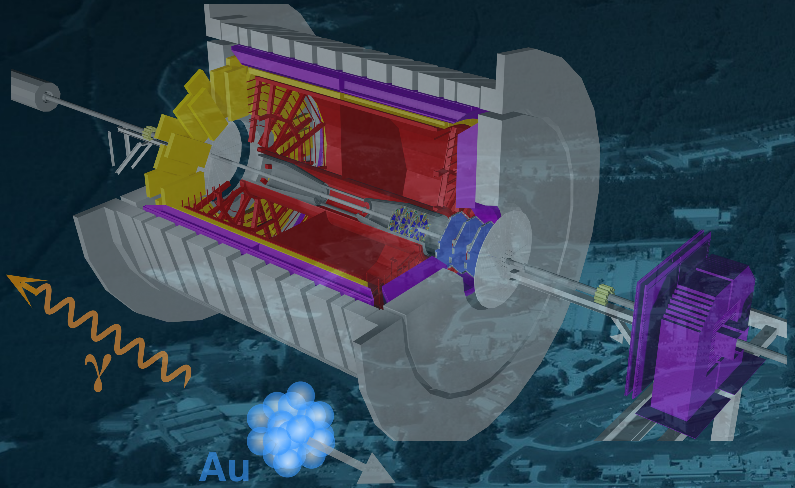


Brookhaven National Laboratory

U.S. DEPARTMENT OF ENERGY

Baryon asymmetry (and more) in inclusive γ-A interactions at RHIC

Prithwish Tribedy
(Brookhaven National Laboratory)

CFNS workshop on target fragmentation and diffraction physics with novel processes: Ultraperipheral, electron-ion, and hadron collisions
Feb 9-11, 2022

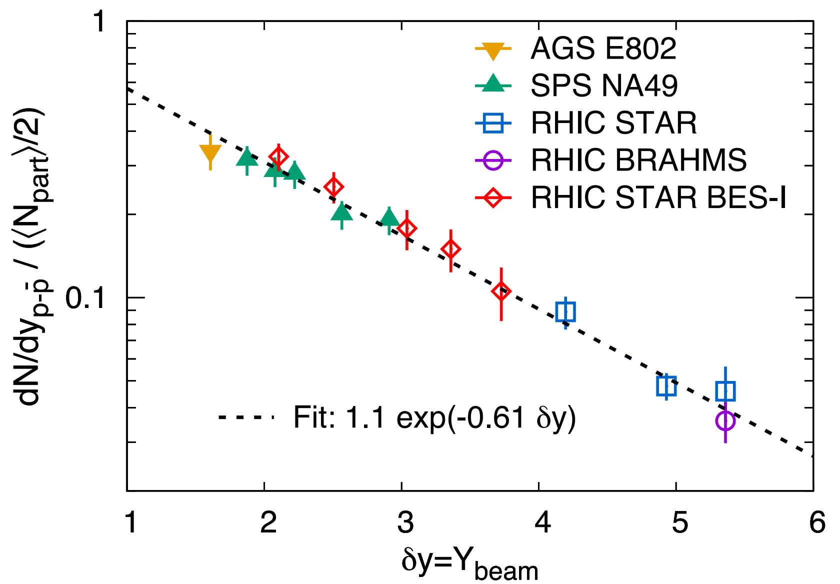
Outline

- Introduction
    - Why baryon asymmetry in high energy collisions is a puzzle?
- Photonuclear processes and measurements from STAR
    - What is offered by inclusive photonuclear interactions ?
- Opportunities with RHIC and STAR upgrade
    - Why extended pseudorapidity and PID capability of STAR is the best choice ?
- What more: Di-hadron correlations, collectivity in photon-induced processes
    - How do understand that microscopic origin of collectivity ?

Introduction: baryon asymmetry in high energy collision

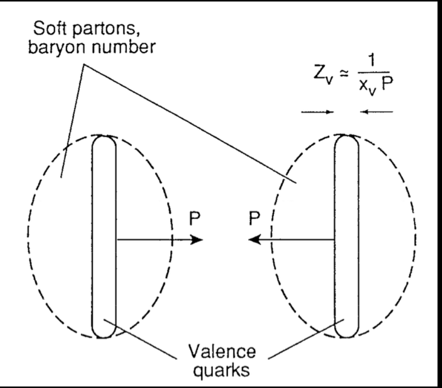
Baryon asymmetry in the central rapidity region

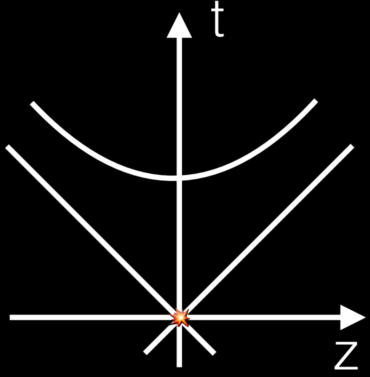
Nicole Lewis, BNL NP seminar



No ab initio theory to explain baryon stopping in hadronic interactions
Also, why the distribution follows an exponential distribution

Kharzeev, Phys. Lett. B, 378 (1996) 238-246





$$t_{\rm coll} \sim (x_V P)^{-1} = (1/3 \times 100)^{-1}\ \mathrm{GeV}^{-1} = 0.006\ \mathrm{fm}$$

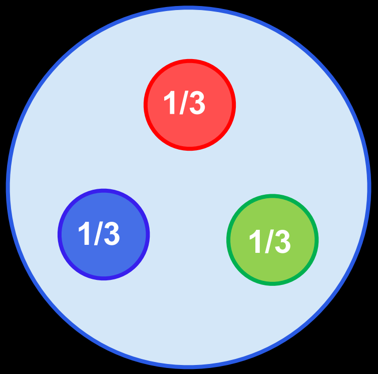
$$t_{\rm int} \sim \mathcal{O}(1)\ \mathrm{fm}$$

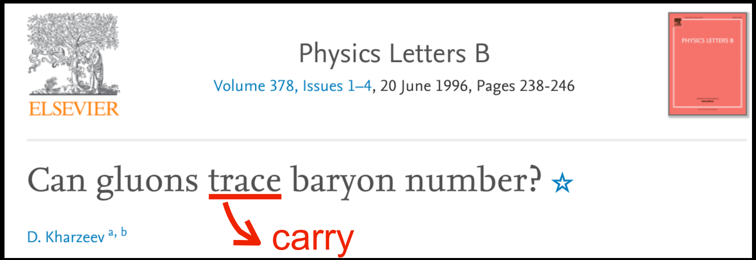
The time available for valence quark is too short to be stopped

What carries the baryon number ?

Kharzeev, Phys. Lett. B, 378 (1996) 238-246

Conventional picture




Physics Letters B

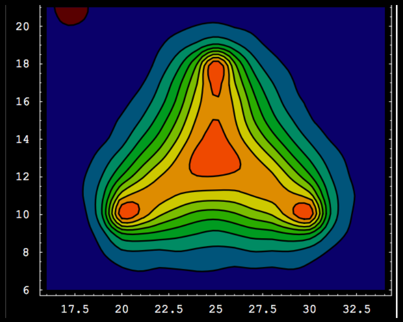
Volume 378, Issues 1–4, 20 June 1996, Pages 238-246

ELSEVIER

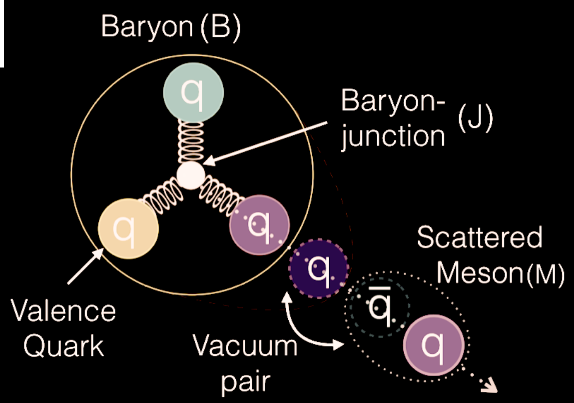
Can gluons trace baryon number? ☆

D. Kharzeev [a, b]

carry



Baryon junction picture



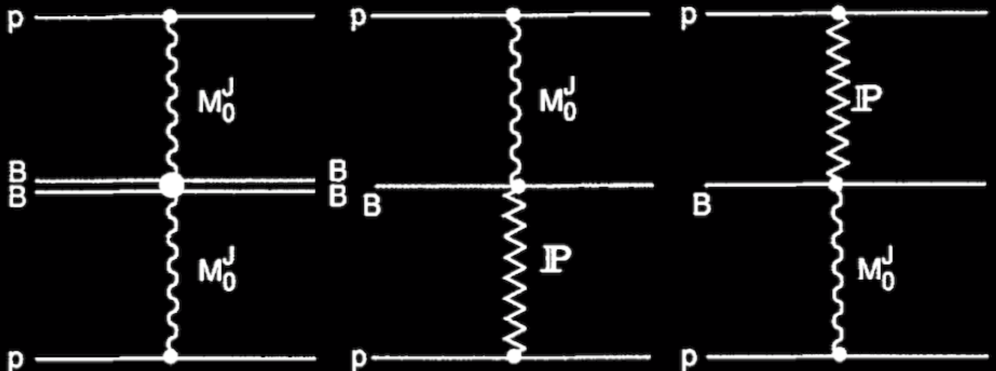
The conventional picture of baryon assumes baryon number is carried by three individual quarks — this is however an assumption

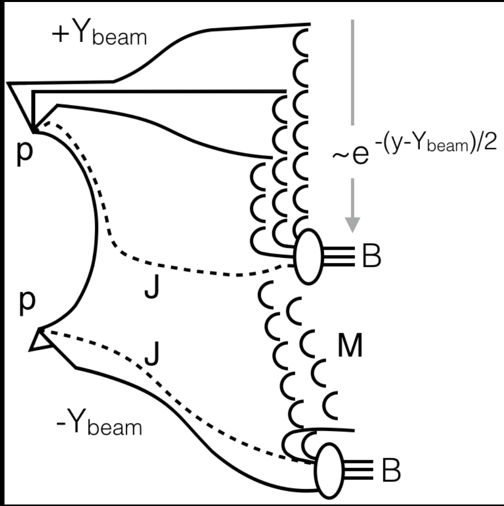
The gauge invariant configuration of the baryon wave function describes it has a string-junction made of gluons. If this junction carries baryon number they can be easily stopped in collisions

$$x_J \ll x_V \qquad ((x_J P)^{-1} \gg (x_V P)^{-1})$$

How a junction can be stopped?

Kharzeev, Phys. Lett. B, 378 (1996) 238-246





$$
\begin{aligned}
E_B \frac{d^3\sigma^{(1)}}{d^3 p_B} &= 8\pi G_p^M(0) G_p^P(0)\ f_B^{MP}(m_t^2) \\
&\times \left(\frac{\sqrt{s}\, m_t}{s_0}\right)^{\alpha_0^J(0)+\alpha_P(0)-2} \\
&\times (\exp[y^*(\alpha_P(0)-\alpha_0^J(0))] \\
&+ \exp[-y^*(\alpha_P(0)-\alpha_0^J(0))]).
\end{aligned}
$$

A string-junction from a target can be stopped by the soft parton field of the projectile, the cross section will drop exponentially with the rapidity loss ($y-Y_{beam}$), pions will fill the gap between y and Y_{beam}

This can provide a natural explanation of baryon asymmetry at (y=0)

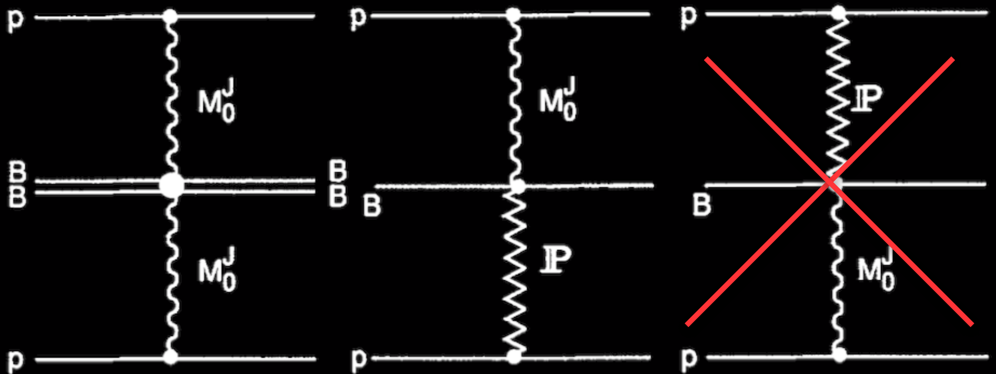
projectile $(\sim \exp(\alpha_0^J(y - Y_{\mathrm{beam}}))$

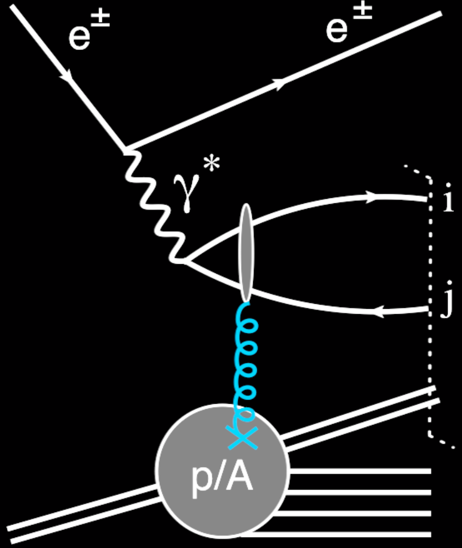
target $(\sim \exp(-\alpha_0^J(y - Y_{\mathrm{beam}}))$

