Di-hadron correlations and implication of gluon saturation

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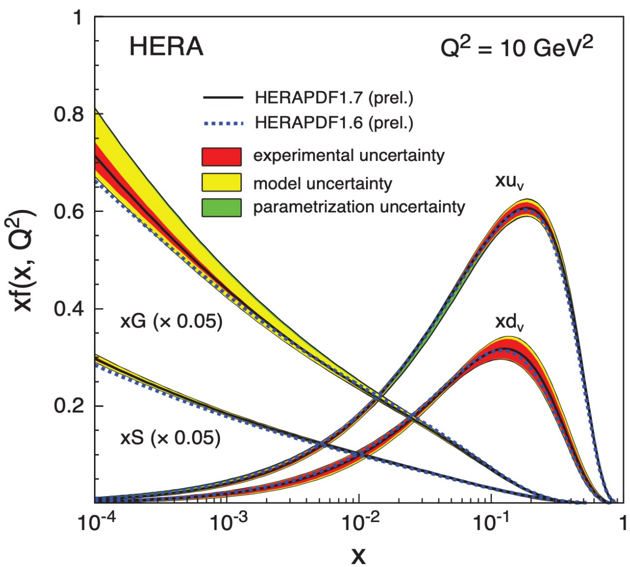
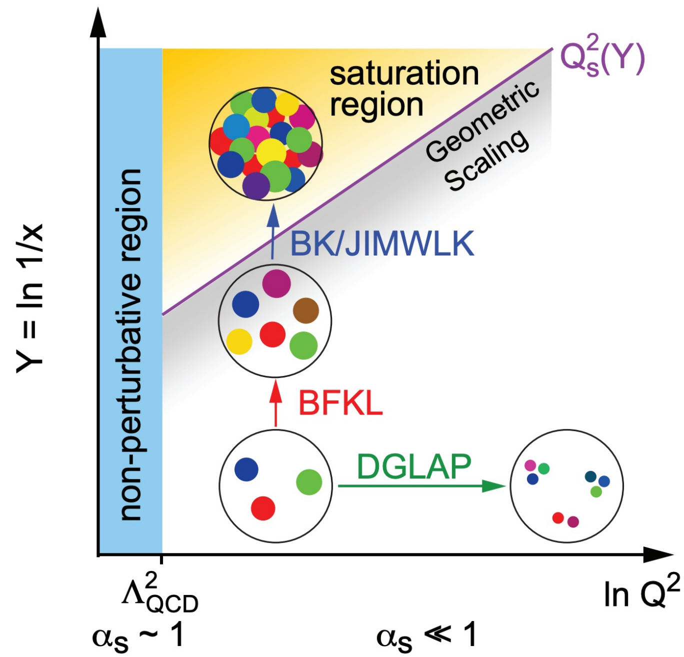
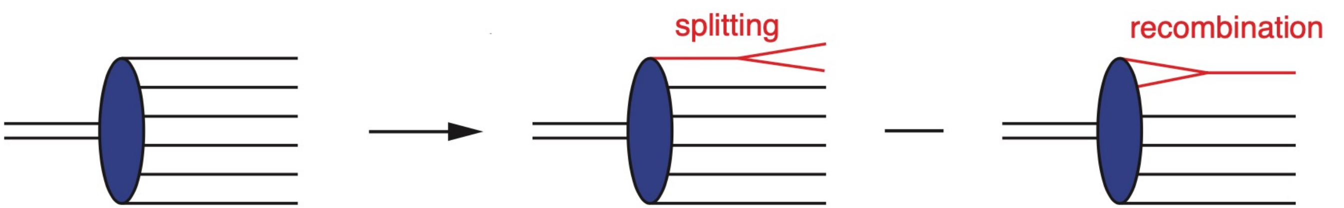
CFNS workshop
May 24-26, 2021

Gluon saturation



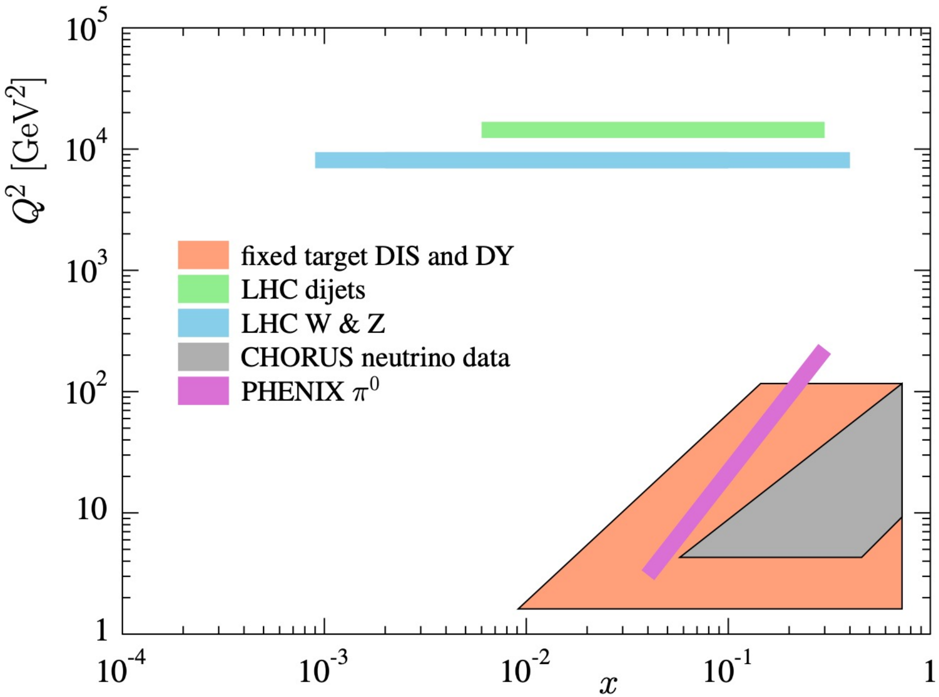




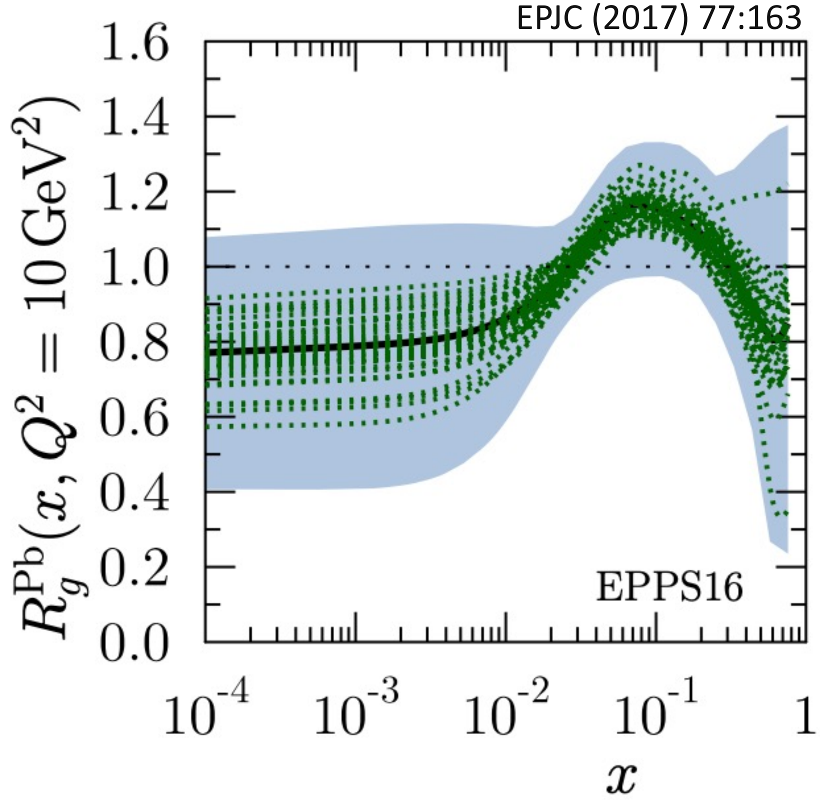
$$\boxed{\frac{\partial N(x,r_T)}{\partial \ln(1/x)} = \alpha_s K_{\mathrm{BFKL}} \otimes N(x,r_T)} - \boxed{\alpha_s [N(x,r_T)]^2}$$

