Low-x and diffraction measurements at RHIC

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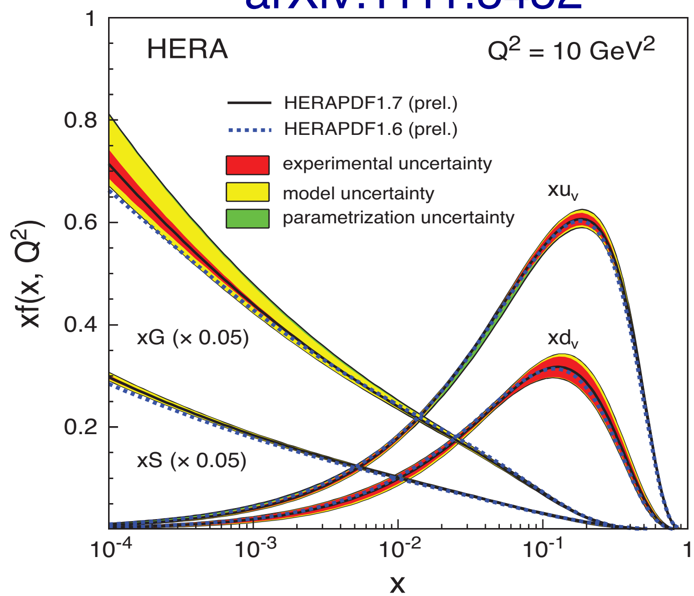
Outline

- Gluon saturation observables and measurements at RHIC
  - Di-hadron/jet correlations
  - R_{pA}
  - Ridge and v_2-like behaviors in p-A : link to pre-thermalization glasma, or thermalized hydrodynamics in small system?
  - A_N in polarized proton-Au collisions
- Diffraction measurements in STAR using forward tagged proton
- Summary and outlook

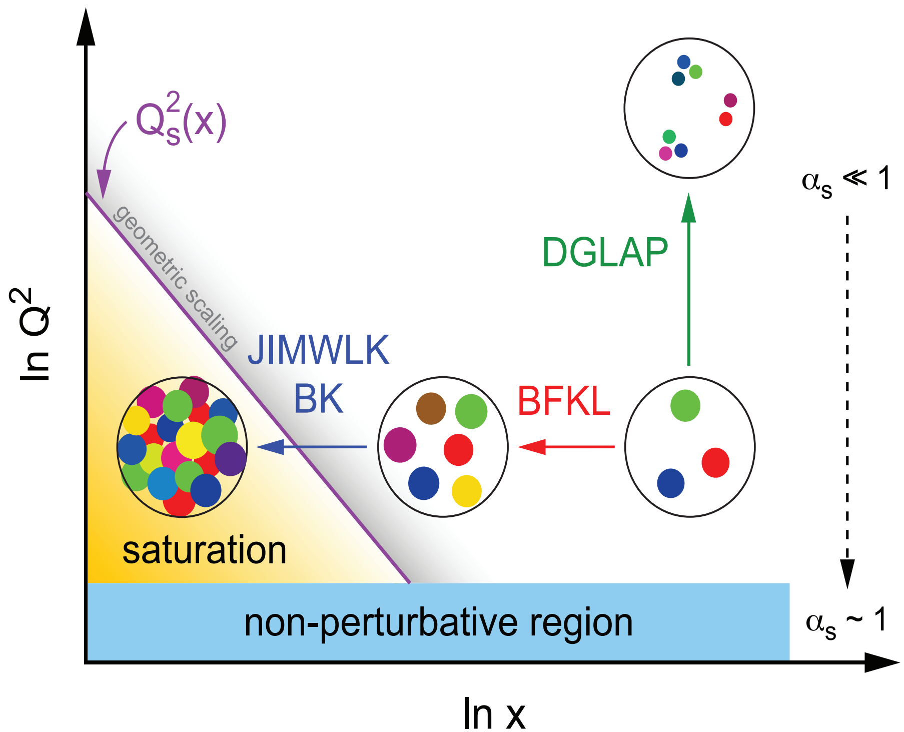
Gluon Saturation

arXiv:1111.5452



Low x → forward rapidity

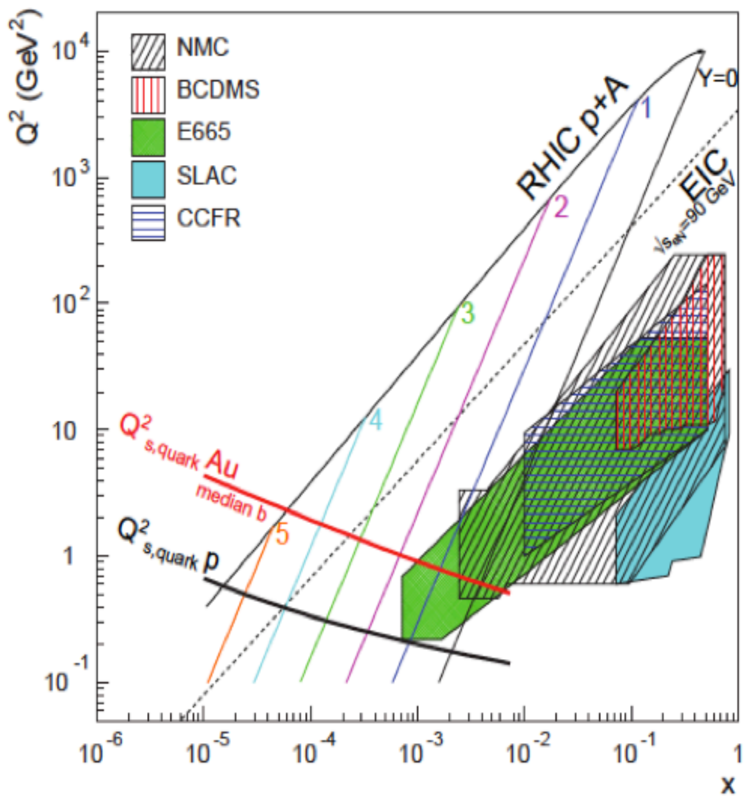
$$x \sim \frac{2p_T}{\sqrt{s}} e^{-y}$$



Forward rapidity ← midrapidity

- Densities of gluons and sea quarks are **high at low x**
- **Leading to Saturation of parton density,** called **C**olor **G**lass **C**ondensate (CGC).

What do we expect at RHIC?

