# Surprising transverse single spin asymmetry of $\pi^0$ at almost zero degree in 510 GeV polarized $p + p$ collisions

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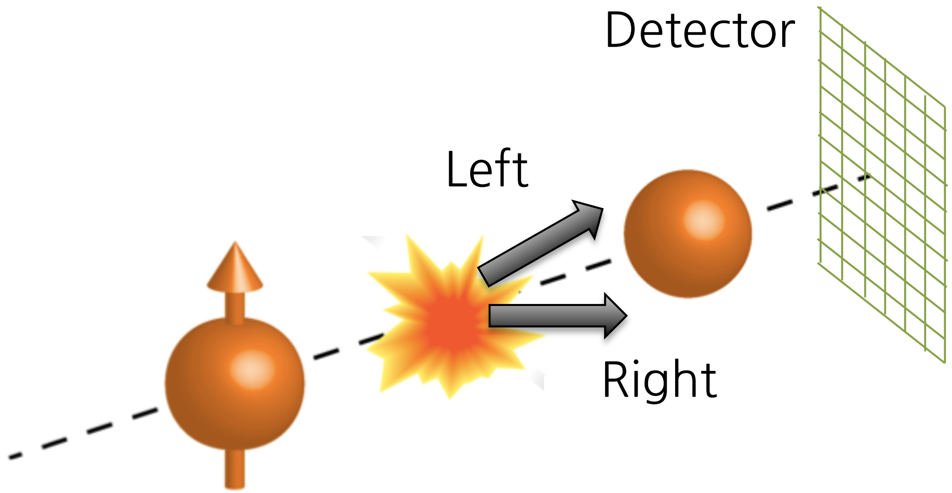
**on behalf of the RHICf collaboration**

12 Oct. 5th Japan-Korea meeting

# Transverse single spin asymmetry ($A_N$)



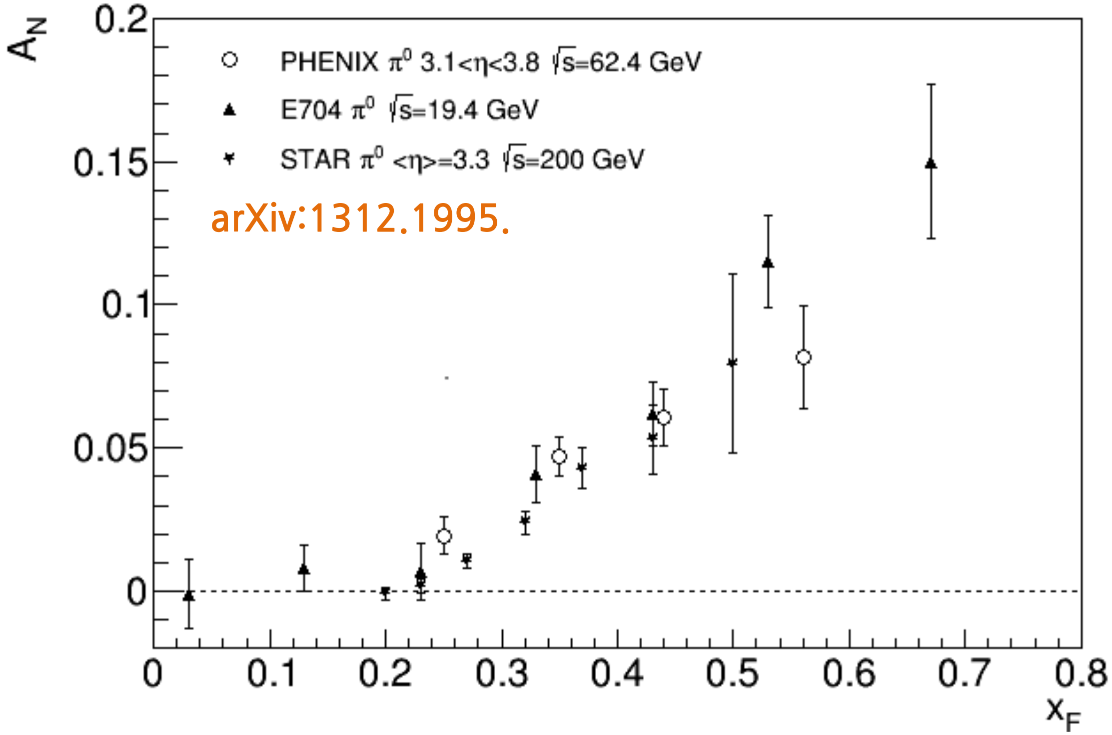

$$A_N = \frac{\sigma_L^{\uparrow} - \sigma_R^{\uparrow}}{\sigma_L^{\uparrow} + \sigma_R^{\uparrow}} = \frac{\sigma_L^{\uparrow} - \sigma_L^{\downarrow}}{\sigma_L^{\uparrow} + \sigma_L^{\downarrow}}$$

- In polarized p+p collision, $A_N$ is defined as a left-right cross section asymmetry of a specific particle.

- Non-zero $A_N$ of $\pi^0$ has been a starting point of the study for the parton's spin-related transversity and more detailed interaction mechanism among quarks and gluons.

# $A_N$ in forward $\pi^0$ production

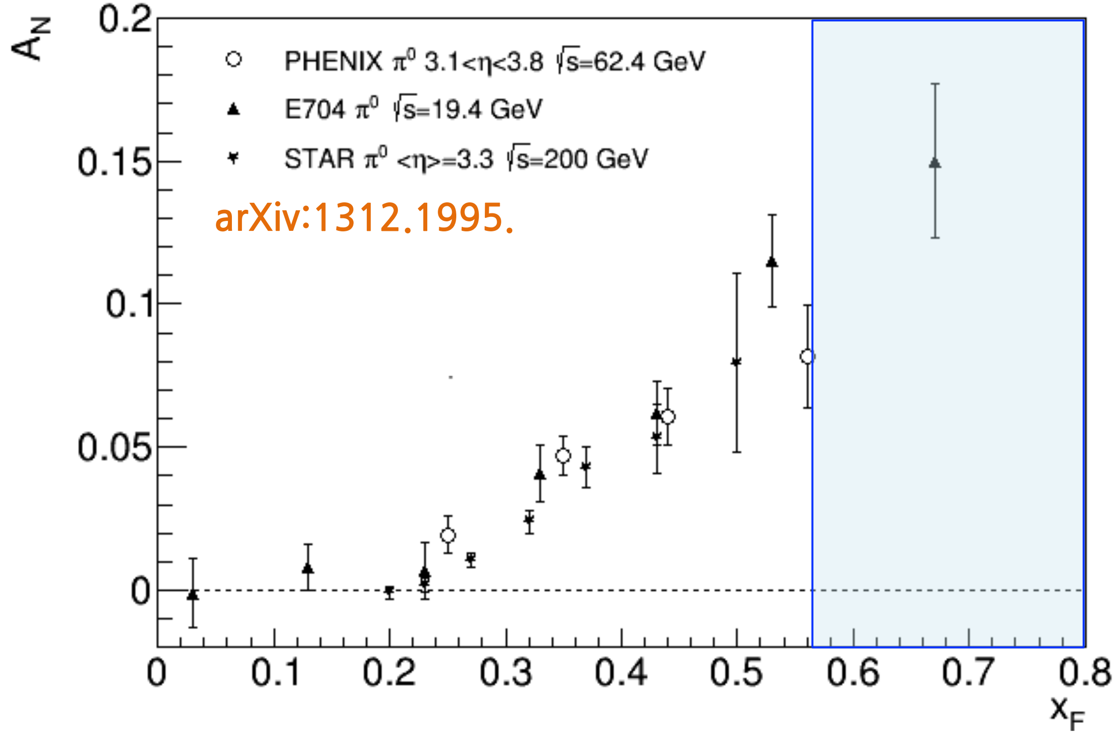
$3 < \eta < 4$




- Observed non-zero $A_N$ of $\pi^0$ ever has been interpreted based on only perturbative picture theoretically.

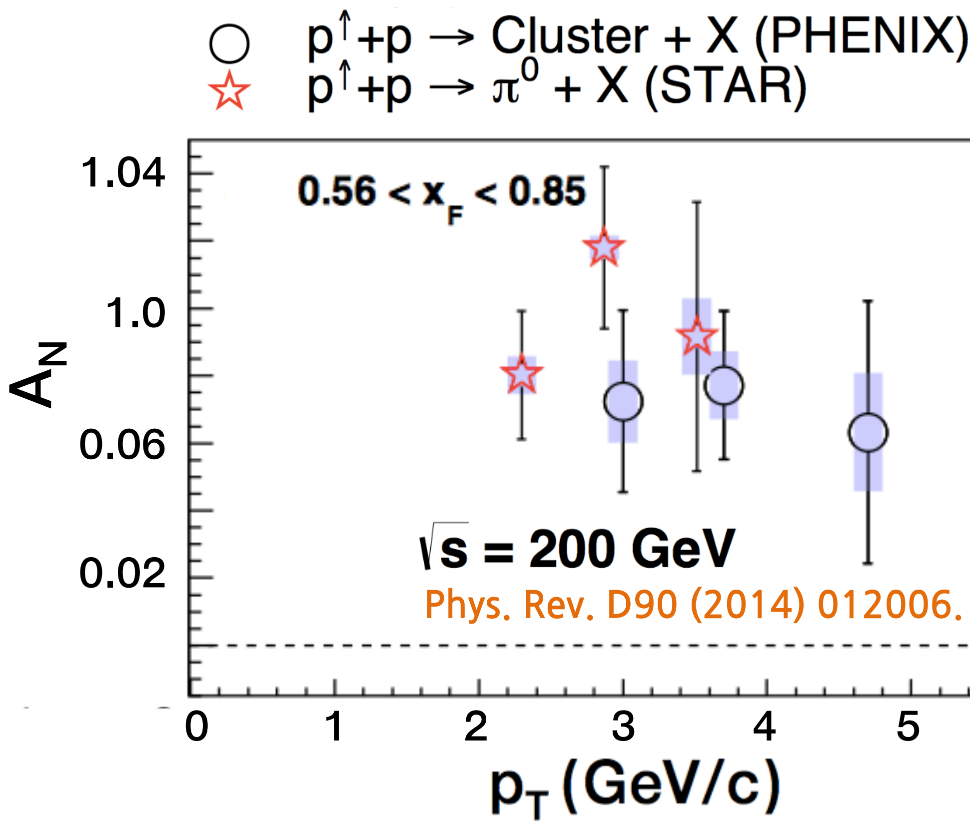
# $A_N$ in forward $\pi^0$ production

3 < $\eta$ < 4




- Observed non-zero $A_N$ of $\pi^0$ ever has been interpreted based on only perturbative picture theoretically, but NOT exactly understood yet.

