Transverse Momentum Dependent Forward Neutron Transverse Single Spin Asymmetries in Proton-Proton Collisions at $\sqrt{s} = 200$ GeV

ASP ONLINE SEMINAR

BY

B. MULILO (PhD)
DEPARTMENT OF PHYSICS
UNIVERSITY OF ZAMBIA

THE UNIVERSITY OF ZAMBIA
SERVICE AND EXCELLENCE

NOVEMBER 9, 2021 – 15:00 HRS CAT

PHENIX

EDUCATION

Postgraduate Studies – Ph. D (Nuclear and High Energy Physics)

Korea University (Korea) ⟷ RIKEN (Japan)

Supervisors – RIKEN Research Scientists

Advisor
Prof. B. Hong

KUNPL members

Dr. H. En'yo

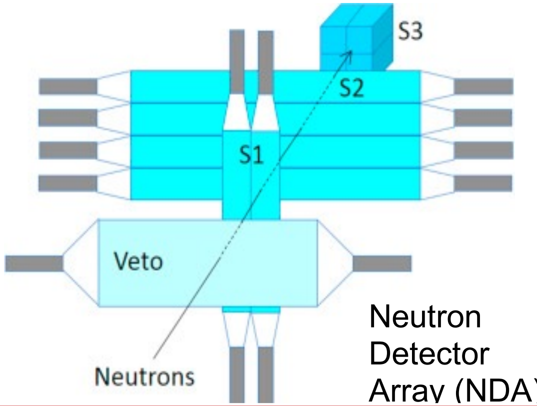
Dr. R. Seidl

Dr. Y. Goto

Dr. I. Nakagawa

EDUCATION

Postgraduate Studies – MSc in Experimental Nuclear Physics)
Korea University
Seoul - Korea



Neutron
Detector
Array (NDA)

EDUCATION AND WORK

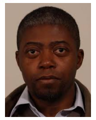
Undergraduate Studies – BSc in Physics University of Zambia Lusaka - Zambia

THE RAINBOW SCHOOL OF PHYSICS [ASP2010 – South Africa]

Students from 17 African countries took part in the first African School of Fundamental Physics and its Applications (ASP2010), which took place this month in South Africa. The school, organized by several physics laboratories including CERN, not only met but in some cases far exceeded the students' expectations. Their enthusiasm made the organizers' efforts worthwhile.

The participants to the first African School of Fundamental Physics and its Applications photographed with some of the school's organizers.





The first ASP received a great deal of interest in the African community and the organizers had a hard time selecting between the very motivated applicants. "The participating students were selected to come from various backgrounds and education levels", says the head organizer, Christine Darve. "At the school the students, lecturers and organizers shared the same dynamism and this allowed everybody to build durable networks in a physics world without borders," she continues enthusiastically.

Participated in first ASP-2010 – interacted with ASP notable people - Ketevi, Christine, Steve, etc.

Talk Outline

Introduction
- Motivation
- Transverse single spin asymmetries

Experimental system
- PHENIX detector at RHIC
- Neutron detector system

Unfolding analysis
- Unfolding procedure
- Re-weighting procedure

Results and discussion
- Unfolded asymmetry results based on polynomial
- Unfolded asymmetry results based on power law
- Unfolded asymmetry results based on exponential
- Combined result with systematic uncertainties

Summary and conclusions

Motivation

Imagine hitting a billiard ball with another billiad several times!

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Observe times the billiard scatters to the left or right!

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Observe times the billiard scatters to the left or right!

PUZZLING OUTCOME??

On several trials, the billiard scatters more to the right than to the left

Motivation

HOW ?

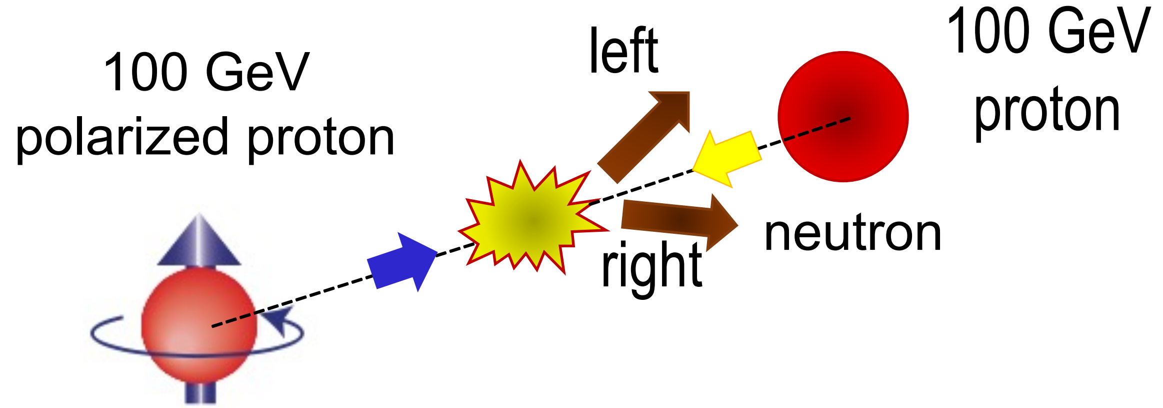
What is the cause of this bias technically known as the 'asymmetry'?

Curiosity and ability to find answers to several natural occurences in our Universe is what has favored man to be on top of the food chain. Need to explore!

Billiad-ball scenario imagination is similar to what we encountered (i.e. the PHENIX Collaboration at Brookhaven National Laboratory – BNL) in an experiment of the collision of a proton with another proton at a total collision energy of 200 GeV.

Proton – Proton Collision Experiment at BNL, New York

experiment first done almost
a decade ago

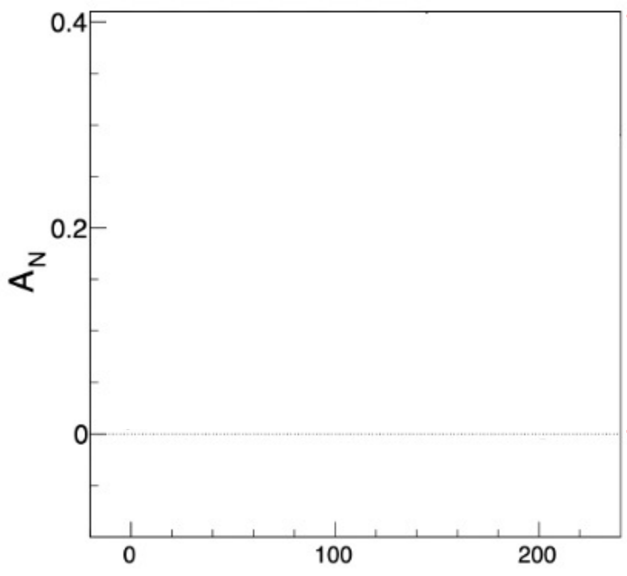


neutrons produced from p+p collisions are more to the right or left → left-right neutron asymmetry.

Since polarization is in transverse orientation →transverse spin asymmetry (A_N).

Proton – Proton Collision at 200 GeV

Graphical illustration of transverse spin asymmetry



positive or left asymmetry (A_N)

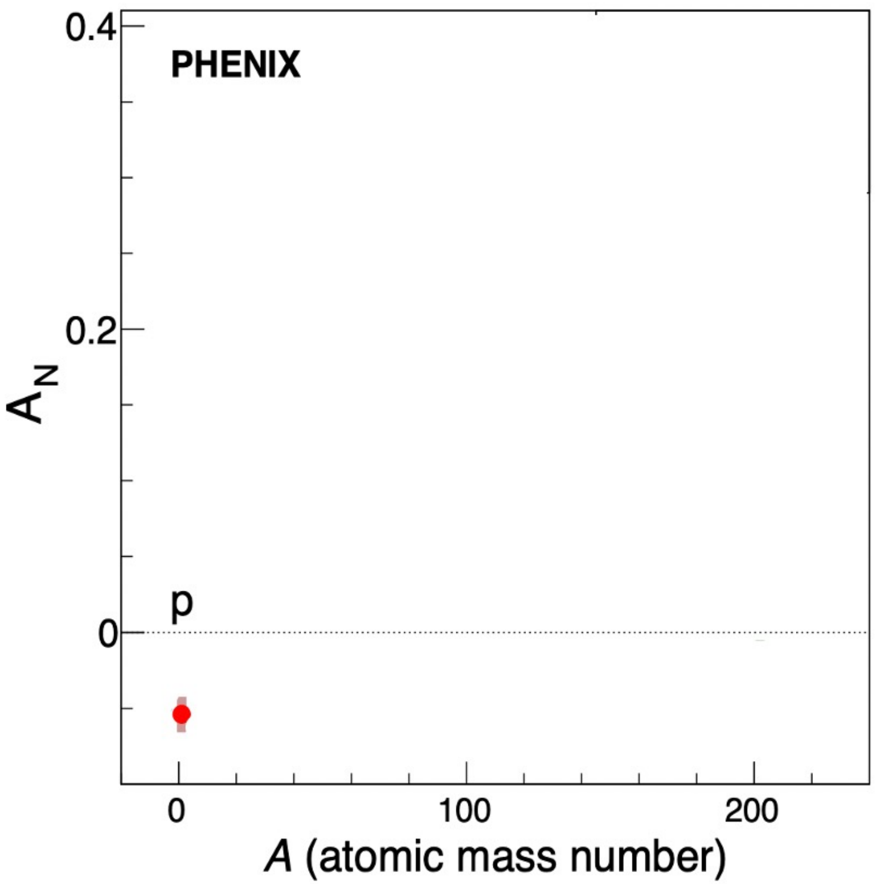
reference (zero point)

negative or right asymmetry (A_N)

Any interesting variable, e.g . mass, energy, momentum, etc.

zero (no) asymmetry

Proton – Proton Collision at 200 GeV 2015 Result



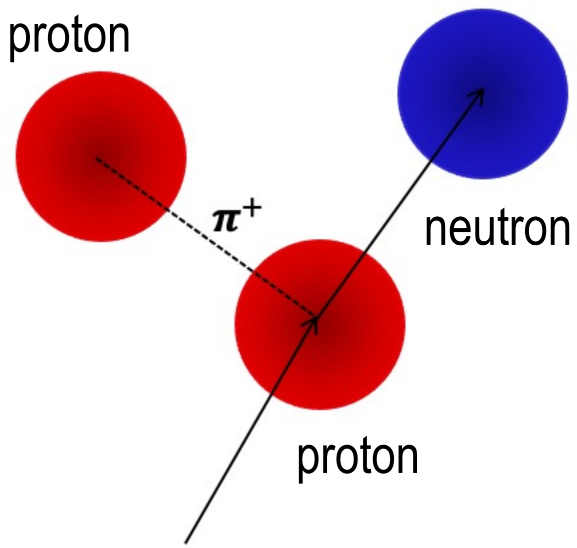
new observation is exciting!

but an understanding of the observation is even more exciting

thus, origin of this large neutron asymmetry (~ 5%) need to be well understood

First Theoretical Attempt to Understand Origin of Large A_N

One pion exchange (OPE) model



forward neutron carries large
fraction of proton energy for $p_T < 0.22$ GeV/c

How successful was OPE model in explaining the large neutron A_N ?

