RHICf Analysis Update

BNL NPP 2019 PAC Meeting

June 10th, 2019

Yuji Goto (RIKEN)

for the RHICf Collaboration

RHICf collaboration

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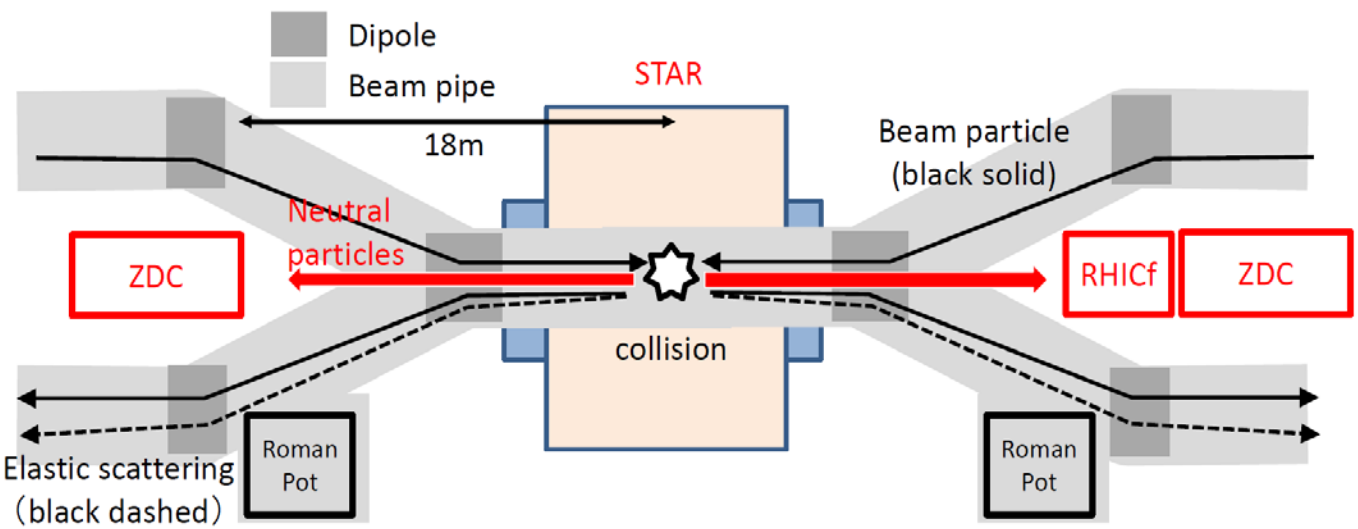
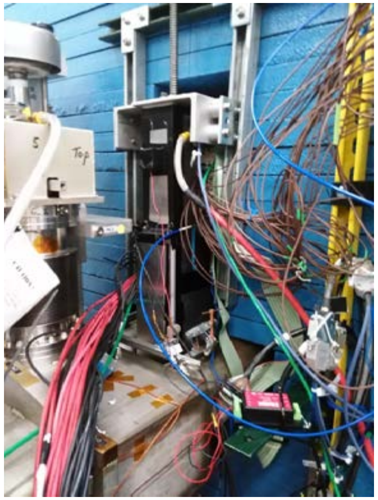
RHICf is partially supported by the U.S.-Japan Science and Technology Cooperation Program in High Energy Physics, and performed by strong collaboration with the STAR collaboration

RHICf experiment

- EM calorimeter (RHICf detector) installed in front of the ZDC+SMD of the STAR experiment
  - Cross section and asymmetry measurement of neutral particle production (neutron, photon, π^0) with $\sqrt{s}$ = 510 GeV polarized proton collisions
  - Wide p_T region covered by changing the position of the RHICf detector vertically (up to 1.2 GeV/c)
  - Much higher position resolution than ZDC+SMD so that enable us higher resolution of p_T measurement



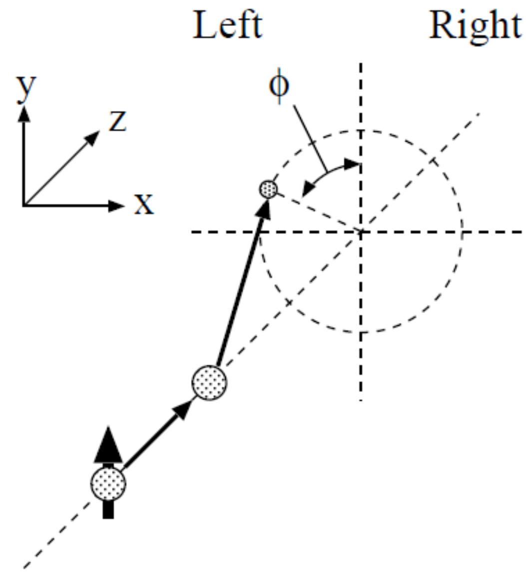


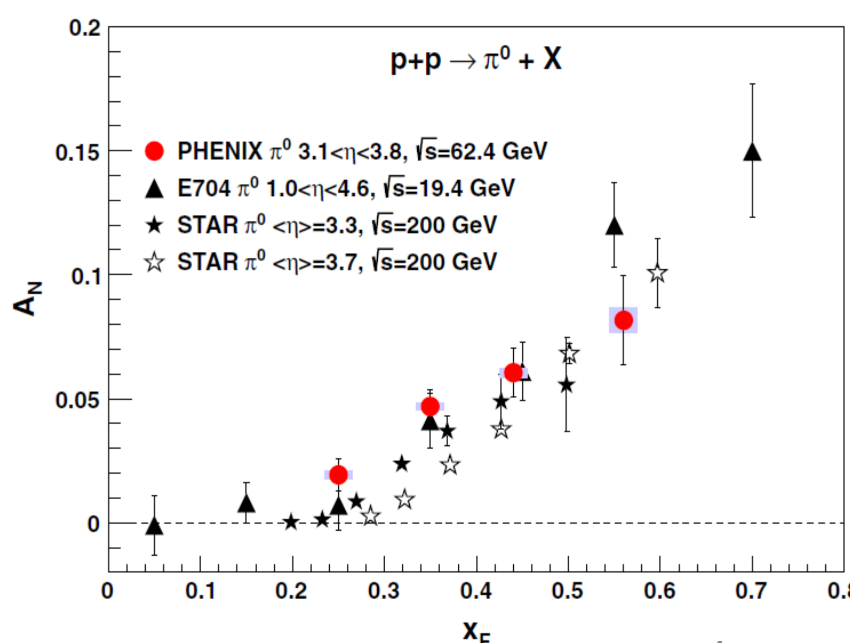
Transverse polarized proton collision

- A_N (transverse single-spin asymmetry) measurement

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

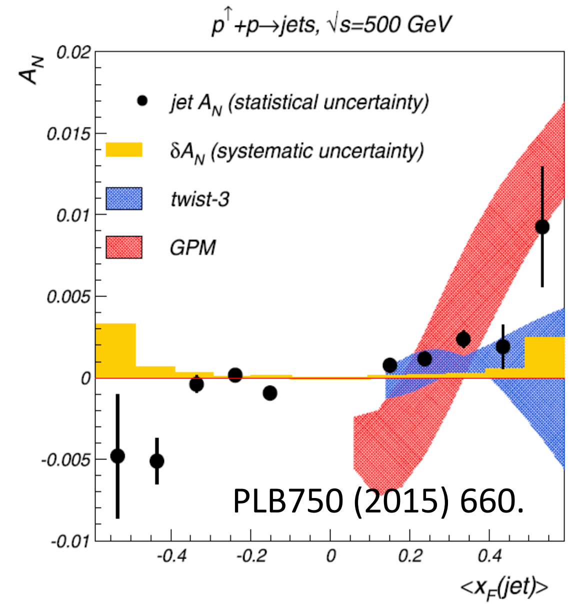
  - Azimuthal angle modulation
- Large A_N for forward hadron production
  - $1 < \eta < 4$, similar results in wide $\sqrt{s}$
- TMD (Transverse Momentum Dependent) function and higher-twist function in pQCD regime
  - Initial-state effect or "Sivers" effect
  - Final-state effect or "Collins" effect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

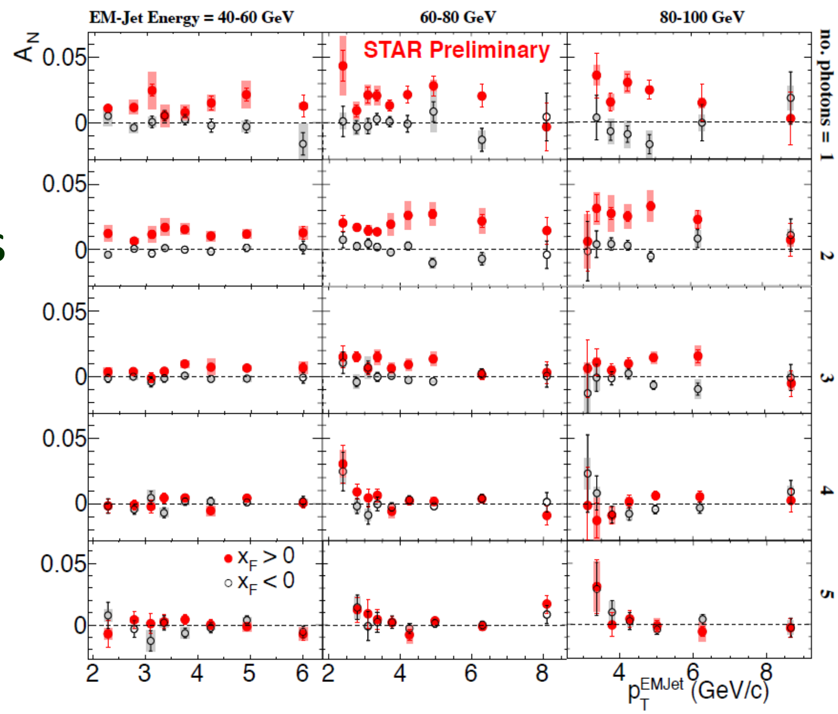




New question

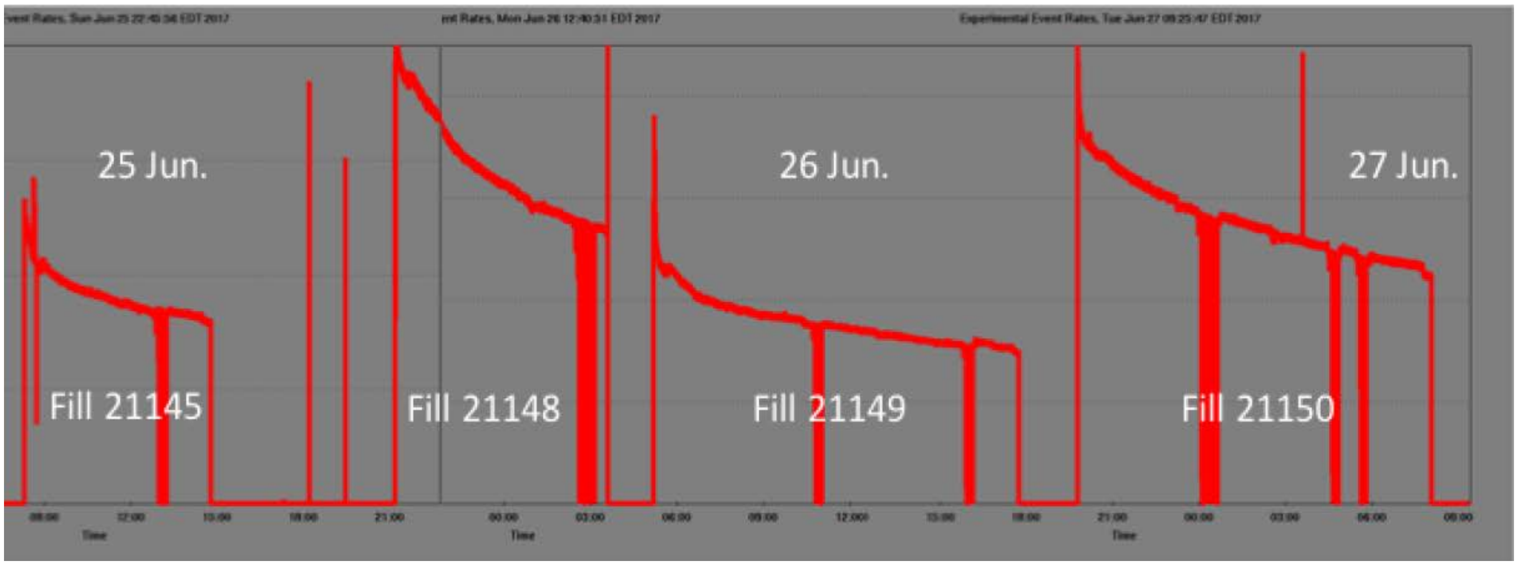
- A_NDY jet asymmetry
  - Small A_N of forward jet production comparing with that of forward hadron production
  - Mixture (cancellation) of u-quark jet and d-quark jet, or other non-perturbative effects?
- STAR multiplicity dependence
  - A_N for different number of photons
  - A_N decreases as the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

