

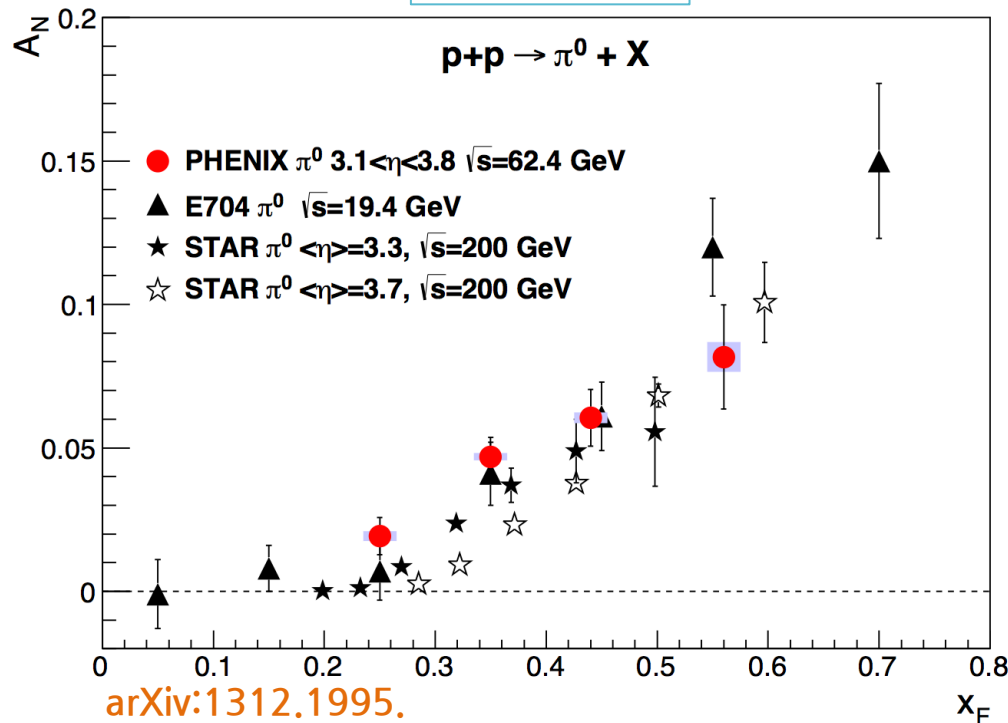
# First result of transverse single spin asymmetry ( $A_N$ ) for very forward $\pi^0$ production in polarized $p + p$ collisions at $\sqrt{s} = 510$ GeV

Minho Kim (Korea Univ./ RIKEN)  
on behalf of the RHICf collaboration



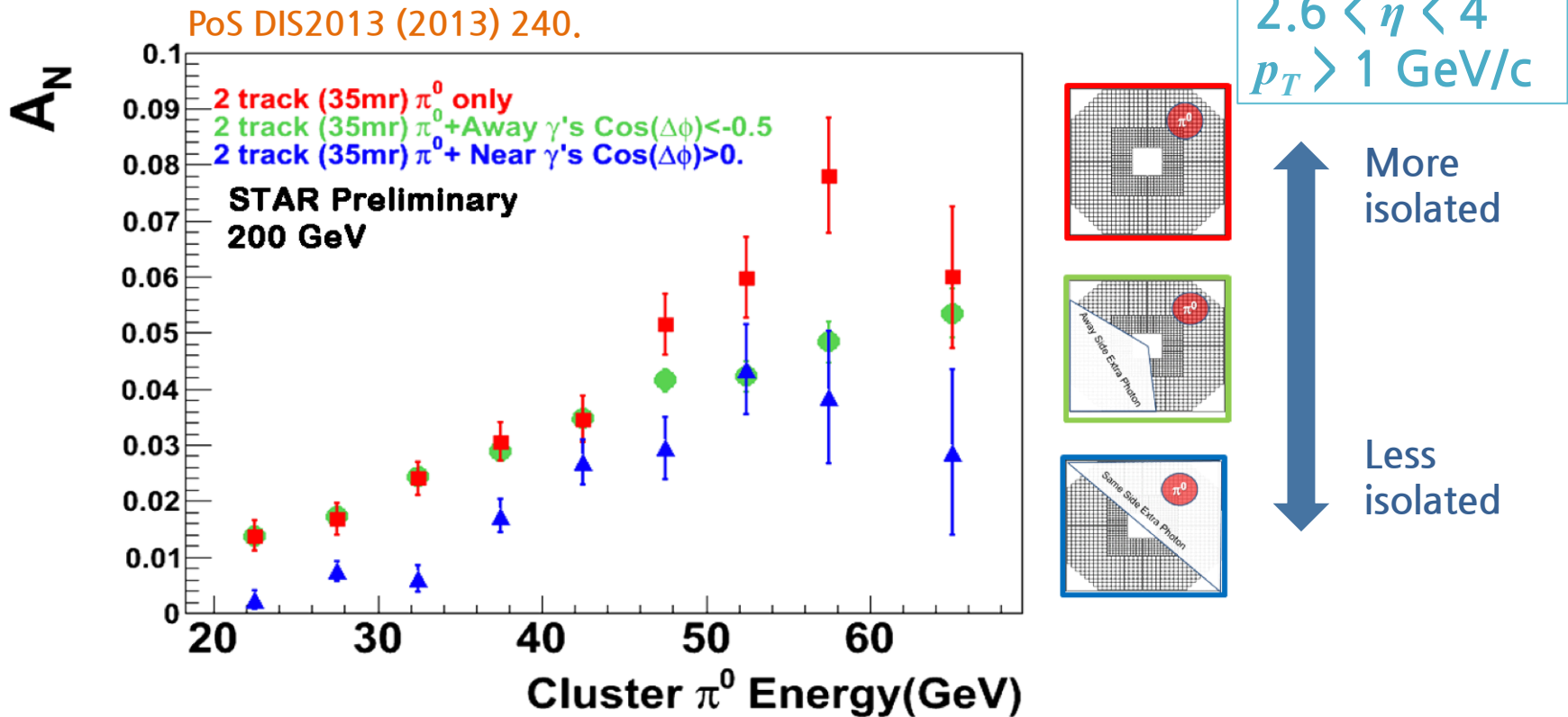
# $A_N$ in forward $\pi^0$ production

$$3 < \eta < 4$$



- Observed non-zero  $A_N$  of  $\pi^0$  ever has been interpreted based on only perturbative picture theoretically.
- Non-zero  $A_N$  comes from an asymmetry of the partonic-level fragmentation process or spin-dependent quark-gluon correlations in the proton.

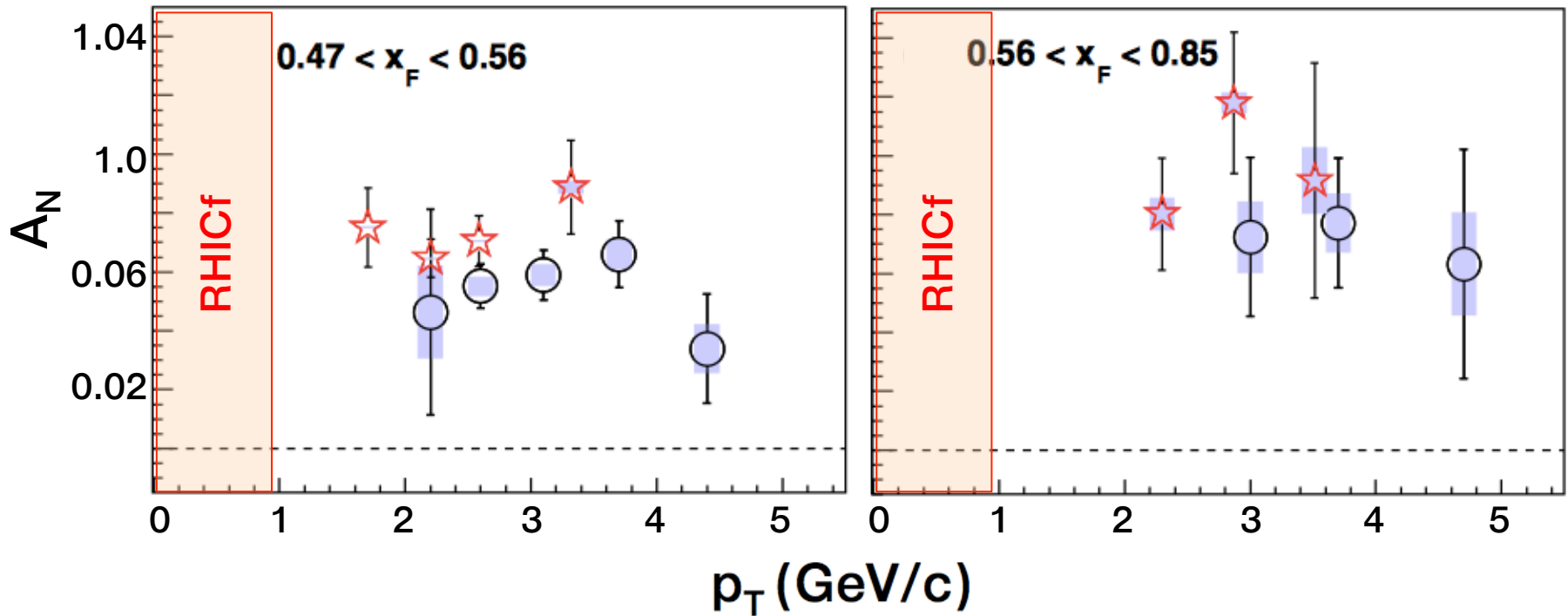
# New question to the $A_N$ of forward $\pi^0$



- 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 very forward $\pi^0$ production

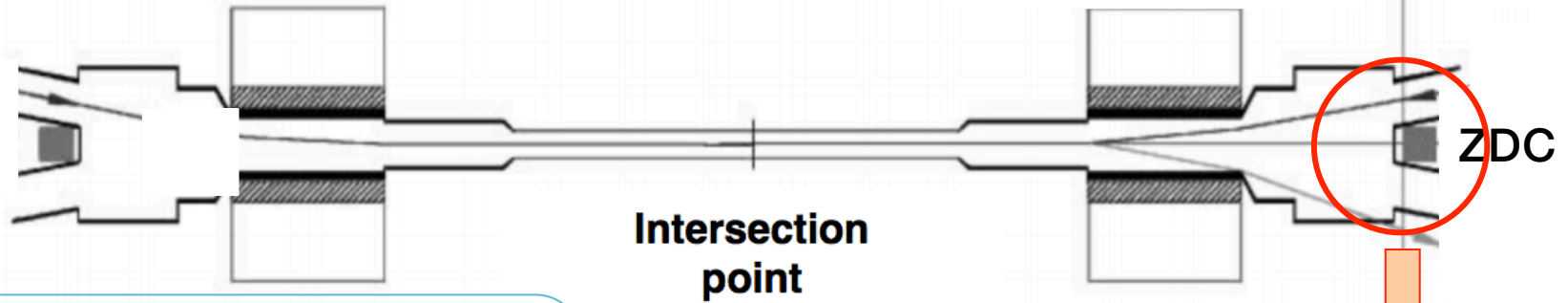
$\sqrt{s} = 200$  GeV     $\circ$   $p^\uparrow + p \rightarrow \text{Cluster} + X$  (PHENIX)  
 $\star$   $p^\uparrow + p \rightarrow \pi^0 + X$  (STAR) *Phys. Rev. D90 (2014) 012006.*