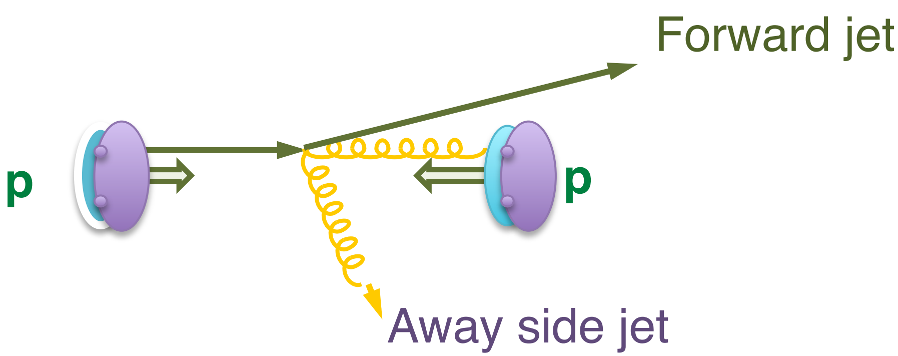


$$(Q_s^A)^2 \approx cQ_0^2\left(\frac{A}{x}\right)^{1/3}$$

Nuclei may allow access to the saturation region at moderate p_T

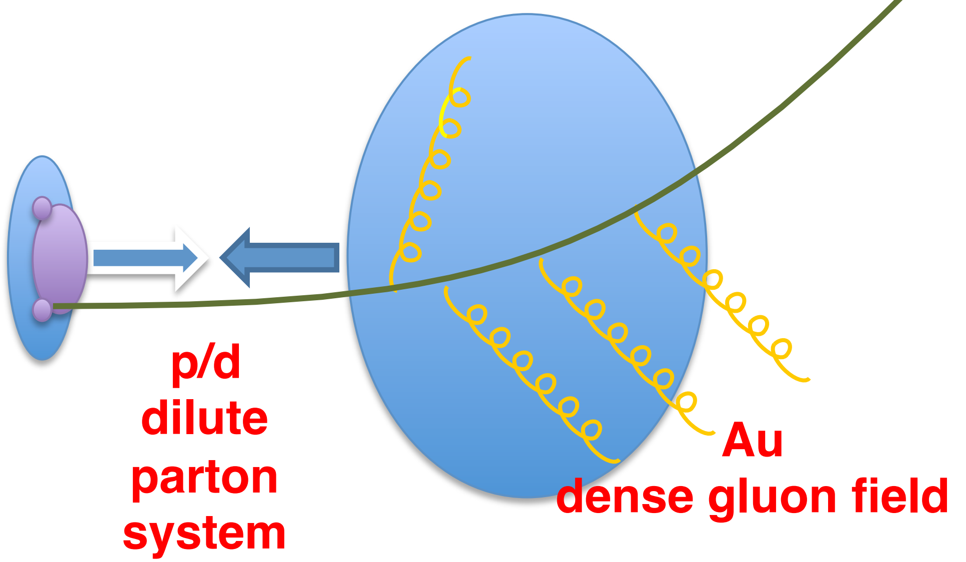
η = 2.5-4.0 in RHIC is a promising region!

Observables : Azimuthal Correlations



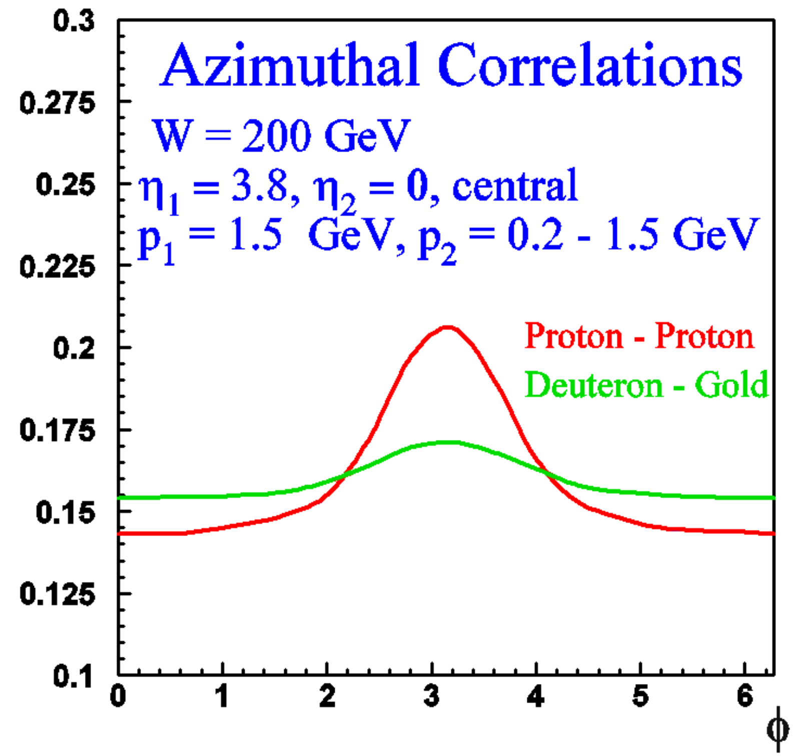
With high gluon density

2→1 (or 2→many) process   Mono-jet



Azimuthal Correlations :

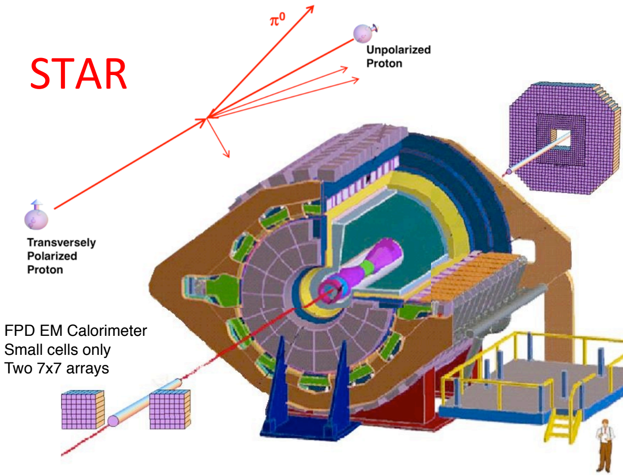
- **Jet-Jet**
- **Di-hadron**



Kharzeev, Levin, McLerran (NPA748, 627)

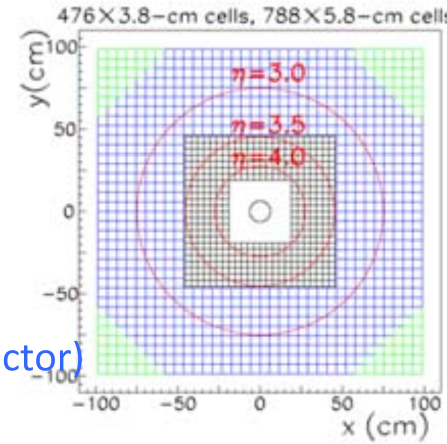
STAR and PHENIX at forward rapidity

STAR

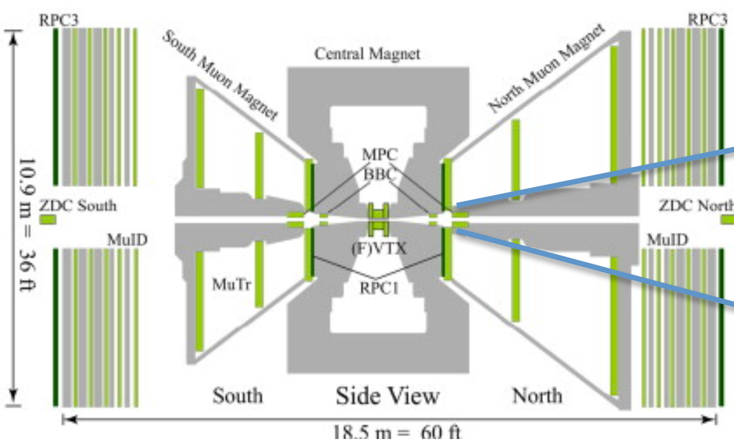


Forward Meson Spectrometer - FMS

2.5< η <4.0, -π<ϕ<π
Detect - π^0,η,
direct photons
(with pre-shower detector)

