PROBING THE GLUON STRUCTURE OF THE NUCLEON THROUGH BARYON STOPPING IN PHOTONUCLEAR COLLISIONS

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BNL Nuclear Physics seminar

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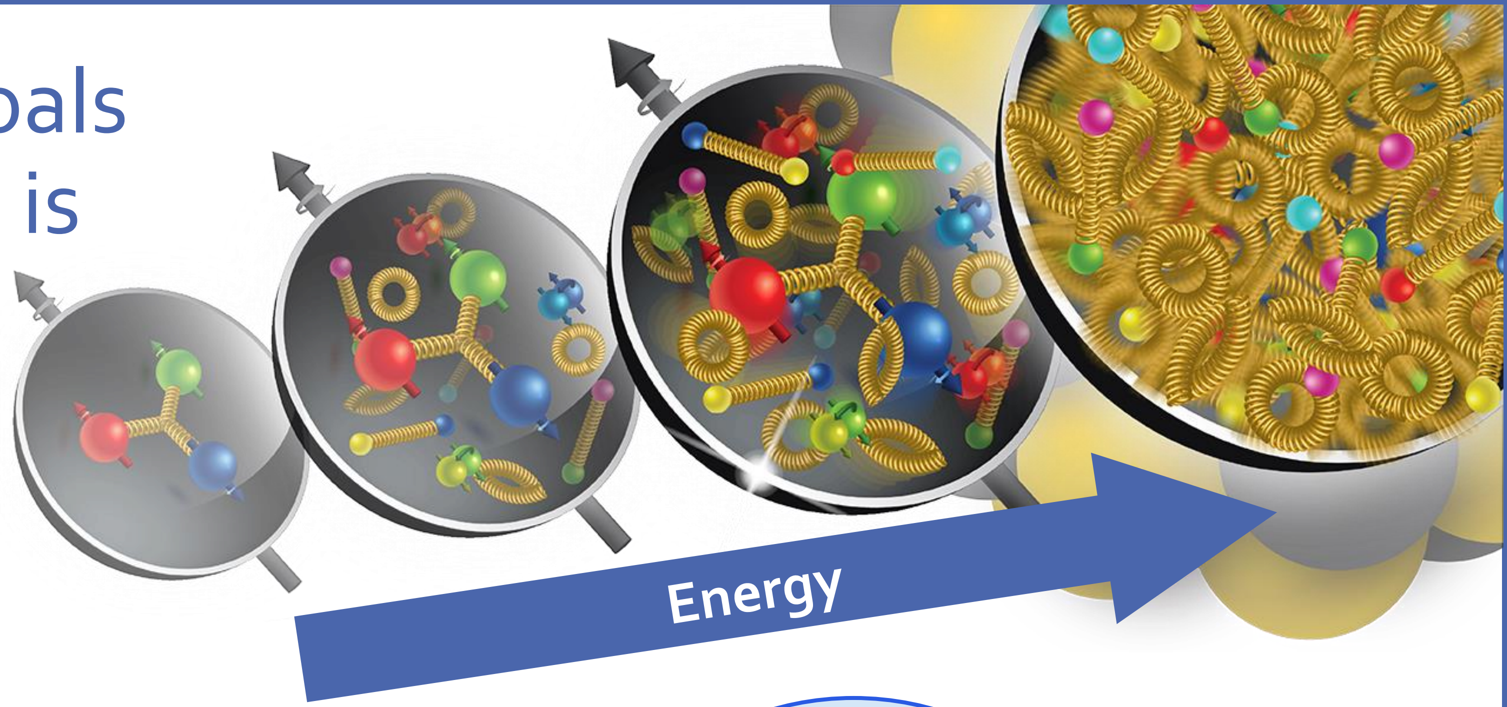
One of the major goals of RHIC and the EIC is to understand the behavior of gluons within the nucleon



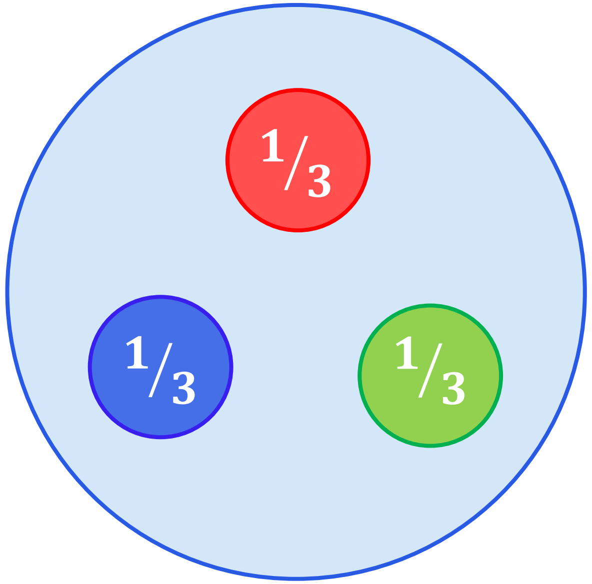
Baryon number – a strictly conserved quantum number

Believed to be carried by the quarks:

$$B = \frac{1}{3}(n_q - n_{\bar{q}})$$

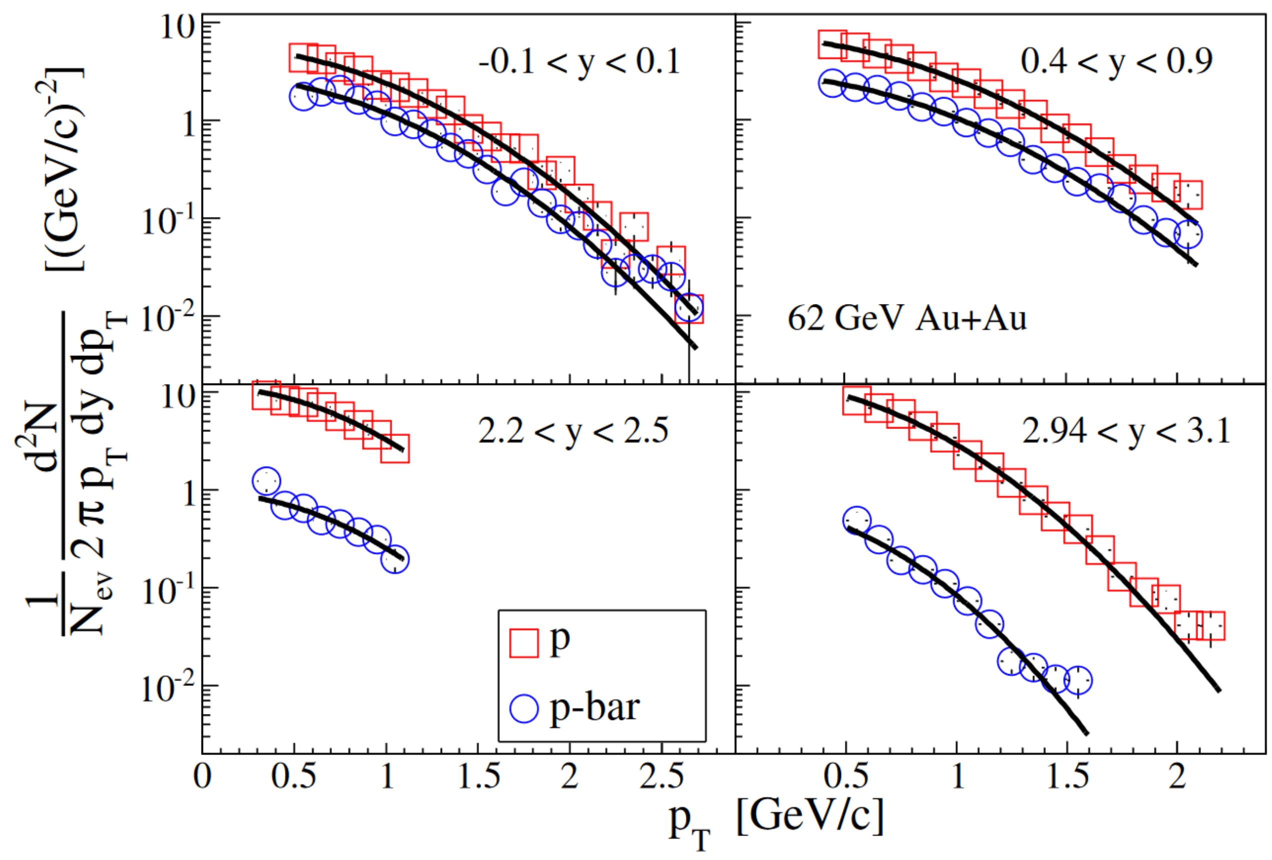
But that is just an assumption

D. Kharzeev, Physics Letters B **378**, 238-246 (1996)



Baryon Stopping

- The energy required for producing particles in heavy-ion collisions comes from the kinetic energy lost by the baryons in the colliding nuclei
  - Larger effect in collisions with higher multiplicity (small impact parameter)
- Net-baryon yield can be estimated from the net-proton yield: difference in number of protons and anti-protons
- Cannot be fully explained by pure string fragmentations



BRAHMS Collaboration, Phys. Lett. B **677,** 267-271 (2009)

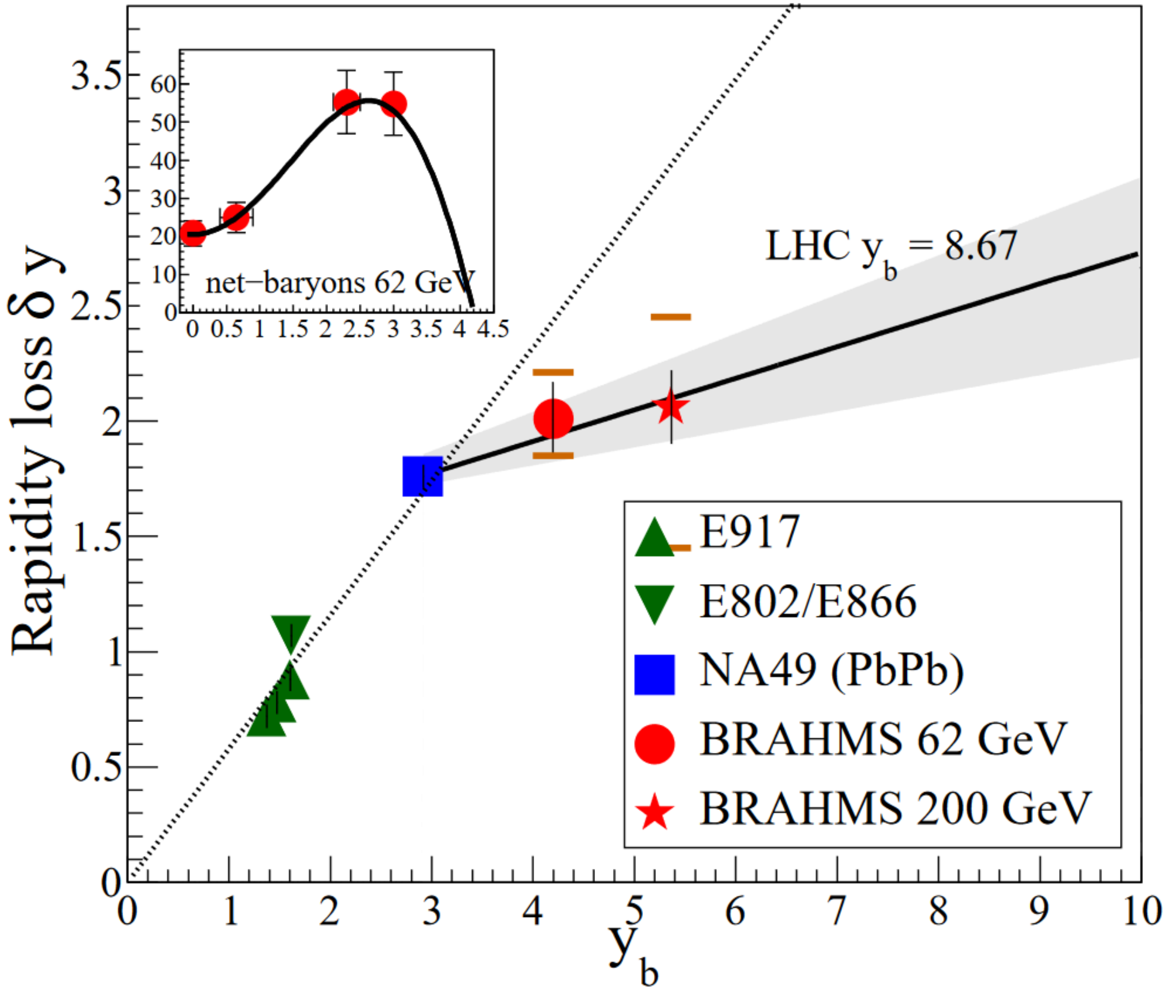
Baryon Stopping Changes with Beam Energy

The average rapidity loss: $\langle \delta y \rangle = y_b - \langle y \rangle$

$$\langle y \rangle = \frac{2}{N_{part}} \int_0^{y_p} y \frac{dN_{(B-\bar{B})}(y)}{dy} dy$$

Where y_b is the beam rapidity

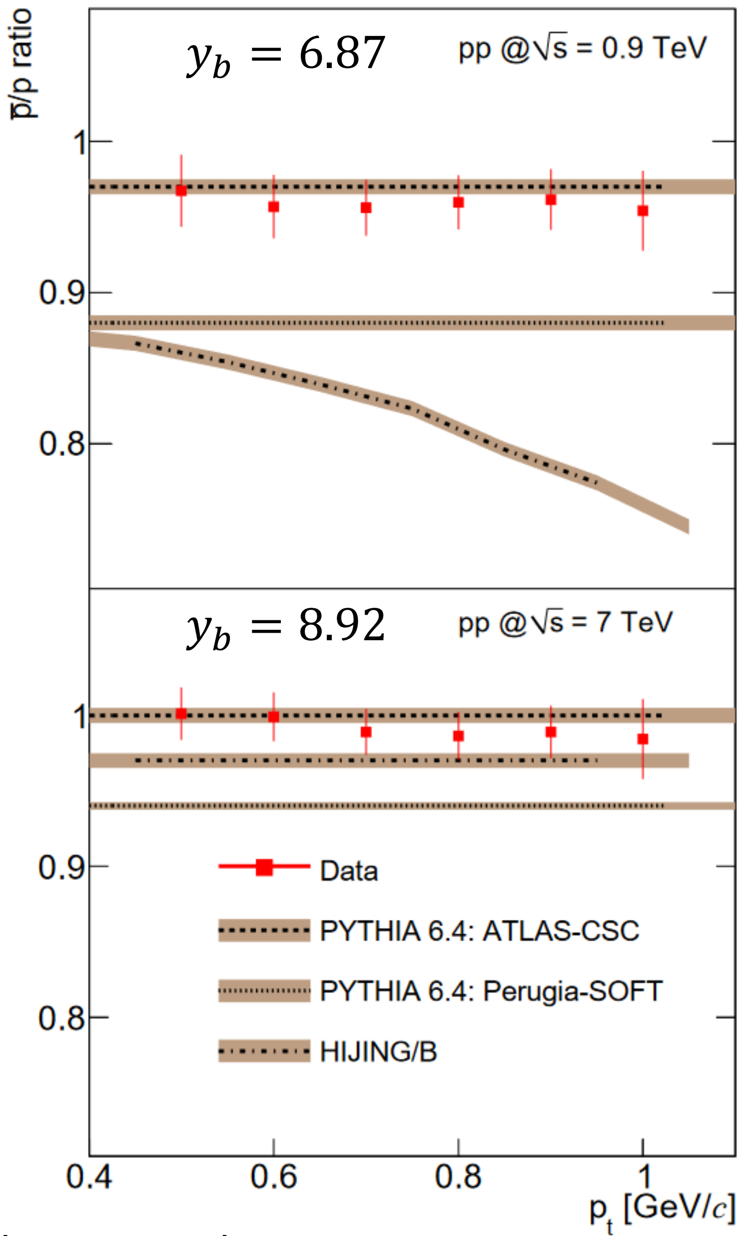
Rapidity loss increases rapidly with beam energies for AGS to SPS, but more slowly from SPS energy to RHIC energies



BRAHMS Collaboration, Phys. Lett. B **677,** 267-271 (2009)

Vanishing Baryon Transport at LHC Energies

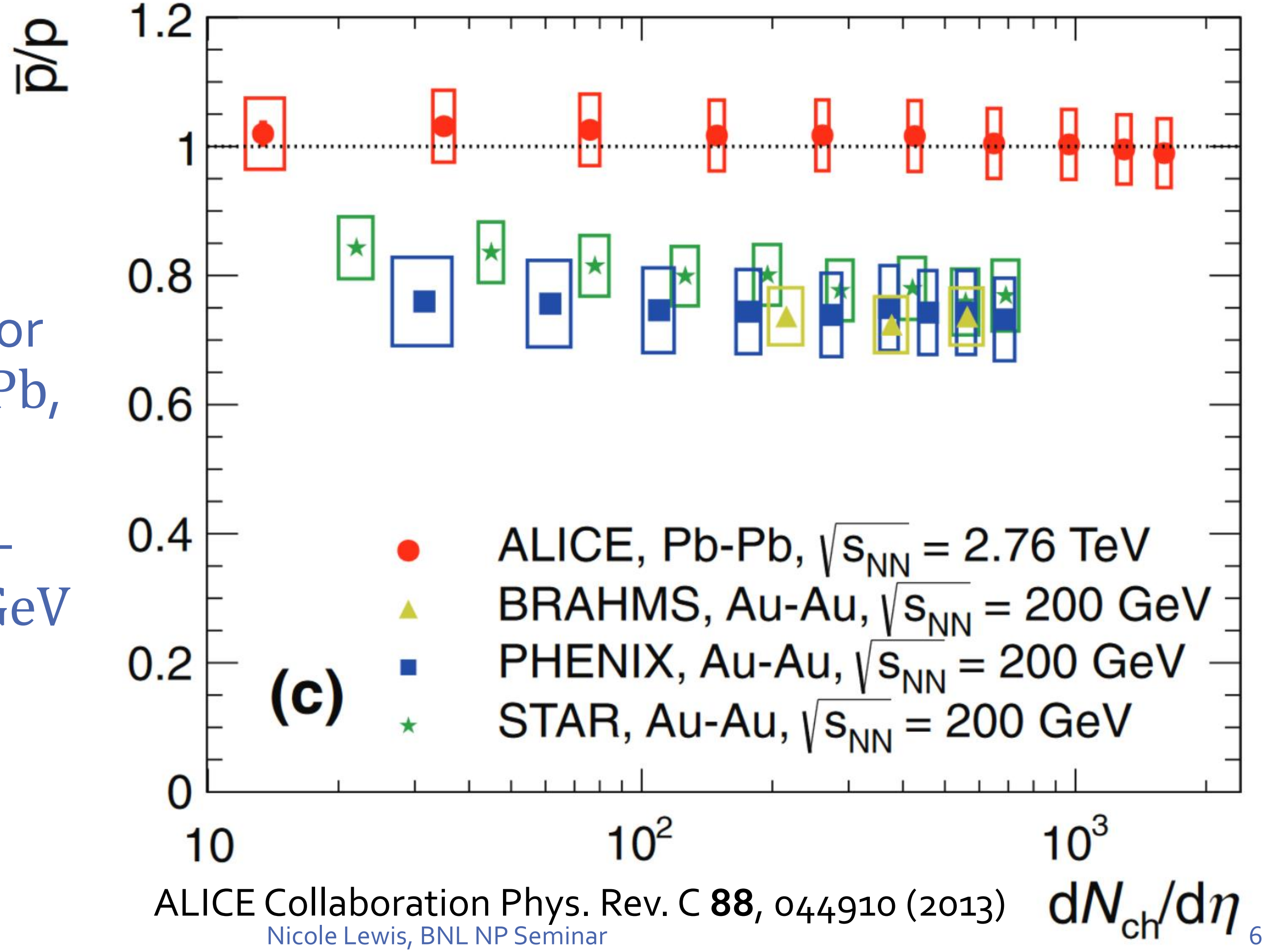
- Small but statistically significant excess of protons at $\sqrt{s} = 0.9$ TeV
  - $\bar{p}/p$ ratio is consistent with 1 for $\sqrt{s} = 7$ TeV
- Compared to two PYTHIA tunes, Perugia-SOFT includes enhanced baryon transfer
- HIJING/B includes the **baryon junction:** gluonic string junction which enhances baryon-transfer
  - Under predicts the data, particularly at $\sqrt{s} = 0.9$ TeV



ALICE Collaboration, Phys. Rev. Lett. **105**, 072002 (2010)

