Forward neutron single transverse spin asymmetry A_N in high energy polarized p+A collisions at PHENIX

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for the PHENIX Collaboration

Content

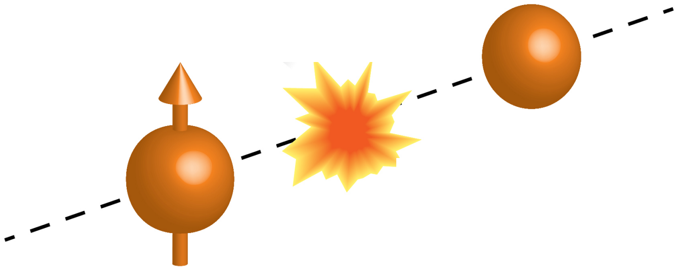
I. A_N definition

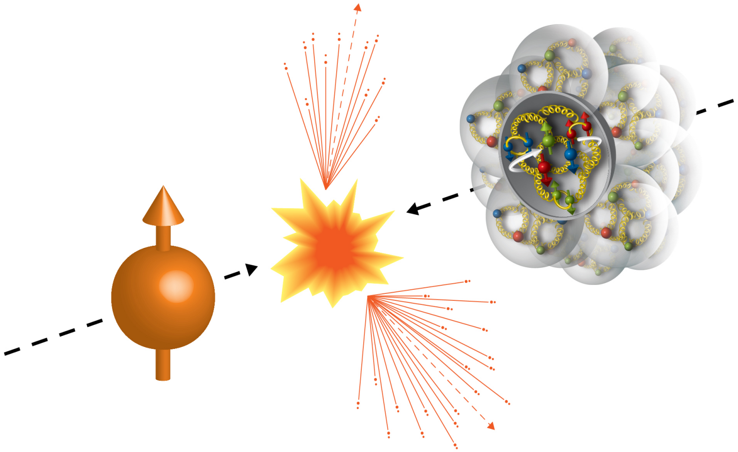
II. $p^{\uparrow} + p \rightarrow n + X$

- History
- Theory for A_N

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

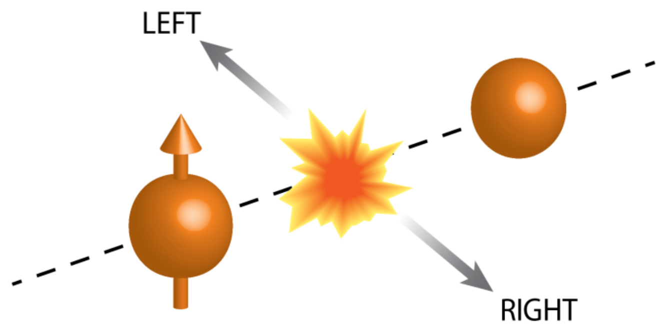
- PHENIX forward neutron detectors
- **Unexpected A dependence on A_N**
- Discussions on origin of A_N
- Further measurements





Transverse Single Spin Asymmetry A_N

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

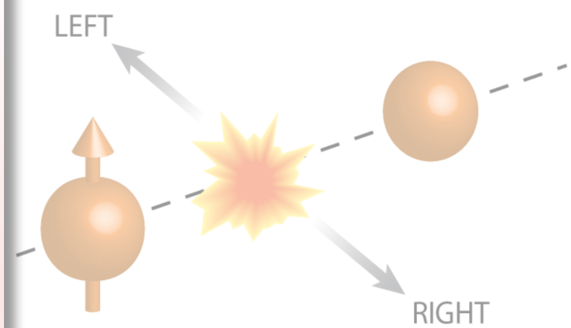


$$\frac{\sigma_L^{\uparrow} - \sigma_L^{\downarrow}}{\sigma_L^{\uparrow} + \sigma_L^{\downarrow}} = \frac{\sigma_L^{\uparrow} - \sigma_R^{\uparrow}}{\sigma_L^{\uparrow} + \sigma_R^{\uparrow}}$$

Transverse Single Spin Asymmetry A_N

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

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

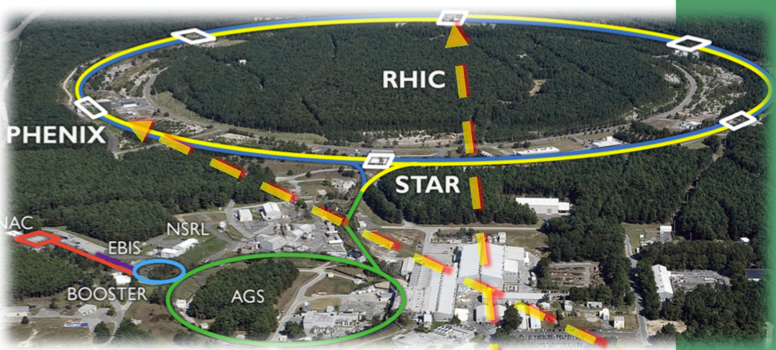


Small $|<nX|T|\uparrow>|^2 + |<nX|T|\uparrow>|^2$ *process may have*
Large $\mathrm{Im} <nX|T|-><+|T^+|nX>$

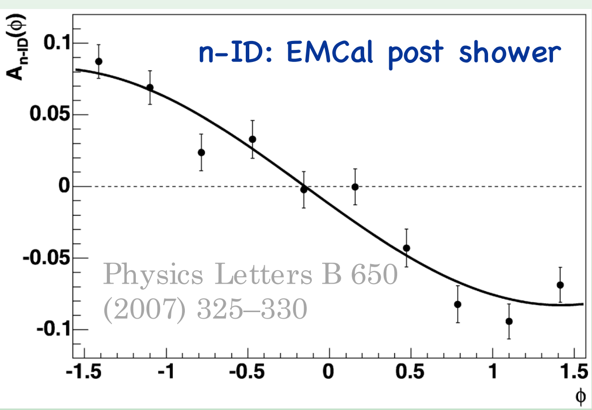
One of the advantages of spin asymmetry data:
Elucidate process which unpolarized cross section is not sensitive to