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

Current knowledge of nPDFs



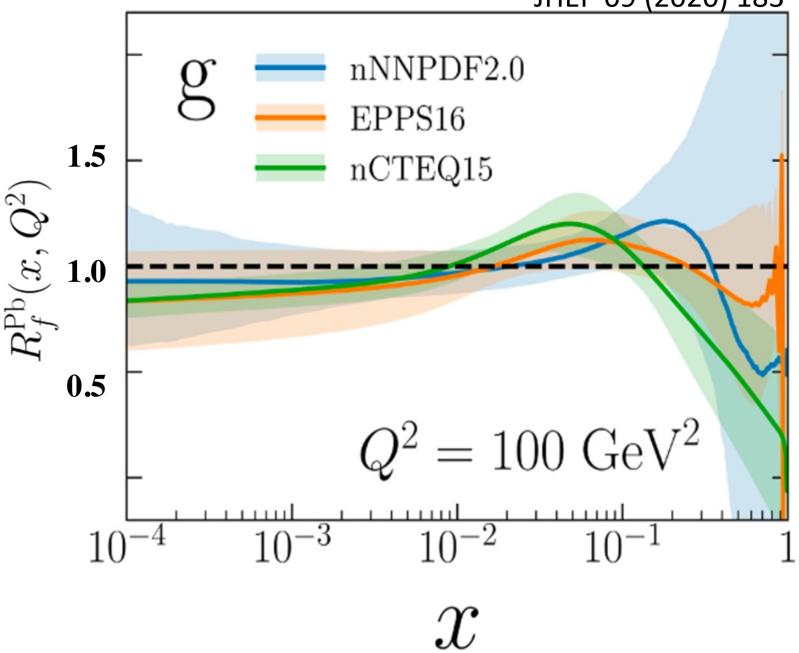
EPJC (2017) 77:163



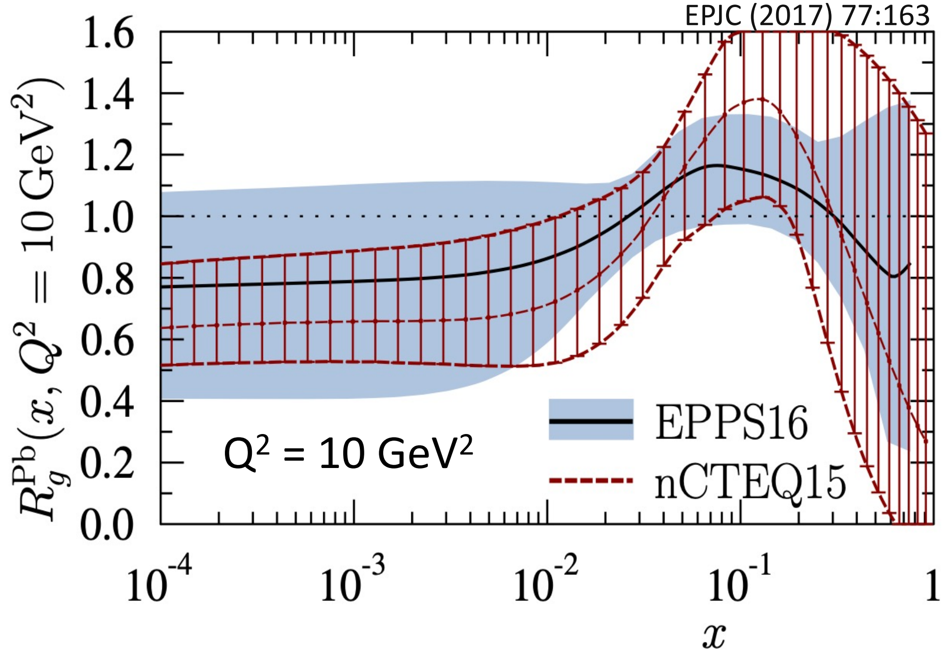
- LHC data in pPb collisions: low x but high Q^2; DIS, DY and PHENIX π^0 data: low/moderate Q^2
- Nuclear gluon distributions still have large uncertainty at small x, moderate Q^2 and low Q^2

Gluon density

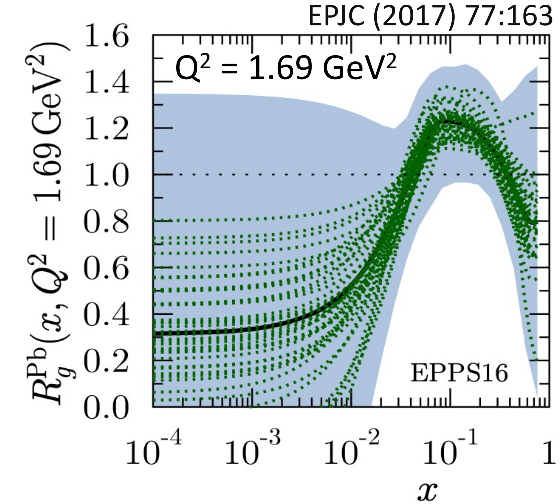
JHEP 09 (2020) 183



EPJC (2017) 77:163



EPJC (2017) 77:163



- RHIC data can probe small x, small and moderate Q^2 region
- Q^2 evolution behavior of suppression, strong Cold Nuclear Matter (CNM) effect at small Q^2
- Amount of suppression varies between fits: data needed to constrain fits

Possible measurements

Inclusive measurement: yields suppressed in forward direction, low p_T

- Forward charged hadron/π^0 production from RHIC
- Forward open charm production from LHC

Two-particle correlations: suppression in back-to-back correlation

- Back-to-back forward π^0/hadron correlations

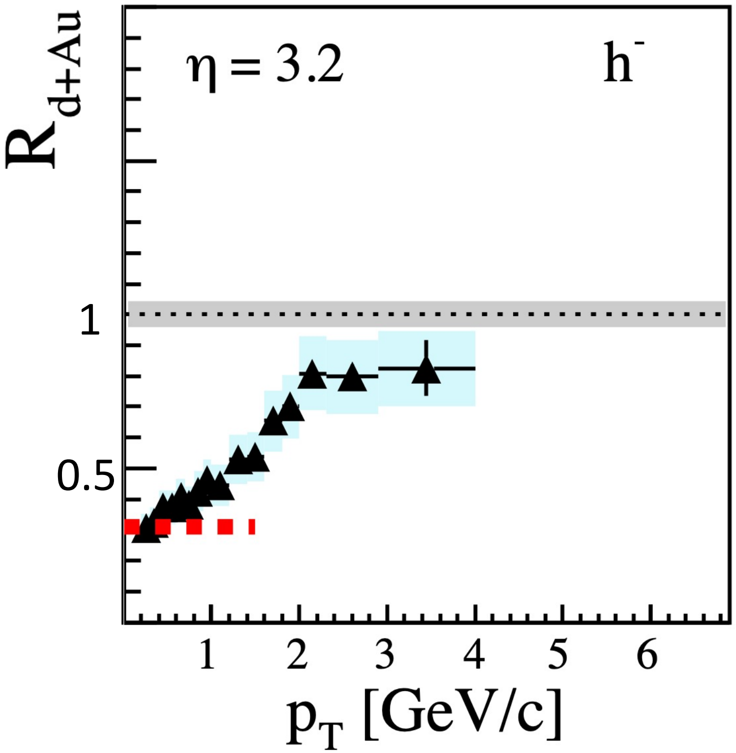
Future directions at STAR and EIC:

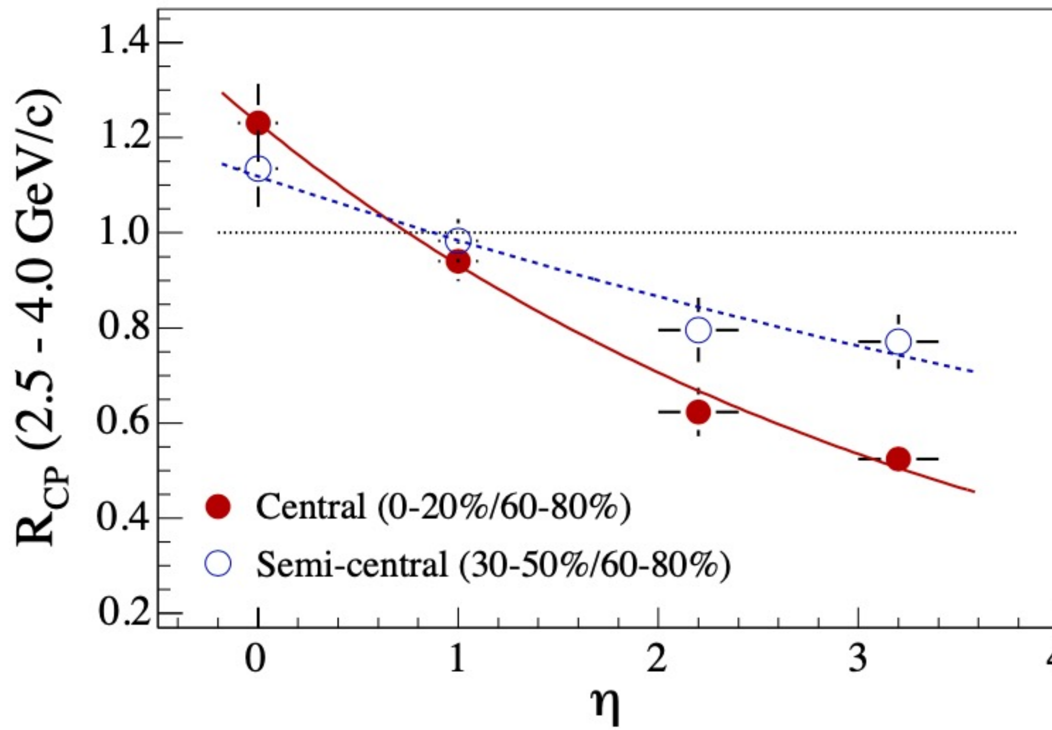
- Direct photon with STAR forward upgrade
- Direct photon-jet/charged hadron correlations with STAR forward upgrade
- Charged hadron correlations at further EIC

Inclusive charged particle at BRAHMS

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

$$R_{cp} = \frac{d^2N^{cen}/dp_T d\eta}{\langle N_{coll}\rangle d^2N^{pre}/dp_T d\eta}$$