Vanishing Baryon Transport at LHC Energies

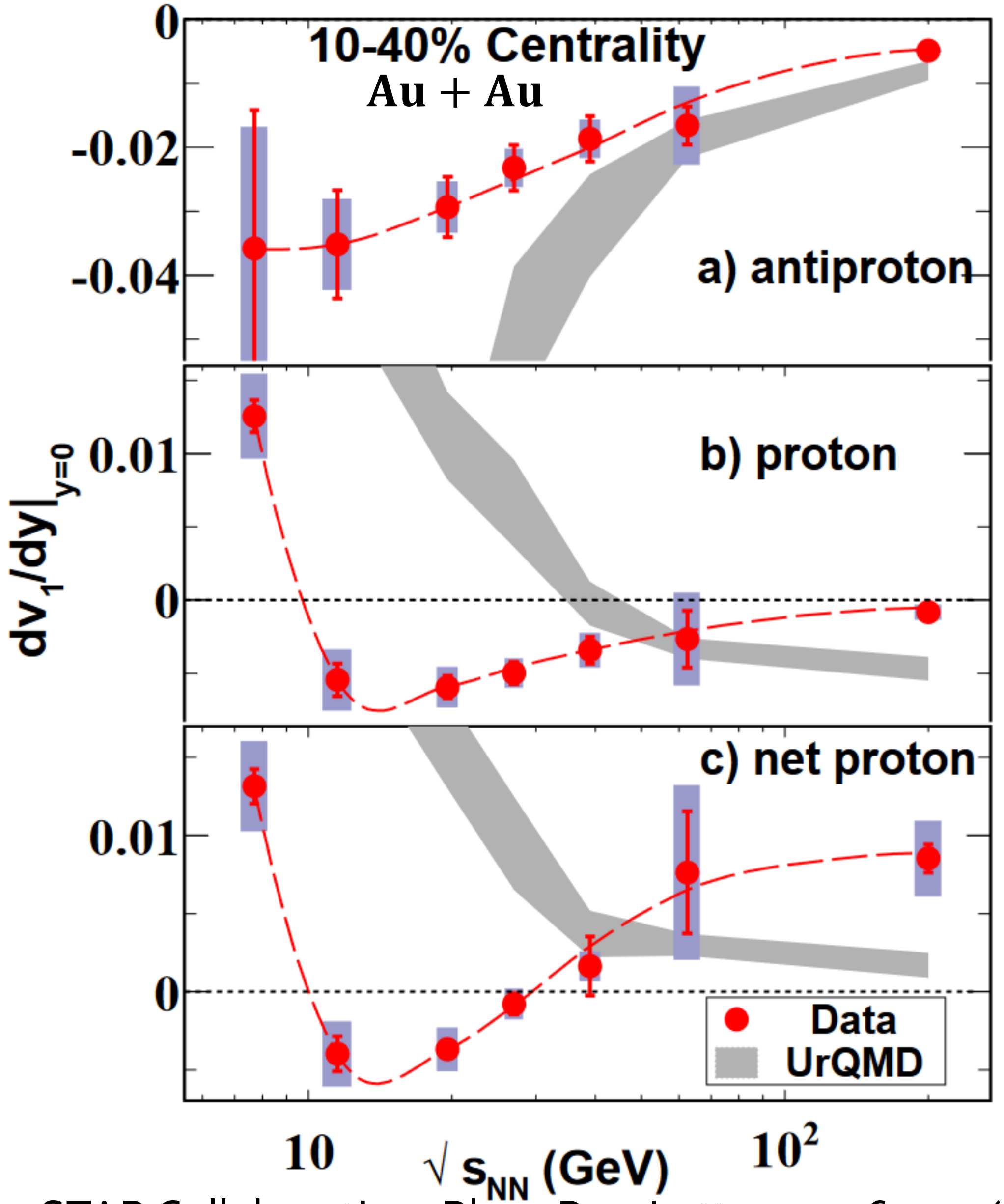
- $\bar{p}/p$ ratio is consistent with 1 for midrapidity $\mathrm{Pb} + \mathrm{Pb}$, $\sqrt{s_{NN}} = 2.76\ \mathrm{TeV}$
- About 0.8 for $\mathrm{Au} + \mathrm{Au}$, $\sqrt{s_{NN}} = 200\ \mathrm{GeV}$



ALICE Collaboration Phys. Rev. C **88**, 044910 (2013)

Baryon Stopping and Direct Flow

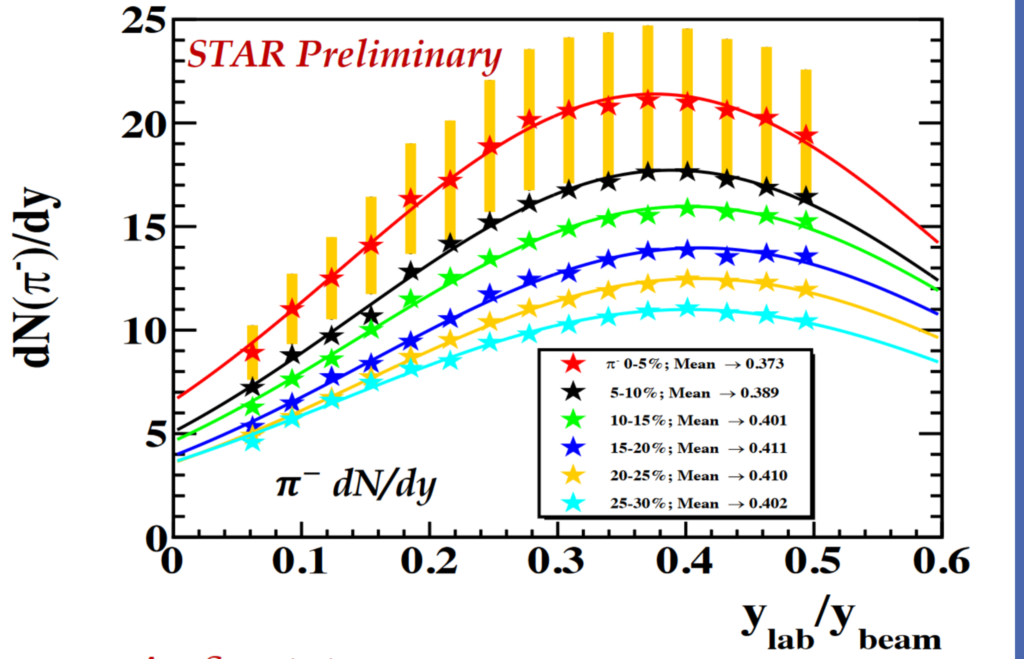
- Directed flow, v_1, of protons has contributions from stopped baryons and from $\bar{p}+p$ pair production
  - Stopping more important at lower beam energies
  - $\bar{p}+p$ production more important at higher beam energies
- Use the $\bar{p}$ $\mathrm{d}v_1/dy$ to approximate the proton $\mathrm{d}v_1/dy$ for protons produced in $\bar{p}+p$ pairs
- Minimum in $v_1(y)$ slope for all protons and net-protons coincides with a high degree of stopping

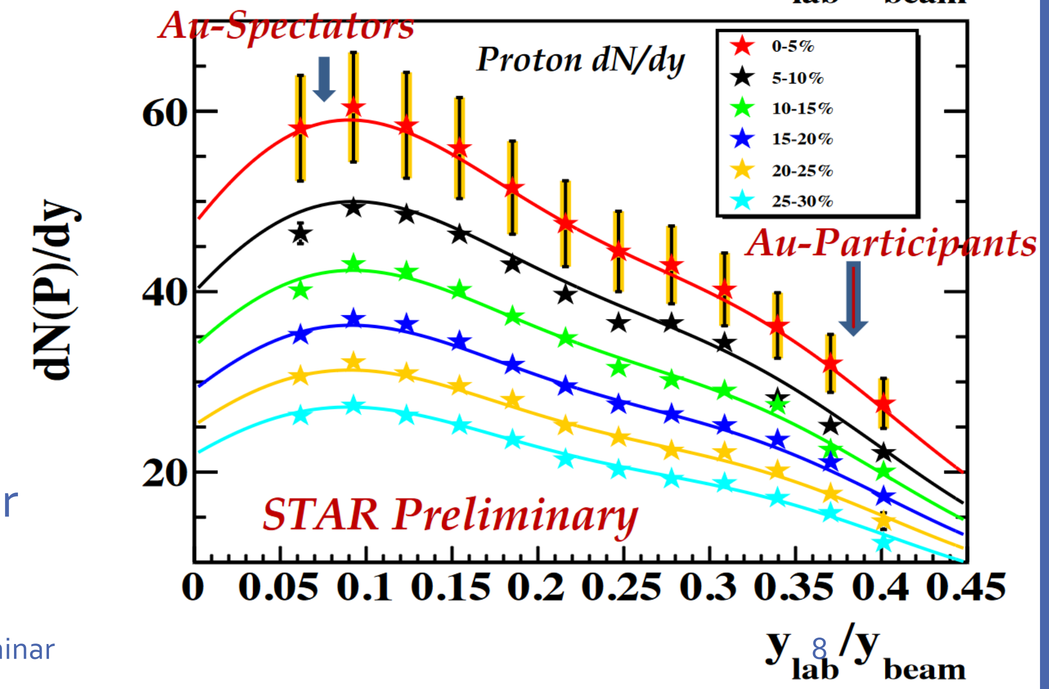


STAR Collaboration, Phys. Rev. Lett. **112**, 162301 (2014)

Baryon Stopping with the STAR Fixed Target Program

- Al beam on Au target, $\sqrt{s_{NN}} = 4.9$ GeV from 2015
  - Varying the system size changes the thickness of the nuclear material that the nucleon passes through
- Asymmetric system, the $\pi^- \, dN/dy$ peak position consistent with the interaction zone rapidity
  - Varies with centrality
  - Peak shifted toward the Au target because it provides more nucleons
- Au-participant proton dN/dy peaks at lower y_{lab}/y_{beam}
  - Doesn't change with centrality → thickness of the projectile does not change significantly with centrality
  - Consistent dN/dy with previous AGS measurements for $\text{Si} + \text{Au}$ and $\text{Si} + \text{Pb}$





Baryon Junction

- Many of the models used for heavy-ion collisions at RHIC (HIJING, AMPT, UrQMD) have implemented a nonperturbative baryon stopping mechanism

  V. Topor Pop, *et al*, Phys. Rev. C **70**, 064906 (2004)

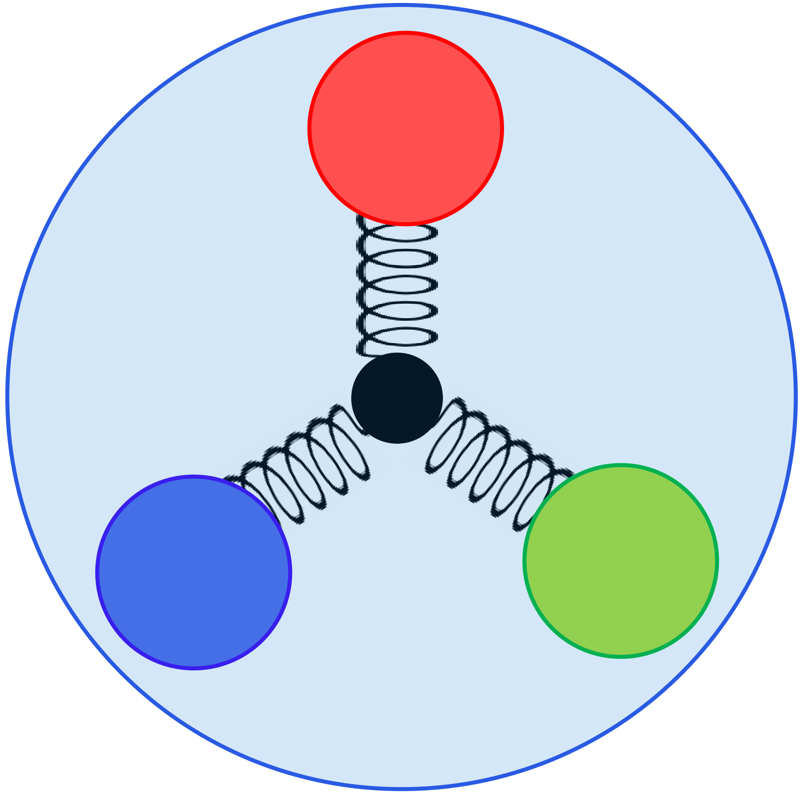
  Zi-Wei Lin, *et al*, Phys. Rev. C **72**, 064901 (2005)

  M. Bleicher, *et al*, J.Phys.G **25,** 1859-1896 (1999)

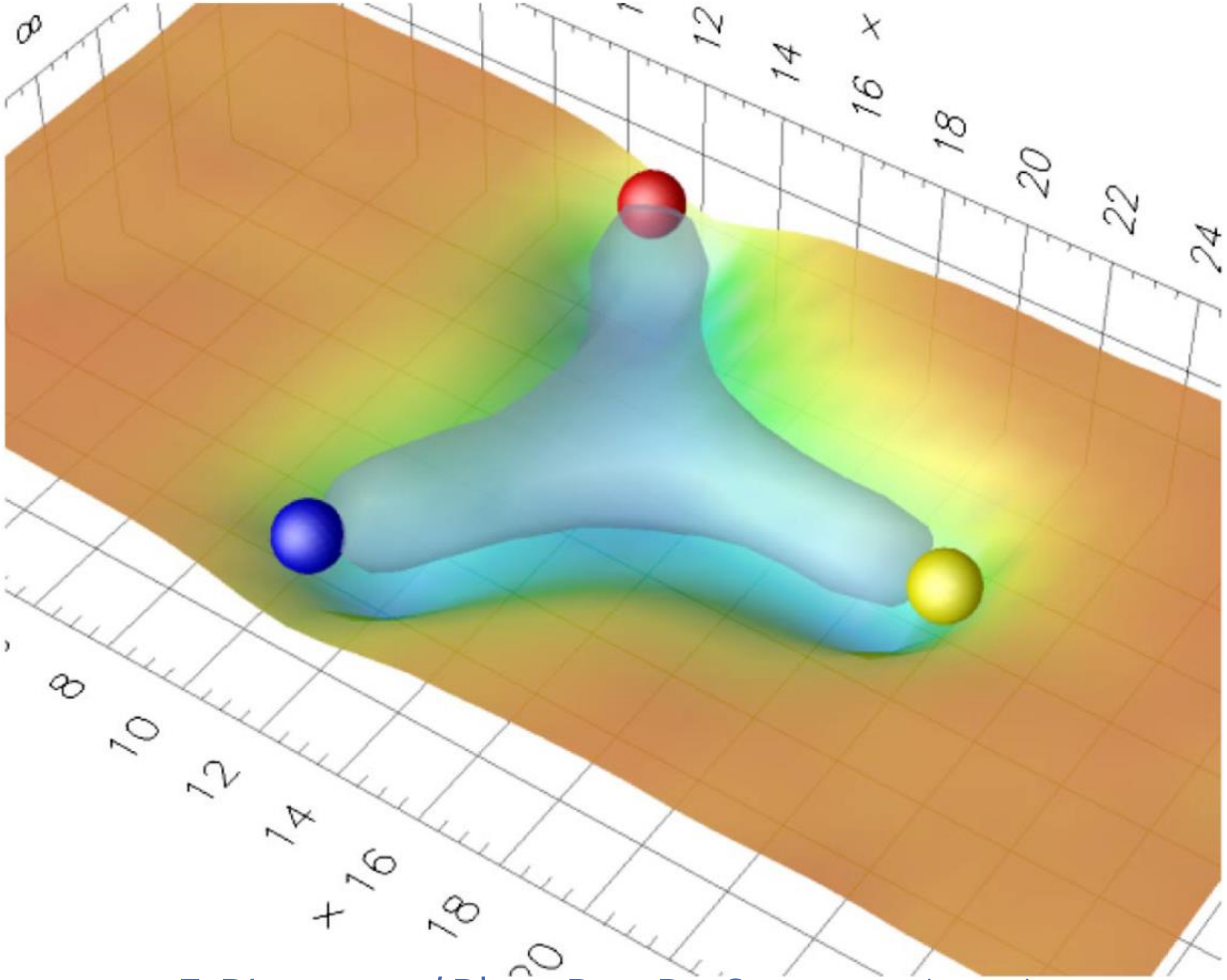
- Baryon Junction: nonperturbative configuration of gluons linked to all three valence quarks
  - Carries the baryon number
  - Theorized to be an effective mechanism of stopping baryons in pp and AA

  D. Kharzeev, Physics Letters B **378**, 238-246 (1996)

- But no signature of baryon junction has been cleanly identified in the experiment



Y-Shaped Baryon Flux-Tube in Lattice QCD



F. Bissey, *et al* Phys. Rev. D **76**, 114512 (2007)

- Some lattice calculations have suggested the formation of a Y-shaped color flux tube among the three quarks at long distances

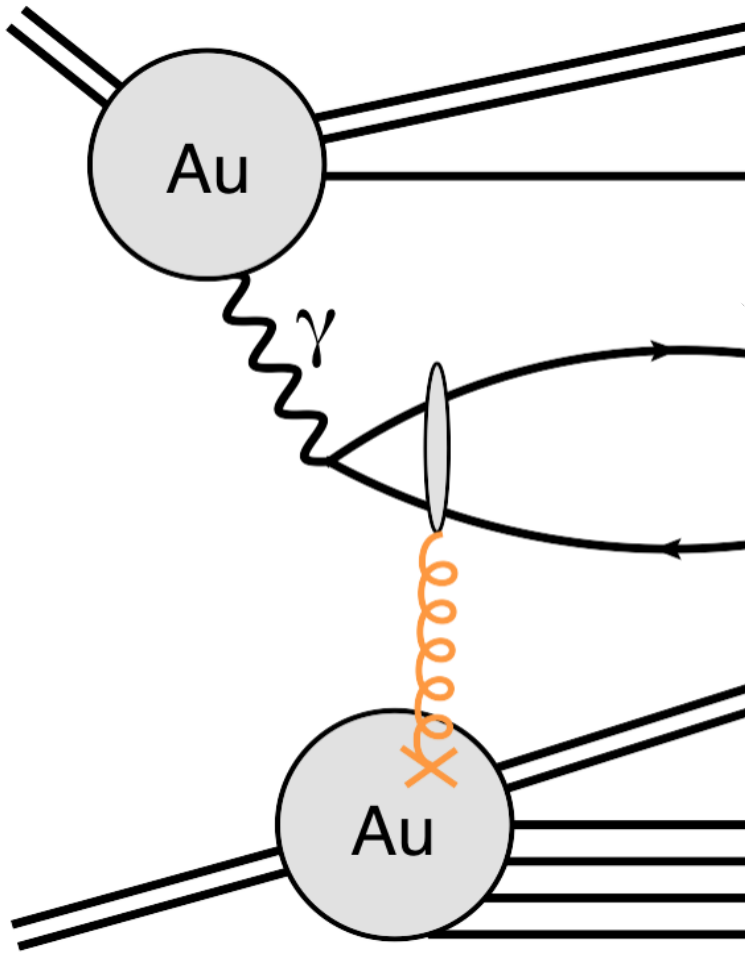
  T. T. Takahashi, *et al* Phys. Rev. Lett. **86**, 18 (2001).