History of forward neutron A_N

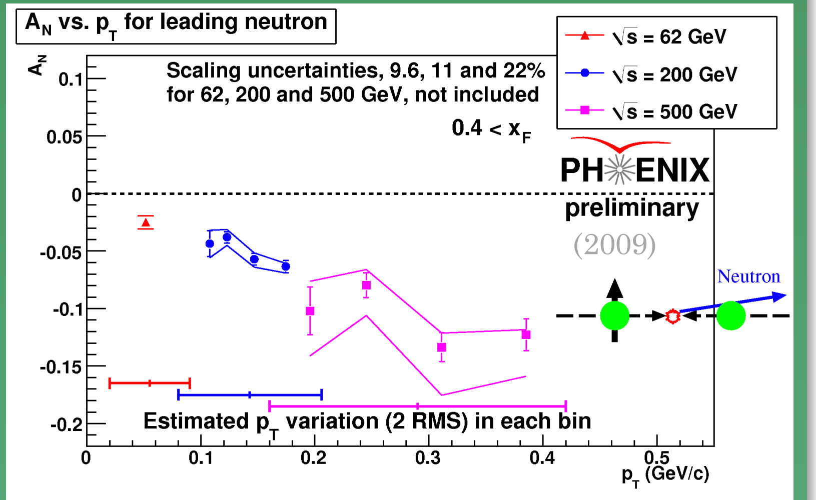
$$A_N = \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}}$$

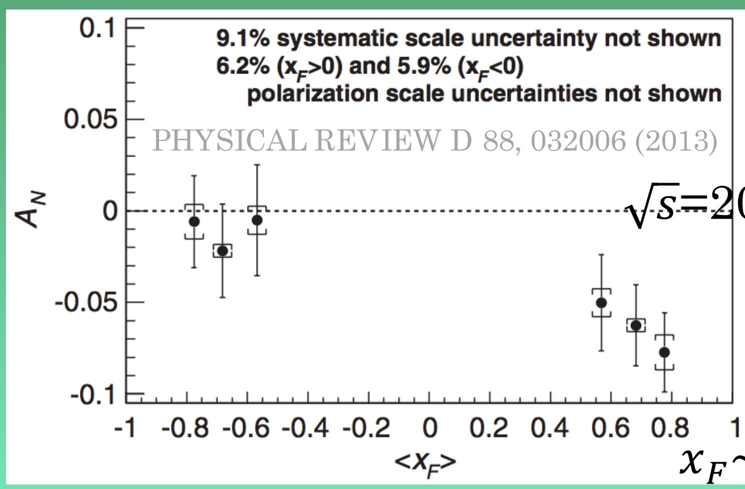


IP12 (2001-2002)



PHENIX (2003~)





$\sqrt{s}$=200 GeV

$x_F \sim E_n/E_p$

2016. 12. 09. Minjung Kim

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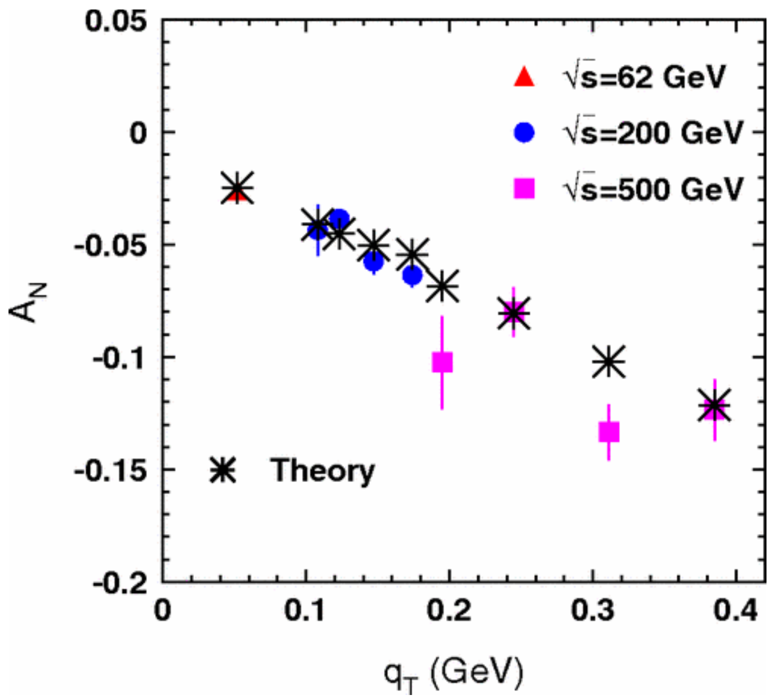
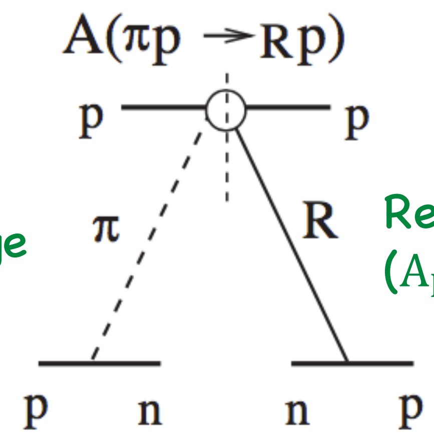
Theory for $p^{\uparrow} + p$ forward neutron

- 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)

