Ongoing Efforts to Study Gluon Saturation at RHIC and at the LHC

Xiaoxuan Chu, BNL

Joint EICUG/ePIC Collaboration Meeting
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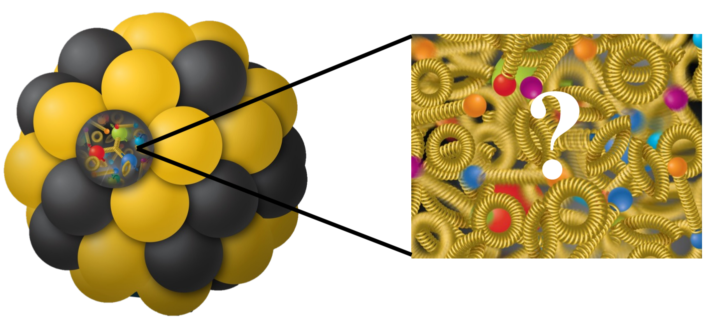
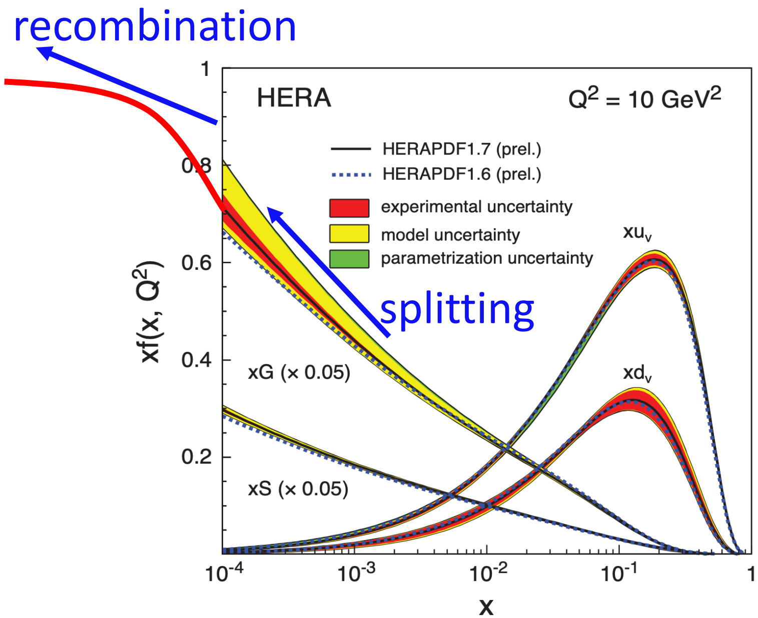
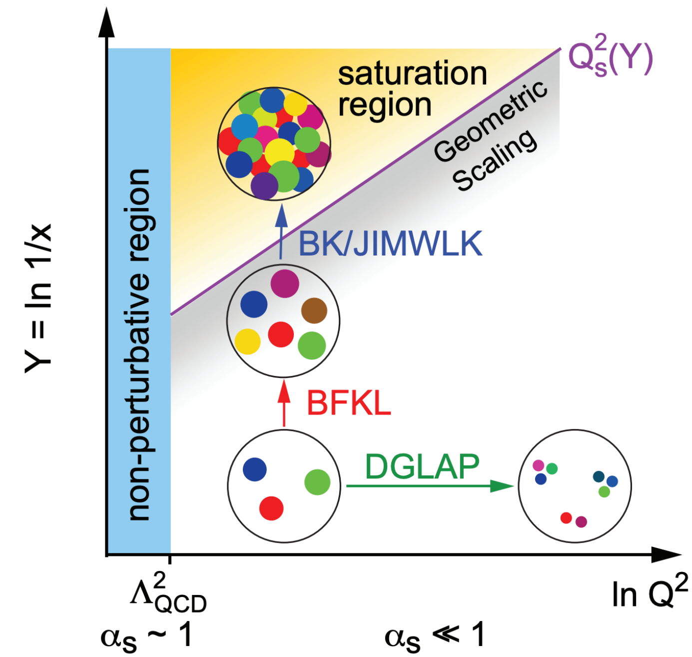
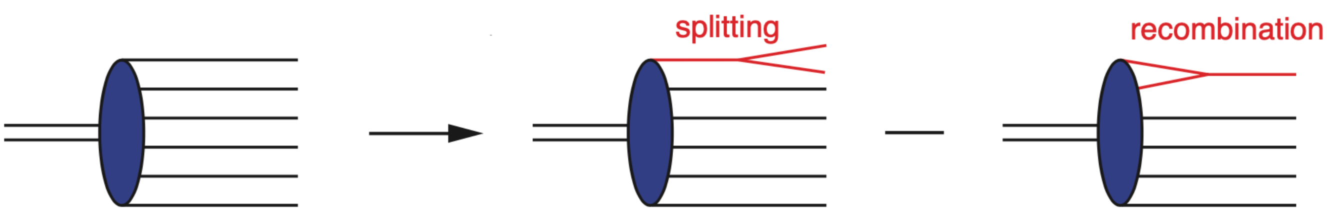


gluon dynamics at small x

Gluon Saturation



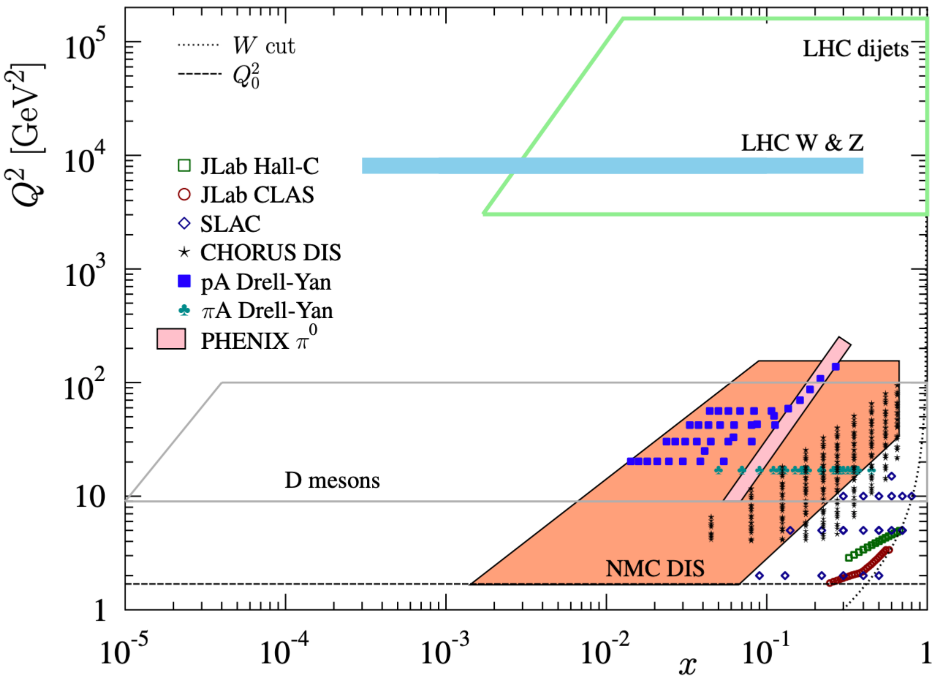




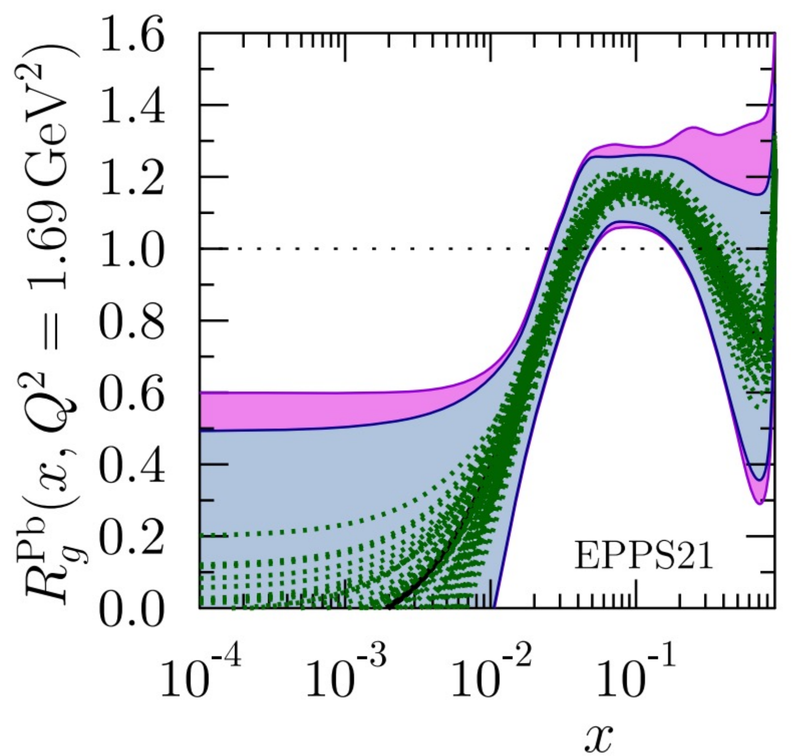
$$\frac{\partial N(x,r_T)}{\partial \ln(1/x)} = \alpha_s K_{\mathrm{BFKL}} \otimes N(x,r_T) - \alpha_s [N(x,r_T)]^2$$

- 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; gluon recombination = gluon splitting, gluon density stays tamped

Current Knowledge of nPDFs



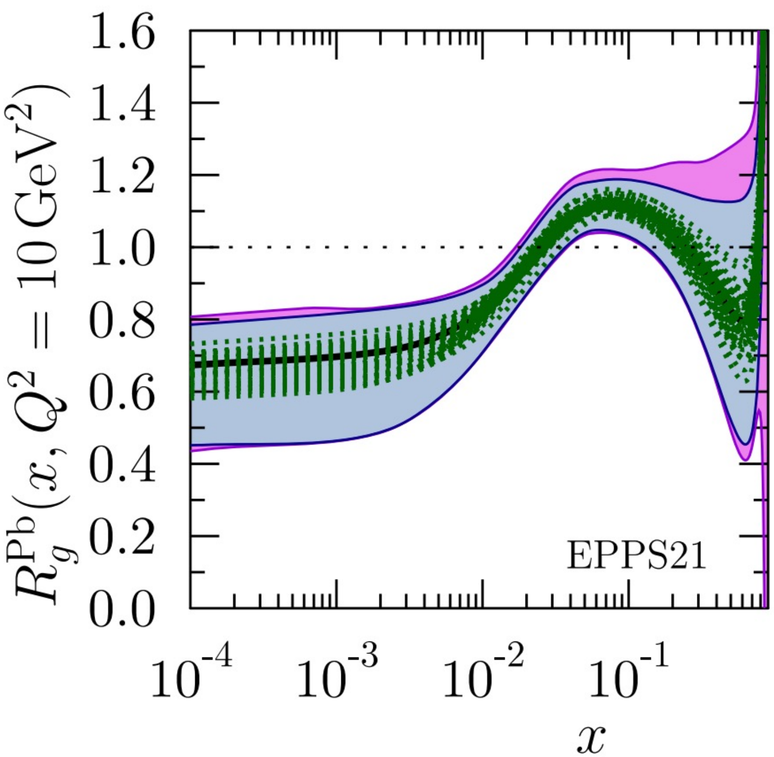
Eskola, Paakkinen, Paukkunen, Salgado, EPJC 82 (2022) 413