  T. Takahashi, *et al*, Phys. Rev. D **65**, 114509 (2002)

- Still under investigation

Photonuclear Collisions

- Inclusive particle production in photonuclear collisions
  - Large flux of quasi-real photons produced by ultra-relativistic large-Z nuclei
  - Similar to $e + A$ collisions except that the photon tends to have a much smaller virtuality
- Can be used to study bulk properties such as collectivity from initial-state effects (i.e. radial flow, rapidity correlation) and hadron chemistry



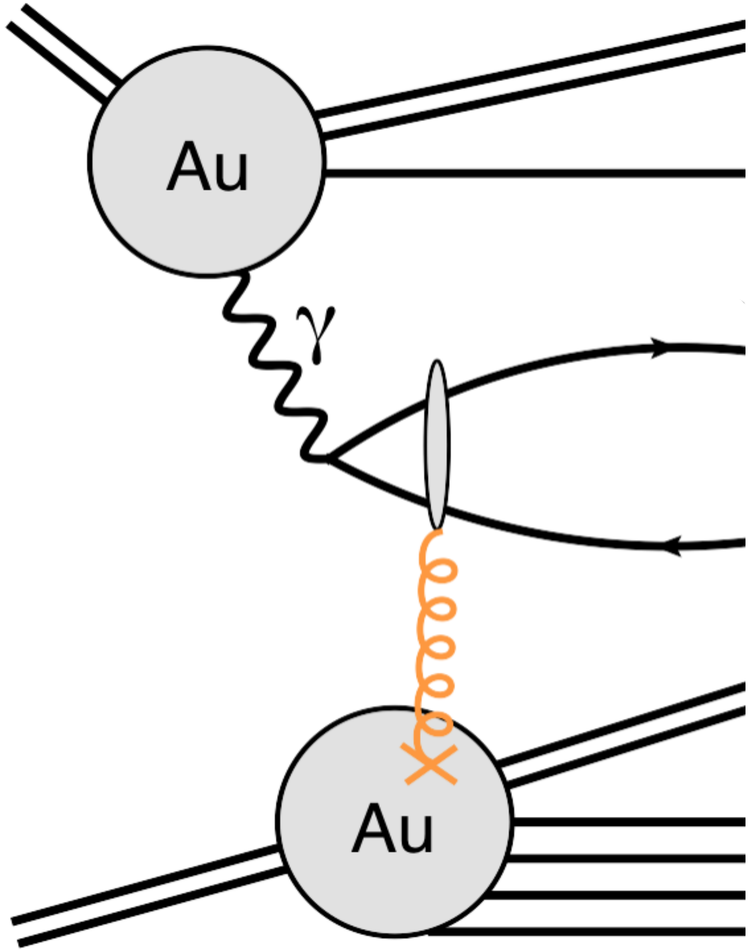
Photonuclear Collisions-Baryon Junction

- Can be used to study baryon stopping with the cleanest possible process ($q\bar{q}$ + Baryon Junction producing a midrapidity proton)
  - Low p_T rapidity distribution of $\frac{dN}{dy} \propto \exp(-y/2)$

  D. Kharzeev, Physics Letters B **378**, 238-246 (1996)

- γA is a good tool to study the gluon junction because
  - **At high x:** photon is a very small color dipole, very small cross section to interact with 3 quarks at the same time
  - **At low x:** A is dominated by the gluons

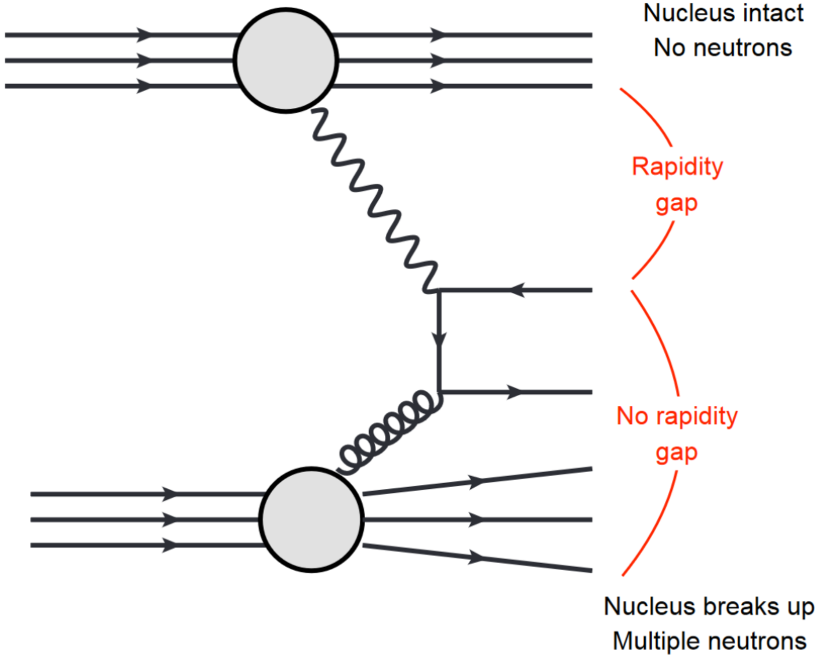
  These enhance the fraction of baryon junction



Photonuclear Collisions

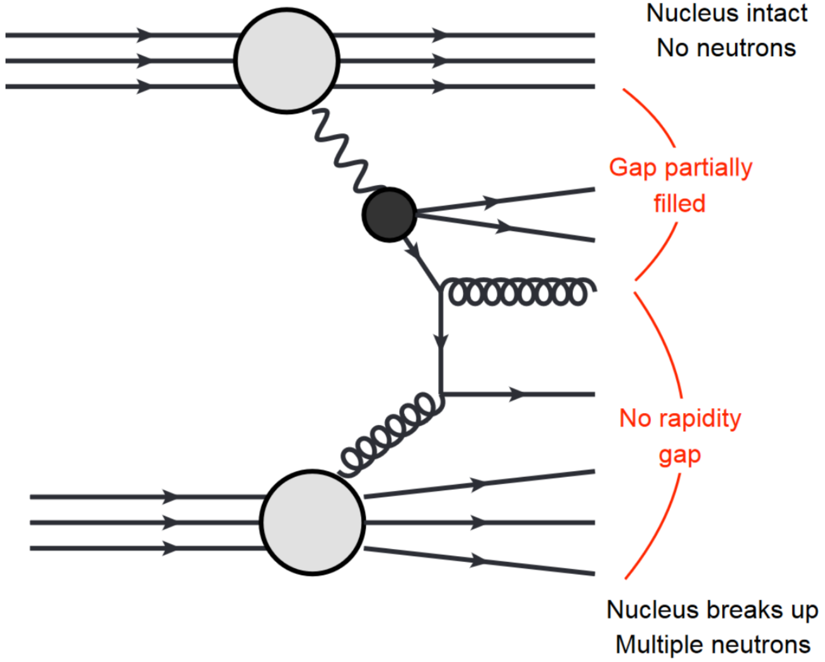
Direct Process

Photon Interacts with the nucleus



Resolved Process Process

Photon fluctuates into a hadronic state



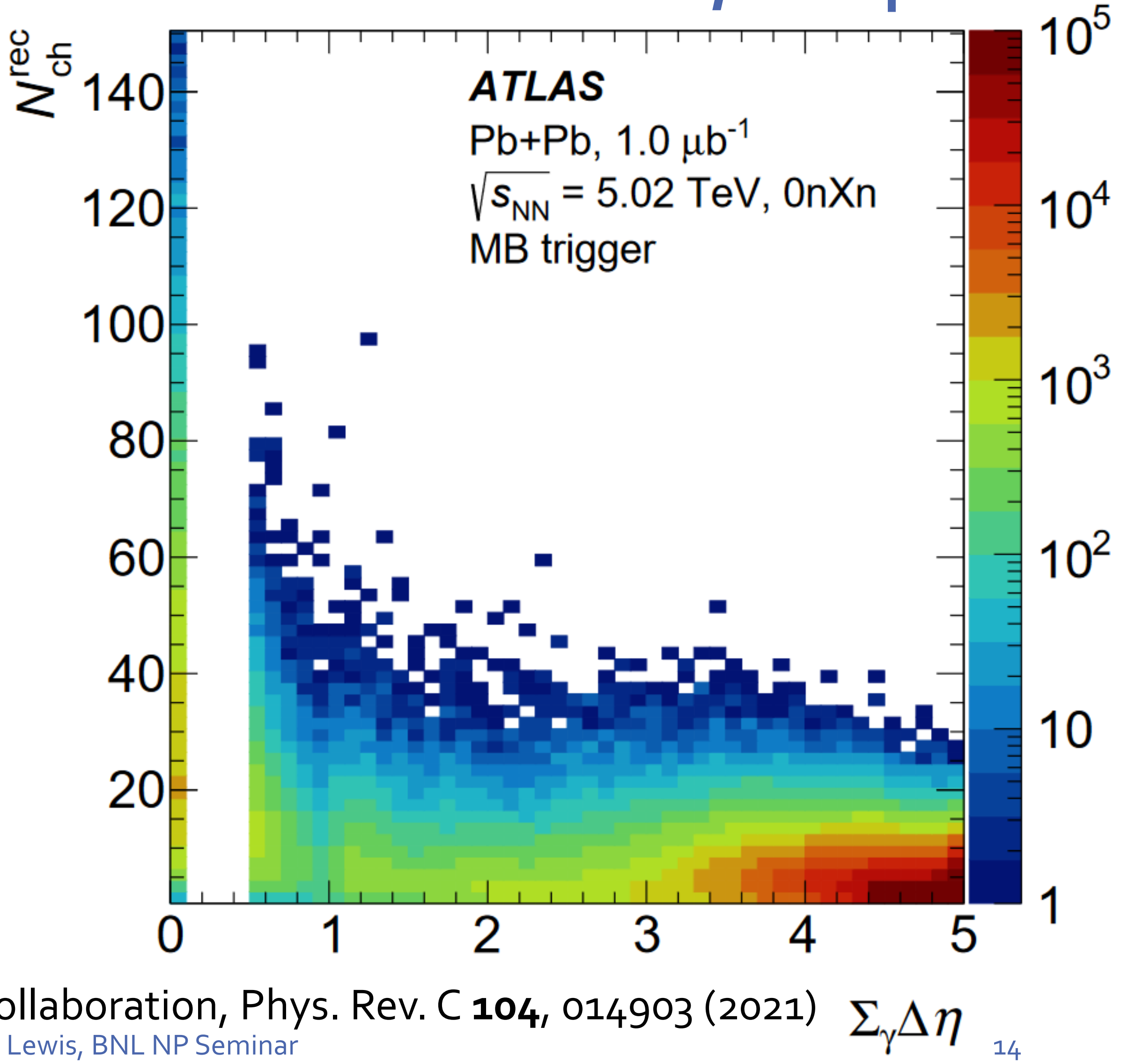
ATLAS Collaboration, Phys. Rev. C **104**, 014903 (2021)

The majority of photonuclear collisions at RHIC energies are resolved

Bertulani, C. A. and Klein, S. R. and Nystrand, J., Annual Review of Nuclear and Particle Science **55**, 271 (2005)

ATLAS - Selecting $\gamma + A$ Events With η Gaps

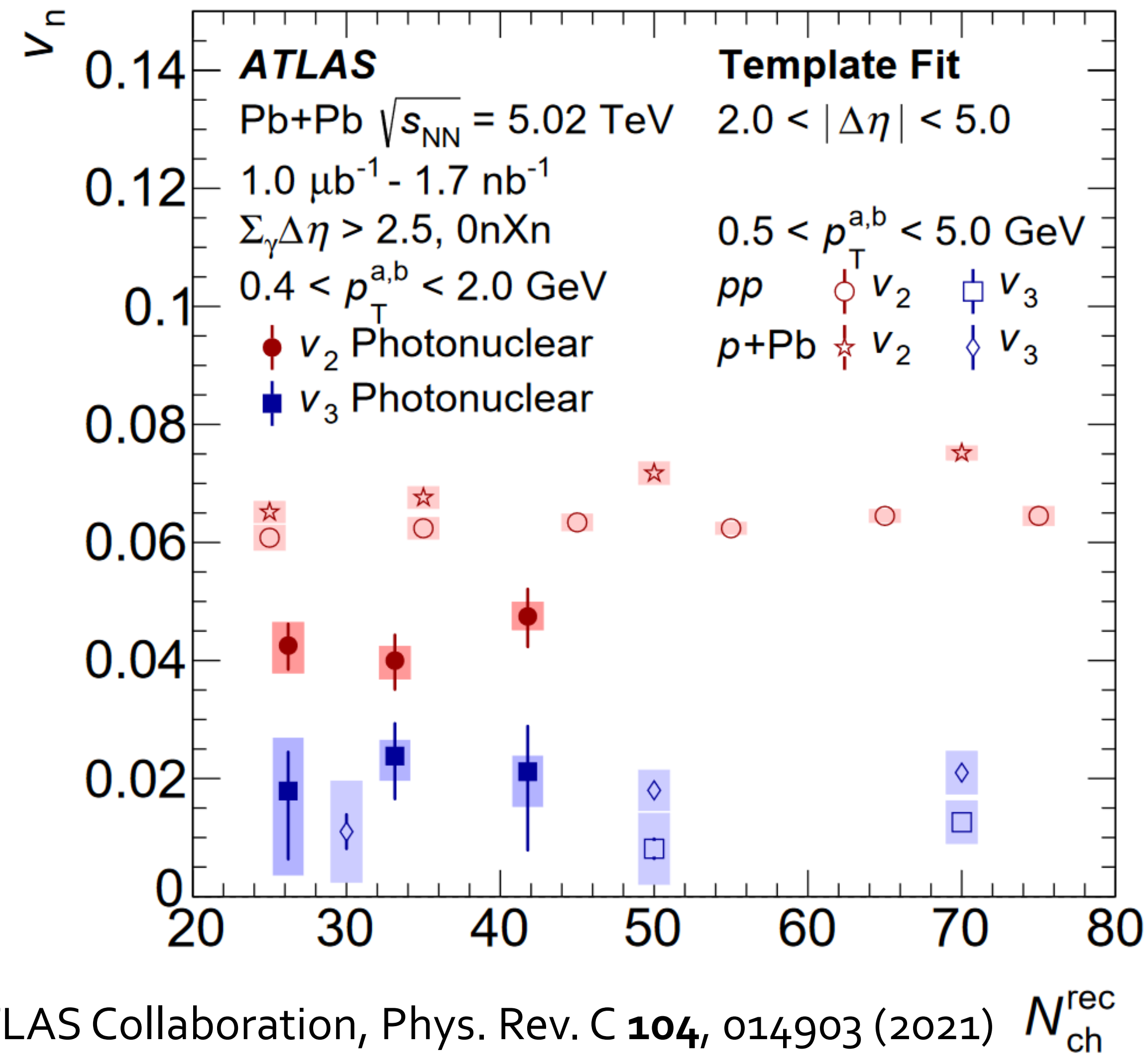
- Select "$0nXn$" events using the ZDC
  - Photon-Going Side has 0 neutrons
  - Pb-Going Side has at least 1 neutron
- Reduce contribution of peripheral $\mathrm{Pb} + \mathrm{Pb}$ events by requiring η gaps on the photon-going side
  - $\Sigma_\gamma \Delta\eta$ - sum of rapidity gaps between particles greater than 0.5
  - Quantifies how far apart in η the measured particles are on the photon-going side
  - Photonuclear events: $\Sigma_\gamma \Delta\eta > 2.5$ Large gap, sharply falling multiplicity distribution



ATLAS Collaboration, Phys. Rev. C **104**, 014903 (2021)

ATLAS - Long-Range Two-Particle Correlations

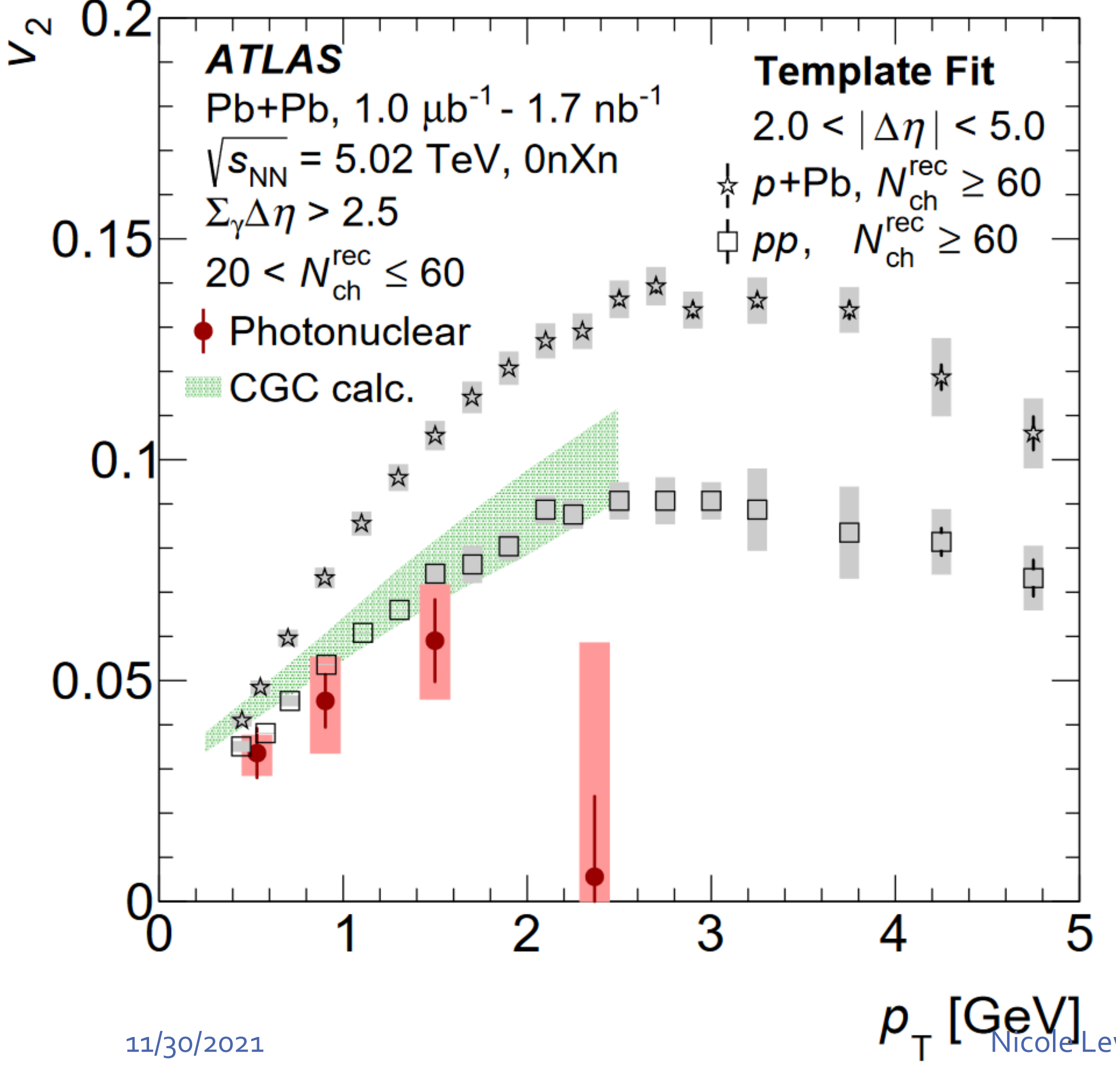
- Probing collectivity from initial-state effects
- Azimuthal correlation functions for pairs of charged particles separated by $2 < |\Delta\eta| < 5$
- Significant, nonzero v_2 and v_3
  - Indicates particles produced in photonuclear events participate in azimuthally dependent, collective motion



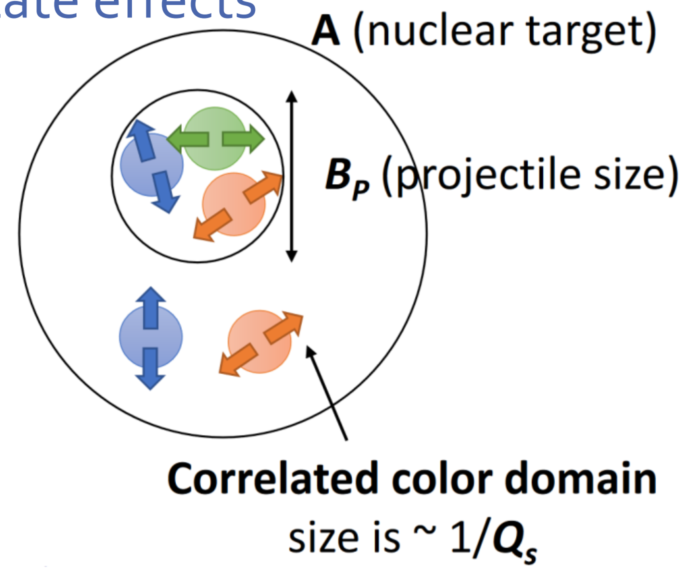
ATLAS Collaboration, Phys. Rev. C **104**, 014903 (2021)

Color Glass Condensate Model Comparison

ATLAS Collaboration, Phys. Rev. C **104**, 014903 (2021)