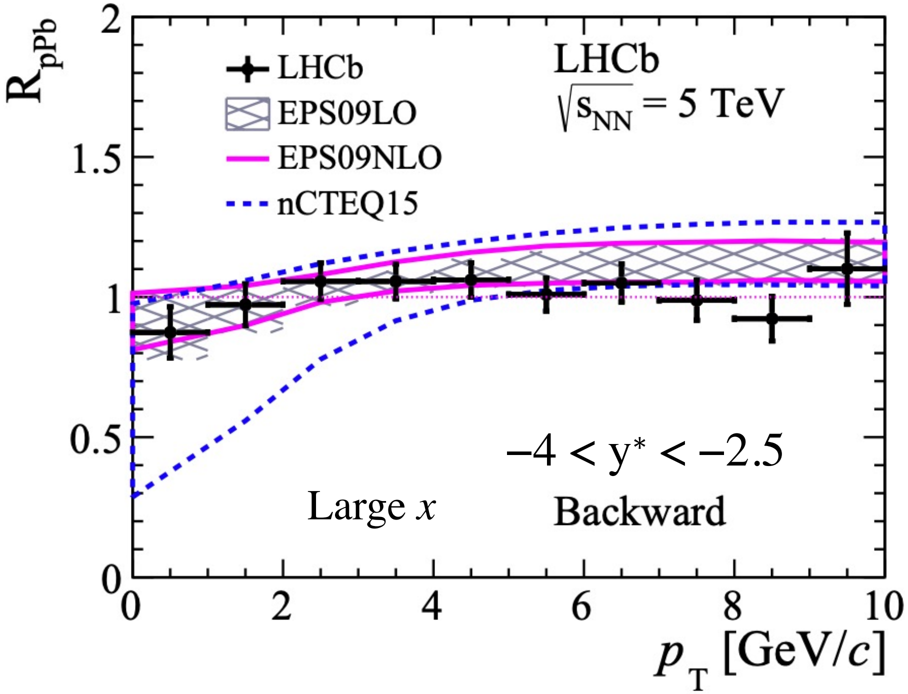
BRAHMS, PRL 93 (2004) 242303

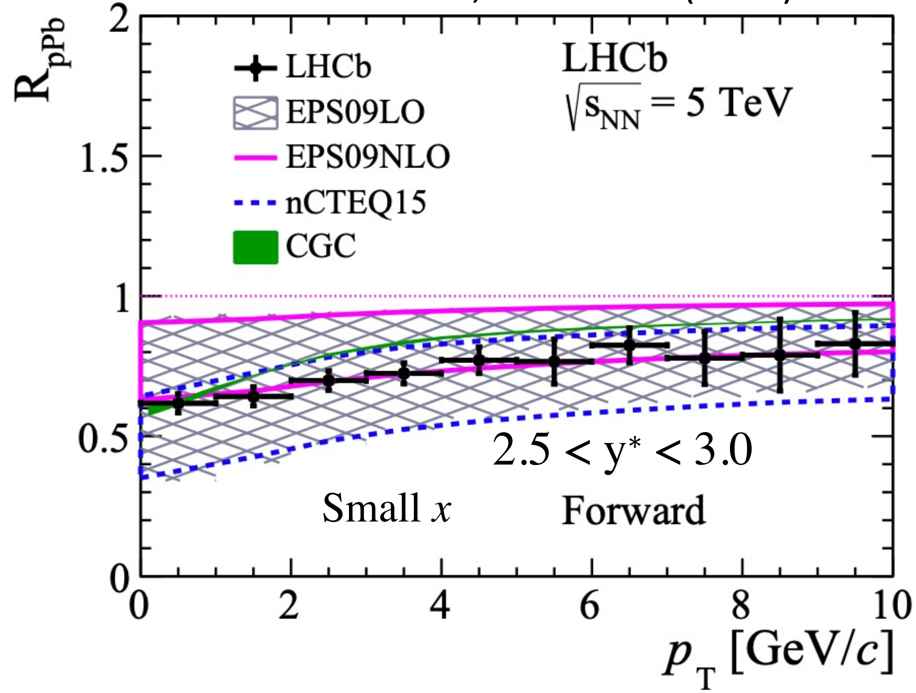
- Yields suppression $R_{dAu} < 1$ at $p_T < 2$ GeV; first hint of strong nuclear effect at small x?
- R_{cp} is more pronounced in central dAu collisions
- R_{cp} decreases with increasing rapidity: scan x by varying rapidity

D_0 production at LHCb

$$R_{p\mathrm{Pb}}(p_\mathrm{T}, y^*) \equiv \frac{1}{A}\frac{\mathrm{d}^2\sigma_{p\mathrm{Pb}}(p_\mathrm{T}, y^*)/\mathrm{d}p_\mathrm{T}\mathrm{d}y^*}{\mathrm{d}^2\sigma_{pp}(p_\mathrm{T}, y^*)/\mathrm{d}p_\mathrm{T}\mathrm{d}y^*}$$

LHCb, JHEP 1710 (2017) 090





- Suppression of D meson production at forward rapidity, not at backward direction (large x)
- Suppression at forward rapidity potentially depends on p_T

Possible measurements

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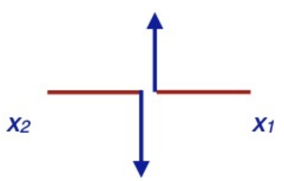
Di-parton kinematics

Kinematics map from Marco van Leeuwen

Both outgoing partons at mid-rapidity



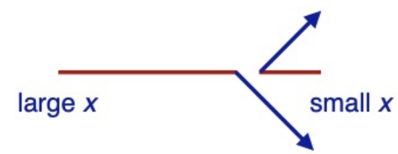
Both incoming partons at moderate x

$$\hat{s} = x_1 x_2 s \approx (2\,p_{\mathrm{T}})^2$$

$$x_1 \approx x_2 \approx \frac{2\,p_T}{\sqrt{s}}$$

Large x → q

Both outgoing partons at forward rapidity



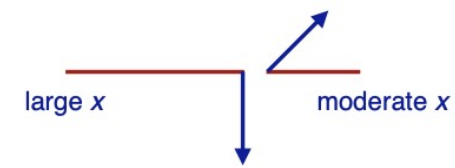
Boosted configuration:
One small-x, one large-x parton

$$\hat{s} = x_1 x_2 s \approx (2\,p_{\mathrm{T}})^2$$

$$x_1 \approx \frac{p_T}{\sqrt{s}}\,e^{-y}$$

Small x → g

One parton forward, one closer to mid-rap



Large mass final state

$$Q^2 = \hat{s} > (2\,p_{\mathrm{T}})^2$$

small probability

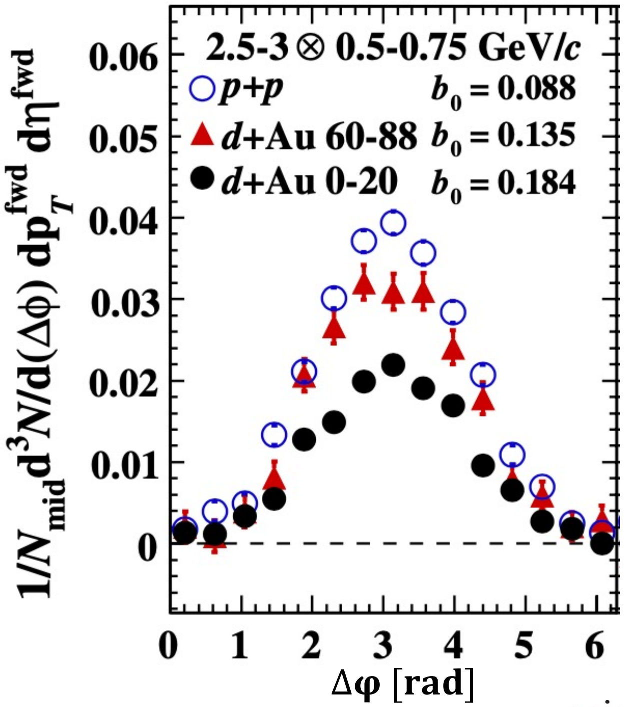
Moderate x

Scan x (and Q^2) by varying p_T and rapidity

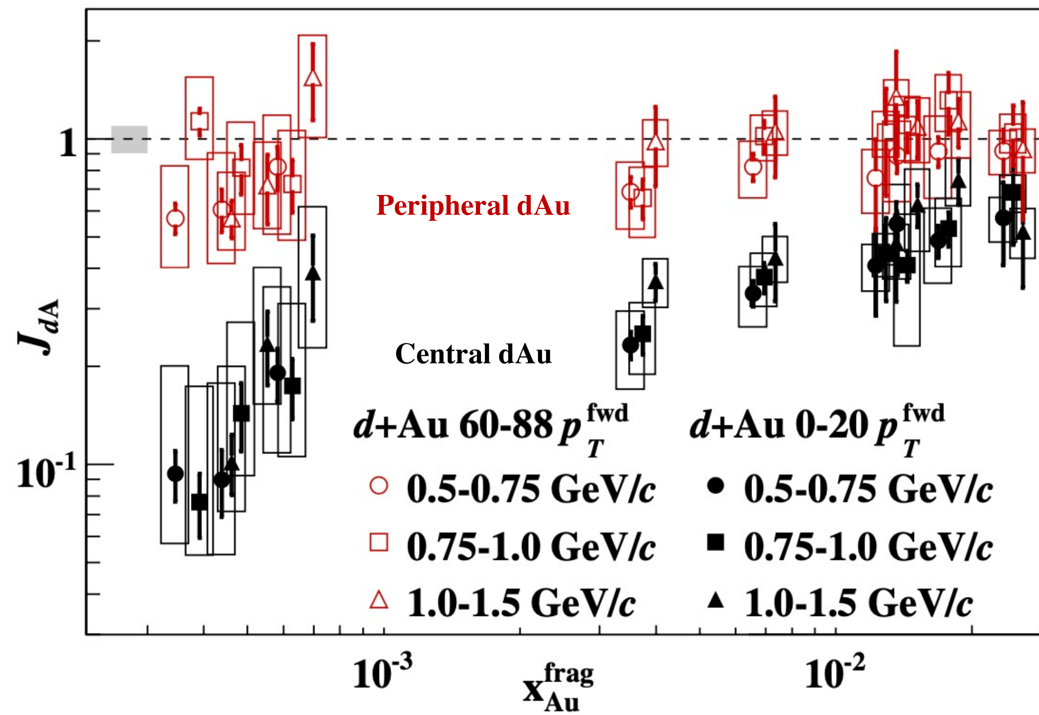
Di-hadron correlations at PHENIX

Middle-forward

|η|<0.35, 3.0 < η < 3.8



Forward-forward Middle-forward



PRL 107 (2011) 172301

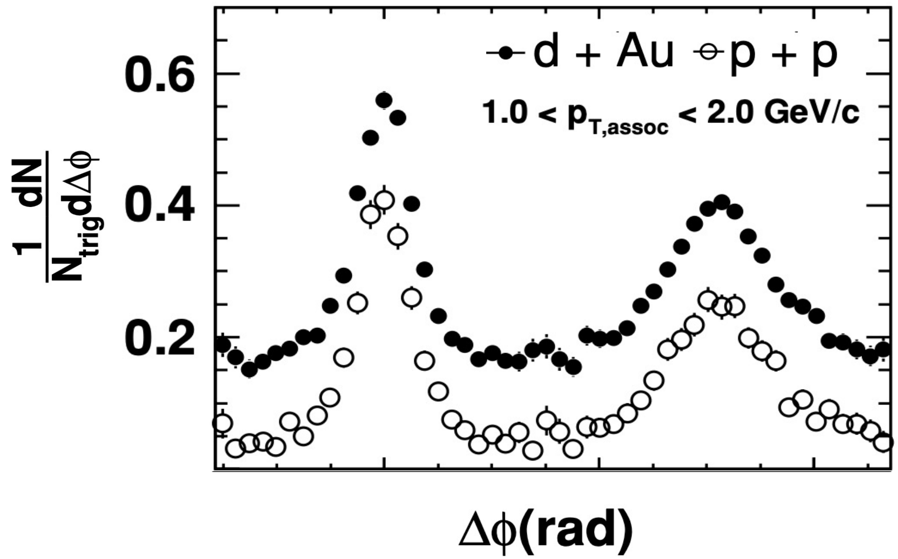
$$J_{dA} = \frac{1}{\langle N_{coll}\rangle} \frac{\sigma_{dA}^{pair}/\sigma_{dA}}{\sigma_{pp}^{pair}/\sigma_{pp}}$$

$$x_{Au}^{frag} = \frac{p_{T1}\, e^{-y_1} + p_{T2}\, e^{-y_2}}{\sqrt{s}}$$

- Scan x by varying rapidity: more suppression in forward-forward rapidity in central dAu collisions
- Suppression increases in more central dAu collisions
- No broadening and high pedestal in dAu compared to pp collisions

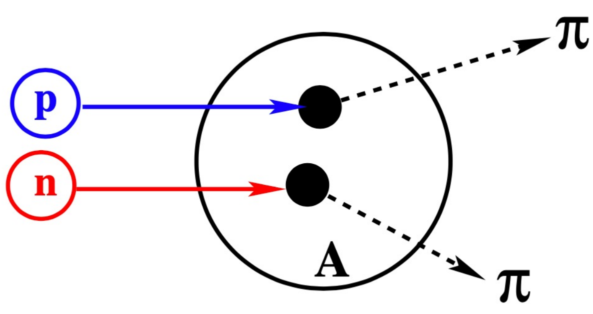
Multi-parton scattering in dAu?

