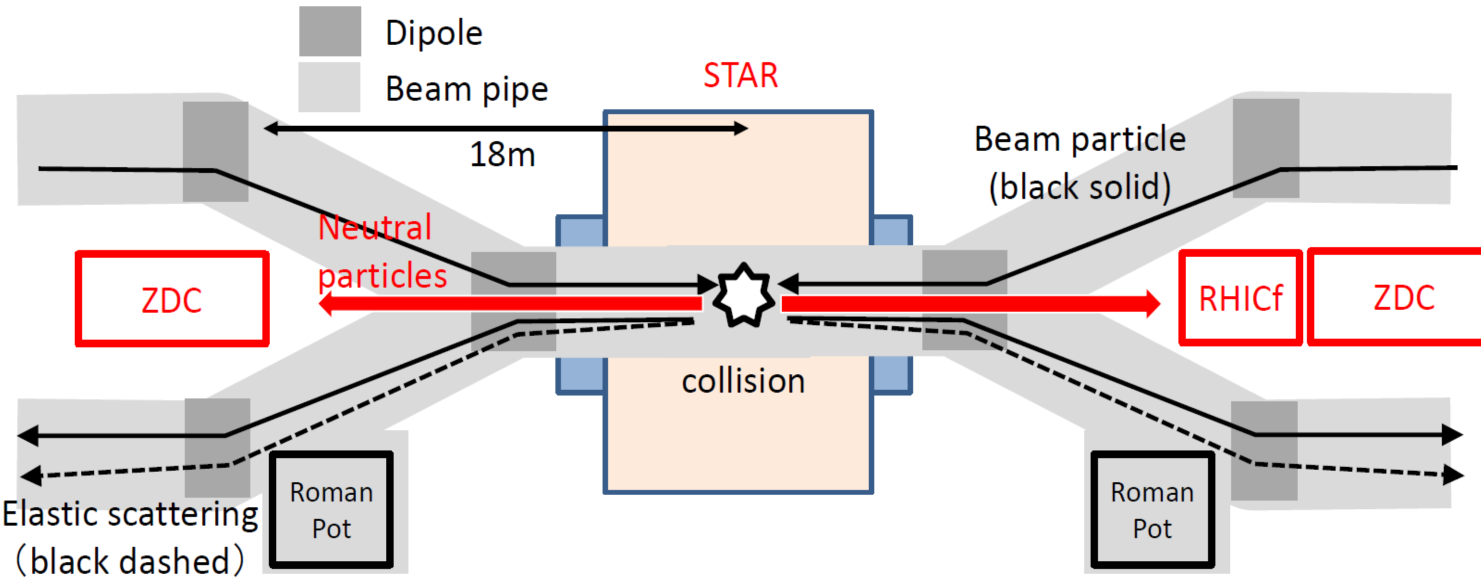
RHICf Spin Physics and Status

6th Korea-Japan
PHENIX/sPHENIX/RHICf/EIC Collaboration
Online Meeting
July 15th, 2021

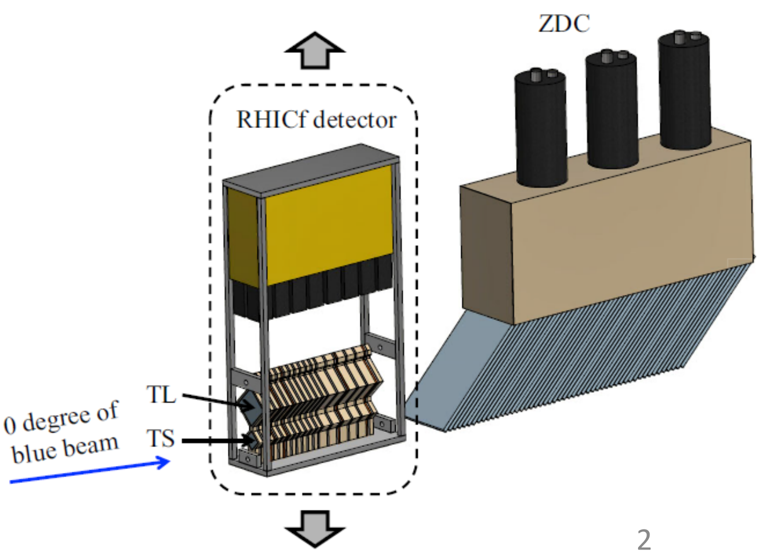
Yuji Goto (RIKEN/RBRC)

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



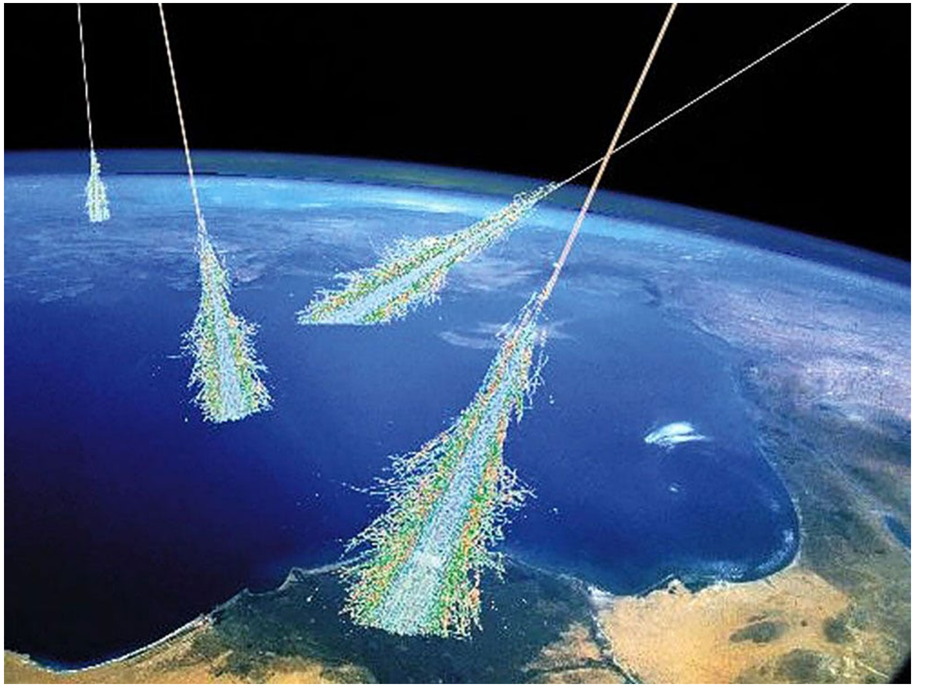
RHICf collaboration

Y. Goto, I. Nakagawa, R. Seidl (RIKEN), J. S. Park (Seoul National Univ.),
B. Hong, M. H. Kim (Korea Univ.), K. Tanida (JAEA),
Y. Itow, H. Menjo, K. Sato, M. Ueno, Q. D. Zhou, M. Ueno (Nagoya Univ.),
T. Sako (ICRR, Univ. of Tokyo), K. Kasahara, T. Suzuki, S. Torii (Waseda Univ.),
N. Sakurai (Tokushima Univ.), O. Adriani, E. Berti, L. Bonechi,
R. D'Alessandro (INFN Firenze), A. Tricomi (INFN Catania)

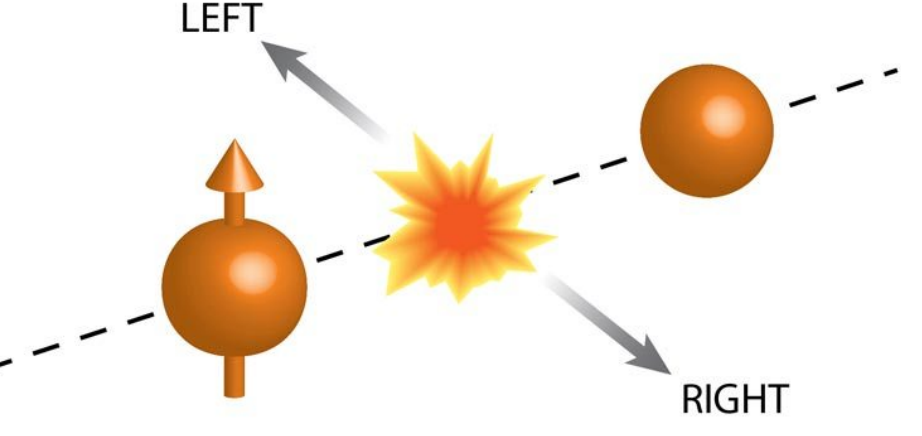
RHICf is partially supported by the U.S.-Japan Science and Technology Cooperation Program in High Energy Physics, and performed by strong collaboration with the STAR collaboration

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

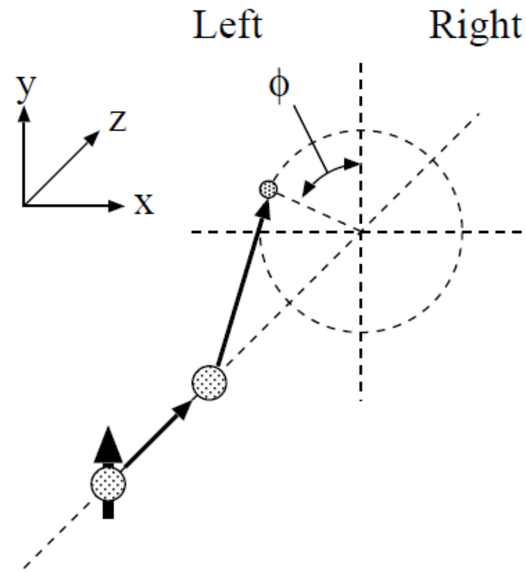


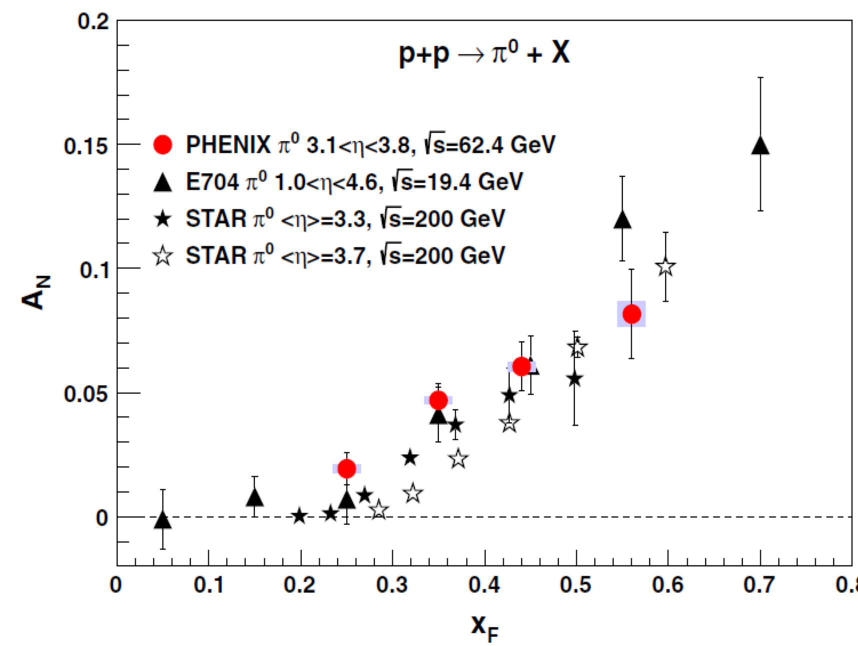
Transverse asymmetry measurement

- A_N (transverse single-spin asymmetry) measurement

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

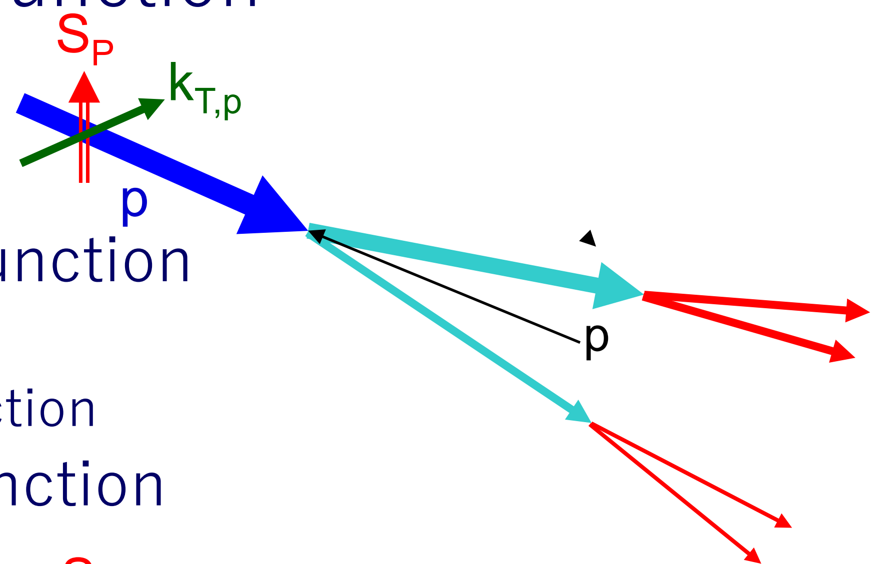
  - Azimuthal angle modulation
- Large A_N for forward hadron production
  - $1 < \eta < 4$, similar results in wide $\sqrt{s}$
- TMD (Transverse Momentum Dependent) function and higher-twist function in pQCD regime
  - Initial-state effect or “Sivers” effect
  - Final-state effect or “Collins” effect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



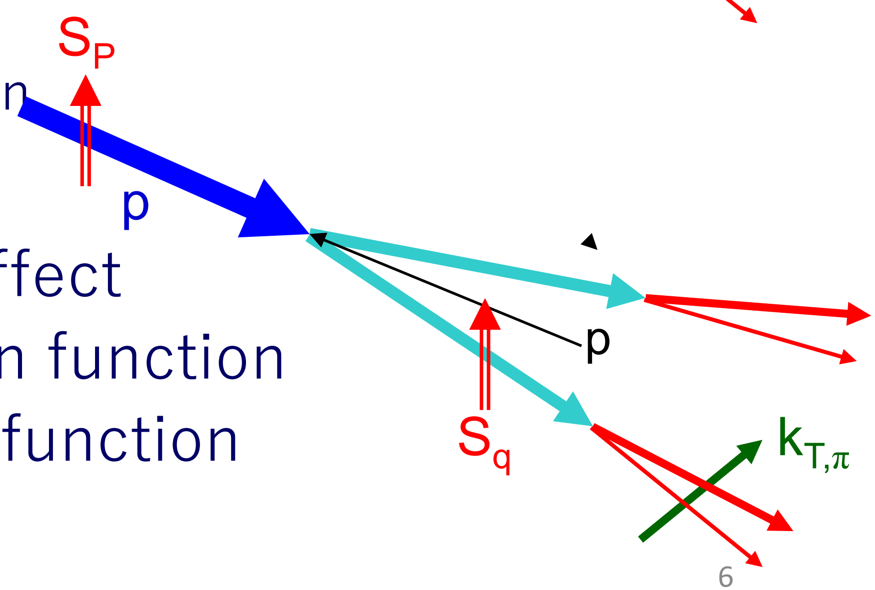


Transverse polarization phenomena

- TMD (Transverse Momentum Dependent) function and higher-twist function
- "Sivers" effect
  - Initial-state effect
  - TMD (Sivers) distribution function
    - Need 2 scales (p_T and Q^2)
    - Drell-Yan, W/Z boson production
  - Higher-twist distribution function
    - Need 1 scale (p_T)
    - Hadron, photon, jet production



