Transverse single-spin asymmetry for very forward neutral particle production in high-energy $p\uparrow + p$ collisions

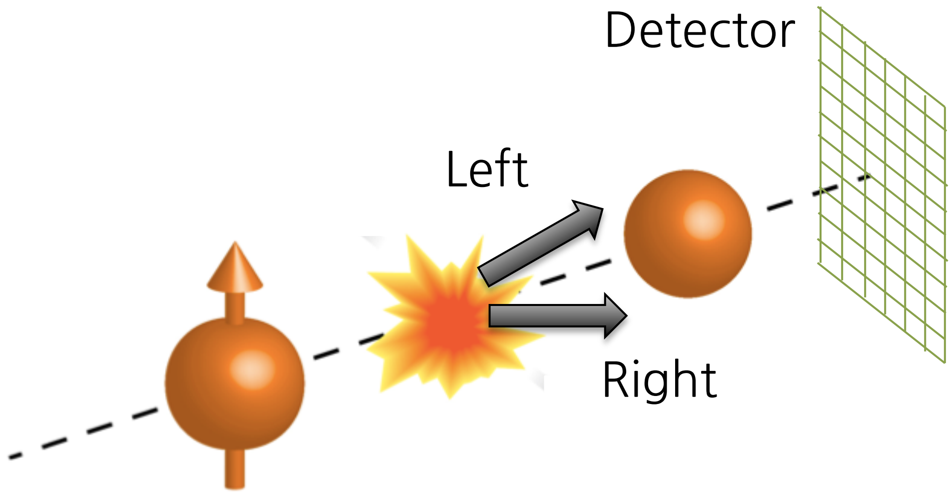
Minho Kim (RIKEN BNL Research Center)

on behalf of the RHICf collaboration

RIKEN's Programs for Junior Scientists

11 May Nishina Center Seminar

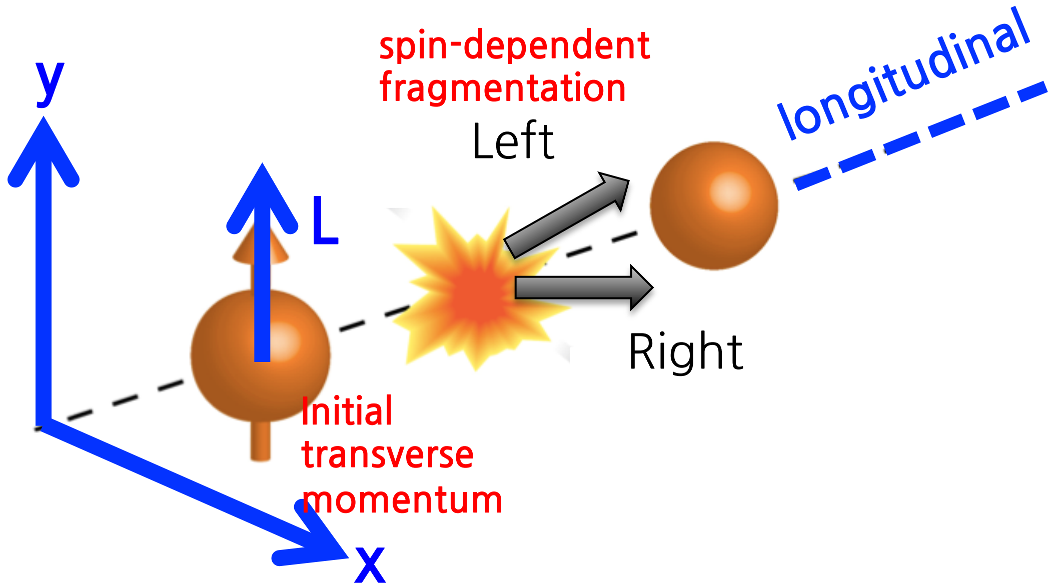
Transverse single-spin asymmetry (A_N)



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

- In p↑ + p collision, A_N is defined as a left-right cross section asymmetry of a specific particle or event.
  - Why do we measure the A_N?
  - Why do we measure the A_N of very forward neutral particle?
  - How can we measure and analyze it?
  - **RHICf experiment**

Transverse single-spin asymmetry (A_N)

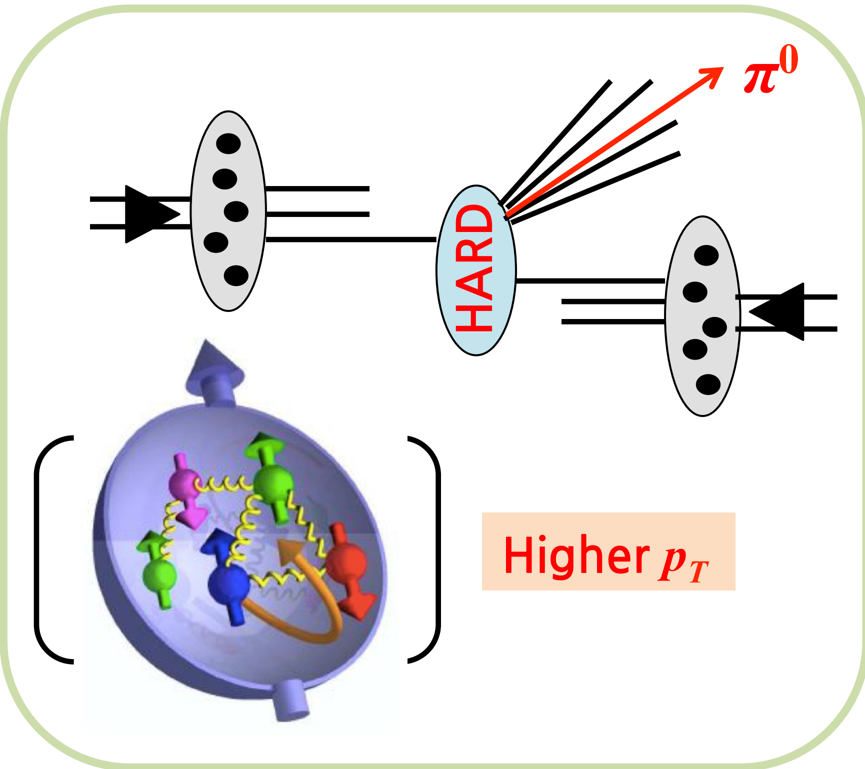


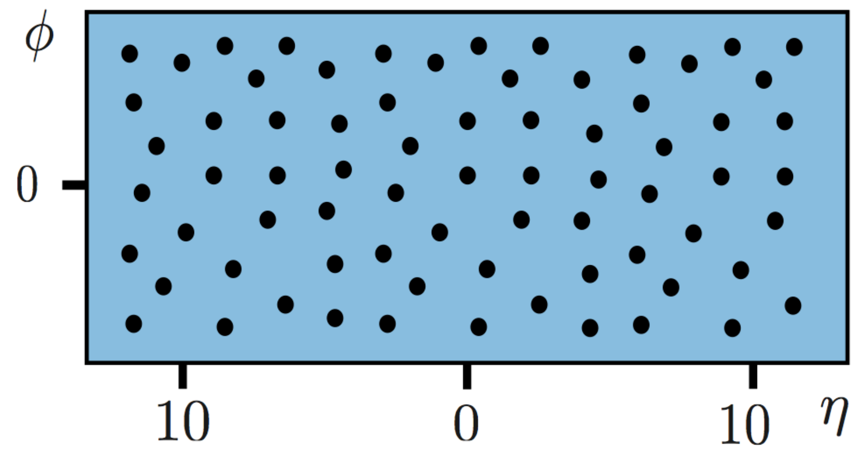
$$A_N = \frac{\sigma_L^{\uparrow} - \sigma_R^{\uparrow}}{\sigma_L^{\uparrow} + \sigma_R^{\uparrow}}$$

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

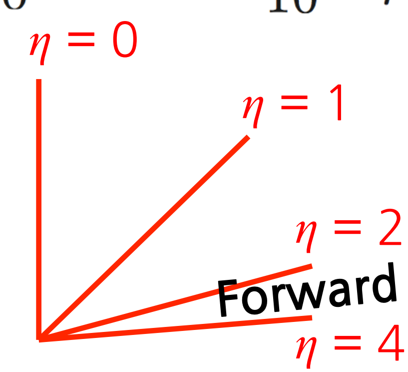
- A_N measurement makes us to approach transverse structure of the proton.
- For non-diffractive particle production, the non-zero A_N has been explained by
  - initial transverse momentum of partons.
  - spin-dependent fragmentation.
  - higher-order quark-gluon correlation

Non-diffractive (partonic) process



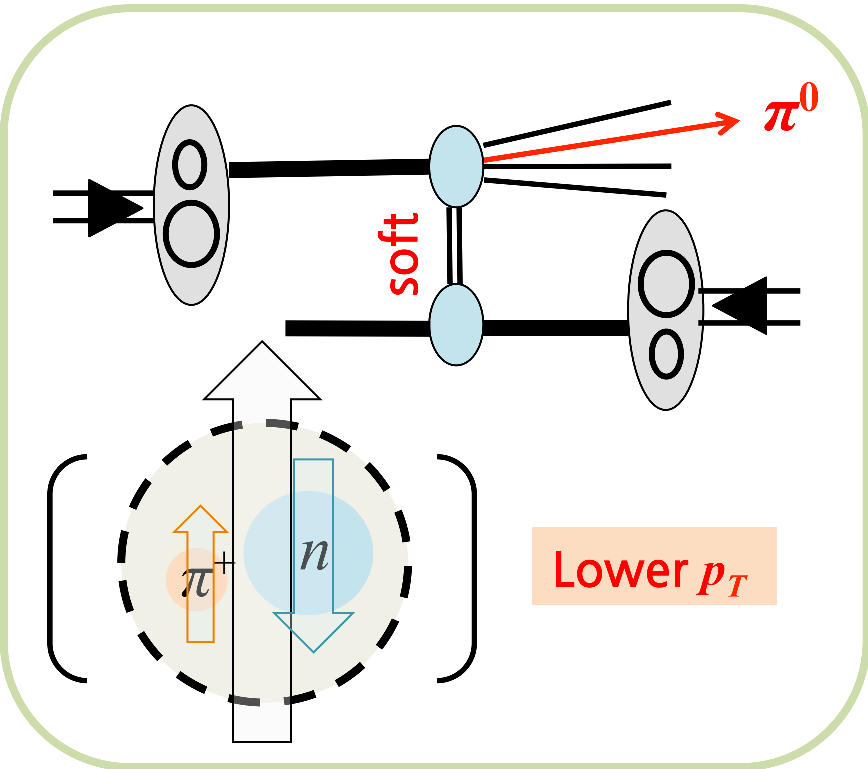


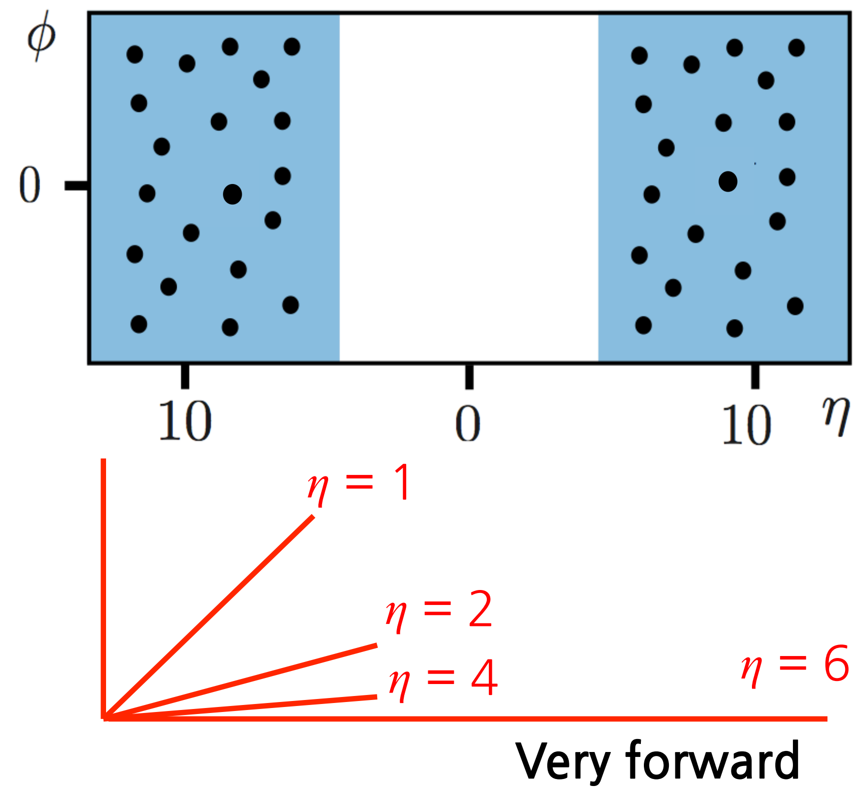
$$\eta \equiv -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$$



- Non-diffractive process usually describes the p + p collision as “hard” scattering between quarks and gluons.
- Higher $p_T > 1$ GeV/c with many particles around.
- Forward particle production: $2 < \eta < 4$.

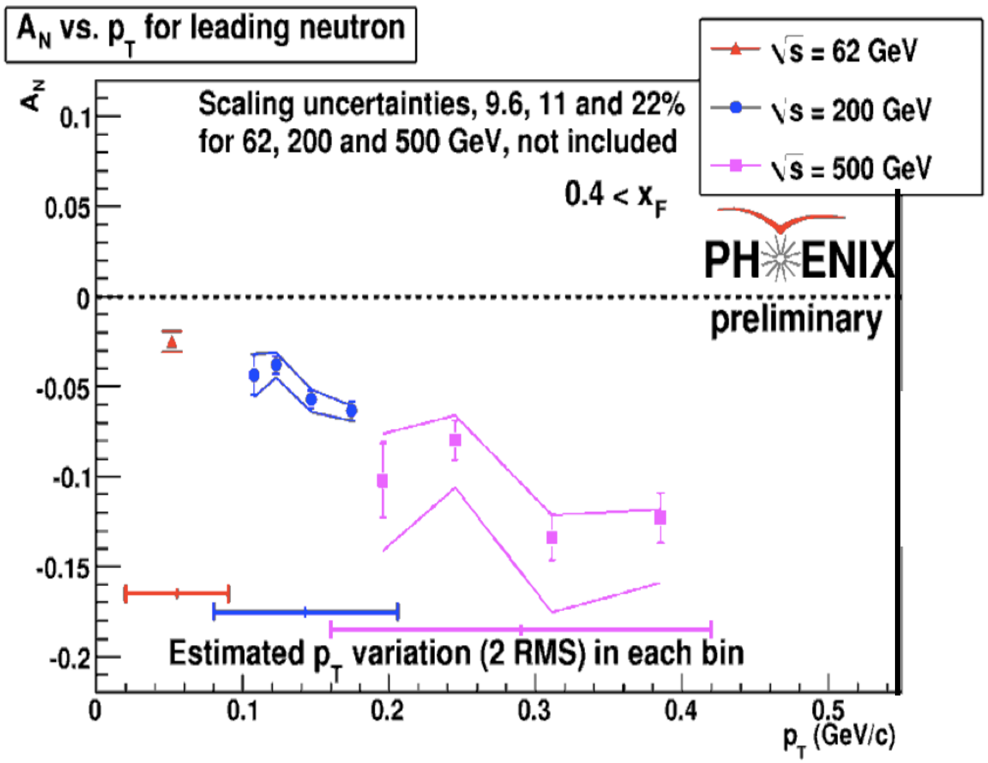
Diffractive (hadronic) process

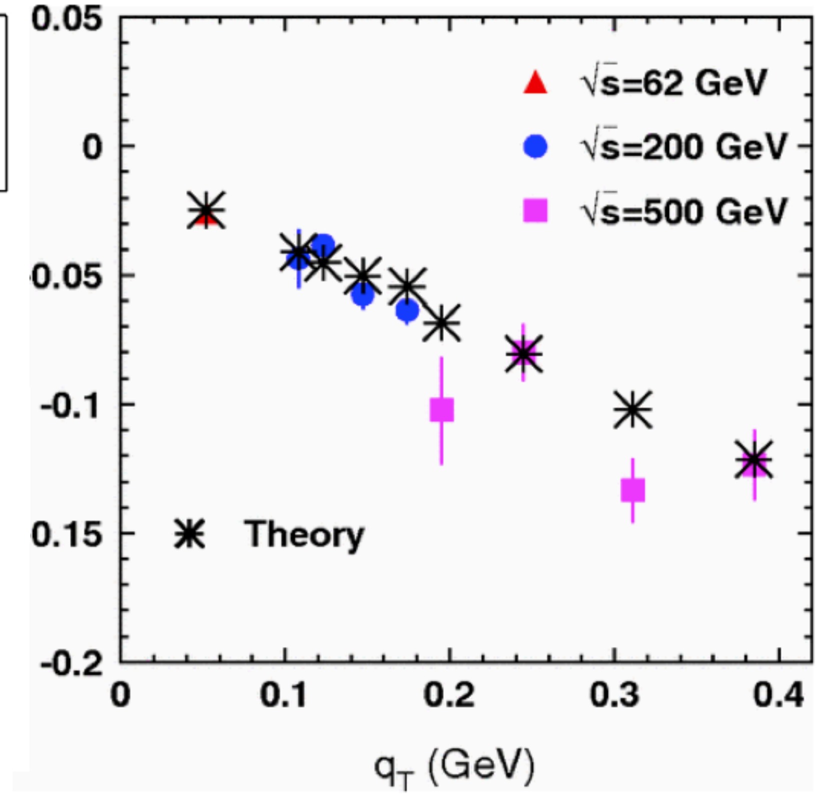




- Diffractive process usually describes the p + p collision as "soft" scattering in the mesonic degree of freedom.
- Lower $p_T < 1$ GeV/c with less particles around (isolated).
- Very forward particle production: $6 < \eta$ (almost zero-degree).

