Single transverse-spin asymmetry of very forward neutron production in polarized pp collisions at PHENIX

WWND2012 in Puerto Rico

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Outline

- Introduction
  - RHIC spin project
  - Very forward neutron asymmetry
  - Measurement at IP12 experiment
- Measurements at PHENIX
  - Cross section measurement
  - Asymmetry measurement in polarized p+p collisions
    - x_F dependence
    - $\sqrt{s}$ dependence
- Production mechanism
- Future outlook

Introduction

- Origin of the nucleon spin 1/2
  - Spin puzzle: polarized DIS experiments found that nucleon's spin was not explained by the quark spin

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta g + L$$

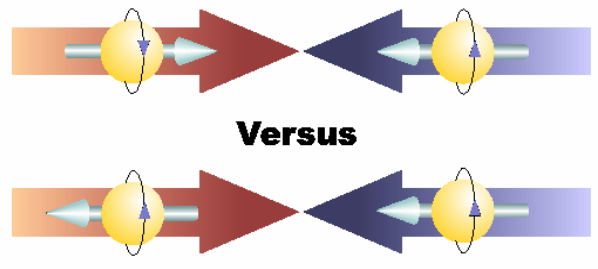
Orbital angular momentum

Gluon spin contribution

Quark spin contribution

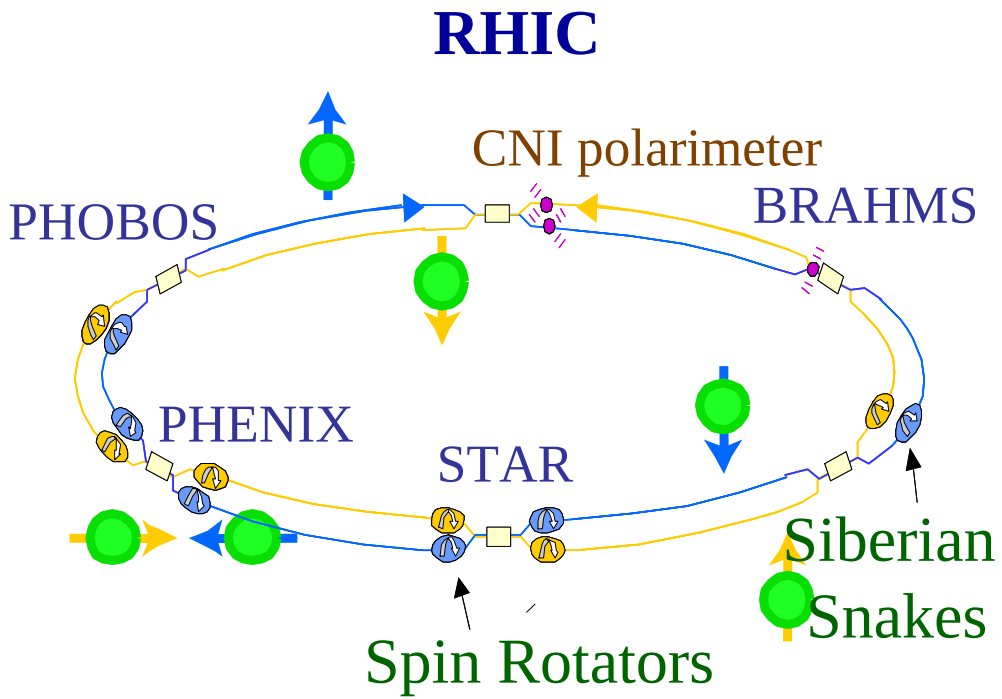
- RHIC spin project
  - First goal: measurement of the gluon spin contribution
  - Helicity structure of the nucleon with double-helicity asymmetry (A_{LL}) measurements

$$A_{LL} = \frac{d\sigma_{++} - d\sigma_{+-}}{d\sigma_{++} + d\sigma_{+-}}$$



Introduction

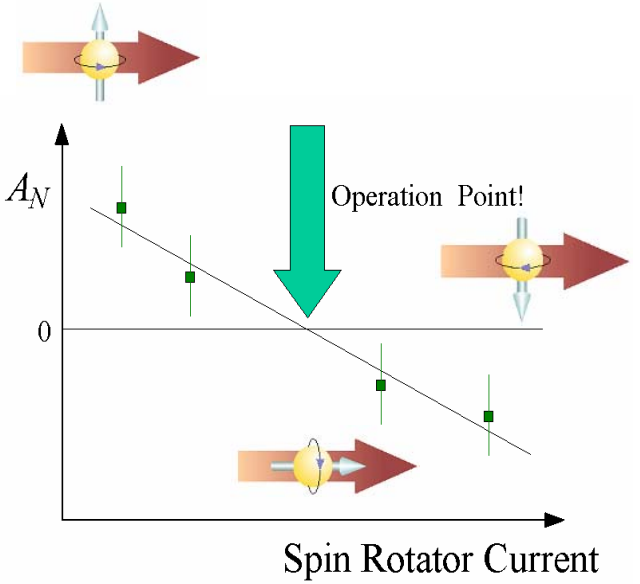
- For A_{LL} measurement at RHIC, we need a good local polarimeter at the IP (interaction point)
- At RHIC, protons are stored with transverse polarization
  - Monitored by the CNI polarimeter and pol. Hydrogen gas-jet polarimeter
- Spin rotator magnets rotate the proton polarization into the longitudinal direction at PHENIX (IP8) and STAR (IP6)



Single transverse-spin asymmetry

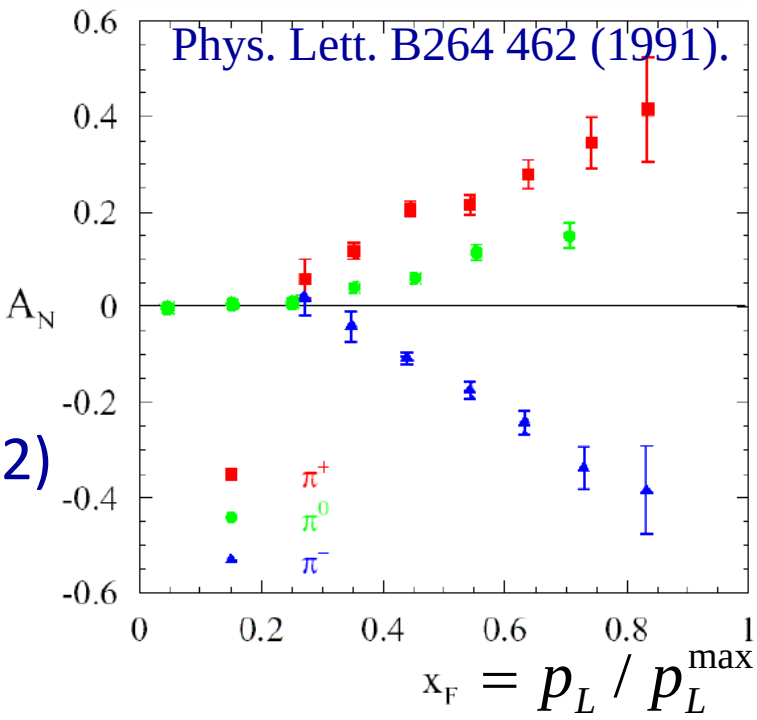
- Longitudinal-spin is monitored by the local polarimeter by using physics processes with left-right asymmetry (A_N)

$$A_N = \frac{d\sigma_{Left} - d\sigma_{Right}}{d\sigma_{Left} + d\sigma_{Right}}$$



- A_N of forward π^0 found at FNAL-E704
  - But, not at very forward…

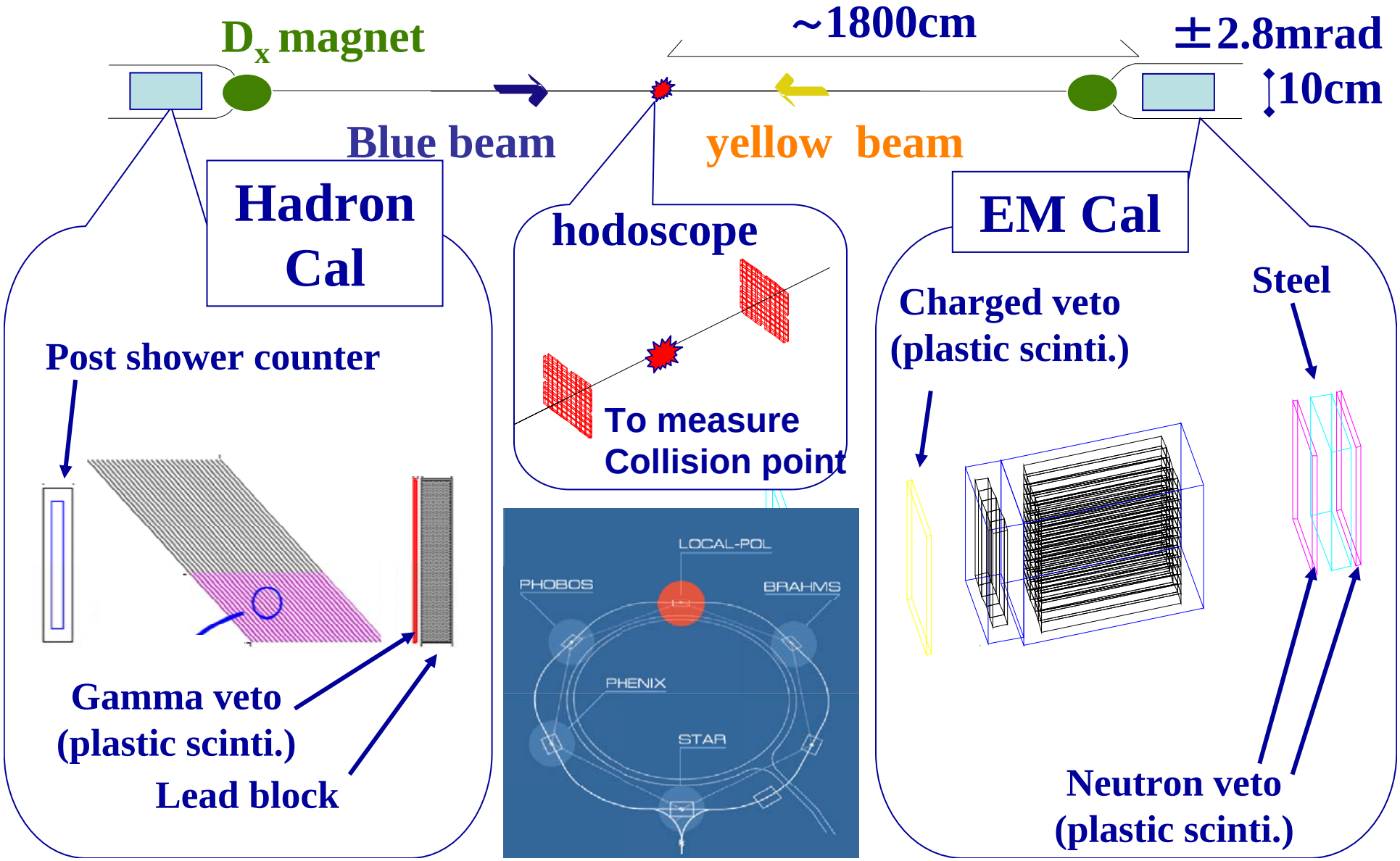
$pp \rightarrow \pi^{\pm 0} X$
$\sqrt{s} = 19.4$ GeV
$0.2 < p_T < 2.0$ GeV/c



- Measurement at IP12 in Run2 (2001-02)
  - With EM calorimeter to measure A_N of photons mainly from π^0 decay