- "Collins" effect
  - Transversity + final-state effect
  - TMD (Collins) fragmentation function
  - Higher-twist fragmentation function



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

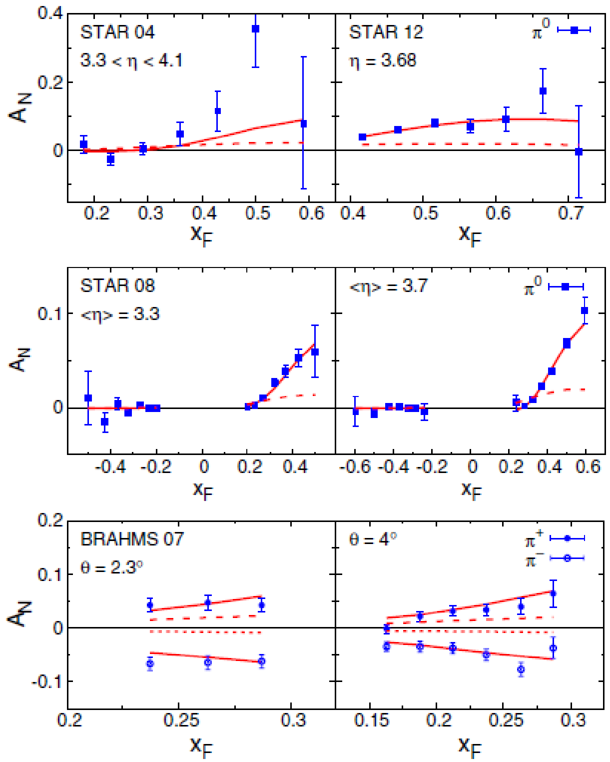


FIG. 1 (color online). Fit results for $A_N^{\pi^0}$ (data from [35–37]) and $A_N^{\pi^\pm}$ (data from [38]) for the SV1 input. The dashed line (dotted line in the case of π^-) means $\hat{H}_{FU}^{\Im}$ switched off.

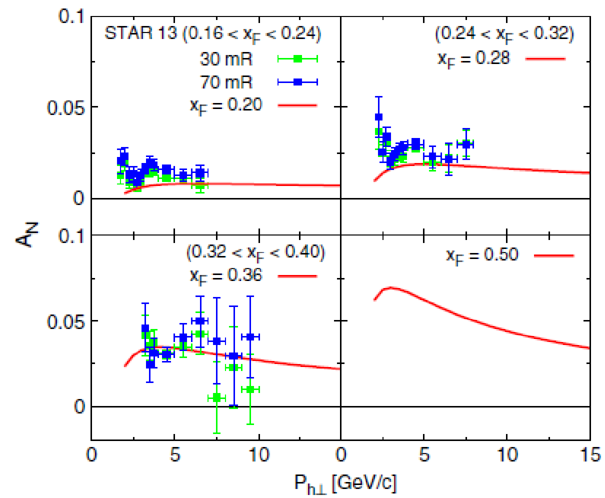
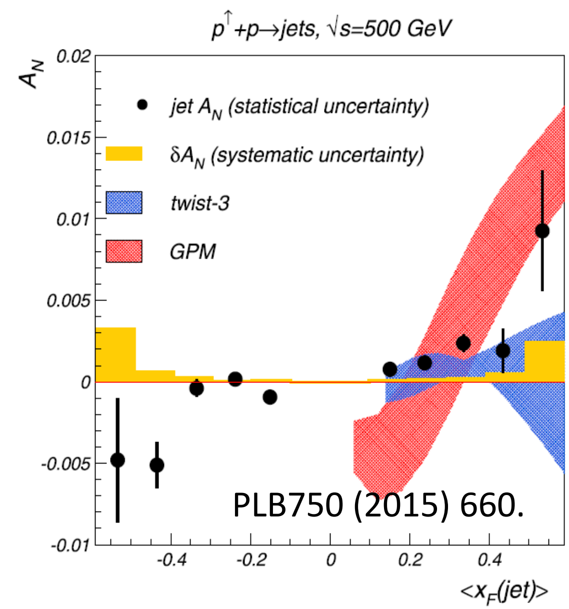


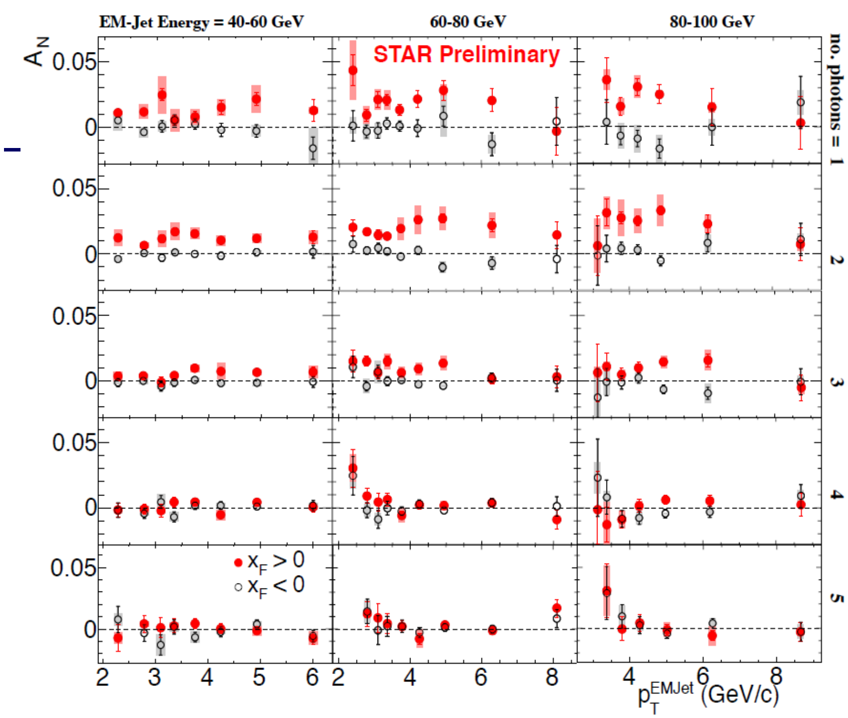
FIG. 4 (color online). A_N as function of $P_{h\perp}$ for SV1 input at $\sqrt{S} = 500$ GeV (data from [48]).

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

Questions

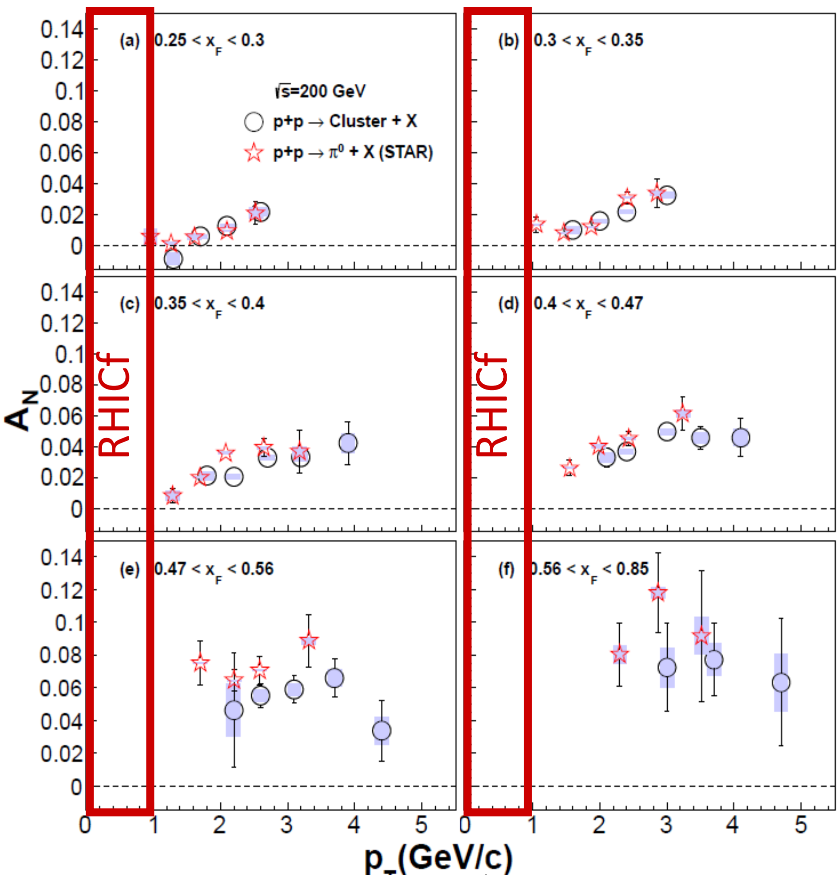
- A_NDY jet asymmetry
  - Small A_N of forward jet production comparing with that of forward hadron production
  - Mixture (cancellation) of u-quark jet and d-quark jet, or other non-perturbative effects?
- STAR multiplicity dependence
  - A_N for different number of photons
  - A_N decreases as the 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



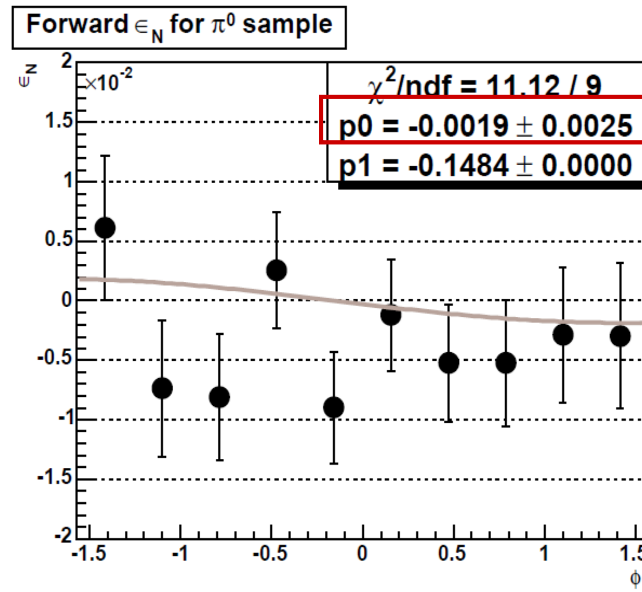


π^0 asymmetry at RHICf

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

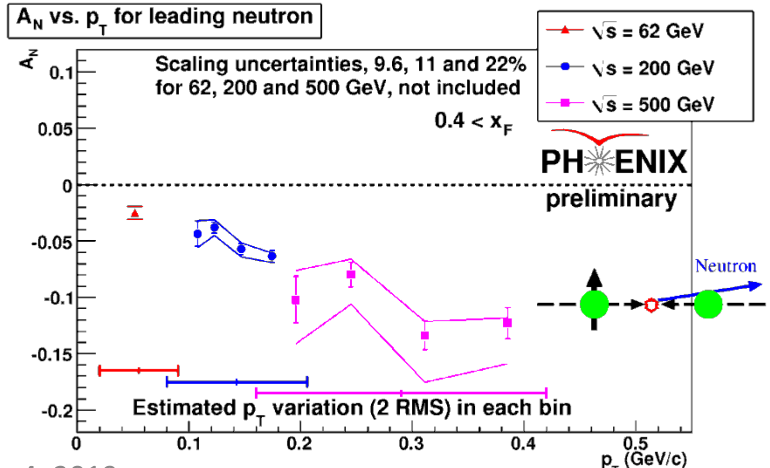
	Forward	Backward
Neutron	$-0.090 \pm 0.006 \pm 0.009$	$0.003 \pm 0.004 \pm 0.003$
Photon	$-0.009 \pm 0.015 \pm 0.007$	$-0.019 \pm 0.010 \pm 0.003$
π^0	$-0.022 \pm 0.030 \pm 0.002$	$0.007 \pm 0.021 \pm 0.001$

Phys. Lett. B650 (2007) 325.

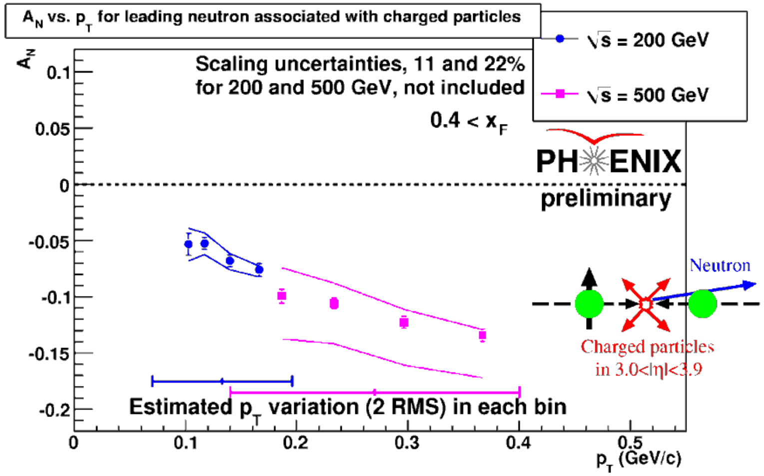
Neutron asymmetry

- 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 GeV/c) at $\sqrt{s} = 510$ GeV in the RHICf experiment