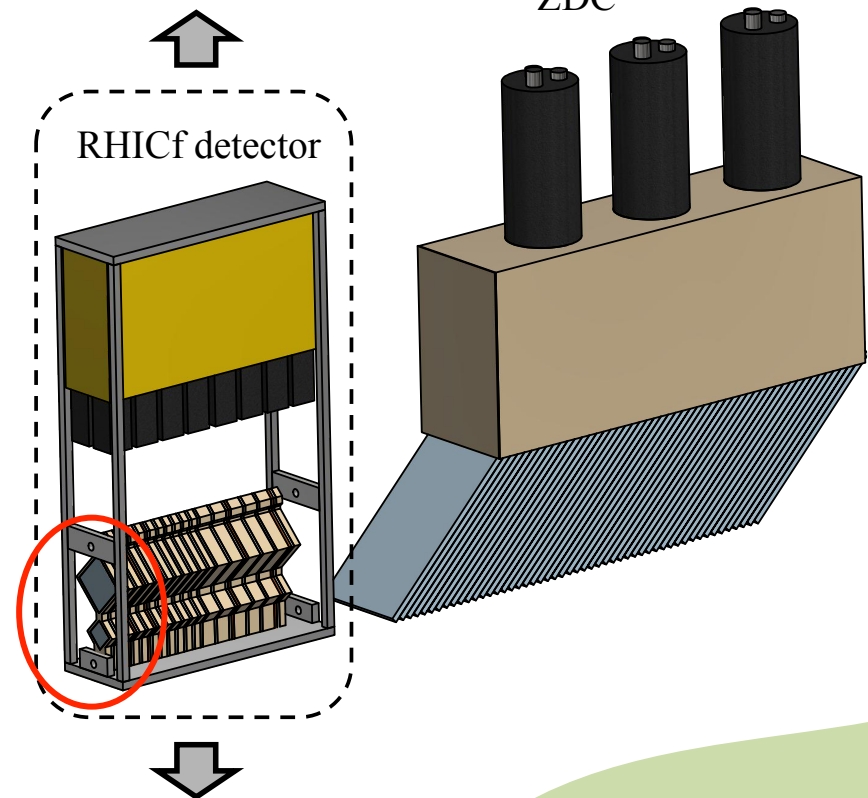
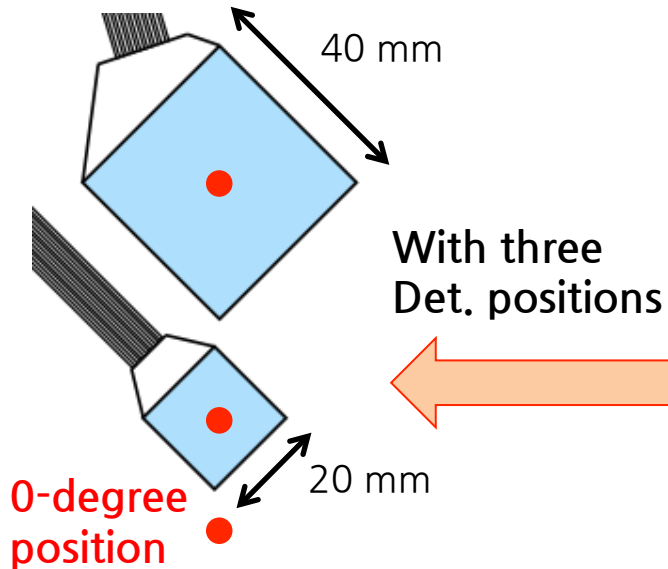
- No measurement ever for the  $p_T$  range below 1 GeV/c.
- RHICf experiment measured the  $A_N$  of very forward  $\pi^0$  ( $6 < \eta$  and  $p_T < 1$  GeV/c) where the non-perturbative process is expected to be dominant.

# RHIC forward (RHICf) experiment

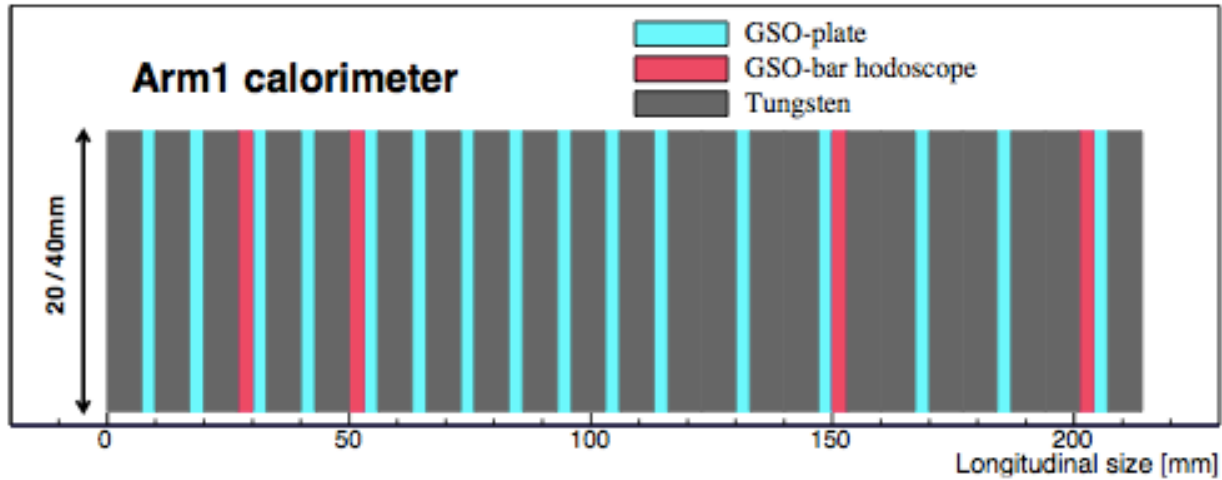
STAR experiment



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



# RHICf detector & $\pi^0$ measurement

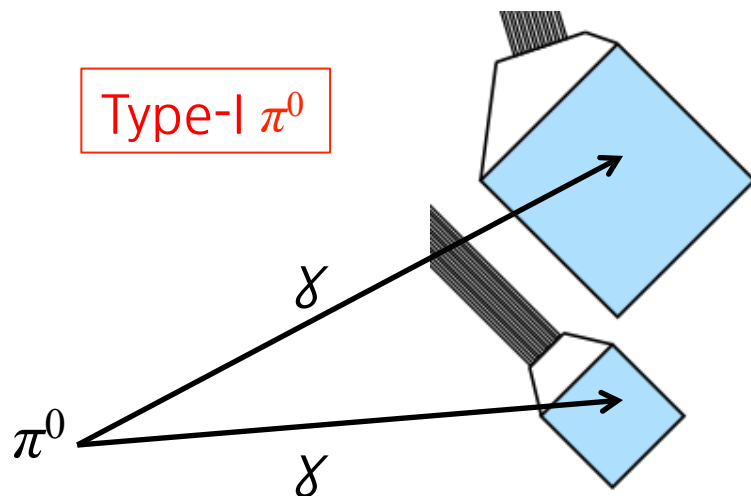


Small tower: 20/20 mm  
Large tower: 40/40 mm

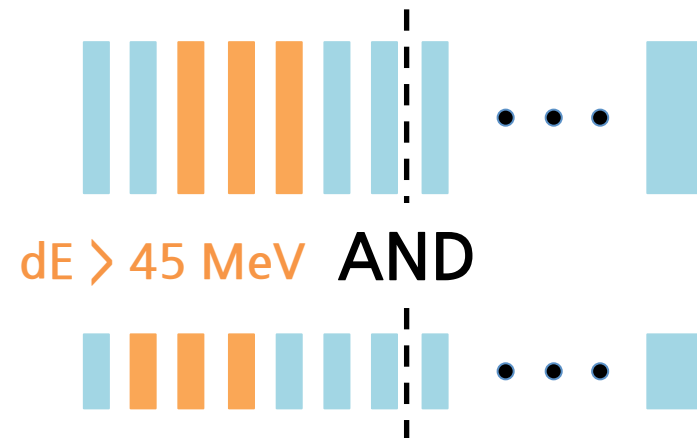
17 Tungsten absorbers  
( $44 X_0$ ,  $1.6 \lambda_{int}$ )

16 GSO plates for  
energy measurement

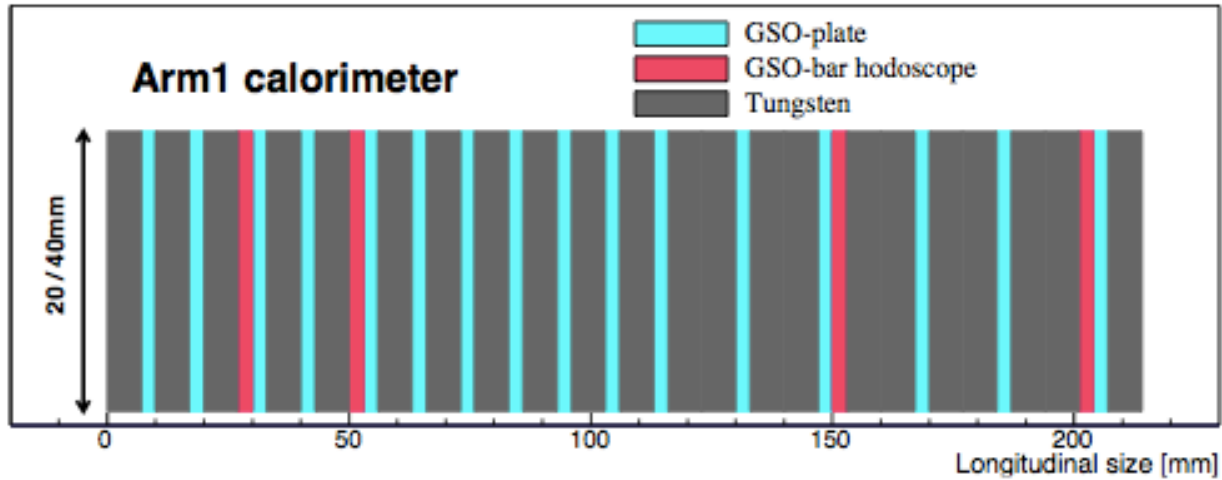
4 GSO bar layers for  
position measurement