FAILED!

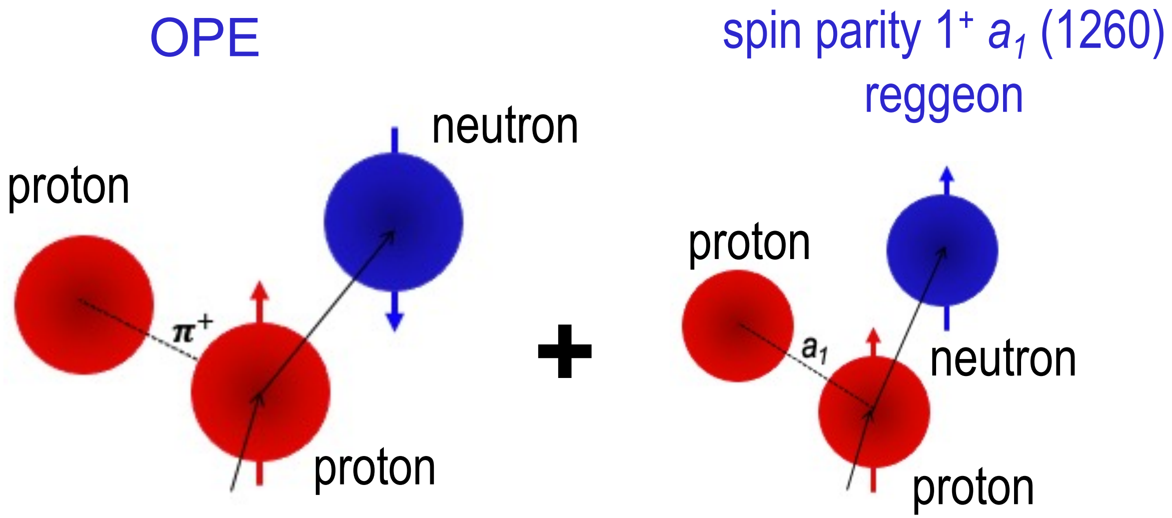
OPE calculated A_N value was too small to reproduce experimentally measured A_N value by PHENIX

but, successful in explaining neutron cross section within

$$0 < p_T \left(\frac{GeV}{c}\right) < 0.22$$

Second Theory Attempt to Understand Origin of Large A_N

Regge model (OPE + a_1 reggeon)

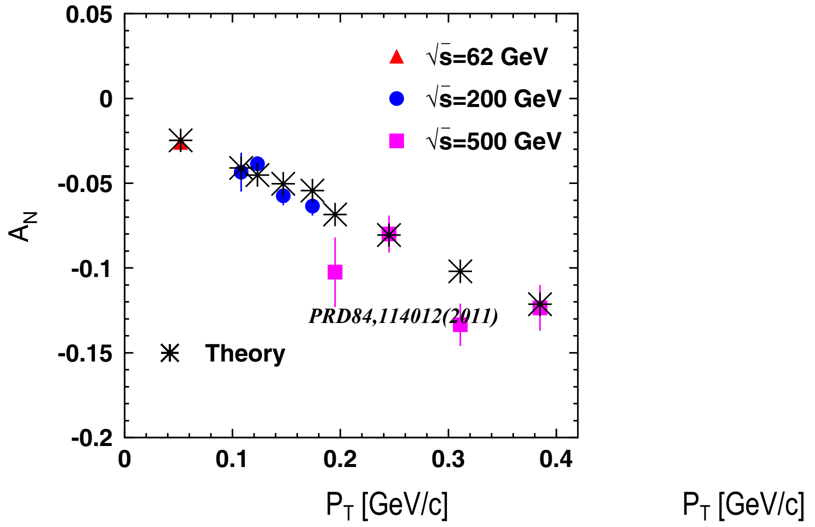


$$A_N \approx \frac{|\sigma_{non-flip}||\sigma_{flip}|sin\delta}{\underbrace{\sigma^2_{non-flip} + \sigma^2_{flip}}_{\text{cross section}}}$$

δ: phase shift

Uncorrected PHENIX A_N data at 62, 200, 500 GeV unpublished.

p_T was not explicitly measured.