Inclusive neutron

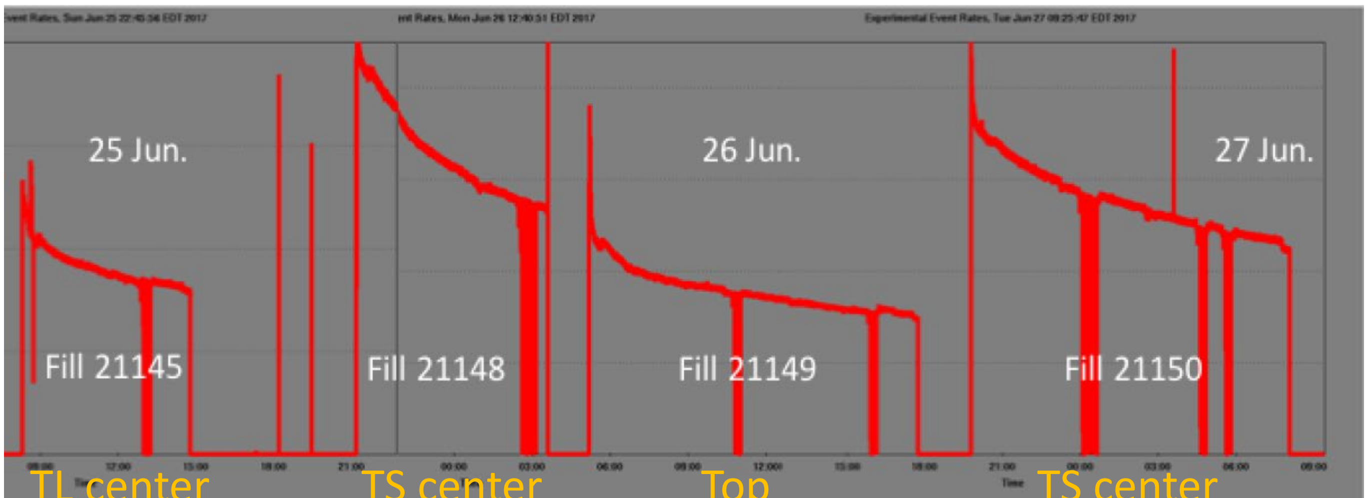


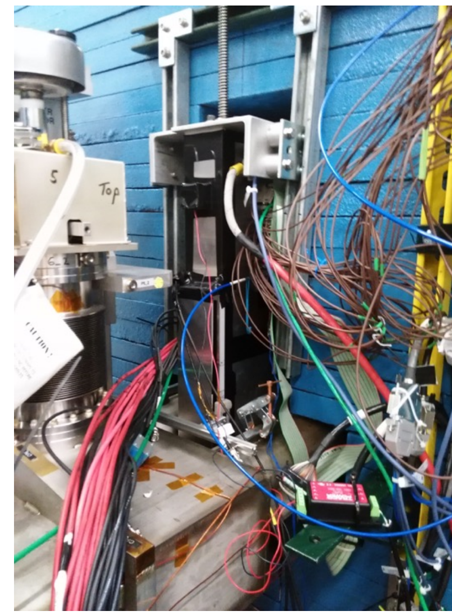
Neutron with charged particles

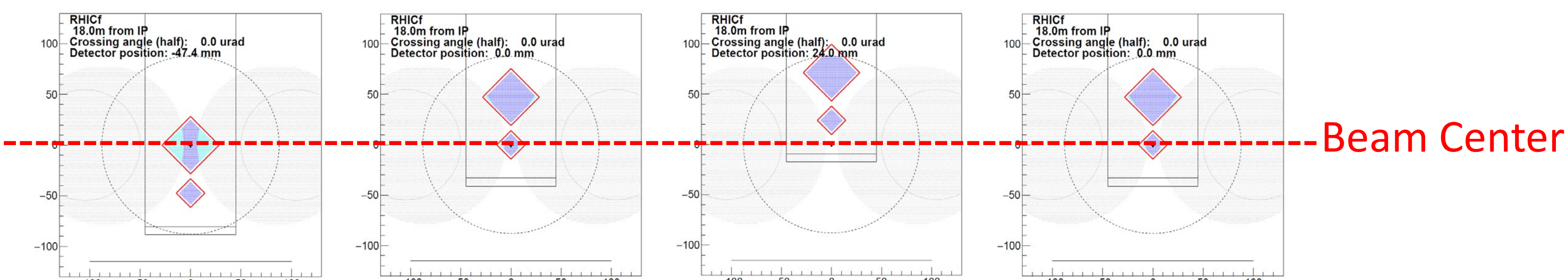


2017 operation

- 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

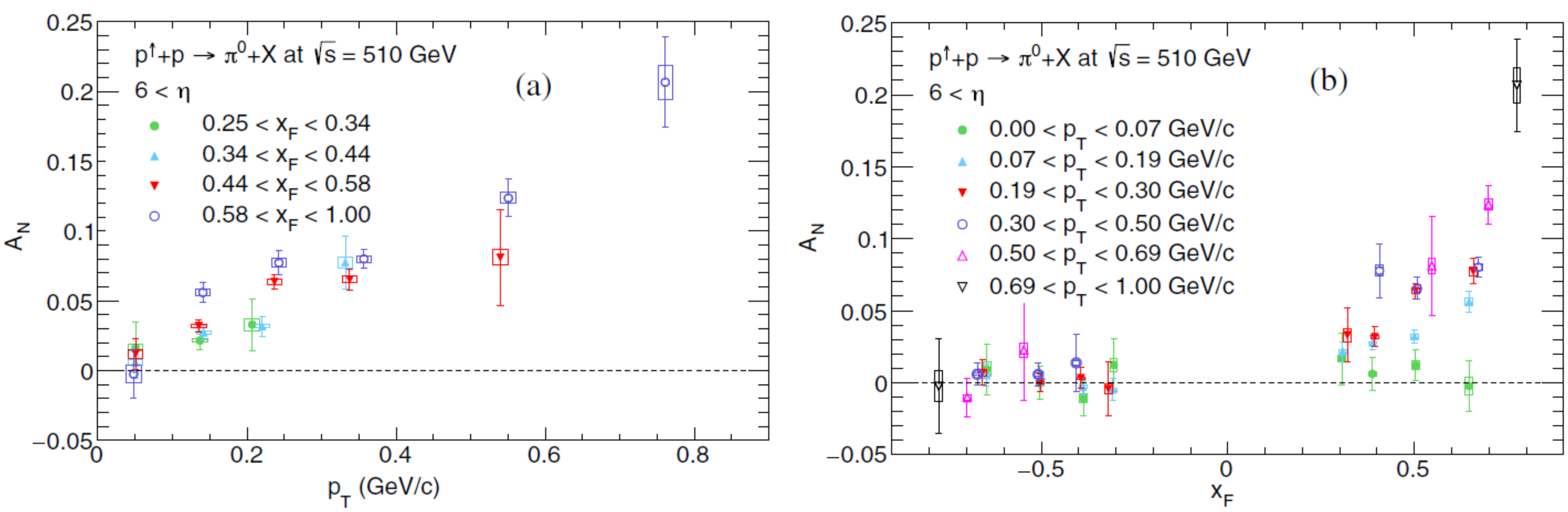






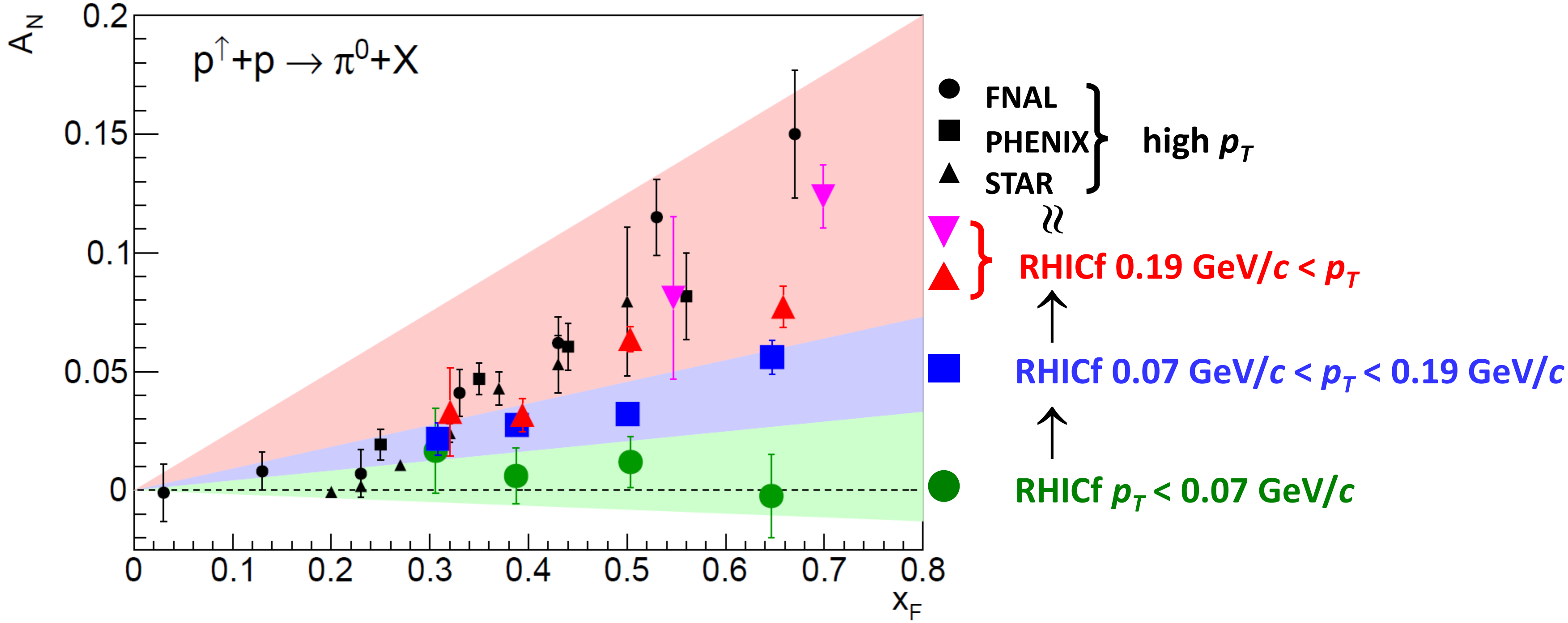
2017 run results

- 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



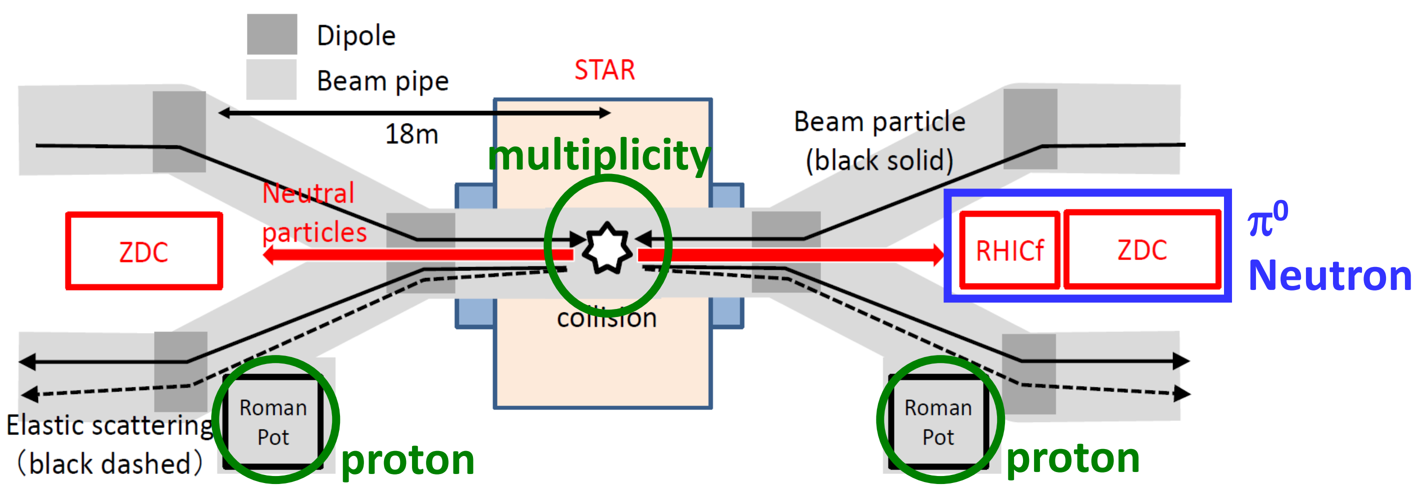
2017 run results

- 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



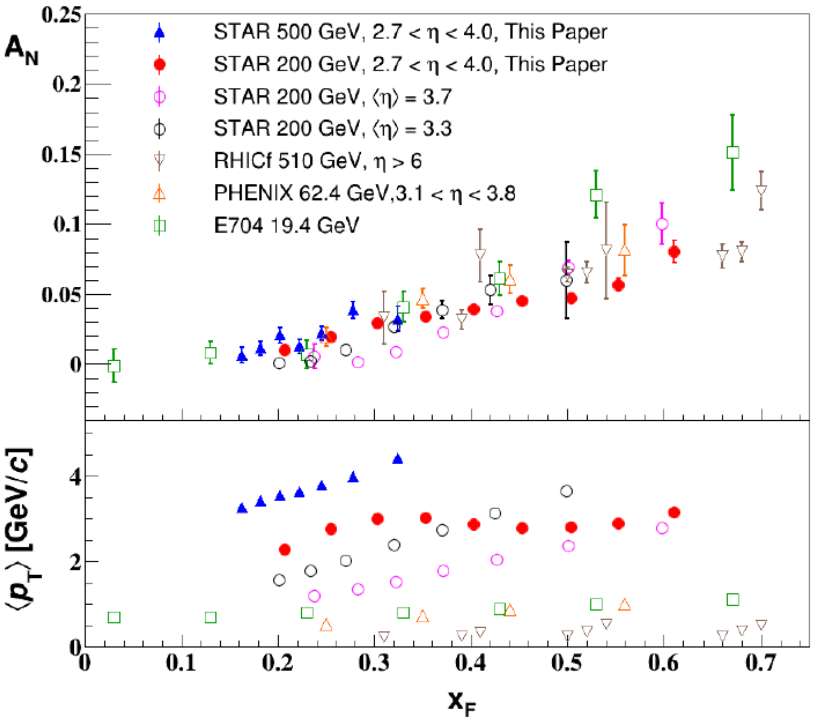
2017 run results

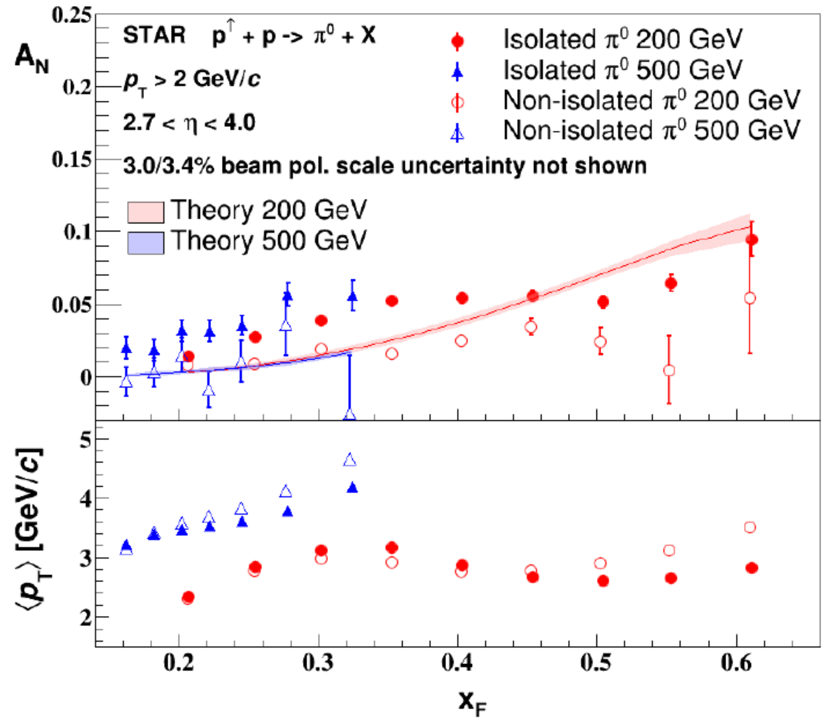
- Other analyses ongoing
  - π^0 & neutron cross section analysis
  - Neutron asymmetry (RHICf + ZDC)
  - Combined analysis with STAR detectors
    - Event type categorization
    - Diffraction + resonance tagging with STAR + RHICf combined data analysis
    - Event type, multiplicity (FMS) dependence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



