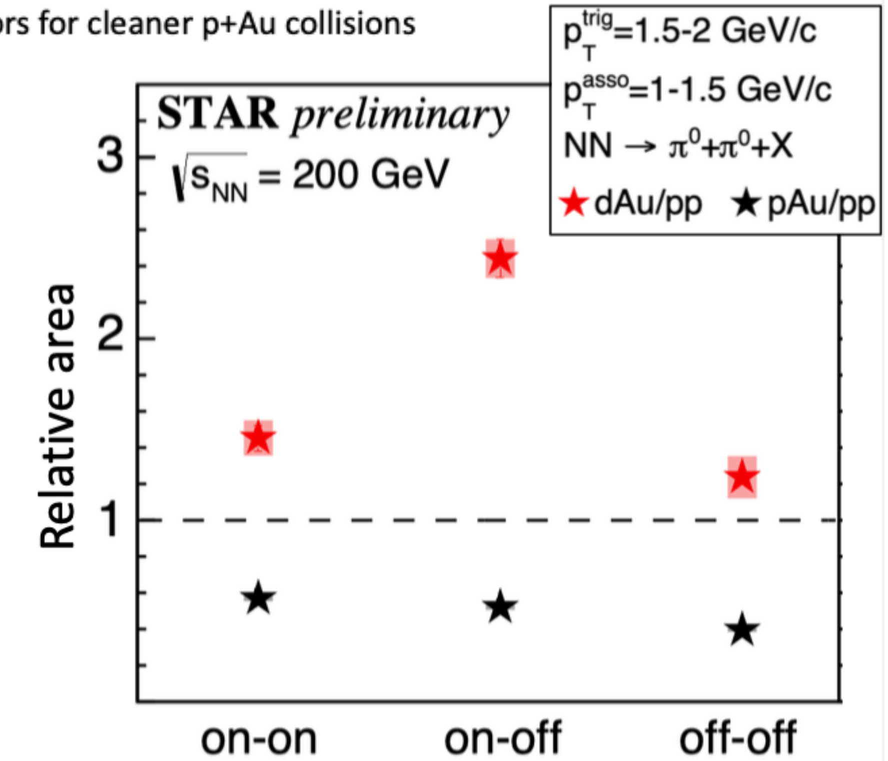


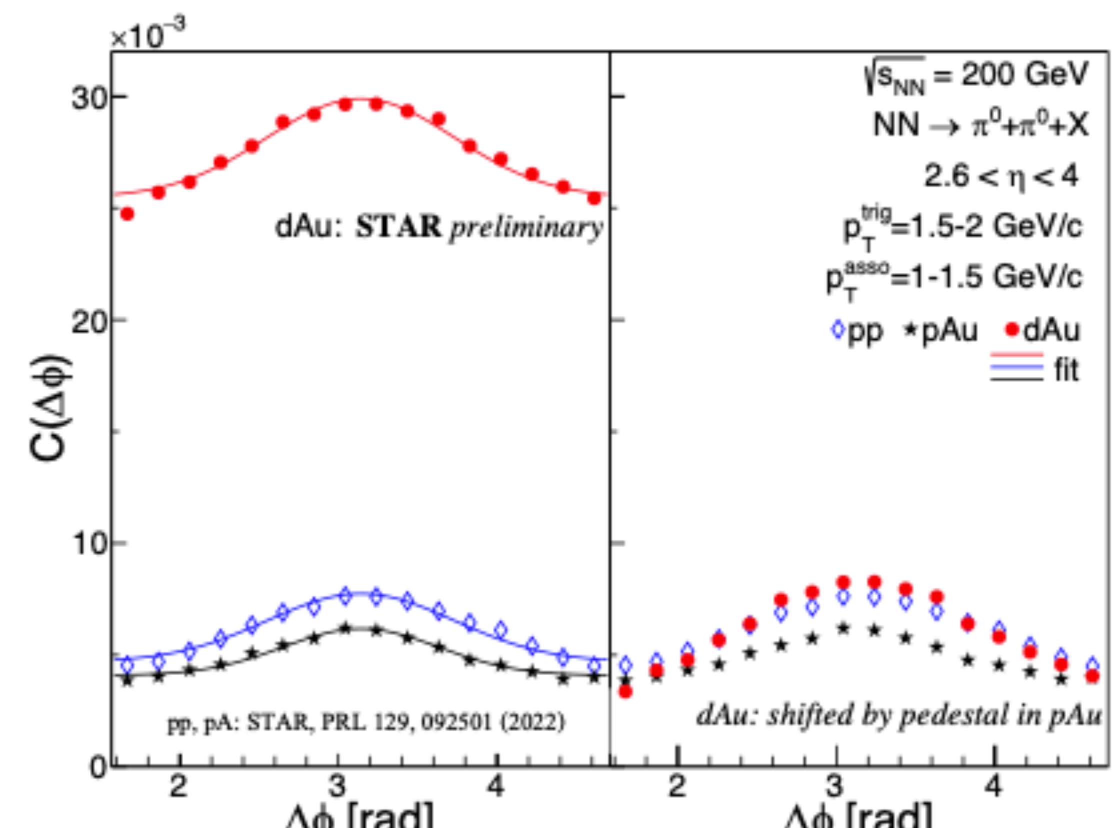


Background from dAu vs pAu

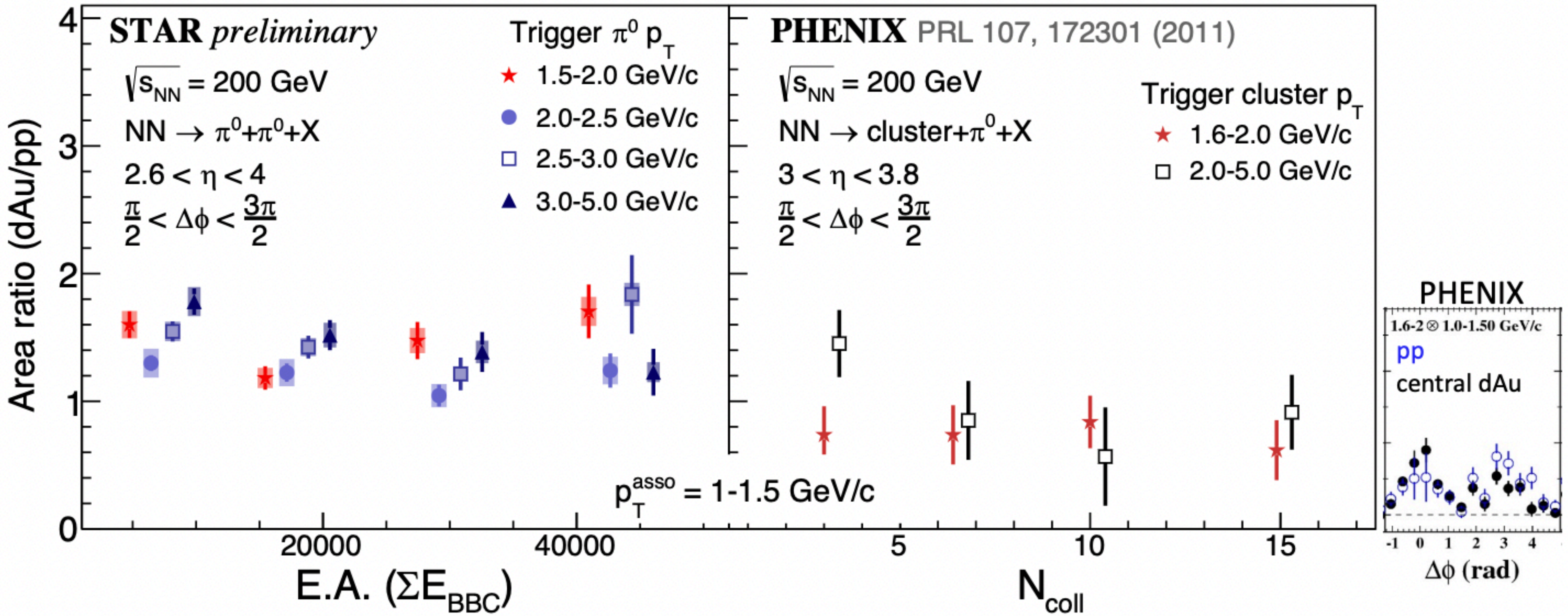
- π^0 PID: much higher background in d+Au than p+p/Au
- Combinatoric contributions are different in d+Au and p+p/Au: much higher in d+Au than p+p/Au
- Challenging to perform the forward π^0- π^0correlation measurement in d+Au: Favors for cleaner p+Au collisions