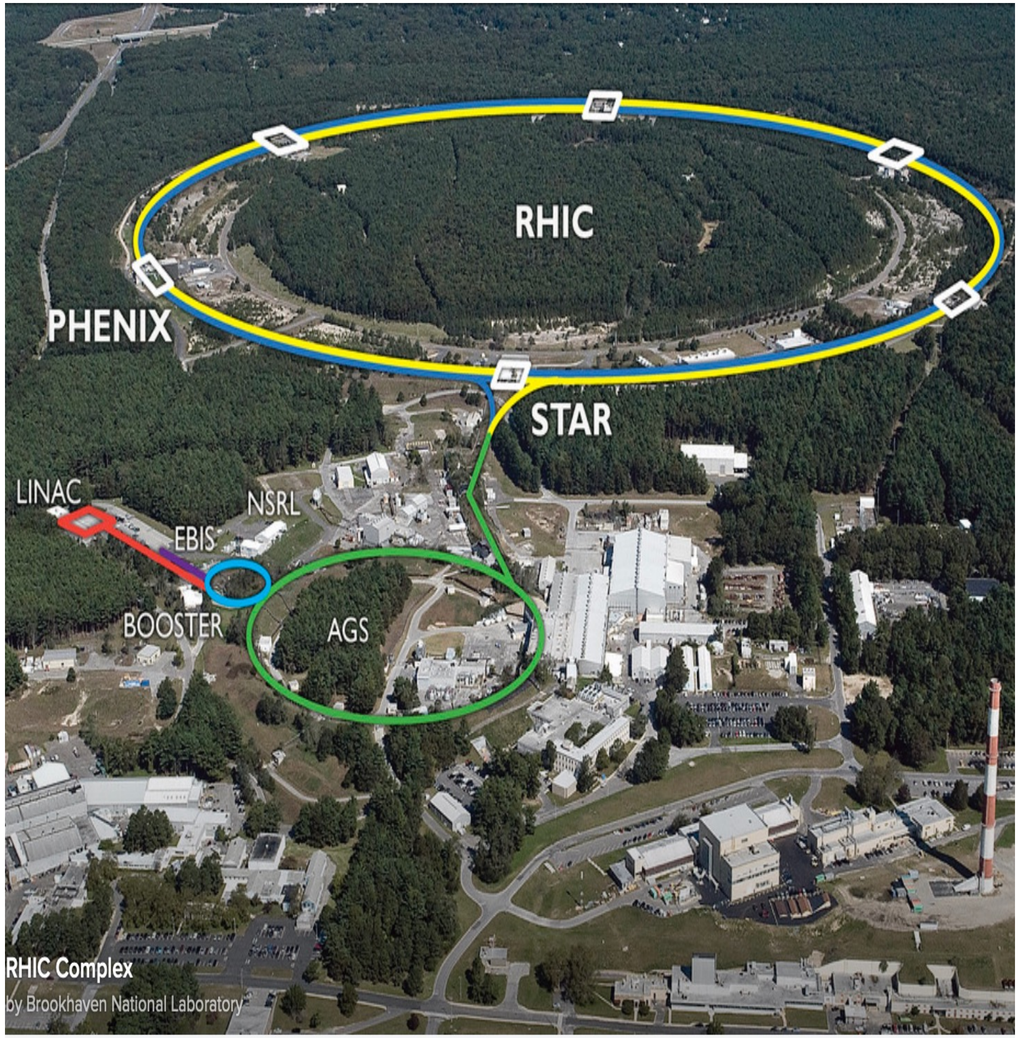


theory points (*) published

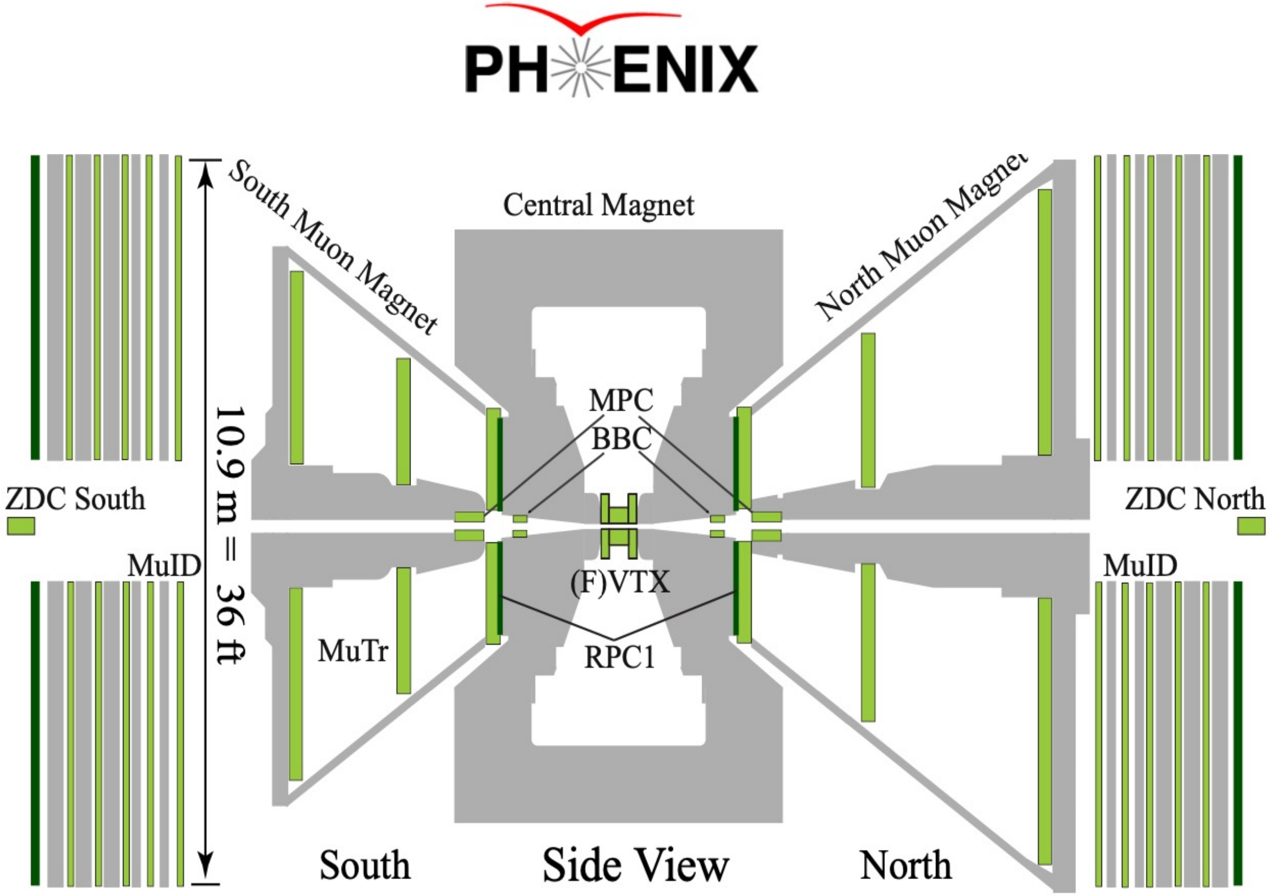
A_N in p+p is produced by interference of π^+ and a_1 amplitudes (Regge theory)

A_N production mechanism is still not well understood, need to explicitly measure the p_T dependence.

Experimental System at the Relativistic Heavy Ion Collider

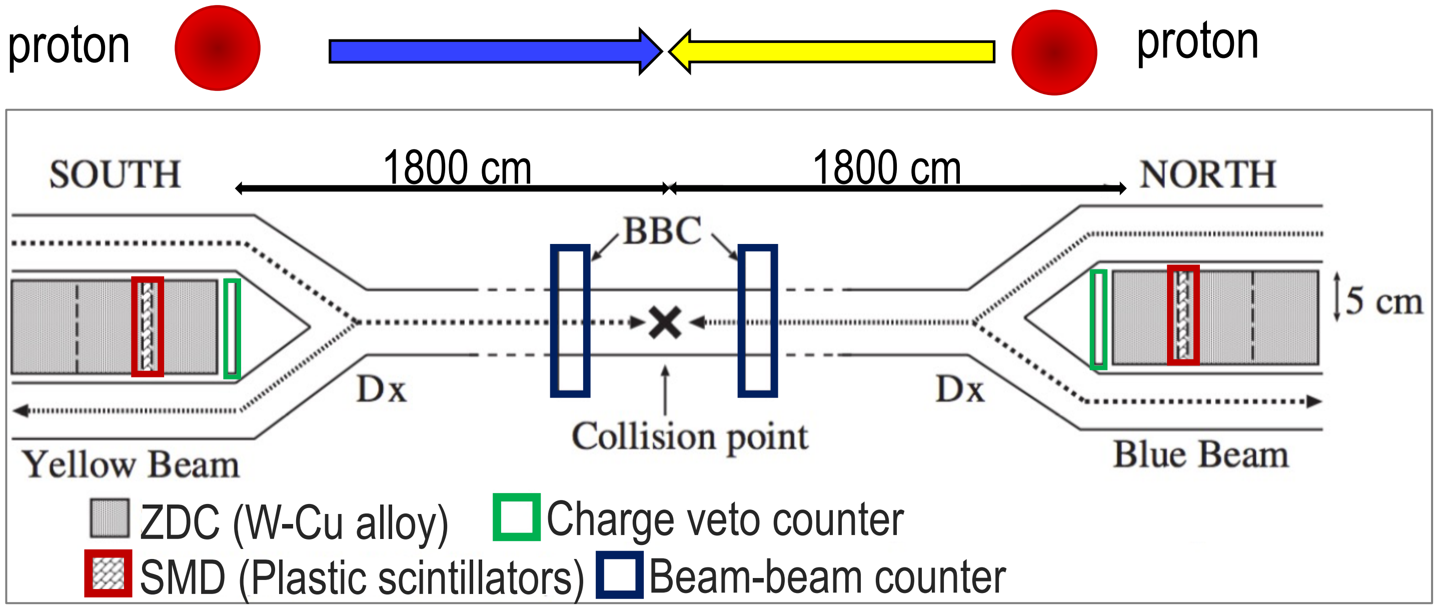


Relativistic Heavy Ion Collider (RHIC) at the BNL



Side view of the PHENIX detector system at RHIC

Forward Neutron Measurement – Zero Degree Calorimeter



ZDC

- 3 modules
- 10 x 10 cm^2
- 1.7 nuclear interaction length/module
- 51 radiation lengths

SMD

7 strips for x-position
8 strips for y-position
$\sigma_{pos} \sim 1\ cm$

Shower max detector (SMD, σ ~ 1 cm): neutron position
ZDC's energy resolution is ~ 20% for 100 GeV neutrons.

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

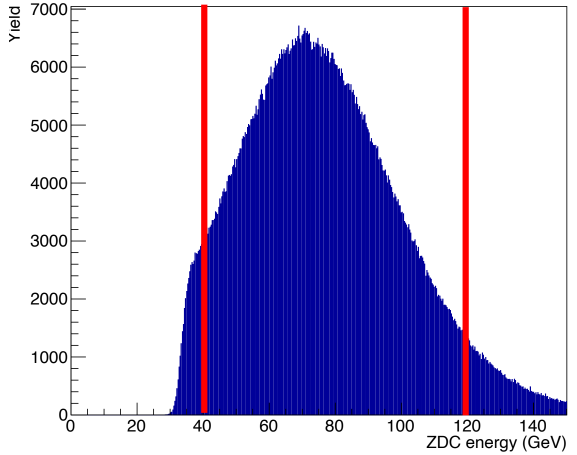
Measured variables are smeared due to limited acceptance and resolution of ZDCs.
Thus A_N as a function of p_T need to be corrected for smearing induced by ZDCs using unfolding.

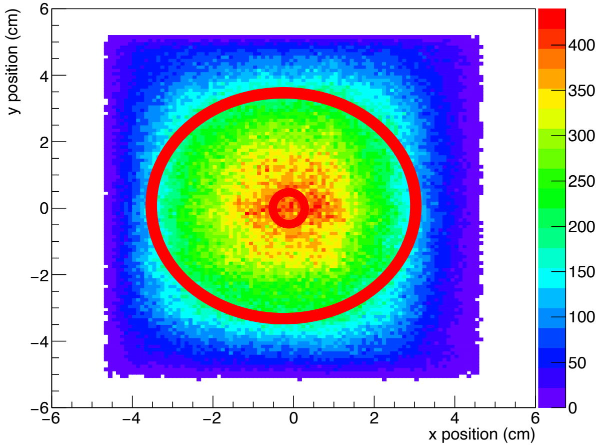
Neutron Selection for the Unfolding of the Observed A_N

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

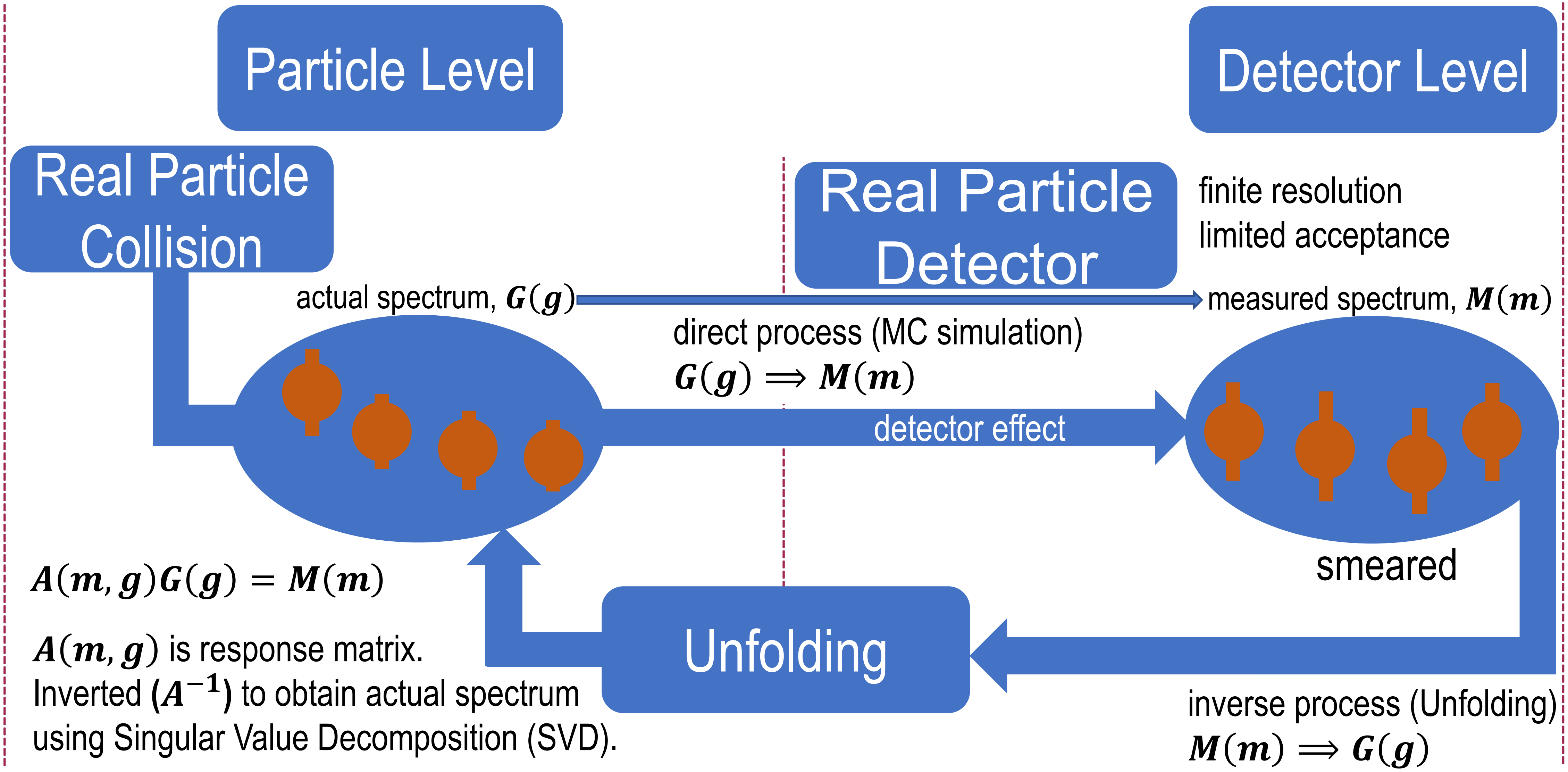
- Acceptance cut: 0.5 cm < r < 4.0 cm
  0.5 cm to counteract left-right dilution
  $\sigma_{pos.}$ of SMD ~ 1.0 cm.
  4.0 cm used to reduce neutron edge dilution