New STAR results

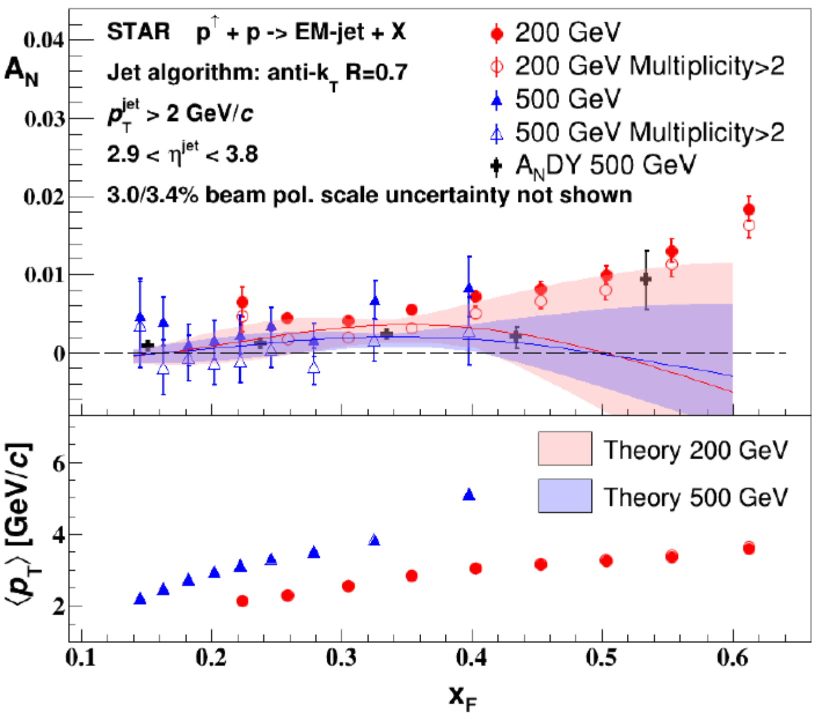
- arXiv:2012.11428, Phys.Rev.D 103 (2021) 092009
  - $\sqrt{s}$ = 200 GeV & 500 GeV
  - Forward π^0, $2.7 < \eta < 4.0$
  - Asymmetries for the isolated π^0 are larger than these for the non-isolated π^0
  - Possible explanation is that a significant part of the isolated π^0 are from diffractive processes

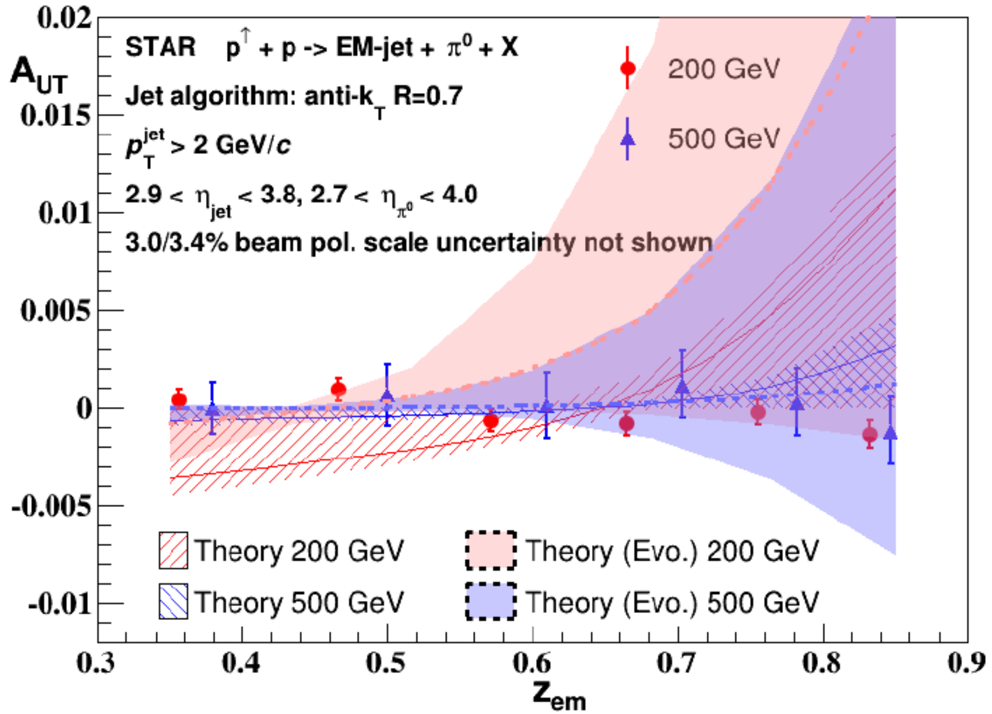




New STAR results

- arXiv:2012.11428, Phys.Rev.D 103 (2021) 092009
  - Small EM-jet asymmetry, consistent with AnDY result
  - $z_{em} = E_{\pi 0} / E_{jet}$
  - Hadron in jet Collins asymmetries small
    - Cancellation of the Collins effect of the u/d quark?





RHICf-II

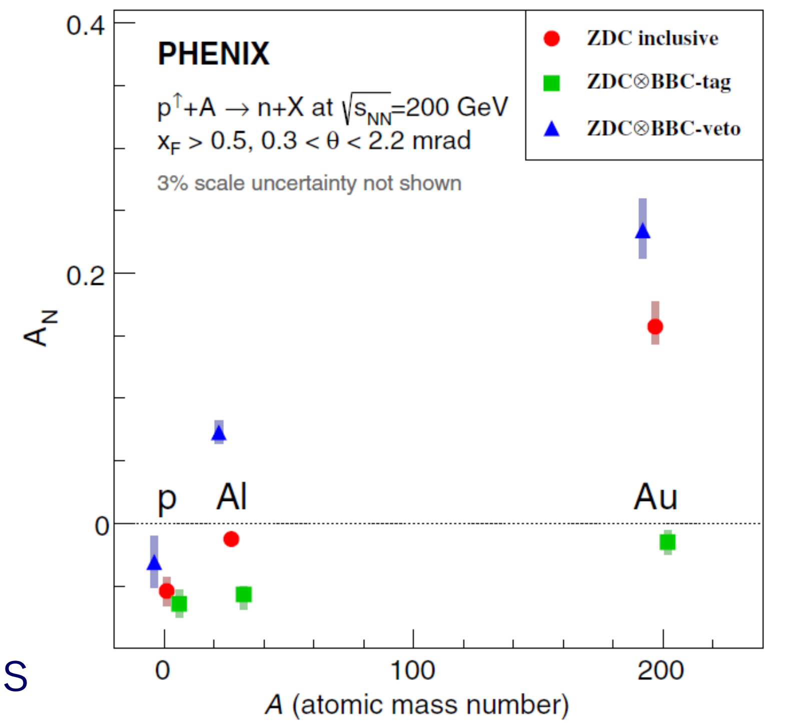
- We propose a second run for RHICf in 2024
- RHICf-II LoI was discussed by the PAC in 2020.9.
- PAC's recommendation:
  - The PAC recommends that RHICf approach STAR or sPHENIX management and determine how RHICf-II could best be integrated, as was previously done with RHICf-I and STAR. The PAC does not see a scenario in which dedicated high-beta running would be justifiable given the tight overall schedule, and recommends planning running in a parasitic mode and at nominal beta* and polarization parameters appropriate for STAR and sPHENIX.
- We're collaborating with ALICE-FoCal group and want to use the FoCal-E prototype EM calorimeter

RHICf-II Collaboration

- Y. Goto, I. Nakagawa, R. Seidl (RIKEN)
- B. Hong, M.H. Kim (Korea Univ.)
- K. Tanida (JAEA)
- T. Chujo (Tsukuba Univ.) ← New
- M. Inaba (Tsukuba Tech Univ.) ← New
- Y. Itow, H. Menjo (Nagoya Univ.)
- T. Sako (ICRR, Univ. of Tokyo)
- K. Kasahara (Shibaura Tech.)
- O. Adriani, L. Bonechi, R. D'Alessandro (INFN Firenze)
- A. Tricomi (INFN Catania)

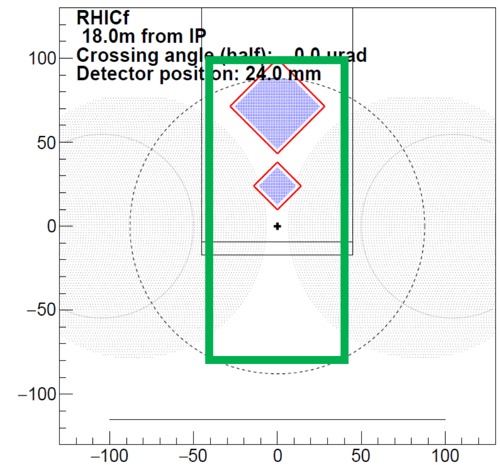
New topics at RHICf-II

- p + A collisions
  - Measurement of nuclear effect (p+A / p+p)
- Strong A-dependence of the neutron asymmetry
  - Measured at PHENIX in Run 15
  - Phys. Rev. Lett. 120, 022001 (2018)
  - UPC vs hadronic component
- A-dependence of the π^0 asymmetry
  - Correlation between asymmetries of forward neutron and π^0
- p + Oxygen collision
  - Ideal condition for cosmic-ray interaction studies measuring π^0, neutron, photon, K^0_S

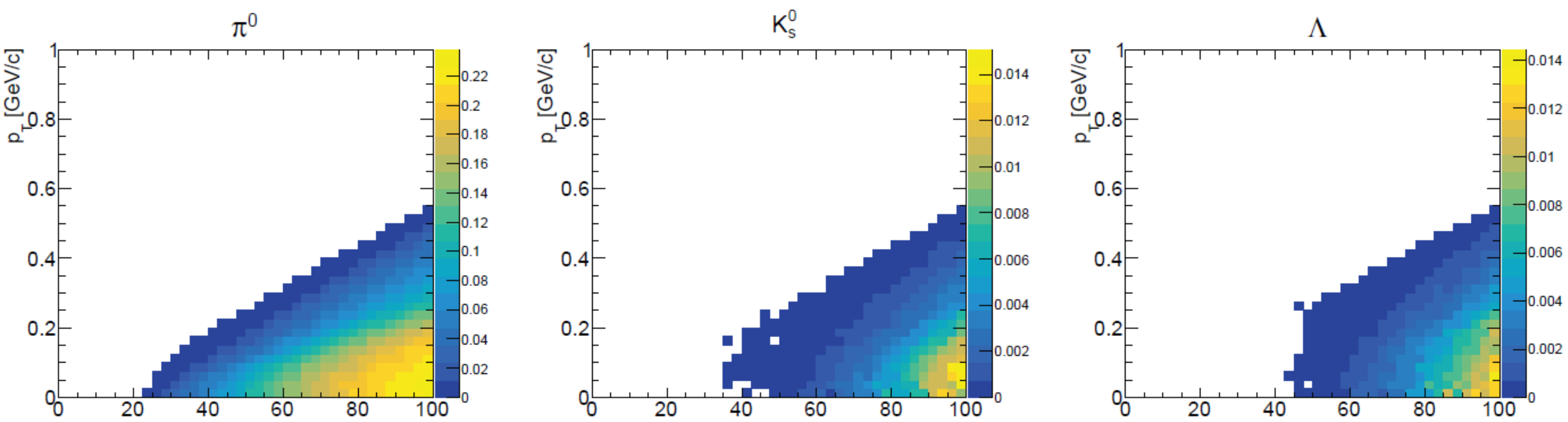


New topics at RHICf-II

- Large acceptance detector
  - 8cm x 18cm
  - For more particles: K^0_S and Λ

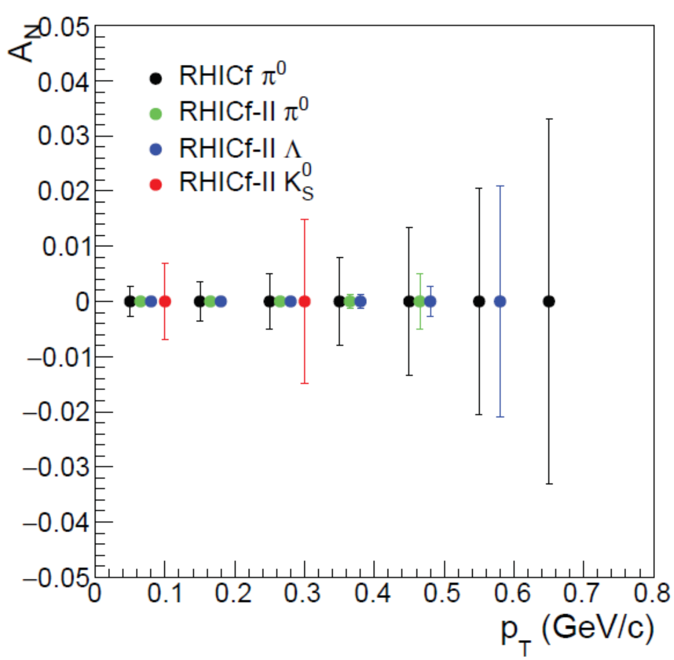


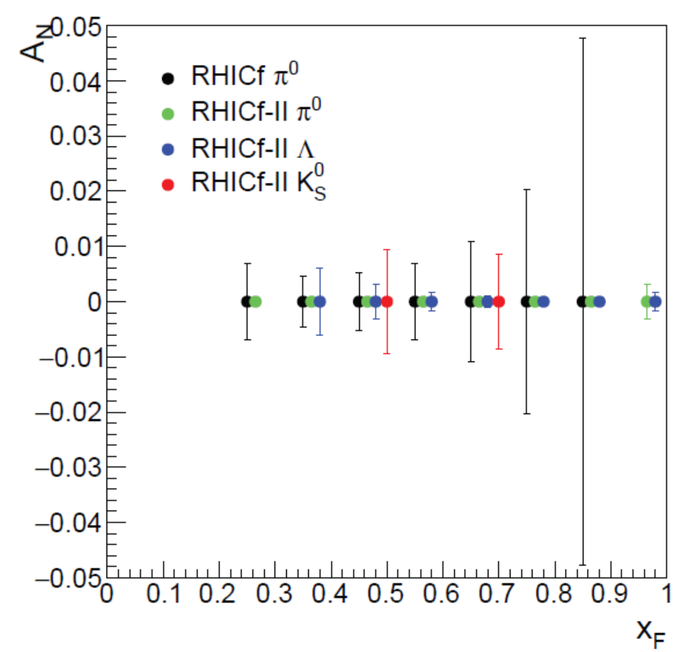
- $K^0_S \rightarrow 2\pi^0 \rightarrow 4\gamma$ (B.R. 30.7%)
  - 0.2 K^0_S /sec = 10^4 K^0_Ss in 14 hours operation
- $\Lambda \rightarrow n + \pi^0 \rightarrow n + 2\gamma$ (B.R. 35.9%)
  - 12 Λ /sec = 10^5 Λs in 2.5 hours operation
- Geometric acceptance of π^0, K^0_S and Λ



