Inclusive photonuclear processes: recent search for collectivity & opportunities with the STAR detector

Prithwish Tribedy

BROOKHAVEN NATIONAL LABORATORY

RHIC Science Programs Informative Toward EIC in the Coming Years
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Center for Frontiers in Nuclear Science
Workshop series

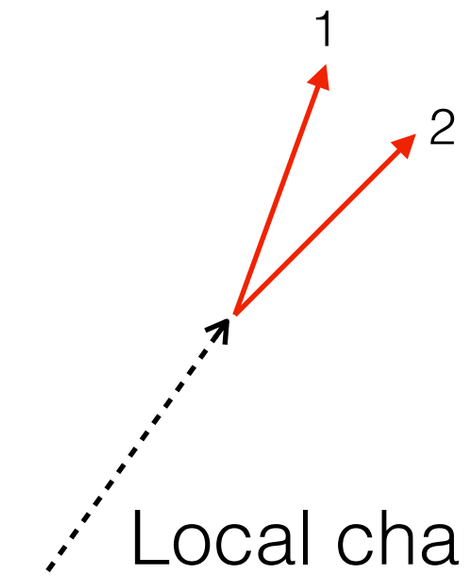
U.S. DEPARTMENT OF ENERGY | Office of Science

Outline

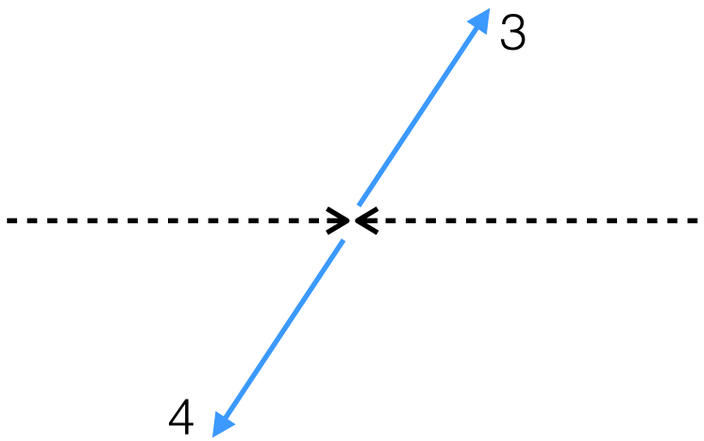
- Introduction
- Lessons from HERA and LHC
- Opportunities with the STAR detector (model studies)

Correlation measurements

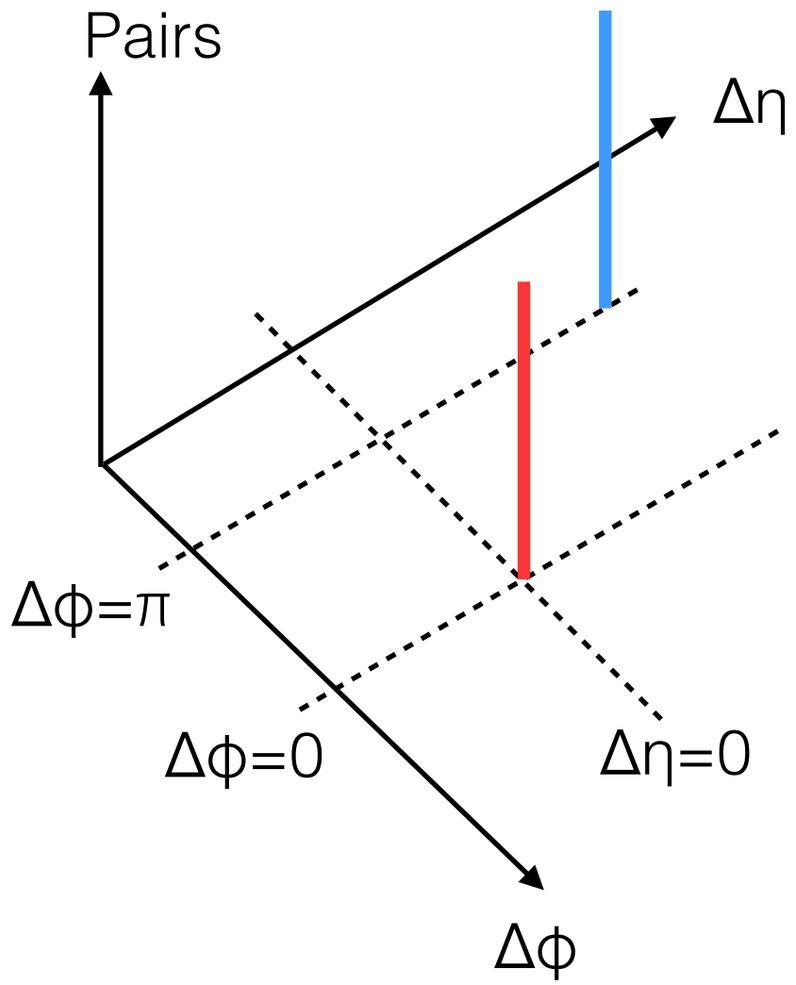
At fundamental levels conservation laws determine correlation among few particles



Local charge conservation



Momentum conservation



Correlation measurements

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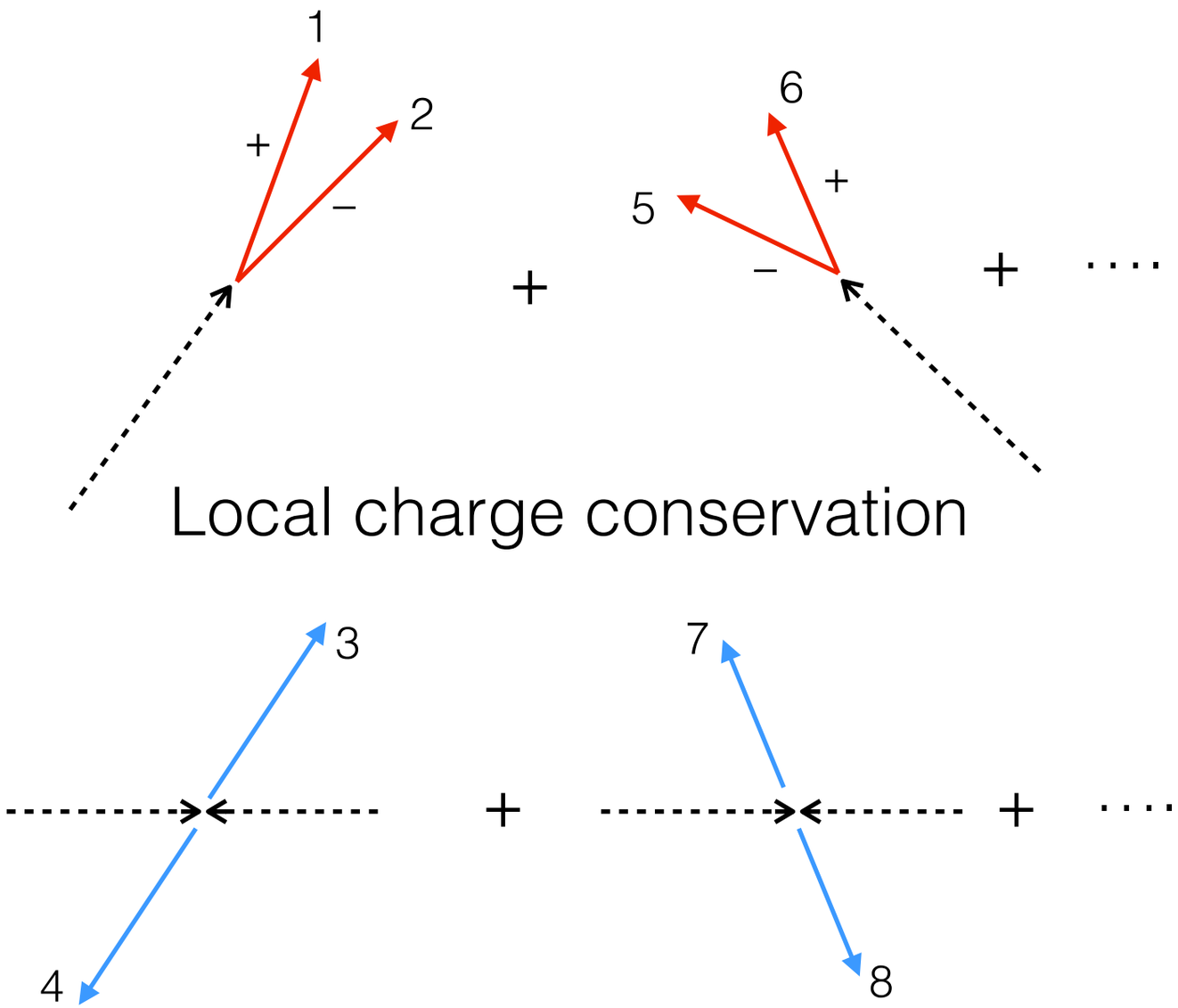
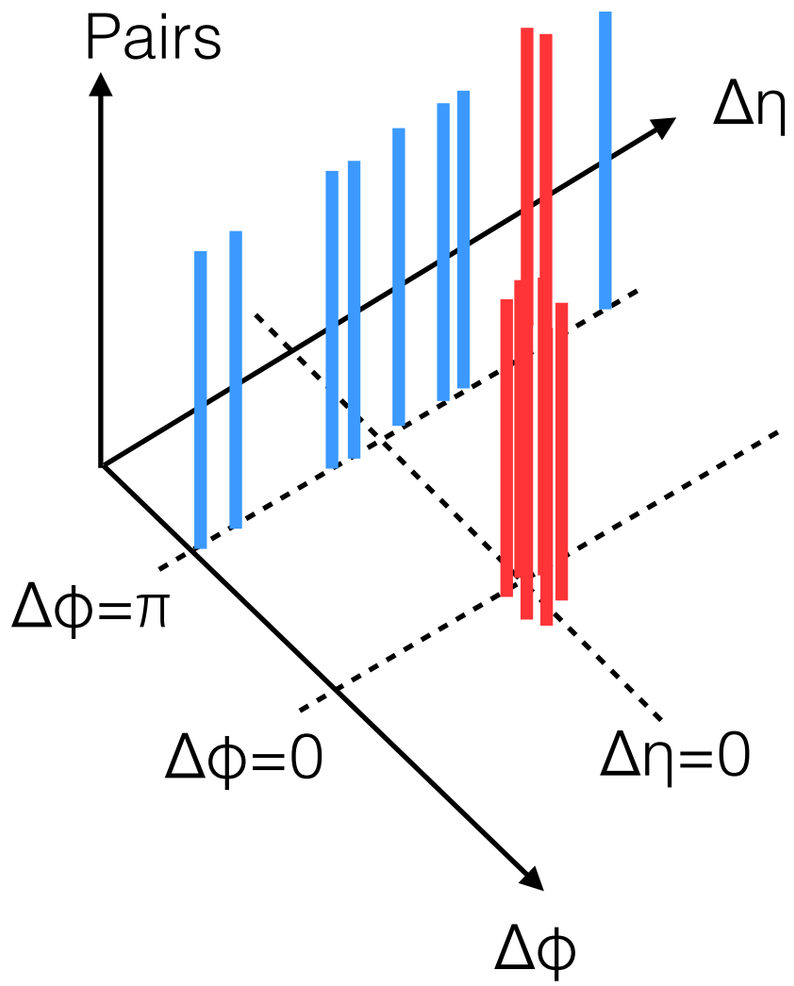


Local charge conservation

Momentum conservation



These correlations will not fill the full-phase space

Correlation measurements

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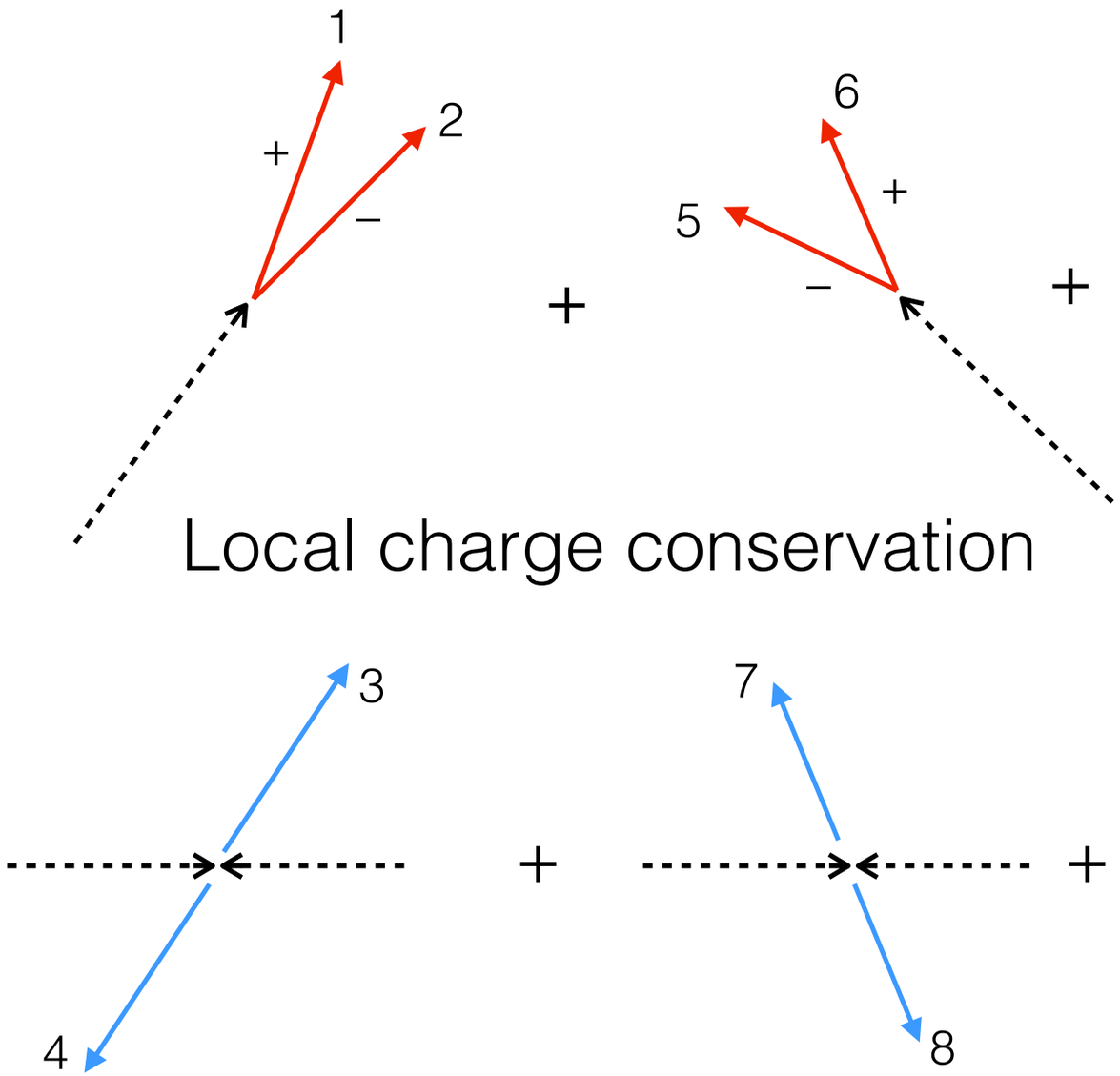
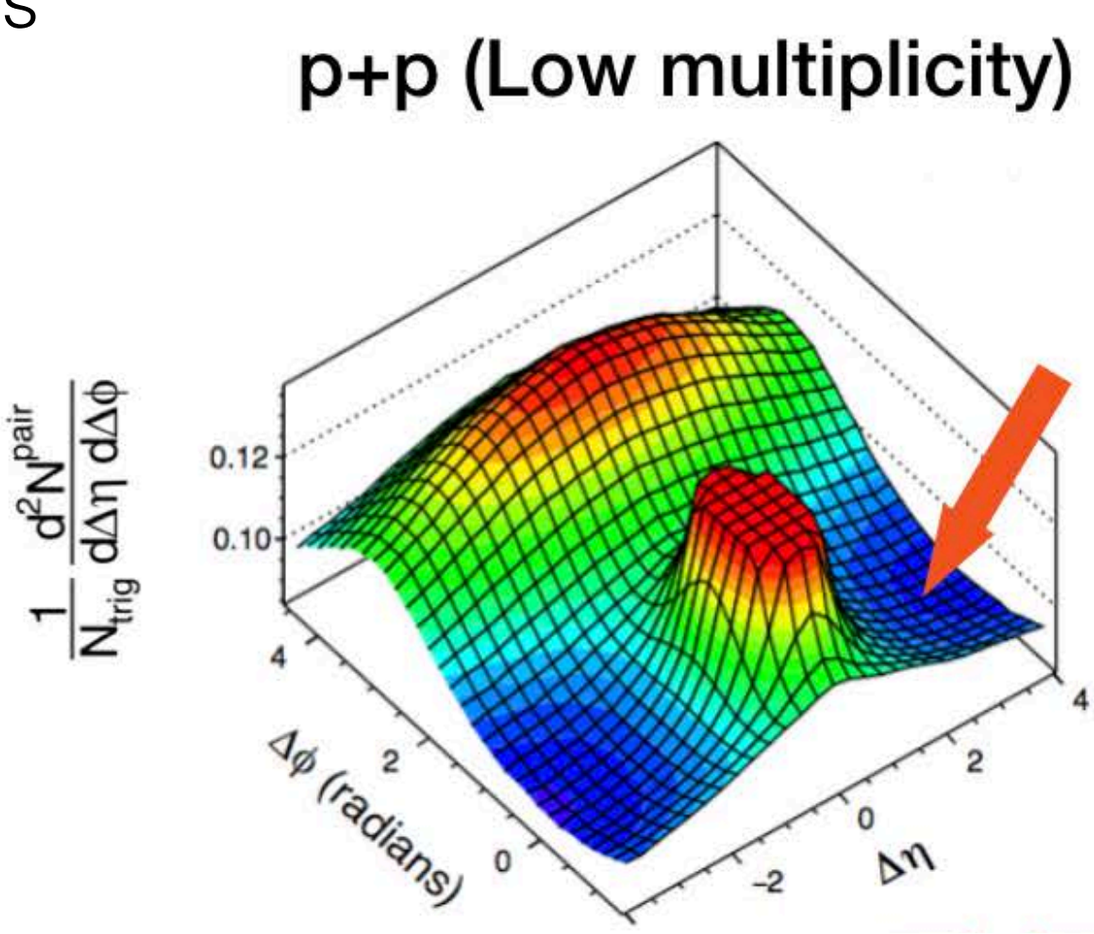


Local charge conservation

Momentum conservation

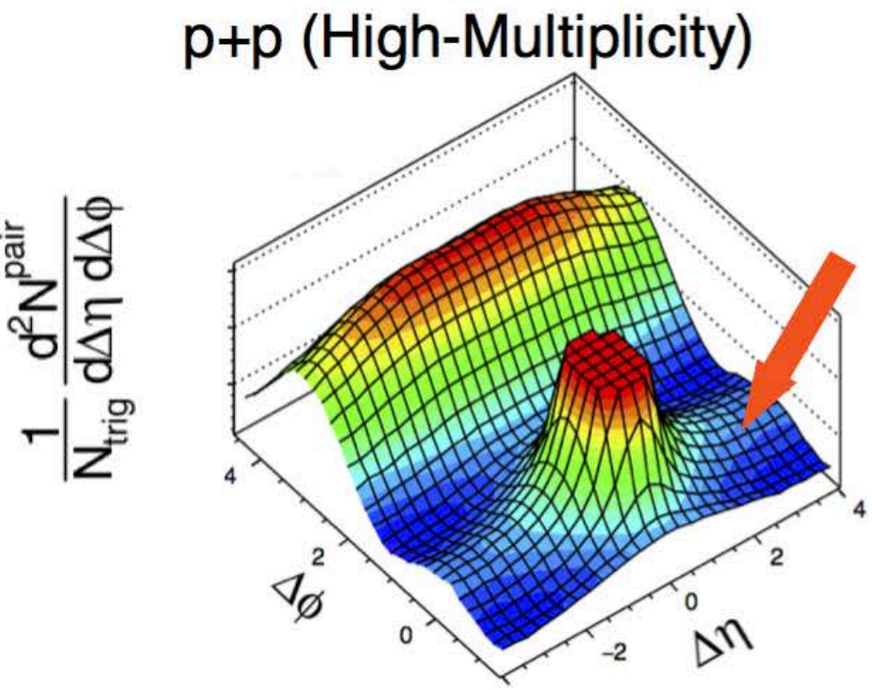


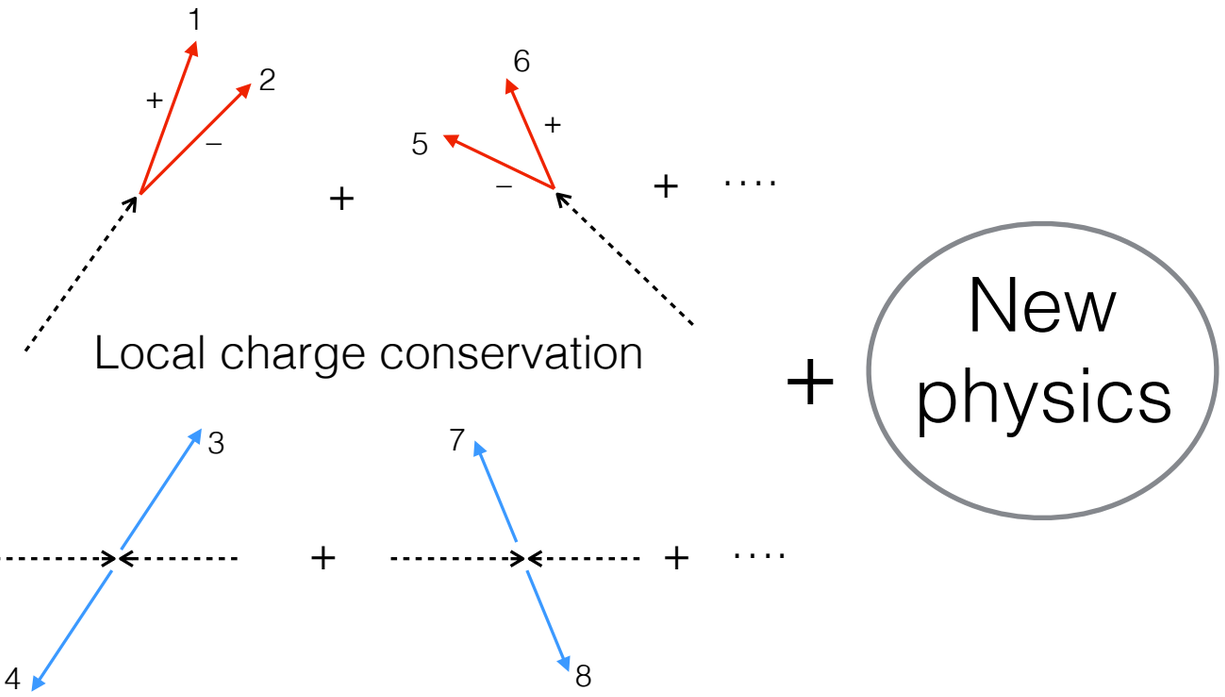
These correlations will not fill the full-phase space