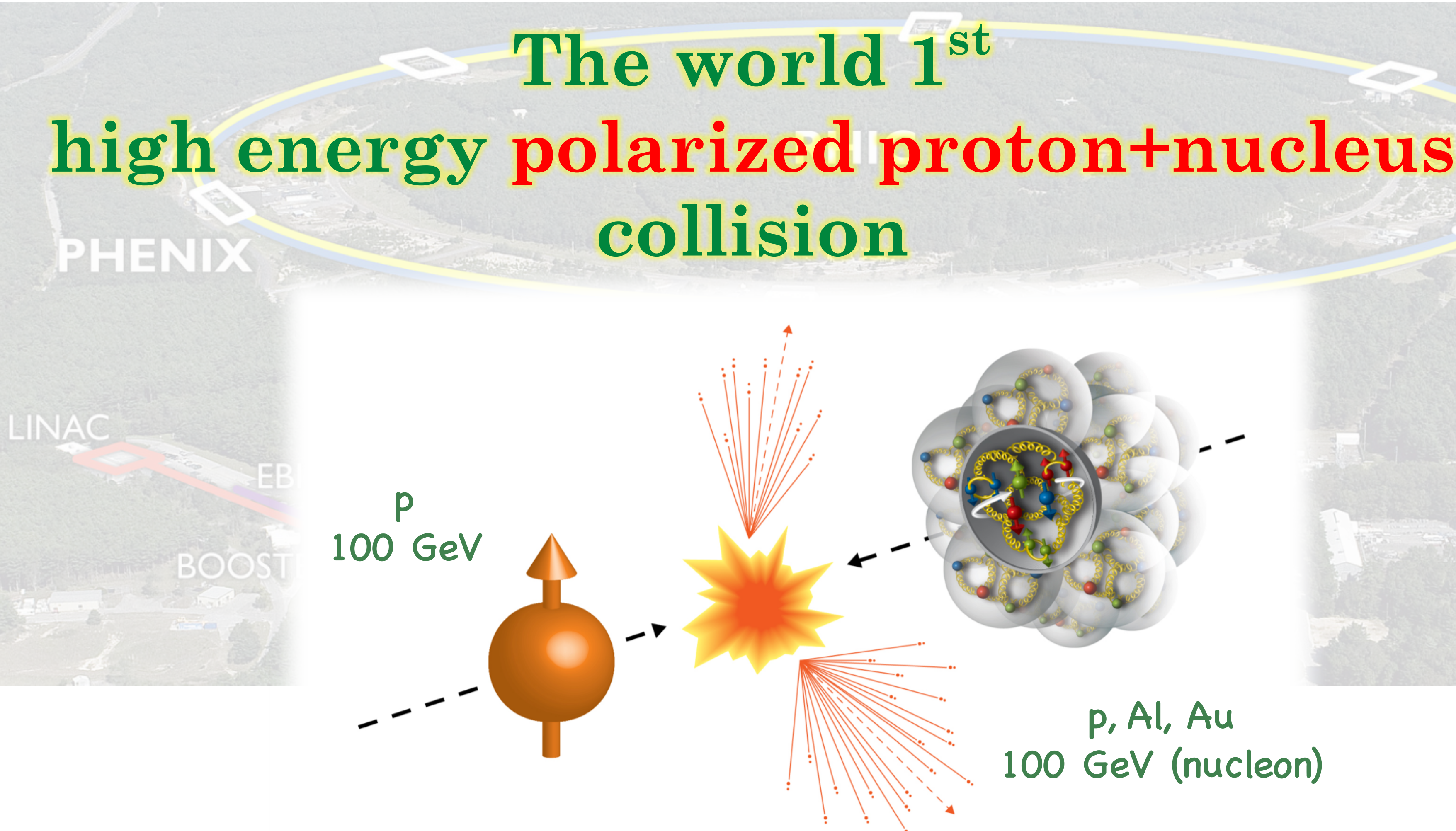
B. Kopeliovich et al PRD 84, 114012 (2011)

Theoretical Development

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 data • Same phase for spin flip & non-flip amplitude -> $A_N = 0$
2. One π exchange with absorptive correction	○	△	• Survival probability multiplied to final state function -> suppr essed 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 • Uncertainties: e.g. a_1 form factor is not known. A model is applied for this calculation.

