# *Far-forward neutral particle asymmetry measurements in the RHICf experiment*

PSTP 2024 @ Jefferson Lab

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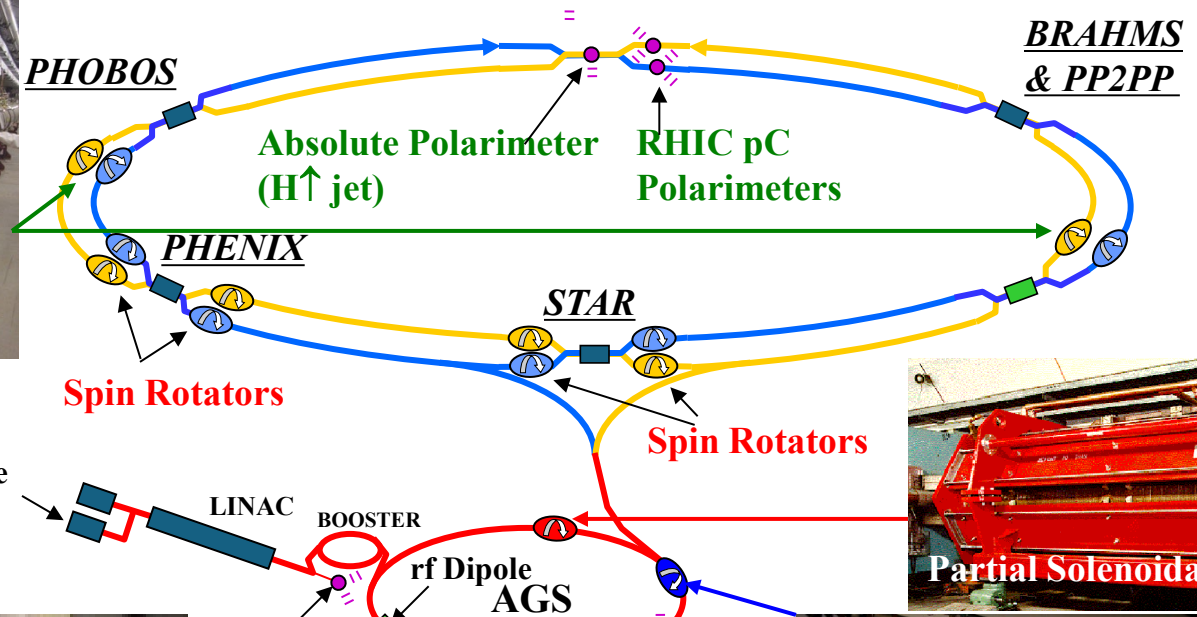
Yuji Goto (RIKEN)

# *Outline*

- Motivation (or history)
- RHICf experiment in 2017
- Far-forward neutron asymmetry
- Far-forward $\pi^0$ asymmetry
- Combined analysis with STAR detectors

# Polarized proton acceleration at RHIC

- Keeping and monitoring polarization from the polarized proton source

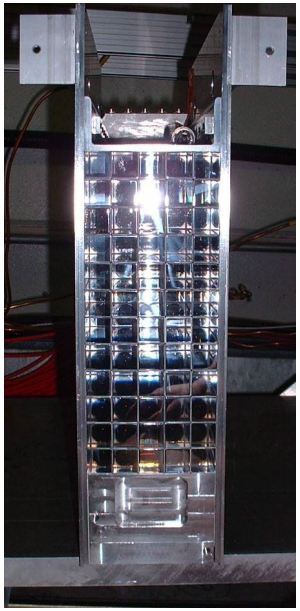








# Motivation (or history)

- Polarimeter at RHIC interaction point
  - Rotation angle (setting & measurement)
    - No transverse polarization component in longitudinal-spin collisions
- Far-forward calorimeter test at IP12
  - Discovery of large neutron single transverse-spin asymmetry
    - Phys. Lett. B 650 (2007) 325.
    - Large yield



$$A(\phi) = \frac{1}{P_B} \frac{\sqrt{N_{\uparrow,\phi} N_{\downarrow,\phi+\pi}} - \sqrt{N_{\uparrow,\phi+\pi} N_{\downarrow,\phi}}}{\sqrt{N_{\uparrow,\phi} N_{\downarrow,\phi+\pi}} + \sqrt{N_{\uparrow,\phi+\pi} N_{\downarrow,\phi}}} = A_N \sin(\phi - \phi_0)$$

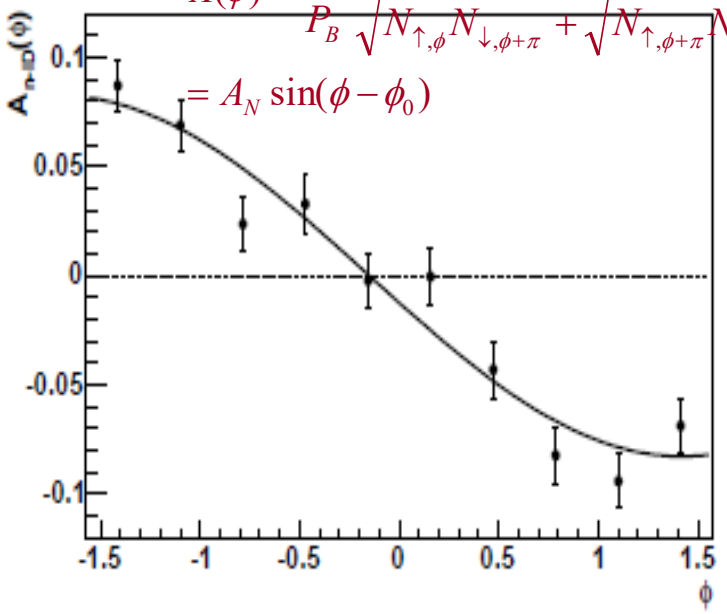
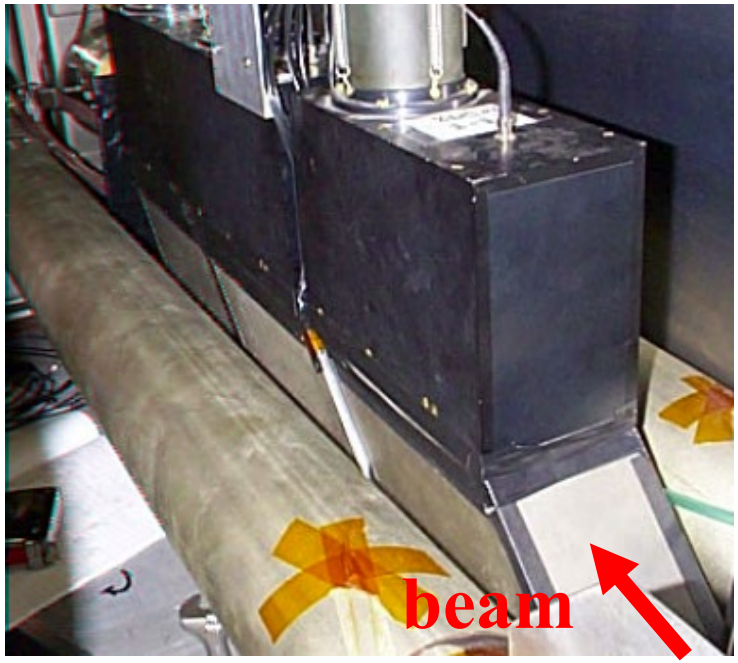
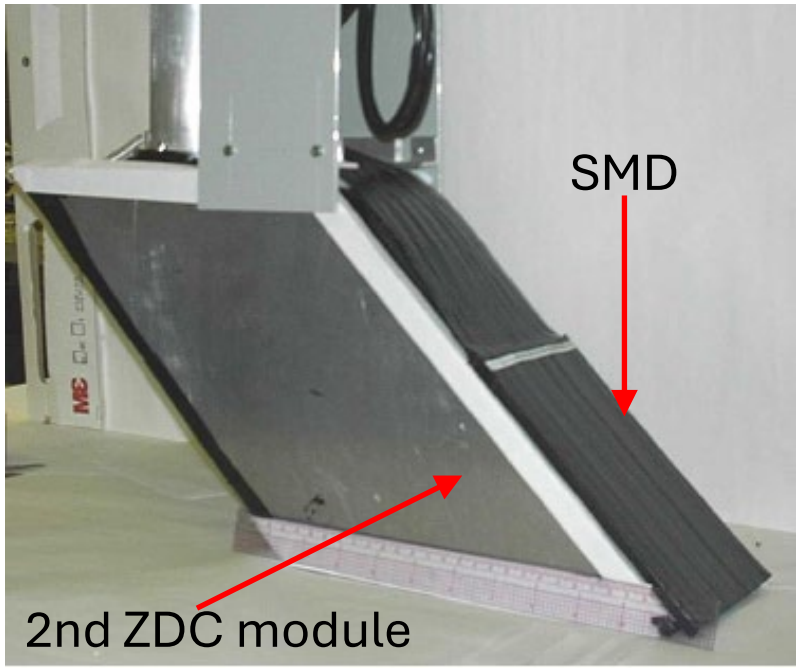



FIG. 4: Azimuthal dependence of asymmetry for the $n$-ID sample produced forward with respect to the polarized proton direction, based on the east detector. The error bars are statistical.

# ZDC (Zero Degree Calorimeter)

- Hadron sampling calorimeter made of Tungsten plate and fibers
  - 5.1 $\lambda_{int}$ & 149$X_0$ (3 ZDCs), Energy resolution ~ 20% @ 100GeV
- To measure the neutron hit position, SMDs (Shower Maximum Detector) installed between 1st and 2nd modules of ZDC
  - arrays of plastic scintillators
  - x: segmented by 7, y: segmented by 8



# *Motivation (or history)*

- ZDC polarimeter @ PHENIX/STAR/BRAHMS
  - Spin rotator commissioning in 2003 run

Spin Rotators OFF

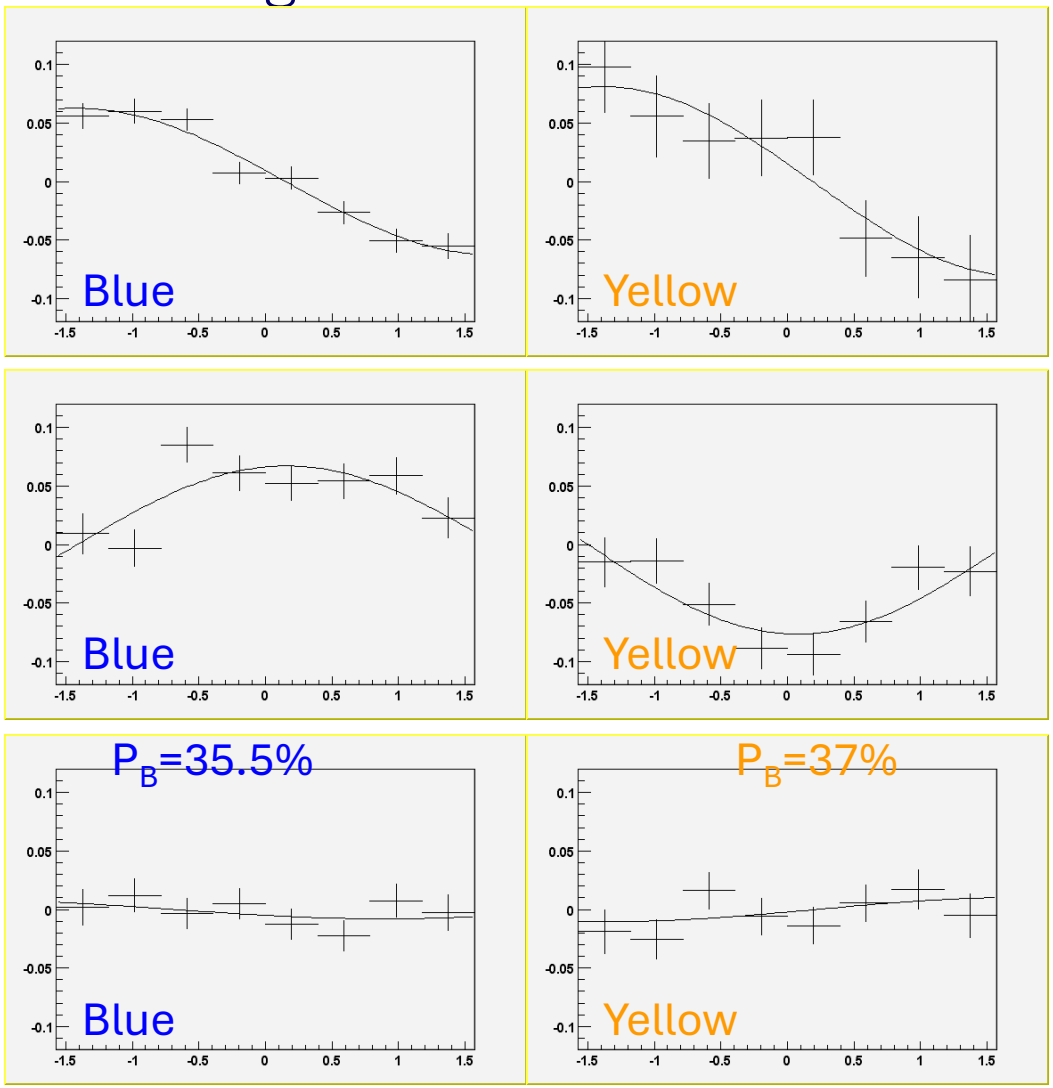
transversely-polarized proton collisions