(Conservation ⟹ perfect configurations)

Correlation measurements

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



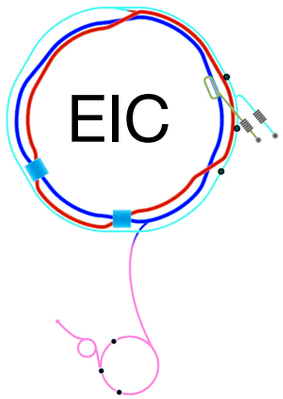


Collectivity ⟹ observation of a specific pattern or behavior that is followed by most of its constituents in a system

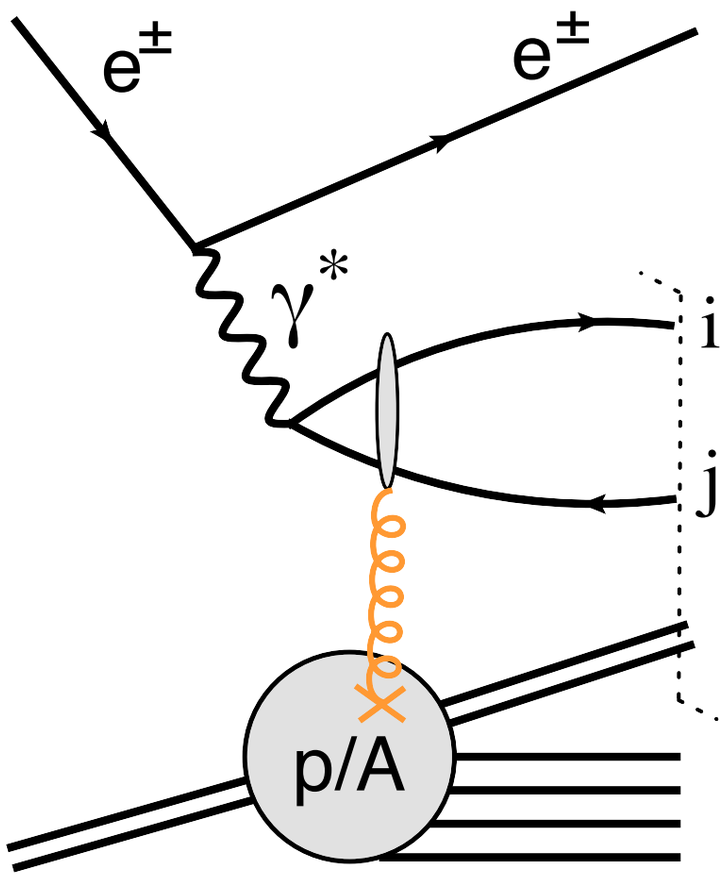
Observing correlations among many must be accompanied by a large scale deviation ⟹ interesting to study with decreasing system size

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

Inclusive processes in DIS

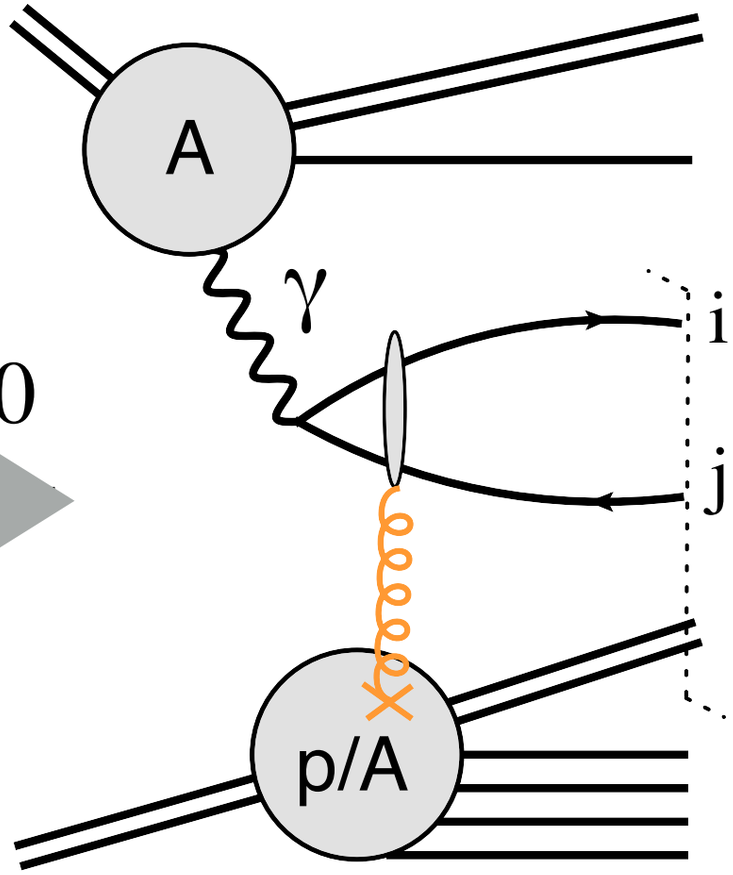


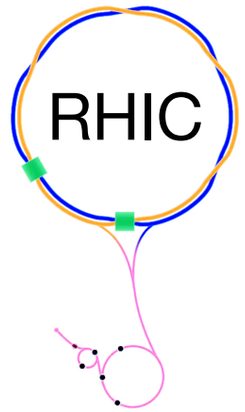
Inclusive DIS at HERA/EIC



$Q^2 \rightarrow 0$

Inclusive UPC at the LHC/RHIC





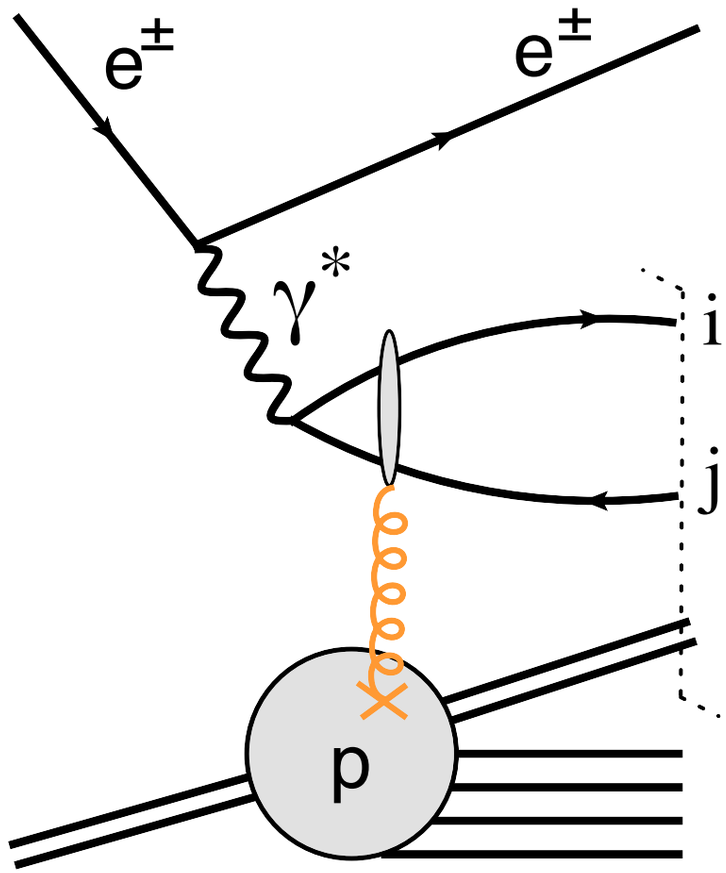
Events with $Q^2 > 1$ are conventionally regarded as DIS
Most ep events have $Q^2 << 1$ and $Q^2 \rightarrow 0$ photoproduction processes

Until the BNL EIC is built UPCs provide an opportunity to study high-energy photoproduction processes (low virtuality limit of DIS)

Lessons from HERA

Inclusive processes in DIS

Inclusive DIS at HERA



Typical HERA kinematics

E_e=27.5 GeV
E_p=920 GeV

$0.0001 < x < 0.01$

$5 < Q^2 < 100$ GeV^2 (DIS)

$W_{\gamma p} \sim 270$ GeV (Photoproduction)

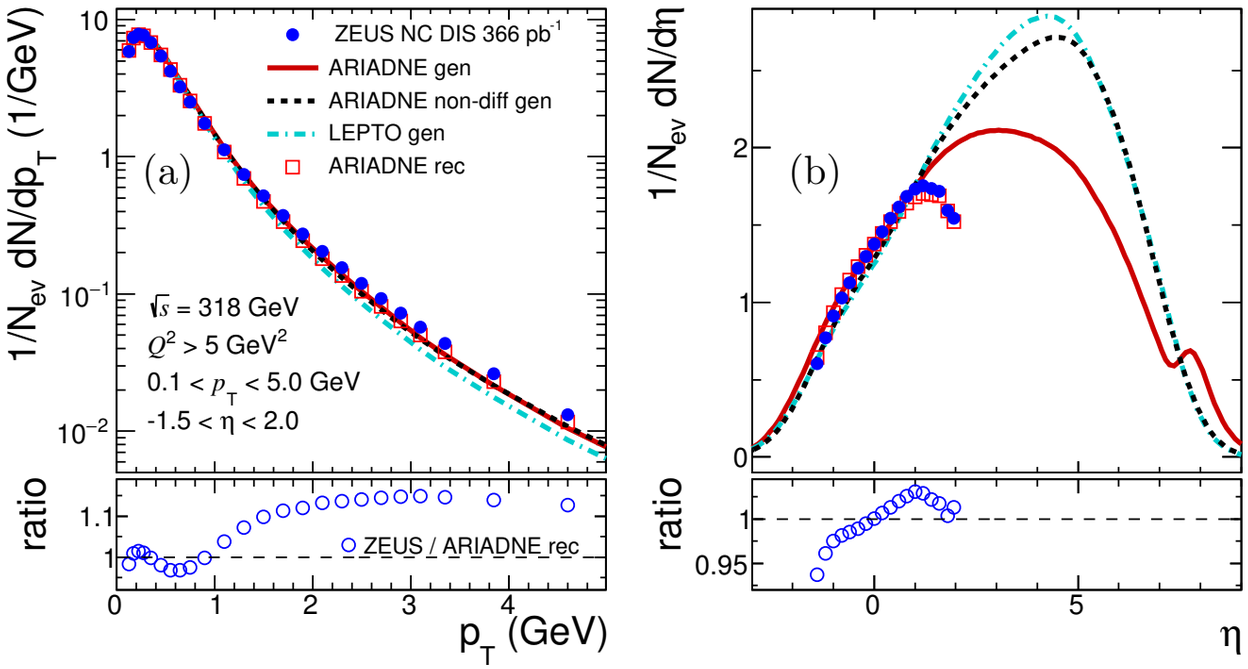
N_{trk} (HM) < 30

Search for collectivity in DIS

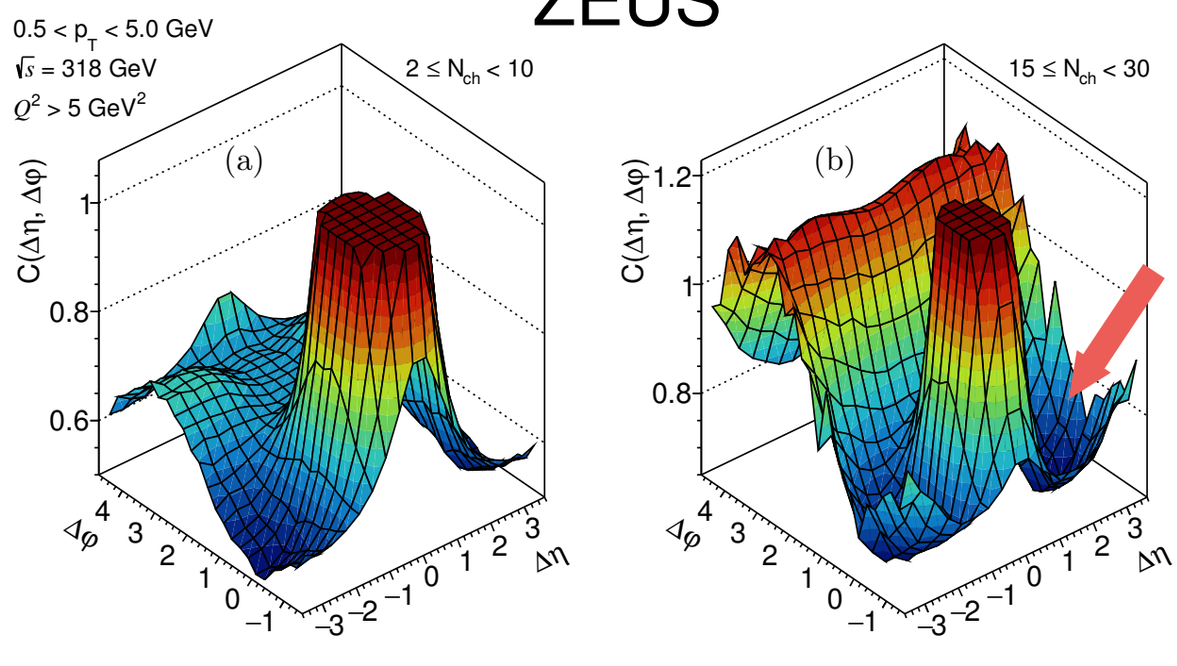
Search for collectivity in e-p collisions with ZEUS data

JHEP 04 (2020) 070,1912.07431 [hep-ex]

ZEUS



ZEUS



No sign of ridge

Azimuthal correlations —> consistent with expectations from momentum conservation & hard processes, well described by DIS models

Collectivity in ep DIS with H1 data

Chuan Sun, H1 Collaboration, DIS 2021

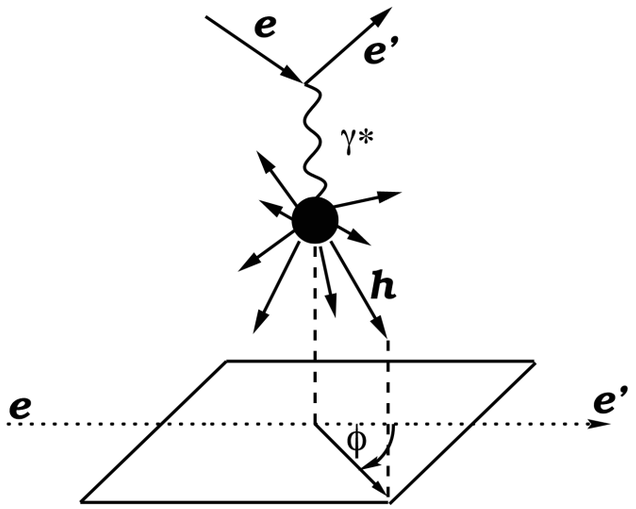
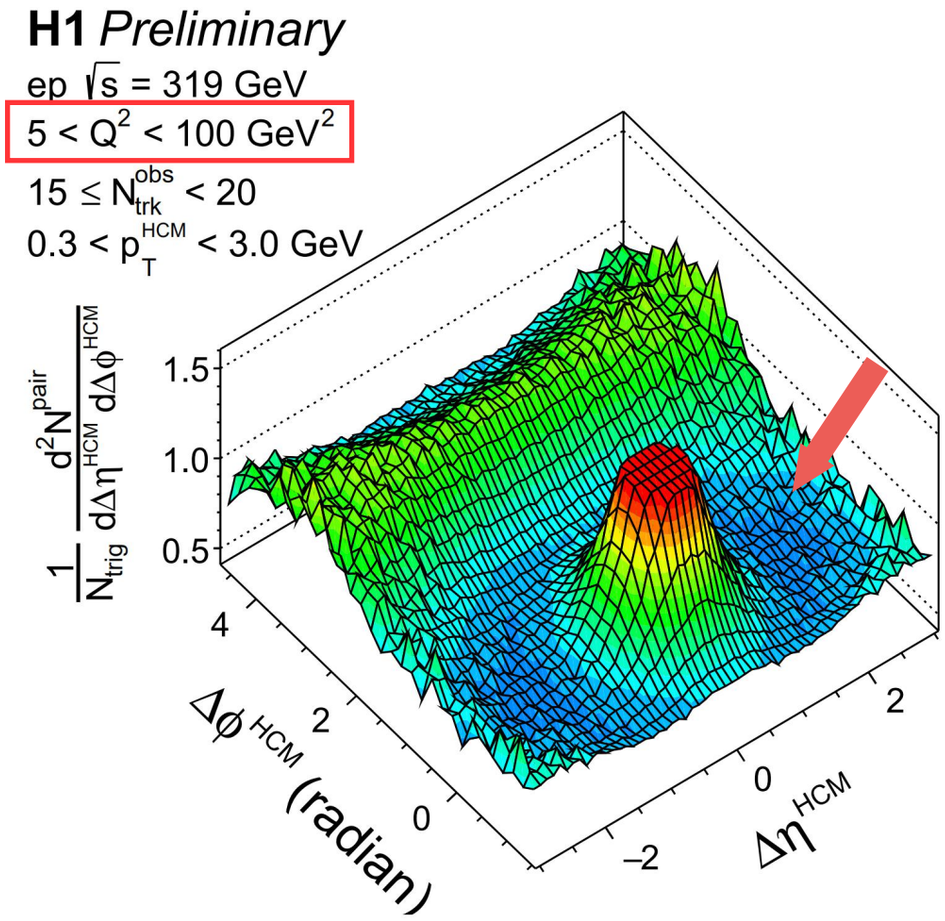
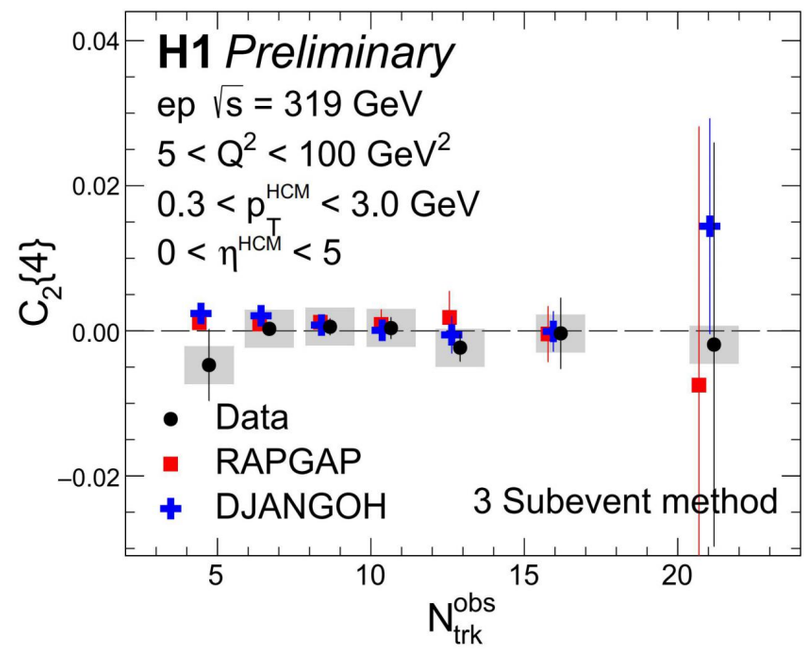


fig: hep-ex/0003017



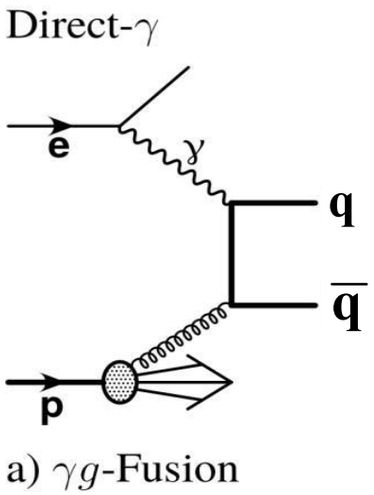


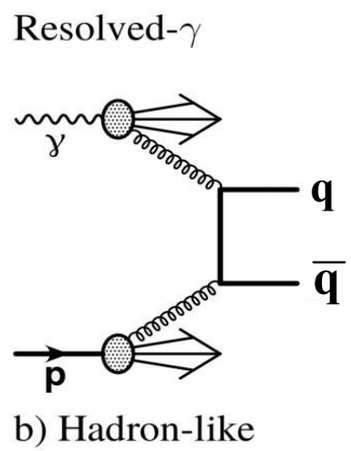
https://www-h1.desy.de/h1/www/publications/htmlsplit/H1prelim-20-033.long.html