Exponential rapidity dependence cannot be seen in p+p/A+A due to this compensation

Baryon free projectile

Kharzeev, Phys. Lett. B, 378 (1996) 238-246





$$E_B \frac{d^3\sigma^{(1)}}{d^3 p_B} = 8\pi G_p^M(0) G_p^P(0)\; f_B^{MP}(m_t^2) \times \left(\frac{\sqrt{s}\, m_t}{s_0}\right)^{\alpha_0^J(0)+\alpha_P(0)-2} \times \left(\cancel{\exp[y^*(\alpha_P(0) - \alpha_0^J(0))]} + \exp[-y^*(\alpha_P(0) - \alpha_0^J(0))]\right).$$

projectile $\cancel{(\sim \exp(\alpha_0^J(y - Y_{\rm beam}))}$

target $(\sim \exp(-\alpha_0^J(y - Y_{\rm beam}))$

In photon-induced processes we should be able to see exponential rapidity dependence

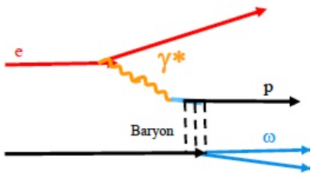
Connections to other recent work: baryon-VM swap

Spencer Klein, POETIC, Sept 2019
Ayerbe Gayoso et al., Eur.Phys.J.A 57 (2021) 12, 342 [arXiv: 2107.06748]

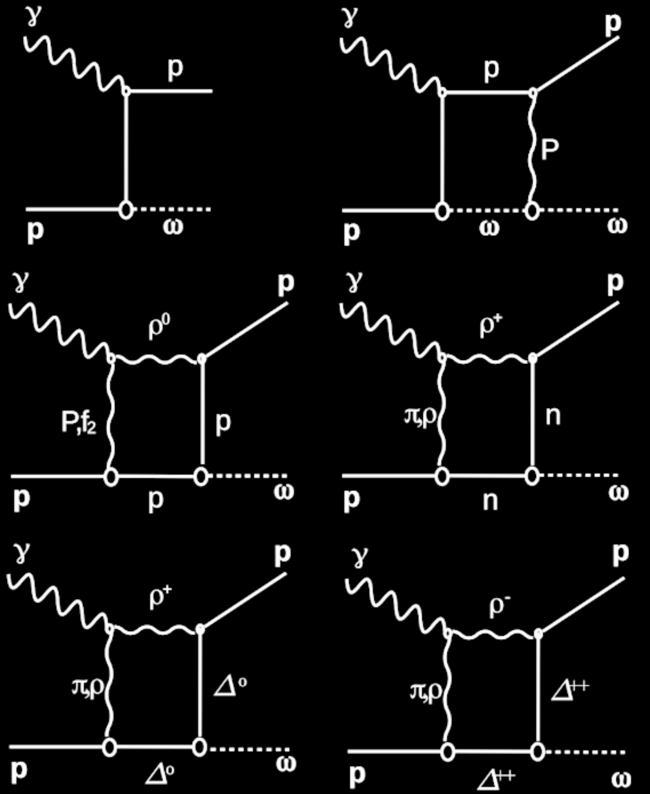
J.M. Laget, Phys. Rev. C 104, 025202 (2021) [arXiv:2104.13078]

Rapidity distributions for UPCs and an EIC

- Model as forward production, except:
  - In γp CM frame, swap ω and p rapidities
    - Photon is soft
    - ω is in far-forward region (near beam rapidity)
    - Proton is at mid-rapidity



In a purely hadronic interaction picture the exchange of the baryonic quantum number. A baryon is found at mid-rapidity whereas a vector meson is found near target fragmentation.



See the recent measurements:
W. B. Li et al. (Jefferson Lab F_π Collaboration)
Phys. Rev. Lett. 123, 182501

Connections to other recent work: baryon-VM swap

Spencer Klein, POETIC, Sept 2019
Ayerbe Gayoso et al., Eur.Phys.J.A 57 (2021) 12, 342 [arXiv: 2107.06748]

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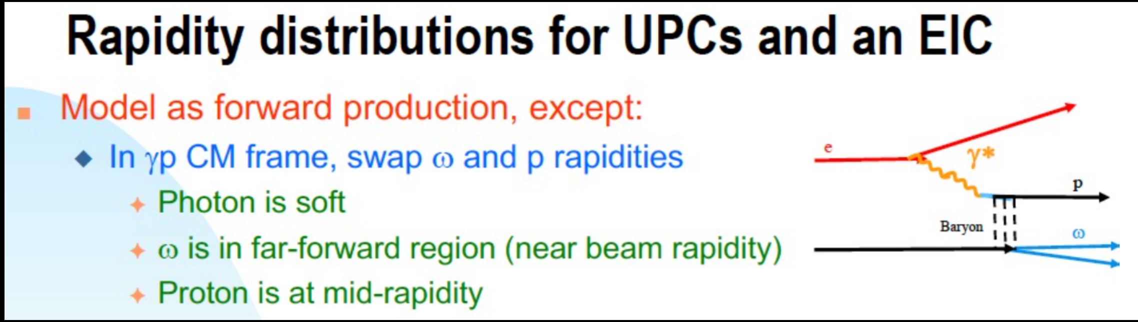
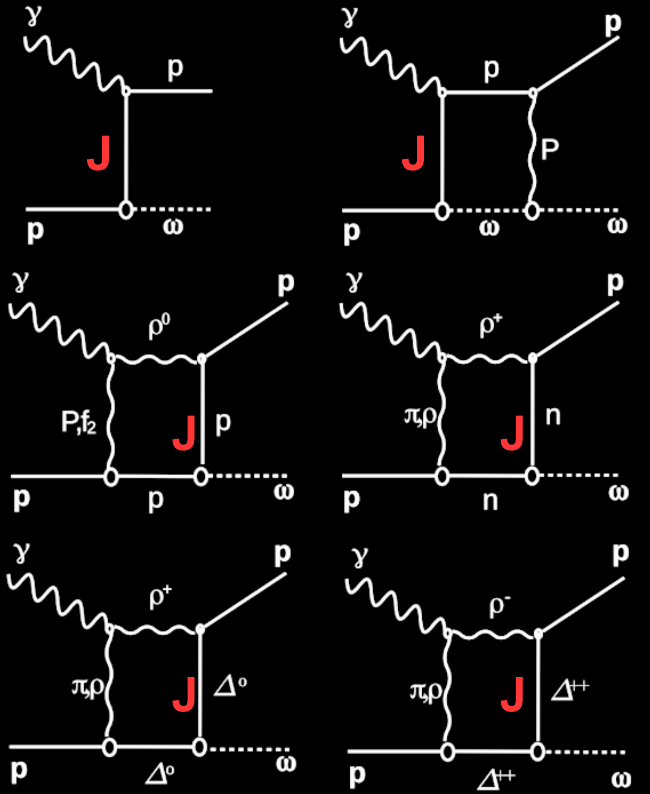


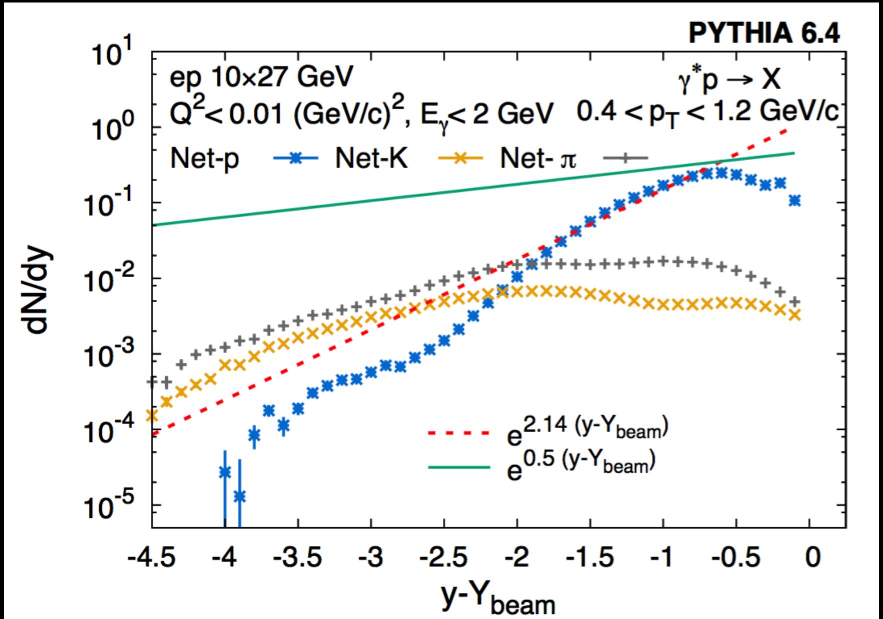


In a purely hadronic interaction picture the exchange of the baryonic quantum number. A baryon is found at mid-rapidity whereas a vector meson is found near target fragmentation

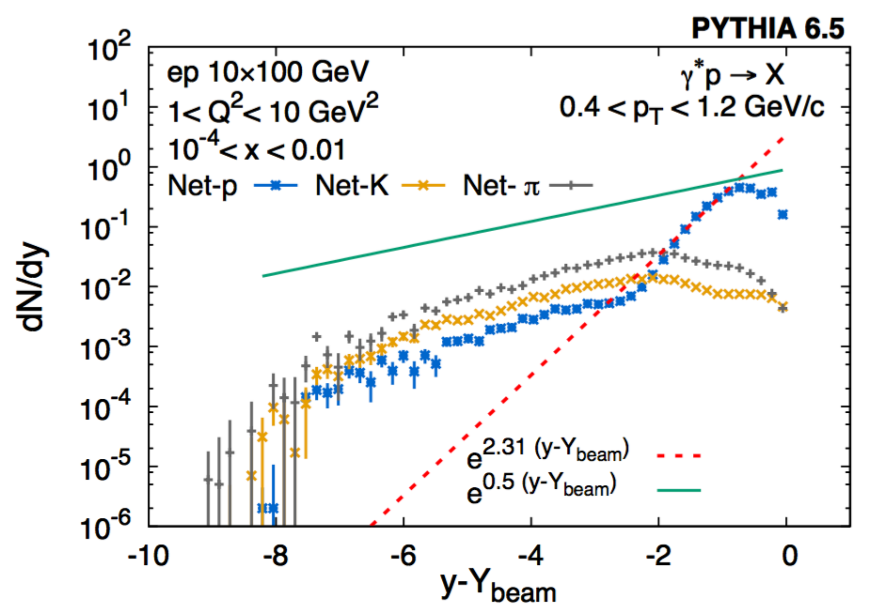
Connections to the microscopic picture of baryon junction?

What does Pythia predict ?

RHIC photonuclear kinematics



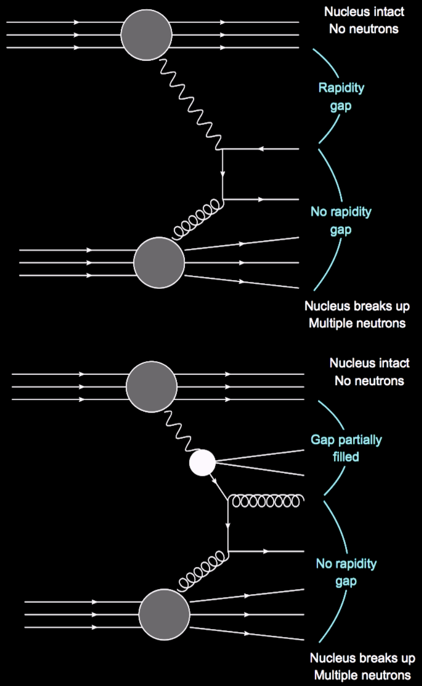
Possible EIC DIS kinematics



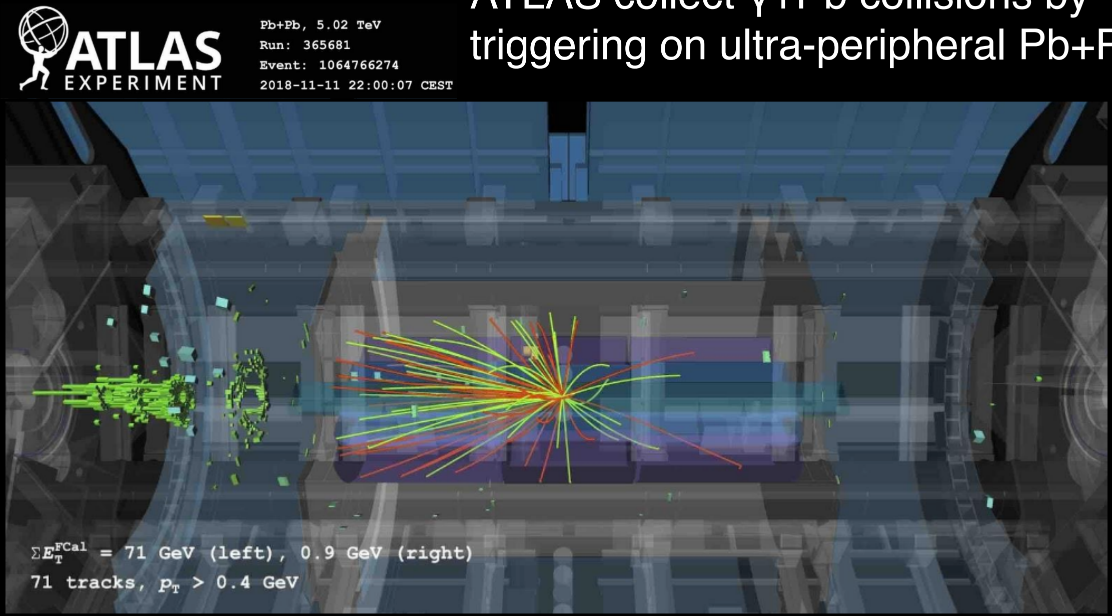
PYTHIA produces much steeper slope for net-proton that is incompatible with global data on baryon stopping in A+A or what is predicted by baryon junction picture

