Single transverse spin asymmetries of forward neutron production in $\sqrt{s_{NN}}$= 200 GeV polarized p+A collisions at PHENIX

Minjung Kim (Seoul National Univ./RIKEN)

for the PHENIX Collaboration

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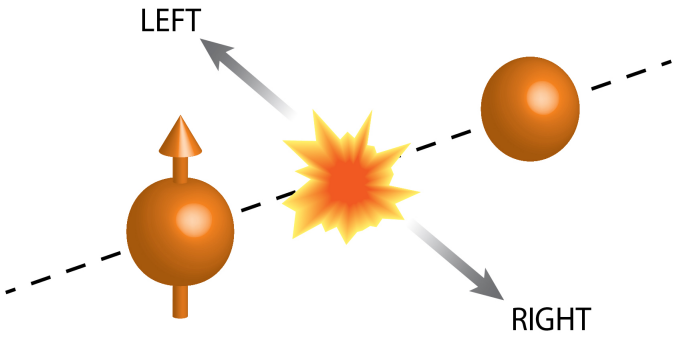
- Theory for A_N



II. $p^{\uparrow} + \mathbf{A} \rightarrow n + X$

- PHENIX forward neutron detectors
- **Unexpected A dependence on A_N**
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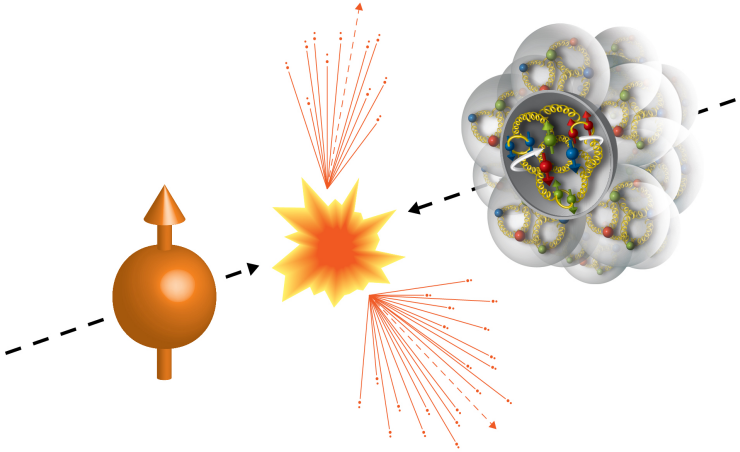
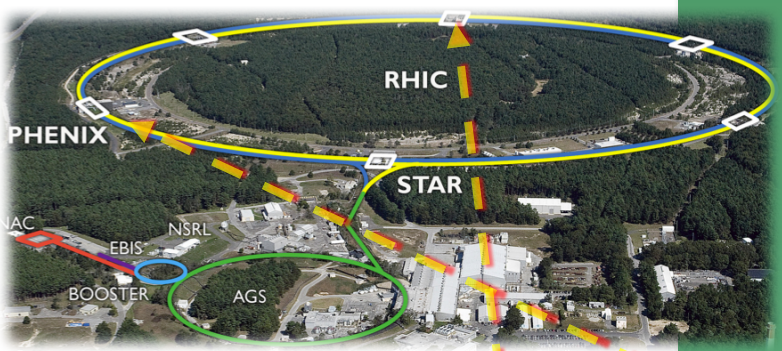
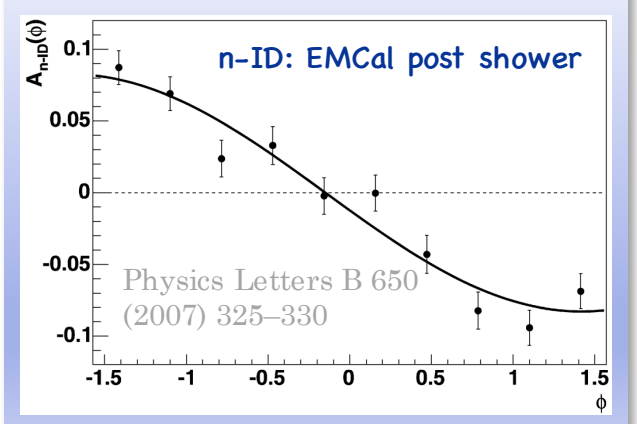


History of forward neutron A_N

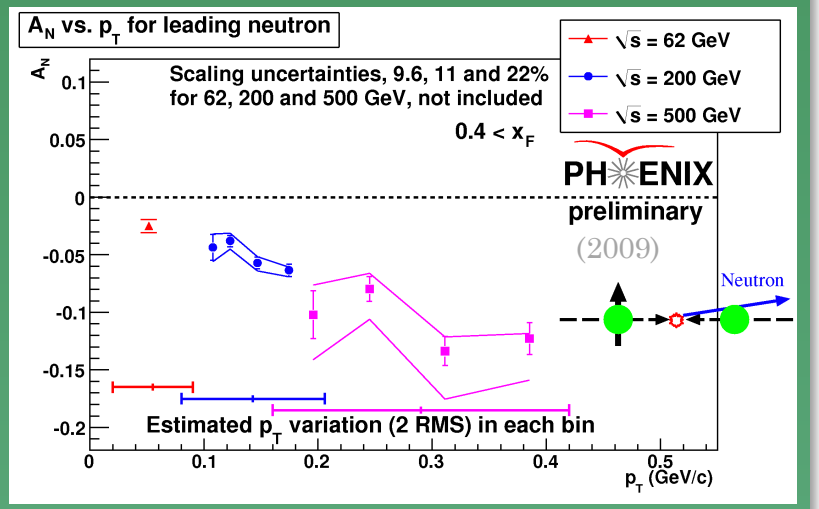
$$A_N = \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}}$$

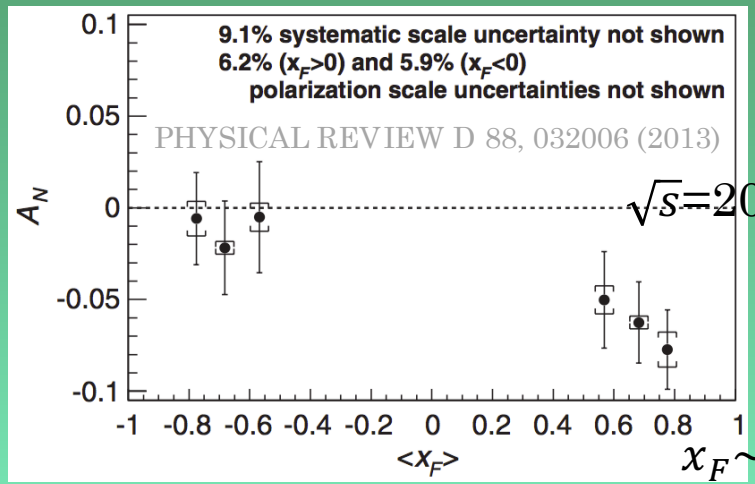


IP12 (2001-2002)