Type-I  $\pi^0$  trigger



# RHICf detector & $\pi^0$ measurement

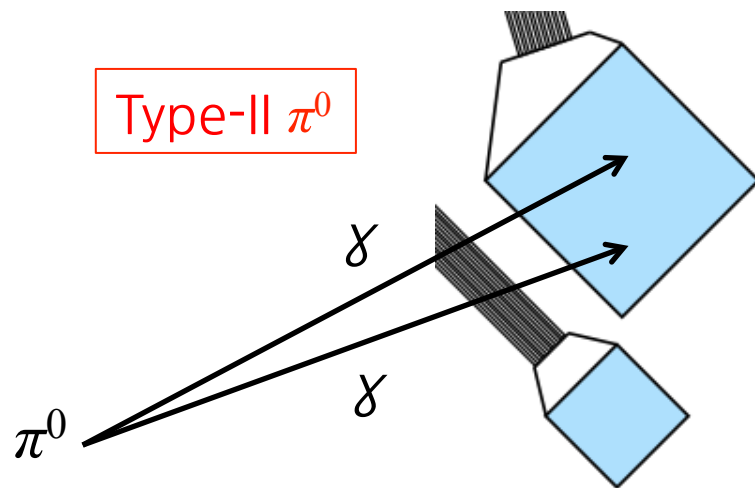


Small tower: 20/20 mm  
Large tower: 40/40 mm

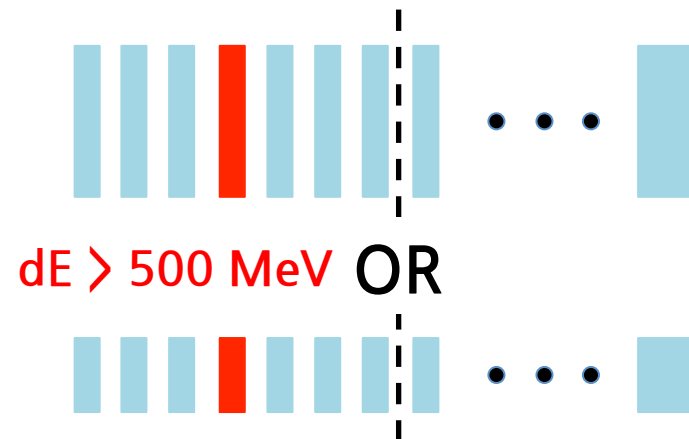
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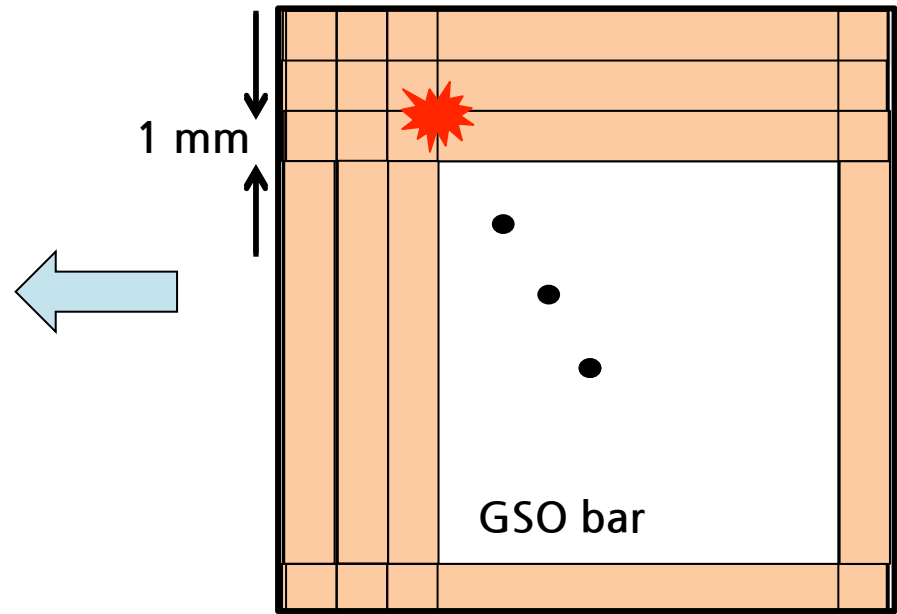
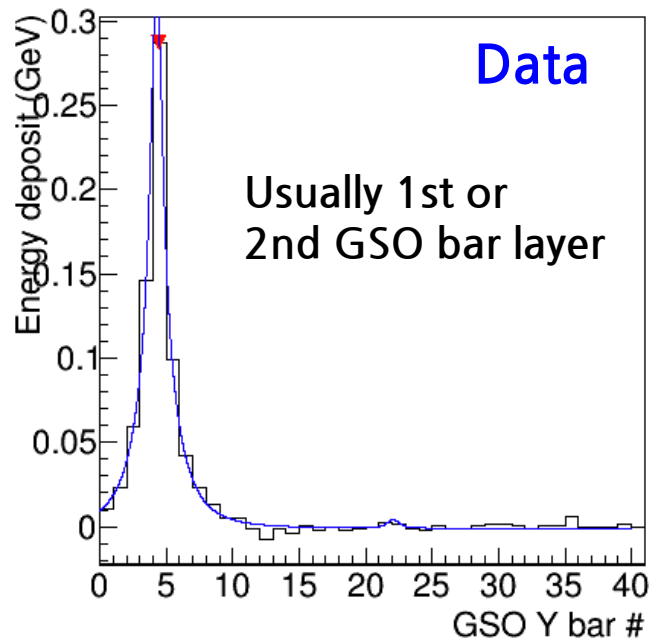
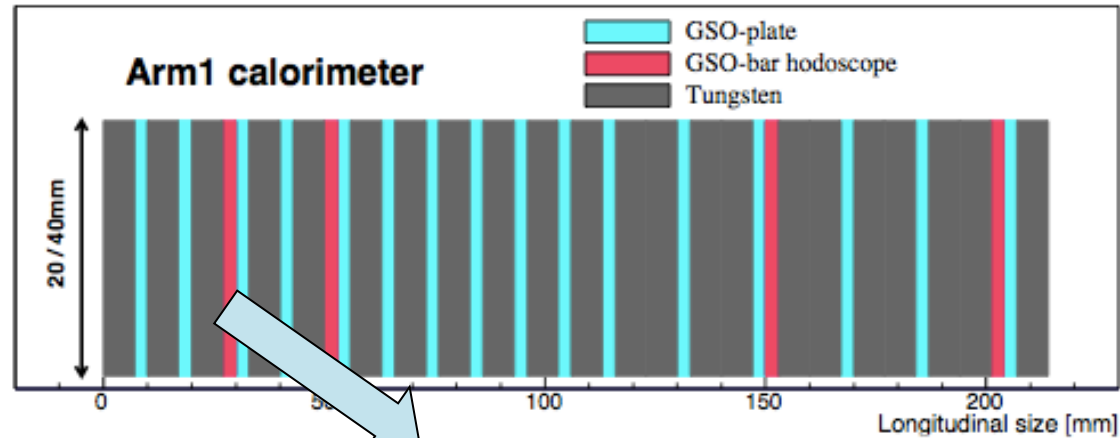
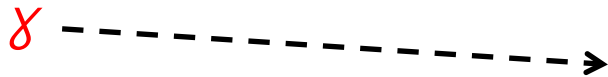


High EM trigger



# Position reconstruction of photon

- If a photon hit a tower,

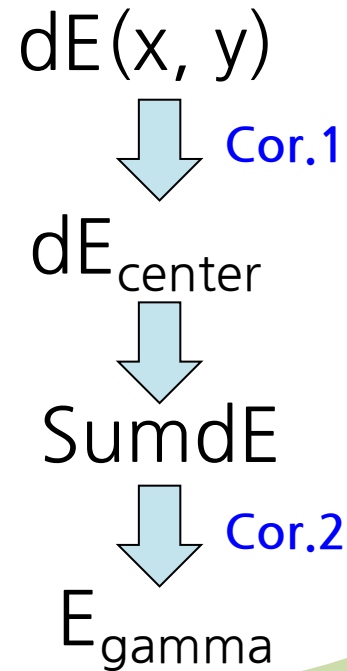
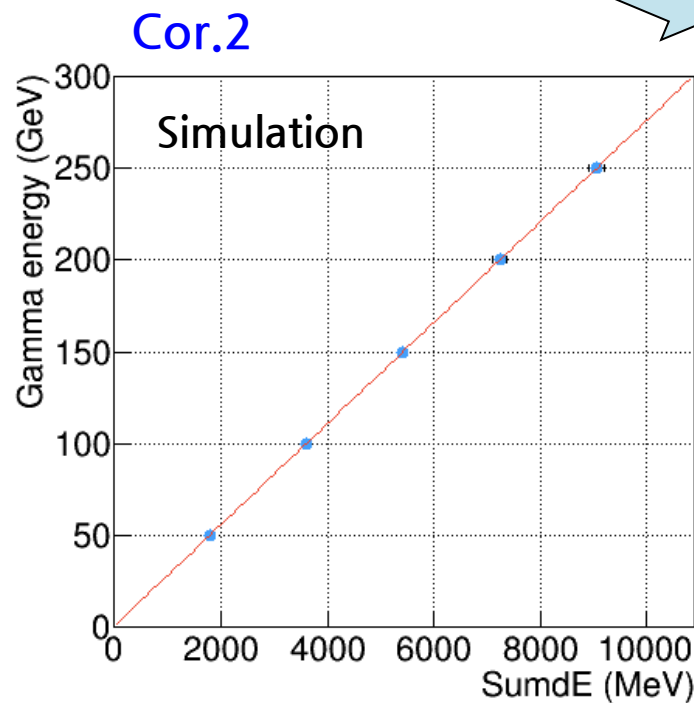
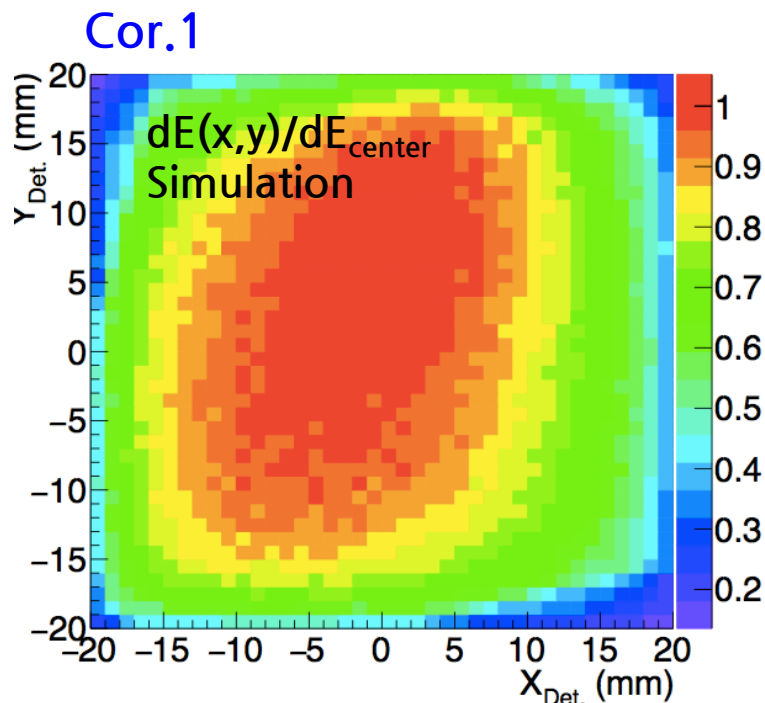
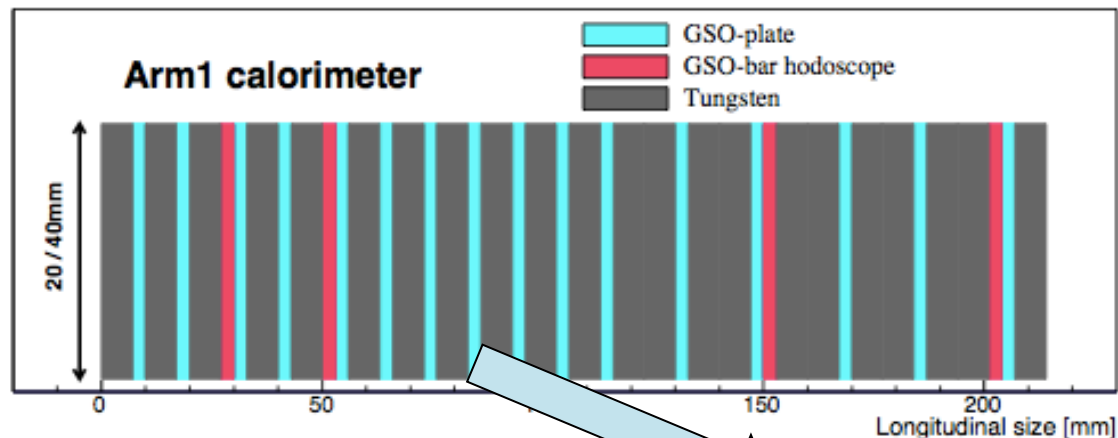
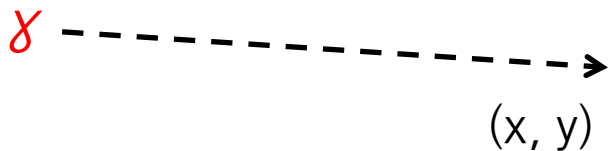