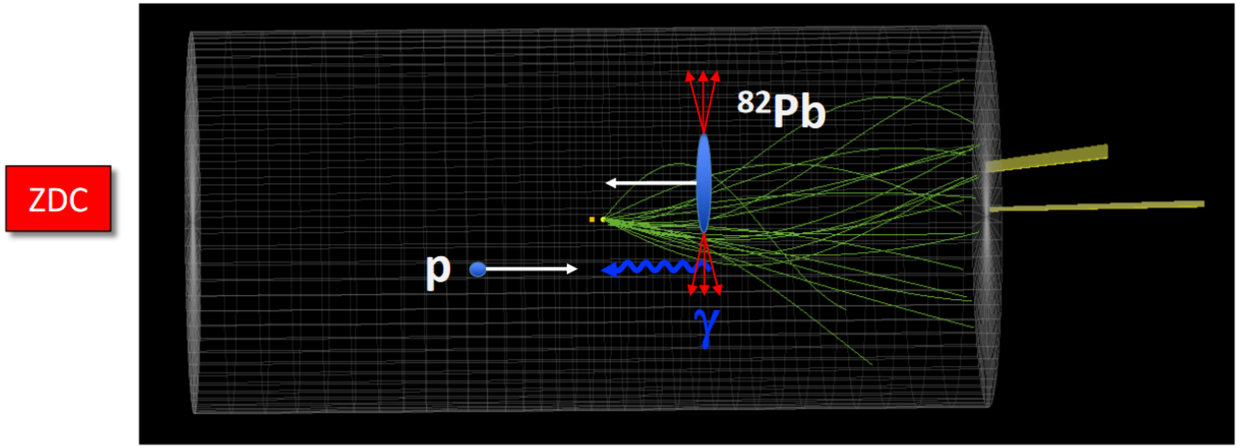
- Similar trend in $v_2(p_T)$ as other hadronic systems, but systematically lower in γPb compared to pPb
- Color Glass Condensate (CGC) explains this with a color domain picture, initial-state effects calculation
- Difference in v_2 comes from a larger B_p in γPb compared to pPb
  - Hits more color domains→ has a smaller v_2



Cartoon from B. Seidlitz, IS2021

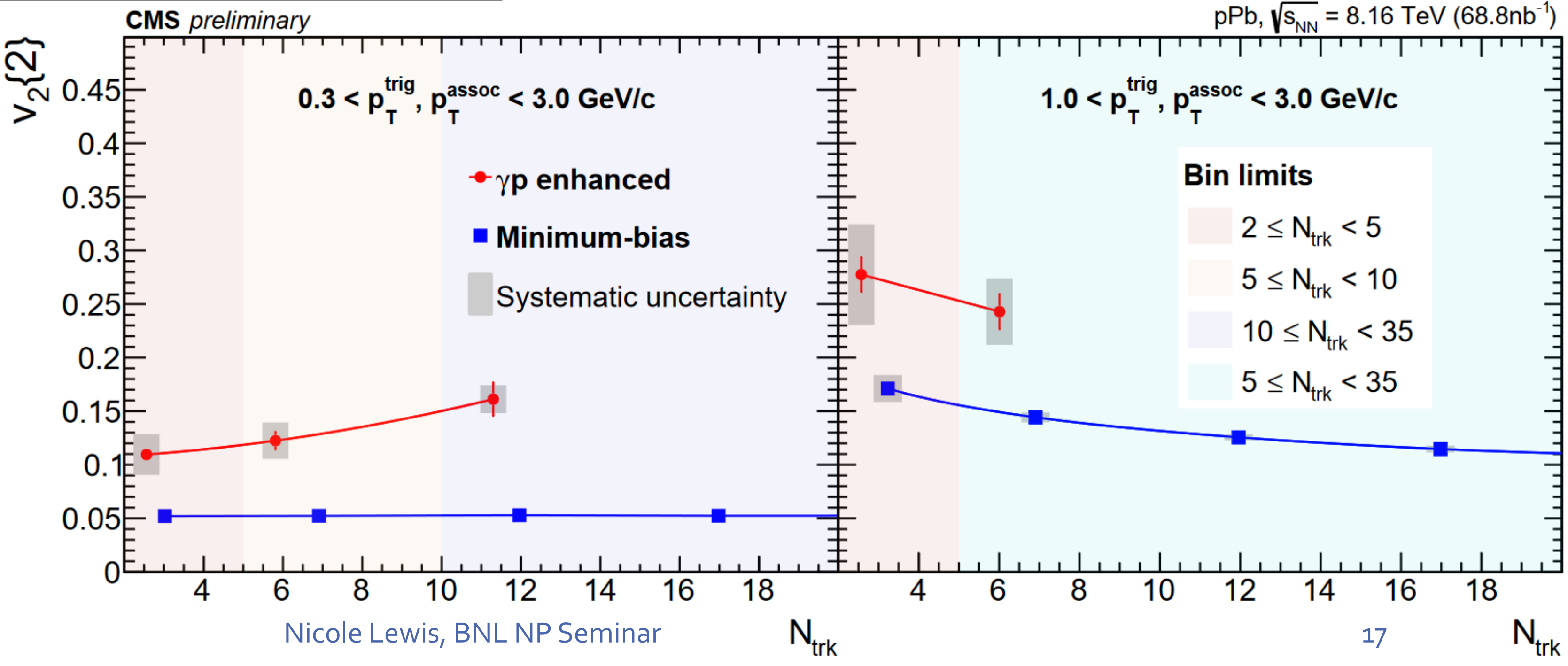
CMS photonuclear in pPb

Quan Wang
CMS Collaboration
IS2021

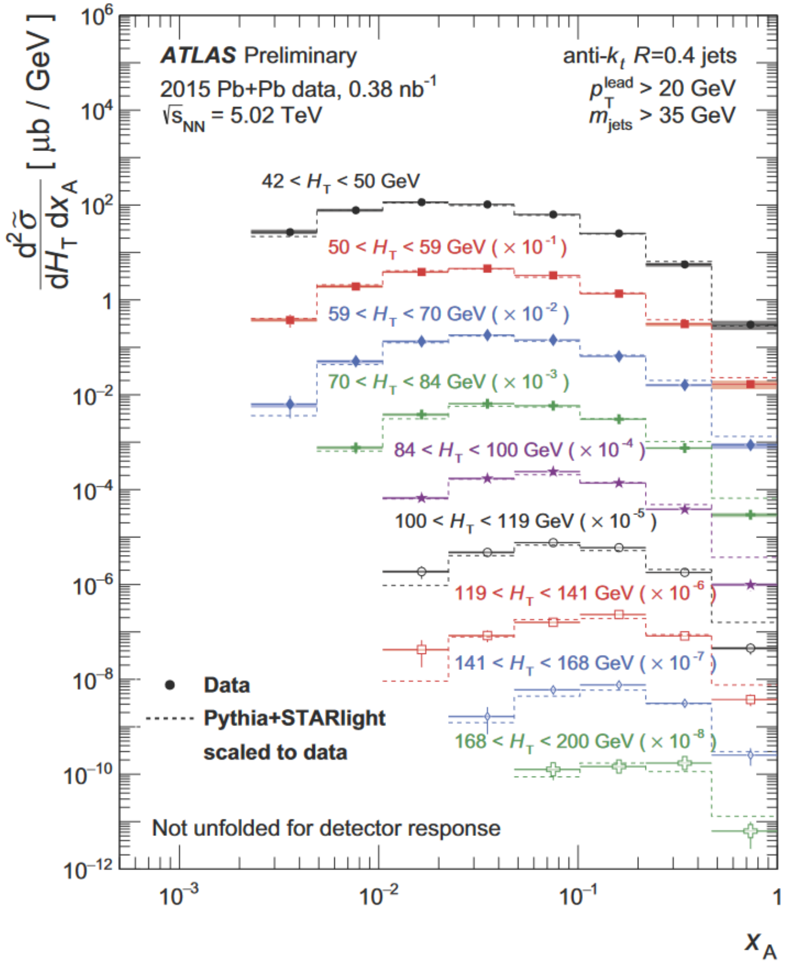


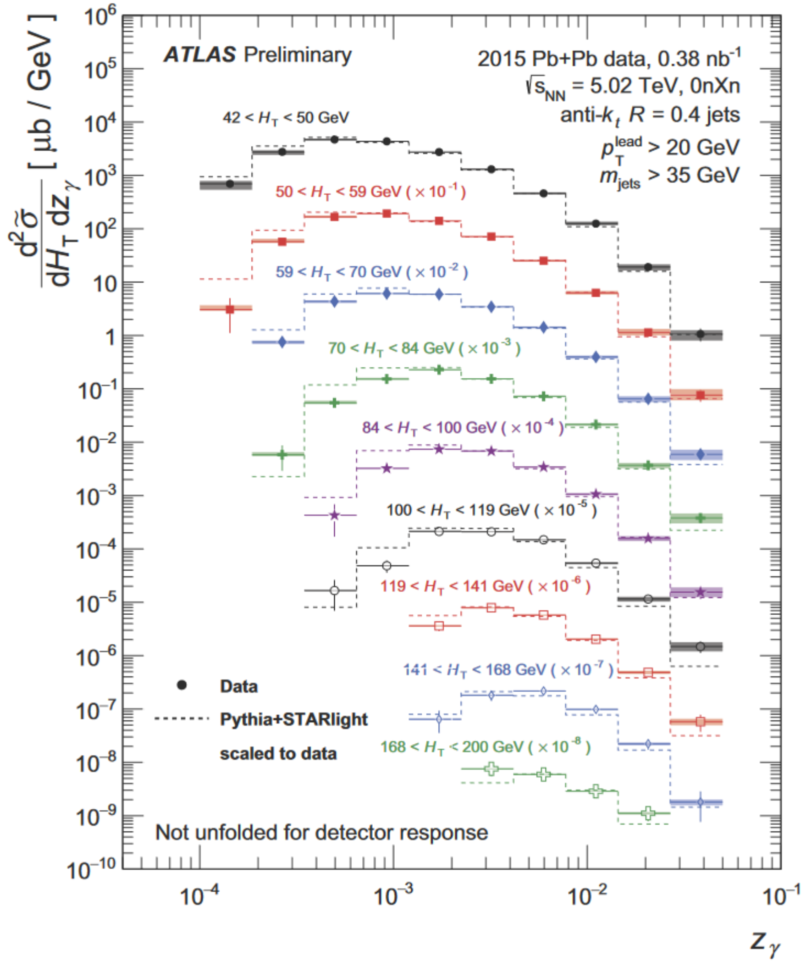
- No neutrons detected in ZDC on Pb-going side
- Pb-going side is quiet, lots of activity on the p-going side
- 95% γp purity

- v_2 grows with multiplicity at low p_T, unlike in hadronic events
- Consistent with jet-like momentum conserving non-flow effect



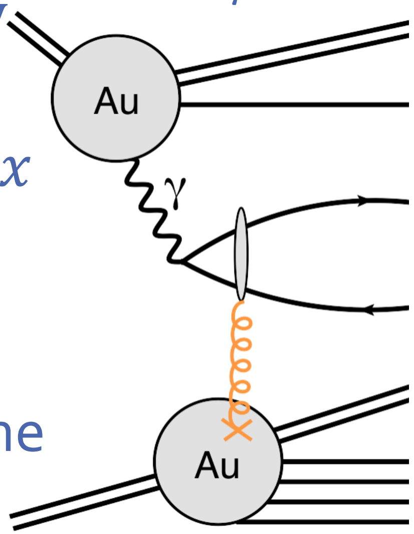
Di-Jet Cross Section in γPb





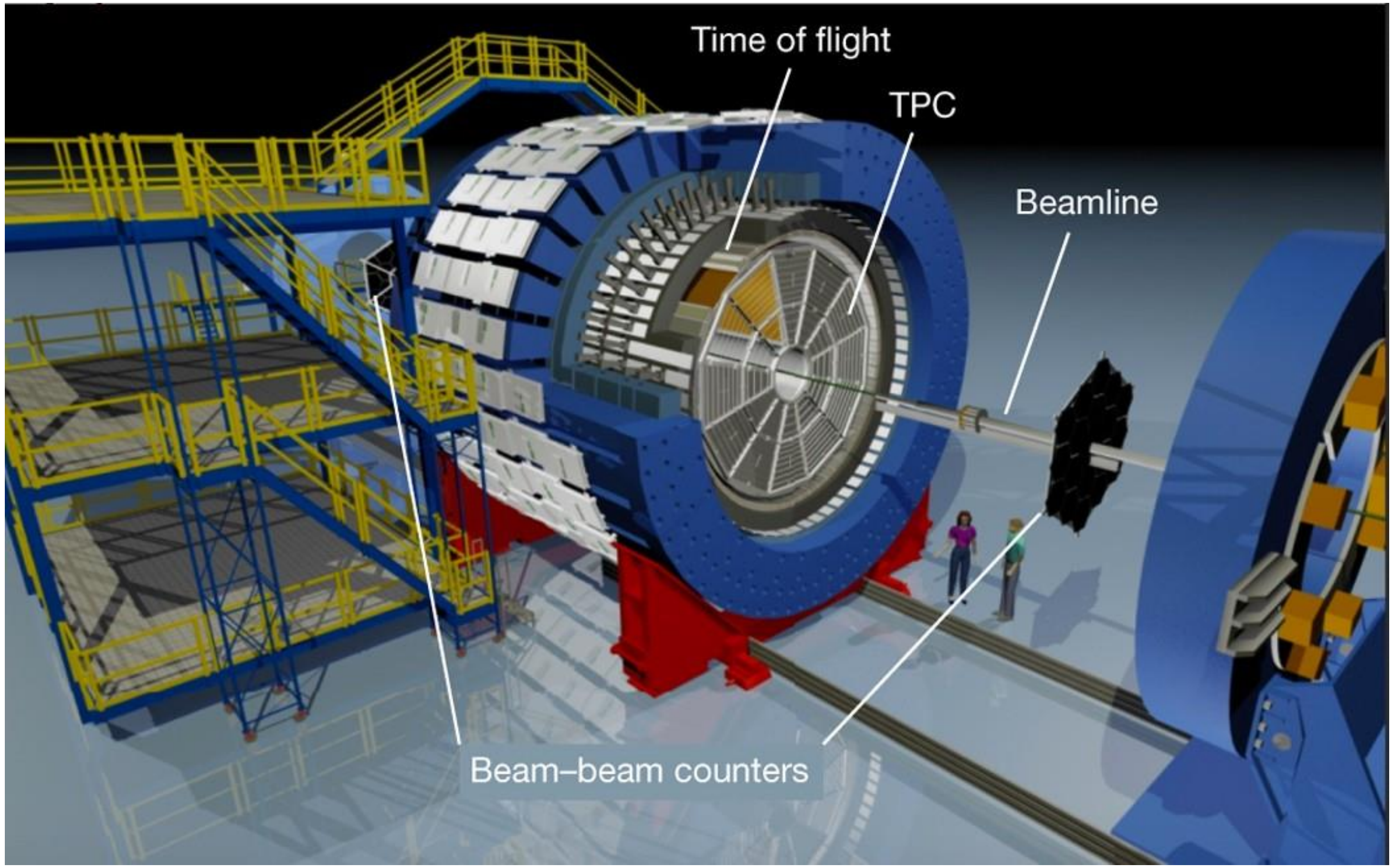
A. Angerami for the ATLAS Collaboration, Nuclear Physics A **967**, 277 (2017)

- Photonuclear collisions as a way of probing nuclear structure
  - Sensitive to nuclear PDFs
  - At LHC energies $E_\gamma \lesssim$ 40 GeV



- x_A~ Bjorken x of the struck parton within the nucleus
- z_γ~ Fraction of energy of the radiating nucleus that the particle probing the nucleus carries

Particle Identification with the STAR Detector



Time Projection Chamber (TPC) identifies particles at lower p_T using ionization energy loss, dE/dx

Time of Flight (TOF) identifies particles at higher p_T

Beam-Beam Counter (BBC) used for rapidity gap cuts

Data collected in 2017, $\mathrm{Au+Au}$ collisions with $\sqrt{s_{NN}} = 54.4$ GeV, trigger did not require coincidence in both sides of the detector ~700 million events

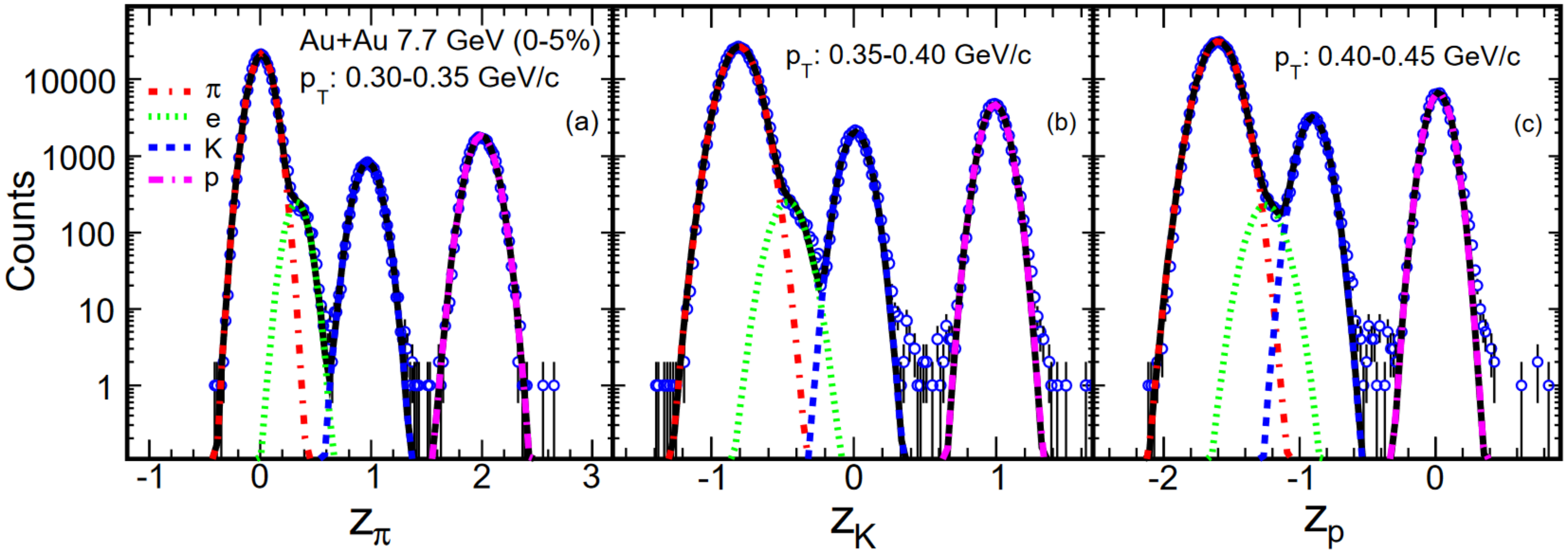
Particle Identification Using the TPC

The ionization energy loss, dE/dx, of a charged particle traveling through the TPC, depends on the particle's mass

Identify the particle at low p_T using the z_X value and the TPC resolution

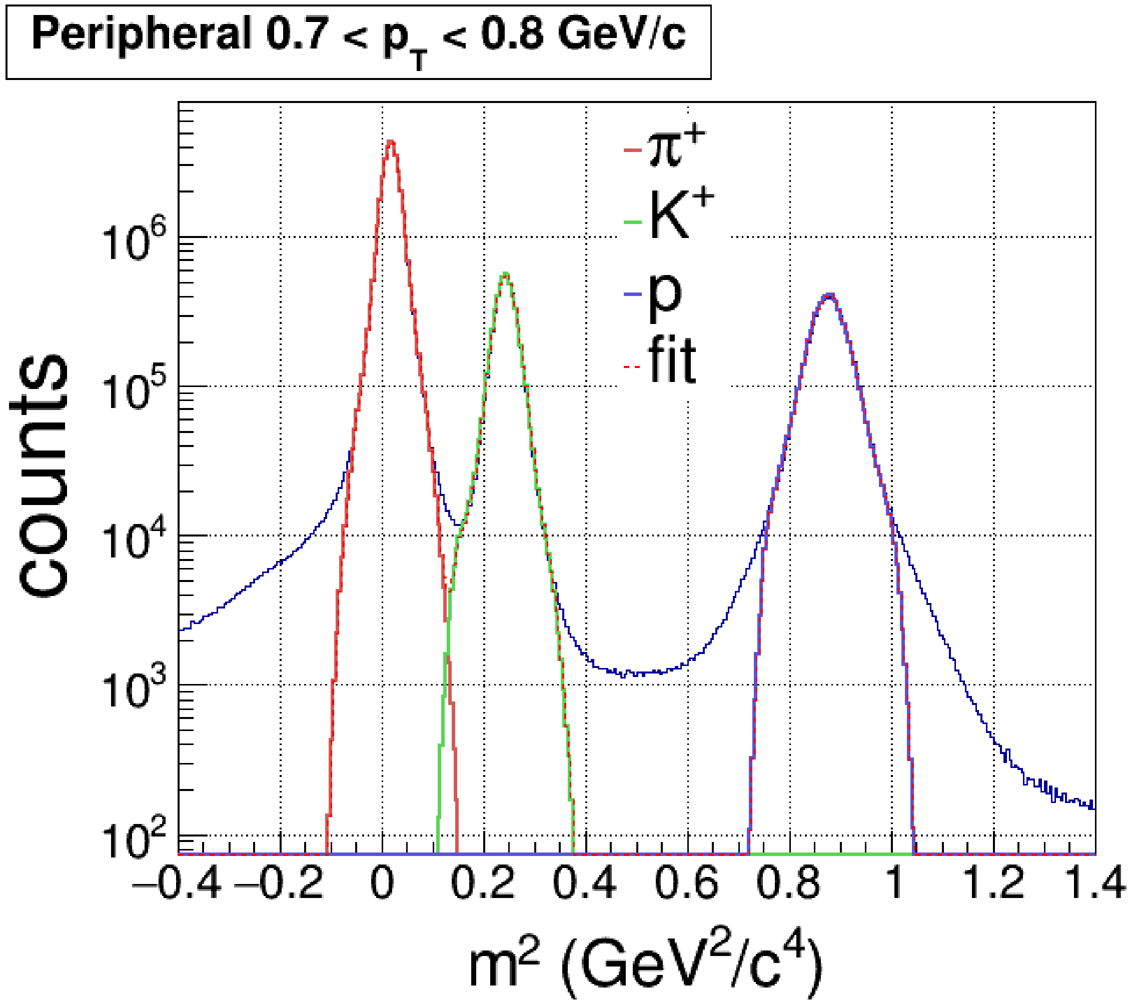
$$z_X = \ln\left(\frac{\langle dE/dx \rangle}{\langle dE/dx \rangle_X^B}\right)$$