PHENIX (2003~)

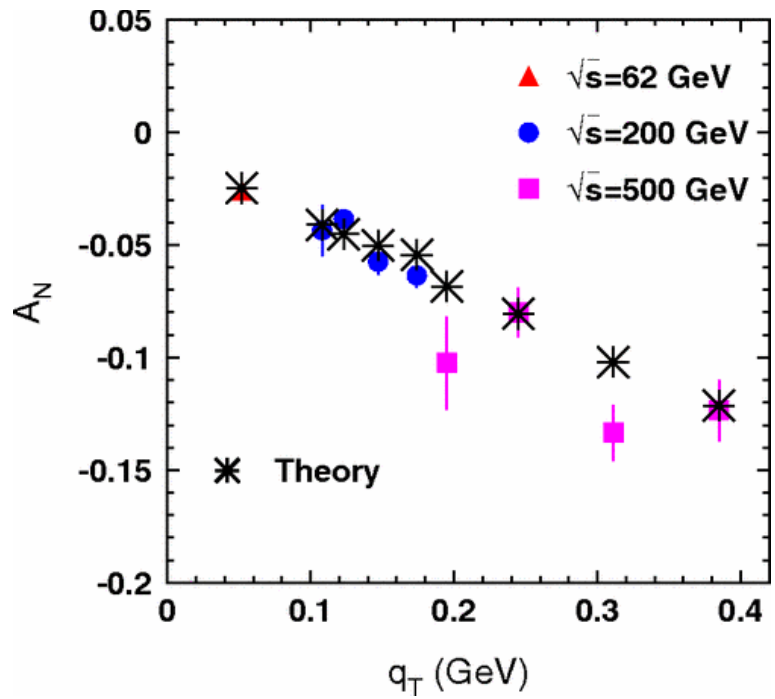




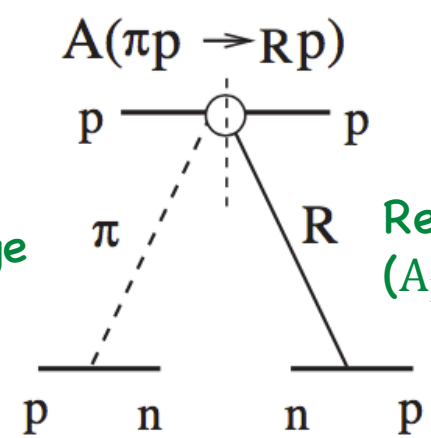
$x_F \sim E_n/E_p$

Theory for $p^{\uparrow} + p$ forward neutron

- Non-perturbative region ($p_T < 0.2$ GeV/c for $\sqrt{s}$=200 GeV)
- One Pion Exchange (OPE) model in Regge theory describes PHENIX A_N data well



Interference between two amplitudes



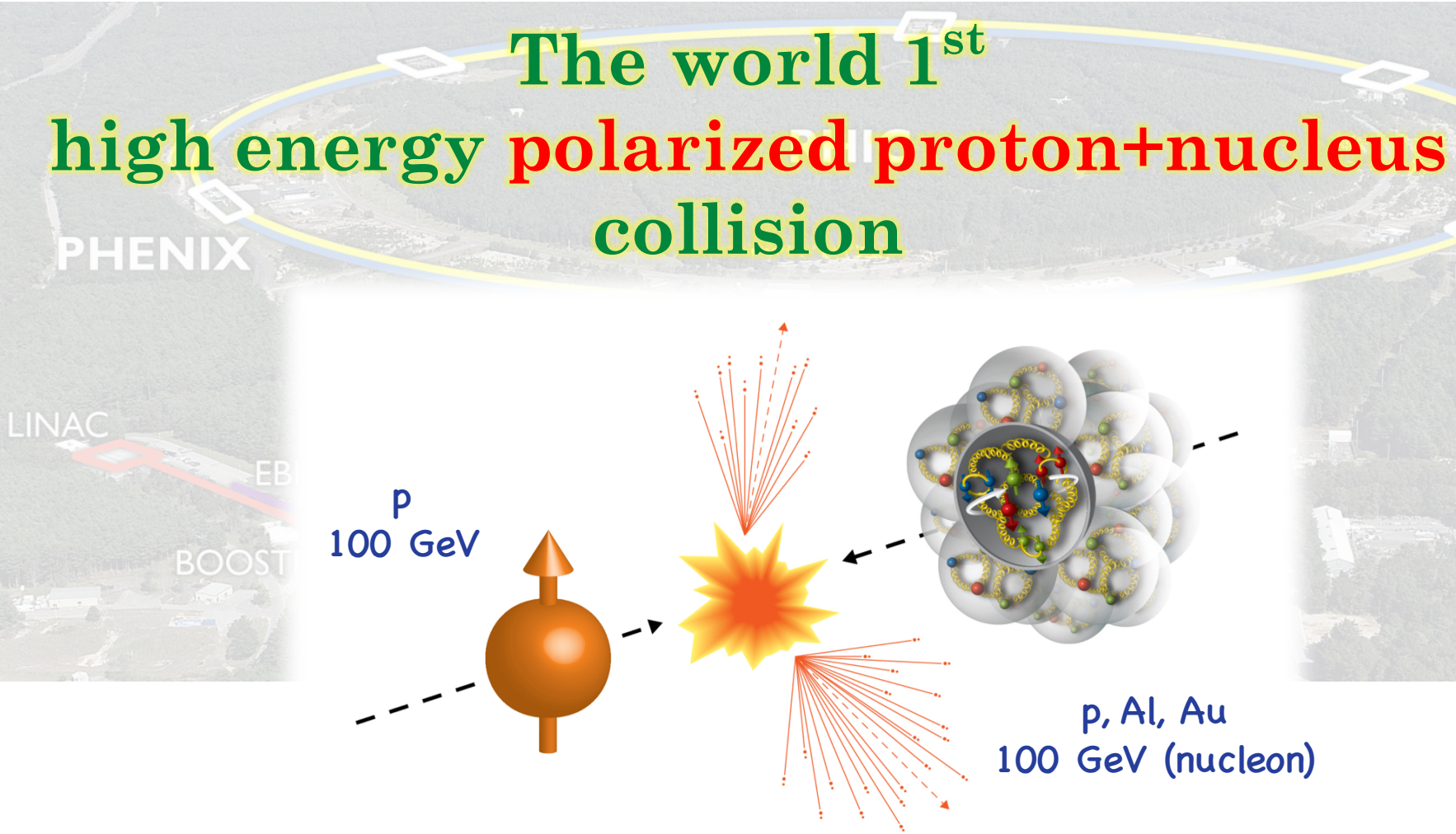
π^+ exchange

Reggeon exchange
(A_N dominantly arise from a_1)