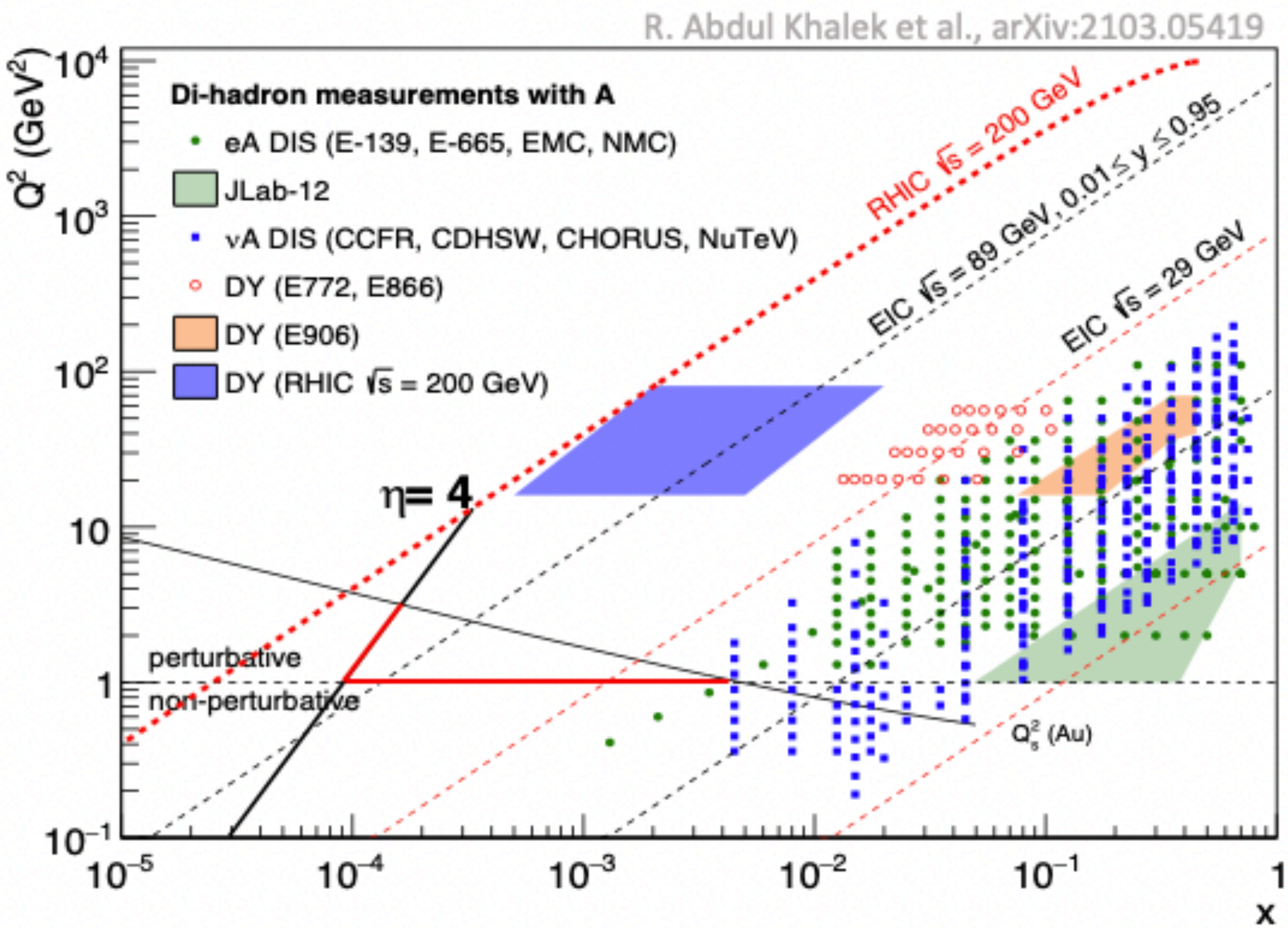


E.A. dependence in d+Au



- 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

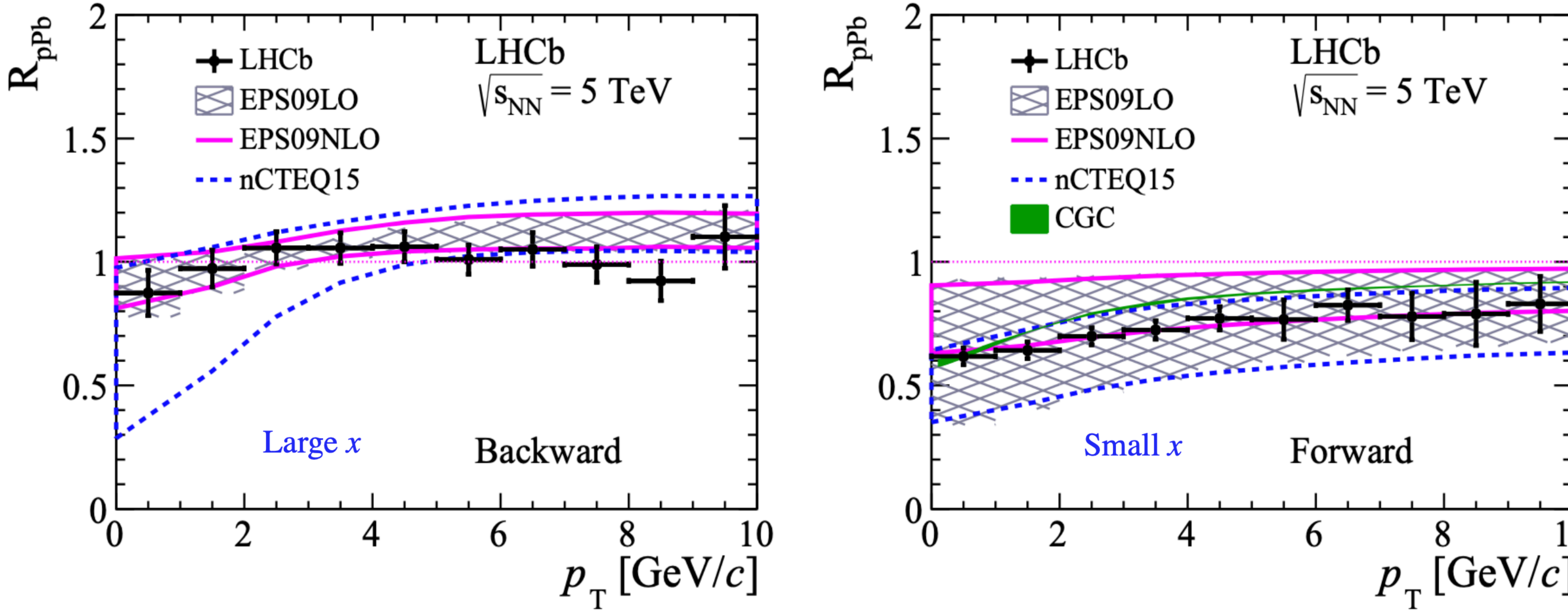
Future measurements at RHIC



STAR data can access linear-nonlinear transition region

Forward D_0 production at LHC

LHCb, JHEP 1710 (2017) 090

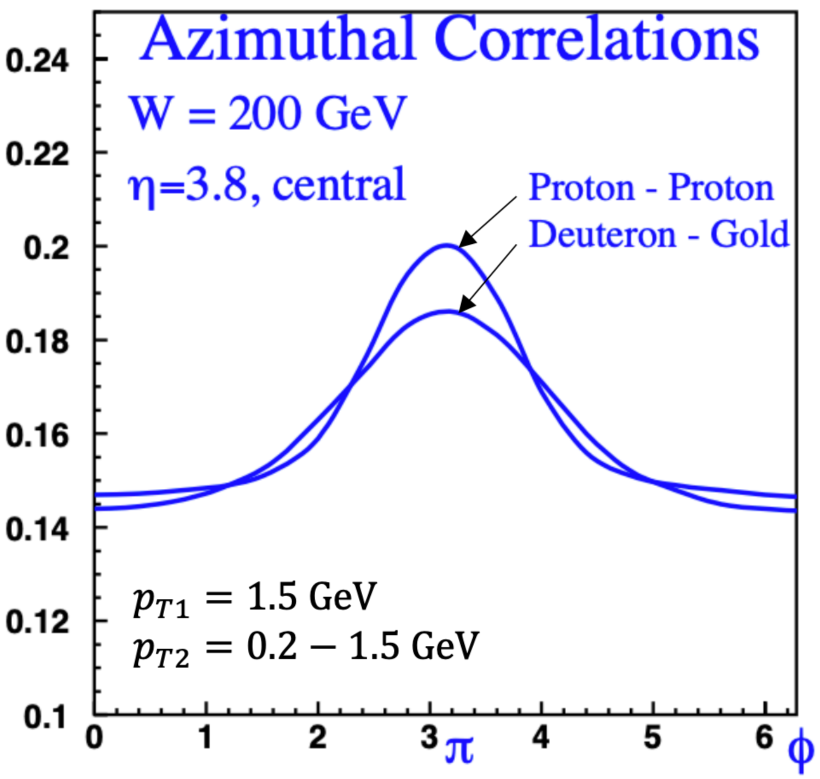


