RHICf experiment for forward QCD studies

Forward QCD: open questions and future directions

University of Kansas, Lawrence

May 24th, 2022

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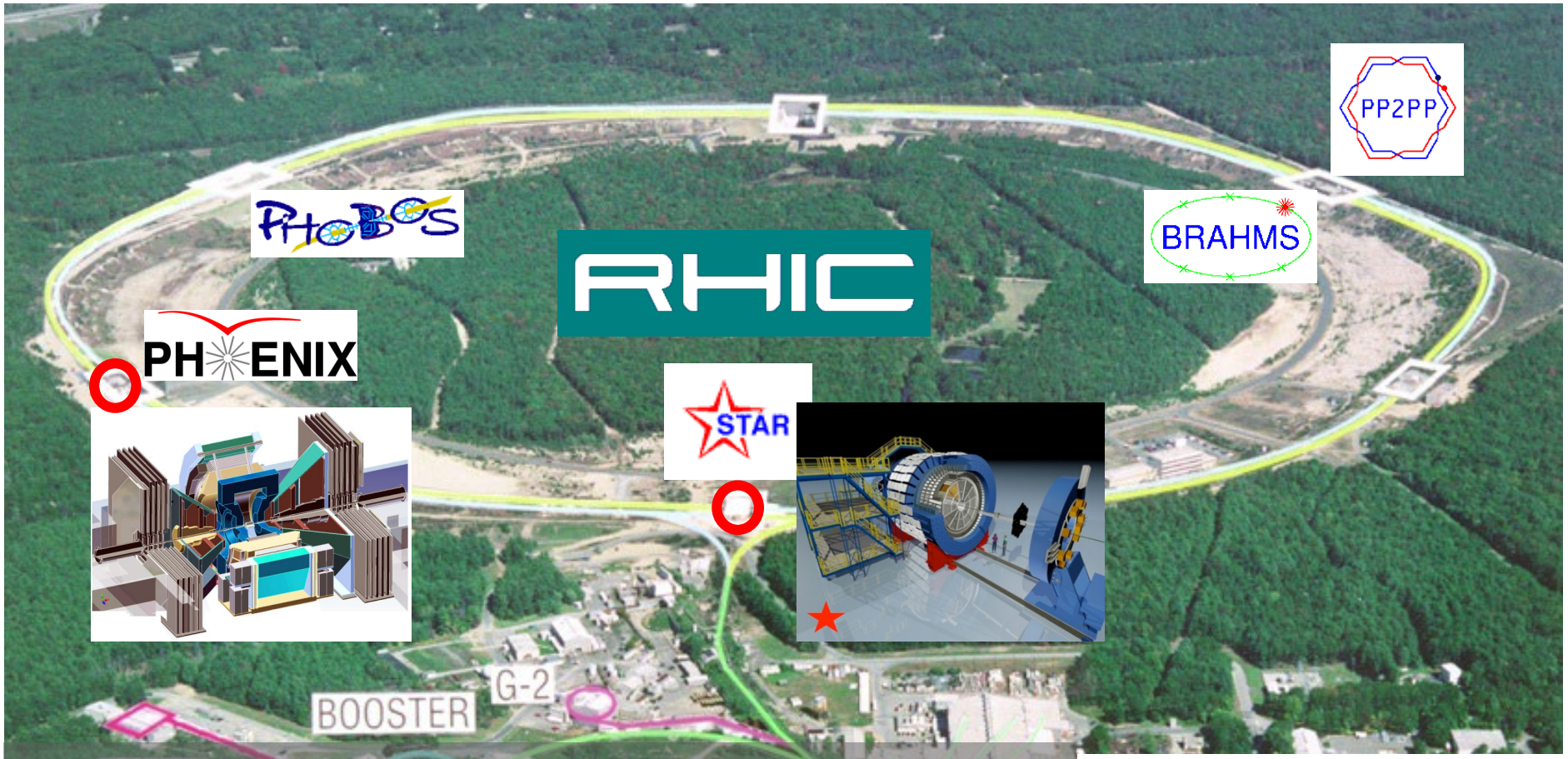
RHIC (Relativistic Heavy-Ion Collider)



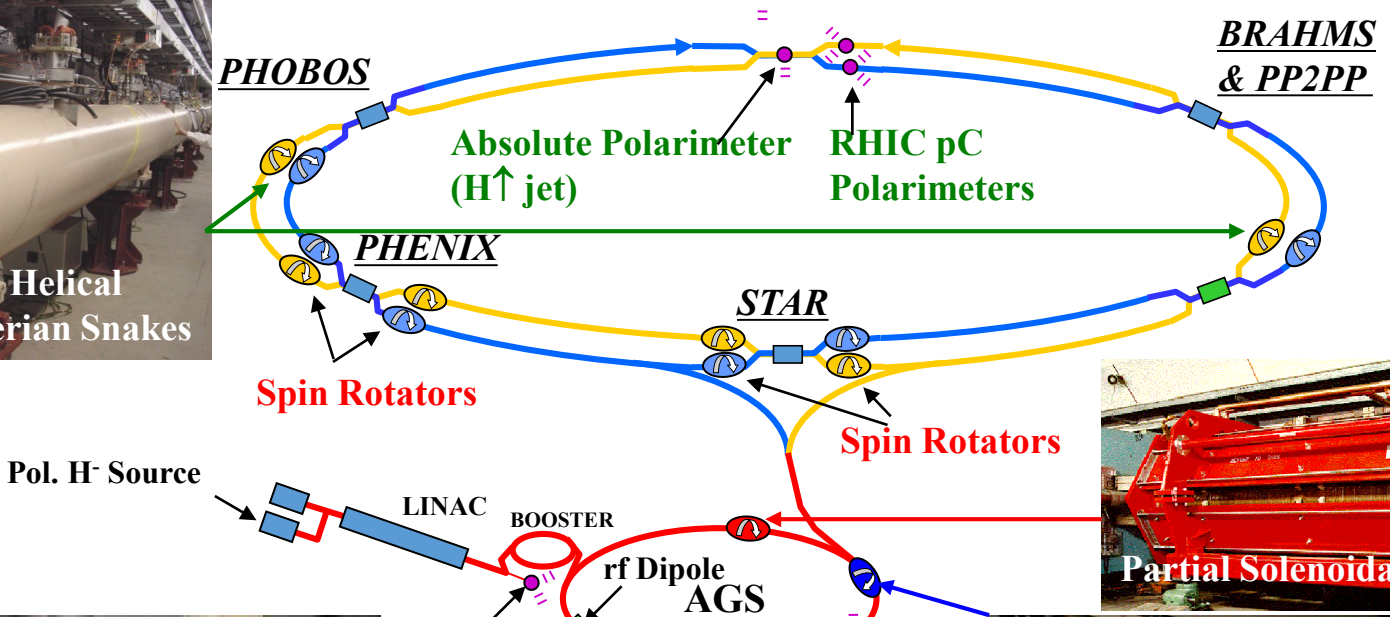
High-energy collision experiments with heavy-ion collisions, polarized proton collisions, and many other combinations of particle species and collision energies

- Au+Au collisions of 7.7 – 200 GeV/A
- polarized proton collisions of 62.4 – 510 GeV
- d+Au, Cu+Cu, U+U, Cu+Au, ^{3}He+Au, polaeized-p+Au/Al