Photonuclear processes at RHIC and LHC

Photonuclear processes at the LHC



ATLAS collect γ+Pb collisions by triggering on ultra-peripheral Pb+Pb

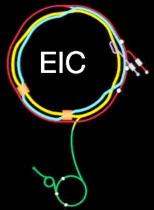


ATLAS Collaboration, Phys. Rev. C 104, 014903 (2021) [2101.10771]

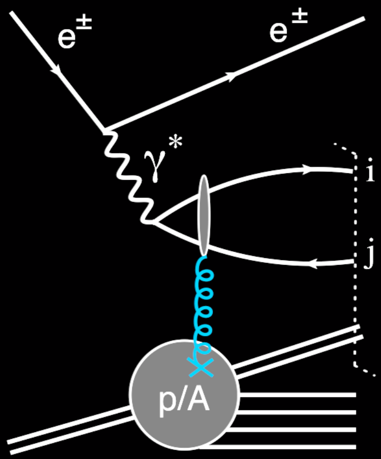
$Q^2 \sim (\hbar c/R_A)^2 \rightarrow 0$, γ^L(p, LHC)=6.51e3,
E_γ (LHC) ~ γ^L $(\hbar c/R_A)$ ~71 GeV
$W_{\gamma Pb}$ (LHC) ~ 844 GeV, $dN_{trk}/d\eta$ (HM) > 10

ATLAS collaboration performed this pioneering measurements of collectivity in γ+Pb collisions
CMS has performed the same in γ+p collisions

Inclusive photonuclear processes at RHIC

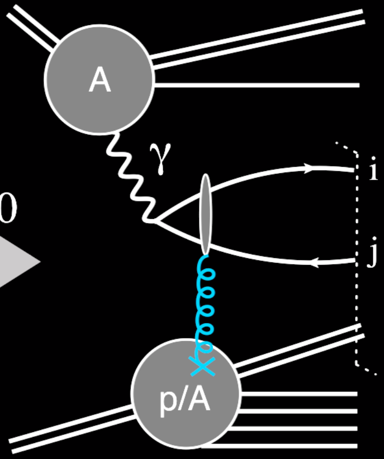


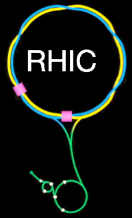
Inclusive DIS at HERA/EIC



$Q^2 \rightarrow 0$

Inclusive UPC at the LHC/RHIC





Approximate RHIC γ+p/Au kinematics:

Gold ion: $A \sim 197, R_A \sim 1.2\,(A)^{1/3}\,\mathrm{fm}$

$\hbar c/R_A \sim 0.03\,\mathrm{GeV}$

$Q^2 = (\hbar c/R_A)^2 \sim 0.001\,(\mathrm{GeV/c})^2 \approx 0$

$E_\gamma \sim \gamma_{\mathrm{Lorentz}}\,(\hbar c/R_A), W_{\gamma,N} \sim \sqrt{4E_\gamma E_A}$

$\gamma_{\mathrm{Lorentz}}(\mathrm{Au,\ RHIC}) = 27 - 100$

$E_\gamma(\mathrm{RHIC}) \lesssim 3\,\mathrm{GeV}$

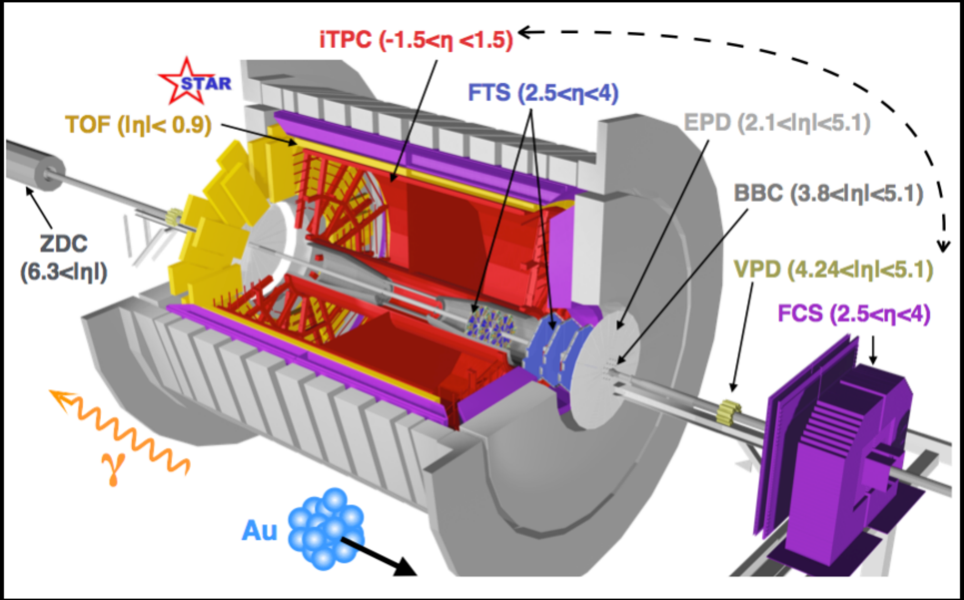
$W_{\gamma,N}(\mathrm{RHIC}) \sim 10 - 40\,\mathrm{GeV}$

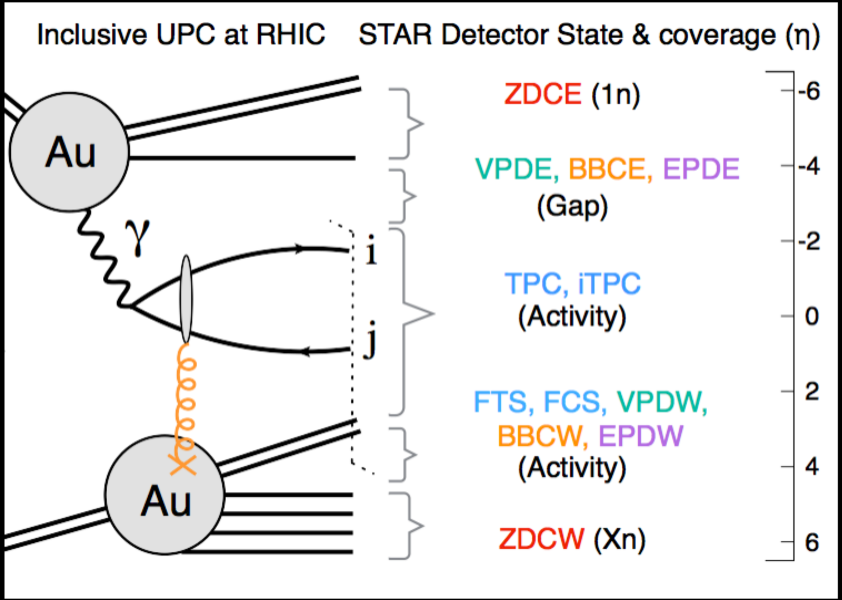
$x \sim (P_T/W_{\gamma,N})^2 : 0.001 < x < 0.01$

(For $P_T \sim 1$ GeV/c & rapidity $y = 0$)

e+p/A DIS (Q^2 >1 GeV^2), most events have $Q^2 \rightarrow 0$, called photoproduction processes
Until the EIC is built ultra-peripheral p/A+A collisions → opportunity to study photoproduction

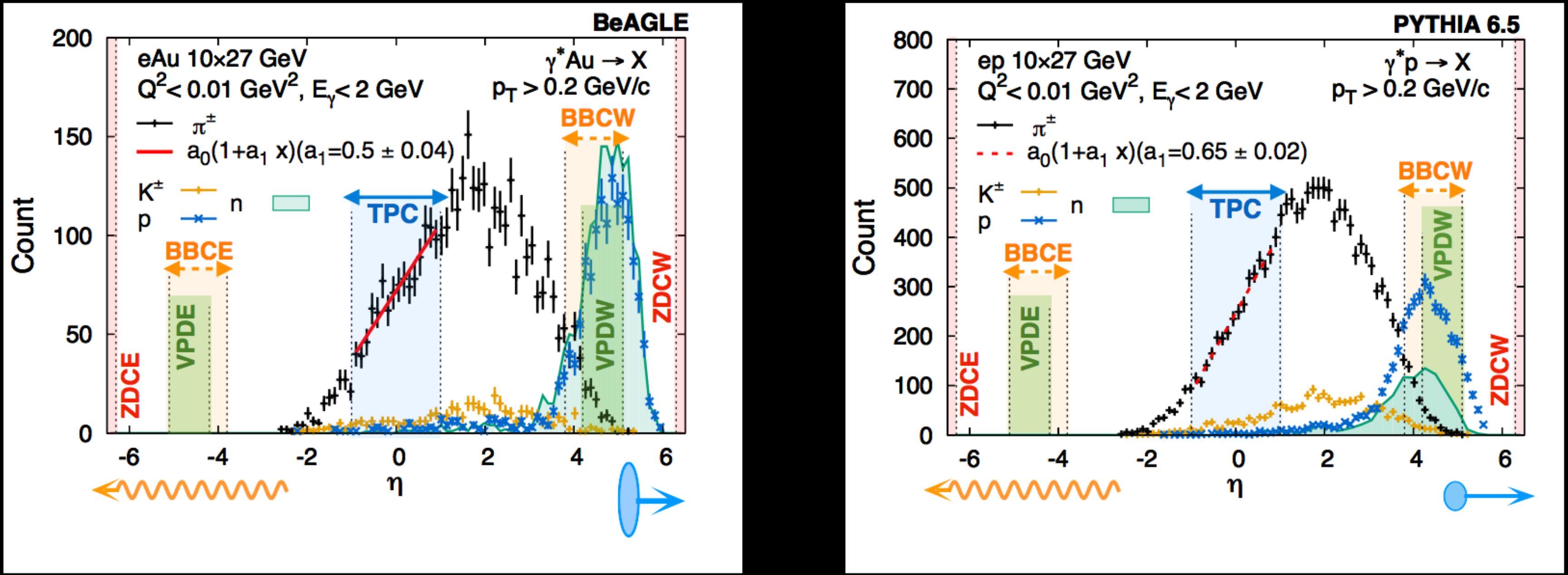
Identifying photonuclear events with the STAR detector





Events like these are eliminated by coincidence triggers, threshold, vetoing and not saved during run, only datasets on tape: 2017 Au+Au 54 GeV (477 μb^{-1}) and 2019 Au+Au 200 GeV (80 μb^{-1}). Recently taken 2021 d+Au data and future 2023 Au+Au data provide unique opportunities.

eAu and ep Monte Carlo simulations



Monte Carlo simulations for e+p/Au indicates which detectors should be active

e+Au with BeAGLE (thanks to Z.Tu) and e+p with PYTHIA (thanks to M.Mondal, K.Kauder)

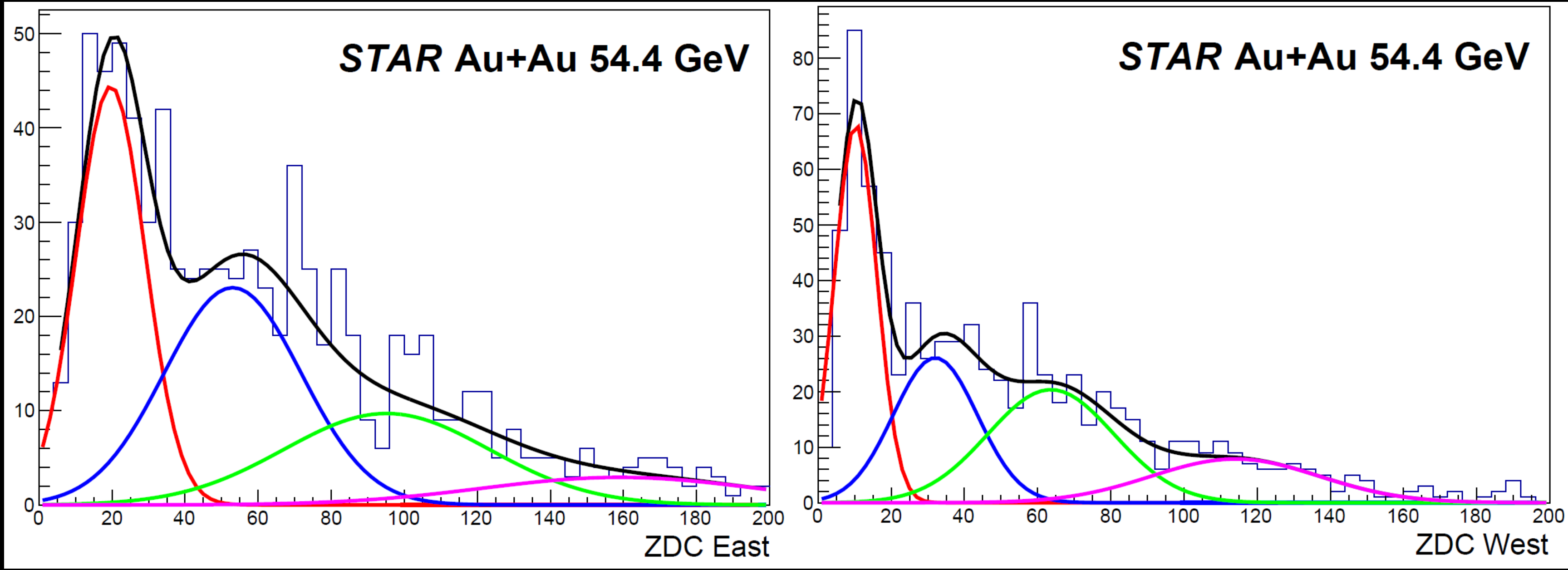
E_e =10 GeV, $E_{p/Au}$ = 27 and 100 GeV, E_γ<2 GeV, 0.001<Q^2<0.01 GeV^2