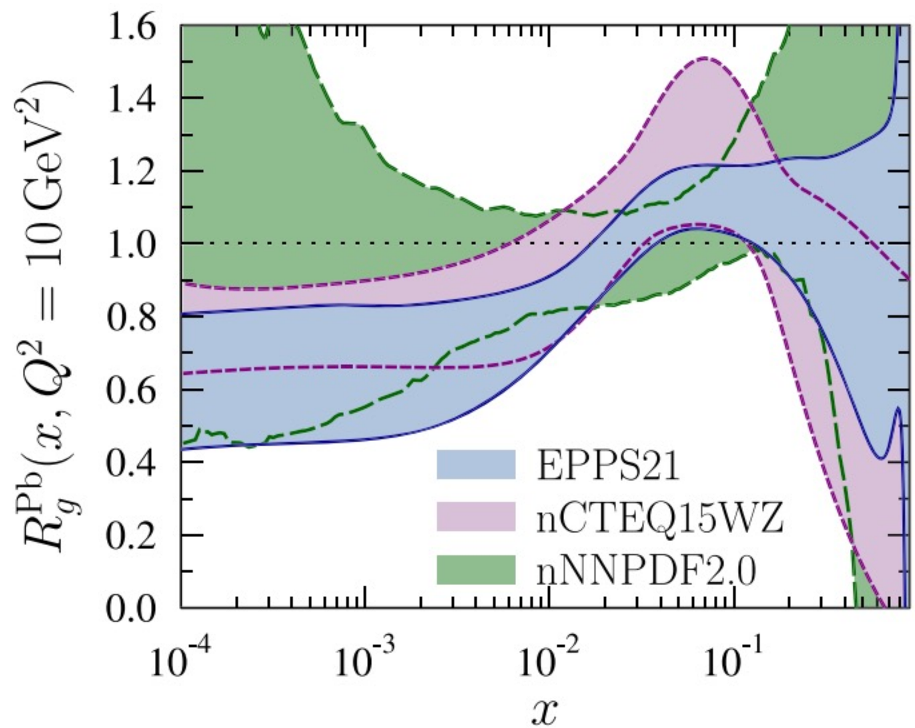


- LHC data in pPb collisions: low x but high Q^2; DIS, DY and PHENIX π^0 data: low/moderate Q^2
- Nuclear gluon distributions still have large uncertainty at small x, low Q^2, and moderate Q^2

Gluon Density at Small x

Eskola, Paakkinen, Paukkunen, Salgado, EPJC 82 (2022) 413





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

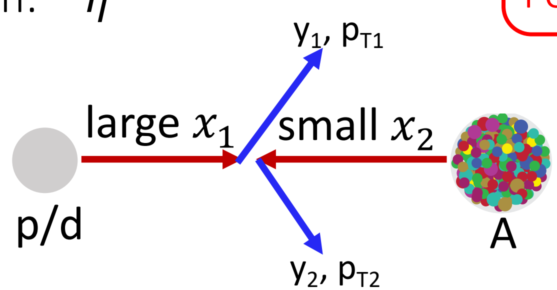
Experimental Approaches

Accessing gluon saturation ($Q^2 < Q_s^2$) region:

1. If Q_s is large enough: $Q_s \propto A^{\frac{1}{3}} \cdot x^{-\lambda} \cdot \frac{1}{b}$; $x_2 \sim \frac{p_{T1}e^{-y_1} + p_{T2}e^{-y_2}}{\sqrt{s}}$

Backward direction: $-\eta$

Forward direction: $+\eta$



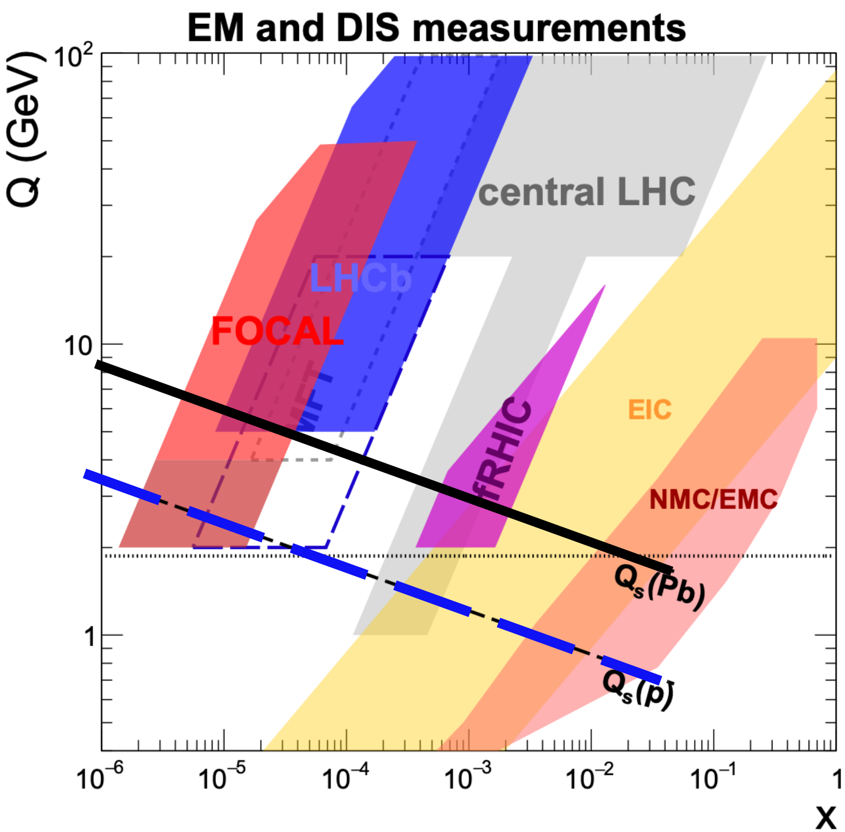
- Larger A: easier to access gluon saturation in heavy nuclei than in nucleons; nucleon serves as baseline
- Smaller x: more forward production and lower p_T
- Smaller b: more central collisions

2. If Q^2 is small enough: $Q \propto \frac{p_{T1}+p_{T2}}{2}$

- Smaller p_T**:** detector requirement for precision measurement

Scan Q^2, x, and Q_s by varying p_T, y, b, and A

$x - Q^2$ phase space

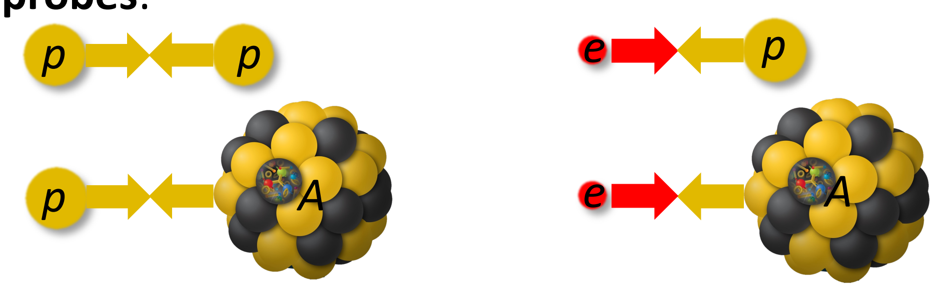


Test universality of gluon saturation at various collision energies → complete phase pace, full evolution:

- **RHIC serves as intermediate energy colliders, accessing low and intermediate Q^2**, share a similar phase space with forward production at the EIC

- **LHC data can probe samller x region gaining from high collision energies**

Test universality of gluon saturation by different probes:



Possible measurements

Inclusive measurement for R_{pA}: < 1 in forward direction, low p_T

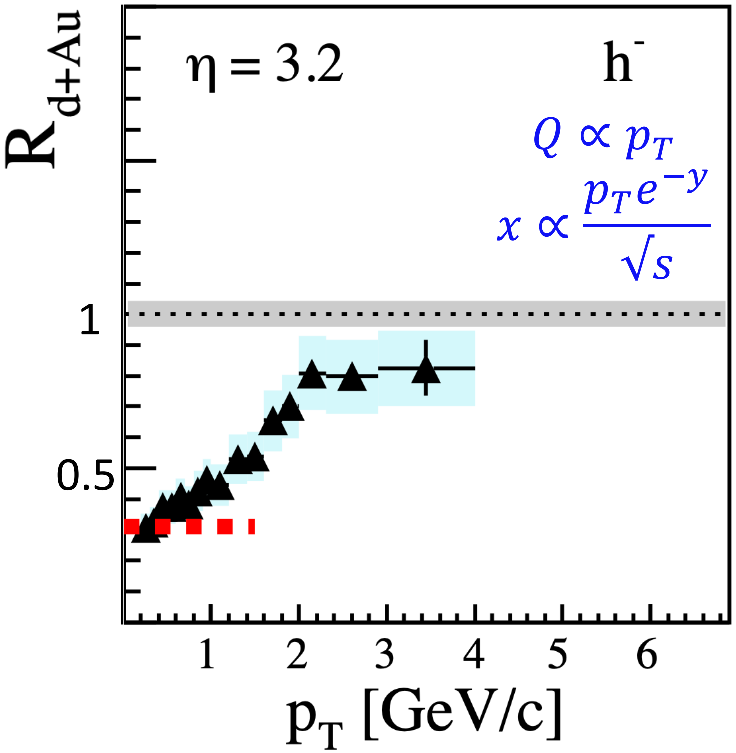
- Forward charged hadron, π^0 production from RHIC and the LHC
- Forward open charm production from the LHC
- UPC J/psi production from the LHC

Two-particle correlations for $C(\Delta\varphi)$: suppression in back-to-back correlation