New topics at RHICf-II

- Asymmetry measurement of K^0_S and Λ
  - Expected statistical uncertainty of asymmetry measurements for π^0, K^0_S, and Λ compared to the RHICf (Run 17) π^0
  - Assuming the similar luminosity



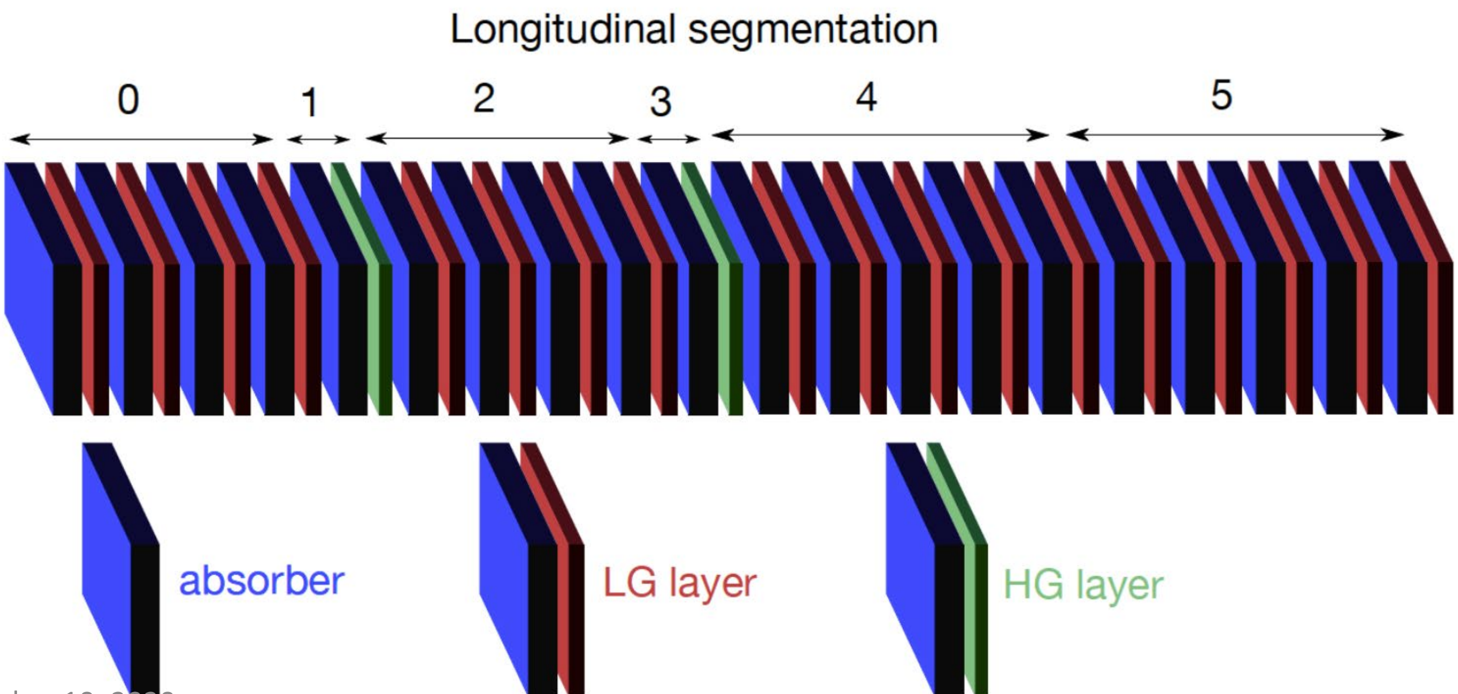


Large acceptance calorimeter

- We plan to transfer ALICE FoCal-E technology for building an approx. 8cm x 18cm detector
  - Kakenhi-Kiban-A (2021-2024) + RIKEN budget
  - Finalize the design of the detector in 2021
  - Construction in 2022-2023
  - Prototype test in 2023 A+A collisions
- Parasitic beam-time in 2024
  - (dedicated beam-time in 2017)
  - Radial polarization
  - Small β^*, normal (high) luminosity
  - High radiation dose
- The detector needs to have enough radiation hardness to work for a small β^* and normal luminosity
  - pad sensor to be tested; e.g. with a small neutron source facility in RIKEN

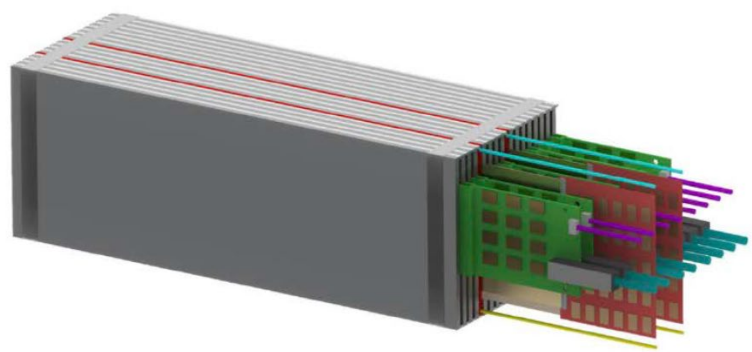
ALICE FoCal-E

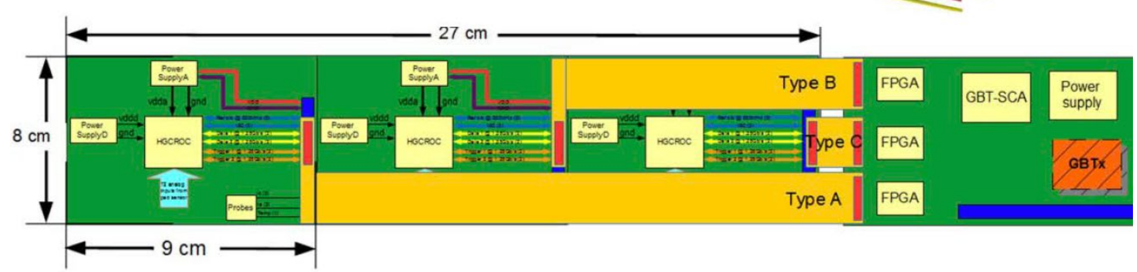
- Led by Tsukuba Univ. group
- Tungsten absorber
- Low granularity (LG) silicon pad for energy measurement
  - σ_E / E = 25% / √E (GeV) ⊕ 2% for photon energy resolution (simulation)
- High granularity (HG) silicon pixel (CMOS-MAPS) for accurate position measurement



ALICE FoCal-E

- Space restriction at RHICf
- Readout electronics based on HGCROC ASIC (CMS)
  - Readout electronics & DAQ integration to the central detector system
  - Working with Grenoble group who is a leader of the HGCROC ASIC development



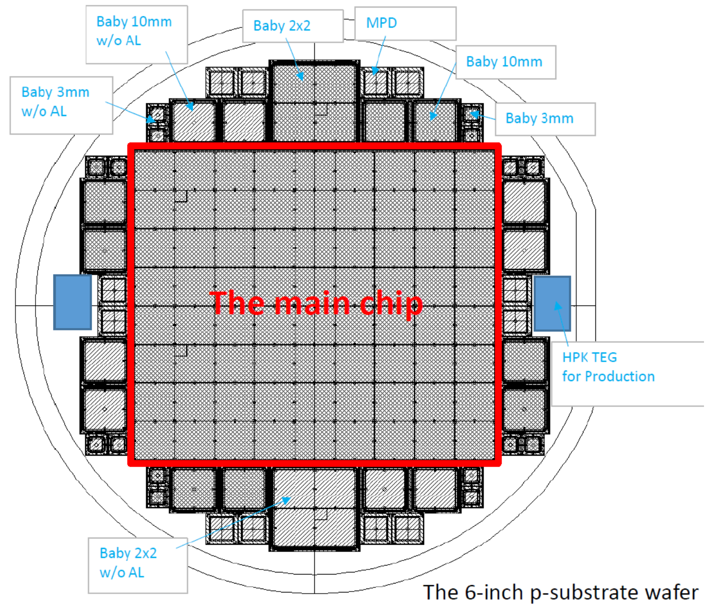


RHICf-II issues

- Experimental cooperation from sPHENIX nor STAR has not been obtained yet
  - sPHENIX cannot accept others for construction and commissioning of the new detector
  - STAR has reduced manpower due to the EIC construction and cannot cooperate as in 2017
- Possible reduction of beamtime in 2023 and 2024
  - Planned to be 28weeks, but it may be 24 weeks or 20 weeks
  - In the case of 20 weeks, the p+A collision in 2024 is expected to be eliminated
- In contact with PAC chair (J. Harris) and a member (J.-C. Peng)
  - No plan was submitted to PAC this year
- Continue discussion with STAR

To-do for prototype detector

- Si-Pad sensor
  - CMS-HGCROC readout to be tested at ELPH in this month
  - p-type sensor with improved sensor mask to be ordered
  - n-type sensor with different type of silicon (resistivity, etc.) under consideration



The 6-inch p-substrate wafer

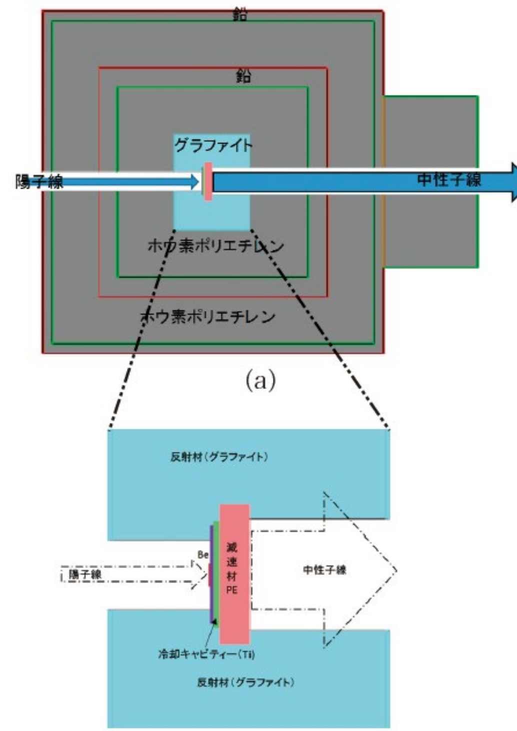
- Tungsten plate
  - Thickness for RHICf-II to be determined soon
- Si-Pixel for RHICf-II prototype
  - ALPIDE sensor
  - Readout procedure
  - Dedicated design necessary
    - Help by European group necessary (Bergen group)
    - Budgetary requirement to be investigated incl. PCB, integration, design, etc.

To-do for prototype detector

- Mechanical design
  - Company in Japan
  - Technical help at BNL (or Stony Brook?) necessary
- Standalone DAQ
  - CRU (Common Readout Univ)
    - Get information from Grenoble group
  - HV module
- Test bench @ RIKEN
  - FPGA test for trigger development
  - HGCROC board, injection board, aggregator board, etc.
- ALICE-FoCal SPS test beam
  - September 2021 & April 2022
  - To be covered by Chujo-san's talk later

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 provided by Kyushu U./g-2 group & foil activation (Indium)
- Online measurement
  - I-V, C-V, etc.
- Proposal to be prepared



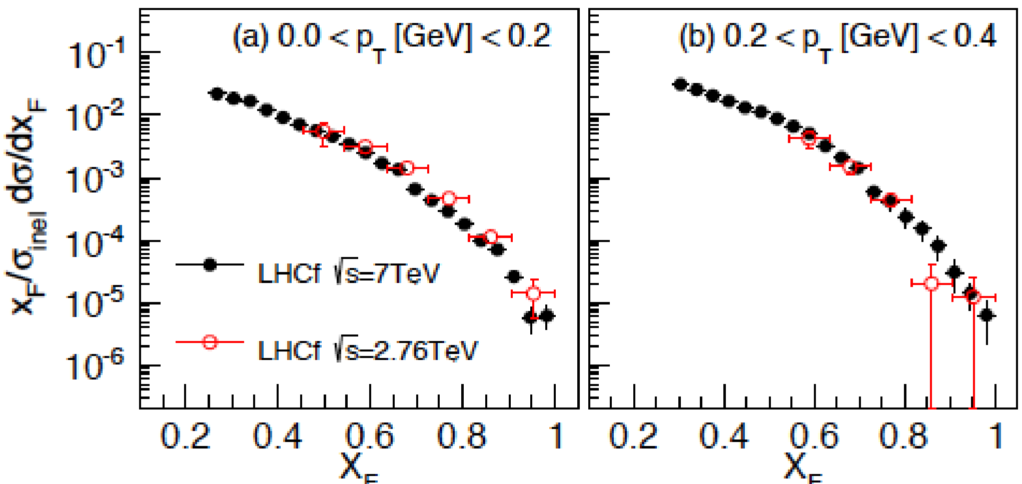
Summary

- Cosmic-ray study and asymmetry measurements
- A_N of very forward π^0 from 2017 run
- Other analyses ongoing
  - Neutron asymmetry
  - Combined analysis with STAR detectors
- We propose a second run for RHICf in 2024 (RHICf-II)
  - Large acceptance calorimeter with ALICE FoCal-E technology
  - Continue experimental cooperation issue with STAR
  - To-do list for the prototype detector

Backup Slides

Cross section measurement

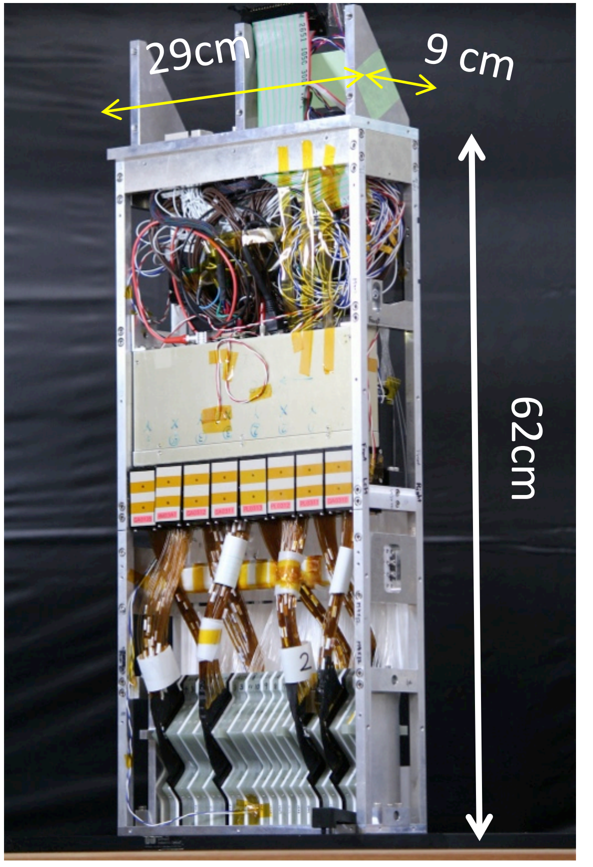
- Majority of energy flow from hadronic collisions concentrated in the very forward region, but reaction mechanism insufficiently understood there
  - Uncertainty to understand air-shower from ultra-high energy cosmic rays
  - Improvement of high-energy collision models based on measurement essential
- Feynman scaling
  - Energy-independent x_F & p_T distribution of the cross section of very forward particle production
  - Wider p_T coverage at RHIC energy (limited at LHC low energy collision)