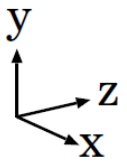
IP12 experiment

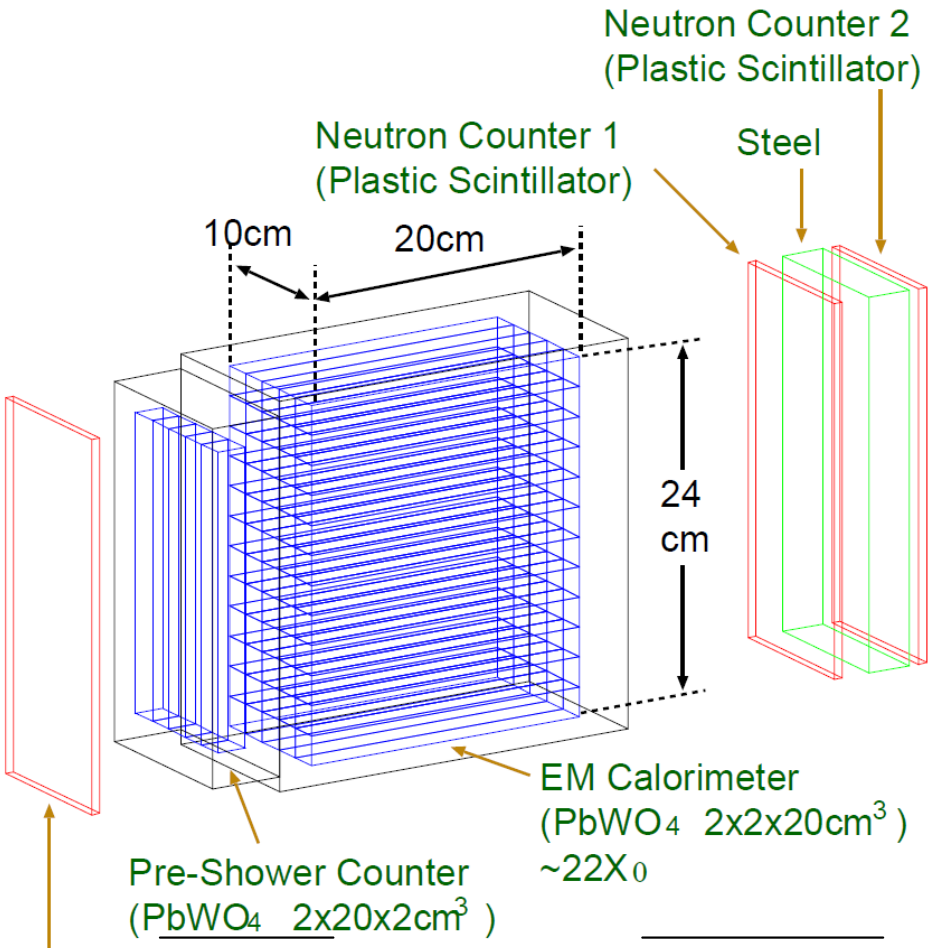
- performed in 2001-2002 with $\sqrt{s}$ = 200 GeV polarized proton collisions at the 12 o'clock collision point



EM calorimeter

- Performance
  - calibrated in the electron beam at SLAC
  - $\Delta E/E \sim 10\%/\sqrt{E(\text{GeV})}$ for γ
  - $\Delta x \sim \Delta y \sim 0.1$ cm for γ
  - $\Delta x \sim \Delta y \sim 0.5$ cm for neutron





$$\gamma\text{-ID} = \text{ch-veto} \times \text{preshower} \times \overline{\text{postshower}}$$

$$(\gamma\text{-purity} \sim 82\%)$$

$$\text{n-ID} = \overline{\text{ch-veto}} \times \overline{\text{preshower}} \times \text{postshower}$$

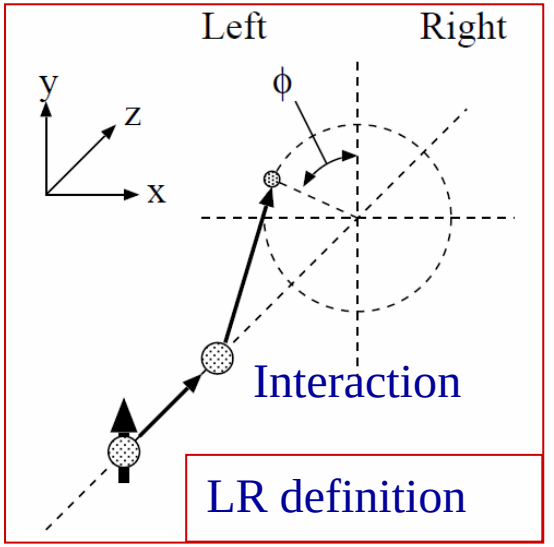
$$(\text{n-purity} \sim 99\%)$$

Forward neutron production

- Asymmetry measurement at RHIC-IP2
  - 2001 – 2002 run
  - Very large asymmetry

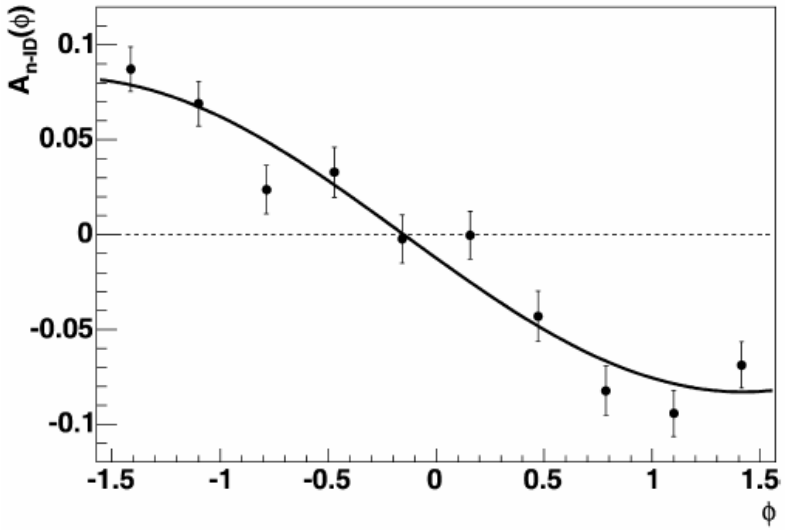
$$A_N = (-0.090 \pm 0.006 \pm 0.009) \times (1.0^{+0.47}_{-0.24})$$

  - Impossible to explain the large asymmetry with one-pion exchange
    - Kopeliovich et al., AIP Conf. Proc. 1056 (2008) 199.
    - e.g. interference between pion and a_1
  - Polarimeter at IP (local polarimeter)



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

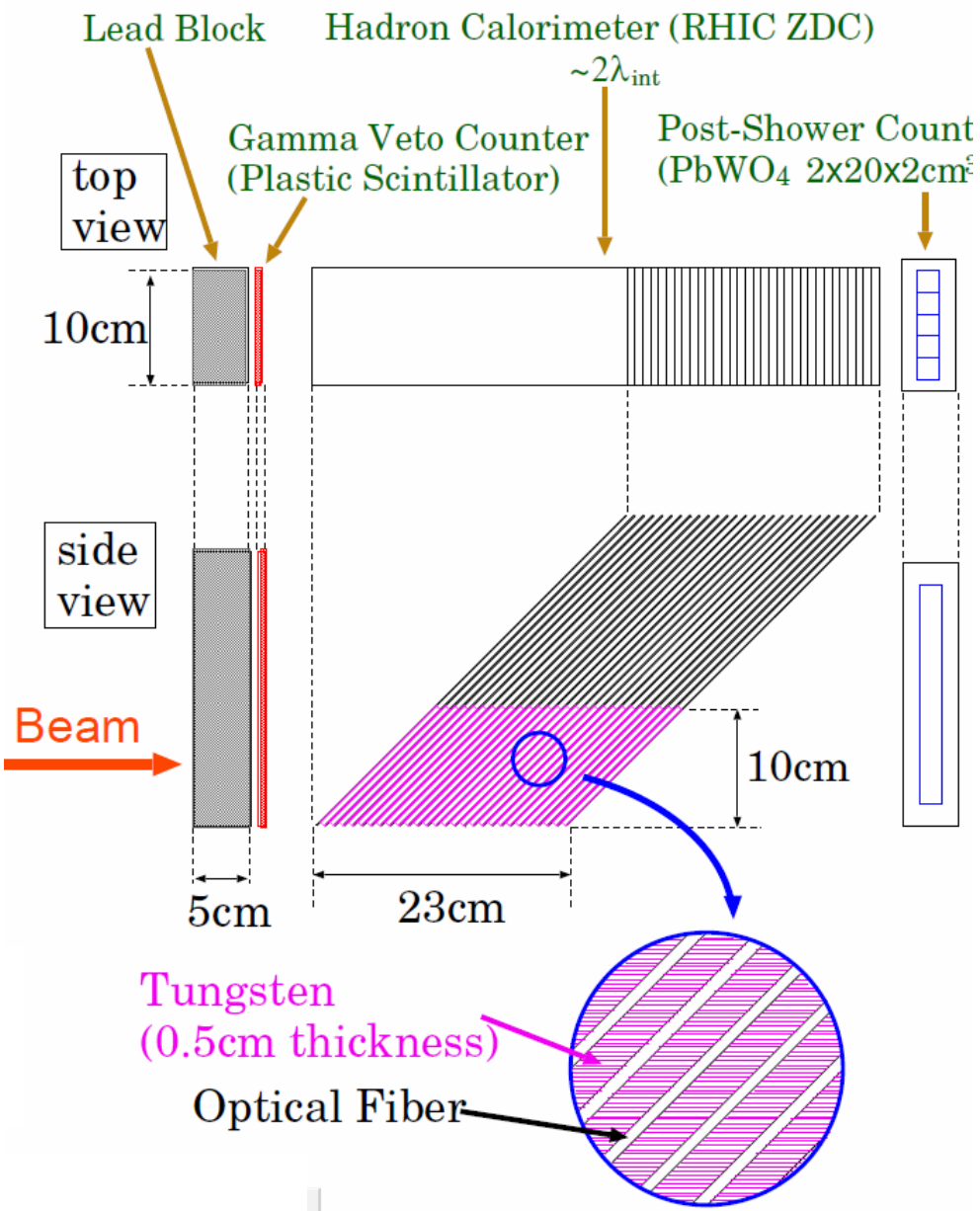
$$A_N = \frac{1}{P} \cdot \varepsilon_N$$



Y. Fukao, et al.,
Phys. Lett. B 650 (2007) 325.

Hadron calorimeter

- One ZDC prototype module (1/3 length)
- Performance
  - Energy is calibrated by using cosmic-ray data and simulation.
  - $\Delta E/E$ ~ 40-50% at E > 20 GeV
  - Δx ~ 3 to 4 cm by the post shower counter



$$n = \overline{\gamma\text{-veto}}$$

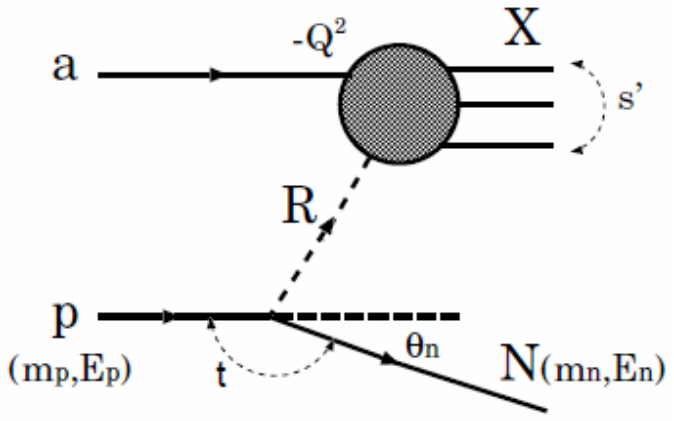
purity~100%

IP12 experiment results

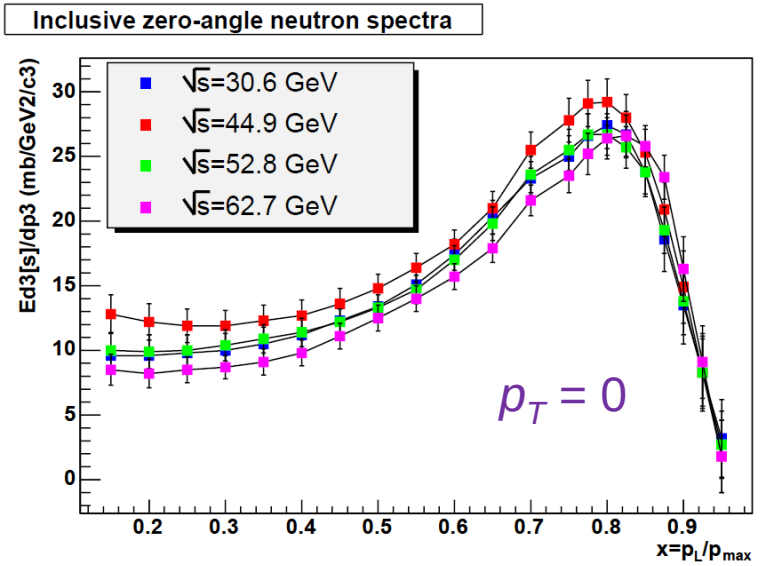
- Forward neutron
  - EMCal result $A_N = -0.090 \pm 0.006 \pm 0.009$
  - HCal result $A_N = -0.135 \pm 0.018$
  - consistent at the 2σ-level
- π^0 and photon
  - A_N consistent with zero
- backward asymmetries
  - A_N consistent with zero