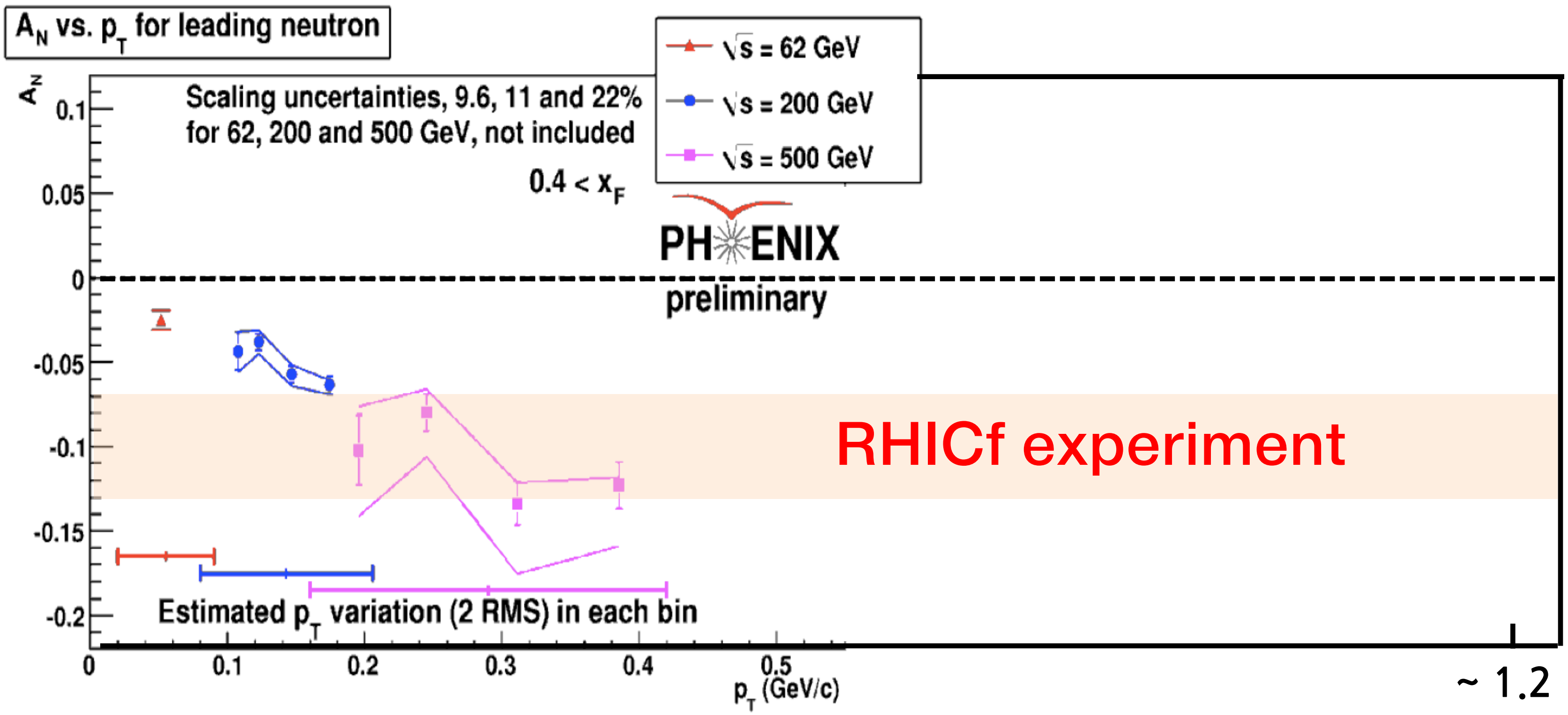
A_N of very forward neutron





- $\sqrt{s}$ and p_T dependences of the neutron A_Ns were largely smeared by insufficient position resolution.

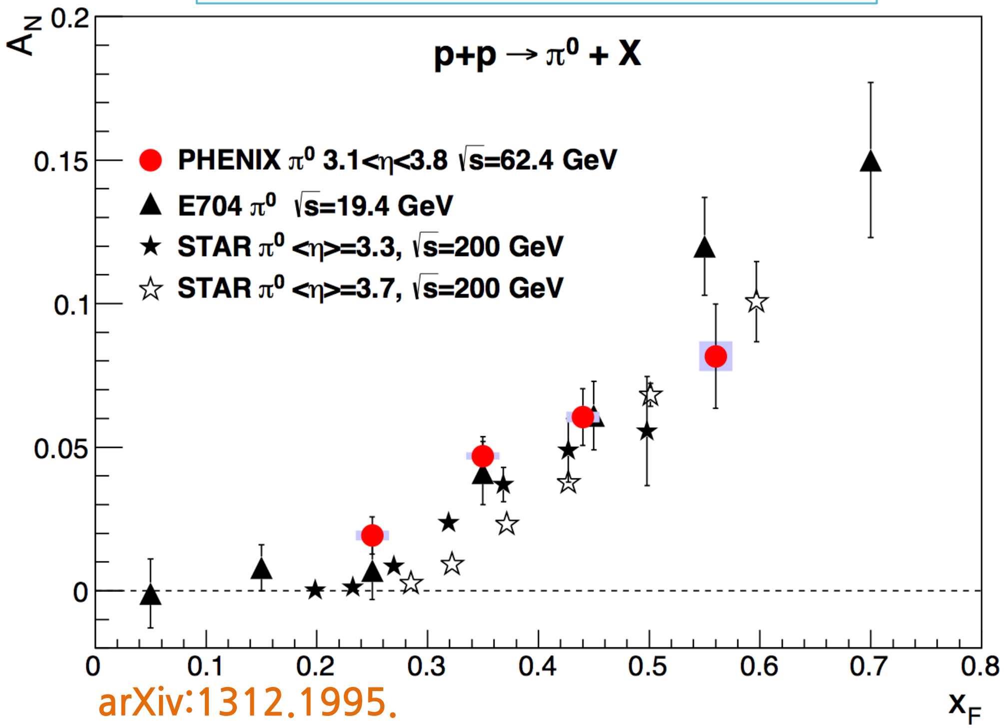
A_N of very forward neutron



- $\sqrt{s}$ and p_T dependences of the neutron A_Ns were largely smeared by insufficient position resolution.
- RHICf experiment will show precise tendency of the neutron A_N as a function of p_T.

A_N of forward π^0

$3 < \eta < 4, p_T > 1$ GeV/c

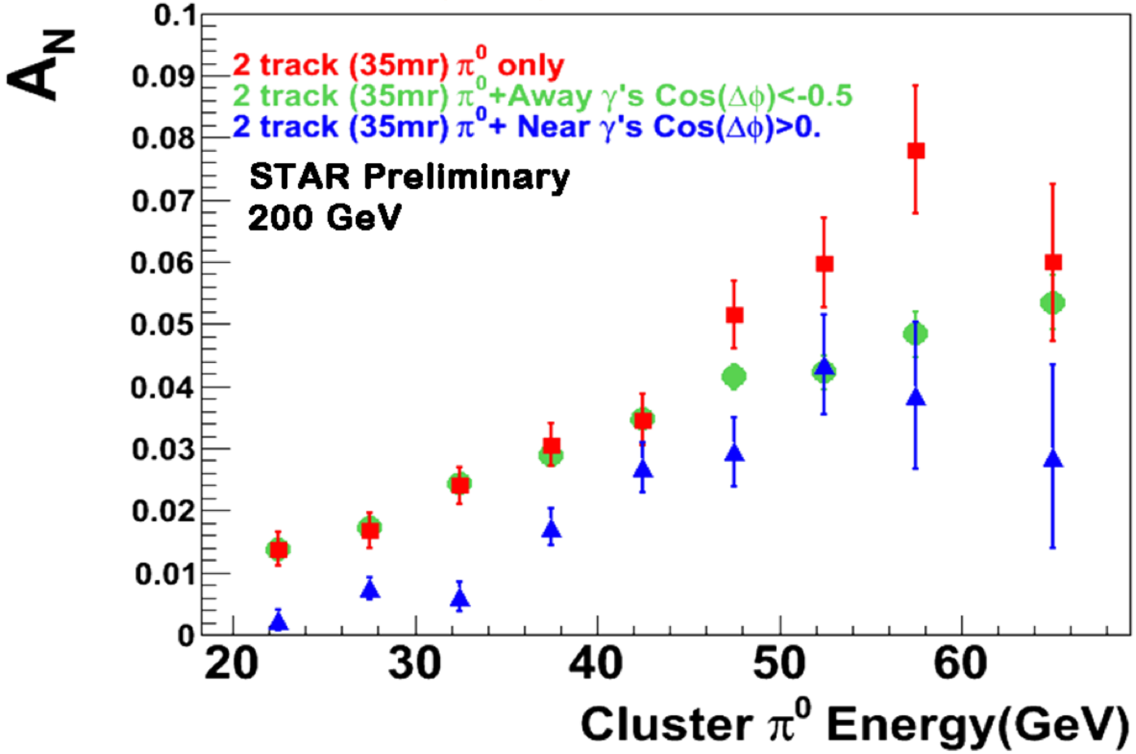


arXiv:1312.1995.

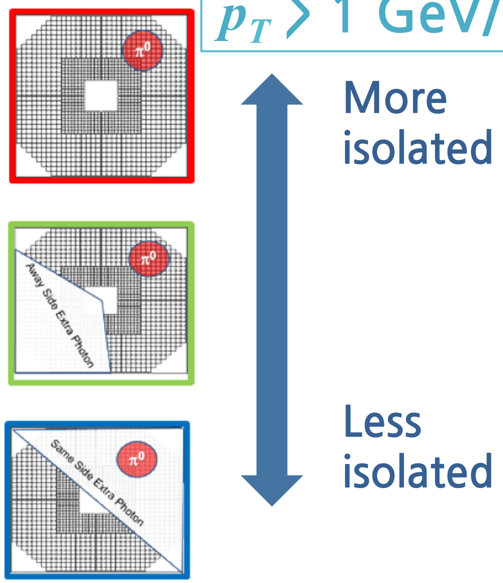
- In contrast to the neutron, non-zero A_N of forward π^0 has been measured by many experiments.
- Observed non-zero A_N has been interpreted based on quarks and gluons' degrees of freedom theoretically.

A_N of isolated forward π^0

PoS DIS2013 (2013) 240.



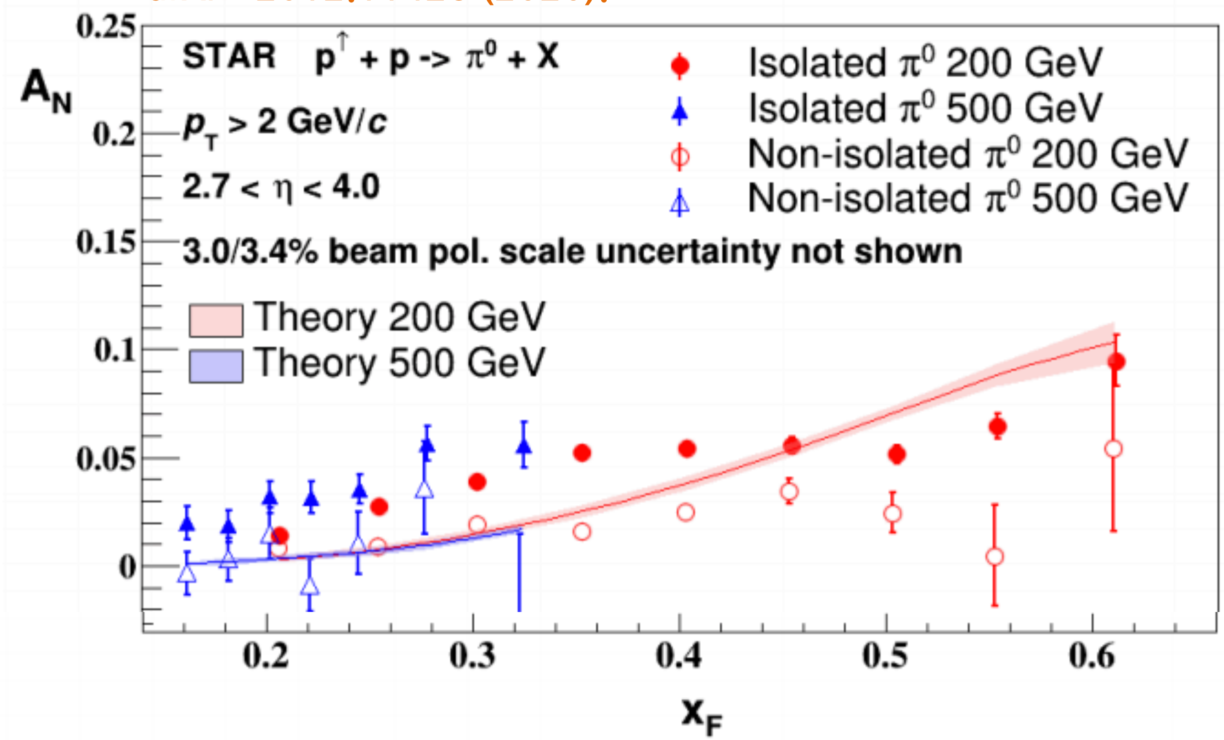
$2.6 < \eta < 4$
$p_T > 1$ GeV/c



- Larger A_N was observed by more isolated π^0 than less isolated one.
- Diffractive process may have a finite contribution to the π^0 A_N as well as non-diffractive one.

A_N of isolated forward π^0

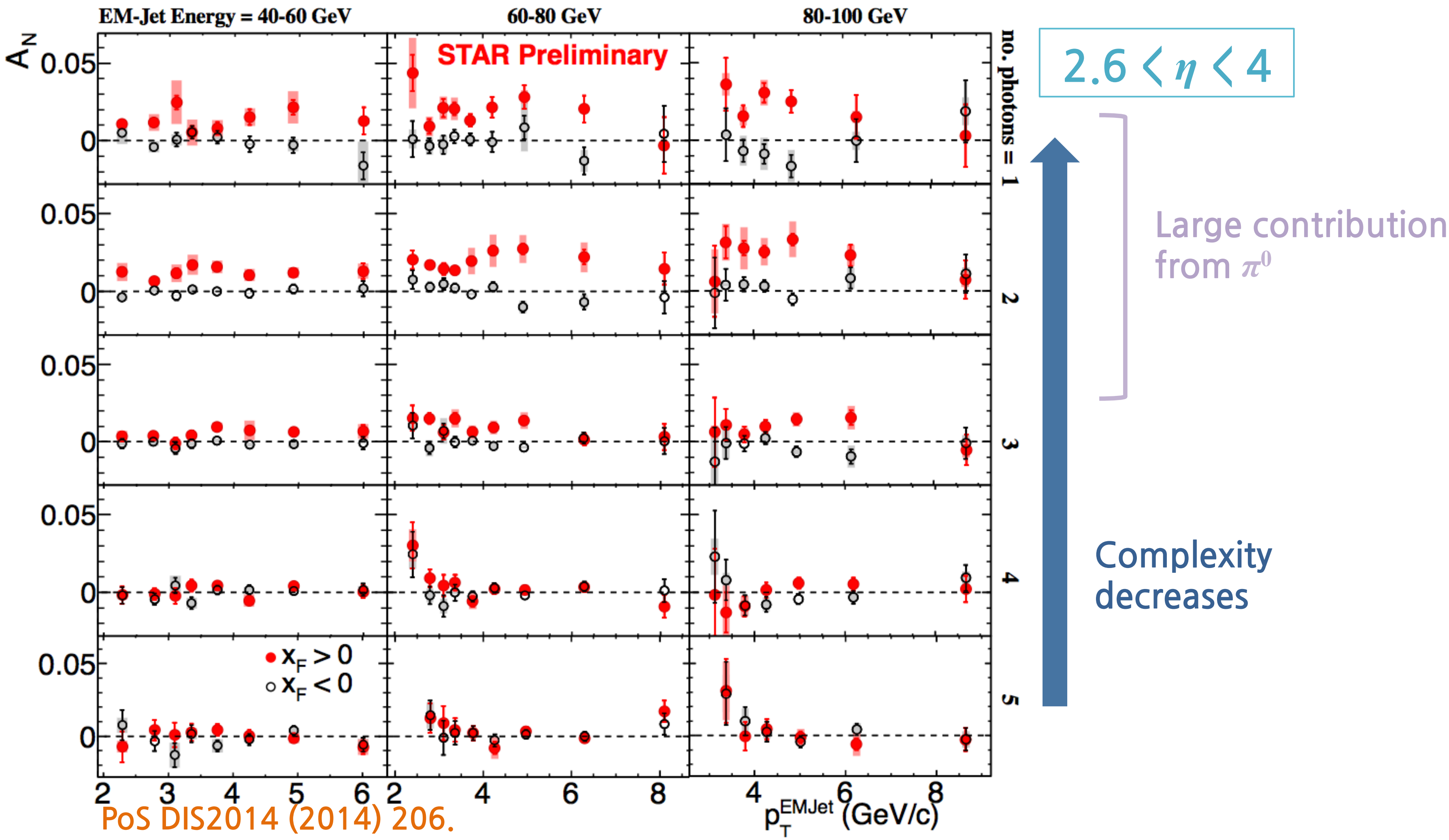
arXiv: 2012.11428 (2020).



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

- Larger A_N was observed by more isolated π^0 than less isolated one.
- Diffractive process may have a finite contribution to the π^0 A_N as well as non-diffractive one.
- In this analysis, isolated = energy fraction close to 1.