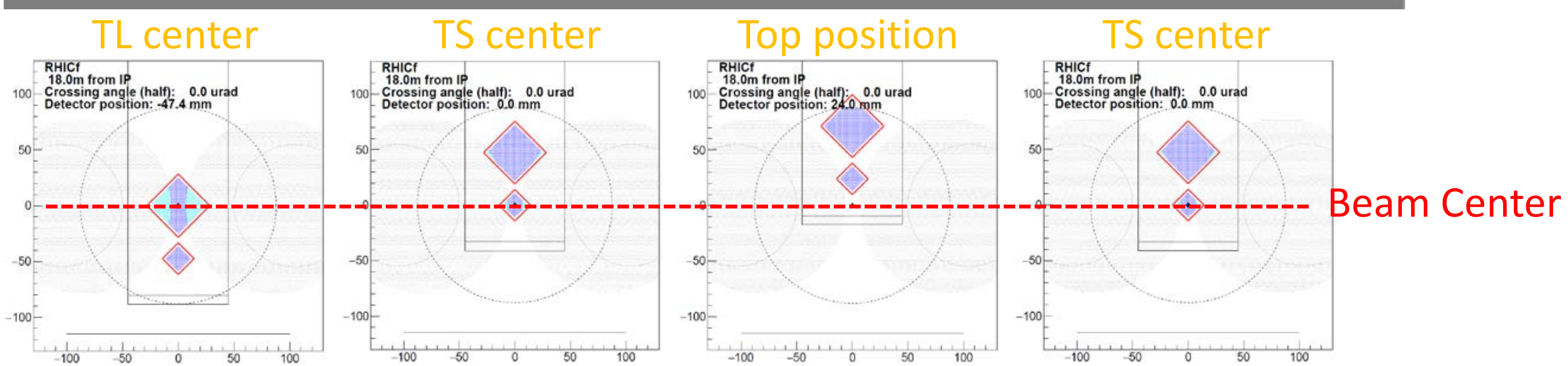




2017 operation

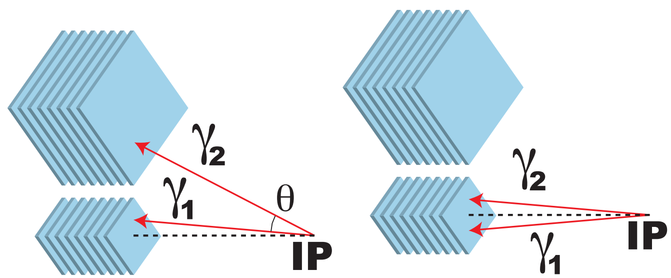
- June 24 – 27 physics data acquisition
  - β^* = 8m, radial polarization
  - 27.7 hours, ~110M events, ~700 nb^{-1}
- 3 detector positions: TL center / TS center / Top position





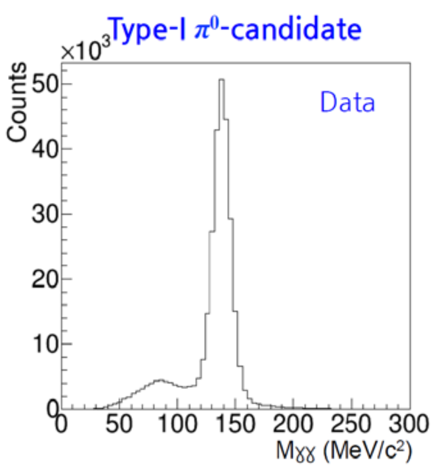
π^0 reconstruction

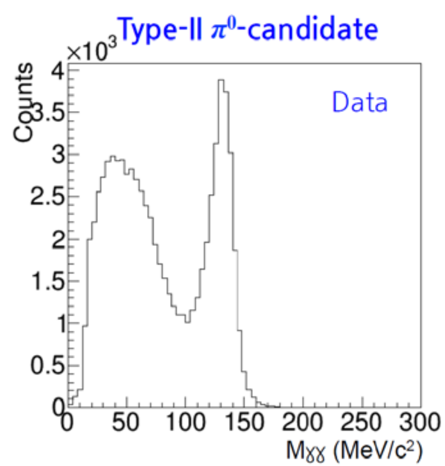
- π^0 peak with ~10 MeV/c^2 width
  - 3σ region selected as π^0 candidates

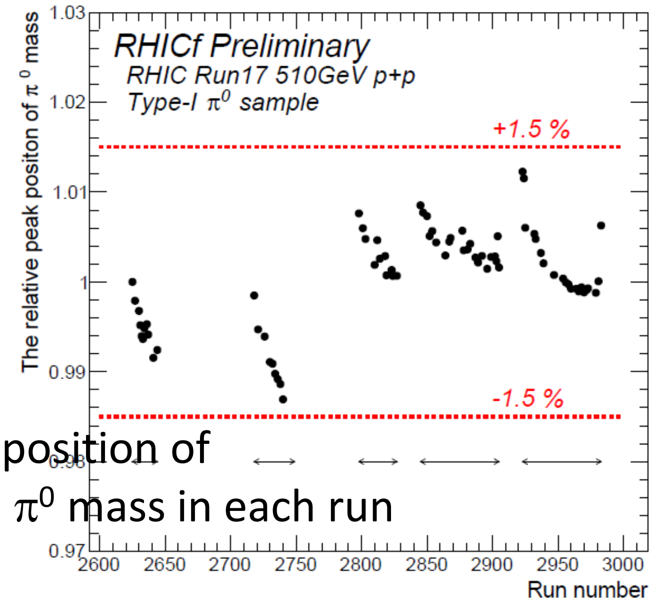


Type-I

Type-II
(same as single high-E photon)

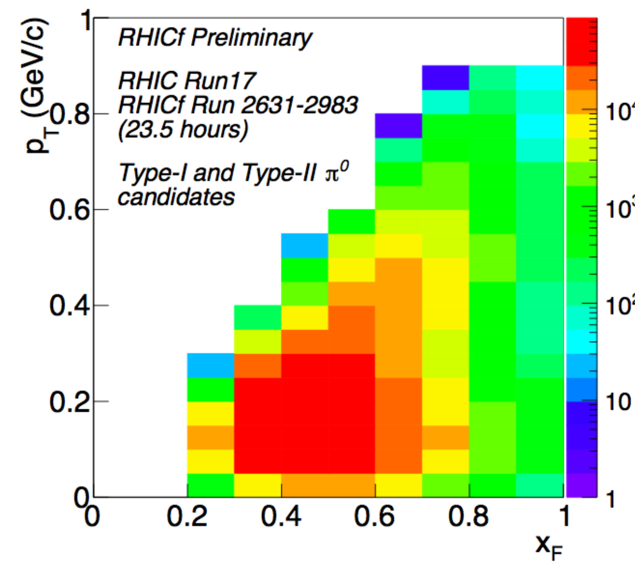






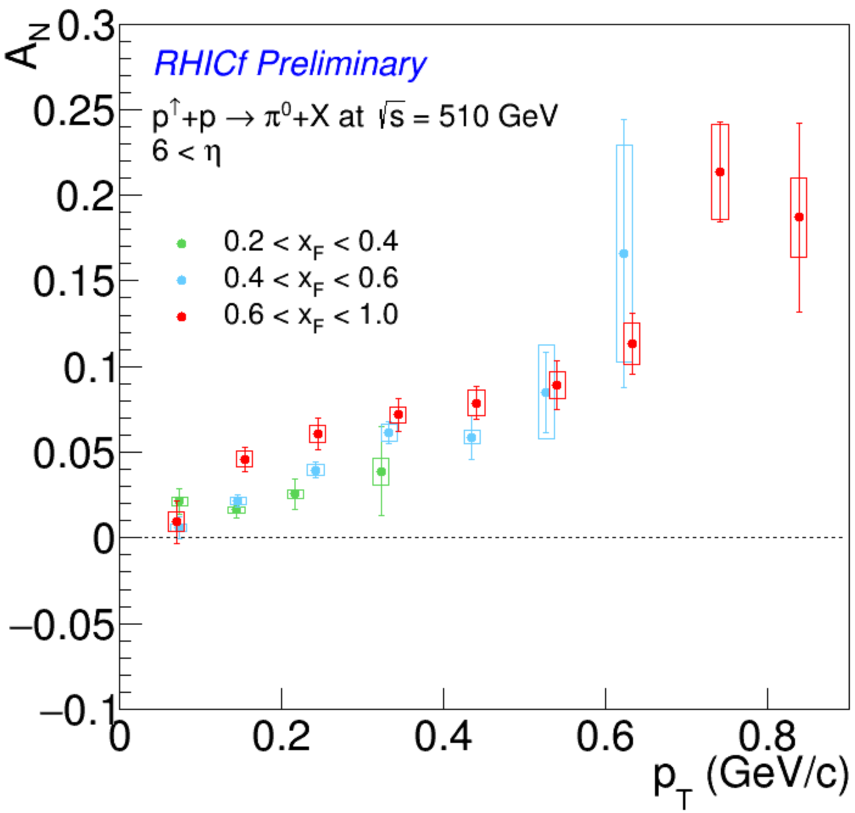
Relative peak position of reconstructed π^0 mass in each run

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



A_N of very forward π^0

- p_T dependence
  - Large asymmetry (up to 0.1) even at low p_T ($p_T < 0.6$ GeV/c)
  - Becoming larger (more than 0.1) at high p_T (0.6 GeV/$c < p_T$)



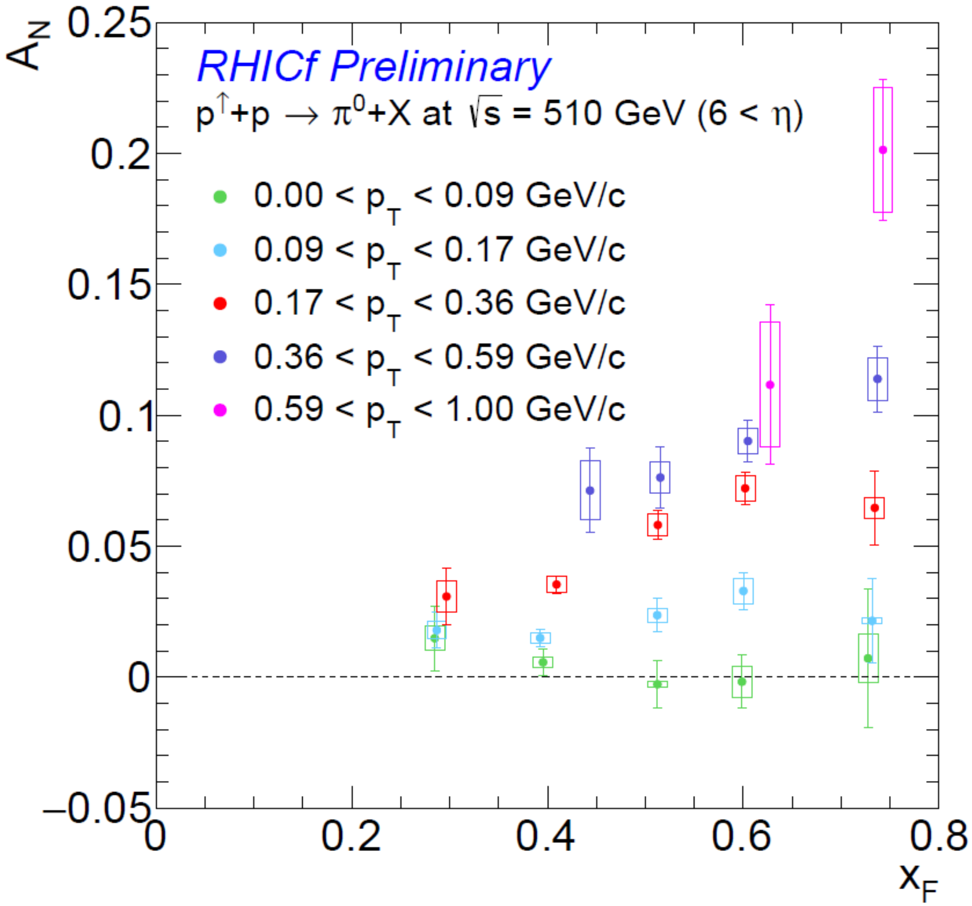
Data analysis has been performed by Minho Kim (Korea Univ.)