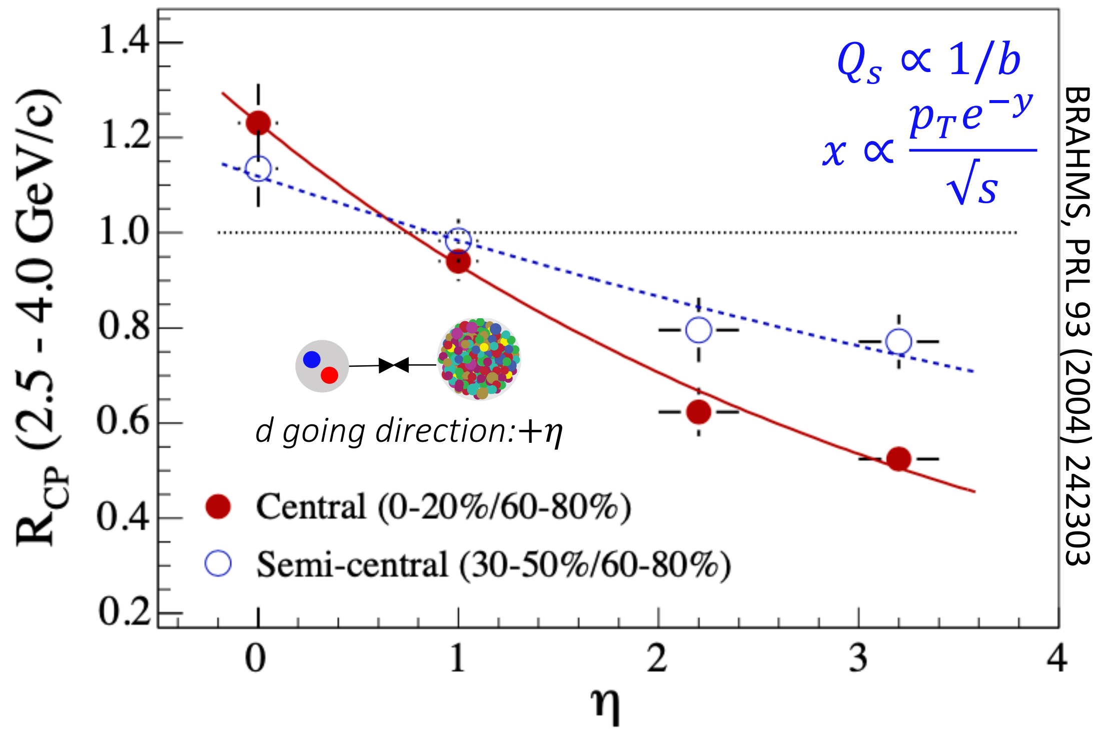
- Forward back-to-back π^0/hadron correlation from RHIC
- Forward back-to-back charged hadron/jet correlation from the LHC

Inclusive Charged Particle at BRAHMS

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



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

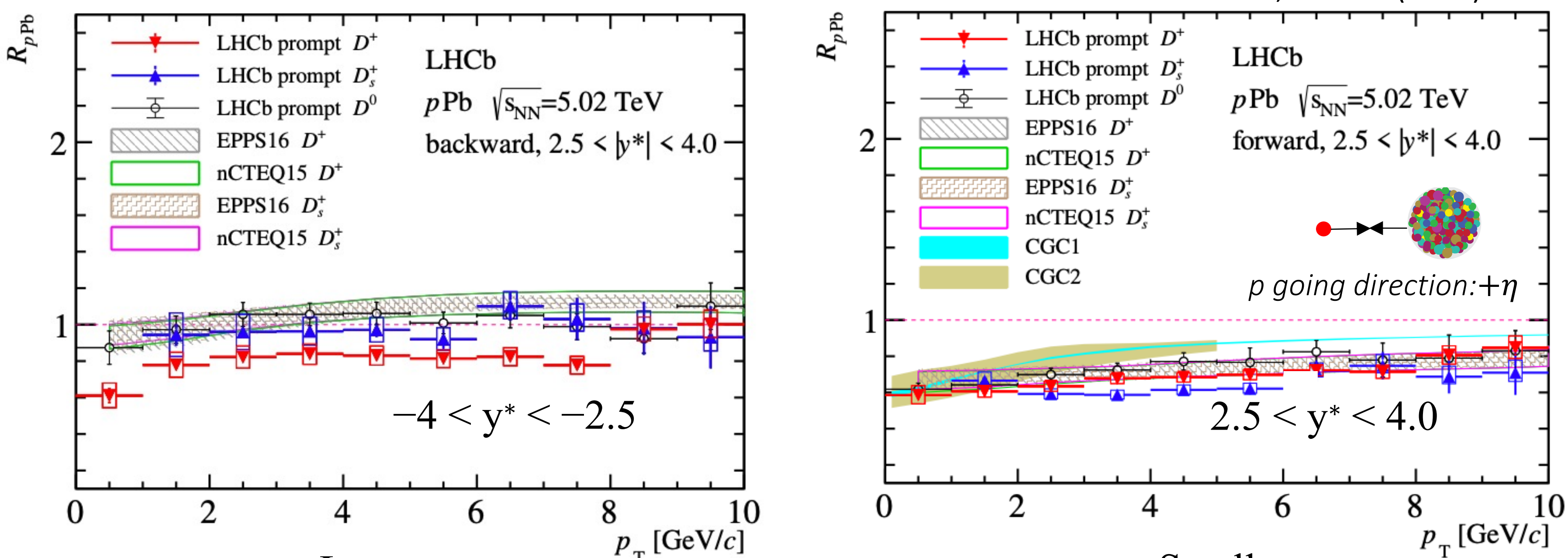


- Yields suppression $R_{dAu} < 1$ at $p_T < 2$ GeV; first hint of strong nuclear effect at small x?
- R_{cp} is more pronounced in more central dAu collisions
- R_{cp} decreases with increasing rapidity: scan x by varying rapidity

D Meson 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, JHEP01 (2024) 070



Large x Small x

CGC1: optical Glauber model; CGC2: c fragmentation function in a TMD framework

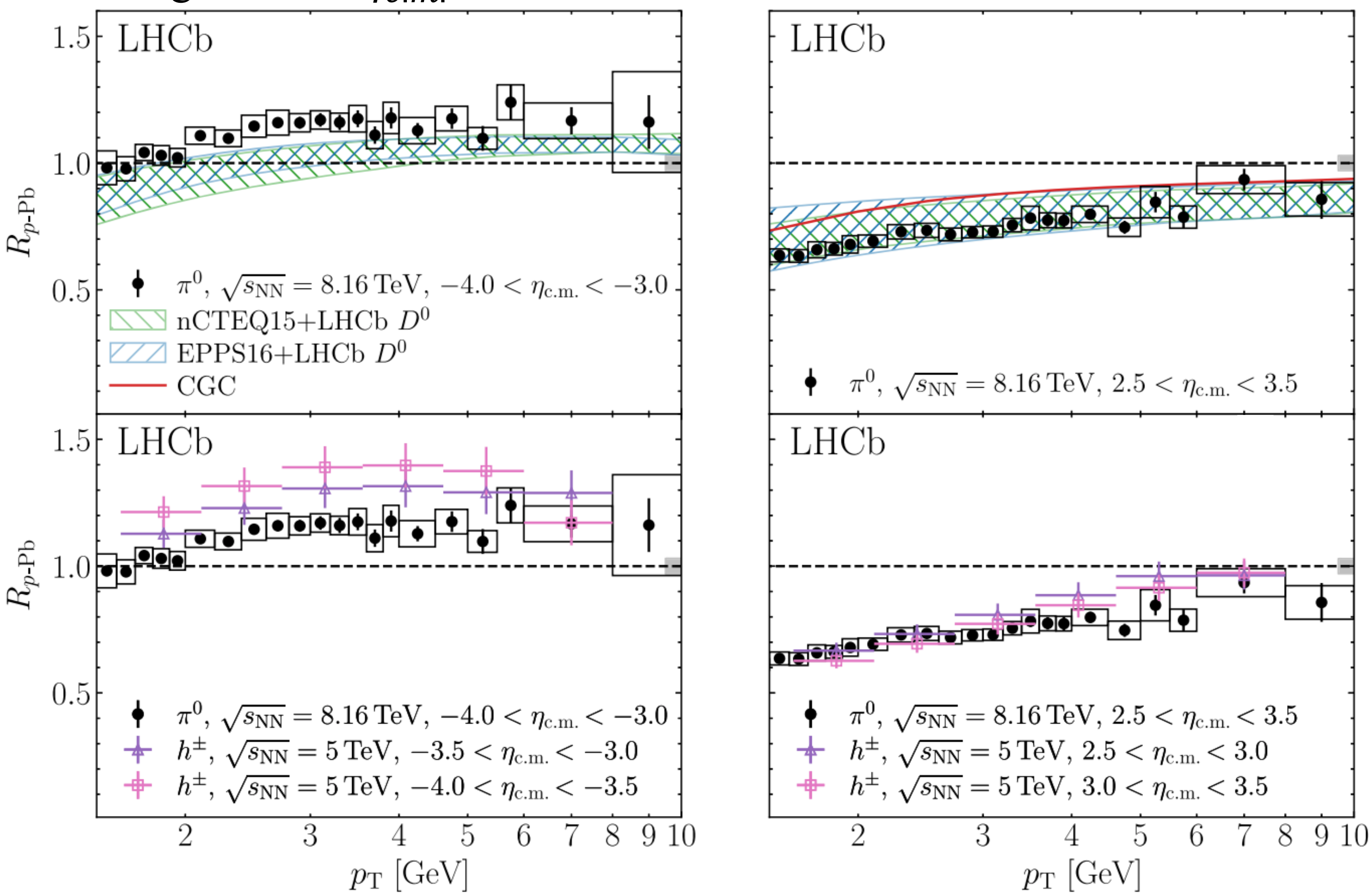
- More suppression of D^0 meson production at forward rapidity than backward direction
- Suppression at forward rapidity potentially depends on p_T

Scan Q^2 and x by varying p_T and y

π^0 and $h^\pm$ Production at LHCb

LHCb, PRL 131, 042302 (2023)
LHCb, PRL 128, 142004 (2022)

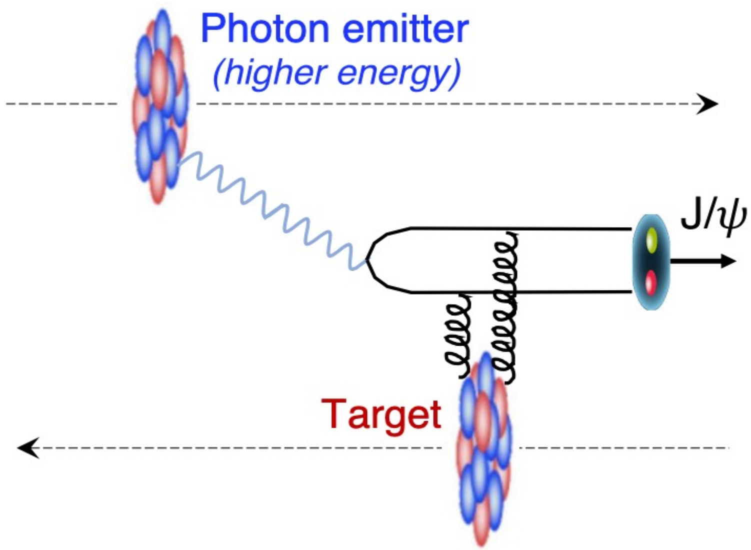
Large x, $-4 < \eta_{c.m.} < -3$ | Small x, $2.5 < \eta_{c.m.} < 3.5$