Au+Au with UrQMD with RHIC-ZDC ToyMC (thanks to S.Choudhuri)

$\sqrt{s}$= 54 GeV, 0<b<15 fm, tuned to STAR TPC vs ZDC correlation

ZDC single neutron peak

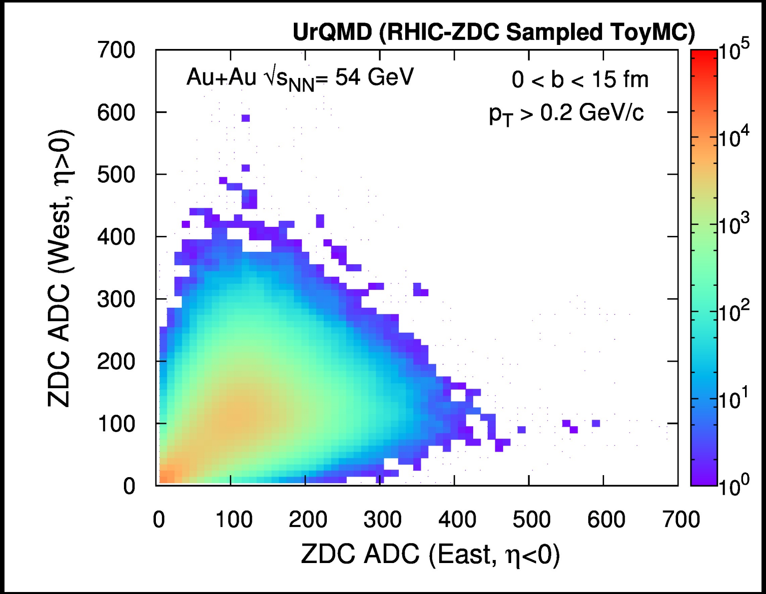
Nicole Lewis for the STAR collaboration, DNP 2021



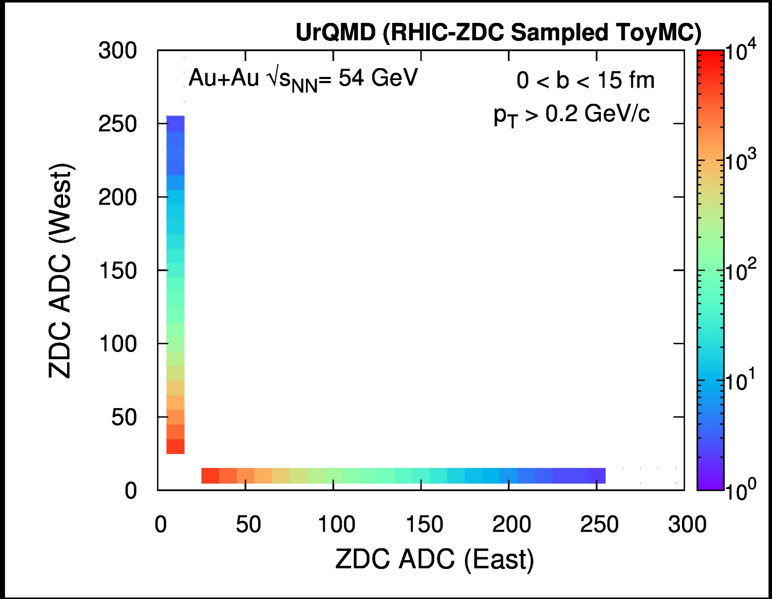
Primary selection based on 1nXn cut on ZDCs, the 1n cut on the photon emitting nucleus in the ZDC reduce beam-gas, FXT events

Background from Au+Au events

Typical response of RHIC-ZDCs



After applying γ+A like trigger

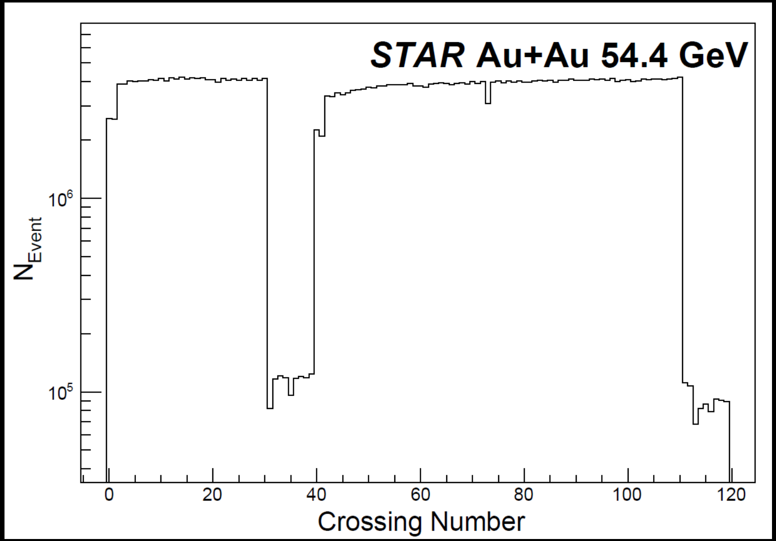


Hadronic events with asymmetry in neutrons and ZDCs are background
(Deformed nuclei, fluctuations of nucleon and clustering of fragment)

Spectator & η-asymmetry are anti-correlated in hadronic events while the opposite is expected for γ+A
(easily identifiable by measuring the slope of dN/dη)

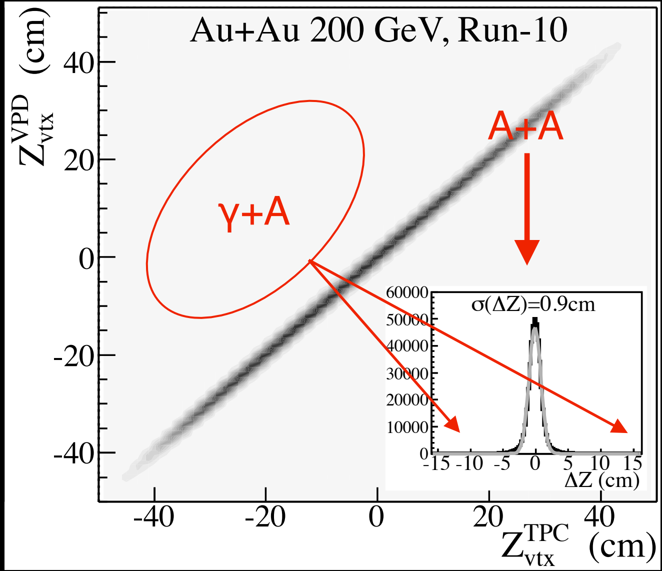
Study of abort gaps and vertex mismatch

Nicole Lewis for the STAR collaboration, DNP 2021



18 out of 120 bunch crossings have only one beam, they are studied to estimate contribution from beam-gas/material (~3%)

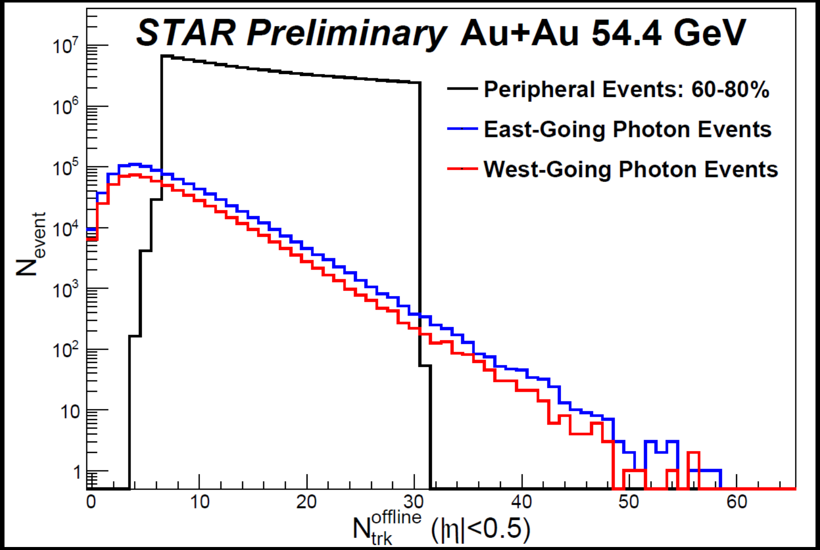
Nucl.Instrum.Meth.A 759 (2014) 23-28, [arXiv:1403.6855]

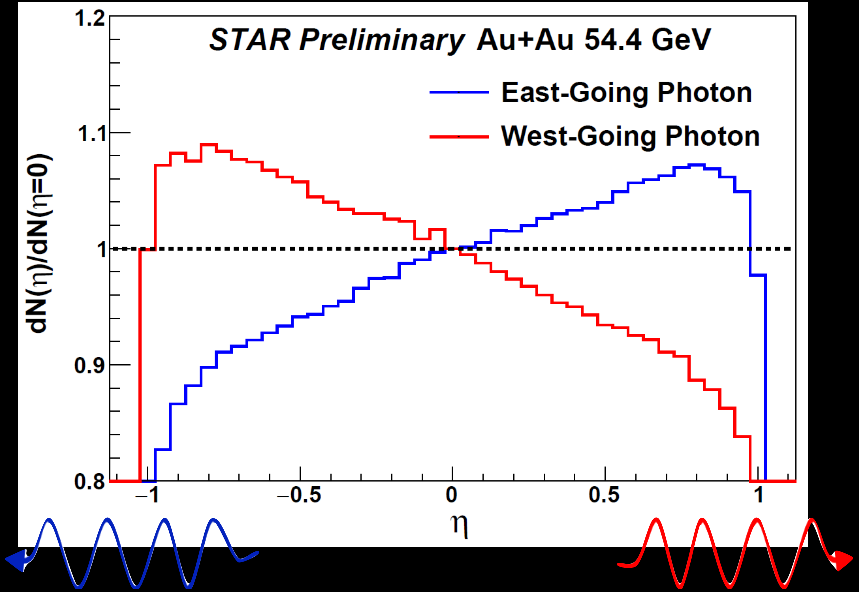


The forward Vertex Position detector (VPDs) are used in γ+A events to force mismatch of vertex from STAR tracking using TPC & timing using VPDs (|ΔZ| >10 cm)

Charged hadron multiplicity distribution and η asymmetry in γ+Au

Nicole Lewis for the STAR collaboration, DNP 2021





Our triggered Photonuclear (γ+Au rich events) sample have multiplicities close to 80-100% peripheral Au+Au events

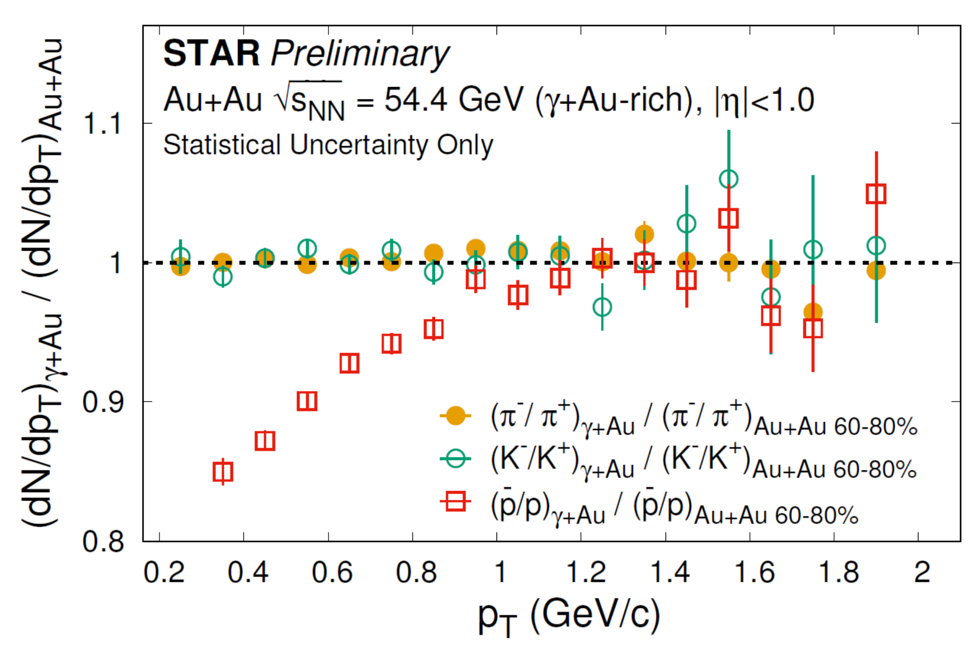
Charged hadron distributions show rapidity asymmetry in TPCs

particle/anti-particle ratio in γ+Au-rich events compared to Au+Au

Nicole Lewis for the STAR collaboration, DNP 2021

STAR preliminary measurements available for the double ratio of spectra in γ+Au over Au+Au