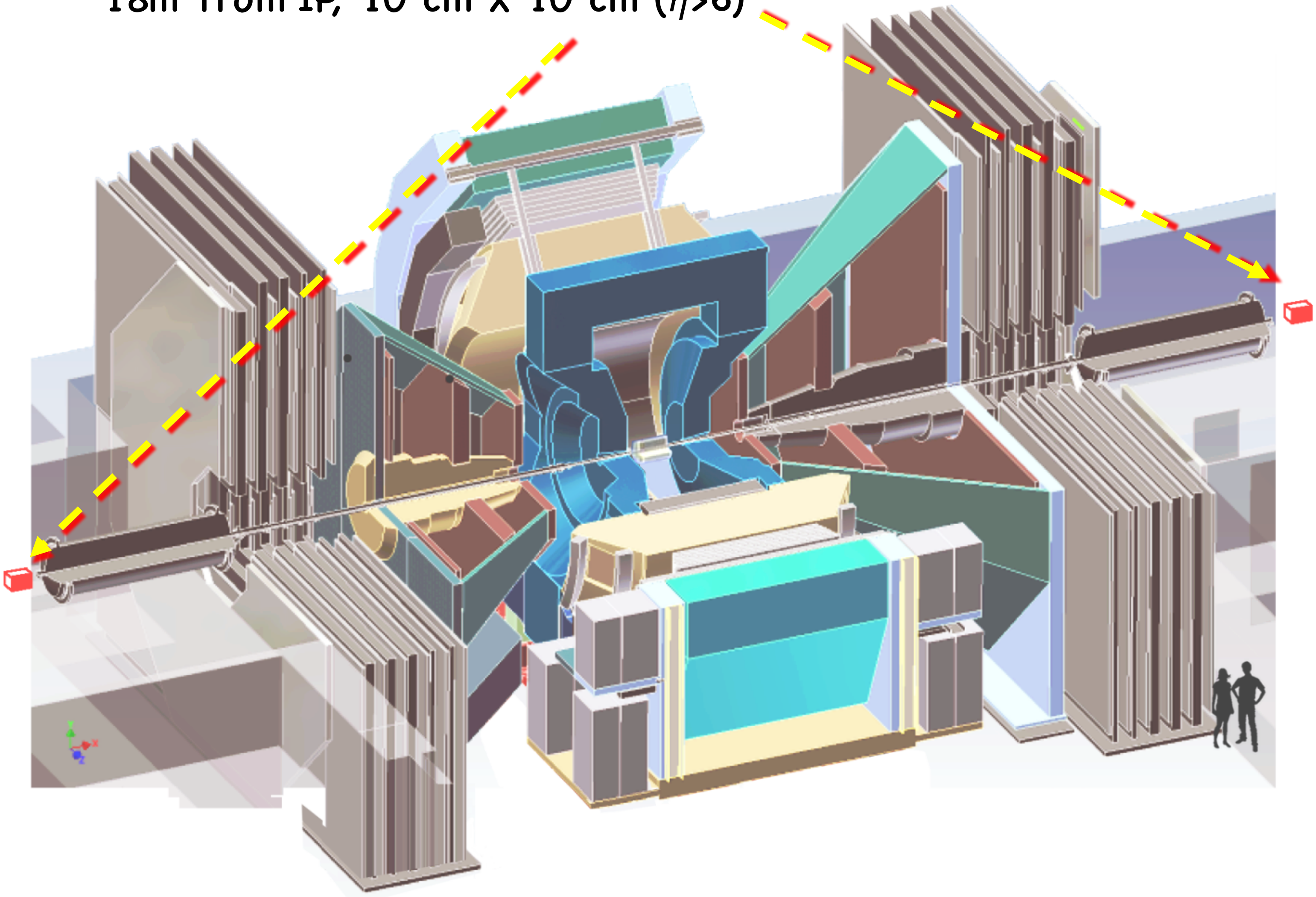
RHIC Run15 (2015)

The world 1st high energy polarized proton+nucleus collision



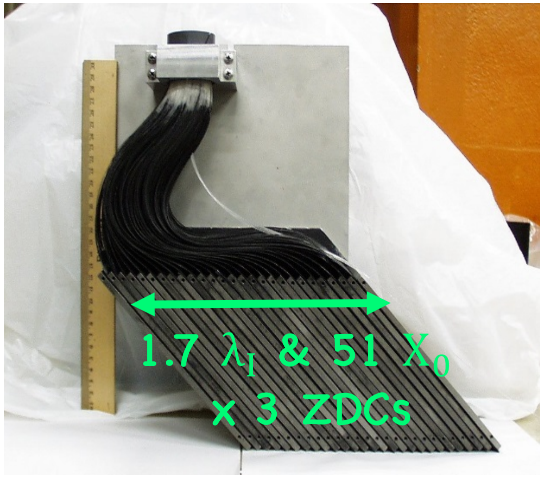
Neutron detector location

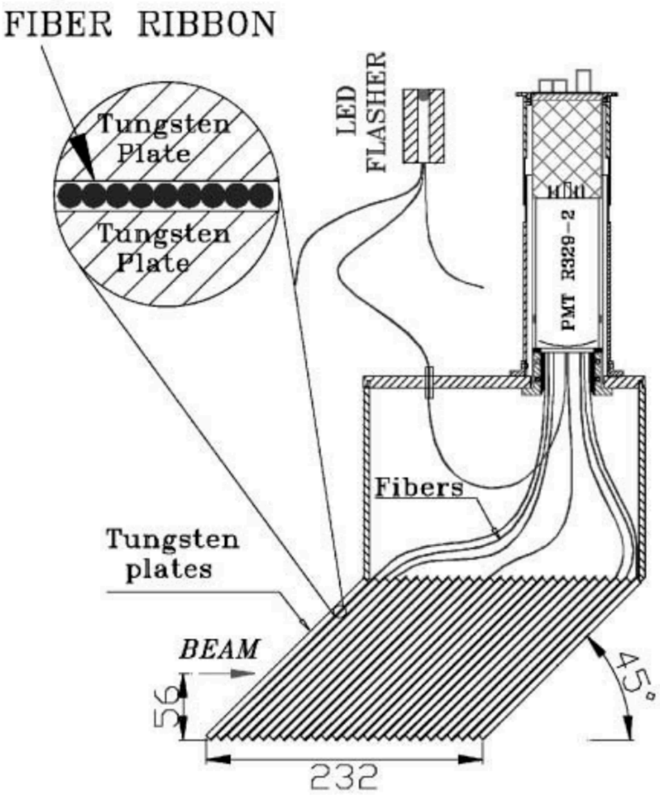
18m from IP, 10 cm x 10 cm (η>6)



Zero Degree Calorimeter (ZDC)

- Cherenkov sampling hadron calorimeter
- Cu-W alloy + Optical fibers
- Tilted to 45 degree to maximize cherenkov photon
- $\Delta E/E$ = 20~30%