- Positions of decayed photons are measured by 1 mm dimension GSO bars.

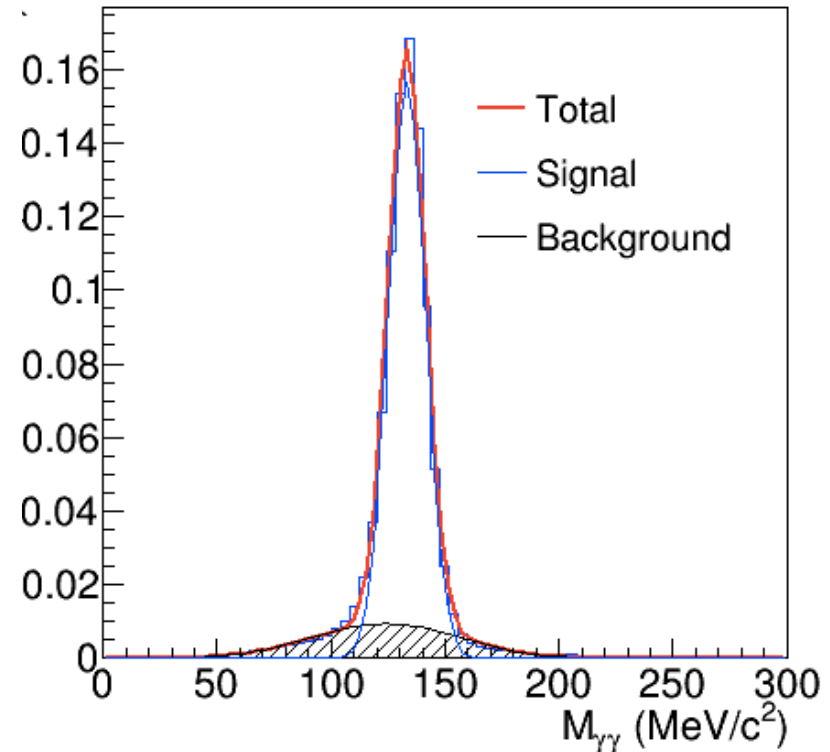
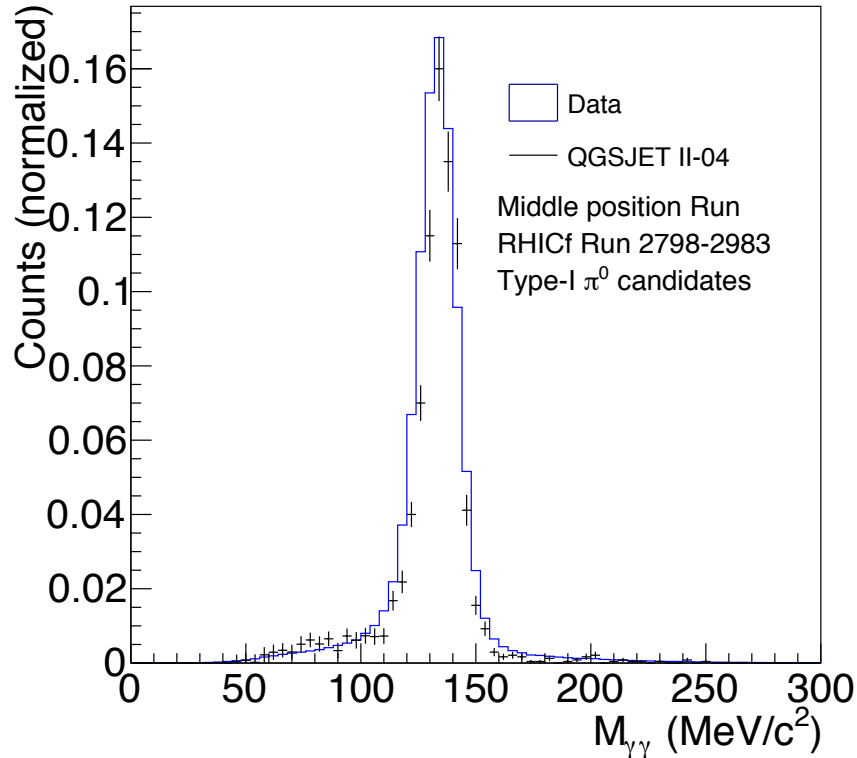


# Energy reconstruction of photon

- If a photon hit a tower,

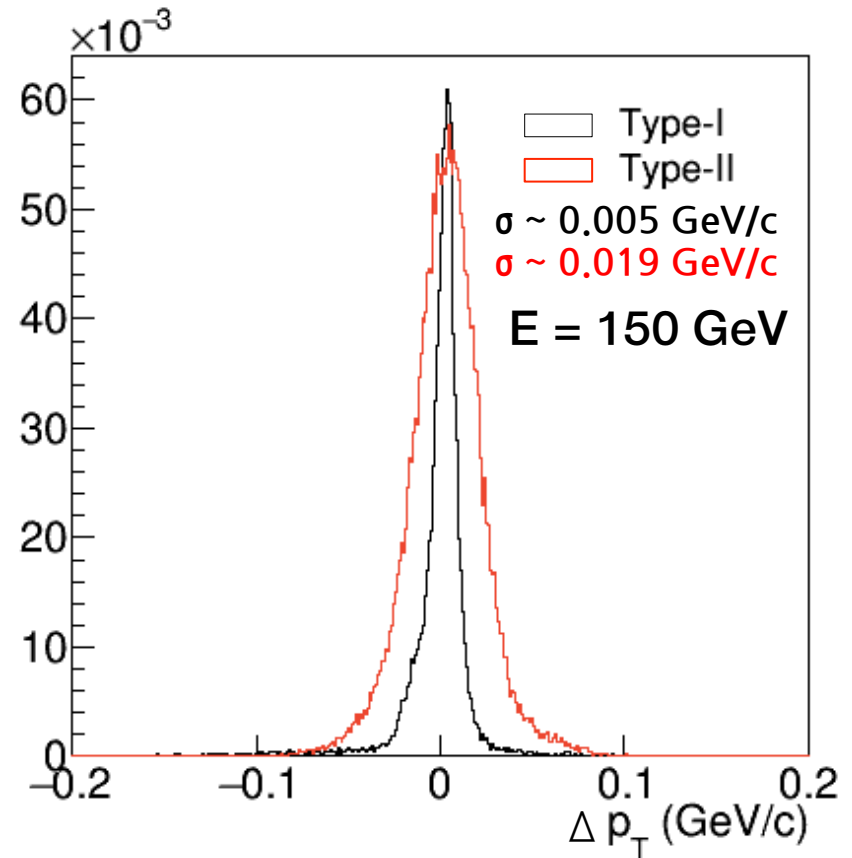
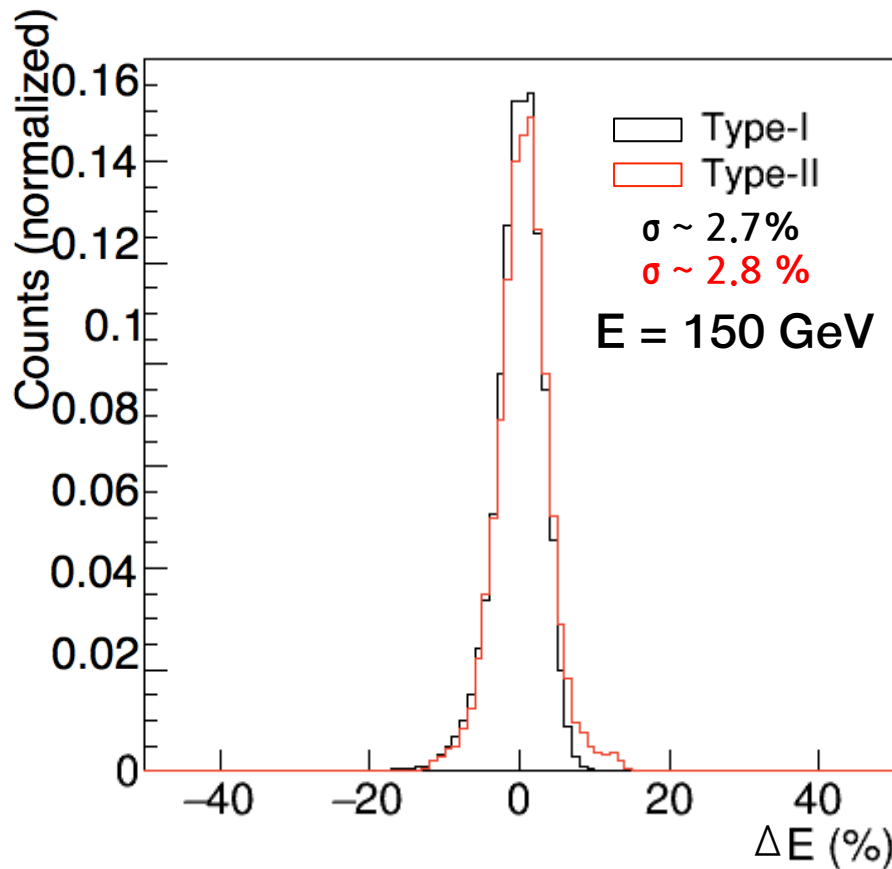


# Invariant mass of two photons



- Data is well matched with simulation showing clear  $\pi^0$  peak around 135 MeV/c<sup>2</sup> with  $\sim 8$  MeV/c<sup>2</sup> 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.