(to minimize the effects of efficiency)

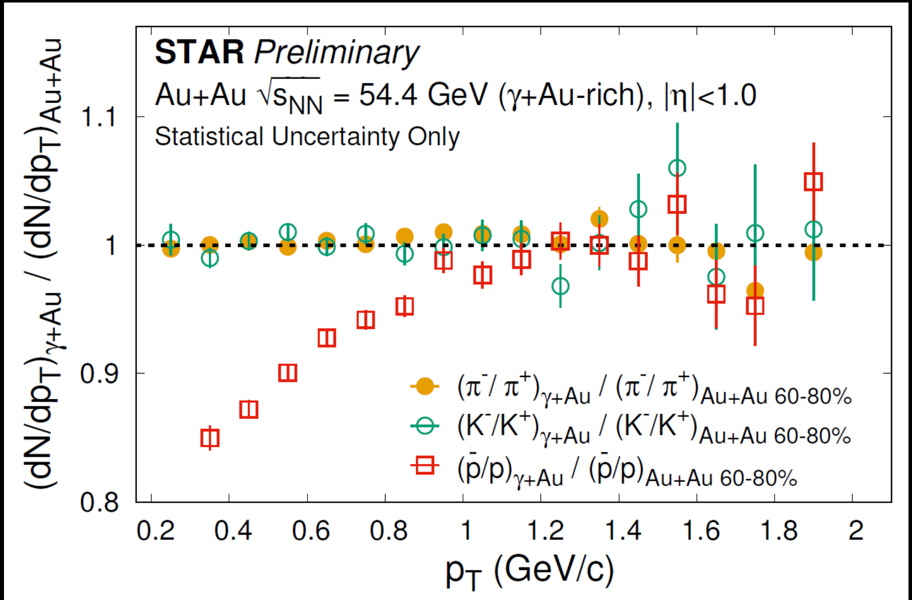


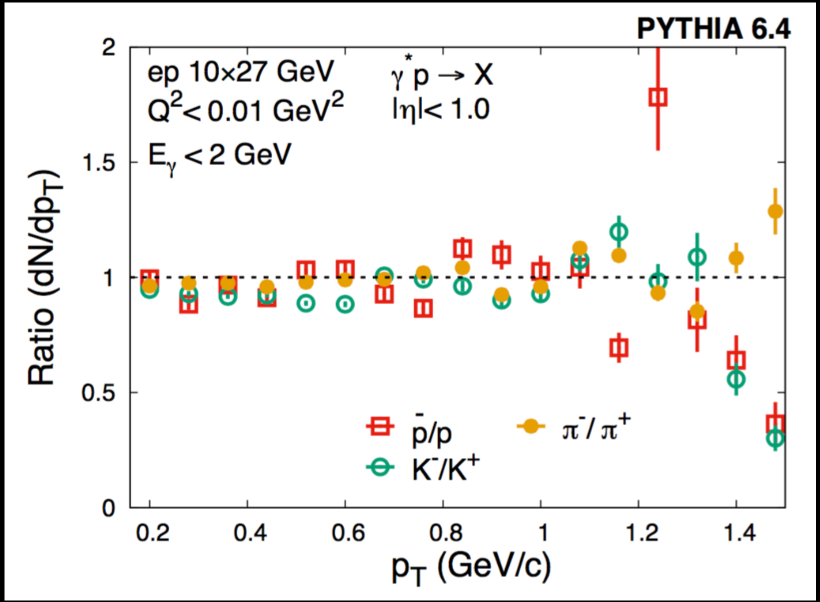
Excess soft proton over antiproton at mid-rapidity for $pT \lesssim 1\ \mathbf{GeV}/c$ in γ+Au-rich events compared to Au+Au events

Excess disappears at high p_T and for pions and kaons

Comparison to PYTHIA

Nicole Lewis for the STAR collaboration, DNP 2021

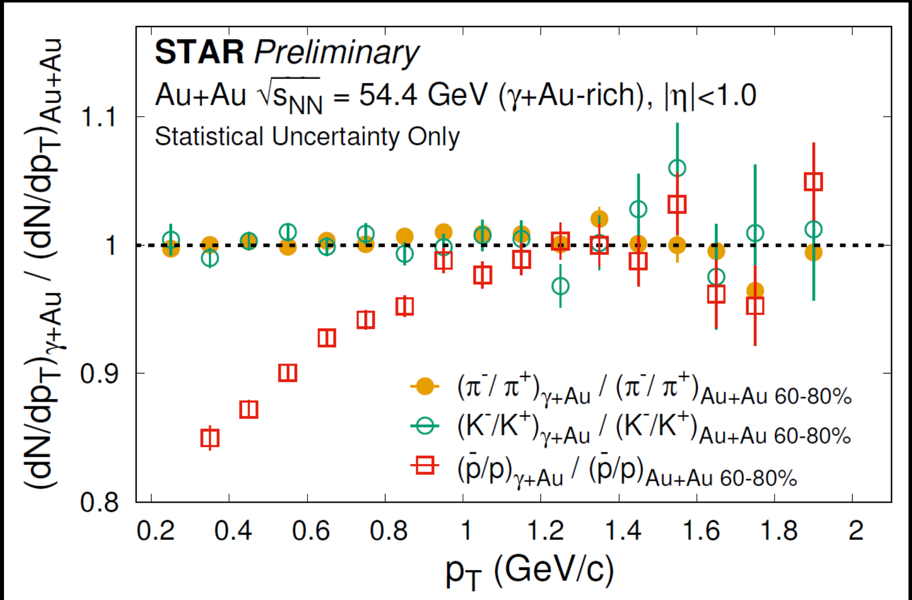


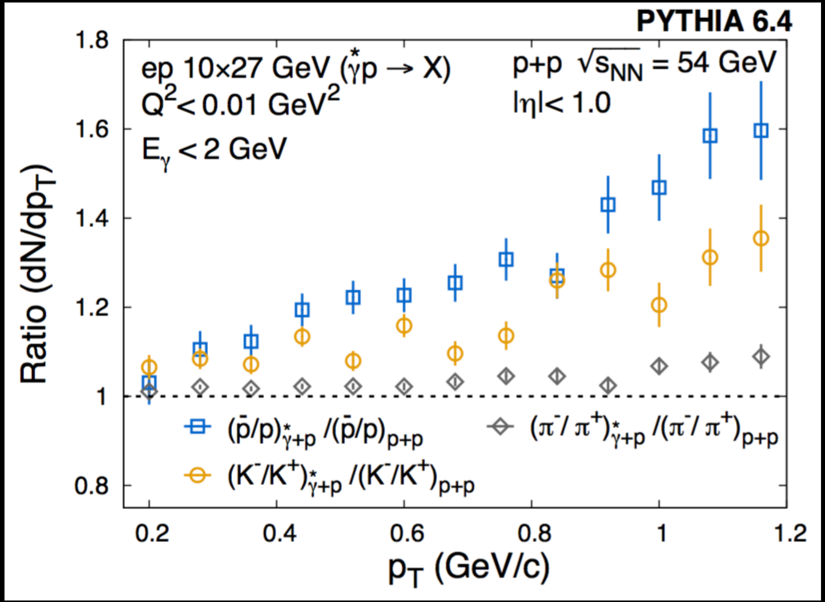


PYTHIA6 γ*+p simulation predicts pion, kaon, and proton ratios to be consistent with unity within uncertainty

Comparison to PYTHIA ep/pp

Nicole Lewis for the STAR collaboration, DNP 2021

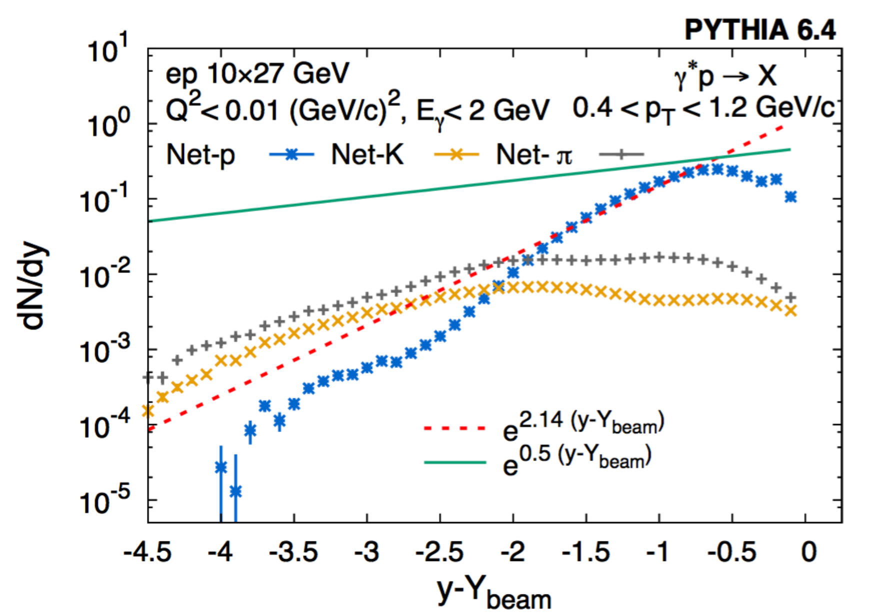




PYTHIA6 γ*+p simulation predicts pion, kaon, and proton ratios to be consistent with unity within uncertainty, scaling by p+p does not produce the trend

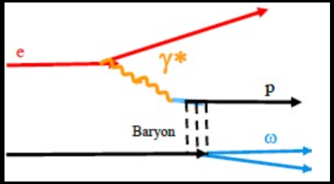
What happens to the rapidity dependence of baryons

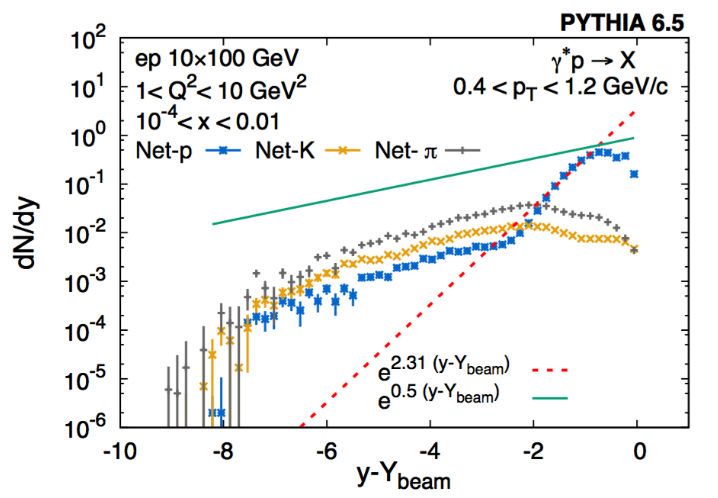
STAR measurements in γ+Au-rich events are coming soon



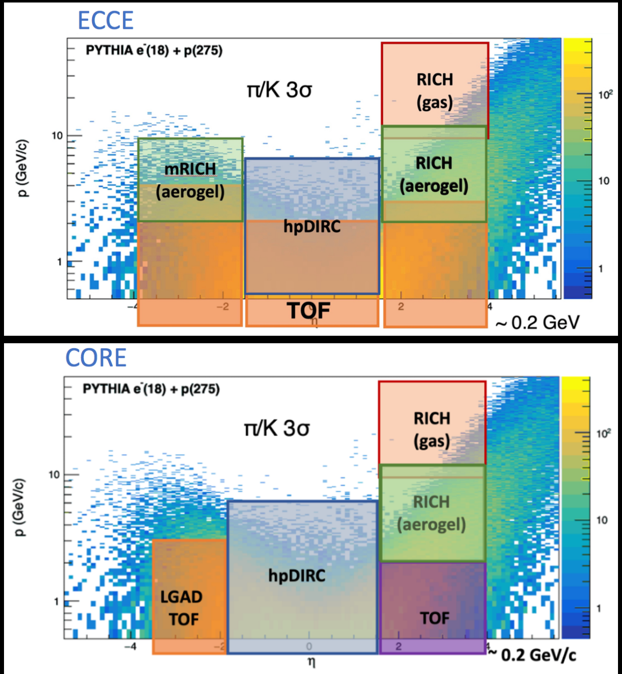
Rapidity dependence of net-baryon in γ+Au events would be interesting, baryon junction predicts exponential dependence at low p_T

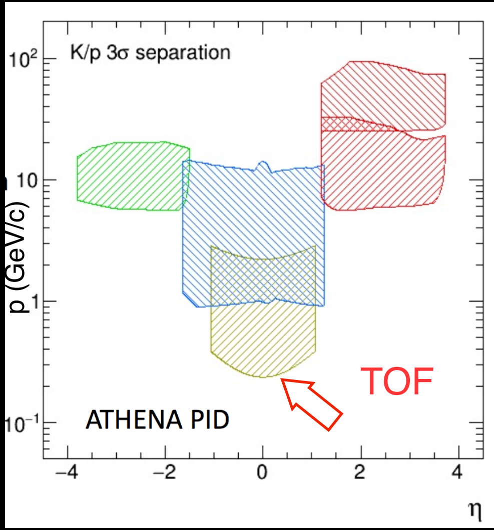
Opportunities at the EIC





Zhangbu Xu, BES-Tea Seminar





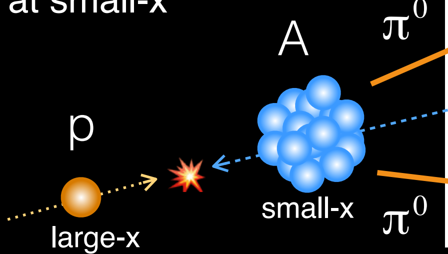
All three detector proposals have low p PID capable detectors such as TOF: exciting opportunity