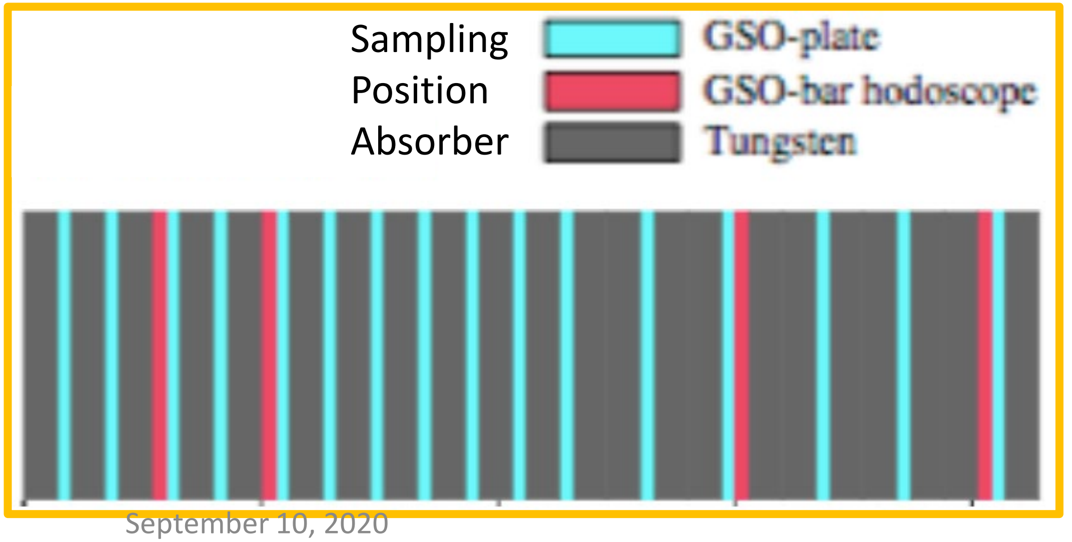


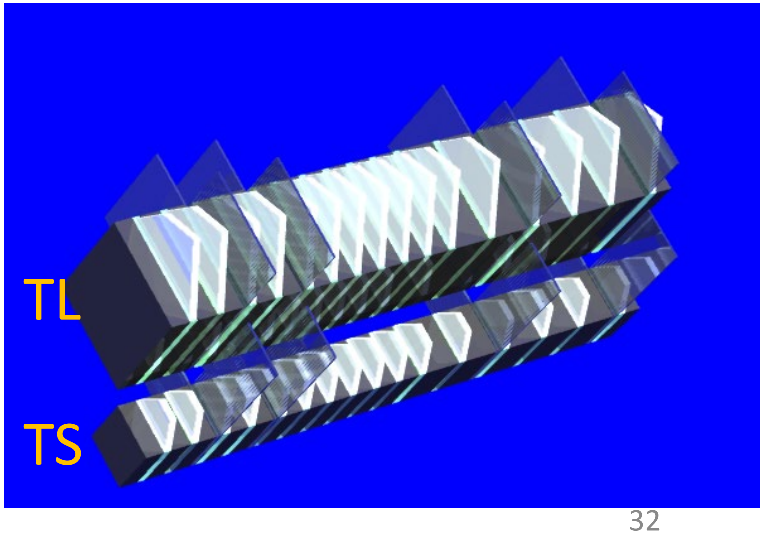
LHCf results of π^0 production cross section at $\sqrt{s}$=7TeV and 2.76TeV
Phys.Rev.D94 (2016) 032007

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 λ_{int})
  - 16 GSO sampling layers
  - 4 XY pairs of GSO-bar position layers (MAPMT readout)

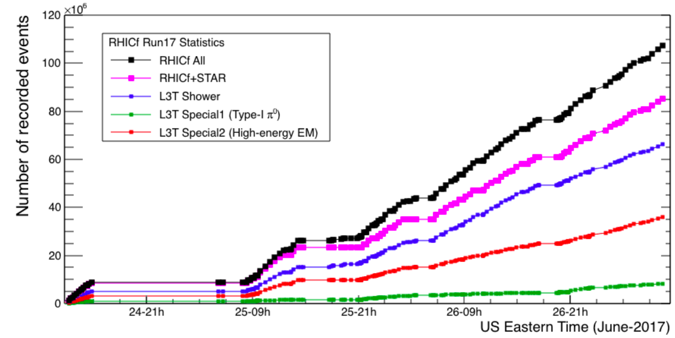




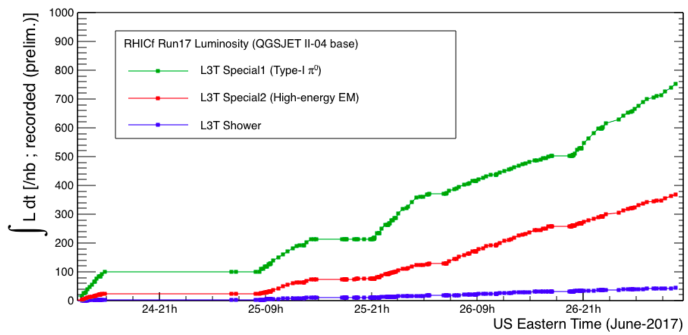


Data accumulation & statistics

- ~700 nb^{-1} integrated luminosity, ~110 M events recorded
- Common data taken by RHICf DAQ and STAR DAQ
  - separated data streams and records
- RHICf triggers
  - Shower (baseline)
    - Hits in 3 consecutive layers on TS or TL
    - Large prescale
  - 2 photons (for π^0)
    - Hits in 3 consecutive layers in upstream 7 layers of both TS and TL
    - No prescale
  - High-energy photon (for γ and π^0)
    - Large energy deposit in the 4th layer of TS or TL
    - Small prescale (~2)
- STAR trigger
  - With or without TPC data
  - Roman Pot + TPC data
    - for diffraction event selection

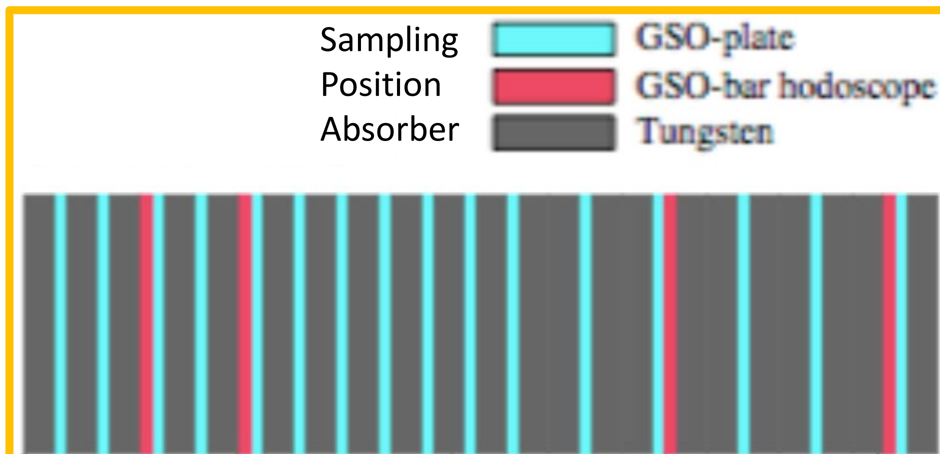


All data ~110M
RHICf+STAR
Shower
High-energy photon
2 photon



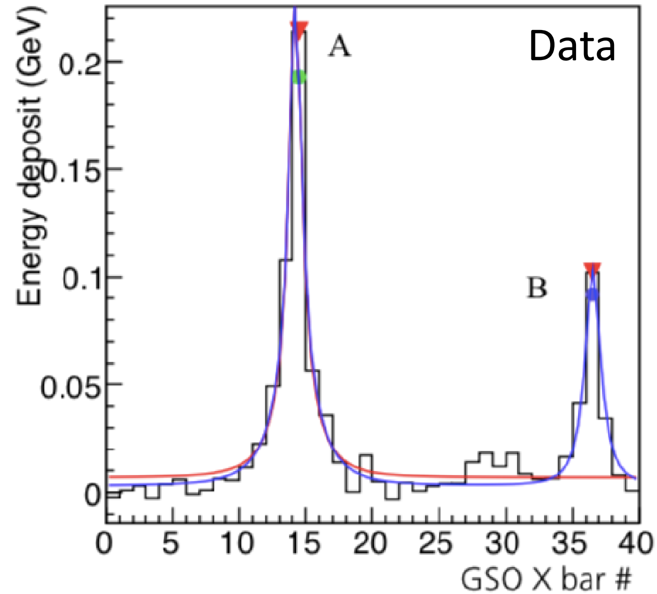
2 photon ~700 nb^{-1}

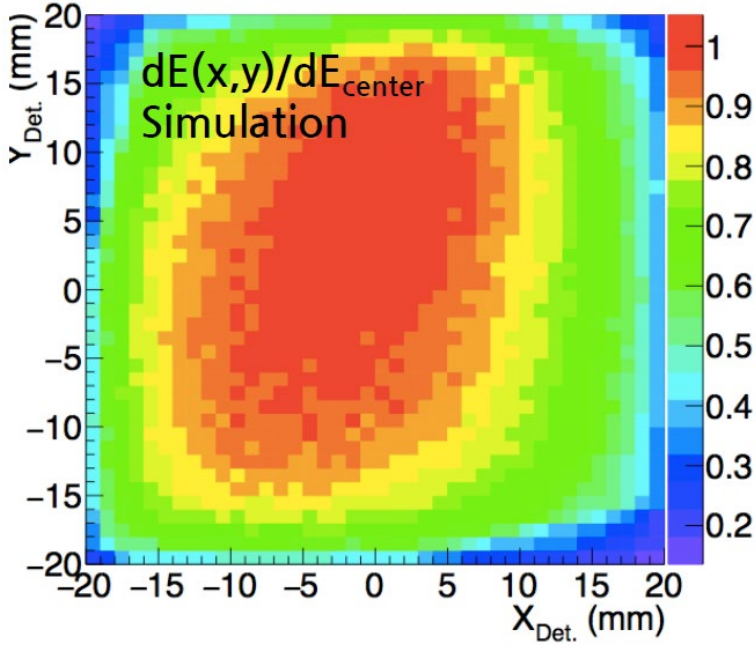
High-energy photon
Shower

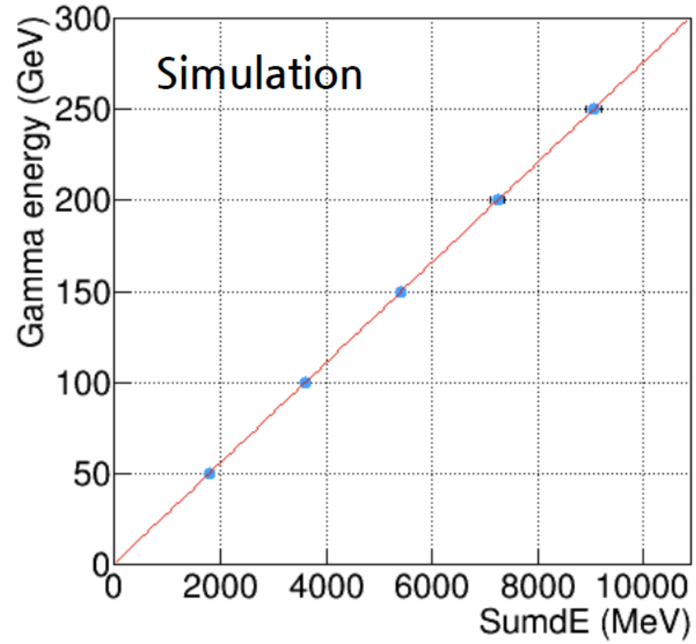


π^0 reconstruction

- Positions of decay photons measured by 1mm dimension GSO bars
- Energy corrections
  - Position dependence
  - Energy scale
  - Performance confirmed with test beams