Background asymmetry (measured, zero consistent) subtracted

Bar: statistical error
Box: systematic uncertainties including beam center correction, acceptance correction, polarization, and background asymmetry subtraction

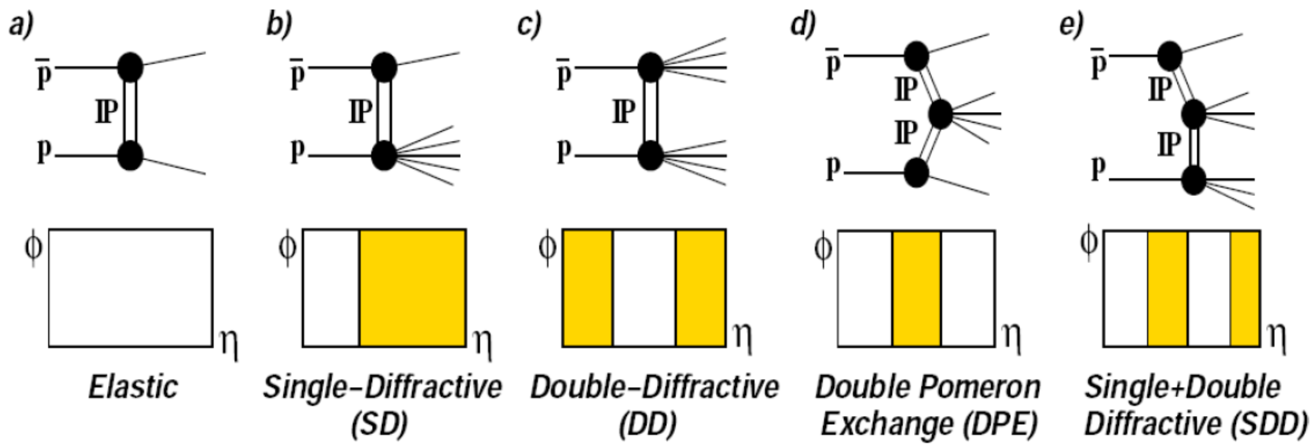
A_N of very forward π^0

- x_F dependence
  - $A_N \sim 0$ at $p_T < 0.09$ GeV/c
  - $A_N > 0$ at 0.09 GeV/$c < p_T$ and rising with x_F



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

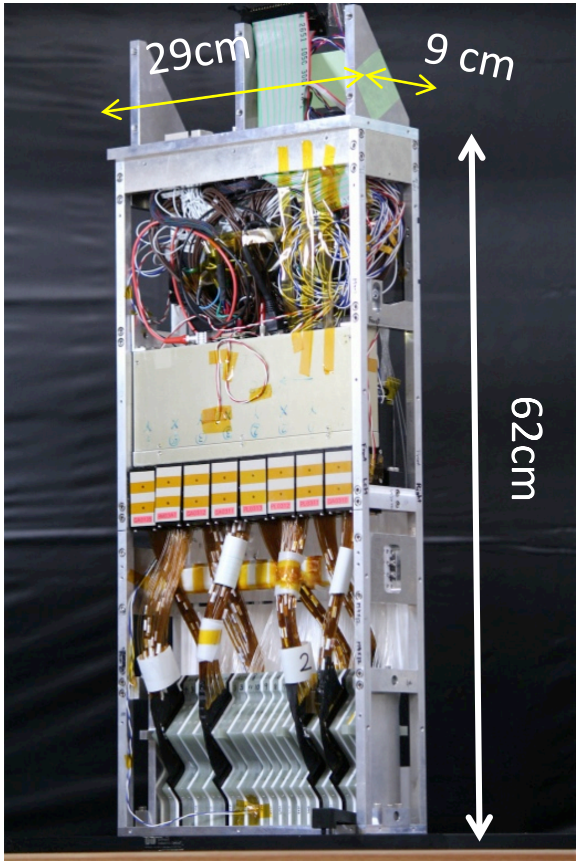
Summary & plan

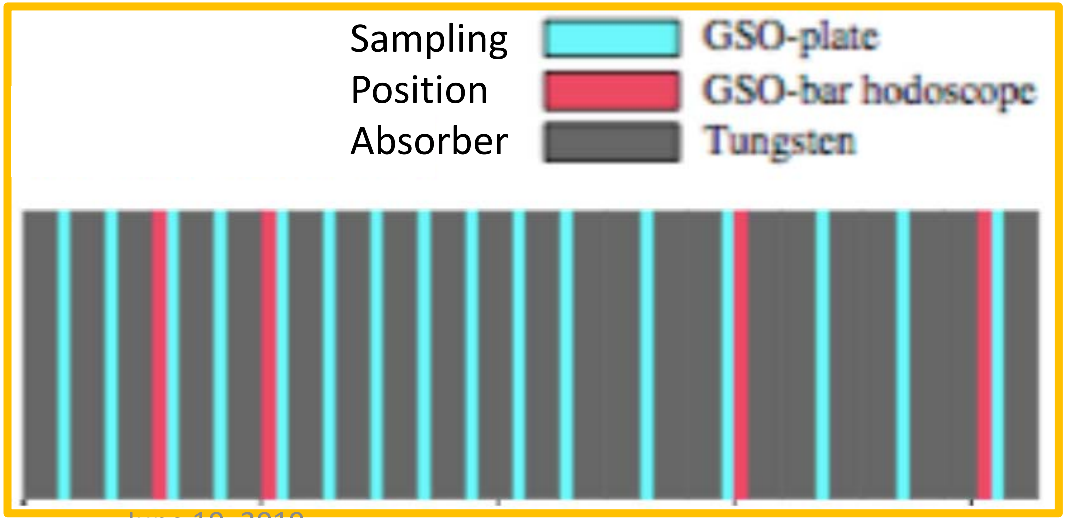
- Preliminary A_N result of very forward π^0 obtained
  - p_T & x_F dependences
  - Large asymmetry in non-perturbative regime
  - Matching to pQCD regime?
- STAR + RHICf combined analysis to be performed
  - For production mechanism, soft & hard components
  - Event type definition with STAR forward detectors and Roman Pot
  - Neutron analysis with RHICf + STAR ZDC
  - Asymmetry of STAR forward and midrapidity detectors with neutron/π^0 tag at RHICf
- Possible future plan
  - STAR at $\sqrt{s}$ = 510 GeV in 2022
    - Possible RHICf proposal of p+p (& p+A ?)
  - sPHENIX at $\sqrt{s}$ = 200 GeV
    - Baseline 2023-2025: p+p & p+A in 2024
  - Detector development in collaboration with people having common interest in position-sensitive calorimeter

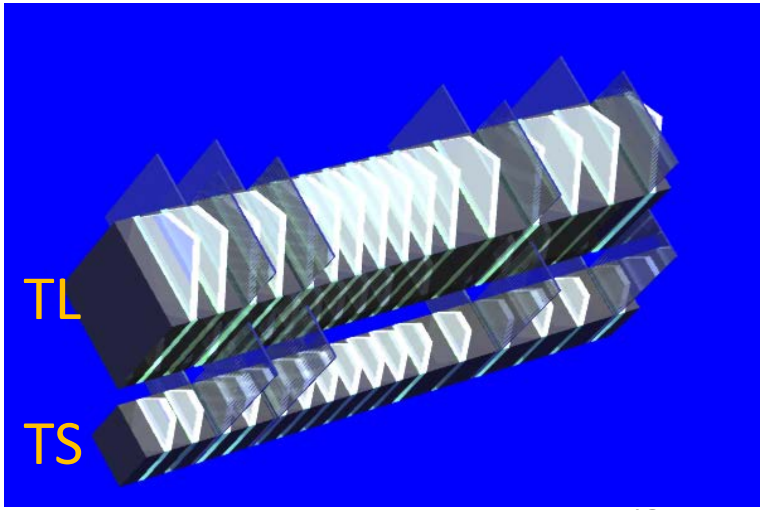
Backup Slides

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)

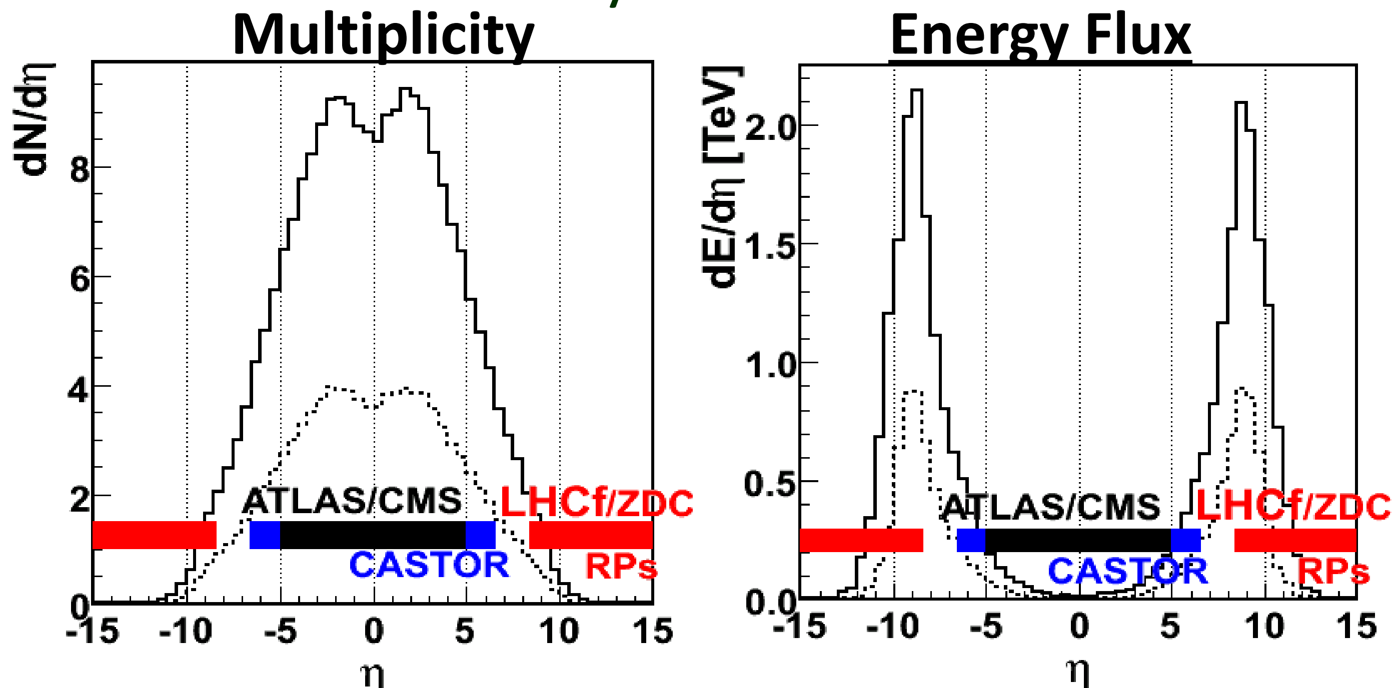






Physics at RHICf

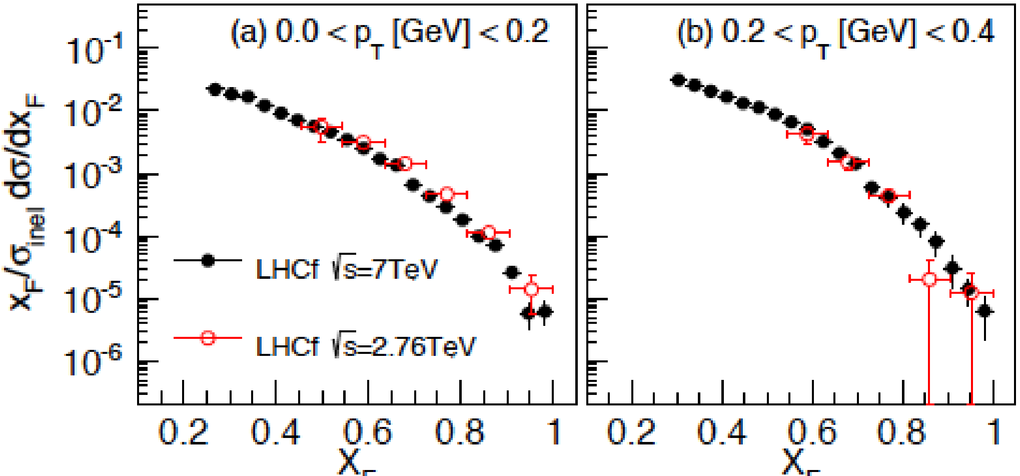
- Majority of energy flow from hadronic collisions concentrated in the very forward region, but reaction mechanism insufficiently understood there