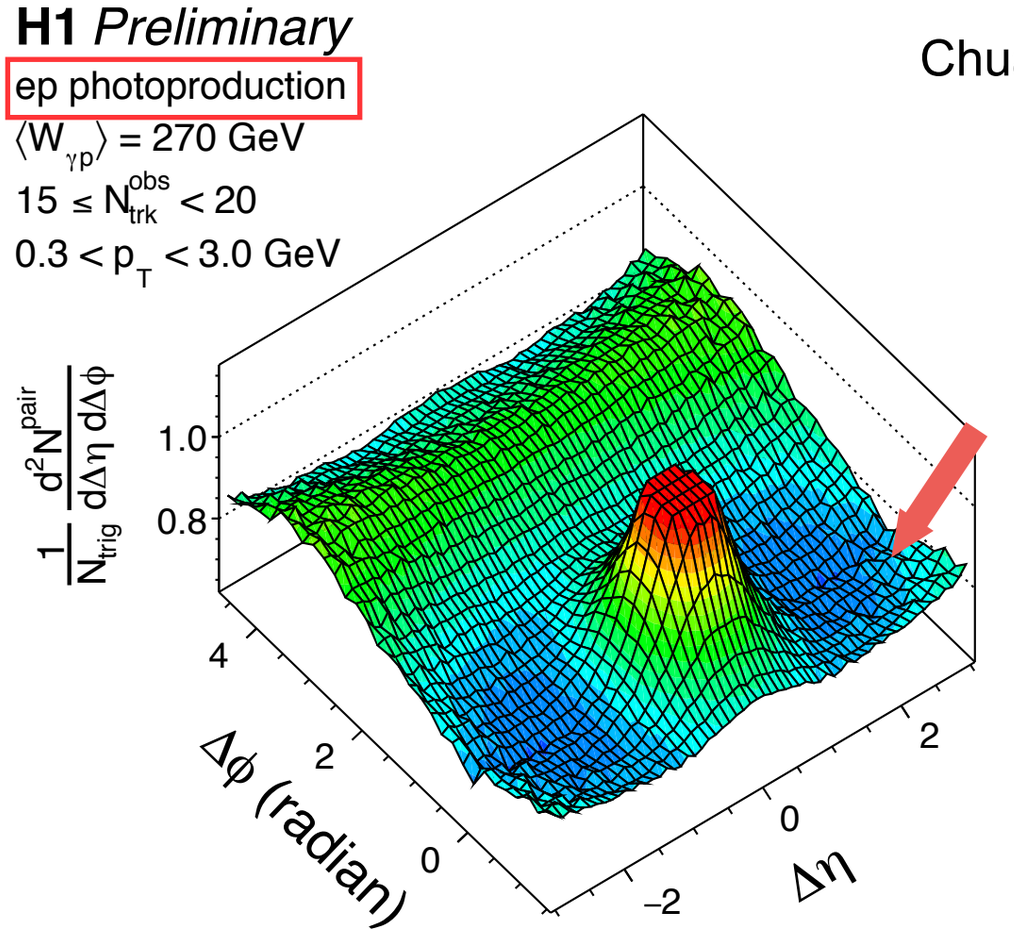
No near-side long-range ridge with H1 DIS data

Results on $V_{n\Delta}$ & $c_n\{4\}$ → no sign of collectivity

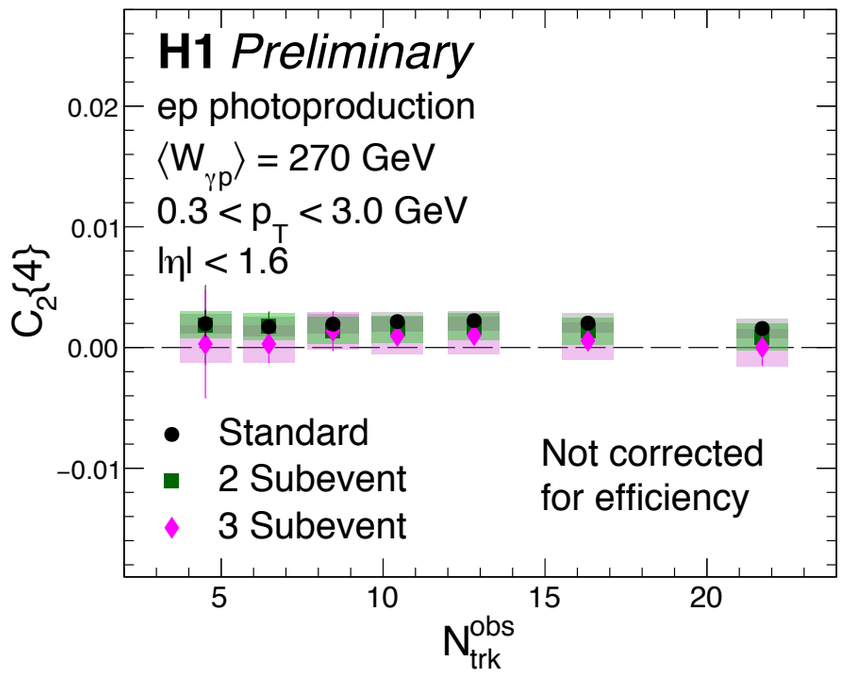
Collectivity in ep photoproduction from H1







Chuan Sun for H1 Collaboration, DIS 2021



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Lessons from LHC

Inclusive UPC at the LHC/RHIC

Typical kinematics at LHC and RHIC:

$Q^2 < (\hbar c/R_A)^2 \rightarrow 0$; $R_A \sim 1.2\,(A)^{1/3}$ fm

A~200, $Q^2 \sim 0.0008$ GeV^2

$E_\gamma \sim \gamma^{Lorentz}\,(\hbar c/R_A)$, $W_{\gamma A} \sim \sqrt{(4\,E_\gamma\,E_A)}$

γ^L (Pb, LHC)=2.51e3, γ^L(p, LHC)=6.51e3

E_γ (LHC) ~ 71 GeV,

$W_{\gamma p}$ (LHC) ~ 1.36 TeV, $dN_{trk}/d\eta$ (HM) > 7

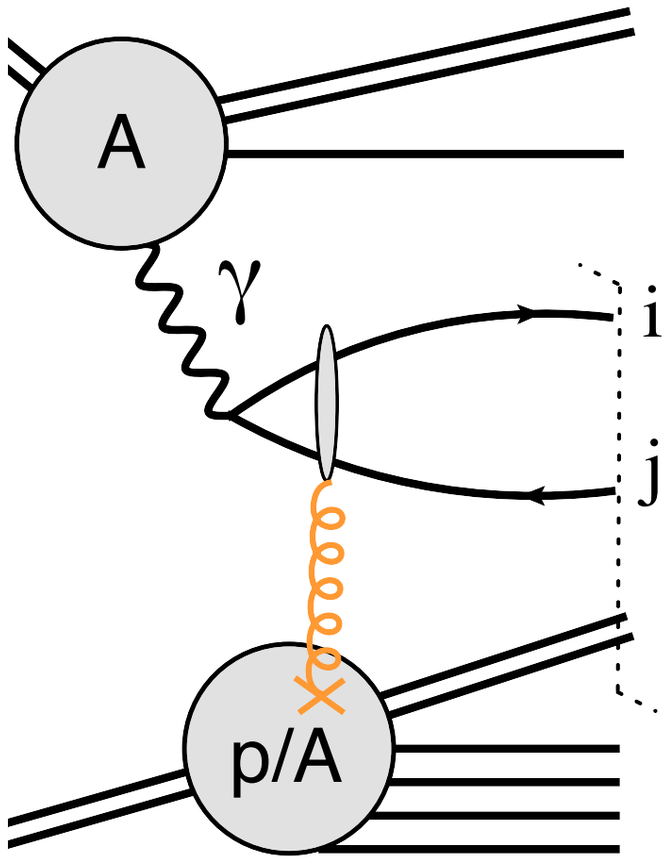
$W_{\gamma Pb}$ (LHC) ~ 844 GeV, $dN_{trk}/d\eta$ (HM) > 10

γ^L(Au, RHIC)= 27,100, γ^L(p/d, RHIC)=100

E_γ (RHIC) ~ 2.86 GeV,

$W_{\gamma(p/d)}$ (RHIC) ~ 33.8 GeV

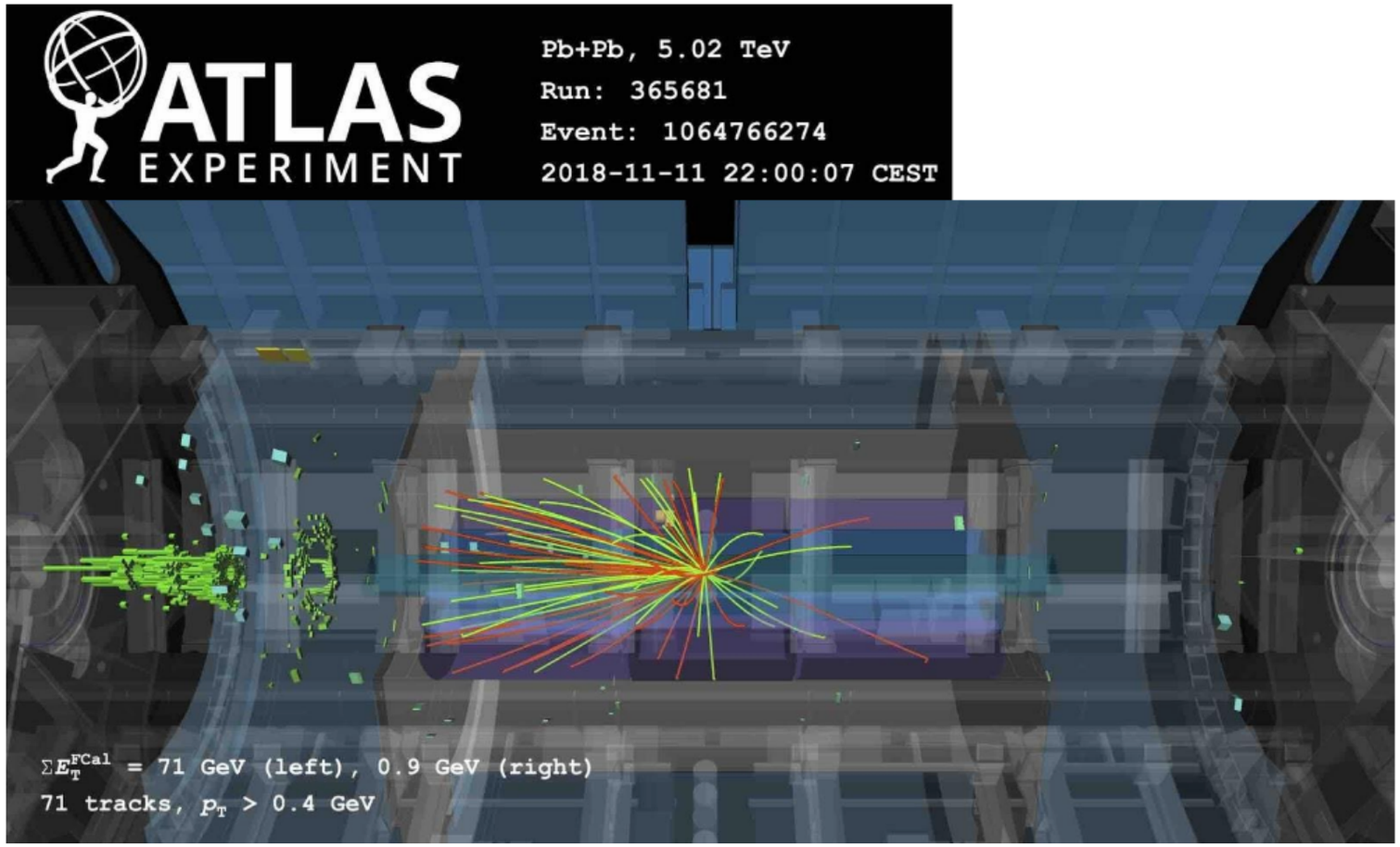
$W_{\gamma Au}$ (RHIC) ~ 17.6, 33.8 GeV

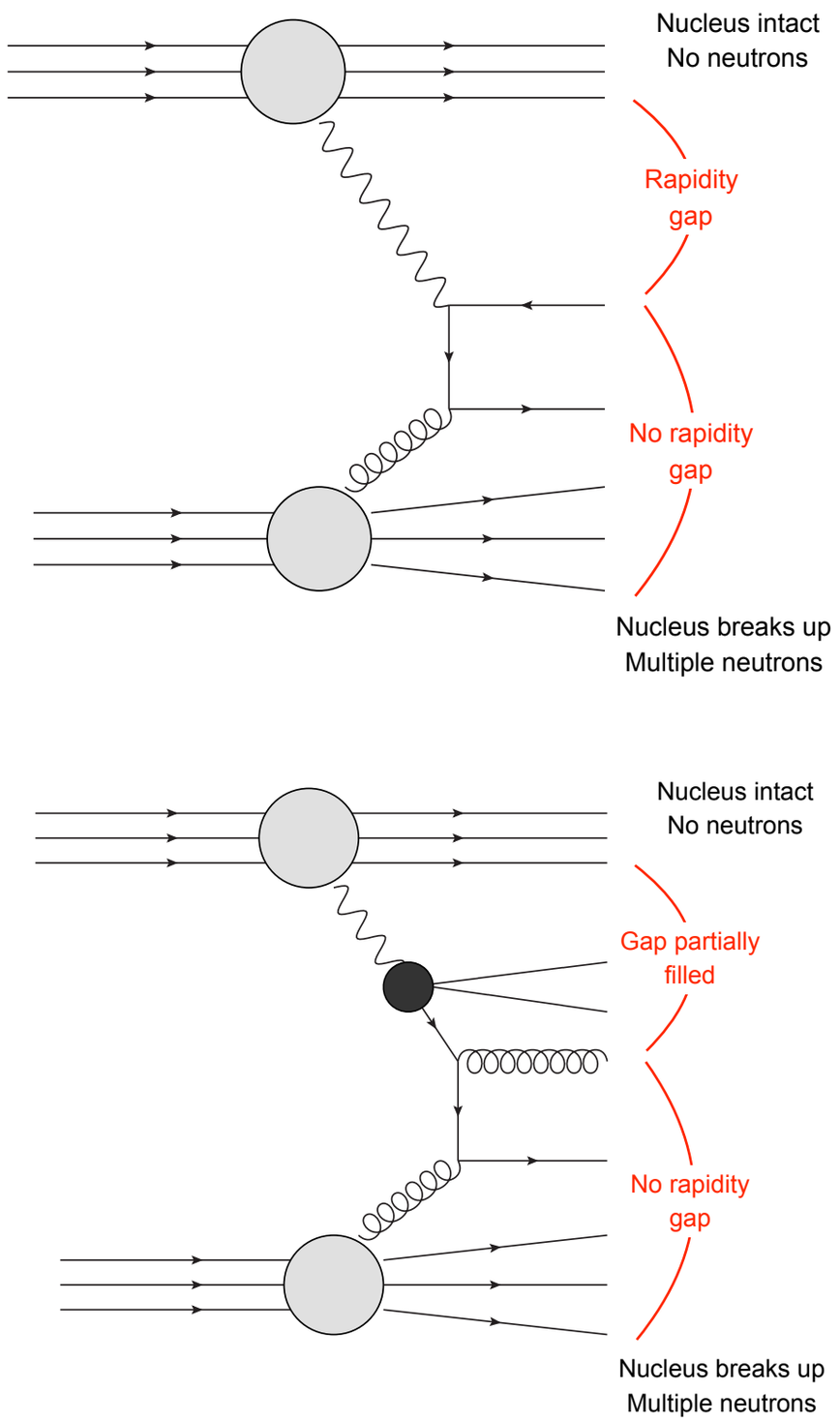


Main challenge is to exclude hadronic events (peripheral AA or pA)

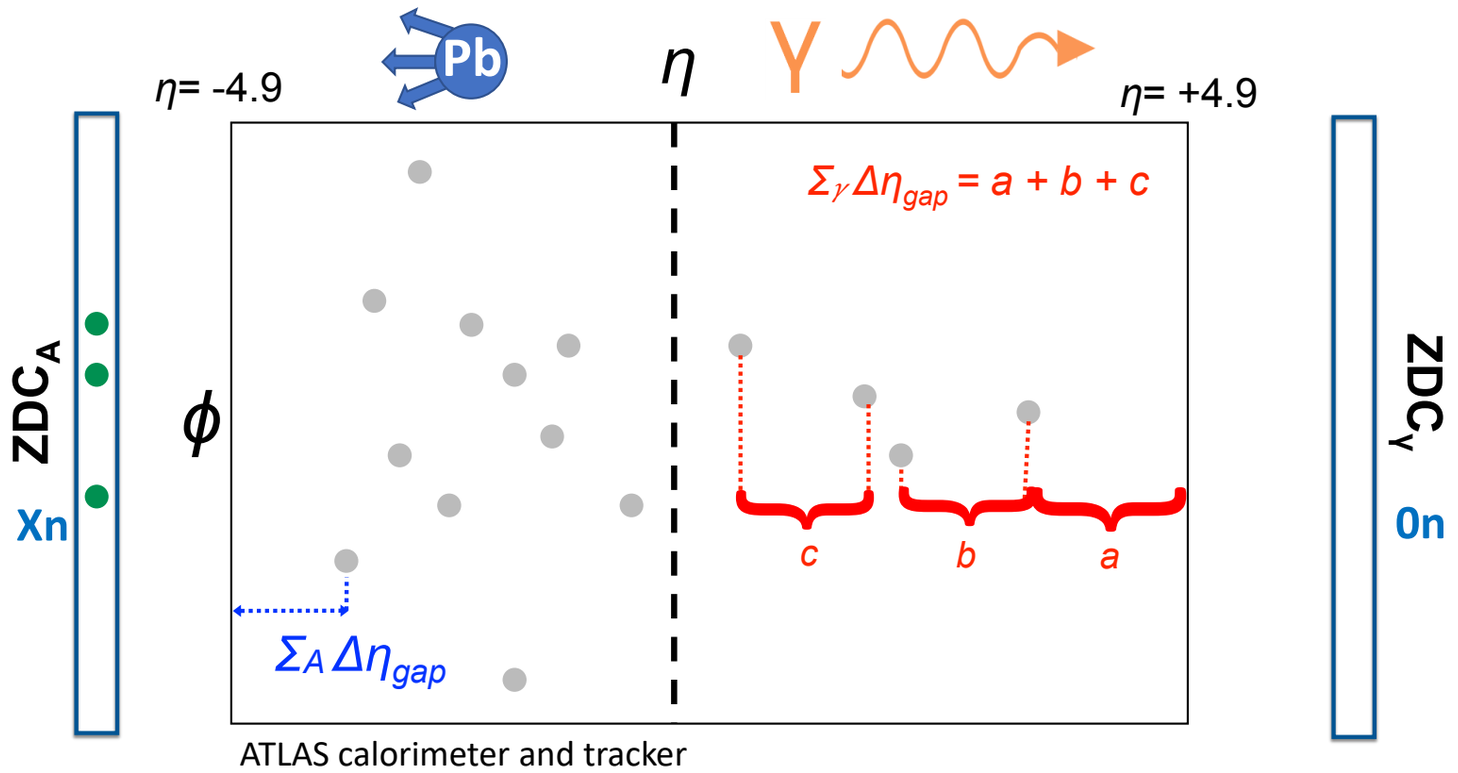
A Photonuclear events from ATLAS

ATLAS Collaboration, e-Print: 2101.10771 [nucl-ex]