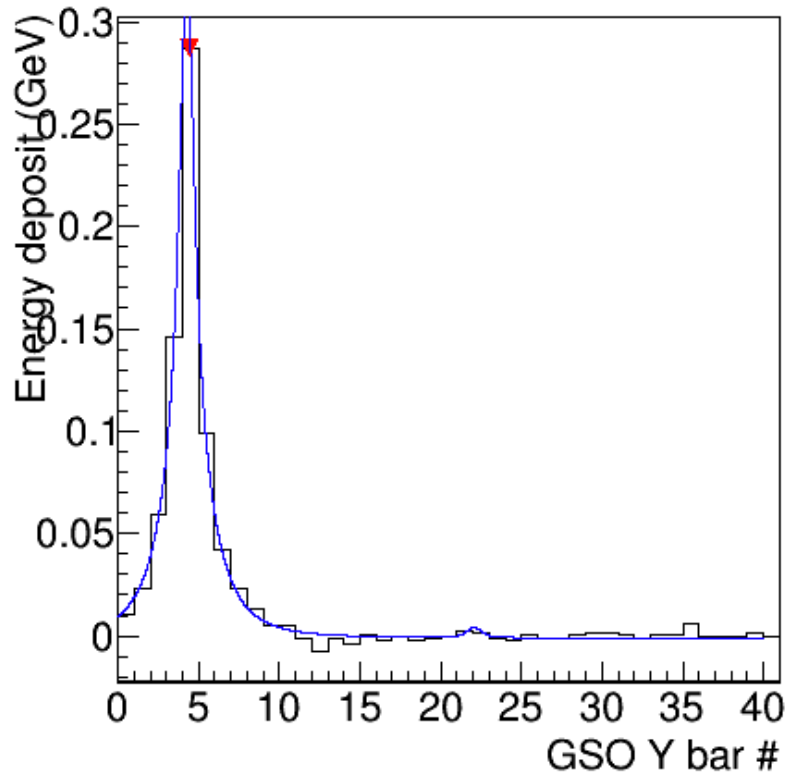
# Energy and $p_T$ reconstruction performances



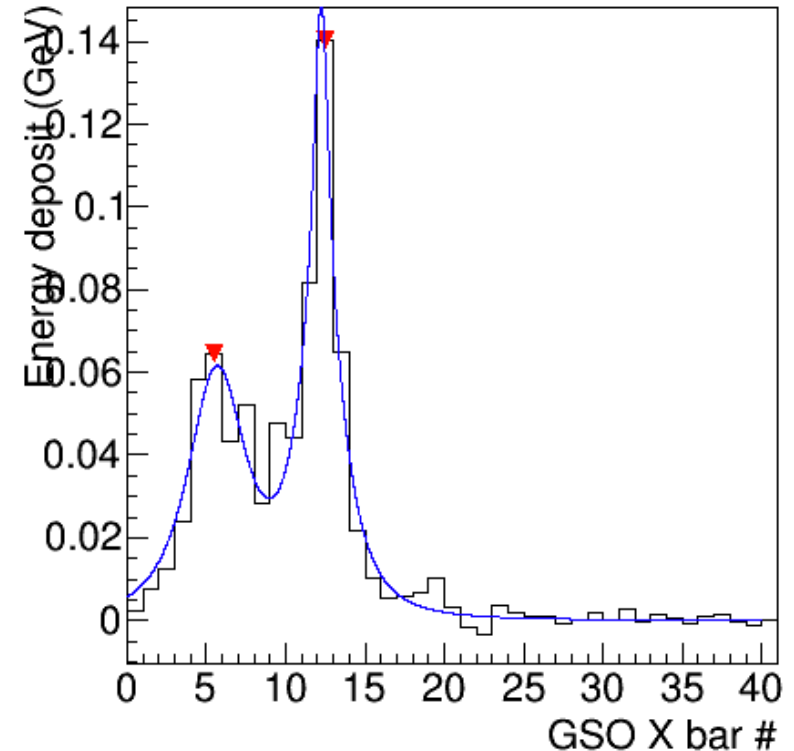
- Less than 3% of energy resolution is expected for both Type-I and Type-II  $\pi^0$ .
- $p_T$  resolution of Type-II  $\pi^0$  is three times worse than Type-I.

# Peak-to-peak contamination of Type-II $\pi^0$

Type-I  $\pi^0$

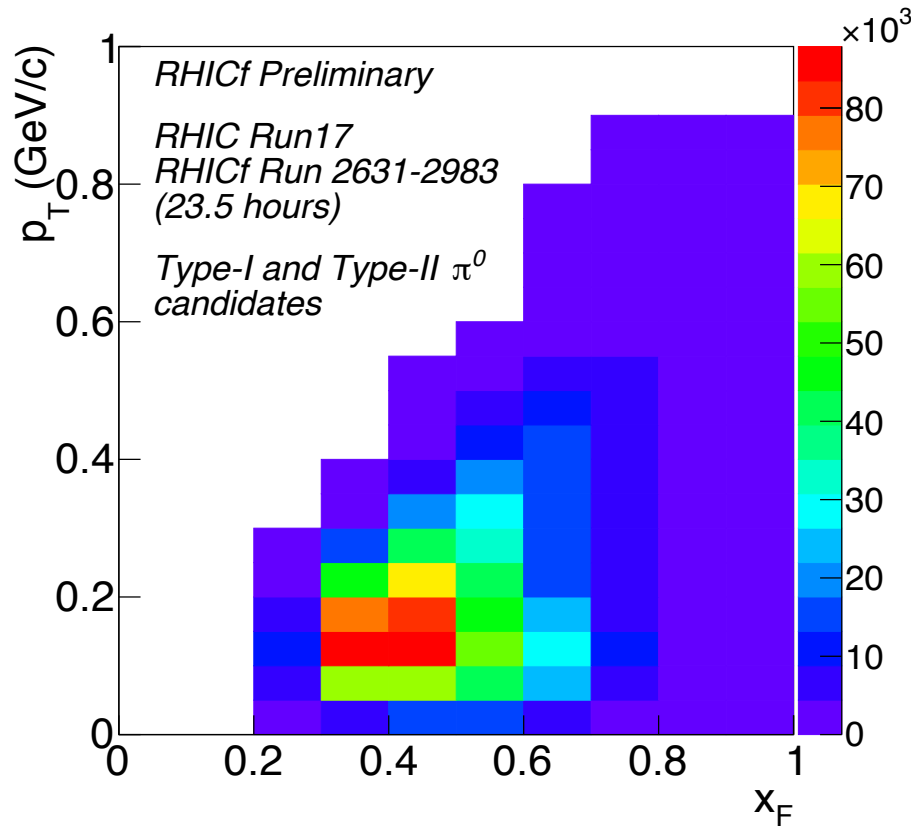


Type-II  $\pi^0$



- If two photons simultaneously develop the EM shower, peak positions get more fluctuated than one photon case.
- Peak-to-peak energy contamination makes the  $p_T$  resolution of Type-II  $\pi^0$  worse than Type-I.

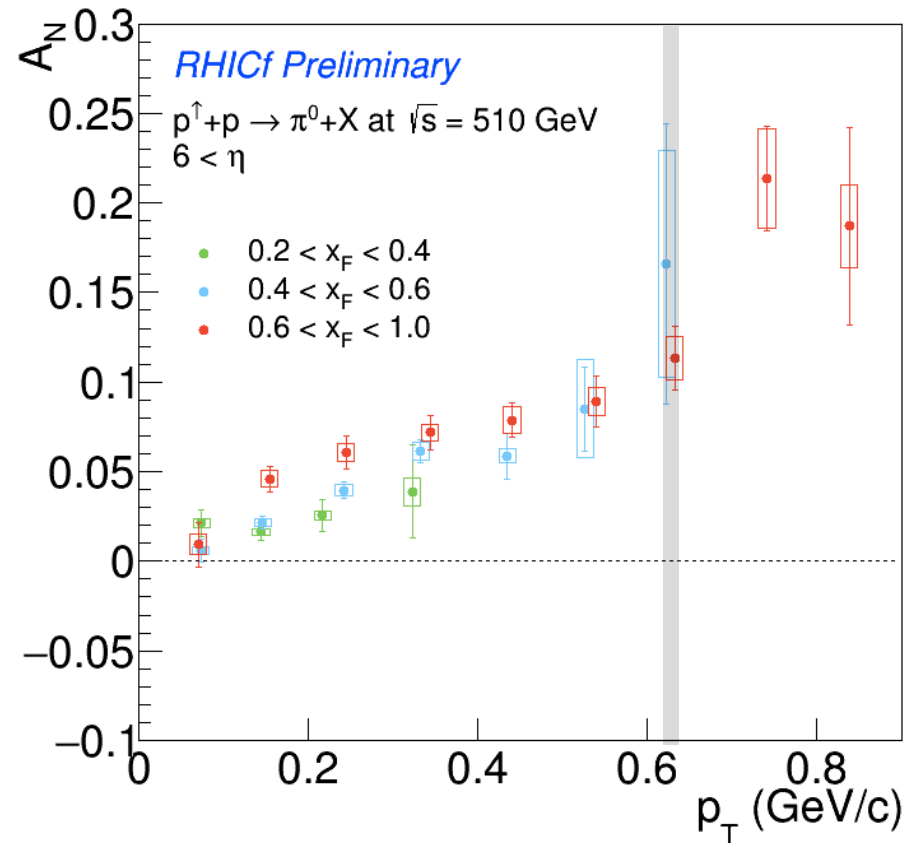
# $\pi^0$ kinematics & $A_N$ calculation