Spin Rotators ON
Current Reversed

radially-polarized proton collisions

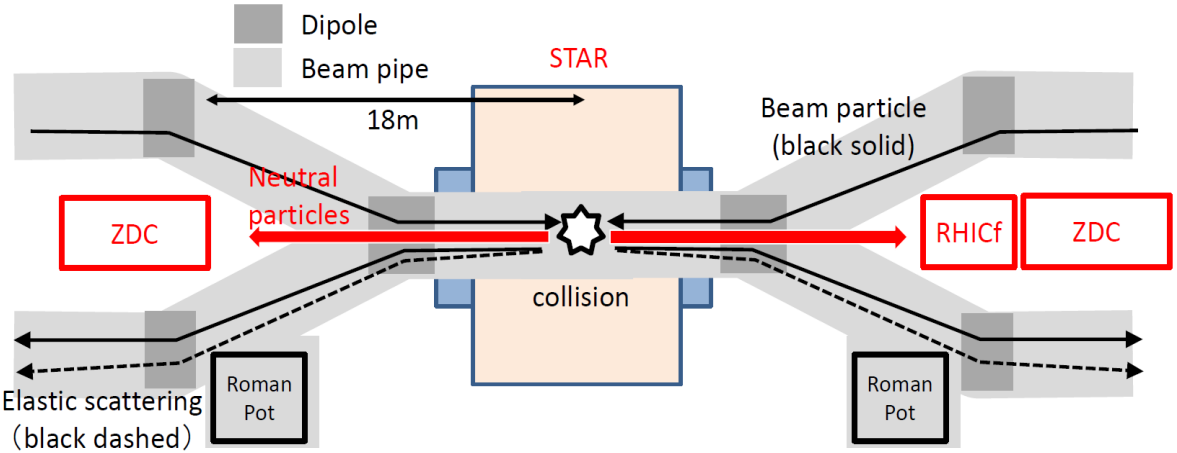
Spin Rotators ON
Correct Current !

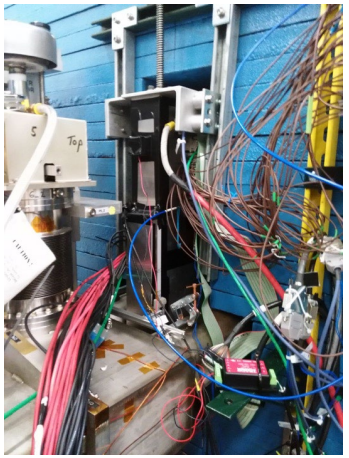
longitudinally-polarized proton collisions

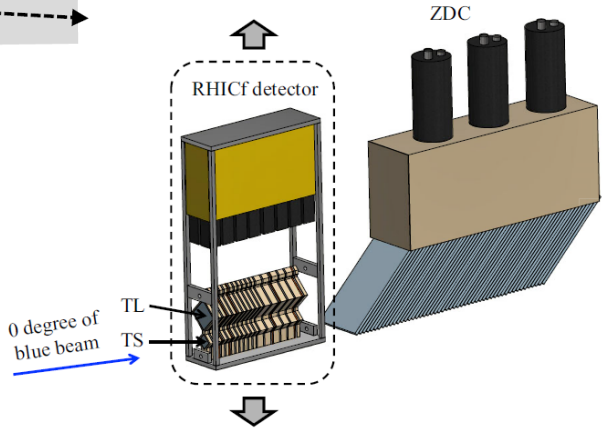


# RHICf experiment in 2017

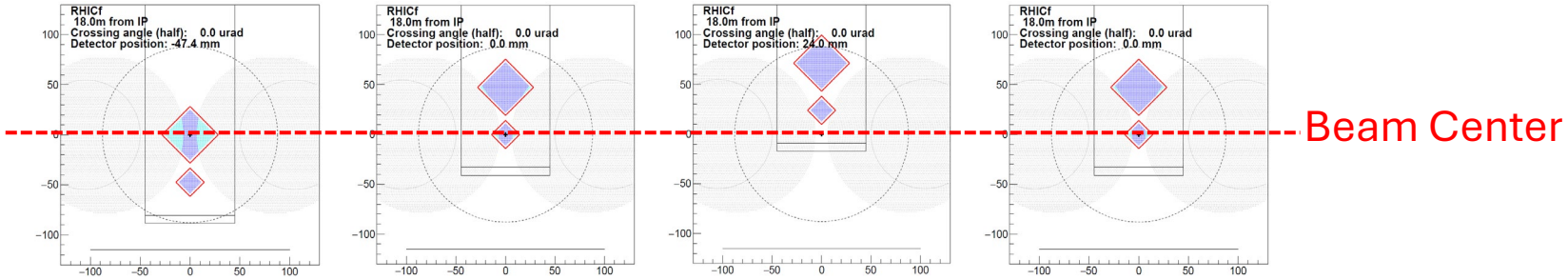
- EM calorimeter (RHICf detector) installed in front of the ZDC+SMD of the STAR experiment



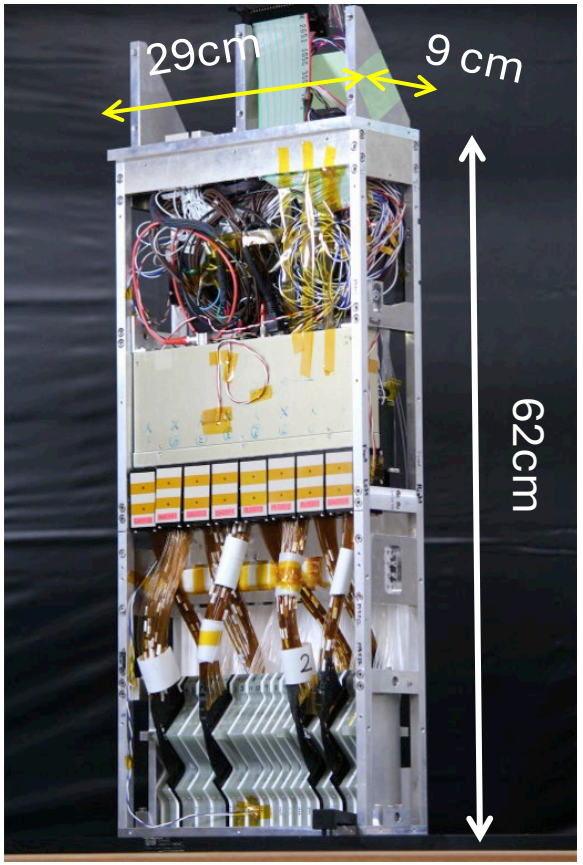


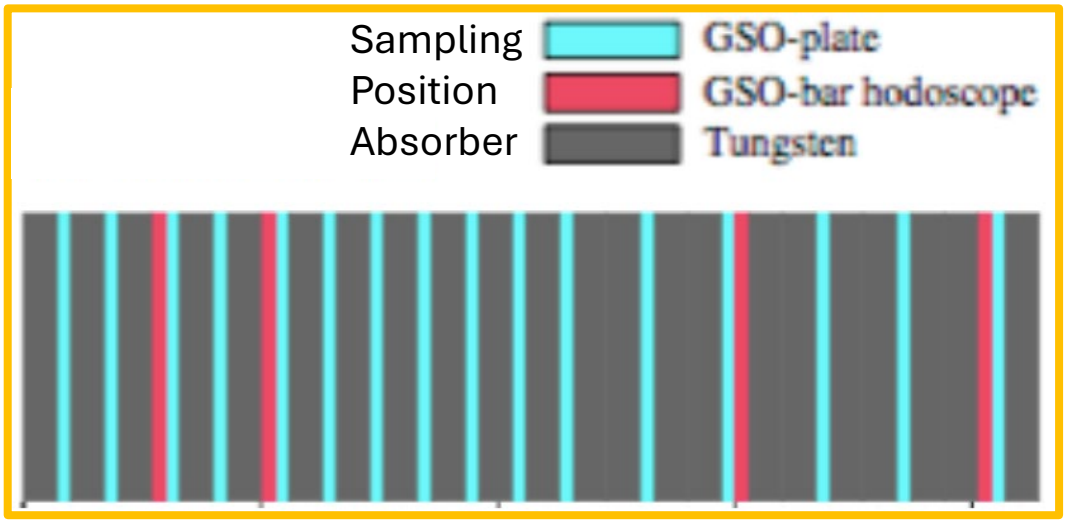

- 2017 operation for RHICf
  - June 24 – 27 physics data acquisition
  - $\beta^* = 8$m, radial polarization
  - 27.7 hours, ~110M events, ~700 nb$^{-1}$
  - 3 detector positions
    - TL center / TS center / Top position

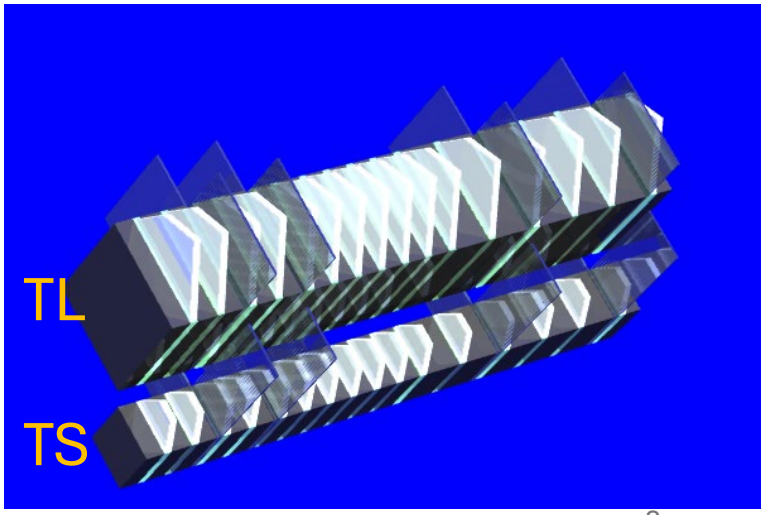


# *RHICf detector*

- Two position-sensitive sampling calorimeters
  - TS (small tower): 20mm x 20mm
  - TL (large tower): 40mm x 40mm
  - Tungsten absorber (44 $X_0$, 1.6 $\lambda_{int}$)
  - 16 GSO sampling layers
  - 4 XY pairs of GSO-bar position layers (MAPMT readout)



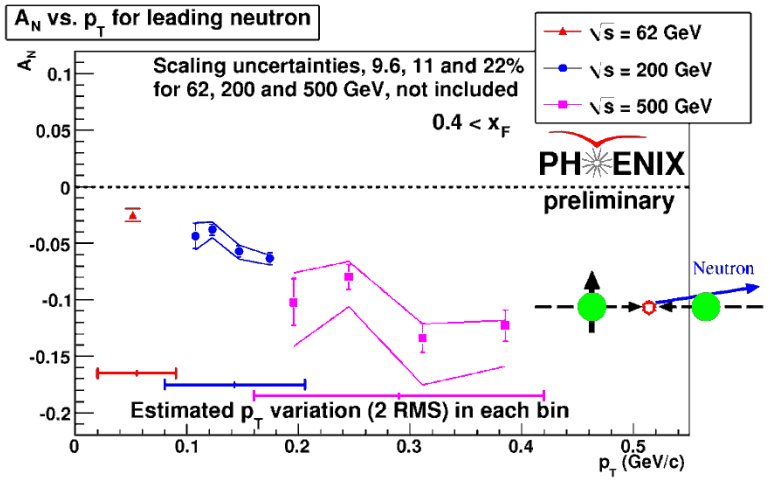



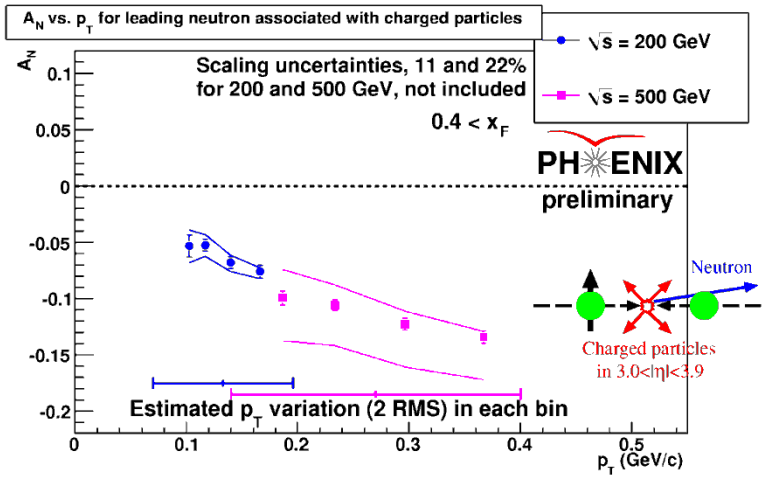
# *Far-forward neutron asymmetry*

- Very large left-right asymmetry ($A_N$) of very forward neutron discovered at RHIC
  - $A_N(62\ \text{GeV}) < A_N(200\ \text{GeV}) < A_N(500\ \text{GeV})$
  - $\sqrt{s}$ dependence or $p_T$ dependence?
- Interference of pion exchange and other Reggeon exchange?
  - Kopeliovich, Potashnikova, Schmidt, Soffer: PRD84, 114012 (2011)
- Improved $p_T$ precision and wider $p_T$ coverage ($p_T < 1.2\ \text{GeV}/c$) at $\sqrt{s} = 510$ GeV in the RHICf experiment