BROOKHAVEN NATIONAL LABORATORY

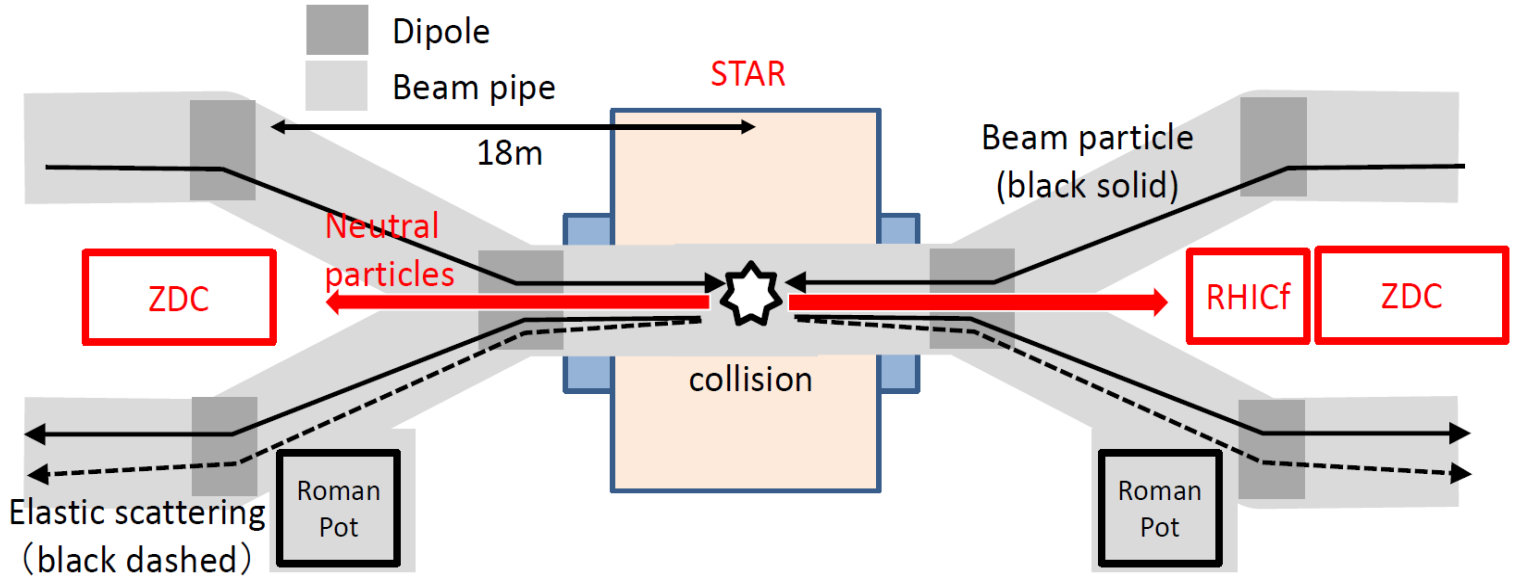
Polarized proton acceleration at RHIC

- Keeping and monitoring polarization from the polarized proton source

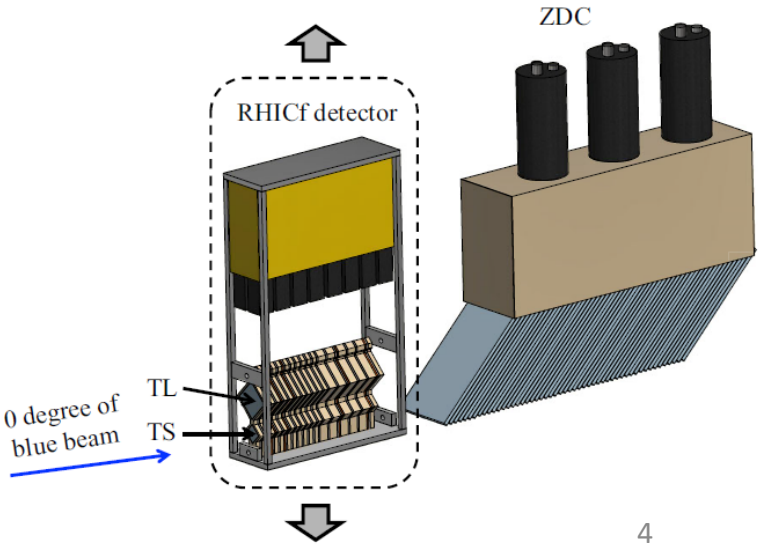


RHICf experiment in 2017

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

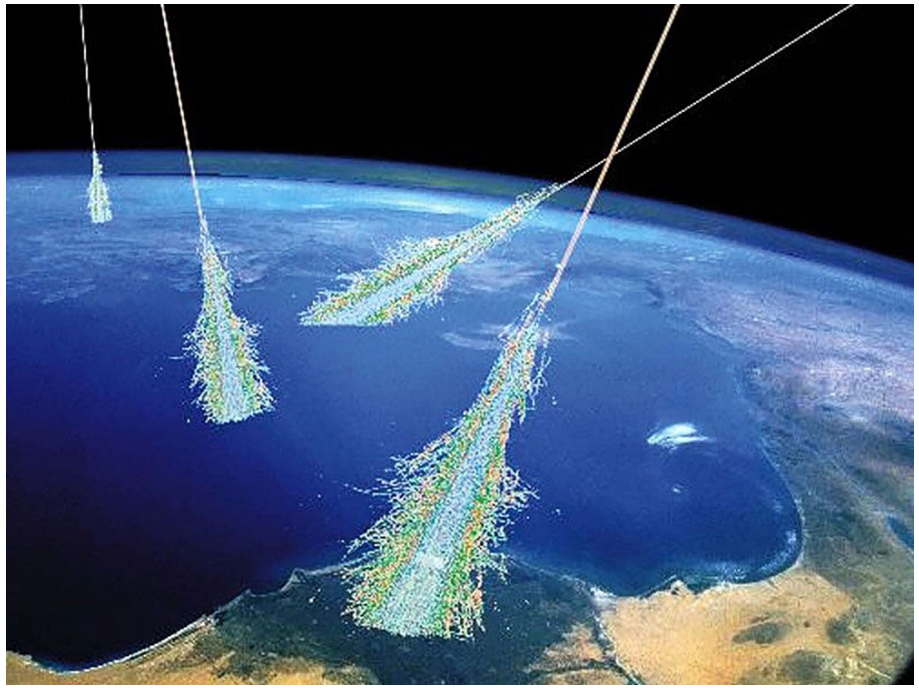


- Two position-sensitive sampling calorimeters
  - TS (small tower): 20mm x 20mm
  - TL (large tower): 40mm x 40mm
  - Tungsten absorber (44 X_0, 1.6 λ_{int})
  - 16 GSO sampling layers
  - 4 XY pairs of GSO-bar position layers

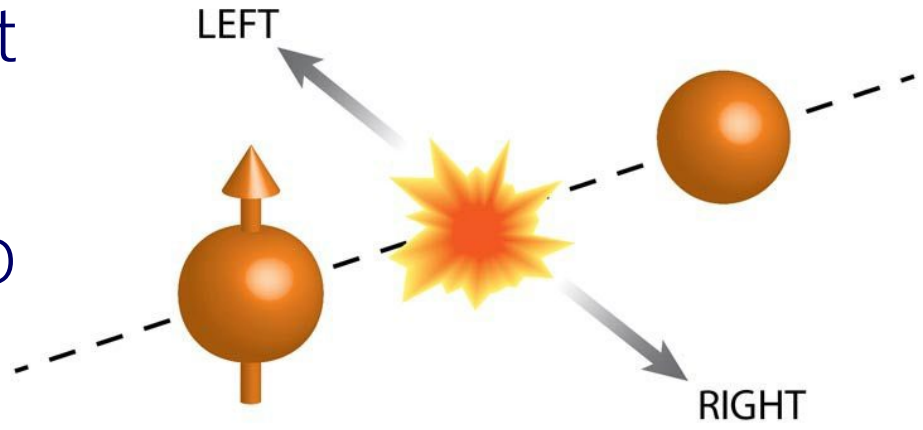


Physics motivation

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



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

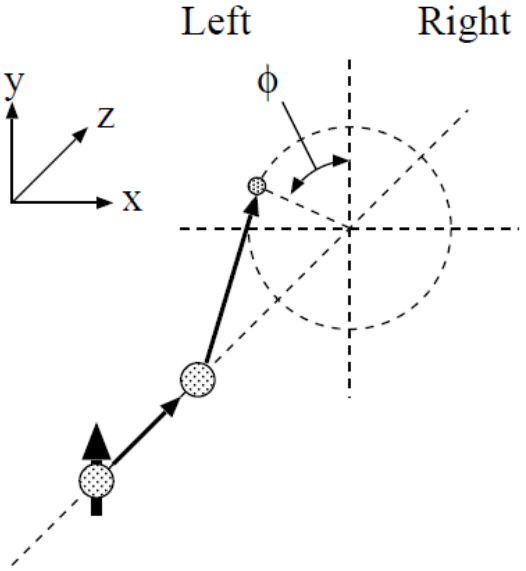


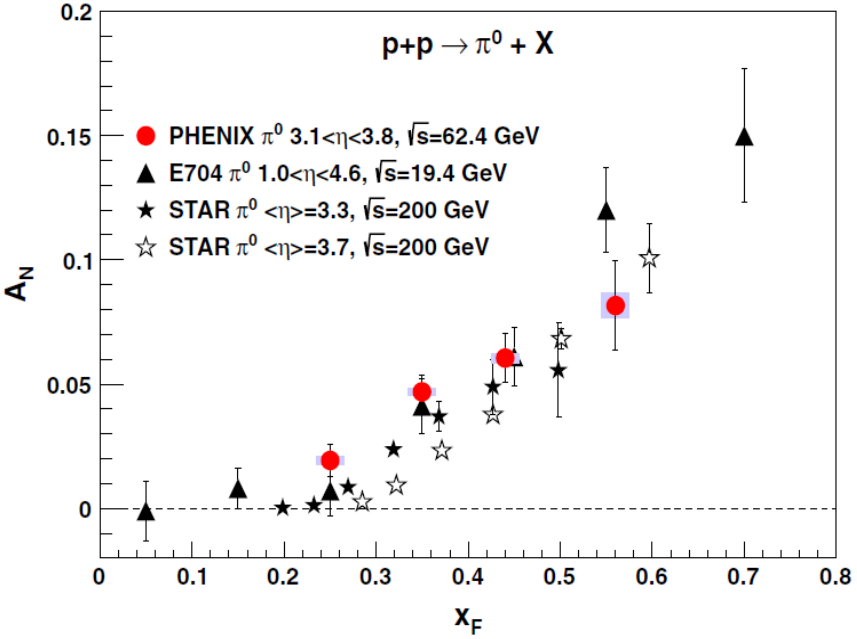
Transverse asymmetry measurement

- A_N (transverse single-spin asymmetry) measurement

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

  - Azimuthal angle modulation
- Large A_N for forward hadron production
  - $1 < \eta < 4$, similar results in wide $\sqrt{s}$
- TMD (Transverse Momentum Dependent) function and higher-twist function in pQCD regime
  - Initial-state effect or "Sivers" effect
  - Final-state effect or "Collins" effect
- Hard scattering and/or non-perturbative effect?





Higher-twist effect

- Quantum many-body correlation among quarks and gluons
  - Based on collinear factorization
  - quark-gluon correlation, tri-gluon correlation, twist-3 fragmentation
- Reproducing experimental data with precision calculation of twist-3 fragmentation function

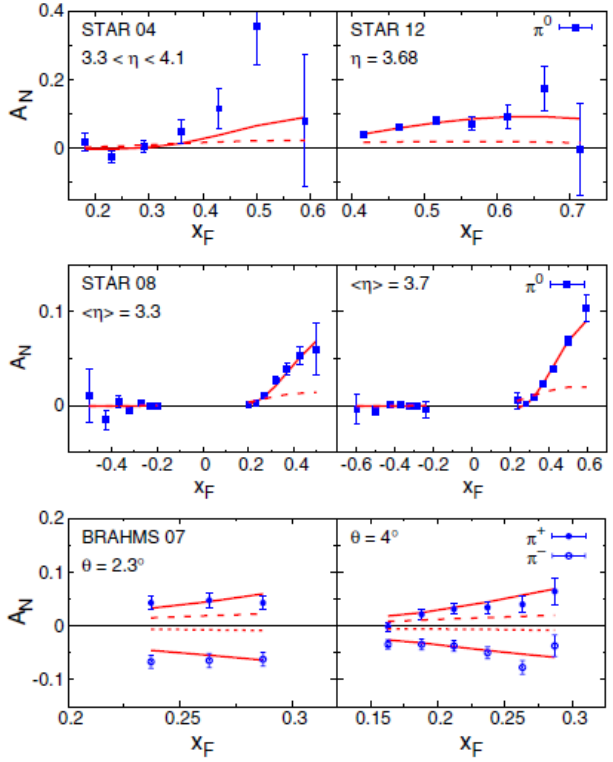


FIG. 1 (color online). Fit results for $A_N^{\pi^0}$ (data from [35–37]) and $A_N^{\pi^\pm}$ (data from [38]) for the SV1 input. The dashed line (dotted line in the case of π^-) means $\hat{H}_{FU}^{\Im}$ switched off.