- How to apply for understanding air-shower from ultra-high energy cosmic rays
  - Phenomenological approach
- How to understand non-perturbative aspect in QCD
  - Asymmetry measurement in addition to cross section

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)



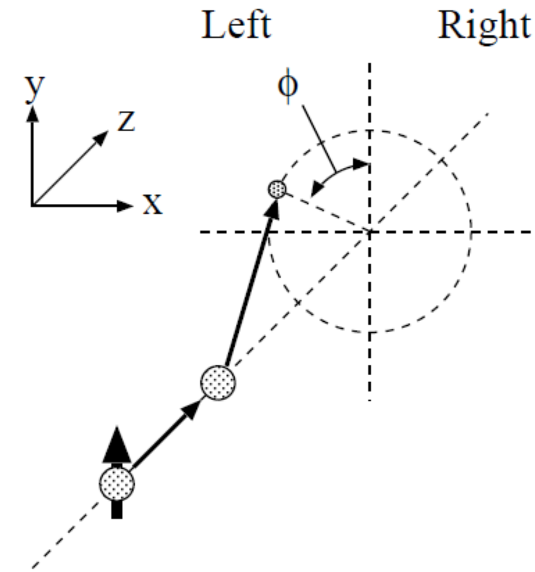
LHCf results of π^0 production cross section at $\sqrt{s}$=7TeV and 2.76TeV
Phys.Rev.D94 (2016) 032007

Transverse polarized proton collision

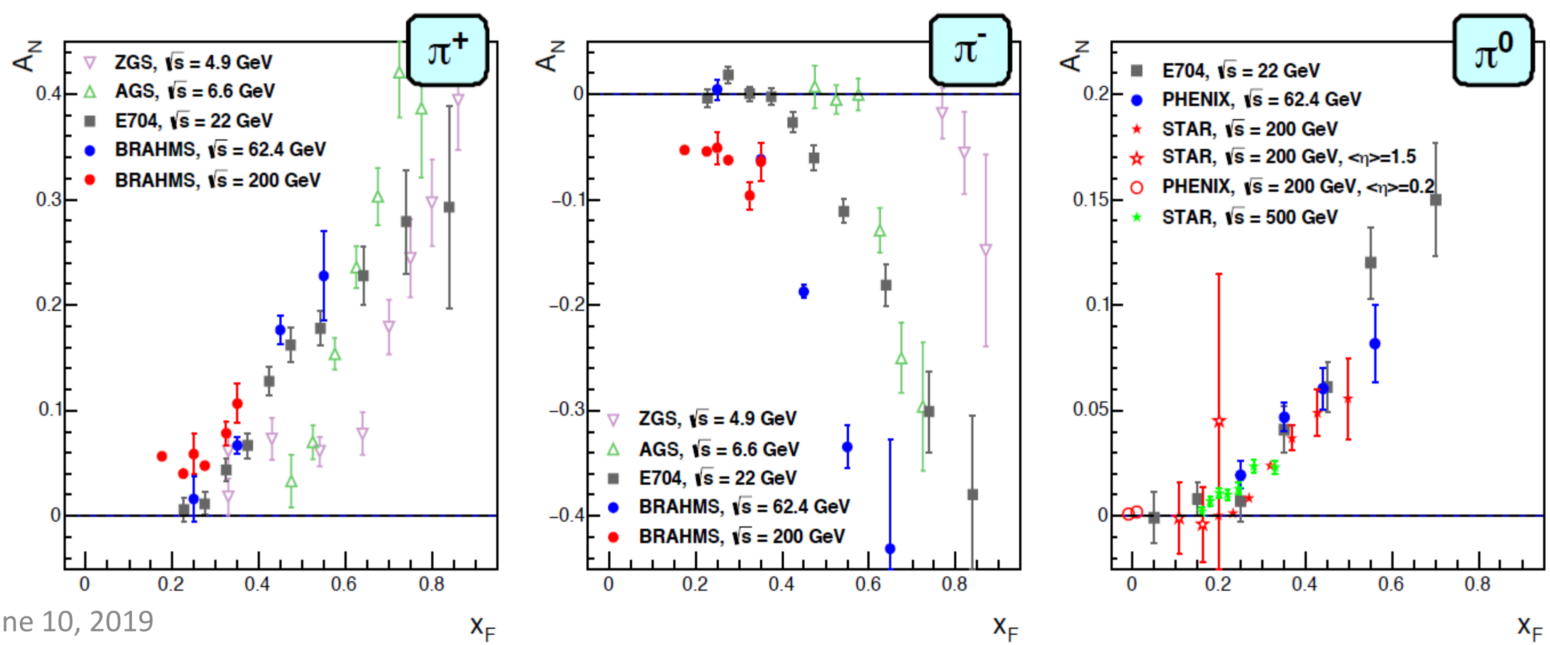
- A_N (transverse single-spin asymmetry) measurement

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

  - Azimuthal angle modulation (or dependence)

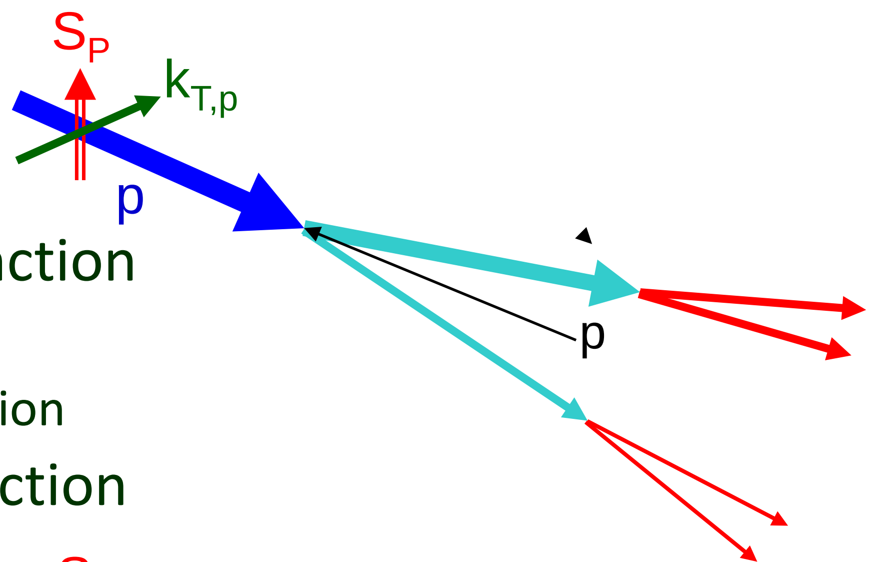


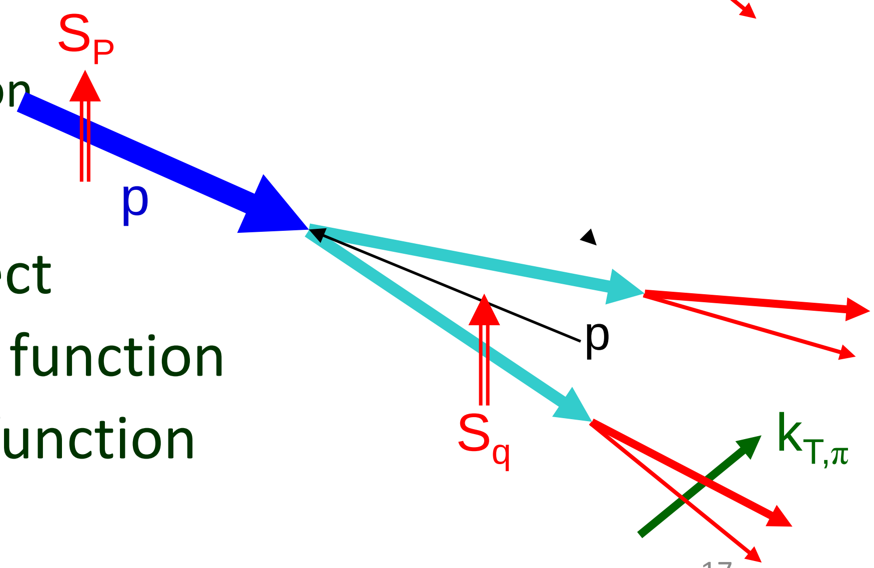
- Large A_N for forward hadron production
  - $1 < \eta < 4$, similar results in wide $\sqrt{s}$



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

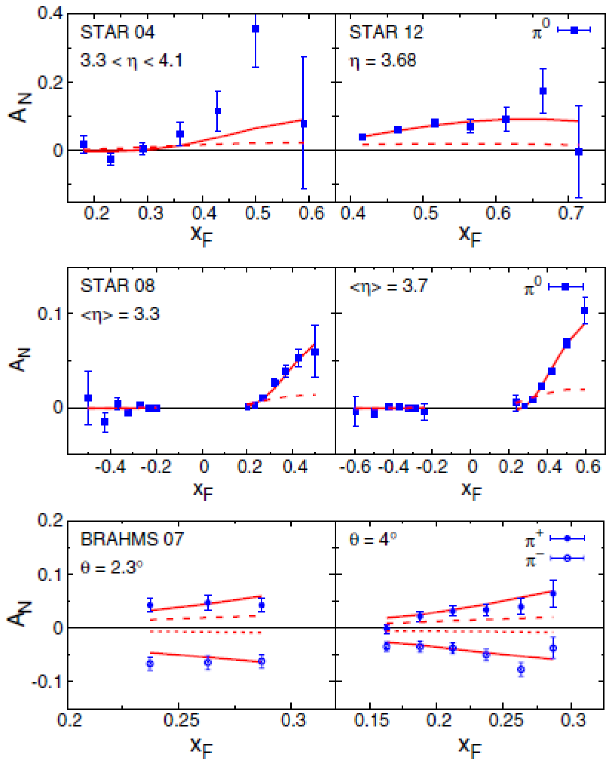


FIG. 1 (color online). Fit results for $A_N^{\pi^0}$ (data from [35–37]) and $A_N^{\pi^\pm}$ (data from [38]) for the SV1 input. The dashed line (dotted line in the case of π^-) means $\hat{H}^{\Im}_{FU}$ switched off.