PHENIX,PRC 73 (2006) 054903



PRD 83 (2011) 034029

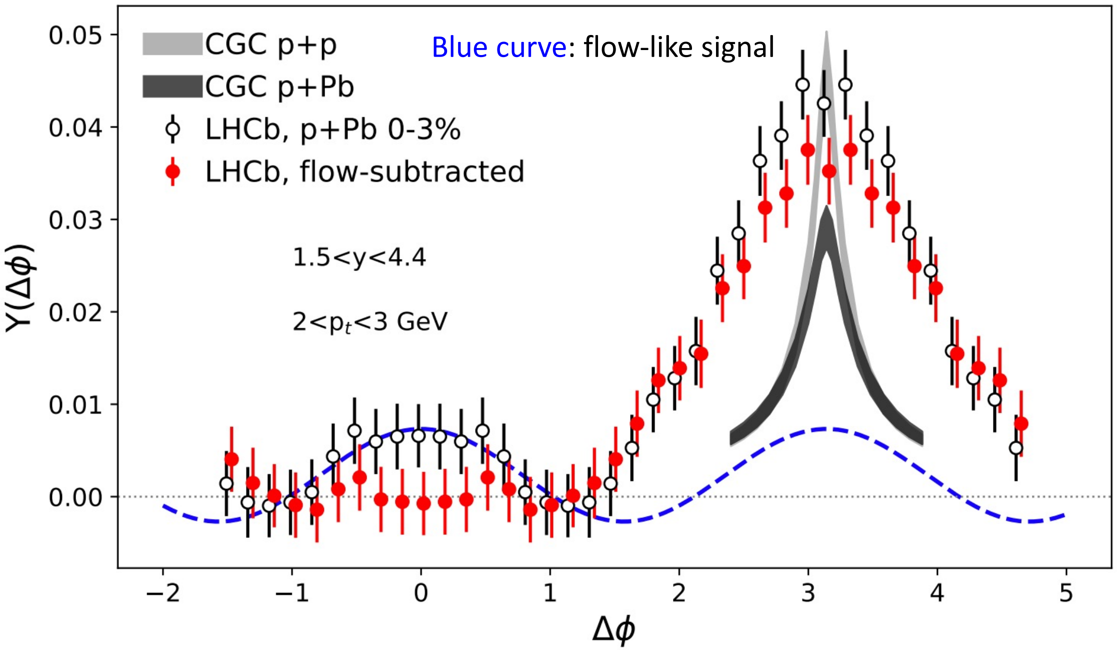
One example of DPS in dAu

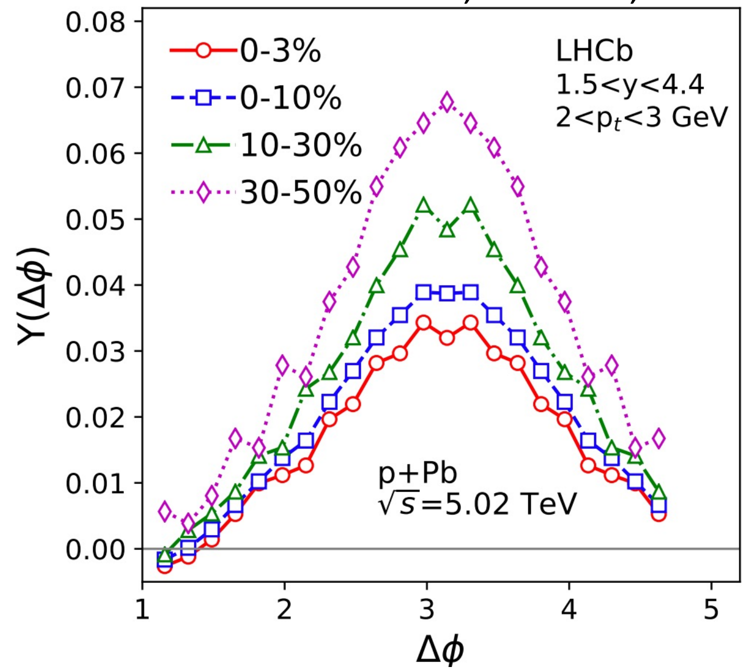


- Pedestal: dAu ≫ pp, Double(multi)-Parton Scattering (DPS)?
- Alternative explanation of suppression in dAu?
    - Uncorrelated π^0s from different parton scatterings
    - Correlated π^0s from single hard parton scattering
- pAu data at STAR can provide possibility to study double parton scattering in comparing with pp and dAu collisions

Di-hadron correlations at LHCb

LHCb, NPA 982, 291

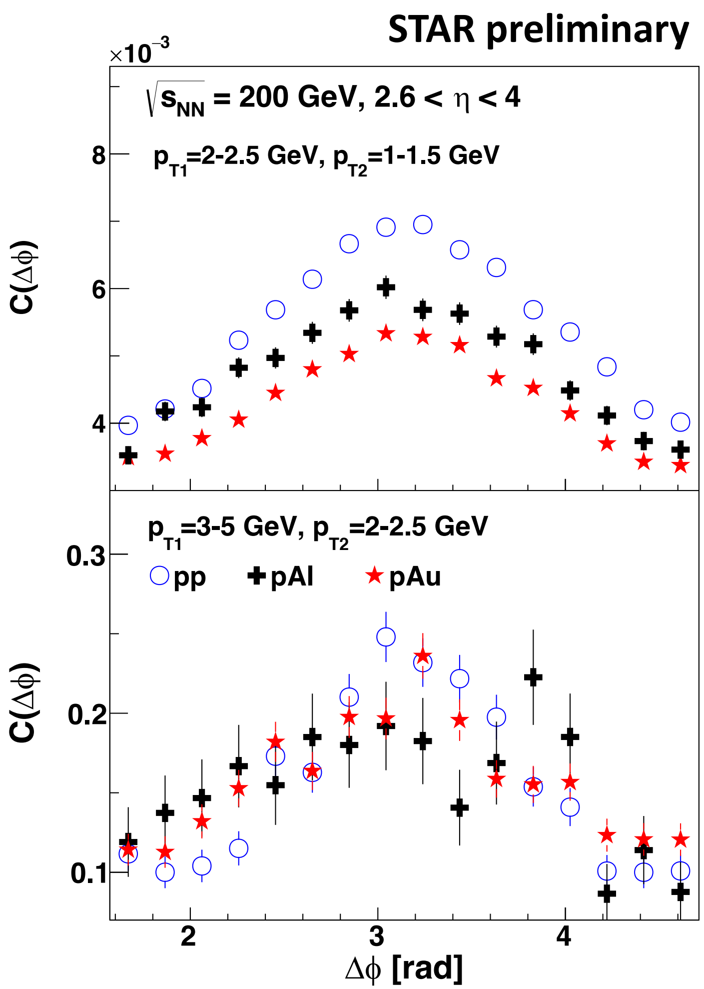


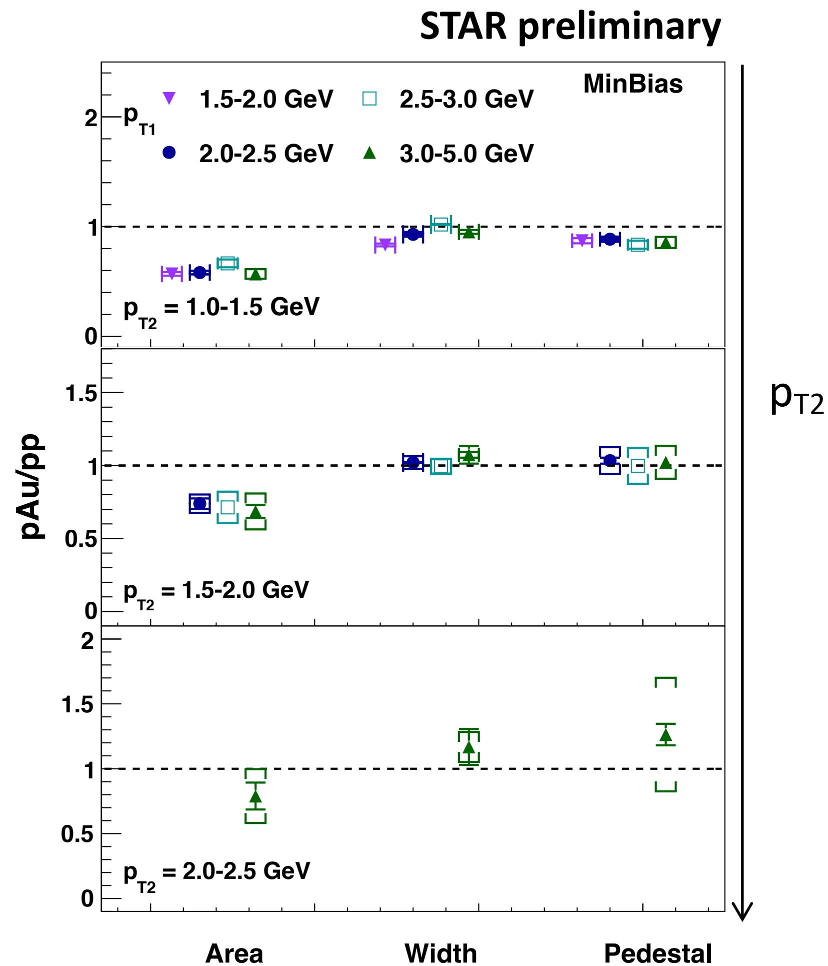


- Pure v_2 ($|\Delta\eta|>2$) at near-side peak; symmetric long-range component at near- and away-side peak
- Yield suppression in pPb at smallest x region → 10^{-5} (over 10 times lower than RHIC); is broadening seen in pPb?
- Theory curve shows narrow peak because of initial- and final-state gluons radiation not included