Forward neutron production

- Cross section measurement at ISR/FNAL
  - Forward peak in the x_F distribution
    - Around x_F~0.8
  - Only a small $\sqrt{s}$ dependence
  - p_T distribution
    - $\sigma \propto \exp(-a \cdot p_T)$, a ~ 4.8 GeV^{-1}



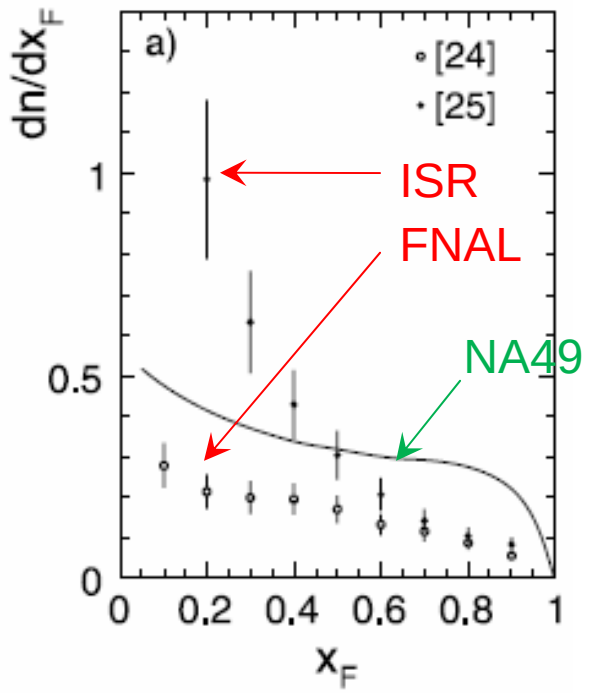
- OPE (one-pion exchange) model gives a reasonable description

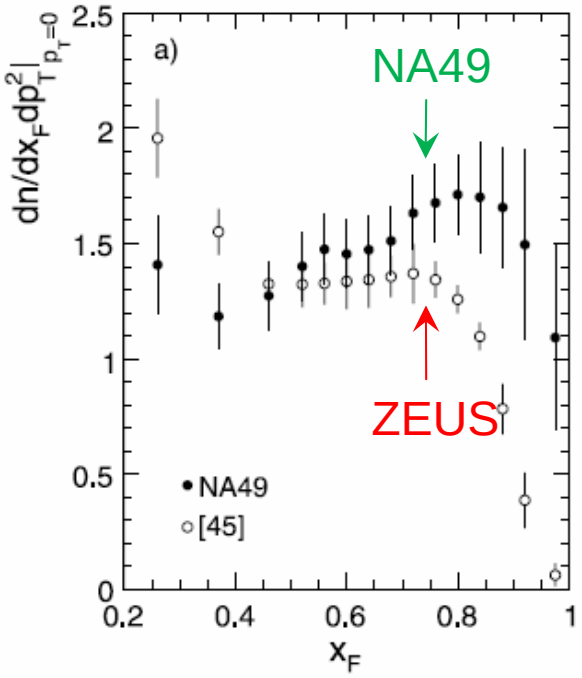


Forward neutron production

- Cross section measurement at HERA(e+p)/NA49(p+p)
  - High resolution p_T distribution
    - $\sigma \propto a(x_F)\cdot\exp(-b(x_F)\cdot p_T^2)$, $b \sim 8$ GeV^{-2} for $0.3 < x_F < 0.85$
  - x_F distribution
    - Suppression of the forward peak at high √s?
      - feed-down correction?
- More data necessary to understand the production mechanism
  - Asymmetry measurement as a new independent input

NA49 Collaboration,
Eur. Phys. J.
C65 (2010) 9.

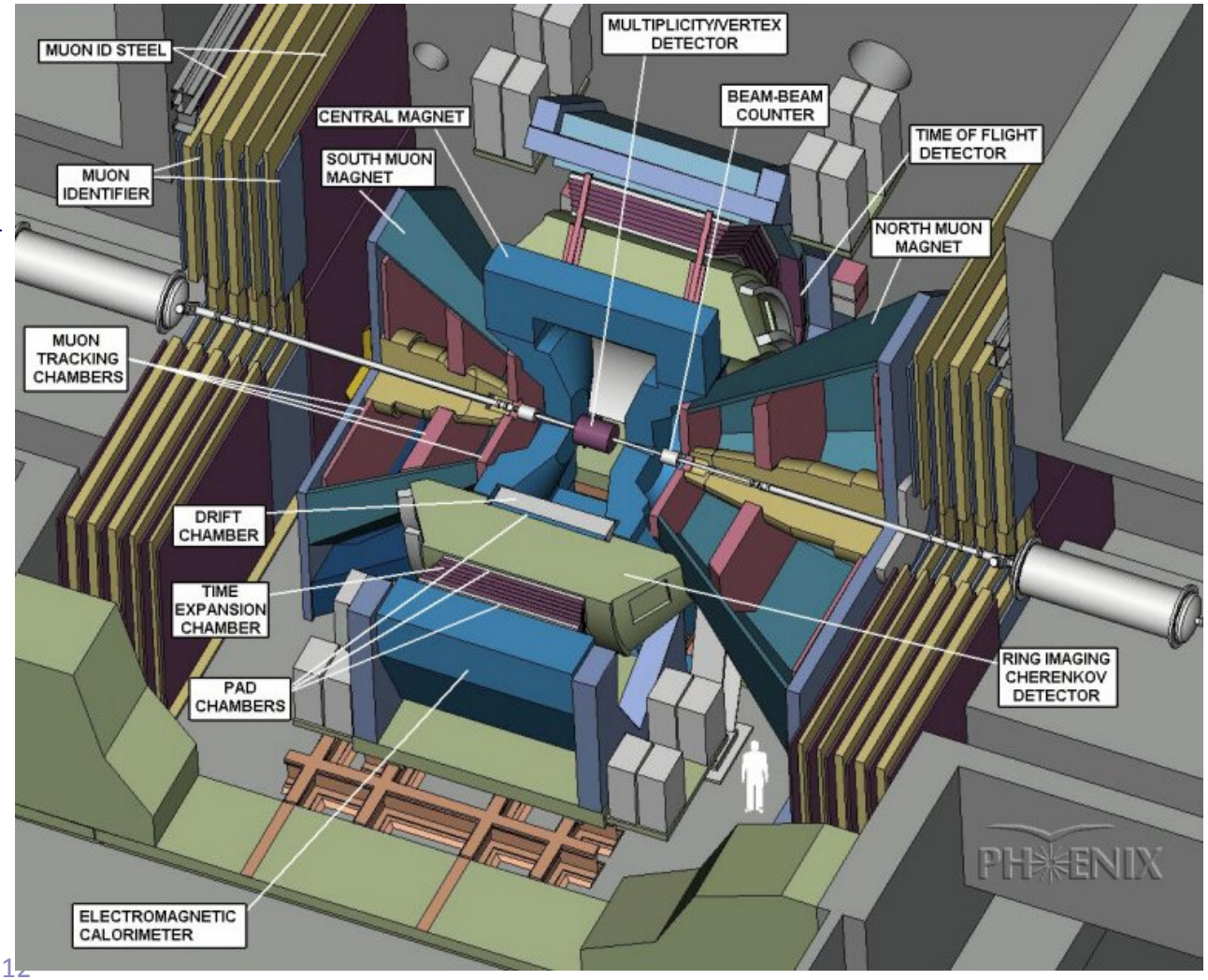




PHENIX local polarimeter

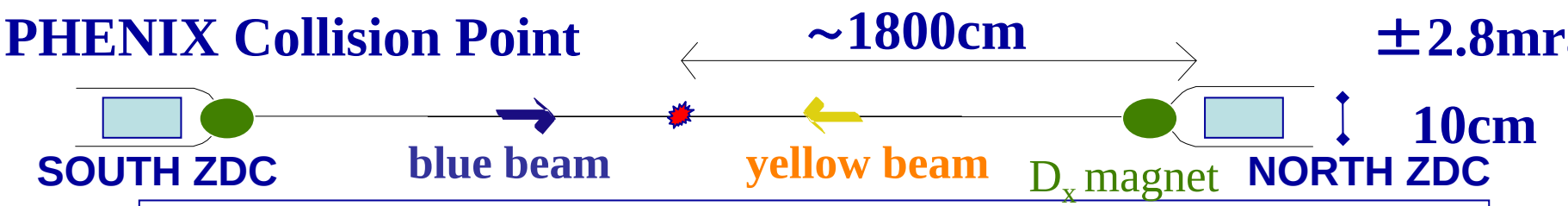
- There have existed ZDCs (Zero Degree Calorimeter) to detect neutrons at PHENIX
- SMDs (Shower Maximum Detector) were added to measure the hit position of neutrons

ZDC



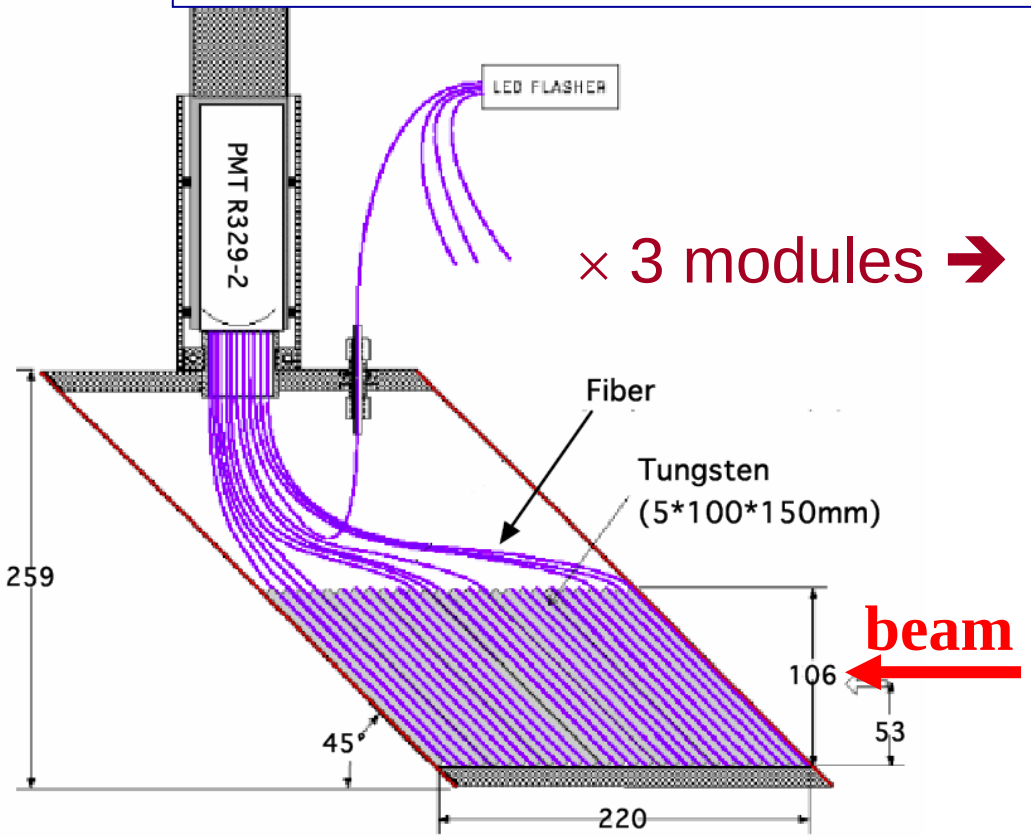
ZDC
@ 18m away
from the IP

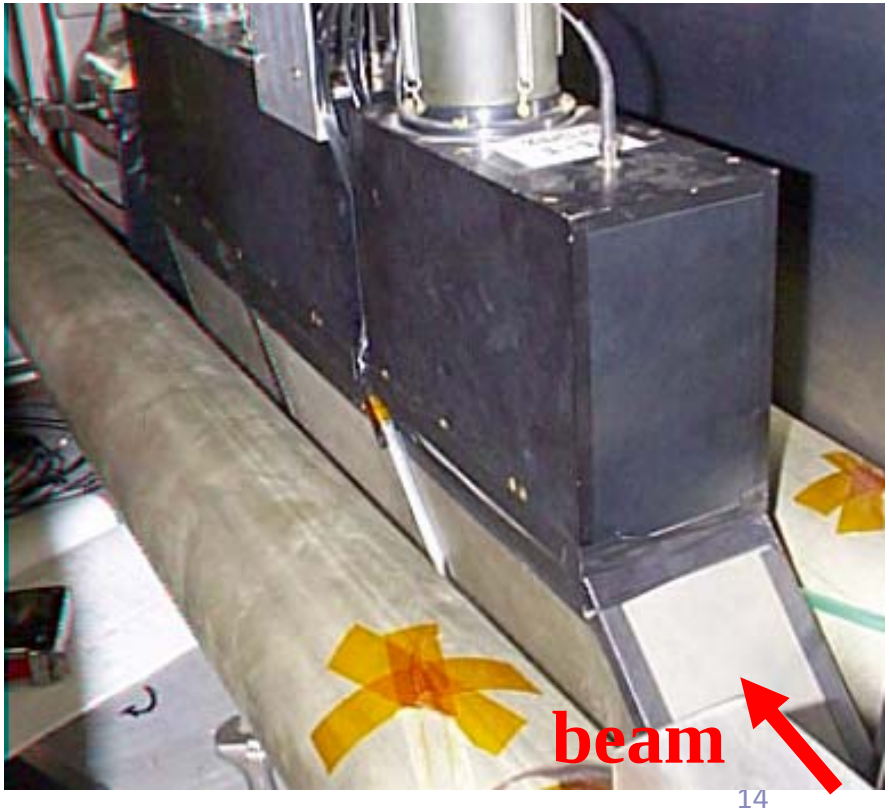
ZDC (Zero Degree Calorimeter)