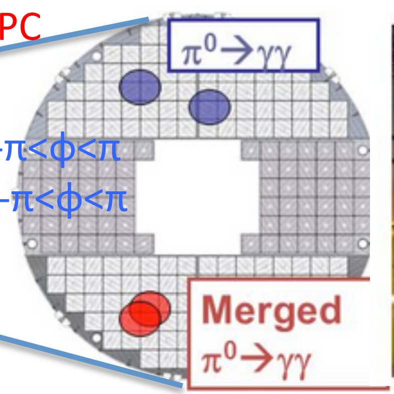


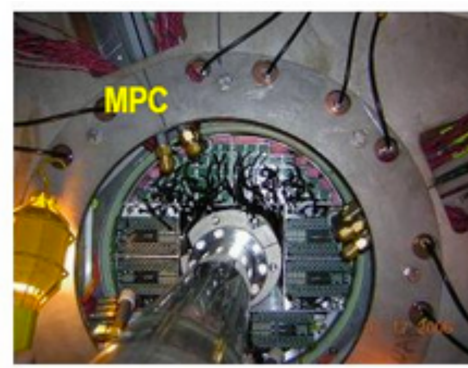
PHENIX



Muon Piston Calorimeter - MPC

3.1 < η <3.9, -π<ϕ<π
-3.1 < η <-3.7, -π<ϕ<π
Detect - π^0,η

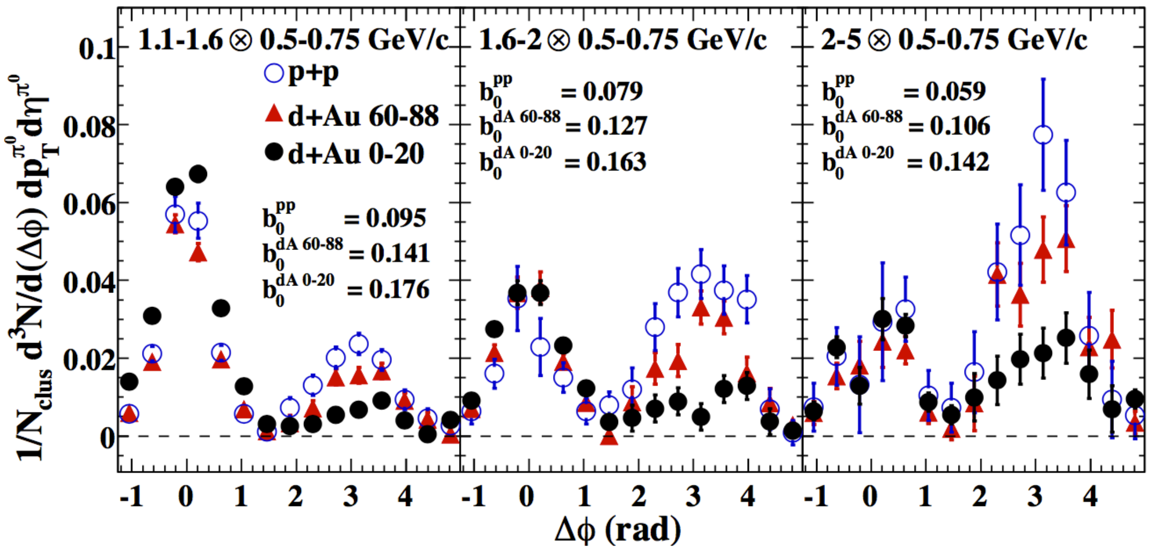




Both STAR and PHENIX capable of doing low x physics with neutral particles

Back-to-back angular correlations

PHENIX, PRL 107, 172301



CGC predicts suppression of the away-side peak.
PHENIX observed suppression of the away-side peak in 0-20% d+Au collisions at (√s = 200 GeV)

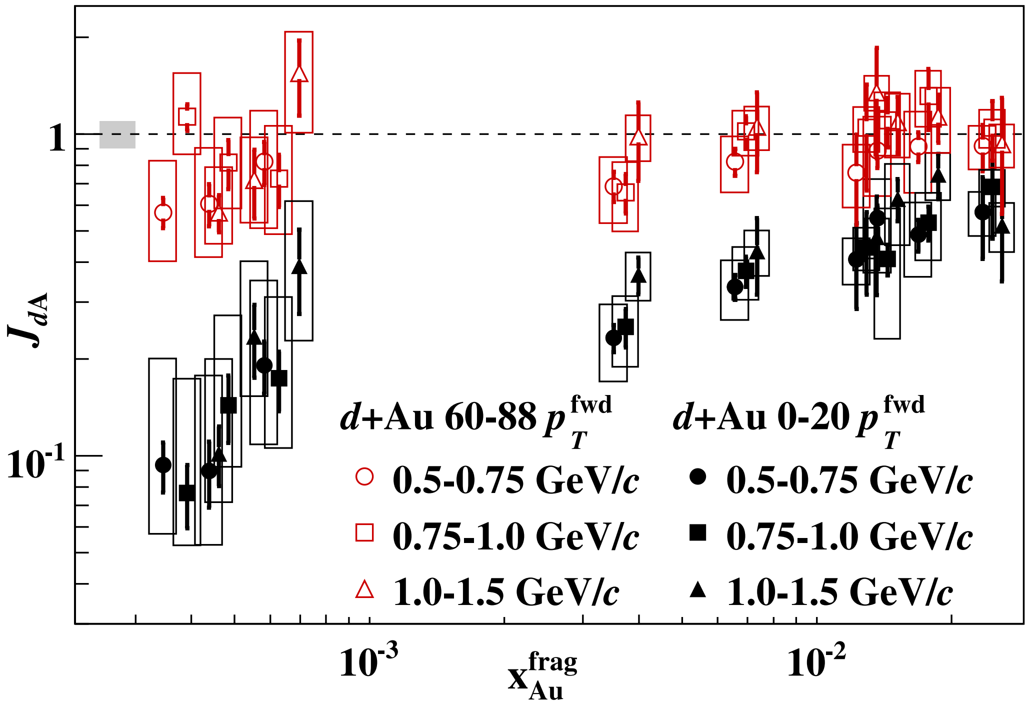
STAR 2015 data are being analyzed for π^0- π^0 and EM jet – EM jet azimuthal correlations in p+p, p+Al, p+Au (and d+Au in 2016)
Working on FMS gain uniformity and stability

Back-to-back angular correlations

$$J_{dA} = I_{dA} \times R^{t}_{dA} = \frac{1}{\langle N_{\rm coll}\rangle} \frac{\sigma^{\rm pair}_{dA}/\sigma_{dA}}{\sigma^{\rm pair}_{pp}/\sigma_{pp}}$$

PHENIX : PRL 107, 172301

$$x^{\rm frag}_{\rm Au} = (\langle p_{T1}\rangle e^{-\langle\eta_1\rangle} + \langle p_{T2}\rangle e^{-\langle\eta_2\rangle})/\sqrt{s_{NN}}$$



- Large suppression of J_{dA} at low x

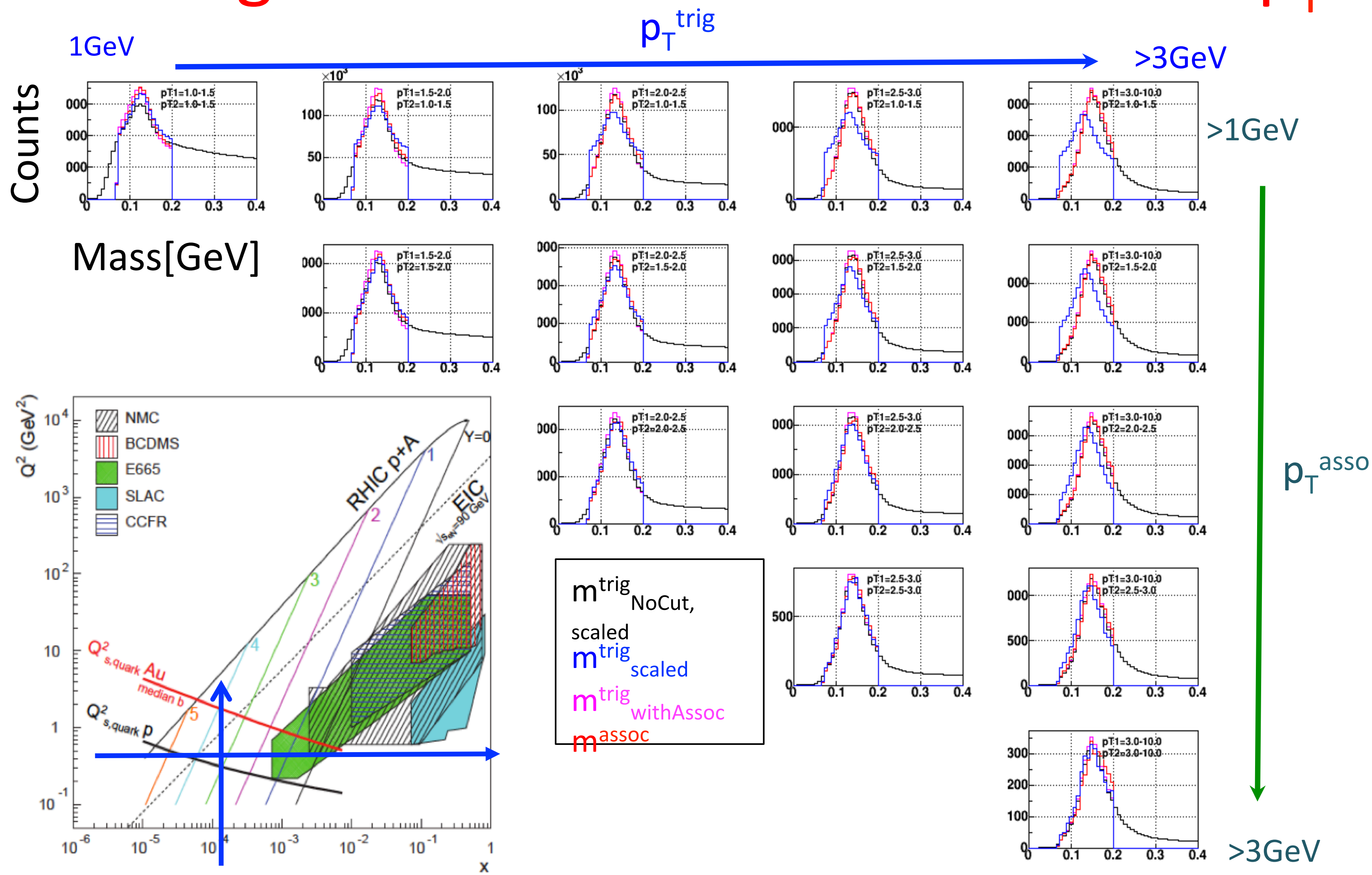
- Need to understand nuclear effect and multiparticle interaction for produced final state particles.