Inclusive neutron

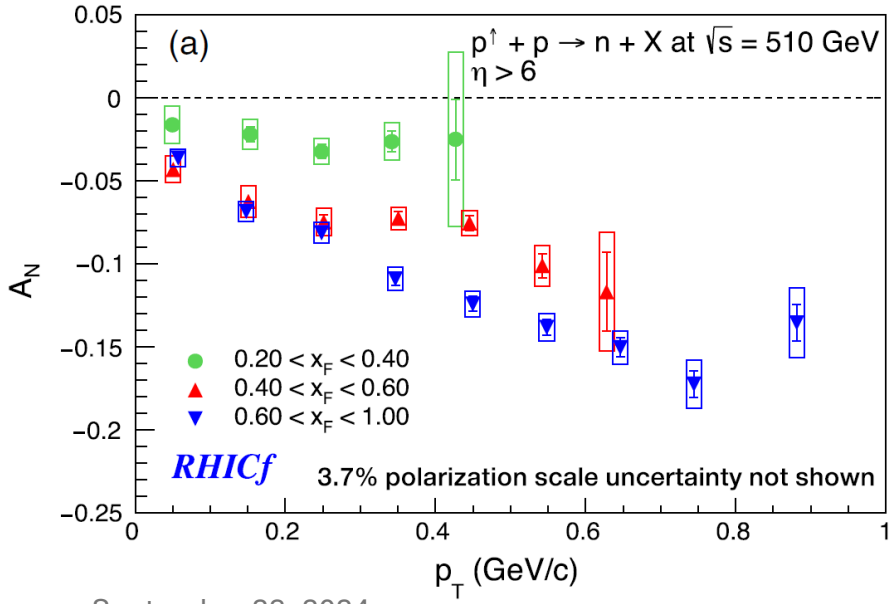


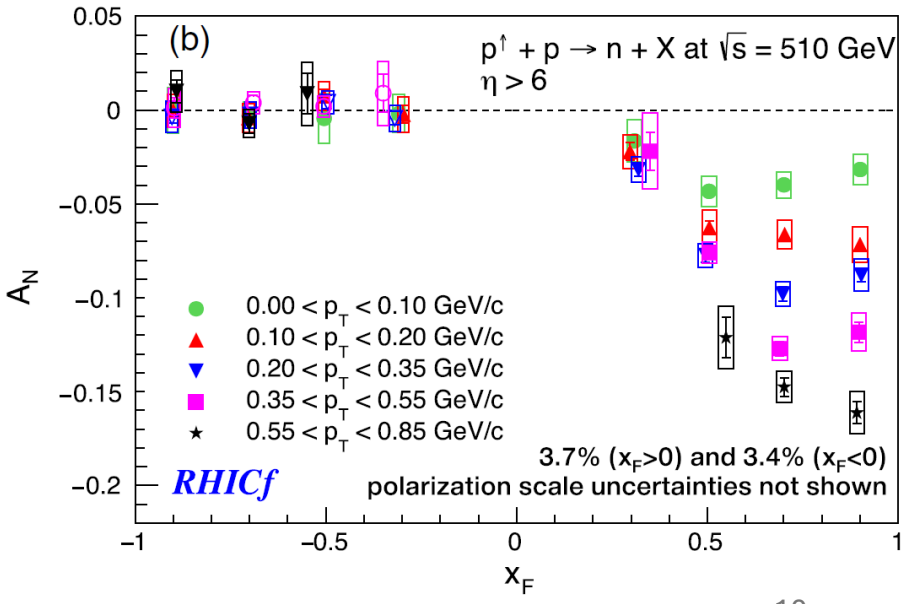

Neutron with charged particles



# Neutron asymmetry at RHICf

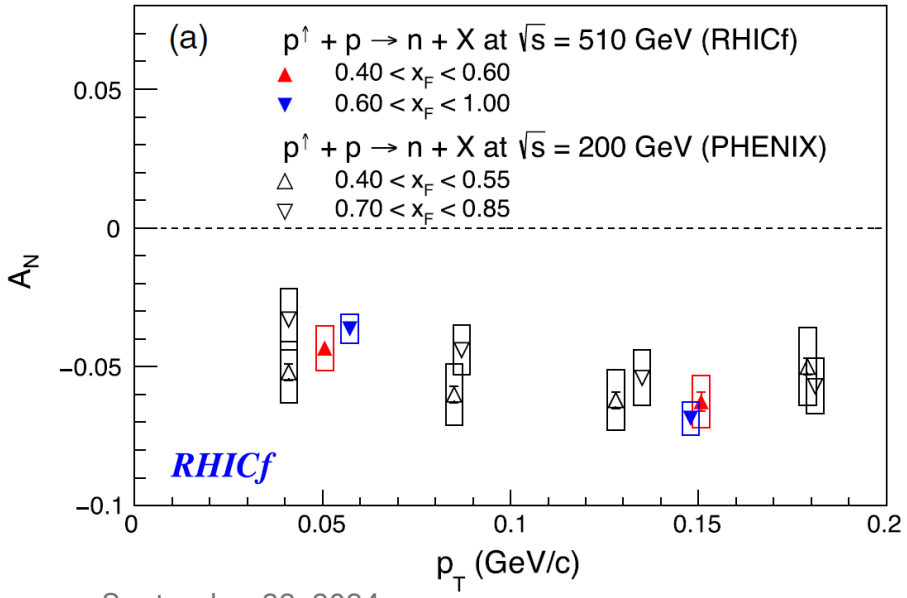
- Phys. Rev. D 109, 012003 (2024)
- In the low $x_F$ range, the neutron $A_N$ reaches a plateau at low $p_T$
- In the high $x_F$ range, the plateau does not seem to be reached yet while the absolute value of the $A_N$ explicitly increases in magnitude with $p_T$
- The backward $A_N$s are all consistent with zero
- In the low $p_T$ range $< 0.20$ GeV/$c$, the forward $A_N$ reaches a plateau of low $A_N$ at low $x_F$ (about 0.5) with little $x_F$ dependence
- In the high $p_T$ range $> 0.20$ GeV/$c$, the asymmetries appear to be leveling off at higher $x_F$ (about 0.7), showing a clear $x_F$ dependence
- The $x_F$ dependence in the high $p_T$ range was observed for the first time by the RHICf experiment

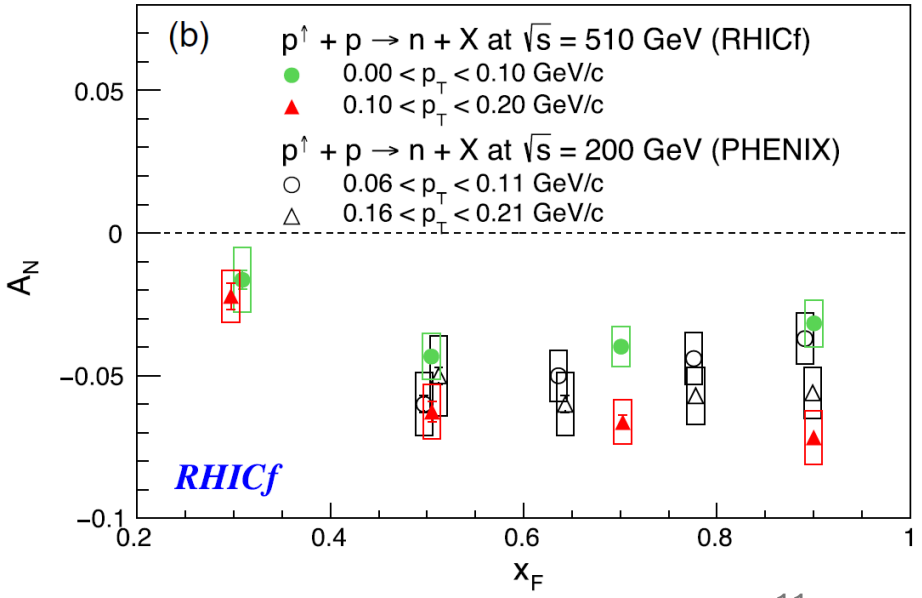


# Neutron asymmetry at RHICf

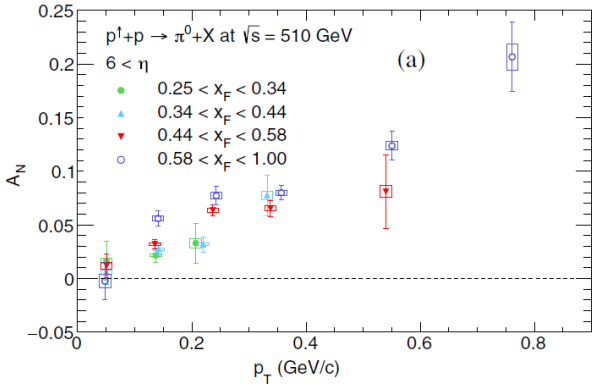
- Comparison between the RHICf and PHENIX data
  - In the range of low $p_T < 0.2$ GeV/$c$ and $x_F > 0.4$ that is overlapping with the PHENIX data at $\sqrt{s} = 200$ GeV
    - Phys. Rev. D 105 (2022) 032004
  - The asymmetries are consistent with those by RHICf at $\sqrt{s} = 510$ GeV
  - The asymmetries are again consistent at both energies and show a flat $x_F$ dependence
  - There is no or only a weak $\sqrt{s}$ dependence

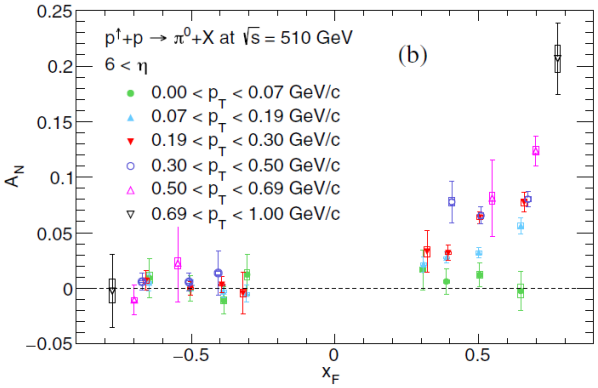


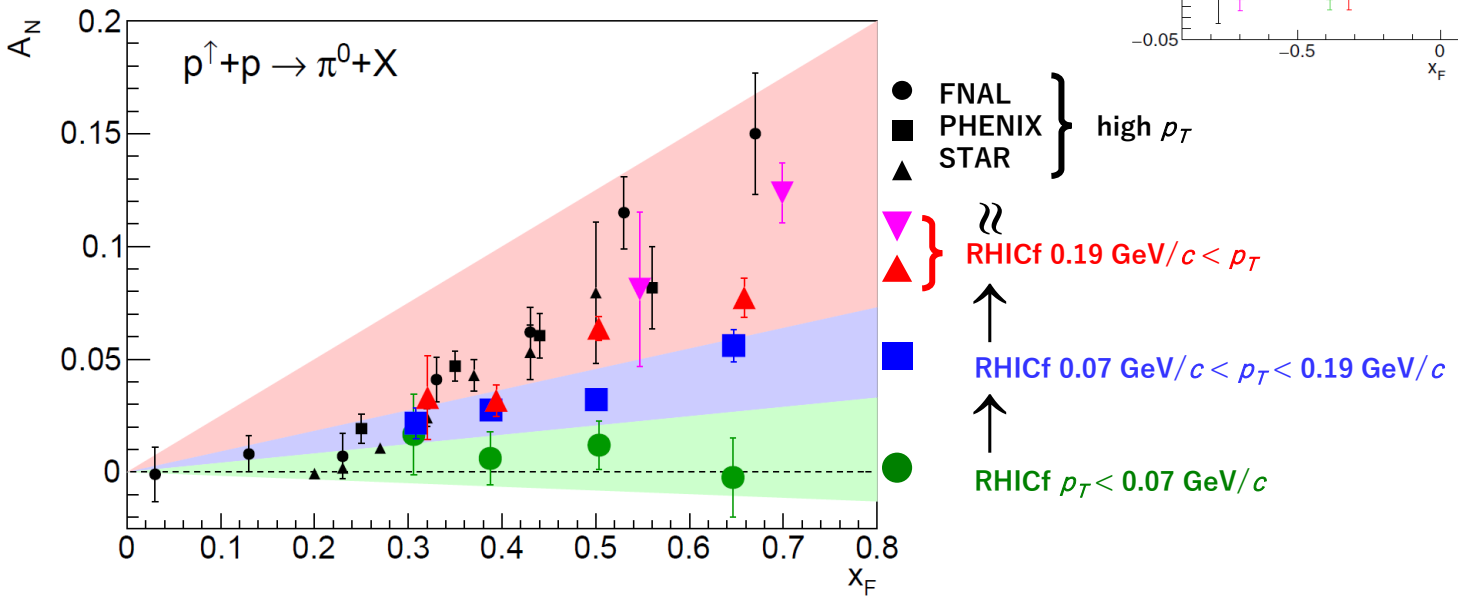



# $\pi^0$ asymmetry at RHICf

- Phys. Rev. Lett. 124, 252501 (2020)
- Asymmetry ~ 0 backward & forward $p_T <$ 0.07 GeV/$c$
- Comparison with high $p_T >$ 0.5 GeV/$c$ data of the past experiments
- Nearly the same large asymmetry is reached at low $p_T <$ 0.2 GeV/$c$
- Contribution of other mechanisms, diffraction and resonance, may provide a hint to the mystery