hadron sampling calorimeter made of Tungsten plate and fibers

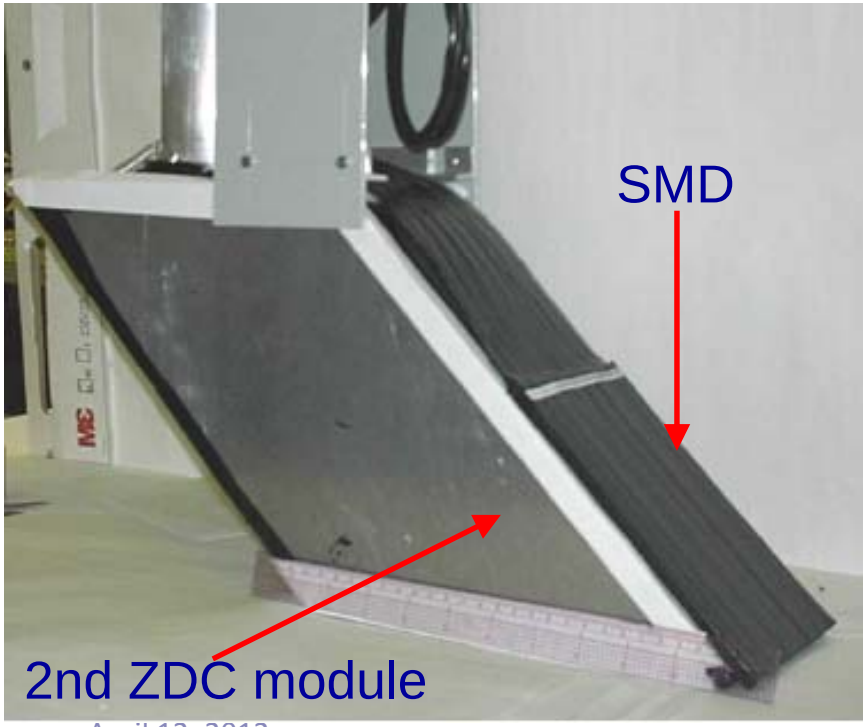
5.1 λ_T 149X_0 (3 ZDCs), Energy resolution ~ 20% @ 100GeV

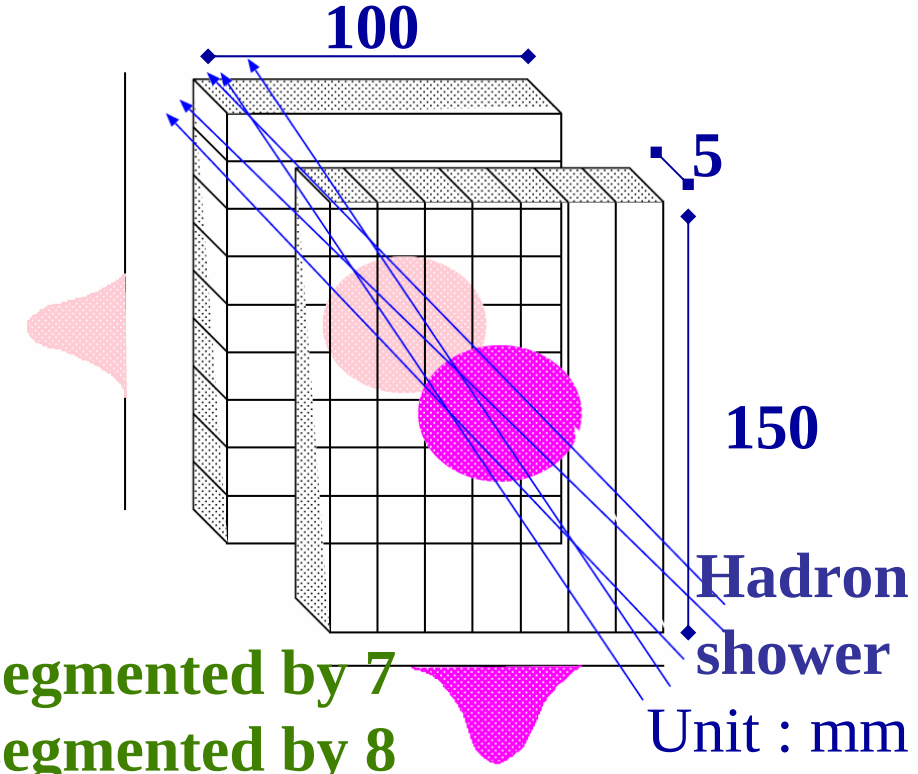




Shower Maximum Detector

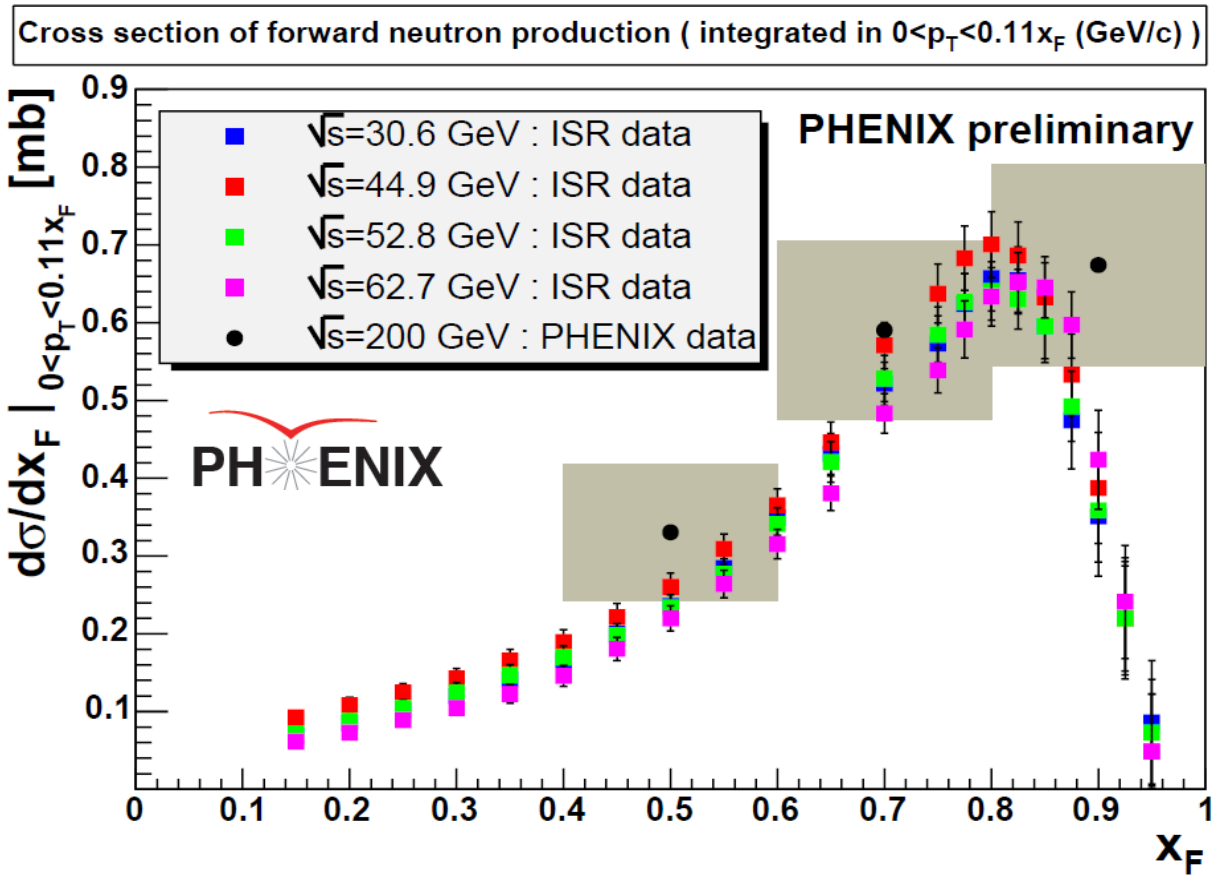
- To measure the neutron hit position, SMDs (Shower Maximum Detector) were installed between 1st and 2nd modules of ZDC
  - arrays of plastic scintillators
  - giving a position by calculating the center of gravity of shower generating in the 1st ZDC module
  - position resolution ~1cm @ 50GeV neutron (simulation study)





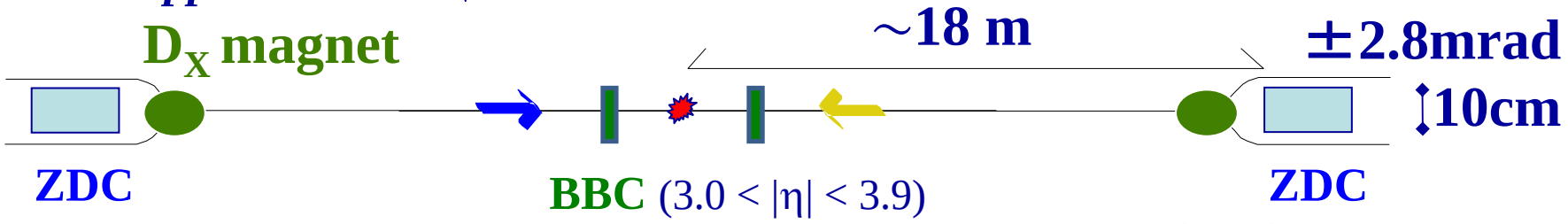
Cross section

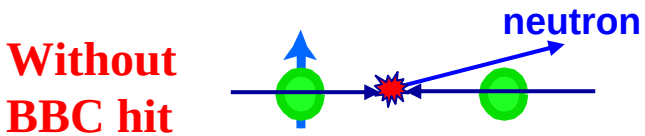
- Coarse cross section result is consistent with ISR data
- No indication of violation of x_F scaling at higher energy
  - integrated p_T region: $0 < p_T < 0.11\ x_F$ GeV/c in each point
  - p_T distribution assuming the ISR result