- Might not probe gluon saturation

Measurement with direct photons is very important :

- STAR 2015 pA data is being analyzed for direct photons

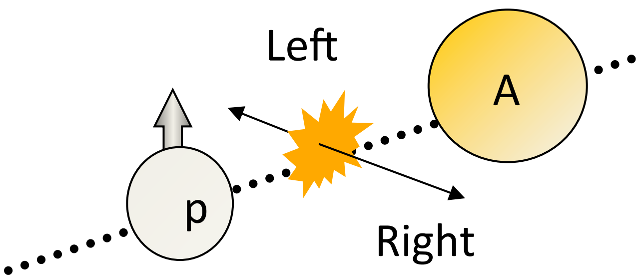
Scanning the FMS π^0- π^0 correlations in p_T



With 2015 data STAR can study evolution of Q_s^2 (x) with A

π^0 in Polarized p+A as a tool to study Gluon saturation

$$A_N = \frac{1}{P}\frac{\sigma_L^{\pi} - \sigma_R^{\pi}}{\sigma_L^{\pi} + \sigma_R^{\pi}}$$



$$\left.\frac{A_N^{pA\to h}}{A_N^{pp\to h}}\right|_{P_{h\perp}^2 << Q_{sA}^2} \approx \frac{Q_{sp}^2}{Q_{sA}^2} e^{P_{h\perp}^2 \delta^2 / Q_{sp}^2}$$

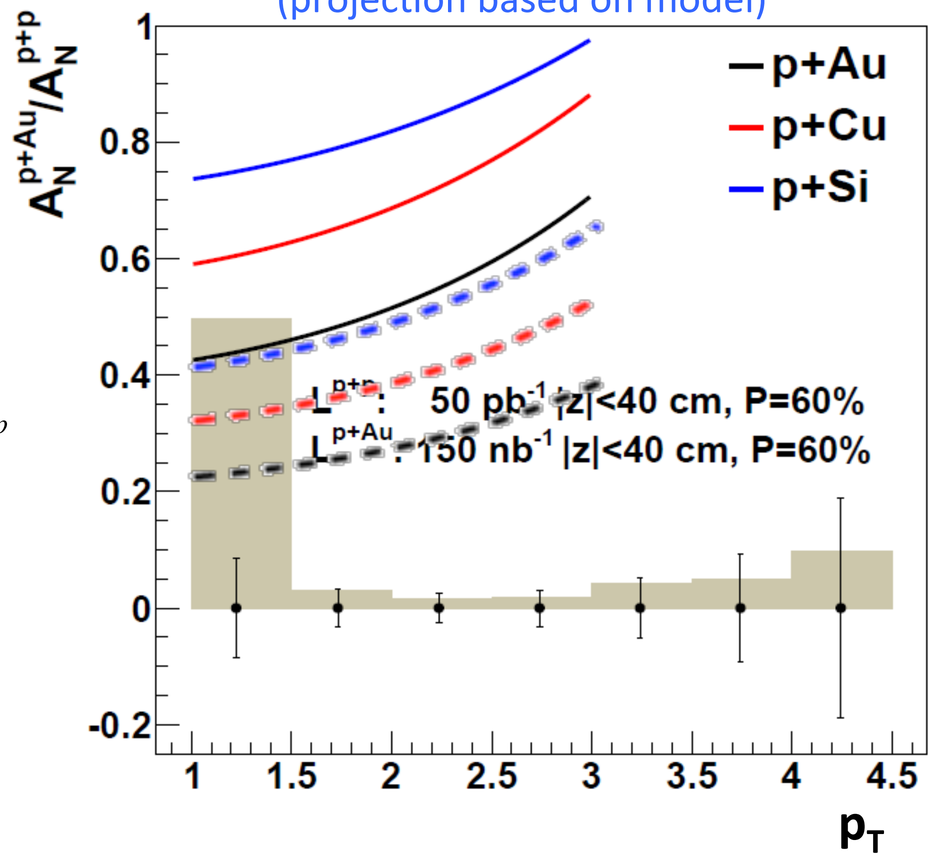
$$Q^2_{sat,A} = cA^{1/3} Q^2_{sat,proton}$$

PRD 74, 074018

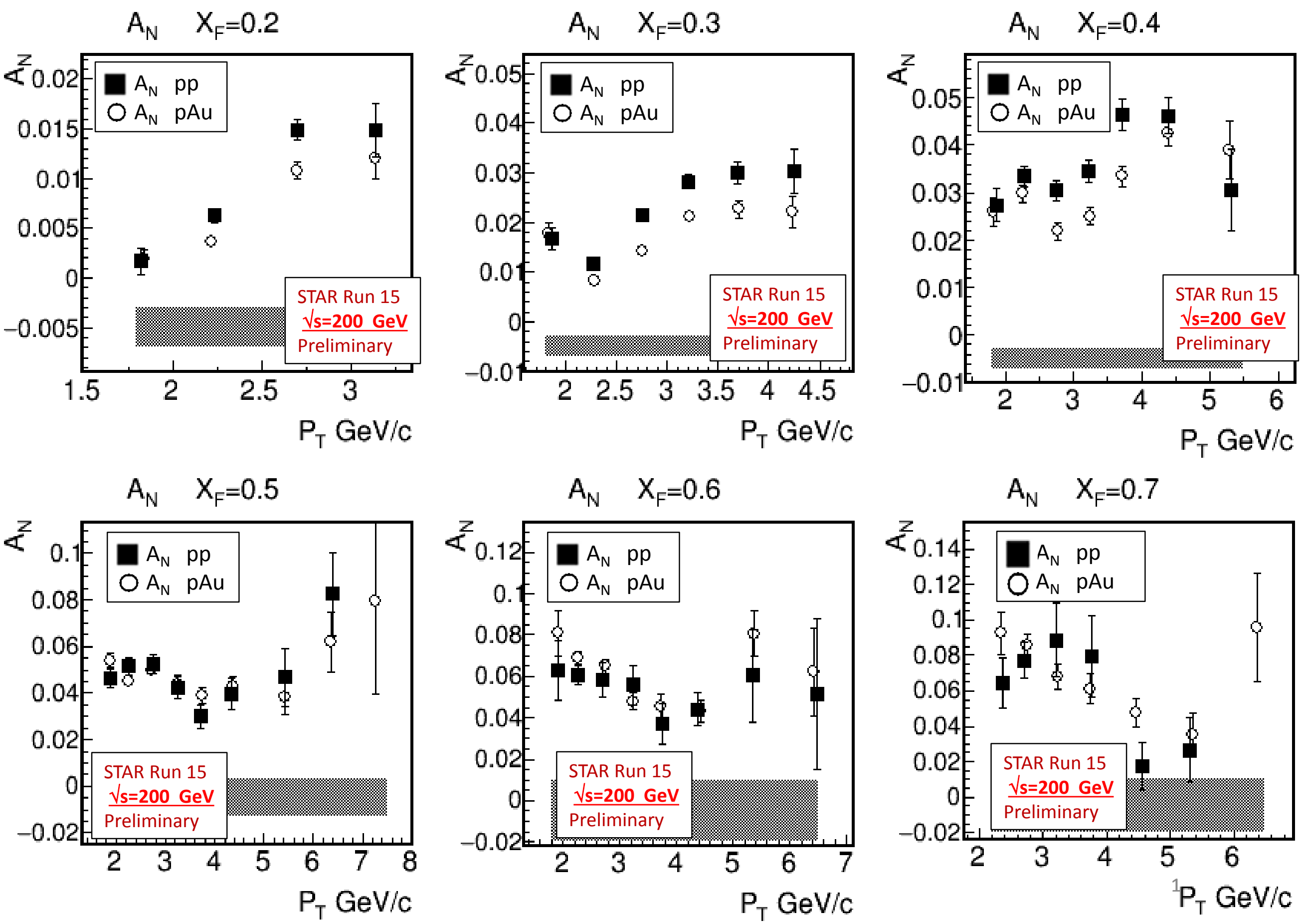
p,d,e+A Workshop - June 25, BNL, 2013: Richard Seto