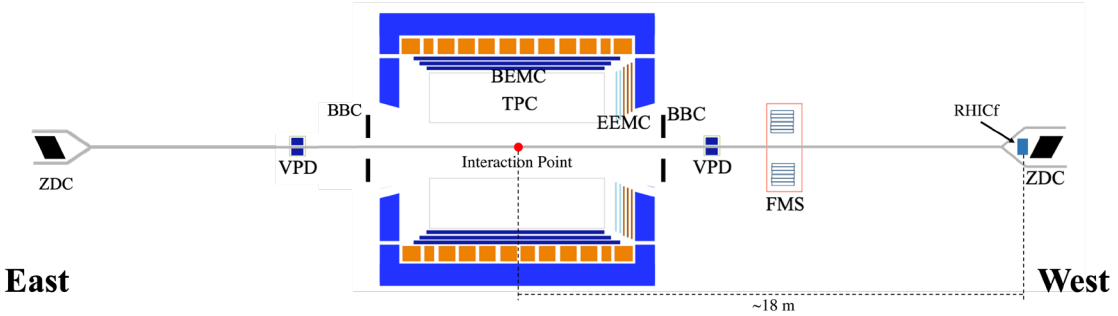


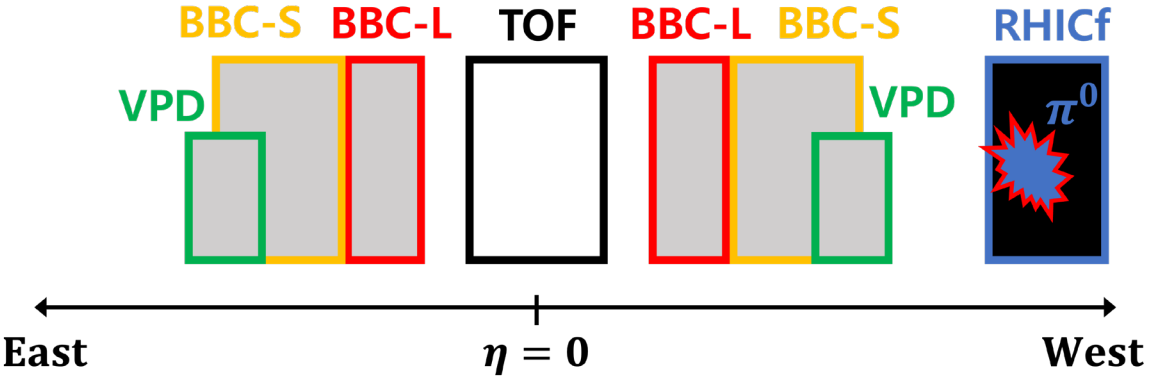



# *Combined analysis with STAR detectors*

- Extending the RHICf standalone analysis to a combined analysis with STAR detectors to study the origin of the far-forward production
- Identify diffractive and non-diffractive events by using the STAR detectors,



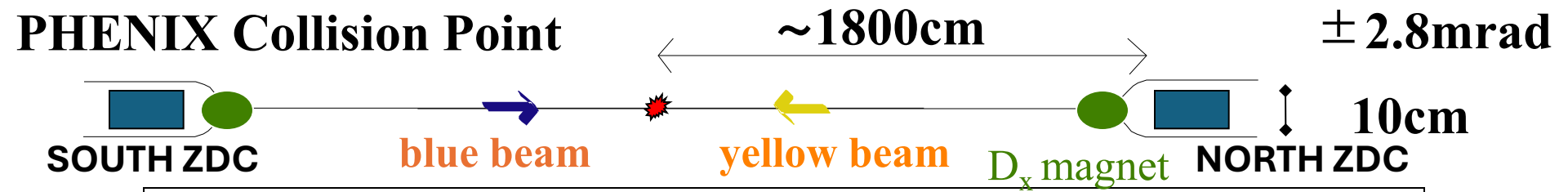



# *Summary*

- RHICf experiment in 2017
  - EM calorimeter (RHICf detector) installed in front of the ZDC+SMD of the STAR experiment
- Far-forward neutron asymmetry
  - Improved $p_T$ precision and wider $p_T$ coverage ($p_T < 1.2$ GeV/$c$) at $\sqrt{s} = 510$ GeV in the RHICf experiment
- Far-forward $\pi^0$ asymmetry
  - Contribution of other mechanisms, diffraction and resonance, may provide a hint to the mystery
- Combined analysis with STAR detectors

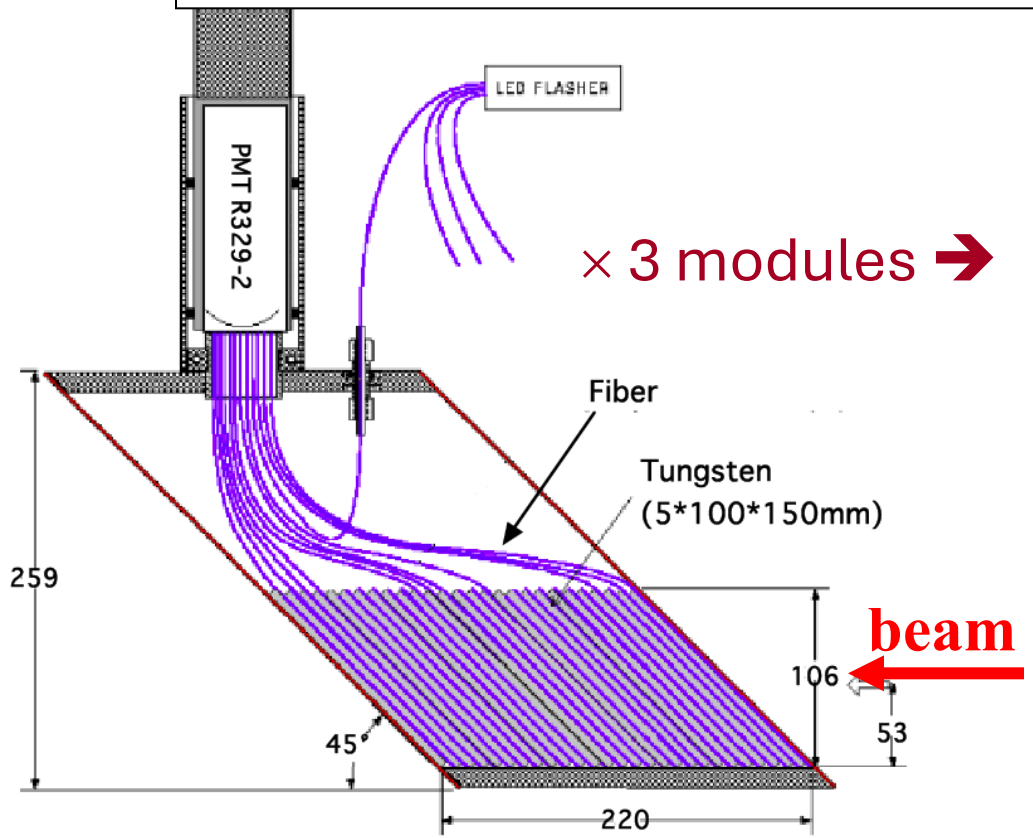
# *Backup Slides*

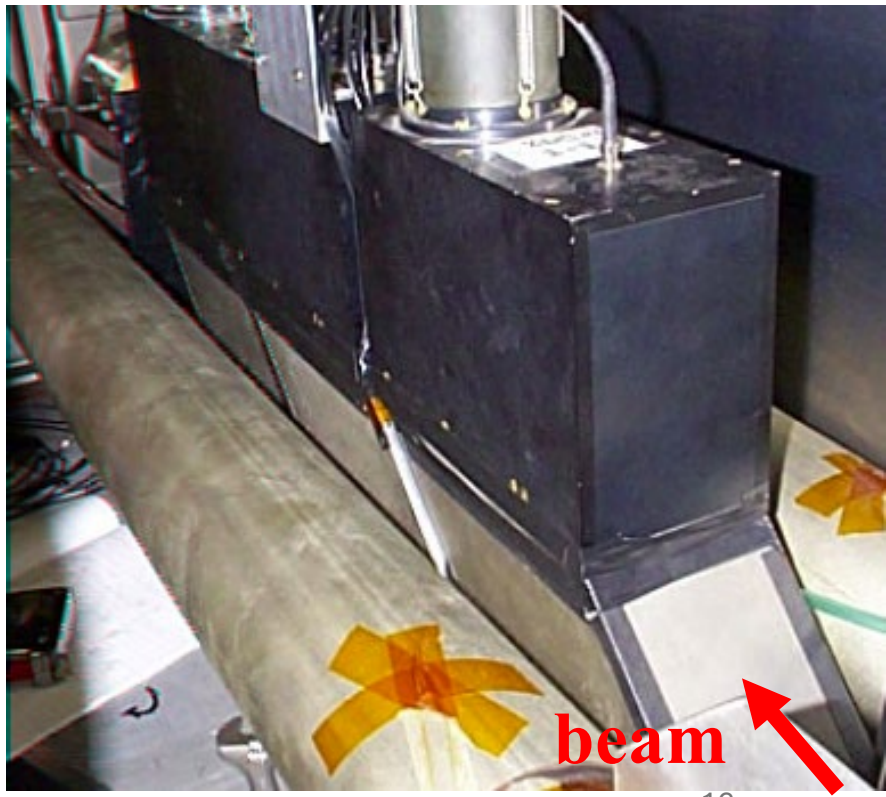
# ZDC (Zero Degree Calorimeter)




hadron sampling calorimeter made of Tungsten plate and fibers

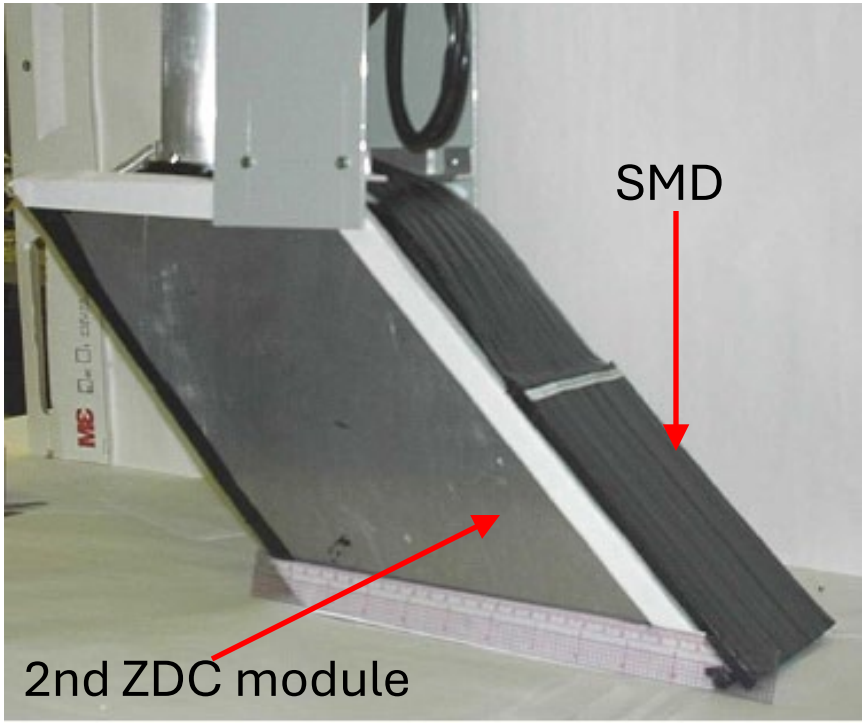
**$5.1\lambda_T$ $149X_0$ (3 ZDCs), Energy resolution ~ 20% @ 100GeV**