# $A_N$ in forward $\pi^0$ production




- Observed non-zero $A_N$ of $\pi^0$ ever has been interpreted based on only perturbative picture theoretically.
- No experimental necessity and effort to measure the very forward $\pi^0$ production below 1 GeV/c.

# New question to the $A_N$ of forward $\pi^0$

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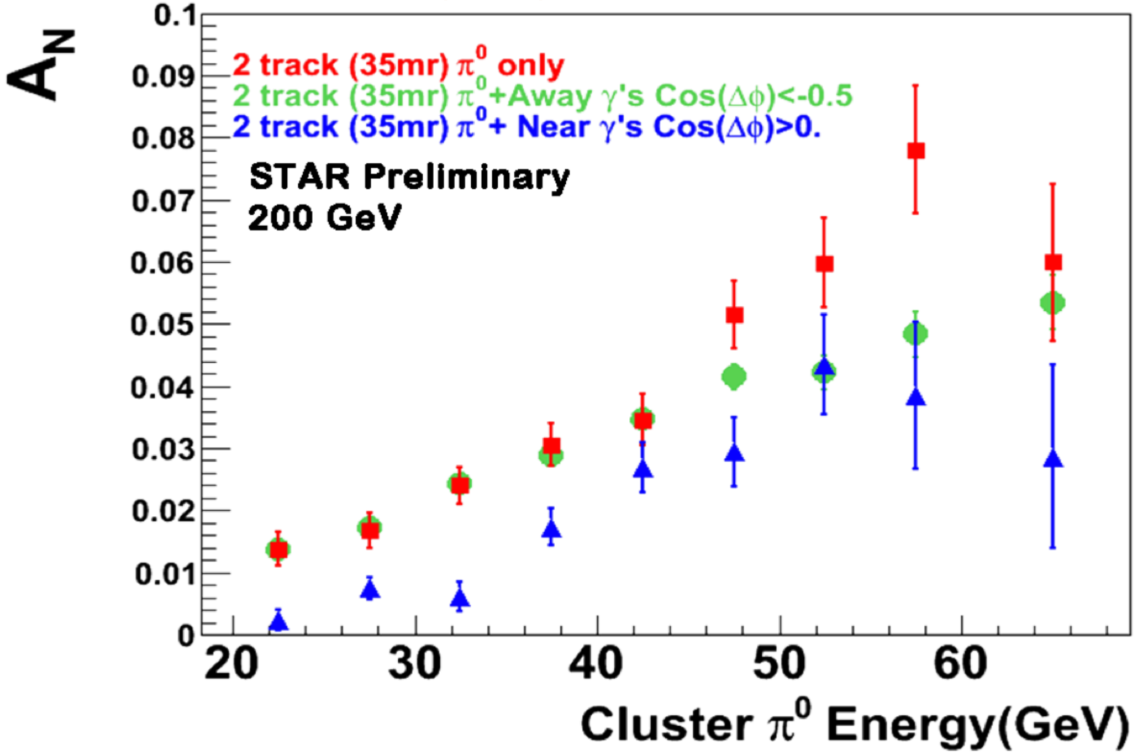
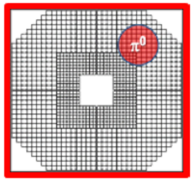
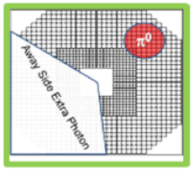
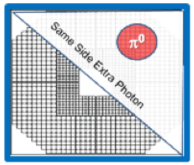



$2.6 < \eta < 4$
$p_T > 1$ GeV/c



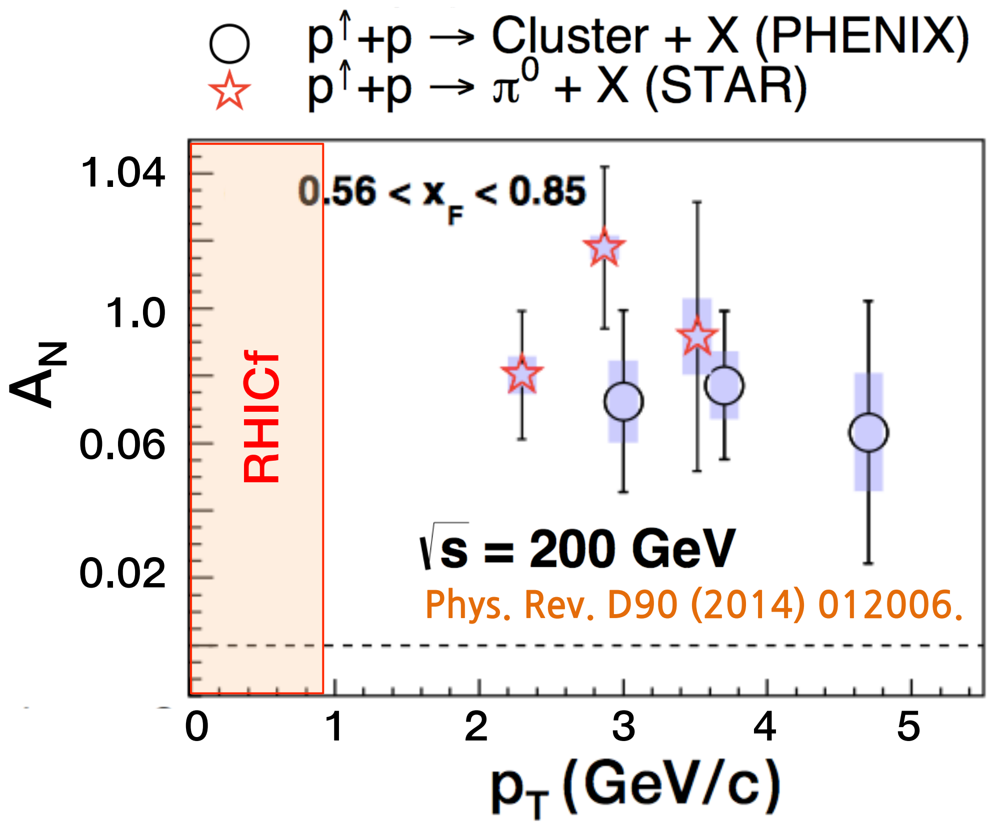




More isolated

Less isolated

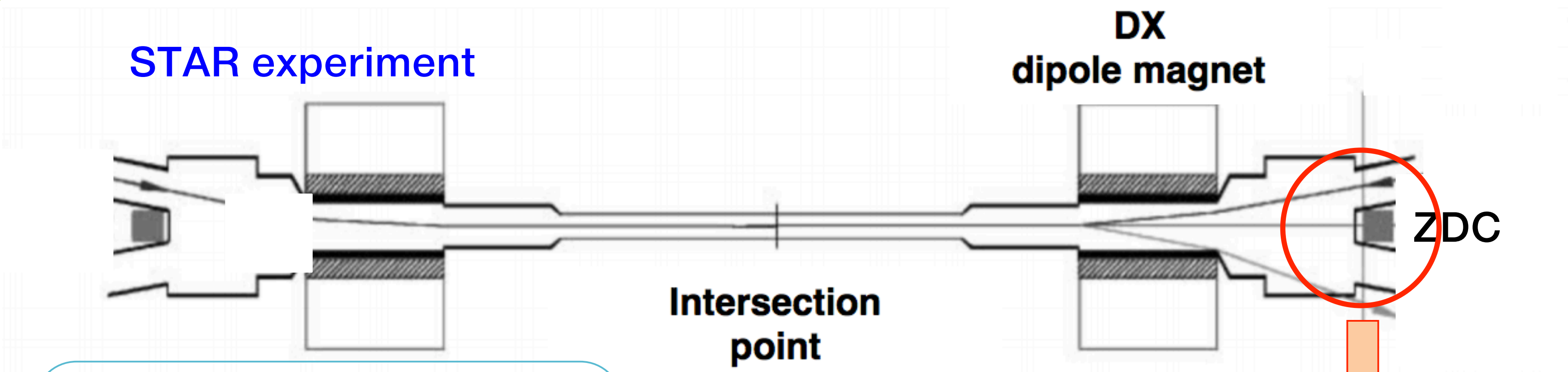
- Larger $A_N$ was observed by more isolated $\pi^0$ than less isolated one.
- Non-perturbative process may have a finite contribution to the $\pi^0$ $A_N$ as well as perturbative one.