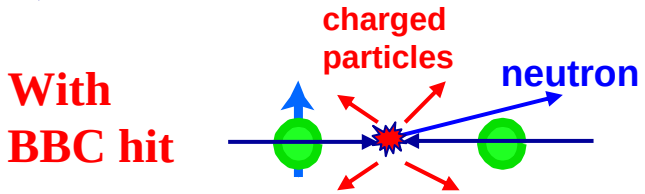


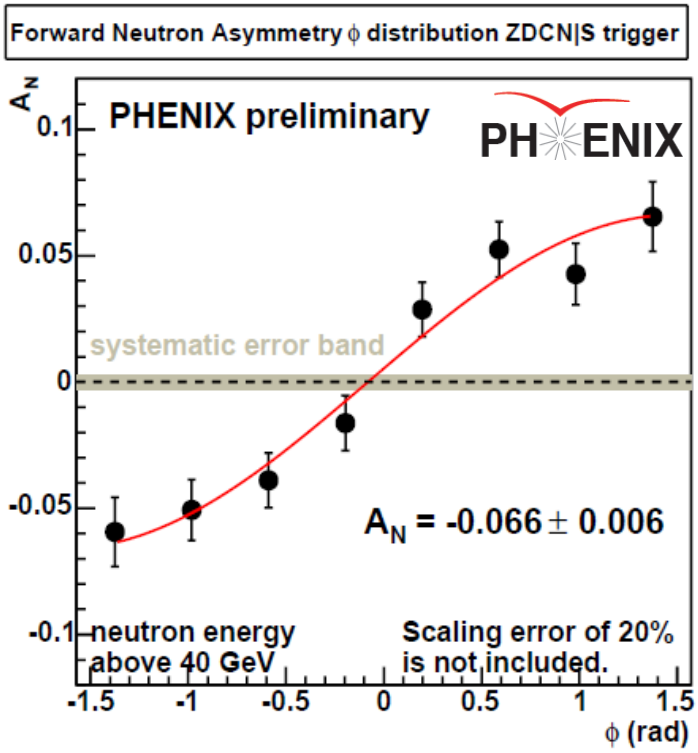
Single transverse-spin asymmetry (A_N)

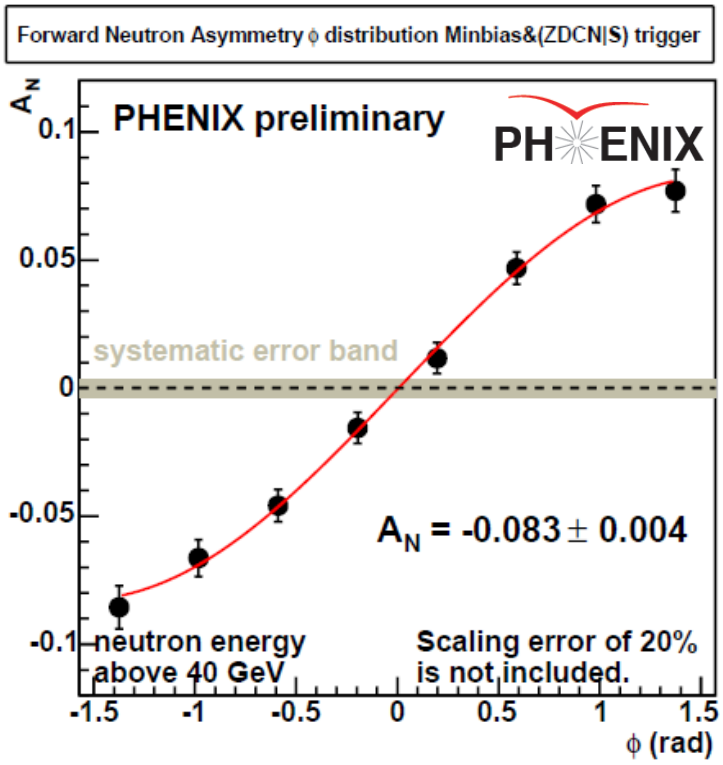
***Polarized pp* collision at $\sqrt{s}$ = 200GeV**









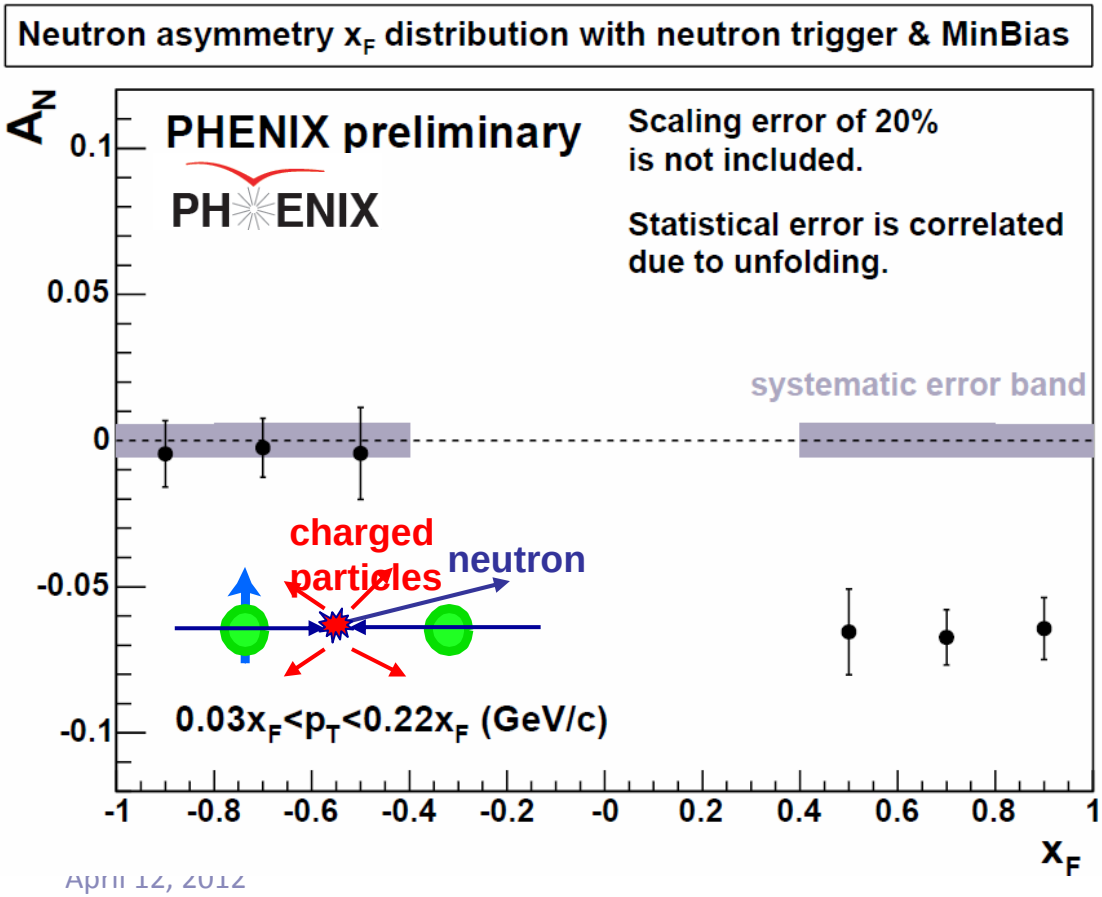


x_F-dependence of A_N

- Smearing effect is evaluated by simulation.
- For asymmetry calculation, square root formula is used.

$$A_N \equiv \frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow} \approx \frac{1}{Pol.} \frac{\sqrt{N_L^\uparrow N_R^\downarrow} - \sqrt{N_L^\downarrow N_R^\uparrow}}{\sqrt{N_L^\uparrow N_R^\downarrow} + \sqrt{N_L^\downarrow N_R^\uparrow}}$$

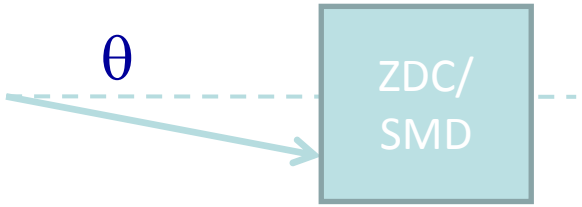
Pol.~48%



Expected mean p_T are estimated by simulation assuming ISR p_T distribution.

x_F	Expected mean p_T (GeV/c)
0.4~0.6	0.088
0.6~0.8	0.118
0.8~1.0	0.144

√s dependence



- θ distribution
  - Inclusive neutron

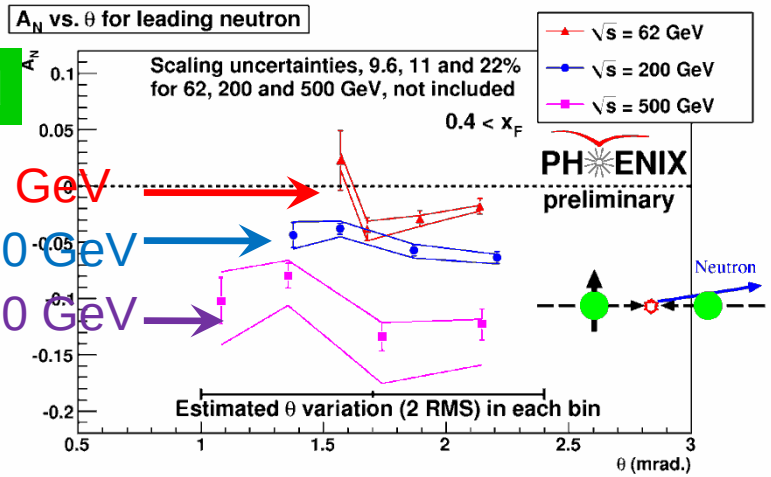
forward

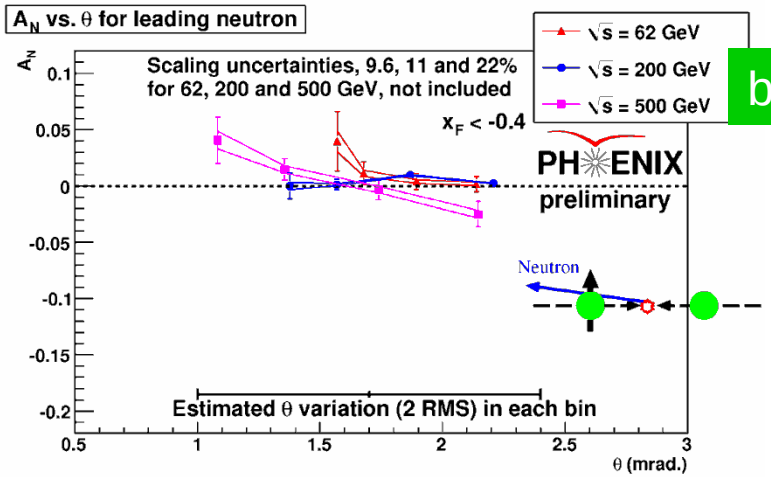
backward

√s = 62 GeV

√s = 200 GeV

√s = 500 GeV

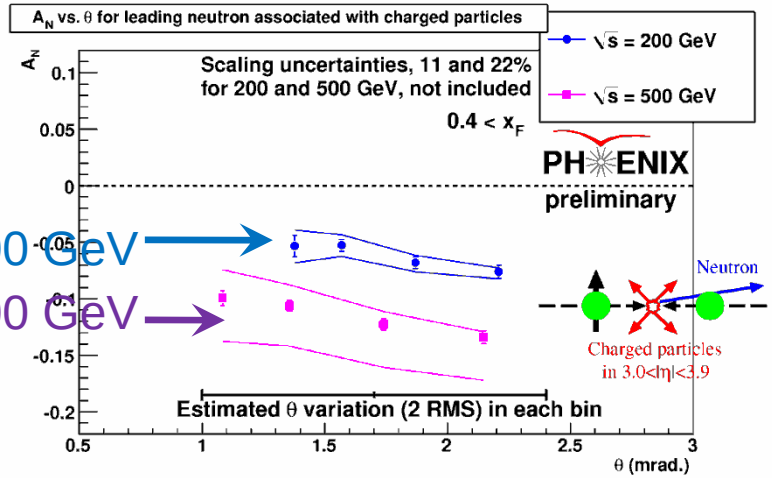


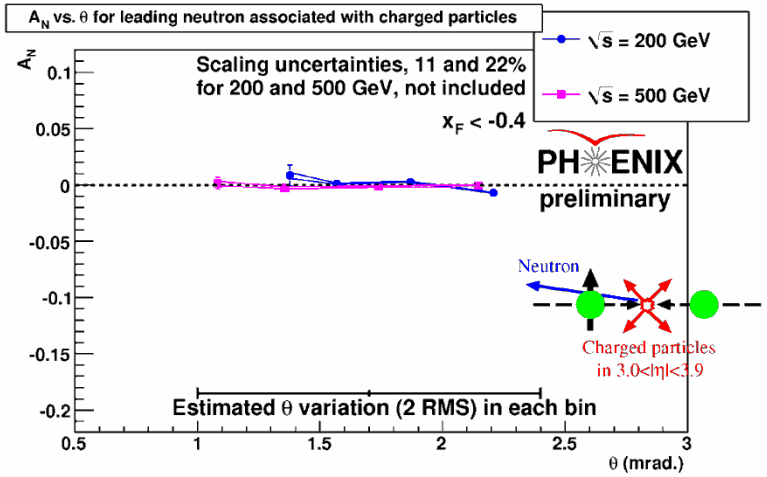


  - Neutron with charged particles (in beam-beam counter)