$Q^{proton}_{sat,gluons} = 1.0\ GeV^2$ $c = 1.0$ (nuclear diluteness)

(projection based on model)



First π^0 results from polarized p+Au

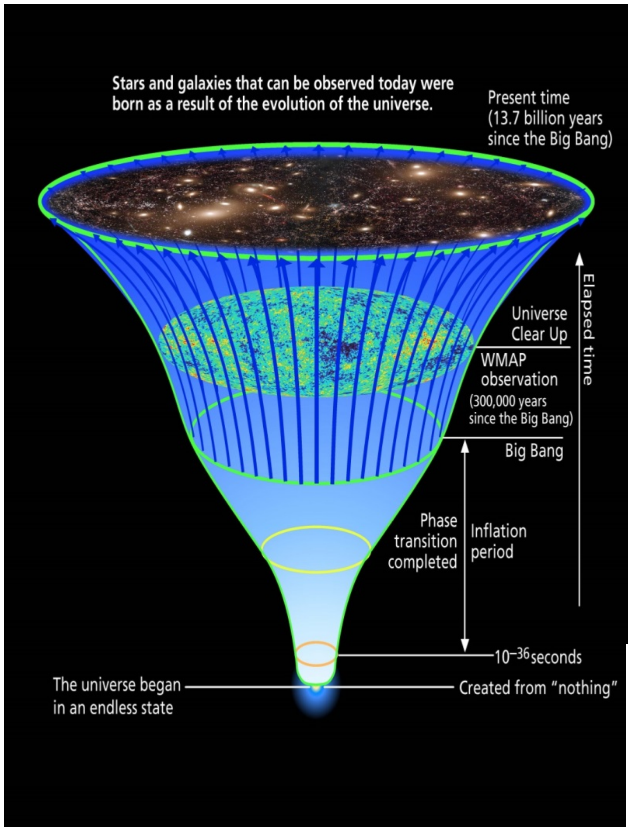


Shaded bands show systematic uncertainty, dominated by dependence of A_N on observed BBC multiplicity → central vs. peripheral collisions

Preliminary results from STAR find little suppression in A_N as suggested by some CGC calculations

Small system : p+Pb, d+Au

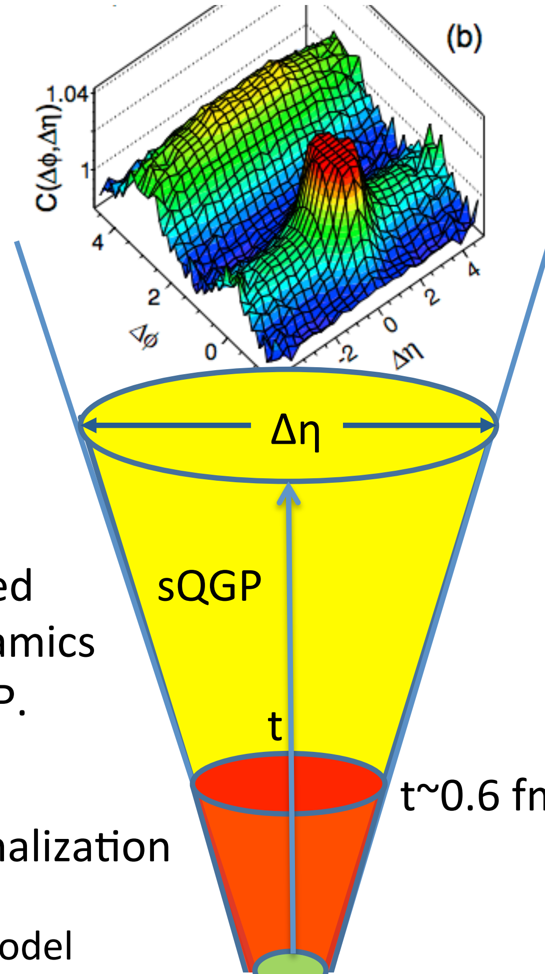
Glasma? Long range rapidity Correlations
Initial state fluctuations “inflated” to long range correlations?
Flow? sQGP in small systems?



ATLAS data in Glasma model
Q_0^2(proton)=0.168 GeV^2
Dusling, Venugopalan
PRD 87, 094034

Thermalized
Hydrodynamics
Flow: sQGP.