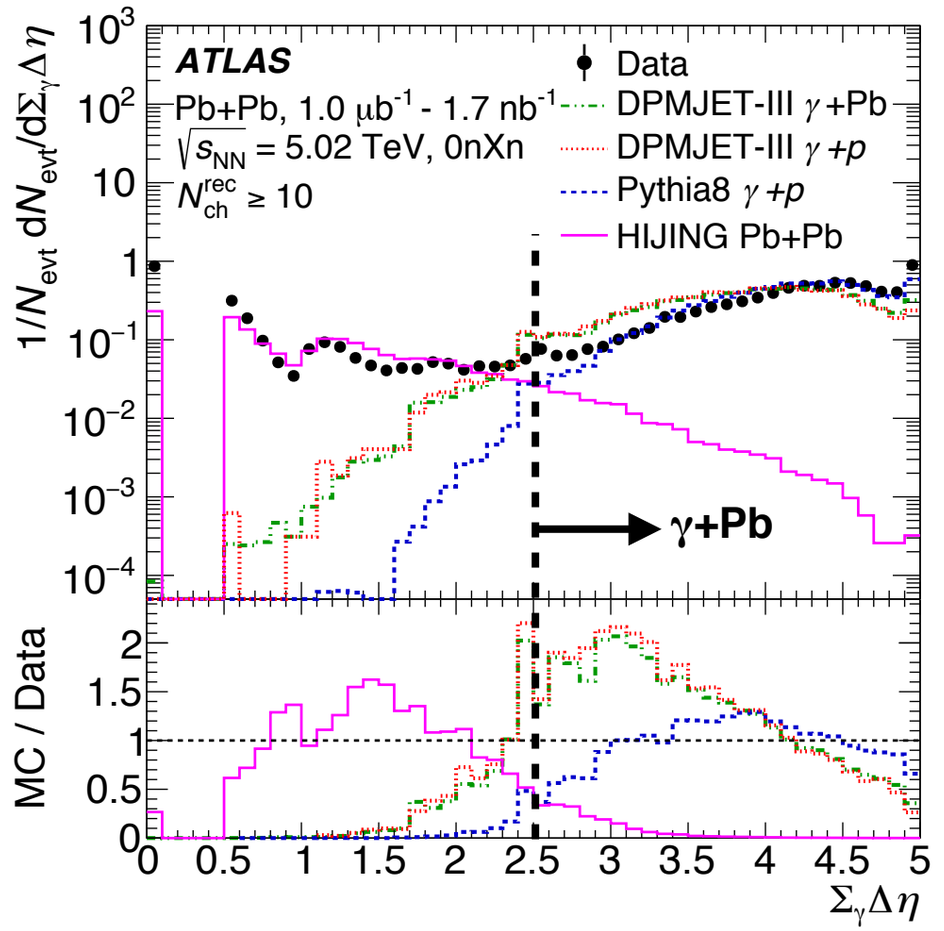


Challenge : purity of γA events



Event Selection: $\Sigma_A \Delta\eta_{gap} < 3$ $\Sigma_\gamma \Delta\eta_{gap} > 2.5$

Blair Seidlitz, ATLAS Collaboration, IS2021



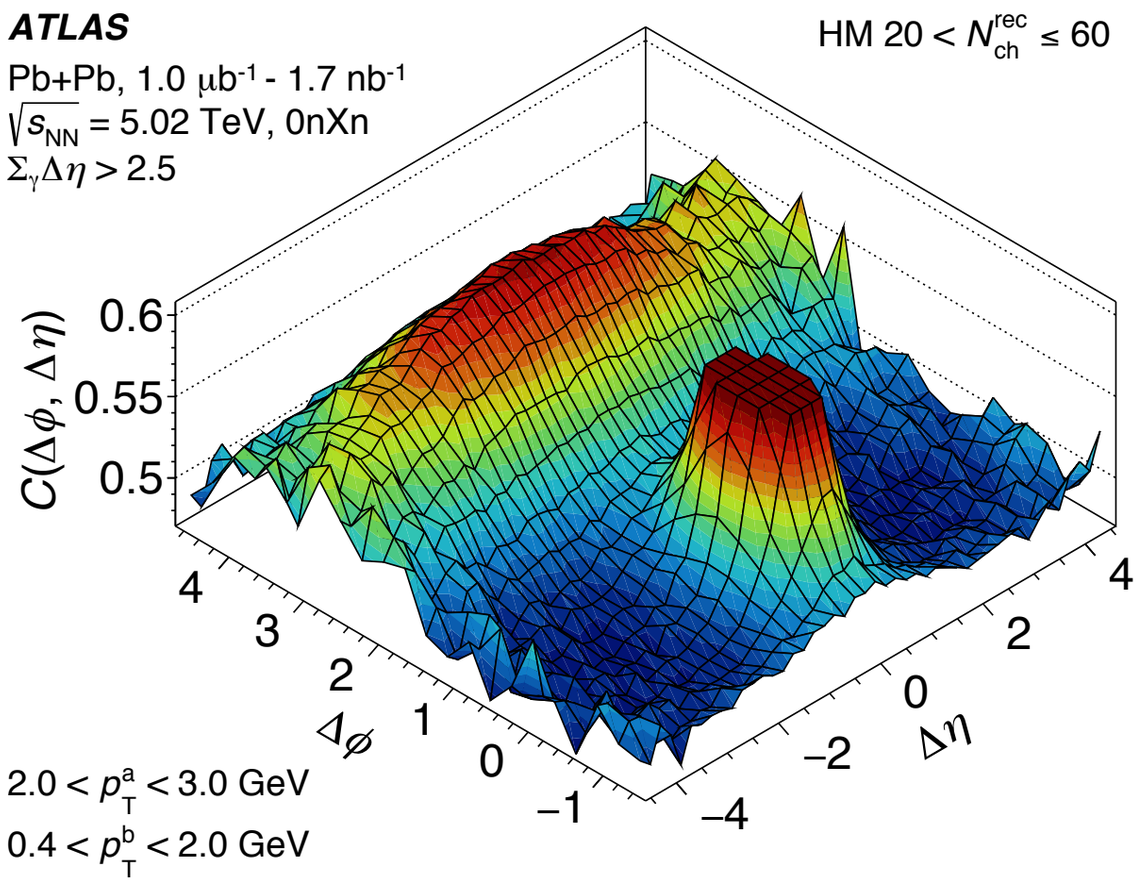
Primarily cut: "0nXn" events using the ZDC.
Major discrimination of Pb+Pb using sum-gap

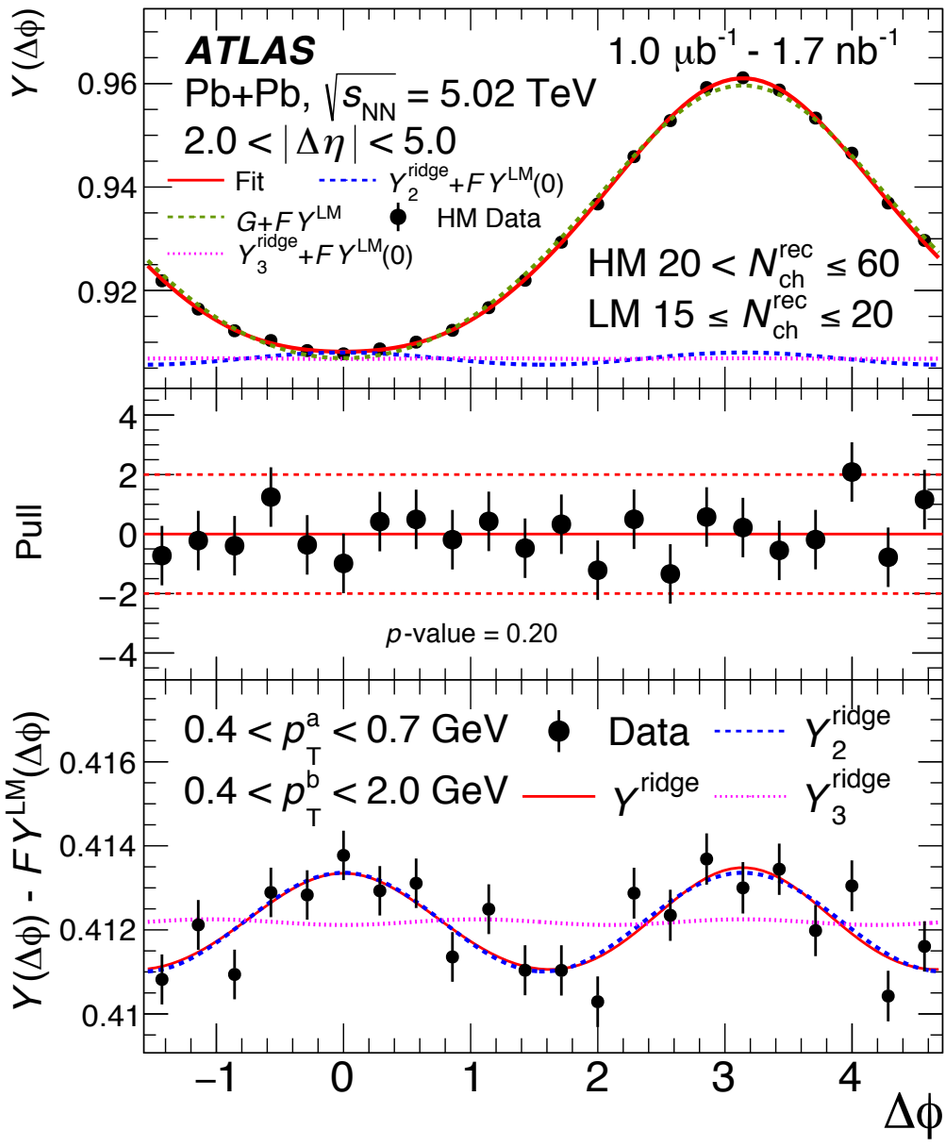
Can achieve > 97% purity for γ+Pb events

γ+Pb: broader sum-gap distribution
Pb+Pb: narrow sum-gap distribution

Ridge yield extracted in γ+Pb events

ATLAS Collaboration, e-Print: 2101.10771 [nucl-ex]





Use template to extract ridge & anisotropy:

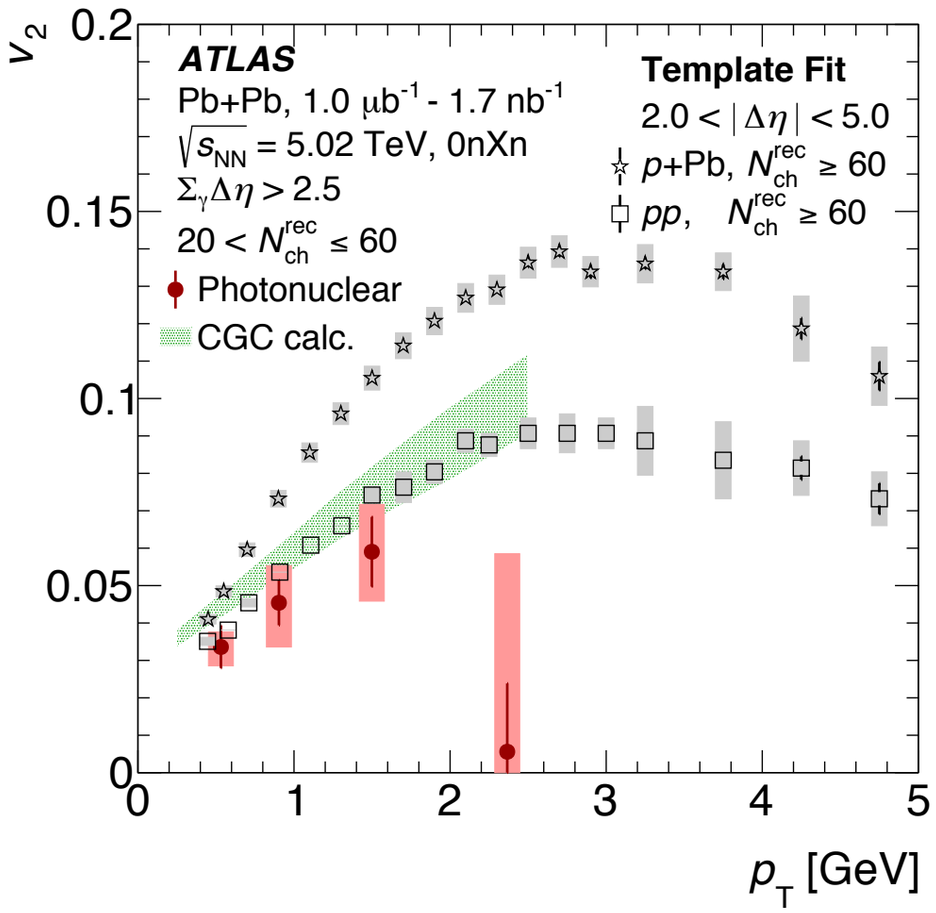
$$Y(\Delta\phi, 2<|\Delta\eta|<5) = \frac{1}{N_{\rm trig}}\frac{d^2N_{\rm pair}}{d\Delta\phi} = \frac{N_{\rm asco}}{2\pi}\left(1+\sum_n 2a_n\cos(n\Delta\phi)\right)$$

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

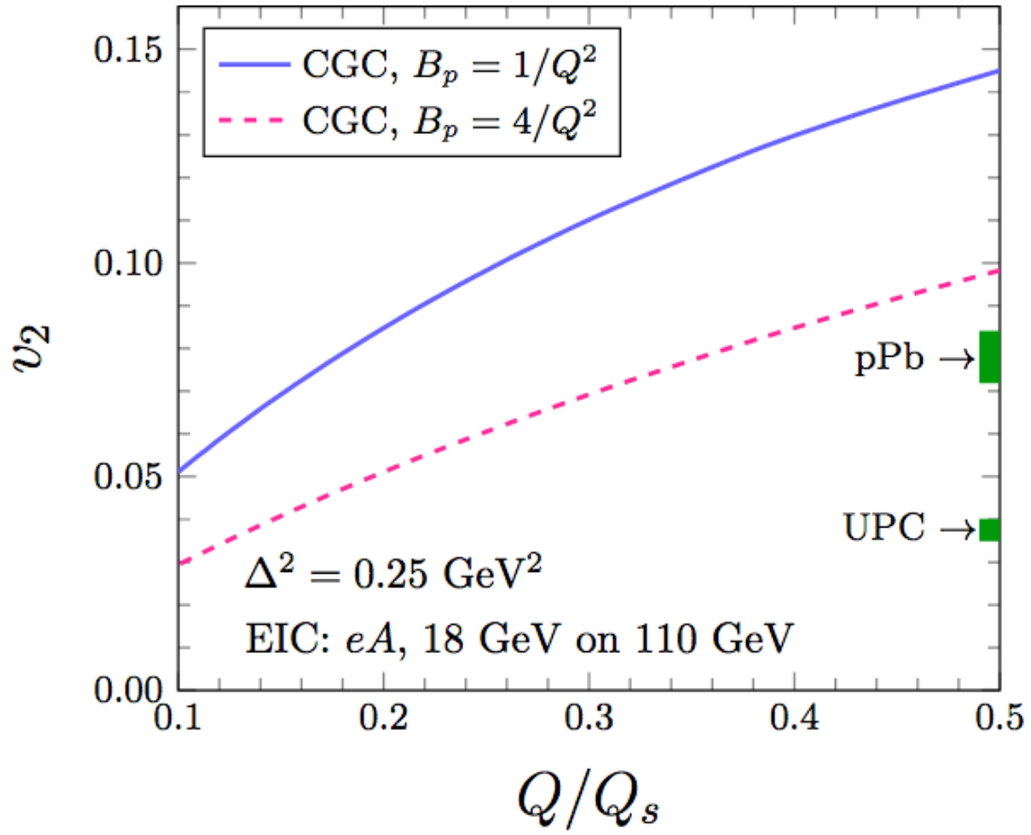
$$Y(\Delta\phi)^{\rm ridge}(HM) = G\{1+2a_2\cos(2\Delta\phi)+2a_3\cos(3\Delta\phi)+2a_4\cos(4\Delta\phi)\}$$

Elliptic anisotropy in γ+A and CGC

ATLAS Collaboration, e-Print: 2101.10771 [nucl-ex]



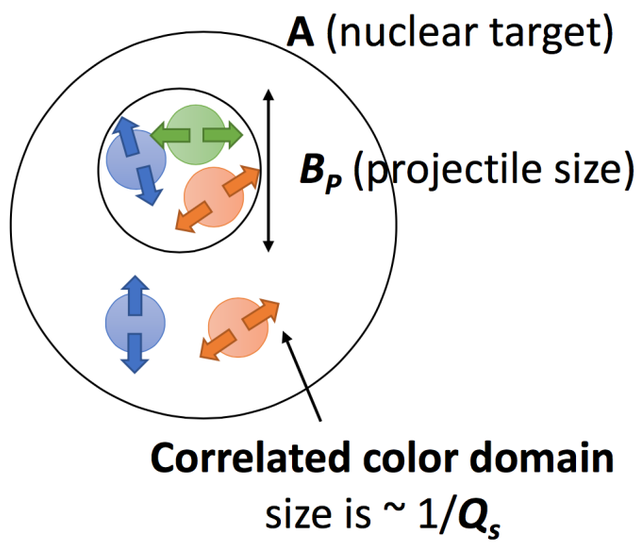
CGC calculation arXiv: 2008.03569



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

CGC calculations provide an explanation based on color domain picture.

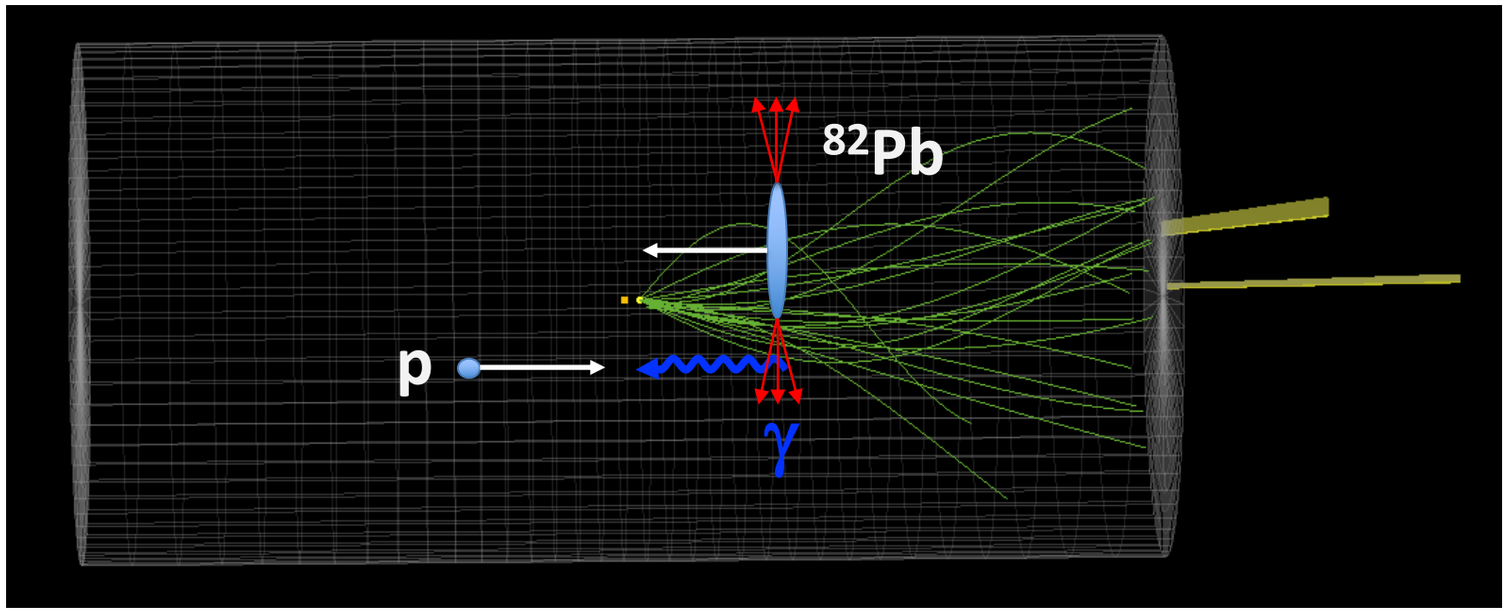
EIC will provide much control to explore this