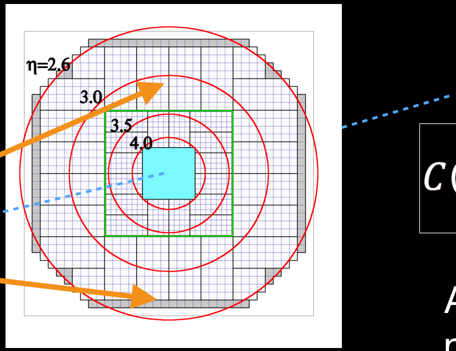
What else: di-hadron correlations, CGC & collectivity

Forward di-hadron correlations in p+A from STAR

STAR Collaboration, arXiv:2111.10396

Kinematics probe gluons inside nuclei at small-x





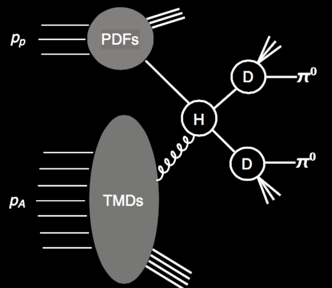
Forward Meson Spectrometer

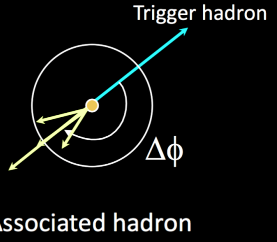
$$C(\Delta\phi) = \frac{N_{pair}(\Delta\phi)}{N_{trig} \times \Delta\phi}$$

Area of C(Δϕ) :
p+p > p+Al > p+Au

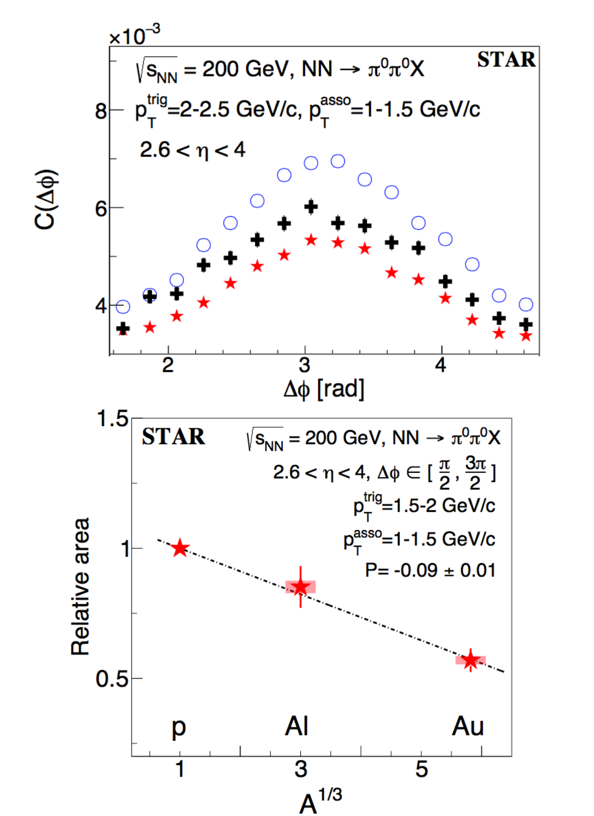
Width of C(Δϕ) :
p+p ~ p+Al ~ p+Au

Pedestal:
p+p ~ p+Al ~ p+Au





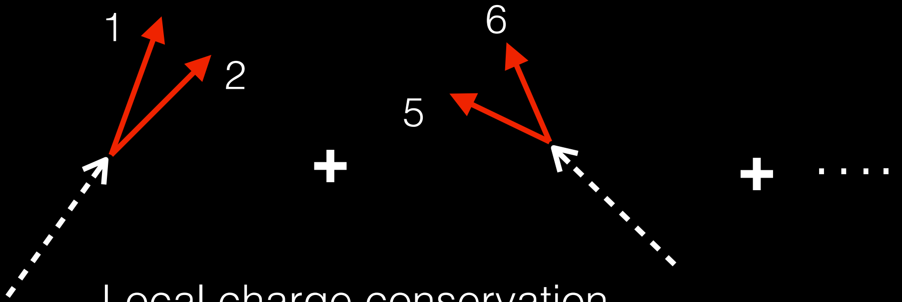
Albacete et al., Phys. Rev. D 99, 014002



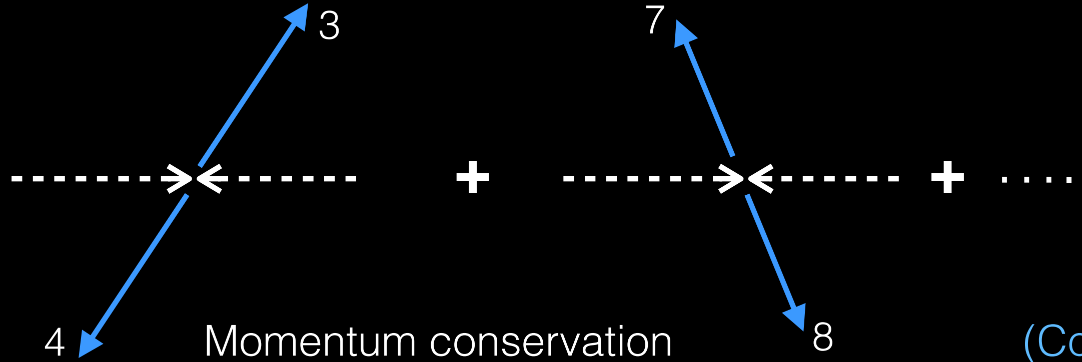
Suppression of back-to-back π^0 pairs in p+A relative to p+p follow ~$A^{1/3}$ dependence
—> consistent with expectations from gluon saturation

di-hadron correlations and collectivity due to gluon saturation

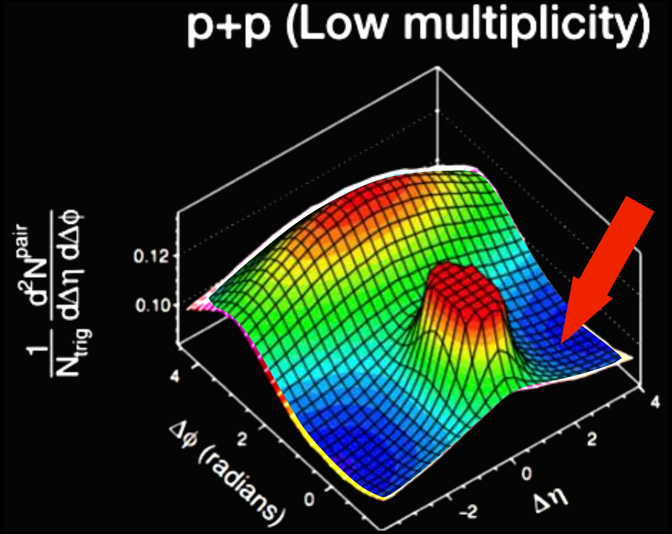
At fundamental levels conservation laws
determine correlation among few particles



Local charge conservation



Momentum conservation

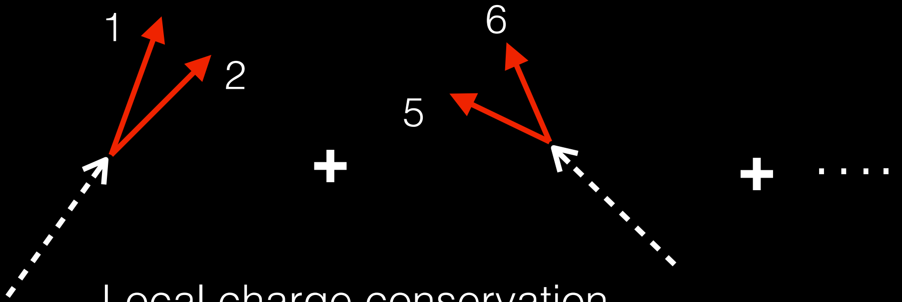


These correlations will not fill
the full-phase space
(Seen in experiment)

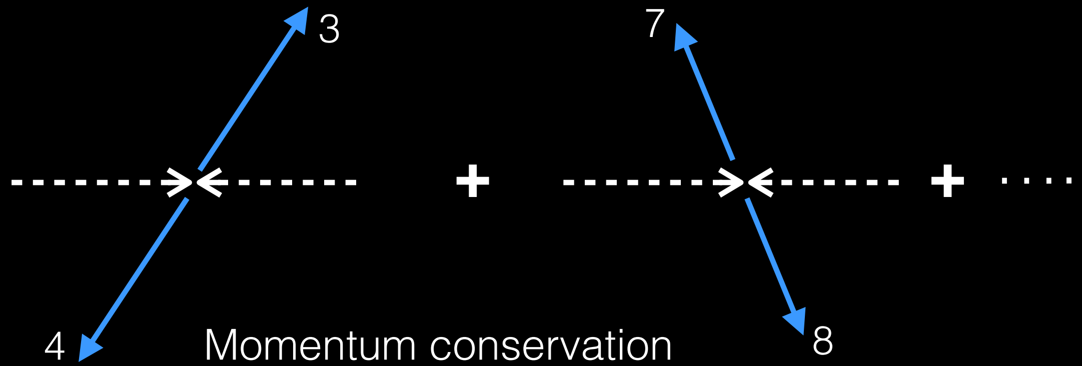
(Conservation $\Longrightarrow$ perfect configurations)

What is collectivity ?

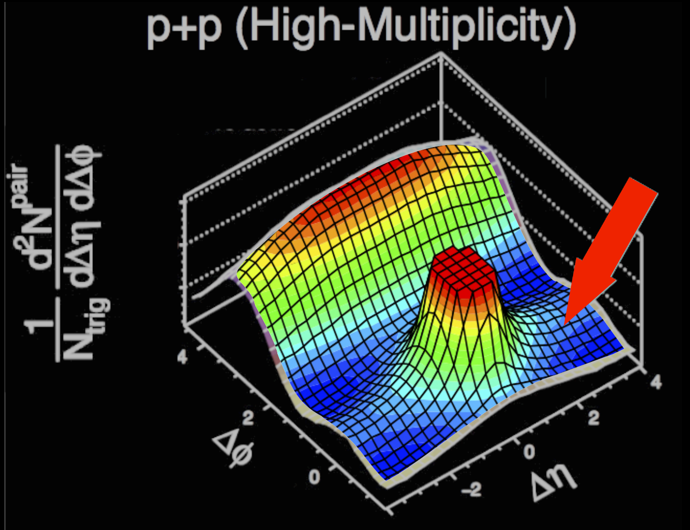
At fundamental levels conservation laws
determine correlation among few particles



Local charge conservation



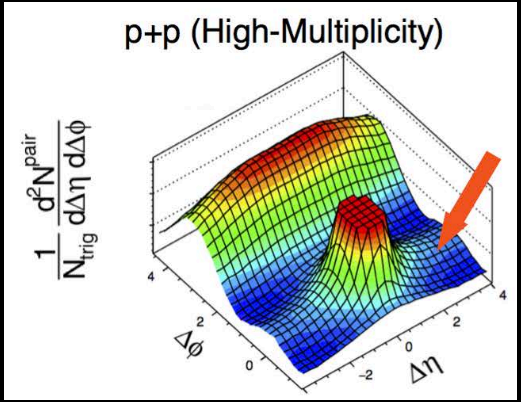
Momentum conservation

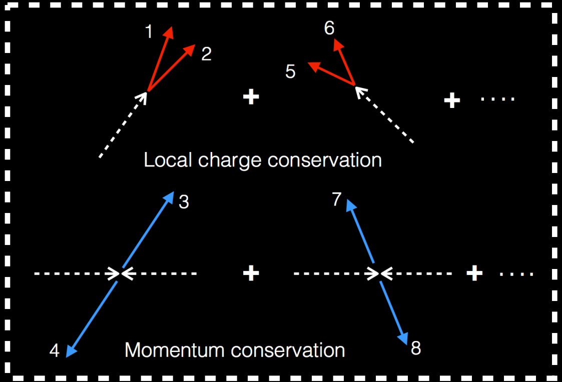


Violation from such
scenario is striking

What is collectivity ?