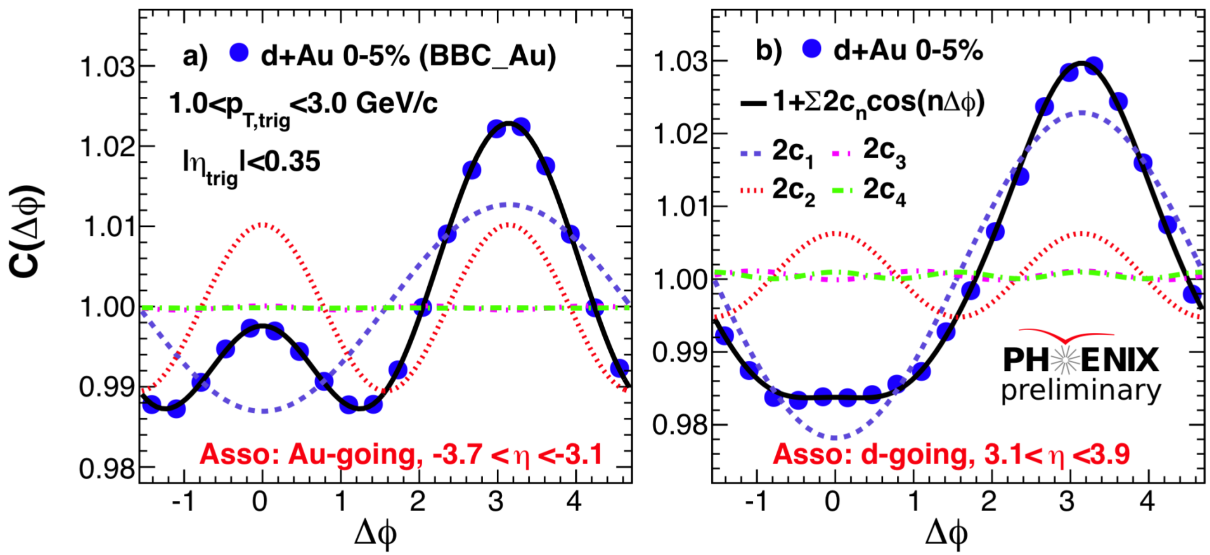
Pre-thermalization

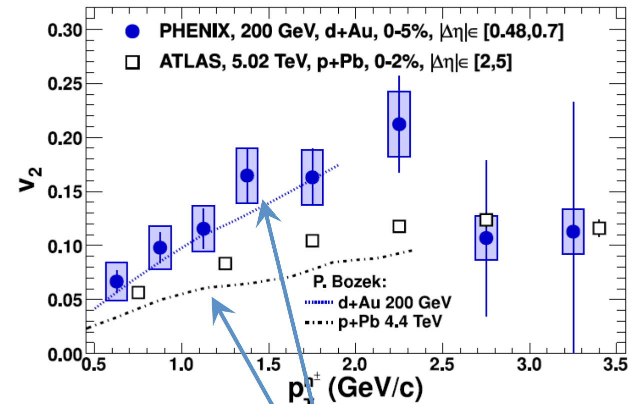


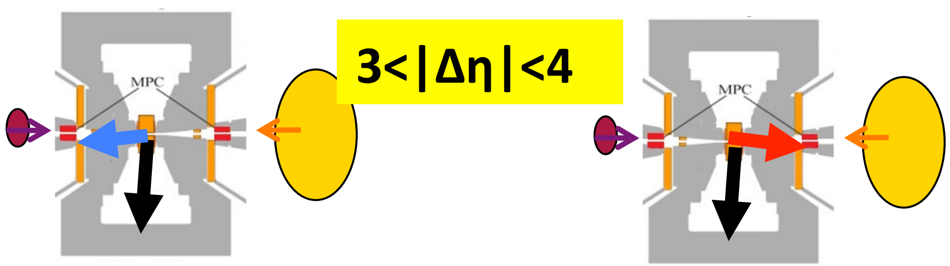
Initial state
Color Glass Condensate?
t=0.0 fm

Mid-Forward Particle/Energy Correlations

d+Au : *Phys. Rev. Lett. 114, 192301*
He^3+Au : *Phys. Rev. Lett. 115, 142301*
P+Au : *arXiv 1609,02894*







Hydrodynamic Calculations
P. Bozek PRC 85, 014911

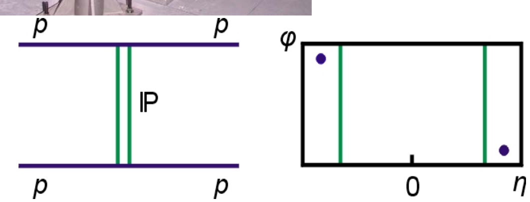
Need better understanding : Initial state – Glasma? Final state effect - Flow (Hydro) in a thermalized sQGP?

Diffraction measurements

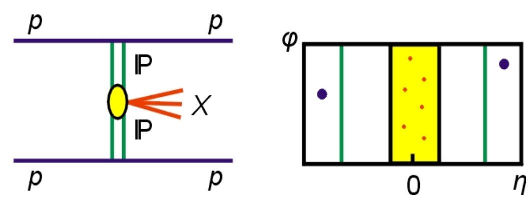
Roman pots in STAR

- Roman pots installed prior to 2009 RHIC run – Phase-I
- In phase-II roman pots were moved much closer prior to 2015 RHIC run (operate with normal beam optics)

Recorded a large fraction of the total delivered luminosity in the 2015 ($\sqrt{s}$ = 200 GeV) and 2017 ($\sqrt{s}$ = 500 GeV)



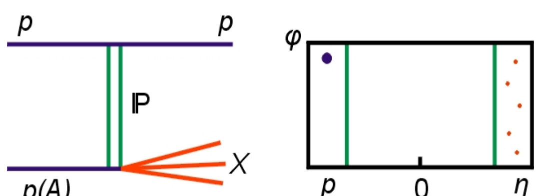
Elastic scatterings



Central Exclusive Production (CEP)