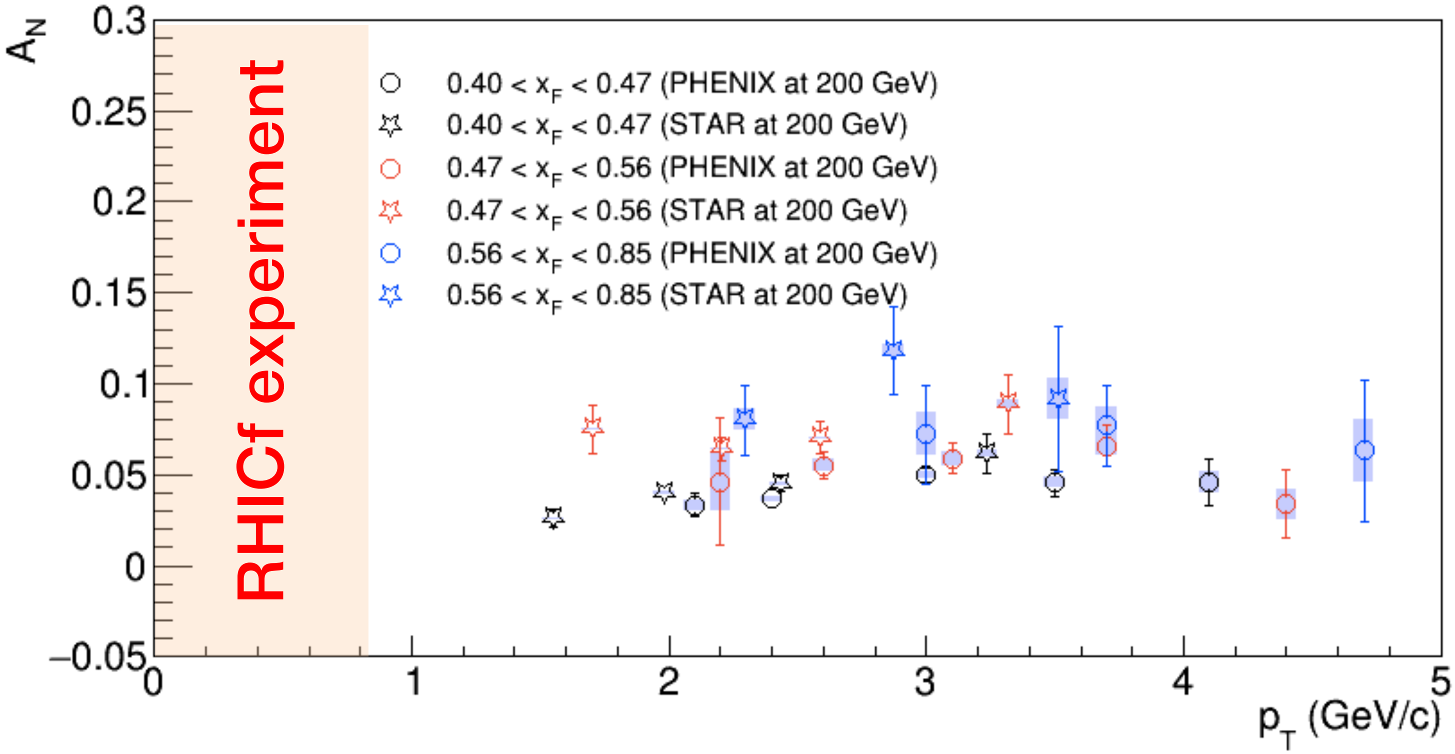
A_N of isolated forward π^0



PoS DIS2014 (2014) 206.

- Larger A_N was observed with decreasing multiplicity of photons (close to diffractive process event topology).

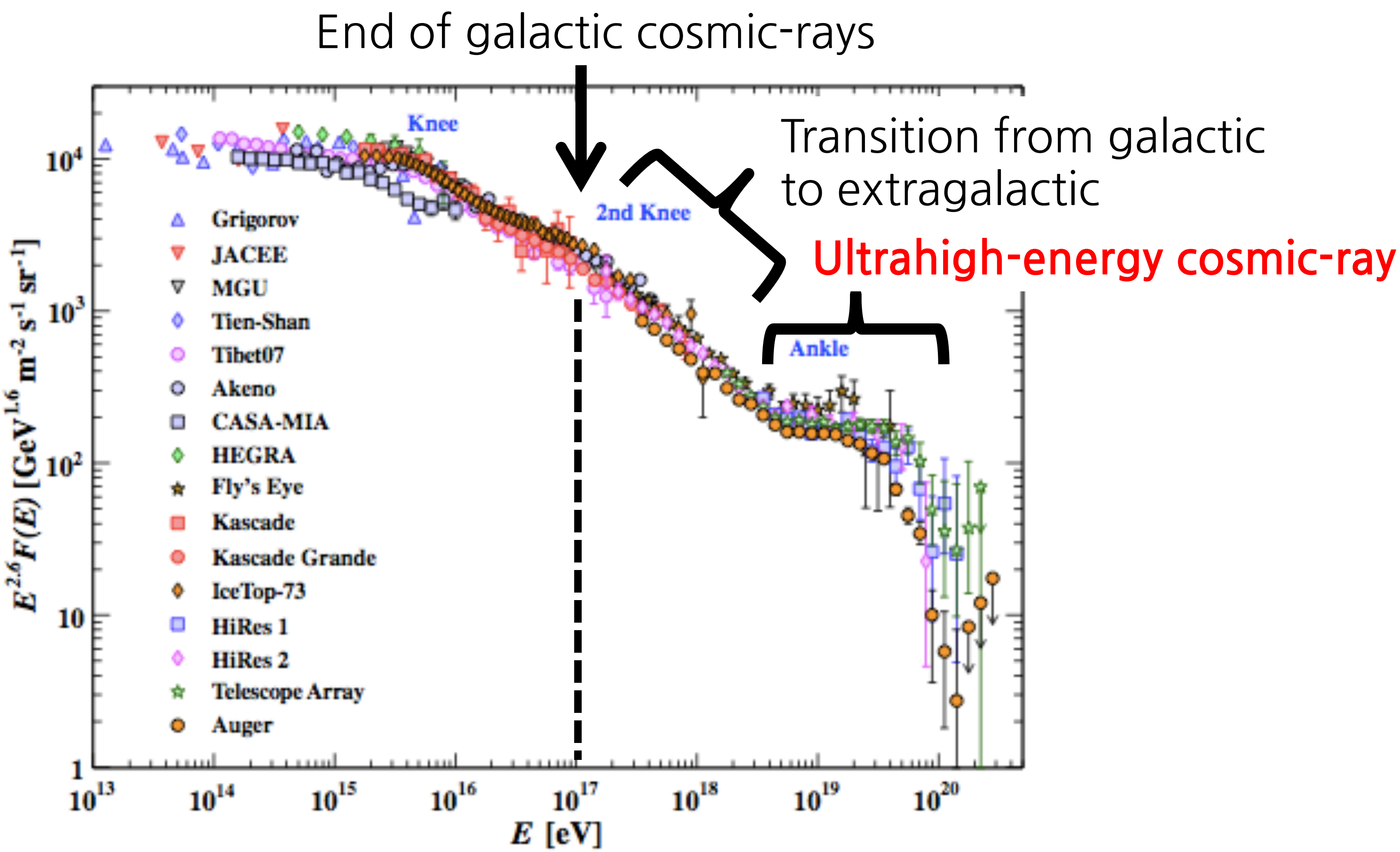
A_N of very forward π^0



- No detailed measurement ever for the $p_T < 1$ GeV/c.

- In June, 2017, the RHICf experiment firstly measured the A_N of very forward π^0 ($6 < \eta$) to study the role of the diffractive process to the π^0 A_N.

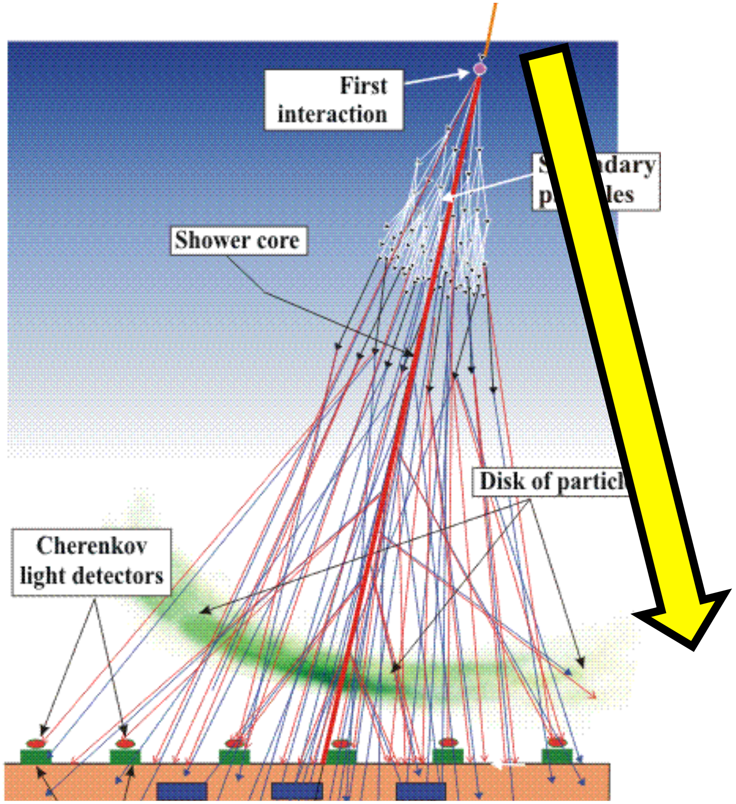
Cosmic-ray physics



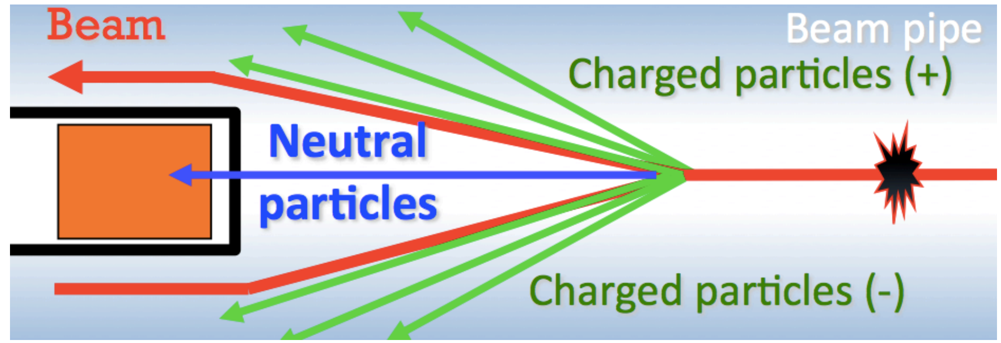
- Cosmic-rays above 10^{18} eV are called ultrahigh-energy cosmic rays (UHECRs).

- Though there has been decades of many efforts, the origin of the UHECRs has been not understood yet.

Role of the hadronic interaction model



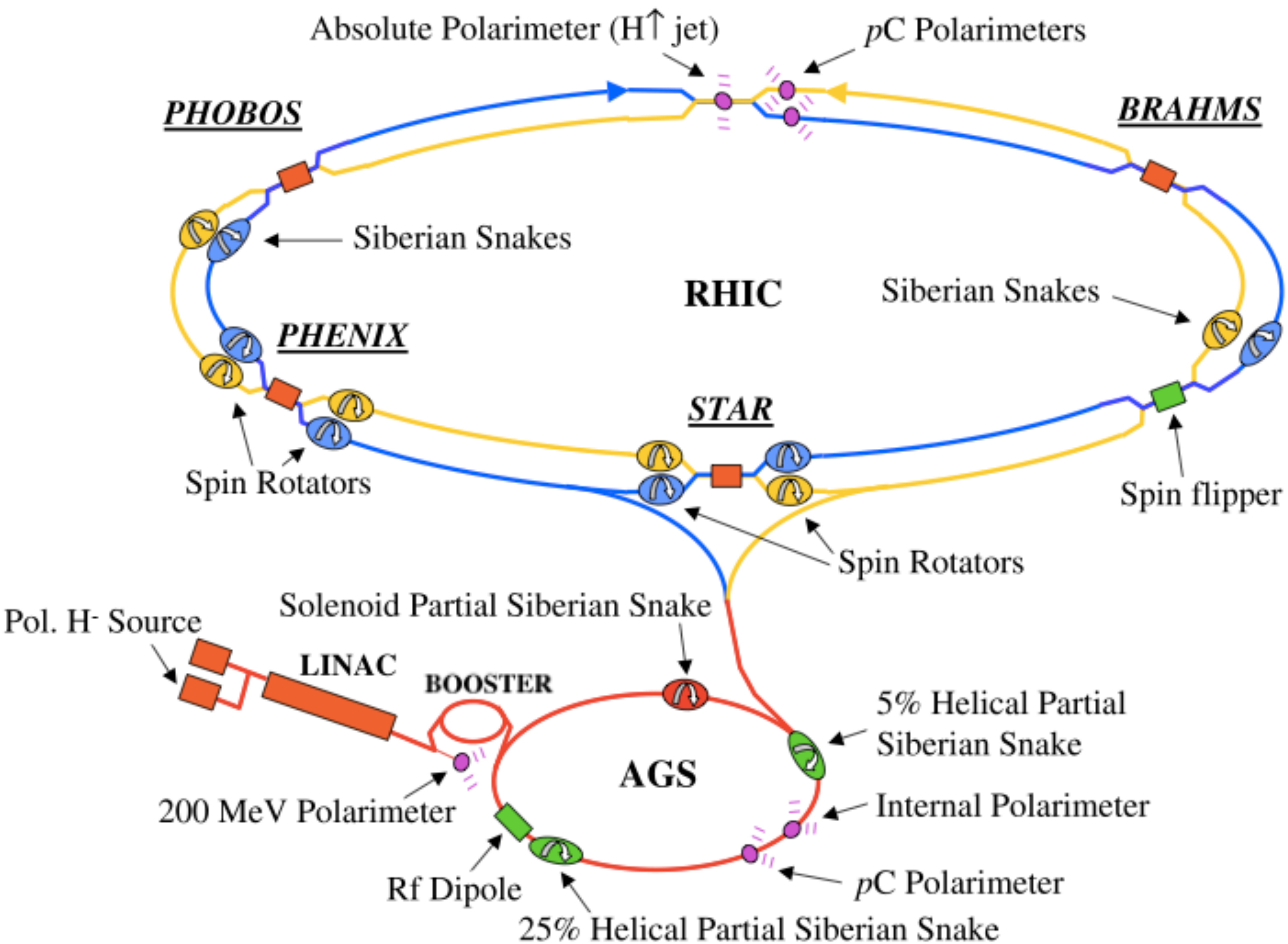
p + p collision



Secondary particle production.

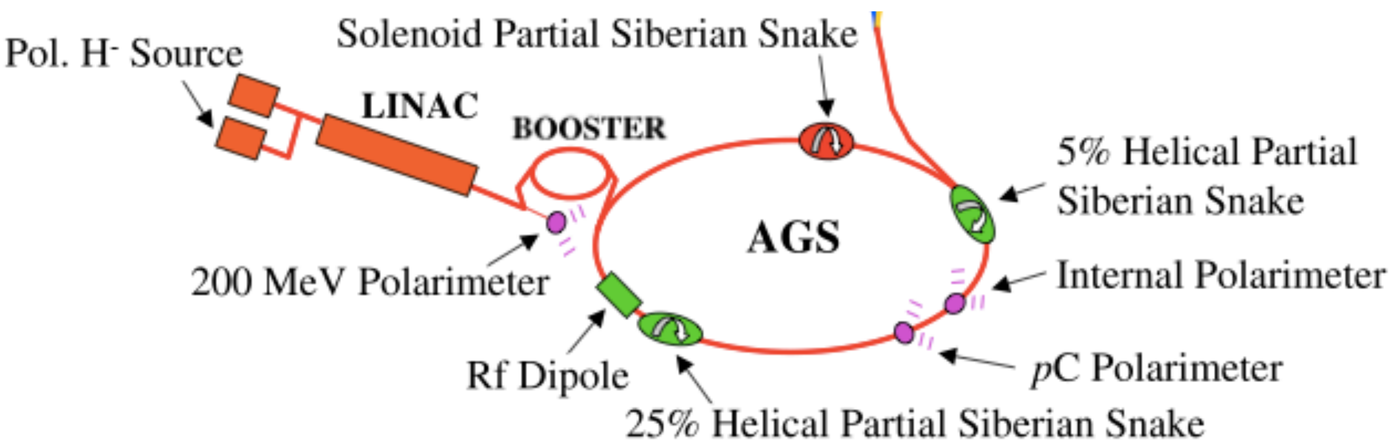
- A proper hadronic interaction model needs to precisely predict the secondary particle production.
- Cross section measurement of the very forward particle production can be a powerful way to constrain the existing models.