# $A_N$ in forward $\pi^0$ production

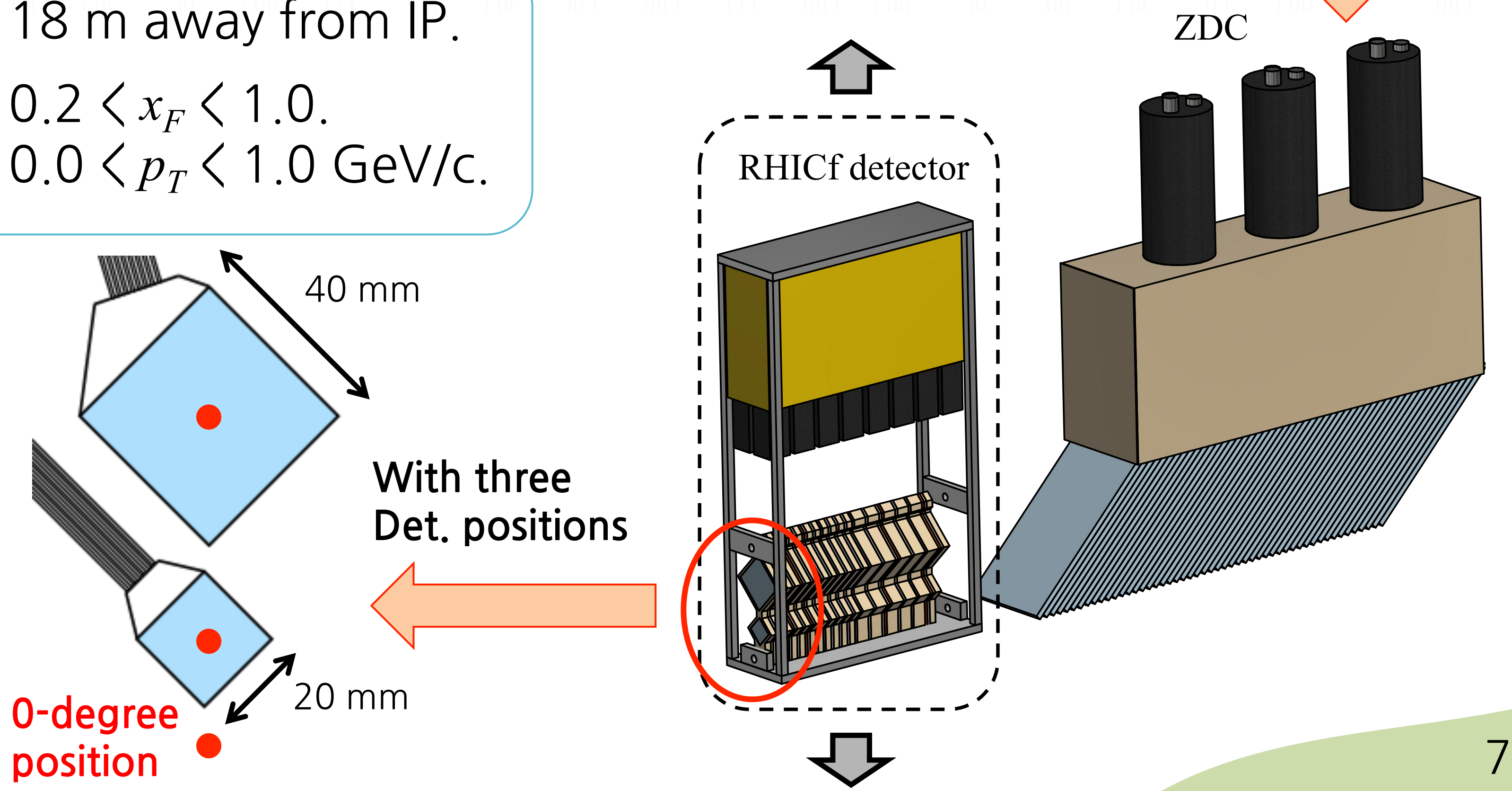



- Now, we have a strong motivation to measure the $A_N$ of very forward $\pi^0$ production.
- RHICf experiment measured vey forward ($6 < \eta$) $\pi^0$ $A_N$ to study the non-perturbative contribution to it in detail.

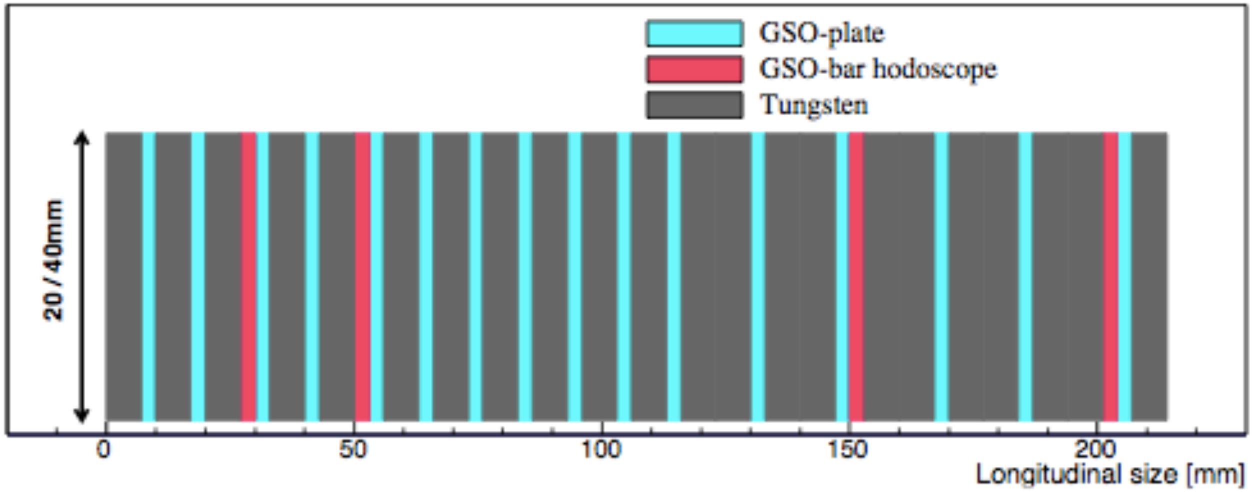
# RHIC forward (RHICf) experiment

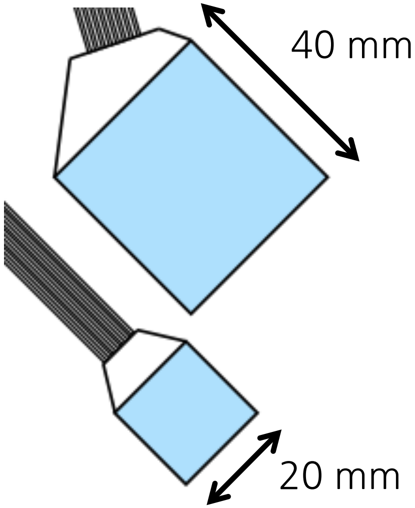



- 18 m away from IP.
- $0.2 < x_F < 1.0.$
  $0.0 < p_T < 1.0$ GeV/c.



# RHICf detector

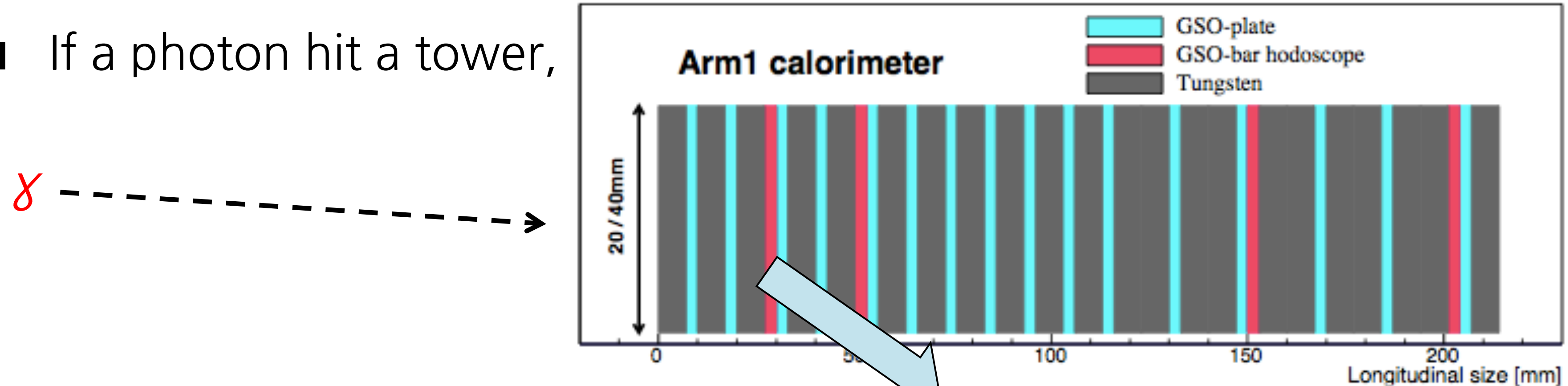


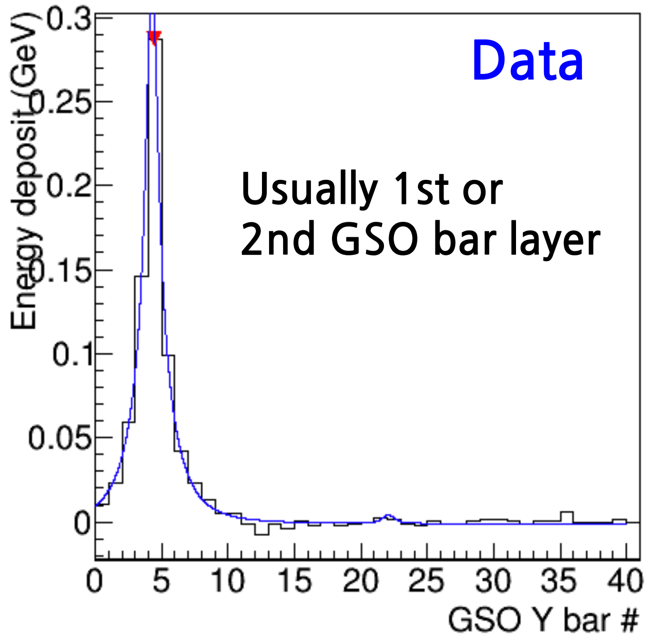



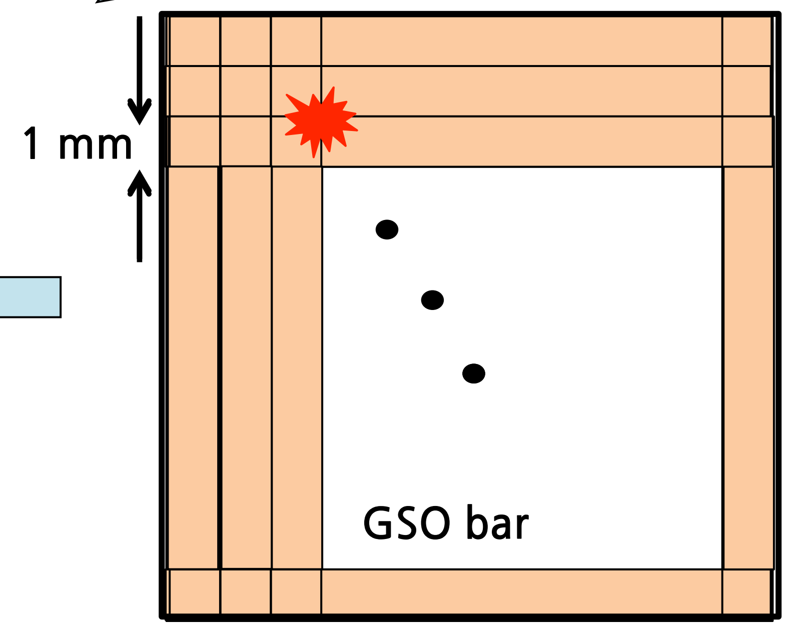

- Combination of small (20 mm) and large (40 mm) sampling calorimeters.
- 17 tungsten absorbers, 16 GSO plates (energy) and 4 GSO bar layers (position).
- 44 $X_0$: EM shower development is stopped in the middle of the Det.