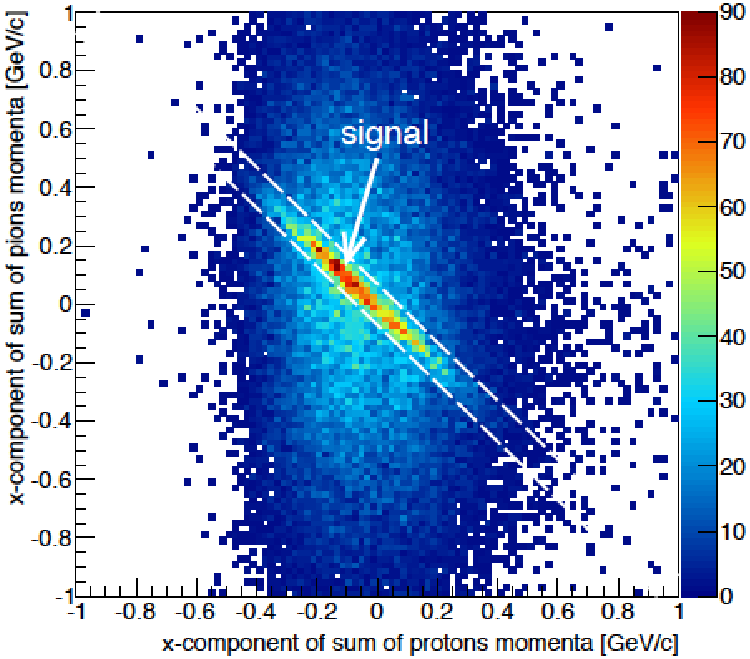
p+p → p + X + p

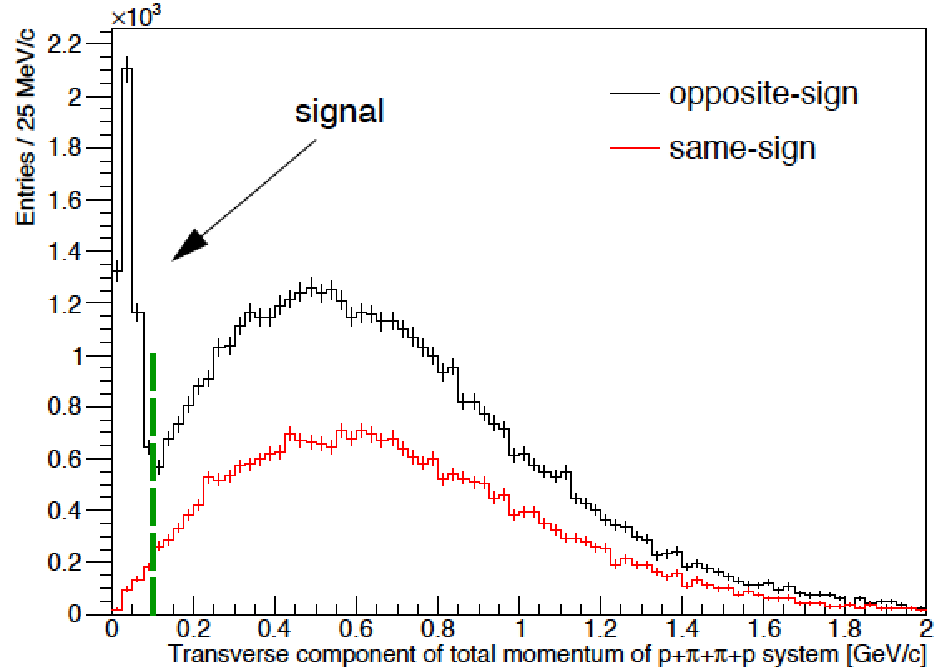
Diffractive X = particles, glueballs



Single Diffractive Dissociation

Identifying CEP : the $\pi^+\pi^-$ case

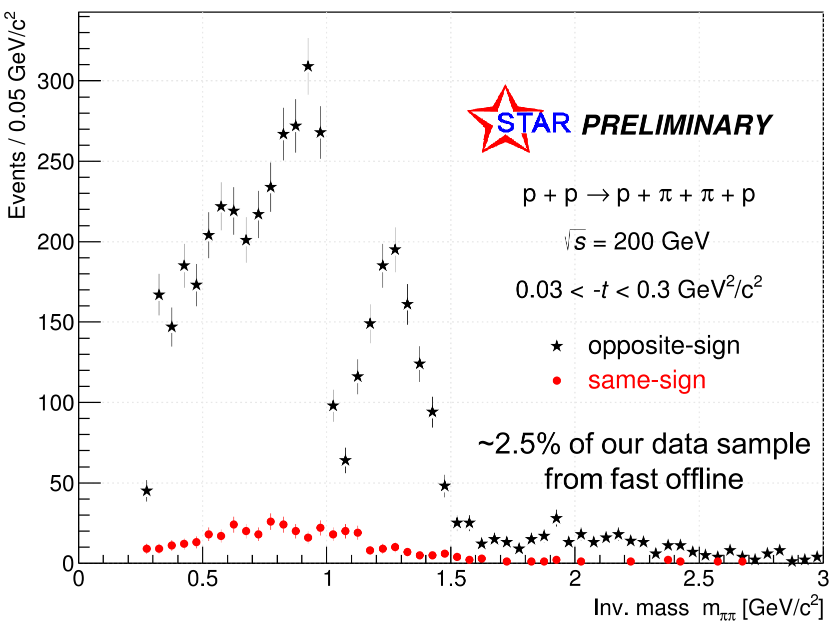


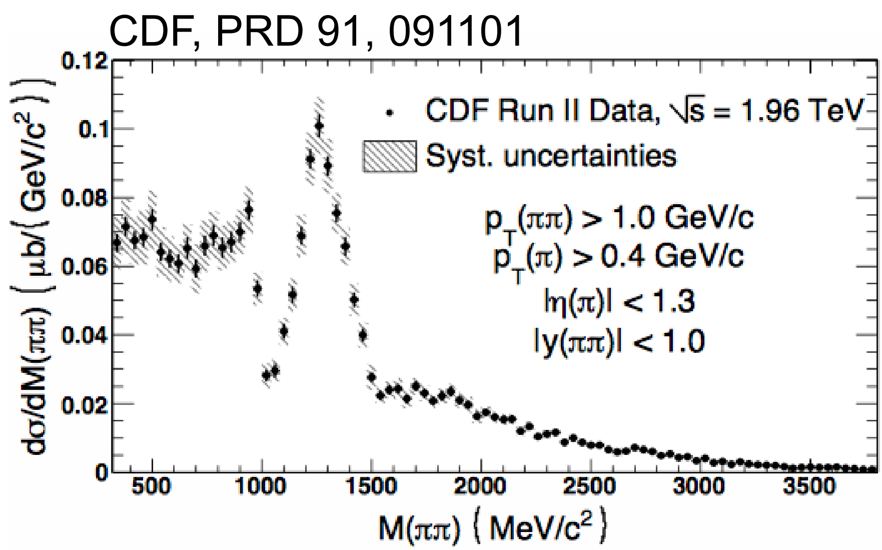


Identification and momentum reconstruction of all final state particles provide the ability to ensure exclusively of the system via momentum balance check

Very small background!

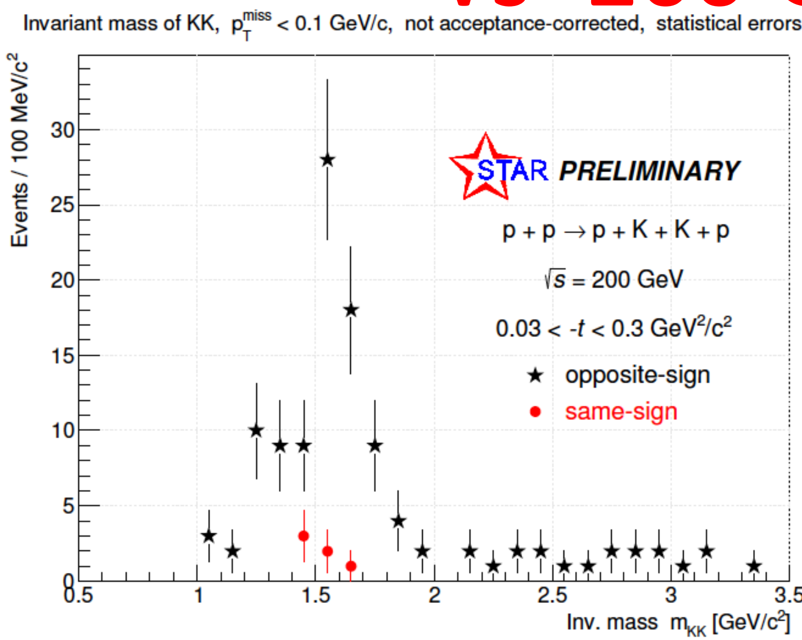
$\pi^+\pi^-$ invariant mass distributions at √s=200 GeV

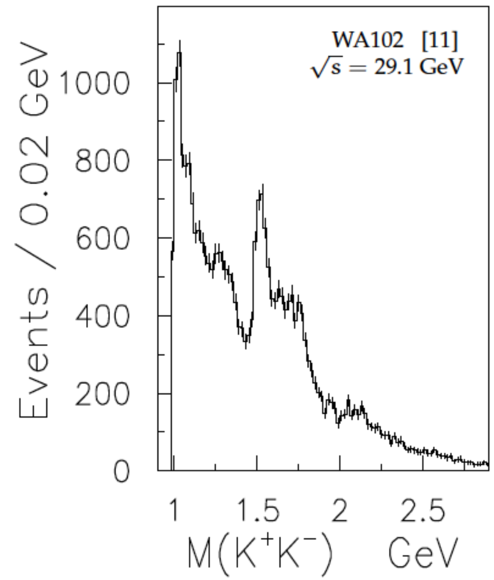




- Broad structure extending from $\pi^+\pi^-$ threshold to ~1GeV/c²
- Sharp drop at about 1 GeV/c²
- Resonance-like structure between 1-1.5 GeV/c²
  (Expect ~70k events with M($\pi^+\pi^-$) > 1 GeV/c² from full 2015 data set
- Essential features are similar to measurements in p+p collisions at √s=63 GeV (AFS at ISR) and p+p-bar at √s=1.96 TeV (CDF)

K^+K^- invariant mass distributions at $\sqrt{s}$=200 GeV





- Prominent peak around 1.4-16 GeV/c²
- Some enhancement in the f2(1270)/f0(1370) region
- In spectrum measured by WA102 (fixed target), there is significant contribution from f0(980) not seen by STAR
  (K acceptance is very small at such low p_T)

- Expect ~10^4 exclusive K^+K^- events in the full 2015 data set
  (Will permit cross section and partial wave analysis)

Summary

- RHIC probes at low x region of nuclei with forward detectors where gluon saturation effects may manifest themselves.
- Previous RHIC measurements showed a hint of saturation in 0-20% d+Au collisions. STAR 2015 p+A data is being analyzed for π^0- π^0 and EM jet – EM jet azimuthal correlations.
- PHENIX data show long range correlations in ridge like structure for small systems : Glasma or Flow effects?
- Preliminary measurement of A_N for polarized p+A collisions shows little suppression.

- $\pi^+\pi^-$ and K^+K^- mass distribution for Central Exclusive Production (CEP) extracted from a fraction of the available data. Results from the full statistics are under-way.