For particle type X ($e^{\pm}$, $\pi^{\pm}$, $K^{\pm}$, p, or $\bar{p}$) and corresponding Bichsel function $\langle dE/dx \rangle_X^B$



STAR Collaboration Phys. Rev. C **96**, 044904 (2017)

Particle Identification Using the TOF



- The TOF extends STAR's PID capabilities to higher p_T:

$$m^2 = p^2\left(\frac{c^2t^2}{L^2} - 1\right)$$

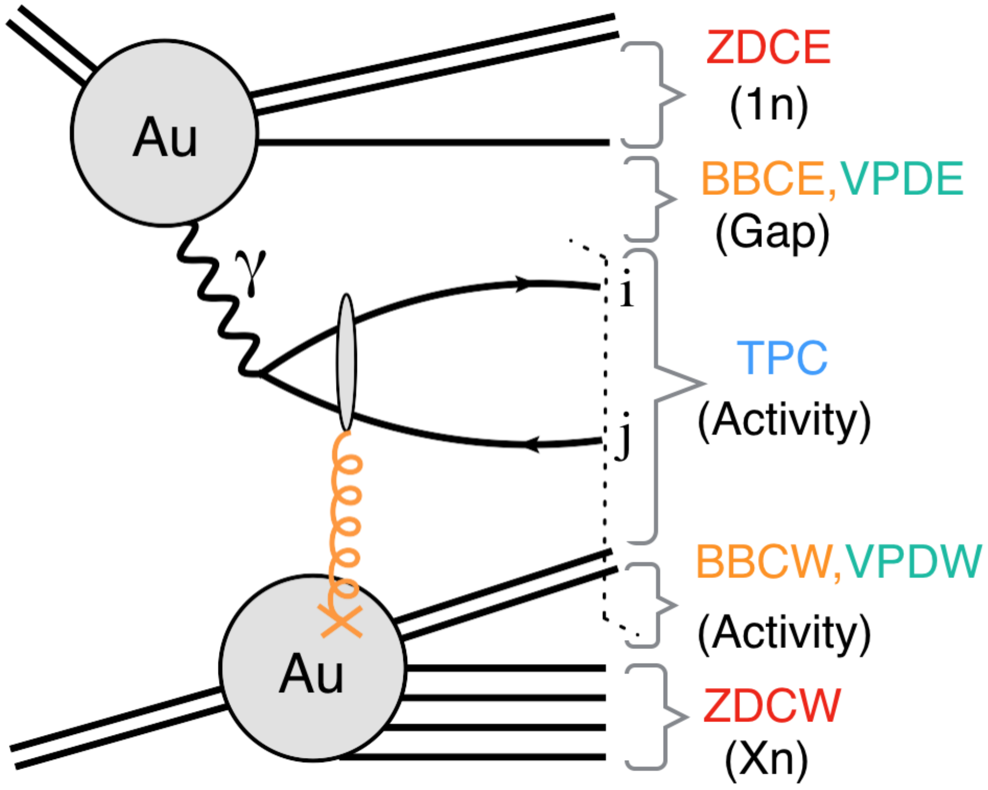
- Measure the timing resolution as a function of p_T using input from the TPC

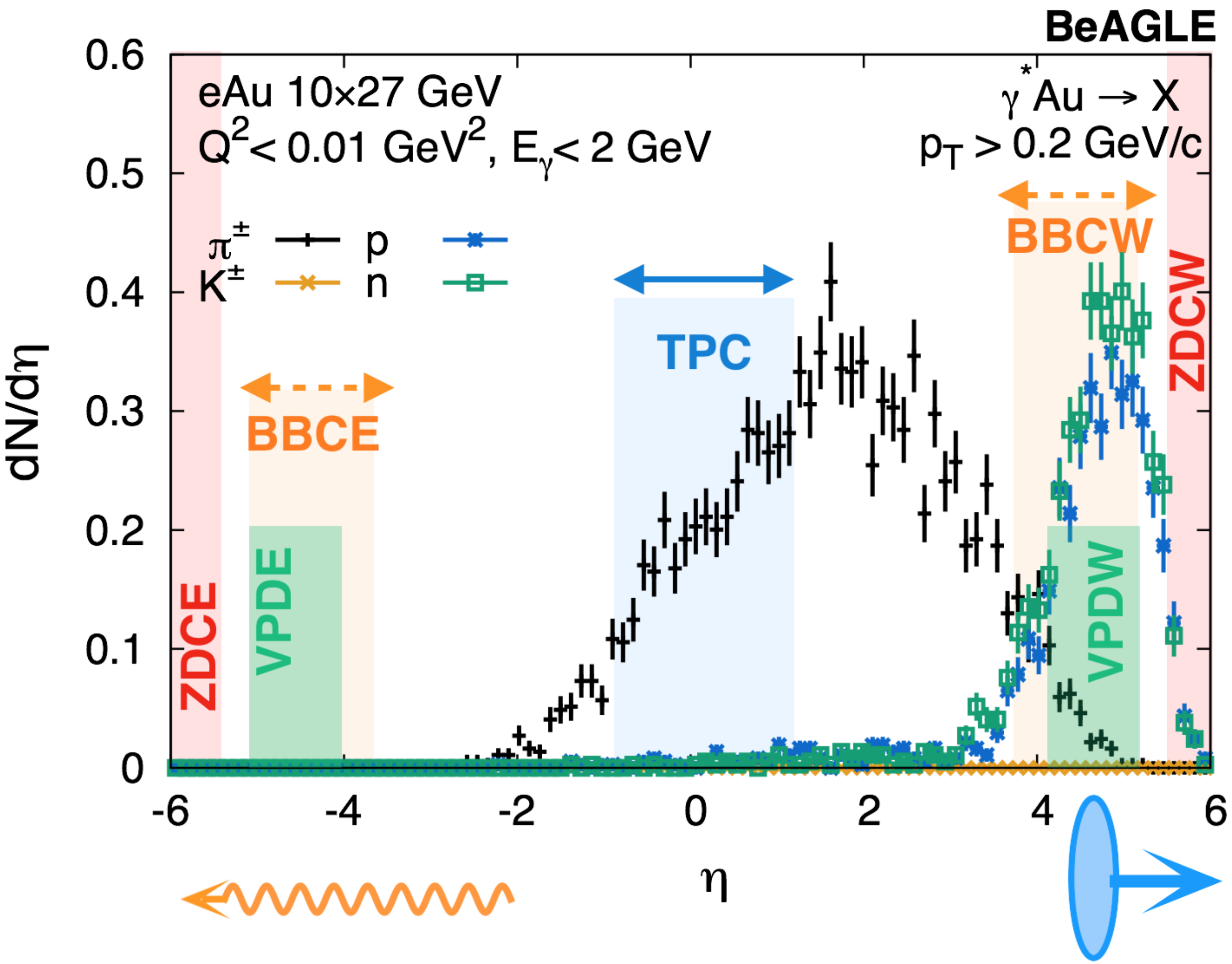
$$\Delta t = t_{\text{measured}} - t_{\text{expected}}$$

  where t_{expected} is calculated based on the track information measured by the TPC and the assumed particle mass

- Randomly sample this Δt distribution to get $t_{\text{predicted}} = t_{\text{expected}} + t_{\text{random}}$ and use this to make $m^2_{\text{predicted}}$

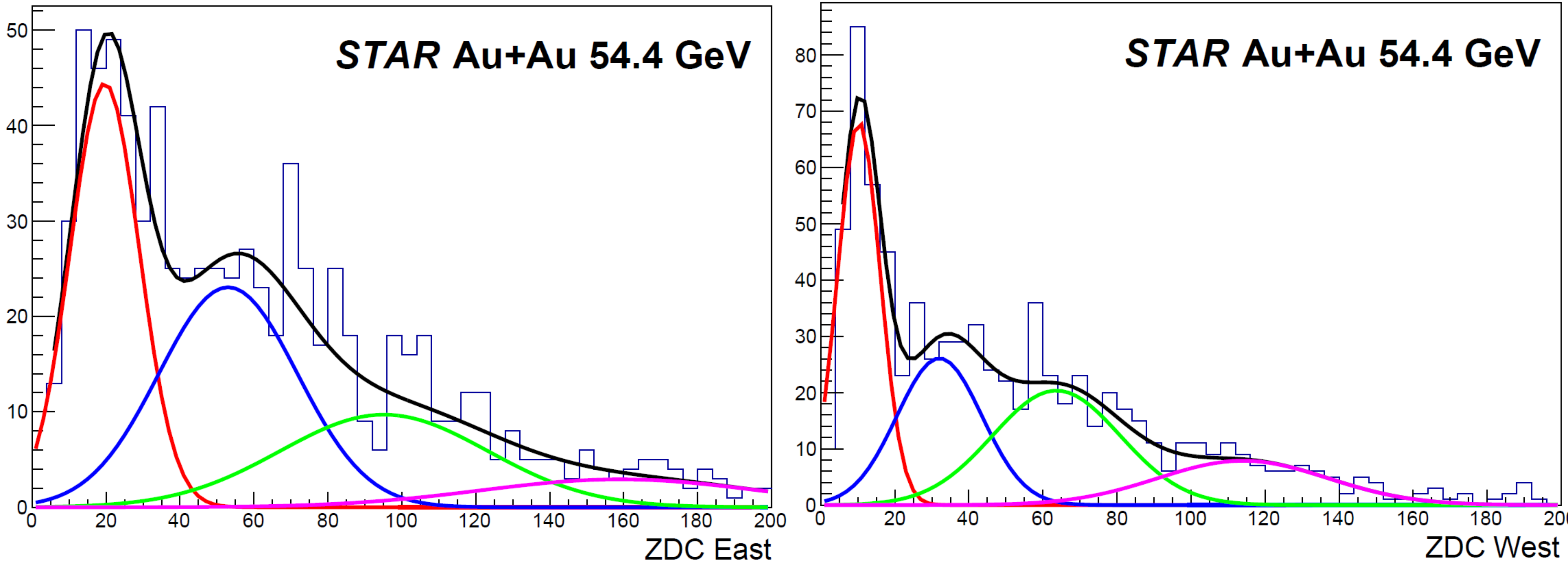
Photonuclear Events Are Selected With Rapidity Gaps





Similar to the technique used in ATLAS and CMS photonuclear measurements

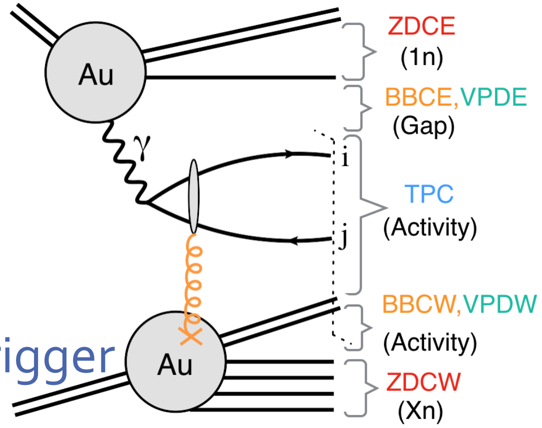
Identifying the Single Neutron Peak



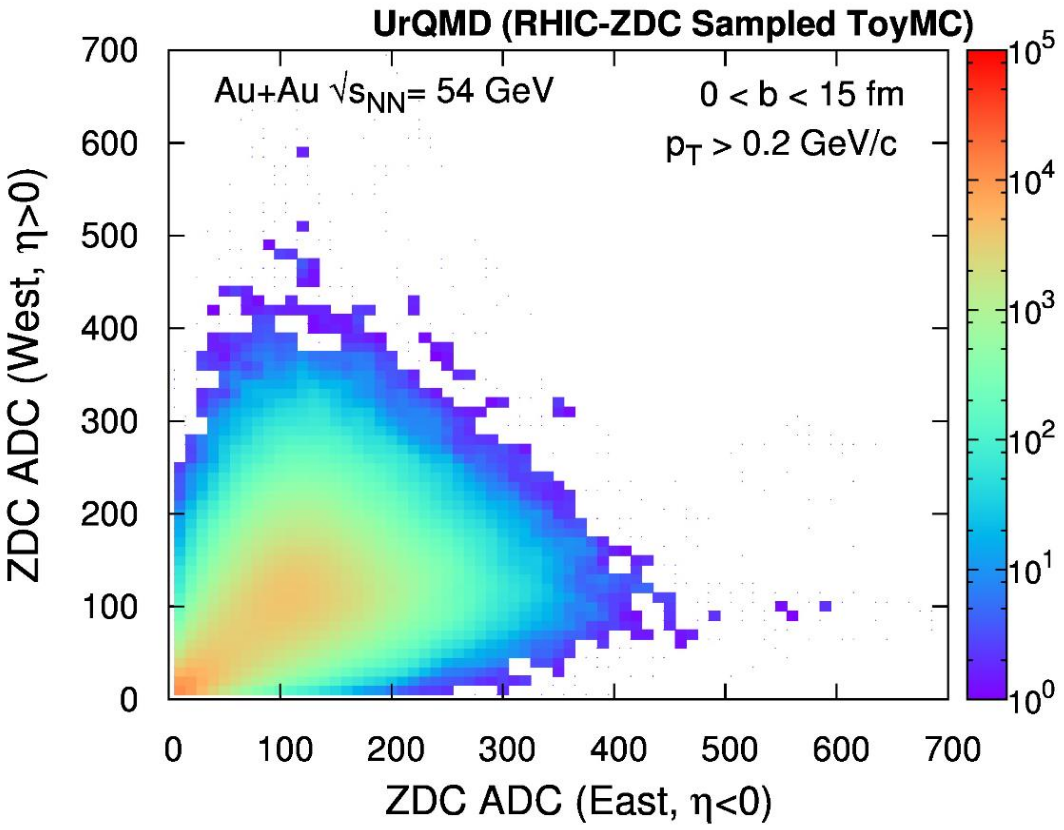
Low multiplicity events collected with ZDC triggers