Cartoon: Blair Seidlitz, IS2021

CMS γ+p collisions

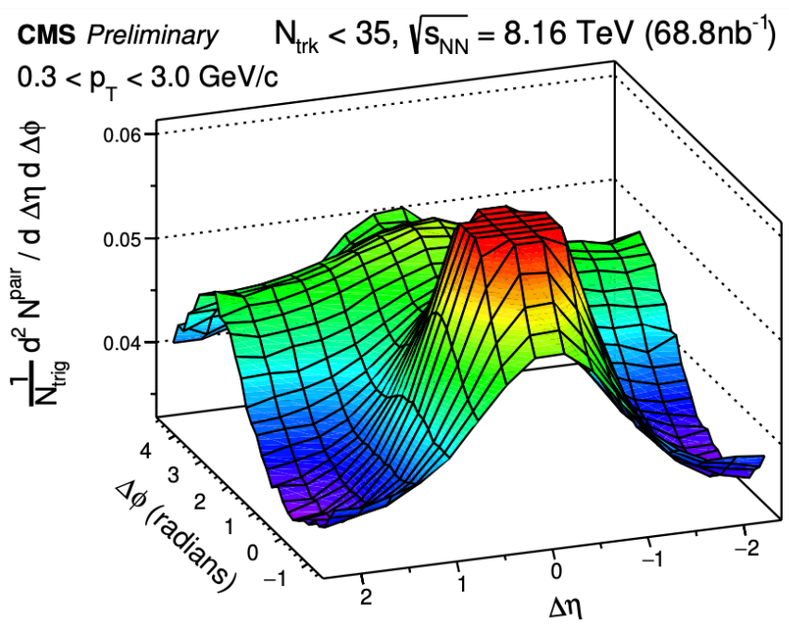
Quan Wang, CMS Collaboration, IS2021



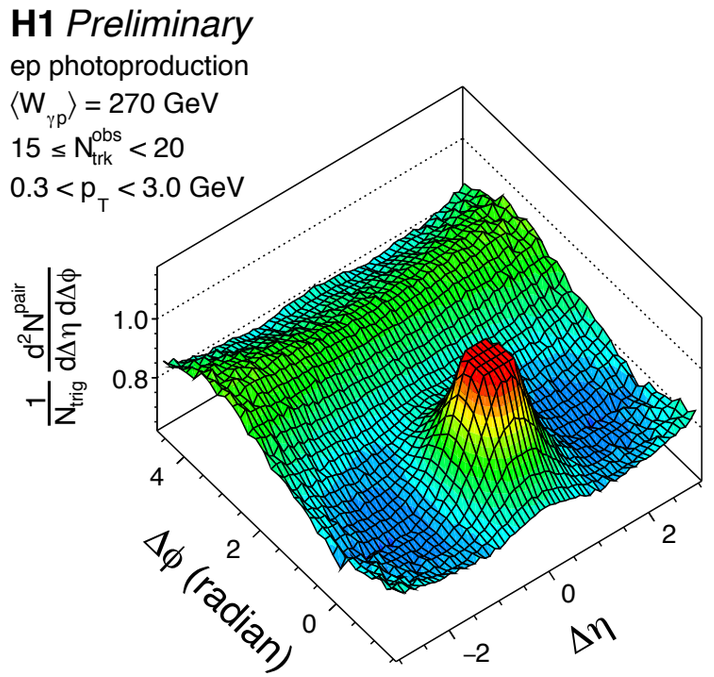
Pb-going side detector is quiet but a lot of activity in p-going side

Already gives 95% γp purity

Big step towards UPC-DIS complimentarily although kinematics is different



Similar observation in UPC & DIS PhP



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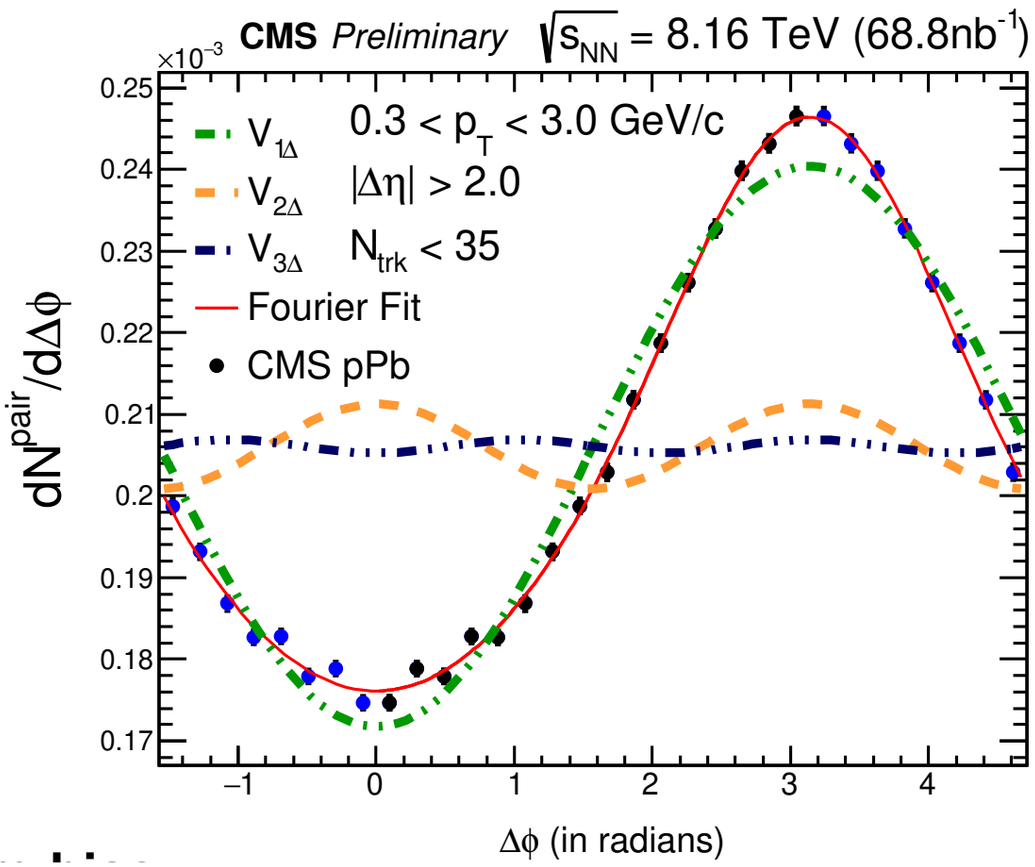
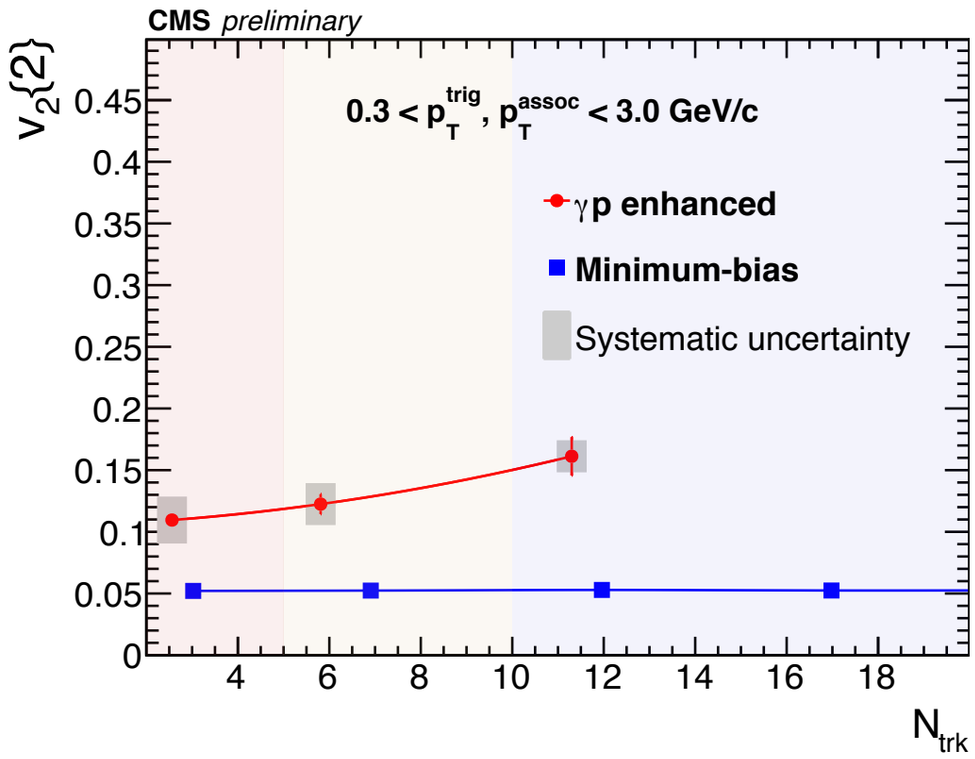
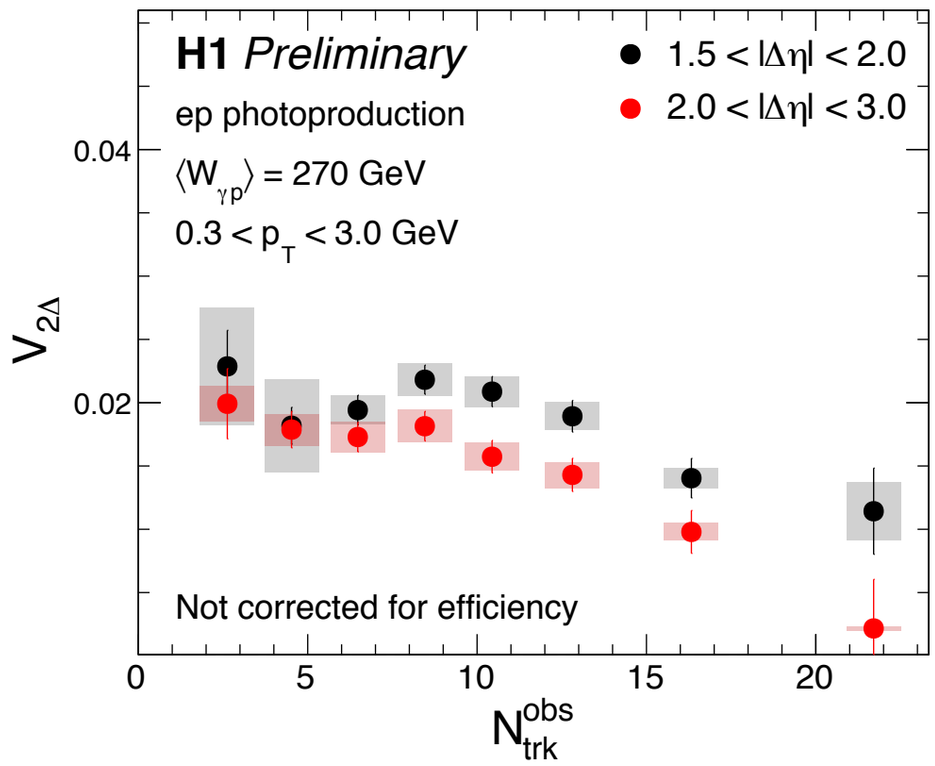


$$\frac{1}{N_{\rm trig}}\frac{dN^{\rm pair}}{d\Delta\phi} = \frac{N_{\rm assoc}}{2\pi}\left[1+\sum_n 2V_{n\Delta}\cos(n\Delta\phi)\right]$$





v_2 coefficient grows with multiplicity in γ+p UPC unlike hadronic events or ep photoproduction

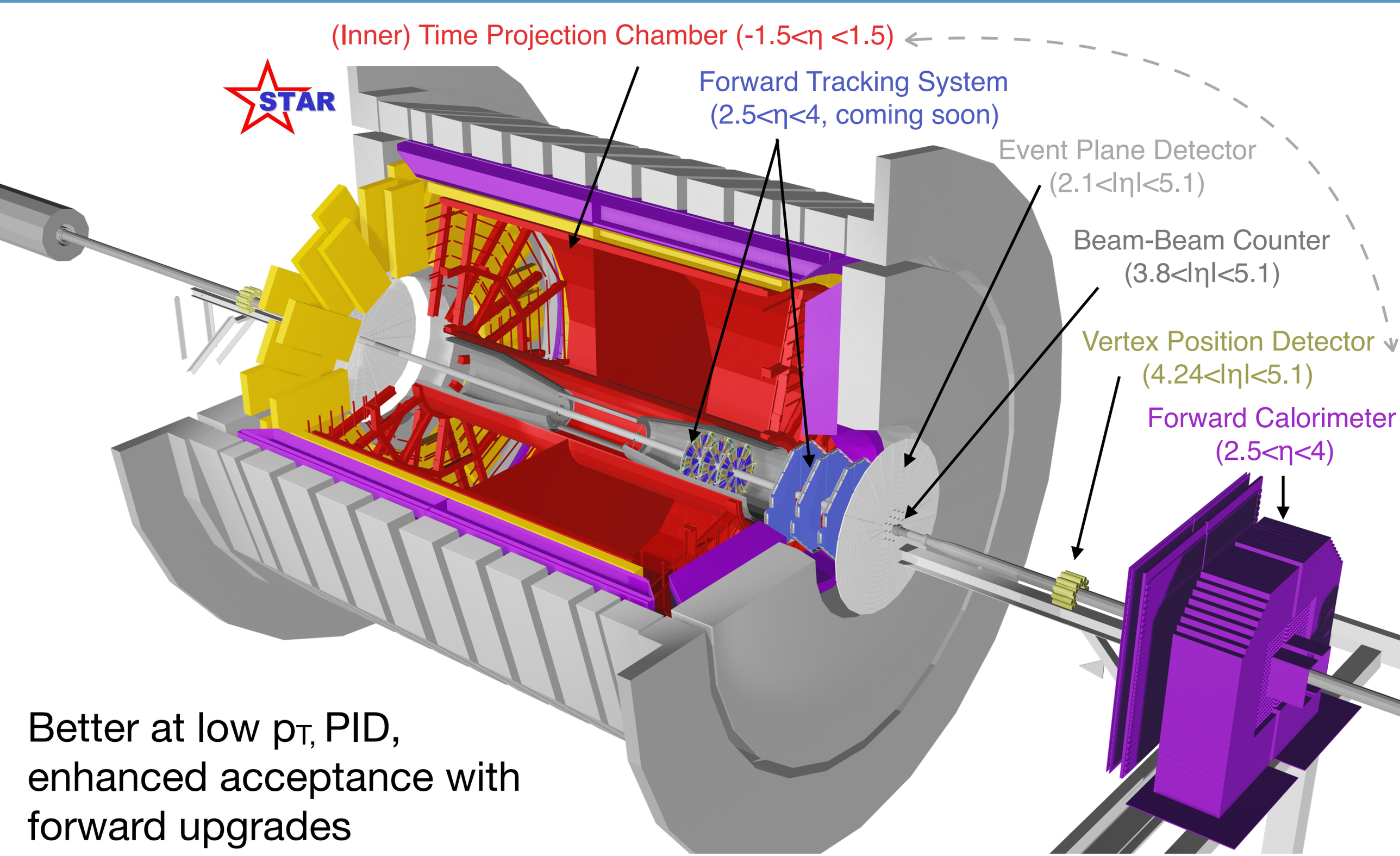
Bird's-eye view : signatures of collectivity

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

Since RHIC will make transition to EIC with similar p/A energies, how about search at RHIC (STAR or sPHENIX)?

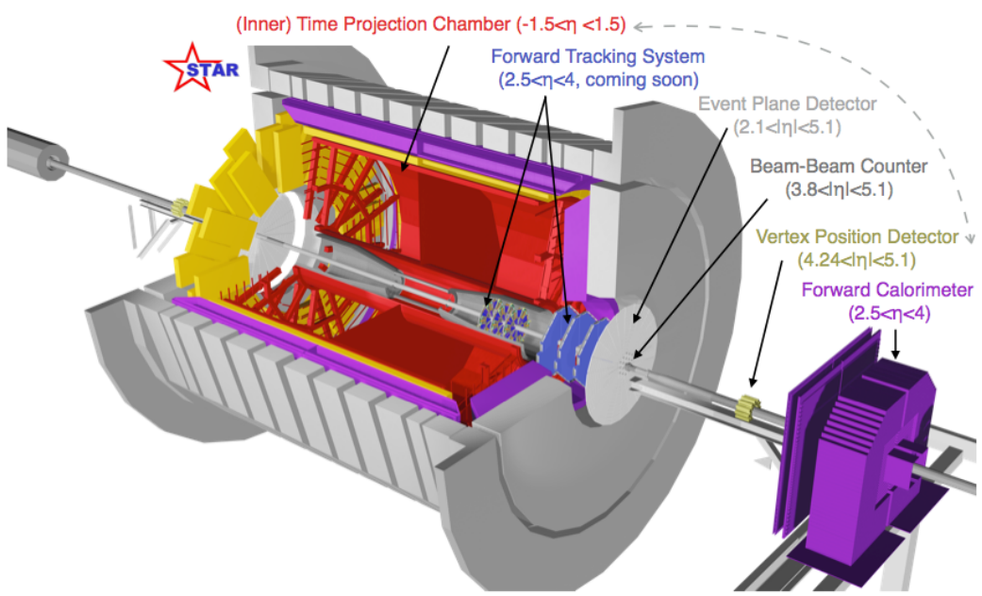
Opportunities with STAR

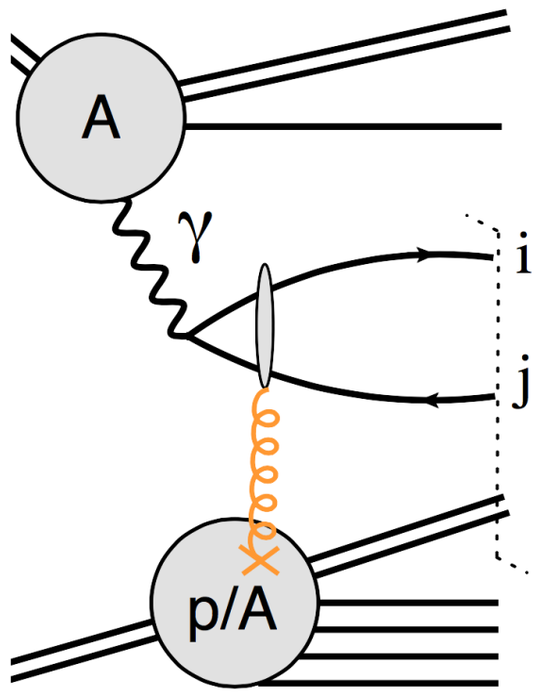
STAR now and in near future



Better at low p_T, PID, enhanced acceptance with forward upgrades

Inclusive photonuclear processes with STAR





Events like these are eliminated by coincidence triggers, threshold, vetoing and not saved during run

Only datasets on tape:
Au+Au 54 GeV (477 μb^{-1})
Au+Au 200 GeV (80 μb^{-1})

Feasibility study with models:

e+Au with BeAGLE (thanks to Z.Tu, Z.Xu)

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

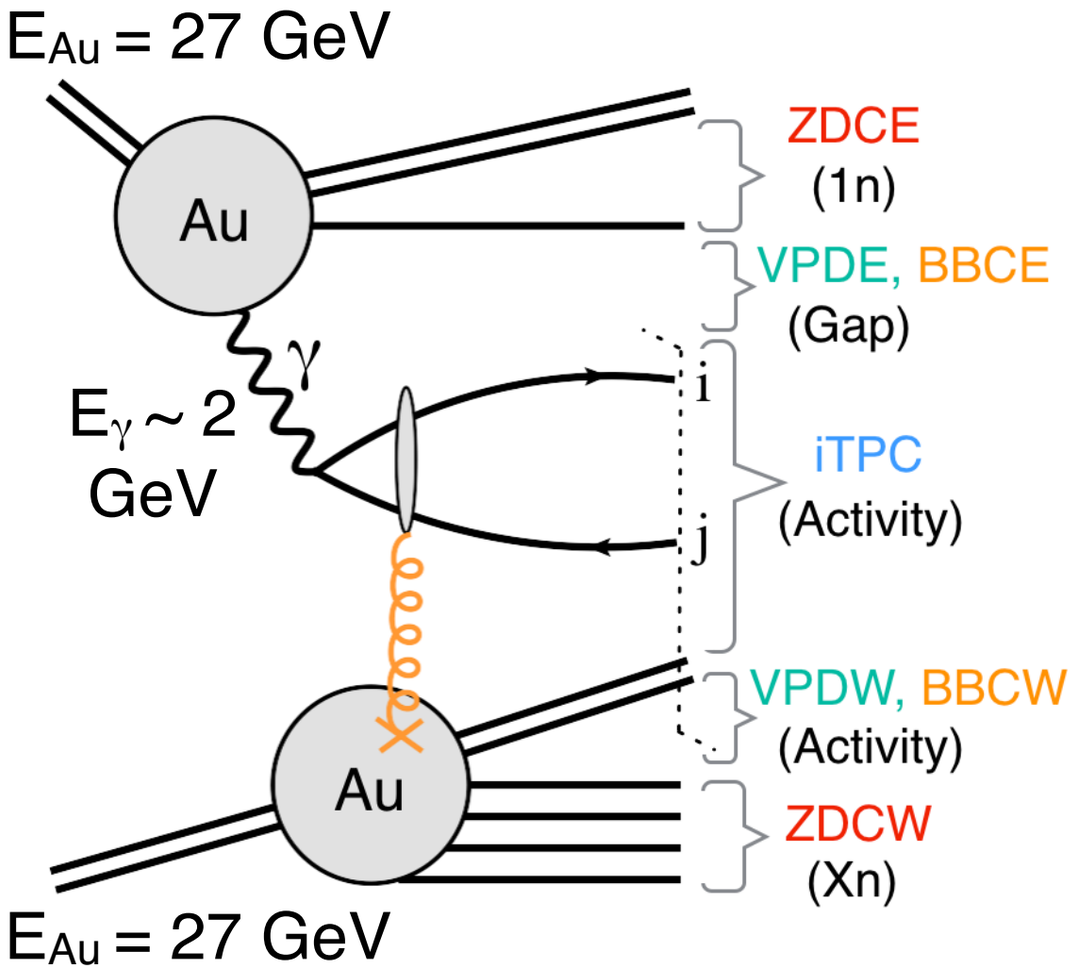
e+p with PYTHIA (thanks to M.Mondal, K.Kauder)