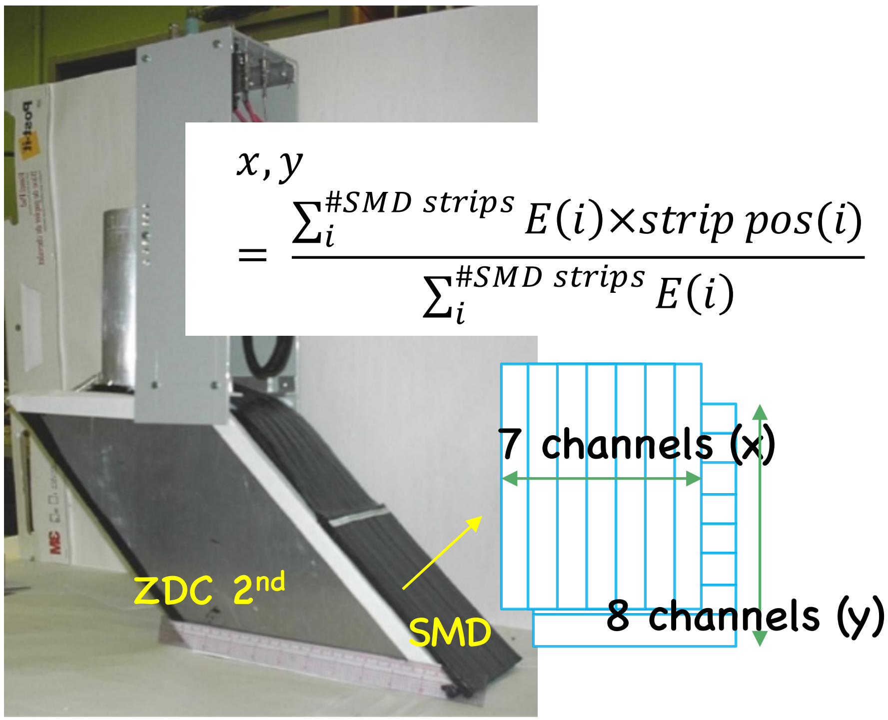


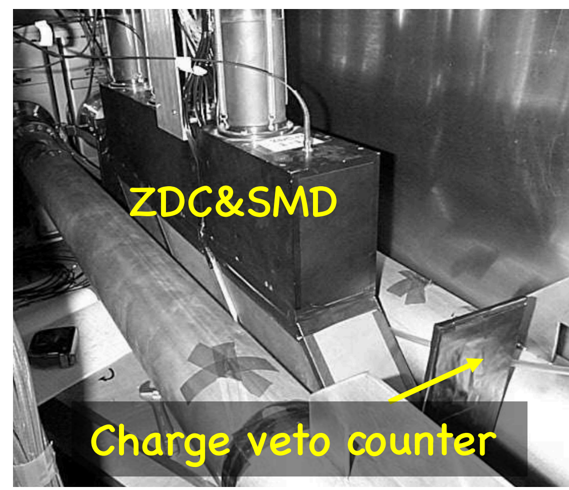


Shower Max Detector (SMD) & Charge veto counter

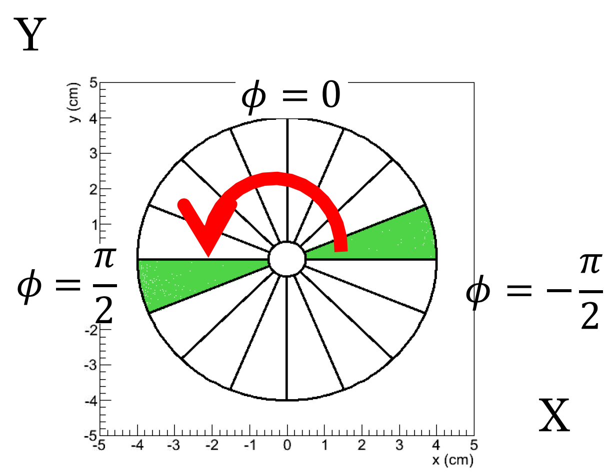
- SMD (Shower Max Detector): X-Y plastic strip scintillator hodoscopes ($\Delta x, \Delta y$ ~1 cm)
- Charge veto counter: plastic scintillator pad at front

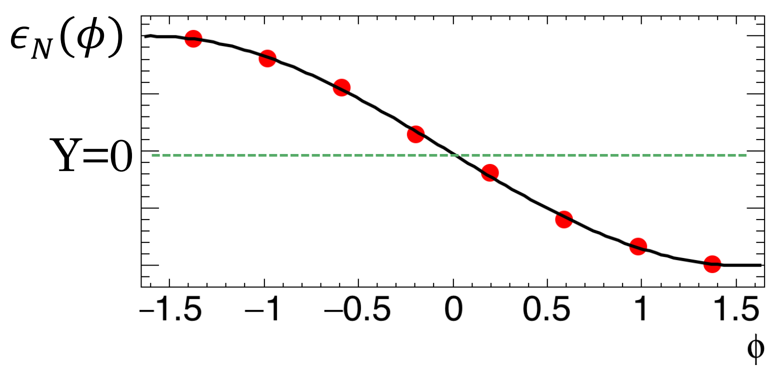
$$x, y = \frac{\sum_{i}^{\#SMD\ strips} E(i) \times strip\ pos(i)}{\sum_{i}^{\#SMD\ strips} E(i)}$$