Relativistic Heavy Ion Collider (RHIC)



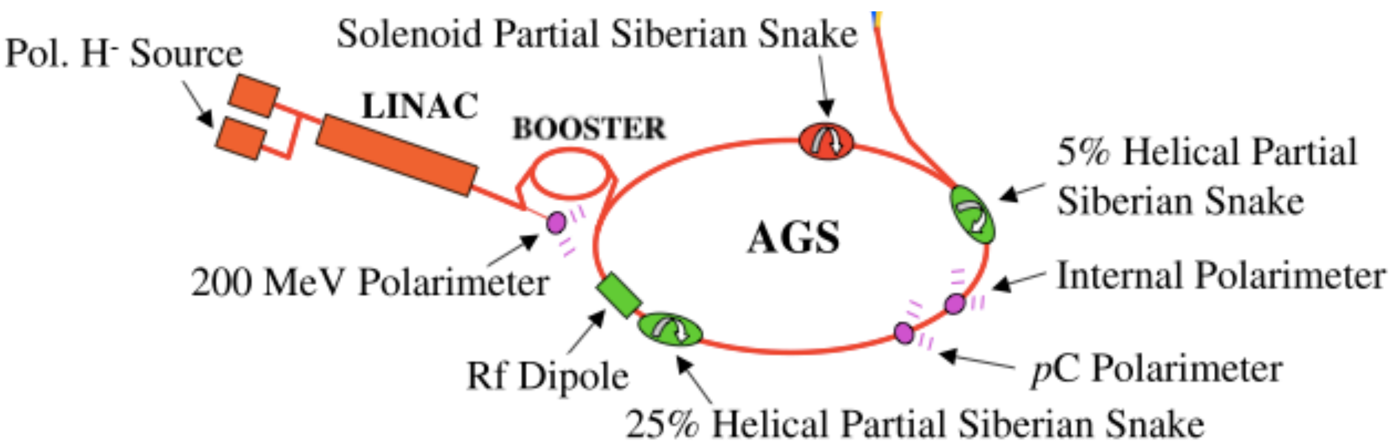
Polarized proton beam

H^+ ⟵ ECR ⟵ H_2

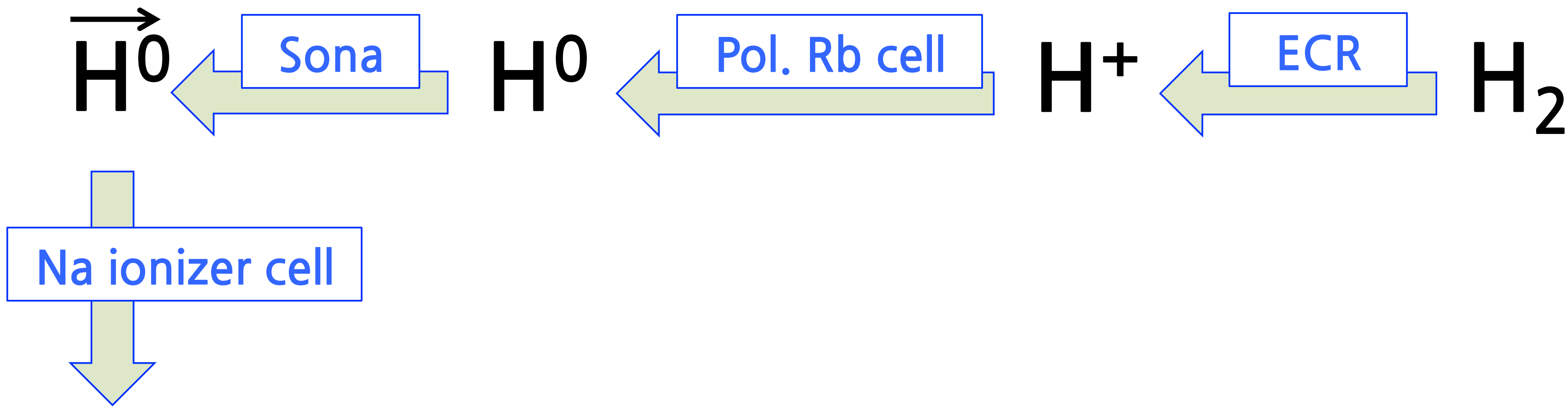


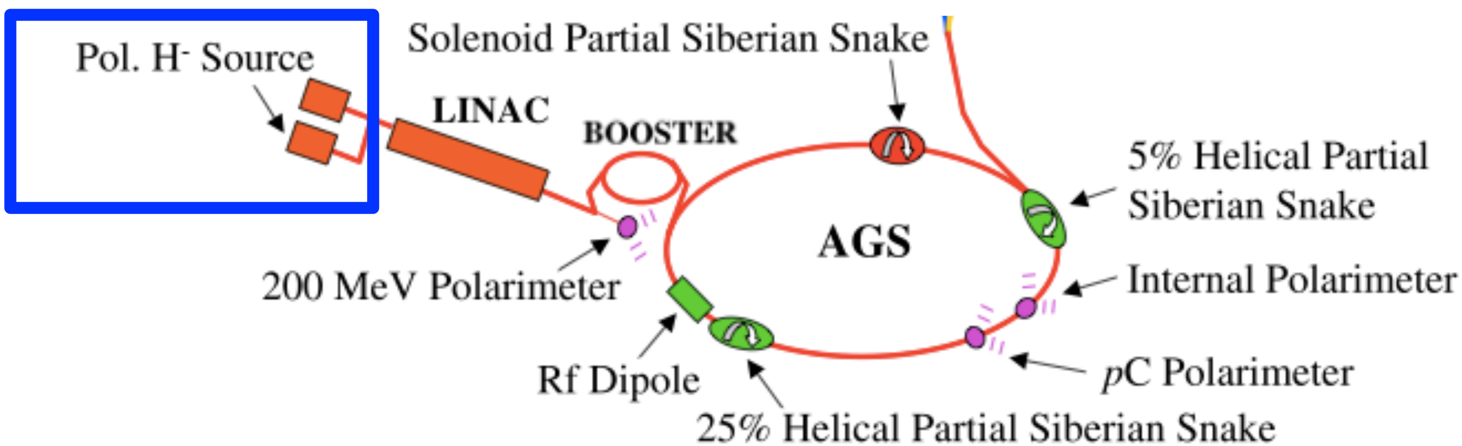
Polarized proton beam

H^0 ← Pol. Rb cell ← H^+ ← ECR ← H_2

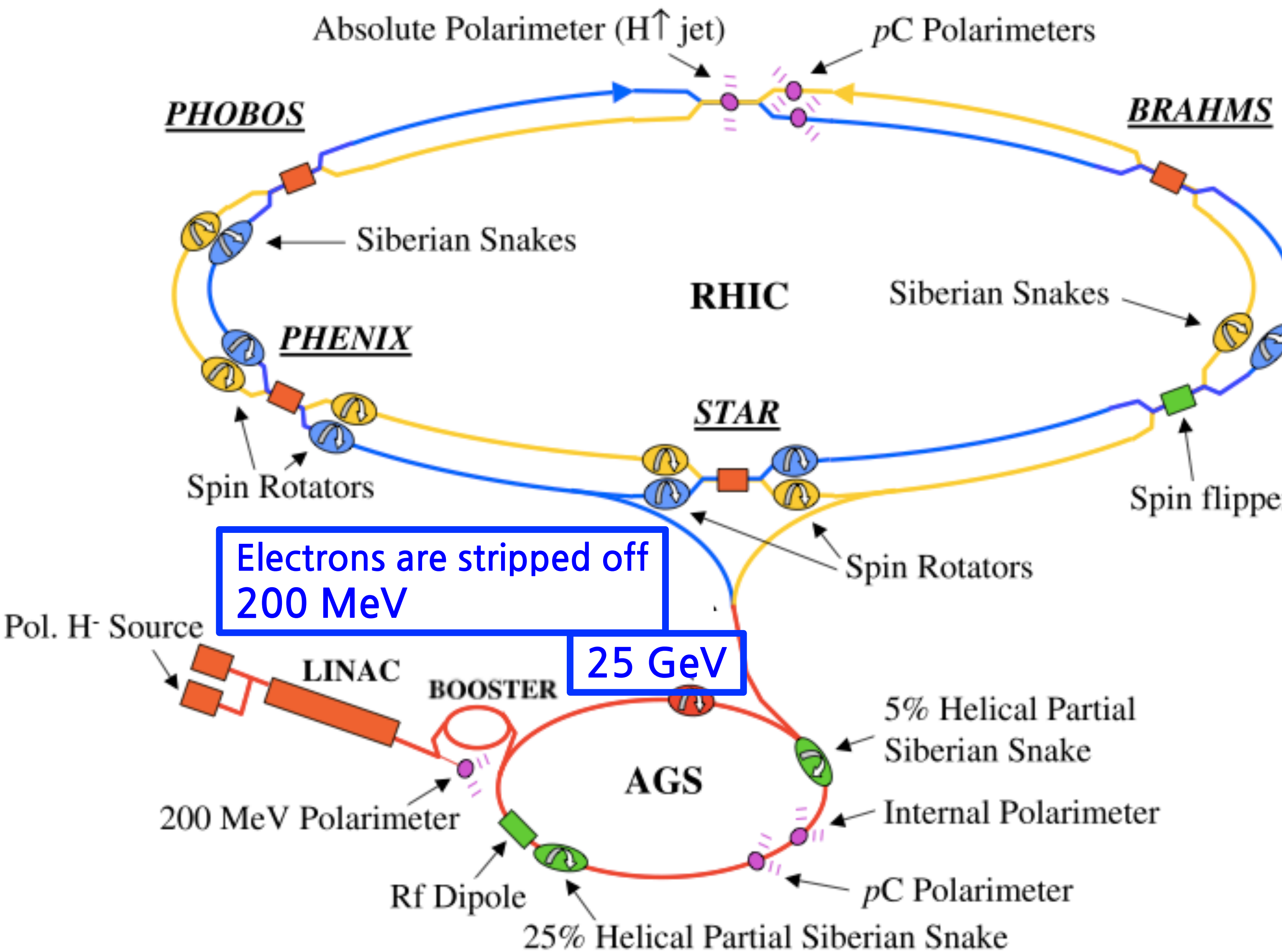


Polarized proton beam

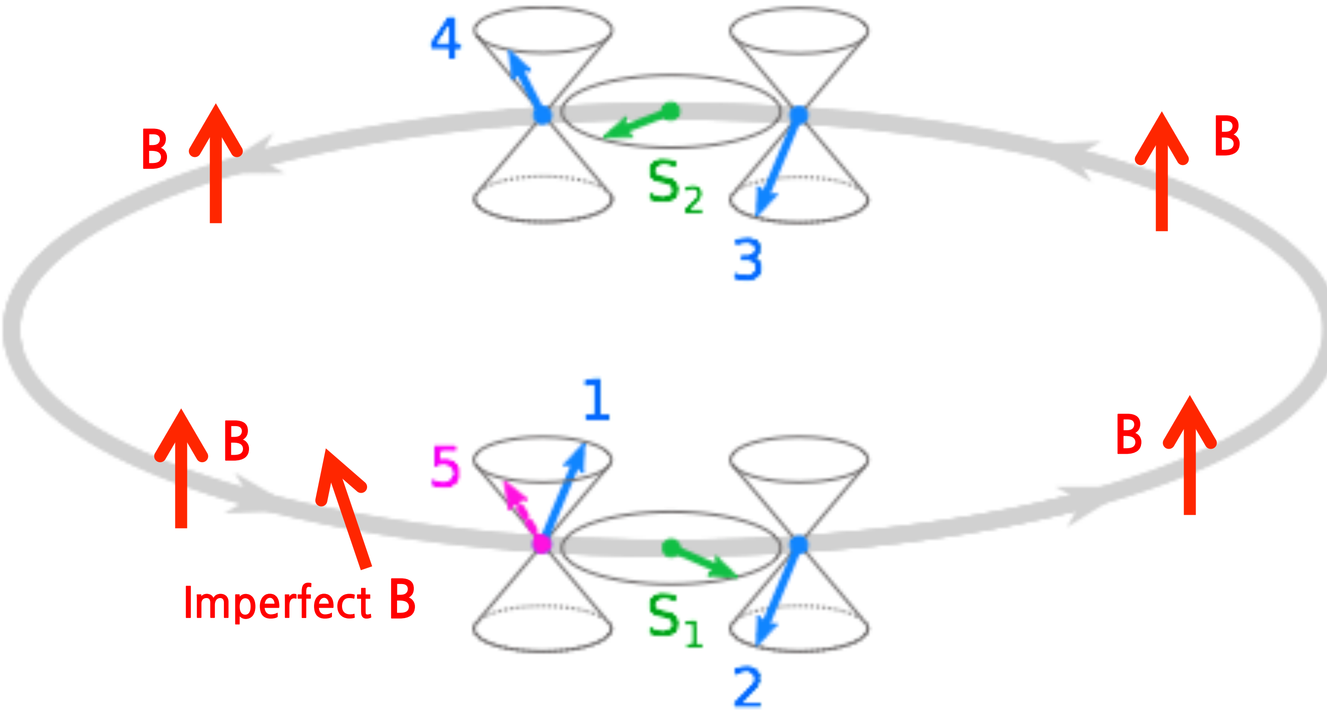




Beam polarization



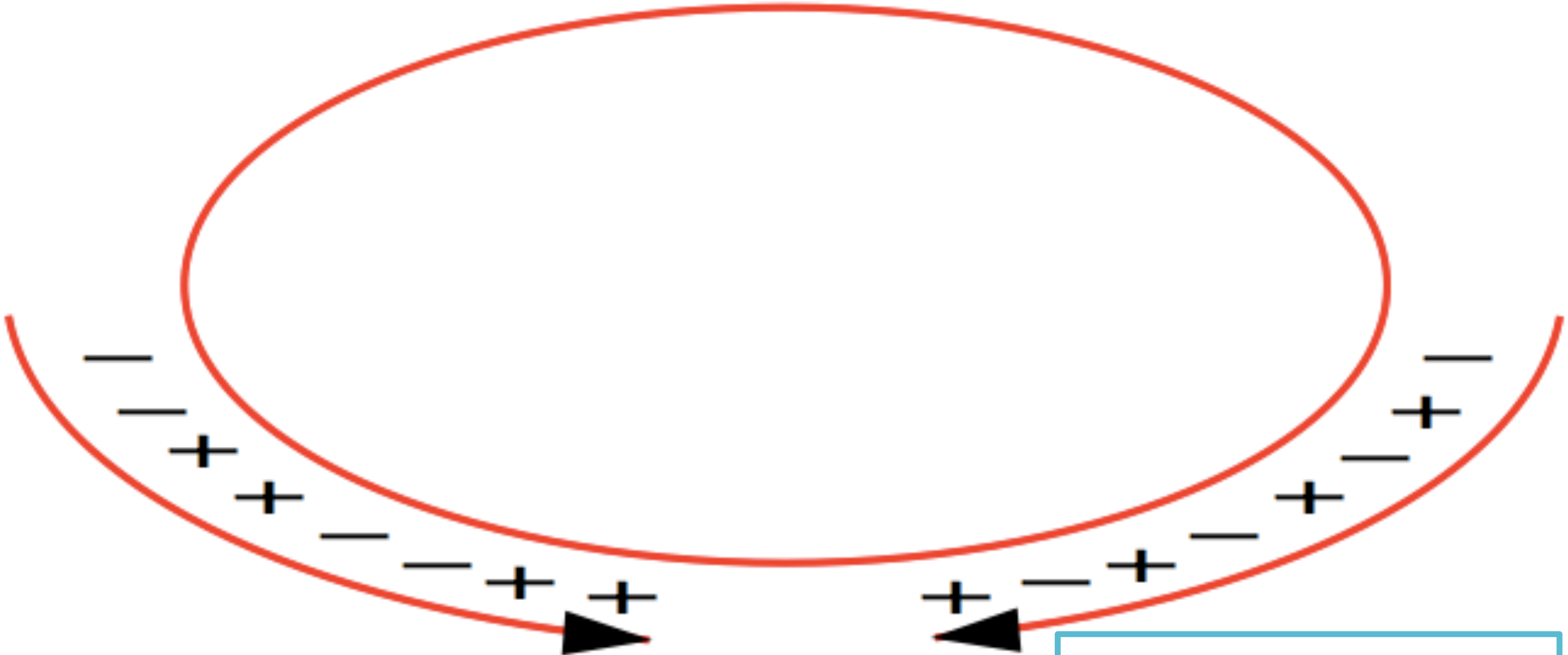
How the polarization can be conserved?



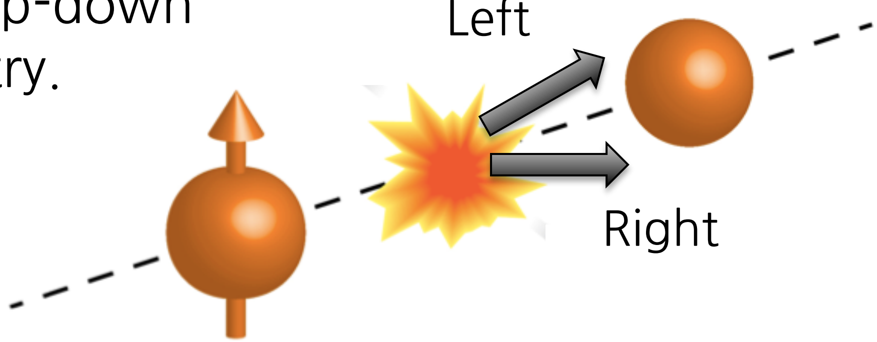
- There is always imperfection in the magnetic field, which can make depolarization resonance.

- A composition of four superconducting helical dipole magnets rotate the spin direction by 180° in every half revolution.

Spin pattern

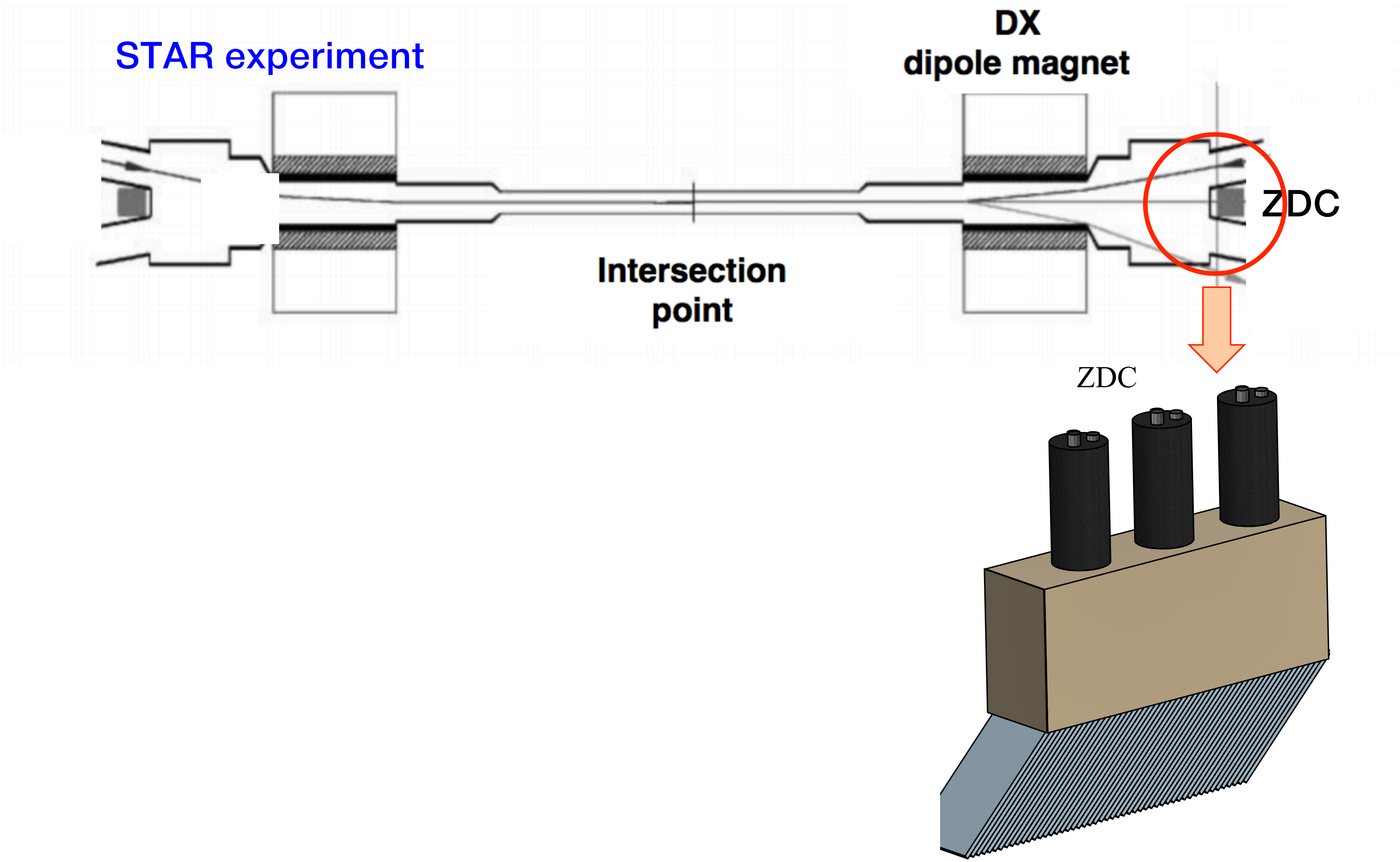


- Due to rotational and parity invariance, the left-right asymmetry can be measured by spin up-down asymmetry.