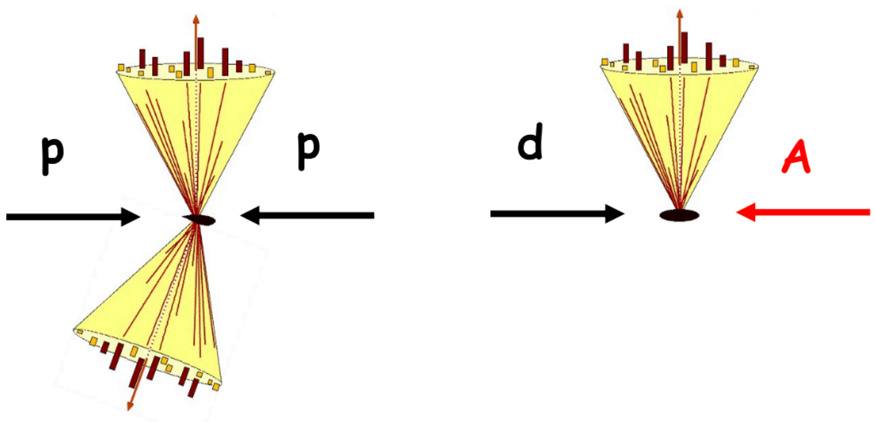
- Weakness of D meson production at forward rapidity, not at large x in backward direction

Di-hadron measurement

- **CGC** successfully predicted the strong **suppression of the inclusive hadron yields** in p(d)+A 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