√s = 200 GeV

√s = 500 GeV

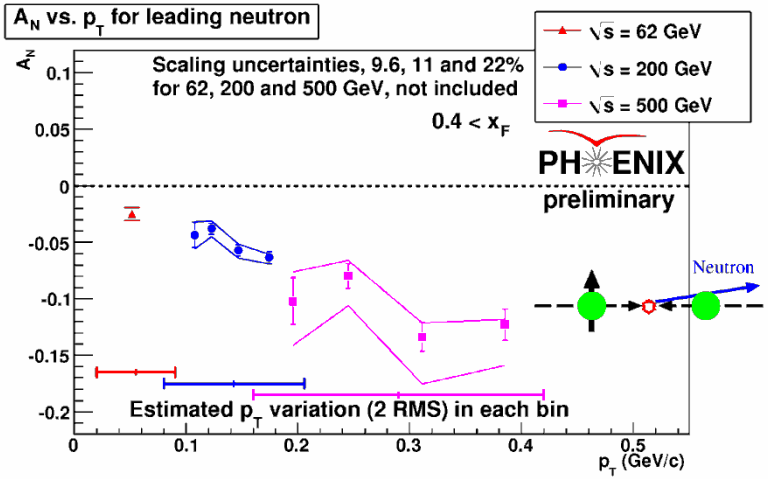




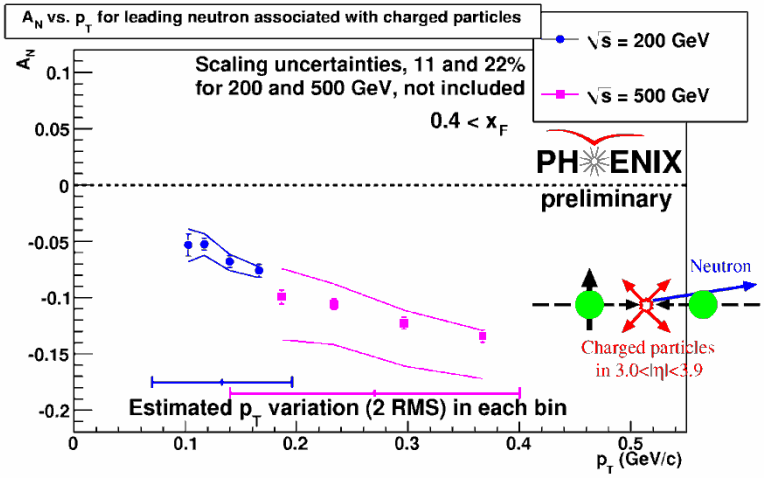
√s dependence

- p_T distribution
  - $p_T \sim x_F \cdot \sqrt{s} / 2 \cdot \theta$
  - Assuming p_T shape of ISR
  - No smearing correction (no-unfolding)
    - wide p_T deviation for each bin

Inclusive neutron



Neutron with charged particles



- $A_N(62\ \text{GeV}) < A_N(200\ \text{GeV}) < A_N(500\ \text{GeV})$
- √s dependence or p_T dependence?

Forward neutron production

- Interference between spin-flip and non-flip with a relative phase

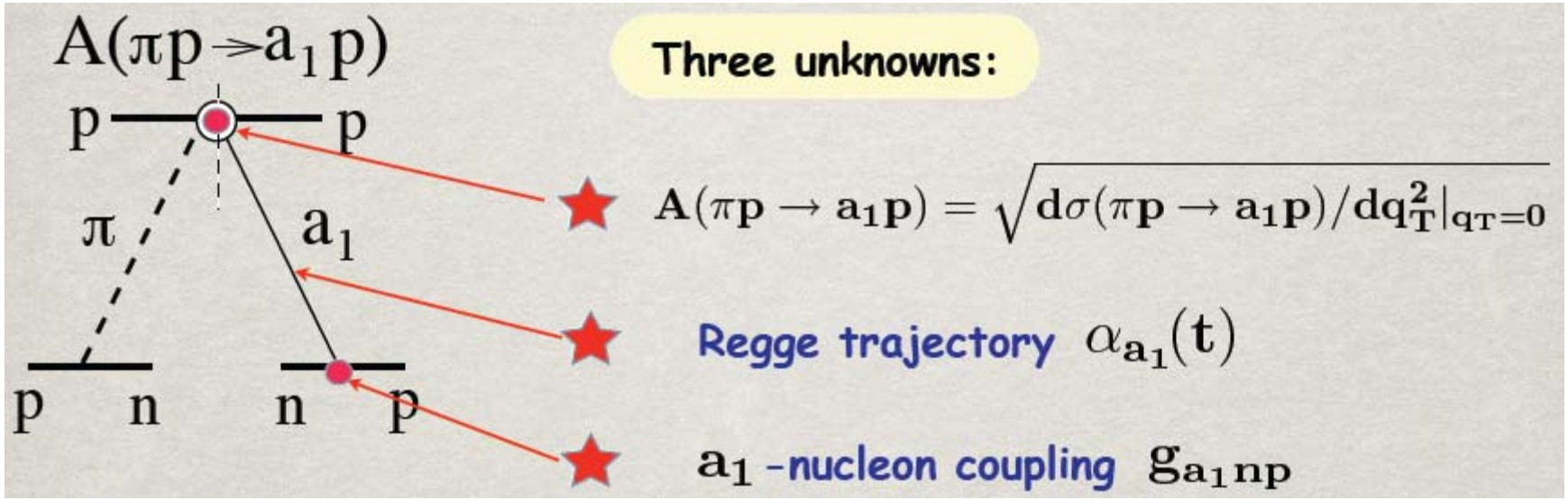
$$A_N \approx \frac{2\,\mathrm{Im}\left(fg^*\right)}{|f|^2+|g|^2}$$

f : spin non-flip amplitude
g : spin flip amplitude

- Pion exchange
  - Kopeliovich, Potashnikova, Schmidt, Soffer: Phys. Rev. D78 (2008) 014031.
- Spin-flip amplitude and non-flip amplitude have the same phase
  - No single transverse-spin asymmetry can appear
- Absorption correction for a relative phase
  - Initial/final state interaction
  - Also important for cross section calculation
  - Gained shift between spin-flip and non-flip amplitudes is too small to explain the large asymmetry

Forward neutron production

- Interference with other Reggeons
  - Kopeliovich, Potashnikova, Schmidt: arXiv:1109.2500
  - a_1 axial-vector meson
  - Pion-a_1 interference



  - B. Kopeliovich, Veli Losinj, Aug.28-Sep.3, 2011
  - π-ρ in 1^+S state instead of a_1

Forward neutron production

- Pion-a_1 interference: results
  - The data agree well with independence of energy
- The asymmetry has a sensitivity to presence of different mechanisms, e.g. Reggeon exchanges with spin-non-flip amplitude, even if they are small amplitudes

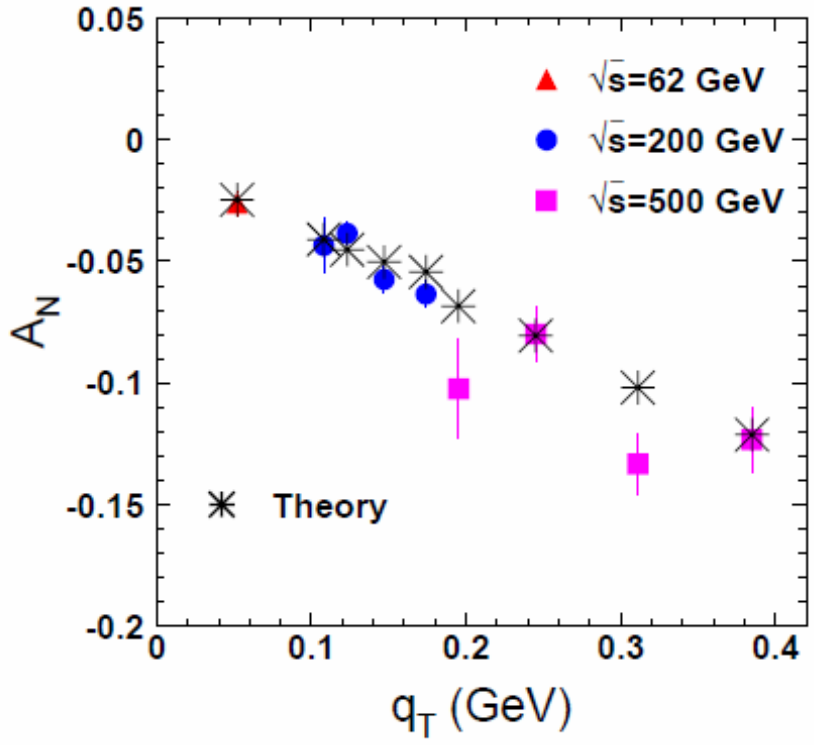
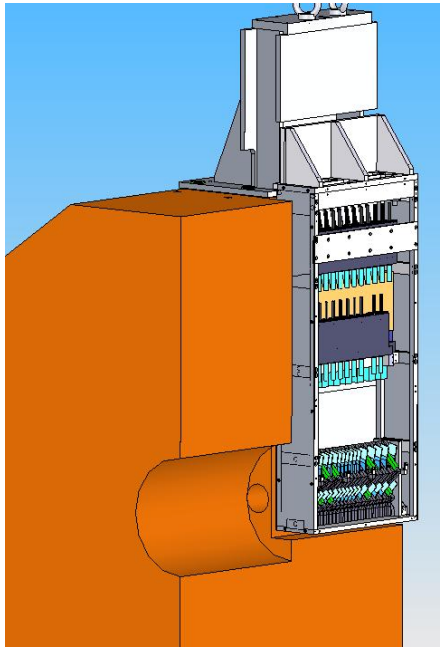
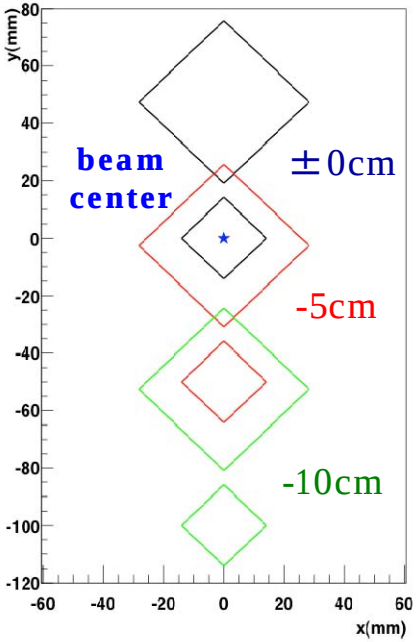


FIG. 1: (Color online) Single transverse spin asymmetry A_N in the reaction $pp \to nX$, measured at $\sqrt{s} = 62,\ 200,\ 500\,\text{GeV}$ [1] (preliminary data). The asterisks show the result of our calculation, Eq. (38), which was done point by point, since each experimental point has a specific value of z (see Table I).