B. Kopeliovich et al PRD 84, 114012 (2011)

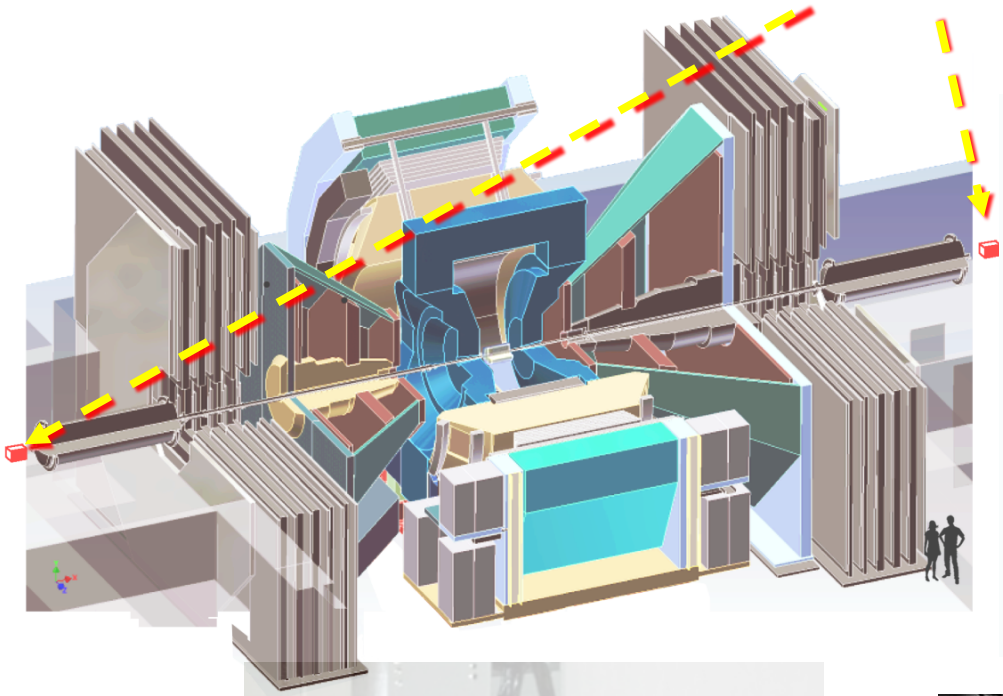
RHIC Run15 (2015)

The world 1st high energy polarized proton+nucleus collision

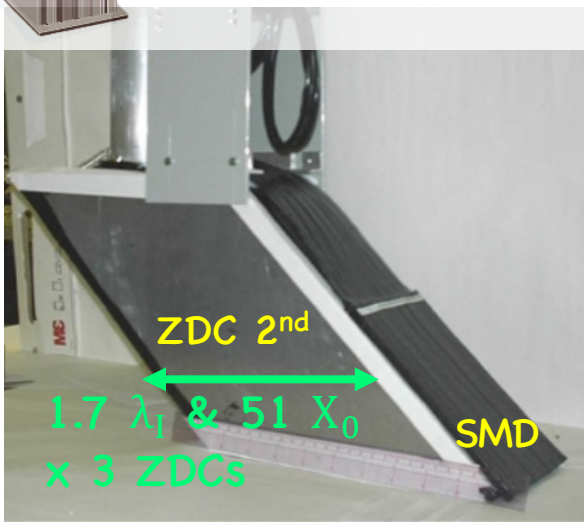


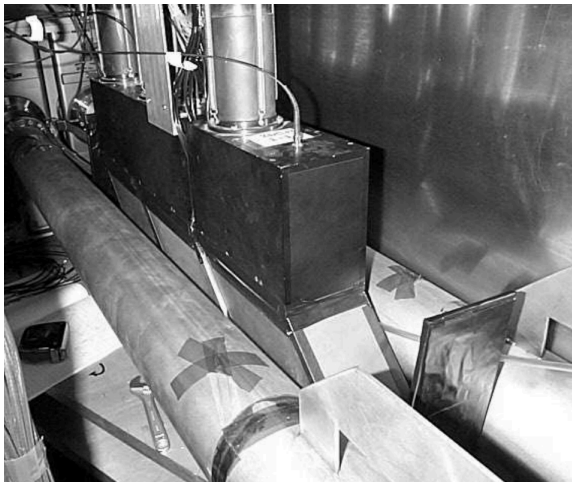
PHENIX forward neutron detectors

18m from IP, 10 cm x 10 cm (η>6)

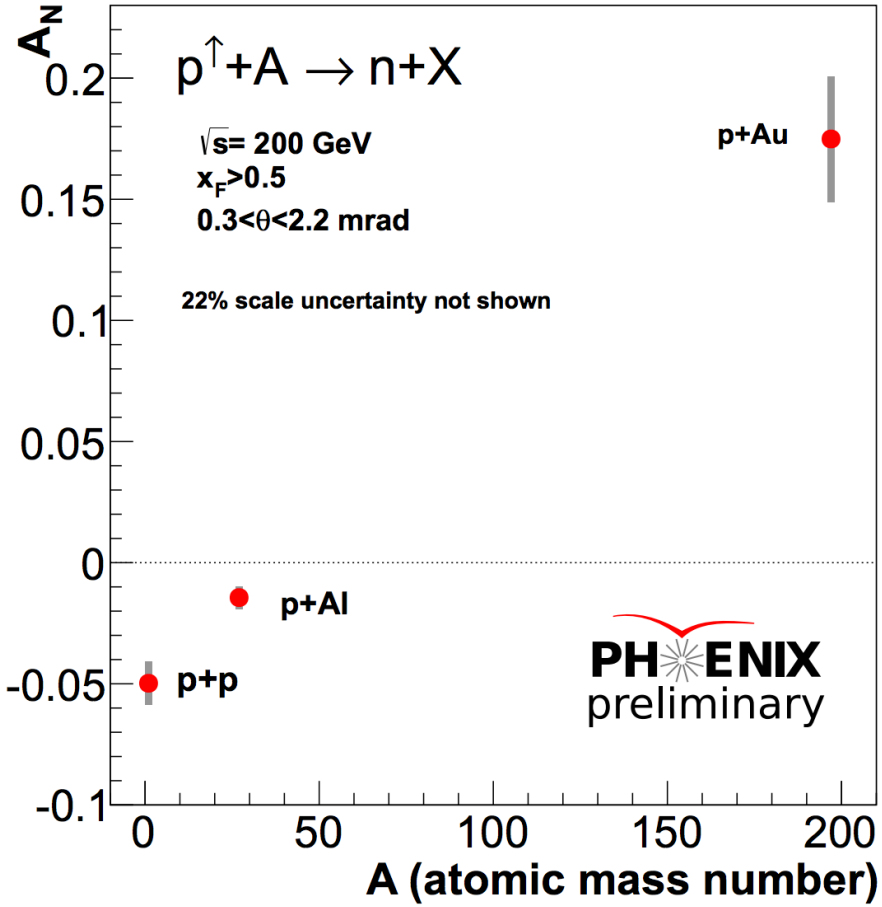


- ZDC (Zero Degree Calorimeter): Cherenkov sampling hadron calorimeter ($\Delta E/E$ = 20~30%)
- SMD (Shower Max Detector): X-Y plastic strip scintillator hodoscopes ($\Delta x, \Delta y$ ~1 cm)
- Charge veto counter: plastic scintillator pad at front





