Explicit Study of Forward Neutron's Transverse Single Spin Asymmetries as a Function of p_T and x_F in p+p, p+Al, and p+Au Collisions at $\sqrt{s_{NN}}$ = 200 GeV

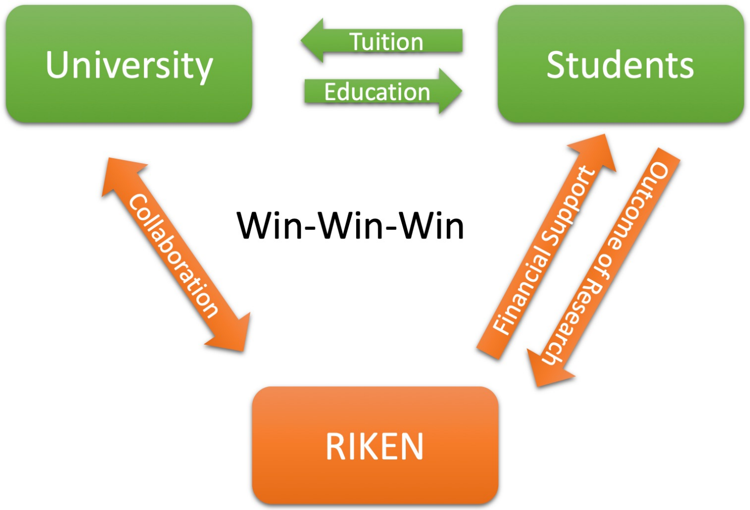
R.Seidl (RIKEN), Y. Goto (RIKEN), *B. Mulilo (UNZA)

6th Korea-Japan PHENIX/sPHENIX/RHICf/EIC Collaboration Meeting

Online

July 15 – 16, 2021

Brief self-introduction



Prof. B. Hong (Advisor-Korea University)

Dr. H. En'yo (Chief Scientist-
RIKEN Radiation Laboratory)

Dr. Y. Akiba (Spokesperson-PHENIX)

KUNPL/HANUL

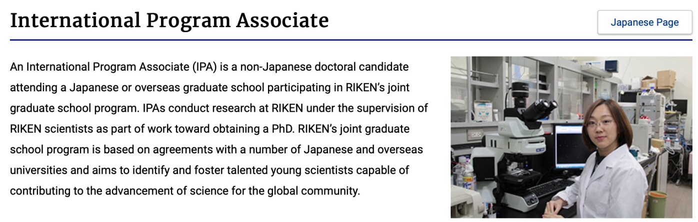
Dr. R. Seidl (Supervisor–RIKEN)
Convener-PHENIX Spin PWG

Dr. Y. Goto (Supervisor–RIKEN)

Dr. I. Nakagawa (Supervisor–RIKEN)

Brief self-introduction

Dr. H. En'yo (Chief Scientist–RIKEN (left), Dr. R. Seidl (my supervisor-RIKEN (middle), and myself (right)

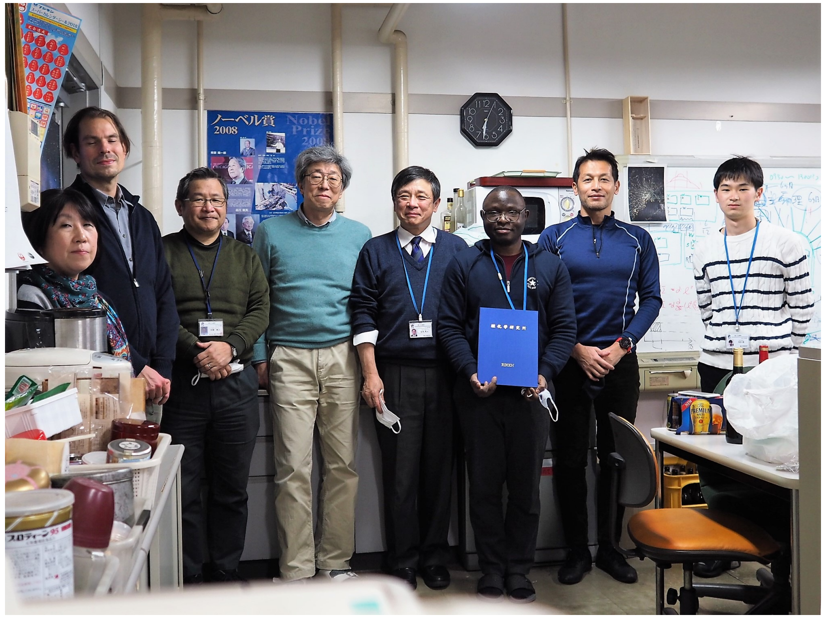


International Program Association

Japanese Page

An International Program Associate (IPA) is a non-Japanese doctoral candidate attending a Japanese or overseas graduate school participating in RIKEN's joint graduate school program. IPAs conduct research at RIKEN under the supervision of RIKEN scientists as part of work toward obtaining a PhD. RIKEN's joint graduate school program is based on agreements with a number of Japanese and overseas universities and aims to identify and foster talented young scientists capable of contributing to the advancement of science for the global community.

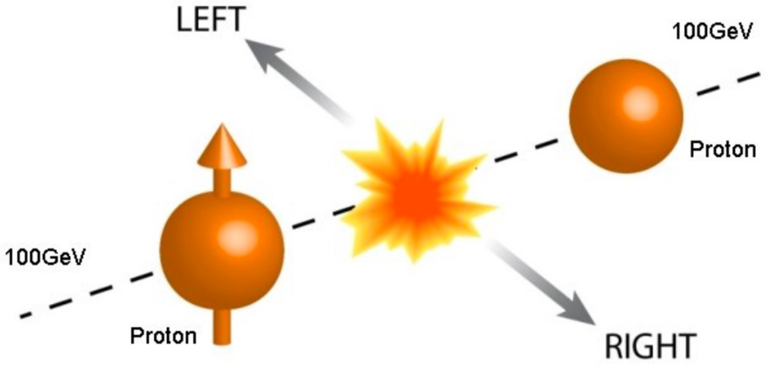
RIKEN International Program Associate completion and farewell party pictures.



RIKEN Radiation Laboratory staff during my farewell party

- Left RIKEN this year in February for Zambia after IPA completion.
- Currently at University of Zambia (UNZA), School of Natural Sciences, Physics Dept.
- Graduation with Korea University in collaboration with RIKEN is this August, 2021.

Transverse single spin asymmetry (A_N)



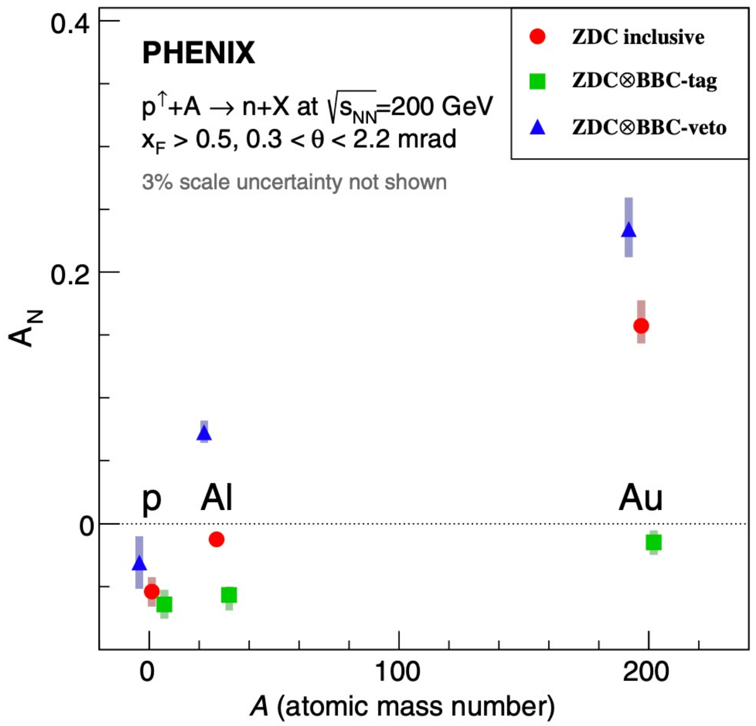
- Transverse single spin asymmetry is quantified by counts on either side of a transvesrely polarized proton beam-going direction (i.e. measure azimuthal asymmetry)

$$A_N = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R}$$

- A_N of particle species (neutrons, pions, eta mesons, electrons, photons, etc.) is calculable this way.

