Transverse single spin asymmetry measurement at the RHICf experiment

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on behalf of the RHICf collaboration

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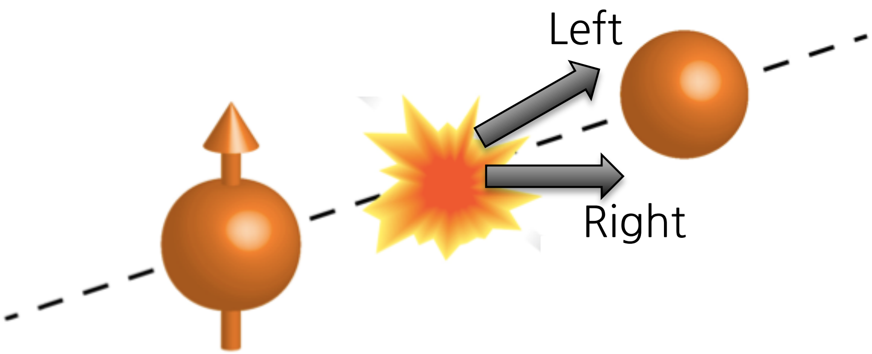
2nd APCTP Workshop on the Physics of EIC:
ePIC Physics and Detectors

Transverse single spin asymmetry (A_N)

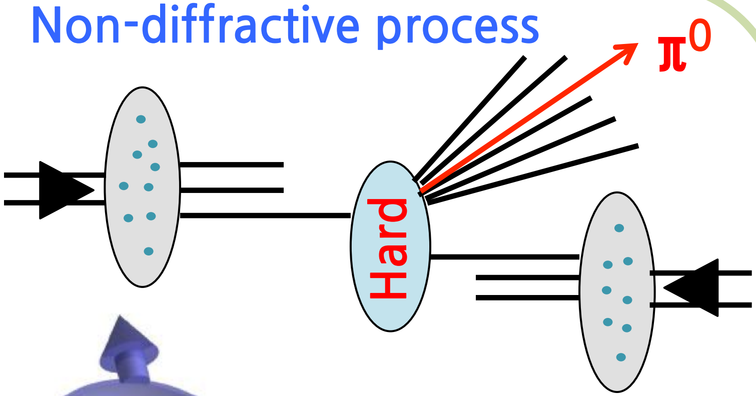


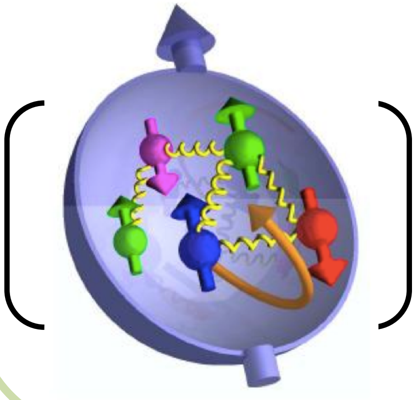
$$A_N = \frac{\sigma_L^{\uparrow} - \sigma_R^{\uparrow}}{\sigma_L^{\uparrow} + \sigma_R^{\uparrow}} = \frac{\sigma_L^{\uparrow} - \sigma_L^{\downarrow}}{\sigma_L^{\uparrow} + \sigma_L^{\downarrow}}$$

- In polarized p+p collisions, the A_N is defined by a left-right cross section asymmetry of a specific particle or event.
- Due to the rotational invariance, the left-right asymmetry can also be defined by the spin up-down asymmetry.
- A_Ns of the very forward ($6 < \eta$) particles enable us to study the spin-involved diffractive particle production mechanism.