- SMD threshold cut→
  photon rejection
  required Nx and Ny > 1 fired above 0.003 GeV





Unfolding – Recovers an Actual from Measured Distribution



Monte Carlo (MC) Sampling – the Detector Smearing Matrix

Composition, energy, momentum, etc. for forward region not well understood → Sampled 5 MCs to gauge impact on the unfolded asymmetries.

Sampling MC	Interactions
DPMJet	hadronic (HAD)
PYTHIA6(8)	hadronic (HAD)
OPE	hadronic (HAD)
UPC	electromagnetic (EM)

DPMJet, PYTHIA6(8) full event generators chosen because they treat diffractive events differently.

- OPE (HAD interaction): Phenomenological description of forward hadronic cross sections in terms of one pion exchange.

- UPC (EM interaction): STARLIGHT generator of photon generation in proton-nucleus collisions.

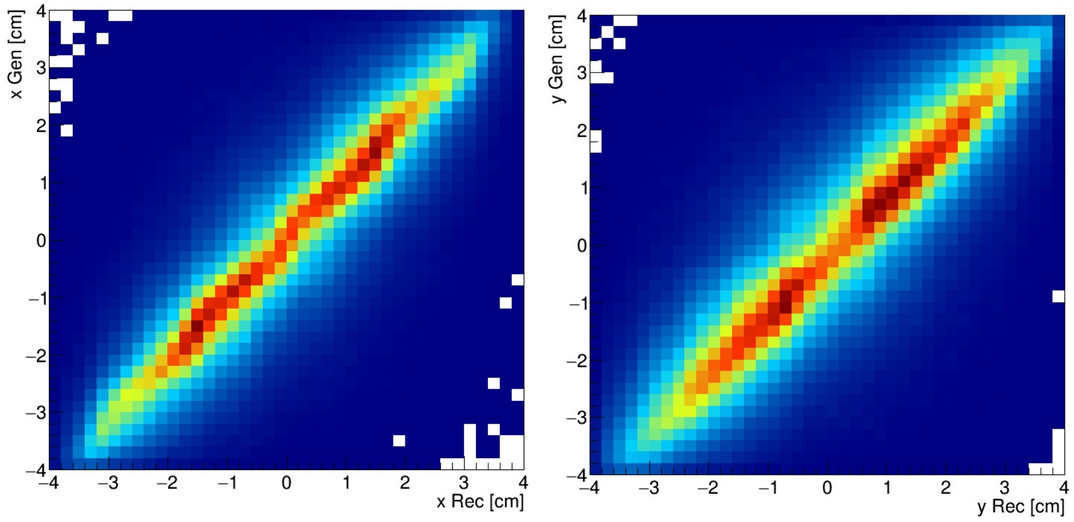
Smearing in Position (x, y) and Azimuthal Angle (ϕ) Spectra

Position and azimuth angle are correlated:

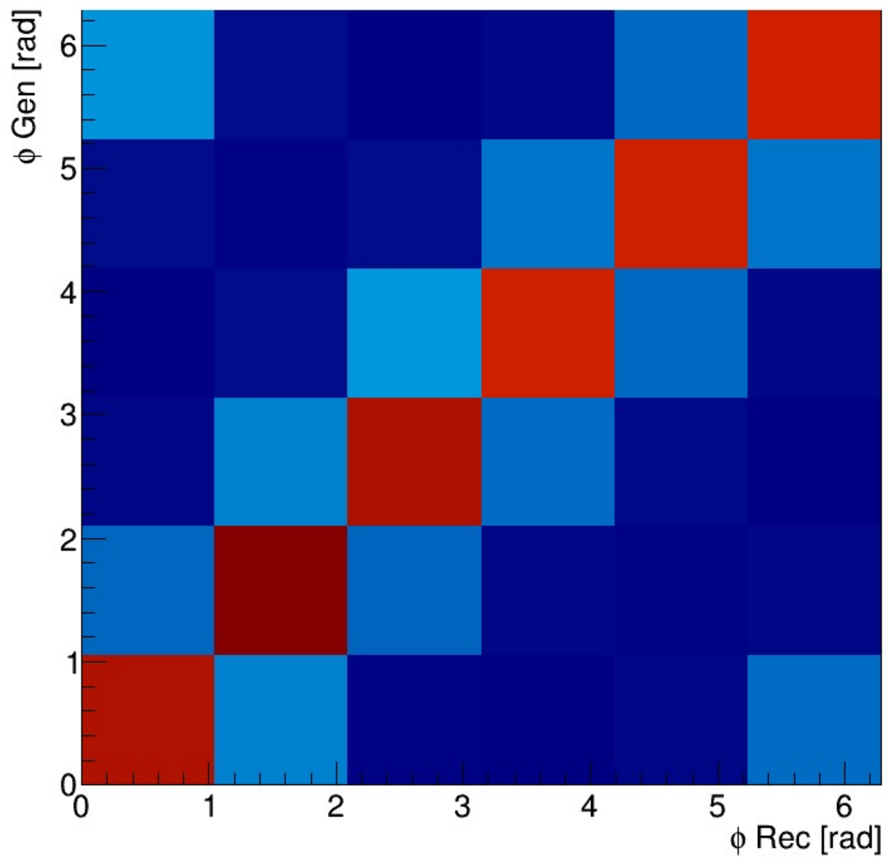
$$\phi = tan^{-1}\left(\frac{y}{x}\right)$$

$\phi =$ azimuth angle

x, y = forward neutron positions in SMD



Azimuth angle smearing was checked by the correlation of measured and generated ϕ.



Smearing in the Transverse Momentum (p_T) Distribution

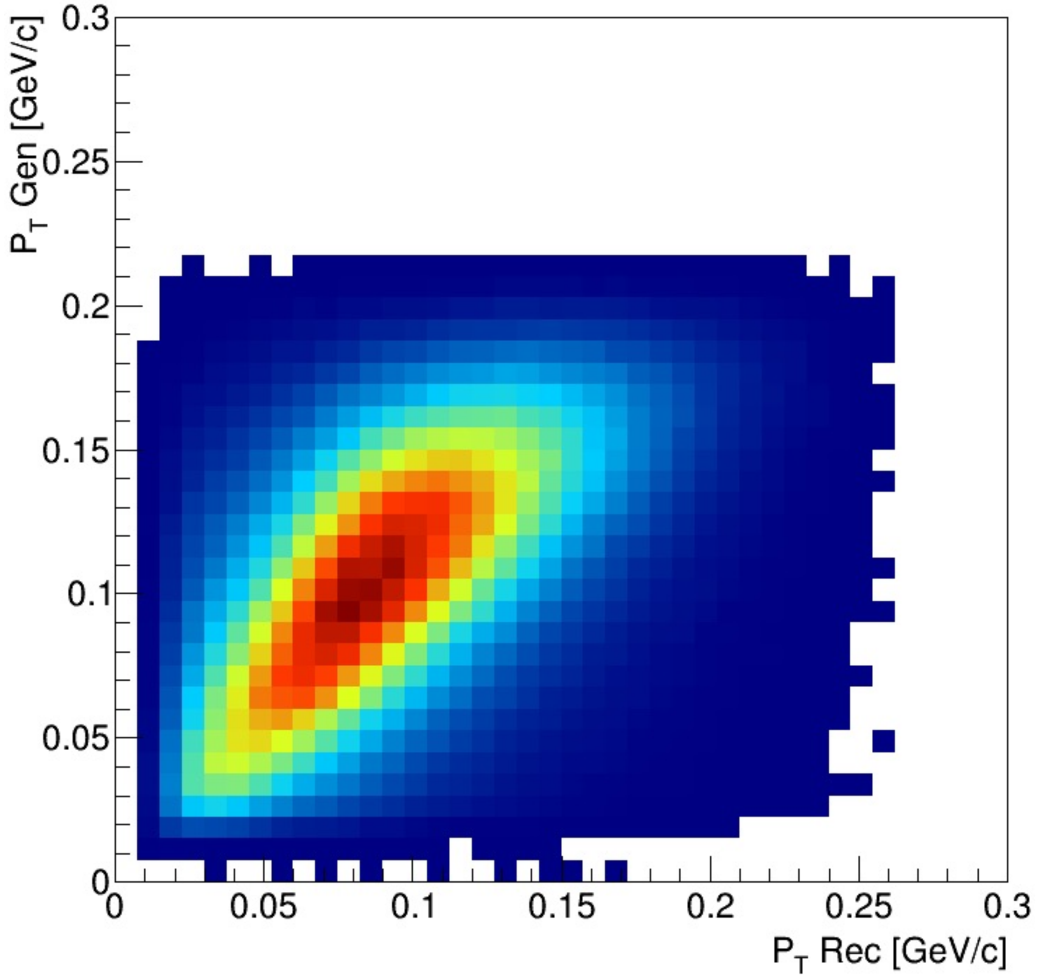
Position and transverse momentum are related:

$$P_T = E_n sin\theta_n = E_n \frac{r}{\sqrt{r^2 + d^2}} \approx E_n \frac{r}{d}$$