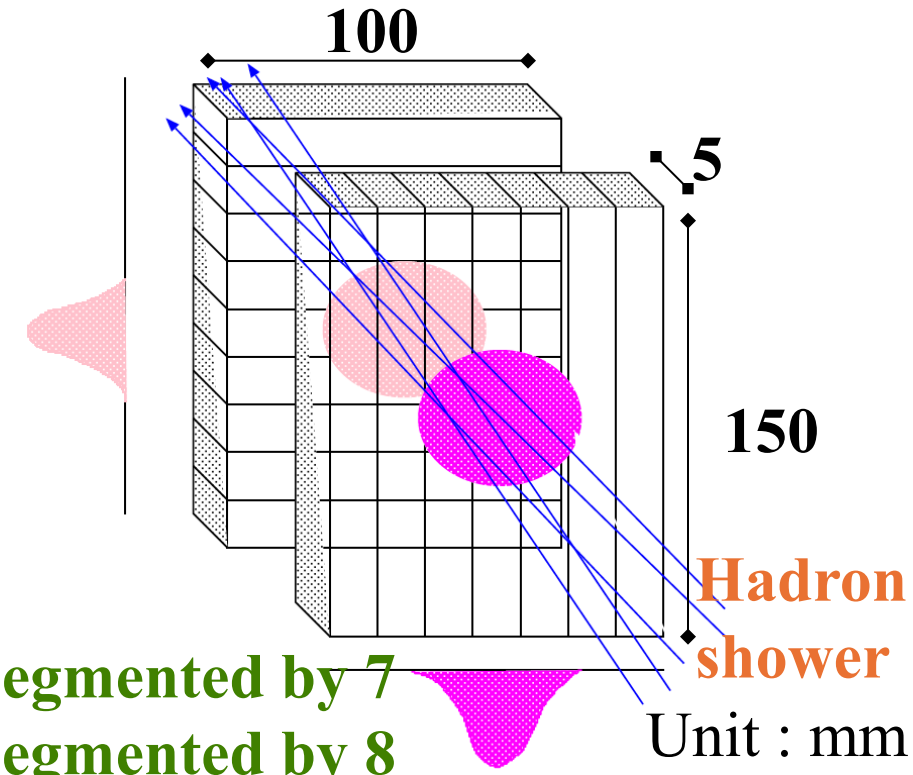


# Shower Maximum Detector

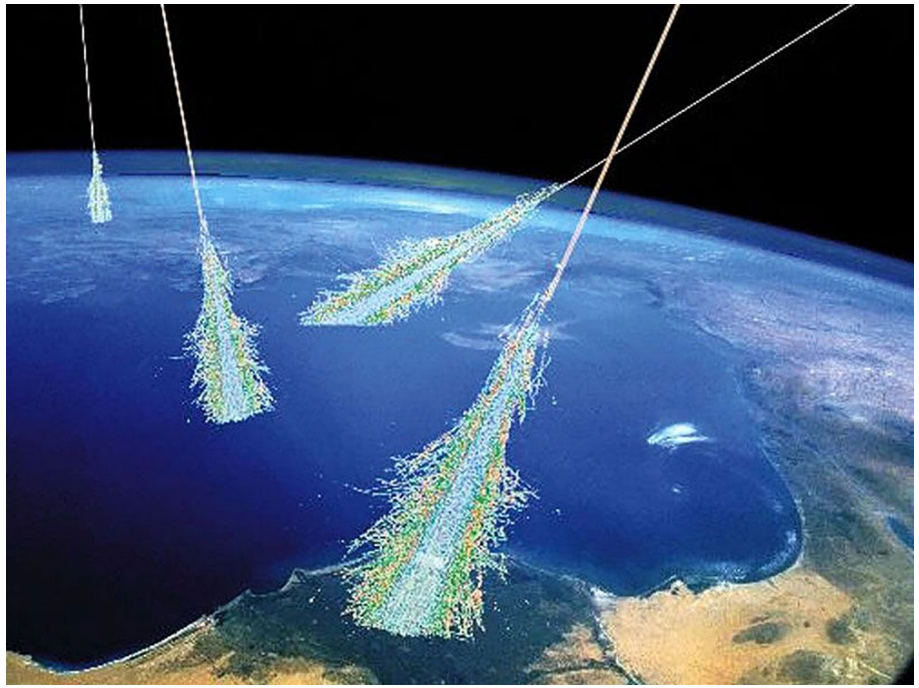
- To measure the neutron hit position, SMDs (Shower Maximum Detector) were installed between 1st and 2nd modules of ZDC
  - arrays of plastic scintillators
  - giving a position by calculating the center of gravity of shower generating in the 1st ZDC module
  - position resolution ~1cm @ 50GeV neutron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



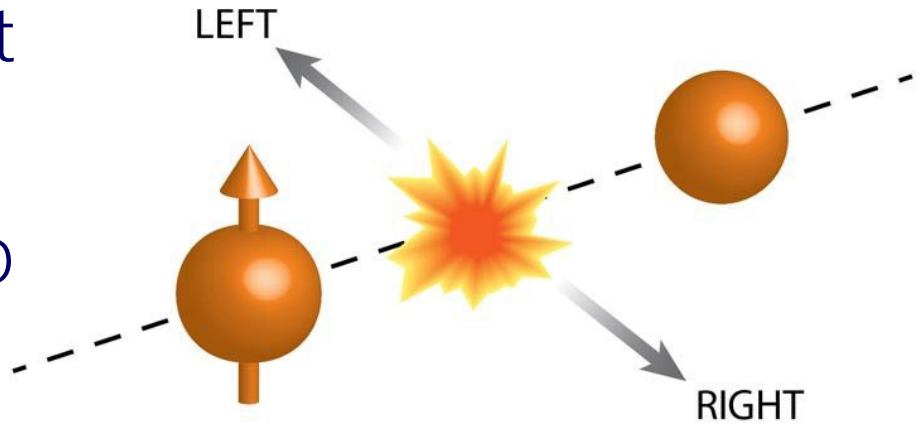



# *Physics motivation*

- Cosmic-ray study
  - Cross section measurement to understand ultra-high energy cosmic rays



- Asymmetry measurement
  - To understand the hadronic collision mechanism based on QCD



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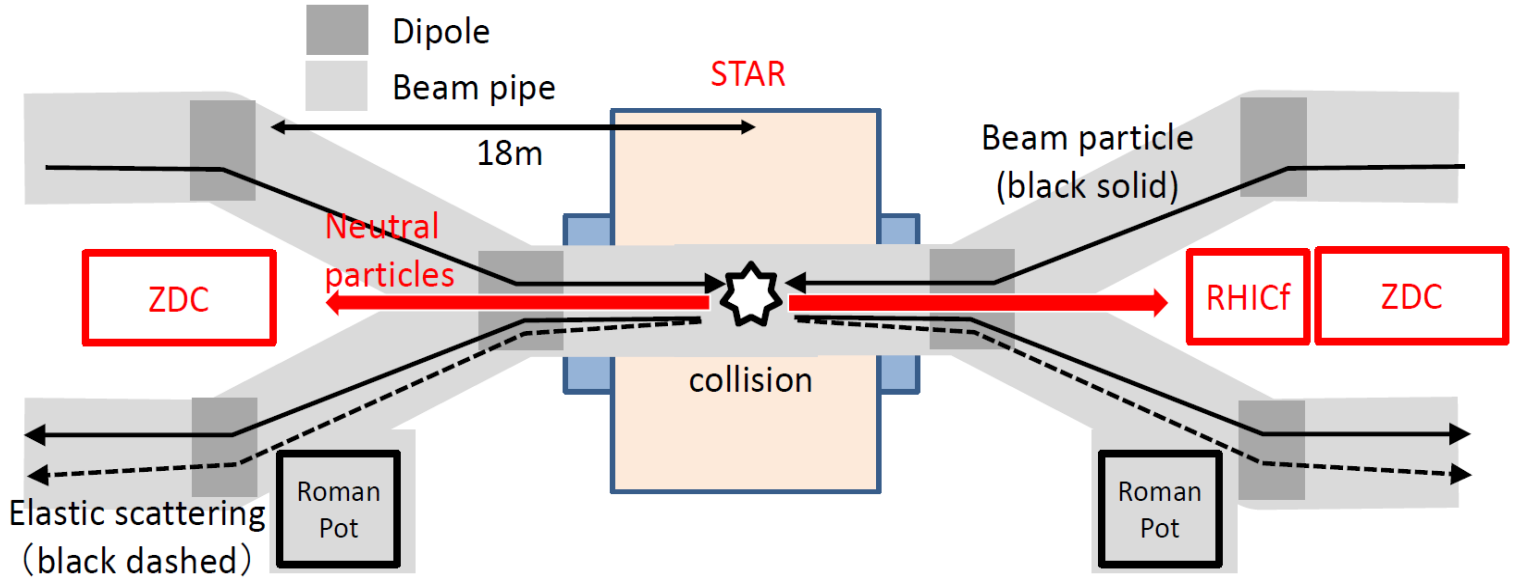


- Two position-sensitive sampling calorimeters
  - TS (small tower): 20mm x 20mm
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  - 16 GSO sampling layers
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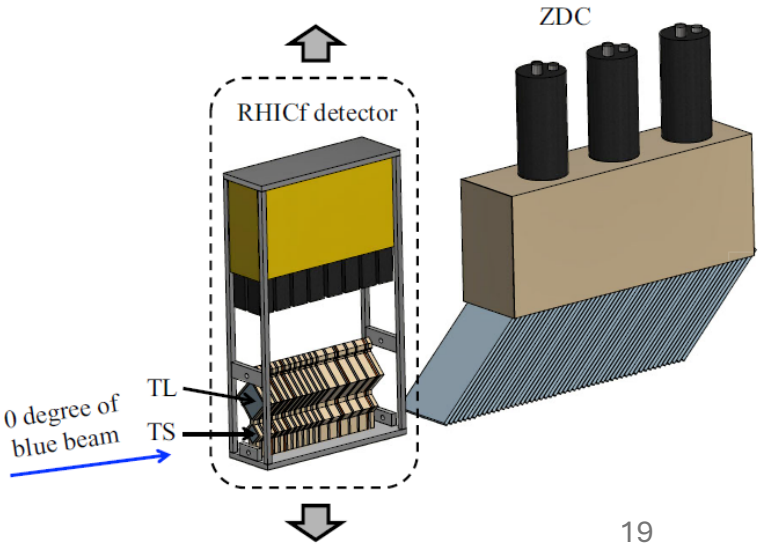
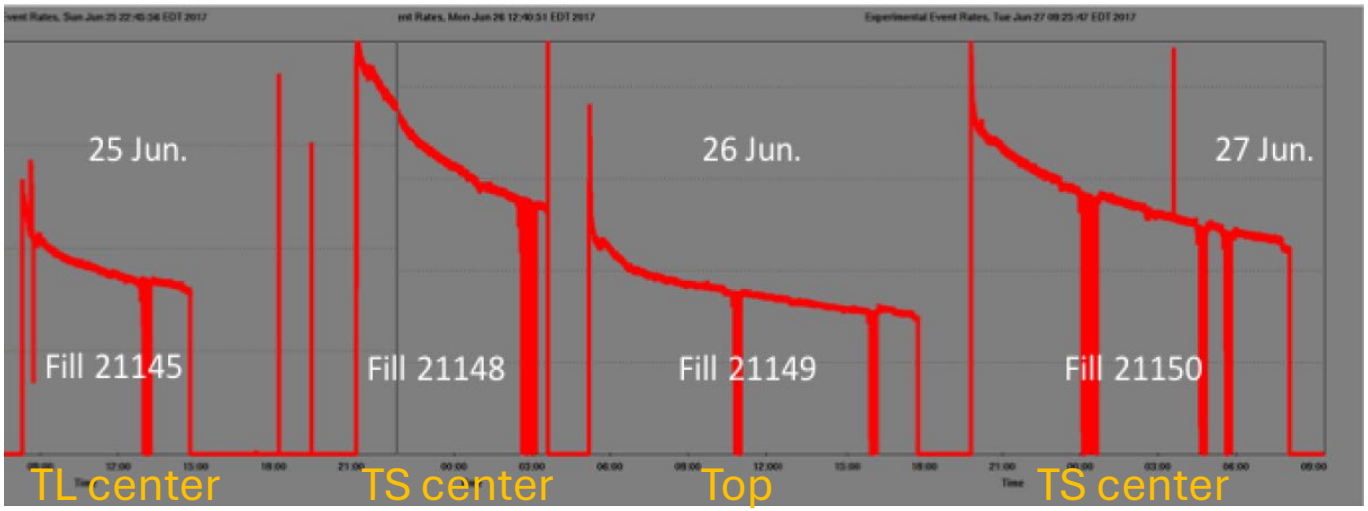
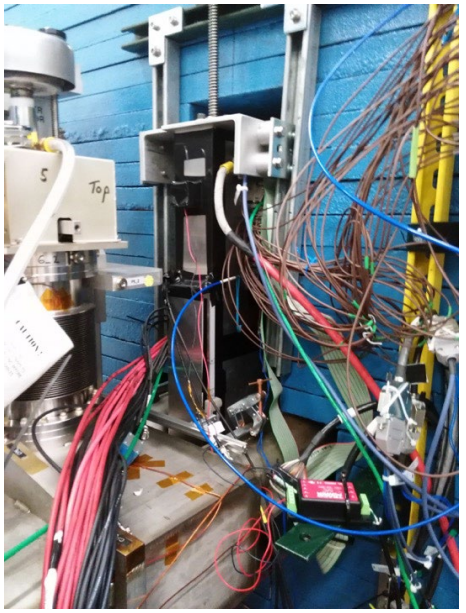
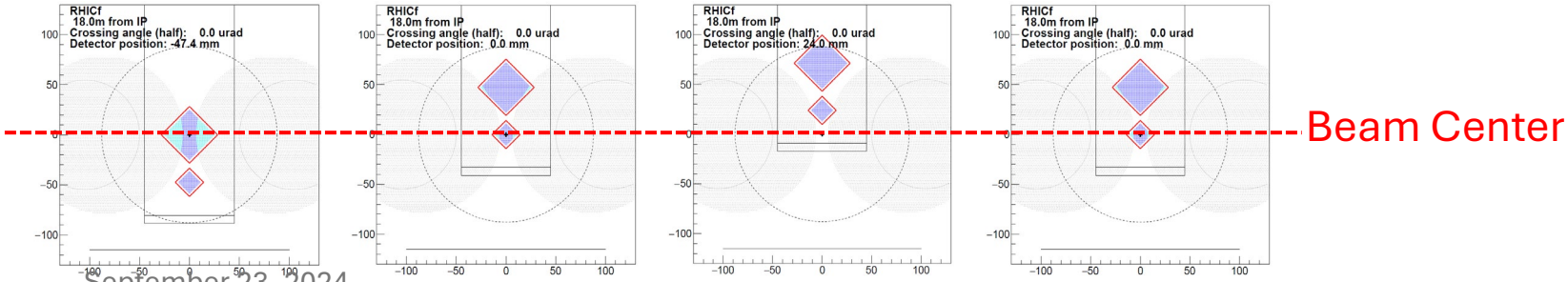