Di-π^0 correlations at STAR

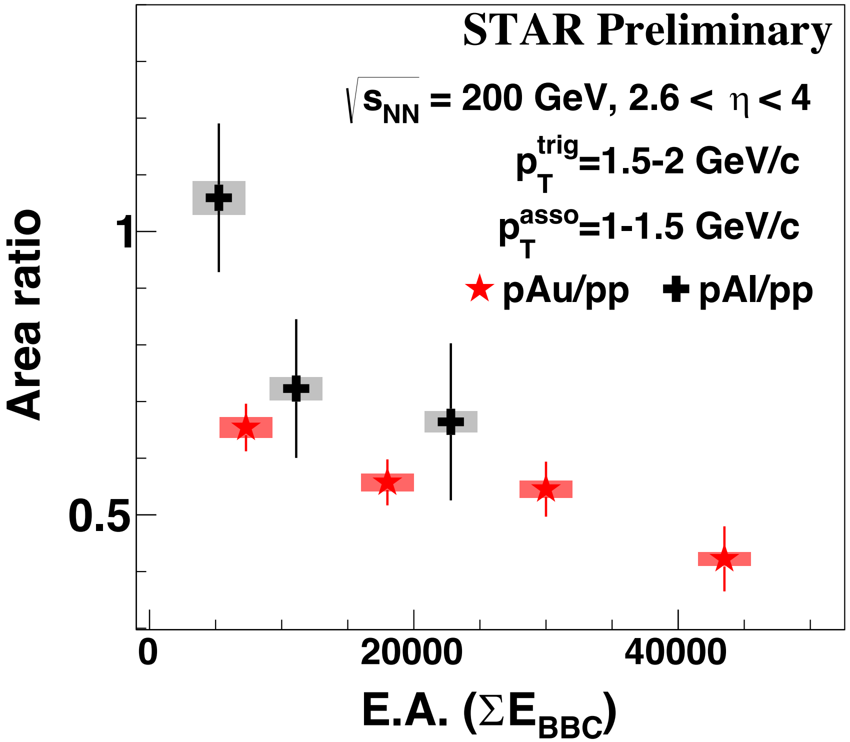
Area (integral from $\frac{\pi}{2}$ to $\frac{3\pi}{2}$), Width (σ) and Pedestal from Gaussian fit

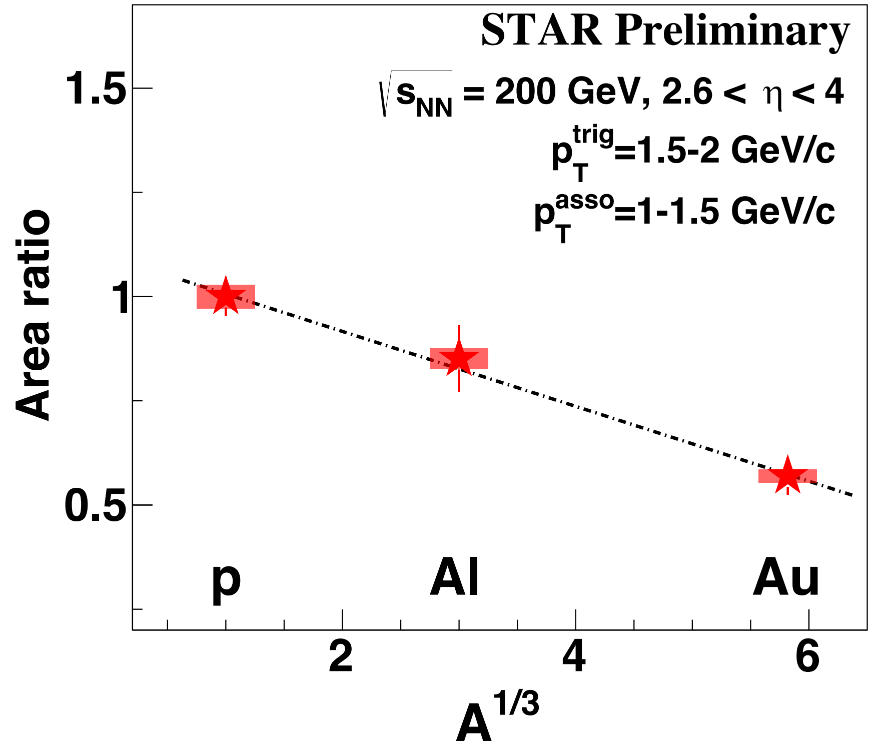




- Scan x (and Q^2) by varying p_T: suppression at low p_T in pA but not high p_T
- Stable pedestal and width: no broadening

Di-π^0 correlations at STAR

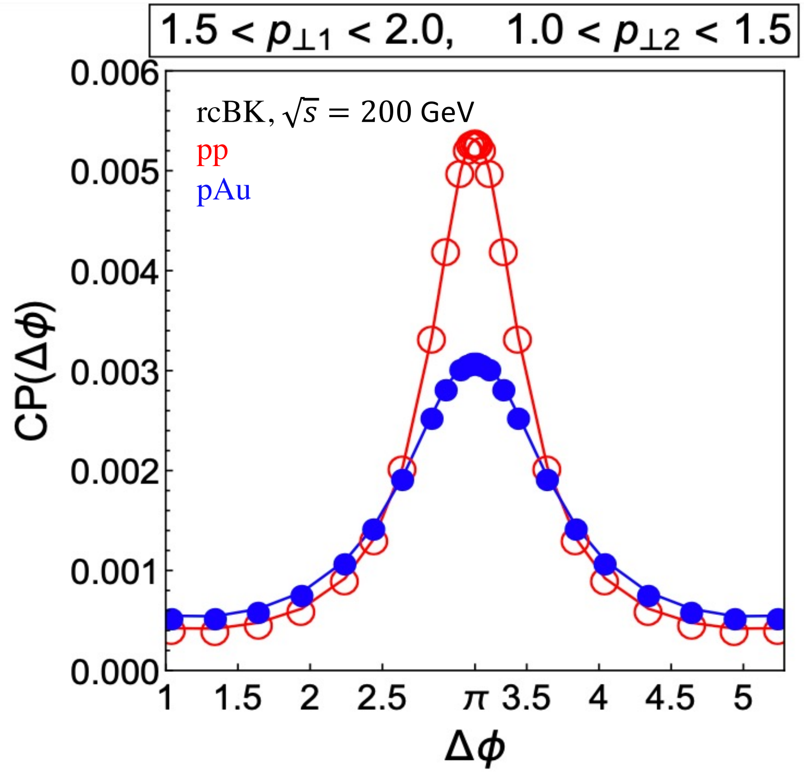




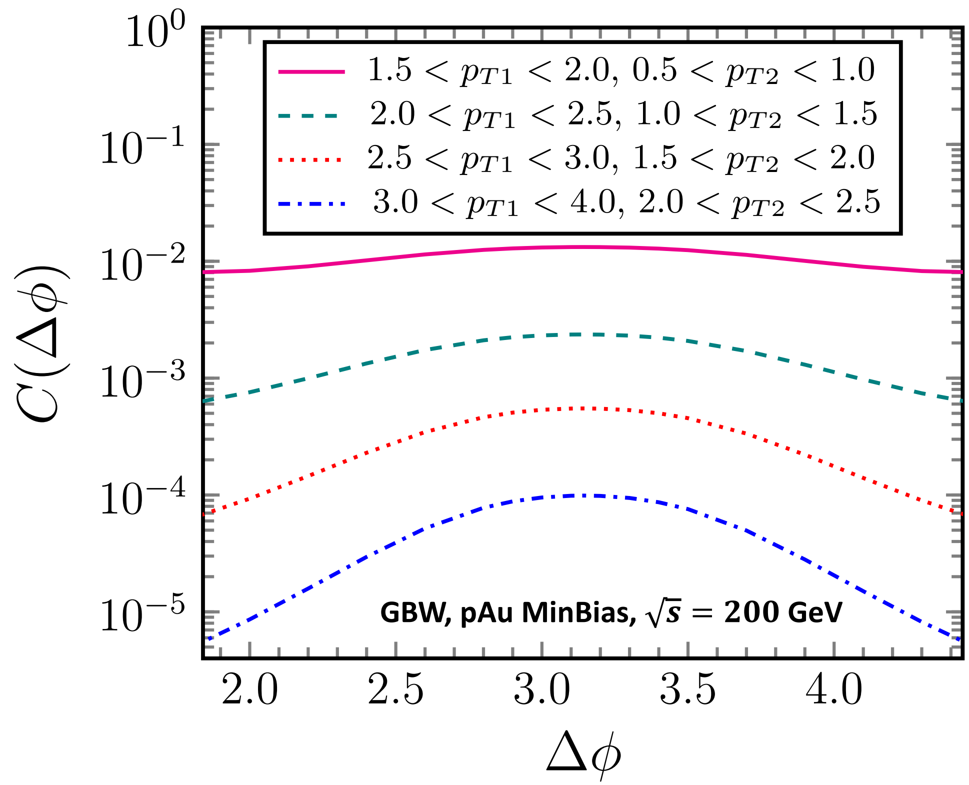
- Same trend for pAu and pAl on event activity: enhanced suppression at high E.A.
- Suppression linearly enhanced as $A^{1/3}$, unique measurement at STAR