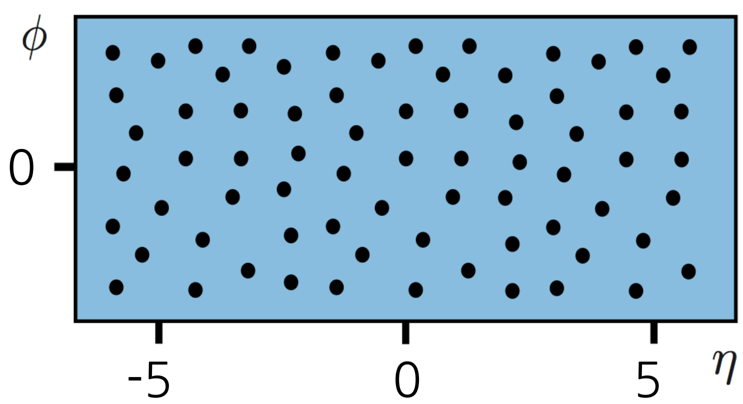
Non-diffractive Vs. Diffractive process

Non-diffractive process

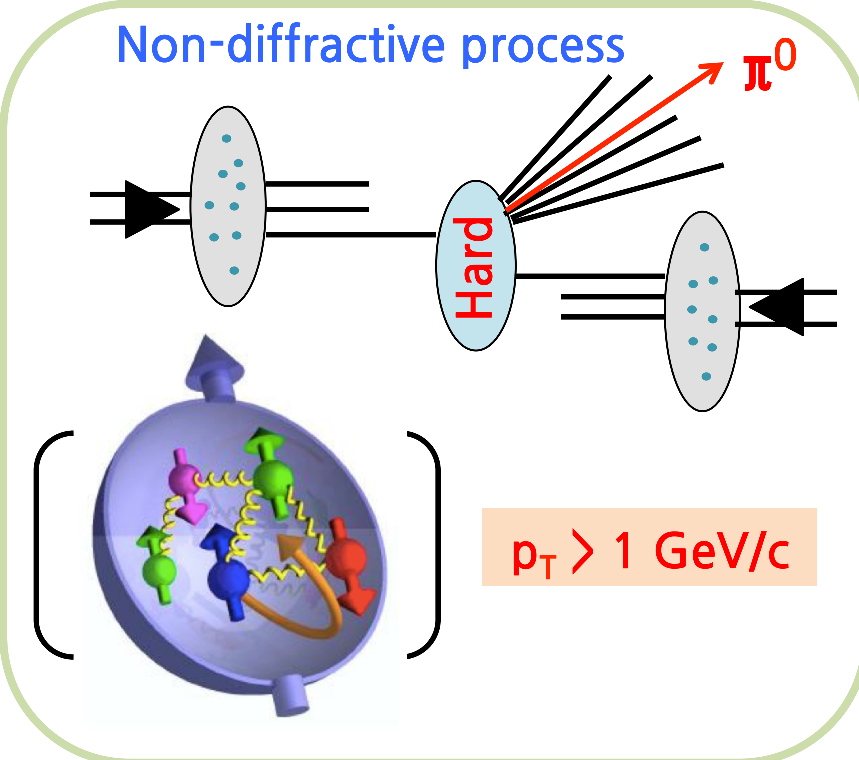


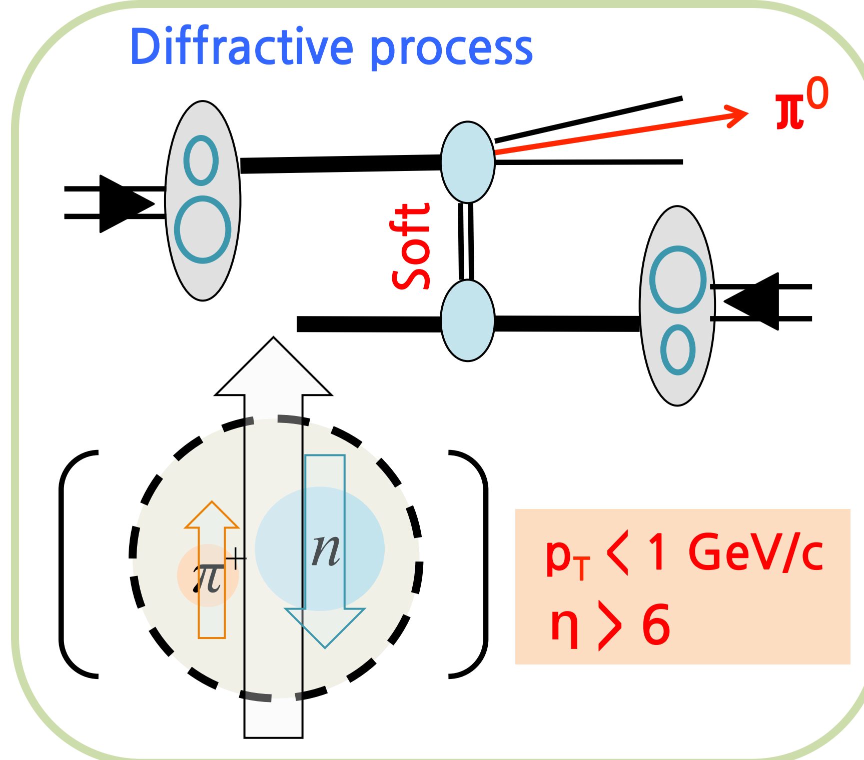


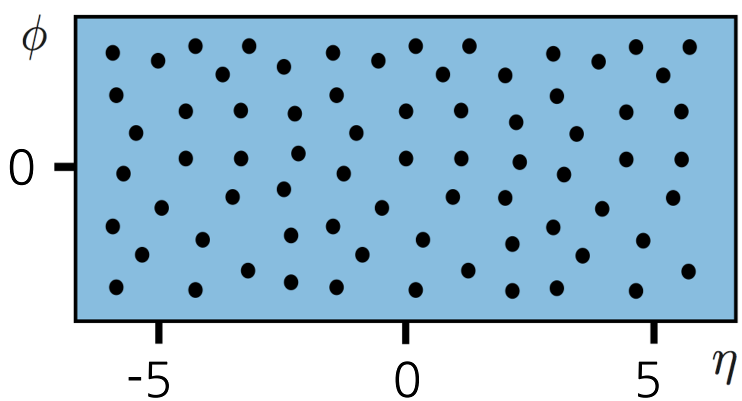
$p_T > 1$ GeV/c

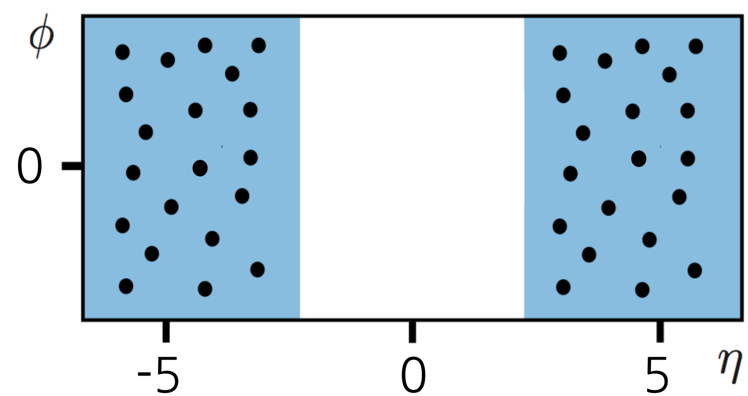


Non-diffractive Vs. Diffractive process



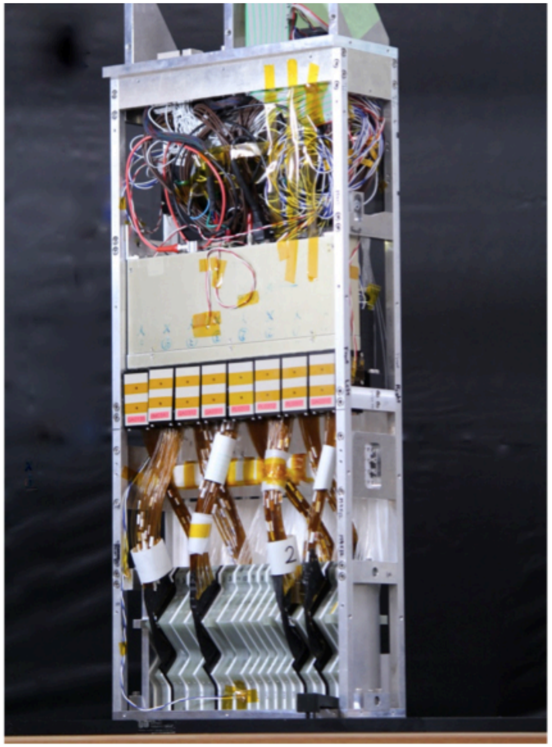


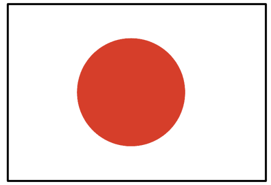




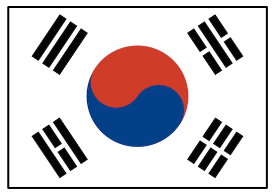
RHICf collaboration

RHICf detector





RIKEN (Y. Goto, I. Nakagawa, R. Seidl, M. H. Kim), **Nagoya Univ.** (Y. Itow, H. Menjo, K. Sato, K. Ohashi), **Univ. of Tokyo** (T. Sako), **JAEA** (K. Tanida), **Waseda Univ.** (S. Torii), **Shibaura Inst. of Tech.** (K. Kasahara), **Tokushima Univ.** (N. Sakurai)

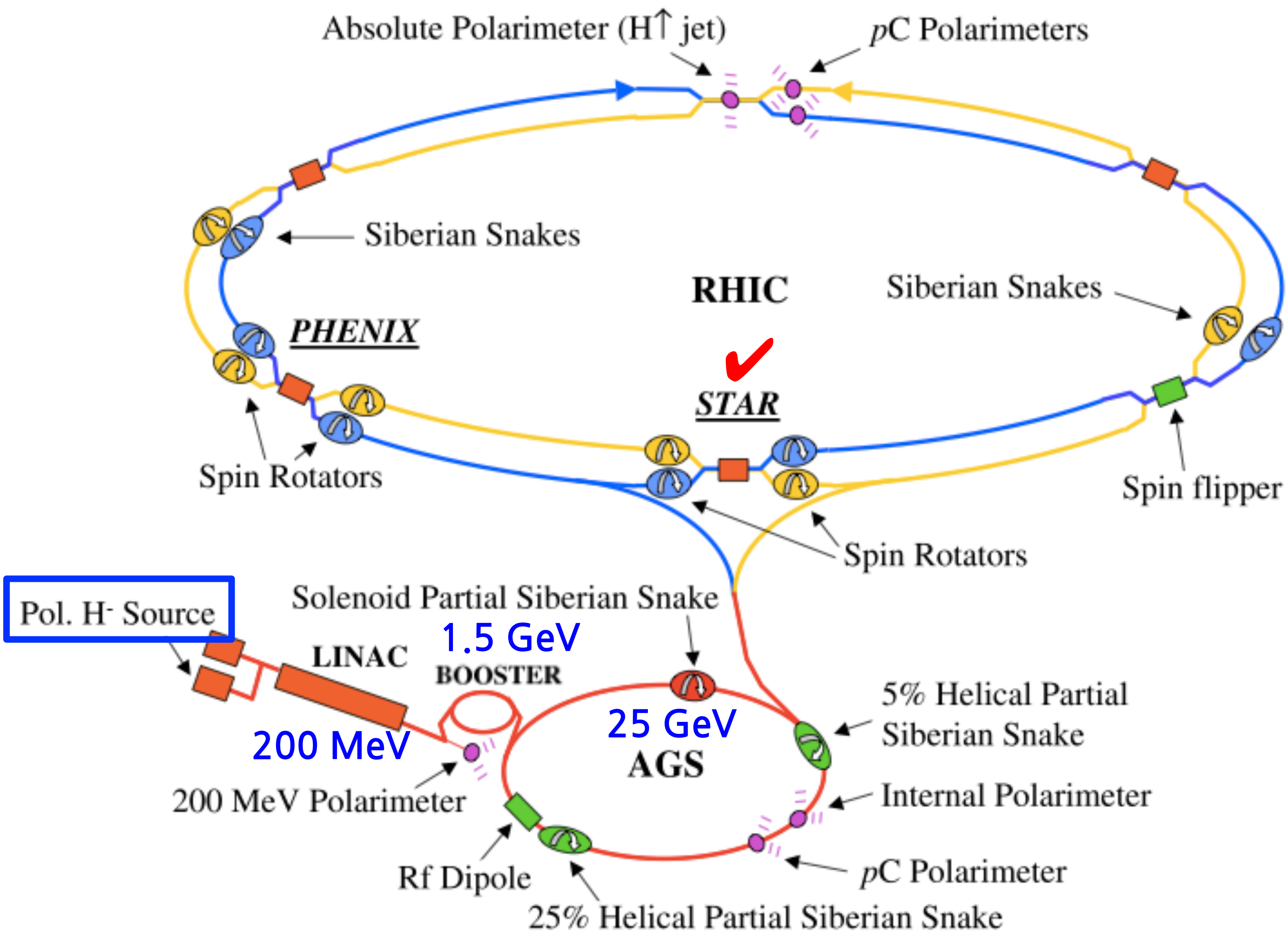


Korea Univ. (B. Hong), **Sejong Univ.** (Y. Kim, S. Oh, S. H. Lee)

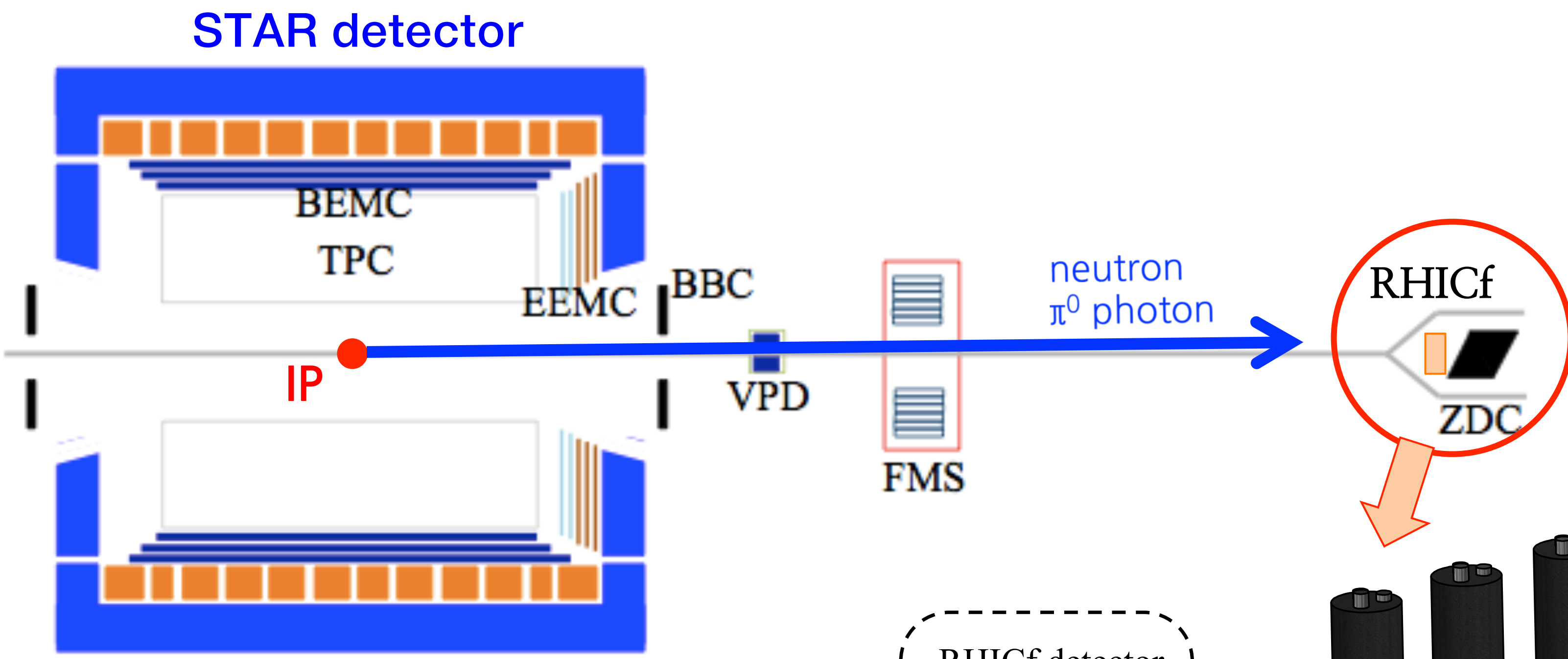
INFN (O. Adriani, E. Berti, L. Bonechi, R. D'Alessandro, A. Tricomi)