Asymmetry calculation is vital in understanding particle production mechanism leading to an understanding of the proton spin puzzle.

Background: Forward neutron A_N - Nuclear dependence in $p^{\uparrow} + A$ collisions at $\sqrt{s_{NN}} = 200$ GeV (2015 Data)



- Neutron A_N in p+A for $A = 1$ (p), 27 (Al) and 197 (Au) for ZDC inclusive, ZDC ⊗ BBC-tag, ZDC ⊗ BBC-veto triggered samples.

- Strong nuclear dependence of asymmetries observed in p+A contrary to p+p expectation. This was quite surprising.

PRL 120, 022001 (2018)

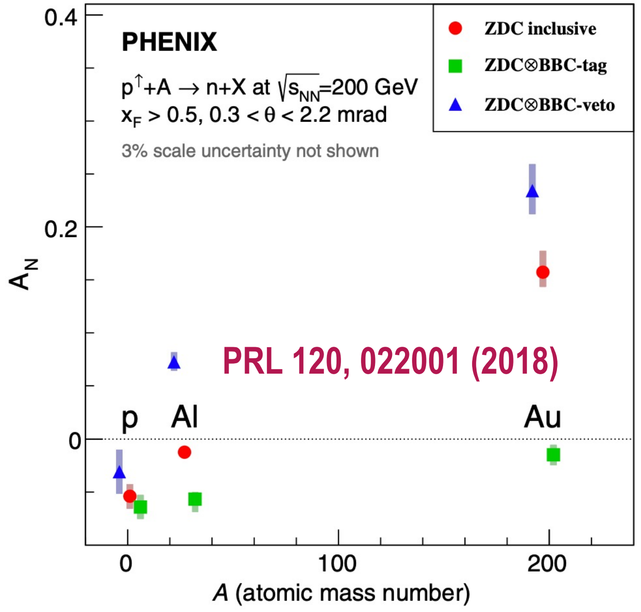
Motivation for further and explicit study to understand p_T and x_F dependence of forward neutron asymmetries and invoking unfolding.

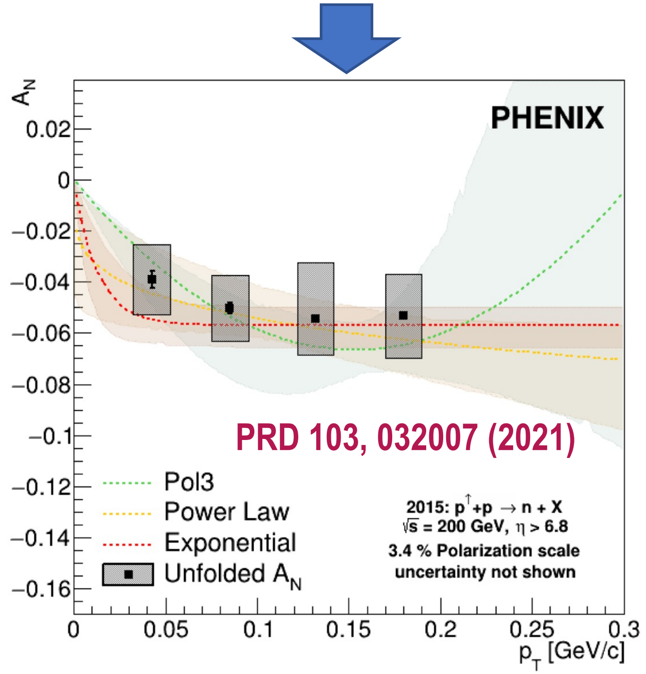
Electromagnetic (EM) and hadronic (HAD) contributions

Transverse momentum dependent forward neutron single spin asymmetries in transversely polarized $p+p$ collisions at $\sqrt{s} = 200$ GeV

U.A. Acharya,[20] C. Aidala,[40] Y. Akiba,[53,54,*] M. Alfred,[22] V. Andrieux,[40] N. Apadula,[27] H. Asano,[33,53] B. Azmoun,[7] V. Babintsev,[23] N.S. Bandara,[39] K.N. Barish,[8] S. Bathe,[5,54] A. Bazilevsky,[7] M. Beaumier,[8] R. Belmont,[11,46] A. Berdnikov,[56] Y. Berdnikov,[56] L. Bichon,[63] B. Blankenship,[63] D.S. Blau,[32,43] J.S. Bok,[45]