Cutting on single neutron peak, dominated by $\gamma + A$ events

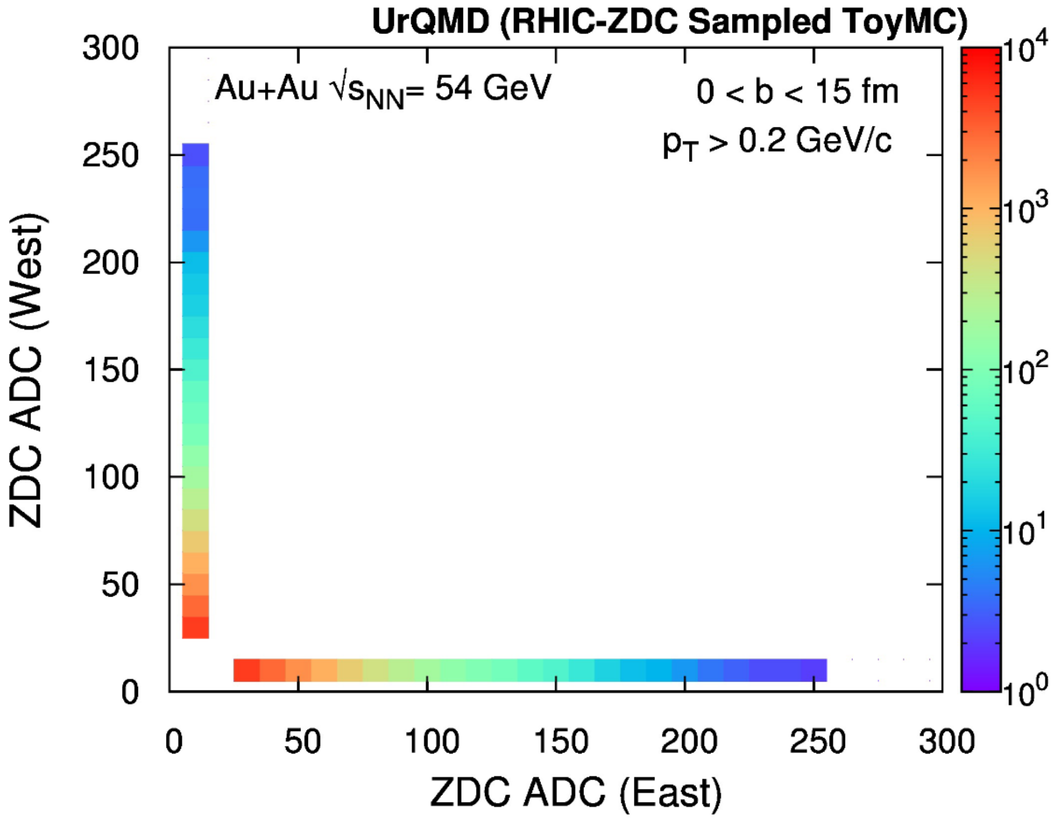
Predictions from AA Monte-Carlo



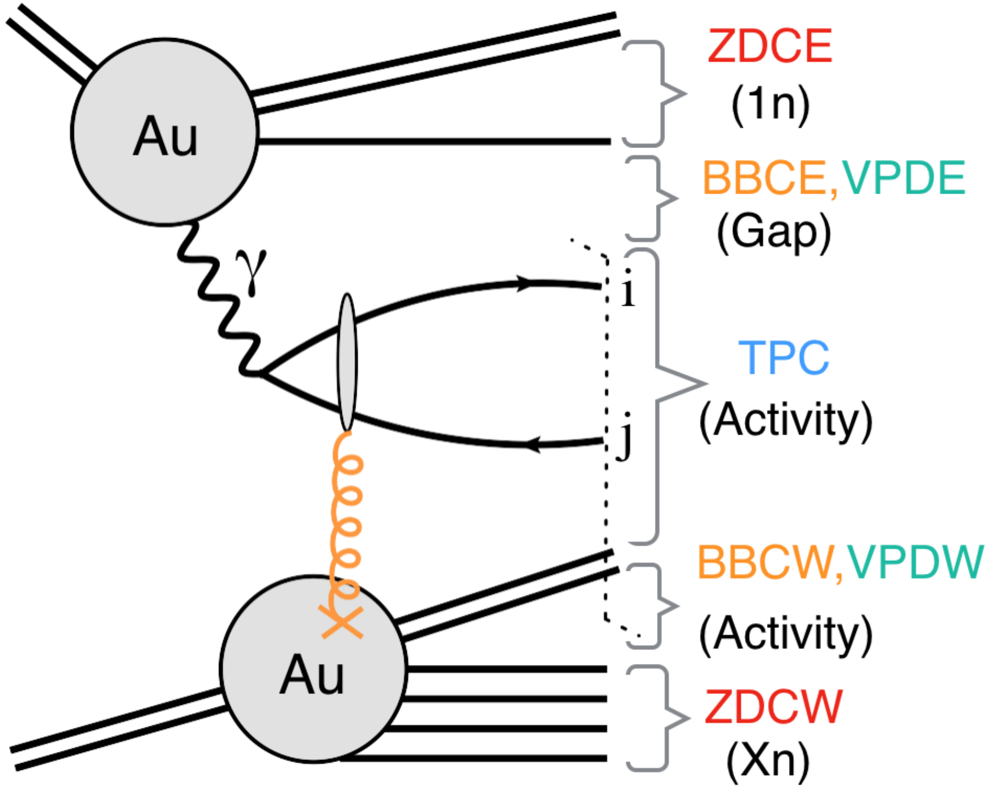
Typical Response of STAR ZDCs

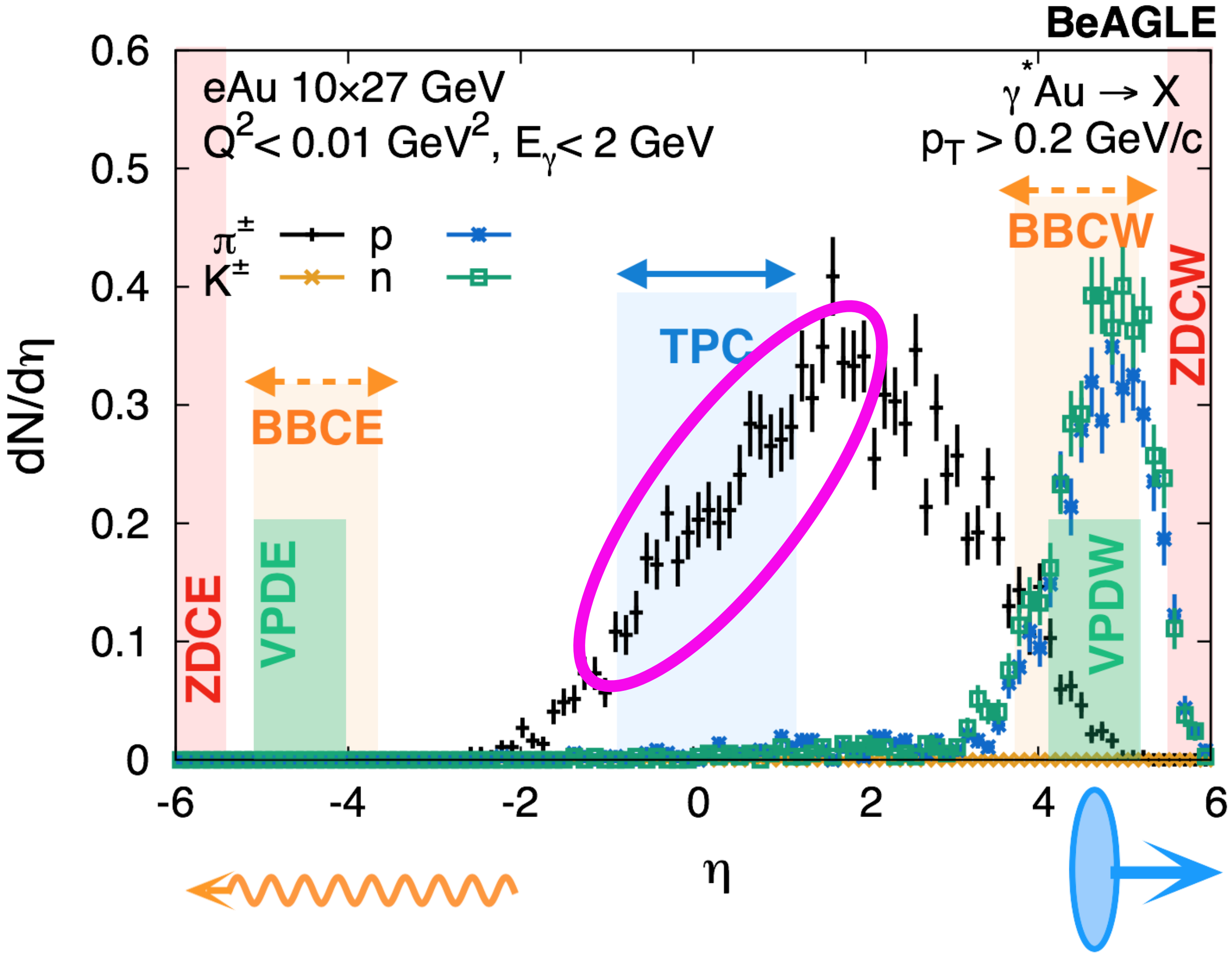


After applying γA-like trigger

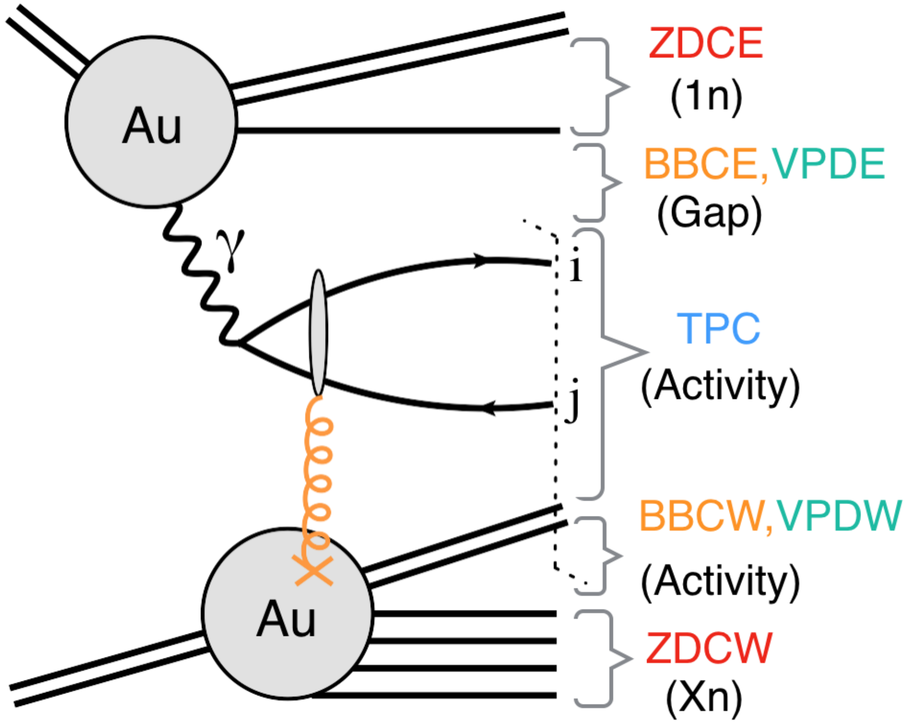


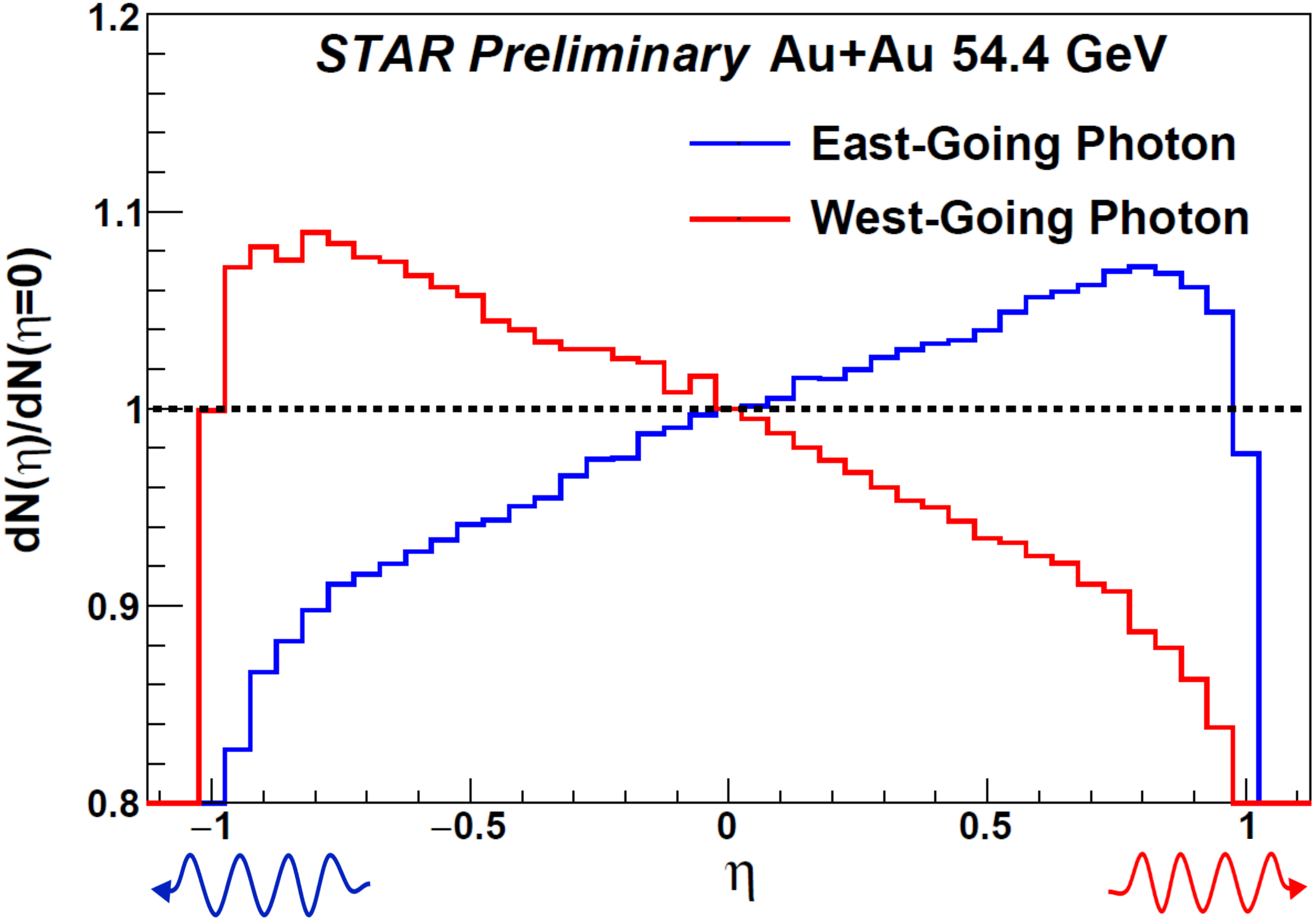
Photonuclear Events Are Selected With Rapidity Gaps



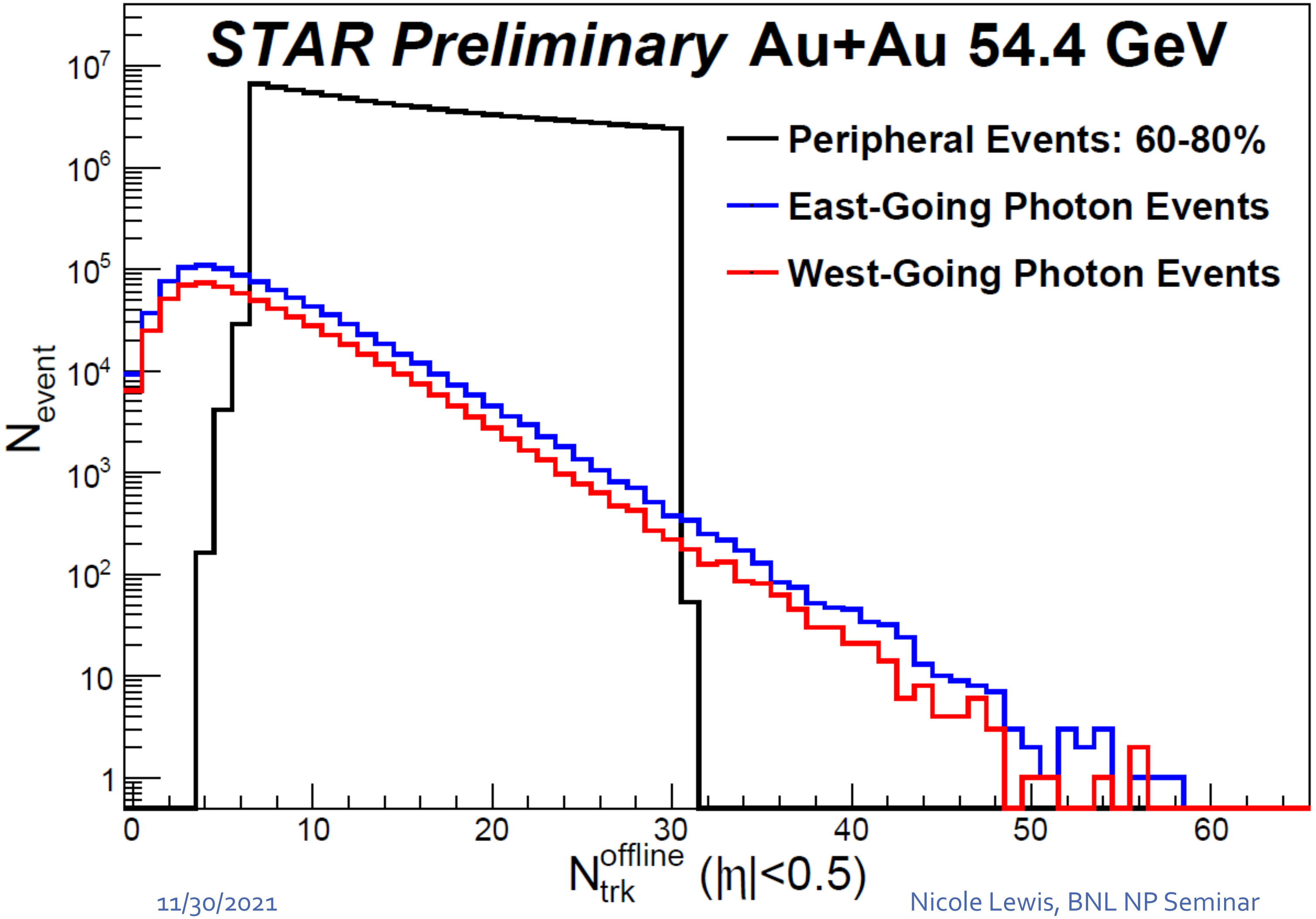


Rapidity Asymmetry in γA-Rich Events





Defining γA and AA Event Classes



Most photonuclear events have low multiplicity, concentrated at equivalent $\text{Au} + \text{Au}$ centrality of roughly 80%

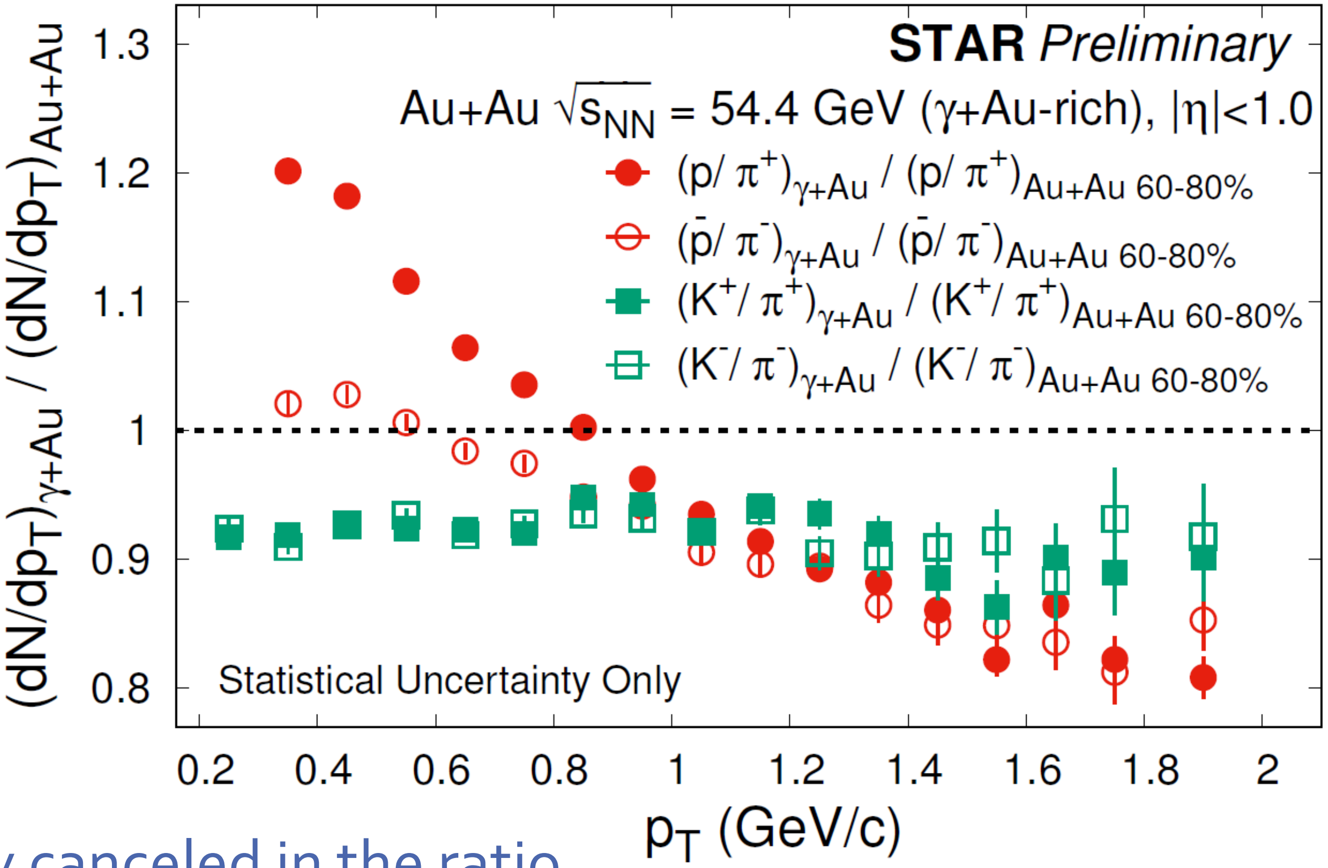
Using peripheral events as a baseline comparison, multiplicity consistent with $60 - 80\%\ \text{Au} + \text{Au}$

p_T Dependence of Particle Ratios in $\gamma A/AA$

$K/\pi < 1$ and flat with p_T
→ less access to strangeness in γA events

$\bar{p}/\pi^-$ and p/π^+ steeper than K/π
→ larger radial flow in $60-80\%$ Au + Au