Future outlook

- Possible collaboration with LHCf experiment
  - Interest in understanding air-shower development of very-high energy cosmic-ray
  - EM calorimeter with good energy resolution and position resolution
  - Possible installation in front of ZDC at RHIC
  - Interest in d-N (or p-N) collisions
- New collaborators are very welcome





Summary

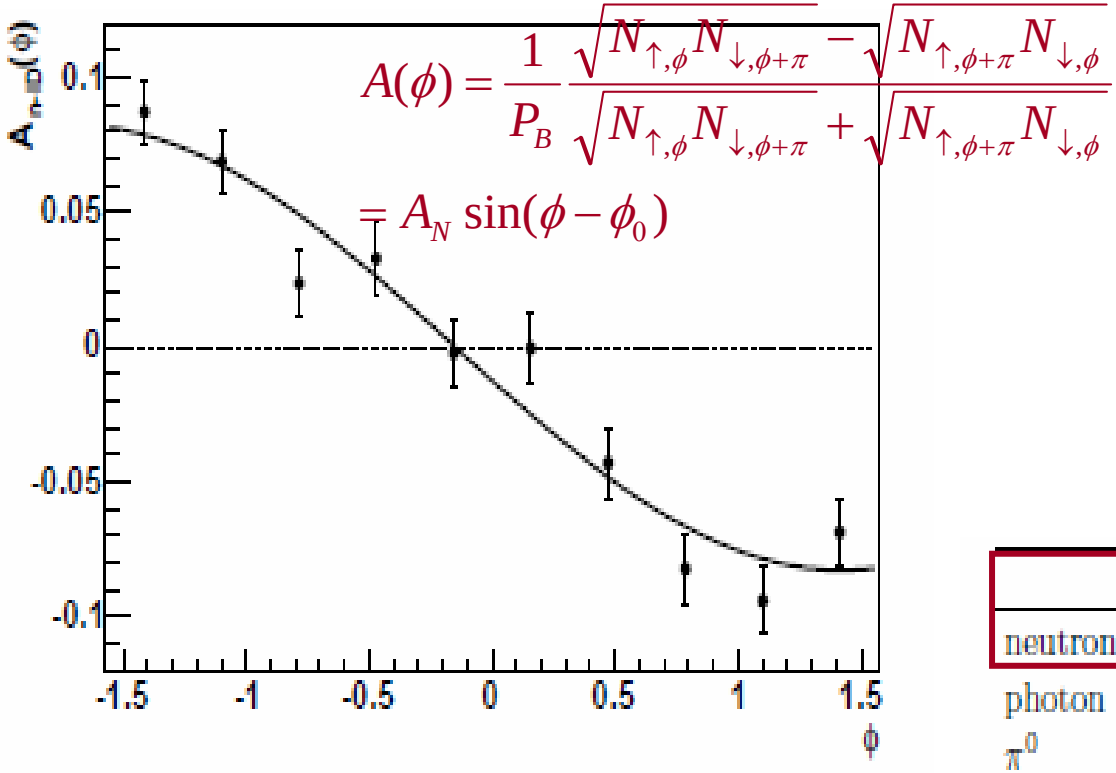
- Data to understand production mechanism of very forward neutrons
  - Cross section measurement
    - ISR/FNAL/HERA/NA49
  - Asymmetry measurement
    - First measurement at RHIC spin, very large asymmetry
- Asymmetry measurements in polarized p+p collisions at PHENIX
  - x_F dependence
  - $\sqrt{s}$ dependence or p_T dependence
    - $A_N(62\ \text{GeV}) < A_N(200\ \text{GeV}) < A_N(500\ \text{GeV})$
- Production mechanism
  - Pion-a_1 interference
  - Sensitivity of asymmetry measurement to presence of different mechanism

PHENIX

Backup Slides…

Result

- Phys. Lett. B 650 (2007) 325.



$$A(\phi) = \frac{1}{P_B} \frac{\sqrt{N_{\uparrow,\phi} N_{\downarrow,\phi+\pi}} - \sqrt{N_{\uparrow,\phi+\pi} N_{\downarrow,\phi}}}{\sqrt{N_{\uparrow,\phi} N_{\downarrow,\phi+\pi}} + \sqrt{N_{\uparrow,\phi+\pi} N_{\downarrow,\phi}}}$$

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

FIG. 4: Azimuthal dependence of asymmetry for the n-ID sample produced forward with respect to the polarized proton direction, based on the east detector. The error bars are statistical.

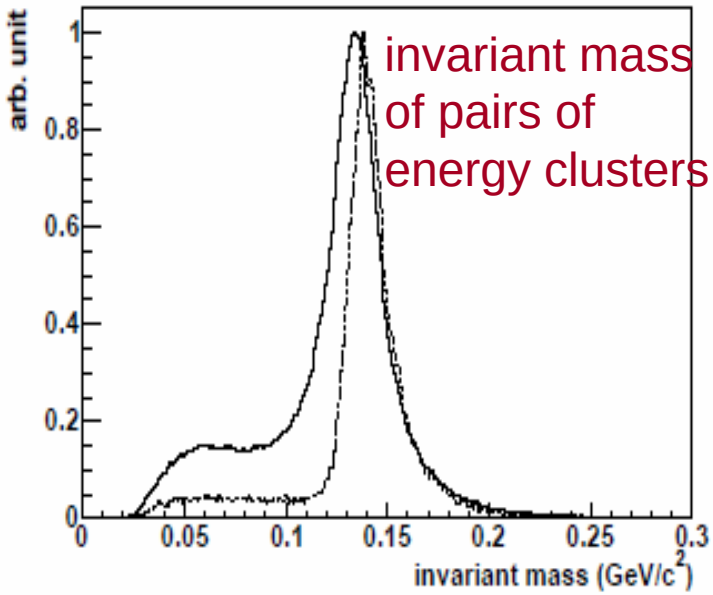
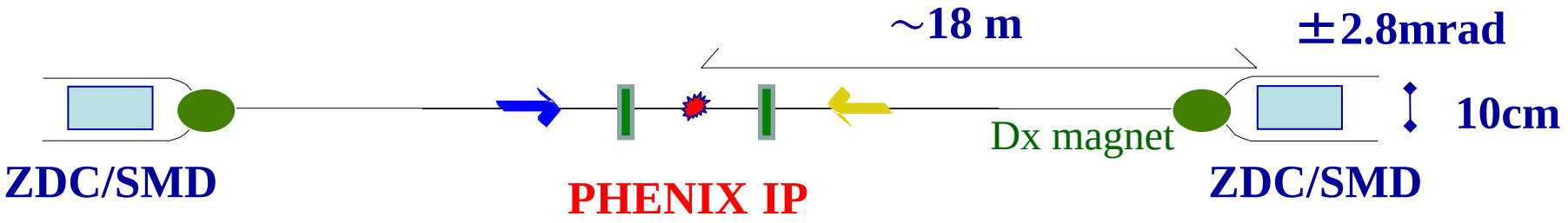


FIG. 3: Invariant mass of pairs of energy clusters in the EMCal, for 444K events with no additional selection requirements (solid) and for 35K events with photon identification (dashed).

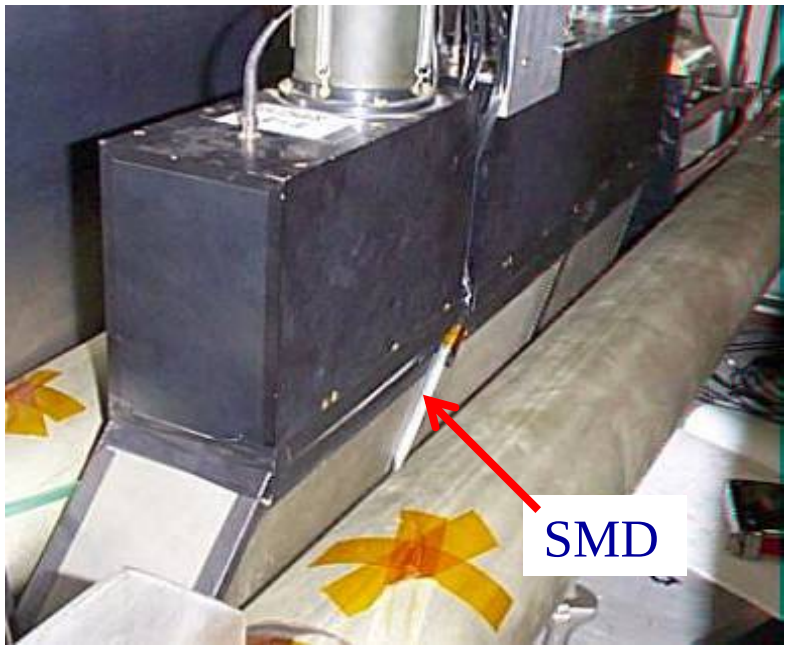
	forward	backward
neutron	$-0.090 \pm 0.006 \pm 0.009$	$0.003 \pm 0.004 \pm 0.003$
photon	$-0.009 \pm 0.015 \pm 0.007$	$-0.019 \pm 0.010 \pm 0.003$
π^0	$-0.022 \pm 0.030 \pm 0.002$	$0.007 \pm 0.021 \pm 0.001$

TABLE I: Asymmetries measured by the EMCal. The errors are statistical and systematic, respectively. There is an additional scale uncertainty, due to the beam polarization uncertainty, of $(1.0^{+0.47}_{-0.24})$.

PHENIX local polarimeter

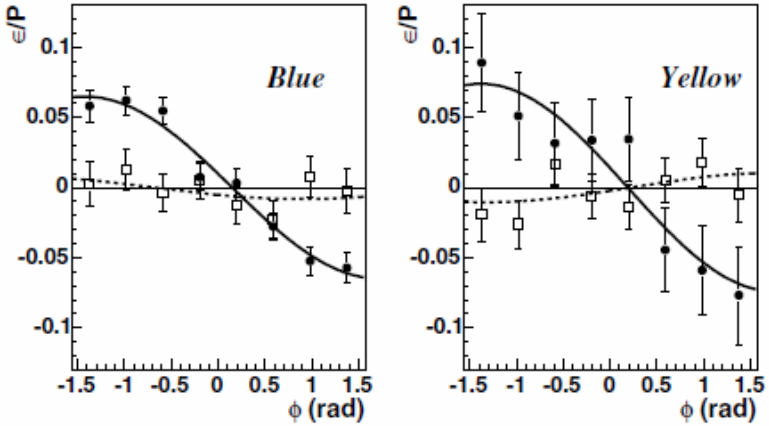


- ZDC (Zero-Degree Calorimeter)
  - 3 modules, 5.1 interaction length
  - ΔE/E ~ 20% for 100 GeV neutron
- SMD (Shower Max Detector)
  - Scintillator hodoscope in X and Y
  - ~1 cm position resolution for 50 GeV neutron (by simulation)



PHENIX local polarimeter

- Similar asymmetry measured at PHENIX with ZDC+SMD
- Operated as the local polarimeter

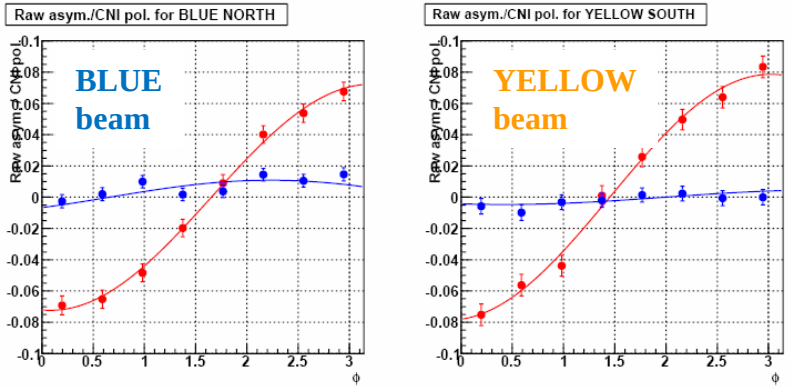


2003 run
$\sqrt{s}$ = 200 GeV

Phys. Rev. Lett. 93 (2004) 202002.

- 2009 run
  - First $\sqrt{s}$ = 500 GeV polarized pp collisions

2009 run
$\sqrt{s}$ = 500 GeV
14 pb^{-1} 35% pol.
$\sqrt{s}$ = 200 GeV
16 pb^{-1} 55% pol.