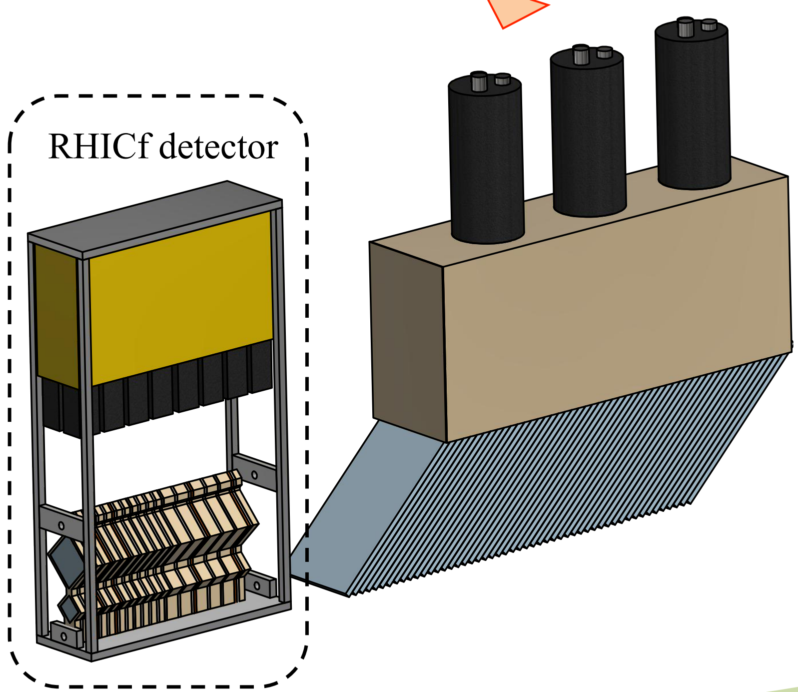
- A_N measurement to study the spin-involved diffractive particle production mechanism.
- Cross section measurement to study the origin of the ultra-high energy cosmic ray.

Relativistic Heavy Ion Collider (RHIC)



RHIC forward (RHICf) experiment

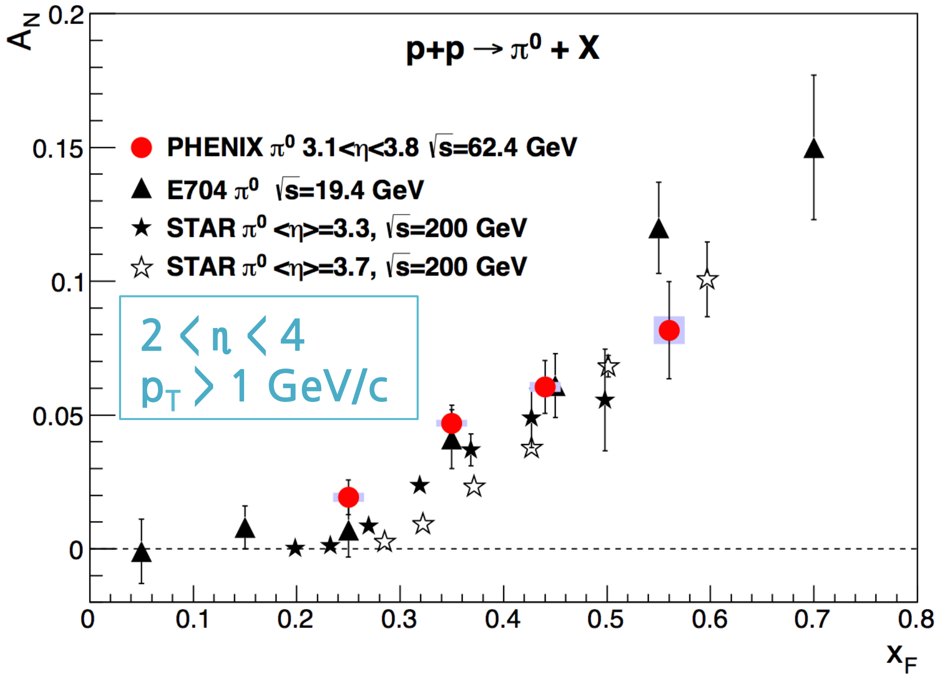


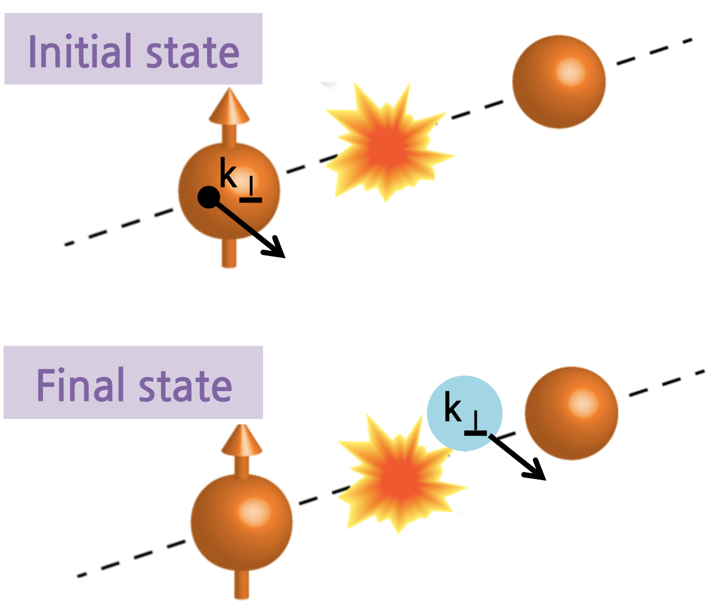


- In June 2017, the RHICf experiment was operated at STAR in polarized p+p collisions at $\sqrt{s}$ = 510 GeV.
- We installed the RHICf detector in front of the ZDC.

A_N of forward π^0

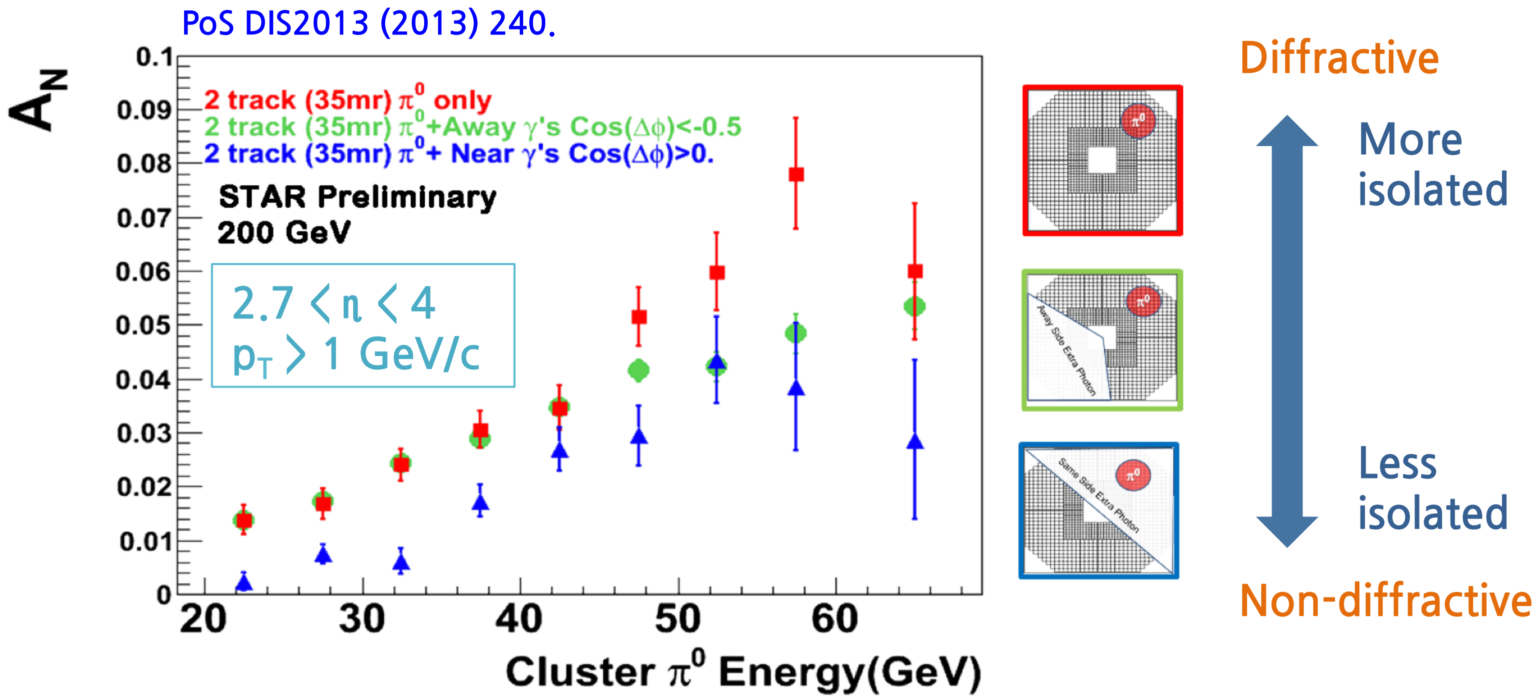
PRD 90, 012006 (2014).