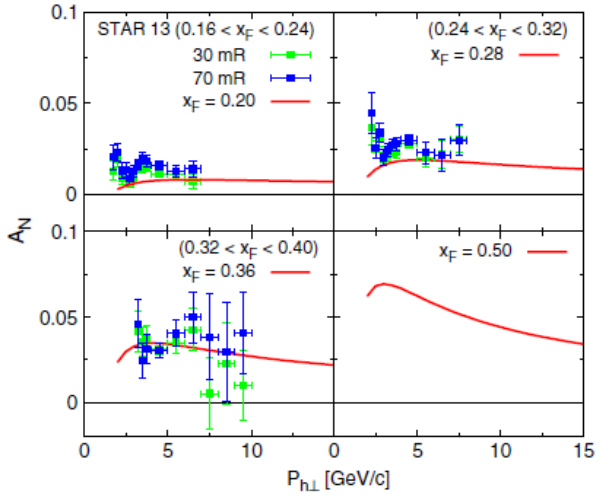
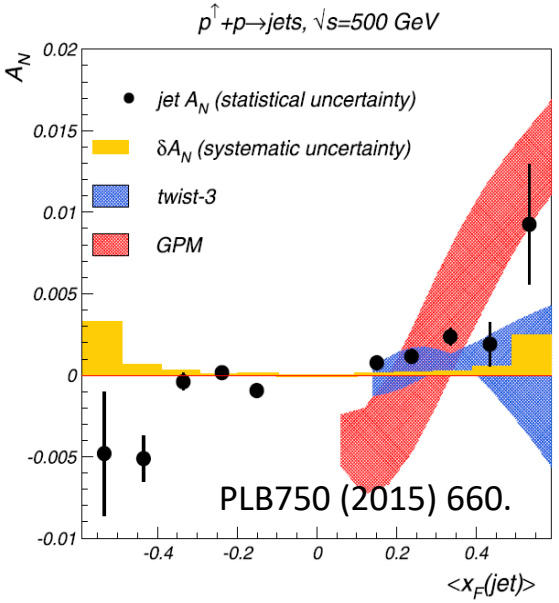


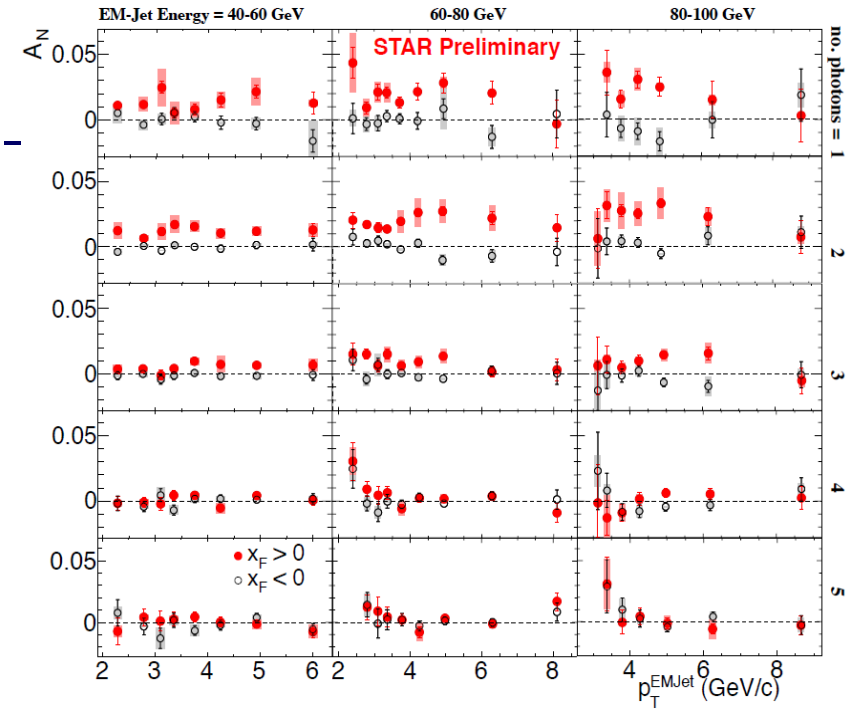
FIG. 4 (color online). A_N as function of $P_{h\perp}$ for SV1 input at $\sqrt{S} = 500$ GeV (data from [48]).

Kanazawa, Koike, Metz, Pitonyak
PRD 89, 111501 (2014).

Questions

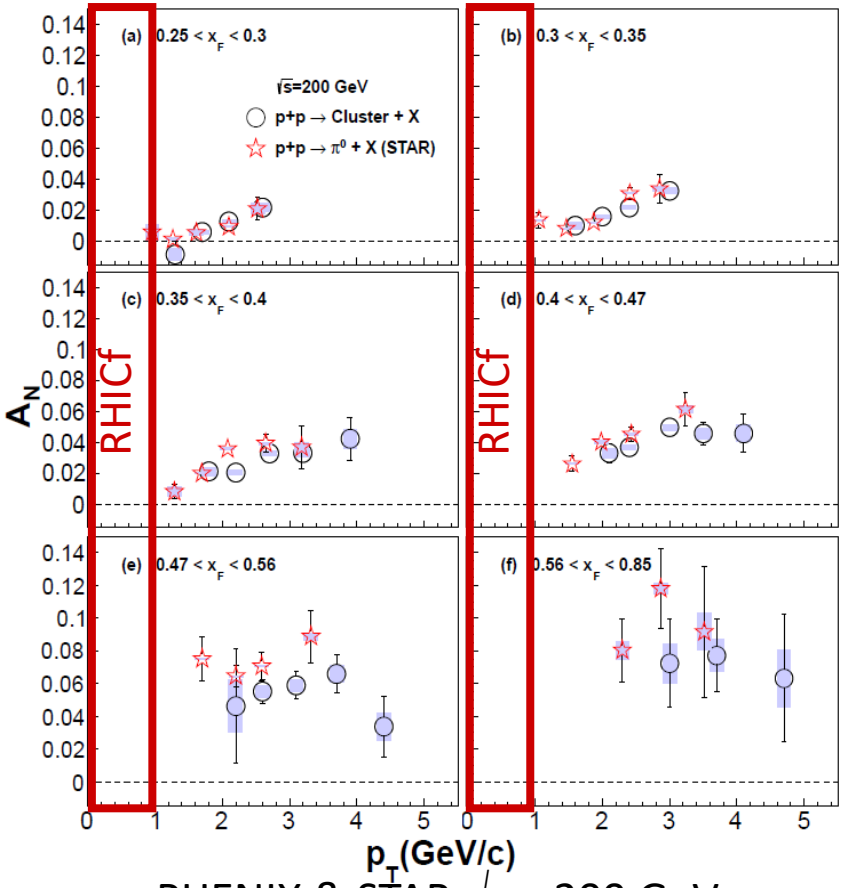
- A_NDY jet asymmetry
  - Small A_N of forward jet production comparing with that of forward hadron production
  - Mixture (cancellation) of u-quark jet and d-quark jet, or other non-perturbative effects?
- STAR multiplicity dependence
  - A_N for different number of photons
  - A_N decreases as the event complexity increases (more jet-like)
  - How much of the large π^0 A_N comes from hard scattering?
- π^0 asymmetry at RHICf?
  - $p_T < 1$ GeV/c, $\eta > 6$
  - Limited by the shadow of the beam pipe
  - Non-perturbative regime



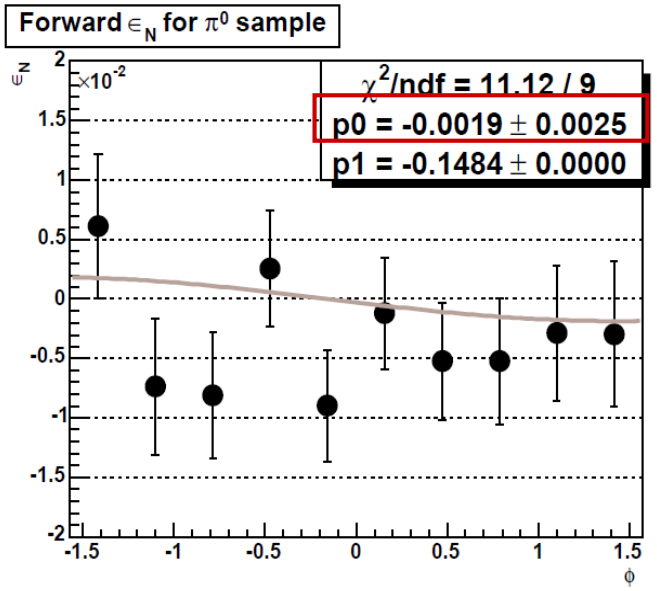


π^0 asymmetry at RHICf

- $p_T < 1$ GeV/c, $\eta > 6$
- Non-perturbative regime
  - How much π^0 asymmetry?
  - Matching to pQCD regime?



PHENIX & STAR $\sqrt{s}$ = 200 GeV
Phys. Rev. D90 (2014) 012006.



RHIC-IP12 $\sqrt{s}$ = 200 GeV $p_T < 0.1$ GeV/c
Very forward π^0 raw asymmetry
M. Togawa, PhD thesis (2008).

Table 1
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 $(1.0^{+0.47}_{-0.24})$

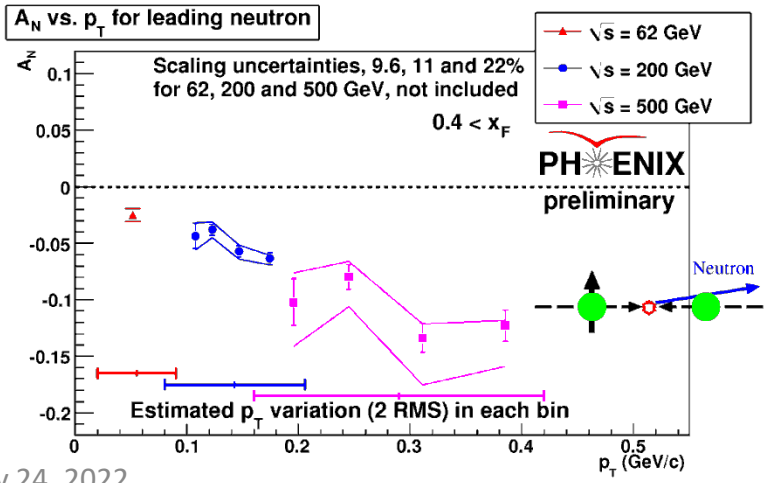
	Forward	Backward
Neutron	$-0.090 \pm 0.006 \pm 0.009$	$0.003 \pm 0.004 \pm 0.003$
Photon	$-0.009 \pm 0.015 \pm 0.007$	$-0.019 \pm 0.010 \pm 0.003$
π^0	$-0.022 \pm 0.030 \pm 0.002$	$0.007 \pm 0.021 \pm 0.001$

Phys. Lett. B650 (2007) 325.