E_n = neutron energy

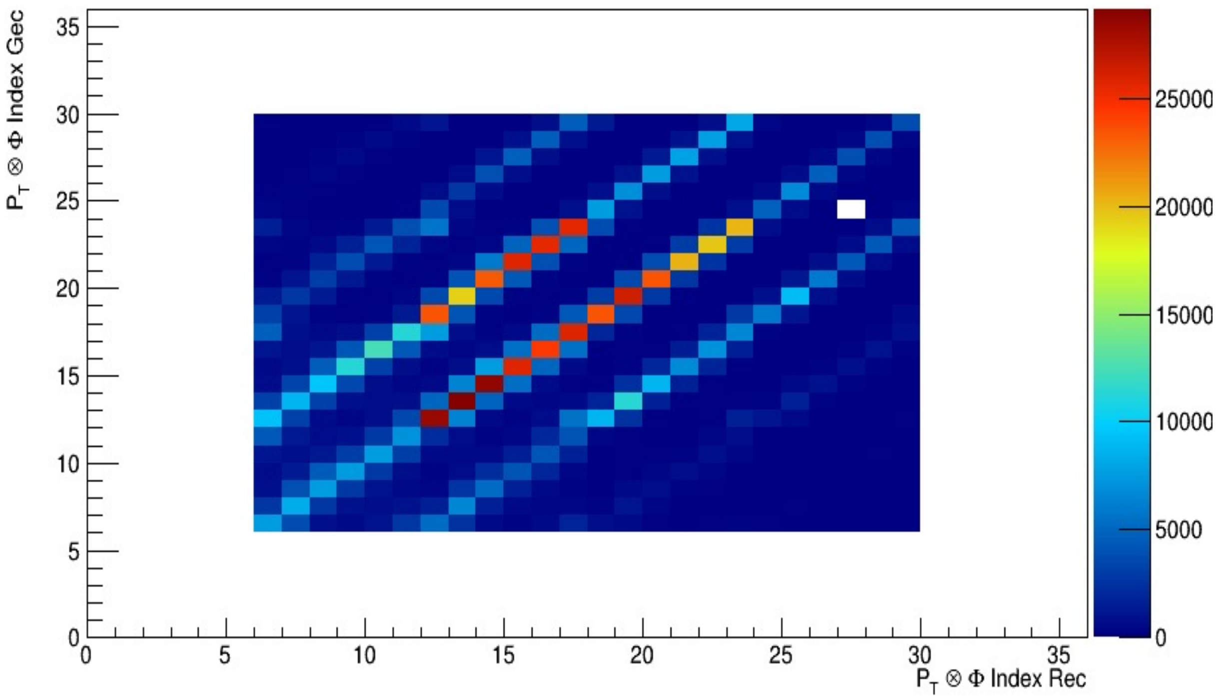
r = radial distance $=\sqrt{x^2 + y^2}$

p_T dependent A_N must be corrected for p_T and azimuth angle (ϕ) smearing



Zero Degree Calorimeter (ZDC) Smearing Response Matrix

ZDC smearing response matrix was obtained as generated (Gen) p_T–ϕ index versus reconstructed (Rec) p_T-ϕ index. Mapping to 1D p_T-ϕ index (I) was done according to:



$$i = p_{T(i)} * \phi_{nbin} + \phi_i$$

Transverse momentum (p_T) binned as:
[0.01-0.06],[0.06-0.11],
[0.11-0.16],[0.16-0.21].

Azimuth (ϕ) binned into 6 bins spanning a full range, i.e. (0 – 2π).

SVD of response matrix was finally executed to correct off-diagonal smearing in p_T and azimuth (ϕ)

Unfolding and Asymmetry Extraction Procedure

Asymmetry extraction and unfolding technique:

$$A_{N(\phi)} = \frac{1}{\langle P \rangle} \frac{N^{+}(\phi) - RN^{-}(\phi)}{N^{+}(\phi) + RY^{-}(\phi)}$$

1. obtain spin dependent two-dimensional data yields in p_T and ϕ.
2. execute unfolding via TSVD in CERN's ROOT using weighted smearing matrices.
3. asymmetries were finally calculated using the relative luminosity formula:

- $\langle P \rangle$ = beam polarization
- $N^{\pm}(\phi)$ = neutron yields
- R = ratio of luminosities
- A_N = unfolded asymmetry

Reweighting Procedure using Various Function Forms

Three different parameterizations ultilized for the re-weighting and introducing spin effect (↑)(↓)

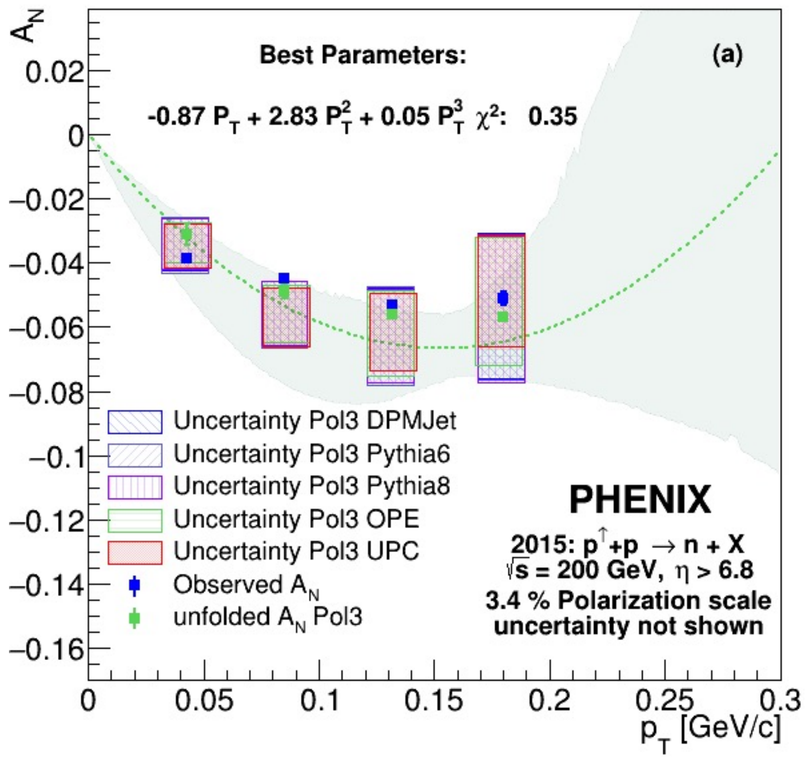
- Polynomial function (Pol3)
  $$w = \left(a \cdot P_{T,g} + b \cdot p_{T,g}^{2} + c \cdot p_{T,g}^{3}\right) sin\left(\varphi_g + \lambda\pi\right)$$
- Power law
  $$w = \left(a \cdot P_{T,g}^{b}\right) sin\left(\varphi_g + \lambda\pi\right)$$
- Exponential
  $$w = a\left(1 - exp^{P_{T,g} \cdot b}\right) sin\left(\varphi_g + \lambda\pi\right)$$
  where *a*, *b* and *c* are valid free parameters.

Chi-square between data yields and measured yields.

$$\chi^2 = \frac{(N^{Exp} - N^{Rec})^2}{\Delta(N^{Exp})^2 + \Delta(N^{Rec})^2}$$

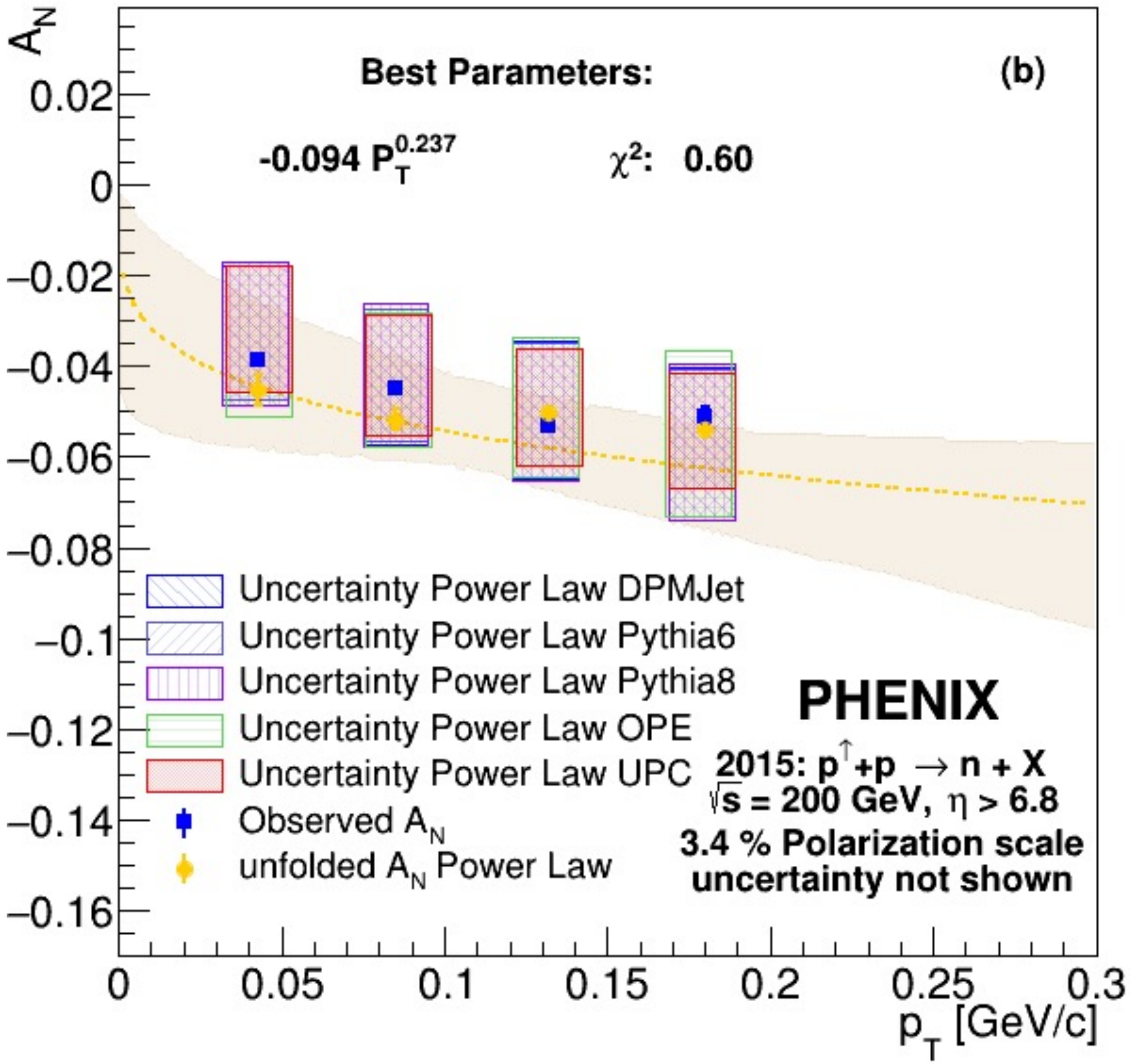
- N^{Exp} is the data yield.
- N^{Rec} is measured yield from Monte Carlo simulation.
- χ^2 is Chi-square between data and reconstructed yields.