A_N Measurement

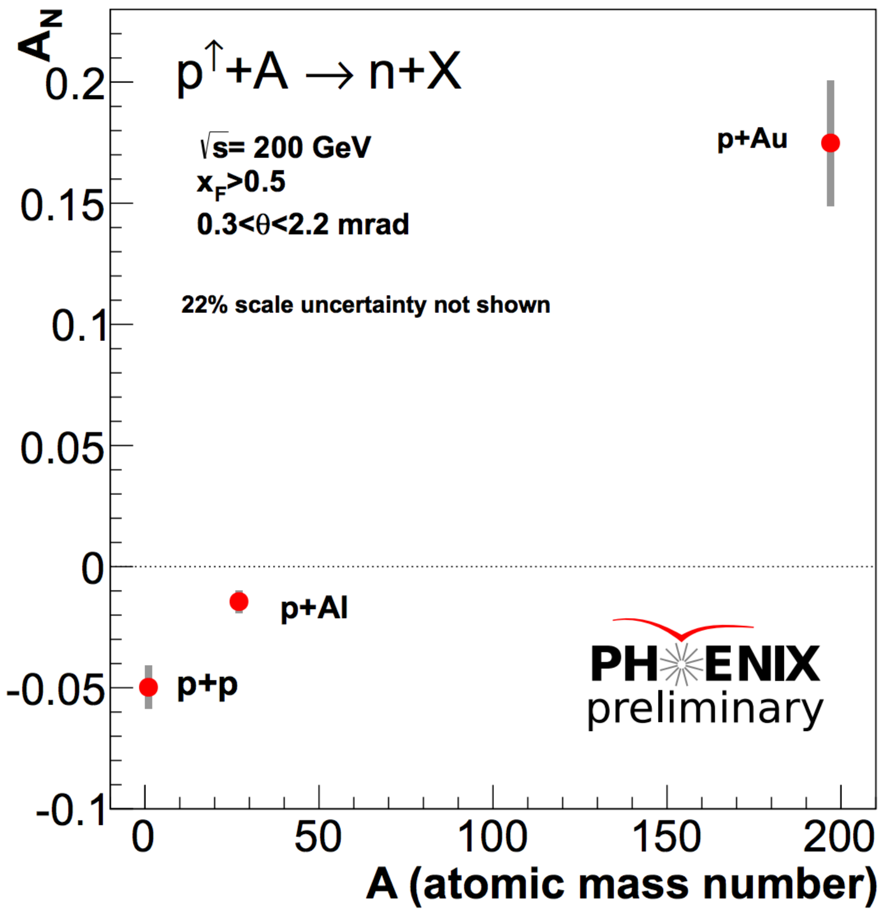




$$\epsilon_N(\phi) \equiv \frac{\sqrt{N_\phi^\uparrow N_{\pi-\phi}^\downarrow} - \sqrt{N_\phi^\downarrow N_{\pi-\phi}^\uparrow}}{\sqrt{N_\phi^\uparrow N_{\pi-\phi}^\downarrow} + \sqrt{N_\phi^\downarrow N_{\pi-\phi}^\uparrow}}$$

$$= P \boldsymbol{A_N} \sin(\phi - \phi_0)$$

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

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

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

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

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

EM only

EM & Strong interference

Strong only

Origin of A_N

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

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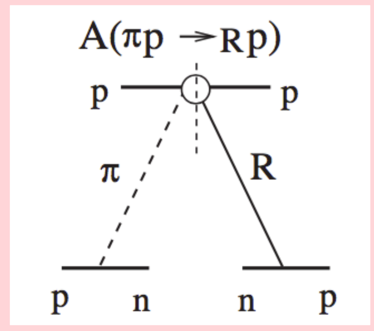

$$A_N \propto \mathrm{Im}\left(f_{\mathrm{flip}}^{\mathrm{EM+h}*} f_{\mathrm{non-flip}}^{\mathrm{EM+h}}\right)$$

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

EM only — EM & Strong interference — Strong only

Negligible for p+p

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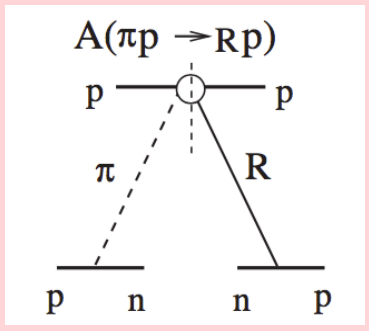
Origin of A_N

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

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



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

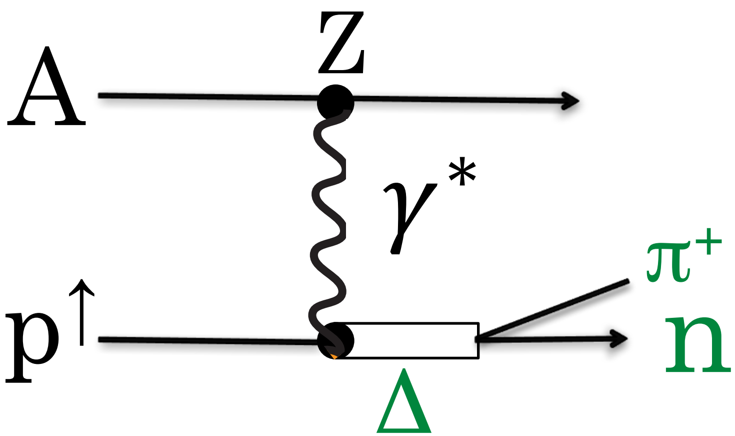
$$= \mathrm{Im}\left(\underbrace{f_{\mathrm{flip}}^{\mathrm{EM}*} f_{\mathrm{non-flip}}^{\mathrm{EM}}}_{\text{EM only}} + \underbrace{f_{\mathrm{flip}}^{\mathrm{EM}*} f_{\mathrm{non-flip}}^{\mathrm{h}} + f_{\mathrm{flip}}^{\mathrm{h}*} f_{\mathrm{non-flip}}^{\mathrm{EM}}}_{\text{EM \& Strong interference}}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

EM only — EM & Strong interference — Strong only

Negligible for p+p

How about in p+A?