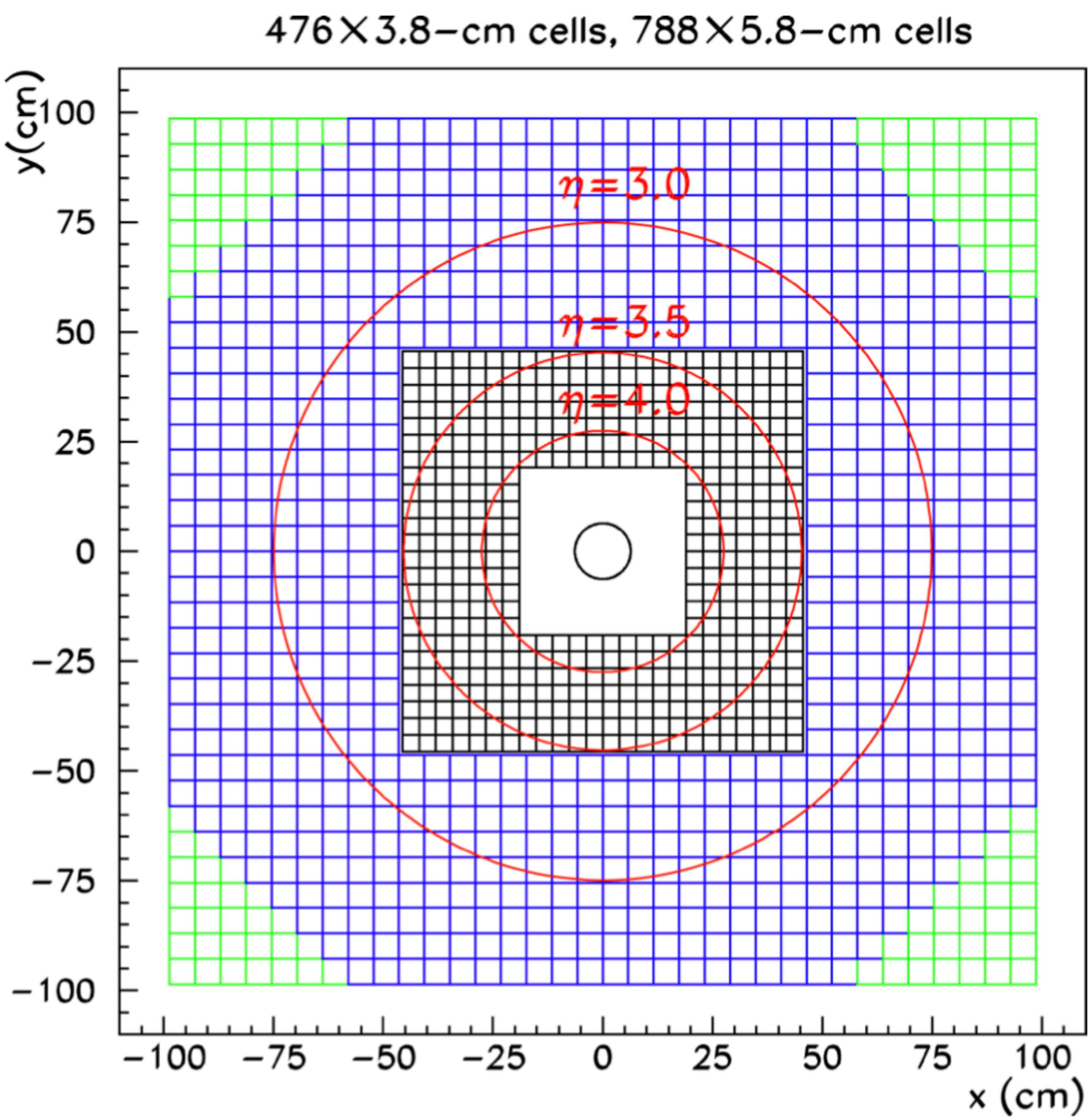
Observable: $C(\Delta\phi) = \frac{N_{pair}(\Delta\phi)}{N_{trig} \times \Delta\phi_{bin}}$

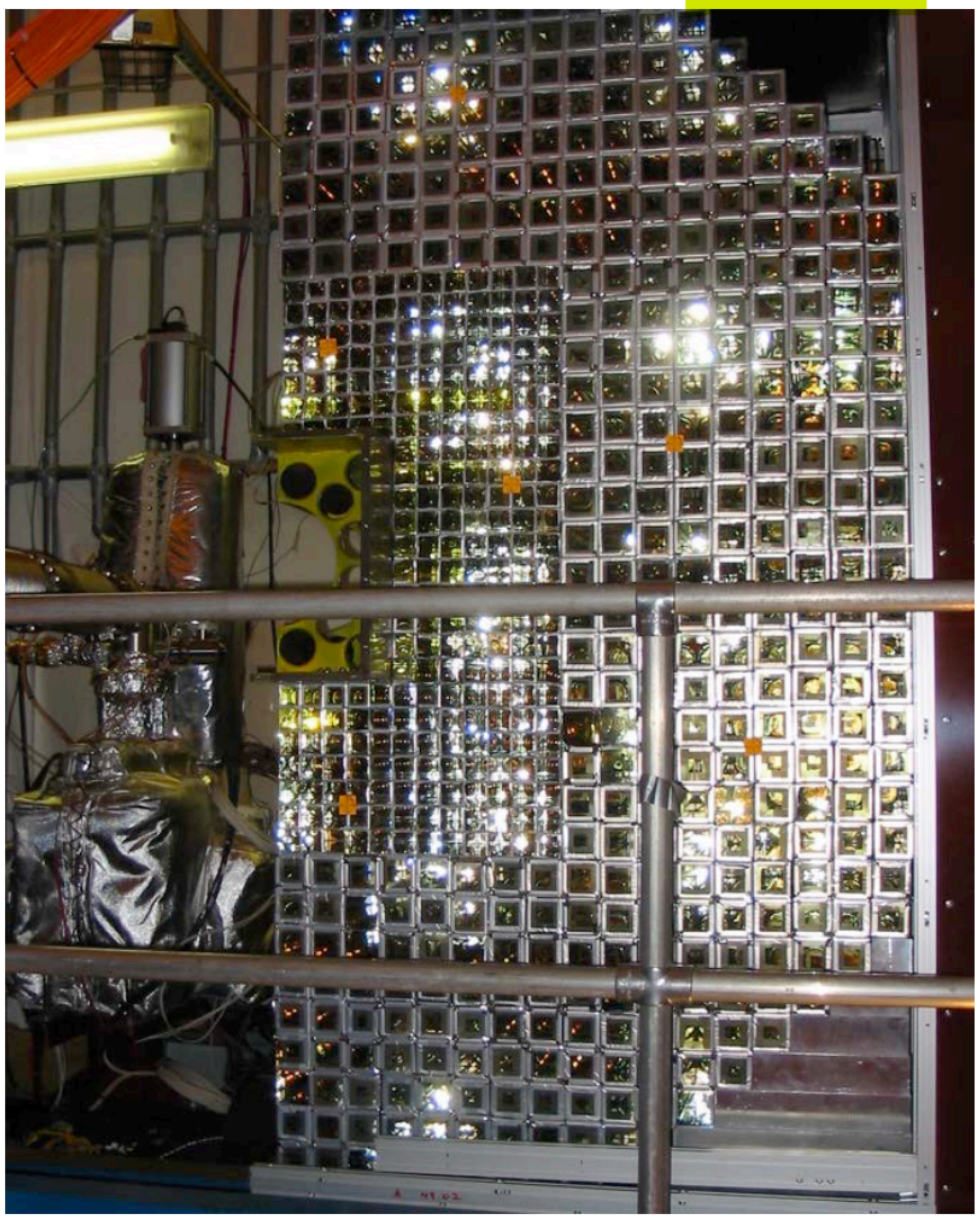
- Di-hadron in p+p as baseline: 2-to-2 process