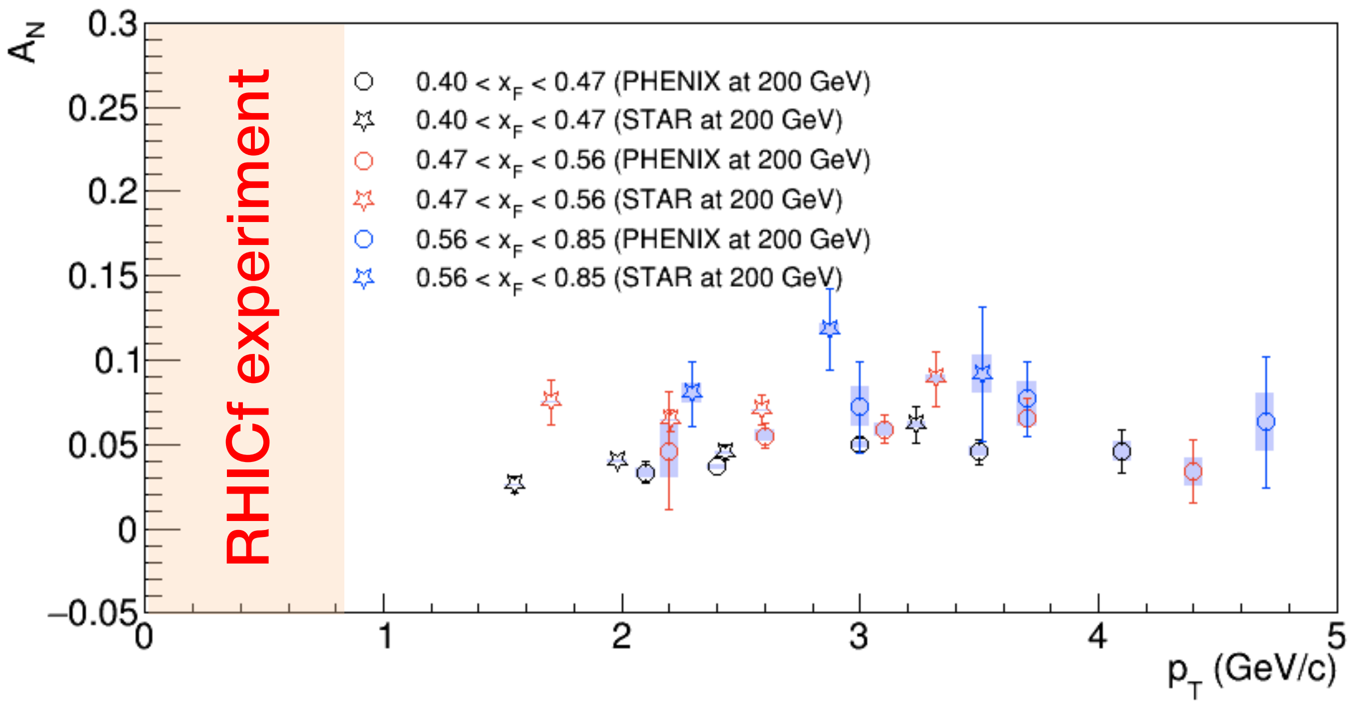
- Before the RHICf experiment, A_N for π^0 production has been mainly measured in the forward ($2 < \eta < 4$) kinematic region.
- The non-zero A_N has been interpreted based on quarks and gluons' degrees of freedom theoretically.

A_N of forward isolated π^0



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

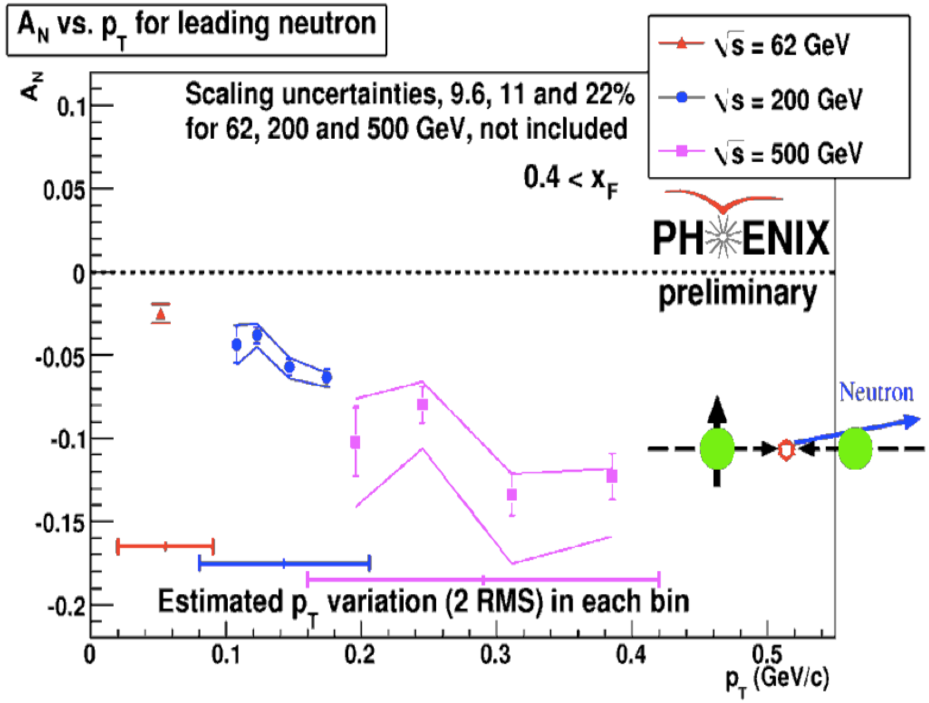
π^0 measurement at RHICf



- No experiment has measured the π^0 in detail in the range of p_T < 1 GeV/c.
- In order to study a possible diffractive contribution to the π^0 A_N, the RHICf experiment firstly measured the A_N for very forward π^0 production.

A_N of very forward neutron

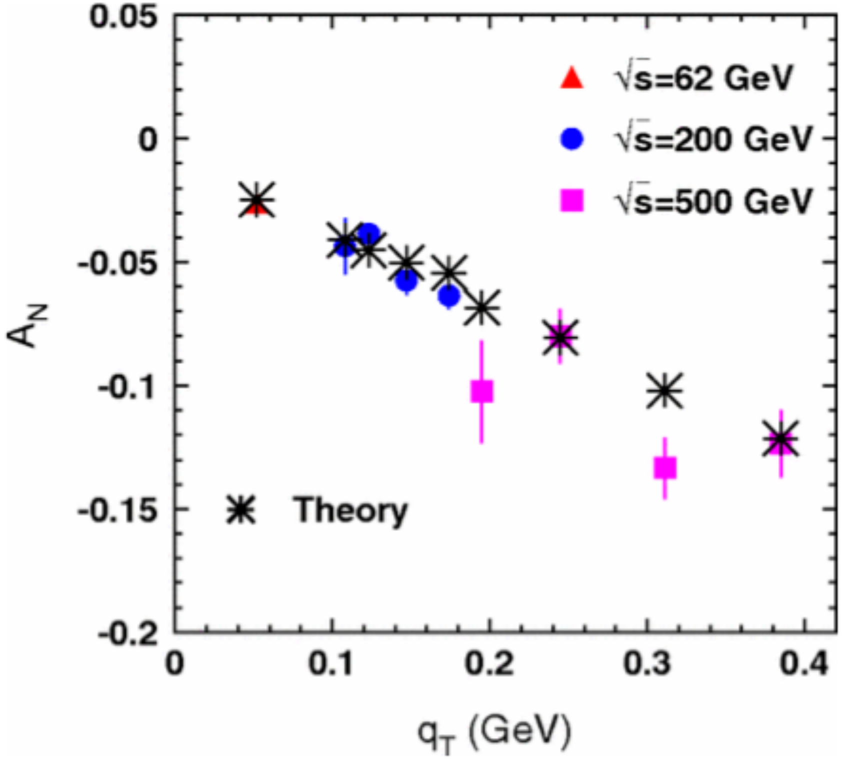
J. Phys. Conf. Ser. 295 (2011) 012097.



- Non-zero A_N for very forward neutron production was first observed by an experiment called IP12. PLB 650, 325 (2007).
- Afterwards, the PHENIX measured the neutron A_N as a function of p_T with three different collision energies.
- The measurement results showed a possible p_T dependence of the neutron A_N.