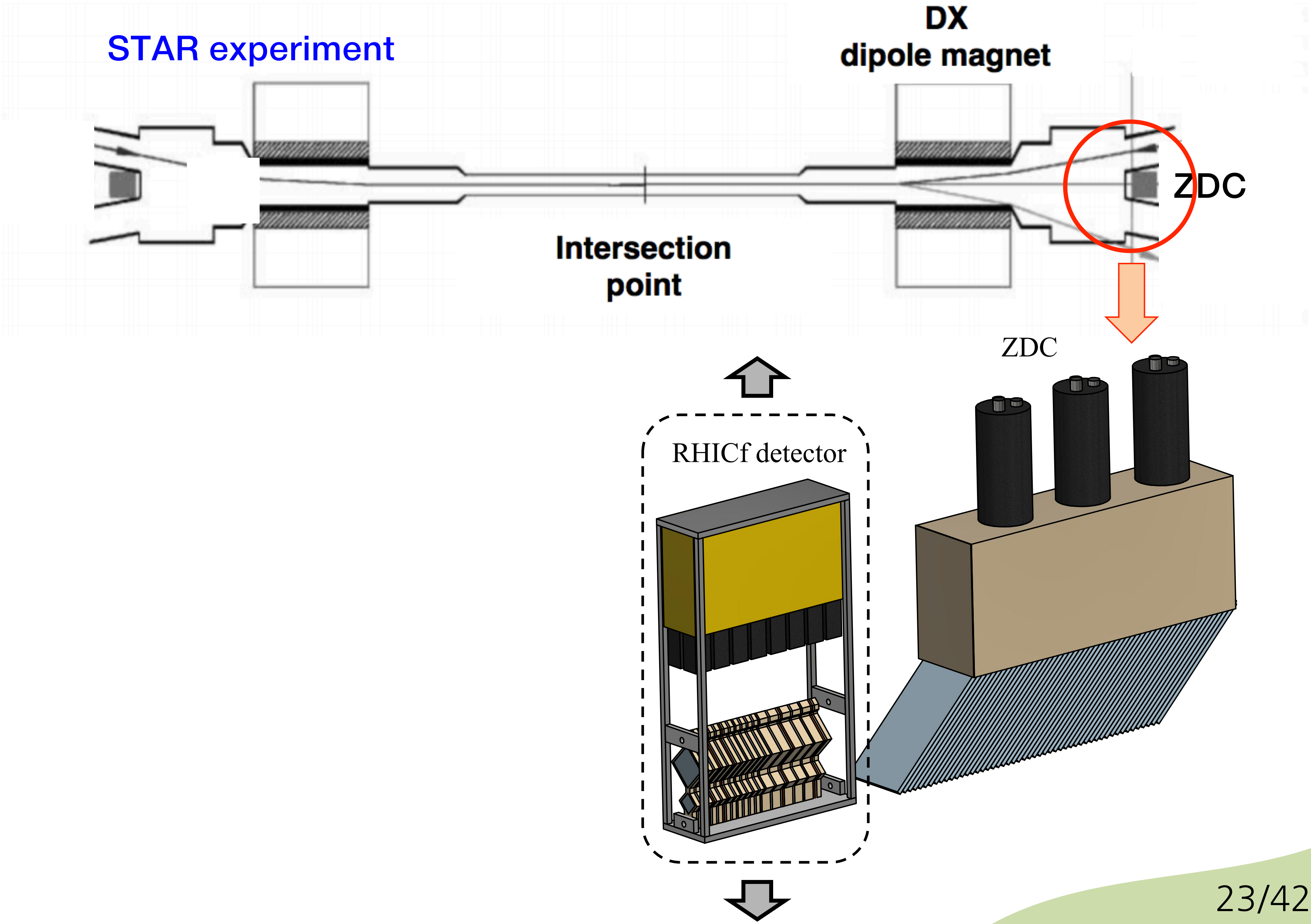


$$A_N = \frac{\sigma_L^{\uparrow} - \sigma_R^{\uparrow}}{\sigma_L^{\uparrow} + \sigma_R^{\uparrow}} = \frac{\sigma_L^{\uparrow} - \sigma_L^{\downarrow}}{\sigma_L^{\uparrow} + \sigma_L^{\downarrow}}$$

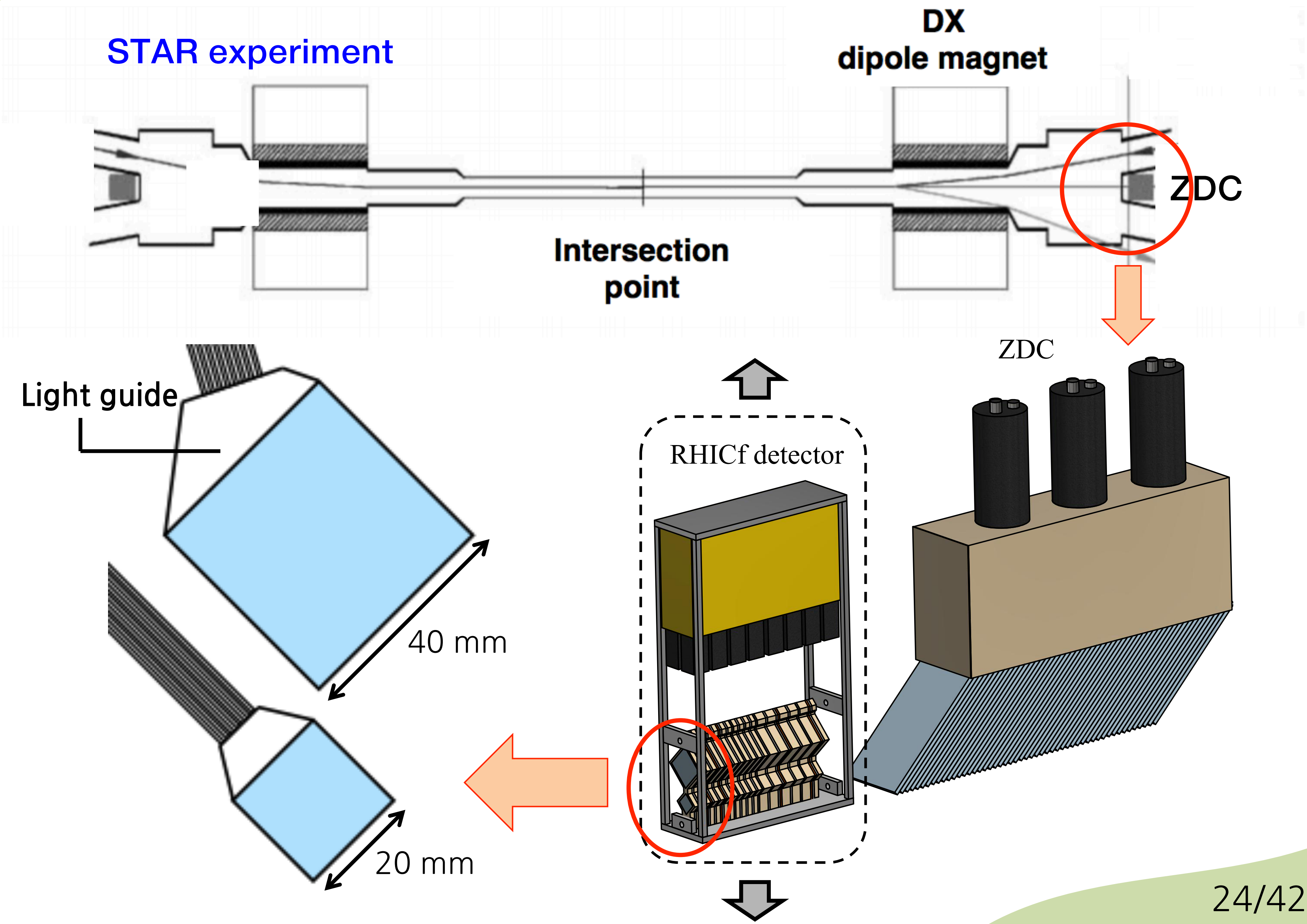
RHIC forward (RHICf) experiment



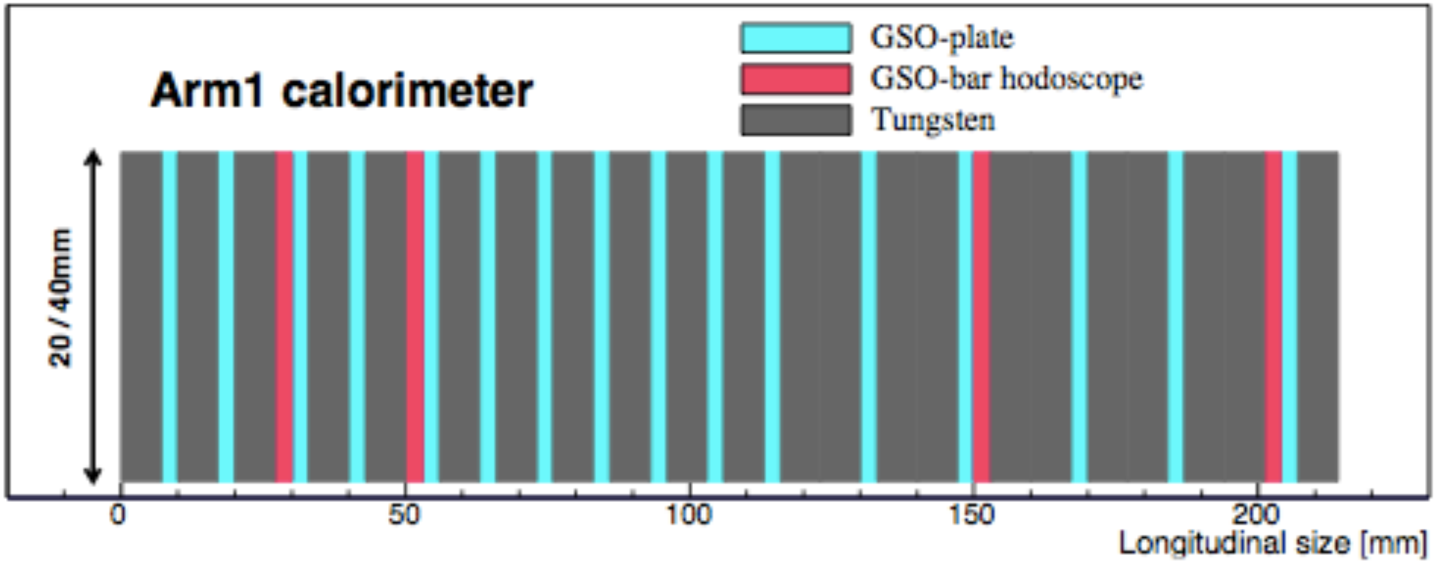
RHIC forward (RHICf) experiment



RHIC forward (RHICf) experiment

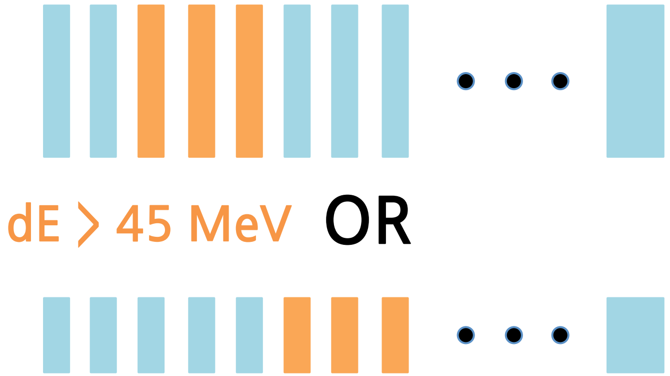


RHICf detector

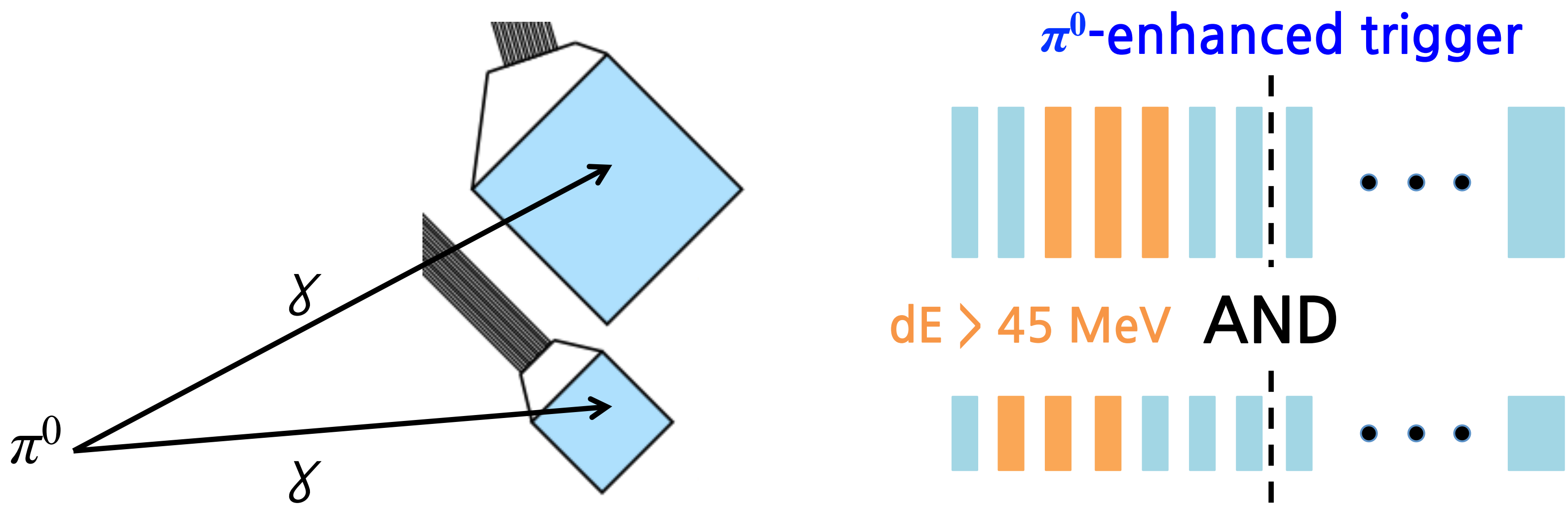


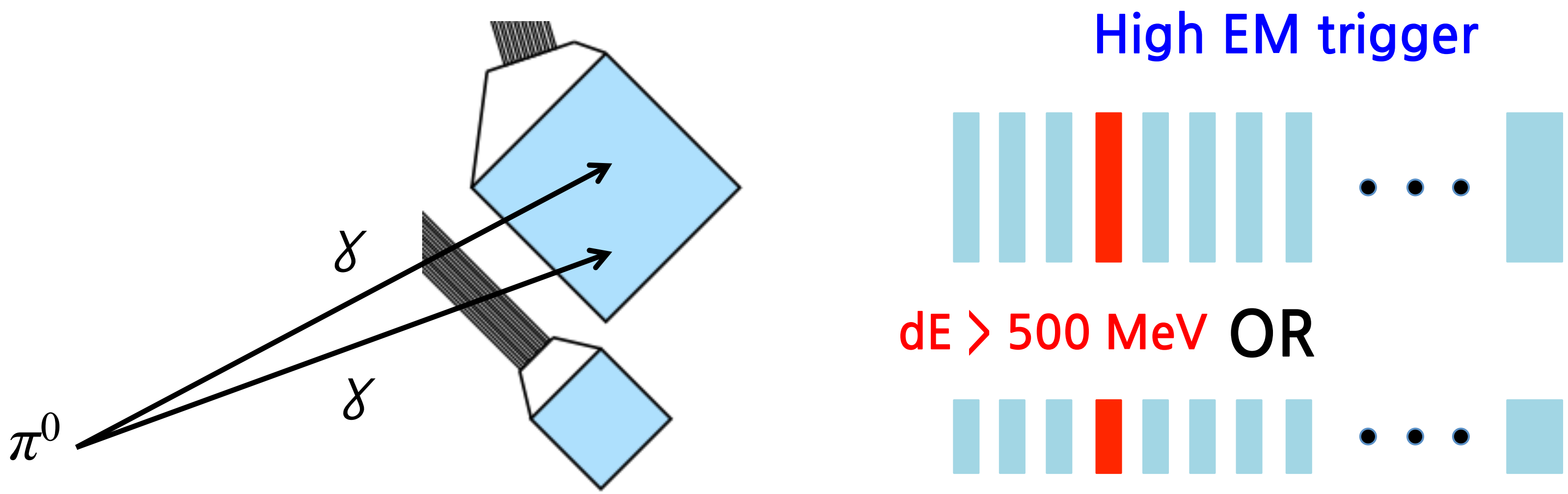
- Both towers are composed of 17 tungsten absorbers, 16 GSO-plates, and 4 GSO-bar layers.
- 44 X_0 and 1.6 λ_{int}.
- Electromagnetic shower stops its development at the middle of the detector.