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

- Following theoretical predictions on di-hadron:

STAR Forward Meson Spectrometer: FMS





Pb-glass EM calorimeter covering 2.6 < η < 4 and full azimuth

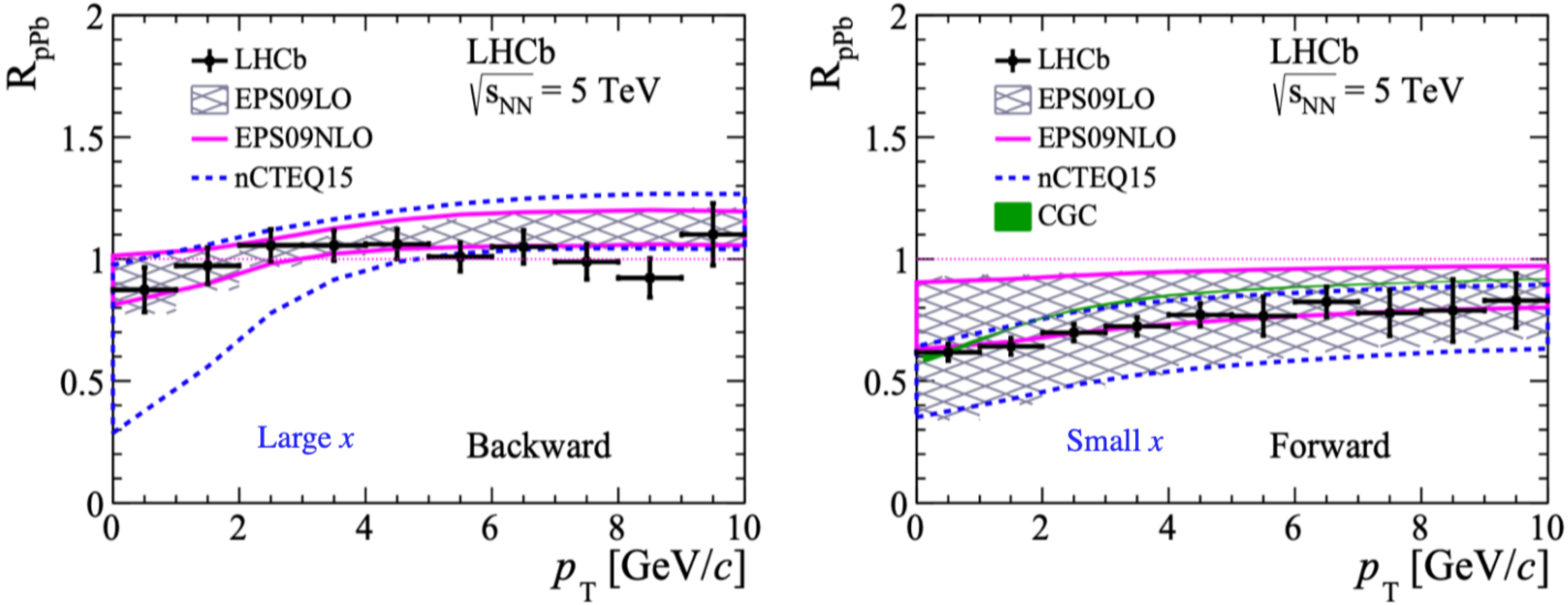
– Neutral pions / eta / EM jet-like events