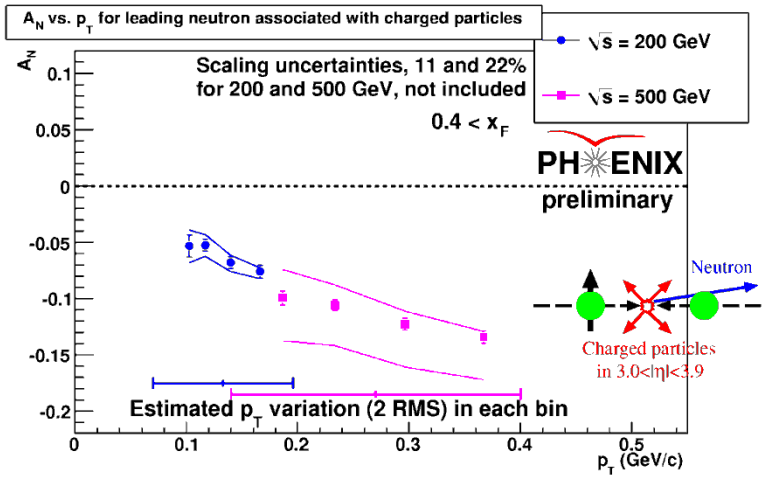
Neutron asymmetry

- 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

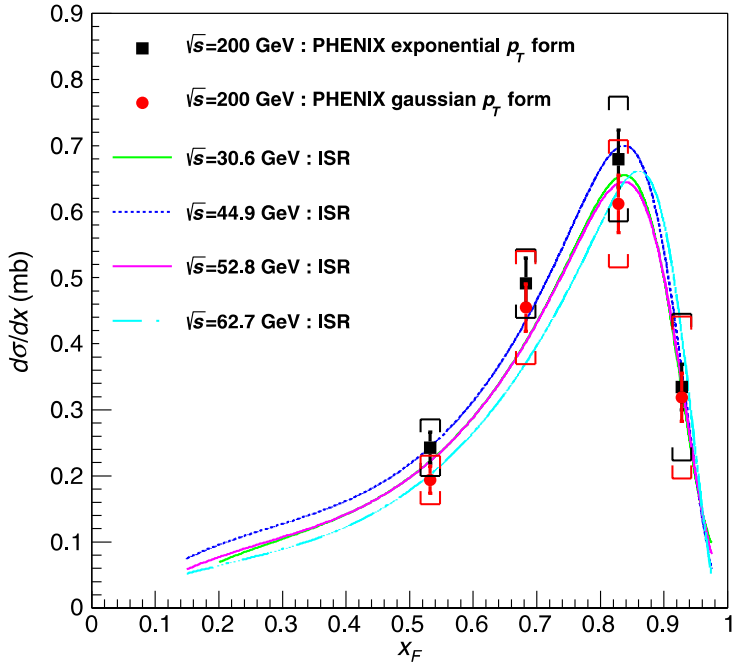


Neutron with charged particles



Forward neutron production

PHENIX 200 GeV



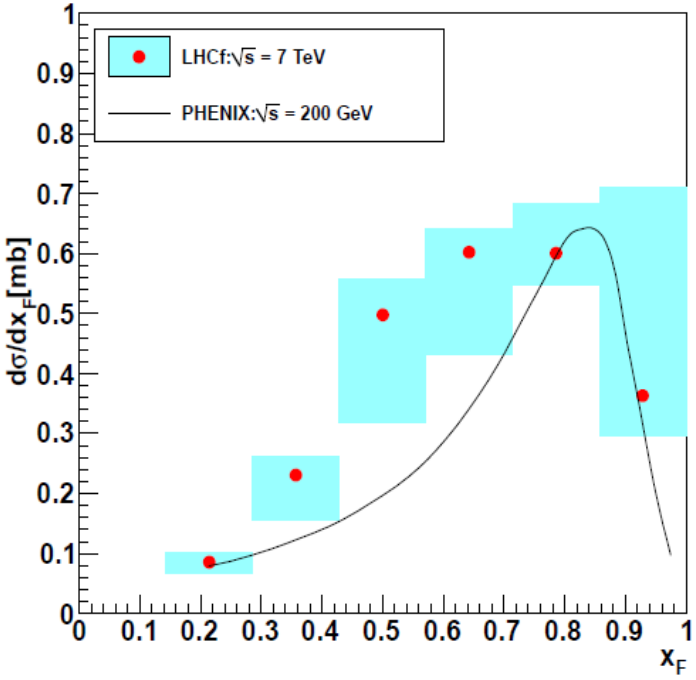
PHENIX, PRD, 88, 032006 (2013)

$p_T < 0.11\ x_F$ GeV/c

√s = 30-60 GeV @ISR

√s = 200 GeV @RHIC

LHCf 7 TeV



LHCf

$p_T < 0.11\ x_F$ GeV/c

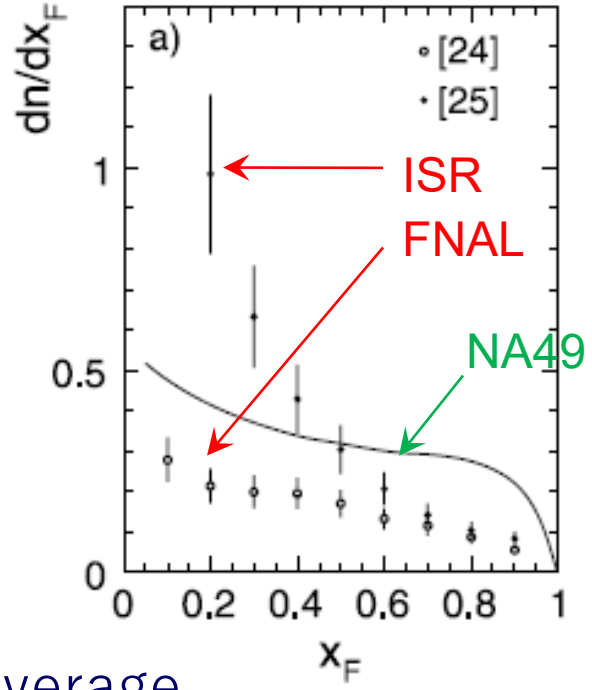
√s = 7000 GeV @LHC

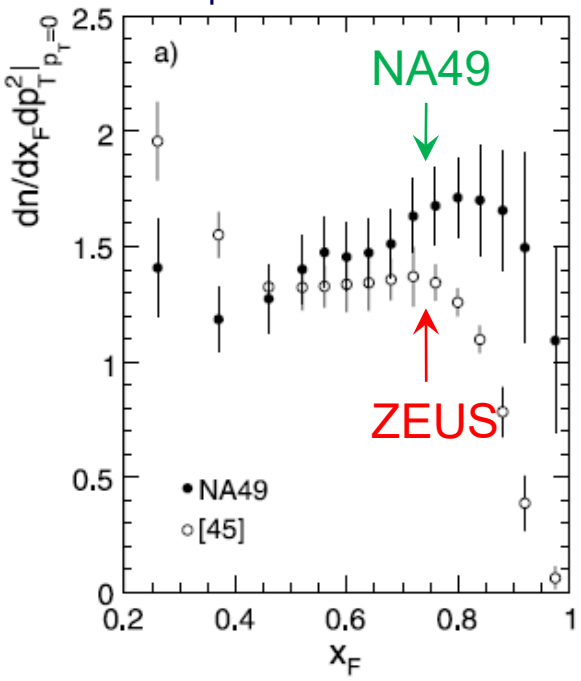
- PHENIX explains the result by 1 pion exchange
- More complicated exchanges at >TeV?

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.