Species	Z	N	A
p	1	0	1
Al	13	14	27
Au	79	118	197

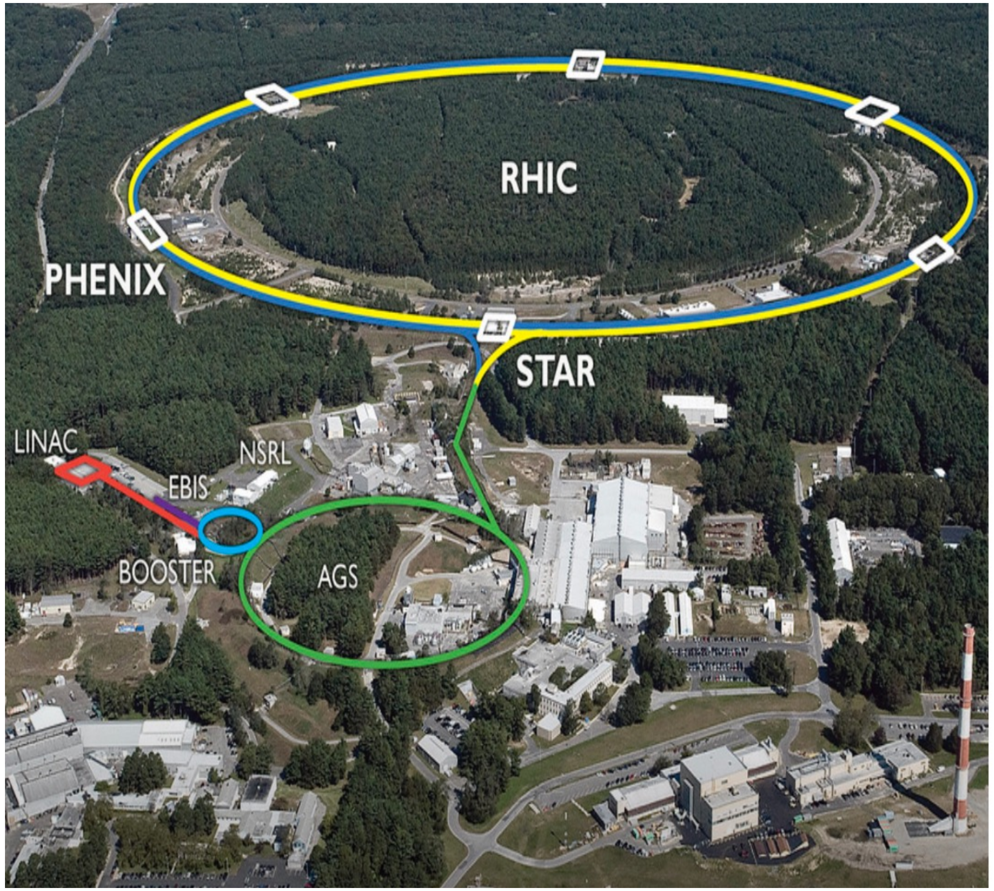


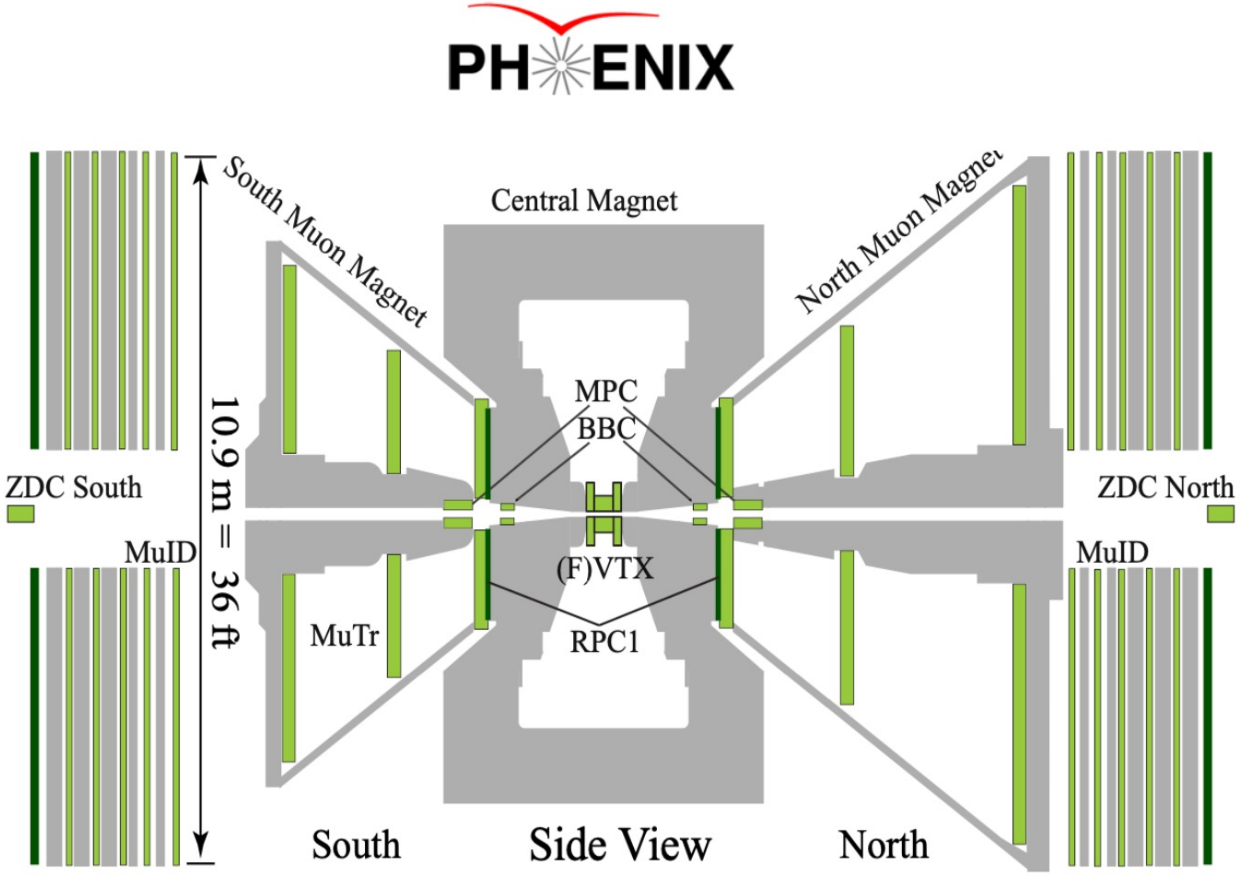


Nuclear dependent single spin asymmetries were large with a sign flip (positive) in p+Au as opposed to asymmetries in p+p.
But just how?

Most obviously, in addition to hadronic, electromagnetic contribution becomes enhanced in p+Au collision than in p+p.
Hence an explicit study of A_N as a function of observables such as p_T and x_F by invoking an unfolding procedure was necessary.

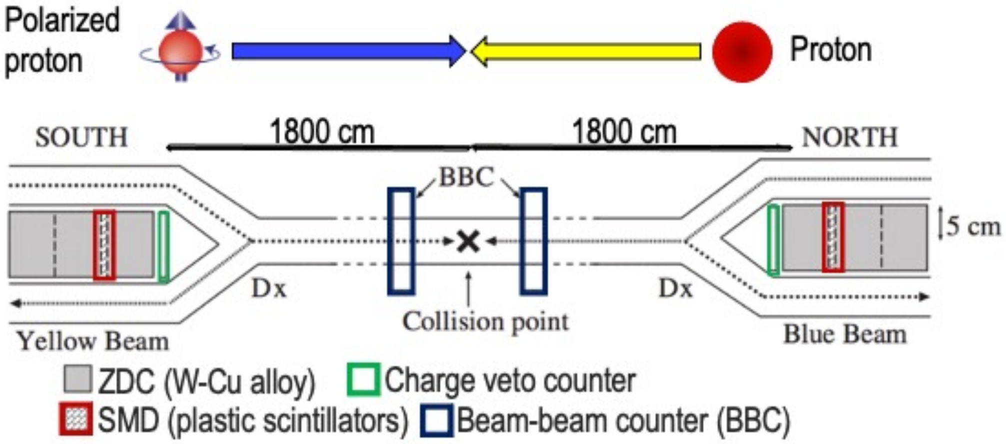
PHENIX detector at RHIC





Zero degree calorimeters (ZDC) on the South and North arms are a detector subsystem utilized for forward neutron measurements.

Zero degree calorimeters (forward neutron measuring detector subsystem of PHENIX)