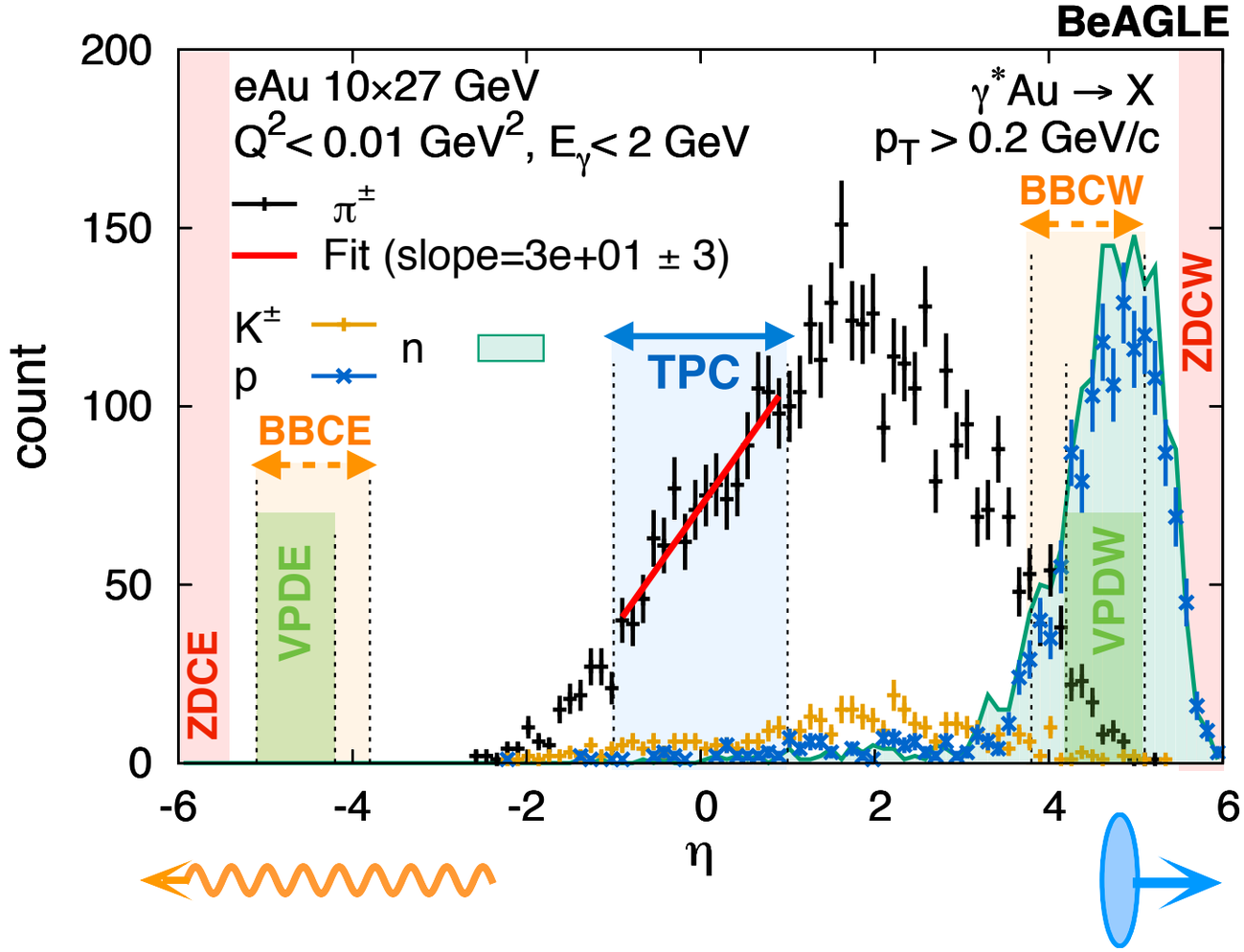
E_e =10 GeV, E_p = 27 GeV, E_γ<2 GeV, $0.001<Q^2<0.01$ GeV^2

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

Predictions form eA Monte-Carlo



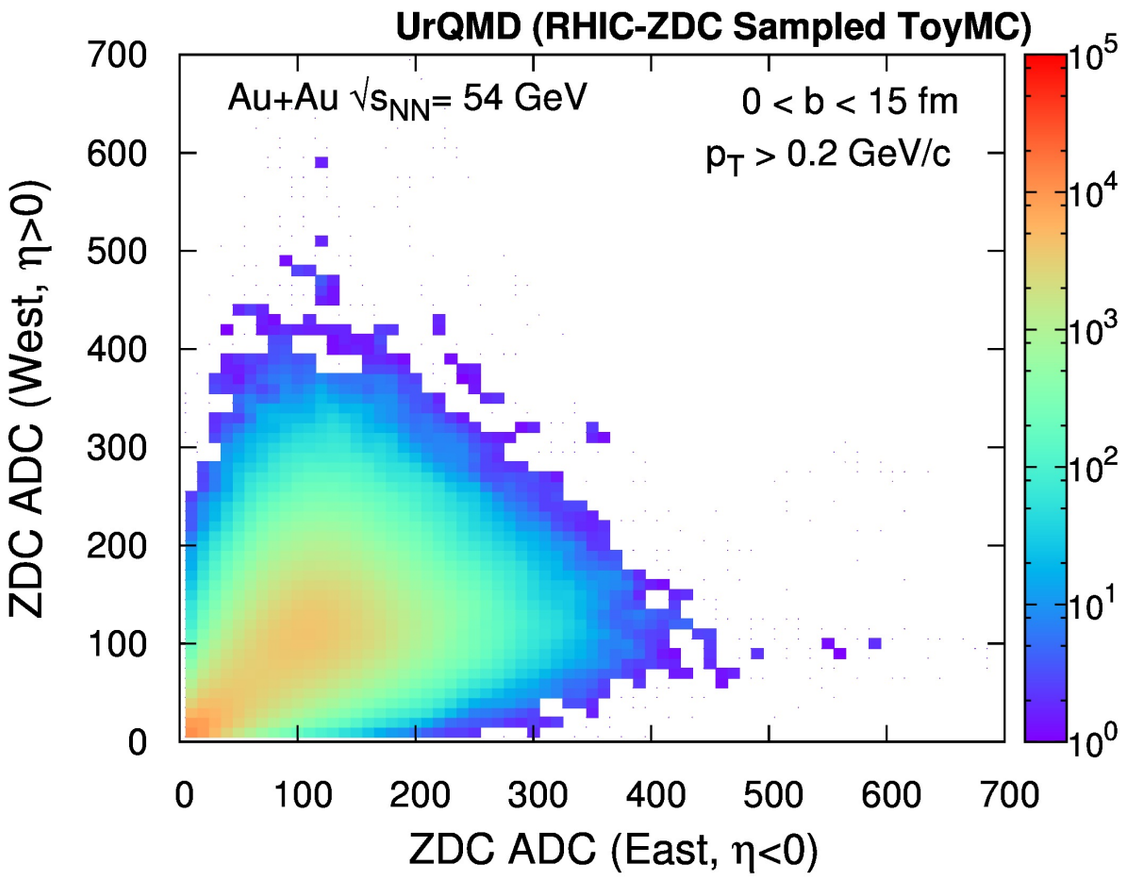


Primary selection can be done based on ZDCs with one neutron from photon emitting nucleus in the ZDC (reduce beam-gas, FXT events)

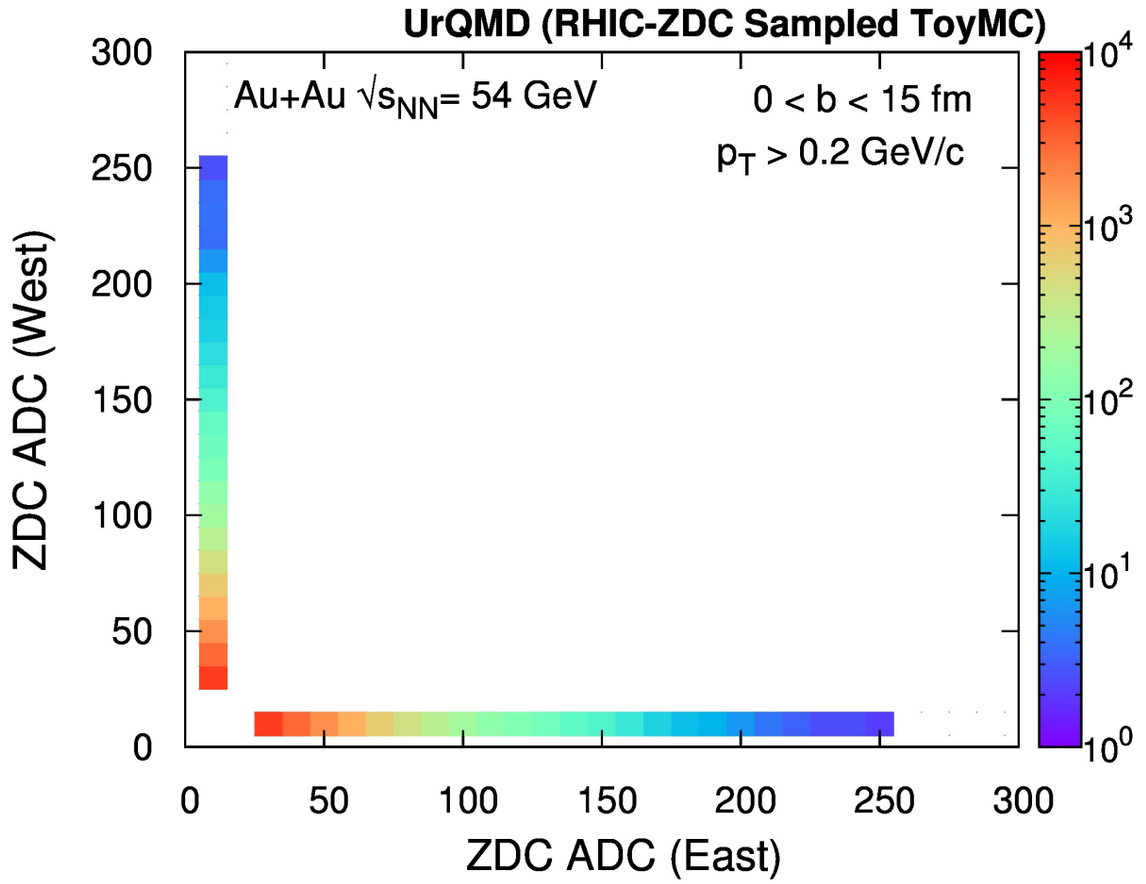
Will be associated with η-asymmetry in TPC, gap in BBC & VPDs

Predictions form AA Monte-Carlo

Typical response of RHIC-ZDCs



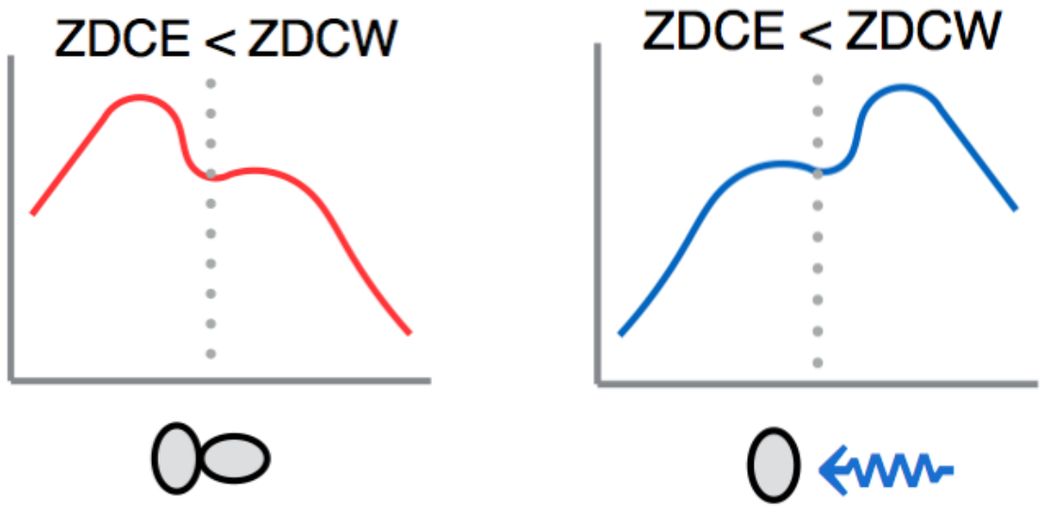
After applying γ+A like trigger

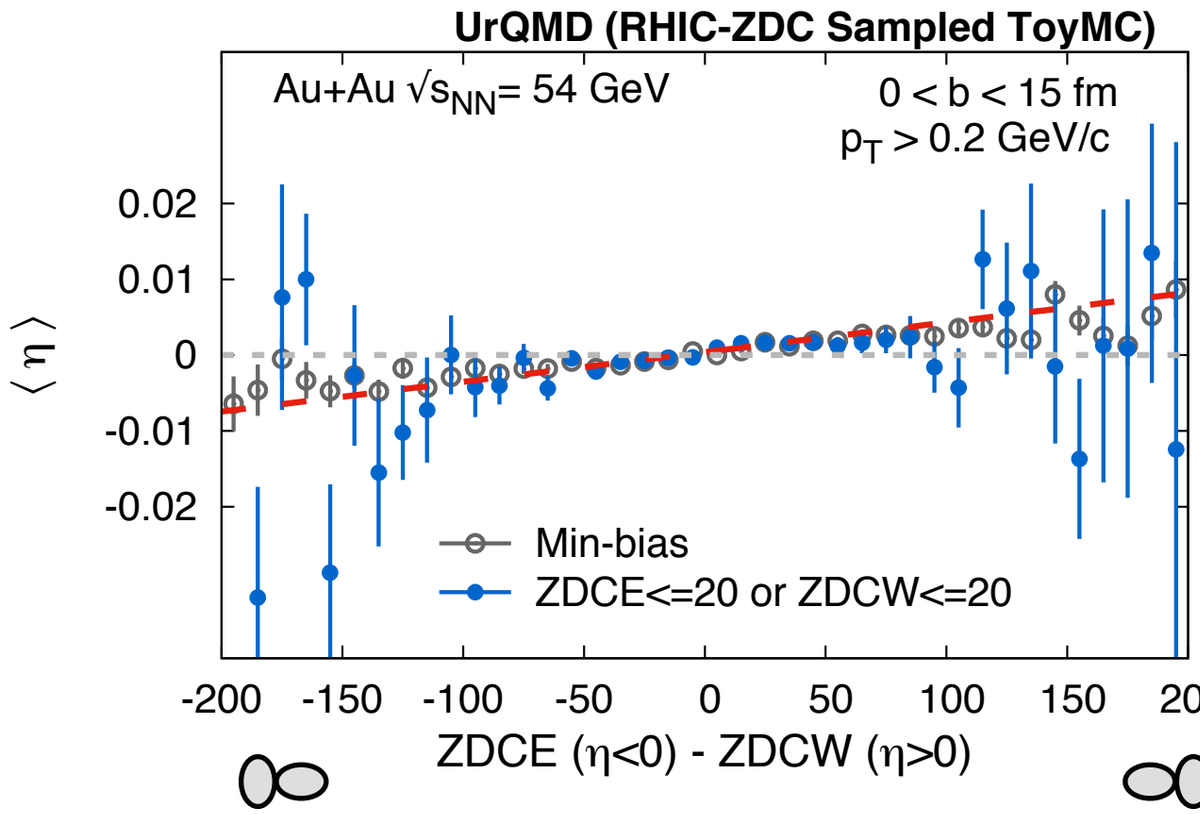


Hadronic events with asymmetry in neutrons and ZDCs are background (Deformed nuclei, fluctuations of nucleon and clustering of fragment)

Will the characteristics of these events be similar to γ+A ?

How to separate γ+A from A+A ?





Spectator & η-asymmetry are anti-correlated in hadronic events while the opposite is expected for γ+A

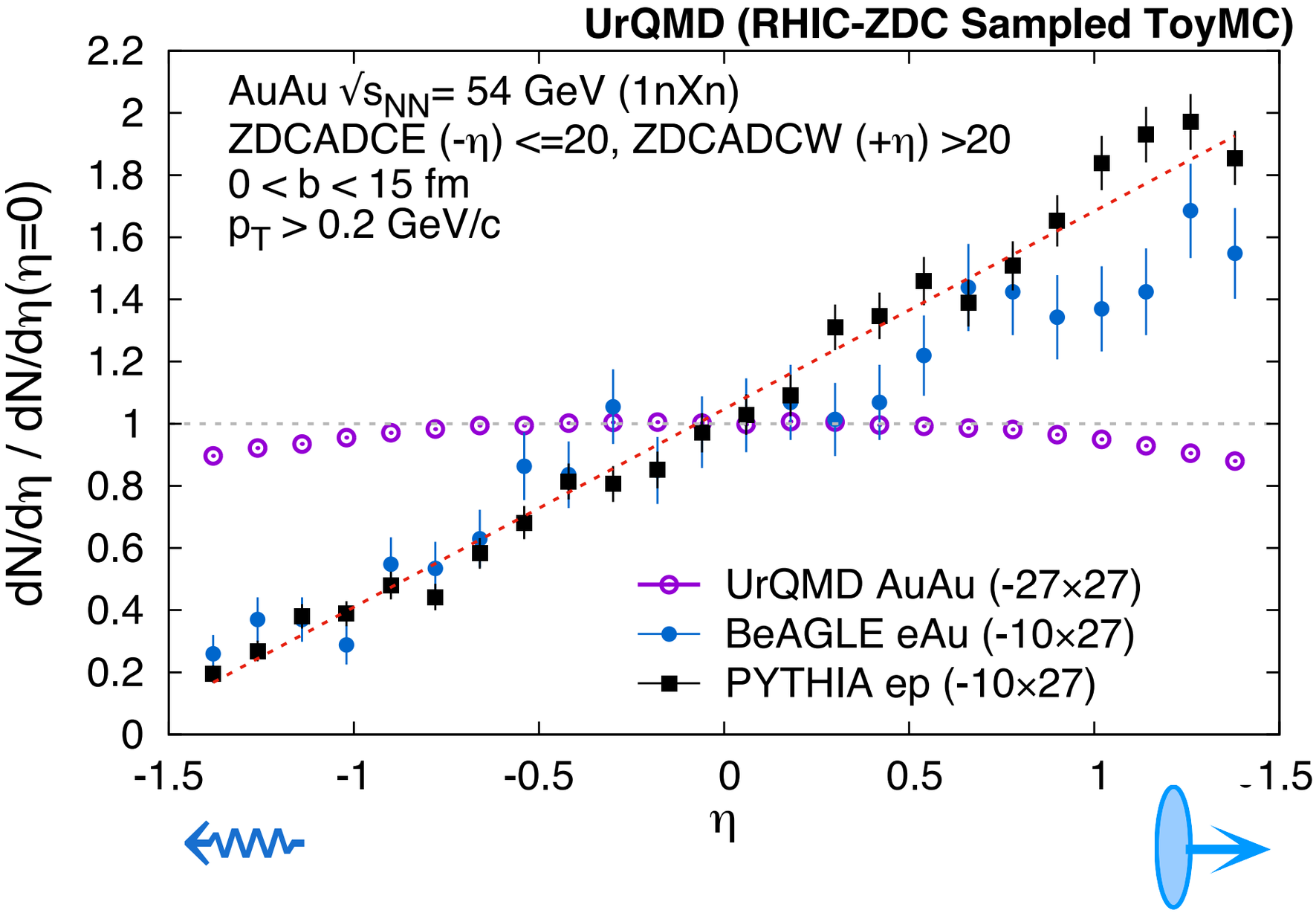
These extreme configurations occur in U+U collisions and have been triggered and studied by STAR

(also see arXiv:1412.5103)