# Position reconstruction of photon

- If a photon hit a tower,



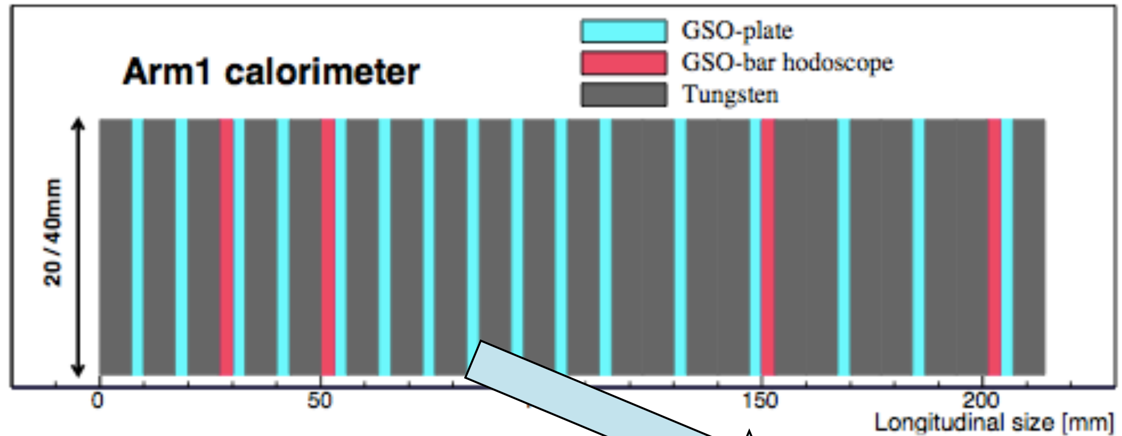



# Energy reconstruction of photon

- If a photon hit a tower,

γ → (x, y)




dE(x, y)

↓ Cor.1

$dE_{center}$

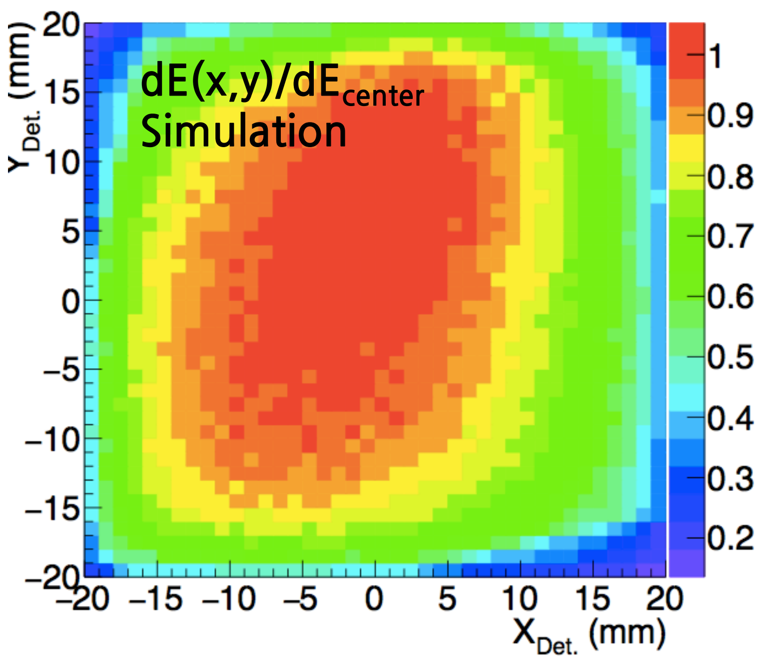
↓

SumdE

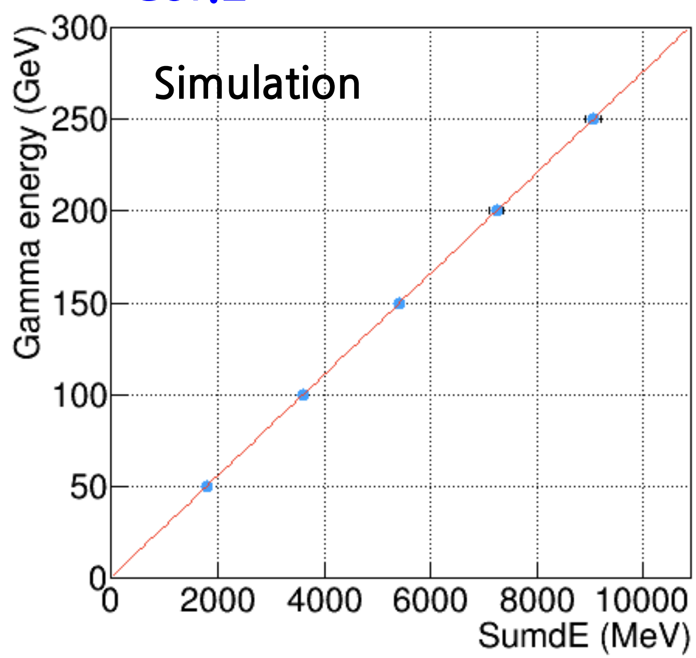
↓ Cor.2

$E_{gamma}$

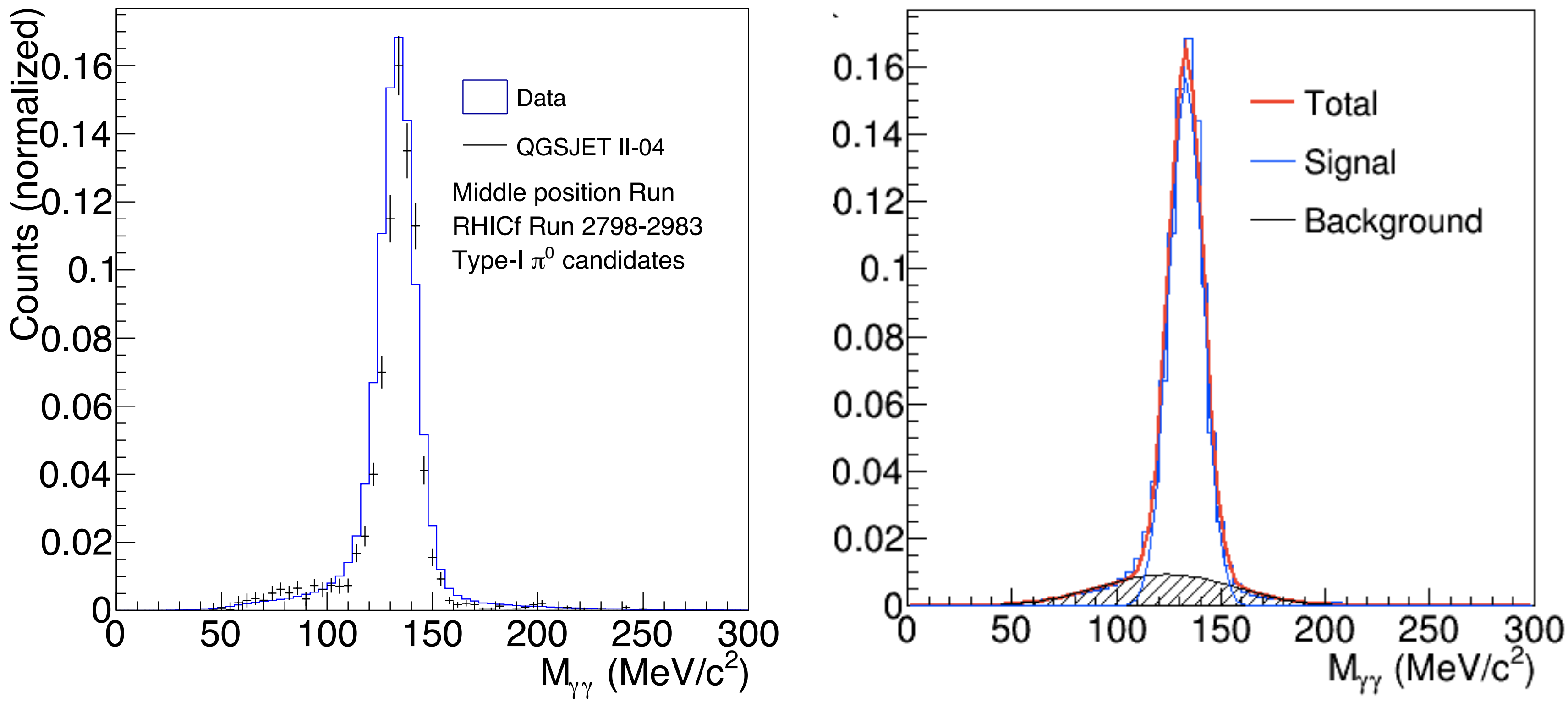
Cor.1




Cor.2

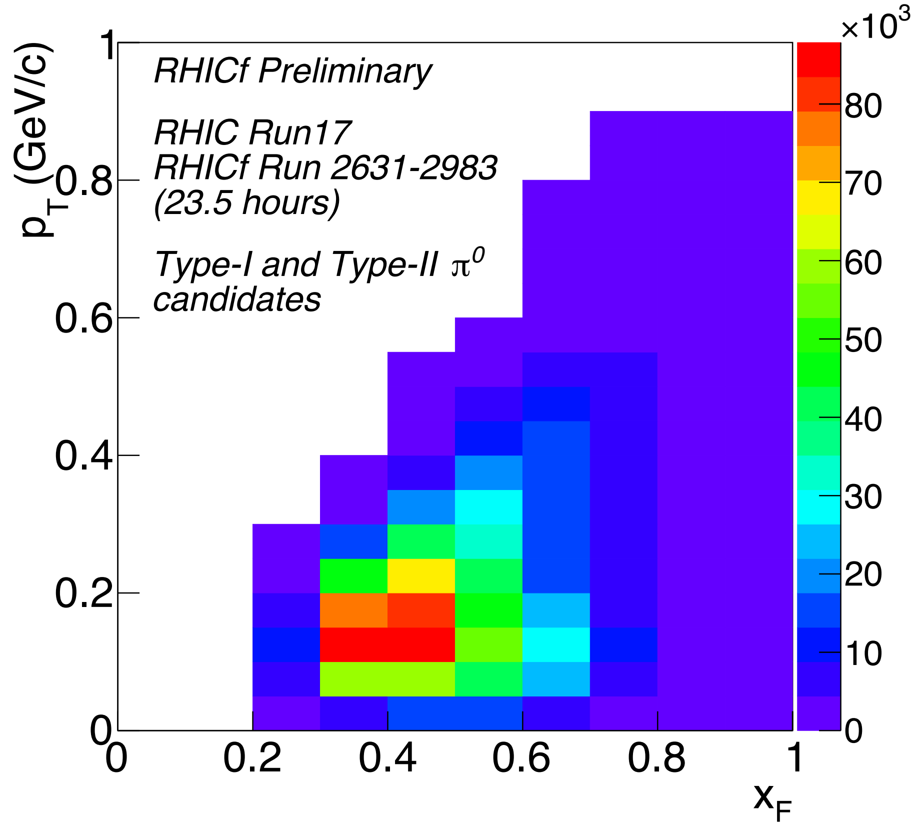


# Invariant mass of two photons




- Data is well matched with simulation showing clear $\pi^0$ peak around 135 MeV/$c^2$ with ~8 MeV/$c^2$ peak width.
- Invariant mass was fitted by polynomial for background and Gaussian for $\pi^0$.
- Background part usually comes from coincidence of two photons from different $\pi^0$, not wrong reconstruction.