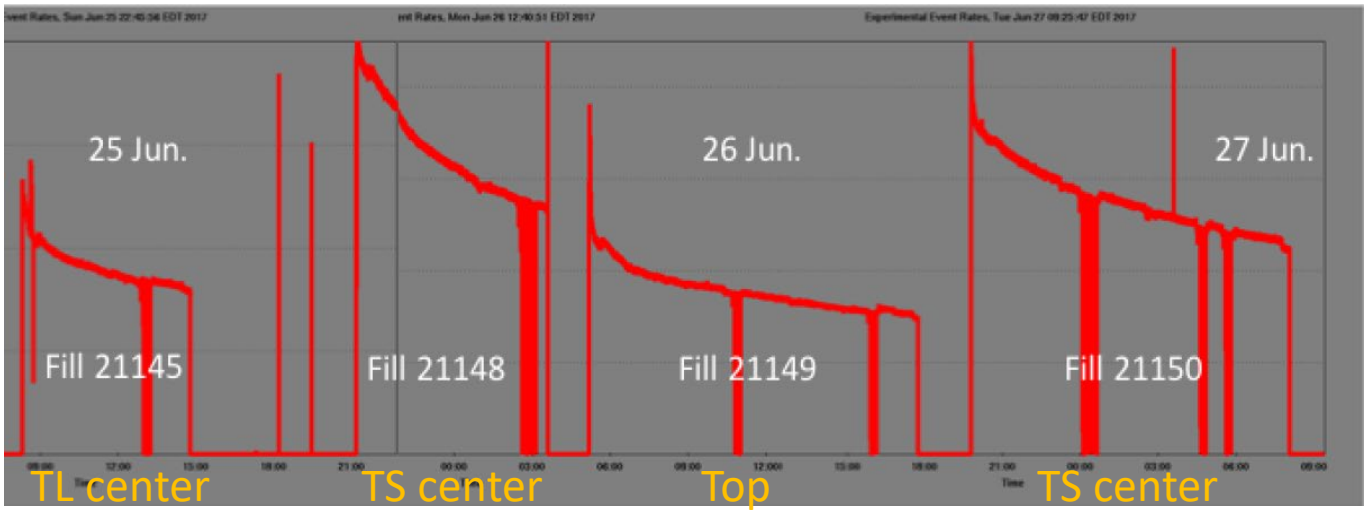


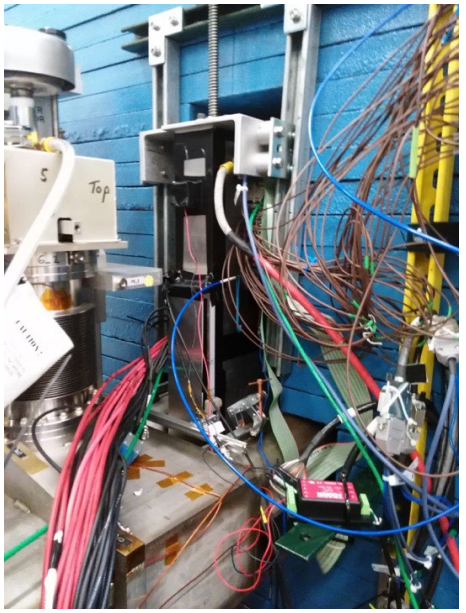


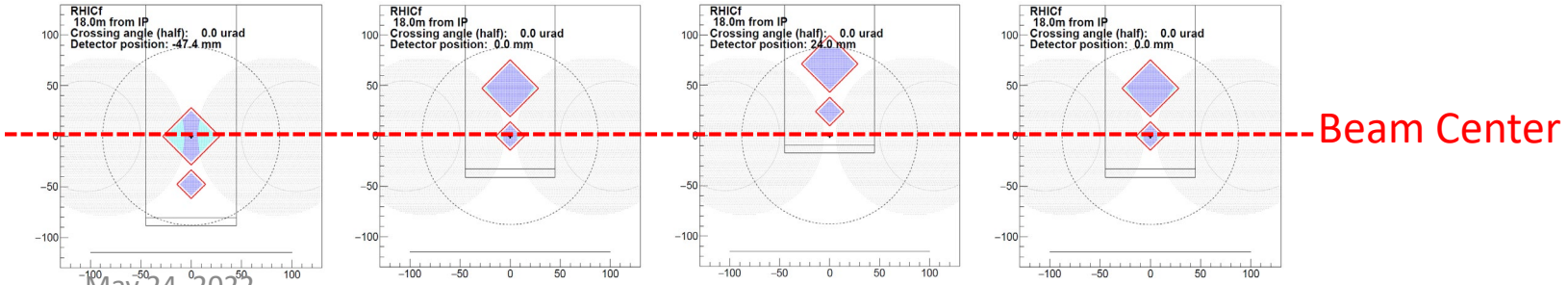
Wide η & p_T coverage

2017 operation

- 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

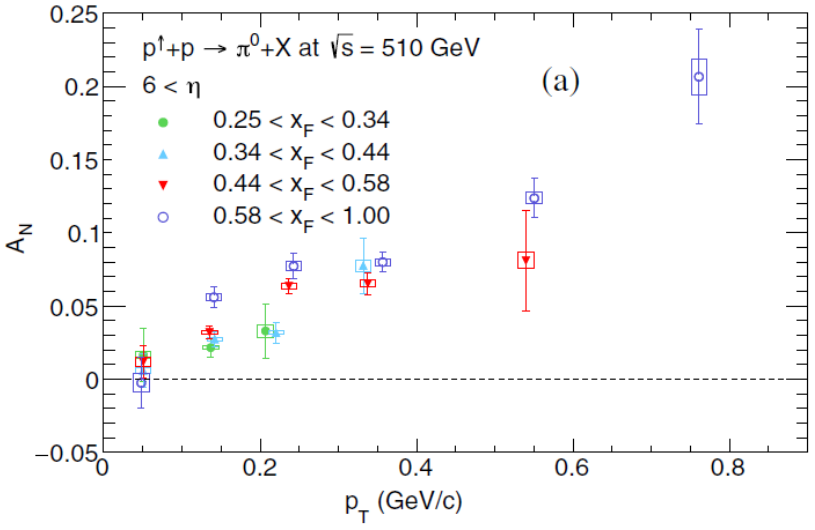


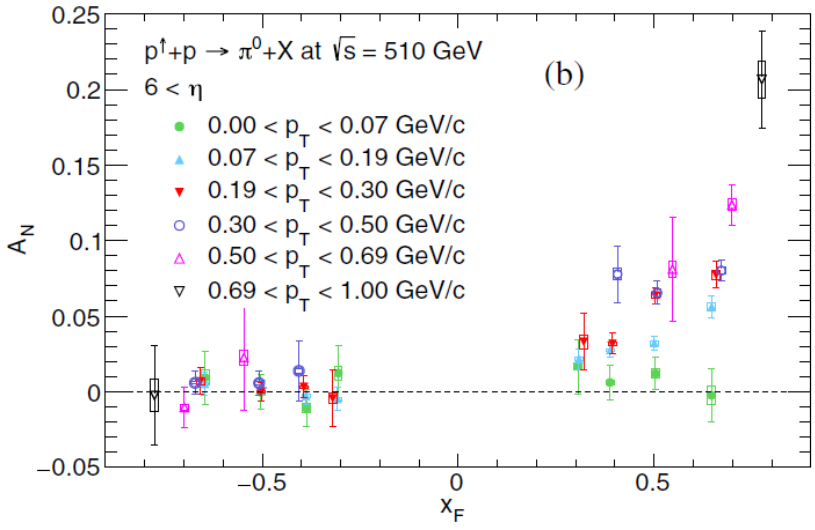




2017 run results

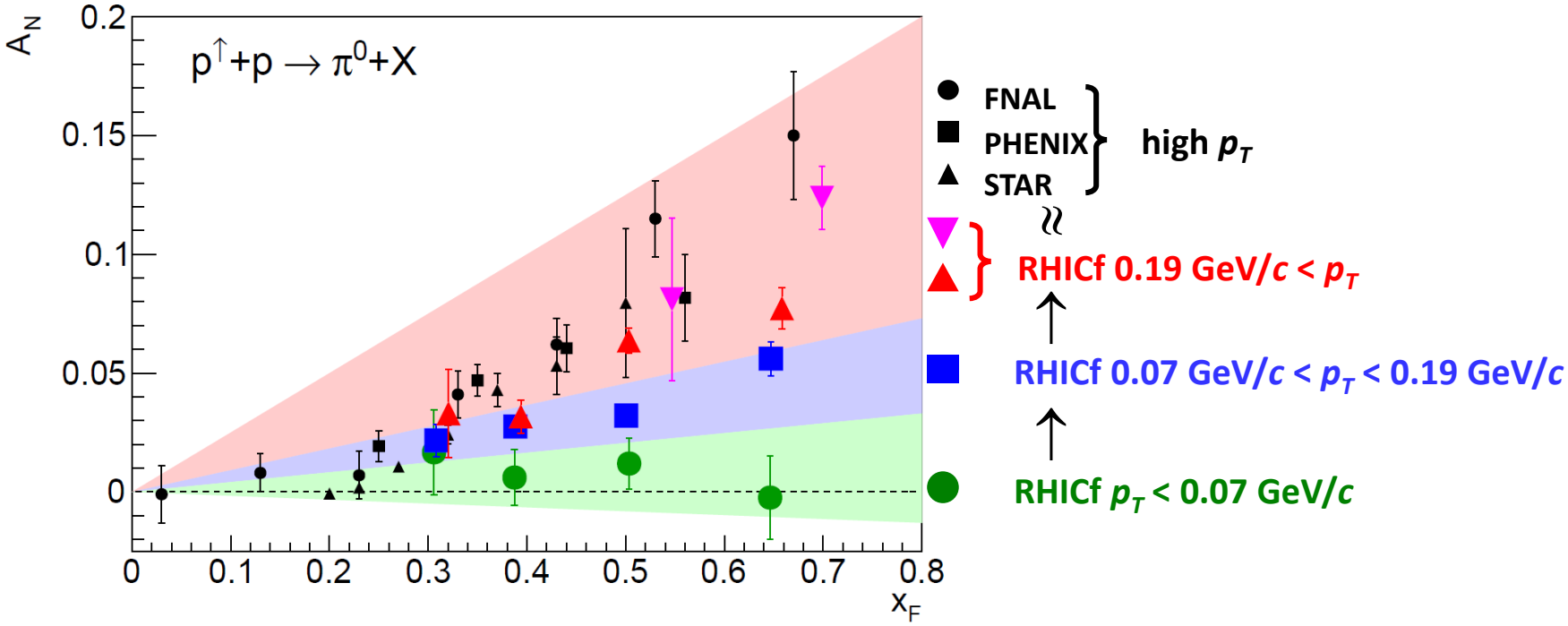
- π^0 asymmetry
  - Transverse single-spin asymmetry for very forward neutral pion production in polarized p+p collisions at $\sqrt{s}$ = 510 GeV
  - Phys. Rev. Lett. 124, 252501 (2020)
  - Research News
    - https://www.riken.jp/en/news_pubs/research_news/pr/2020/20200623_1/index.html (RIKEN)
    -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