Broadening from predictions

PRD 99 (2019) 014002

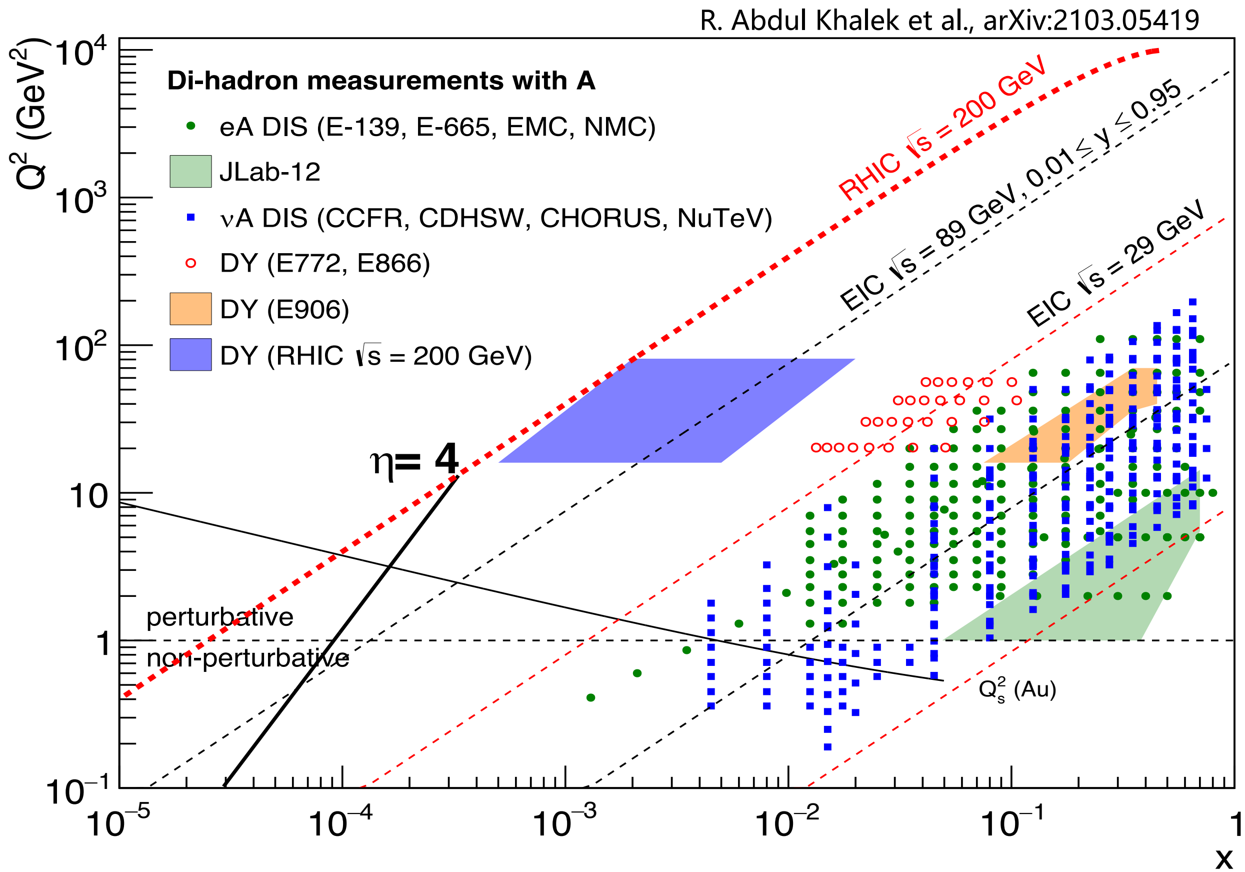


PLB 716(2012) 430



- Value of width in pAu varies between models: GBW >> rcBK in width
- Data can help to constrain width in theoretical models
- Forward upgrade at STAR with high precision can improve measurement of broadening

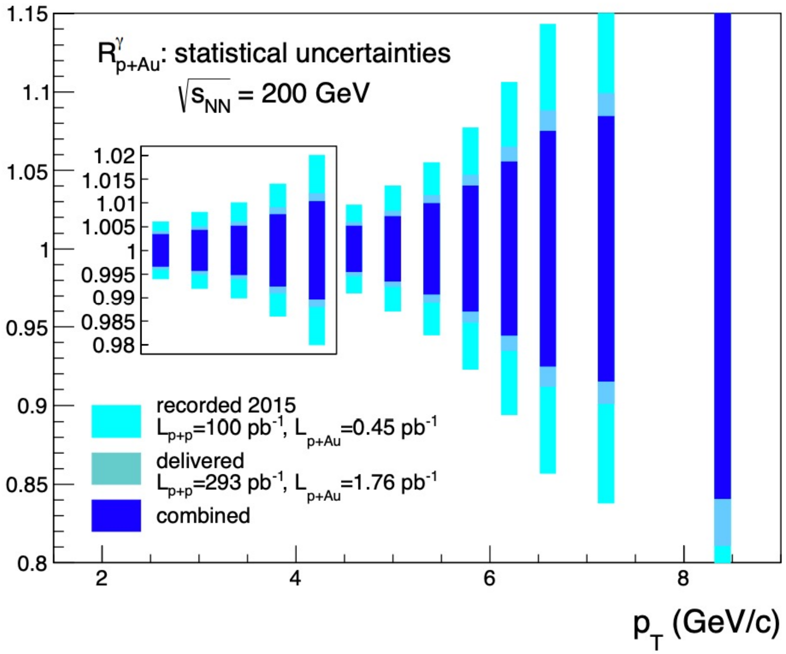
Future measurements at STAR and EIC

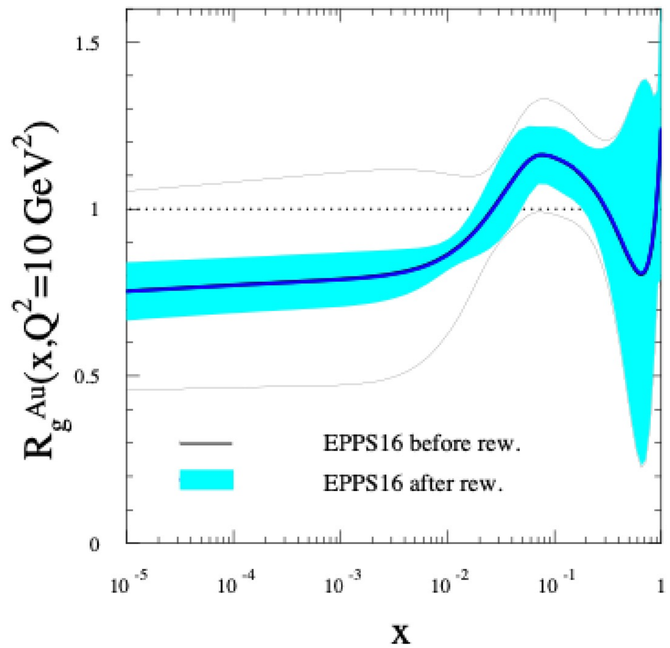


- STAR forward upgrade of Ecal, Hcal and tracking at $2.5 < \eta < 4.0$: expand observables
  - di-charged hadorn, di-jet, γ-hadron/jet, inclusive γ…
- Similar phase space in highest energy eA collisions at EIC with STAR

Direct photon measurements at STAR

RHIC Cold QCD Plan, arxiv:1602.03922



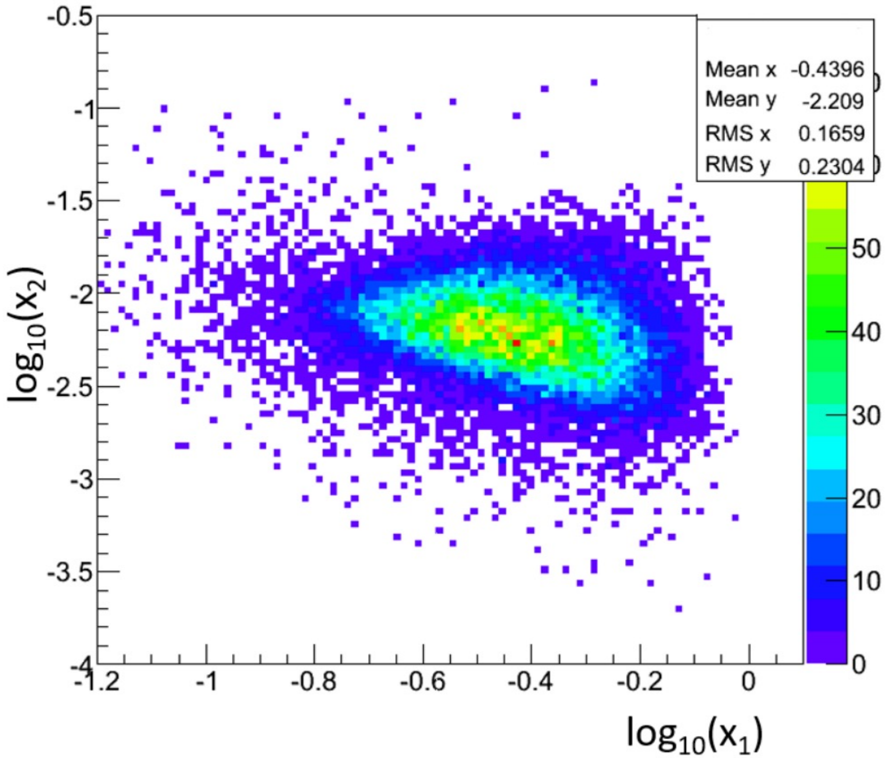


2024 pAu with STAR forward upgrade + 2015 pAu:

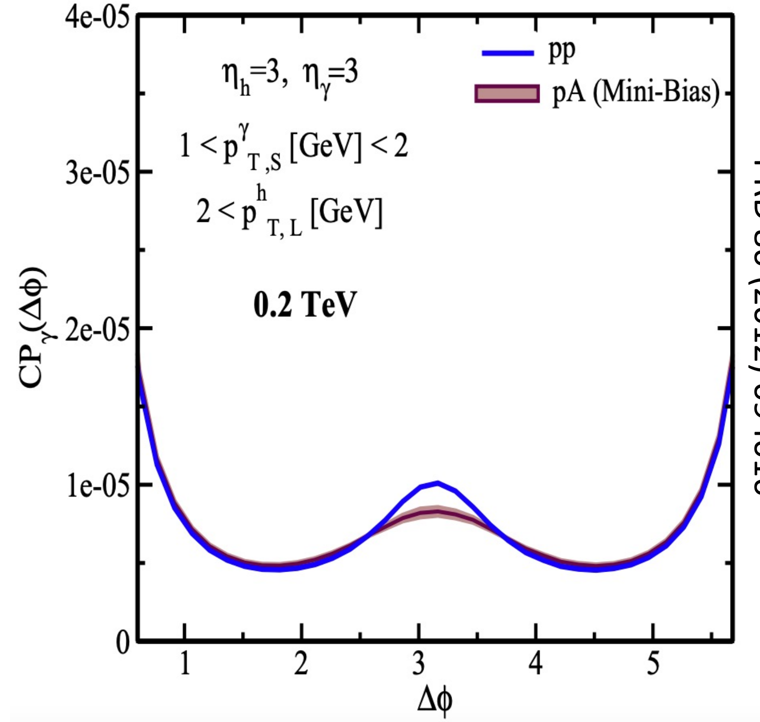
- R^{γ}_{pAu} of direct photons: q+g→q+γ, free from the final state effects
- Higher delivered integrated luminosity data improve the constrain on gluon distributions; test theory predictions
- Challenge: remove photons from fragmentation or hadron decay; small cross section at forward rapidity