Theoretical model

PRD 84, 114012 (2011).



$$A_N = \frac{d\sigma^\uparrow - d\sigma^\downarrow}{d\sigma^\uparrow + d\sigma^\downarrow}$$
$$= \frac{\sum_X |\langle cX|T|\uparrow\rangle|^2 - \sum_X |\langle cX|T|\downarrow\rangle|^2}{\sum_X |\langle cX|T|\uparrow\rangle|^2 + \sum_X |\langle cX|T|\downarrow\rangle|^2}$$
$$= \frac{-2\mathrm{Im}\sum_X \langle cX|T|-\rangle\langle +|T^\dagger|cX\rangle}{\sum_X |\langle cX|T|+\rangle|^2 + \sum_X |\langle cX|T|-\rangle|^2}$$

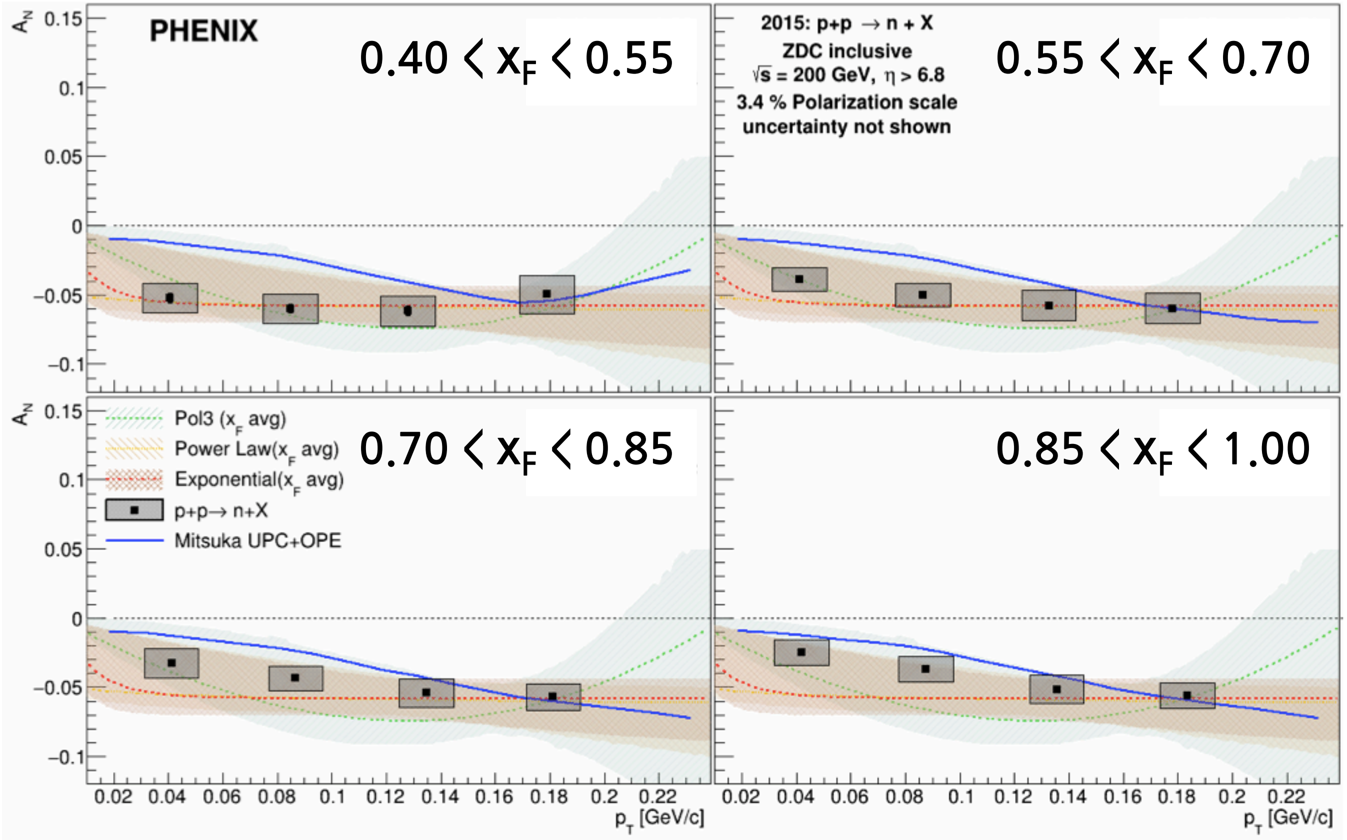
π exchange: spin flip

a_1 exchange: spin non-flip

- Neutron A_N was explained by an interference between spin flip and spin non-flip amplitudes with non-zero phase shift.
- The π and a_1 exchange model showed that the neutron A_N increased in magnitude with increasing p_T with little $\sqrt{s}$ dependence.

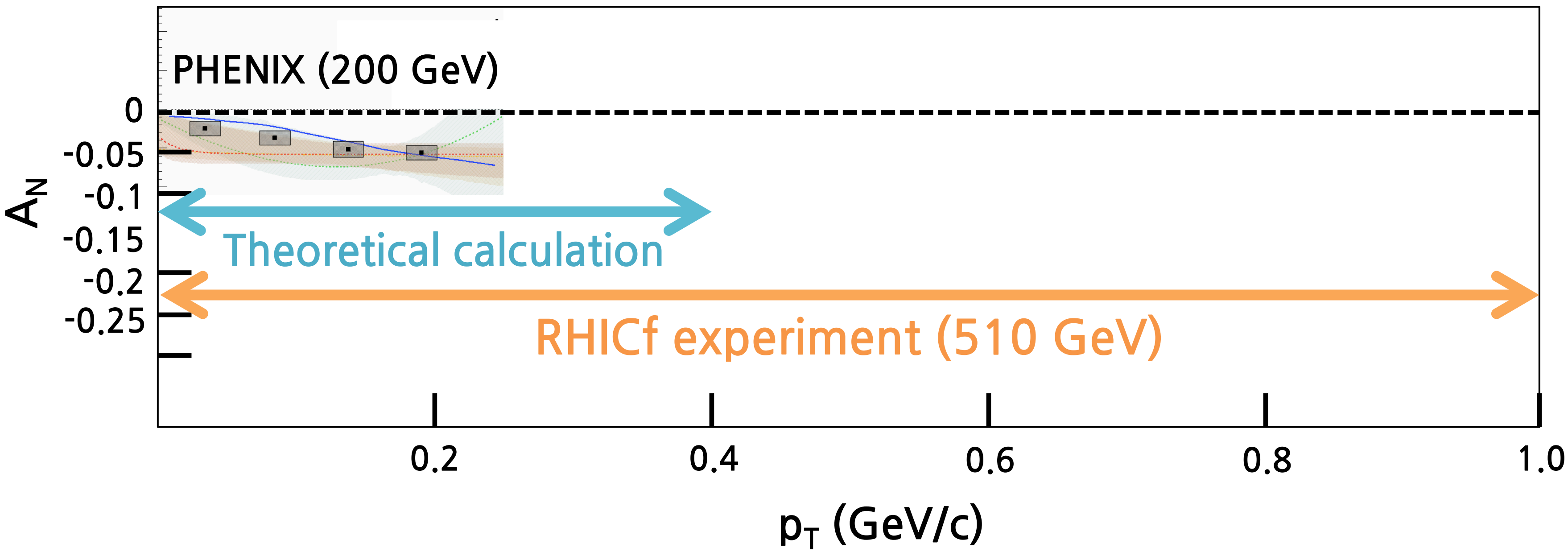
Unfolded neutron A_N at PHENIX

PRD 105, 032004 (2022).