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

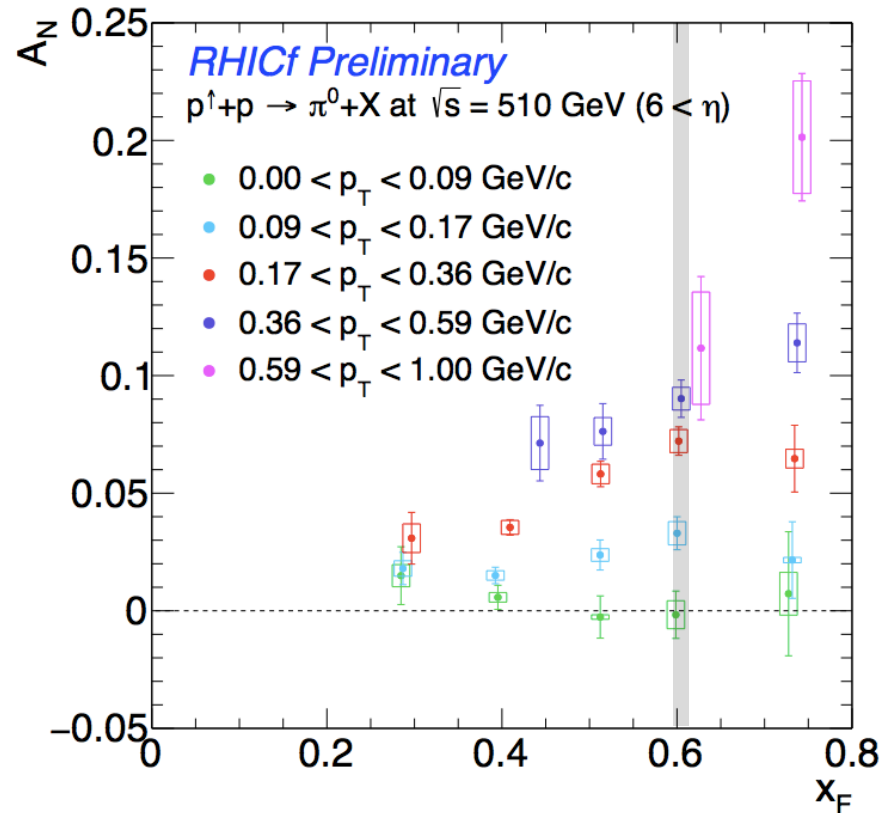
- Very forward  $\pi^0$  over the  $x_F$  range of  $0.2 < x_F < 1.0$  and  $p_T$  range of  $0.0 < p_T < 1.0$  GeV/c was measured.
- Systematic uncertainties by polarization,  $\pi^0$  azimuthal angle, background  $A_N$  subtraction, and beam center was included.

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



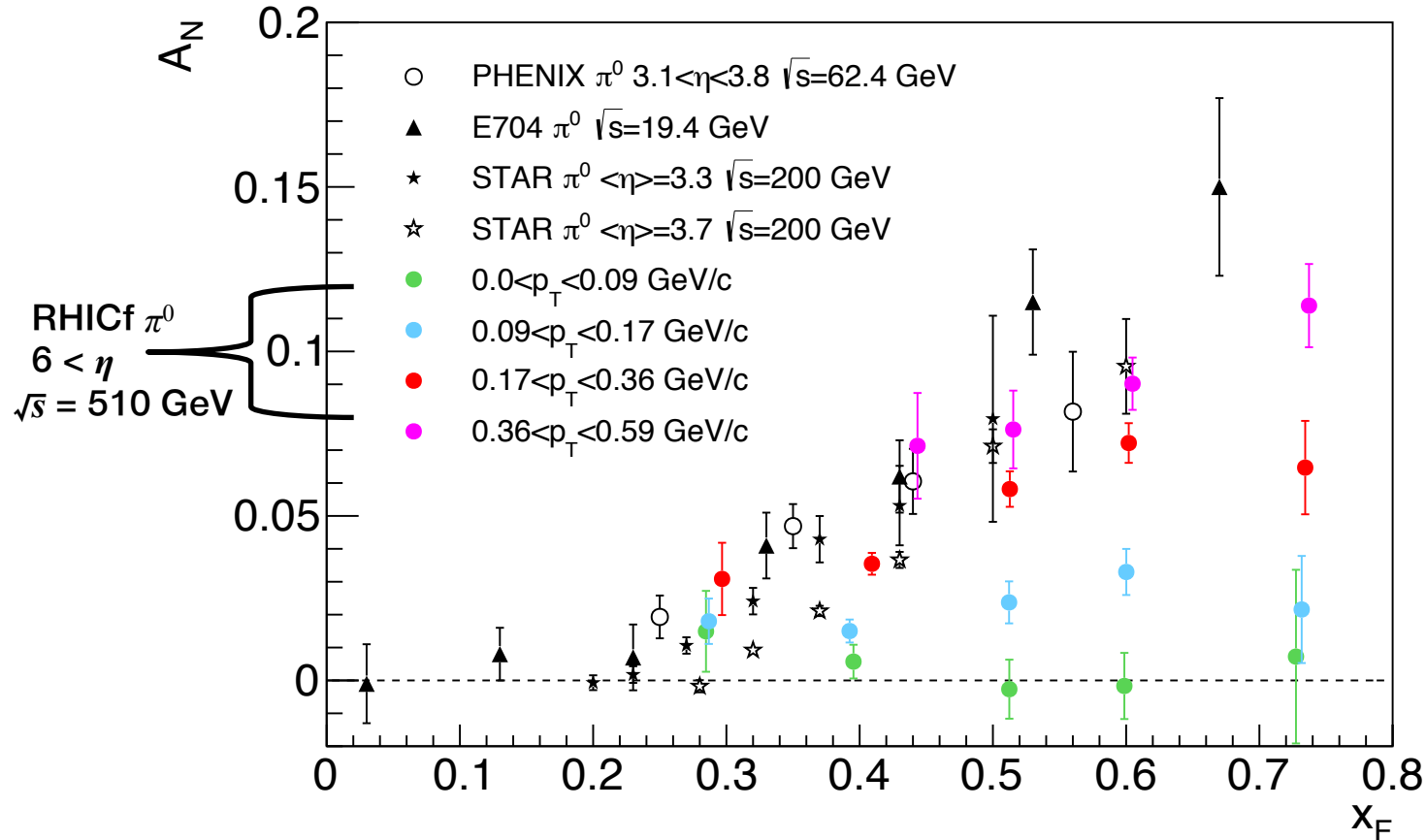
- Non-zero  $A_N$  was observed even in very forward  $\pi^0$  showing clear increasing tendency as a function of  $p_T$ .
- Note that  $p_T$  resolutions of the RHICf detector is much finer than  $p_T$  binning in the preliminary plot.

# 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



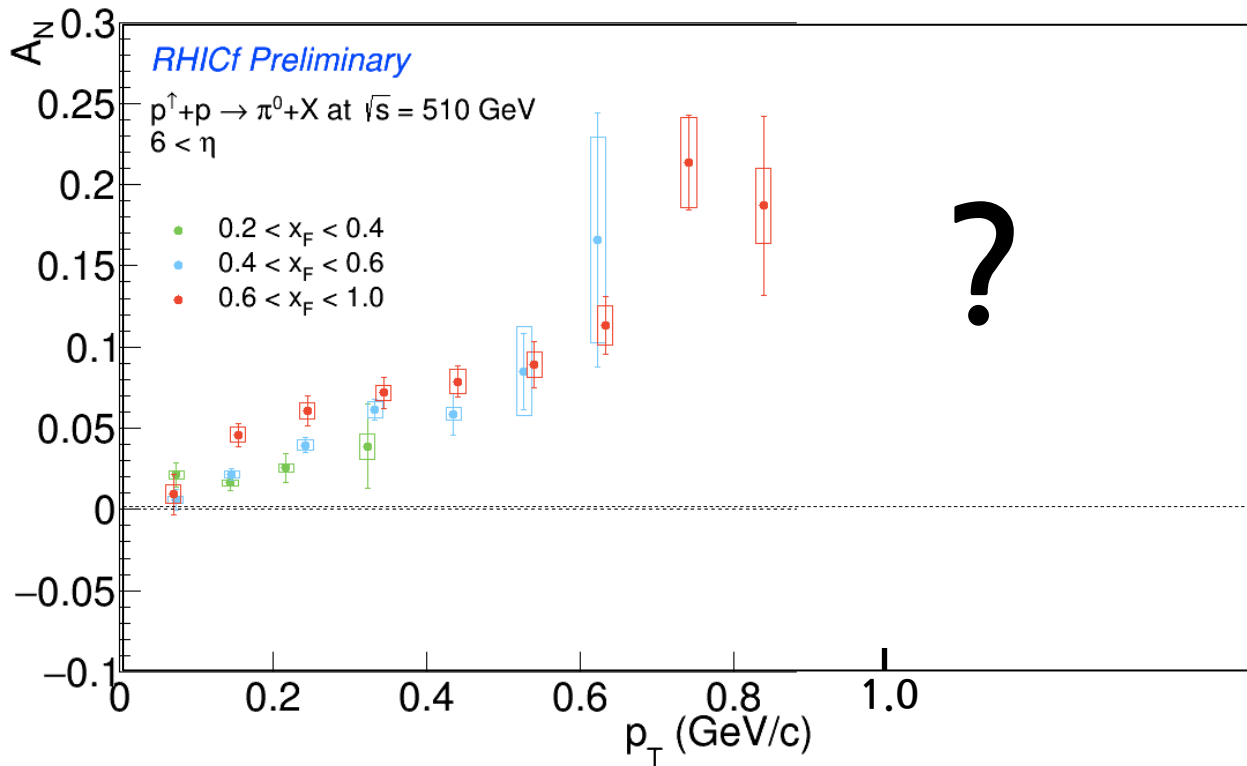
- Scenario 1: There is perturbative contribution even in lower  $p_T$  area.
- Scenario 2: The origin of  $x_F$  scaling is non-perturbative process.
- Scenario 3: Higher (lower) momentum  $A_N$  is just mainly due to (non-) perturbative process respectively.



# What's the next step?

Non-perturbative

Perturbative



- What's the real origin of the non-zero  $A_N$  of  $\pi^0$ ?
- How competitively each perturbative and non-perturbative process contribute to the  $\pi^0 A_N$  will be answered by combined analysis with STAR.