γ-jet/h or di-jet measurements at STAR

RHIC Cold QCD Plan, arxiv:1602.03922



γ-hadron correlation

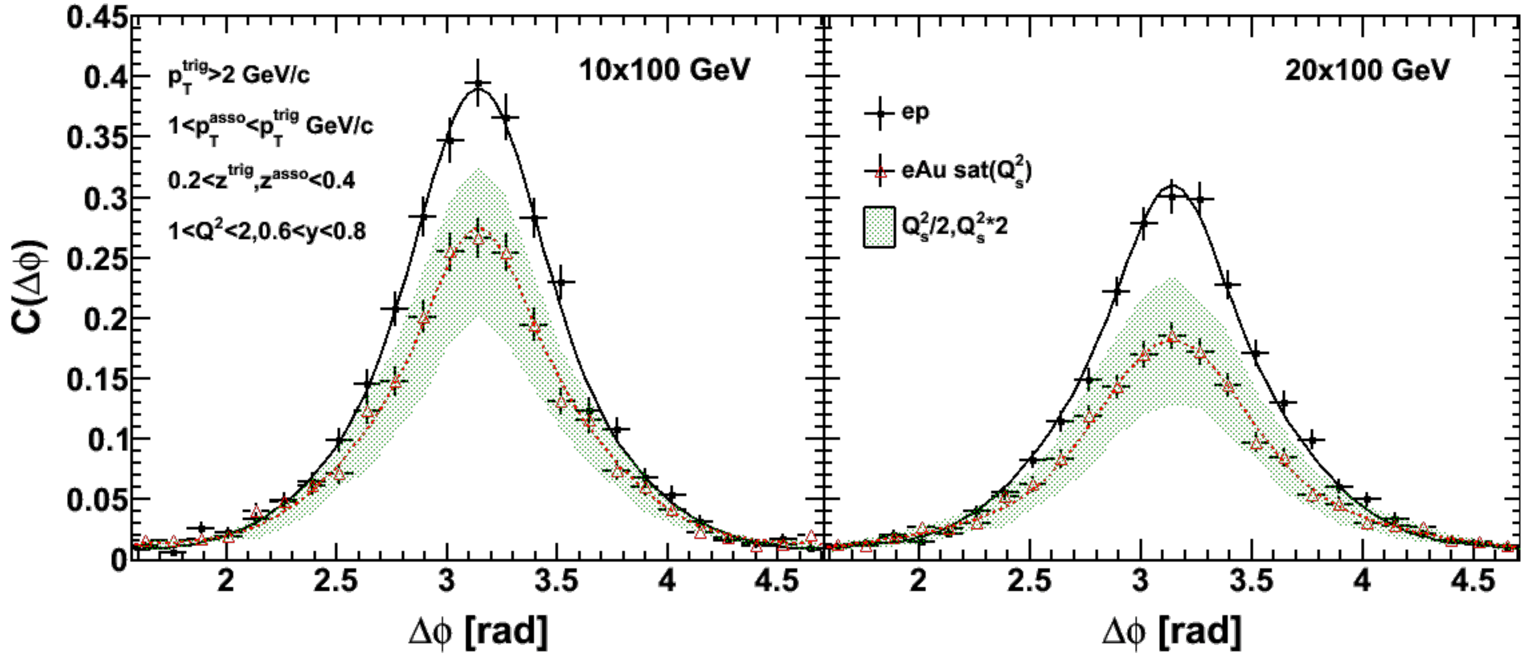


PRD 86 (2012) 094016

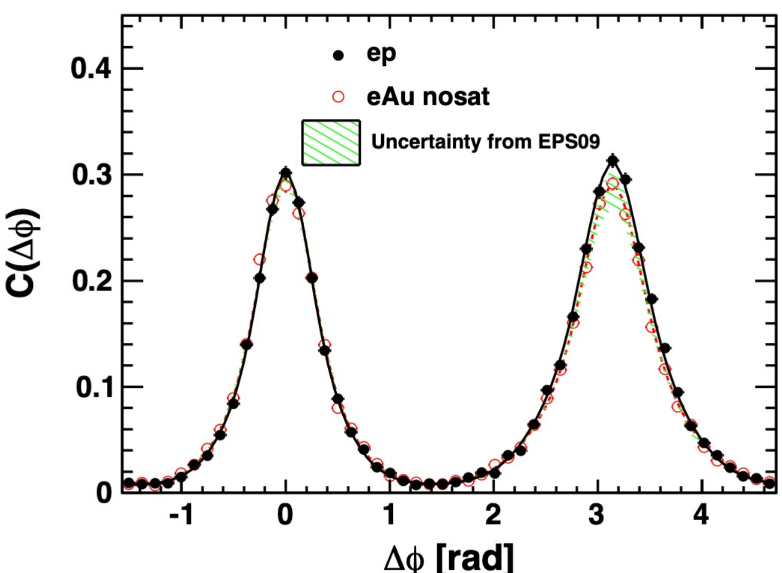
2024 pAu + pAl with STAR forward upgrade, sensitive to the gluon density at small x

- Jets are better mapping to partons, the initial kinematics are better constructed by jets than hadrons:
  - $\frac{p_{T1}e^{-y_1} + p_{T2}e^{-y_2}}{\sqrt{s}} < x_A$ for di-hadron
  - $\frac{p_{T1}e^{-y_1} + p_{T2}e^{-y_2}}{\sqrt{s}} \sim x_A$ for di-jets

Di-hadron correlations at EIC

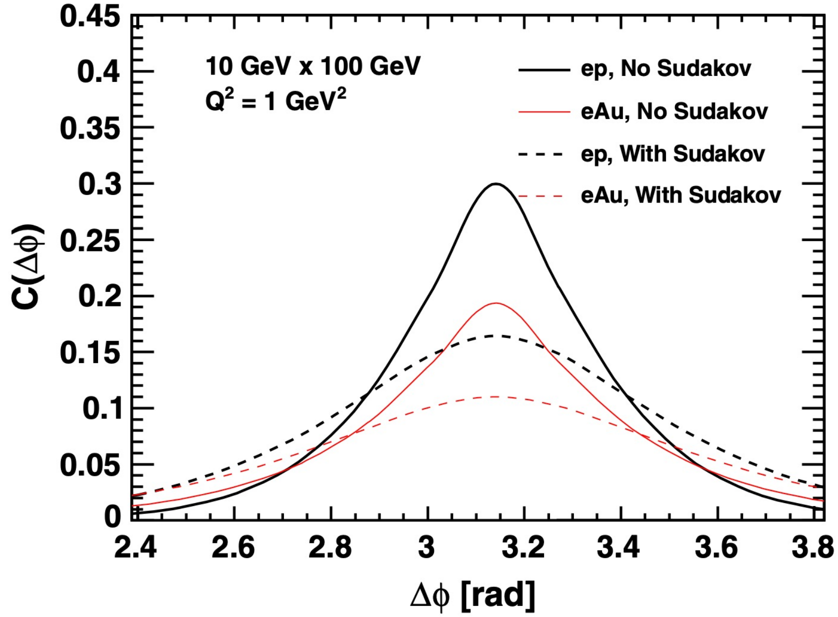


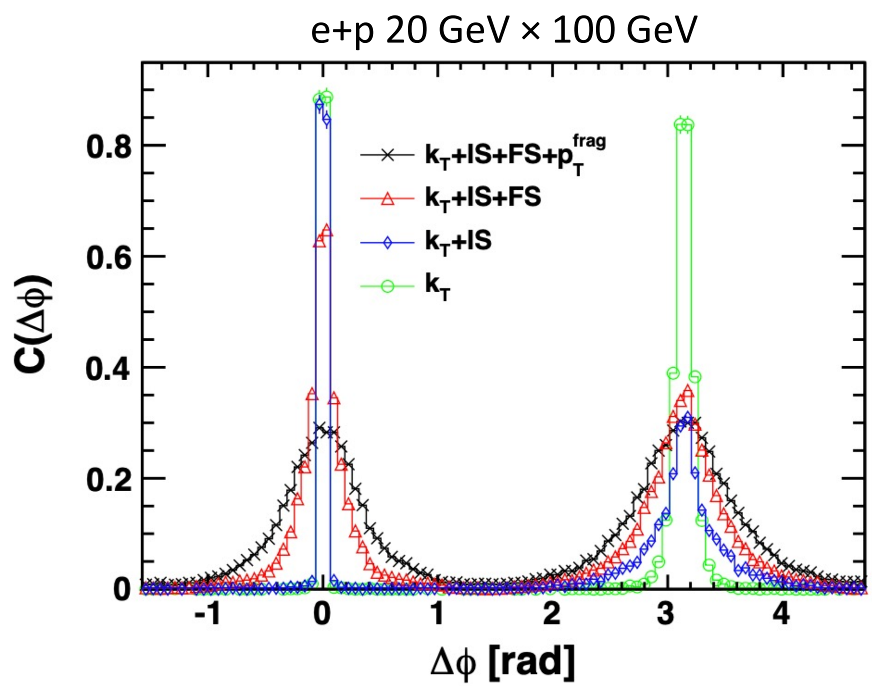
PRD 89 (2014) 074037



- Constraint of sat/nosat models a lot with limited statistics of 1 fb^{-1}
- Strong suppression can not be reproduced by the nosat model
- x and Q^2 can be precisely constructed by scattered electrons