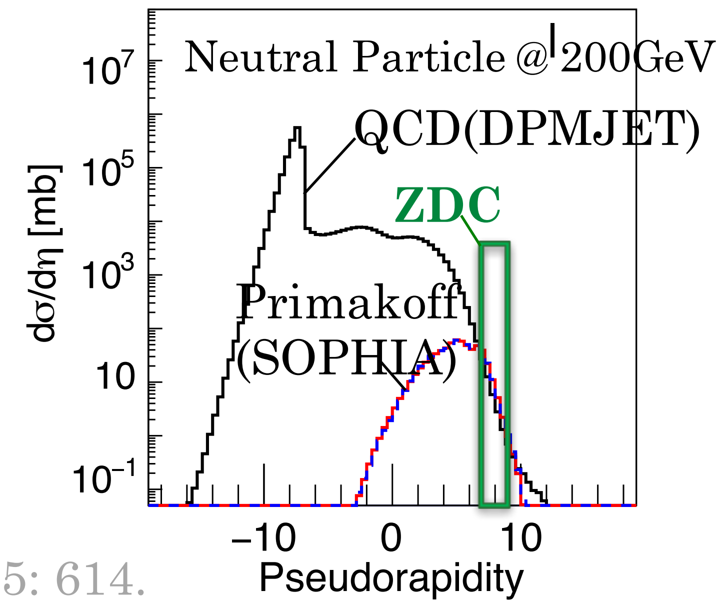
EM process - Primakoff



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

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

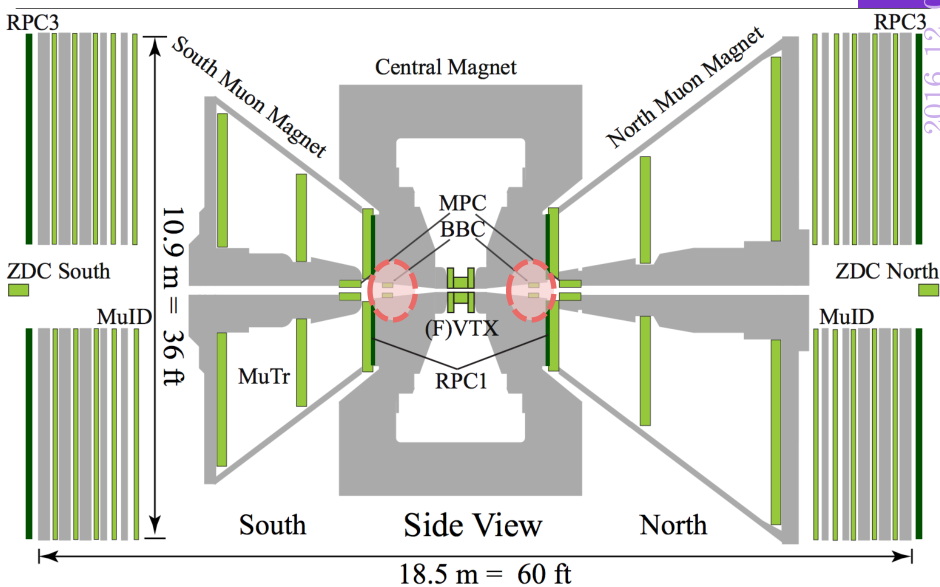
Primakoff MC predicts comparable yields between QCD and Primakoff process for p+Au



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

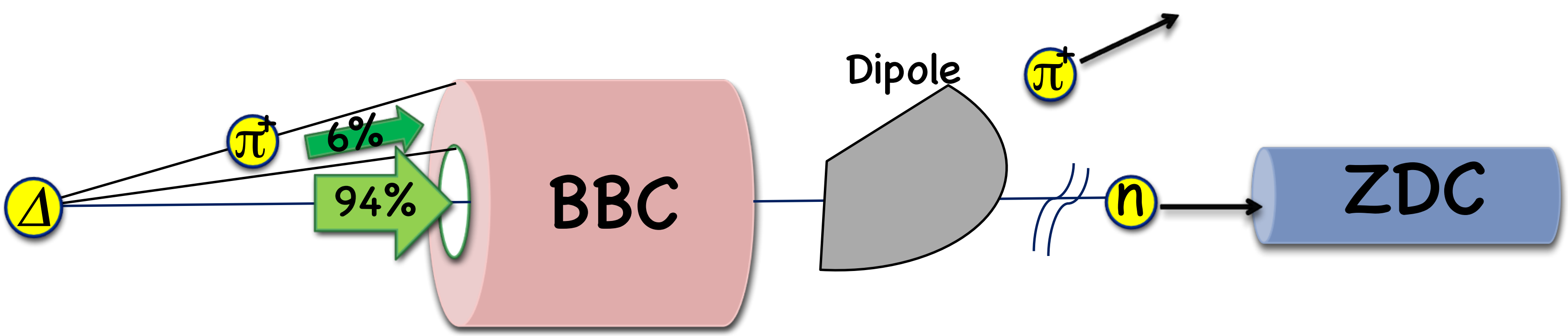
Correlation study – EM ratio

Beam Beam Counter (3<η<4)
- Quartz cherenkov radiator elements
- ~80% efficiency on inelastic collision