# $\pi^0$ kinematics & $A_N$ calculation

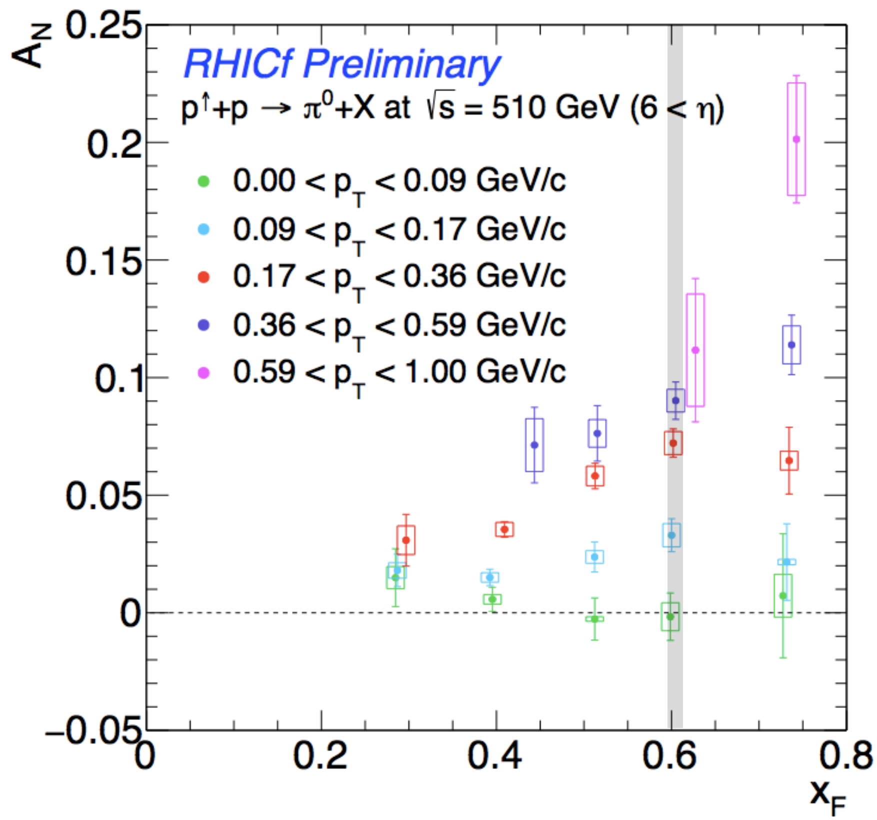



$$A_N = \frac{1}{P}\frac{1}{D_\phi}\left(\frac{N^{\uparrow} - RN^{\downarrow}}{N^{\uparrow} + RN^{\downarrow}}\right)$$

- Very forward $\pi^0$ over the $x_F$ range of $0.2 < x_F < 1.0$ and $p_T$ range of $0.0 < p_T < 1.0$ GeV/c was measured.

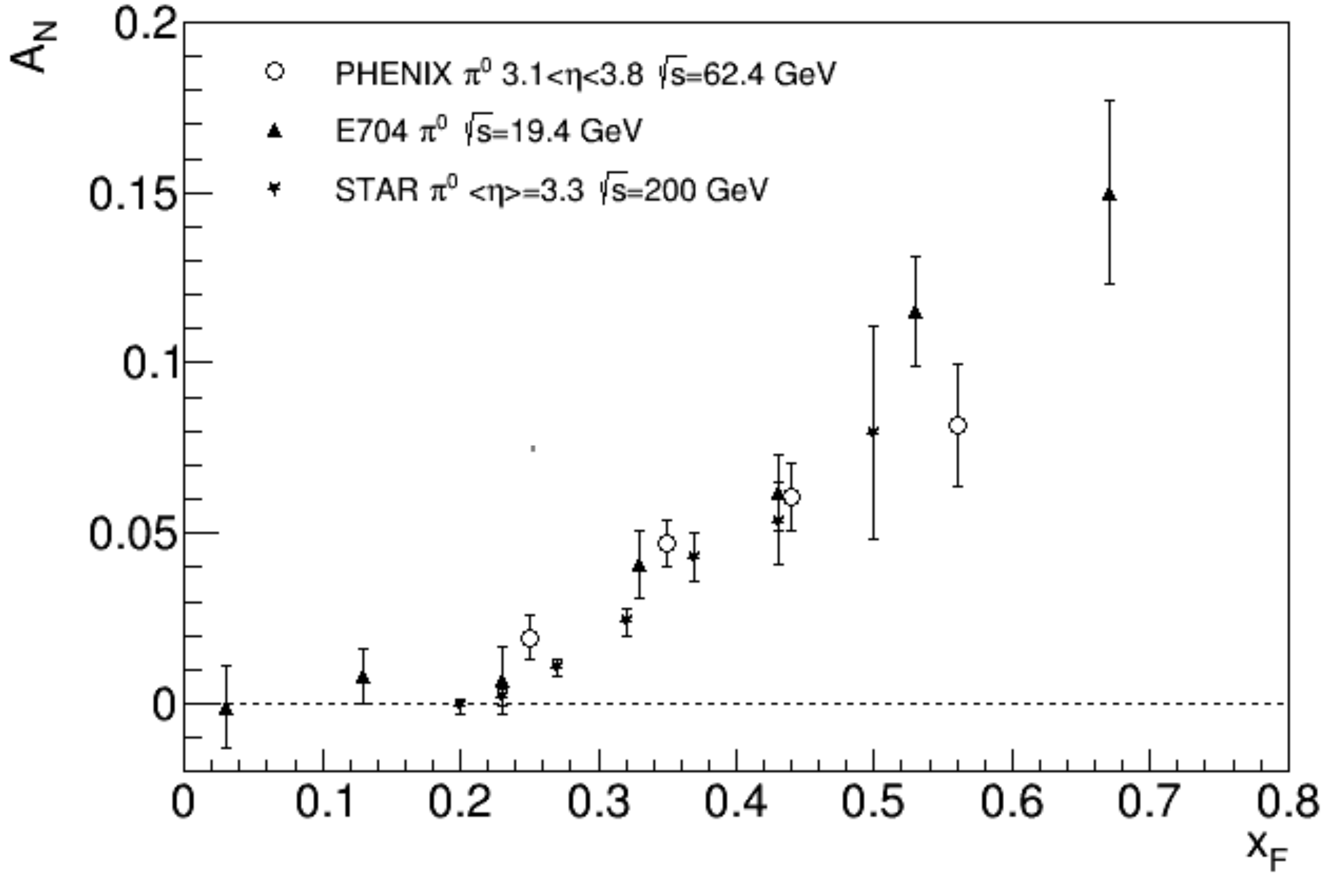
- Systematic uncertainties by polarization, $\pi^0$ azimuthal angle, background $A_N$ subtraction, and beam center was included.

# Very forward $\pi^0$ $A_N$ as a function of $x_F$

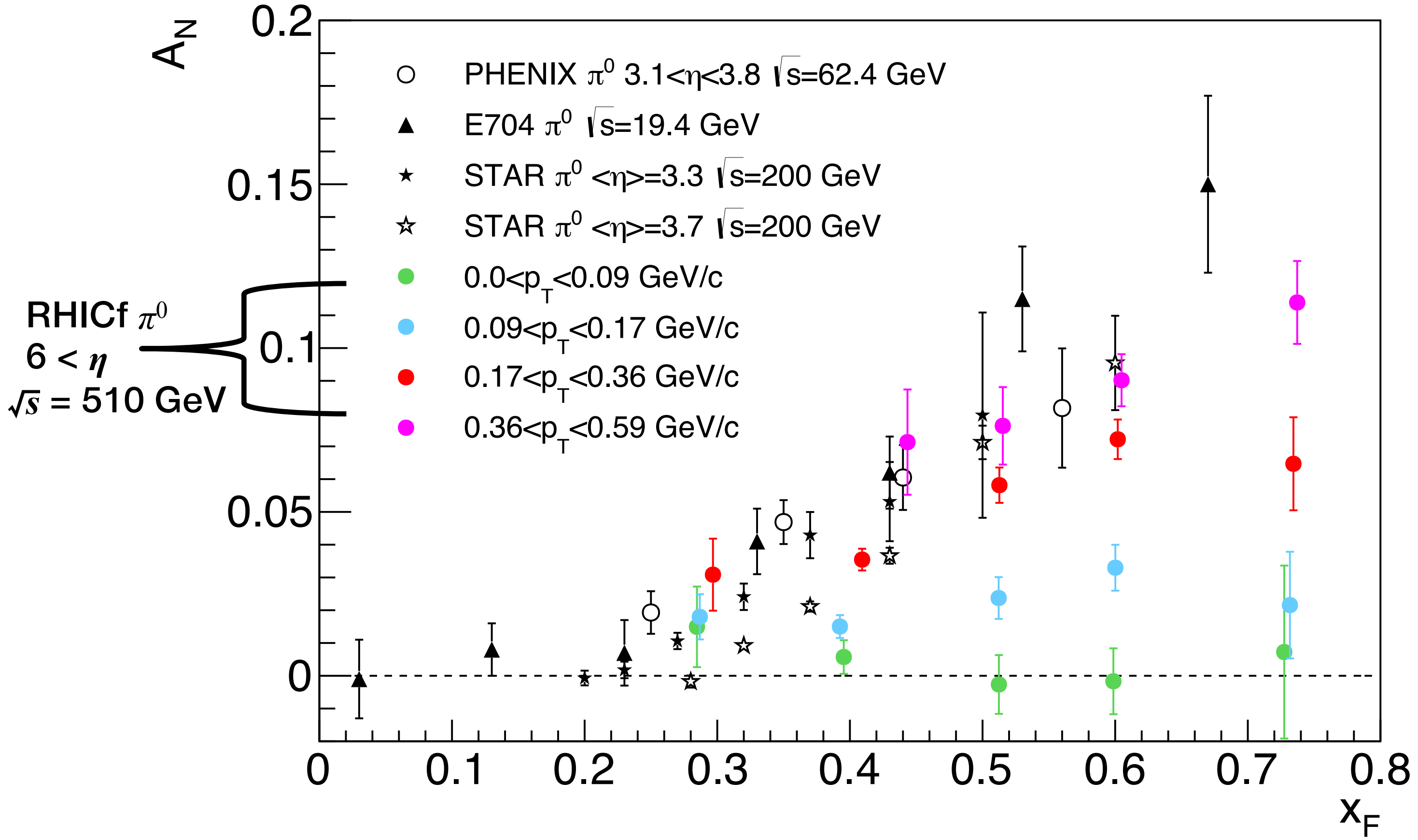



- The higher $p_T$ range the $A_N$ is measured in, the more clearly it increases as a function of $x_F$.
- Note that $x_F$ resolutions of the RHICf detector are also much finer than $x_F$ binning in the preliminary plot.