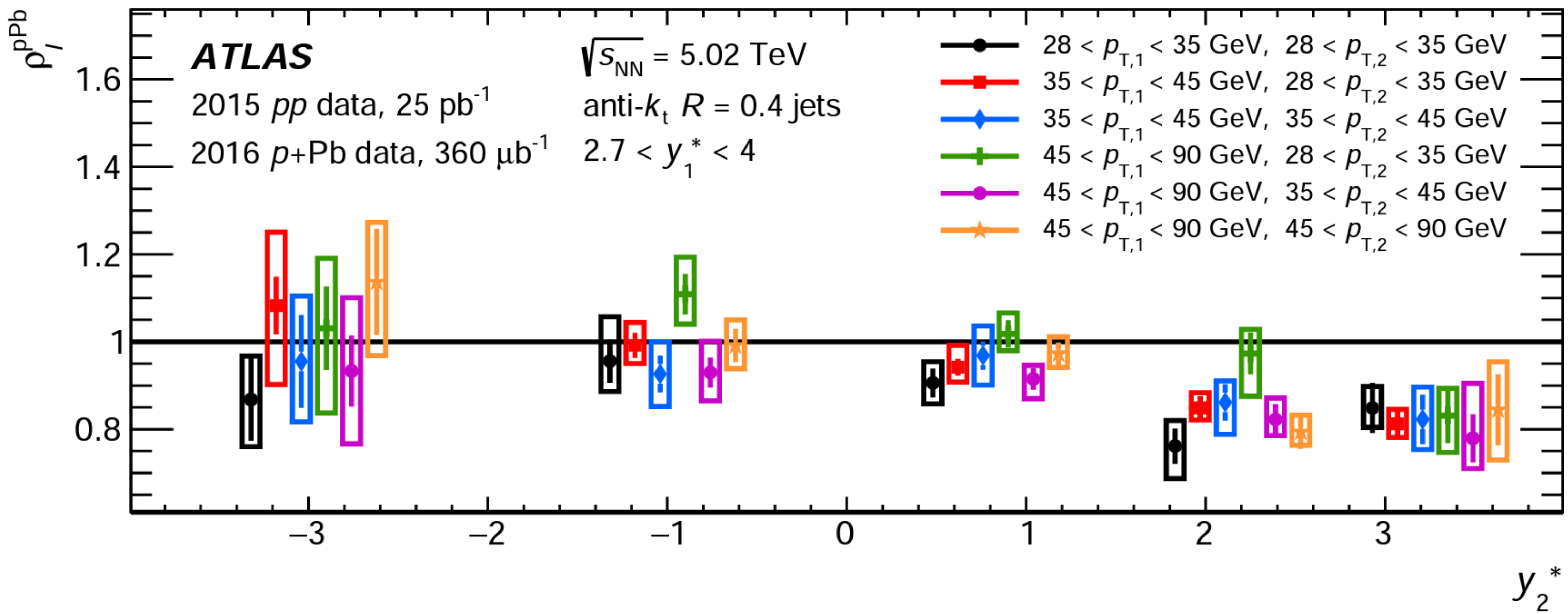
– Direct photons with addition of Pre-shower before 2015 run