Forward neutron $A_N^{p^\uparrow + A \to n + X}$



Prediction before the measurement:

weak A dependence

(OPE & isospin symmetry)

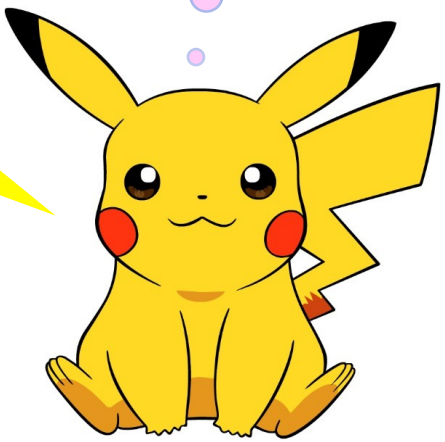
Unexpected strong A-dependence!

Where is the A-dependence from?

EM associated?

Else?

Isospin asymmetry?



Discussions are ongoing!

Origin of A_N

$$A_N \equiv \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}} = \frac{\sum_X |< nX|T| \uparrow >|^2 - \sum_X |< nX|T| \downarrow >|^2}{\sum_X |< nX|T| \uparrow >|^2 + \sum_X |< nX|T| \downarrow >|^2}$$

$$= \frac{-2\mathrm{Im} \sum_X < nX|T| - >< + |T^+|nX >}{\sigma_{tot}}$$

$$A_N \propto \mathrm{Im}\left(f_{\mathrm{flip}}^{\mathrm{EM+h}*} f_{\mathrm{non-flip}}^{\mathrm{EM+h}}\right)$$

$$= \mathrm{Im}\Big(\underbrace{f_{\mathrm{flip}}^{\mathrm{EM}*} f_{\mathrm{non-flip}}^{\mathrm{EM}}}_{\text{EM only}} + \underbrace{f_{\mathrm{flip}}^{\mathrm{EM}*} f_{\mathrm{non-flip}}^{\mathrm{h}} + f_{\mathrm{flip}}^{\mathrm{h}*} f_{\mathrm{non-flip}}^{\mathrm{EM}}}_{\text{EM \& Strong interference}} + \underbrace{f_{\mathrm{flip}}^{\mathrm{h}*} f_{\mathrm{non-flip}}^{\mathrm{h}}}_{\text{Strong only}}\Big)$$

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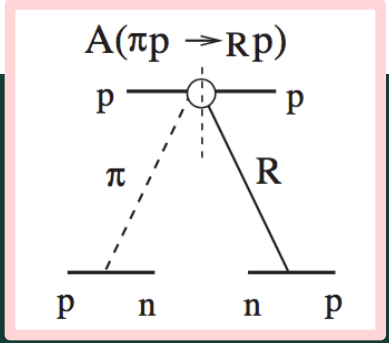

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Negligible for p+p

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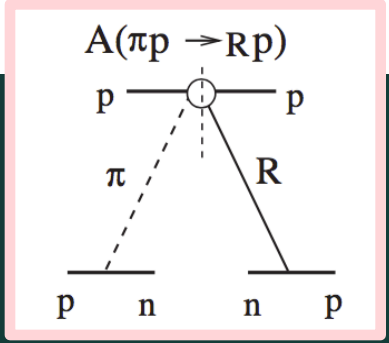

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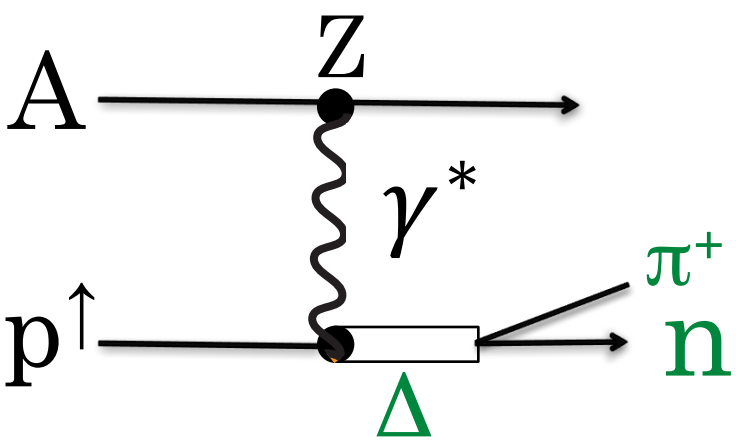
Negligible for p+p

How about in p+A?

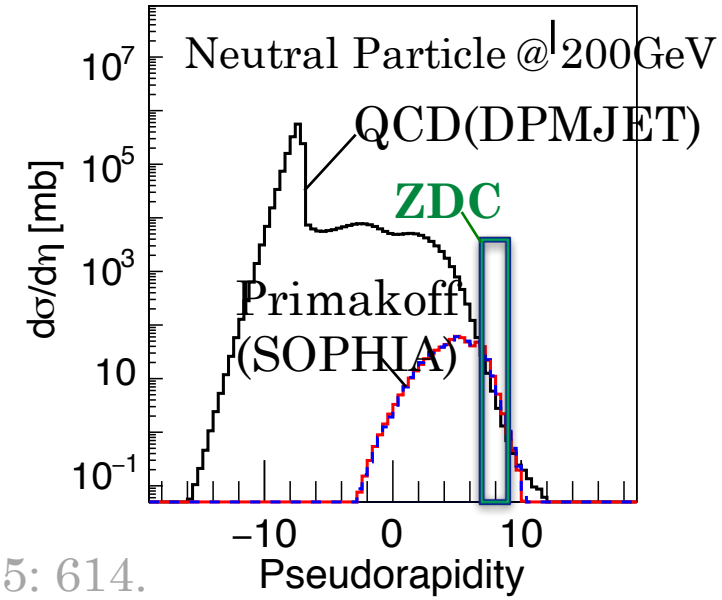
EM process - Primakoff



$\sigma_{\text{Primakoff}} \propto \gamma^{*}$ flux $\propto Z^2$

~ 6000 times larger in p+Au than in p+p

Primakoff MC predicts comparable yields between QCD and Primakoff process for p+Au



Mitsuka, G. Eur. Phys. J. C (2015) 75: 614.