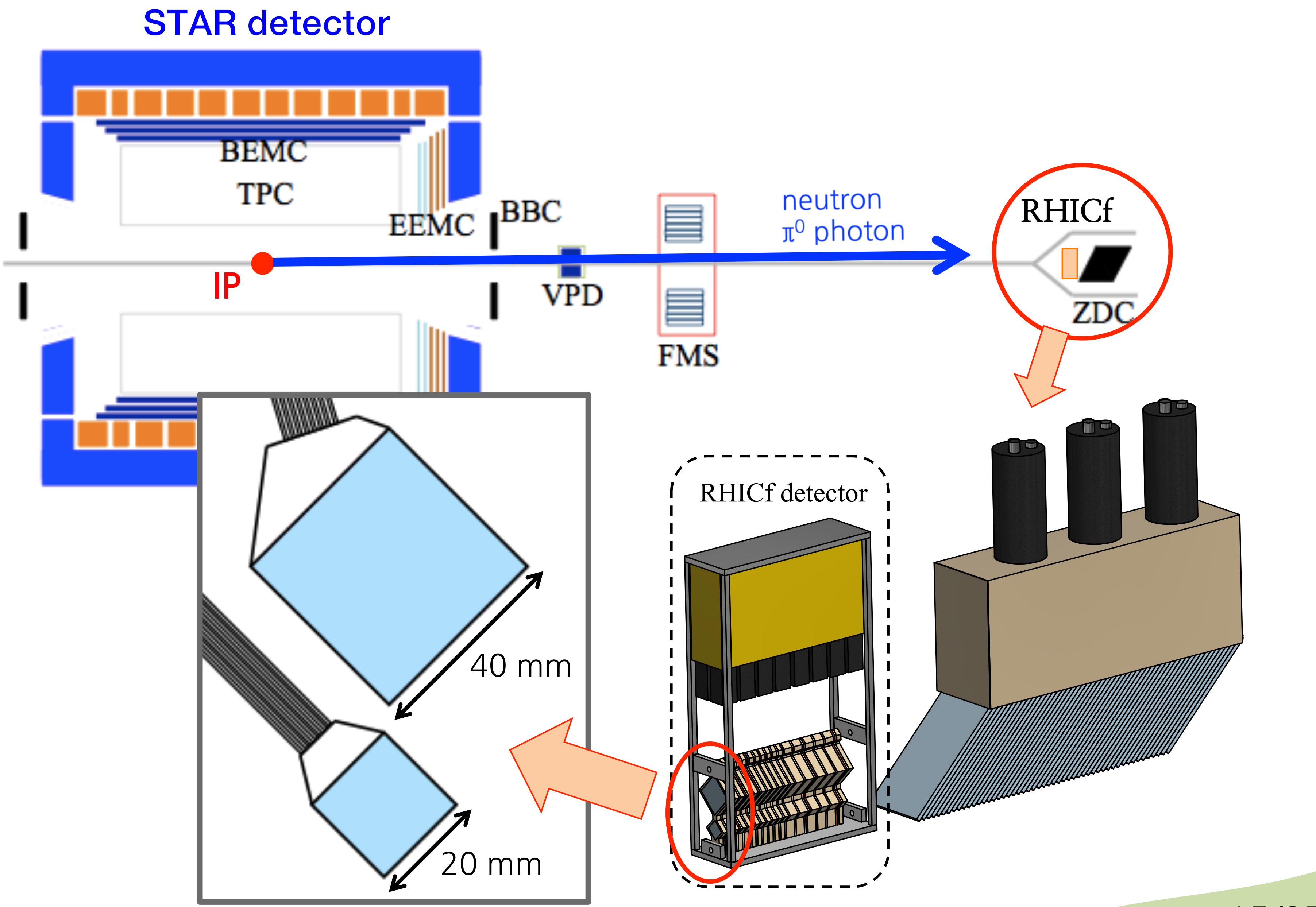
- Recently, p_T dependence of the PHENIX neutron A_N at $\sqrt{s}$ = 200 GeV was obtained by unfolding the data.
- The unfolded data showed the same tendency with the model calculations.

Neutron measurement at RHICf

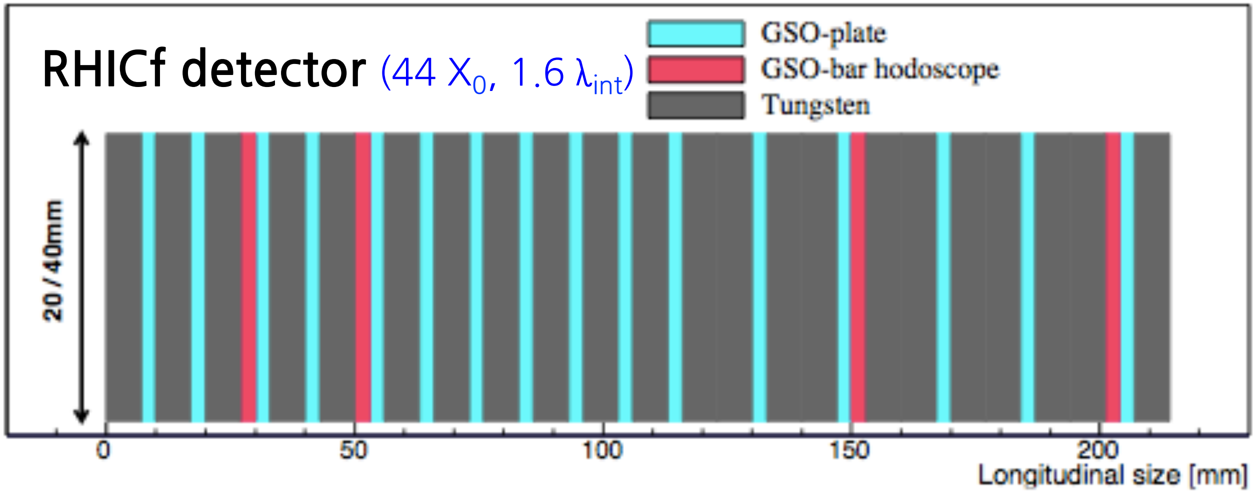


- RHICf the experiment has extended the previous measurements up to 1 GeV/c to study the kinematic dependence of the neutron A_N in more detail.
- RHICf detector has one order of better position resolution (1 cm → 1 mm).
- We can also study the $\sqrt{s}$ dependence of the neutron A_N by comparing the RHICf data with that of the PHENIX.

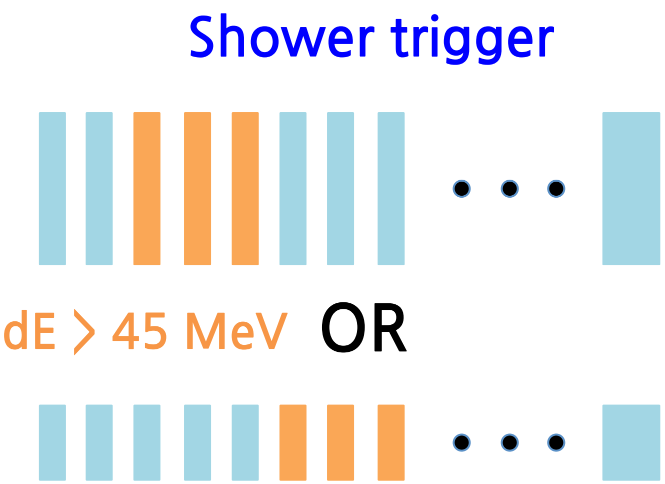
RHIC forward (RHICf) experiment



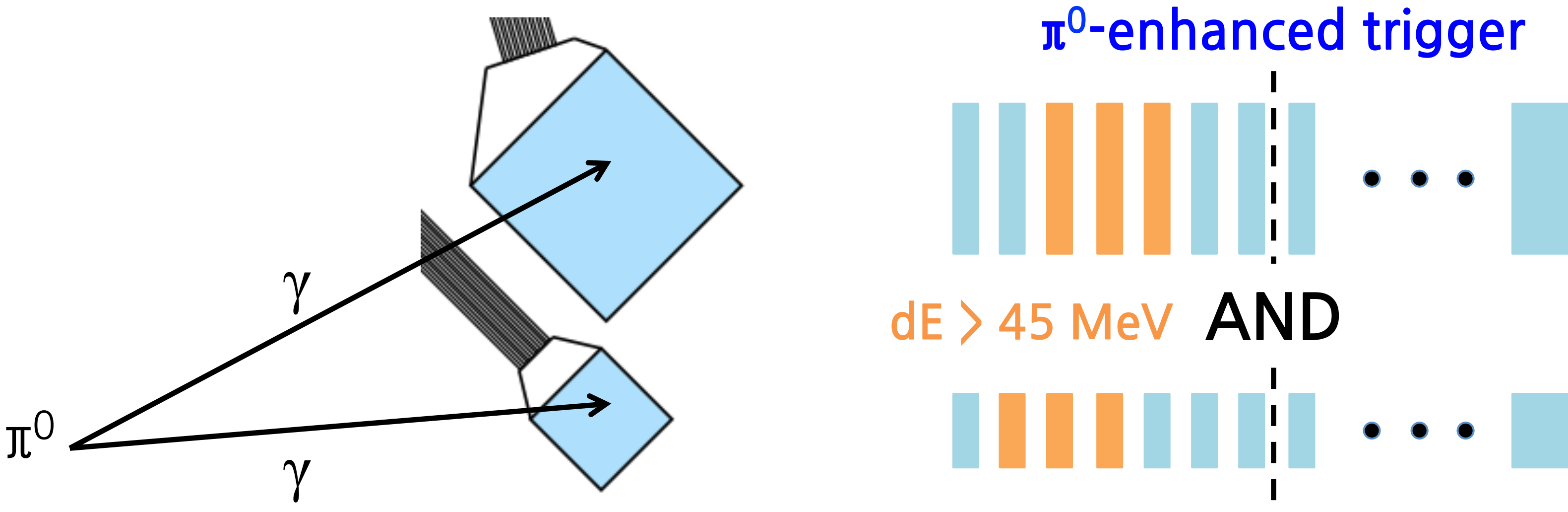
RHICf detector & neutron measurement

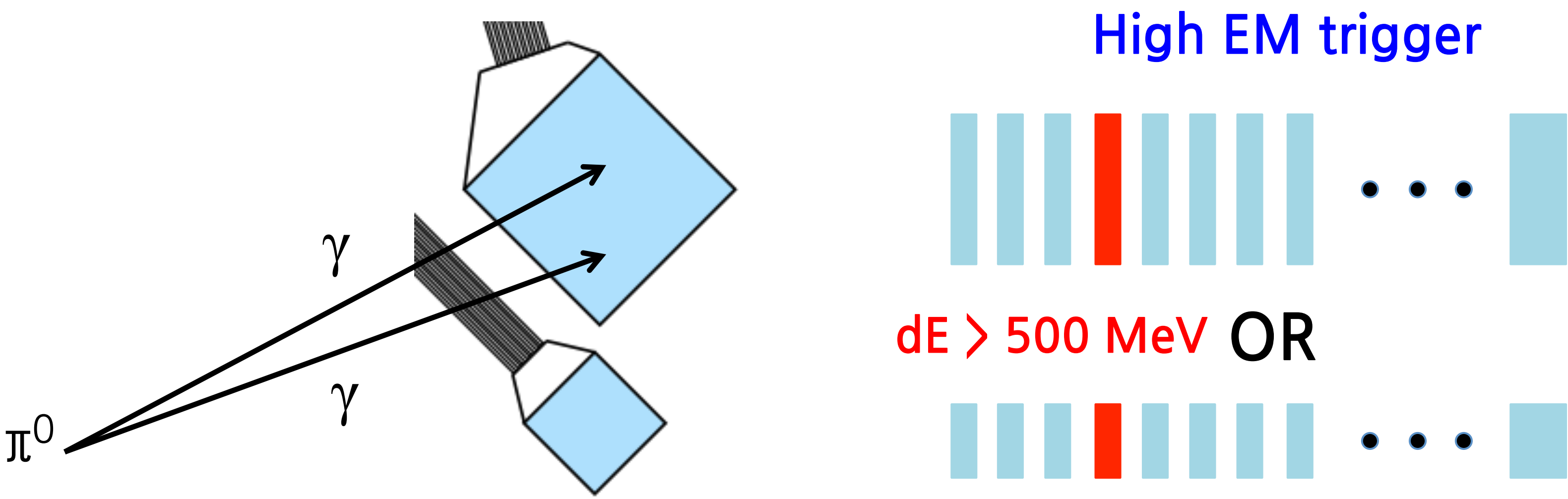


- Each tower is composed of 17 layers of tungsten absorbers, 16 layers of GSO plate, and 4 layers of GSO bar hodoscope.
- Shower trigger is operated when the energy deposits of any three successive GSO plate layers are larger than 45 MeV.