Unfolded A_N as a Function of P_T Based on Pol3 Function

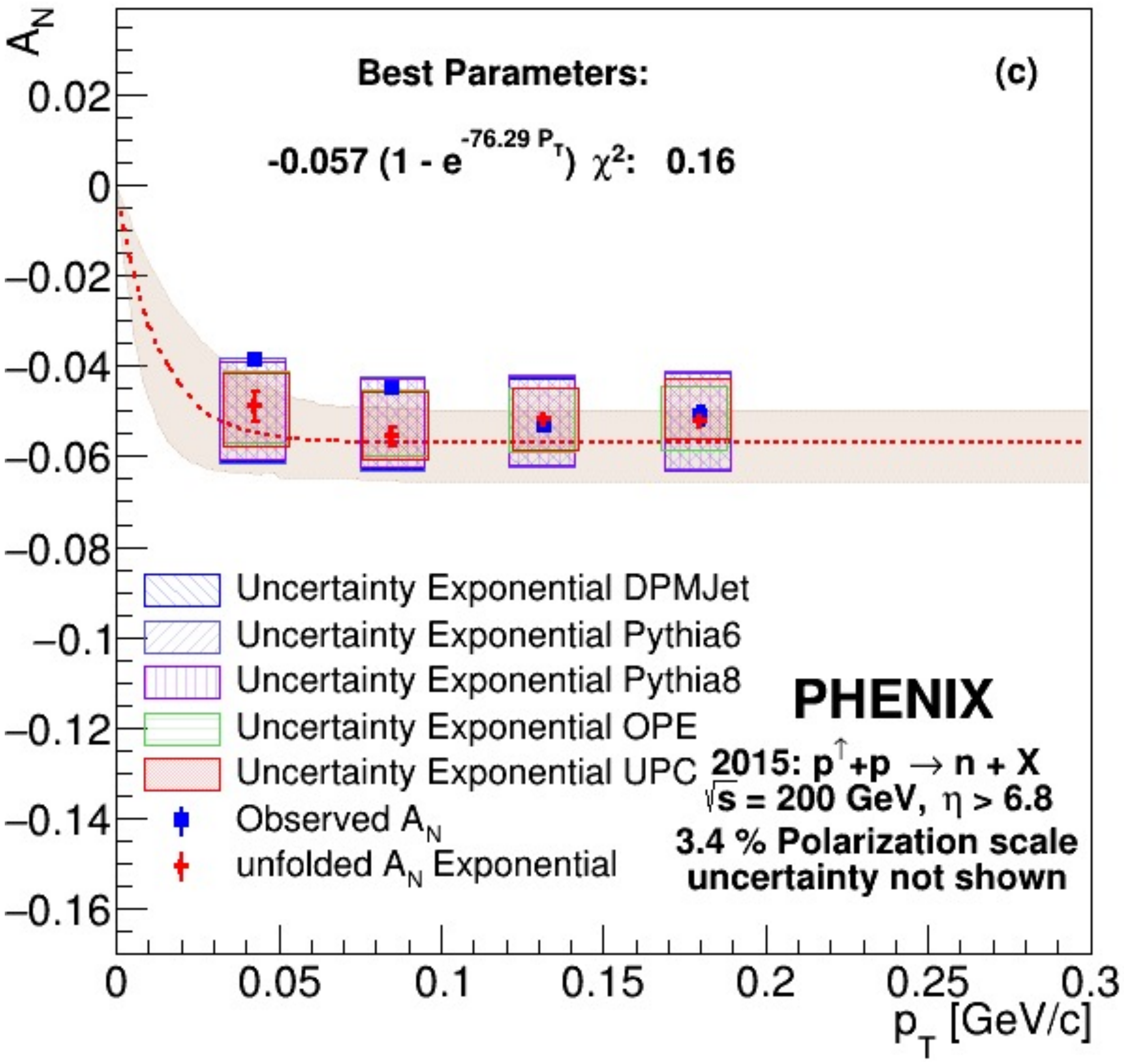


- Light green shaded region shows χ^2 below 10. χ^2 is small below 0.2 GeV/c and large above 0.2 GeV/c.
- Dashed line shows best matching parameters.
- Root Mean Square range of unfolded A_N are visualized as shaded boxes for various Monte Carlo generators.
- UPC used to sample EM process (minimal in p+p & its errors fall within errors from HAD process for PYTHIA6(8), DPMJET and OPE).

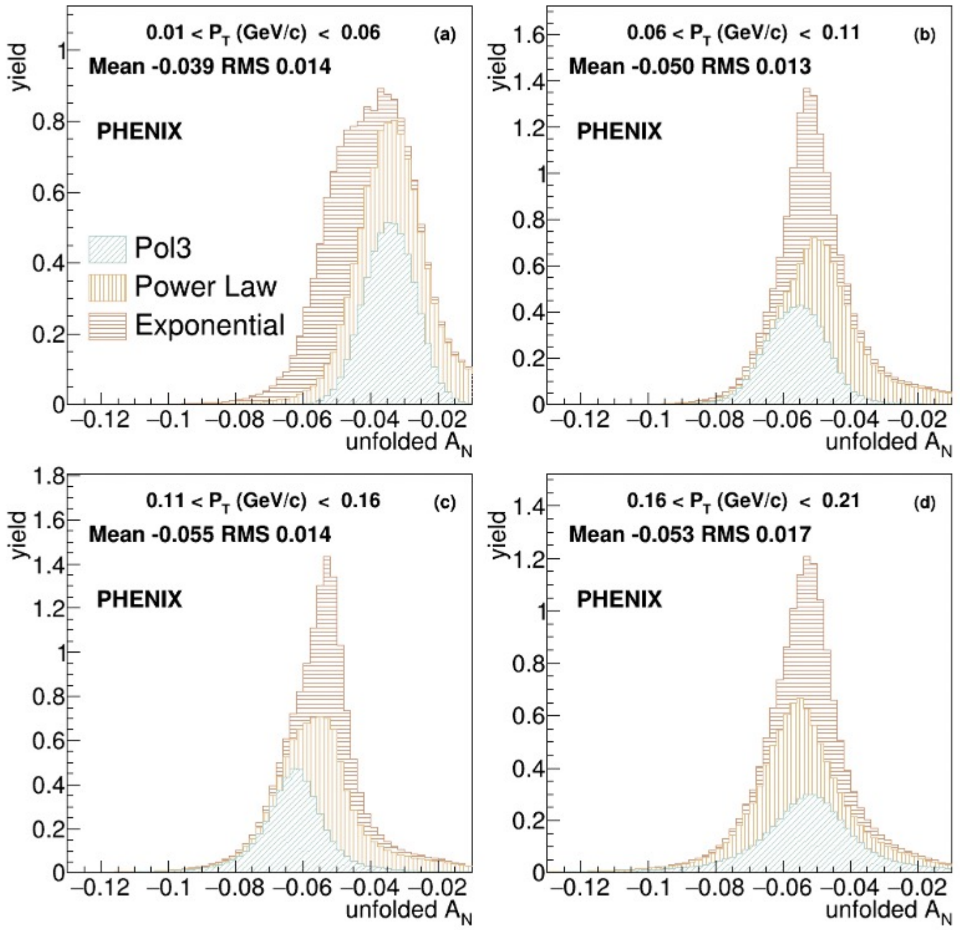
Unfolded A_N as a Function of P_T Based on Exponential Function