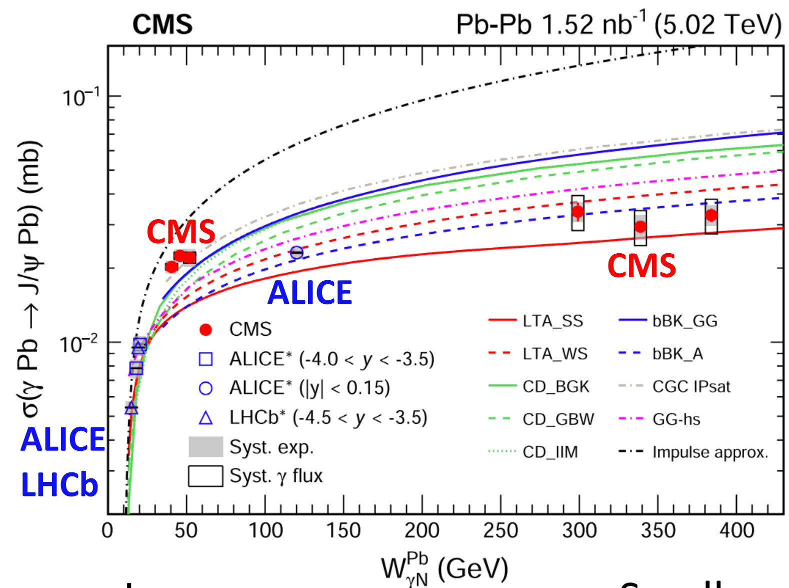
p_T and y dependence also observed by π^0 and $h^\pm$ production

UPC VM Production at the LHC

Carton from CMS PRL (2023)



$$\sigma(J/\psi) \propto [xg(x)]^2$$



$$x \sim \frac{M_{VM}}{\sqrt{s_{NN}}} e^{-y}, W_{\gamma N}^{Pb} = \sqrt{\sqrt{s_{NN}} M_{VM} e^{-y}}$$

- Coherent VM extensively measured at LHC, sensitive to gluon density
- $\sigma(J/\psi)$ rises at low $W_{\gamma N}^{Pb}$ (high $x > 10^{-2}$), and plateaus above 40 GeV up to 400 GeV (low x down to $10^{-4} - 10^{-5}$)

Not the full list:
ALICE, EPJC 81, 712 (2021)
LHCb, JHEP 07, 117 (2022)
CMS, PRL 131, 262301 (2023)
LHCb, JHEP 06, 146 (2023)

Possible Measurements

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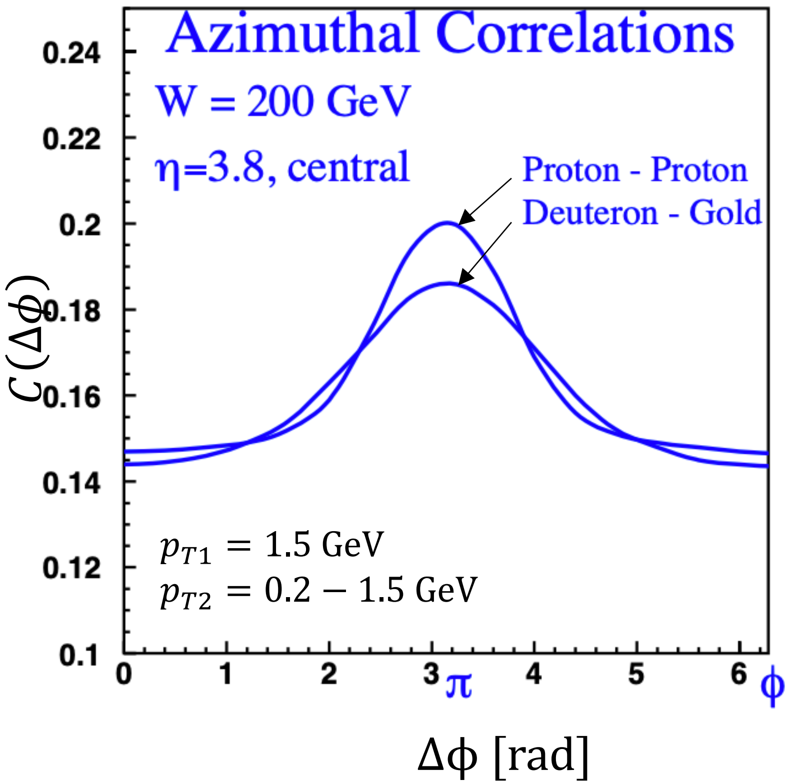
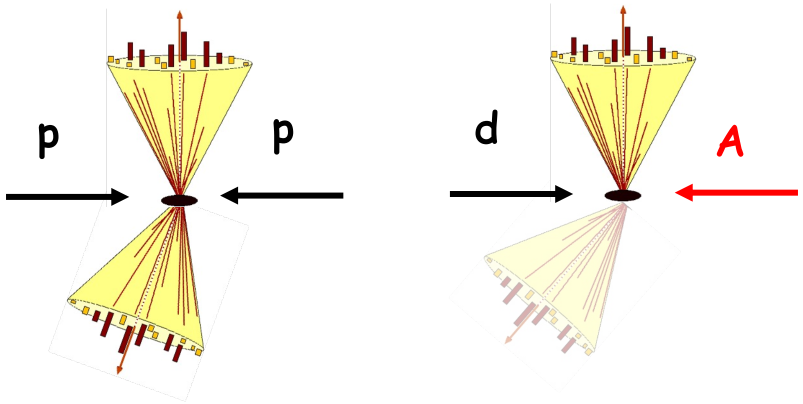
Di-hadron Correlations

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

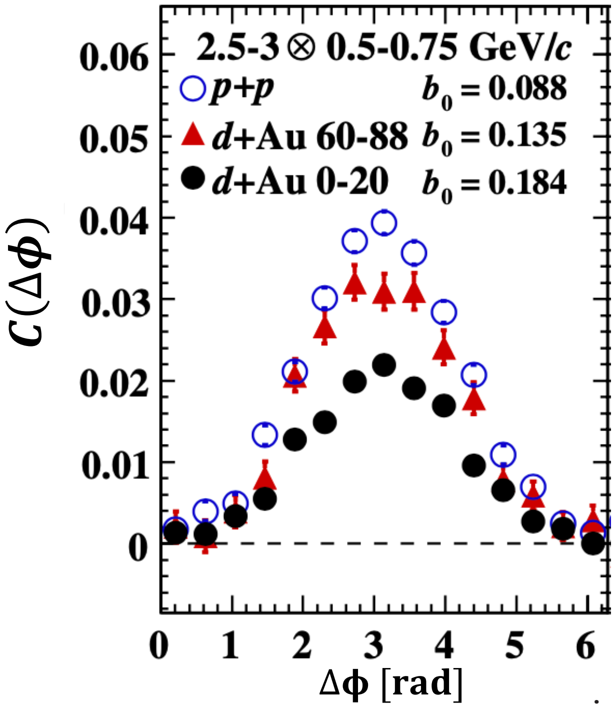
Deletion of away-side peak in d+A relative to p+p as a saturation feature:

- **Suppression**
- **Broadening**

Di-hadron correlations at PHENIX

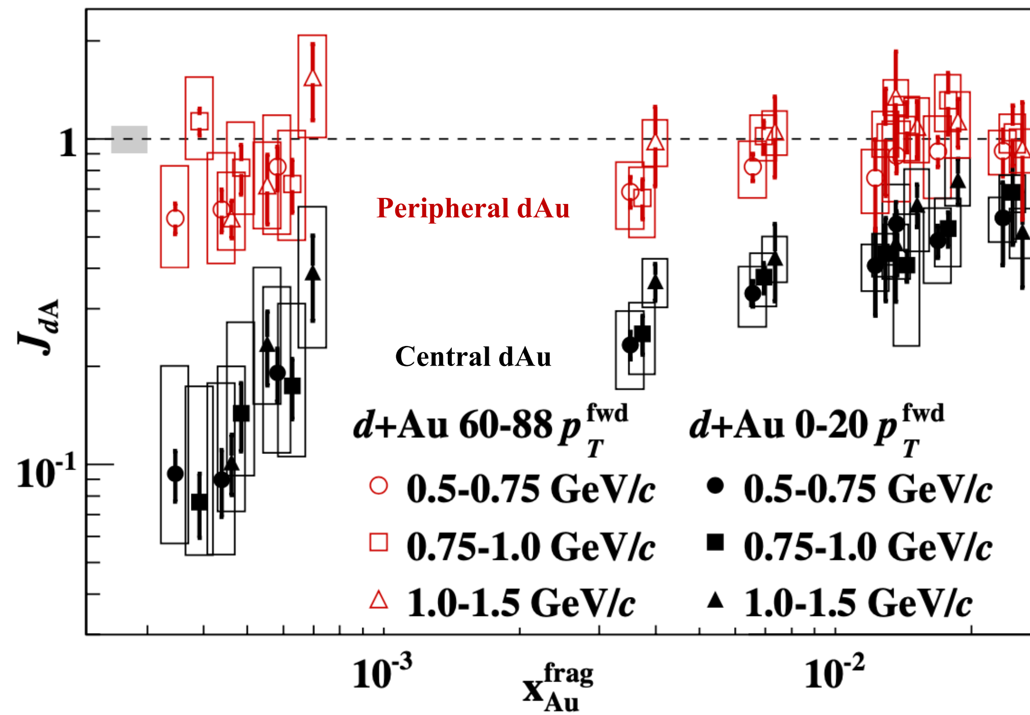
Middle-forward

|η|<0.35, 3.0 < η < 3.8



Forward-forward

Middle-forward



PHENIX, PRL 107 (2011) 172301

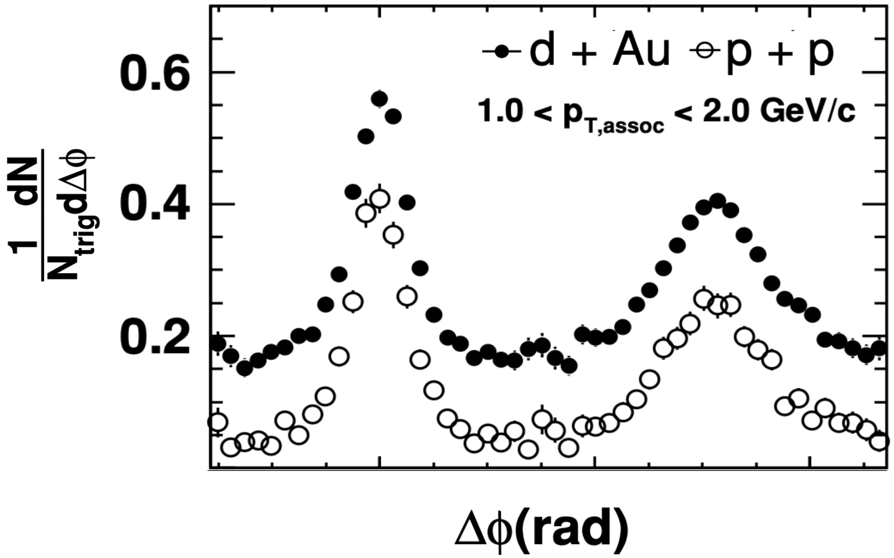
$$J_{dA} = \frac{1}{\langle N_{coll} \rangle} \frac{\sigma_{dA}^{pair} / \sigma_{dA}}{\sigma_{pp}^{pair} / \sigma_{pp}}$$

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

- Scan x by varying rapidity: more suppression in forward-forward than middle-forward correlation
- Suppression increases in more central dAu collisions
- High pedestal in dAu compared to pp collisions

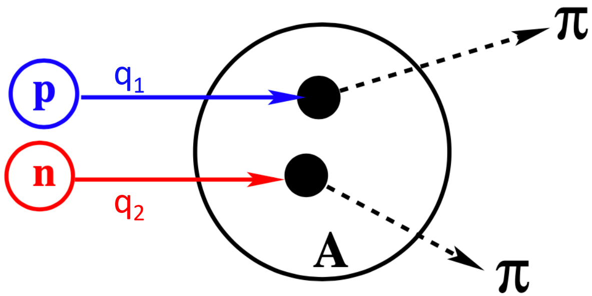
Double Parton Scattering in dAu?