$\bar{p}/\pi^- < p/\pi^+$ for $p_T \lesssim 1$ GeV/c
→ soft baryon stopping

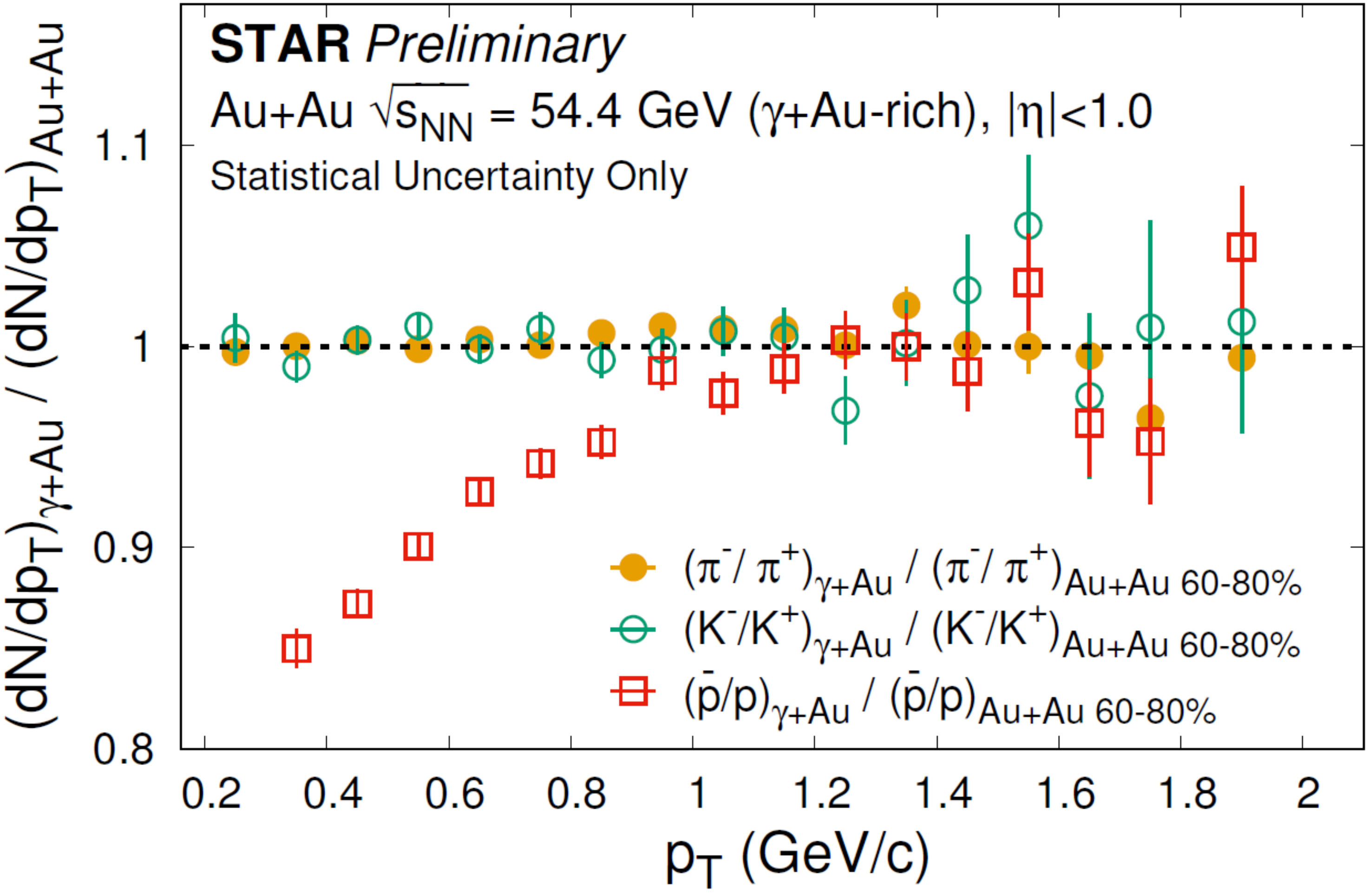


Not corrected for efficiency, but largely canceled in the ratio

Low p_T Baryon Enhancement in γA

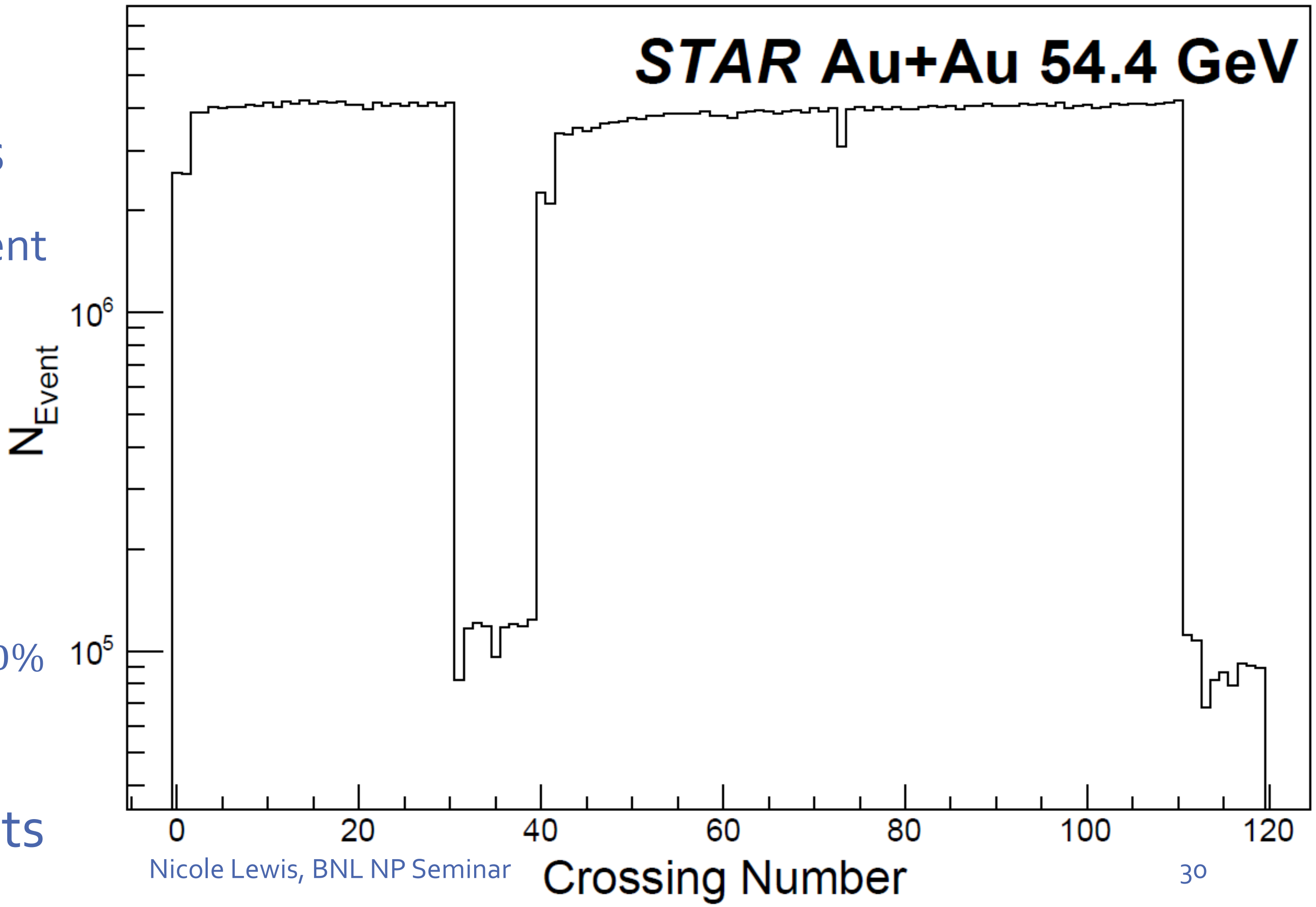
Double ratio: antiparticle/particle in $\gamma A/AA$

$\bar{p}/p < 1$ for $p_T \lesssim 1$ GeV$/c$ → soft baryon stopping that is **stronger** in γA compared to peripheral AA

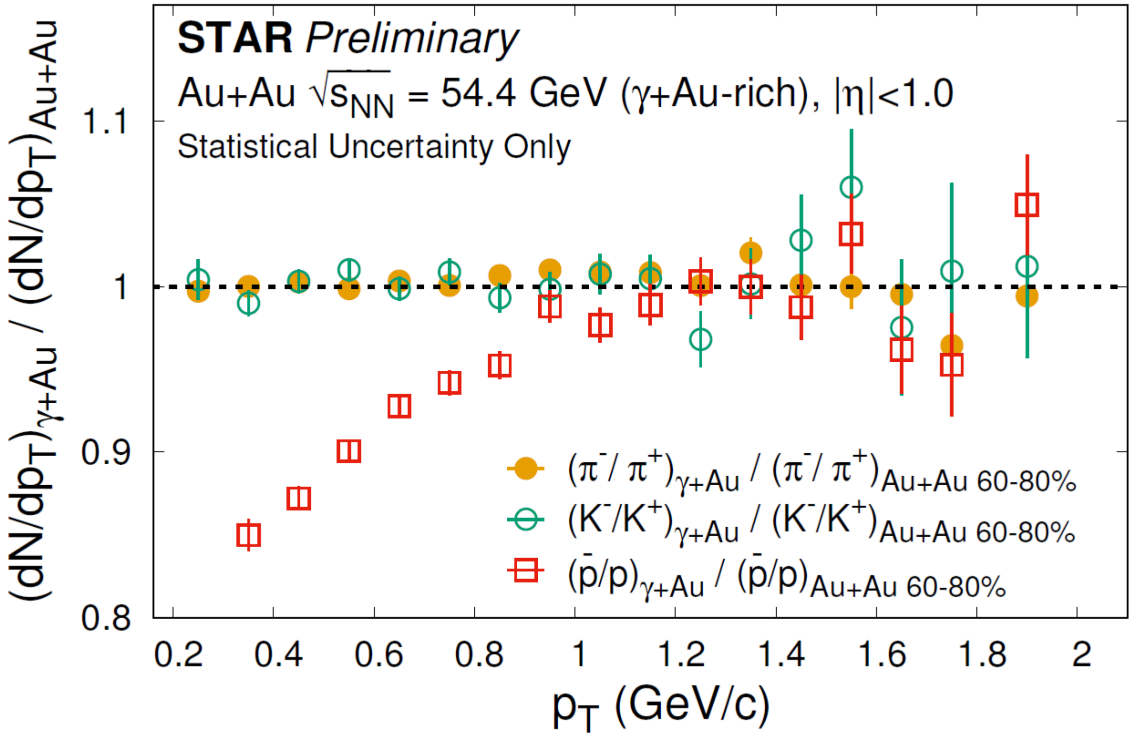


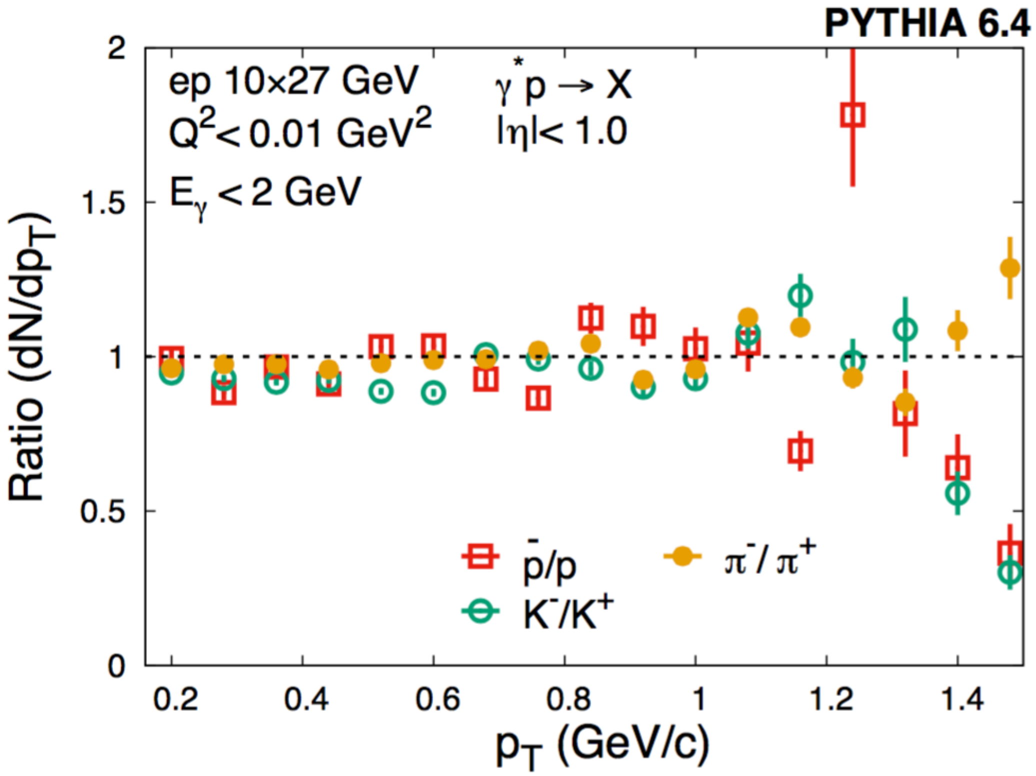
Study Beam Gas Background with Abort Gap Events

- At STAR, 18 out of 120 crossings (31 to 39 and 111 to 119) have only one of the beams filled due to the abort gaps
- Abort gap events occur because of beam gas and beam material interactions
  - Only a small portion of these abort gap events pass our event cuts
- Background contribution estimated to be about 3% for γA events
- For abort gap events the $(\bar{p}/p)_{\gamma+\mathrm{Au}}/(\bar{p}/p)_{\mathrm{Au+Au}\ 60-80\%}$ ratio is flat with p_T and consistent with 1 for the events which pass these cuts



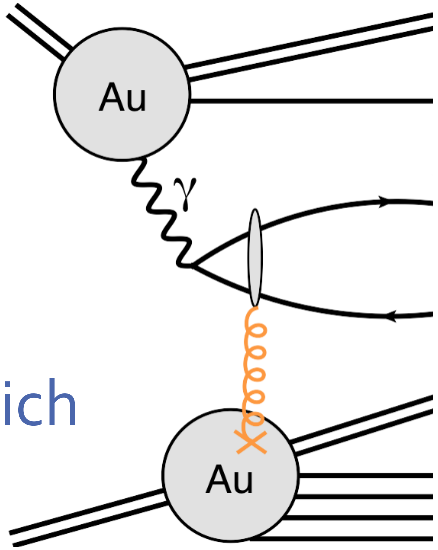
Comparison with PYTHIA





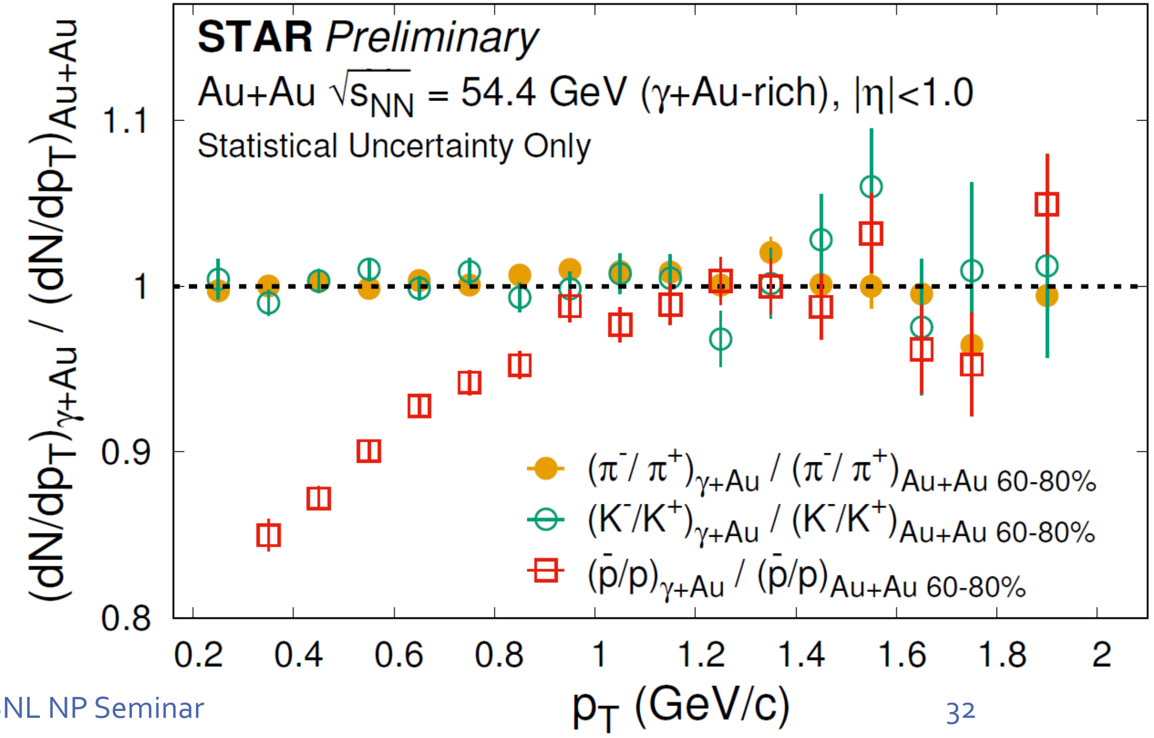
PYTHIA6 $\gamma^* p \rightarrow X$ simulation does not include a baryon junction → pion, kaon, and proton ratios are all consistent with 1 within uncertainty

Baryon Stopping Through the Baryon Junction

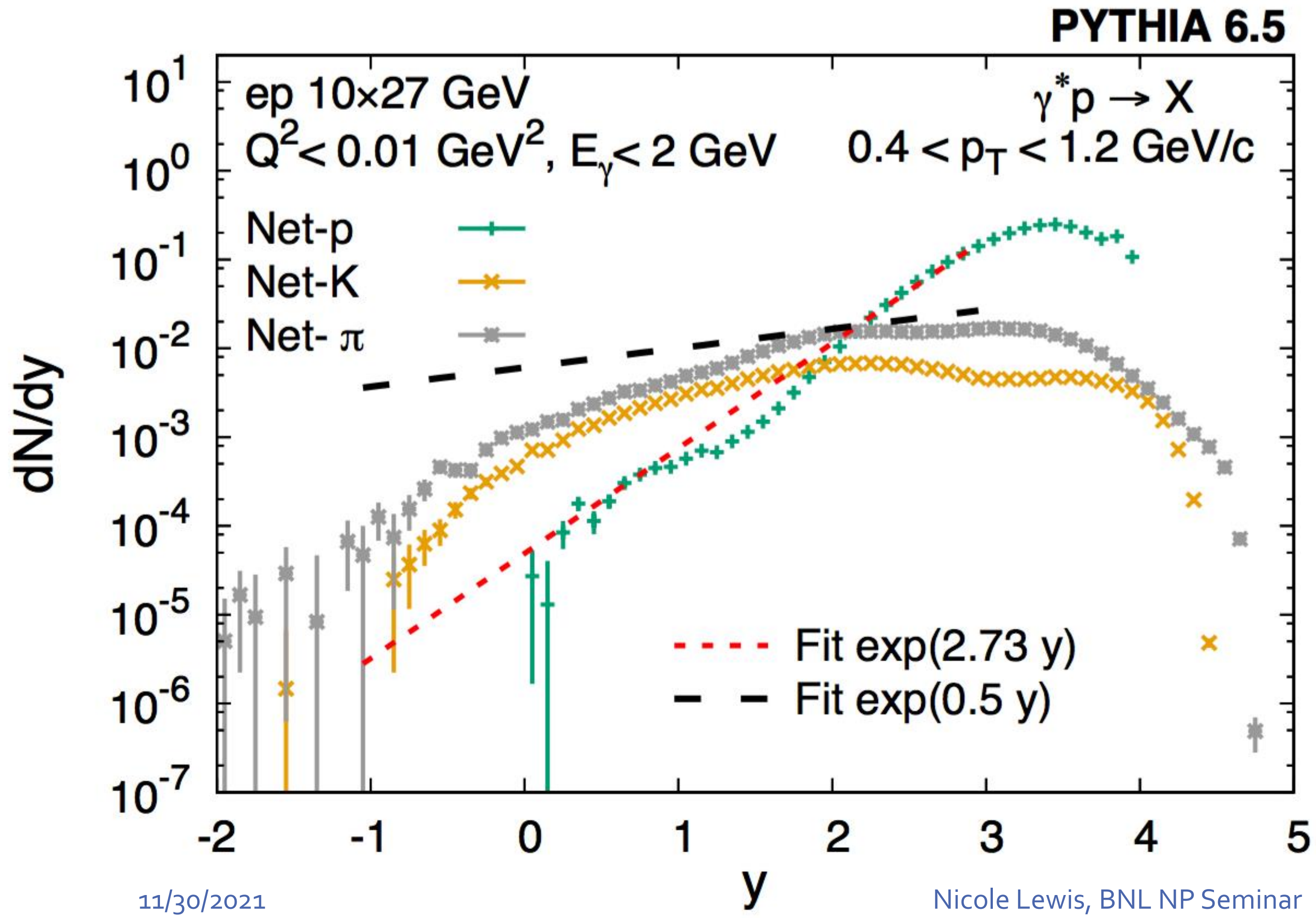


- Possible explanation: photon fluctuates into a $q\bar{q}$ pair which is not able to stop all three valence quarks of the target baryon in the colliding ion
  - Baryon stopping can occur because the $q\bar{q}$ pair interacts directly with the baryon junction
- $\bar{p}/p < 1$ for $p_T \lesssim 1\ \mathrm{GeV}/c \rightarrow$ the baryon junction is a nonperturbative effect
- Prediction for baryon stopping caused by the baryon junction
  - Stopping should correspond to a higher multiplicity event
  - $dN/dy \propto \exp(-y/2)$