Shower trigger



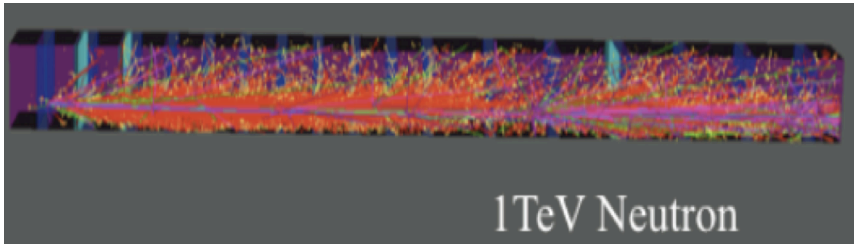
Two types of π^0 measurement

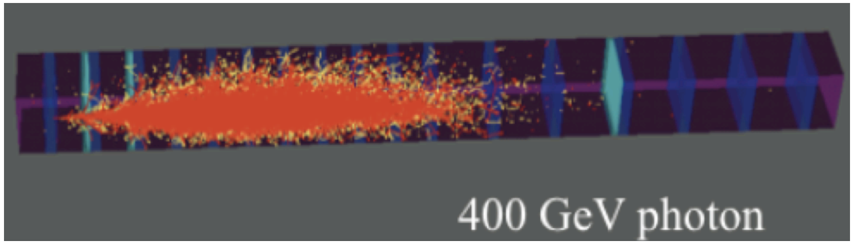


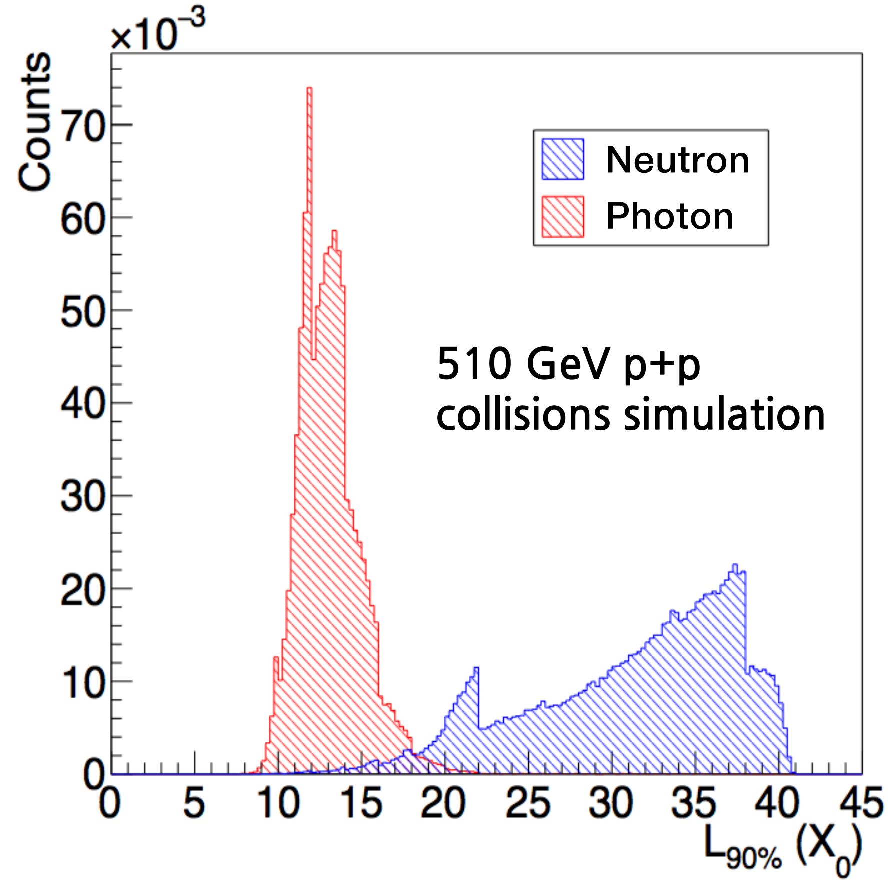


Neutron photon separation

Shower development





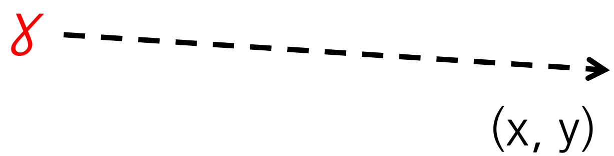


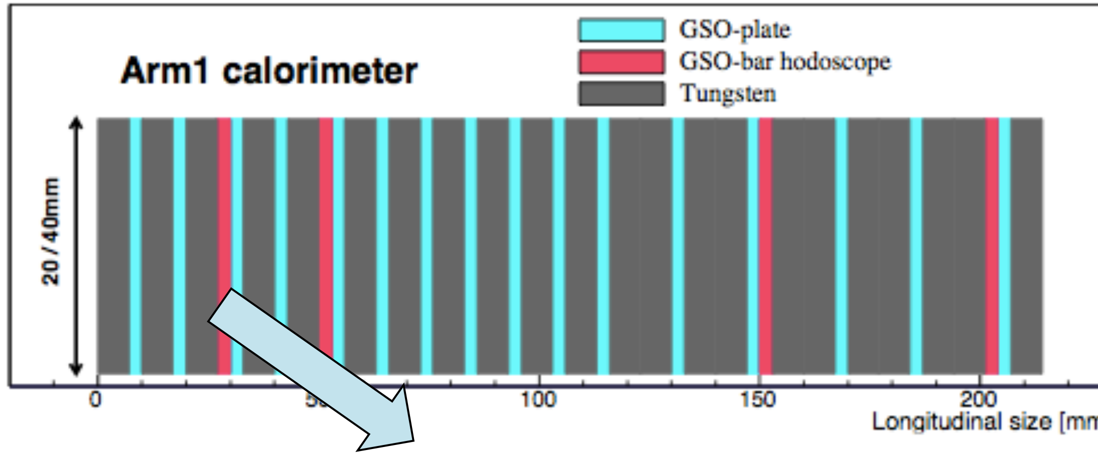
- $L_{90\%}$ is defined as the longitudinal depth whose accumulated energy deposit reaches 90% of total energy deposit in the detector.

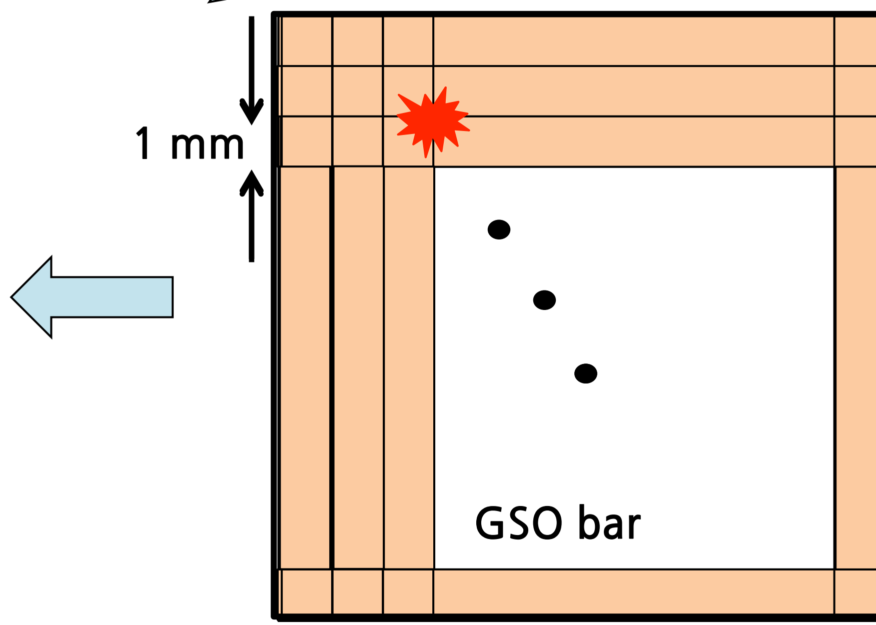
- Electromagnetic shower is developed in more forward area than hadronic one.

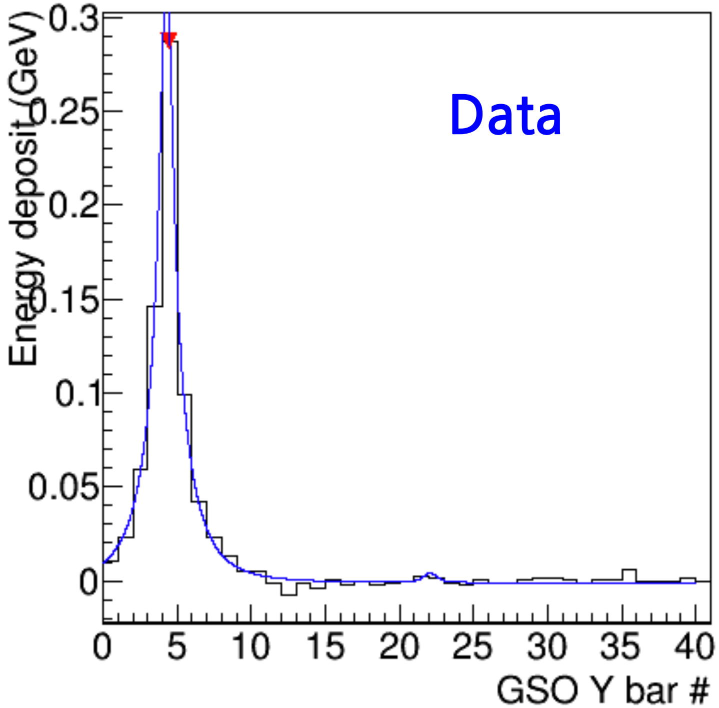
Position reconstruction

- If a photon hit a tower,

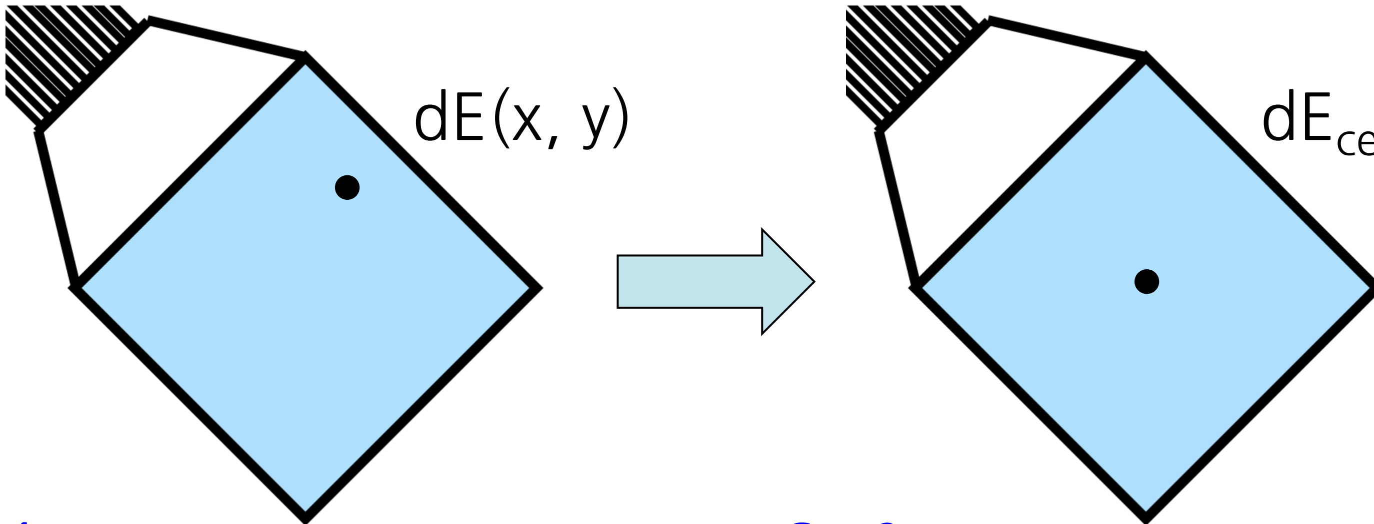




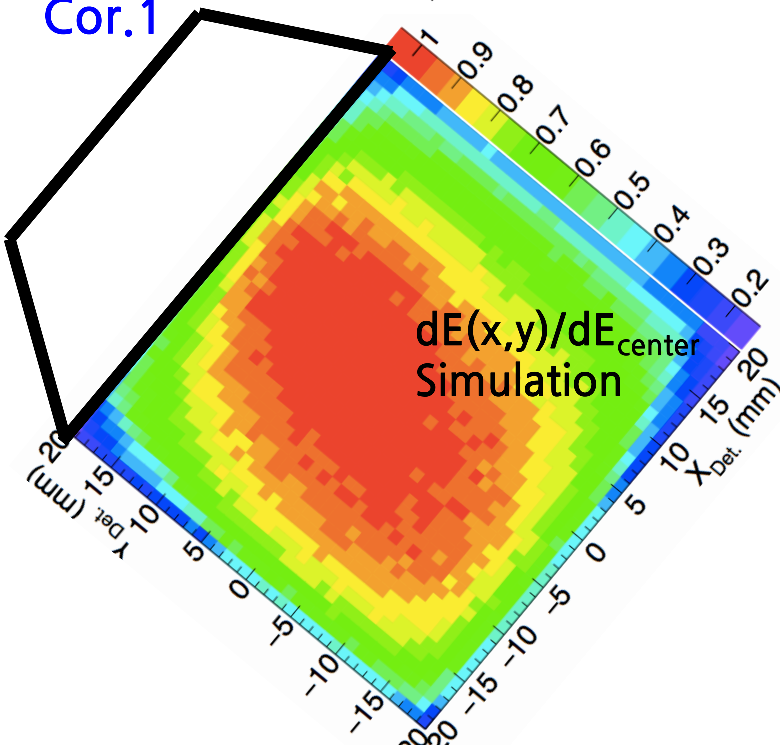




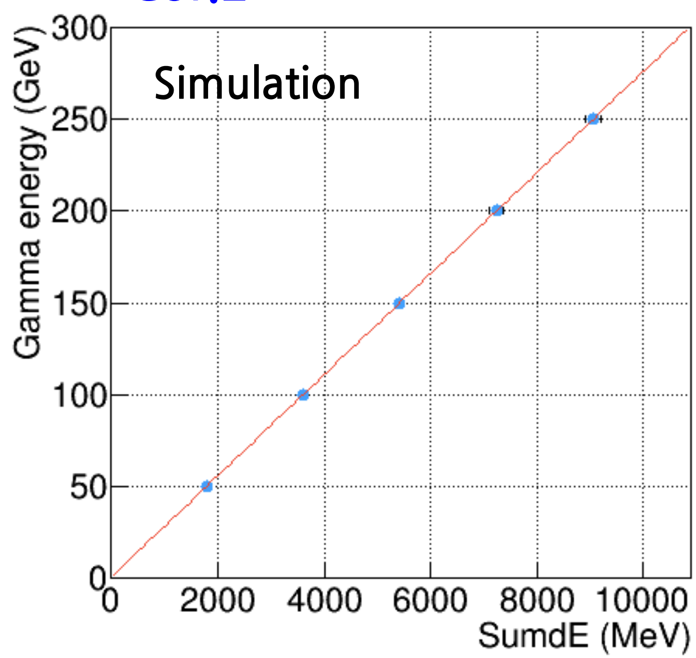
Energy reconstruction



Cor.1



Cor.2



$dE(x, y)$

↓ Cor.1

dE_{center}

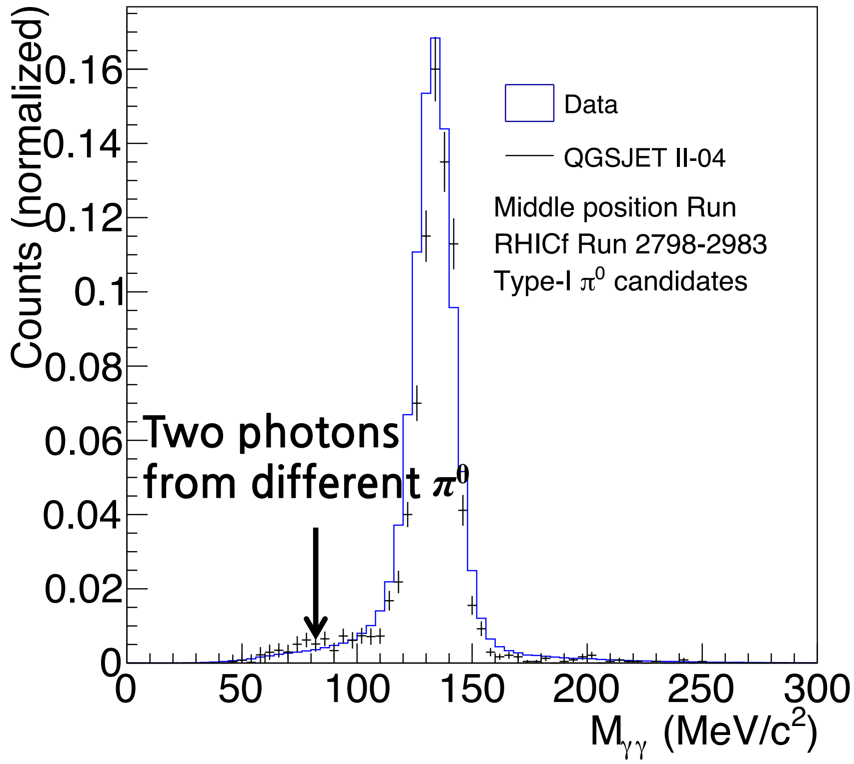
↓

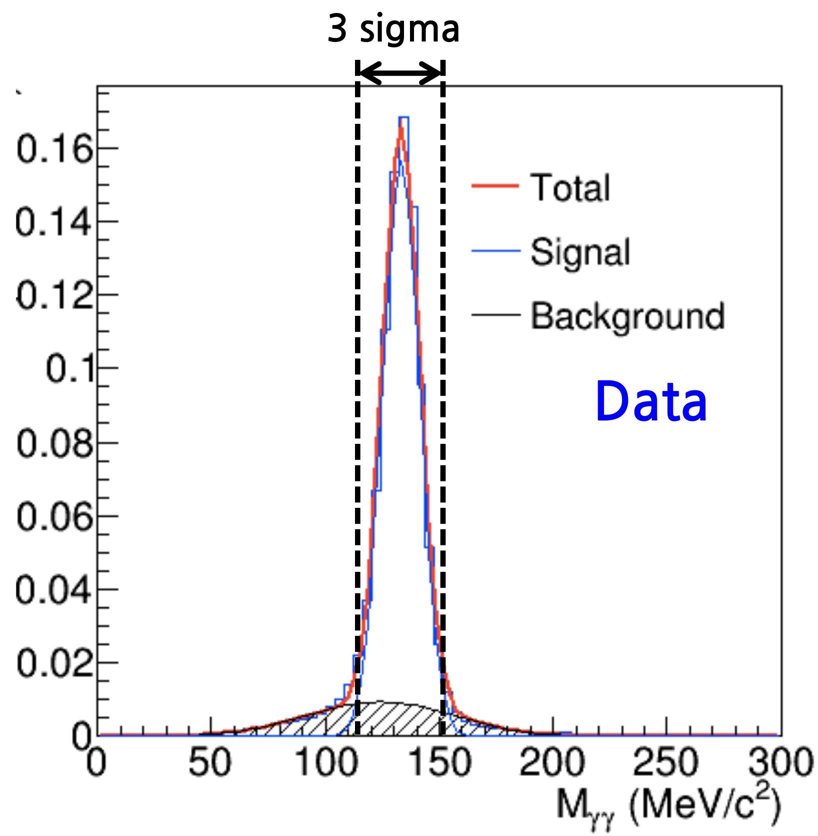
SumdE

↓ Cor.2

E_{gamma}

Invariant mass of two photons





- Data is well matched with simulation showing clear π^0 peak around 135 MeV/c^2 with ~8 MeV/c^2 peak width.
- Invariant mass was fitted by polynomial function for background and Gaussian one for π^0.