Correlation study – EM ratio

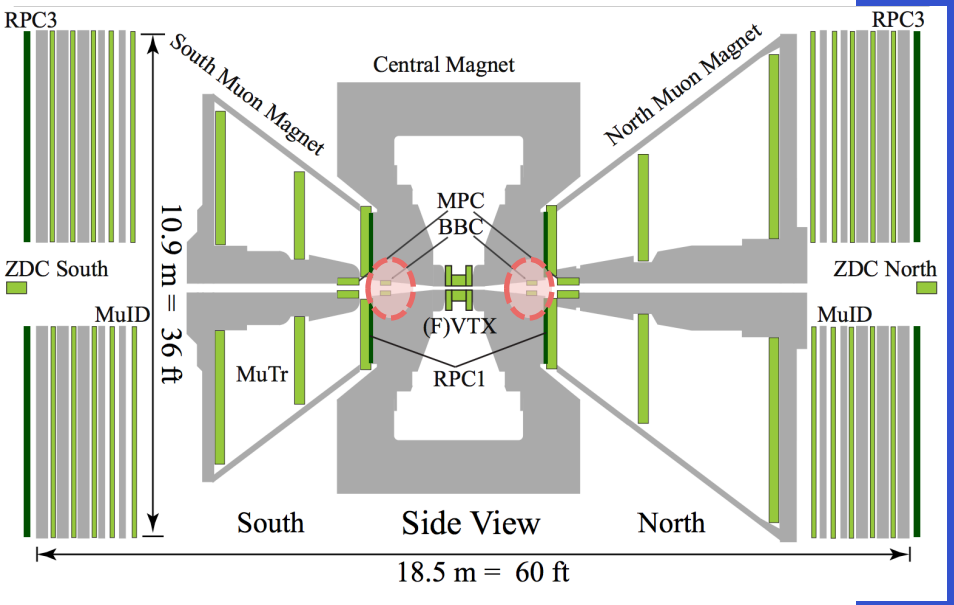
Beam Beam Counter ($3<\eta<4$)

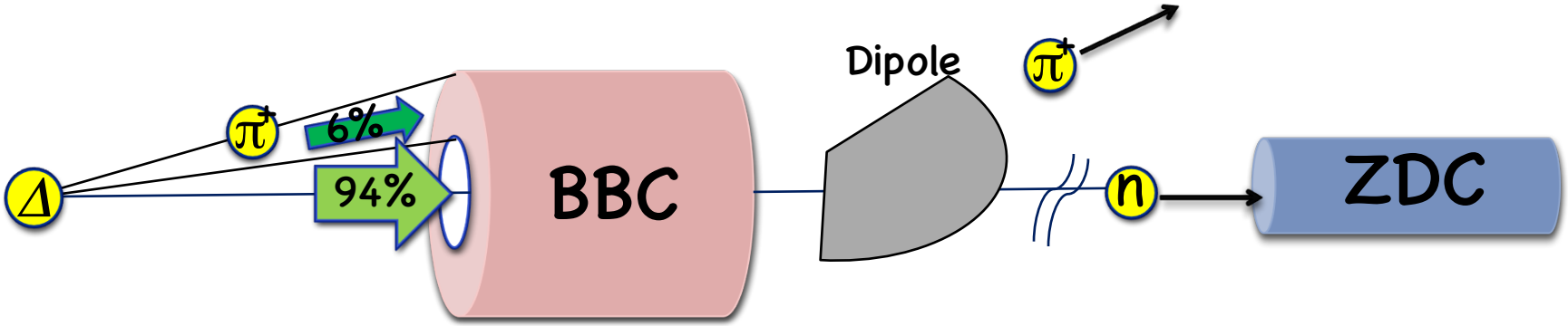
- Quartz cherenkov radiator elements
- ~80% efficiency on inelastic collision

MC predicts suppression of Primakoff events by requiring BBC hit

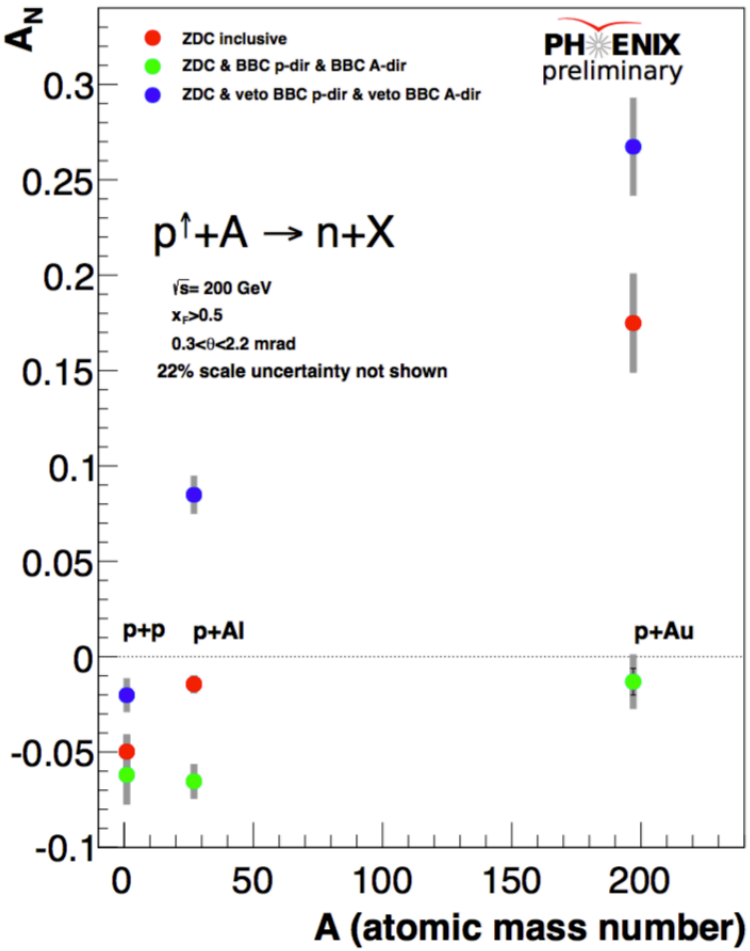
Two further measurements:

1. **ZDC& BBC : suppress EM**
2. **ZDC& BBC veto : enhance EM**





BBC correlation $A_N^{p^\uparrow + A \to n + X}$

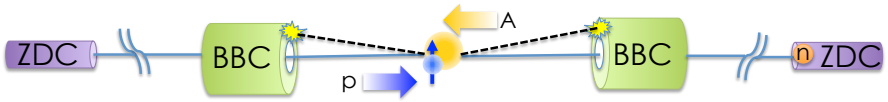


Forward neutron inclusive

- Strong A-dependence

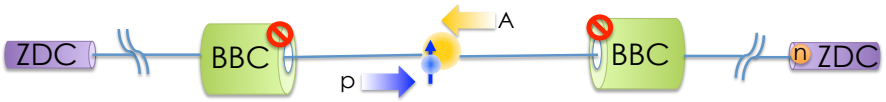
Particle ***HIT*** at lower rapidity - BBC hit

- EM process suppressed
- "Weaker" A-dependence



Particle ***VETO*** at lower rapidity - BBC veto

- EM process enhanced
- "Stronger" A-dependence



Summary

- Forward neutron A_N in p+p collisions is discovered unexpectedly at IP12 (2001-2002), and measured more precisely at PHENIX (2003~)