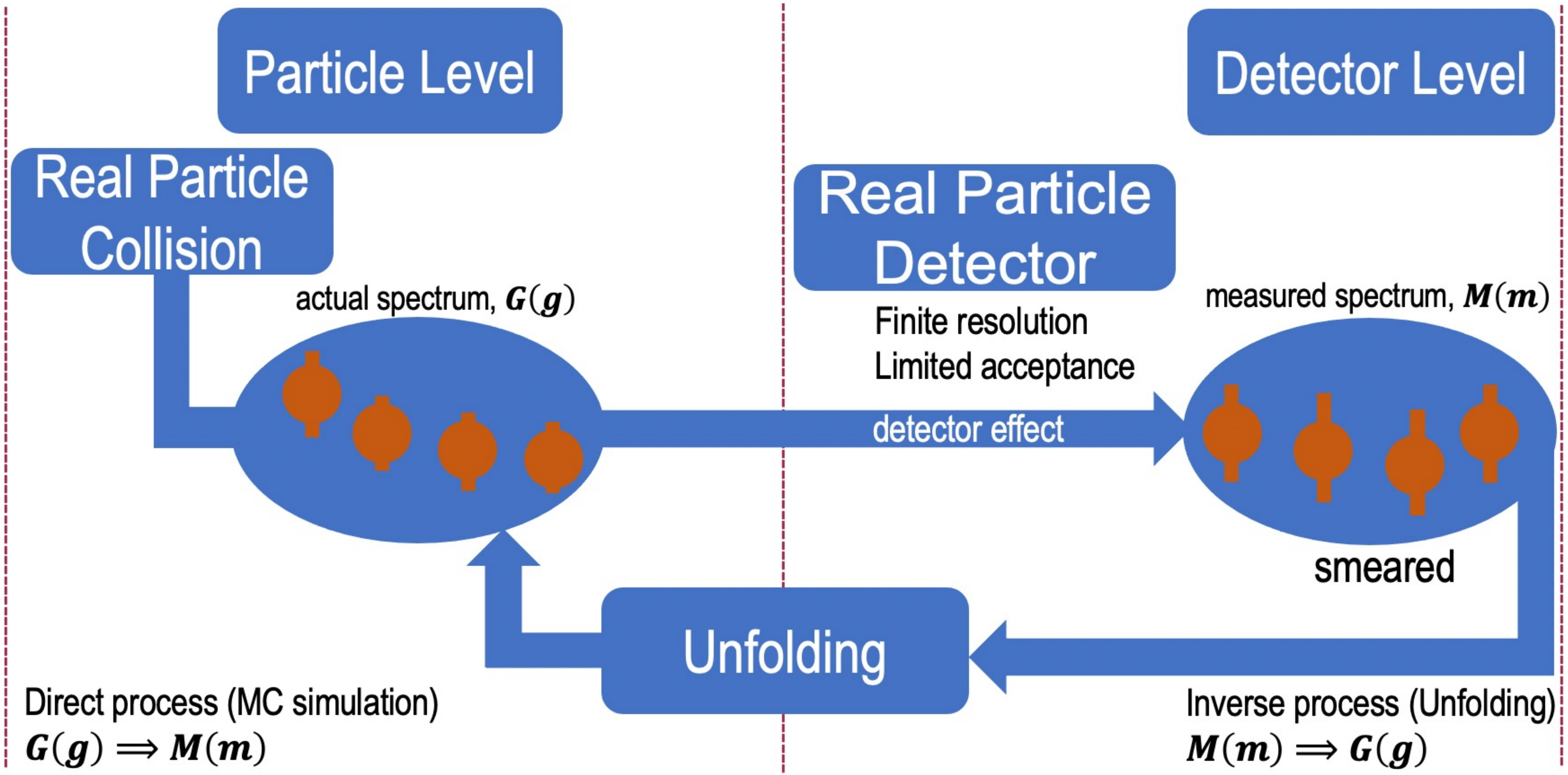
Shower maximum detector ($\sigma \sim 1.0$ cm) between modules 1 and 2 is used for neutron position measurement using a centroid method.

$$\boldsymbol{x} = \frac{\sum_i^{SMD} \boldsymbol{E(i)} \cdot \boldsymbol{x(i)}}{\sum_i^{SMD} \boldsymbol{E(i)}}$$

Measured variables by the zero degree calorimeter are smeared due to the limited acceptance and resolution.

Thus the observed asymmetries need to be corrected for the smearing induced by the zero degree calorimeter using unfolding procedure.

Unfolding overview



Unfolding overview

Direct process (Monte Carlo simulation)

Actual distribution, $\boldsymbol{G}(\boldsymbol{g}) \Longrightarrow \boldsymbol{M}(\boldsymbol{m})$ measured distribution

Inverse process (unfolding)

Measured distribution, $\boldsymbol{M}(\boldsymbol{m}) \Longrightarrow \boldsymbol{G}(\boldsymbol{g})$ actual distribution

Relation

Measured distribution, $\boldsymbol{M}(\boldsymbol{m})$ and actual distribution, $\boldsymbol{G}(\boldsymbol{g})$ are linealy related by

$$A(m, g)G(g) = M(m)$$

$\boldsymbol{A}(\boldsymbol{m}, \boldsymbol{g})$ is a detector smearing response matrix, which is inverted $(\boldsymbol{A}^{-1})$ to obtain an actual distribution using a more robust three-dimensional Bayes unfolding procedure in RooUnfold embedded in CERN's ROOT analysis toolkit.

Monte Carlo (MC) sampling

Composition, energy, momentum, etc. in the forward region is not well understood → sampled five MCs to gauge an impact on the unfolded asymmetries as a function of p_T in x_F bins.

- DPMJet (HAD interaction)
- PYTHIA6 (HAD interactions)
- PYTHIA8 (HAD interactions)

Full event generators chosen because of their different treatment of diffractive events.

- OPE (HAD interactions)
  Phenomilogical description of forward HAD cross sections in terms of a one pion exchange (OPE) model.

- UPC (electromagnetic (EM) interactions): STARLIGHT event generator of the photons in proton-nucleus collisions.

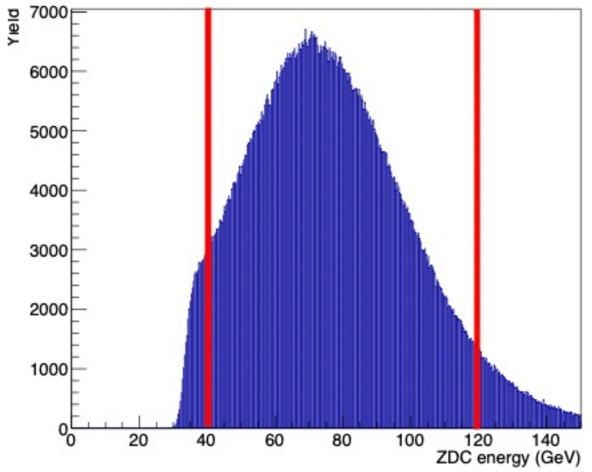
Neutron selection criterion

p+p, p+Al, and p+Au collisions

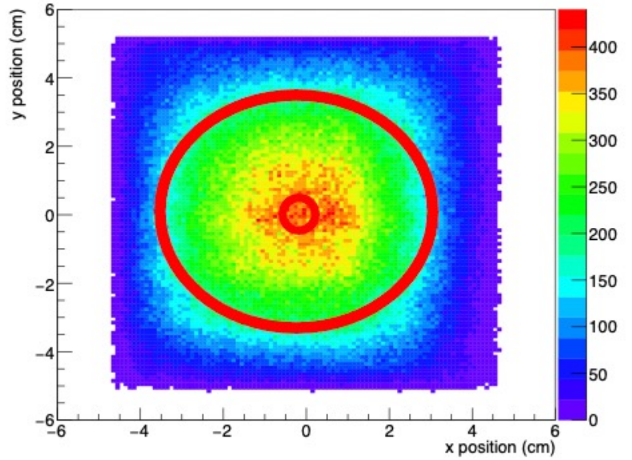
Sample	Detector correlation
Inclusive	• No BBC requirement. • ZDC N I I ZDC S • 86/4/3 runs.
BBC Tag	• BBC requirement. • BBC N > 0 && BBC S > 0 tubes • All 444/4/3 runs.
BBC Veto	• No BBC tubes fired. • ZDC N I I ZDC S trigger only. • 86/4/3 runs.