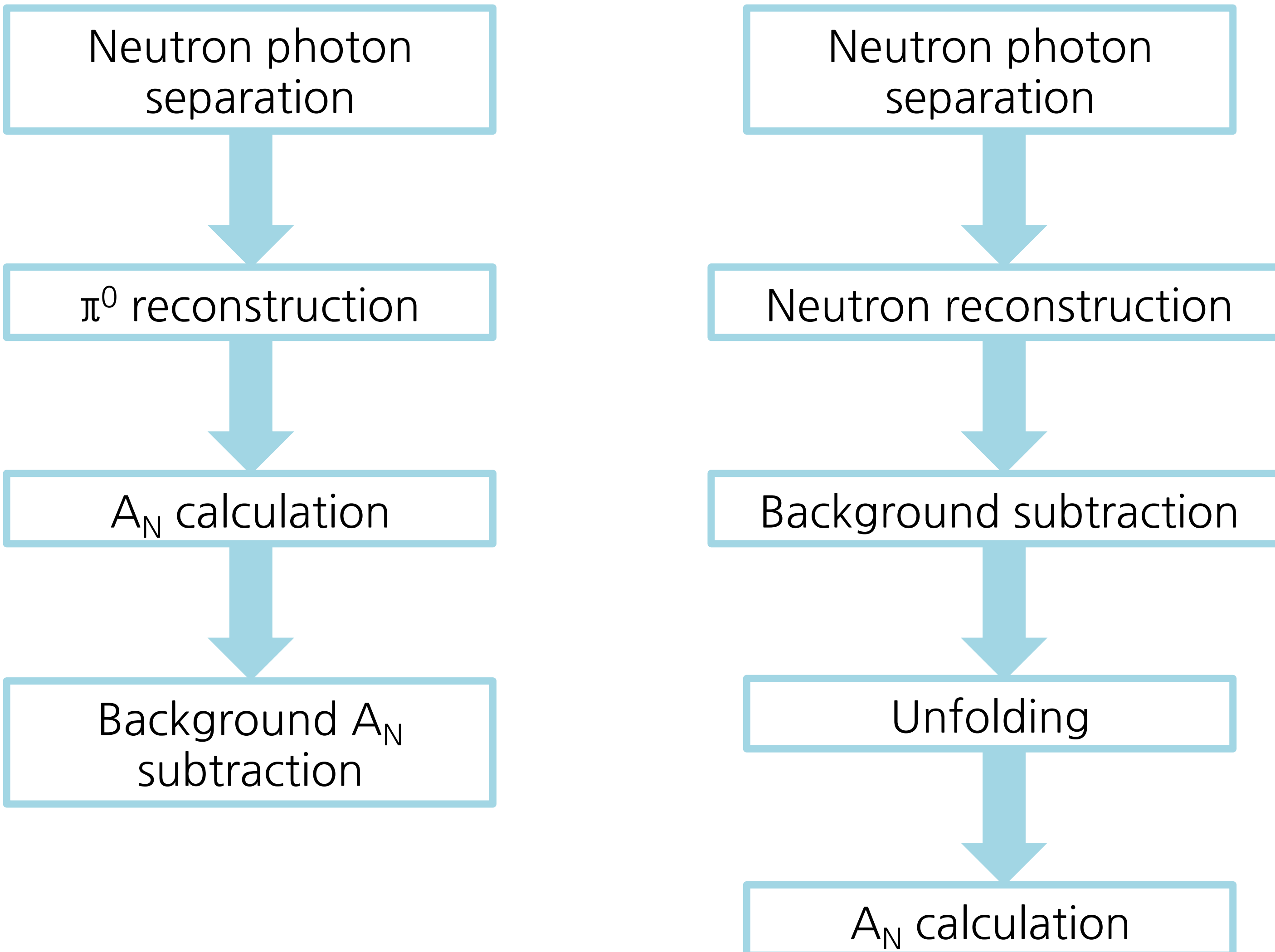
π^0 measurement





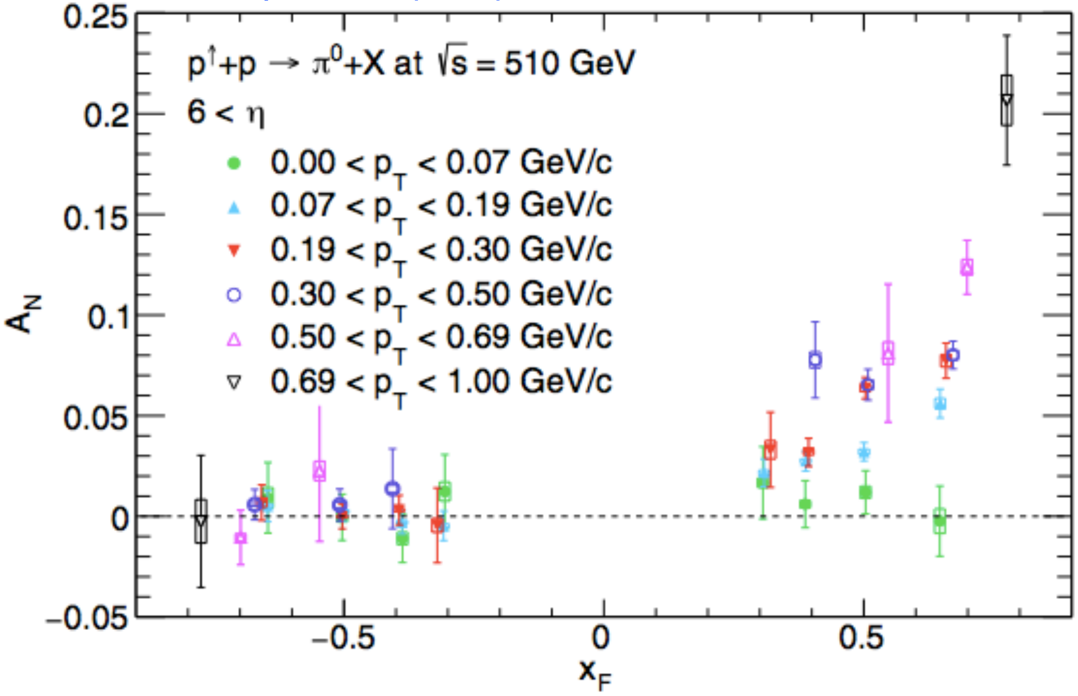
Analysis flow

π^0 | **Neutron**

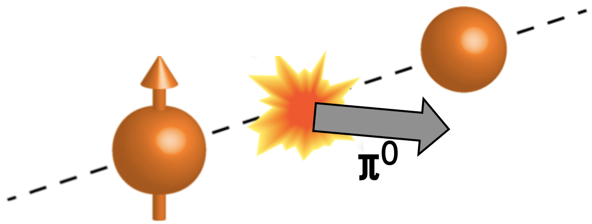


A_N of very forward π^0

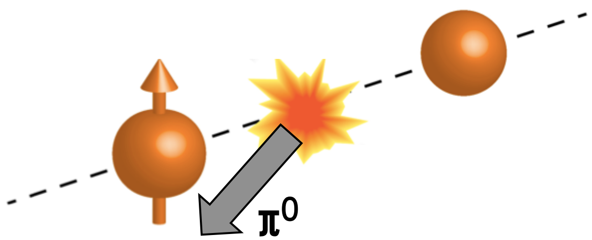
PRL 124, 252501 (2020).



i) $x_F > 0$ (very forward A_N)