$dN/d\eta\ (\eta>0) > dN/d\eta\ (\eta<0)$

$\propto -(ZDC\ (\eta>0) > ZDC\ (\eta<0))$

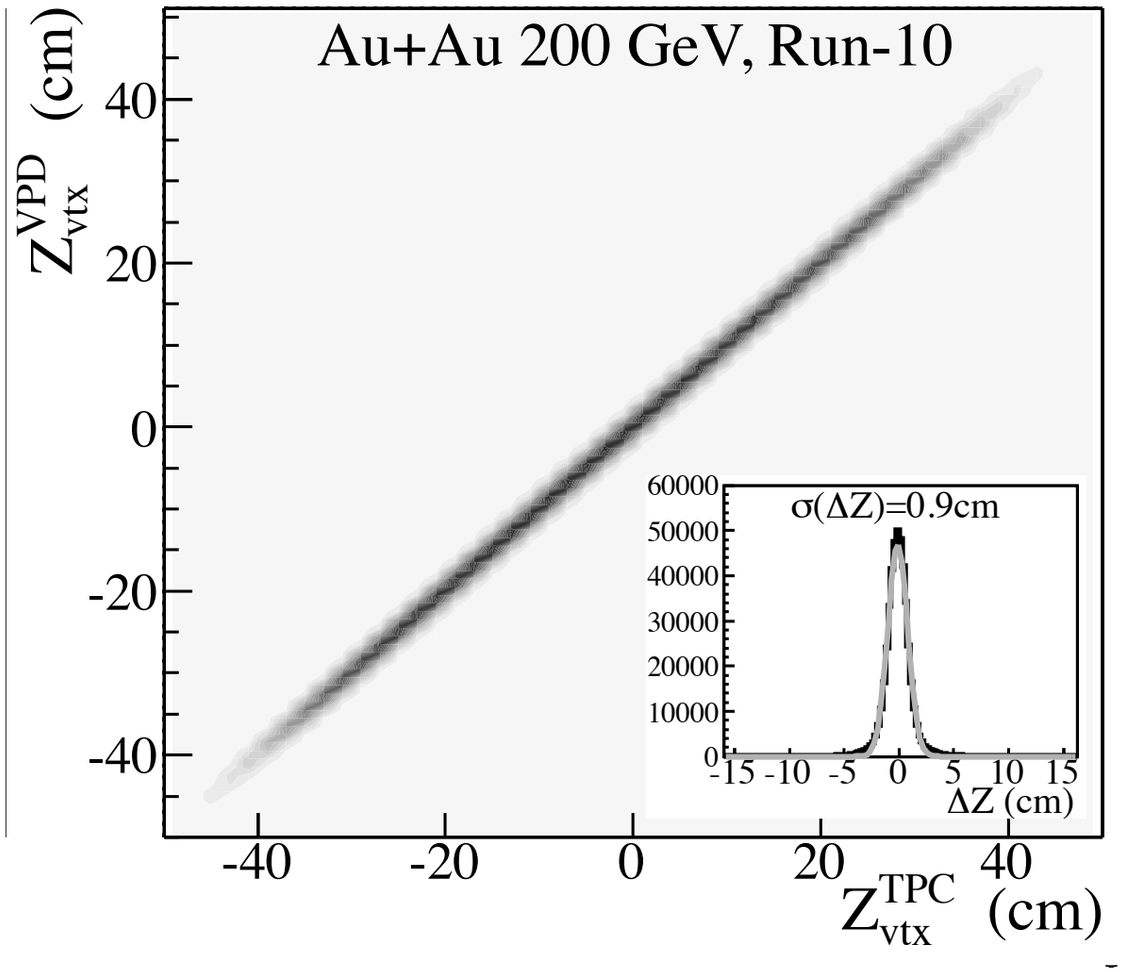
η asymmetry in TPC unique for γ+A



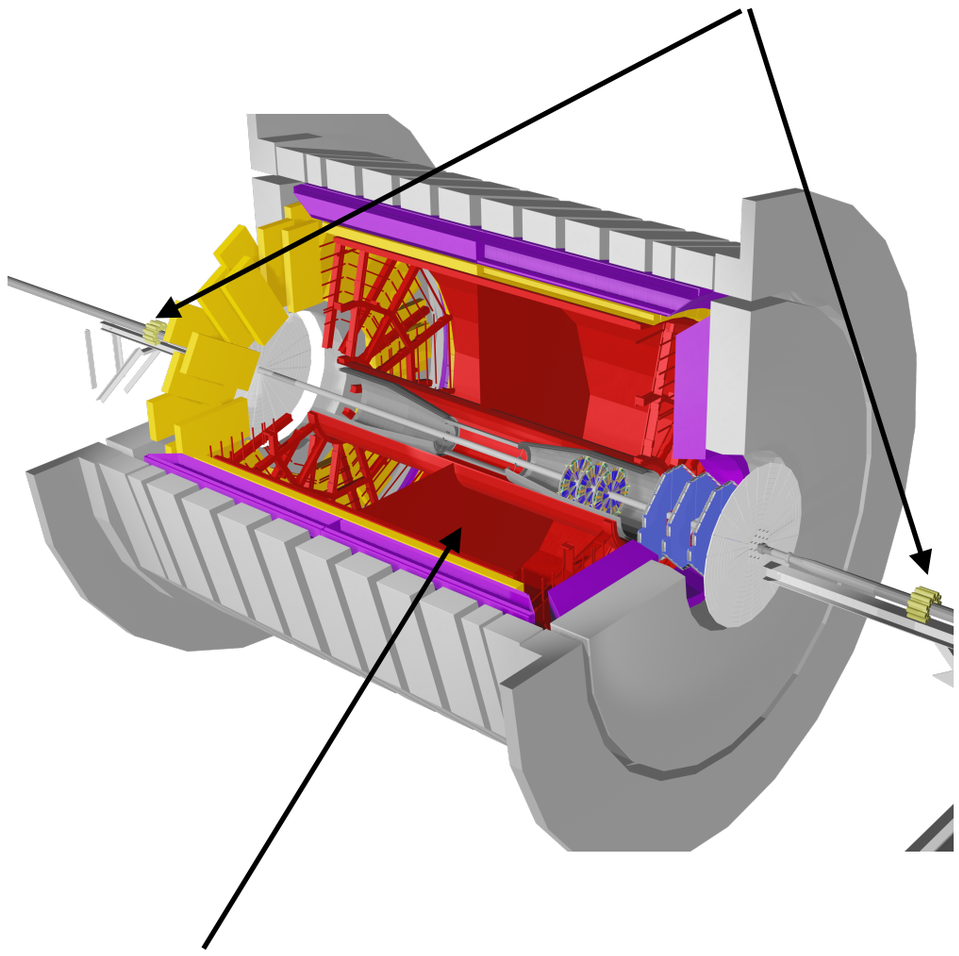
The observation of η-asymmetry in TPC will the very first step.

Using VPDs to identify γ-A-rich events

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



Collision vertex from TPC (Z_{vxt}^{VPD})

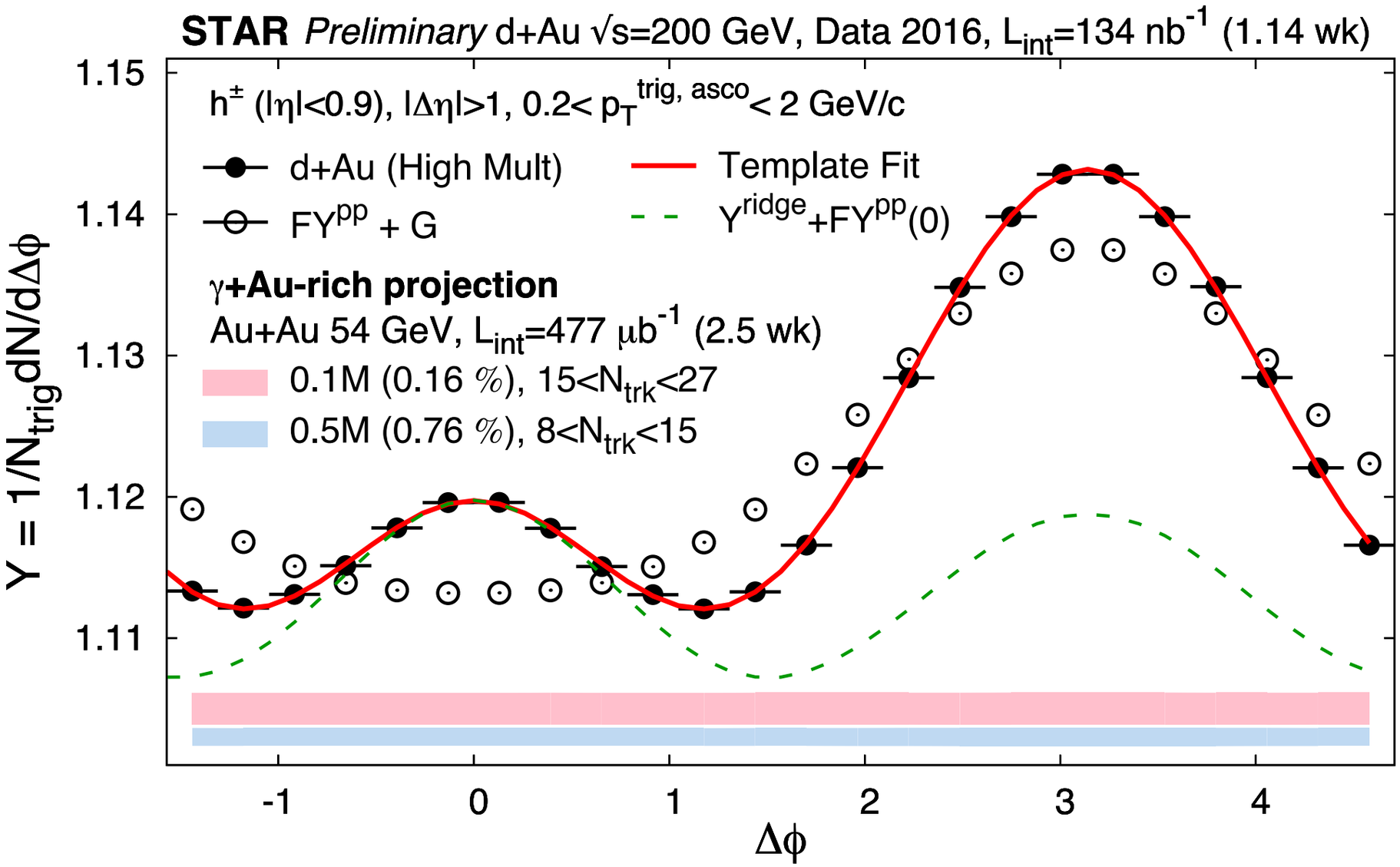


Collision vertex from TPC (Z_{vxt}^{TPC})

The forward Vertex Position detector can be a used in γ+A events to see if there is a mismatch of vertex from TPC & VPDs

Projection with 54 GeV data

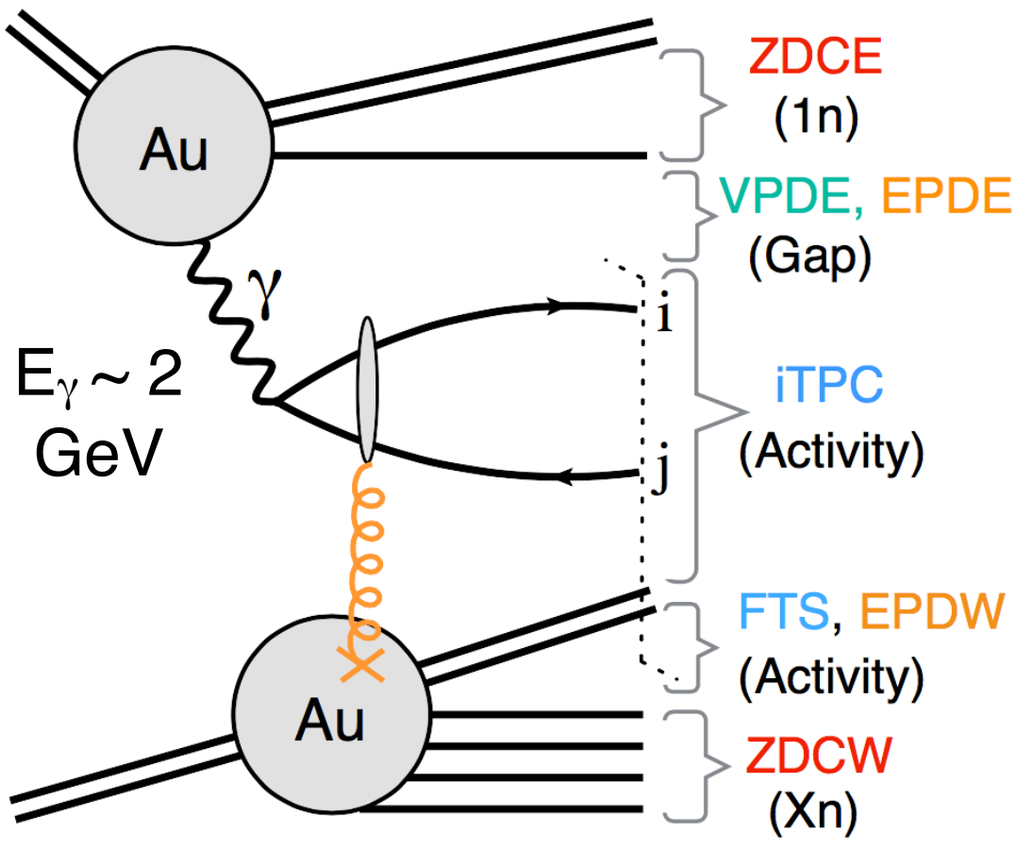
d+Au data are from talk by Shengli Huang, STAR Collaboration, IS2021



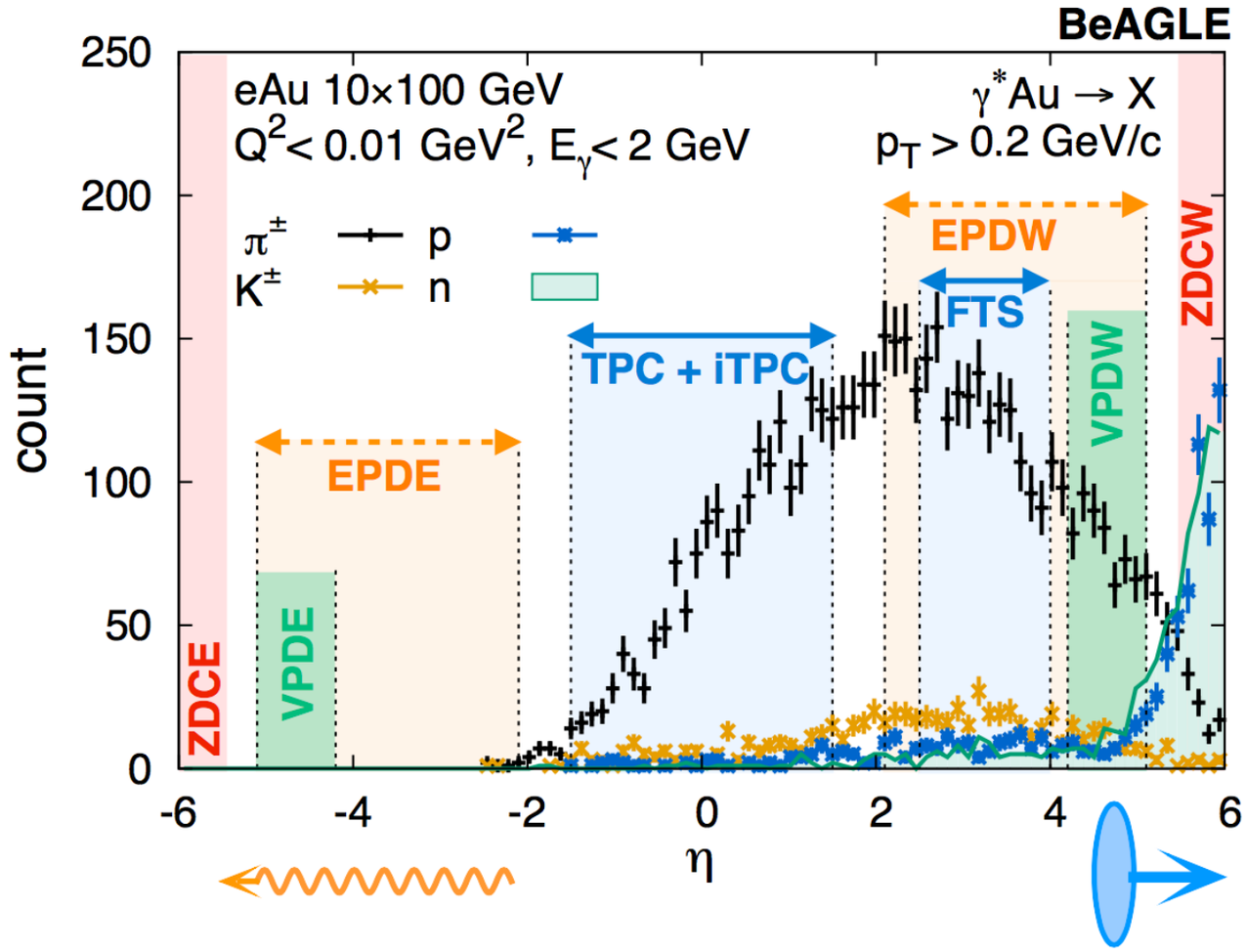
Au+Au 54 GeV from year 2017 and Au+Au 200 GeV data from year 2019 on tape provides an opportunity for an exploratory study for STAR.

Anticipated Run 2023 with Au+Au 200 GeV

E_{Au} = 100 GeV

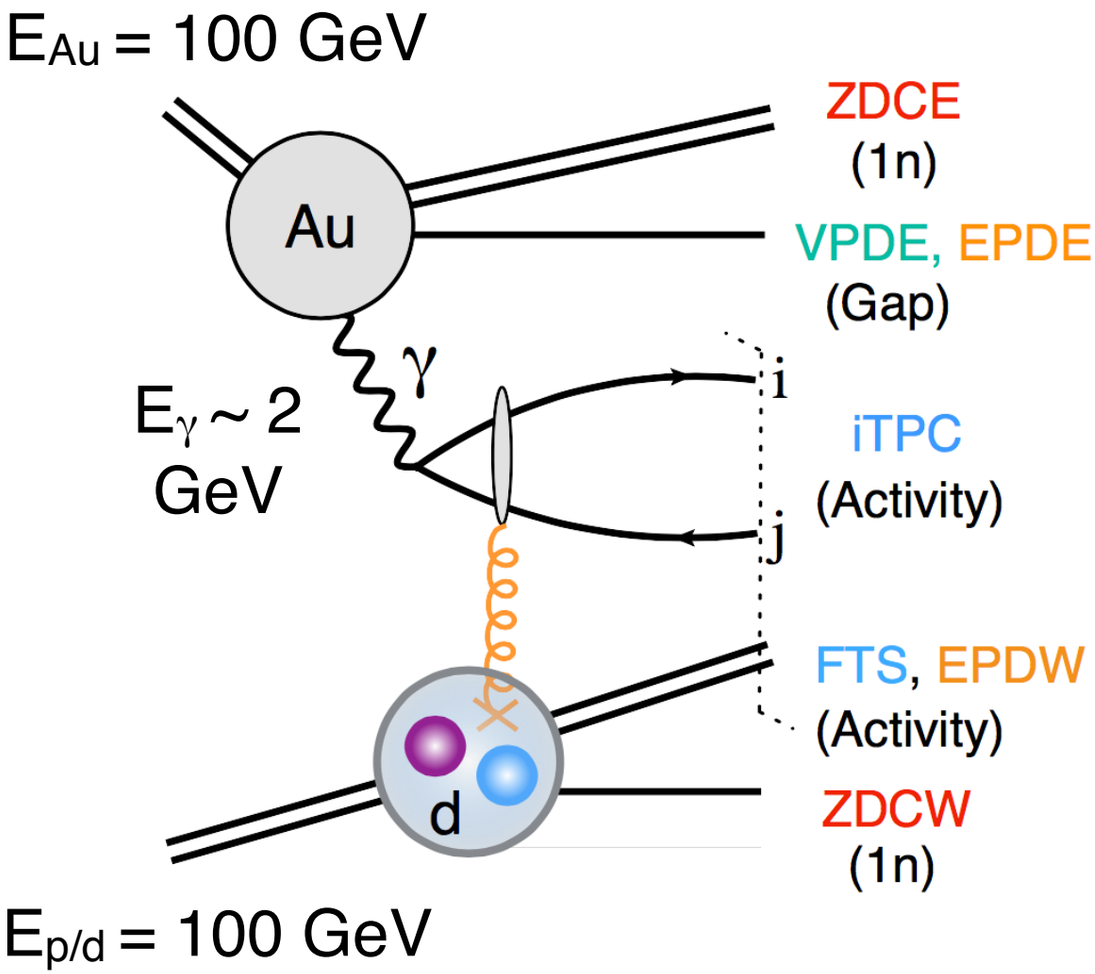


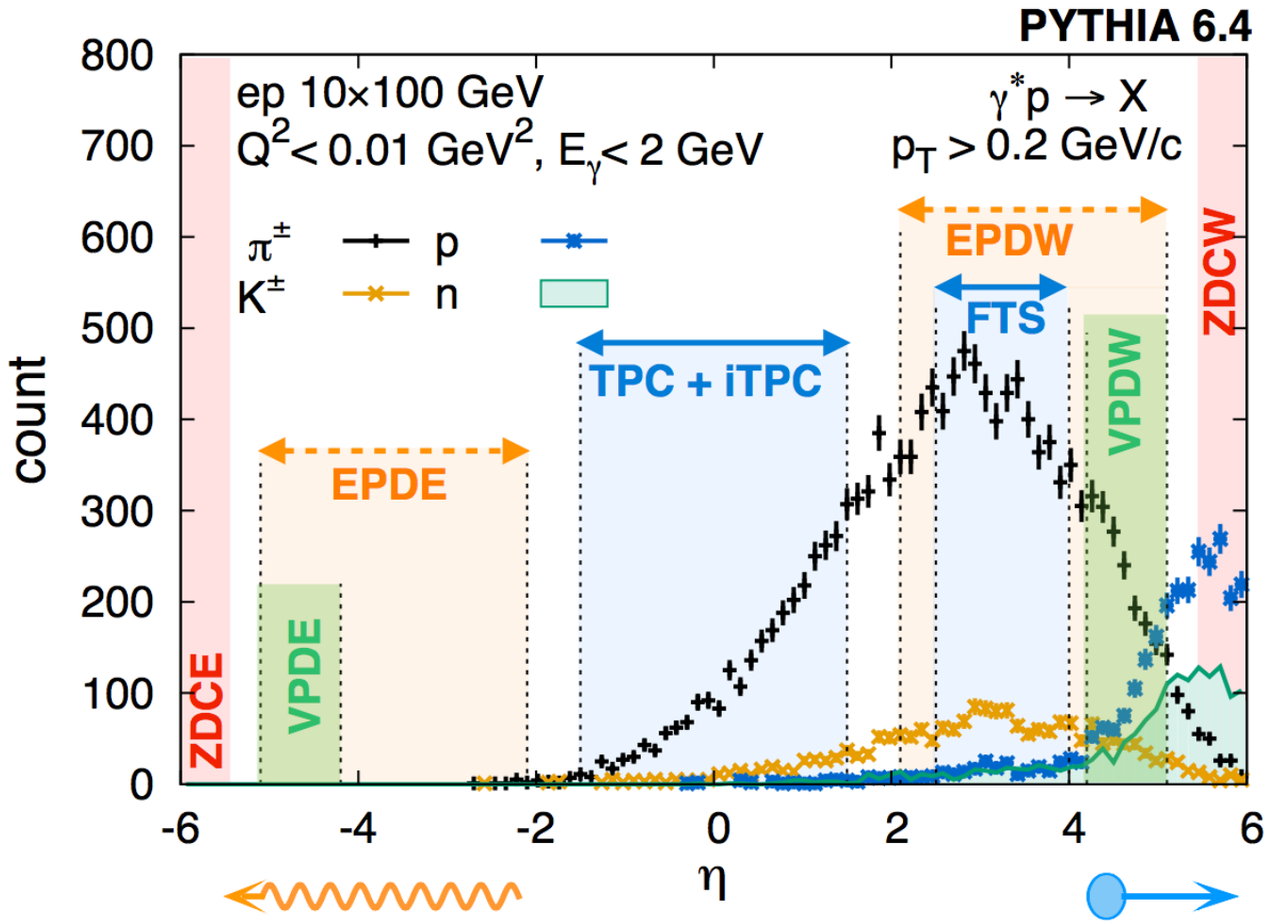
E_{Au} = 100 GeV



If a high statistics Au+Au 200 GeV dataset if accumulated by STAR from the anticipated 2023 run of RHIC it will provide a golden opportunity to study photonuclear events with the forward upgrades. The same can be done in the photo production limit of e+A at EIC. Key measurements: 1. ridge 2. chemistry (pi/k/p yield) and how they change when compared to hadronic events at the same multiplicity.