D. Kharzeev, Physics Letters B **378**, 238 (1996)



Comparison to PYTHIA

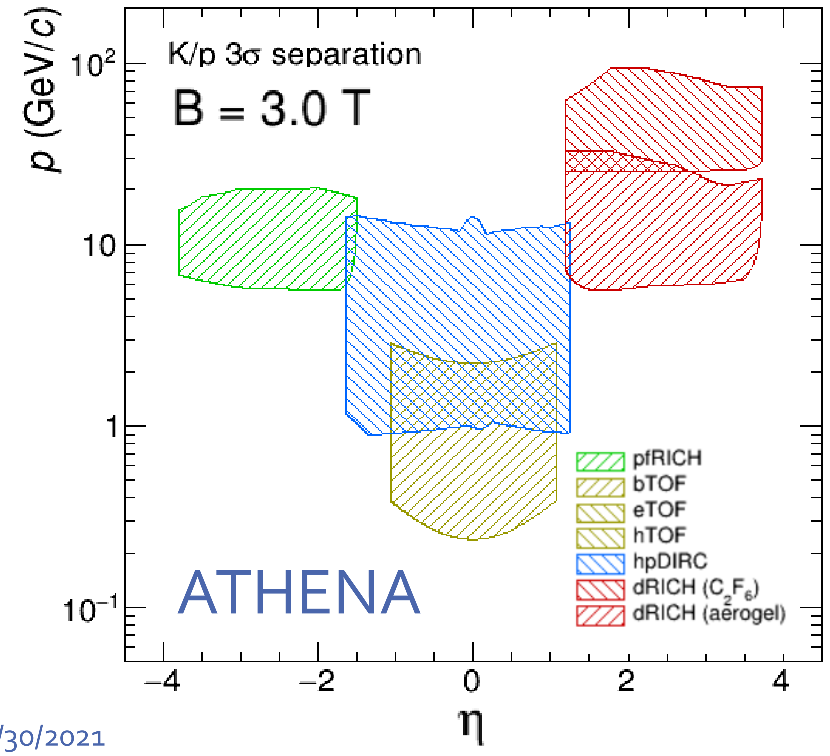


- Prediction for baryon stopping caused by the baryon junction $dN/dy \propto \exp(-y/2)$
- PYTHIA6 does not implement a baryon junction
- Will be measured in γA collisions

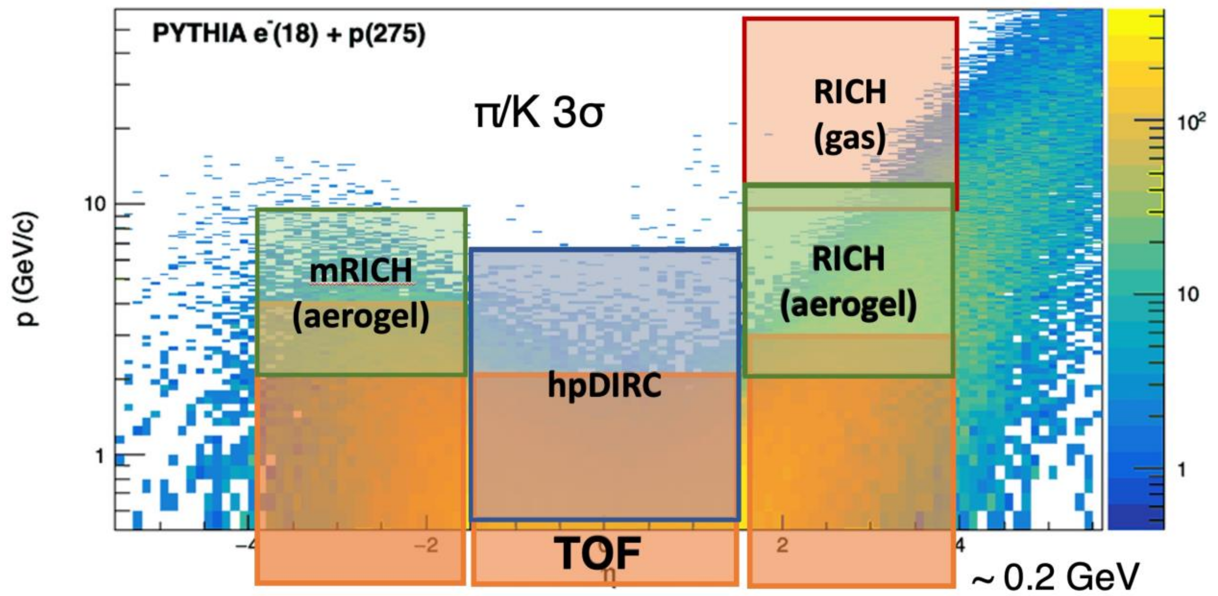
PID at the EIC

PID in photonuclear events will help inform future measurements at the EIC

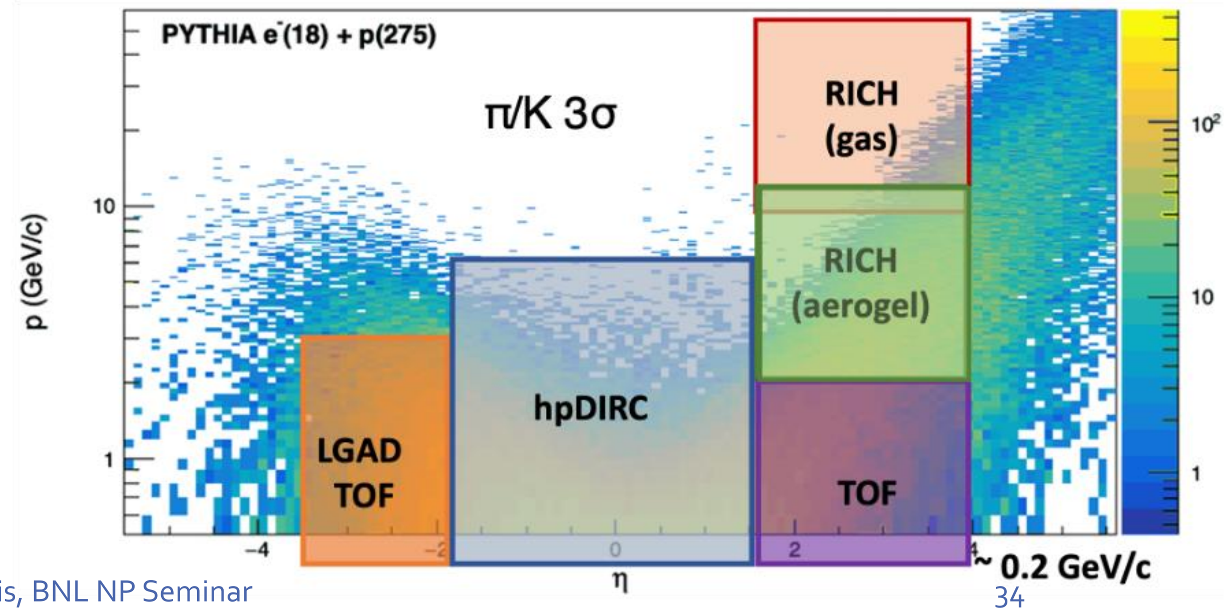
Particle identification for a wide range of momentum will be an essential part of the EIC program



ECCE

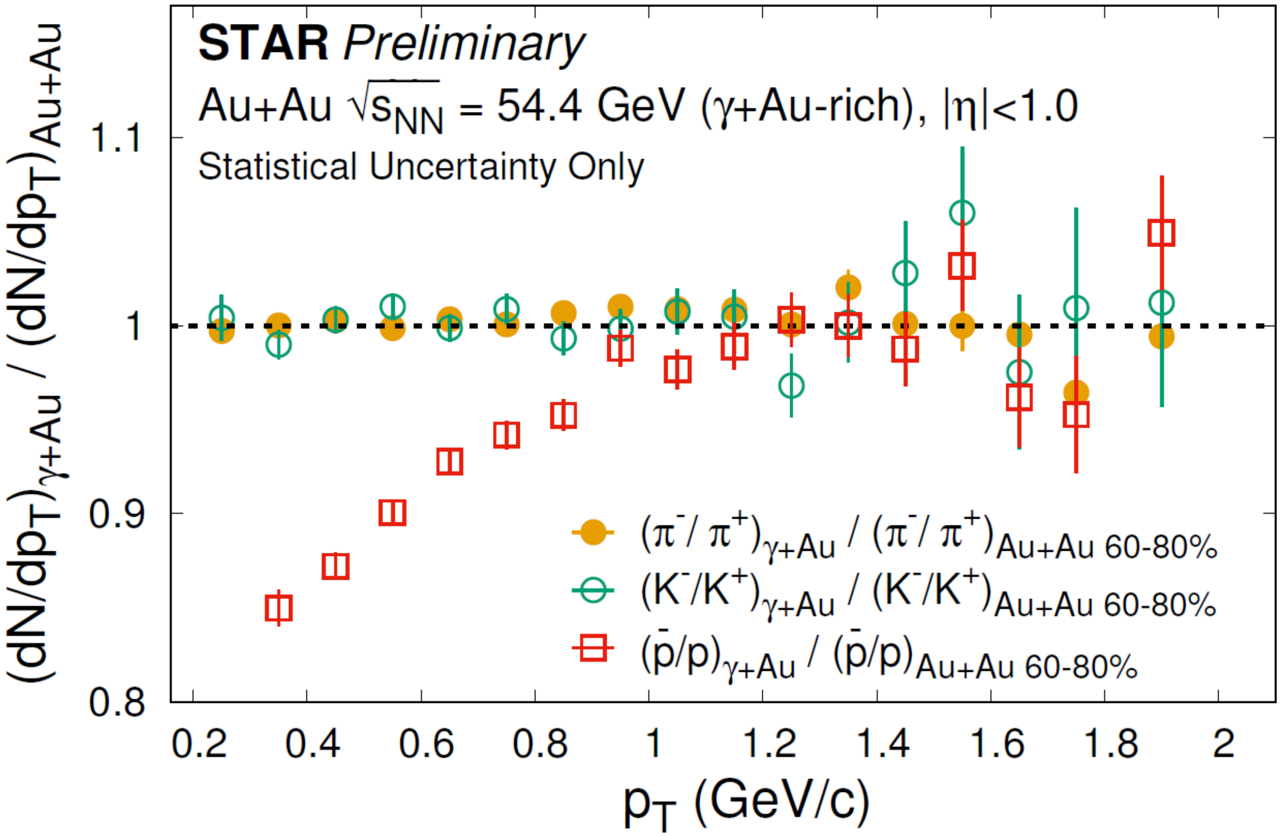


CORE



Summary

- Studied identified particle spectra in photonuclear events via $\sqrt{s_{NN}} = 54.4$ GeV Au + Au ultraperipheral collisions
- Baryon stopping observed at low p_T
  - Possible evidence of a baryon junction existing inside nucleon



Next Steps

- Measure these particle ratios as a function of rapidity and multiplicity
- Measure the spectra and yields vs rapidity to compare with baryon junction prediction $(dN/dy \propto \exp(-y/2))$
- Measure of azimuthal and rapidity correlations in photonuclear events
- Unbiased Au + Au collisions from 2019 data set with $\sqrt{s_{NN}} = 200$ GeV

Back Up

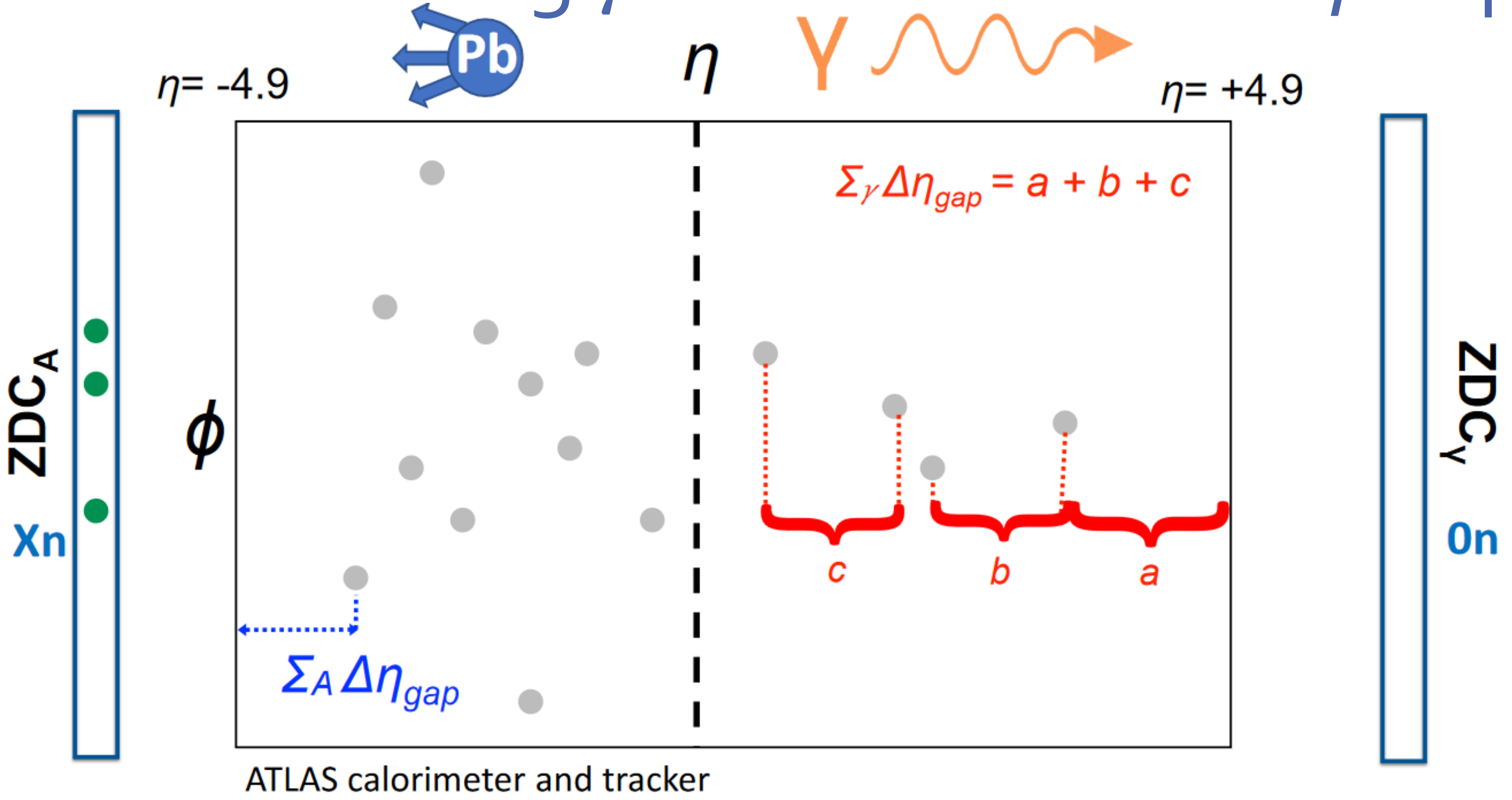
ATLAS - Selecting $\gamma + A$ Events With η Gaps

Pb going direction

photon going direction

Slide from B.D. Seidlitz, Initial Stages 2021

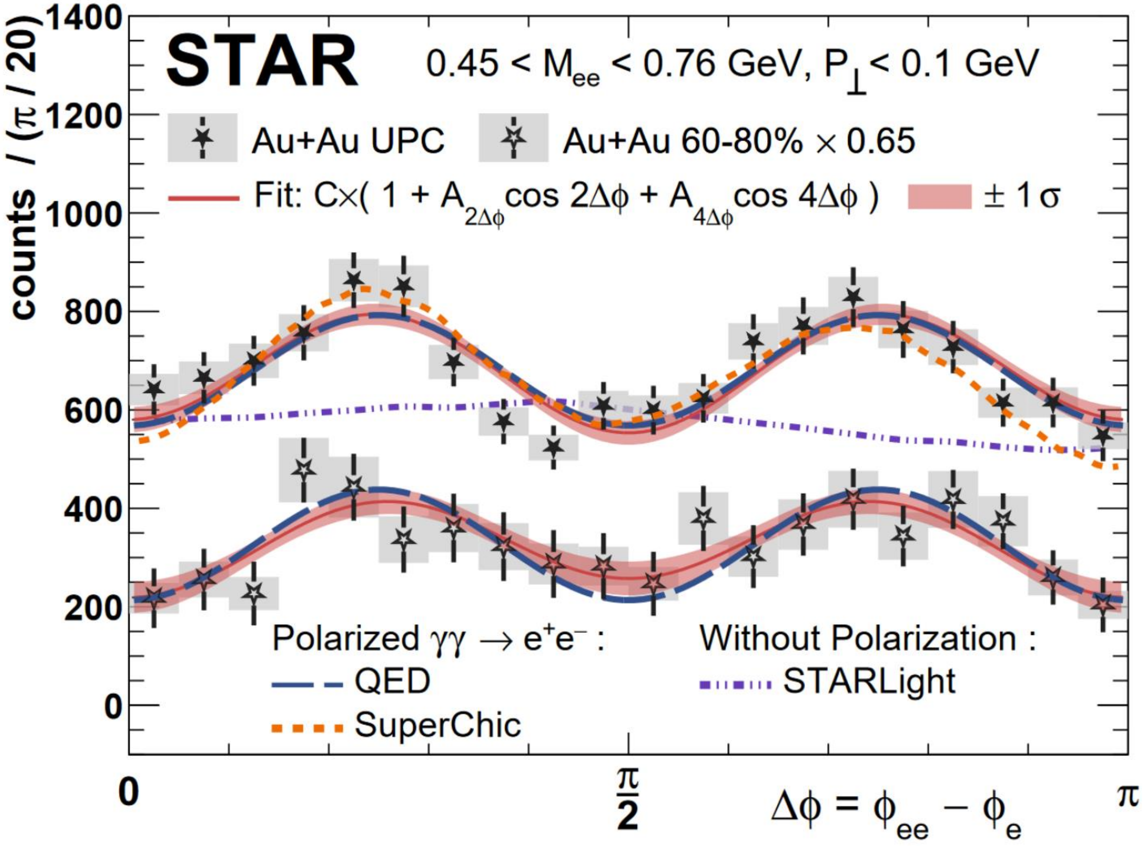
ATLAS - Selecting $\gamma + A$ Events With η Gaps



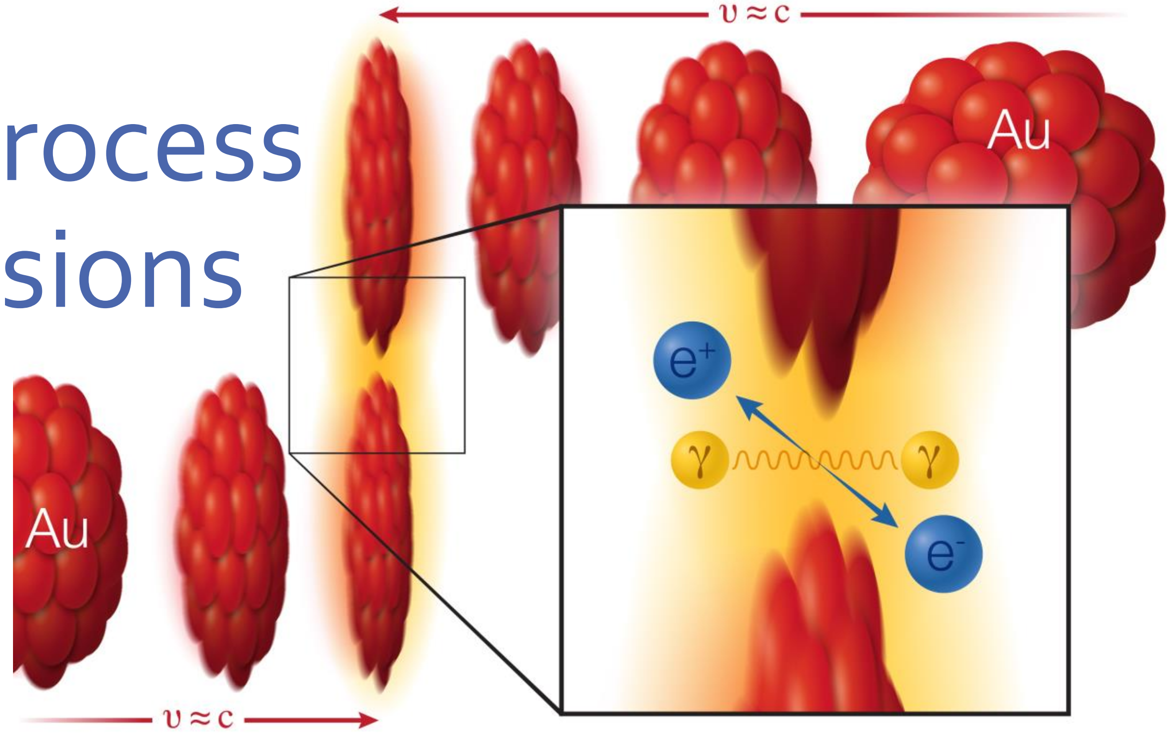
Event Selection: $\Sigma_A \Delta\eta_{gap} < 3$ $\Sigma_\gamma \Delta\eta_{gap} > 2.5$

Slide from B.D. Seidlitz, Initial Stages 2021

STAR-Breit-Wheeler Process in Ultraperipheral Collisions



STAR Collaboration, Phys. Rev. Lett. **127**, 052302 (2021)



"Collisions of Light Produce Matter/Antimatter from Pure Energy". Brookhaven National Laboratory. July 28, 2021

- Photon is quasi-real
- In these UPC collisions, both Au stay intact
  - Photonuclear collisions are asymmetric