High neutron purity basic selection criteria:

- ZDC total energy cut: 40 GeV to 120 GeV
  ZDC is composed of 3 modules: ZDC1, ZDC2, and ZDC3. $E_T = E_{ZDC1} + E_{ZDC2} + E_{ZDC3}$
  Required $E_{ZDC2}/E_T > 3\%$ (photon elimination)



- Acceptance cut: 0.5 cm < r < 4.0 cm
  Position resolution of SMD ~ 1.0 cm.
  0.5 cm to counteract left-right dilution
  4.0 cm used to reduce neutron edge dilution



- SMD threshold cut
  Photon rejection
  Required Nx and Ny > 1 fired above 0.003 GeV

Transverse momentum (p_T) and longitudinal momentum fraction x_F variables

Collision species:

- p+p
- p+Al
- p+Au

Collision energy:

- $\sqrt{s_{NN}} = 200$ GeV

Pseudo rapidity:

- $\eta > 6.8$

Neutron sample:

- Inclusive
- BBC tag
- BBC veto

$$p_T = \frac{r}{z_{ZDC}} E$$

$$x_F = \frac{\sqrt{E^2 - p_T^2}}{100}$$

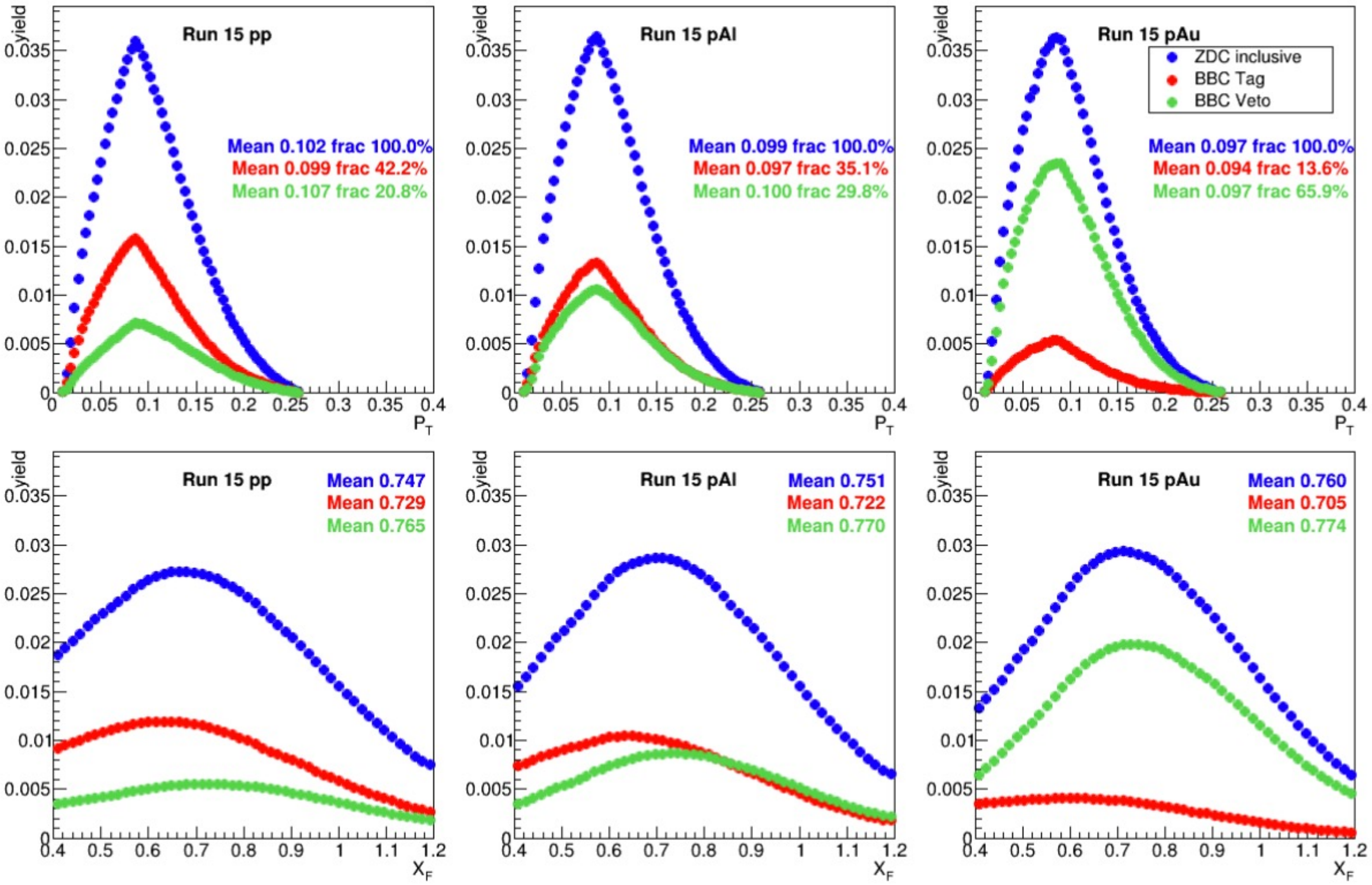
p_T binning:

- $0.01 < p_T < 0.06$ [GeV/c]
- $0.06 < p_T < 0.11$ [GeV/c]
- $0.11 < p_T < 0.16$ [GeV/c]
- $0.16 < p_T < 0.21$ [GeV/c]

x_F binning:

- 0.01 < pT < 0.06 [GeV/c]
- 0.06 < pT < 0.11 [GeV/c]
- 0.11 < pT < 0.16 [GeV/c]
- 0.16 < pT < 0.21 [GeV/c]

Transverse momentum (p_T) and longitudinal momentum fraction x_F variables



Asymmetry extraction

Asymmetries were calculated in each of transverse momentum and longitudinal momentum fraction bins as:

$$A_N(\phi) = \frac{1}{P}\frac{N_L^{\uparrow}(\phi) - \mathcal{R}N_L^{\downarrow}(\phi)}{N_L^{\uparrow}(\phi) + \mathcal{R}N_L^{\downarrow}(\phi)}$$

- P =Average beam polarization
- $N^{\uparrow\downarrow}$ = Neutron yields with the polarized proton beam spin oriented up or down.
- $\mathcal{R}$ = Ratio of accumulated luminosities ($\mathcal{R} = 1$)
- Asymmetries were then fit with a sine modulation.
- For systematic studies, phase and absolute normalization were left to vary.

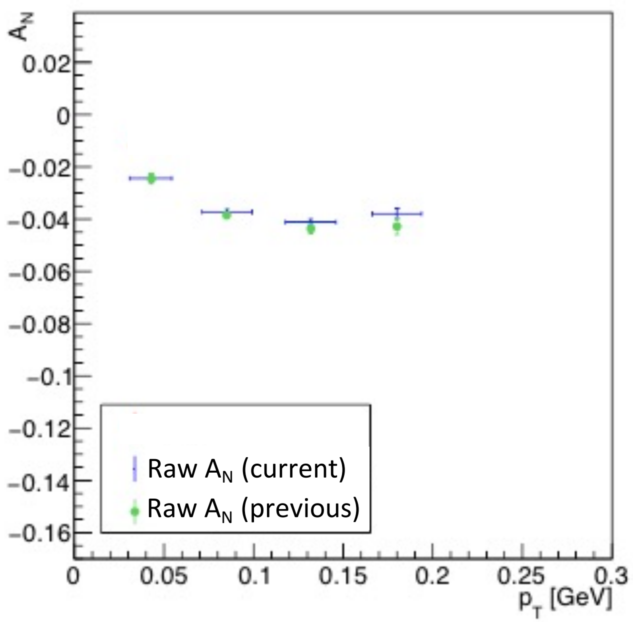
Raw asymmetries were confirmed by using a square-root formula:

$$A_N = \frac{1}{P}\frac{\sqrt{N^{\uparrow}(\phi)N^{\downarrow}(\phi+\pi)} - \sqrt{N^{\downarrow}(\phi)N^{\uparrow}(\phi+\pi)}}{\sqrt{N^{\uparrow}(\phi)N^{\downarrow}(\phi+\pi)} + \sqrt{N^{\downarrow}(\phi)N^{\uparrow}(\phi+\pi)}}$$

Geometric mean left/right yields cancel out differences in detector acceptance and luminosities between two spin orientations.