PHENIX, PRC 73 (2006) 054903



Strikman and Vogelsang, PRD 83 (2011) 034029

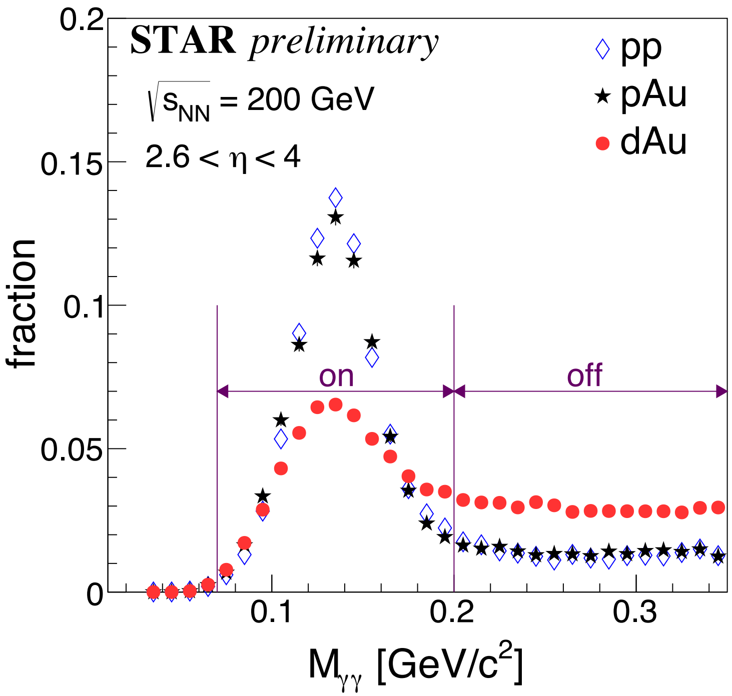
One example of DPS in dAu

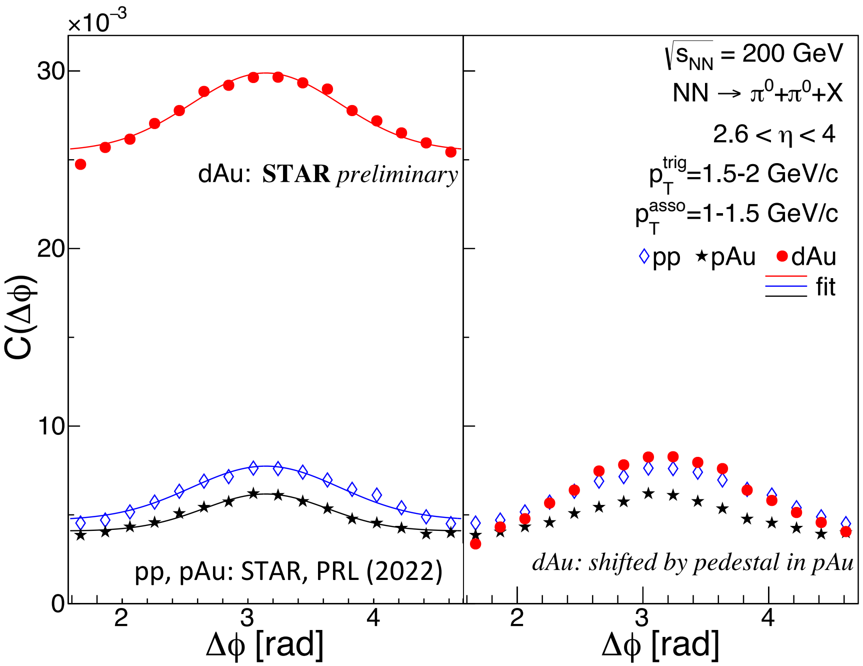


Comparison of p+p, p+Au and d+Au → study the individual source of DPS

- **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 will modify the correlation function
  - q_1,q_2 uncorrelated: DPS will only enhance pedestal

Revisit dAu data at STAR



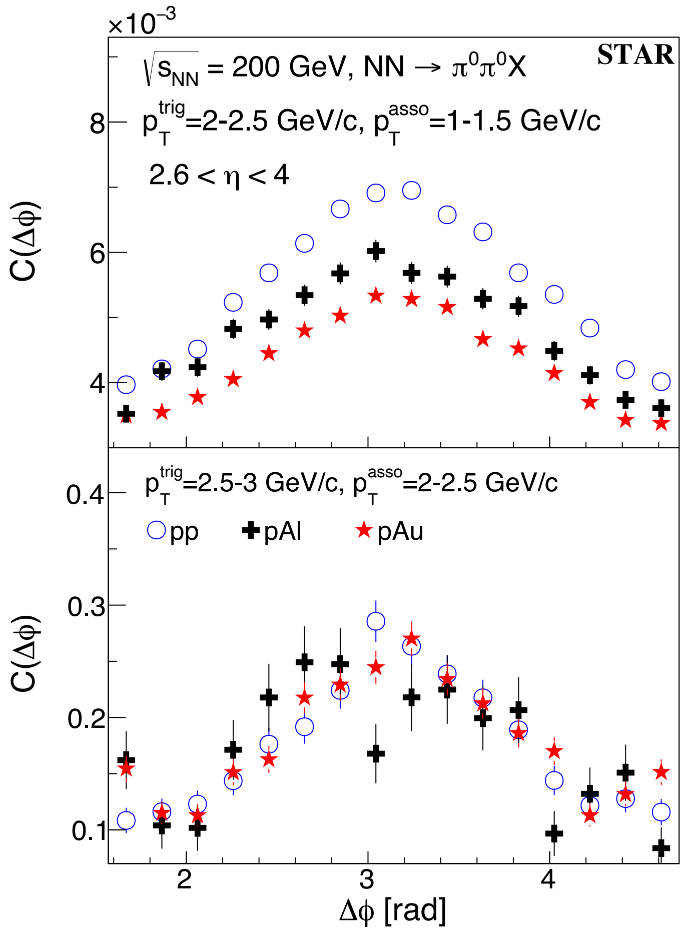


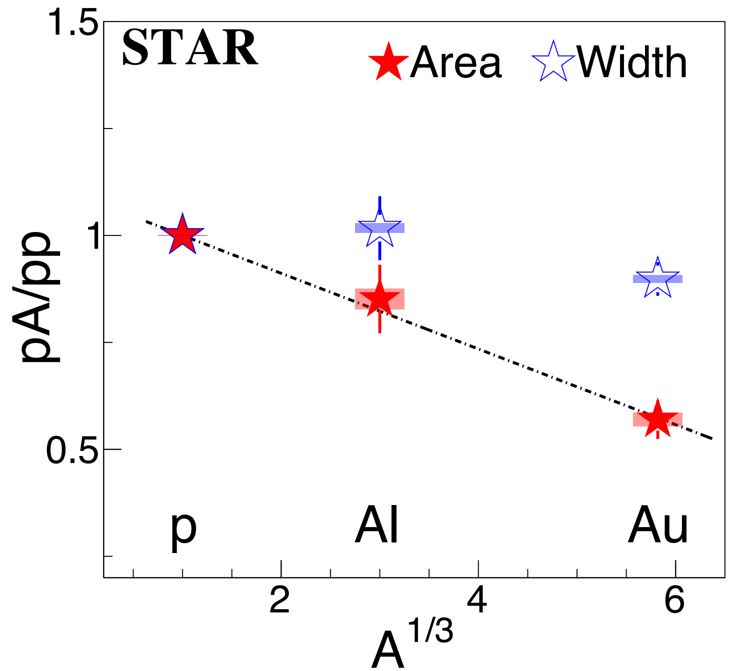
- π^0 PID: much higher background in d+Au than p+p (Au); p+p and p+Au are similar
- Very high pedestal: d+Au > 5 times higher than p+p (Au); much larger combinatorial background in d+Au than p+p(Au)
- Correlation from d+Au is similar as p+p, but higher than p+Au

Di- π^0 measuremtn favors cleaner p+Au collisions than d+Au collisions!

Di-π^0 correlations at STAR

STAR, PRL 129, 092501 (2022)





- Suppression at low p_T not high p_T
- Suppression linearly depends on $A^{1/3}$
- No broadening: other contributions not negligible → parton shower, fragmentation p_T