# 2017 operation for RHICf

- June 24 – 27 physics data acquisition
  - $\beta^* = 8$m, radial polarization
  - 27.7 hours, ~110M events, ~700 $nb^{-1}$
- 3 detector positions: TL center / TS center / Top position

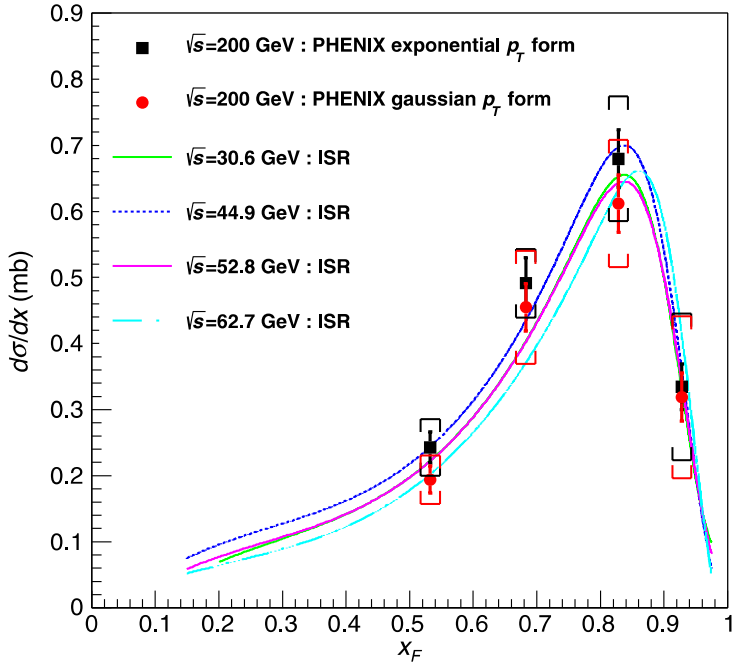


# *Far-forward neutron production*

## PHENIX 200 GeV



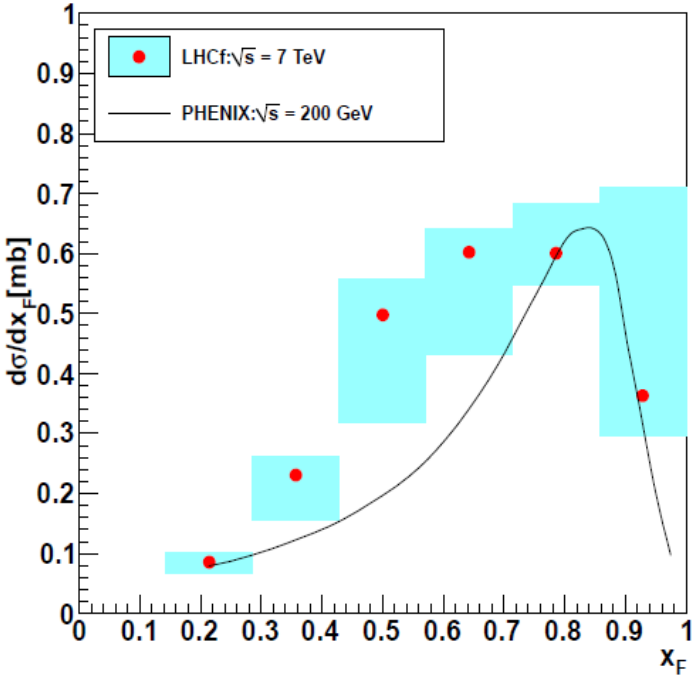

PHENIX, PRD, 88, 032006 (2013)

$p_T < 0.11\ x_F$ GeV/c

$\sqrt{s}$ = 30-60 GeV @ISR

$\sqrt{s}$ = 200 GeV @RHIC

## LHCf 7 TeV




LHCf

$p_T < 0.11\ x_F$ GeV/c

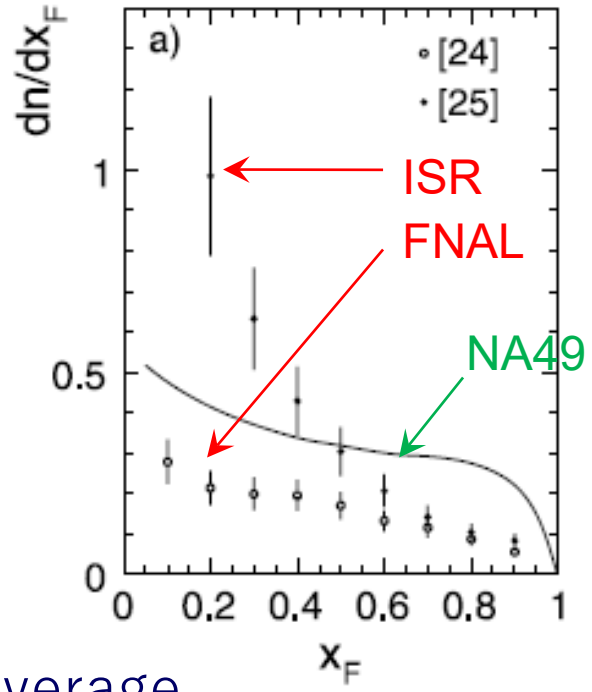
$\sqrt{s}$ = 7000 GeV @LHC

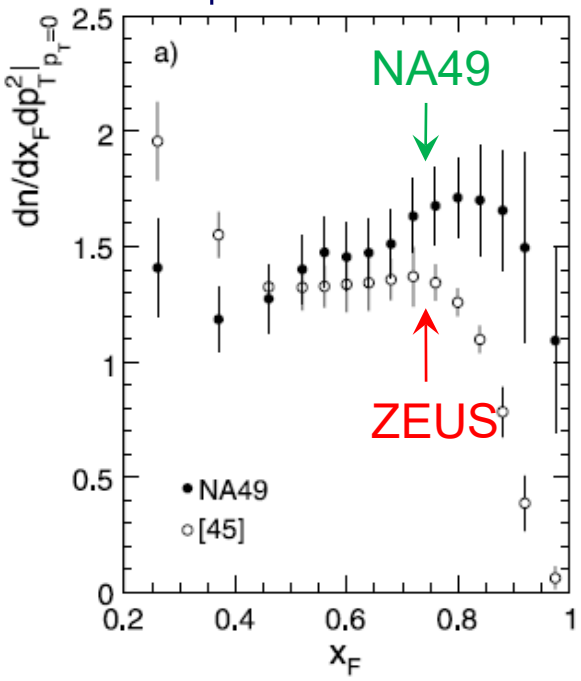
- PHENIX explains the result by 1 pion exchange
- More complicated exchanges at >TeV?

# *Far-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?
- More data necessary to understand the production mechanism
  - Asymmetry measurement as a new independent input

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

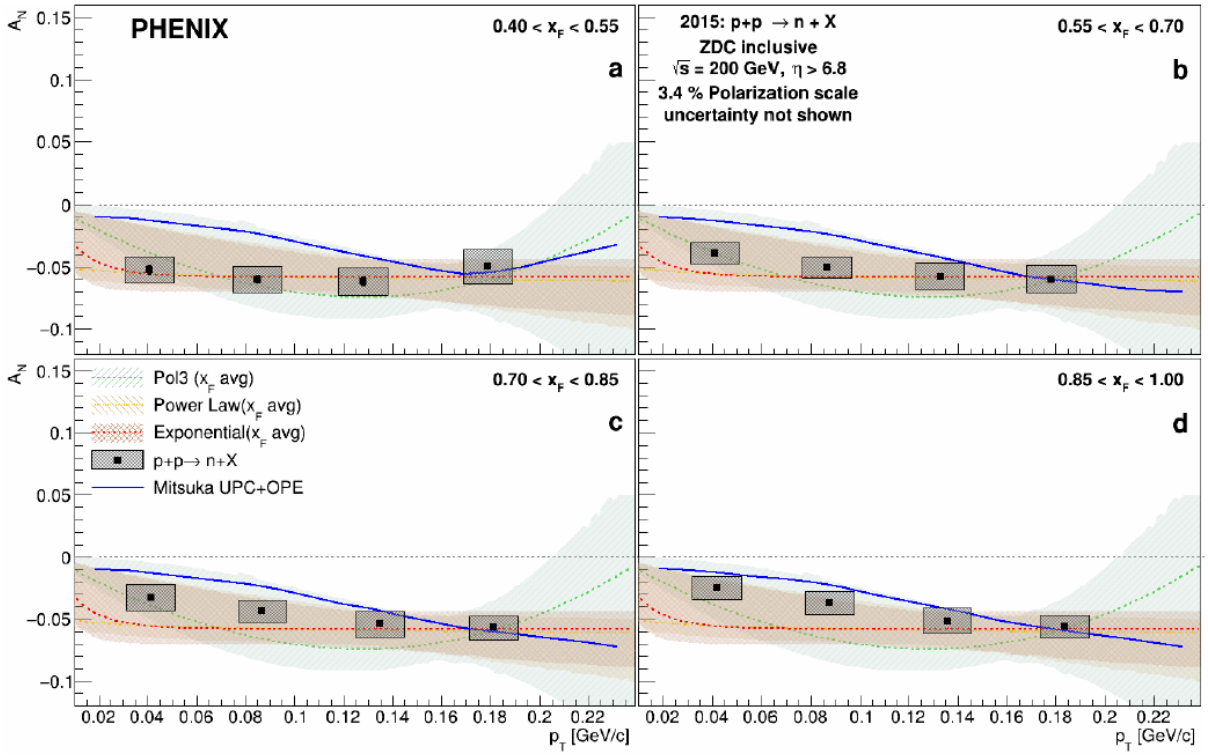



➡ Wide $\eta$ & $p_T$ coverage

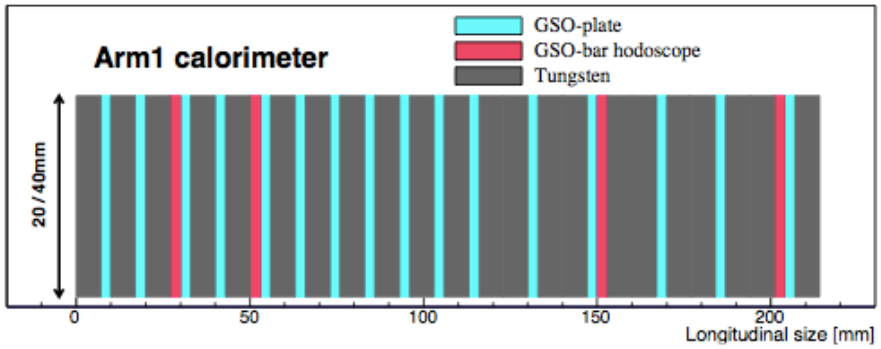
# *Neutron asymmetry @ PHENIX*

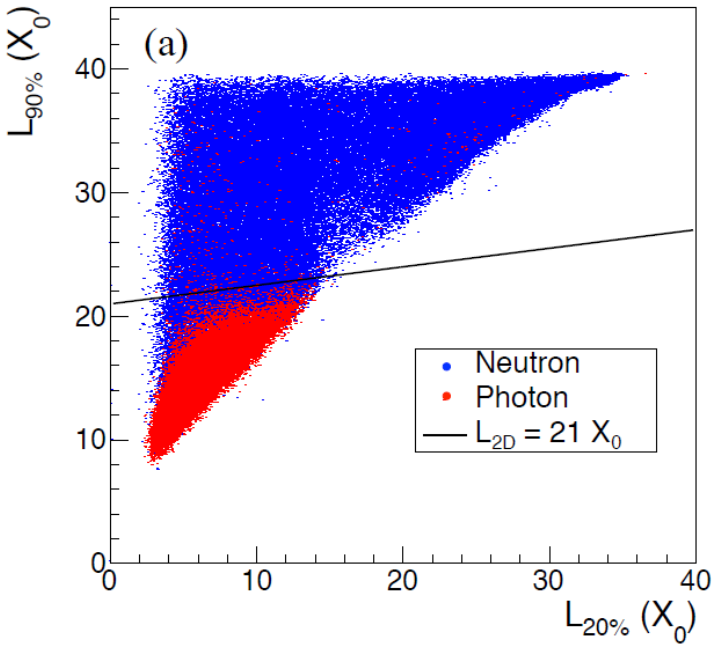
- Recent PHENIX publication
  - Phys. Rev. D 105 (2022) 032004
  - $p_T$ dependence at $\sqrt{s} = 200$ GeV
    - $A_N$ increases in magnitude with $p_T$ at high $x_F$
    - No clear $x_F$ dependence