# 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 both theoretical and experimental spin physicists!

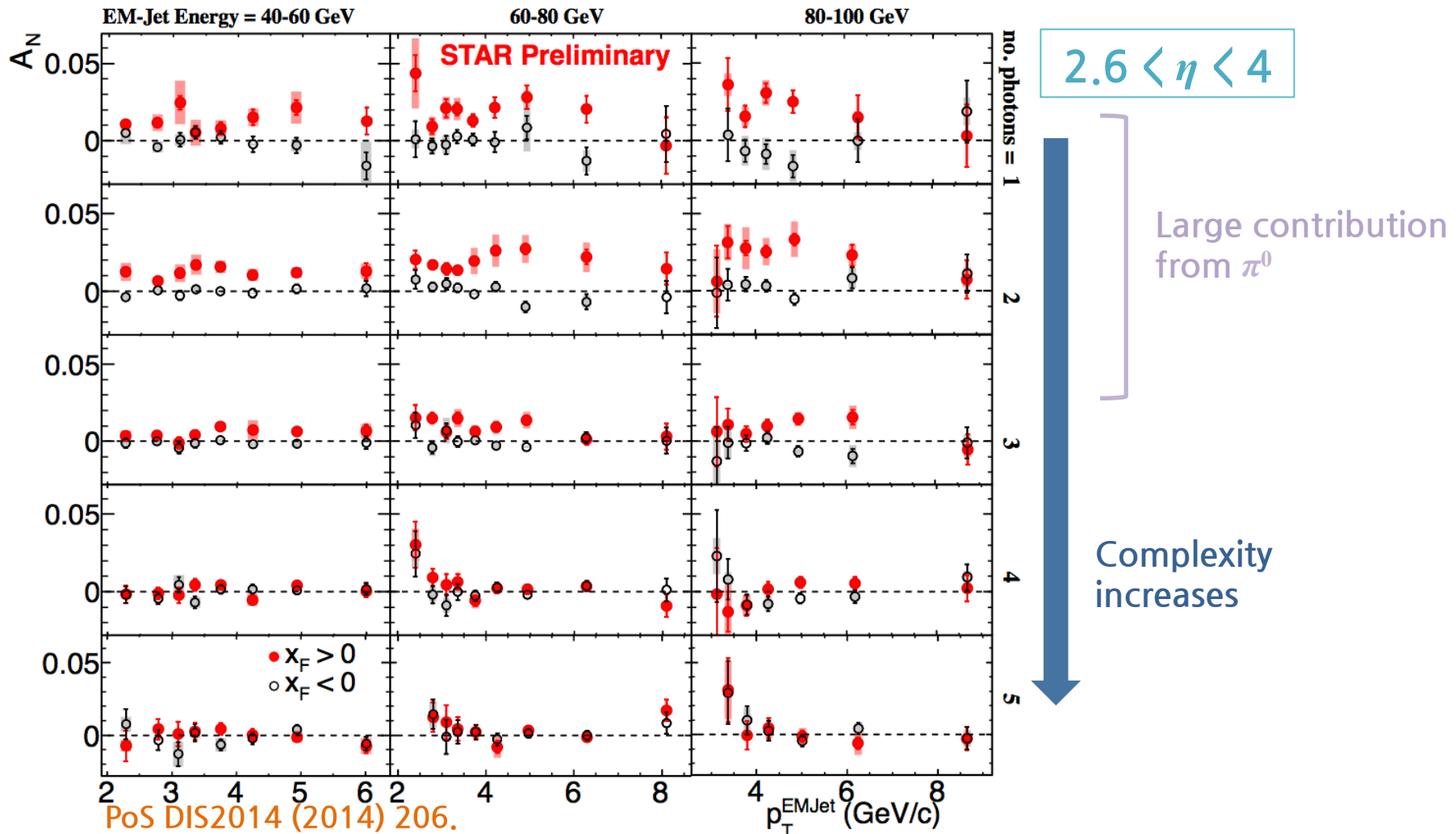
# Backup

# Subject..

- Contents..

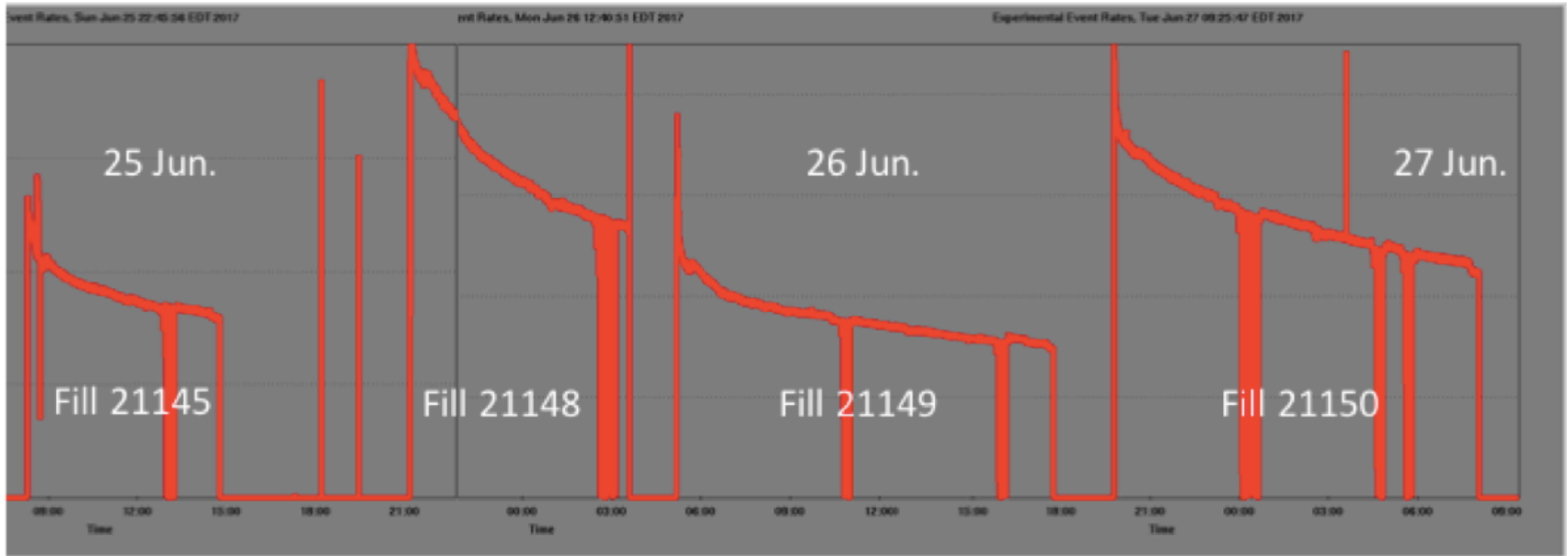
-

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



- 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:  $10^{31} \text{ cm}^{-2}\text{s}^{-1}$  than usual.

# Triggers of RHICf detector



OR

**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  $\pi^0$ )



OR



**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.

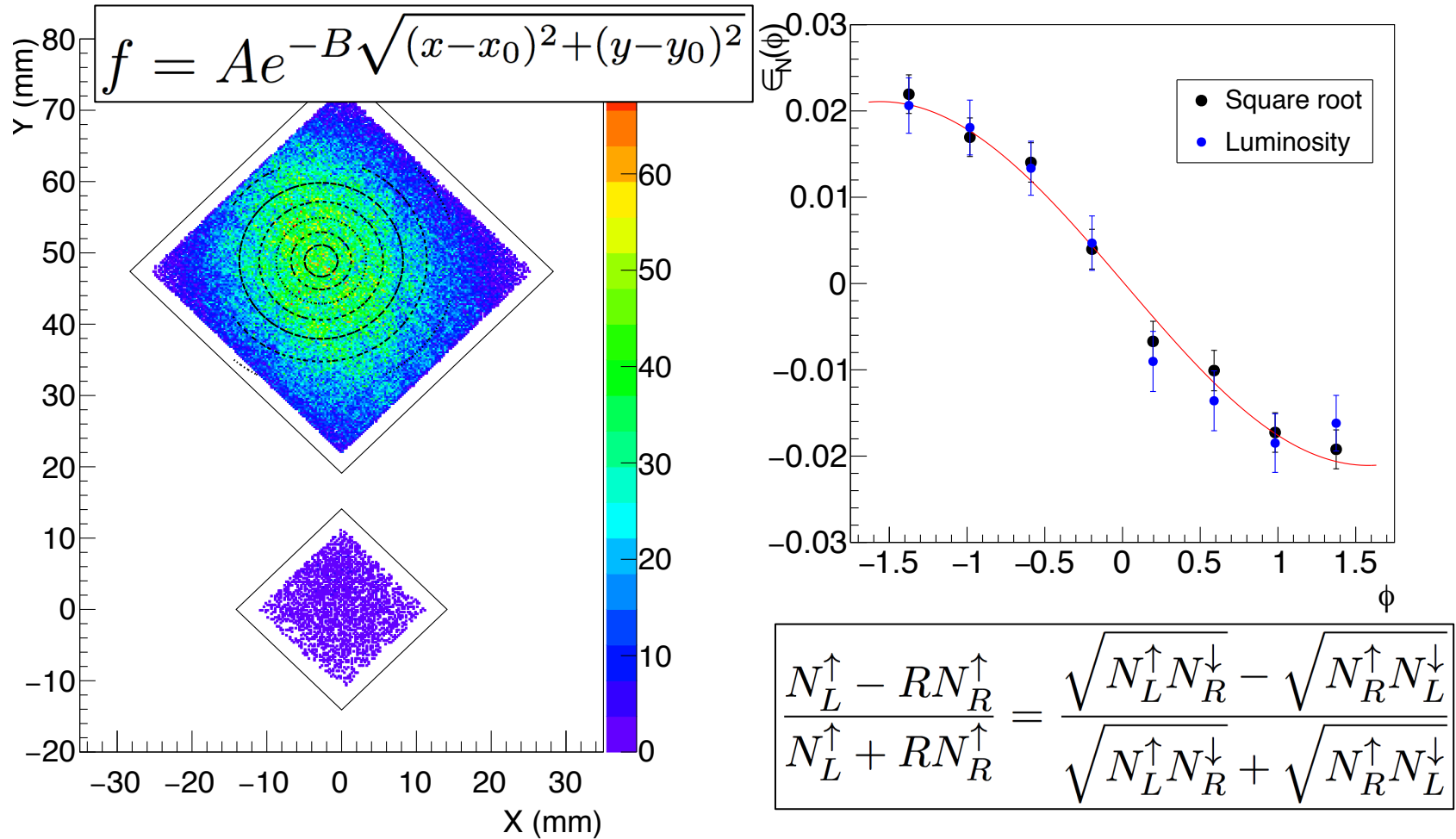
(for Type-I  $\pi^0$ )