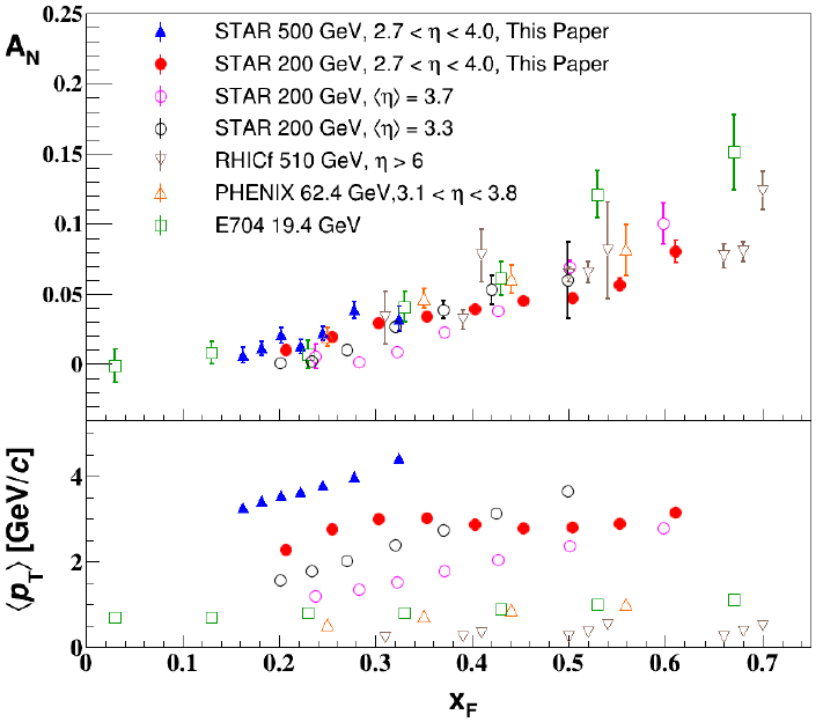
2017 run results

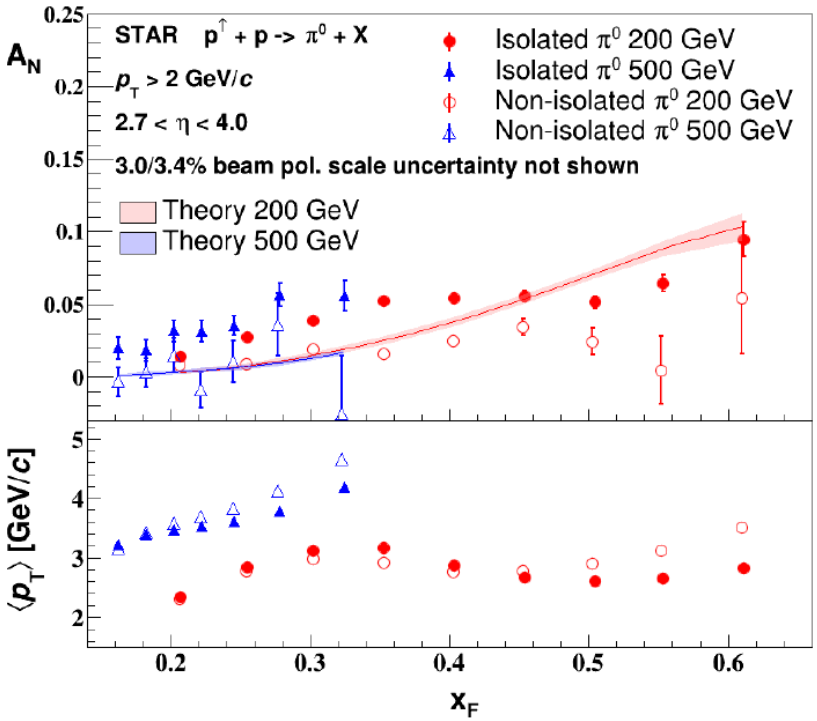
- π^0 asymmetry
  - Comparison with high $p_T > 0.5$ GeV/c data of the past experiments
  - Nearly the same large asymmetry is reached at low $p_T < 0.2$ GeV/c
  - Contribution of other mechanisms, diffraction and resonance, may provide a hint to the mystery



New STAR results

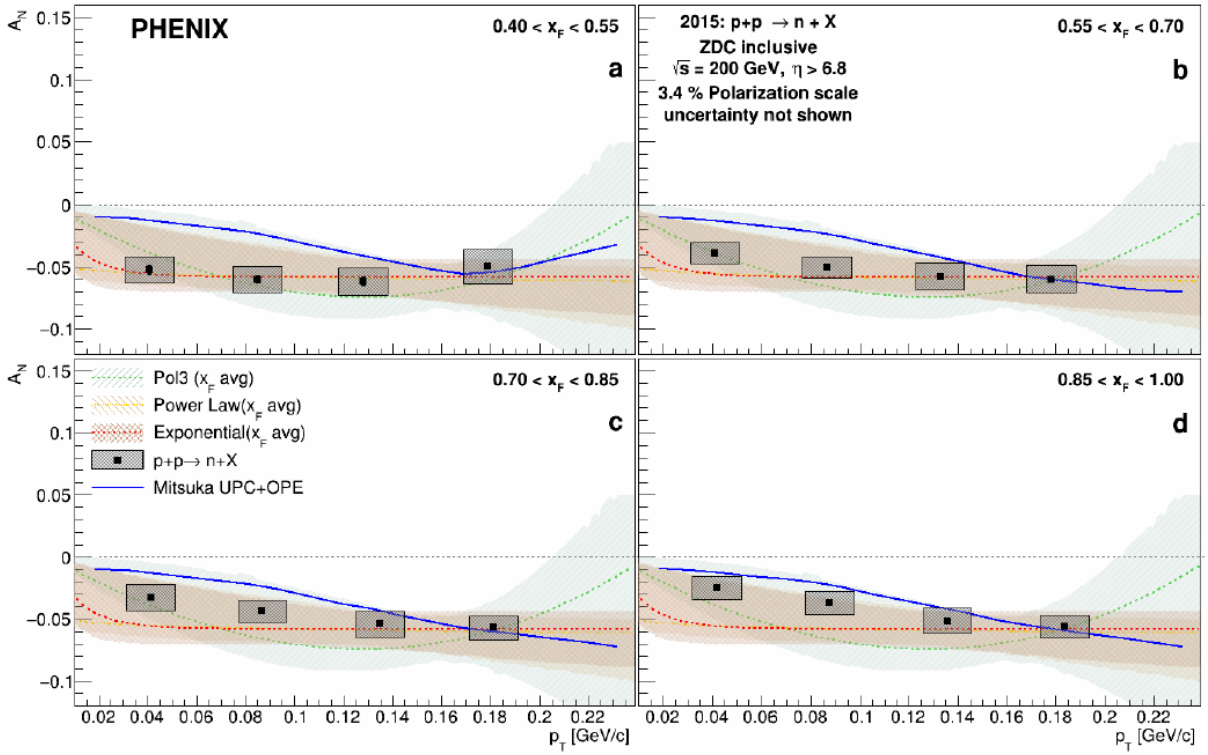
- arXiv:2012.11428, Phys.Rev.D 103 (2021) 092009
  - $\sqrt{s}$ = 200 GeV & 500 GeV
  - Forward π^0, $2.7 < \eta < 4.0$
  - Asymmetries for the isolated π^0 are larger than these for the non-isolated π^0
  - Possible explanation is that a significant part of the isolated π^0 are from diffractive processes





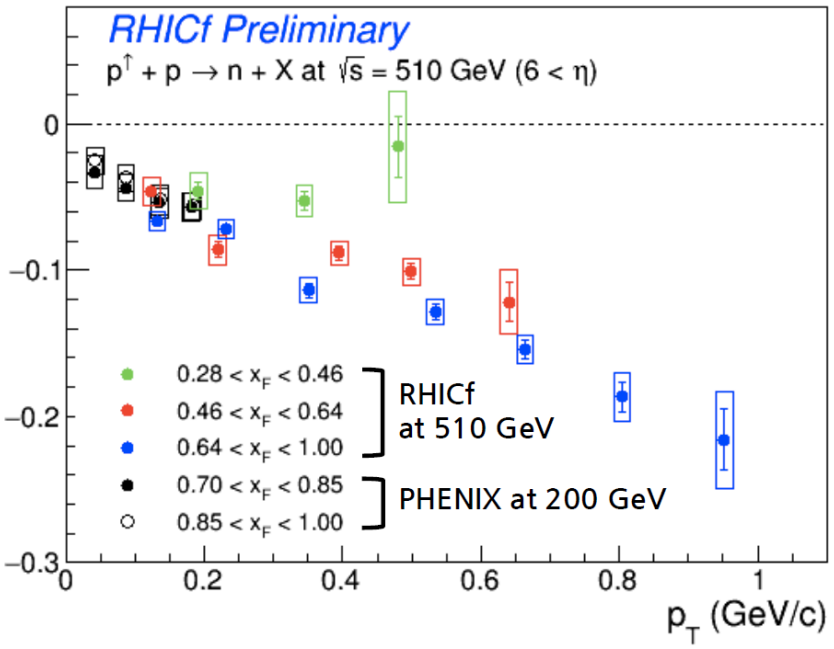
Neutron asymmetry

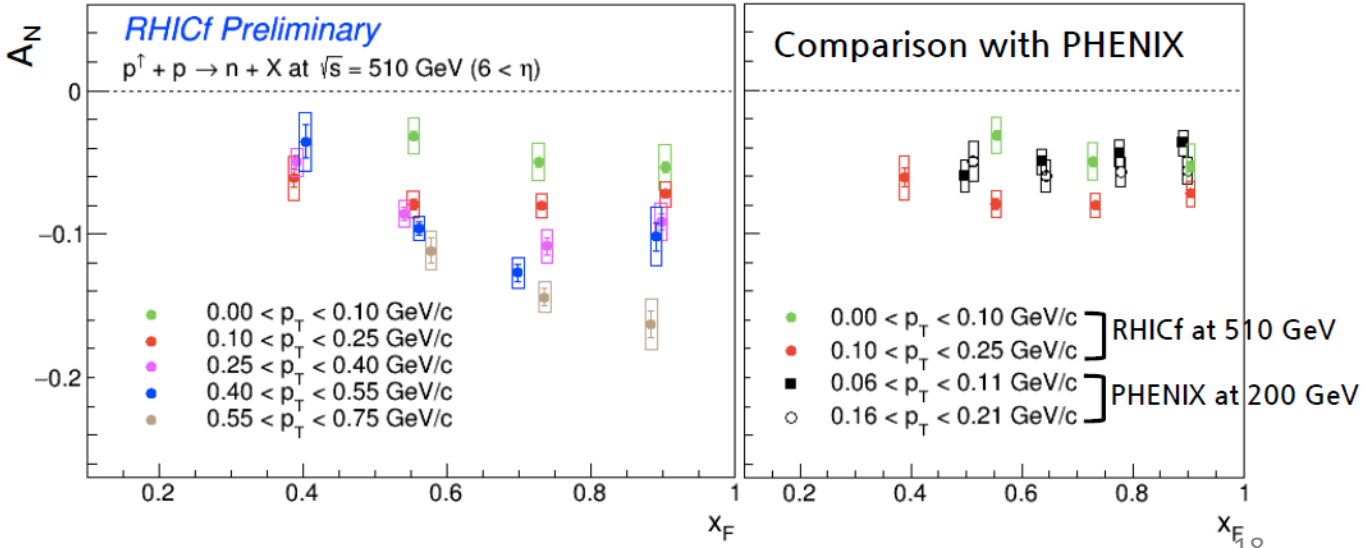
- Recent PHENIX publication
  - Phys. Rev. D 105 (2022) 032004
  - p_T dependence at $\sqrt{s} = 200$ GeV
    - A_N increases in magnitude with p_T at high x_F
    - No clear x_F dependence