Di-hadron correlations at EIC





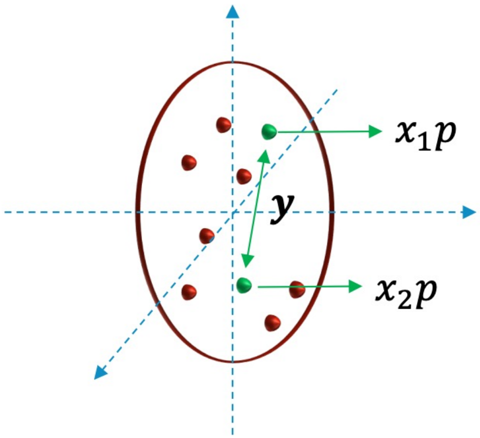
PRD 89 (2014) 074037

- 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 width dominated by initial state parton shower
- Near side peak width mainly affected by final state parton shower and fragmentation p_T

Summary and outlook

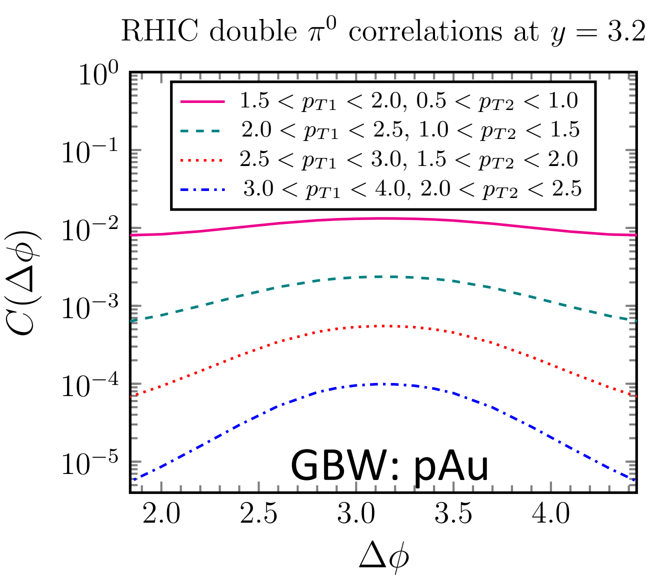
- The evidence of a novel universal regime of non-linear gluon dynamics in nuclei is indicated by forward particle production, forward di-hadron correlation
- STAR forward di-hadron correlation: suppression depends on p_T, event activity and A
- Open questions: multi-parton interaction, Sudakov effect, intrinsic k_T…
- Future directions at STAR with forward upgrade and EIC:
  - Forward charged hadron and direct photon production
  - Complementary forward correlations: i.e., γ-jet, di-jet

Back up



Double parton distributions (**DPDs**) contribute to correlated $\boldsymbol{\pi^0}$s : $F_{ik}\,(x_1, x_2, y)$

- between x_1 and x_2 dependence (**longitudinal correlations**)
- between x_1, x_2 dependence and y (**transverse correlations**)



pAu: width = 0.64 >> rcBK at associated
p_T = 1.0-1.5 GeV

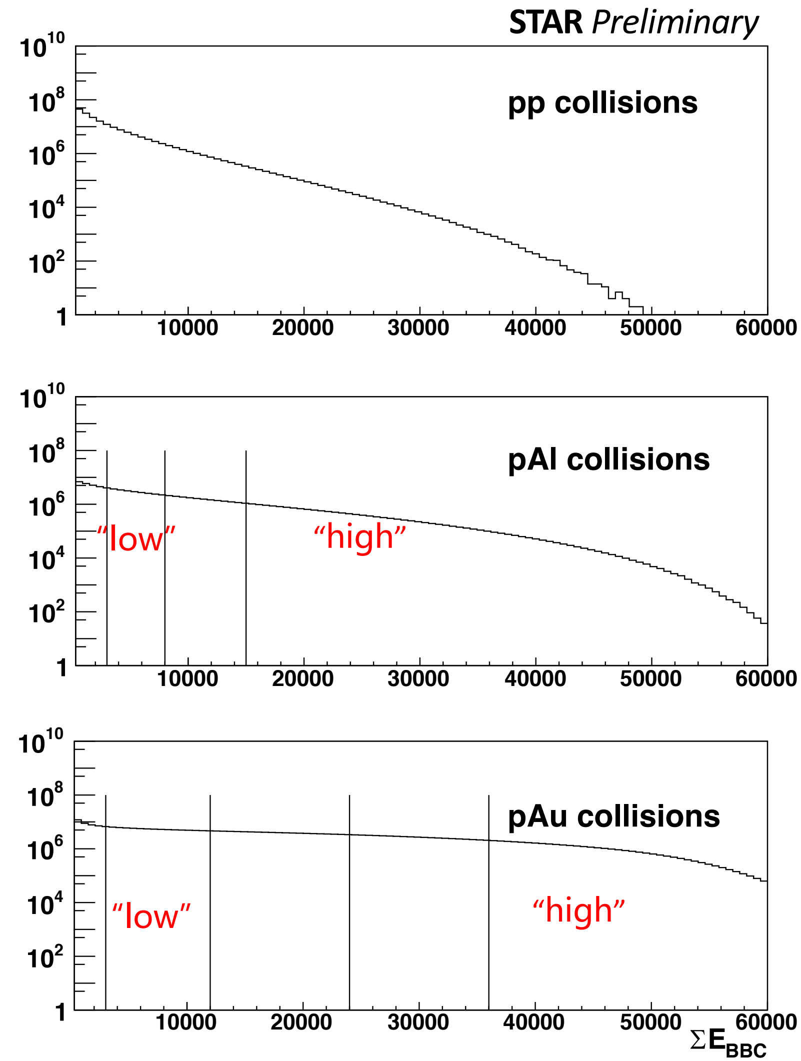
Event activity

Energy deposited at EAST BBC (ΣE_{BBC}) quantifies "event activity"

- East: nucleus beam going direction; backward rapidity
- High energy deposition refers to "high activity" collisions

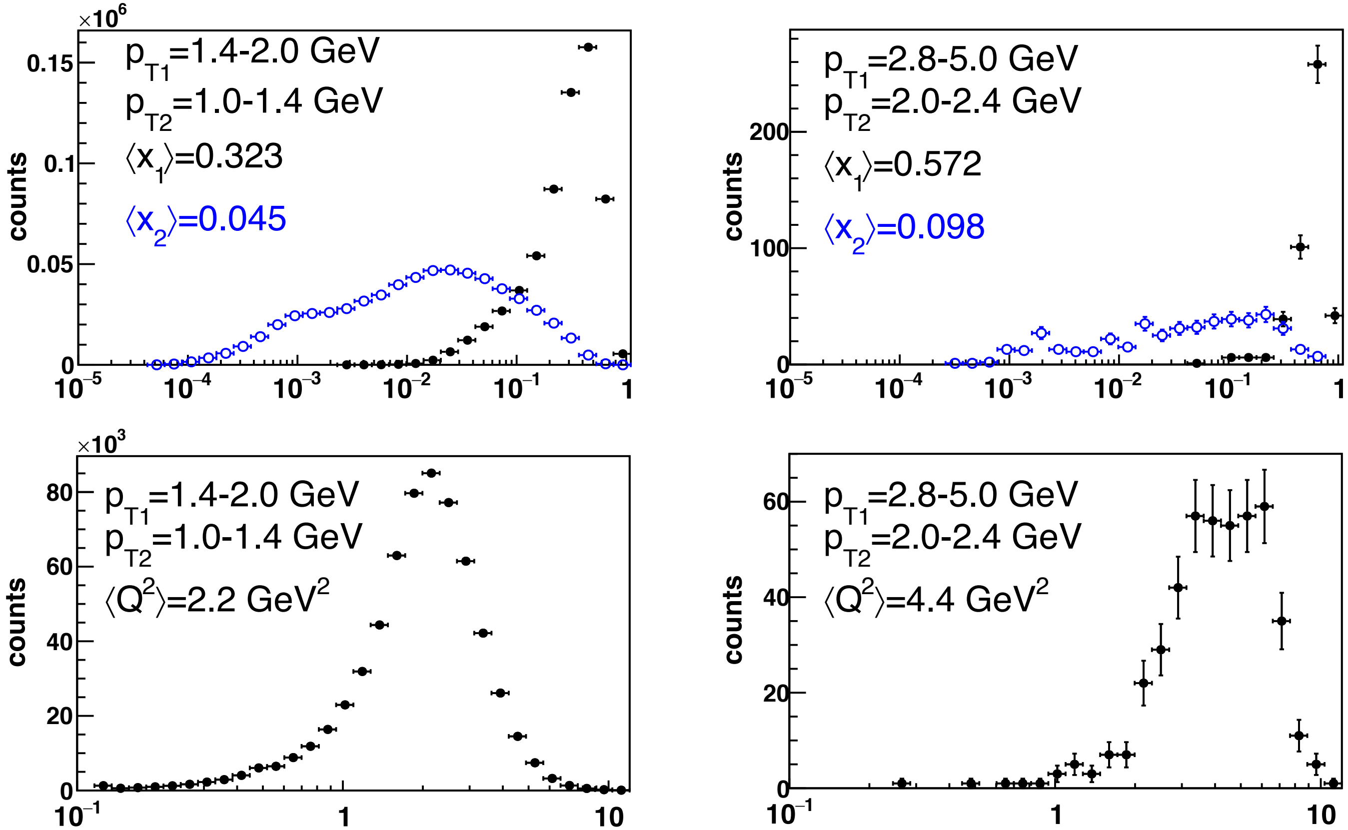
Event activity in pAl and pAu

Beam species	Event activity	$\Sigma E_{\rm BBC}$ range ($\times 10^3$)	Class
p+**Al**	Lowest	3-8	31%-60%
	Medium	8-15	60%-81%
	Highest	>15	81%-100%
p+**Au**	Lowest	3-12	15%-43%
	Medium low	12-24	43%-69%
	Medium high	24-36	69%-88%
	Highest	>36	88%-100%



PYTHIA Kinematics: x_1, x_2 and Q^2

pp collisions at $\sqrt{s} = 200$ GeV, $2.6 < \eta < 4.1$



- x_1 , x_2 and Q^2 increase with p_T, low p_T helps to access saturation regime
- x_1 (x_2) dominates at high (low) x regime; well separated