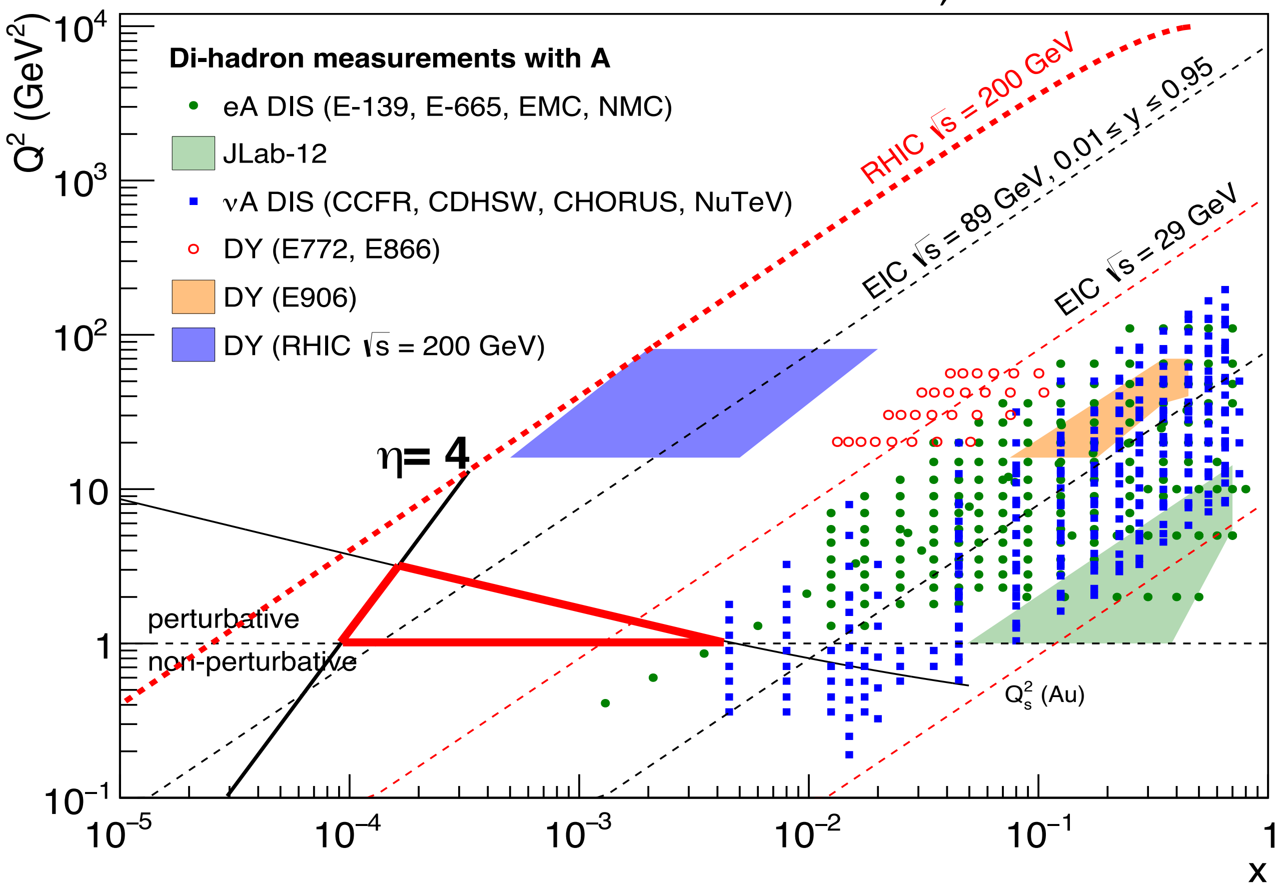
see back up S26/27

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

Relative area: $\frac{Area_{pA}}{Area_{pp}}$

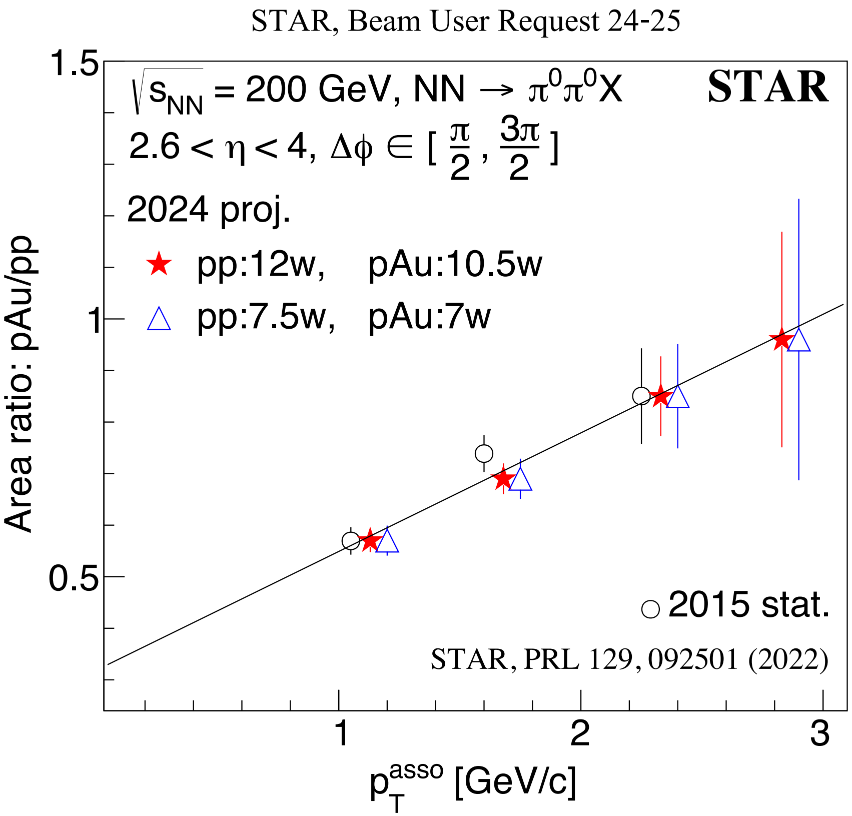
Future measurements at STAR

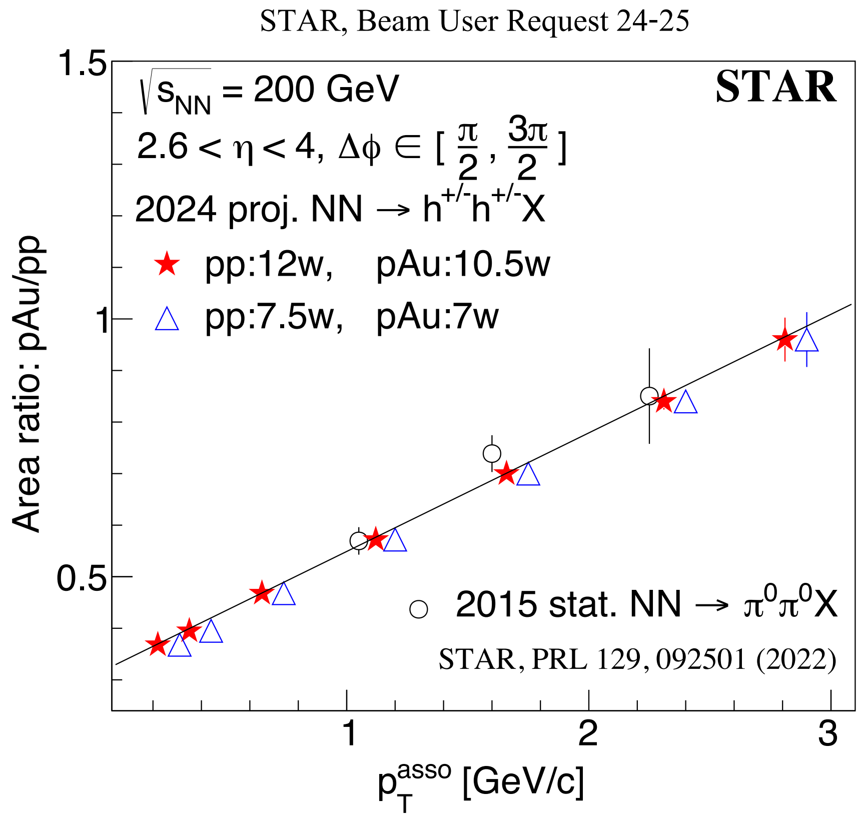
R. Abdul Khalek et al., arXiv:2103.05419



- **STAR forward upgrade of EMcal, Hcal and tracking at 2.5 < η < 4.0**: expand observables
  - di-charged hadorn, di-jet, γ-hadron/jet, inclusive γ…

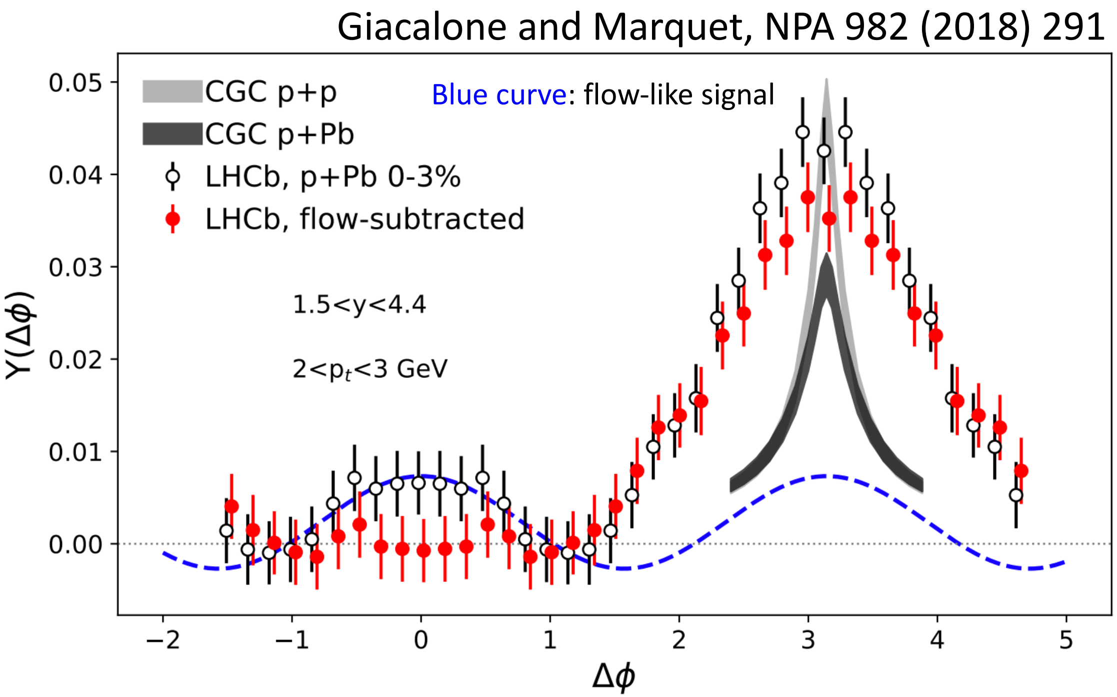
Di-h Correlation Projections

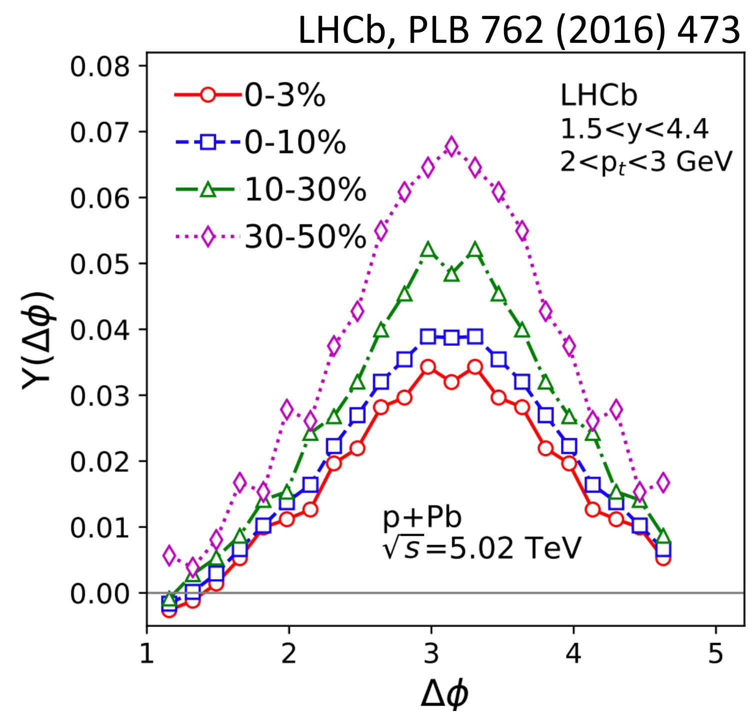




- **Run24/25 di-π^0 projection**: Best statistic indicates $\sim 35\%$ reduction of the statistical error compared to 2015 data
- **Run24/25 di-$h^{\pm}$ projection**: Higher statistic than di-π^0; $\geq 80\%$ reduction of the statistical error compared to 2015 data; the strongest suppression expected at the lowest p_T where forward upgraded detectors can probe