Unfolded A_N as a Function of P_T Based on the Power Law

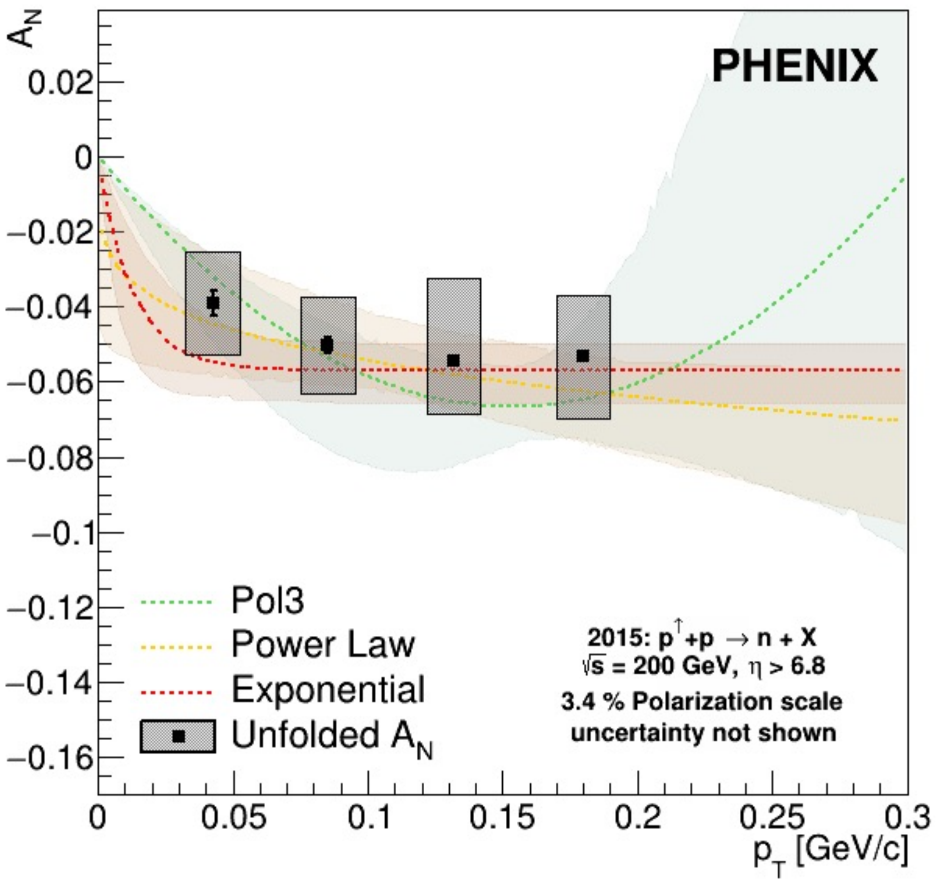


Combined Variation (Spread) of All Unfolded Asymmetries



- Combined spread of unfolded A_N in each p_T bin of all sets of parameters used for each functional form.
- All MC generator distributions are combined in each panel.
- Overall mean and RMS values are shown.

Unfolded A_N Combined Result with the Total Uncertainty



- Overall unfolded A_N as a function of p_T.
- Data points are unfolded A_N obtained from average over all parameterizations.
- Boxes are total uncertainties arising from the unfolding, MC generators and parameterizations.
- Unfolded A_N tend to rapidly increase at low p_T and slowly levelling off at high p_T.

Summary and Conclusions

- PHENIX has measured first explicit p_T dependent A_N results for forward neutrons in transversely polarized $p + p$ collisions at $\sqrt{s}$ = 200 GeV.

- With this measurement, first reliable tests of mechanisms that produce these asymmetries have been performed.

- Overall asymmetries show a tendency to rapidly increase at low transverse momentum.

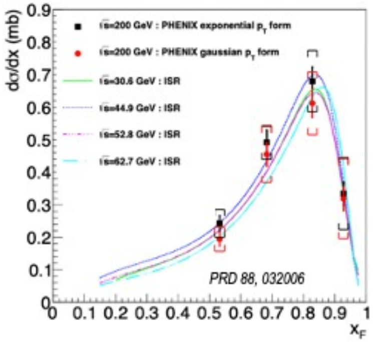
- At higher p_T, A_N slowly levels off. This trend seems not to follow a simple linear p_T dependence theoretical prediction in Phys. Rev. D84, 114012 (2011).

- To understand beyond current A_N results, correlation analyses with other detectors like the BBC in pp and pA collisions are ongoing. Hope to give another seminar talk in the nearby future on pA and correlation studies.

BACKUP

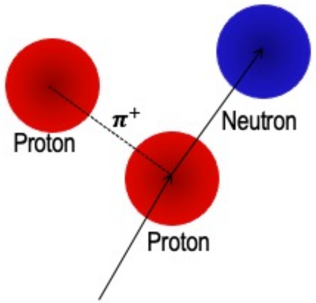
Forward neutron (x_F > 0.5) cross section in p+p studied at CERN (ISR) and PHENIX (RHIC)

$x_F = E_n/E_p$



Cross section of forward neutron is well understood using One Pion Exchange (OPE)

One Pion Exchange (OPE) model



Forward neutron carries large fraction of proton energy for p_T < 0.22 GeV/c

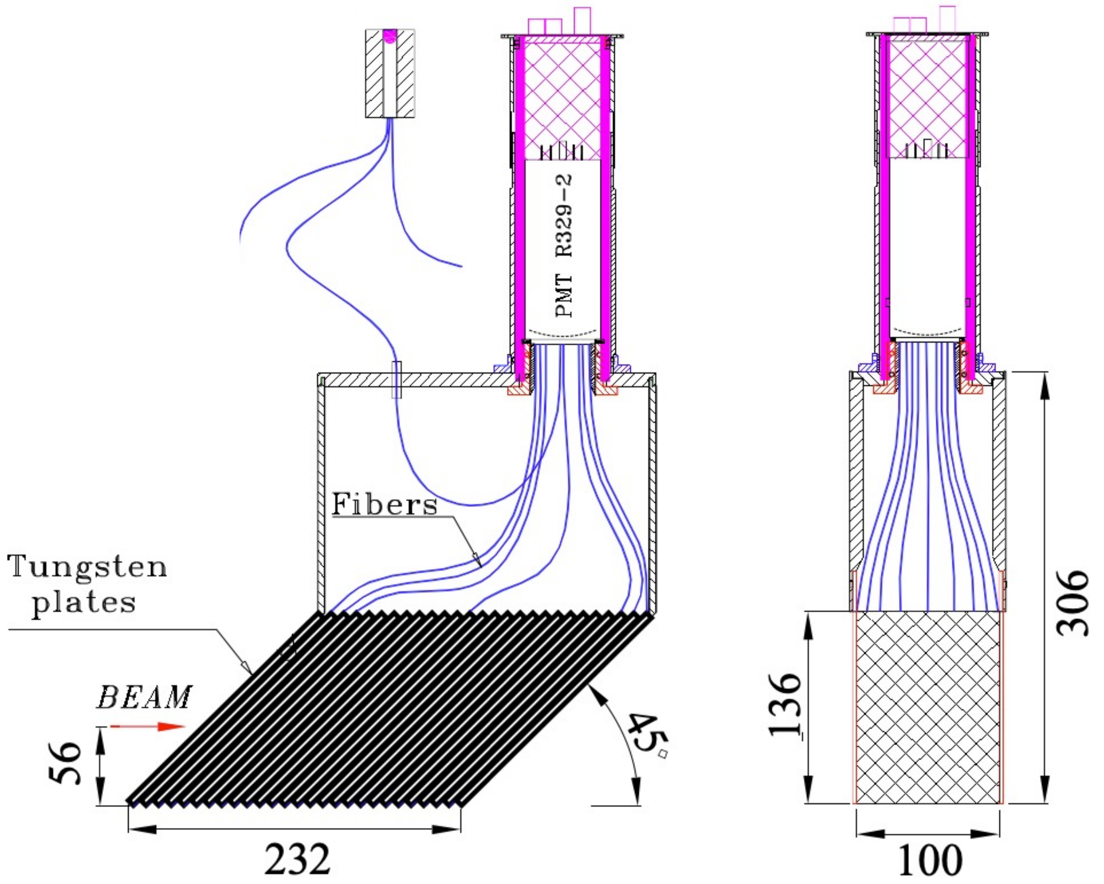
Study of Top-Bottom Effect in P_T-Φ Index Plots

Previously studied in PhD thesis of (Manabu Togawa) using GEANT3.

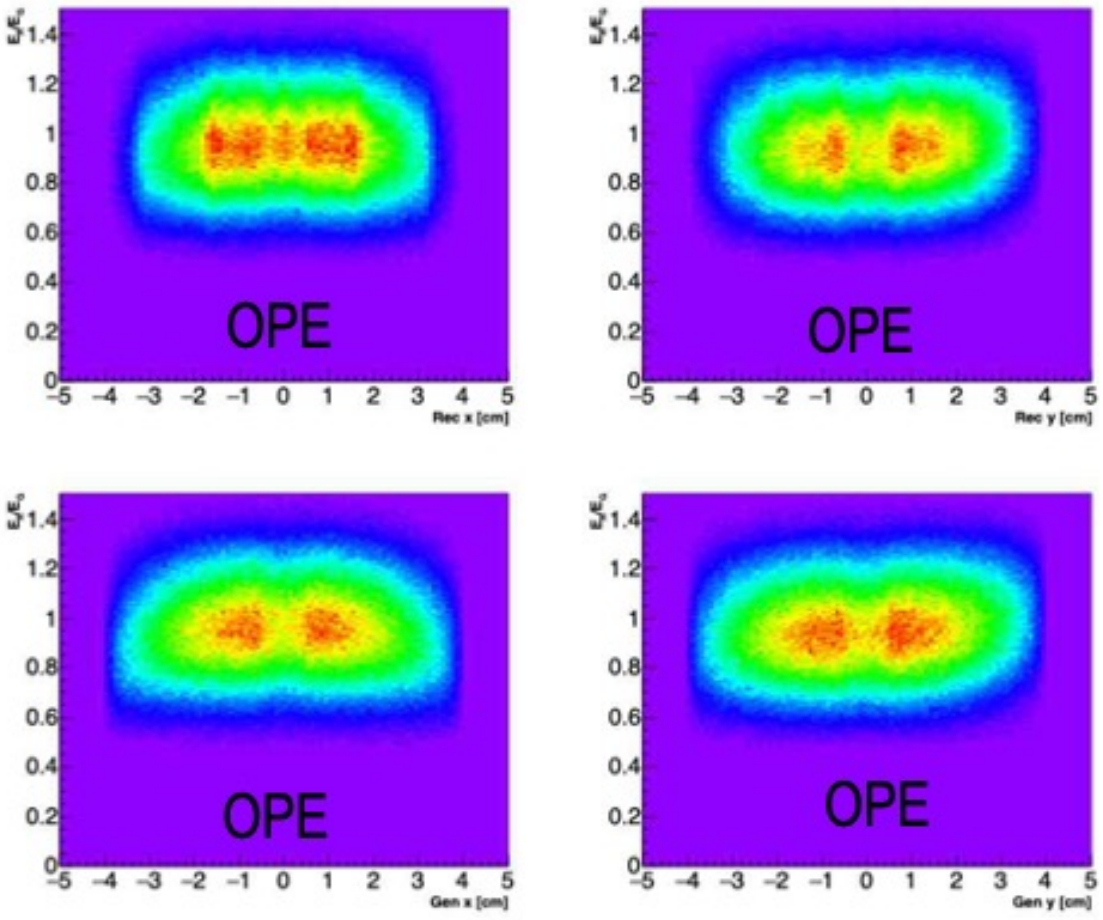
Top-bottom effect is caused by light collection and back-scattering in top part of ZDC (i.e. (y)-position). Readout system top part only.