# Comparison with previous measurements

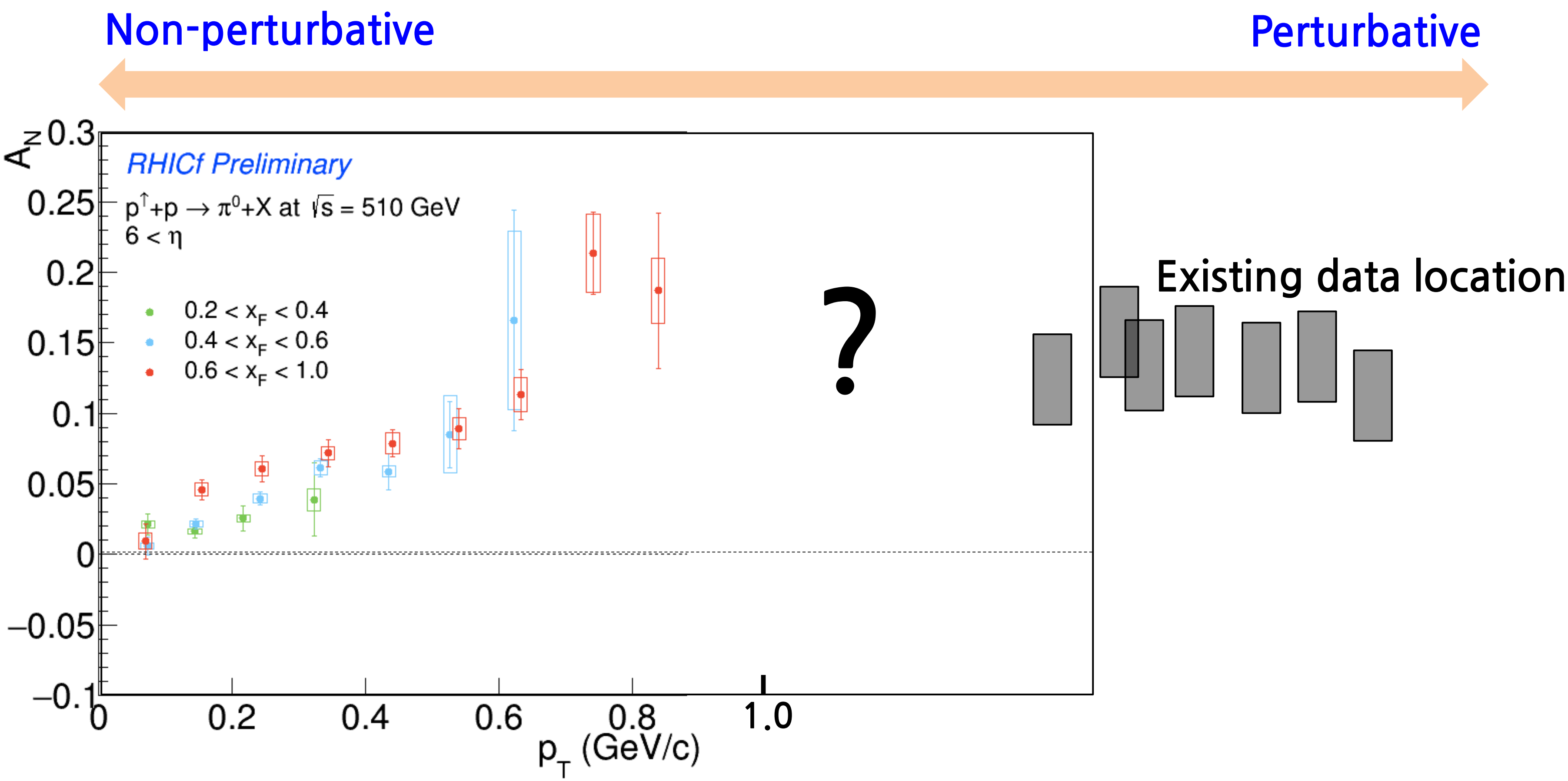


# Comparison with previous measurements




- Is there perturbative contribution even in lower $p_T$ area?
- The origin of $x_F$ scaling may be non-perturbative process.
- Now, understanding the low momentum $\pi^0$ $A_N$ (< 1 GeV/c) should be a necessary tool to understand the origin of the $\pi^0$ $A_N$ itself.

# What's the next step?




- What made the non-zero $\pi^0$ $A_N$?
- How competitively each perturbative and non-perturbative process contribute to the $\pi^0$ $A_N$ will certainly provide a powerful input for it.

# Summary

- RHICf experiment measured the $A_N$ of very forward ($6 < \eta$) neutral particles (neutron, $\pi^0$, single $\gamma$).
- Preliminary results of RHICf $\pi^0$ $A_N$ are meaning possible non-negligible contribution from the non-perturbative process.
- Further analysis with other STAR detectors and data taking will provide a powerful input to understand the origin of the $\pi^0$ $A_N$.
- We hope many interest from many professors and students!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# Backup

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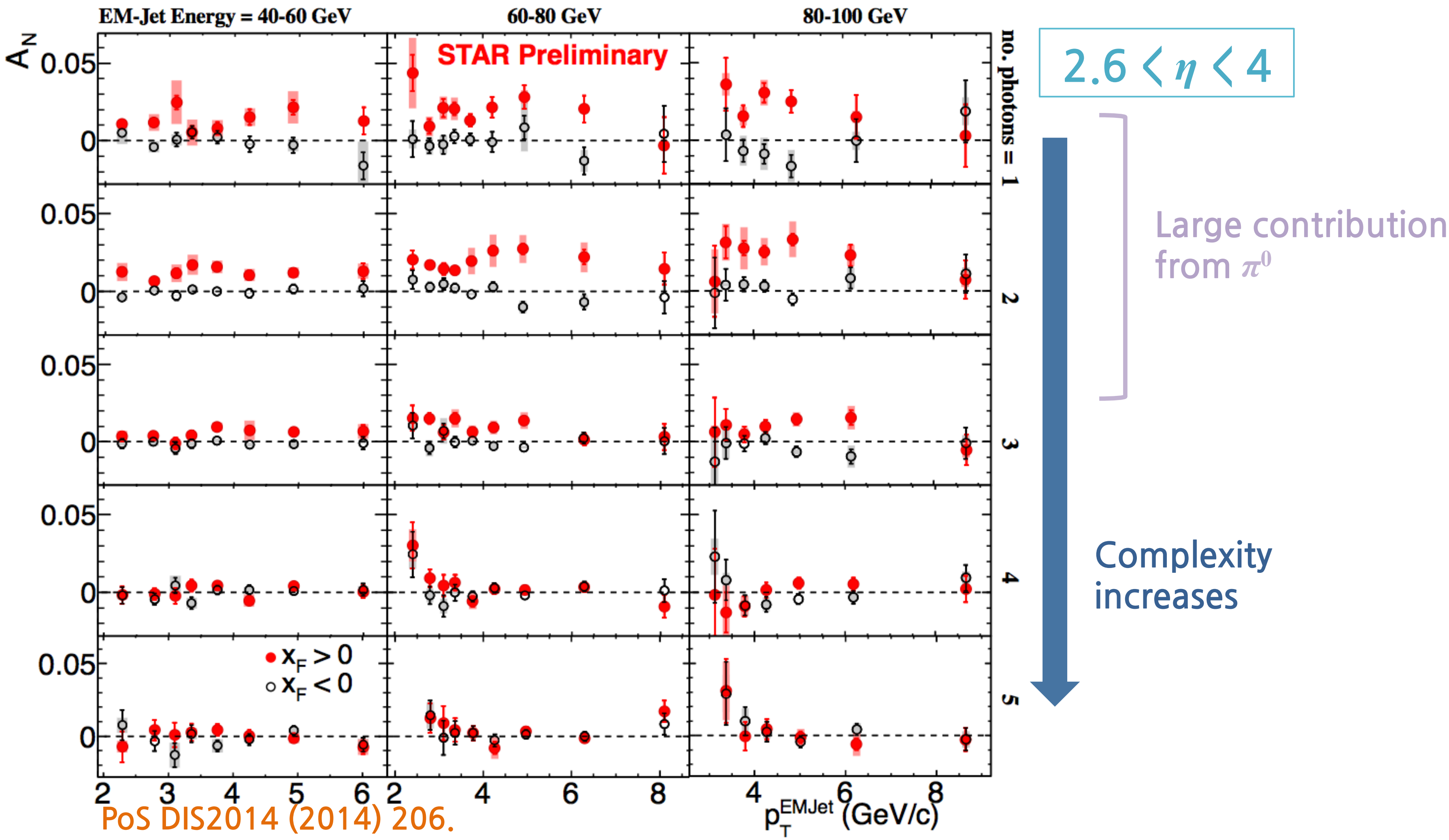
# New question to the $A_N$ of forward $\pi^0$