Di-hadron Correlations at LHCb

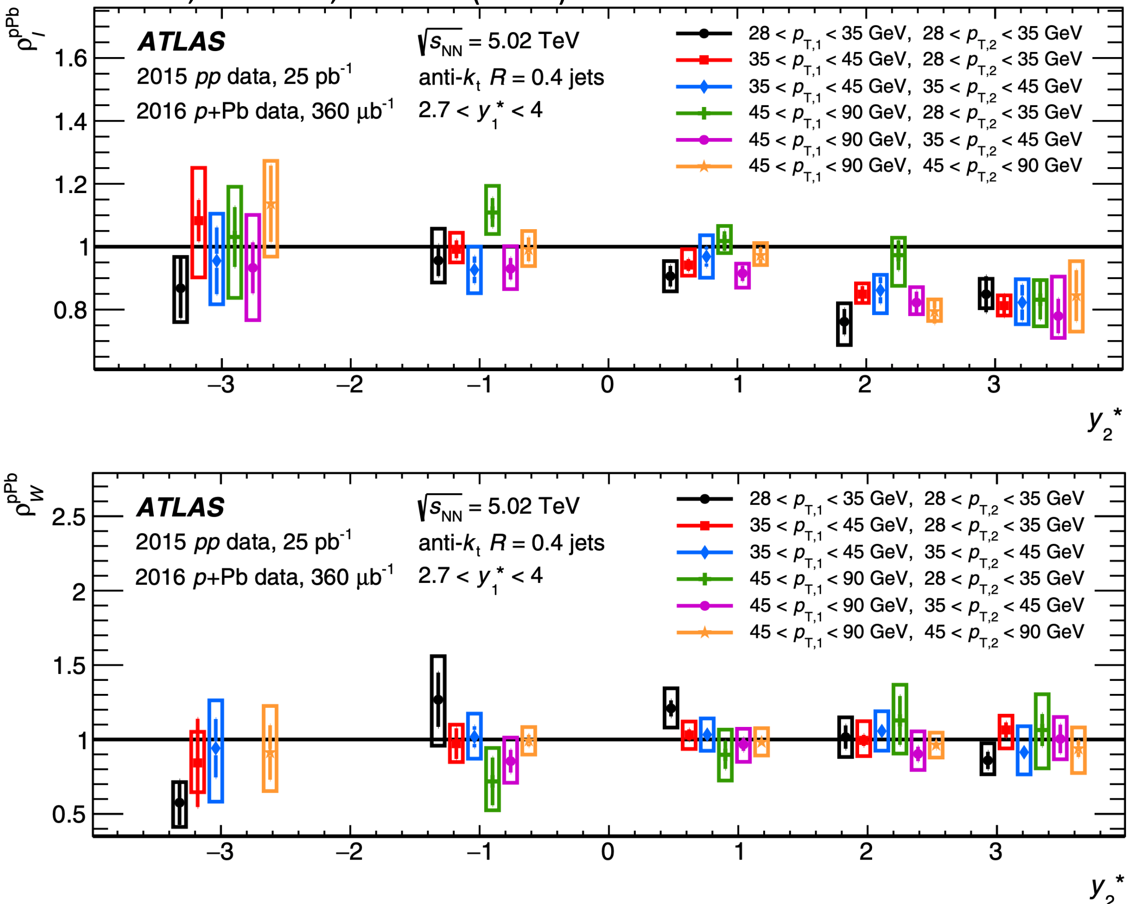




- Pure v_2 ($|\Delta\eta|>2$) at near-side peak; symmetric long-range component at near- and away-side peak
- Yield suppression in p+Pb at smallest x region → 10^{-5} (over 100 times lower than RHIC); is broadening seen in p+Pb?
- Theory curve shows narrow peak as initial- and final-state gluons radiation not included

Di-jet Correlations at ATLAS

ATLAS, PRC 100, 034903 (2019)



Area (A) of the correlation function:

$$\rho_I^{pPb} = \frac{Area_{pPb}}{Area_{pp}}$$

Width (σ) of the correlation function:

$$\rho_W^{pPb} = \frac{\sigma_{pPb}}{\sigma_{pp}}$$

- Rapidity dependence observed
- ρ_I^{pPb}~0.8 at most forward, less suppression than RHIC dihadron, x_{Pb}→10^{-4}; but Q^2 > ~ $800\ GeV^2$, too high?
- Width unchanged in p+p and p+Pb, same with RHIC di-hadron results

Summary

- Numerous efforts have been made to search for gluon saturation, at different collision energies, with different observables, and through different measurements

- Several experiments from RHIC and the LHC have shown various degree of proof of gluon saturation, partially aligning well with the saturation models

  - $h^{\pm}$ production from BRAHMS
  - D meson, π^0, and $h^{\pm}$ production from LHCb
  - VM production from LHCb, CMS, ALICE
  - di- π^0/cluster correlation from PHENIX and STAR
  - di- $h^{\pm}$ from LHCb
  - di-jet from ATLAS

Not the full list

- R_{pA} and $C(\Delta\varphi)$ measured in forward direction, presented p_T, centrality/event activity, rapidity, and A as CGC predicted; while the predicted broadening phenomena was not observed with $C(\Delta\varphi)$

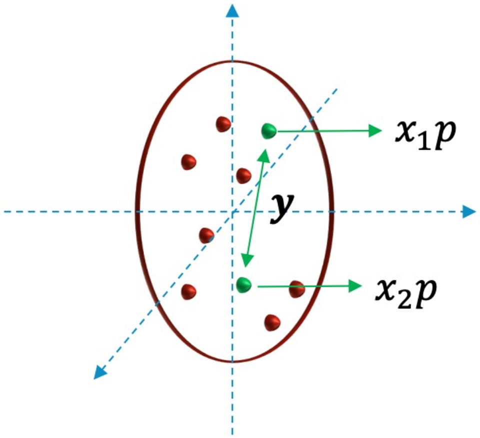
Summary and Outlook

- Color Glass Condensate calculations are now entering the NLO era $(\alpha_s \, ln\left(\frac{1}{x}\right) \sim O(1), NLO = \alpha_s^2 ln(\frac{1}{x}))$; LO cannot explain entire data
    - Heavy quark production (Hanninen et al, 2022)
    - Exclusive J/ψ, ρ, φ, Υ (Penttala, H.M, 2022)
    - Hadron production in pA (Shi et al, 2021; H.M, Tawabutr, 2023)
    - Dihadron correlations in DIS (Caucal et al 2023)

Not the full list

- Experiments are also entering high-precision measurement level; looking forward to
    - ATLAS Fcal dijet
    - LHCb forward open charm, direct photon, and correlation
    - Forward VM from the LHC
    - Measurements with STAR Forward Upgrade
    - Future measurements with ALICE FoCal Upgrade

Back up

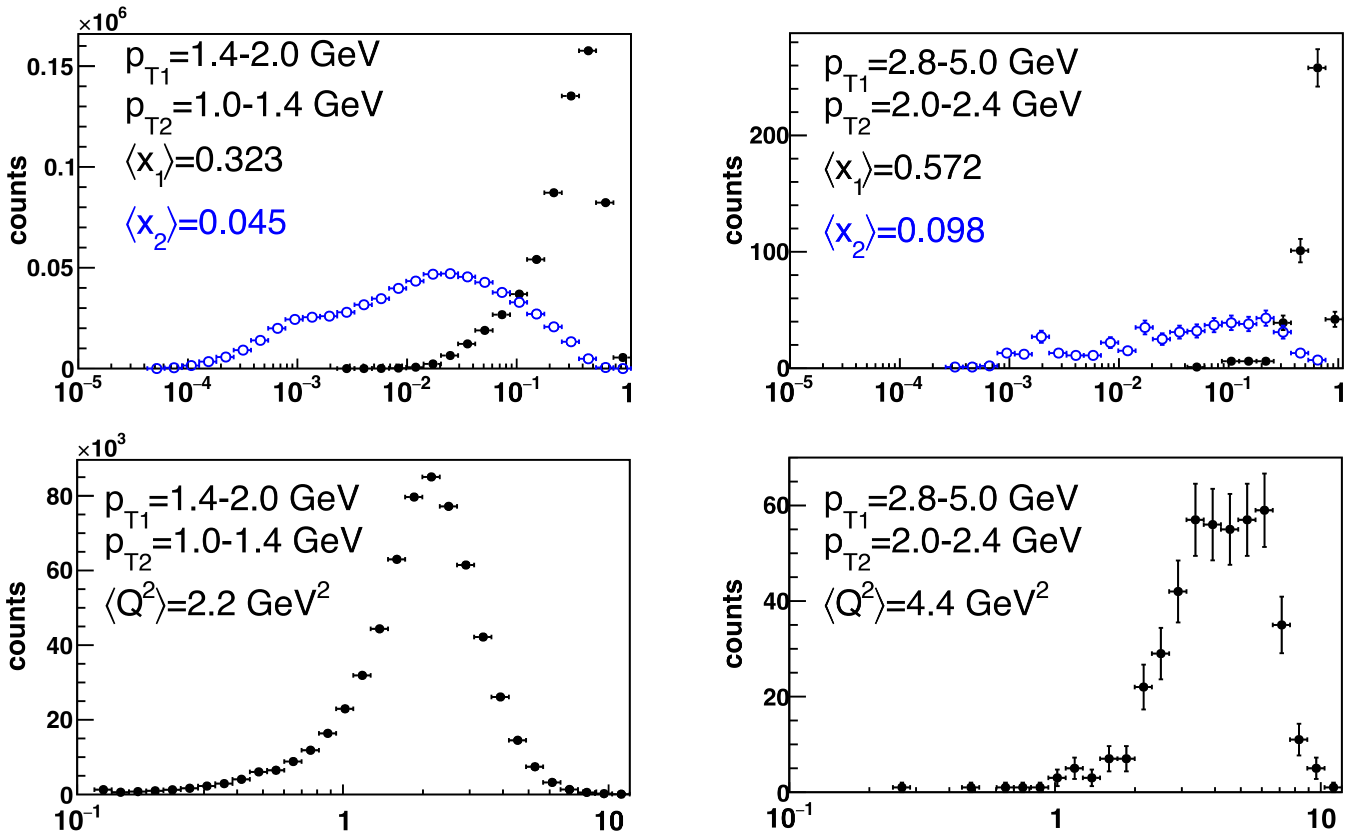


Double parton distributions (**DPDs**) contribute to correlated $\boldsymbol{\pi^0}$s : $F_{ik}\ (x_1, x_2, y)$