- RHIC had the world **1st high energy polarized p+A collisions** in 2015, and **unexpected strong A dependence of forward neutron A_N** is observed

- A OPE model explains p+p forward neutron asymmetry data well, but cannot explain p+A asymmetries

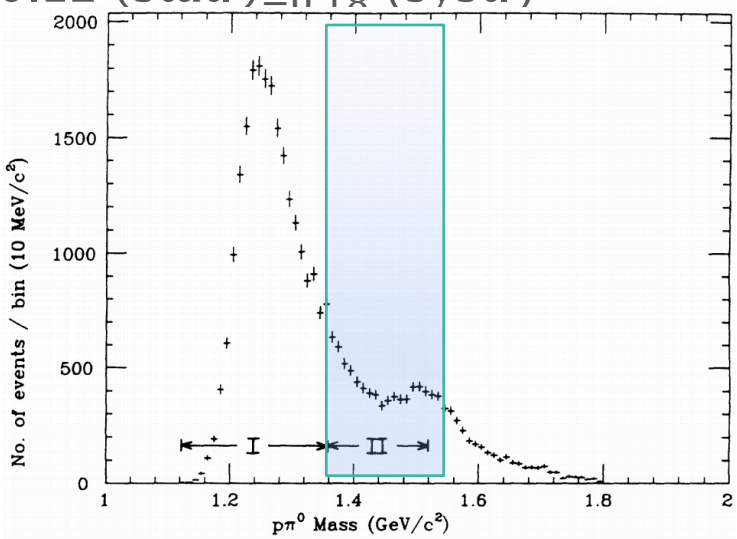
- To get hint about **associated processes**, correlation with other detectors is measured, then **strong correlation with particle production in lower rapidity on A_N** is observed, which may imply the **main contributor of A dependence is EM associated (EM*EM or EM*Strong) process**

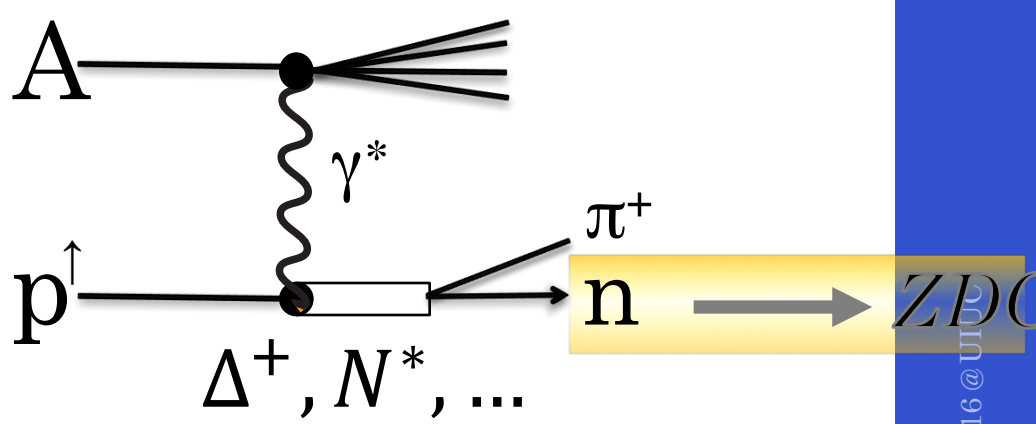
- **Discussions are ongoing**

Back up

$\mathrm{Im}\left(f_{\mathrm{flip}}^{\mathrm{EM}*} f_{\mathrm{non-flip}}^{\mathrm{EM}}\right)$ asymmetry: Primakoff

- Primakoff process: $p + Z \rightarrow \Delta^+ / N^* \rightarrow \pi^0 + p + Z$ PRL 64, 357-360 (1990)
- In $\Delta^+(1232)$ and $N^*(1520)$ resonance region, $A_N = -0.57 \pm 0.12\,(\mathrm{stat.})^{+0.21}_{-0.18}\,(\mathrm{syst.})$



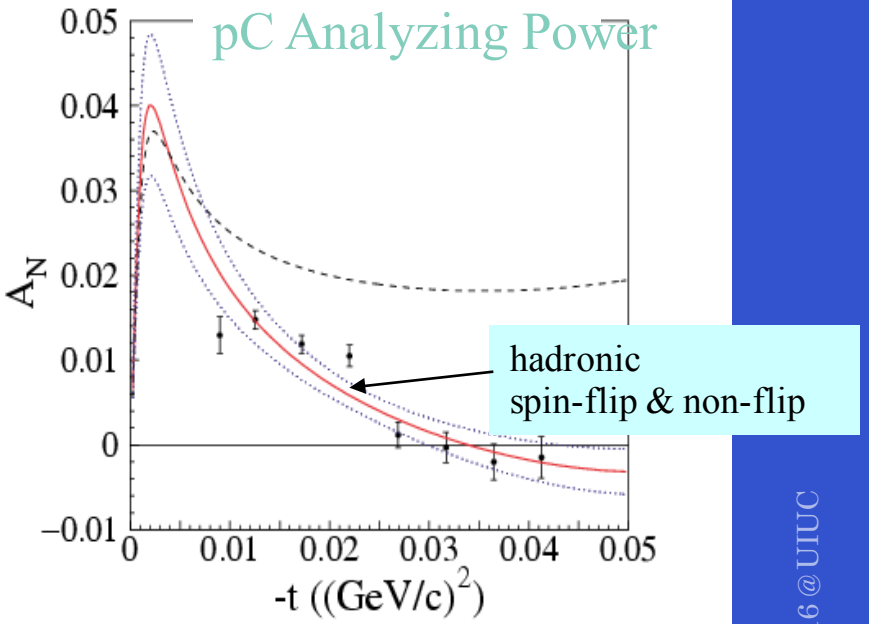


Δ*(1232) P33
↳ Nπ (>99%)

N*(1440 and higher) P11
↳ Nπ (60~70%)
Nππ (30~40%)

$\mathrm{Im}(f^{h*}f^{EM})$ asymmetry: Coulomb Nuclear Interference

- Elastic p+C scattering with smaller –t
- Interference between photon & Pomeron exchange amplitudes
- RHIC polarimeter



Phys.Rev.Lett.,89,052302(2002)

- **Smallness of -t (< ~1 GeV^2) in PHENIX forward neutron production → CNI should be considered?**