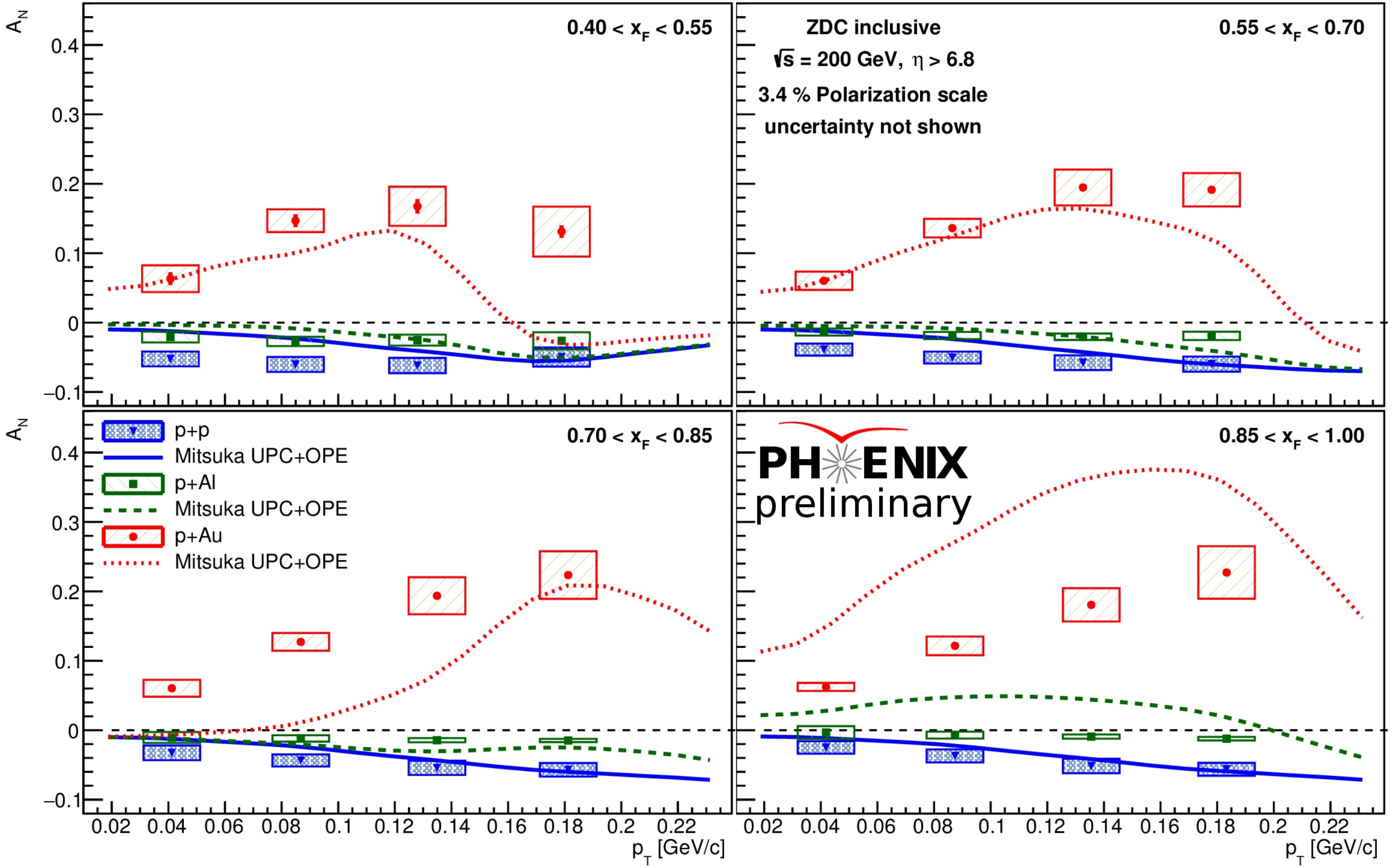
Raw asymmetry cross check

Polarization weighted raw A_N



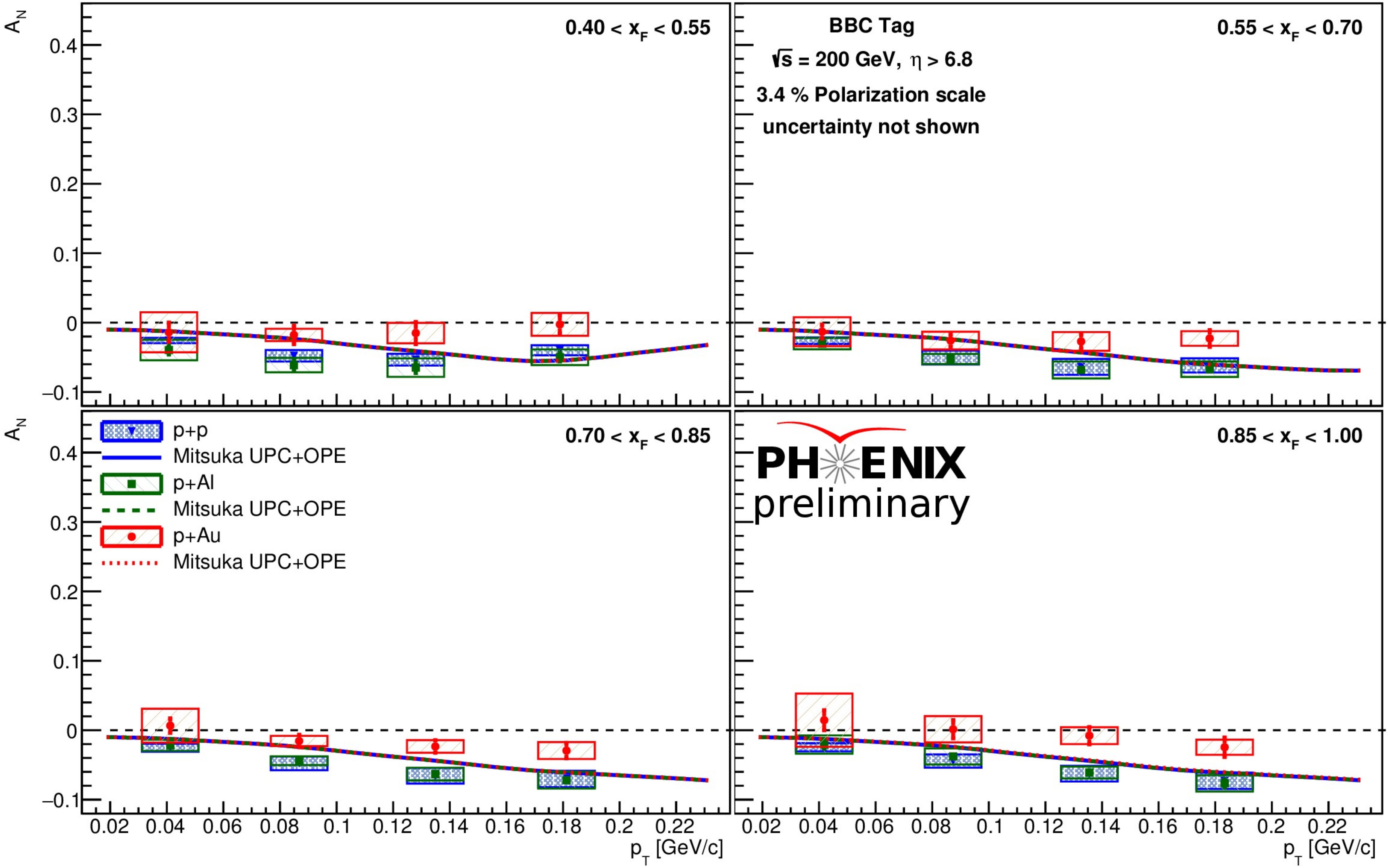
Both raw asymmetry results were consistent to each other and no systematic uncertainty was assigned to the asymmetries.