– Drell-Yan and *J/ψ* with addition of Post-shower before 2017 run

LHC results

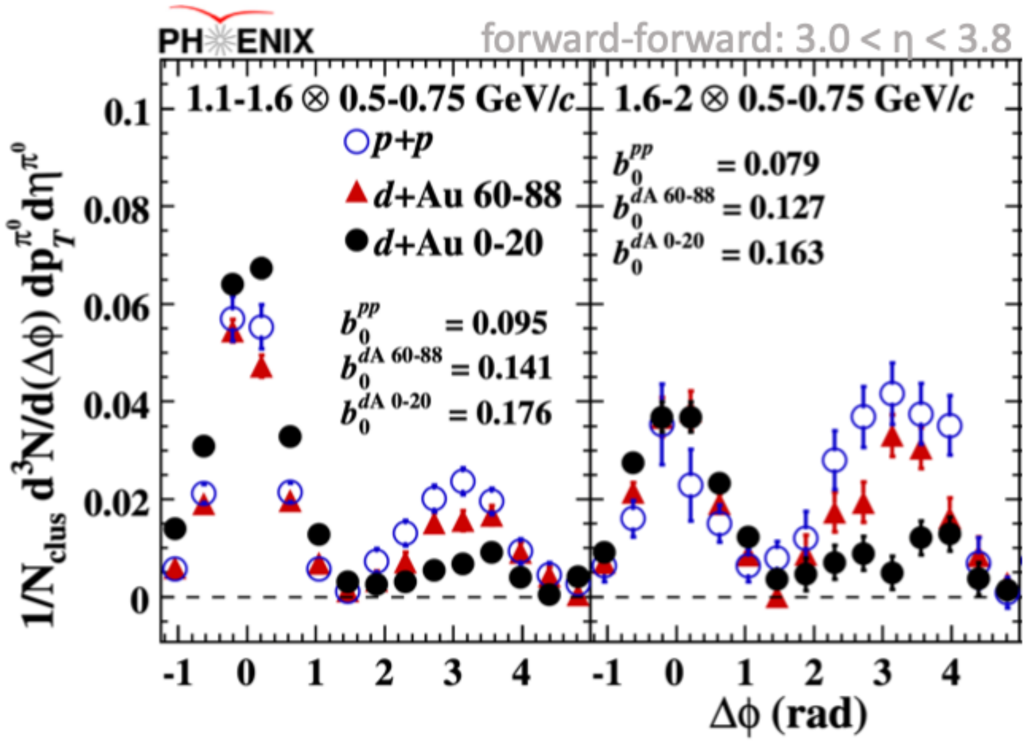
LHCb, JHEP 1710 (2017) 090

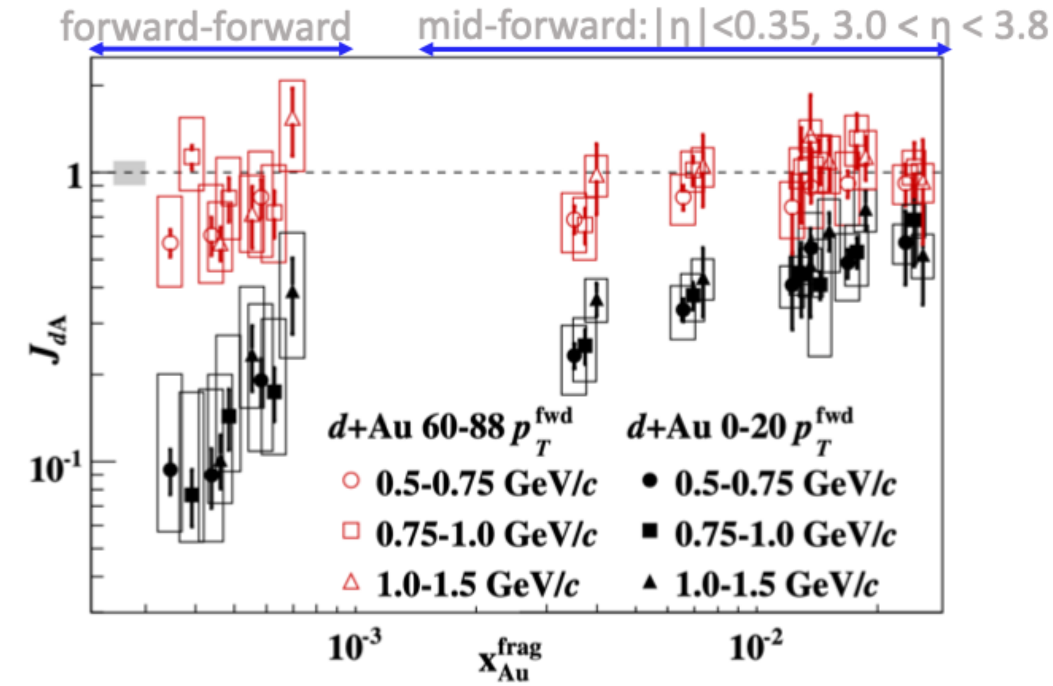




BFKL: $$\frac{\partial N(x, r_T)}{\partial \ln(1/x)} = \alpha_s K_{\mathrm{BFKL}} \otimes N(x, r_T). \qquad N \sim (1/x)^{\lambda}$$

BK: $$\frac{\partial N(x, r_T)}{\partial \ln(1/x)} = \alpha_s K_{\mathrm{BFKL}} \otimes N(x, r_T) - \alpha_s [N(x, r_T)]^2$$



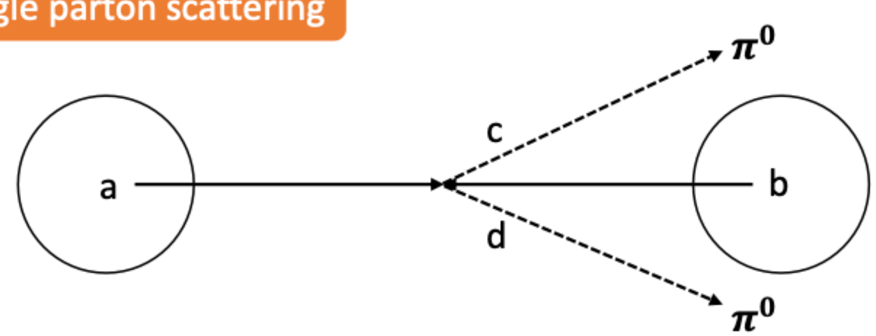


$J_{dA} = R_{dAu} \times I_{dAu}$

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

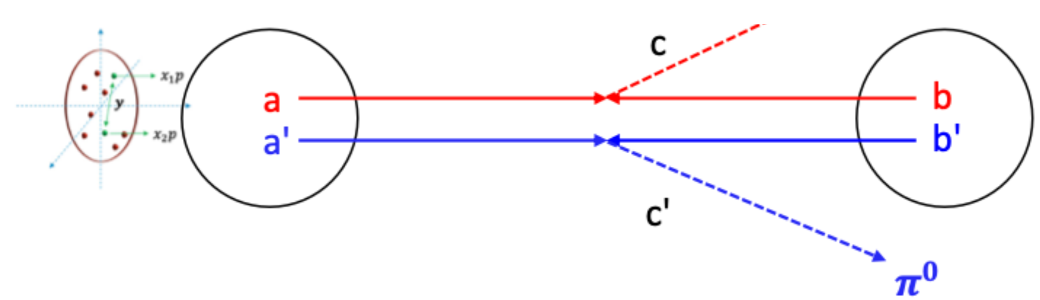
- Away-side correlation: suppression dependence on rapidity and centrality is studied by PHENIX

Single parton scattering

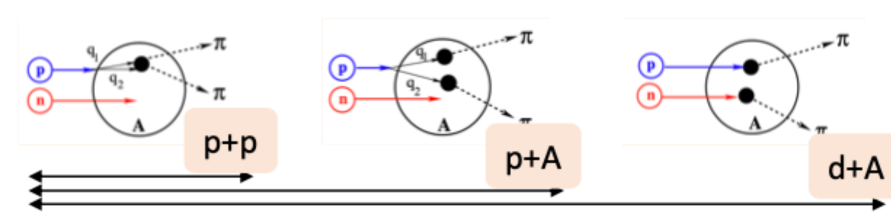


Double parton scattering

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



Two π^0 generated from the same hard 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?