# RHICf data analysis

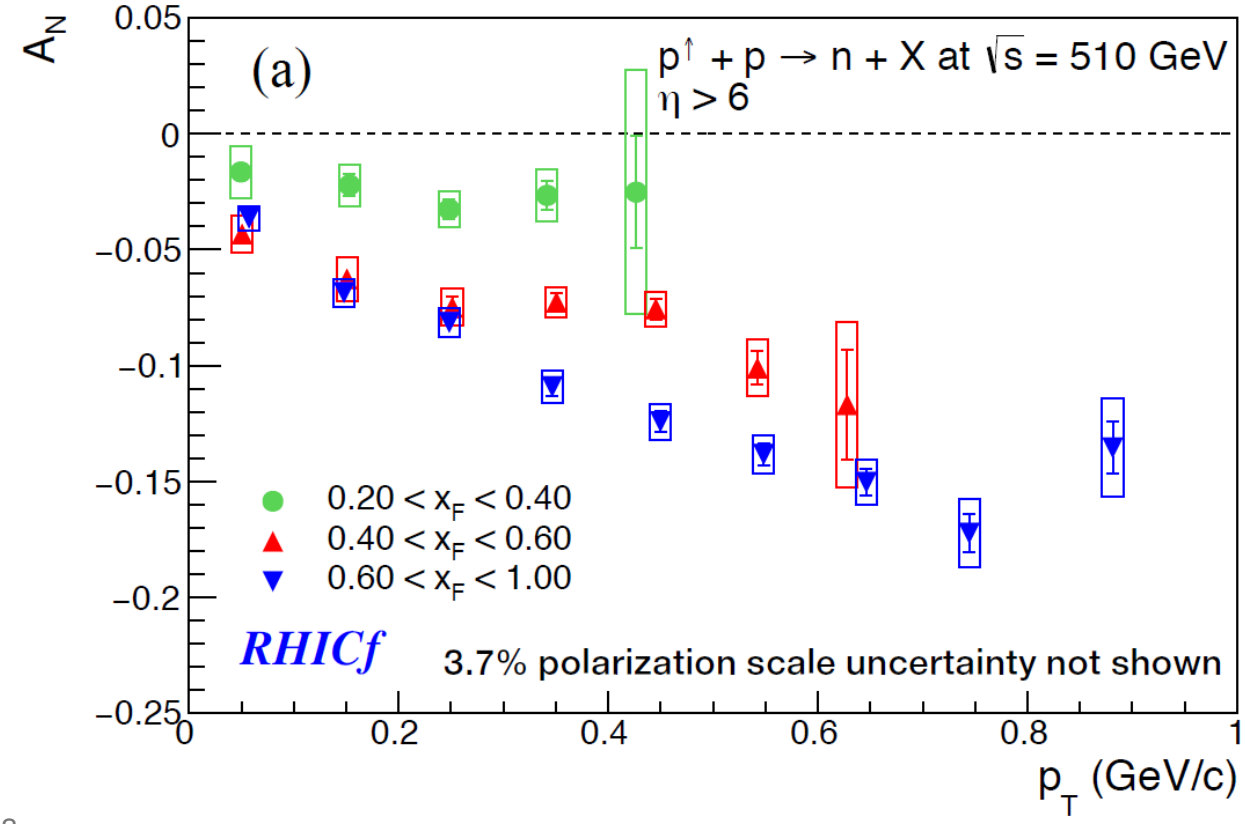
- Shower trigger data
  - Energy deposits of any 3 consecutive GSO plates larger than 45 MeV
- Neutron photon separation
  - $L_{90\%}$ ($L_{20\%}$): longitudinal depth for the integrated energy deposition in the GSO plates to reach 90% (20%) of the total
- Background subtraction
  - photon, charged hadron
- Unfolding
  - $x_F$, $p_T$, and $\phi$
- $A_N$ calculation



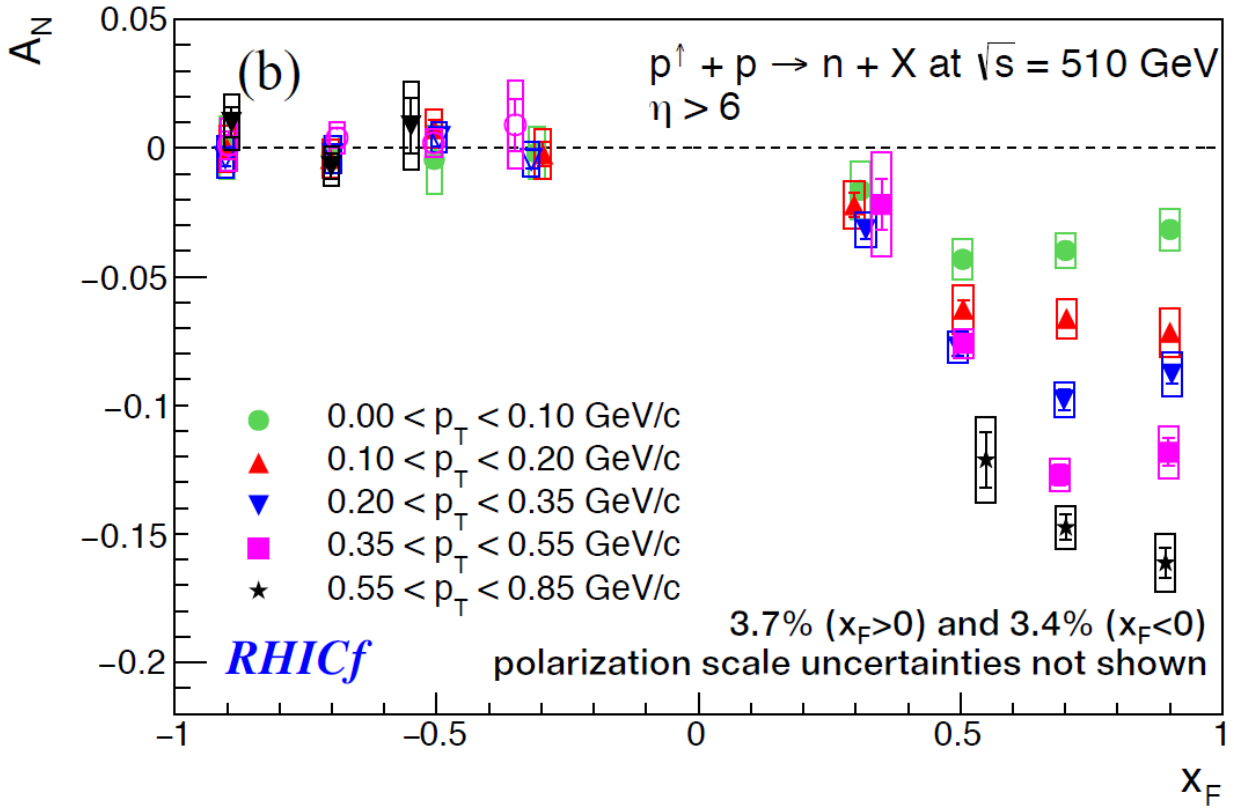
# Neutron asymmetry

- arXiv:2310.09807
- In the low $x_F$ range, the neutron $A_N$ reaches a plateau at low $p_T$
- In the high $x_F$ range, the plateau does not seem to be reached yet while the absolute value of the $A_N$ explicitly increases in magnitude with $p_T$



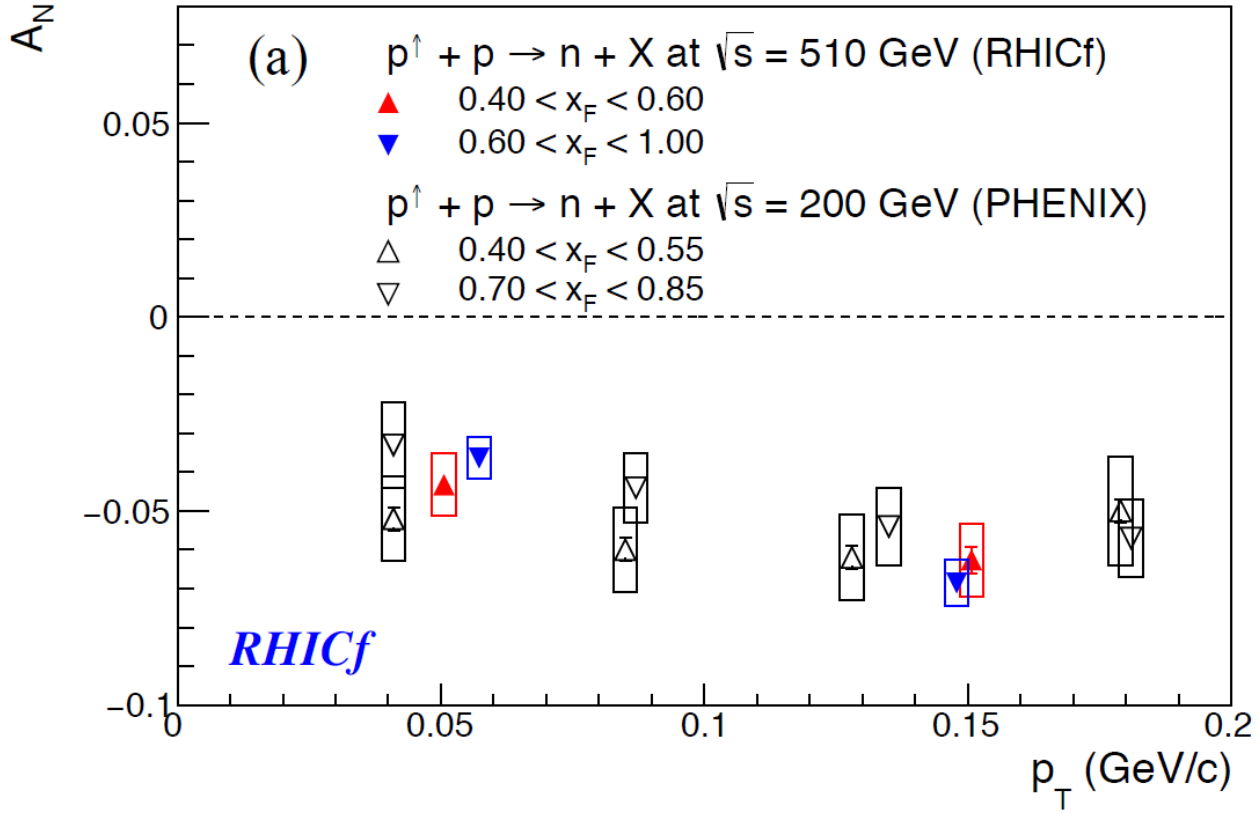
# Neutron asymmetry

- The backward $A_N$s are all consistent with zero
- In the low $p_T$ range $< 0.20$ GeV/$c$, the forward $A_N$ reaches a plateau of low $A_N$ at low $x_F$ (about 0.5) with little $x_F$ dependence
- In the high $p_T$ range $> 0.20$ GeV/$c$, the asymmetries appear to be leveling off at higher $x_F$ (about 0.7), showing a clear $x_F$ dependence
- The $x_F$ dependence in the high $p_T$ range was observed for the first time by the RHICf experiment