Neutron asymmetry

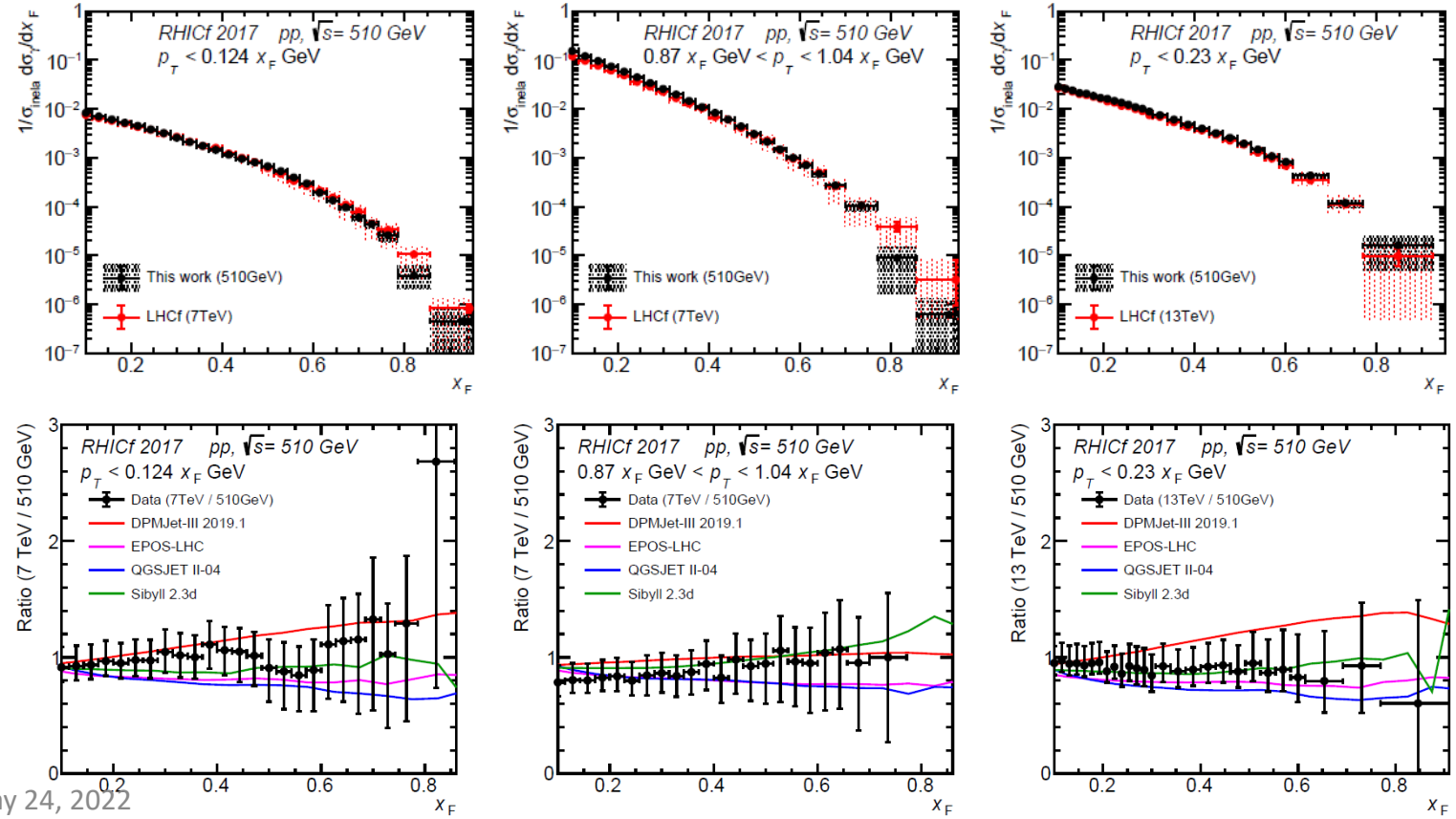
- RHICf preliminary results
  - A_N increases in magnitude with p_T up to 1 GeV/c at high x_F
  - Clear x_F dependence at high p_T
    - increasing in magnitude with x_F
    - though no clear (or flat) x_F dependence at low p_T
  - Consistent with PHENIX results





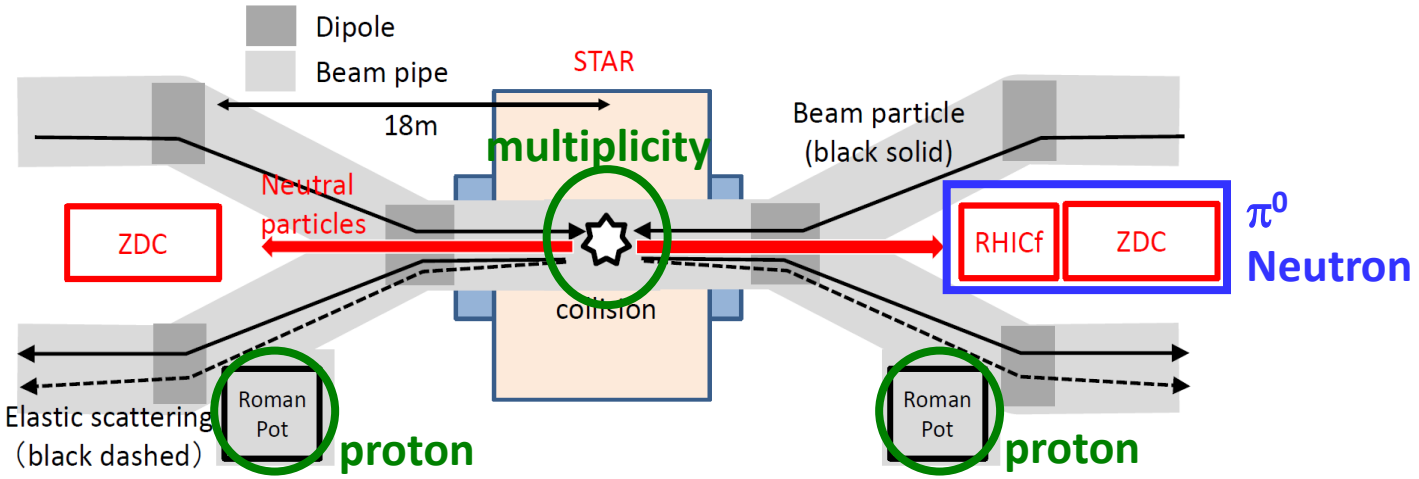
Photon spectrum

- Photon spectrum
  - arXiv:2203.1541 [hep-ex]
  - Comparison with LHCf photon results
  - First confirmation of collision-energy scaling at zero degree photons



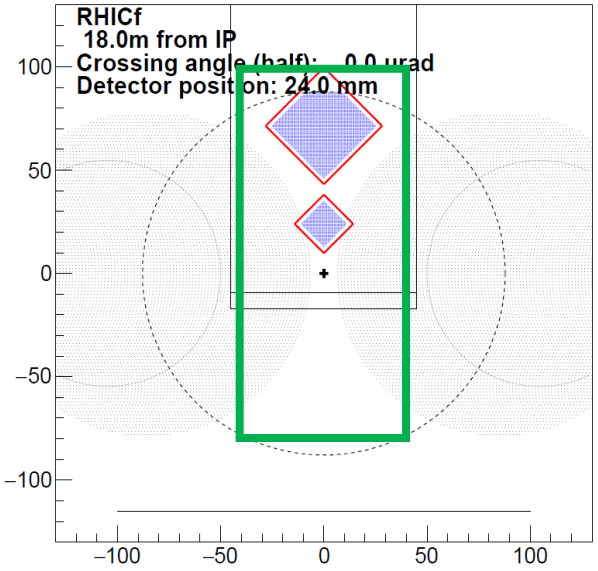
Other analyses ongoing

- π^0 & neutron cross section analysis
- Neutron asymmetry (RHICf + ZDC)
- Combined analysis with STAR detectors
  - Event type categorization
  - Diffraction + resonance tagging with STAR + RHICf combined data analysis
  - Event type, multiplicity (FMS) dependence of cross section & asymmetry to be obtained