Inclusive results



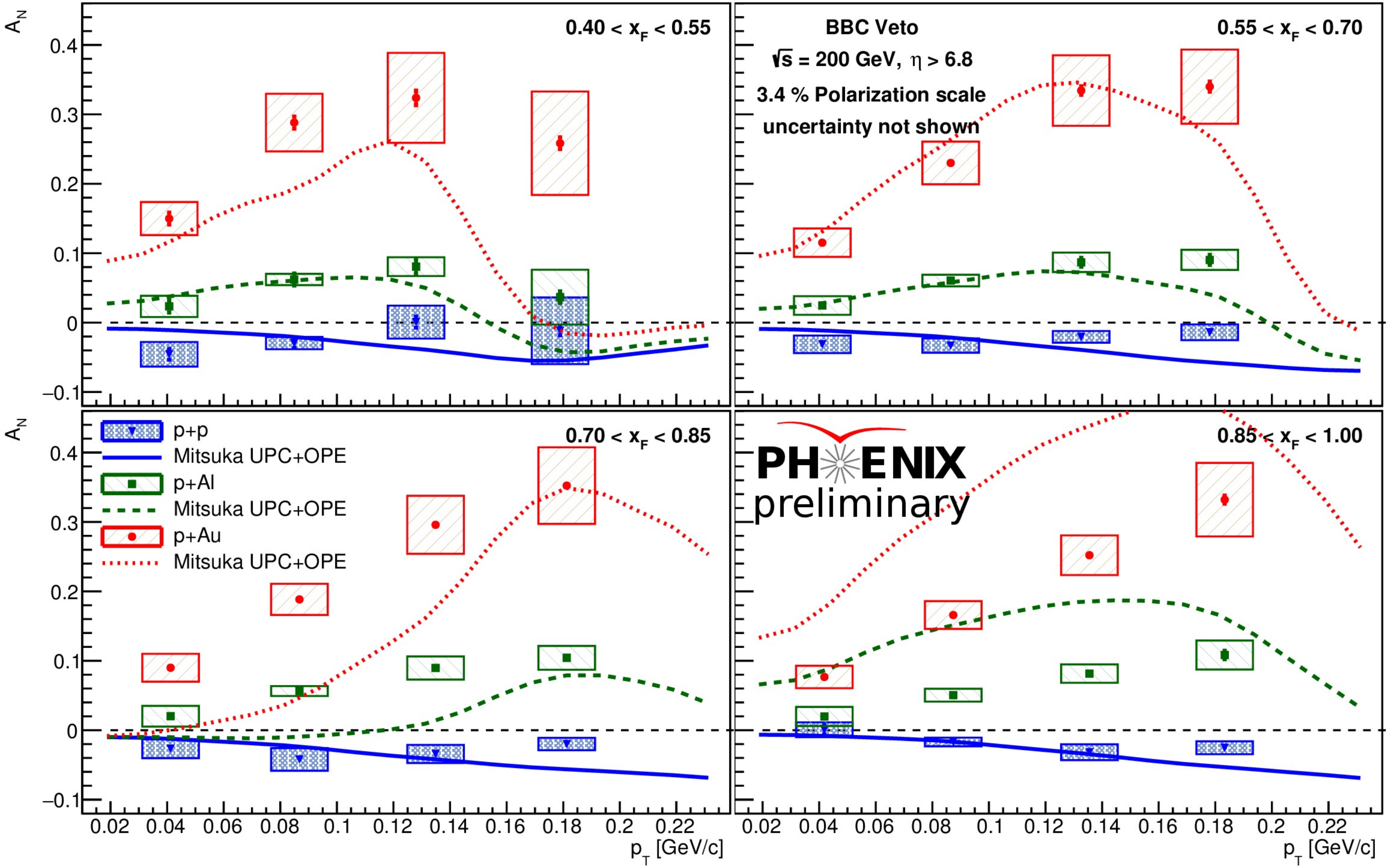
Inclusive neutrons display very different asymmetry behavior likely from the interplay between hadronic and UPC contributions.

BBC-tagged results



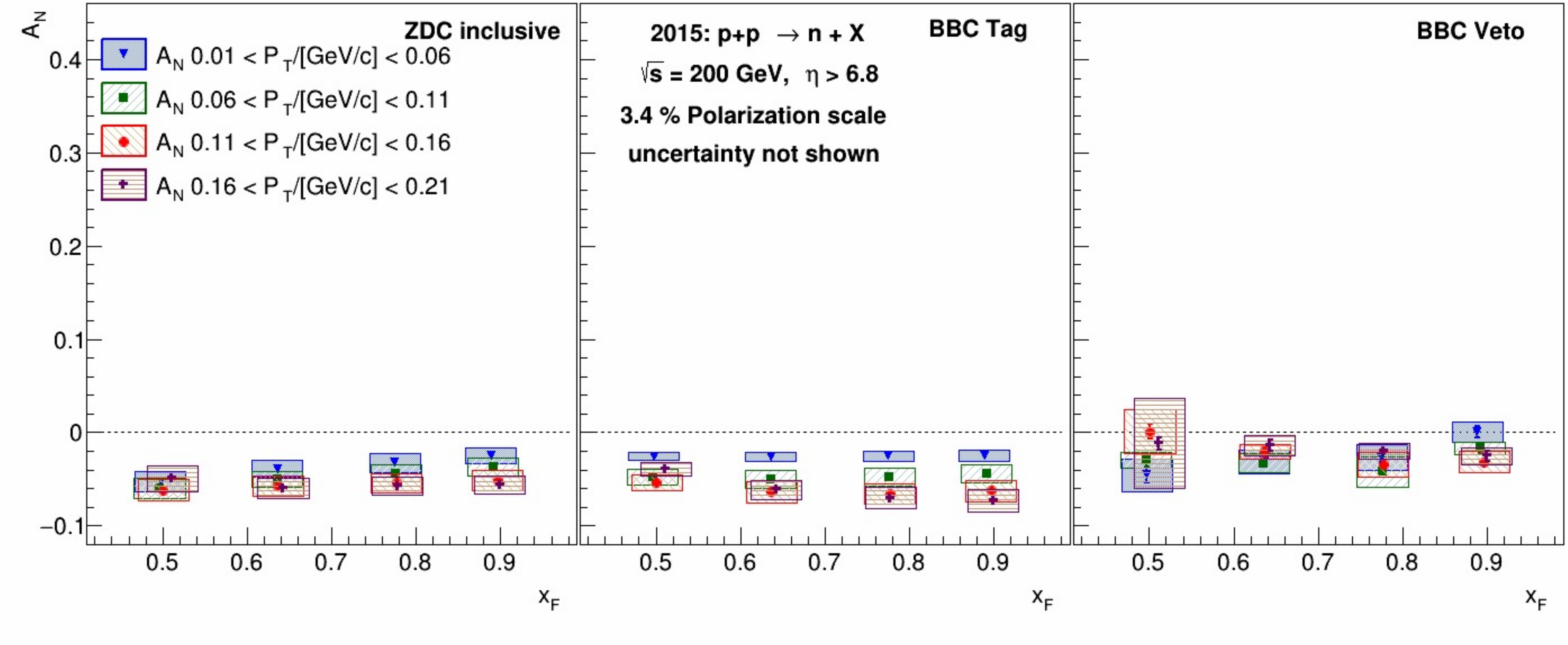
BBC tagging enhances hadronic contributions resulting in asymmetries that are mostly negative for all three collision species.