AND



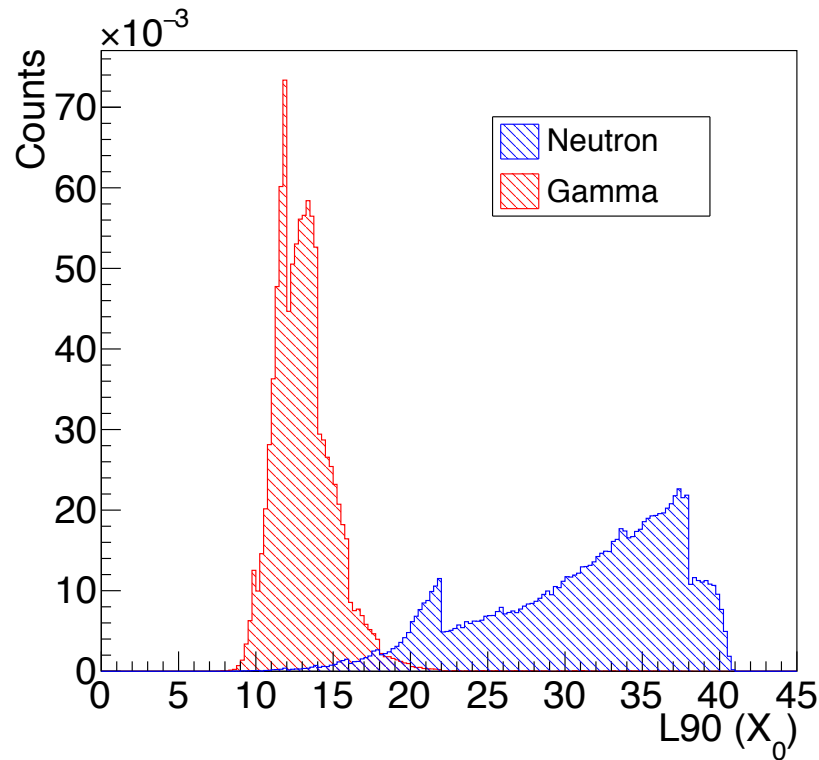
# Beam center calculation (by neutron)



- 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

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

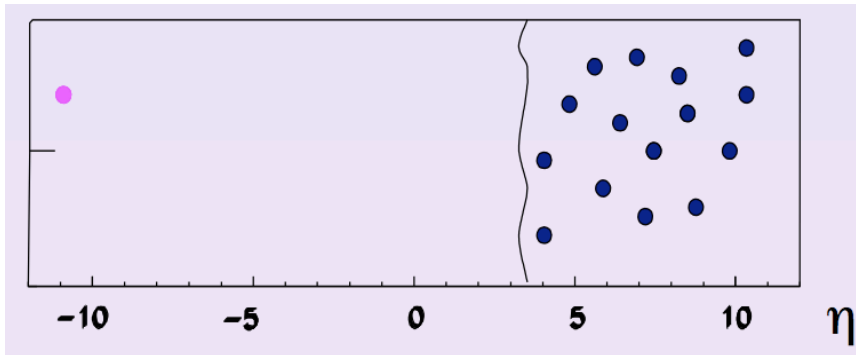
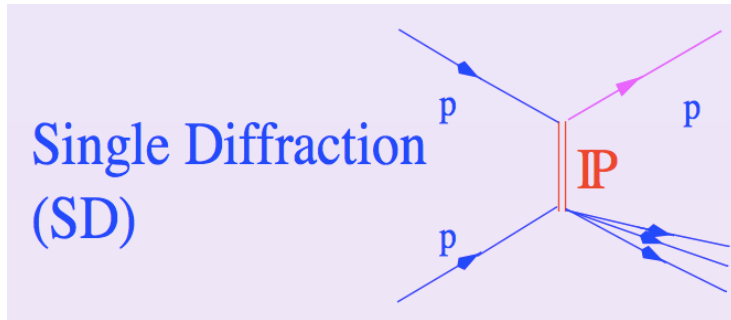
Beam polarization

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

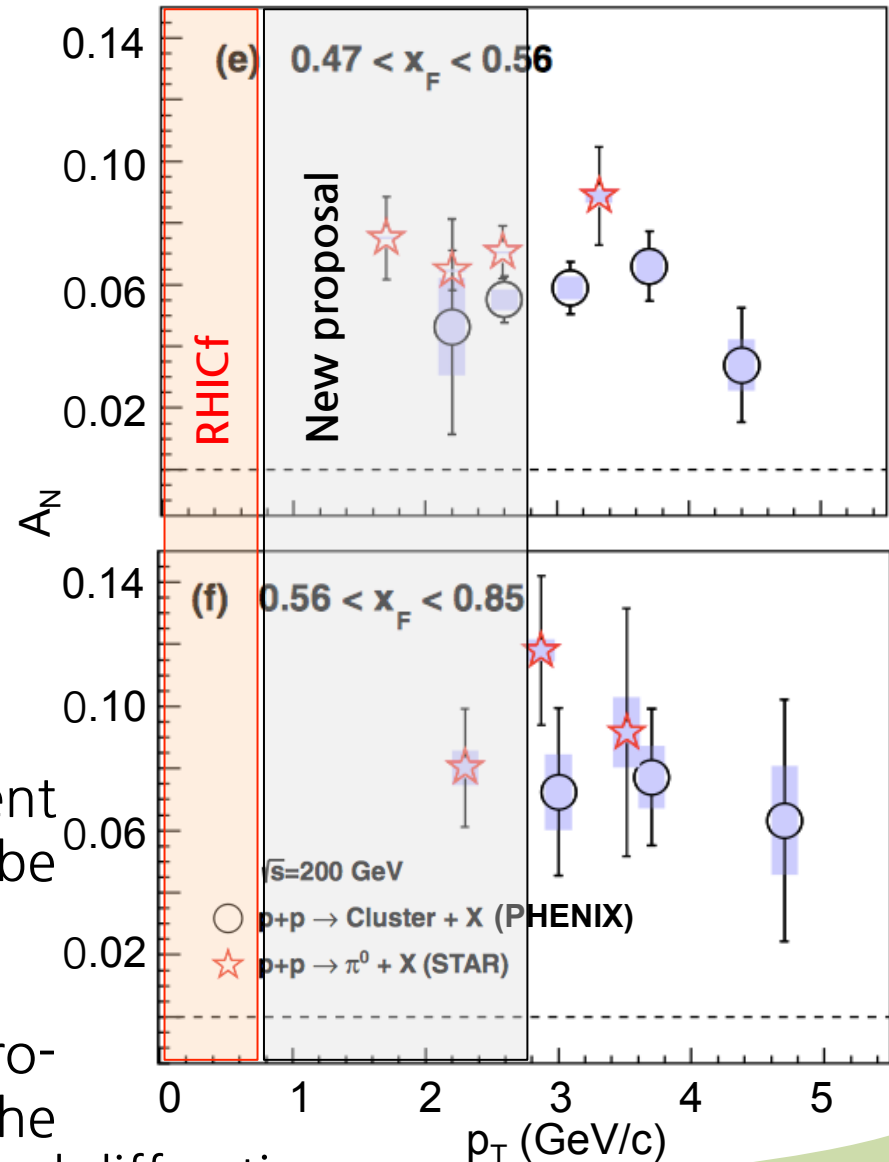
- $P$  ( $\sim 0.55 \pm 0.05$ ) can be calculated by polarization monitor.
- $R$  ( $\sim 0.970 \pm 0.02$ ) is estimated by luminosity ratio of charged particles near IP.
- $\epsilon$  ( $\sim 0.95 \pm 0.05$ ) can be studied by comparing actual and diluted  $A_N$  in simulation.

# What's the next?

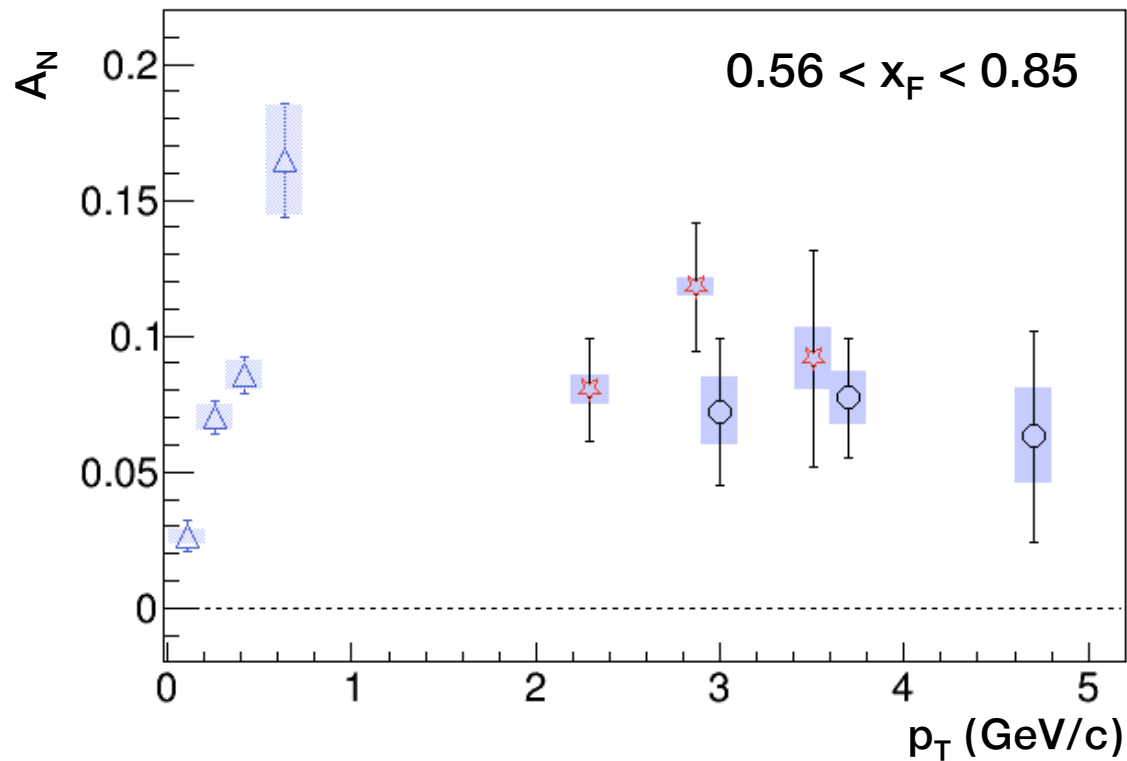
Phys. Rev. D90 (2014) 012006.



- 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 partonic and diffractive process.



# What's the next?



$\sqrt{s} = 200$  GeV

○  $p^\uparrow + p \rightarrow \text{Cluster} + X$  (PHENIX)  
☆  $p^\uparrow + p \rightarrow \pi^0 + X$  (STAR)

$\sqrt{s} = 510$  GeV

△  $p^\uparrow + p \rightarrow \pi^0 + X$  (RHICf)

- 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.