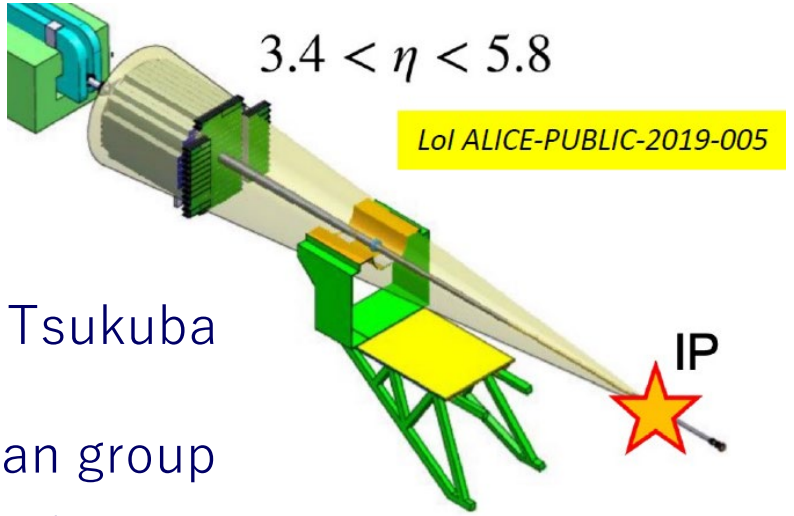
RHICf-II proposal

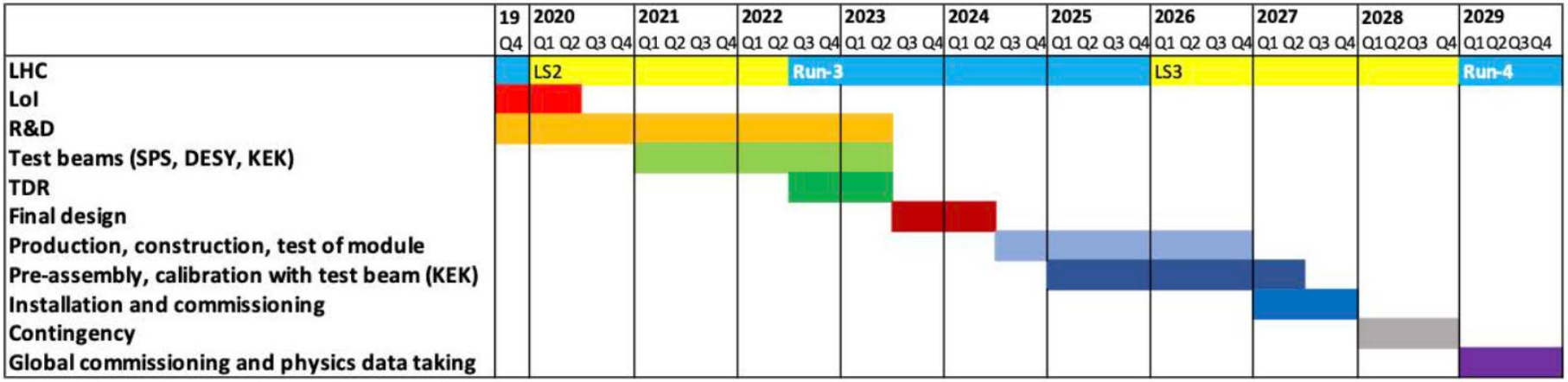
- We proposed a second run for RHICf in 2024 (RHICf-II)
- RHICf-II LoI was discussed by the PAC in 2020
- We're collaborating with ALICE-FoCal group to use the FoCal-E technology
  - 8cm x 18cm detector
  - Kakenhi-Kiban-A (2021-2024) + RIKEN budget
  - The detector have enough radiation hardness to work for a small β* and normal luminosity
- Not accepted in 2022 mainly by human resource issue



Calorimeter development

- ALICE-FoCal
  - 2029-31 LHC Run-4
  - FoCal-E Pad & Pixel
    - Pad detector led by Univ. of Tsukuba group (and Indian group)
    - Pixel detector led by European group
  - Test beam activities ongoing
    - Pad detector at ELPH, Tohoku Univ.
    - Total system at CERN SPS
  - TRD to be made in 2022-23

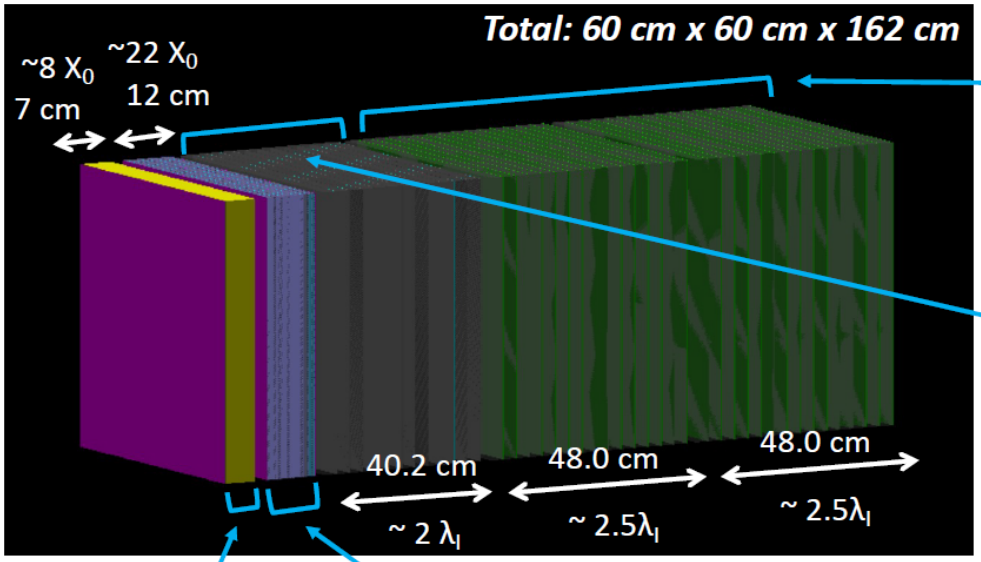




Calorimeter development

- EIC / ECCE
  - EIC-ZDC design study for ECCE
    - FoCal-E technology

*note: space for readout may extend the longitudinal length.



15 layers x 2

Pb 3cm thickness

Scintillator
10 cm x 10 cm x 2 mm

12 layers

Pb 3cm thickness

Silicon pad layer
1 cm x 1 cm x 320 µm

1 layer

Silicon pixel layer
3 mm x 3mm x 300 µm

Crystal (PbWO4)
3cm x 3cm x 7 cm

Si: 3 layers
Si: 20 layers = **Si** + 2 x
W: 22 layers

10 layers

+

1 layer

Tungsten 3.5 mm thickness

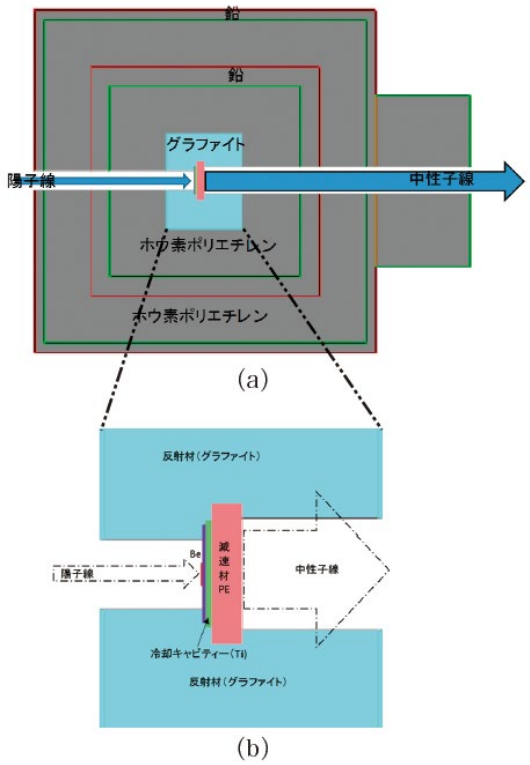
Silicon pad layer
1 cm x 1 cm x 320 µm

Tungsten 3.5 mm thickness

Silicon pixel layer
3 mm x 3mm x 300 µm

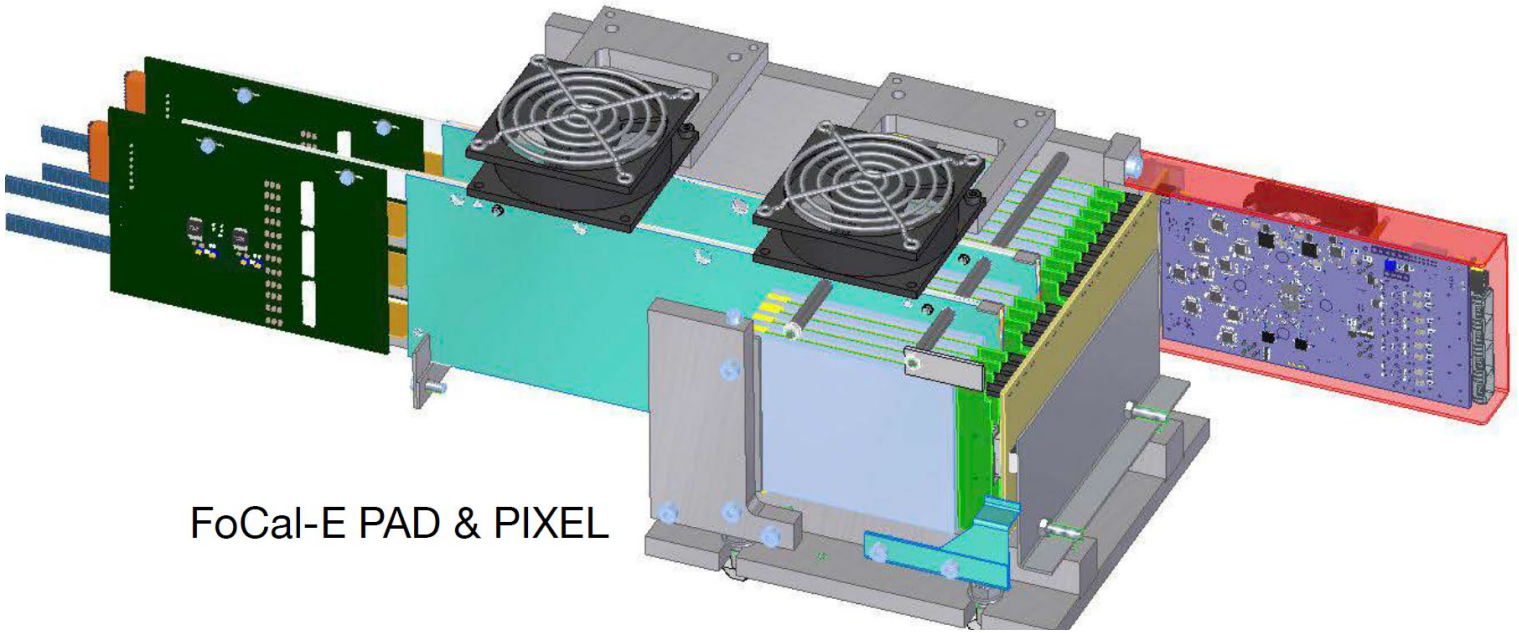
RIKEN RANS irradiation test

- RANS
  - Proton 7MeV, 100μA
    - 6 x 10^{13} proton/s
  - Be target
  - Neutron 5MeV max.
    - 10^{12} neutron/s from the target
- Si-Pad baby-chip test
  - Monitored with Si PD & Indium foil activation
- Online measurement
  - I-V, C-V, etc.
- March 3-4
  - 10^{14} neutron/cm^2 irradiated
  - Analysis ongoing



FoCal PS/SPS test beam in 2022

- June @ CERN-PS
  - FoCal-E 18 single pad and 2 pixel layers
  - HGCROC readout for pad with aggregator board and O^2 (FLP & CRU) system



- September & November @ CERN-SPS

Summary

- RHICf motivation: cosmic-ray study and asymmetry measurements
- RHICf results
  - Very forward π^0 asymmetry
  - Neutron asymmetry
  - Photon spectrum
- Other analyses ongoing
  - π^0 & neutron cross section analysis
  - Combined analysis with STAR detectors
- Proposed a second run for RHICf in 2024 (RHICf-II) not accepted
  - Large acceptance calorimeter with ALICE FoCal-E technology
  - Neutron irradiation test at RIKEN RANS
  - CERN-PS (and SPS) test beam