Background A_N subtraction

$$A_N = \frac{\sigma_L^{\uparrow} - \sigma_L^{\downarrow}}{\sigma_L^{\uparrow} + \sigma_L^{\downarrow}} = \frac{N^{\uparrow} - N^{\downarrow}}{N^{\uparrow} + N^{\downarrow}} = \frac{(N_S^{\uparrow} + N_B^{\uparrow}) - (N_S^{\downarrow} + N_B^{\downarrow})}{(N_S^{\uparrow} + N_B^{\uparrow}) + (N_S^{\downarrow} + N_B^{\downarrow})}$$

$$\Rightarrow A_N^{S+B} = \left(\frac{N_S}{N_{S+B}}\right) A_N^S + \left(\frac{N_B}{N_{S+B}}\right) A_N^B$$

- Spin up-down cross section can be replaced by number of particles measured.
- N_S/N_{S+B} and N_B/N_{S+B} can be calculated by fitting result.
- Background A_N is calculated by where the invariant mass is further than 5sigma from the peak.

A_N calculation

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

A_N calculation

Luminosity ratio between spin up and down

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

- R (0.95 ~ 0.99) is estimated by luminosity ratio of charged particles near IP.

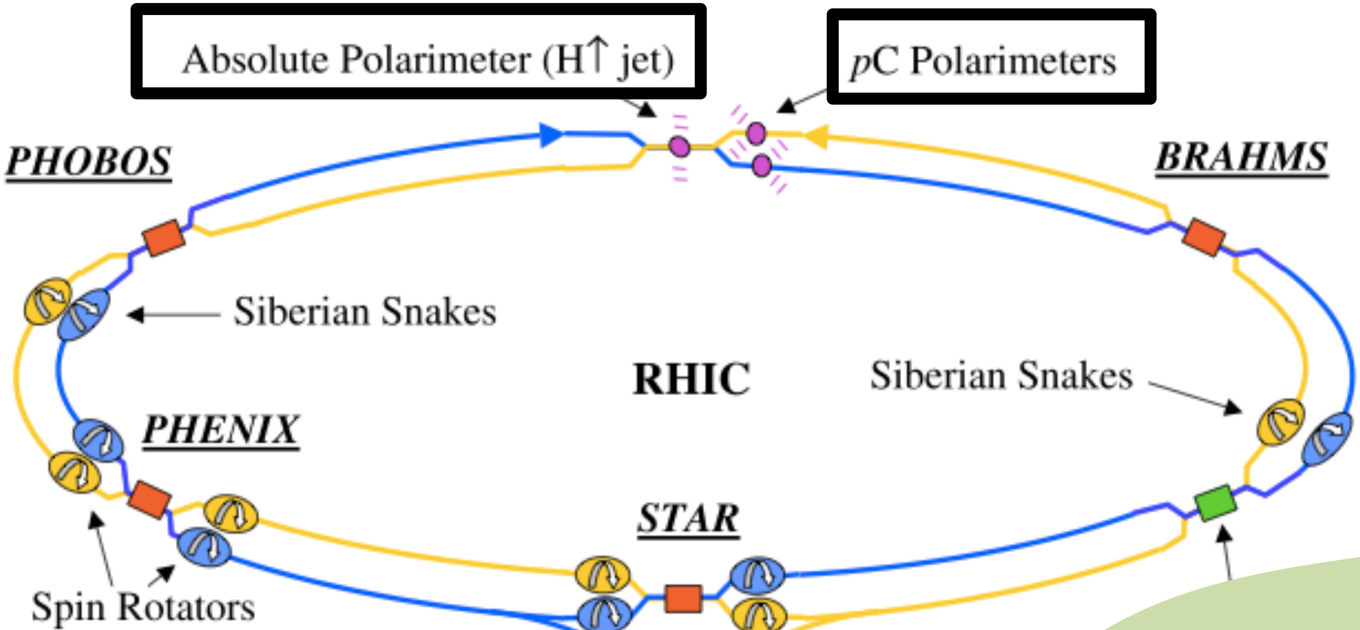
A_N calculation

Luminosity ratio between spin up and down

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

Beam polarization

- P (0.5 ~ 0.6) can be calculated by polarization monitor.



A_N calculation

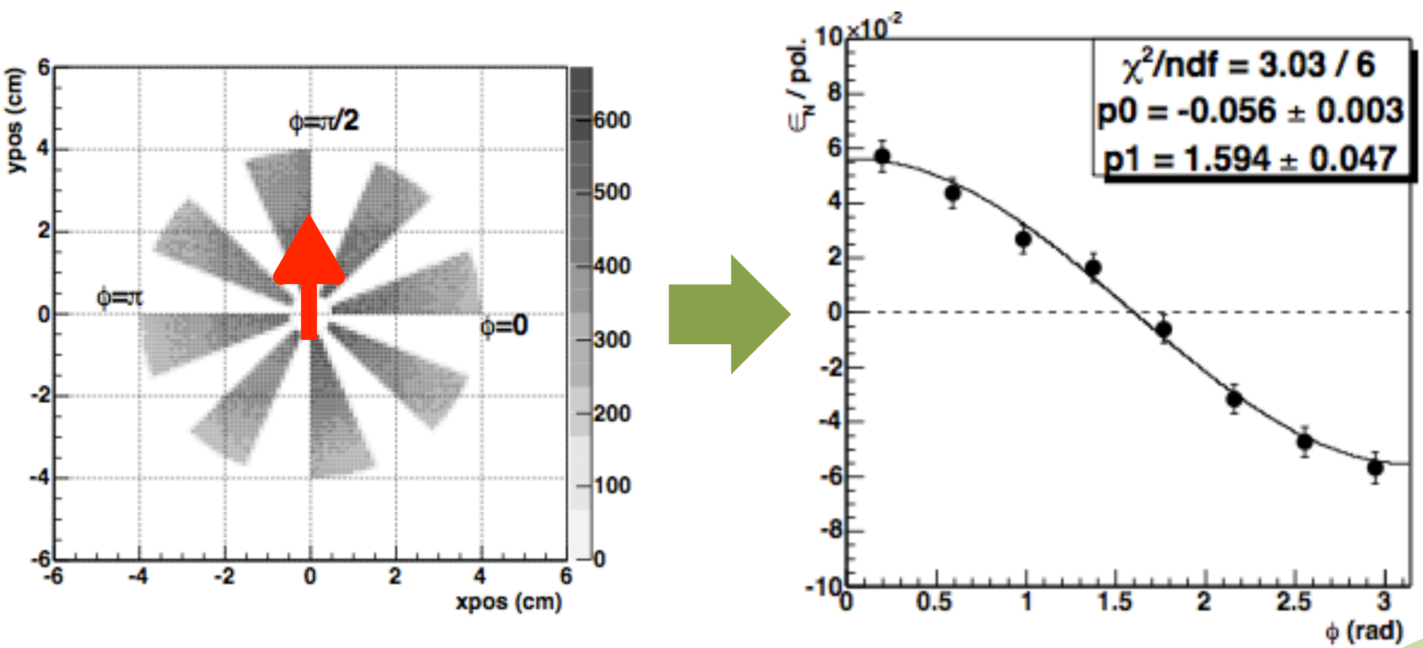
Luminosity ratio between spin up and down

$$A_N = \frac{1}{P D_\phi} \frac{N^{\uparrow} - R N^{\downarrow}}{N^{\uparrow} + R N^{\downarrow}}$$

Beam polarization

Smearing by azimuthal angle distribution of π^0.

- D_ϕ (0.78 ~ 1.00) can be estimated by ϕ distribution of particle.

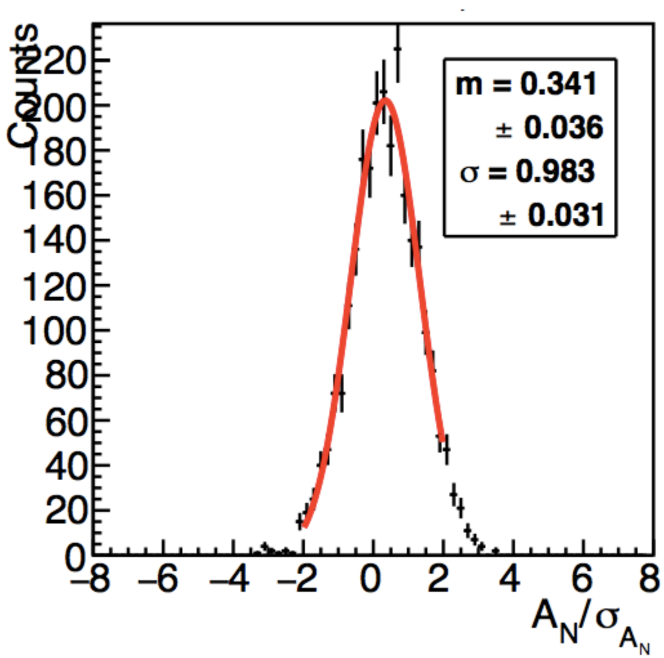


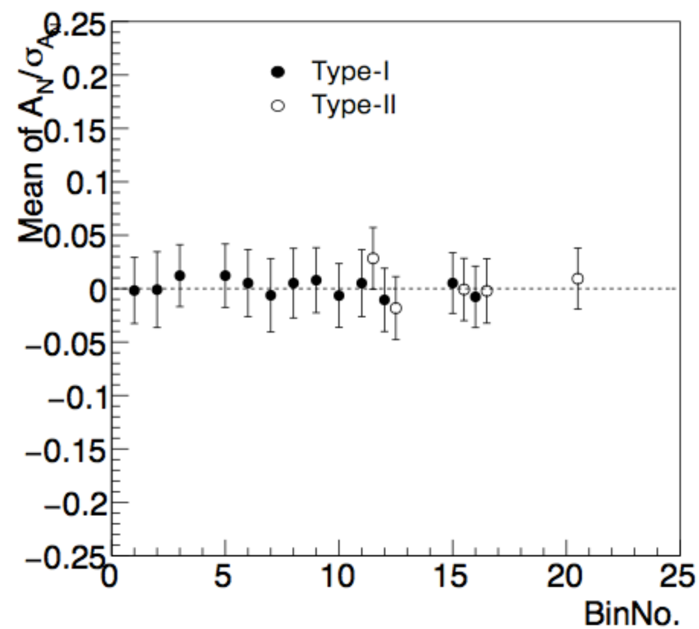
Bunch shuffling

Randomizing

$$A_N = \frac{1}{PD_\phi}\frac{N^{\uparrow} - RN^{\downarrow}}{N^{\uparrow} + RN^{\downarrow}}$$

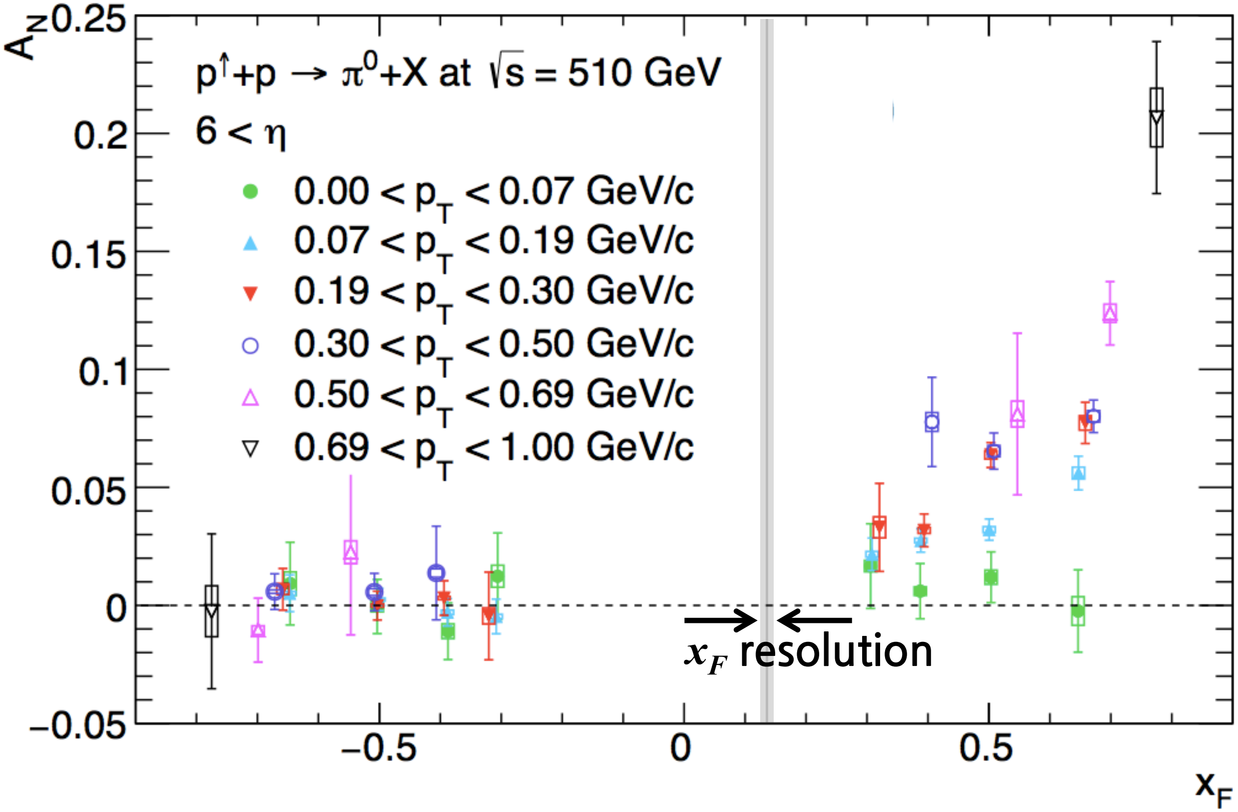
- Bunch shuffling is a technique to confirm it there is unknown systematic uncertainties in the A_N measurement.





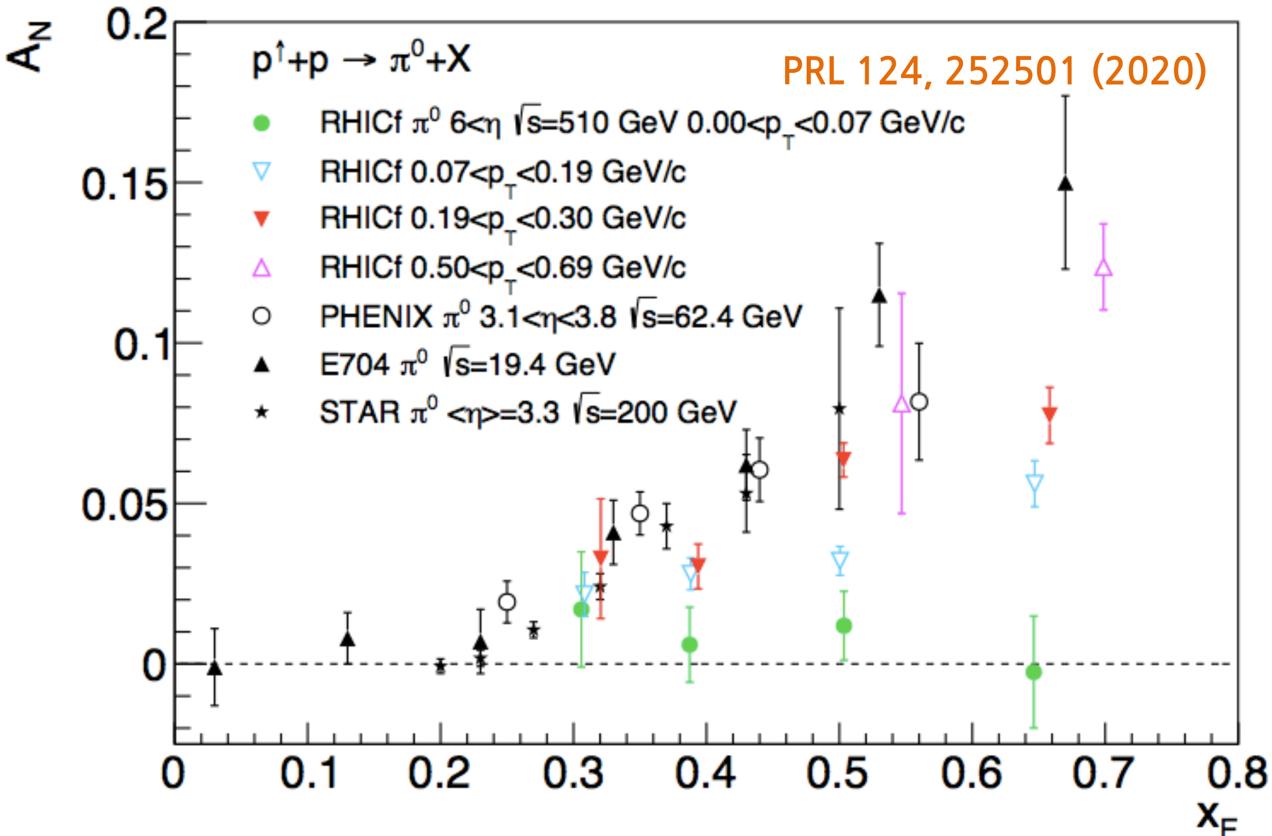
Very forward π^0 A_N as a function of x_F

PRL 124, 252501 (2020)



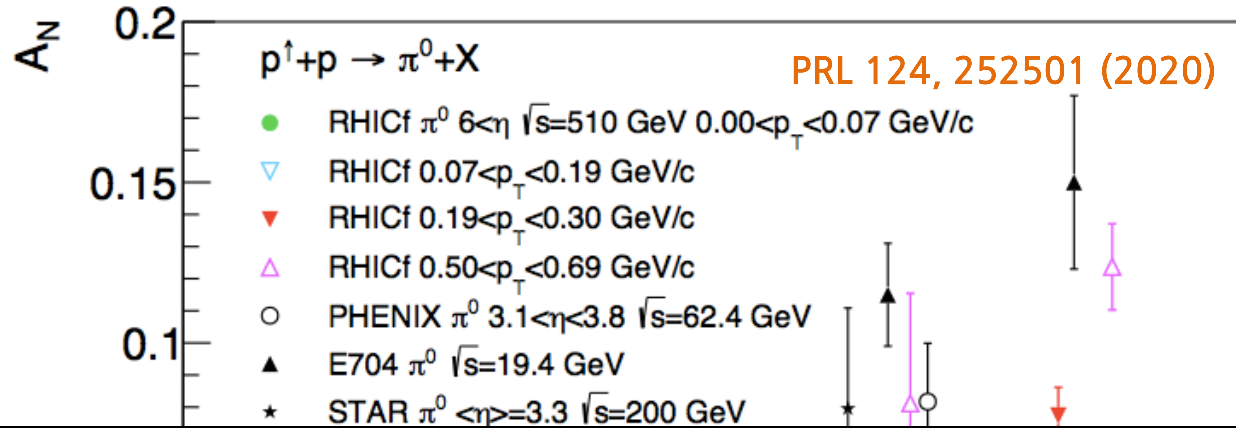
- At very low p_T 〈 0.07 GeV/c, the A_N is consistent with zero.
- However, the higher p_T range the A_N is measured in, the more clearly it increases as a function of x_F.