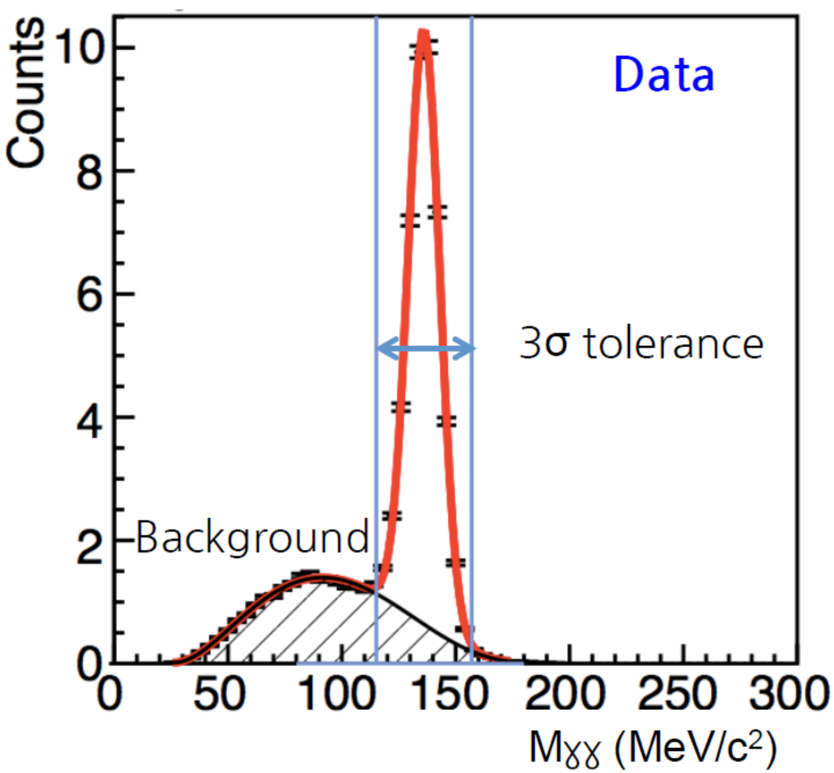


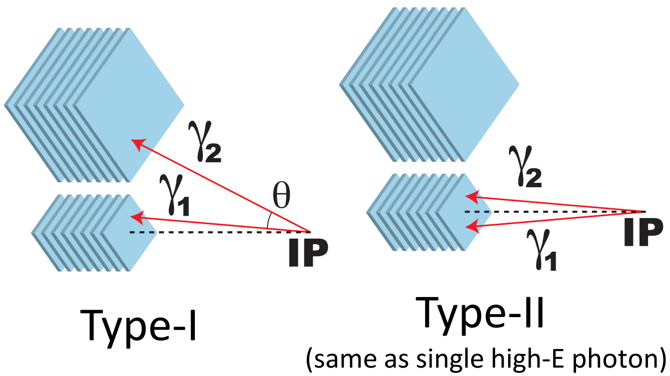


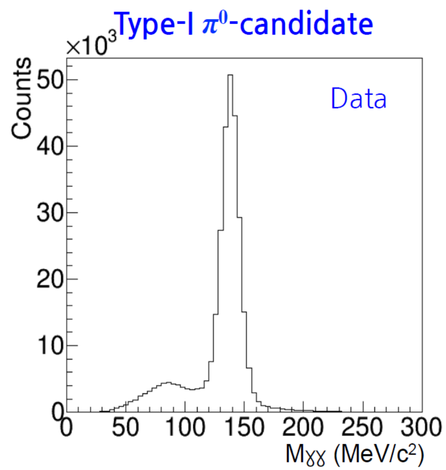


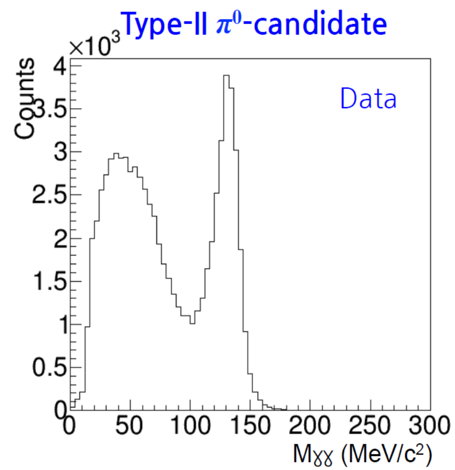
π^0 reconstruction

- π^0 peak with ~10 MeV/c^2 width
  - 3σ region selected as π^0 candidates



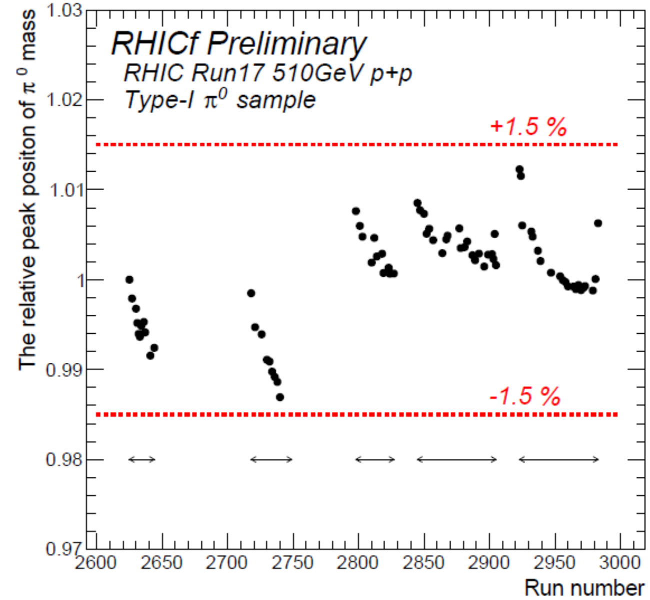




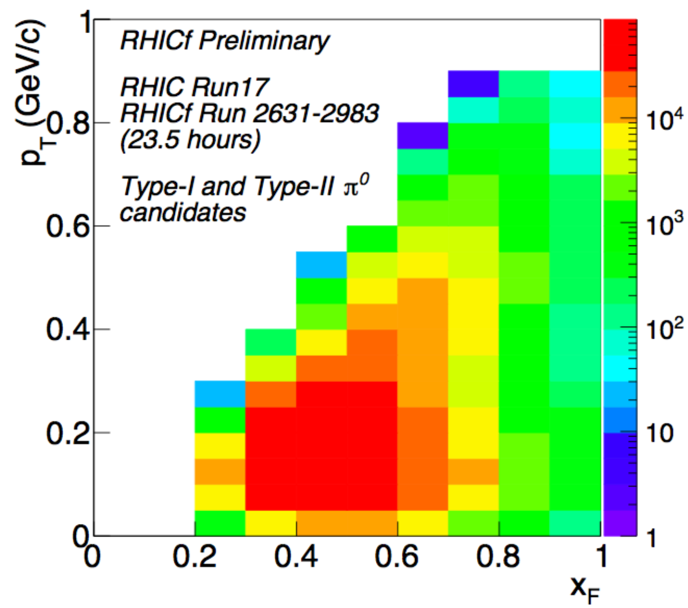


π^0 reconstruction

- Relative peak position of reconstructed π^0 mass in each run

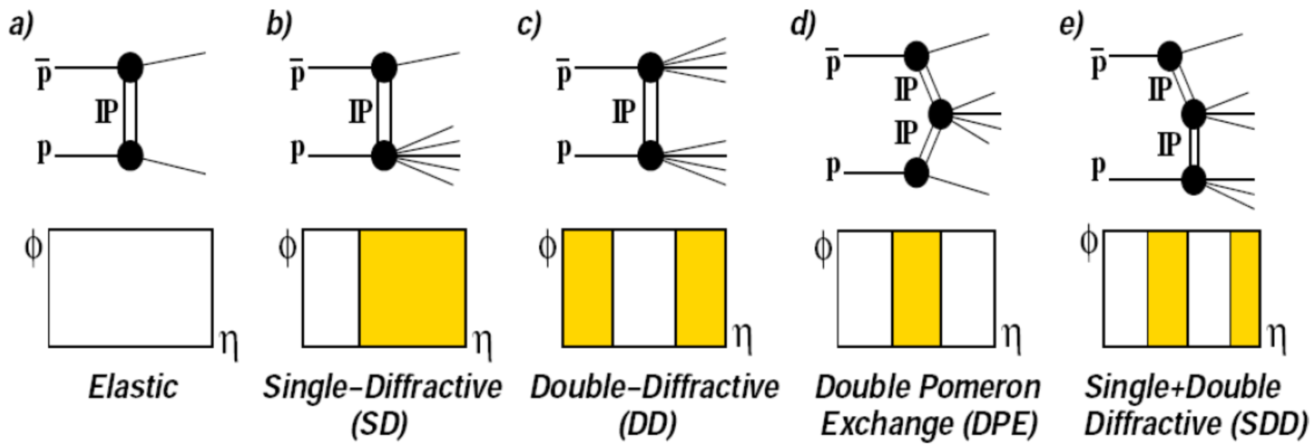


- π^0 kinematics
  - $p_T < 1.0$ GeV/c
  - $0.2 < x_F < 1.0$



To do

- Event type categorization



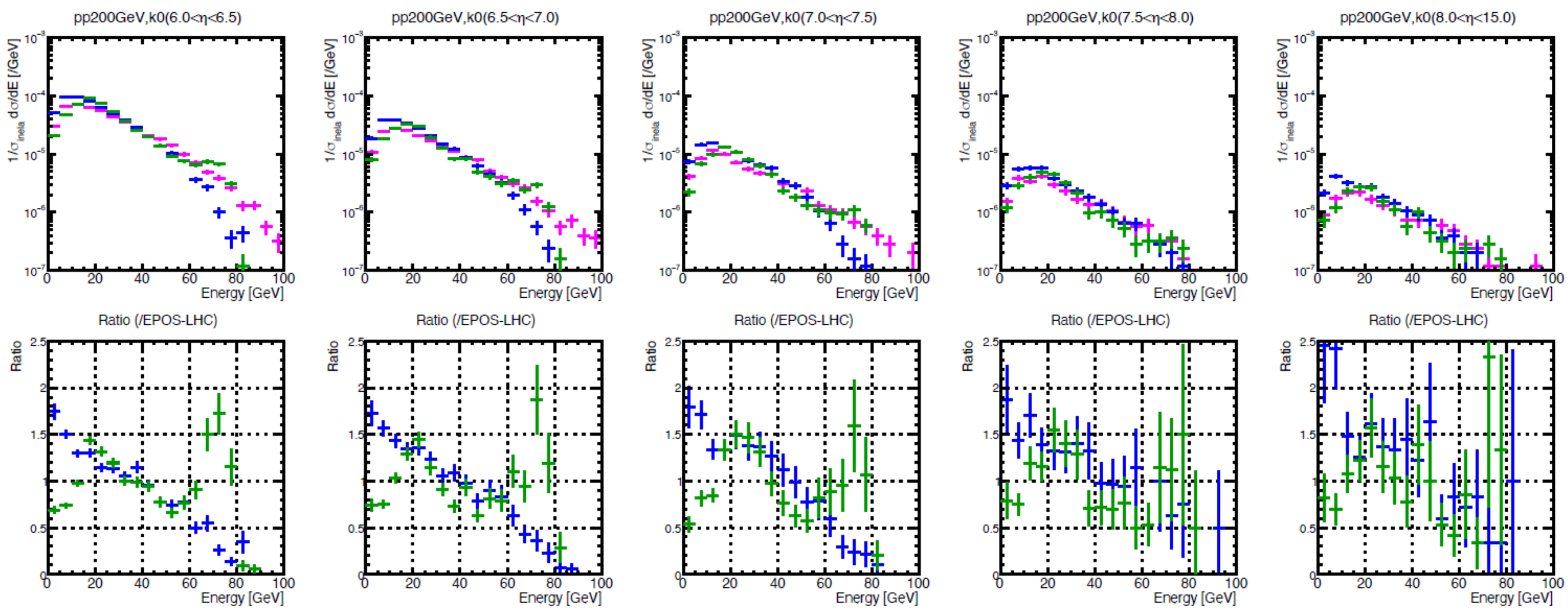
- Diffraction + resonance tagging with STAR + RHICf combined data analysis
  - Resonance with STAR Roman Pot
  - Diffraction with STAR forward detectors（FMS, BBC, VPD)
  - Or no activity
- Event type, multiplicity (FMS) dependence of cross section & asymmetry to be obtained
  - For more information to study production mechanism

Introduction

- In this LoI, we propose a second run for RHICf in 2024 (RHICf-II).
  - PAC recommendation in 2019
  - The prospects for taking additional RHICf data in future pp, pA, and AA runs should also be explored.
- We may need a request of dedicated beam time with special β^* and polarization direction similarly to our run in 2017, and special p + A collisions.
- It will have a large impact on the central detector BUR.

New topics at RHICf-II

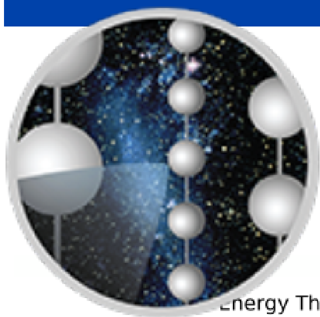
- K^0_S for studying impact on the high-energy atmospheric neutrino flux
  - Differences in p+p collisions at 200 GeV between models: EPOSLHC (magenta), QGSJET II-4 (blue), SIBYLL 2.3 (green)



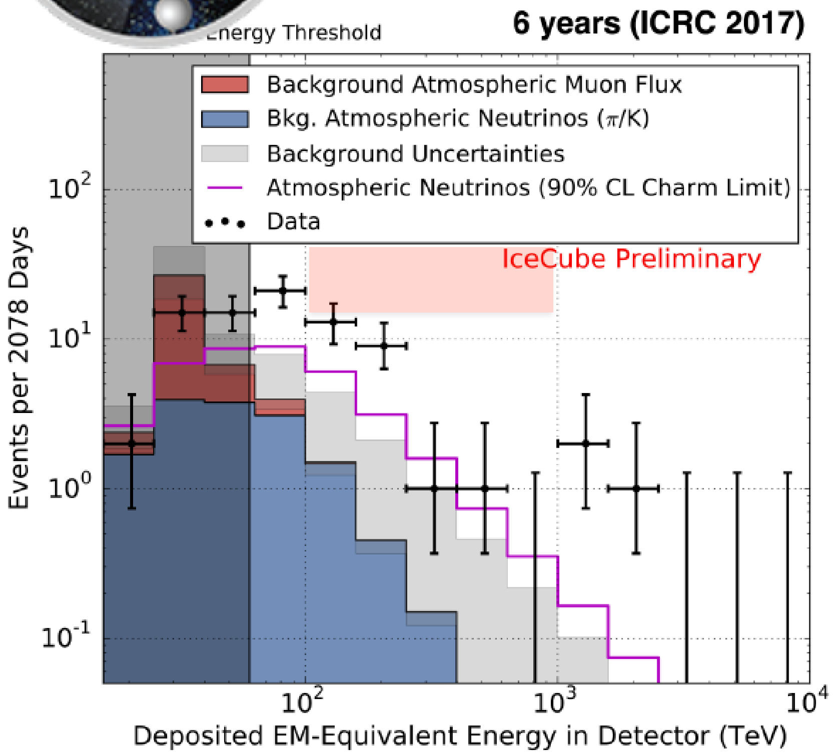
New topics at RHICf-II

Kaons in atm. ν productions

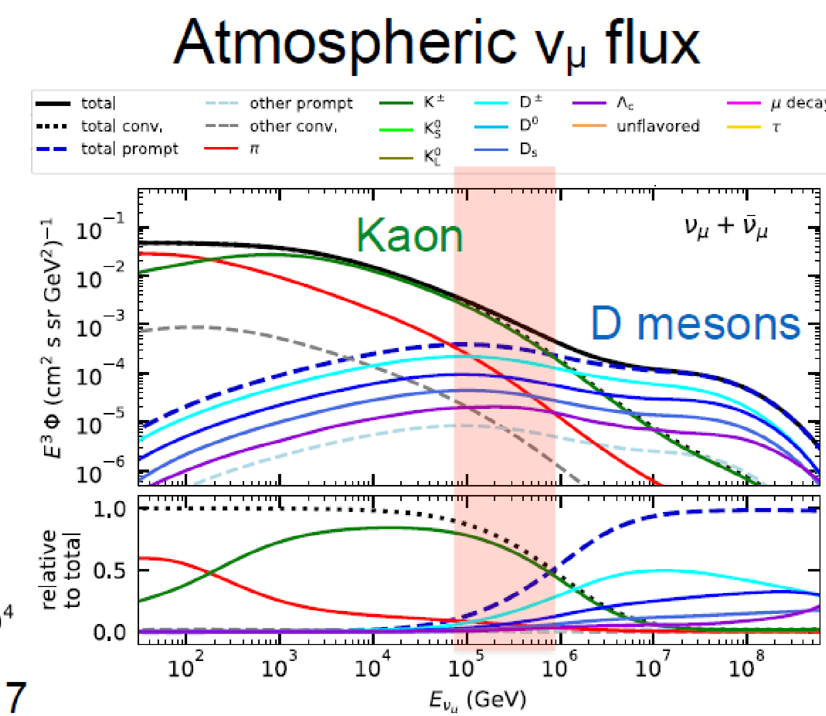
Slide by
H. Menjo



IceCube detected astronomical neutrinos.
Better understanding of background
(Atmospheric neutrinos) is required.