- For 2021+ both STAR and sPHENIX planning for forward detector upgrades to measure fully reconstructed jets at forward rapidities – a step forward for future EIC collider.

backup

Spin Dependent Cross section

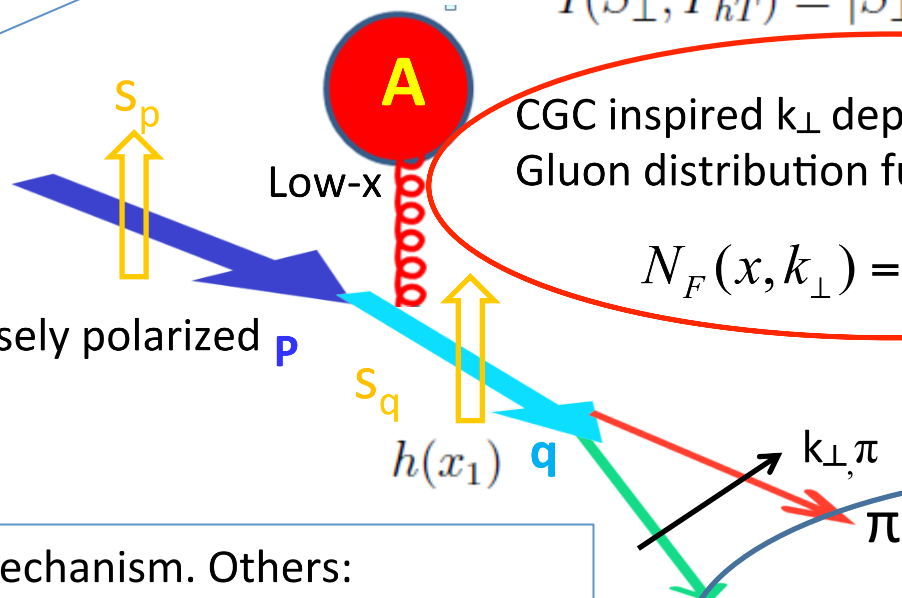
Kang, Yuan: PRD 84, 034019 (2011)

$$\frac{d\Delta\sigma}{dy_h d^2P_{h\perp}} = \frac{K}{(2\pi)^2}\int_{x_F}^{1}\frac{dz}{z^2}\int d^2P_{hT} I(S_\perp, P_{hT}) x_1 h(x_1) N_F(x_2, k_\perp)\delta\hat{q}(z, P_{hT})$$

$$\mathbf{P}_{h\perp} \approx z\,\mathbf{k}_\perp + \mathbf{P}_{hT}$$

Relative to Quark jet

$$I(S_\perp, P_{hT}) = |S_\perp||P_{hT}|\sin(\phi_h - \phi_s)$$



CGC inspired k⊥ dependent unintegrated Gluon distribution function

$$N_F(x, k_\perp) = \frac{1}{Q_S^2} e^{-k_\perp^2/Q_S^2}$$

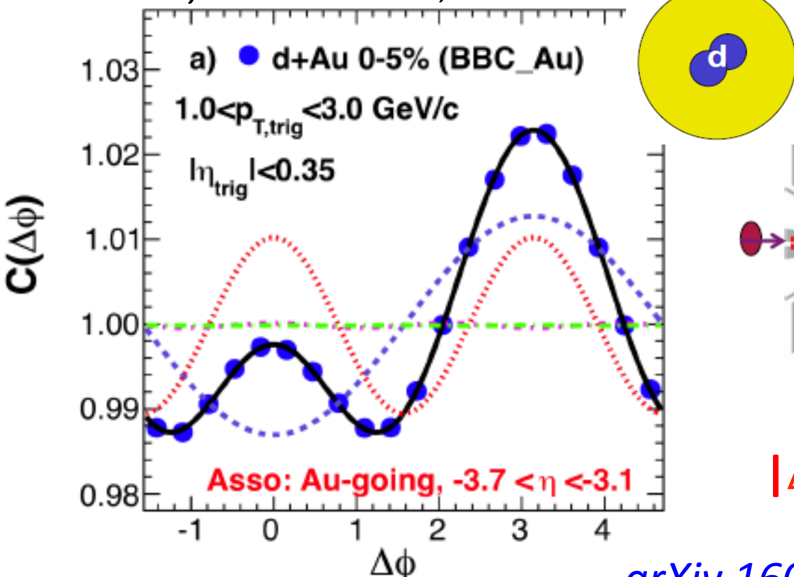
Collins Fragmentation Function

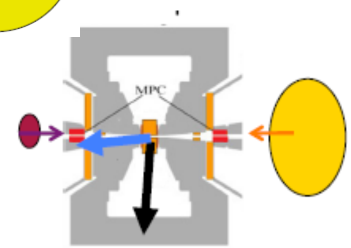
$$\delta\hat{q}(z, p_\perp^2) \sim \frac{1}{(\Delta^2 - \delta^2)^{3/2}} e^{-p_\perp^2/(\Delta^2-\delta^2)}$$

This is one mechanism. Others:
e.g. Sivers: see Boer et al. PRD 74, 074018
Kang-Xiao arXiv 1212.4309
Odderon (3 gluon)exchange: Yovchegov arXiv:1201.5890

The Ridge at RHIC

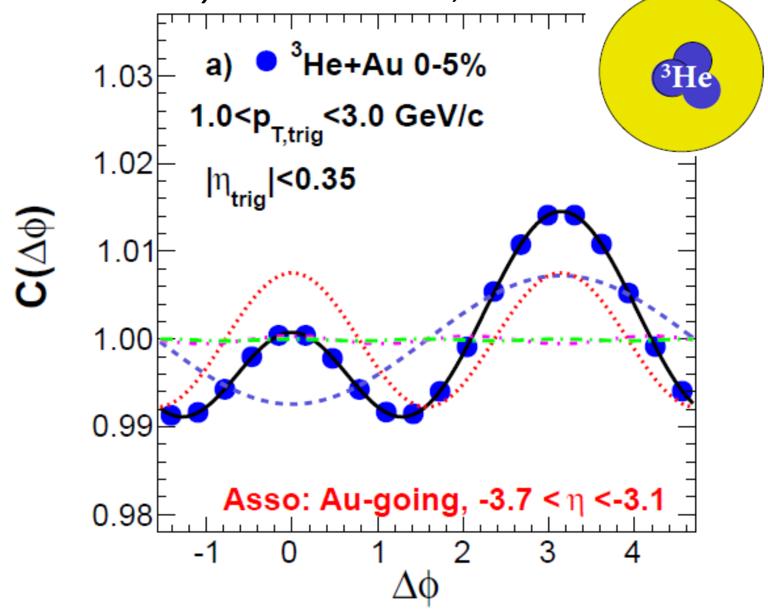
Phys. Rev. Lett. 114, 192301



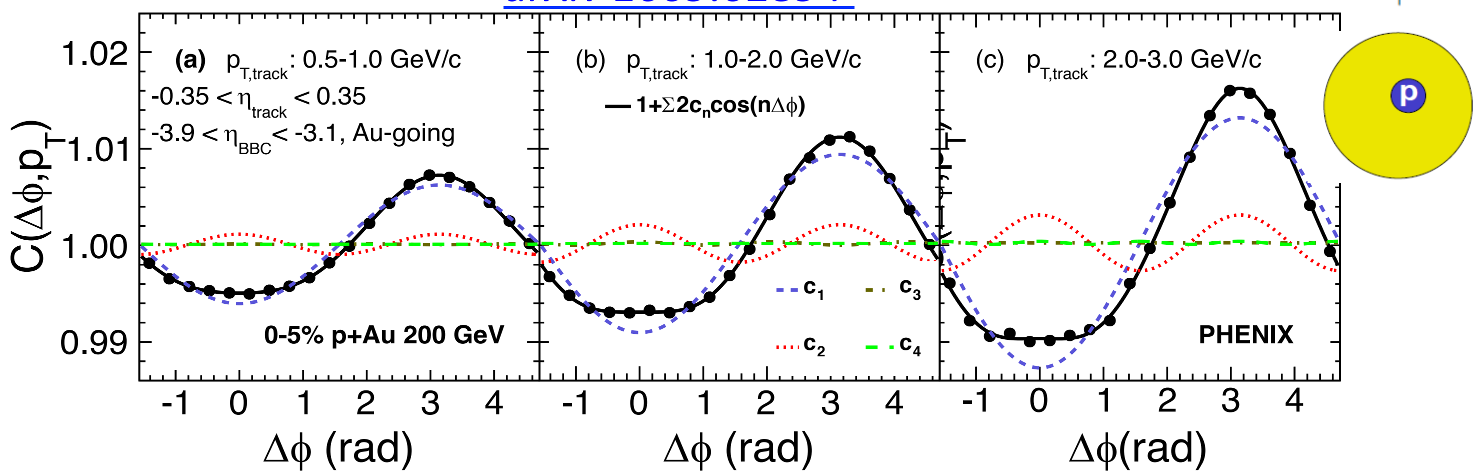


$|\Delta\eta|>2.75$

Phys. Rev. Lett. 115, 142301



arXiv 1609.02894



A clear ridge on the Au-going side in central d+Au, ^{3}He+Au; a more subtle effect in p+Au