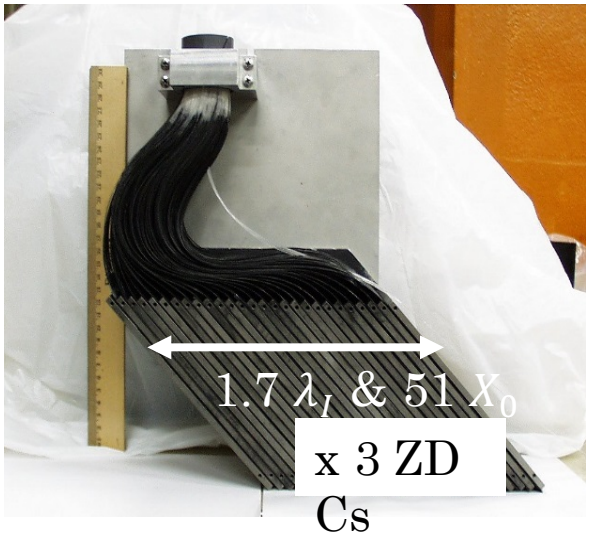
Theoretical Development

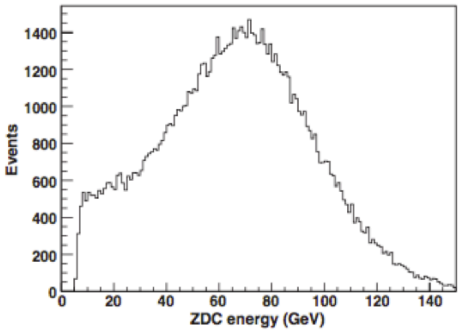
B. Kopeliovich et al
PRD 84, 114012 (2011)

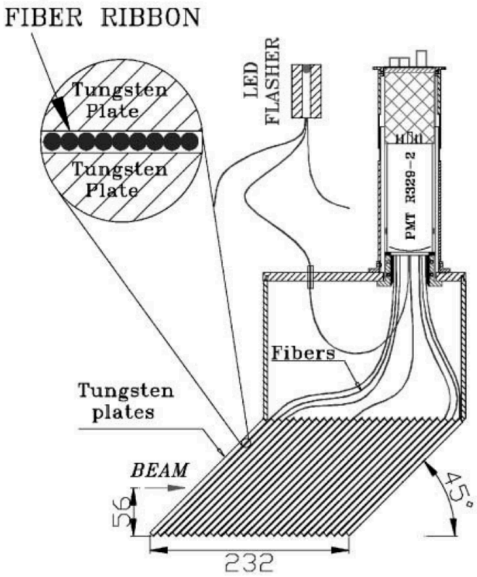
Approach	Cross section	A_N	Details
1. One π exchange with Born approximation	△	✕	• π pole $\frac{1}{m_\pi^2 - t}$ at exchange amplitude -> cross section peak at $x_F \cong 0.8$ • Overshoots cross section • $A_N = 0$: No phase shift with Born Approx.
2. One π exchange with absorptive correction	○	△	• Survival probability multiplied to final state function -> suppressed cross section • $A_N \neq 0$, but too small
3. <u>π exchange + Interference btw π and a_1 Reggeon</u>	○	○	• Interference btw π and a_1 makes large A_N • a_1 form factor is not known. A model is applied for this calculation.

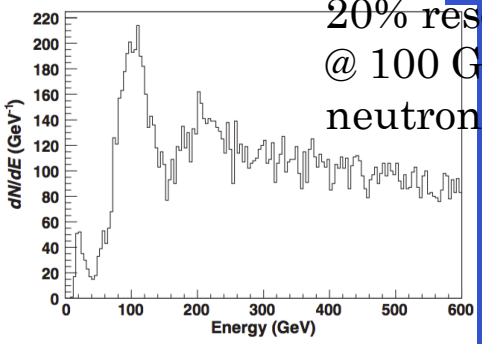
Zero Degree Calorimeter (ZDC)

- Cherenkov sampling hadron calorimeter
- Cu-W alloy + Optical fibers
- Tilted to 45 degree to maximize cherenkov photon input
- Energy resolution: 20~30 %









20% resolution
@ 100 GeV
neutron peak

FIG. 5. The energy distribution in the ZDC for Cu + Cu collisions at $\sqrt{s_{NN}} = 200$ GeV. Peripheral events were selected by requiring BBC inactivity.

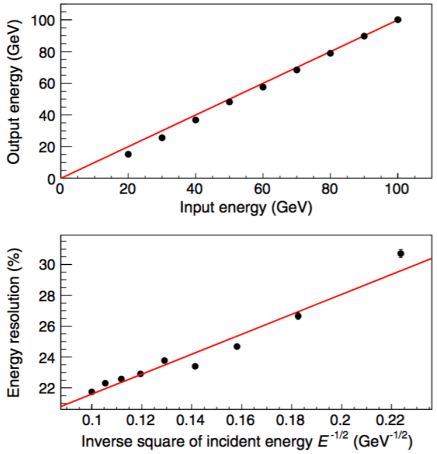
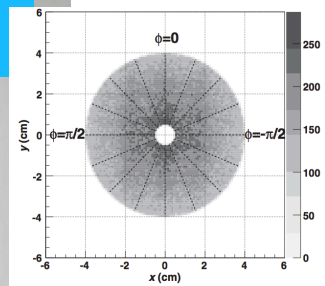
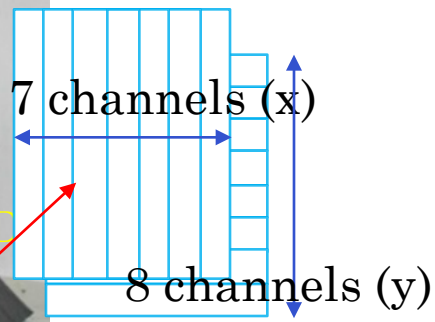


FIG. 4 (color online). (upper) The mean of output energy as a function of the incident neutron energy evaluated by the simulation. The solid line indicates a linear response. (lower) The energy resolution as a function of $1/\sqrt{E}$(GeV$^{-1/2}$). The solid line shows the fit result; $\Delta E/E = 65\%/\sqrt{E} + 15\%$.

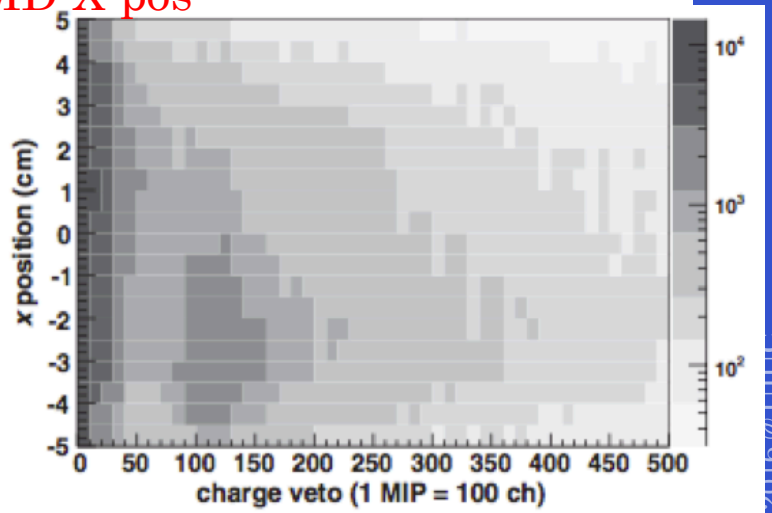
Shower Max Detector (SMD) & Charge veto counter

$$x, y = \frac{\sum_i^{SMD\ strips\ with\ hit} charge(i) \times strip\ position(i)}{\sum_i^{SMD\ strips\ with\ hit} charge(i)}$$