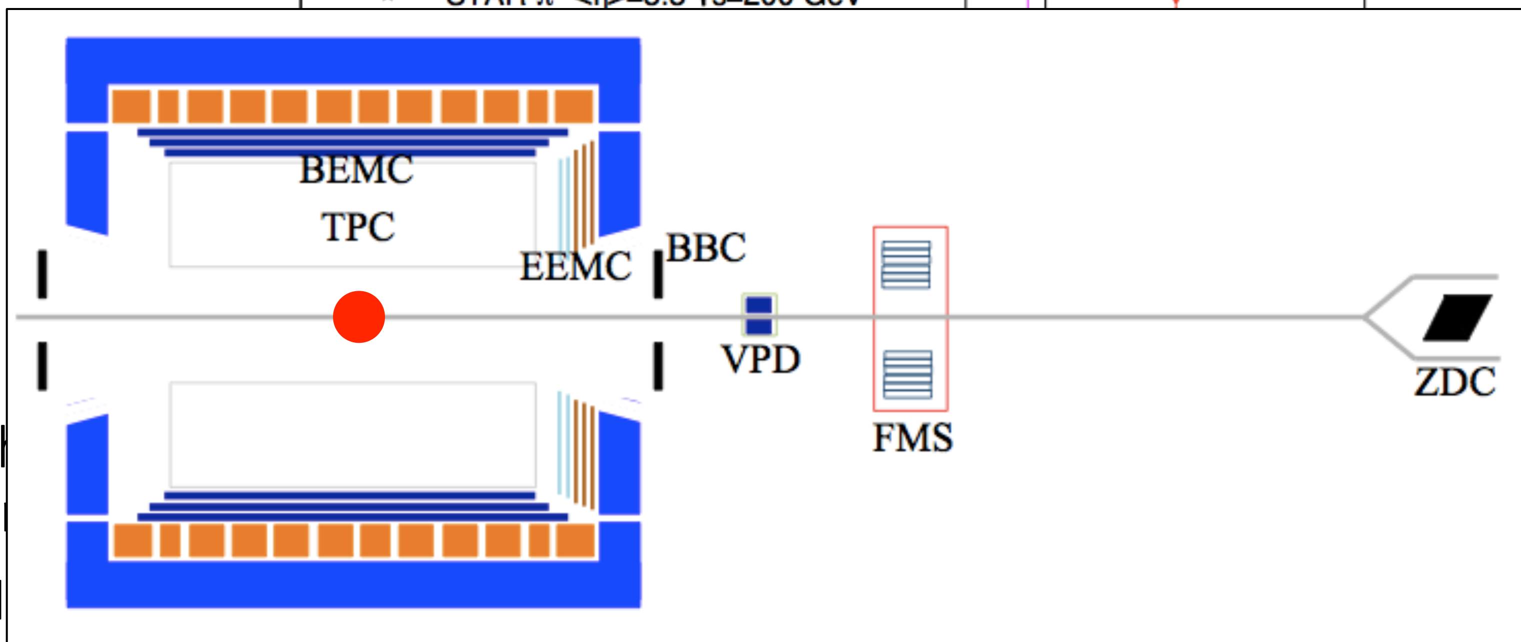
Comparison with previous measurements



- The very forward π^0 A_N seems to be comparable with the forward one even at low $p_T < 1$ GeV/c.
- Non-zero A_N of π^0 may come from not only the non-diffractive process but also the diffractive one.
- The forward and very forward π^0 A_N may share a common underlying production mechanism.

Comparison with previous measurements





- Th ... ward
  o...
- N ... active
  process but also the diffractive one.
- The forward and very forward π^0 A_N may share a common underlying production mechanism.

Very forward π^0 A_N as a function of p_T

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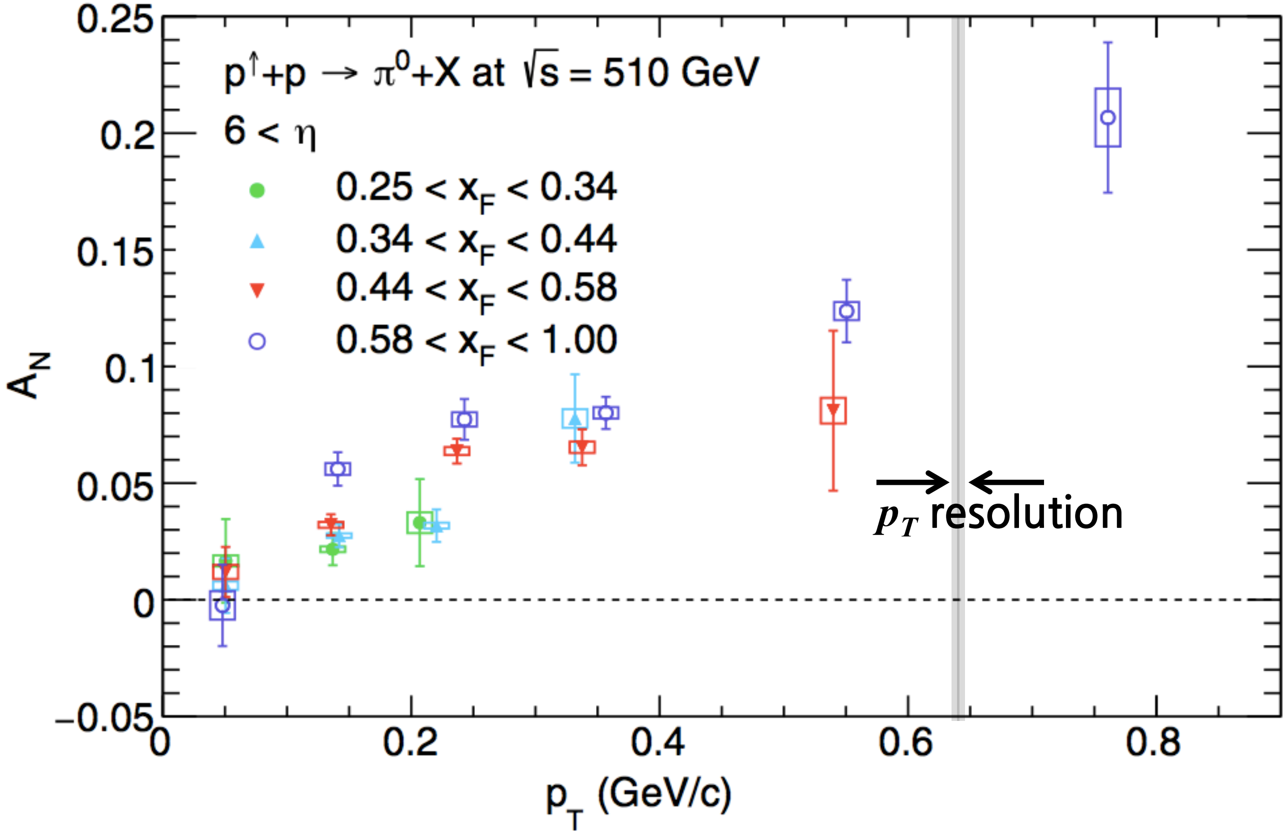
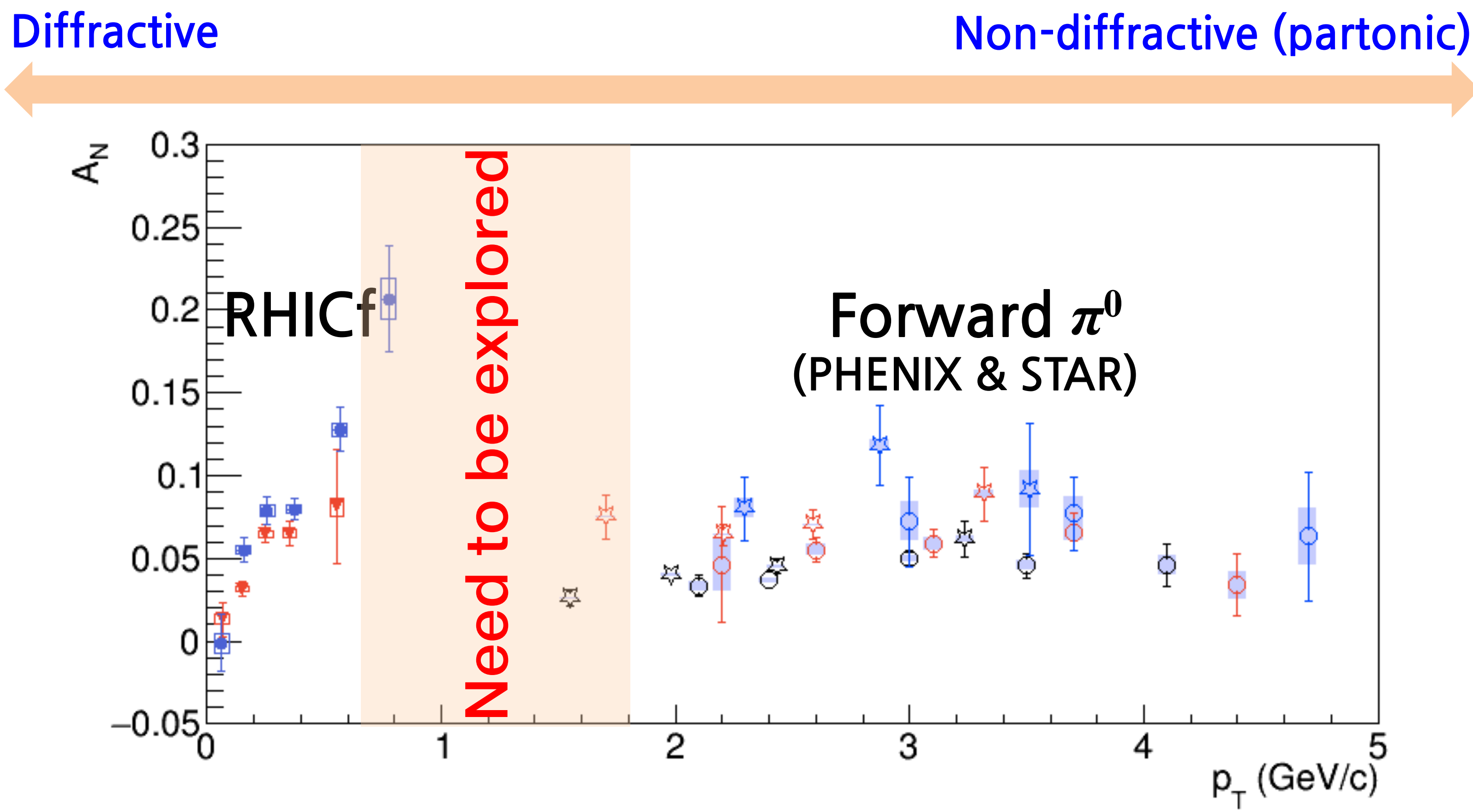


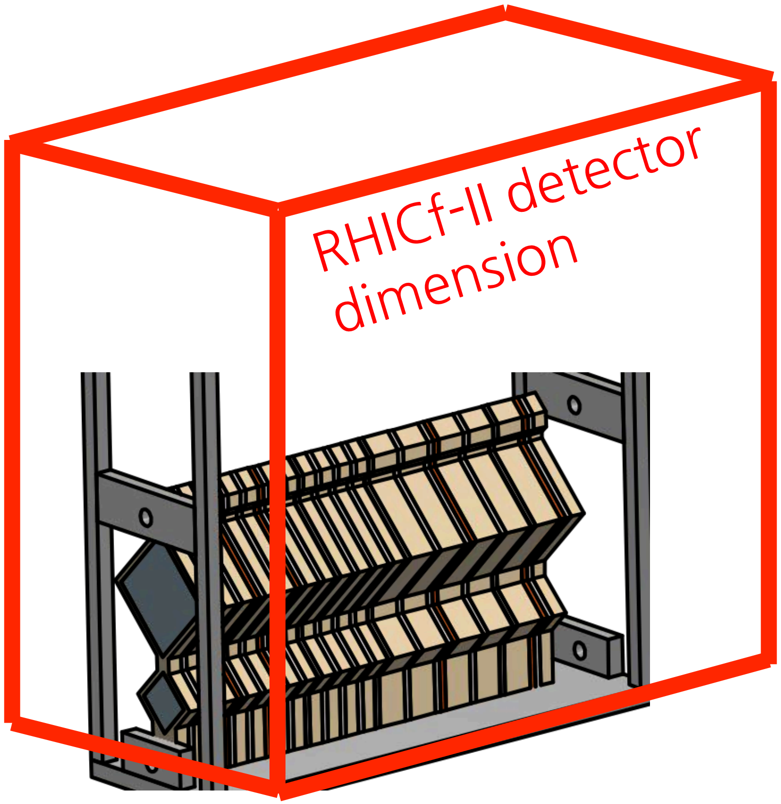
- The very forward π^0 A_N clearly increases as a function of p_T.
- Note that the resolutions of the RHICf detector are much finer than the binning.

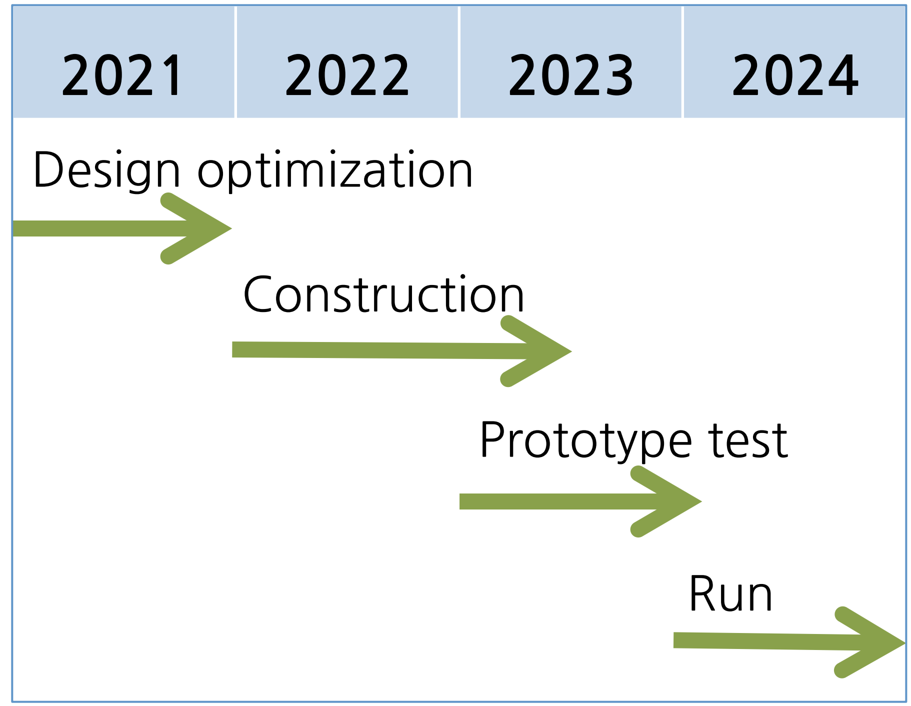
Comparison with previous measurements



- The gap between two data sets will be the connection from the diffractive to non-diffractive process.
- How competitively each process contribute to the non-zero A_N for π^0 production can be studied.

RHICf-II experiment





- RHICf-II detector will have larger active area, longer λ_{int} than RHICf detector.
- We've started discussion with STAR for Run 2024.

Summary

- A_N of very forward neutral particle production makes us to understand the spin-involved production mechanism from the view points of diffractive and non-diffractive interactions.
- To understand the production mechanism of the very forward neutron A_N, the RHICf experiment precisely measured it with wider p_T coverage.
- A large asymmetry for very forward π^0 production was firstly observed by the RHICf experiment.
- To more deeply understand the A_N of very forward neutral particle, we're preparing to operate the RHICf-II experiment and RHICf-STAR combined analysis.