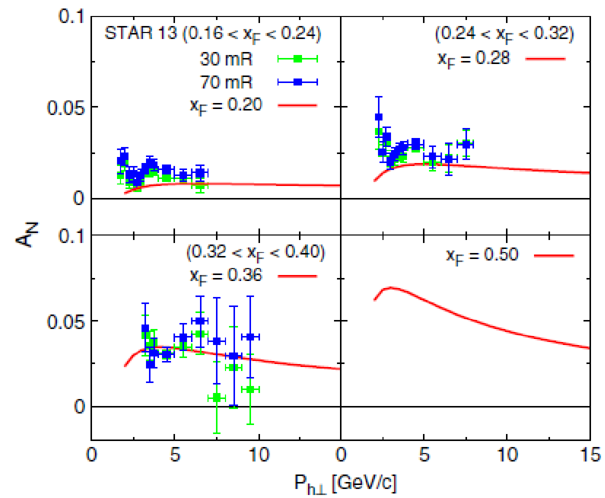
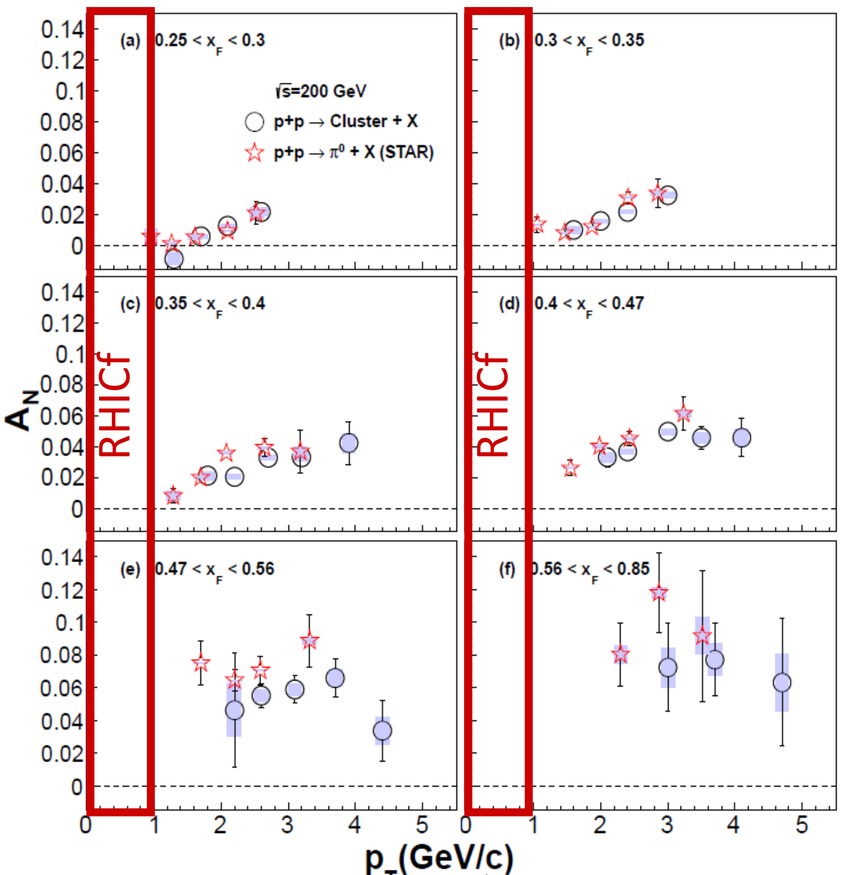


FIG. 4 (color online). A_N as function of $P_{h\perp}$ for SV1 input at $\sqrt{S} = 500$ GeV (data from [48]).

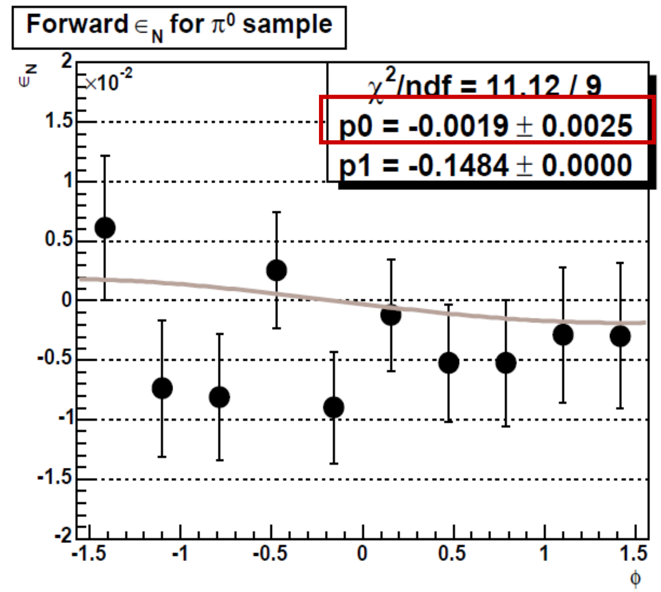
Kanazawa, Koike, Metz, Pitonyak
PRD 89, 111501 (2014).

π^0 asymmetry at RHICf

- p_T < 1 GeV/c, η > 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	$-0.022 \pm 0.030 \pm 0.002$	$0.007 \pm 0.021 \pm 0.001$

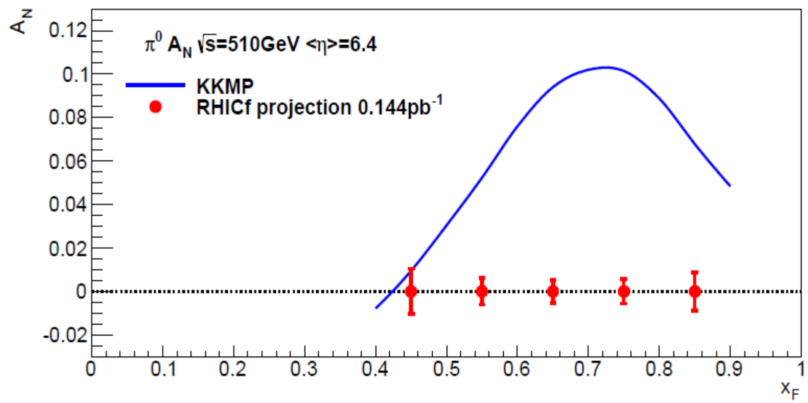
Phys. Lett. B650 (2007) 325.

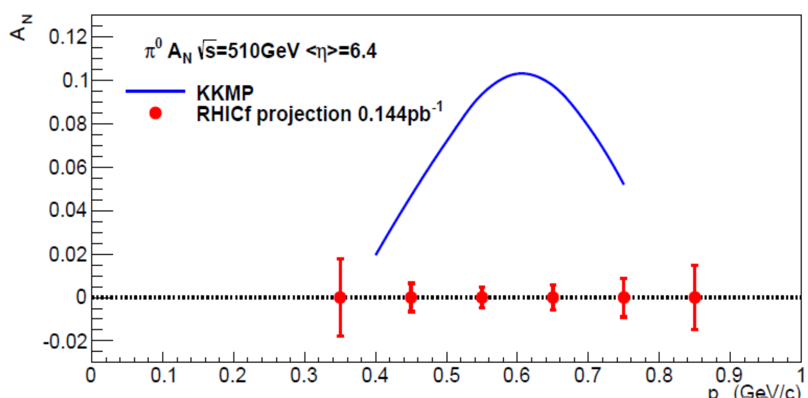
π^0 asymmetry at RHICf

- π^0 A_N measurement using TL at +y=16.6mm, <η> = 6.4, $\sqrt{s}$ = 510 GeV
  - 3×10^5 π^0 detected in 4-hour measurement
  - Comparison of existing η region (3–4) and RHICf high-η region (> 6)

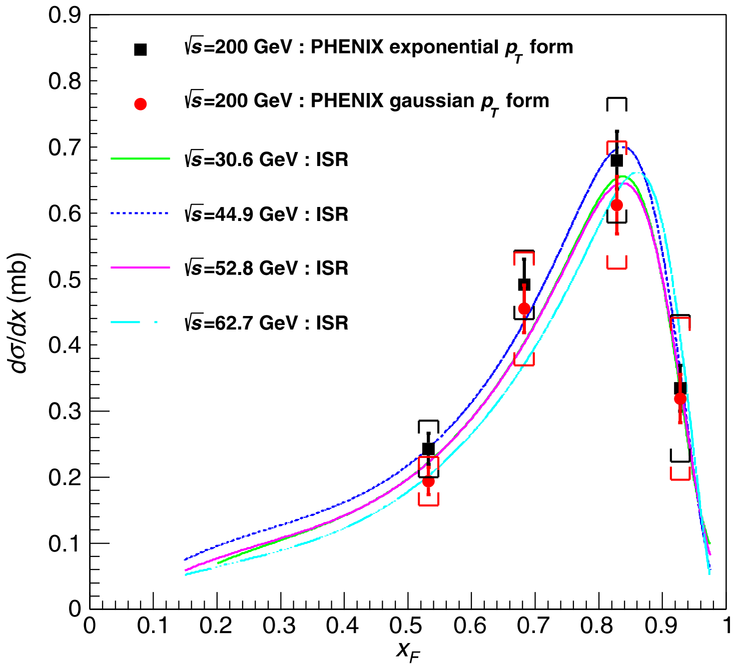
- Higher-twist effect calculation by Pitonyak
- pQCD calculation does not apply for the very low p_T values
- At p_T > 0.75 GeV/*c*, this mechanism cannot generate A_N since phase space vanishes

→ See Minho's presentation of first result from RHICf





Forward neutron production

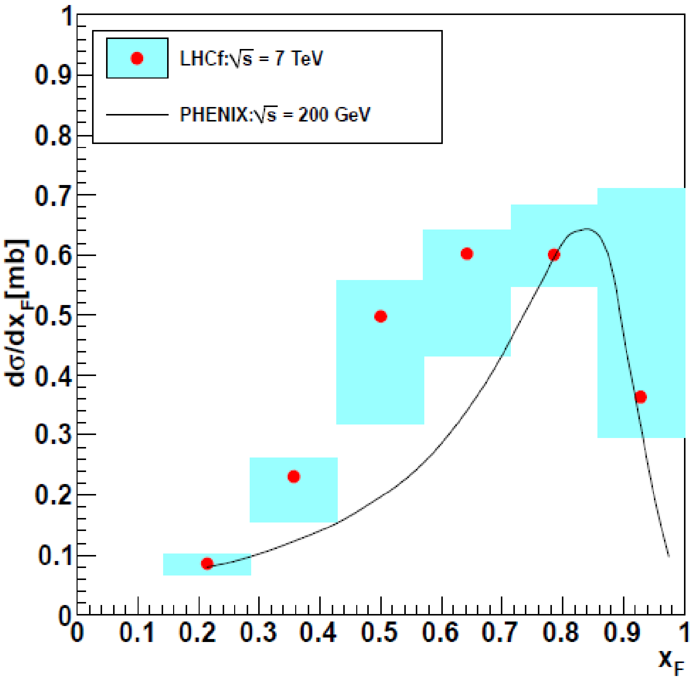


PHENIX, PRD, 88, 032006 (2013)

$p_T < 0.11\ x_F$ GeV/c

√s = 30-60 GeV @ISR

√s = 200 GeV @RHIC



LHCf

$p_T < 0.11\ x_F$ GeV/c

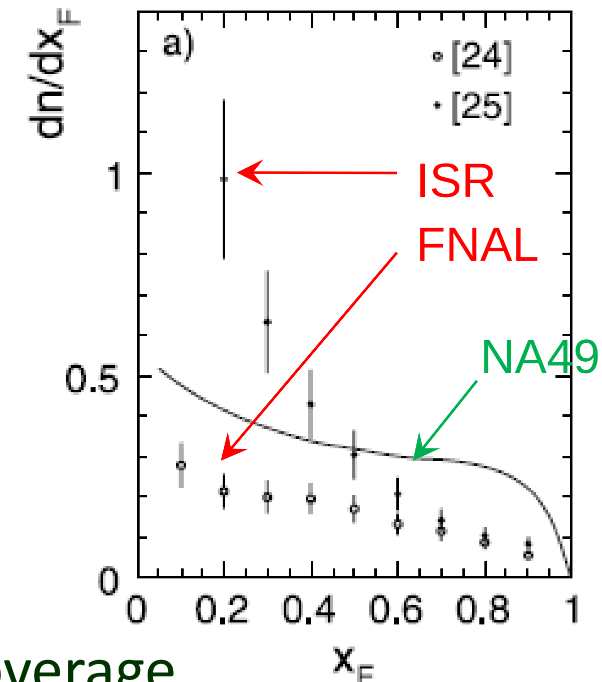
√s = 7000 GeV @LHC

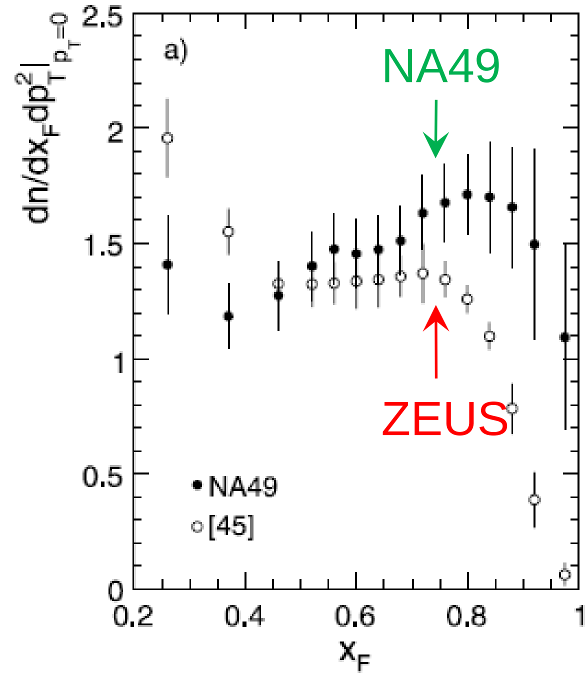
- PHENIX explains the result by 1 pion exchange
- More complicated exchanges at >TeV?