SMD X pos



Charge veto counter

Orientation

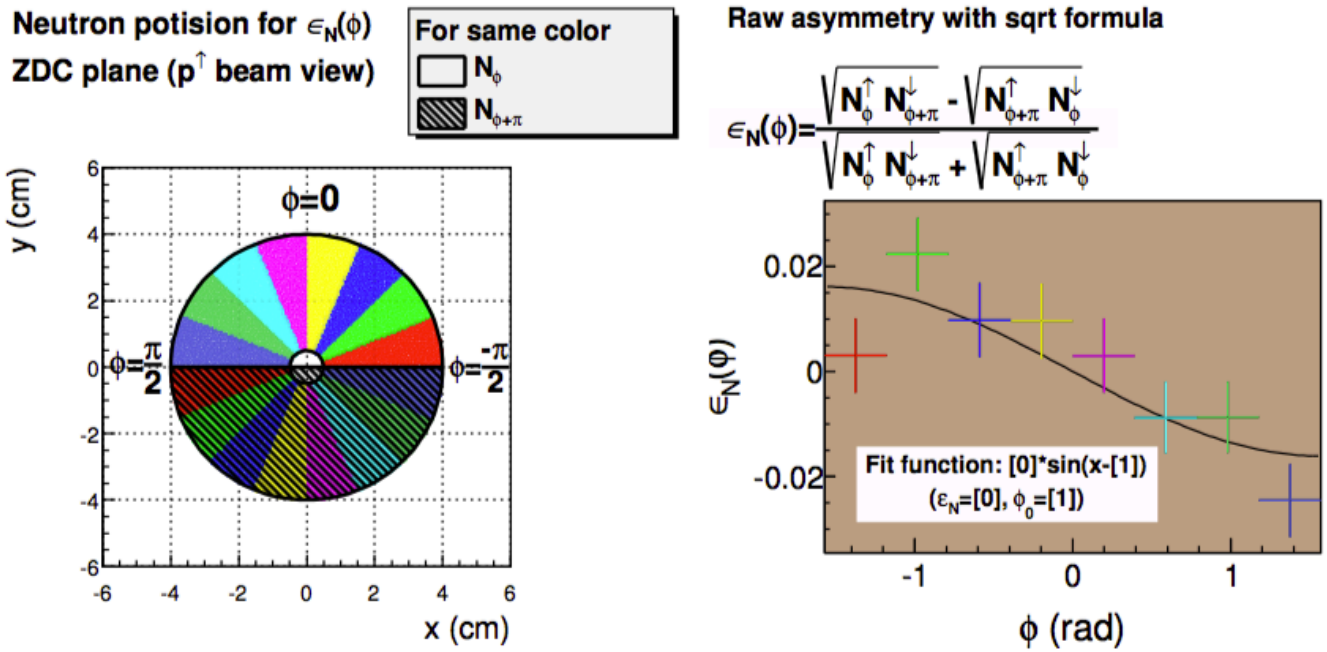
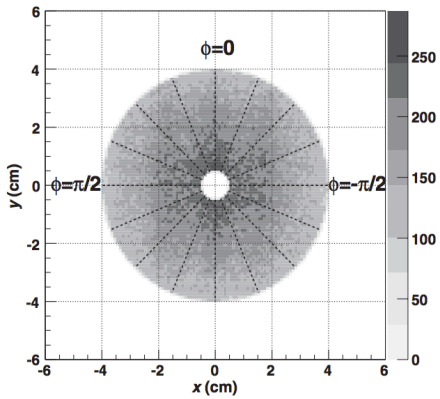
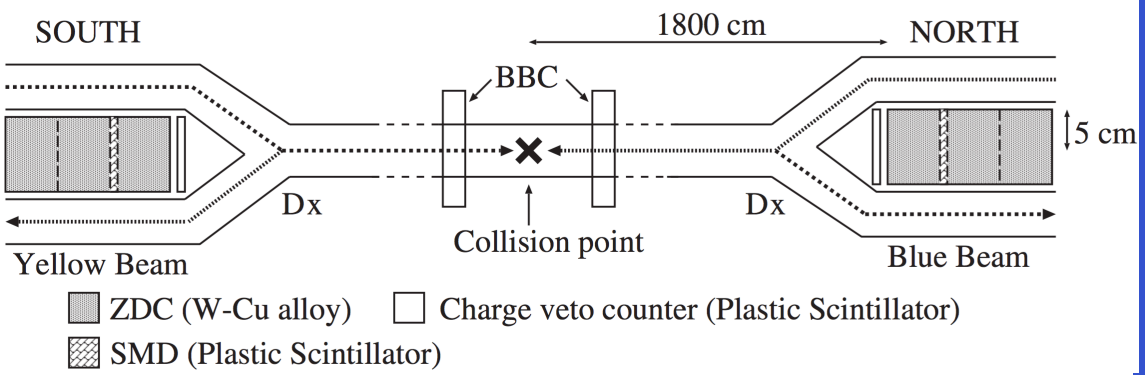


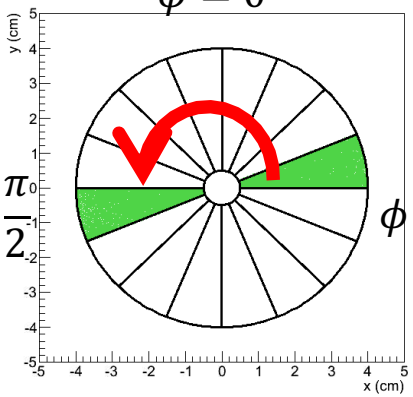
Figure A.1: Hit ϕ and $\phi+\pi$ acceptance for each $\epsilon_N(\phi)$ calculation (left), and $\epsilon_N(\phi)$ histogram (right). For each acceptance with the same color at the left plot, calculated $\epsilon_N(\phi)$ is plotted with the same color on the right plot. $\epsilon_N(\phi)$ in the right histogram is fitted to equation A.4 to get ε_N.

PHENIX neutron measurement





$\phi = 0$



$\phi = \frac{\pi}{2}$ $\phi = -\frac{\pi}{2}$

$$e_N(\phi) \equiv \frac{\sqrt{N_\phi^\uparrow N_{\pi-\phi}^\downarrow} - \sqrt{N_\phi^\downarrow N_{\pi-\phi}^\uparrow}}{\sqrt{N_\phi^\uparrow N_{\pi-\phi}^\downarrow} + \sqrt{N_\phi^\downarrow N_{\pi-\phi}^\uparrow}}$$

$$= P A_N \sin(\phi - \phi_0)$$