Deviations from these perfect configurations or correlation among few particles $\Longrightarrow$ Important physics at play (often non-perturbative)





Non-flow

\+ New physics

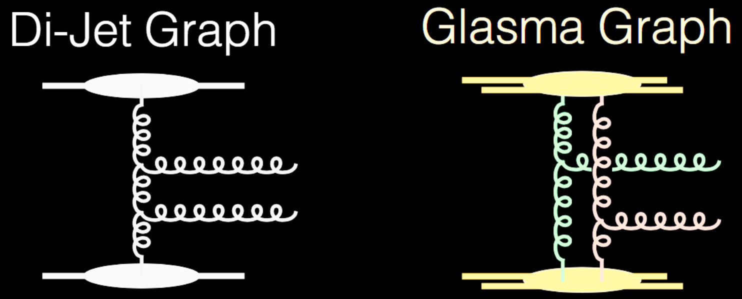
Collectivity $\Longrightarrow$ observation of a specific pattern or behavior that is followed by most of its constituents in a system

Observing correlations among many must be accompanied by a large scale deviation $\Longrightarrow$ interesting to study with decreasing system size

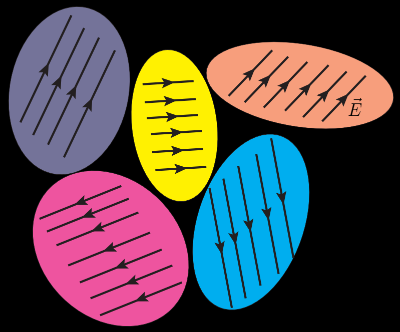
Au+Au → p+A → p+p → e(γ)+A → e(γ)+p → e+e

Origin of collectivity: initial state correlations from CGC

Quantum correlations due to
Bose enhancement / Glasma graphs



Classical correlations due to
local anisotropy 1/Qs



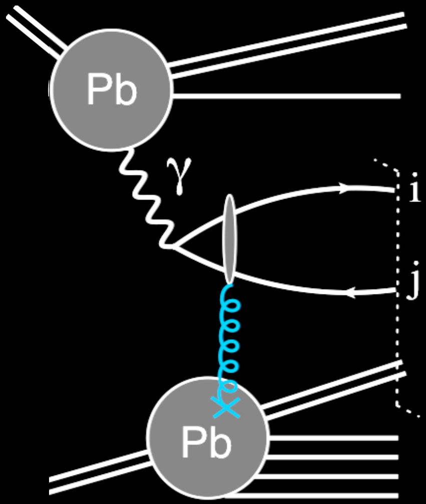
Enhanced probability to find two gluons with the same transverse momentum.

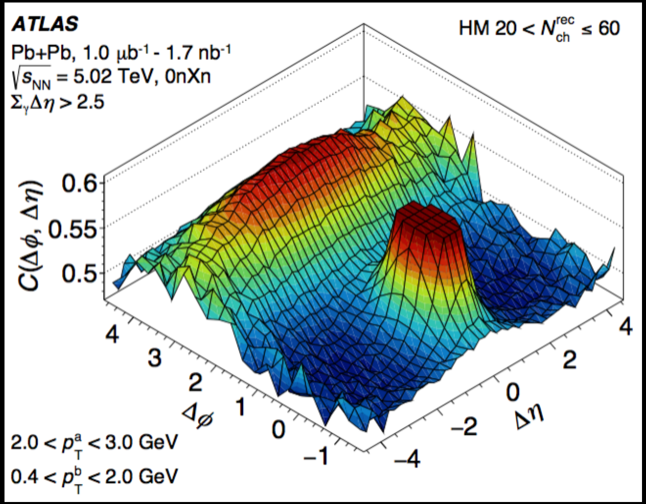
Gluons hitting the same domain in target get scatter in the same direction

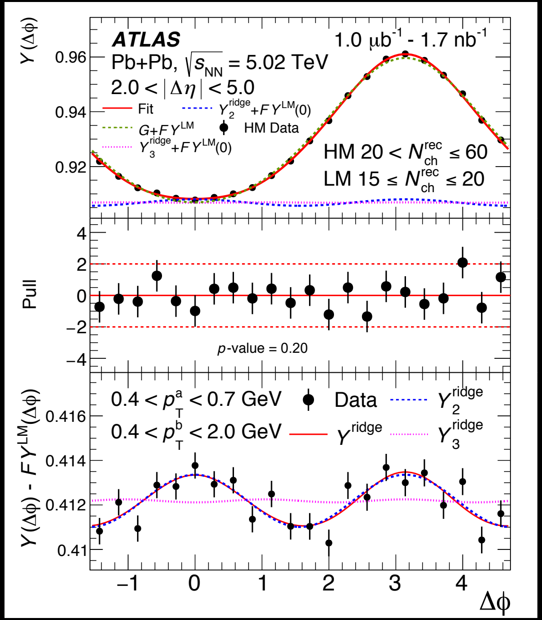
Gelis,Lappi Venugopalan PRD 78 054020 (2008), PRD 79 094017 (2009); Dumitru, Gelis, McLerran,Venugopalan NPA810, 91 (2008); Dumitru, Jalilian-Marian PRD 81 094015 (2010); Dusling, Venugopalan PRD 87 (2013); A. Dumitru, A.V. Giannini, Nucl.Phys.A933 (2014) 212; V. Skokov. Phys.Rev.D91 (2015) 054014; T. Lappi, B. Schenke, S. Schlichting, R. Venugopalan, JHEP 1601 (2016) 061; Kovner, Skokov, Phys.Rev. D98 (2018) no.1, 014004

Search for collectivity UPC collisions at the LHC

ATLAS collab., Phys. Rev. C 104, 014903 (2021)







$$Y(\Delta\phi, 2<|\Delta\eta|<5) = \frac{1}{N_{\rm trig}}\frac{d^2N_{\rm pair}}{d\Delta\phi} = \frac{N_{\rm asco}}{2\pi}\left(1+\sum_n 2a_n\cos(n\Delta\phi)\right)$$

$$Y(\Delta\phi)^{\rm template}(HM) = FY(\Delta\phi)(LM) + Y(\Delta\phi)^{\rm ridge}(HM)$$

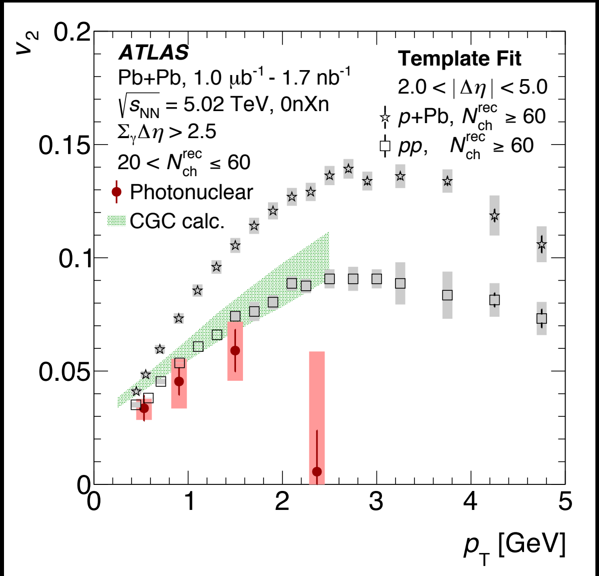
$$Y(\Delta\phi)^{\rm ridge}(HM) = G\{1+2a_2\cos(2\Delta\phi)+2a_3\cos(3\Delta\phi)+2a_4\cos(4\Delta\phi)\}$$

Template fitting of di-hadron correlations

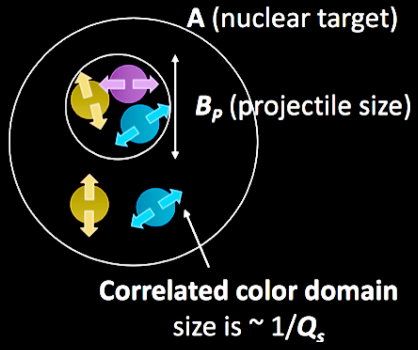
High activity γ+Pb events can accommodate a long-range ridge component (related to collectivity)

Search for collectivity UPC collisions at the LHC

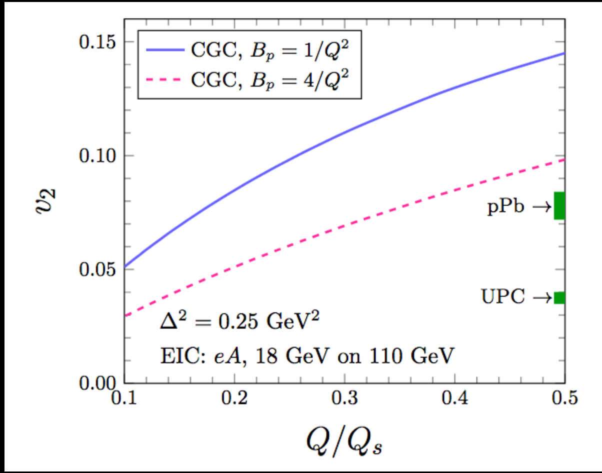
ATLAS collab., Phys. Rev. C 104, 014903 (2021)



Cartoon: Blair Seidlitz, IS2021



Shi et. al.,Phys. Rev. D 103, 054017 (2021)

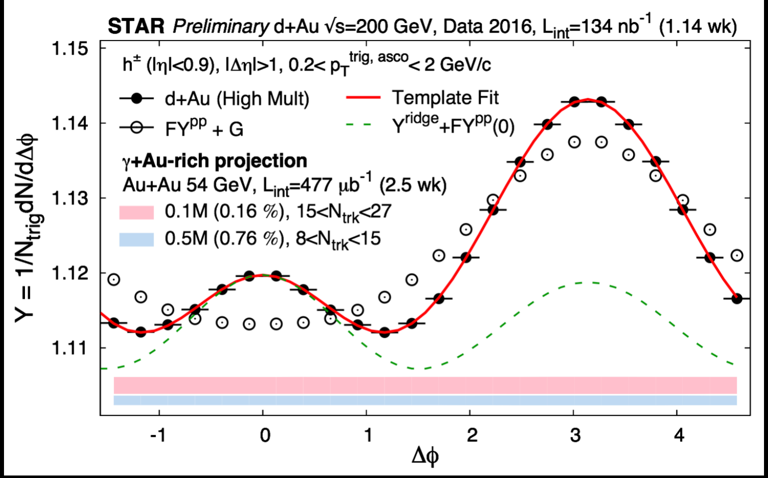


Elliptic anisotropy is lower in γ+Pb than in p+Pb

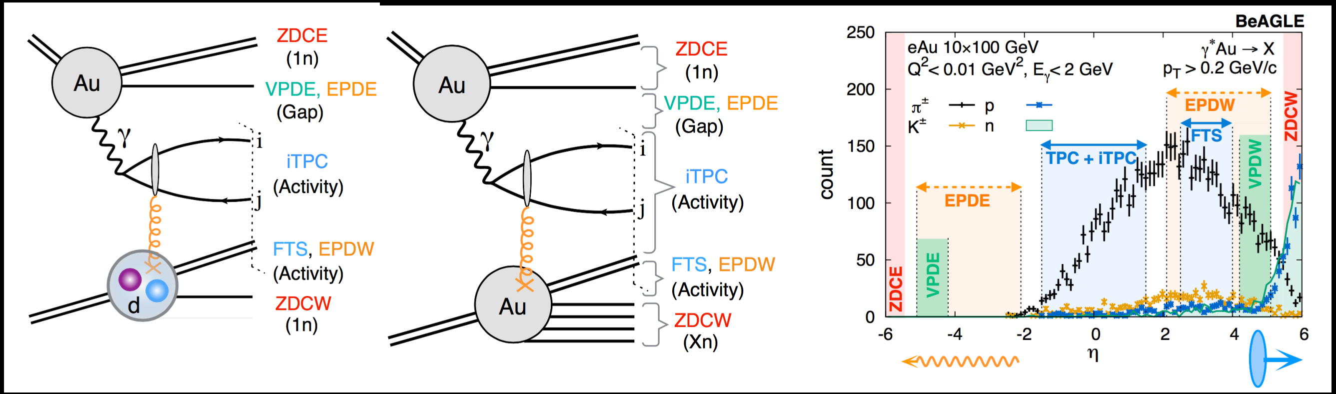
CGC calculations provide an explanation based on color domain picture.

Past and future search for collectivity in photon induced collisions

	EIC (DIS)	EIC (PhP)	LHC (UPC)	RHIC (UPC)	HERA (DIS)	HERA (PhP)
γ+p	? (ATHENA/ CORE/ ECCE)	? (ATHENA/ CORE/ ECCE)	☹ (CMS)	? (STAR, sPHENIX)	☹ (ZEUS, H1)	☹ (H1)
γ+A	? (ATHENA/ CORE/ ECCE)	? (ATHENA/ CORE/ ECCE)	☺ (ATLAS)	? (STAR, sPHENIX)		



High statistics Au+Au 2023 data provides an excellent opportunity for STAR with forward upgrades for collectivity search in photonuclear events



Summary

Baryon asymmetry in photonuclear events:

What carries the baryon numbers and how baryon-asymmetry is generated in central rapidity region of ultra-relativistic collisions is a puzzle

Baryon junction hypothesis may provide a microscopic explanation

Preliminary measurements from the STAR collaboration:

particle spectra in photonuclear events using 54.4 GeV Au+Au ultraperipheral collisions

Significantly large baryon stopping observed at low pT

Rapidity dependence of baryon spectra in photonuclear events and at future EIC will be exciting

di-hadron correlations, saturation & collectivity:

Suppression of STAR forward di-hadron correlation results are consistent with gluon saturation

Gluon saturation also predicts signatures of long-range collectivity in cleaner environment of γ+p/A

ATLAS measurements show exciting hint of collectivity in photonuclear events

UPC can be a doorway to study collectivity at the future EIC

Anticipated Au+Au 200 GeV run of RHIC (2023, 2025) sPHENIX & STAR with forward upgrade