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 ~ 8 GeV^{-2} for $0.3 < x_F < 0.85$
  - x_F distribution
    - Suppression of the forward peak at high $\sqrt{s}$?
- More data necessary to understand the production mechanism
  - Asymmetry measurement as a new independent input

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

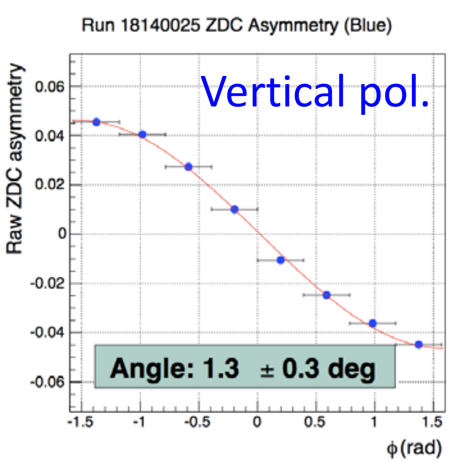


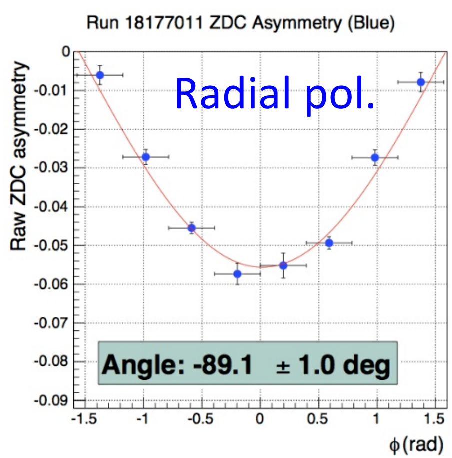


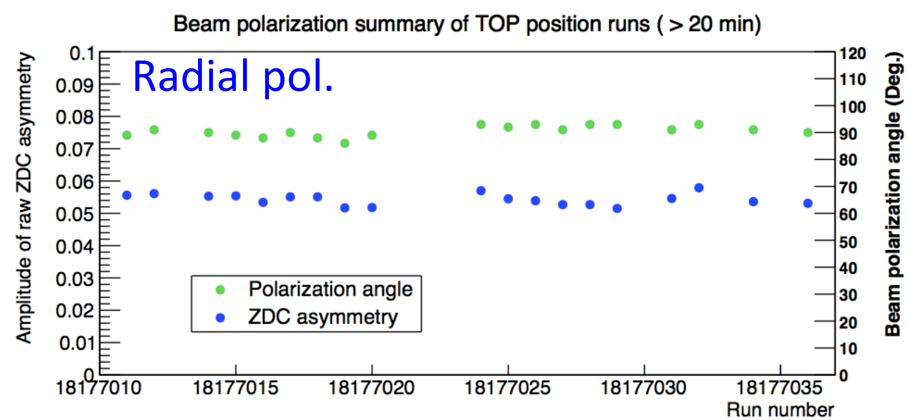
Wide η & p_T coverage

Commissioning

- $\sqrt{s}$ = 510 GeV
- Large β^* = 8 m
  - Requirement of parallel beam for angle and p_T precision
  - Luminosity ~10^{31} $cm^{-2}s^{-1}$
- Vertical → Radial polarization
  - For asymmetry measurement at large angle (or large p_T)
  - Change of polarization direction with Spin Rotator magnet

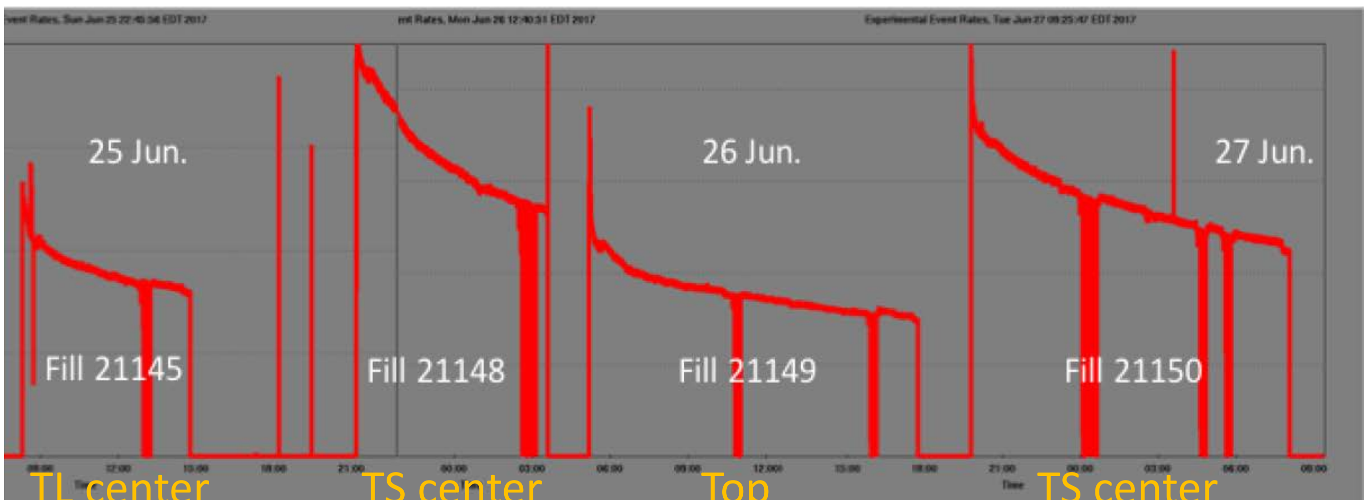


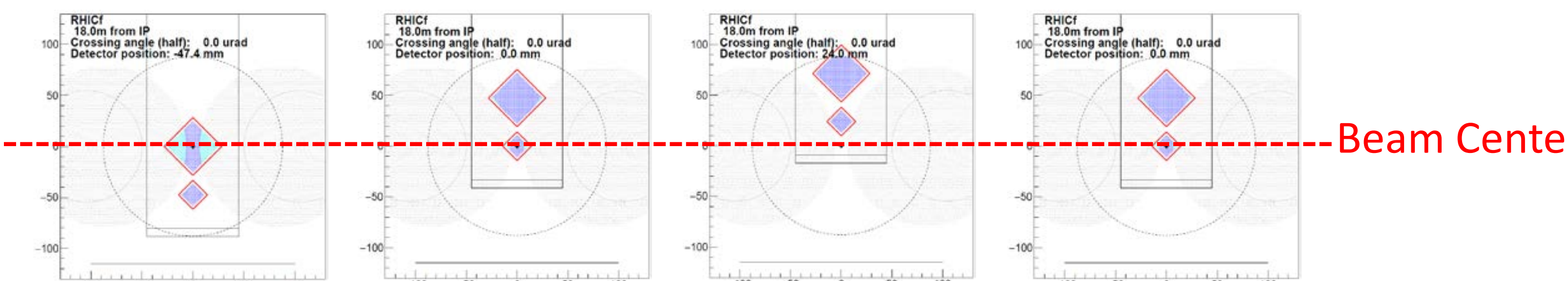




2017 operation

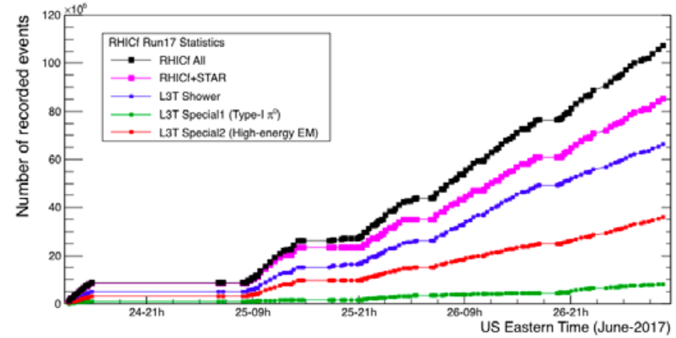
- June 23 commissioning of polarized proton collisions, detector installation at the final position, detector commissioning
  - β^* = 8m, radial polarization
- June 24 – 27 physics data acquisition
  - 27.7 hours, ~110M events, ~700 nb^{-1}
- 3 detector positions
  - TL center / TS center / Top position