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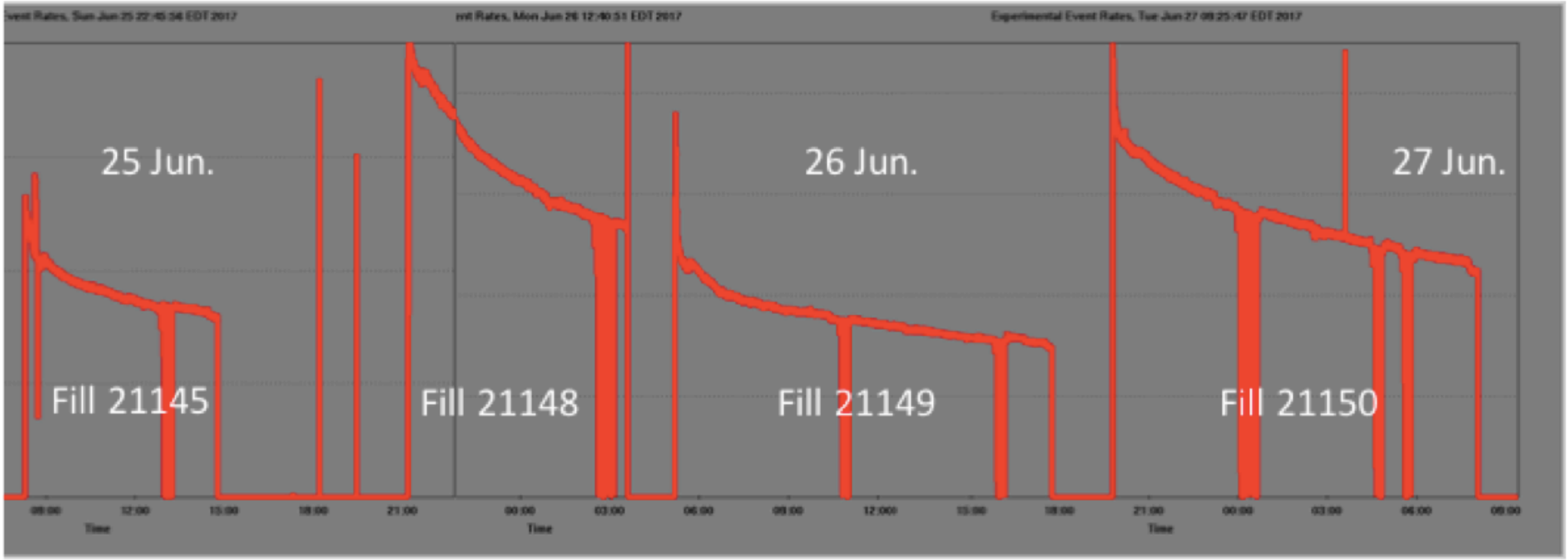
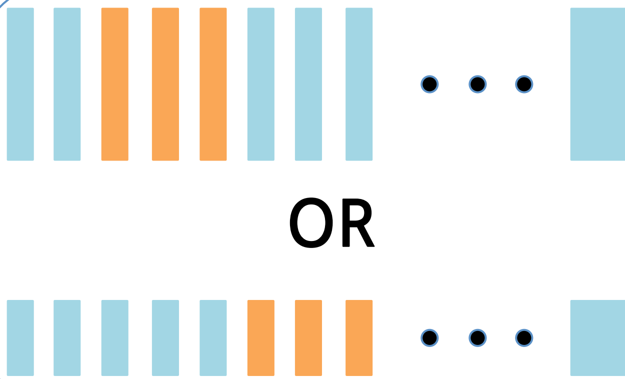
- Smaller $A_N$ was observed with increasing multiplicity of photons (closer to hard scattering event topology).

# Operation summary

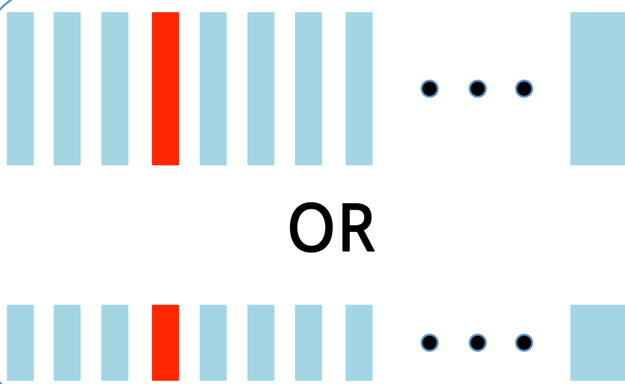



- RHICf experiment was successfully operated in June 2017.
- Total 110 M events were accumulated for neutral particles (neutron, $\pi^0$, and single photon) during 28 hours.
- Radial polarization.
- Higher $\beta^*$: 8 m and lower luminosity: $10^{31}$ $cm^{-2}s^{-1}$ than usual.

# Triggers of RHICf detector



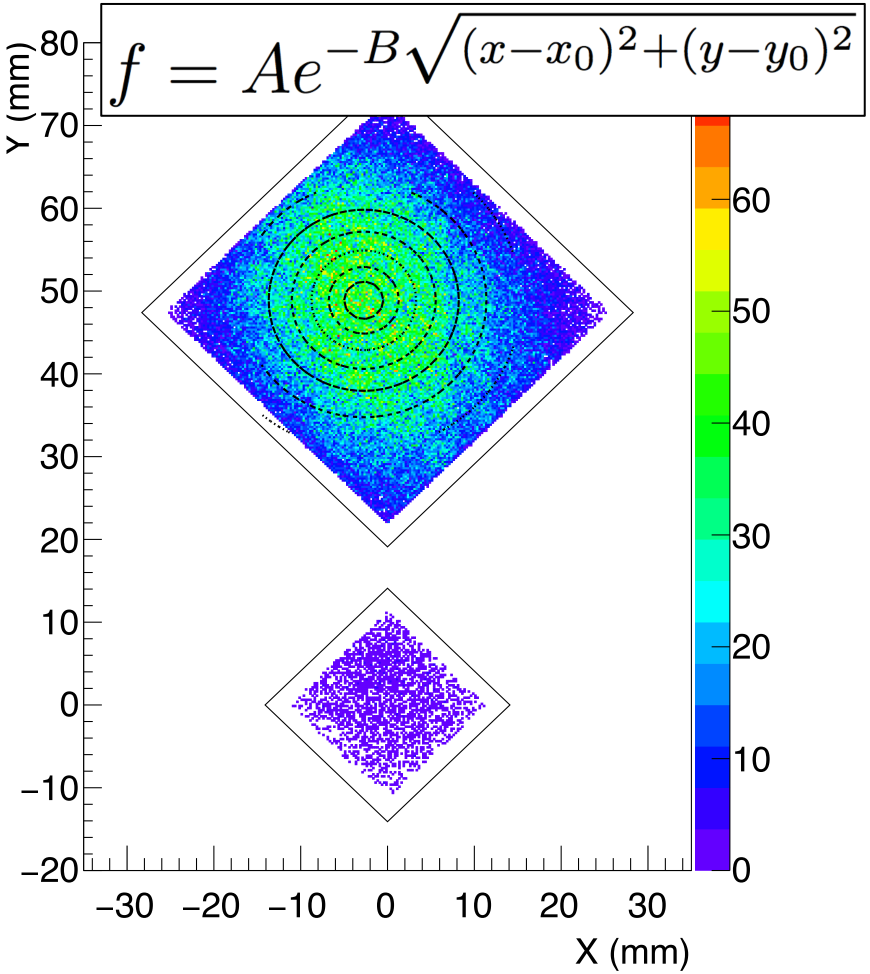

**Shower trigger**: Energy deposits of three successive layers at large or small tower are larger than 45 MeV.
(for neutron and single photon)

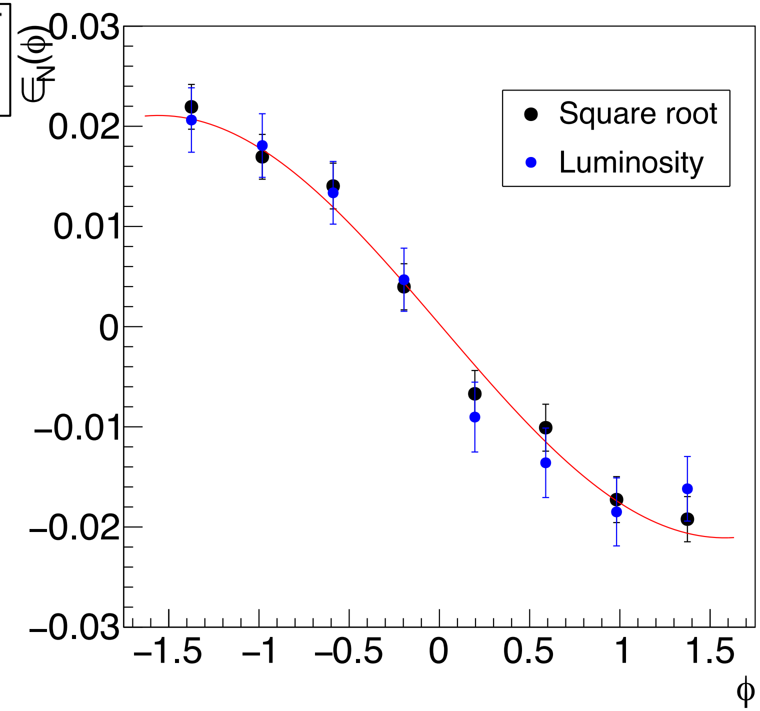



**High EM trigger**: Energy deposit of 4th layer at large or small tower is larger than 500 MeV.
(for high energy photon and Type-II $\pi^0$)


**Type-I $\pi^0$ trigger**: Energy deposits of three forward (up to 7th) successive layers at large and small tower are larger than 45 MeV.
(for Type-I $\pi^0$)

# Beam center calculation (by neutron)

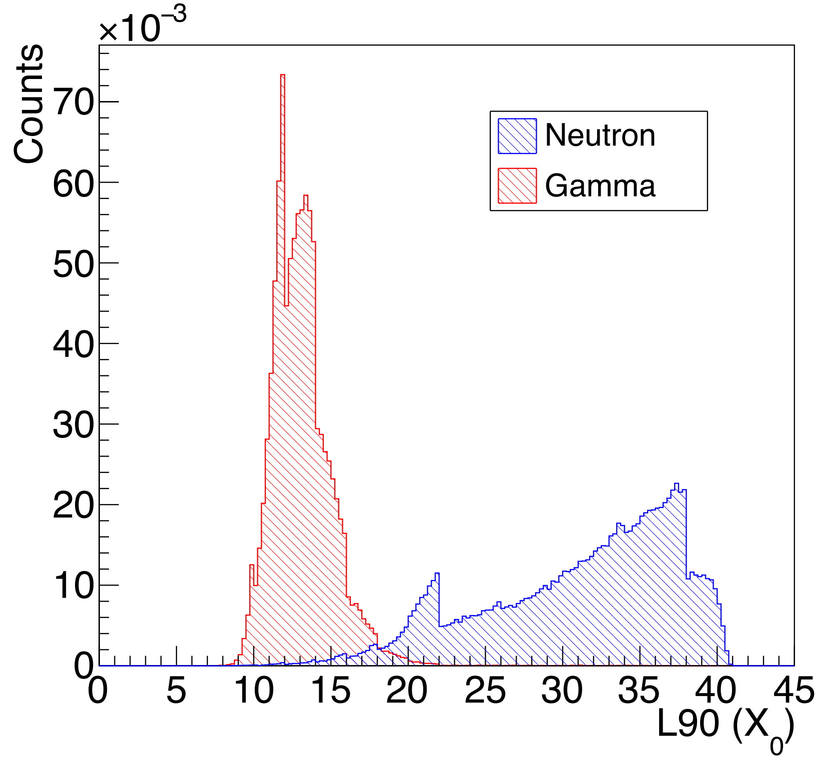



$$\frac{N_L^{\uparrow} - RN_R^{\uparrow}}{N_L^{\uparrow} + RN_R^{\uparrow}} = \frac{\sqrt{N_L^{\uparrow}N_R^{\downarrow}} - \sqrt{N_R^{\uparrow}N_L^{\downarrow}}}{\sqrt{N_L^{\uparrow}N_R^{\downarrow}} + \sqrt{N_R^{\uparrow}N_L^{\downarrow}}}$$

- Neutrons were used for beam center calculation.
- Square root formula shows good agreement with luminosity one.