γ+p in STAR with p/d+Au UPC 200 GeV



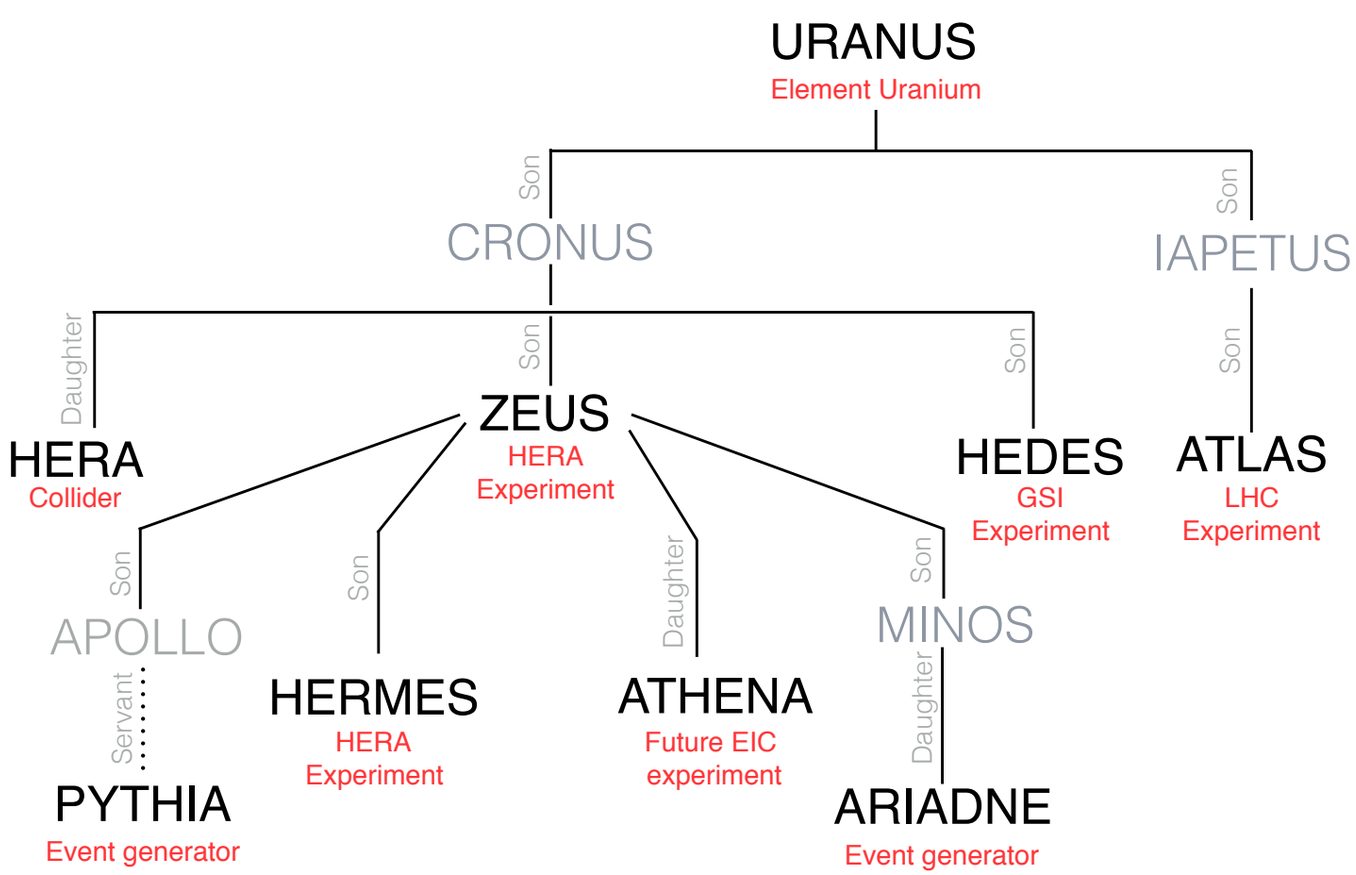


Measurements in γ+p can also be done if opportunity comes to collect d/p+Au data.

Summary

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

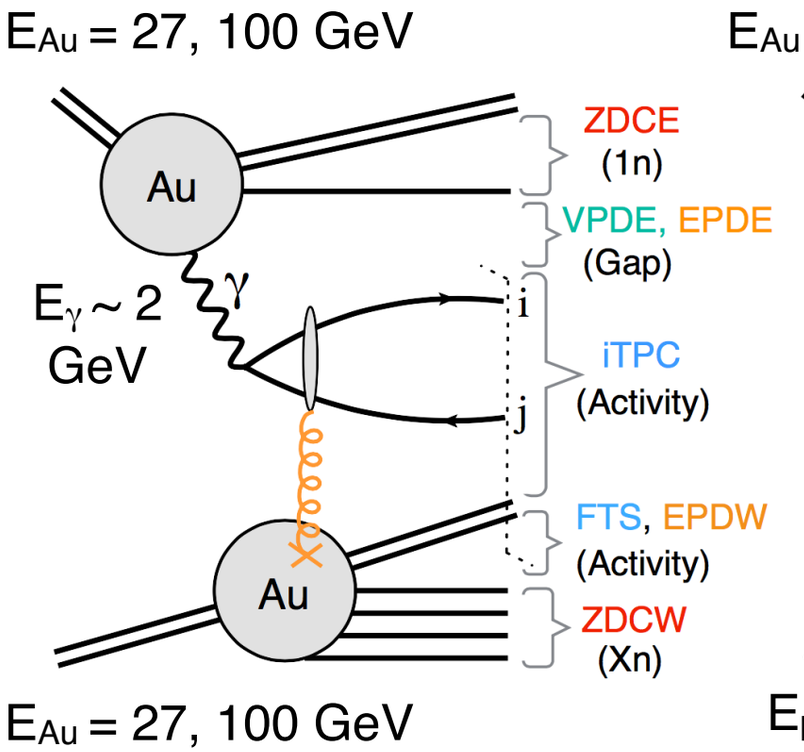
Thanks

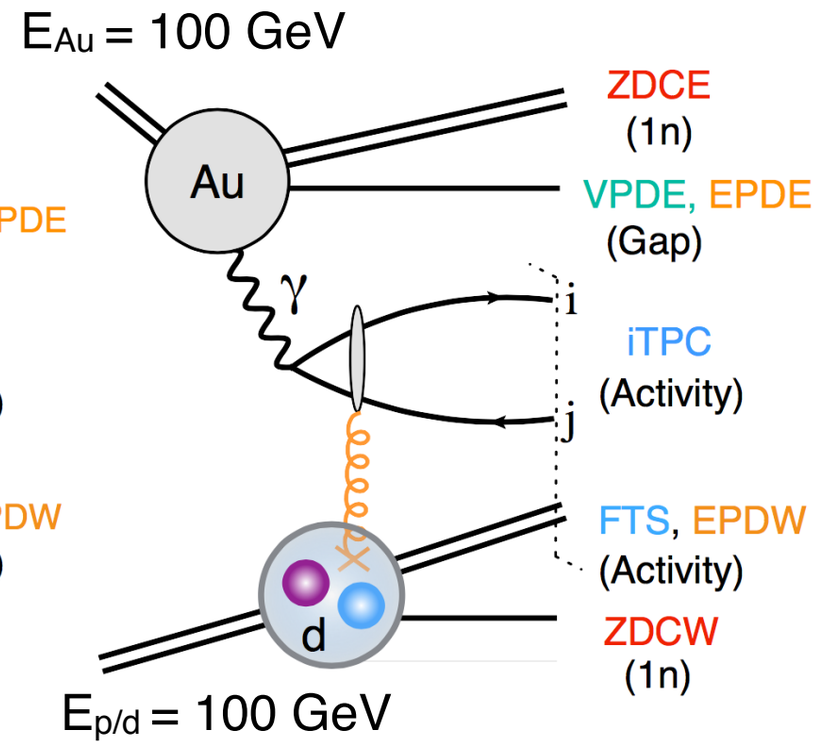


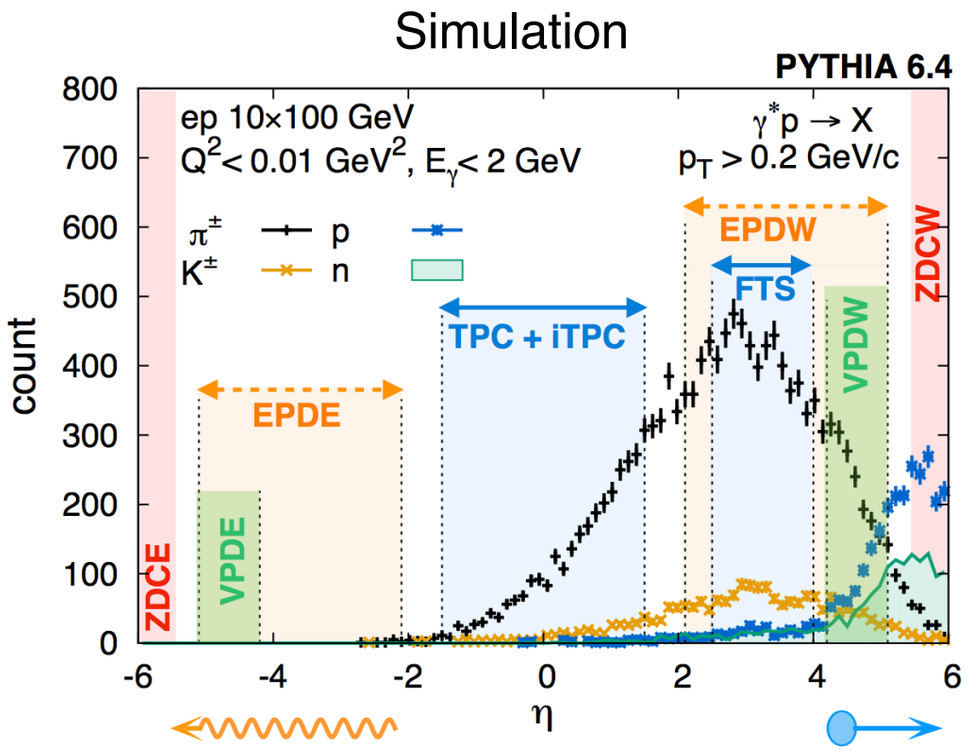
Names we borrowed from Greek pantheon & their correlations

Highlights

Photonuclear processes in UPC from STAR







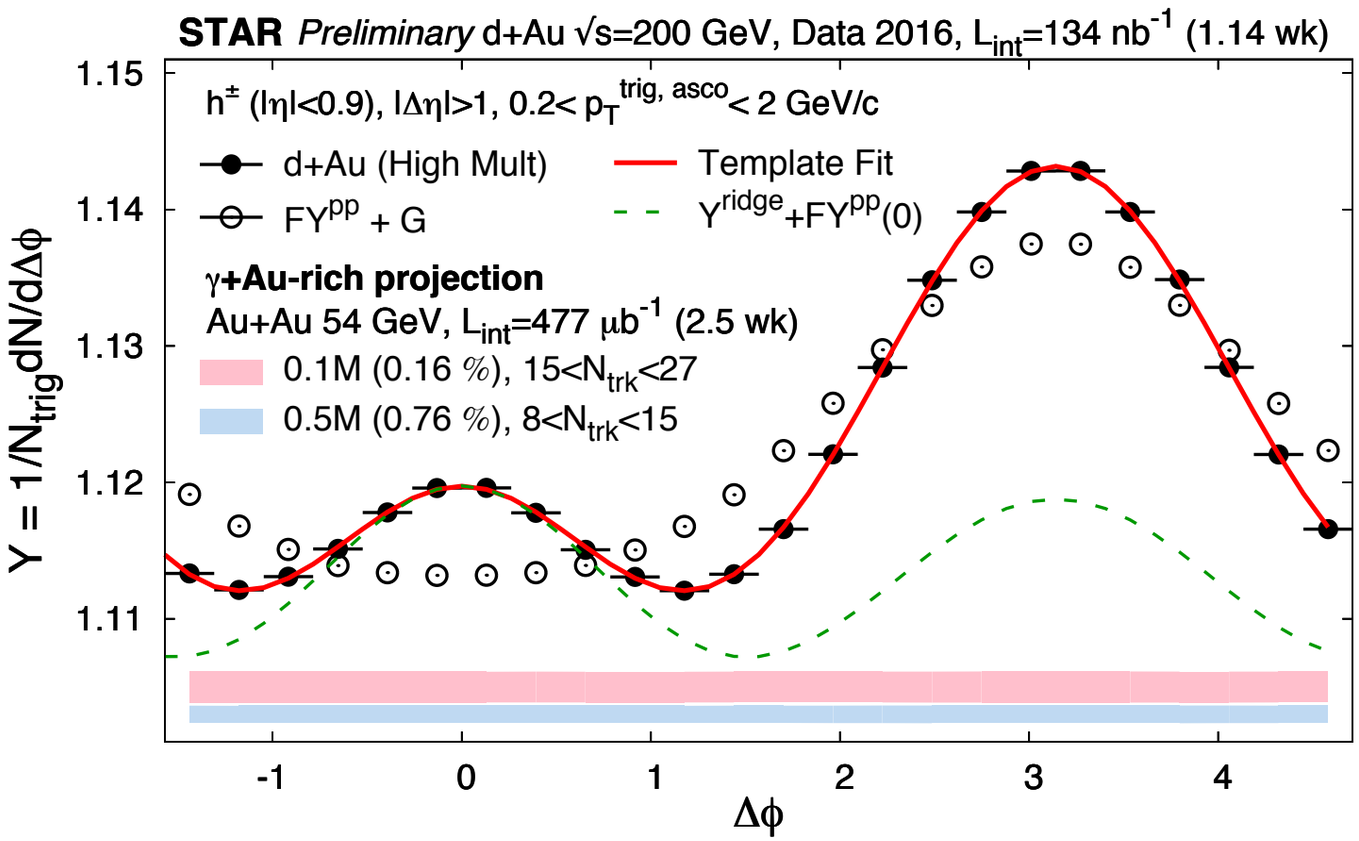
Opportunities and scope:

1. STAR with enhanced pseodorapidity acceptance (iTPC + EPD + FTS/FCS)
2. Anticipated Au+Au 200 GeV run of RHIC (2023, 2025)
3. Data on tape: Au+Au 54 GeV (2017), Au+Au 200 GeV (2019)
4. Opportunistic p+Au or d+Au run at RHIC (2021, 2024)

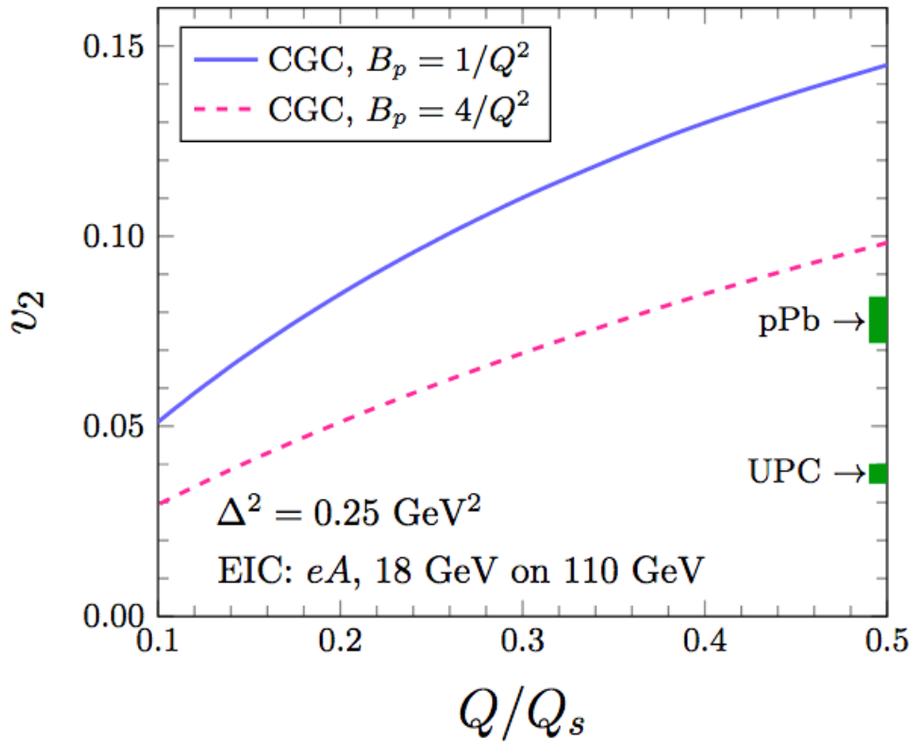
Measurements:

1. Ridge, 2. change of chemistry (pi/k/p yield) & compare to hadronic events

Photonuclear processes in UPC from STAR



CGC calculation arXiv: 2008.03569



Significant difference between correlation in HM (red) & LM (blue) γ+p/Au will be interesting

Understanding anisotropy from CGC:

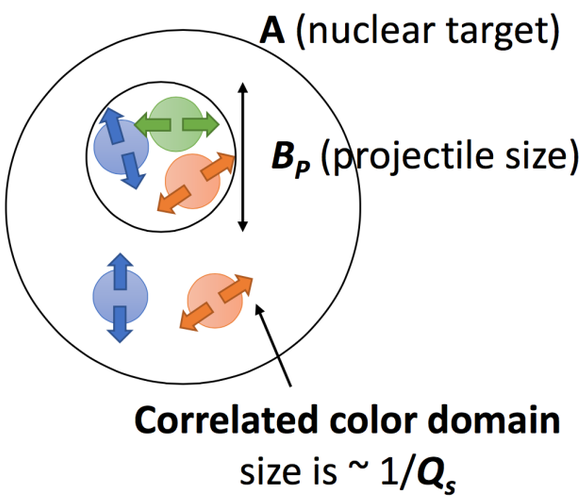
x — Q_s and domain size in Target

Q^2 — Size of the probe #domains

Best opportunity:

Controlled scan of x-Q^2 at EIC

How anisotropy in p+p/Au compare to γ+p/Au @RHIC ?



Cartoon: Blair Seidlitz, IS2021