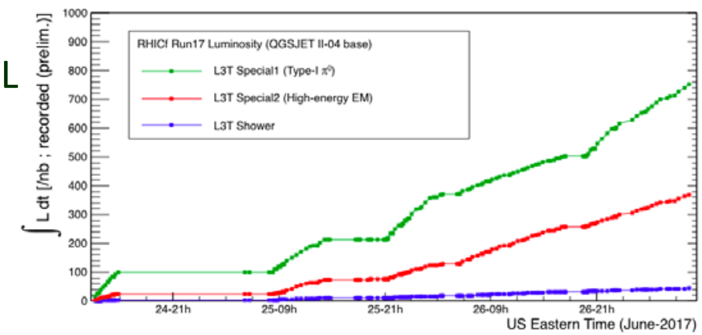


Data accumulation & statistics

- ~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

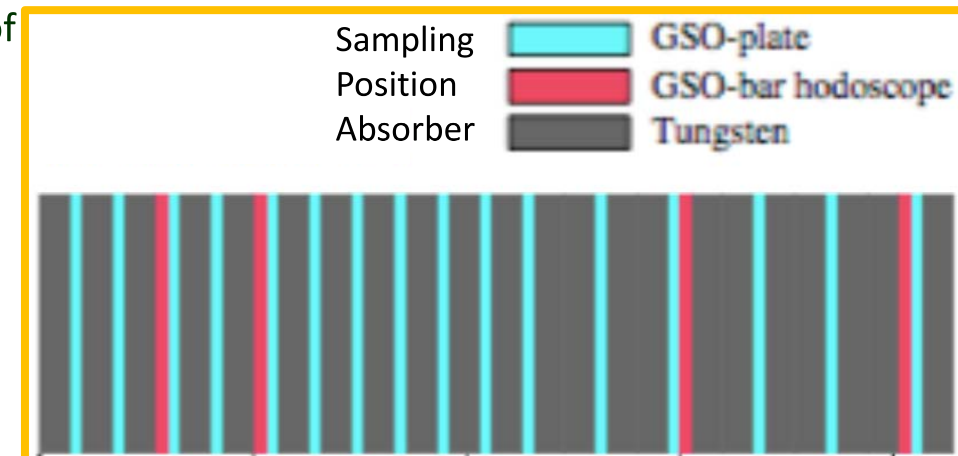


All data ~110M
RHICf+STAR
Shower
High-energy photon
2 photon



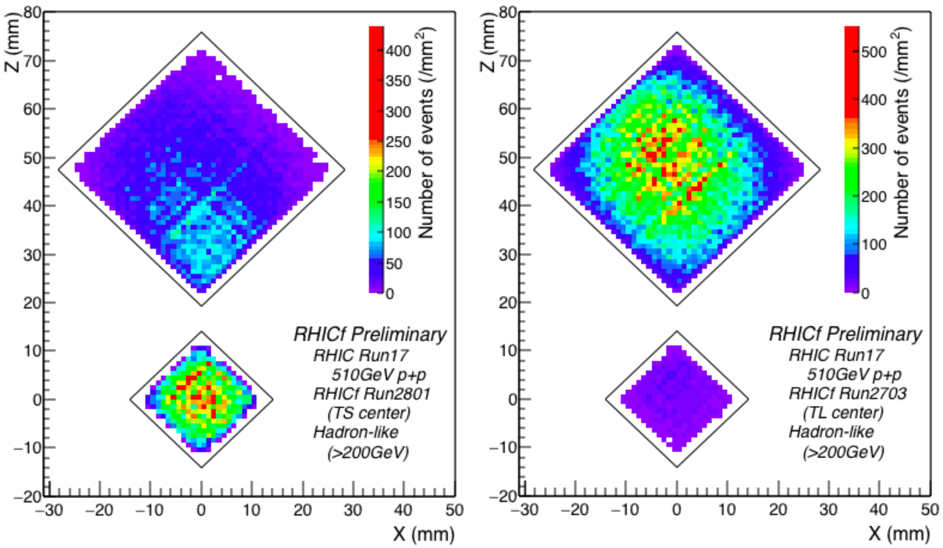
2 photon
~700 nb^{-1}

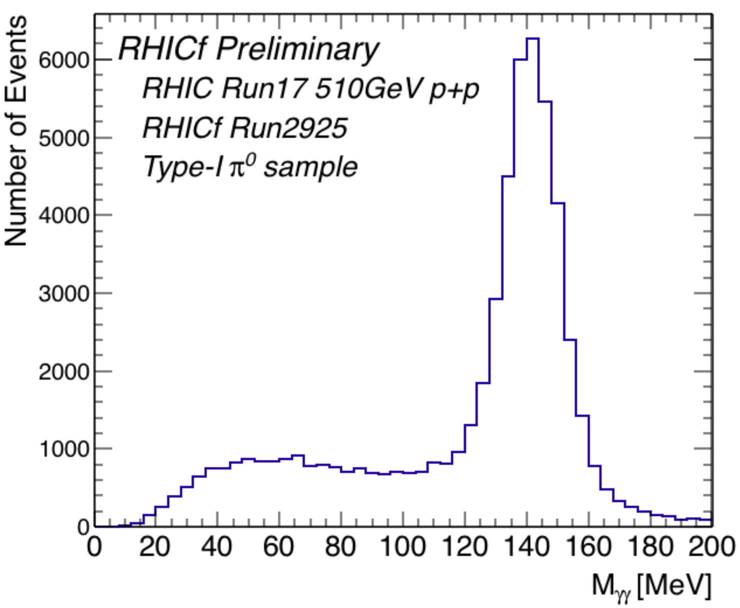
High-energy photon
Shower



Quick performance evaluation

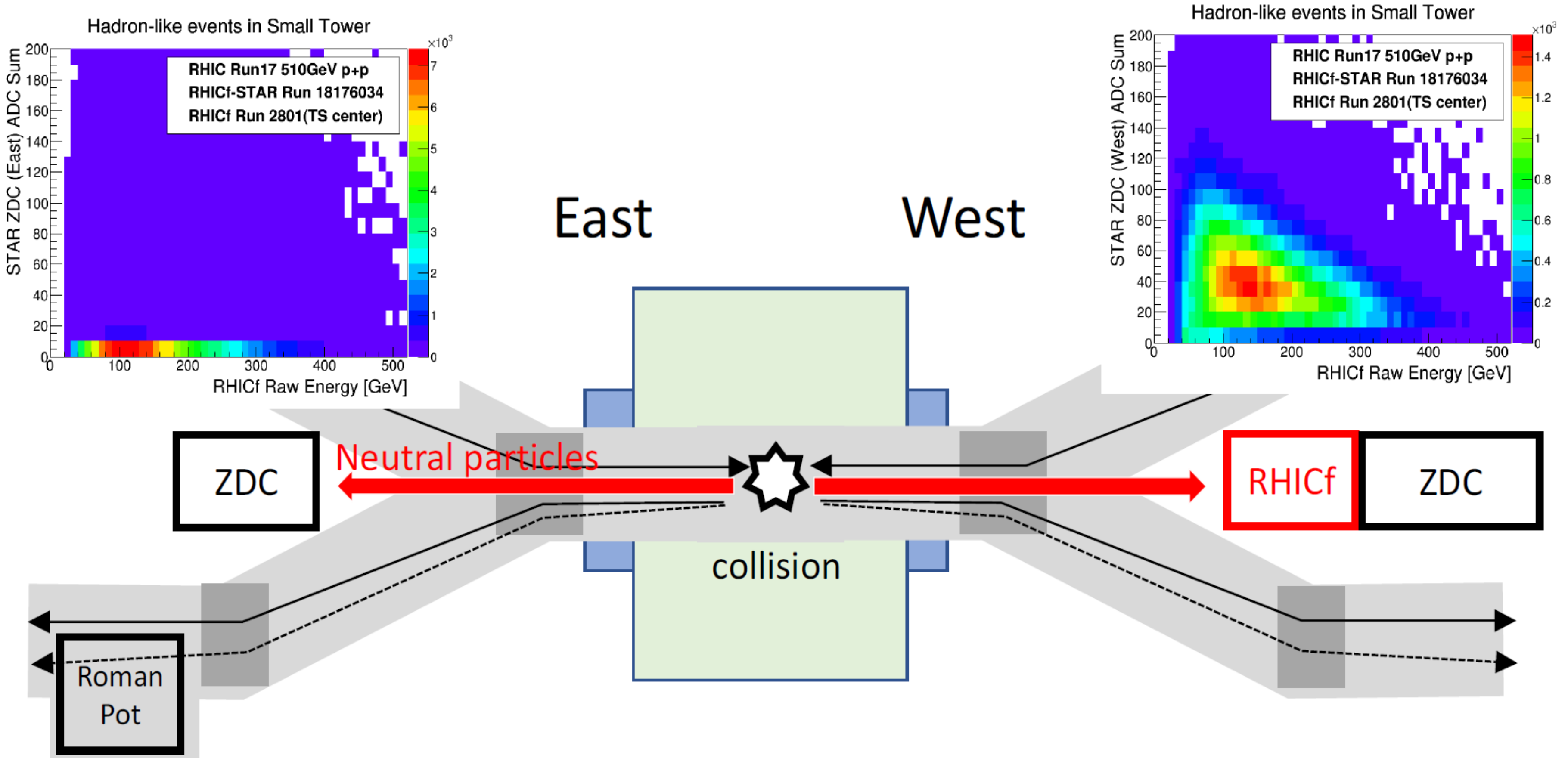
- Beam center position
  - Checked with > 200 GeV hadron shower incident position
- $\pi^0 \to \gamma\gamma$
  - Invariant mass distribution of photon-pair event
  - To be improved by energy calibration and shower leakage correction





RHICf & STAR correlation

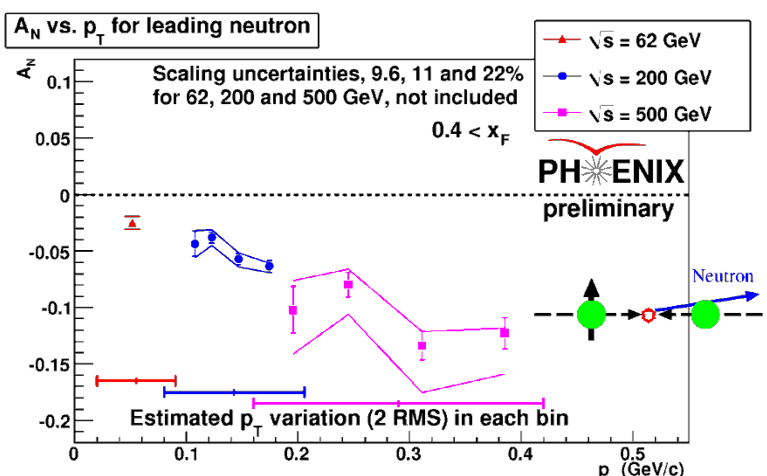
- Correlation of RHICf calorimeter and STAR ZDC
  - (Anti)correlation with deep-penetrating hadronic shower in the RHICf calorimeter and shower leakage measured in the ZDC
  - Correlation only with the West ZDC as expected
  - Event correspondence of RHICf DAQ and STAR DAQ correctly confirmed



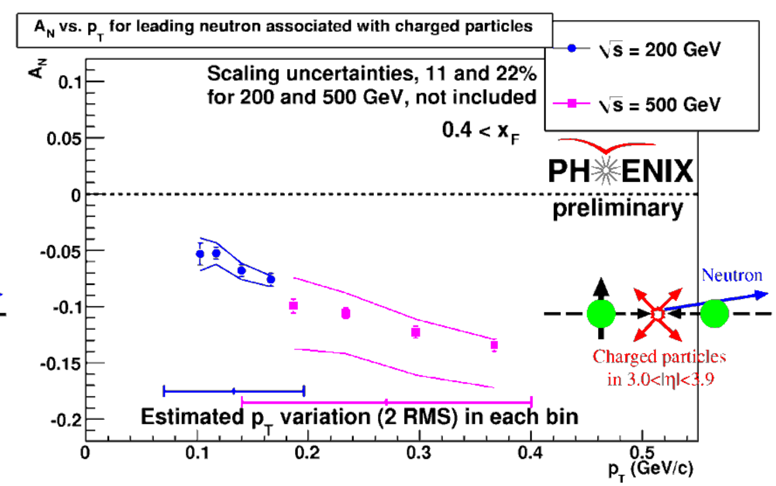
Neutron asymmetry

- Very large left-right asymmetry (A_N) of very forward neutron discovered at RHIC
  - A_N(62 GeV) < A_N(200 GeV) < A_N(500 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