BBC-vetoed results



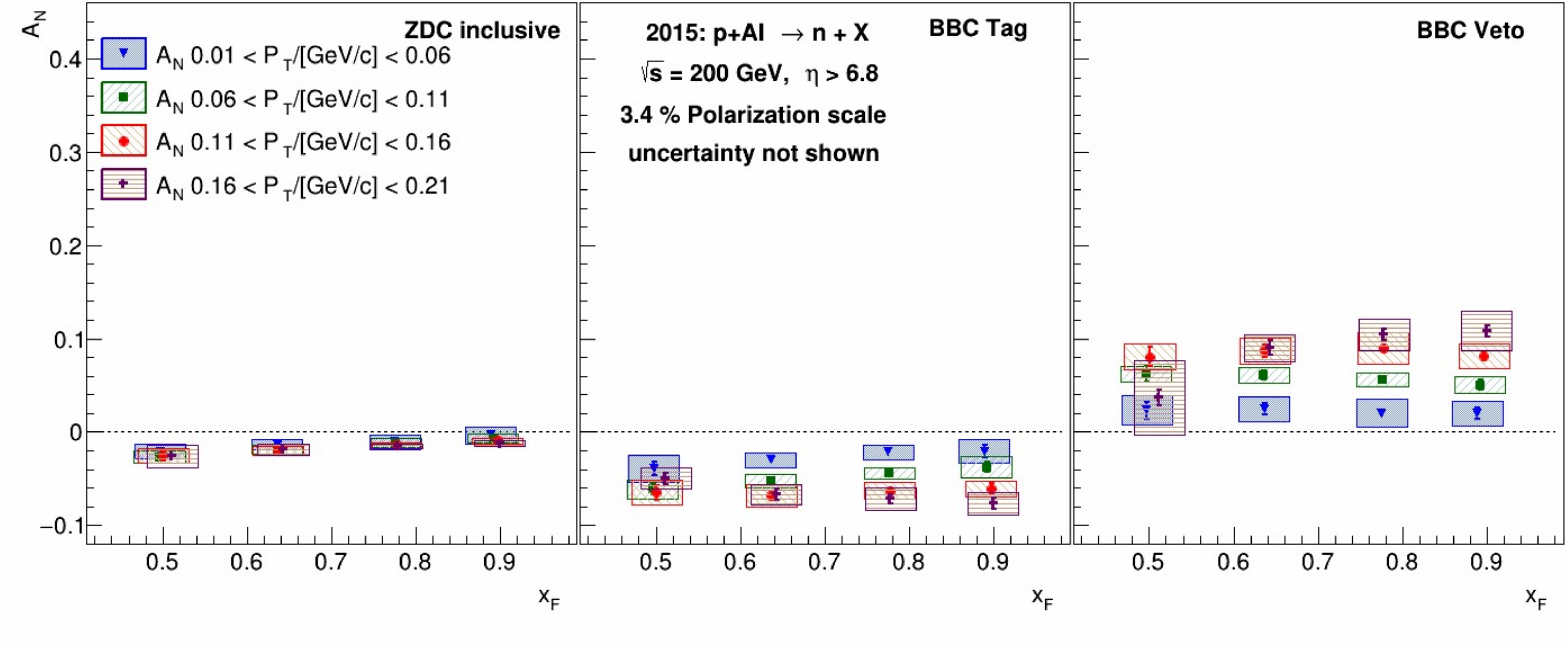
In BBC veto, UPC asymmetry contribution nowdominates over hadronic resulting in large, and now positive asymmetries in pA collisions.

Explicit x_F dependence in p+p



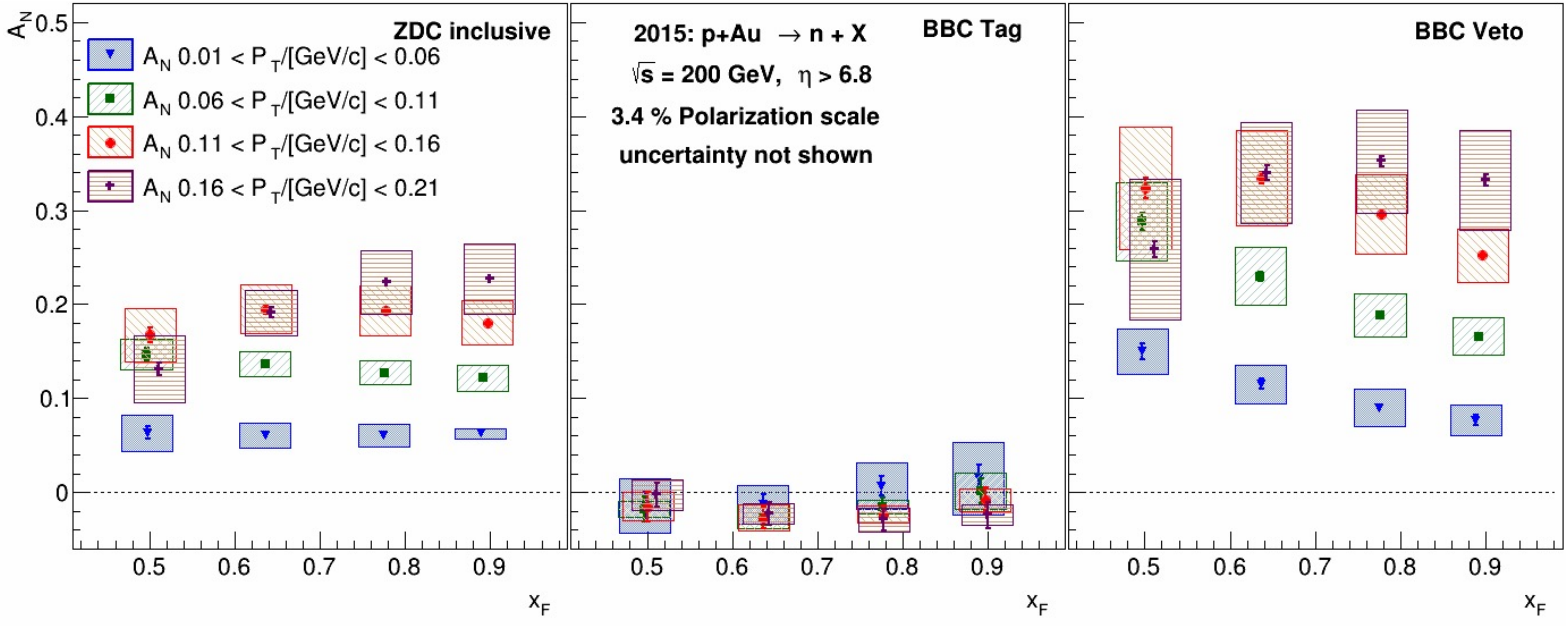
Explicit x_F dependence of the asymmetries in bins of p_T for inclusive, BBC-tagged, and BBC-veto triggered events in p+p collisions.

Explicit x_F dependence in p+Al



Explicit x_F dependence of the asymmetries in bins of p_T for inclusive, BBC-tagged, and BBC-veto triggered events in p+Al collisions.

Explicit x_F dependence in p+Au



Explicit x_F dependence of the asymmetries in bins of p_T for inclusive, BBC-tagged, and BBC-veto triggered events in p+Au collisions.

Summary

- In p+p collisions, hadronic interaction is the main contributing process to the asymmetries than EM interaction.
- As Z increases, the charge also increases giving rise to enhanced A_N via EM contribution in p+A collisions.
- Inclusive neutrons display very different A_N behavior likely from an interplay between HAD and UPC.
- BBC tagging enhances HAD contributions resulting in A_N that is mostly negative for all three collision species.
- In BBC veto, UPC A_N contribution dominates over HAD resulting in large and now positive A_N in p+A collisions.