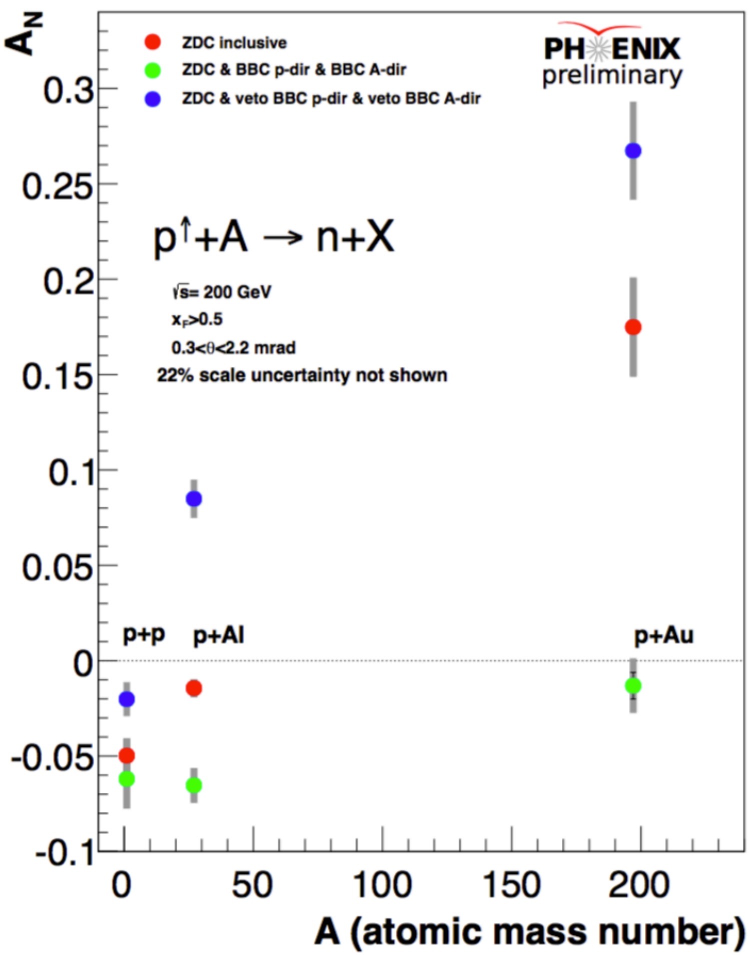


MC predicts suppression of Primakoff events by requiring BBC hit

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



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

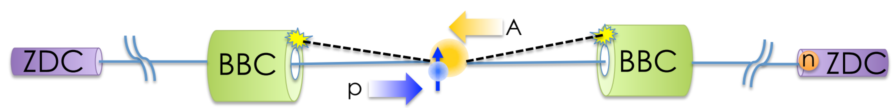


Forward neutron inclusive

- Strong A-dependence

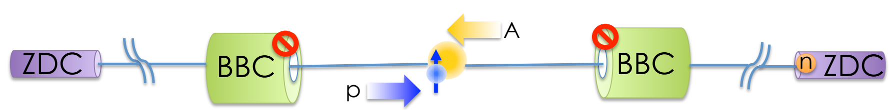
Particle ***HIT*** at lower rapidity - BBC hit

- EM process suppressed
- "Weaker" A-dependence



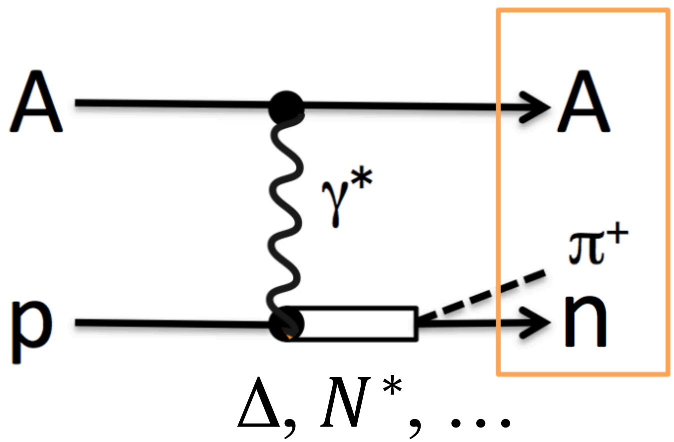
Particle ***VETO*** at lower rapidity - BBC veto

- EM process enhanced
- "Stronger" A-dependence ***p+A sign flip***

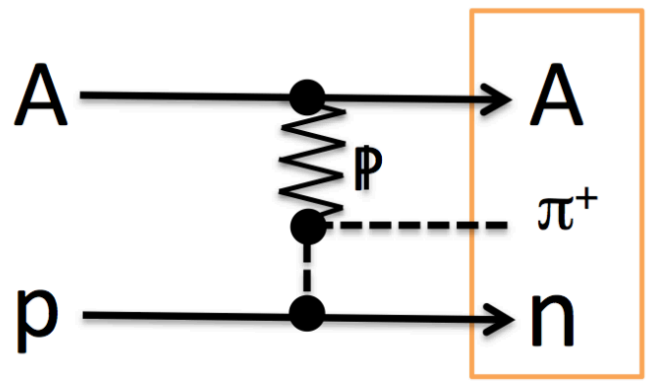


Coulomb-Nuclear Interference

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



Primakoff



Possible example of QCD process w/ same final state

γ* exchange and Reggeon exchange can interfere
→ may give positive A_N

γ* amplitude is proportional to Z → significant for large Z

Summary

- One of the advantages of spin asymmetry measurement is that it elucidate process which unpolarized cross section is not sensitive to
- 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**

Thank you

Köszönöm

Back up

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

- Measured A_N of π^0 from $p + Z \to \Delta^+ / N^* \to \pi^0 + p + Z$
- In $\Delta^+(1232)$ and $N^*(1520)$ resonance region,

$$A_N = -0.57 \pm 0.12\,(\mathrm{stat.})^{+0.21}_{-0.18}\,(\mathrm{syst.}) \quad (\text{zero at region 1})$$

PRL 64, 357-360 (1990)