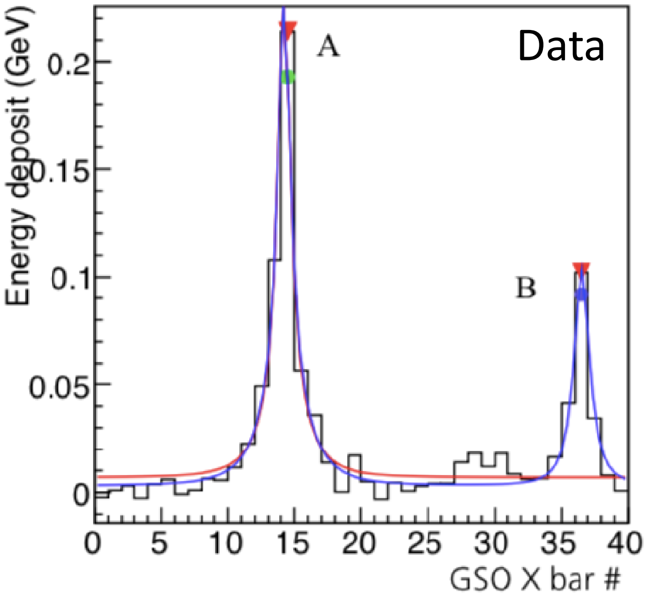


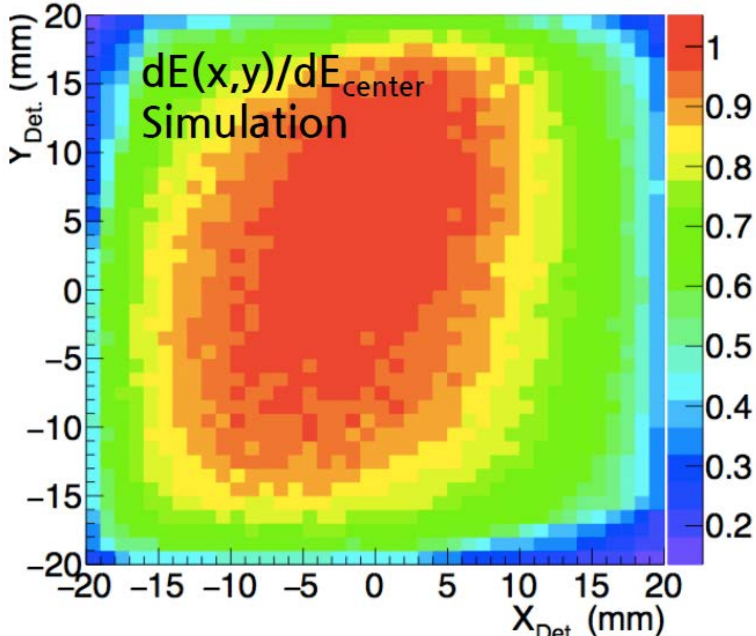
Neutron with charged particles

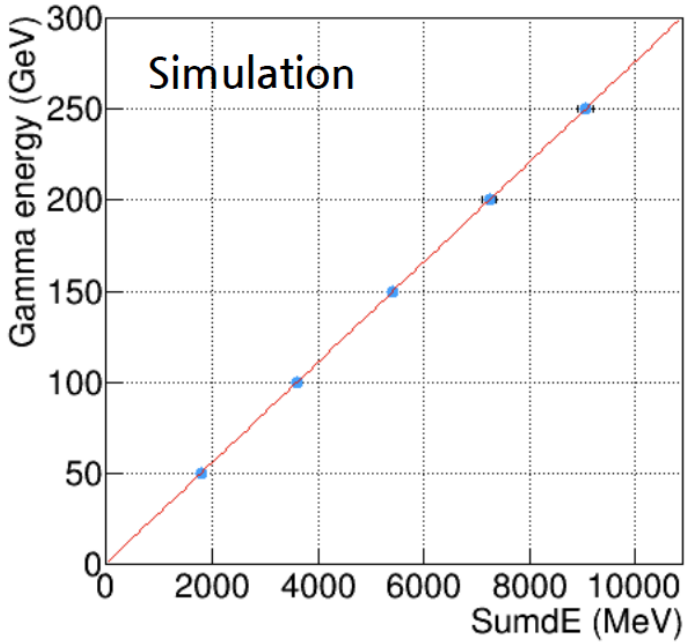


π^0 reconstruction

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

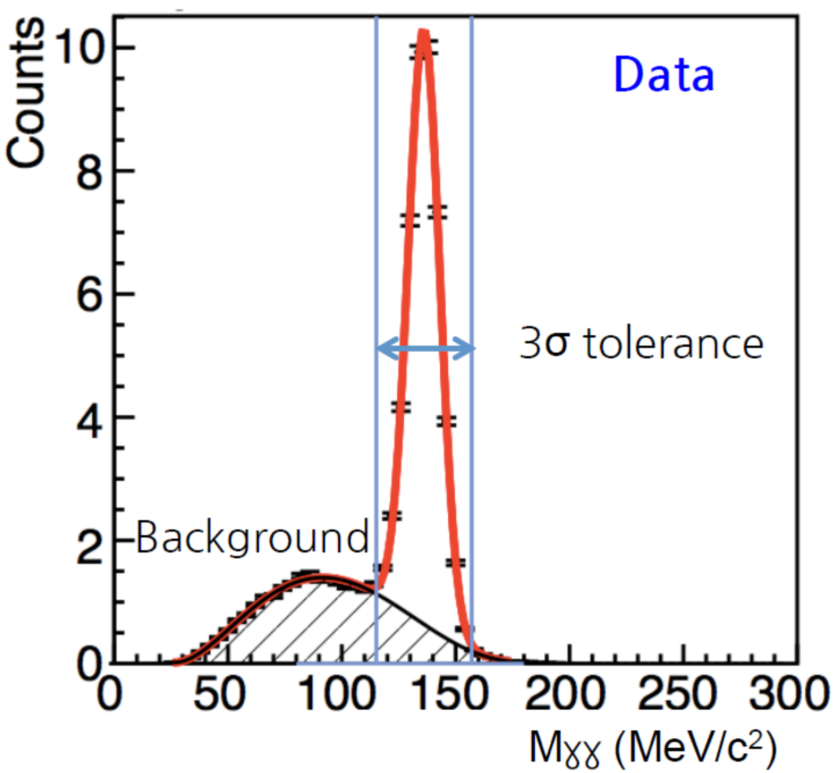


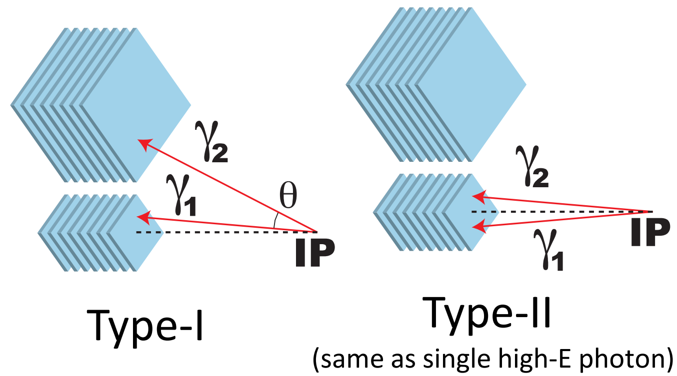


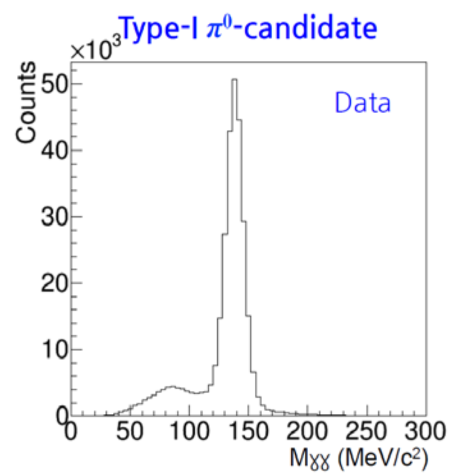


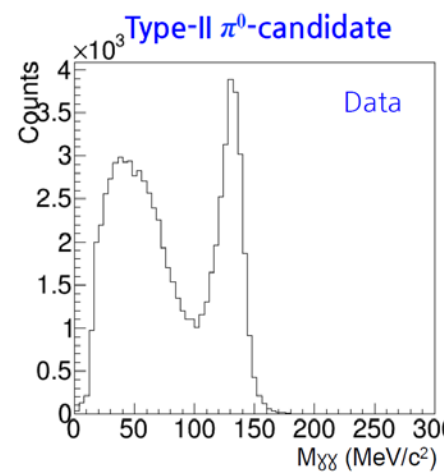
π^0 reconstruction

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



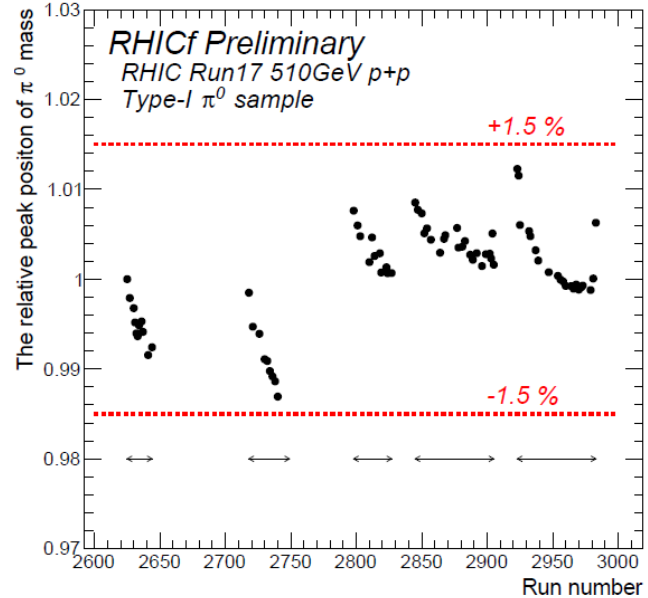




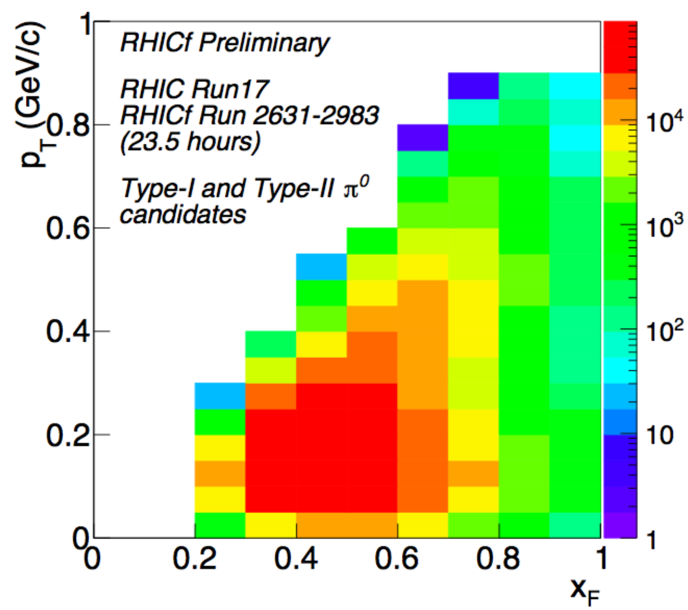


π^0 reconstruction

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

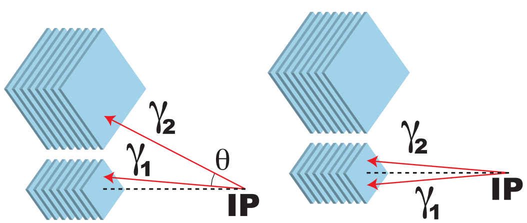


- π^0 kinematics
  - $p_T < 1.0$ GeV/c
  - $0.2 < x_F < 1.0$



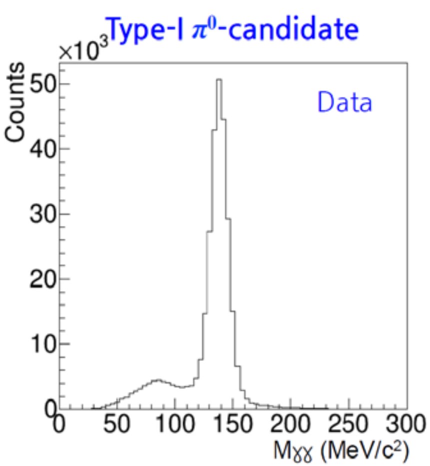
π^0 *kinematics*

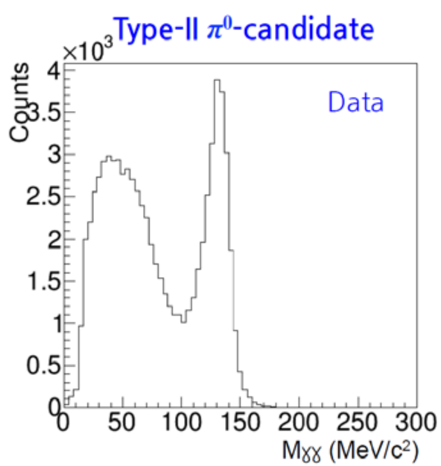
- π^0 peak with ~10 MeV/c^2 width
  - 3σ region selected as π^0 candidates
- $p_T < 1.0$ GeV/c
- $0.2 < x_F < 1.0$

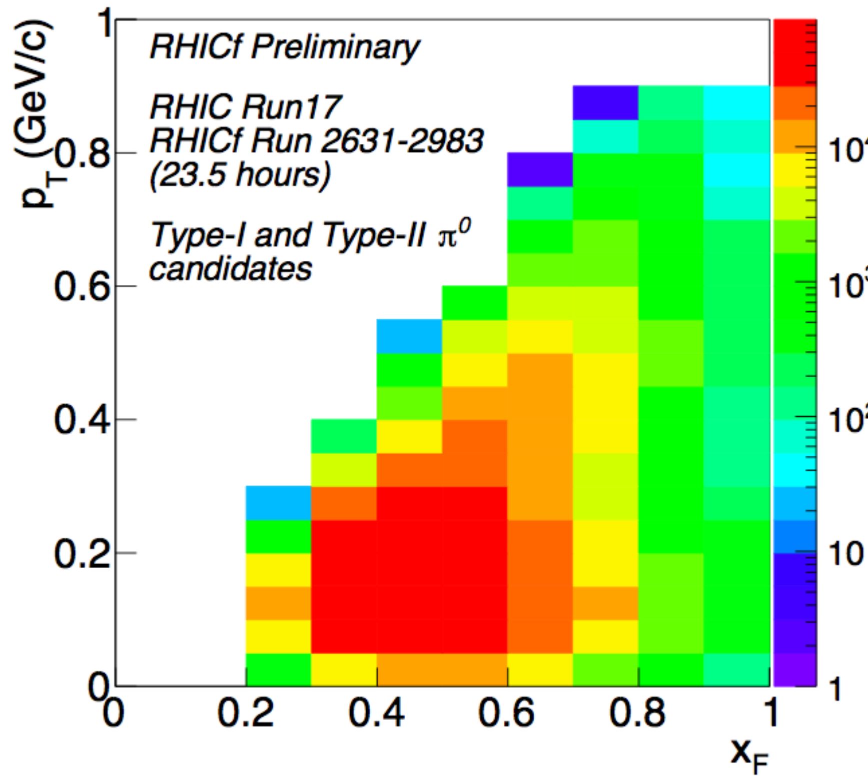


Type-I Type-II

(same as single high-E photon)







Future plan

- RHIC schedule
  - STAR p+p √s = 510 GeV in 2021 (?)
    - Possible RHICf proposal of p+p & p+A
  - sPHENIX p+p √s = 200 GeV & p+A
    - Baseline 2023-2025: p+p & p+A in 2024
    - Extension 2026-2027 (before EIC)
- Detector development
  - Collaboration with people having common interest in position-sensitive calorimeter
  - Possible proposal for EIC R&D program for very forward measurements
    - "Generic Detector R&D for an Electron Ion Collider" operated by BNL
    - Radiation tolerance / position-sensitive calorimeter / EIC IR design (ZDC + spectrometer)