Thanks

Baryon to meson ratio in γ+Au-rich events compared to Au+Au

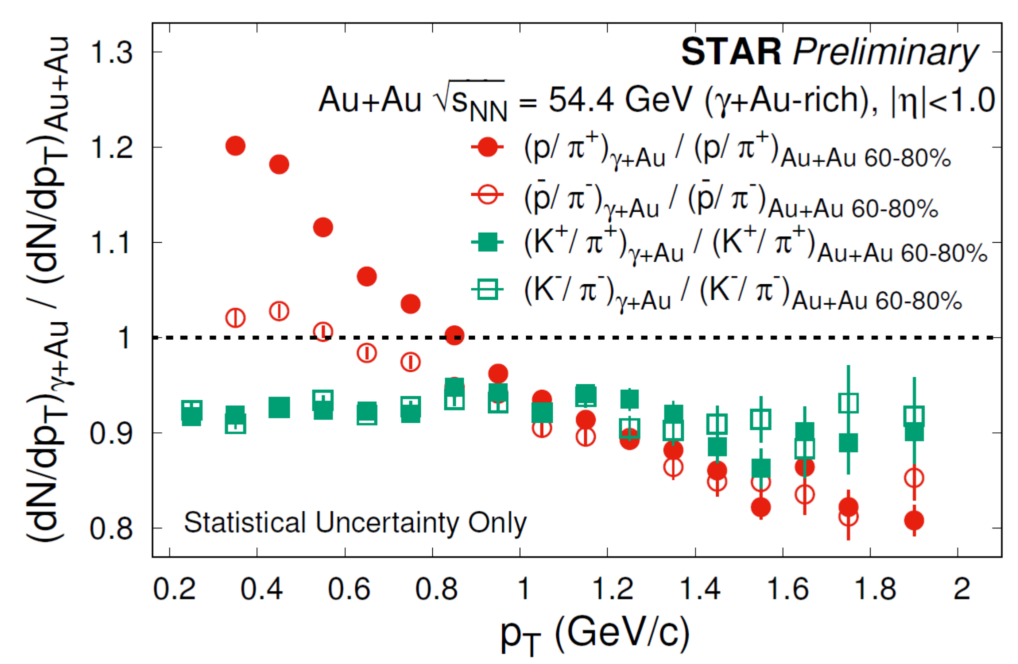
STAR preliminary measurements available for the double ratio of spectra in γ+Au over Au+Au

(to minimize the effects of efficiency)

$\bar{p}/\pi < p/\pi$ for $pT \lesssim 1$ GeV/c → Excess soft proton at mid-rapidity compared to pions observed in γ+Au compared to Au+Au

Kaon to pion ratio serves as a baseline, no p_T dependence is observed

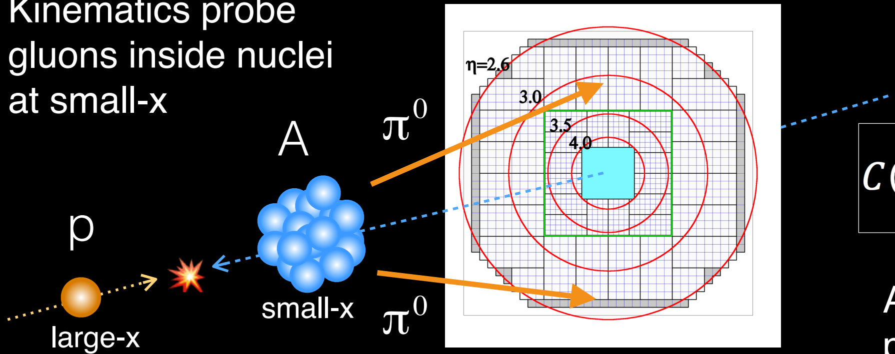
Nicole Lewis for the STAR collaboration, DNP 2021



Forward di-hadron correlations in p+A from STAR

STAR Collaboration, arXiv:2111.10396

Kinematics probe gluons inside nuclei at small-x



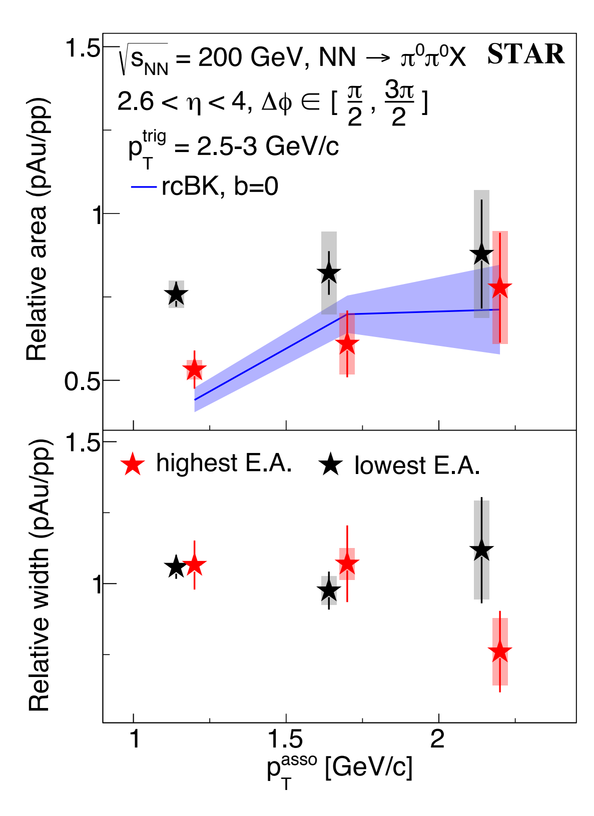
Forward Meson Spectrometer

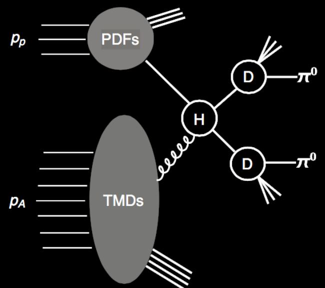
$$C(\Delta\phi) = \frac{N_{pair}(\Delta\phi)}{N_{trig} \times \Delta\phi}$$

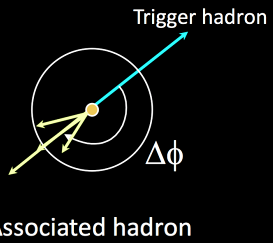
Area of C(Δϕ) :
p+p > p+Al > p+Au

Width of C(Δϕ) :
p+p ~ p+Al ~ p+Au

Pedestal:
p+p ~ p+Al ~ p+Au







Albacete et al., Phys. Rev. D 99, 014002

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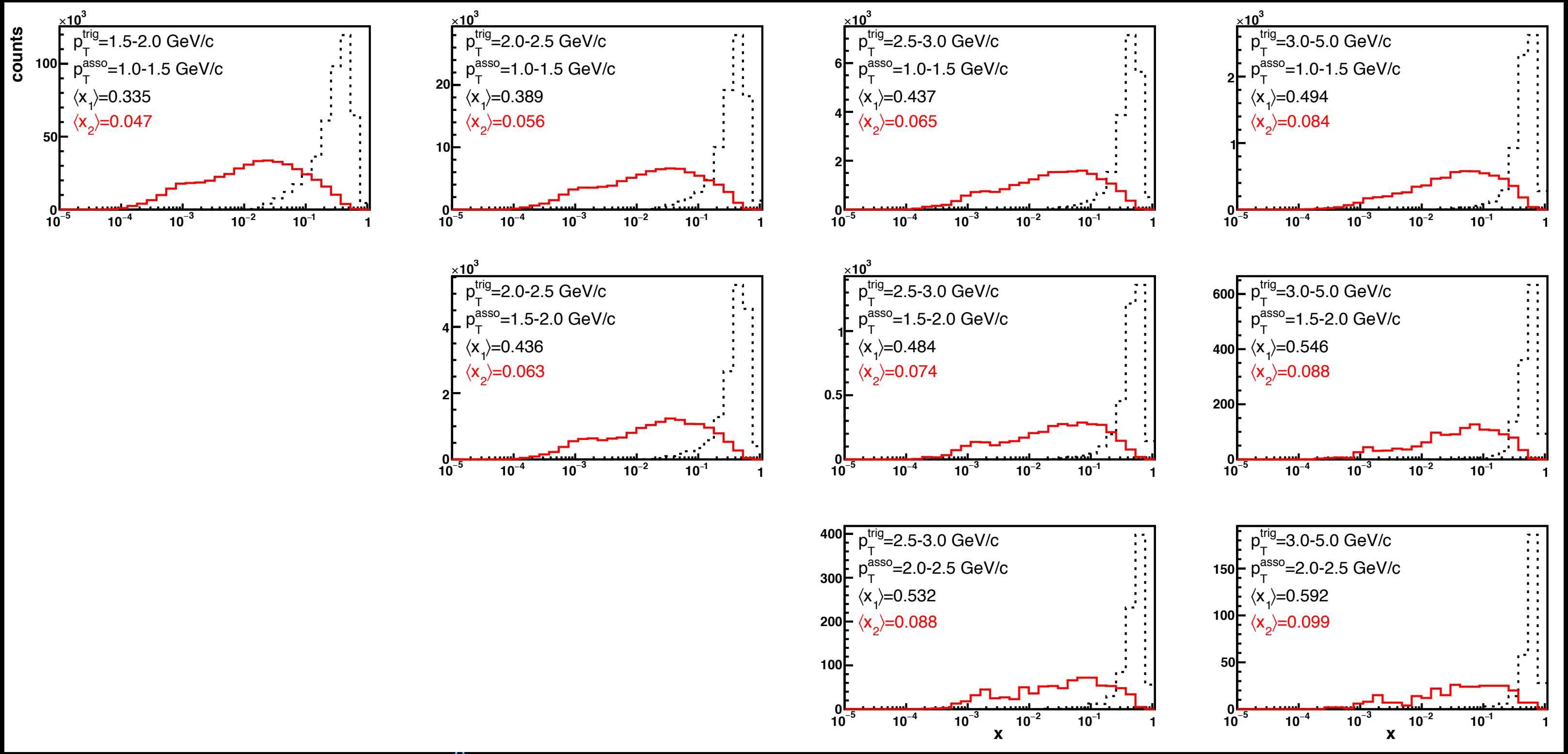

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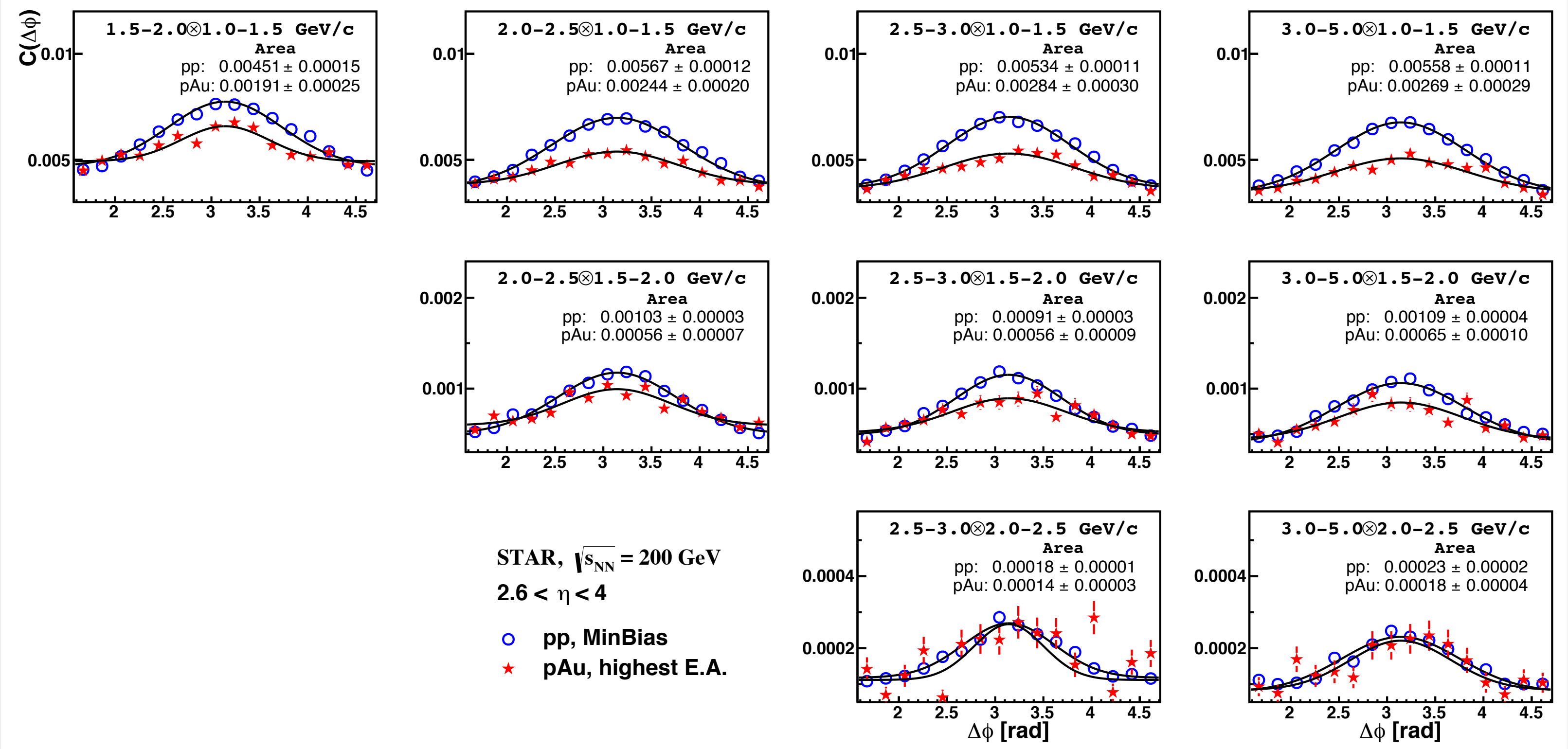

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