# Neutron and gamma PID




- L90 represents the longitudinal depth where the energy deposit reaches 90 % of total energy deposit.
- Gamma events can be distinguished from neutron ones using that EM shower develops more rapidly than hadronic one.

# $A_N$ calculation

Luminosity ratio between spin up and down

Number of $\pi^0$ in specific $x_F$ and $p_T$ range

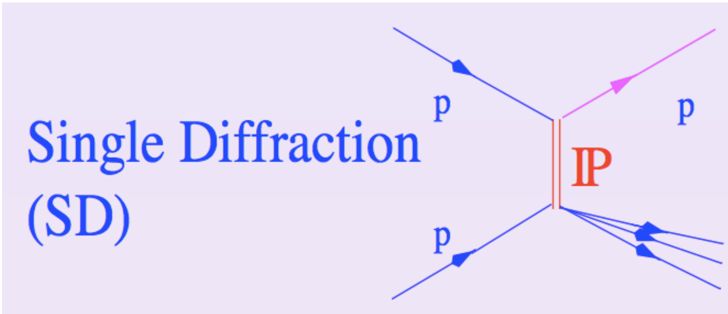
$$A_N = \frac{1}{P\epsilon}\frac{N^{\uparrow} - RN^{\downarrow}}{N^{\uparrow} + RN^{\downarrow}}$$

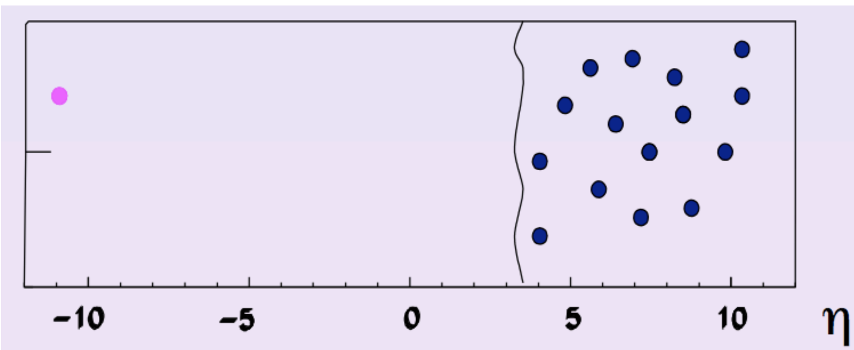
Beam polarization

Smearing by beam emittance, azimuthal angle distribution of $\pi^0$, and detector position resolution

- $P$ (~ 0.55 ± 0.05) can be calculated by polarization monitor.
- $R$ (~ 0.970 ± 0.02) is estimated by luminosity ratio of charged particles near IP.
- $\epsilon$ (~ 0.95 ± 0.05) can be studied by comparing actual and diluted $A_N$ in simulation.

# What's the next?

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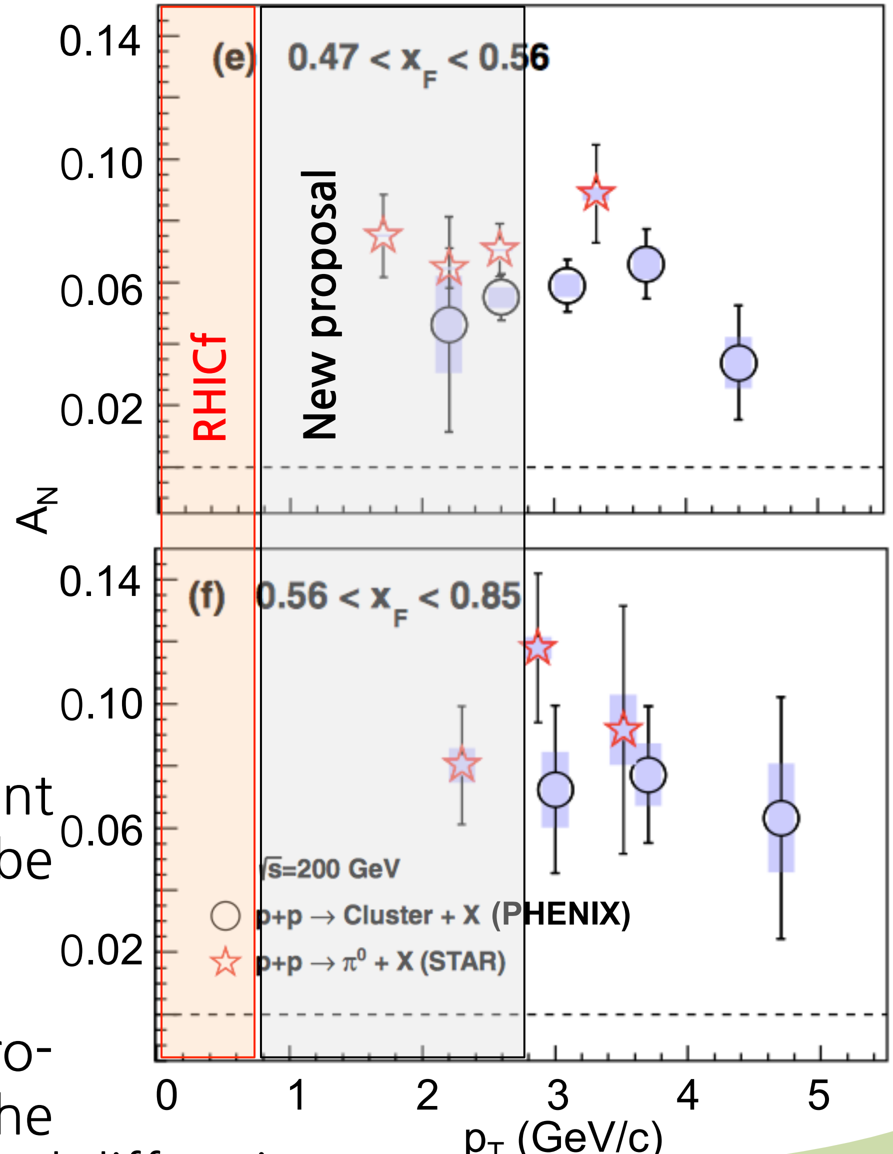
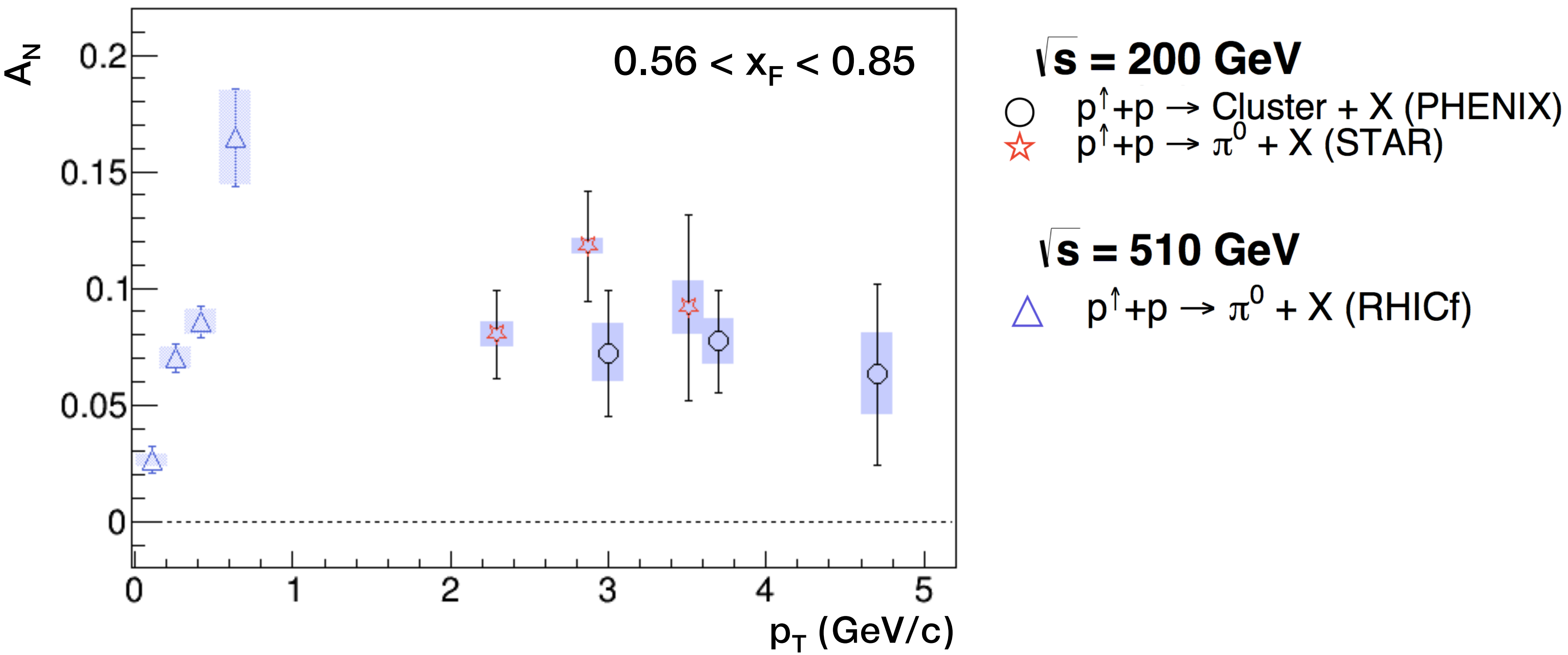



- Using other STAR detectors, event type dependence for the $A_N$ can be studied.
- A follow-up experiment will be proposed to practically compare the each contribution from partnoic and diffractive process.

# What's the next?




- How much both perturbative and non-perturbative process contribute to the $\pi^0\,A_N$ should be exactly studied.
- Combined analysis with STAR will make the comparison of two processes possible.