Checked energy deposit of forward neutrons in ZDC.

Confirmed via scatter plot of deposited energy as a function of measured position.



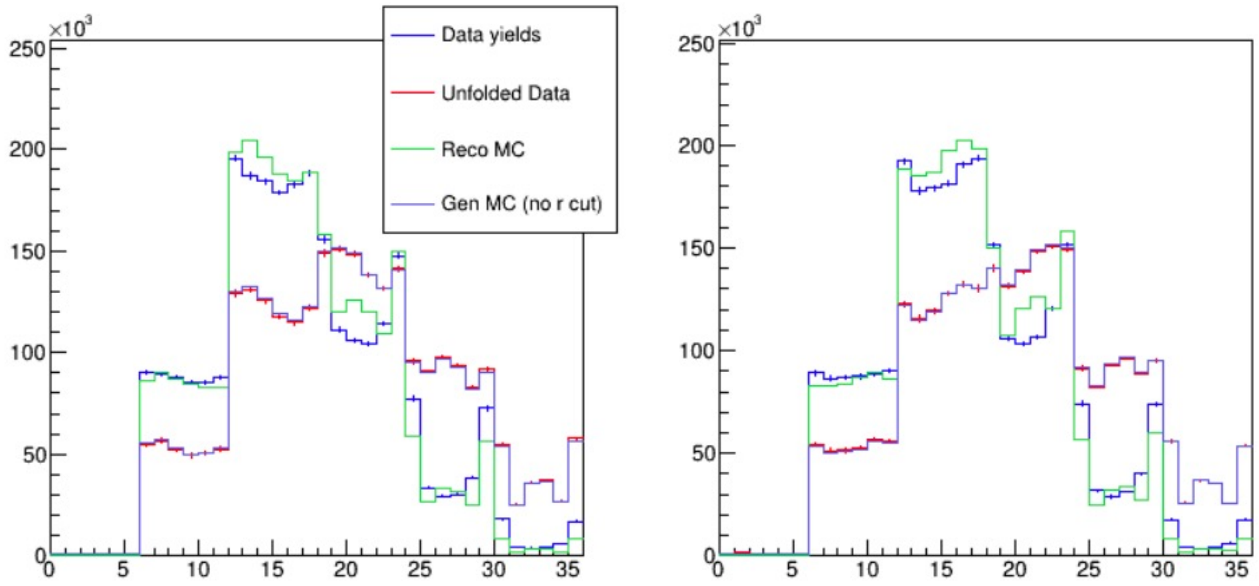
Study of Top-Bottom Effect in P_T-Φ Index Plots

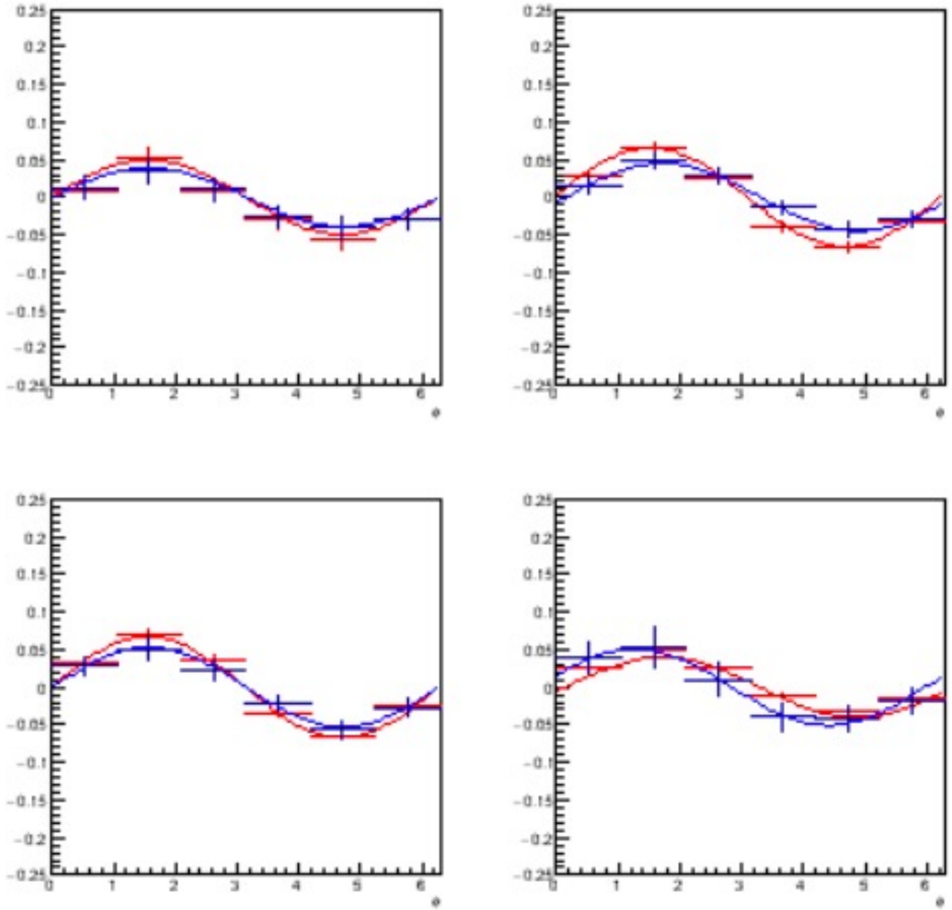


Left side panels plotted as a function of x position have forward neutron deposited energy parallel to the x- axis → no irregularity.

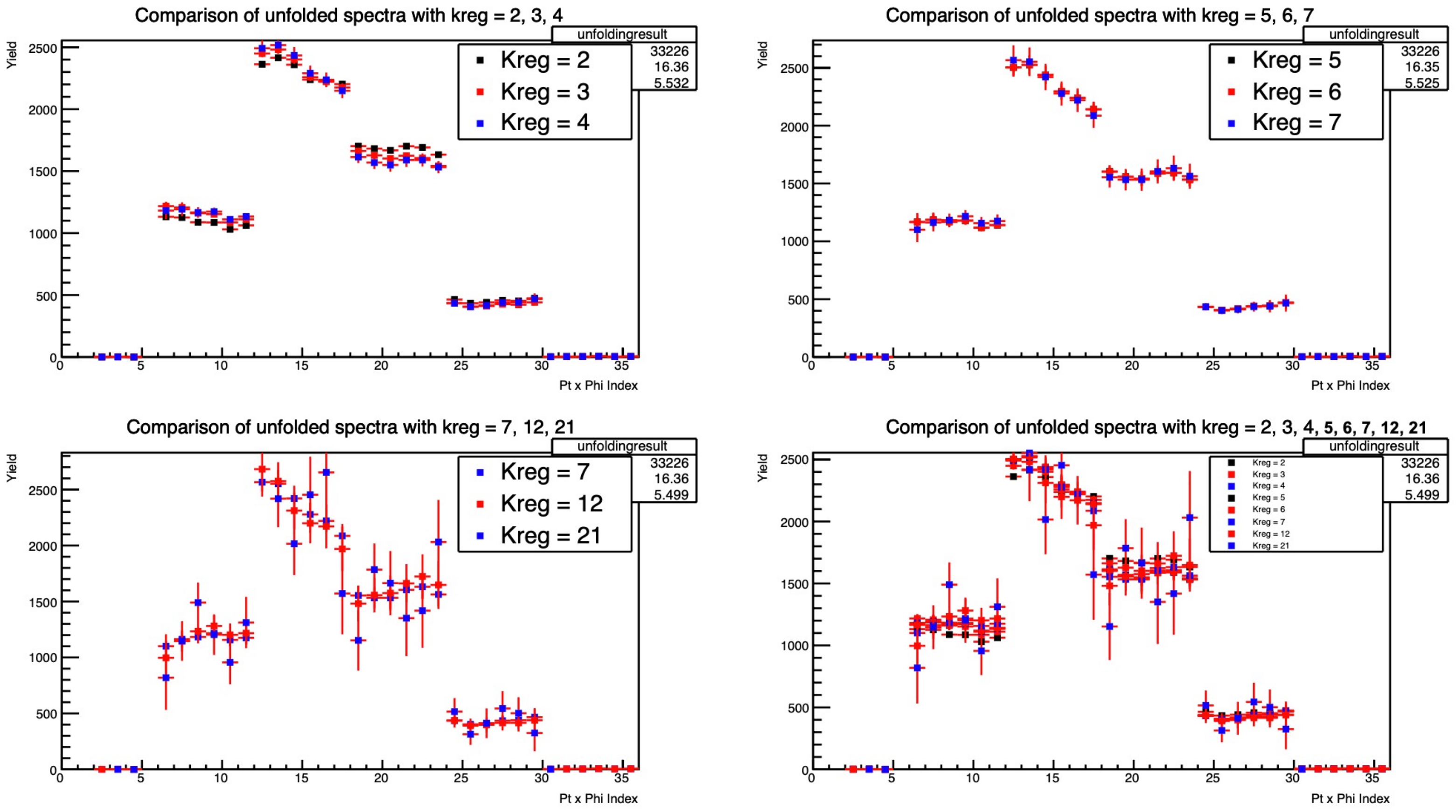
Right side panels have a slope hence anti-parallel to y-axis or y-position. Top-bottom differences exit in the y-position.

Unfolded 2D Yields and Azimuthal Angle Modulation





P_T and ϕ SVD Unfolding Closure Test - Result



Transverse momentum (P_T) and azimuth (phi) unfolding closure test results – all possible parameter comparison