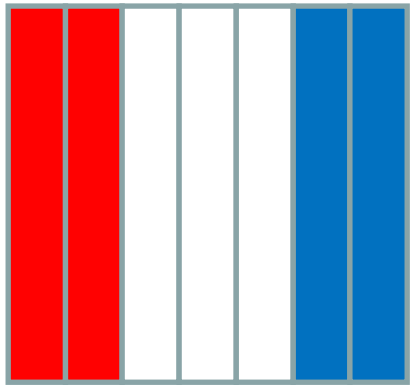
2009 run
$\sqrt{s}$ = 500 GeV

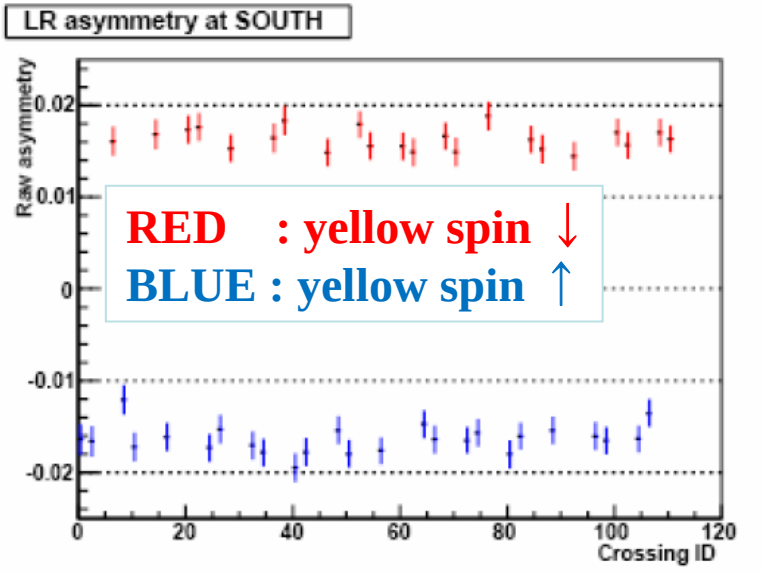
Red : Transverse run (Fill#10340)
Blue : Longitudinal run (Fill#10382)

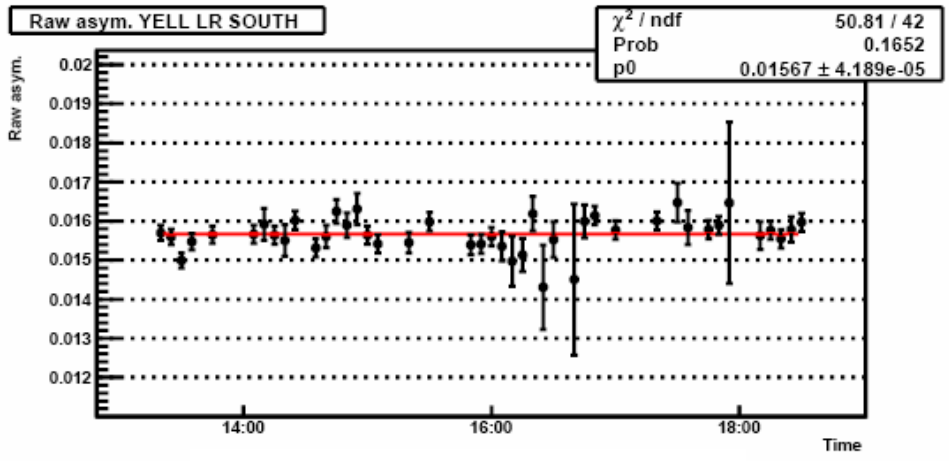
PHENIX local polarimeter

- Performance as the polarimeter
  - Scaler-mode data from 2009 run
    - High-statistics data every 5 minutes
    - Online-monitor analysis
      - High precision, feedback data for accelerator commissioning in real time
    - Time dependence for beam polarization

LR definition for SMD



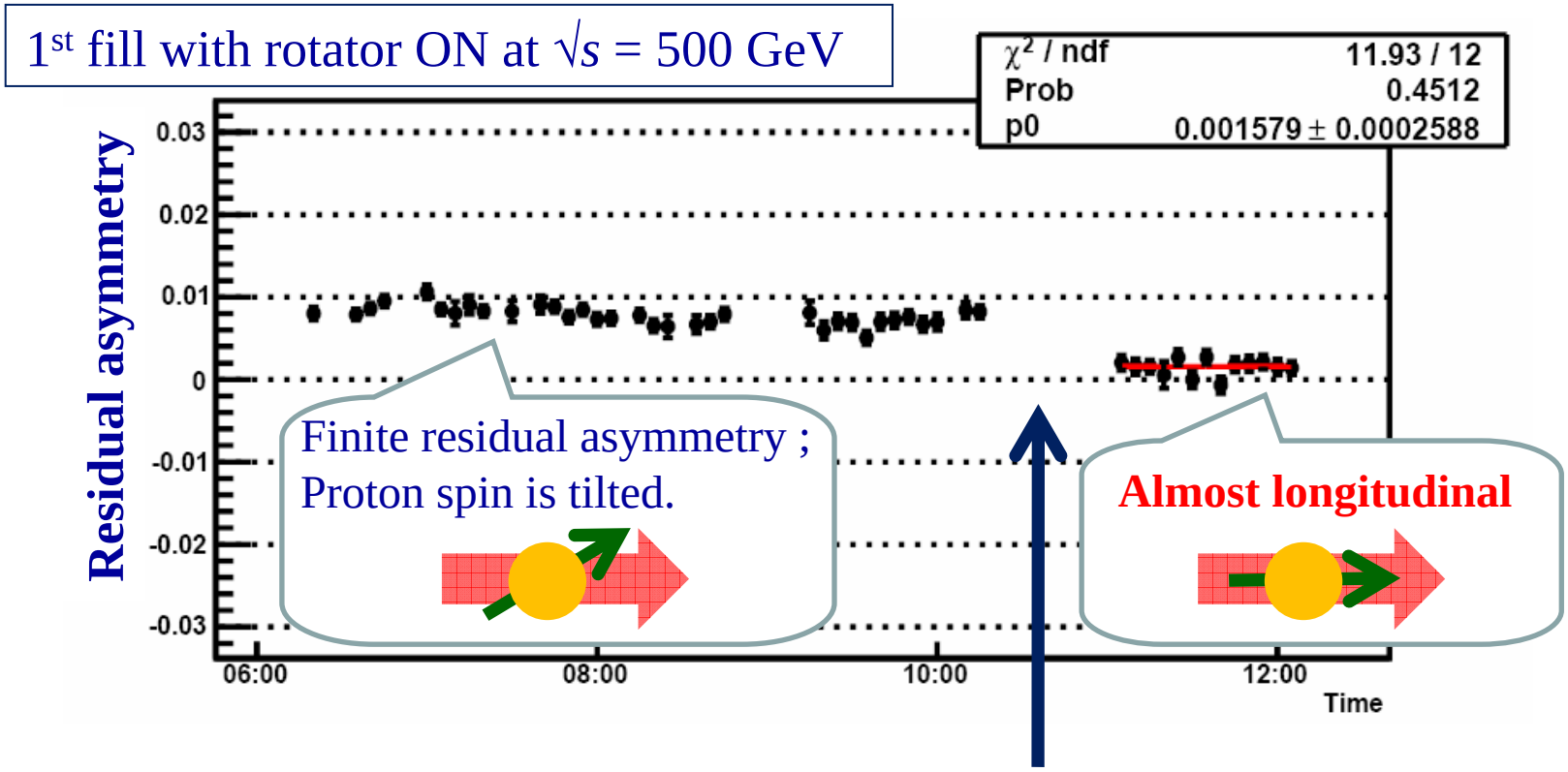




~50 σ / point (5 mins.)

PHENIX local polarimeter

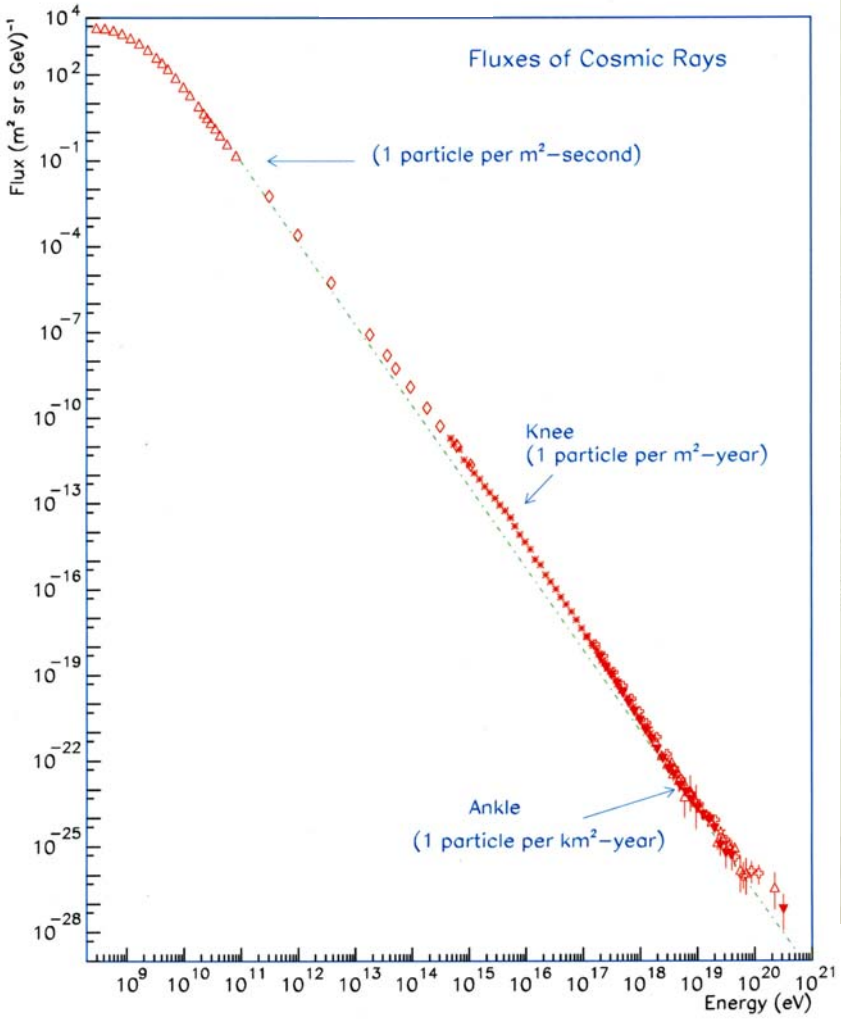
- Adjustment of the rotator current
  - Real-time commissioning and feedback to the accelerator



Rotator current adjusted
(no change at RHIC CNI polarimeter)

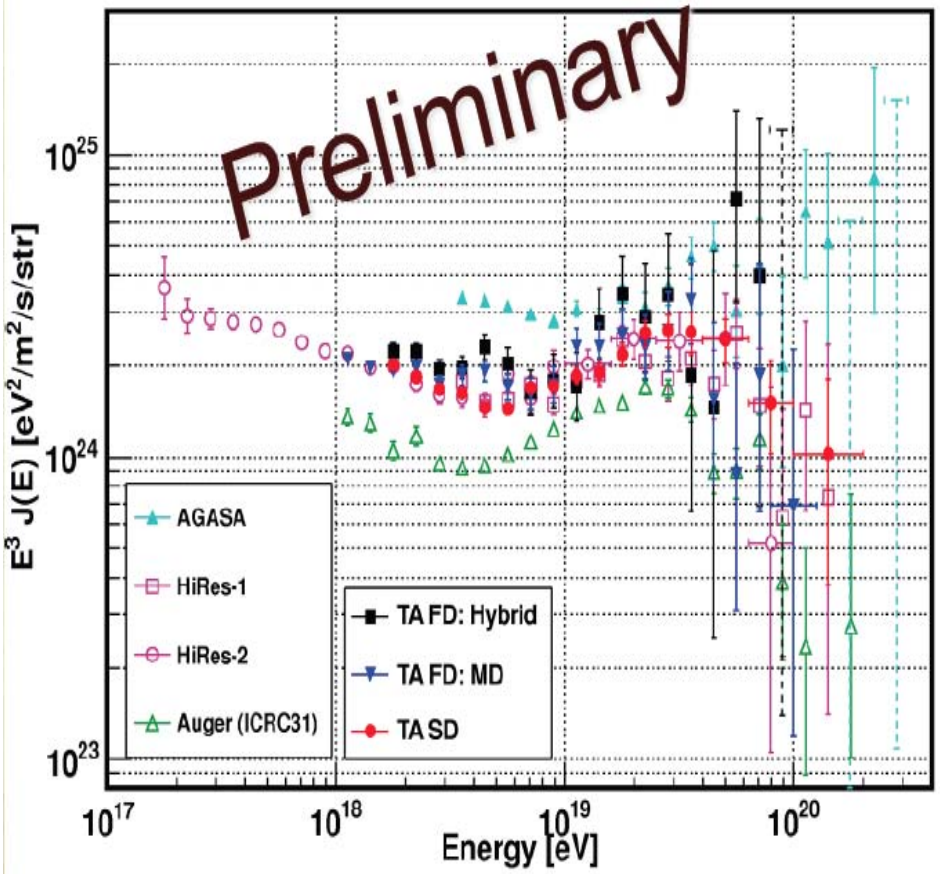
Cosmic-Ray flux

CR flux



10^{10}eV

10^{20}eV



E^3 x(Flux) from AGASA, HiRes, PAO, TA summarized by the TA group