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

PYTHIA Kinematics: x_1, x_2 and Q^2

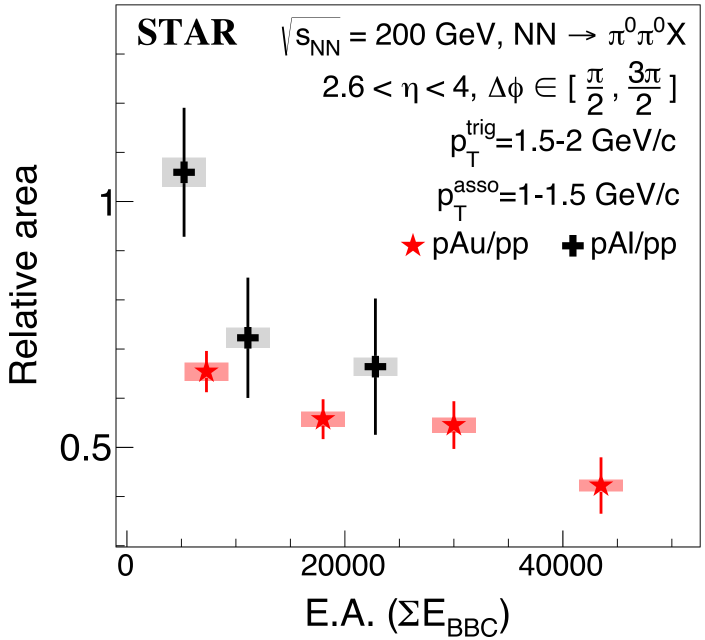
pp collisions at $\sqrt{s} = 200$ GeV, $2.6 < \eta < 4.1$

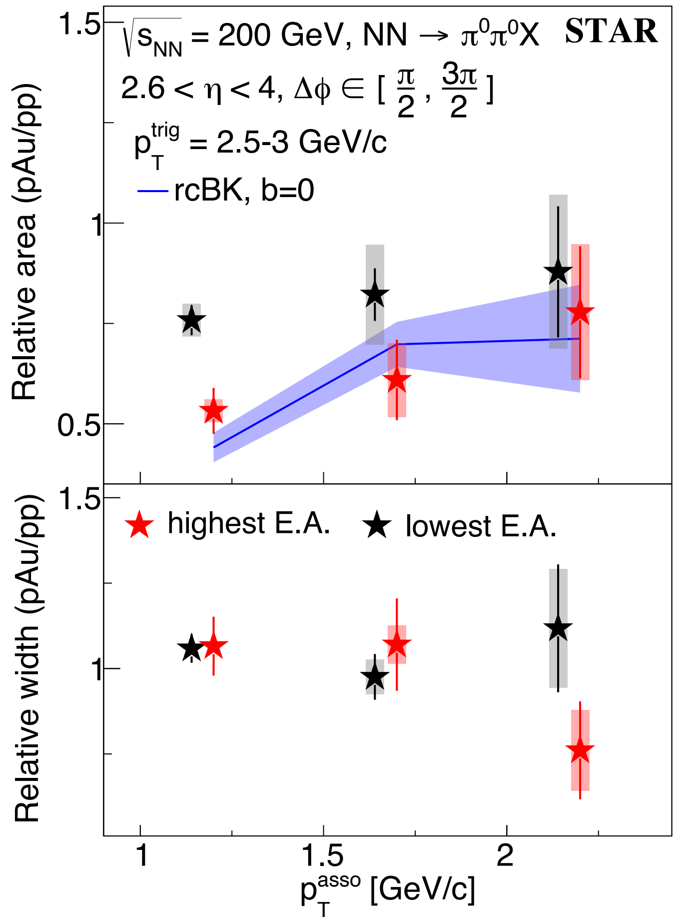


- x_1 , x_2 and Q^2 increase with p_T, low p_T helps to access saturation regime
- x_1 (x_2) dominates at high (low) x regime; well separated

Di-π^0 correlations at STAR

STAR, PRL 129, 092501 (2022)





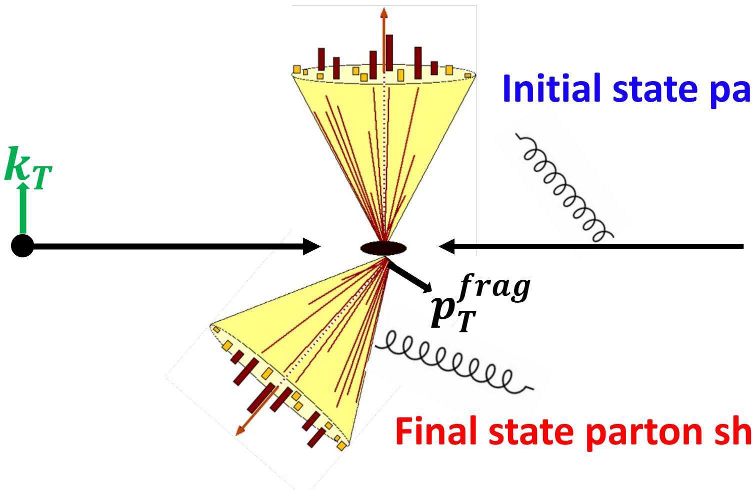
- Suppression increases with *E.A., highest E.A. data is consistent with predictions at $b = 0$; E.A. is not identical to centrality
- No broadening: *see back up S26/27*, NLO contribution not negligible → parton shower, fragmentation p_T

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

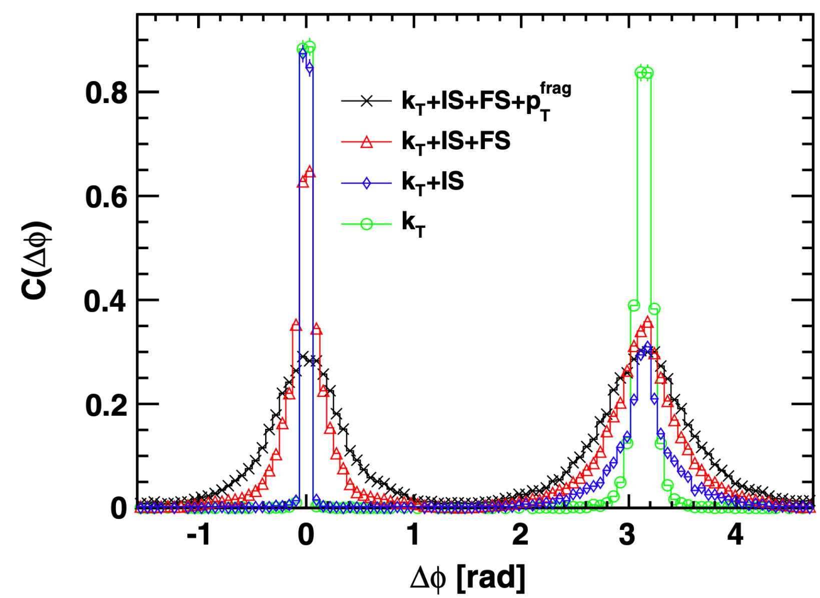
rcBK: J. L. Albacete et al.,PRD 99, 014002 (2019)

Broadening in Simulation

Factors can cause the broadening:



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

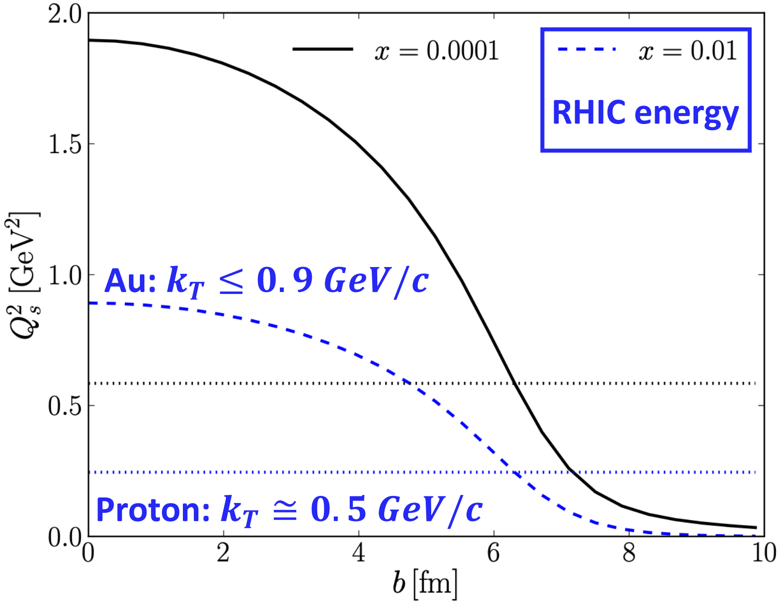


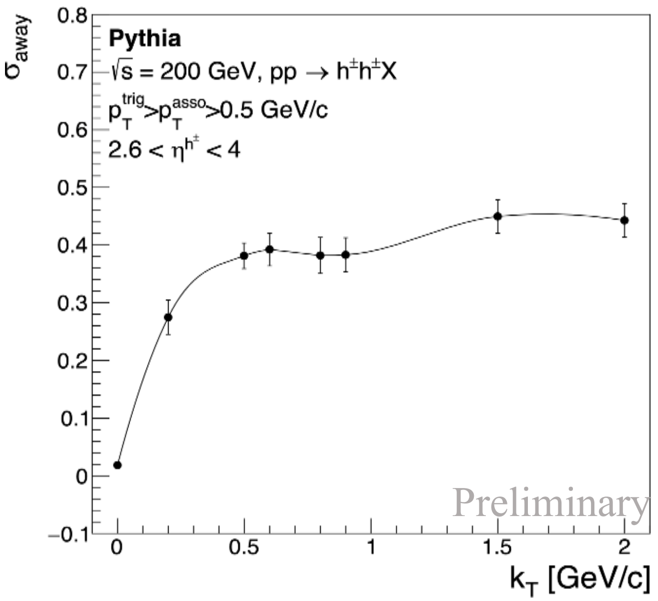
- Intrinsic k_T, parton shower, and p_T^{frag} can lead to broad near- and away-side peaks.

- Different dominate effects lead to a broad away/near-side peak; use near-side peak to calibrate

	Near-side $\Delta\phi$ RMS	Away-side $\Delta\phi$ RMS
k_T	0.21	0.25
k_T + IS	0.30	0.72
k_T + IS + FS	0.65	0.81
k_T + IS + FS + p_T^{frag}	1.00	1.00

Simulation at RHIC





- Saturation implemented in simulation by parameterizing intrinsic $Q_S \sim k_T$: at RHIC energy, for proton: $k_T \cong 0.5\ GeV/c$; for Au: $k_T \leq 0.9\ GeV/c$

- Preliminary simulation studies: with intrinsic k_T, PS, and p_T^{frag} turned on, away-side width stays unchanged at $k_T > 0.5\ GeV/c$, broadening is not expected to occur in p+Au compared to p+p at RHIC; explanation for the experimental results?