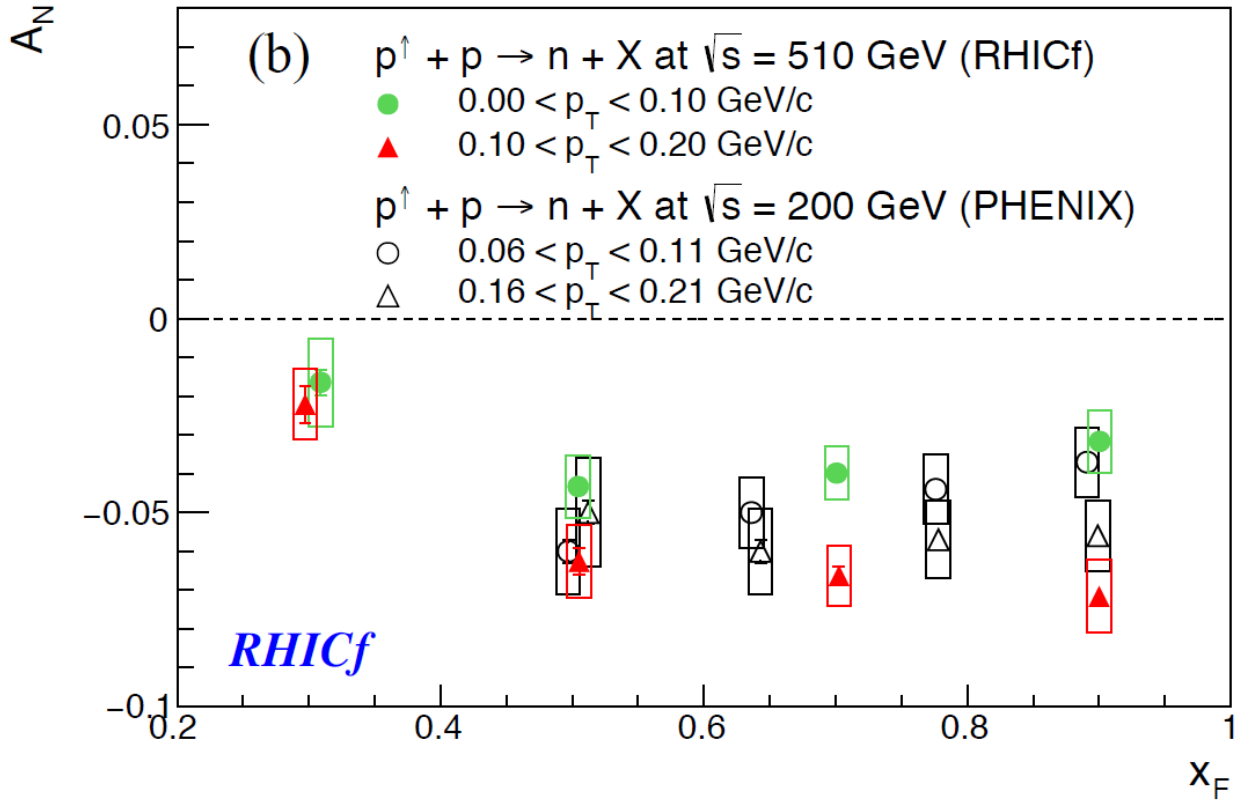
# Neutron asymmetry

- Comparison between the RHICf and PHENIX data
- In the range of low $p_T < 0.2$ GeV/$c$ and $x_F > 0.4$ that is overlapping with the PHENIX data at $\sqrt{s}$= 200 GeV
- The asymmetries are consistent with those by RHICf at $\sqrt{s} = 510$ GeV



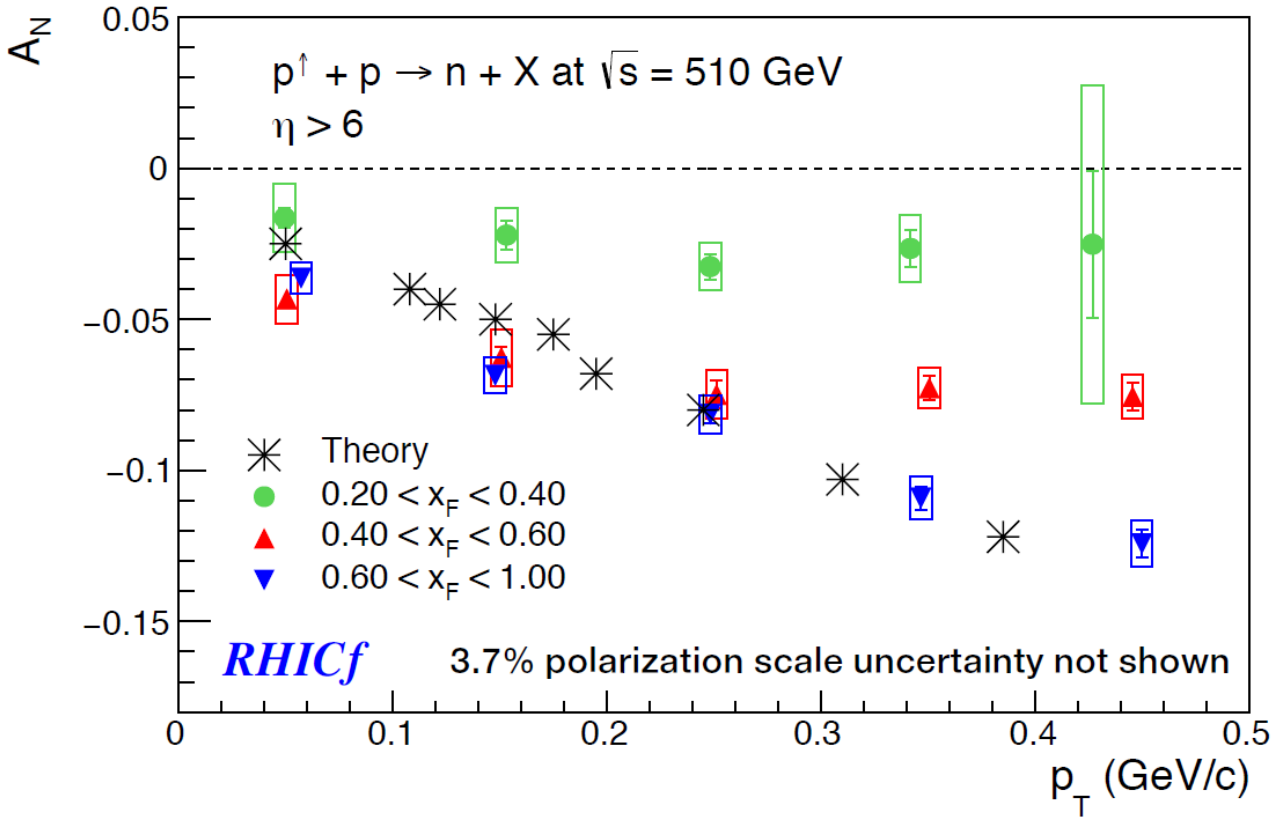
# Neutron asymmetry

- Comparison between the RHICf and PHENIX data
- In the low $p_T$ range that PHENIX covers at $\sqrt{s}$=200 GeV
- The asymmetries are again consistent at both energies and show a flat $x_F$ dependence
- There is no or only a weak $\sqrt{s}$ dependence



# Neutron asymmetry

- Comparison with model calculations based on the $\pi$ and $a_1$ exchange
  - B. Z. Kopeliovich et al., PRD 84 (2011) 114012
- The model did not predict the $x_F$ dependence of the neutron $A_N$
- In the high $x_F$ range, the $A_N$s are mostly consistent with the model calculations
- However, the model does not reproduce the $A_N$s in the low $x_F$ range where the asymmetries are significantly smaller
- This may be because fragmentation is expected to dominate neutron production at low $x_F$ over Reggeon exchange



# Neutron asymmetry

- Comparison between the RHICf and PHENIX data
  - In the range of low $p_T < 0.2$ GeV/$c$ and $x_F > 0.4$ that is overlapping with the PHENIX data at $\sqrt{s}$= 200 GeV
    - Phys. Rev. D 105 (2022) 032004
  - The asymmetries are consistent with those by RHICf at $\sqrt{s}$ = 510 GeV
  - In the low $p_T$ range that PHENIX covers at $\sqrt{s}$=200 GeV
  - The asymmetries are again consistent at both energies and show a flat $x_F$ dependence
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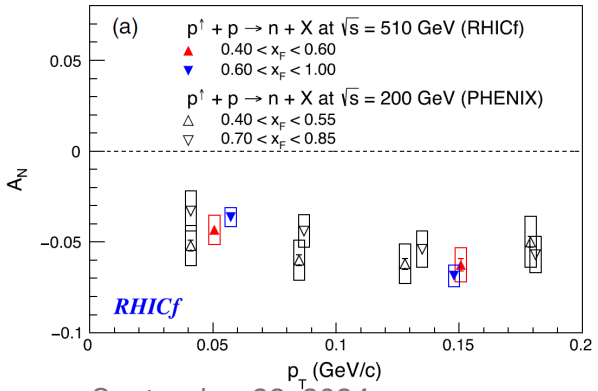
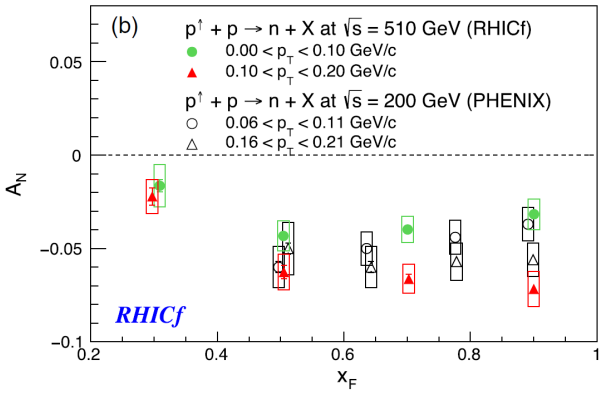
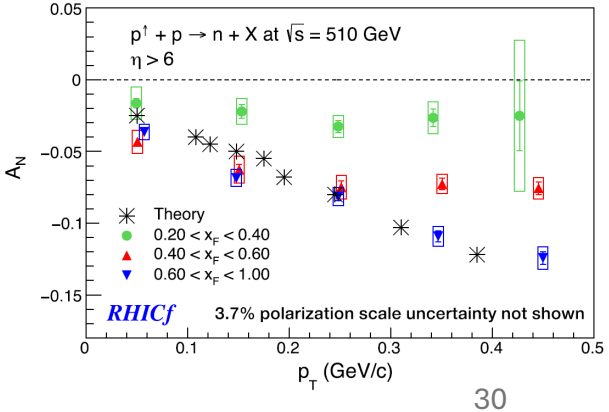
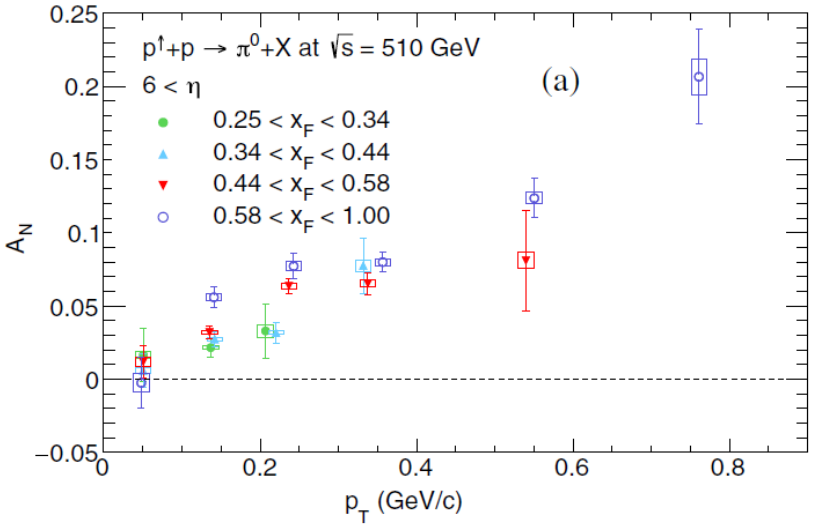


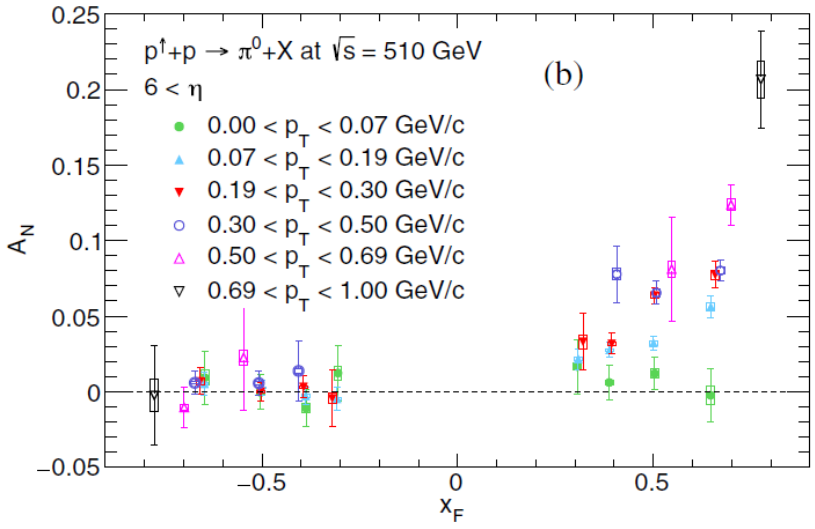



# 2017 run results

- $\pi^0$ asymmetry
  - Transverse single-spin asymmetry for very forward neutral pion production in polarized p+p collisions at $\sqrt{s}$ = 510 GeV
  - Phys. Rev. Lett. 124, 252501 (2020)
  - Research News
    - https://www.riken.jp/en/news_pubs/research_news/pr/2020/20200623_1/index.html (RIKEN)
    - https://www.bnl.gov/newsroom/news.php?a=117099 (BNL)
  - Asymmetry ~ 0 backward & forward $p_T < 0.07$ GeV/$c$



# 2017 run results

- $\pi^0$ asymmetry
  - Comparison with high $p_T > 0.5$ GeV/$c$ data of the past experiments
  - Nearly the same large asymmetry is reached at low $p_T < 0.2$ GeV/$c$
  - Contribution of other mechanisms, diffraction and resonance, may provide a hint to the mystery