IceCube, ICRC2017



Large acceptance calorimeter

- We'll transfer ALICE FoCal-E technology for building an approx. 8cm x 18cm detector to be used at RHIC in 2024
  - Finalize the design of the detector in 2021
  - Construction in 2022-2023 by RIKEN budget + external fund in Japan
- The detector may have enough radiation hardness to work for a small β^* and normal luminosity
  - pad sensor to be tested in this winter with a small neutron source facility in RIKEN

RHICf-II request

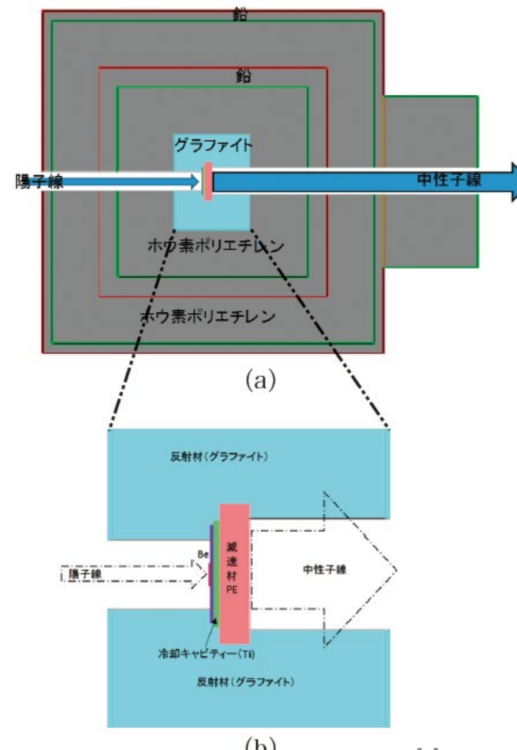
- 2022 at STAR not available
  - ALICE FoCal not available yet
  - LHCf detector not available due to conflict with LHC Run 3 in 2023
  - p+p 510 GeV
- 2024 at sPHENIX or STAR
- Dedicated beam use – 2 weeks
  - Large β^* and radial polarization
  - 1 week for pol-p + A at 200 GeV
    - A = O, Al, Au, $\cdots$
  - 1 week for pol-p + pol-p at 200 GeV
    - Comparison with p+A for A dependence
    - Comparison with 510 GeV (2017 run) for $\sqrt{s}$ dependence
    - K^0_S and Λ
- Or parasitic beam use
  - The detector may have enough radiation hardness to work for a small β^* and normal luminosity
  - We also need sufficient DAQ and trigger capability for high luminosity operation

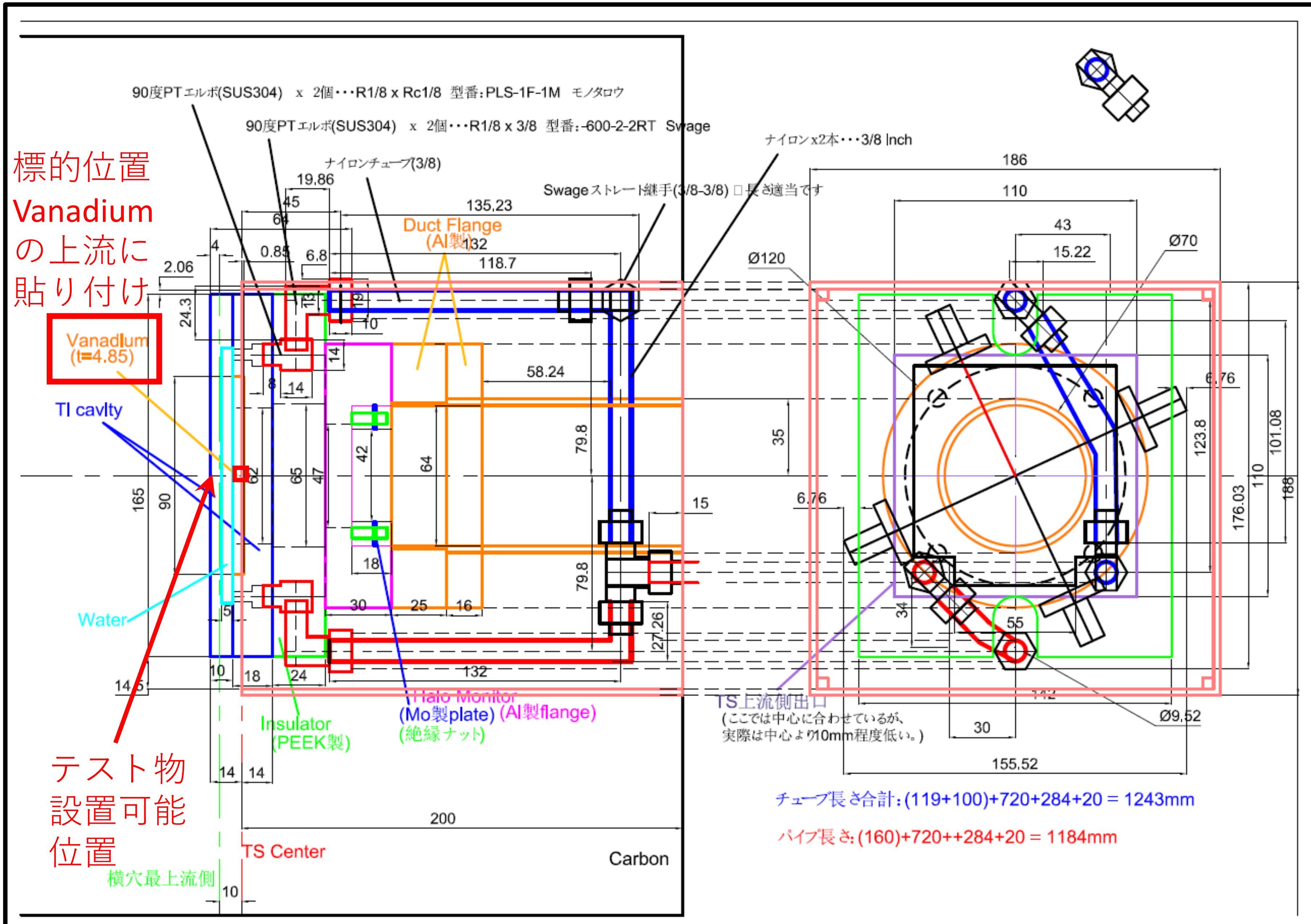
Summary

- In this LoI, we propose a second run for RHICf in 2024 (RHICf-II).
- We may need a request of dedicated beam time with special β^* and polarization direction similarly to our run in 2017, and special p + A collisions.
- It will have a large impact on the central detector BUR.
- We are still considering whether we need dedicated beam use or we can run parasitically.
- We will discuss collaboration with sPHENIX and STAR to locate our detector.

RANS performance

- RANS
  - Proton 7MeV, 100μA
    - 6 x 10^{13} proton/s
  - Be target
  - Neutron 5MeV max.
    - 10^{12} neutron/s from the target
- RANS-II
  - Proton 2.49MeV, 100μA
  - Li target
  - Neutron 0.7MeV max.
- Radiation dose calculation or simulation
  - FLUKA/MARS/PHITS





90度PTエルボ(SUS304) x 2個・・・R1/8 x Rc1/8 型番:PLS-1F-1M モノタロウ
90度PTエルボ(SUS304) x 2個・・・R1/8 x 3/8 型番:-600-2-2RT Swage
ナイロンチューブ(3/8)
Swageストレート継手(3/8-3/8) 長さ適当です
ナイロンx2本・・・3/8 Inch
標的位置
Vanadium
の上流に
貼り付け
Vanadium
(t=4.85)
Ti cavity
Water
Duct Flange
(Al製)
Halo Monitor
(Mo製plate)
(Al製flange)
(絶縁ナット)
Insulator
(PEEK製)
テスト物
設置可能
位置
横穴最上流側
TS Center
Carbon
TS上流側出口
(ここでは中心に合わせているが、
実際は中心より10mm程度低い。)
Ø120
Ø70
Ø9.52
チューブ長さ合計:(119+100)+720+284+20 = 1243mm
パイプ長さ:(160)+720++284+20 = 1184mm

理研 RANS irradiation テストの計画

- neutron数は放射化箔（インジウム）を用いてモニターできる
  - Cr-39と同様
- テストするSi baby chip、モニター用のSi PD（九州大）、放射化箔を設置するjigを製作して、棒で下流から出し入れする
  - Ti cavityに当たるまで押し込み位置を得る
  - the Si PD monitor can be utilized with the accuracy of ~20% even if the annealing effect and detailed temperature correction were not considered.
- 2週間程度でプレゼンする
  - 大竹さんへ説明、延與さん同席できるとよい
  - 目的、スコープ
  - 方法、何をどのように測定するか
    - I-V、C-V、放射線量
    - 固定方法、読み出し方法
  - 期間
- テストしたものはテスト後は放射化が治まるまで外に持ち出すことできない

SiPD monitor

- K. Ueno et al.: Development of Real-Time 1-MeV Equivalent Neutron Fluence Monitor Based on SiPD for COMET Experiment

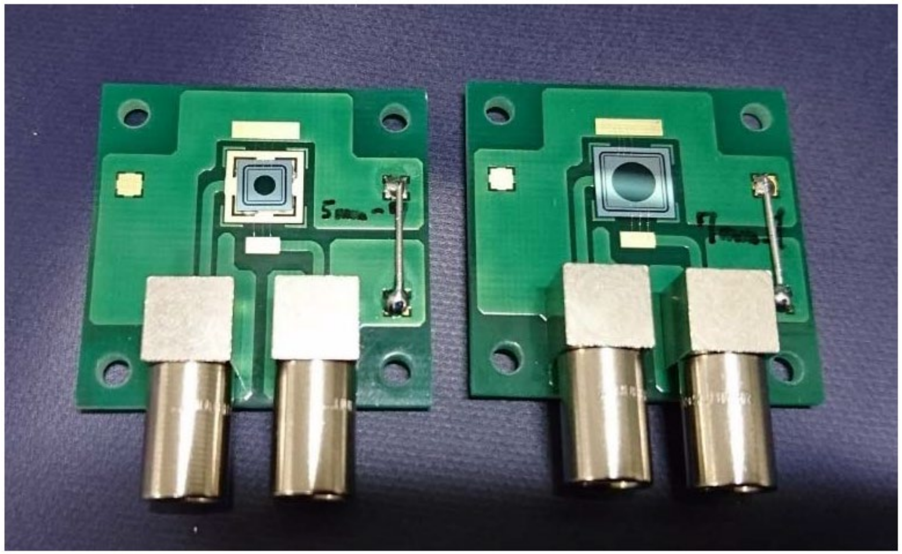


Fig. 2 Photograph of prototype neutron fluence monitors based on . the SiPDs with the thickness of 320 μm and the size of 5 x 5 mm^2 and 7 x 7 mm^2.

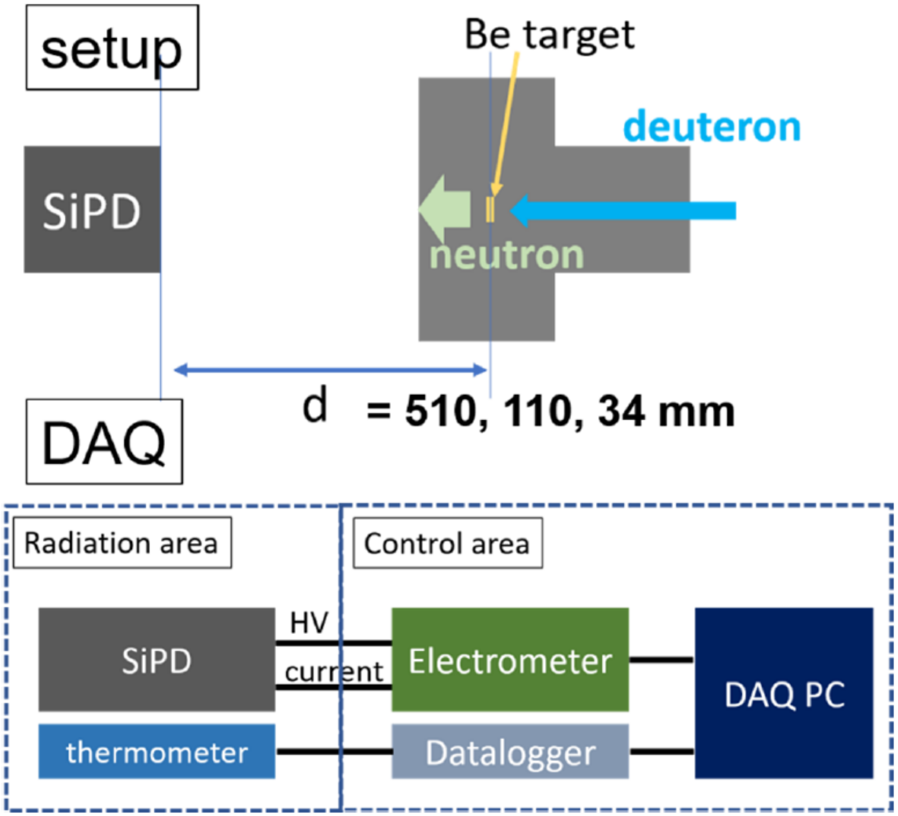
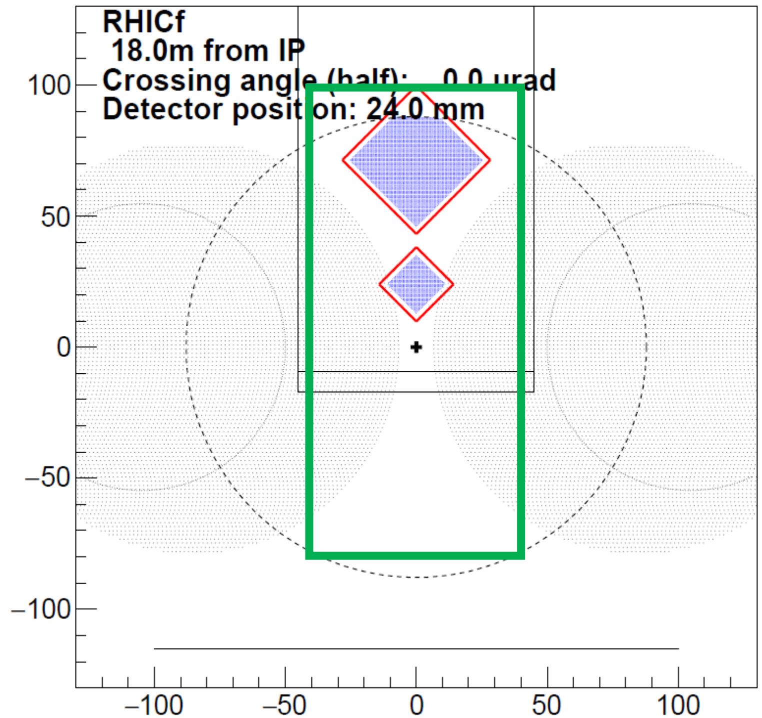


Fig. 4 Experimental setup. Leakage current of SiPD was measured changing distance (d) between SiPD and Be target. Electrometer was used for applying bias voltage and measuring leakage current. Thermometer was also mounted near SiPD and the temperature was recorded with datalogger.


RHICf
18.0m from IP
Crossing angle (half): 0.0 urad
Detector position: 24.0 mm
100
50
0
−50
−100
−100
−50
0
50
100