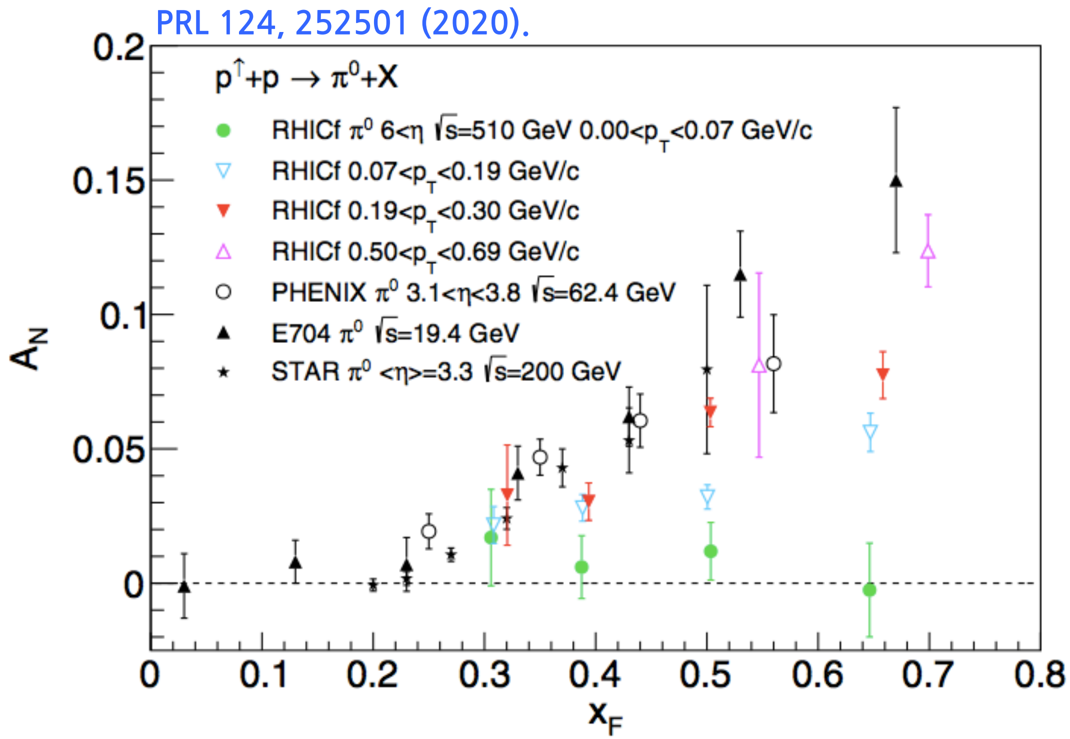


ii) $x_F < 0$ (very backward A_N)



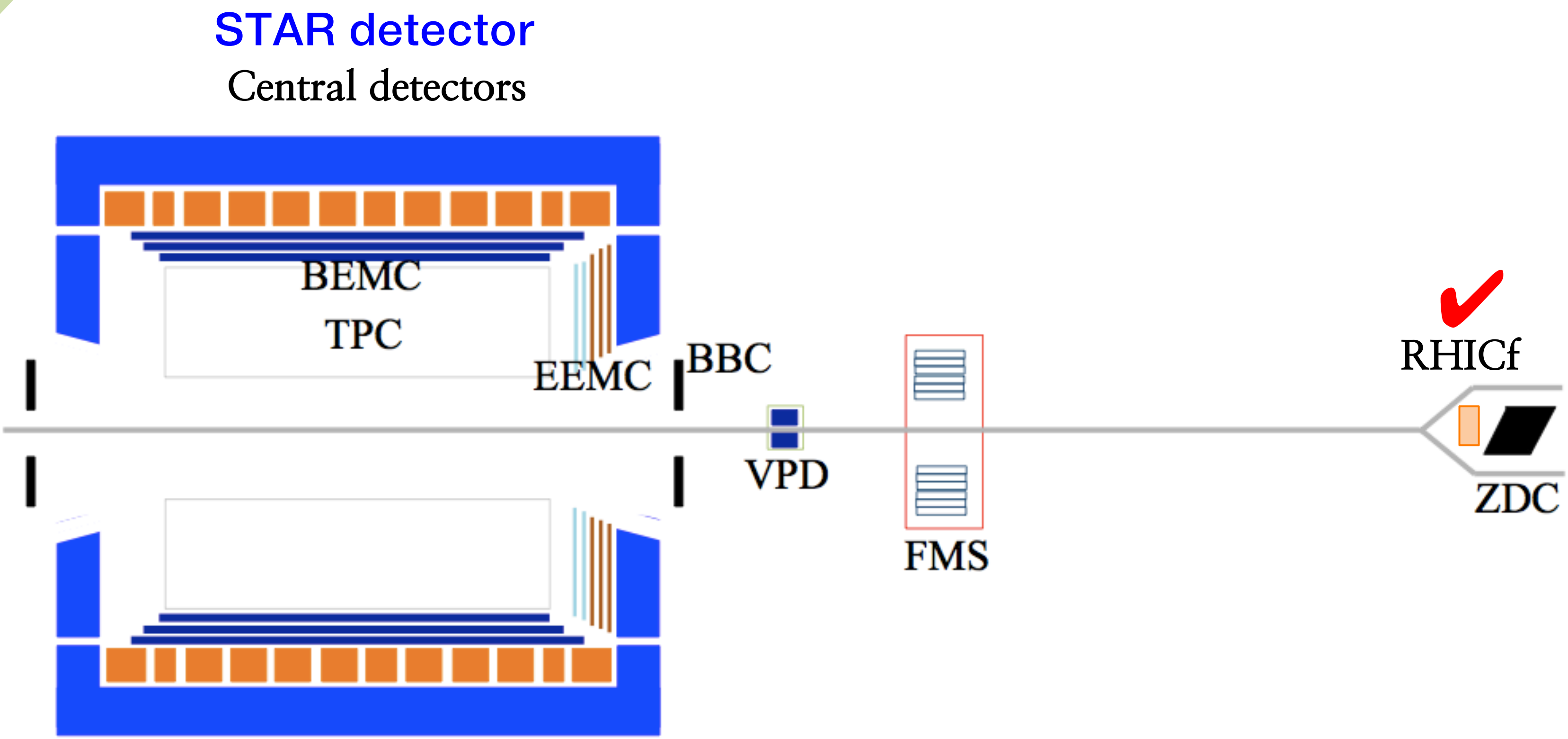
- At very low $p_T < 0.07$ GeV/c, the A_Ns are consistent with zero.
- However, as p_T increases, the A_Ns also increase as a function of x_F even though it is expected that the very forward π^0 comes from the diffractive process.

Comparison with the previous measurements

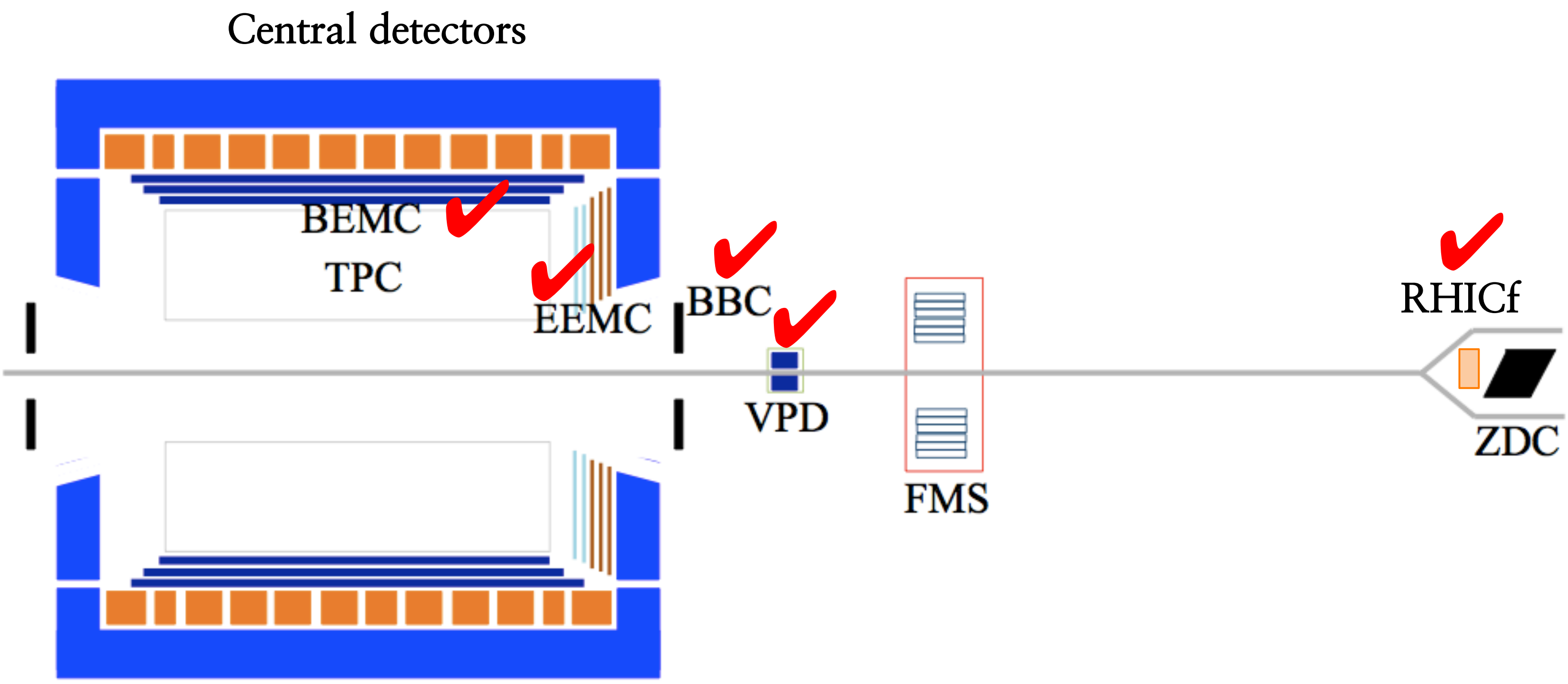


- One very interesting point is that the **A_N of very forward π^0 seems to be comparable with that of forward π^0**.
- They may share a common underlying production mechanism or have their own ones.

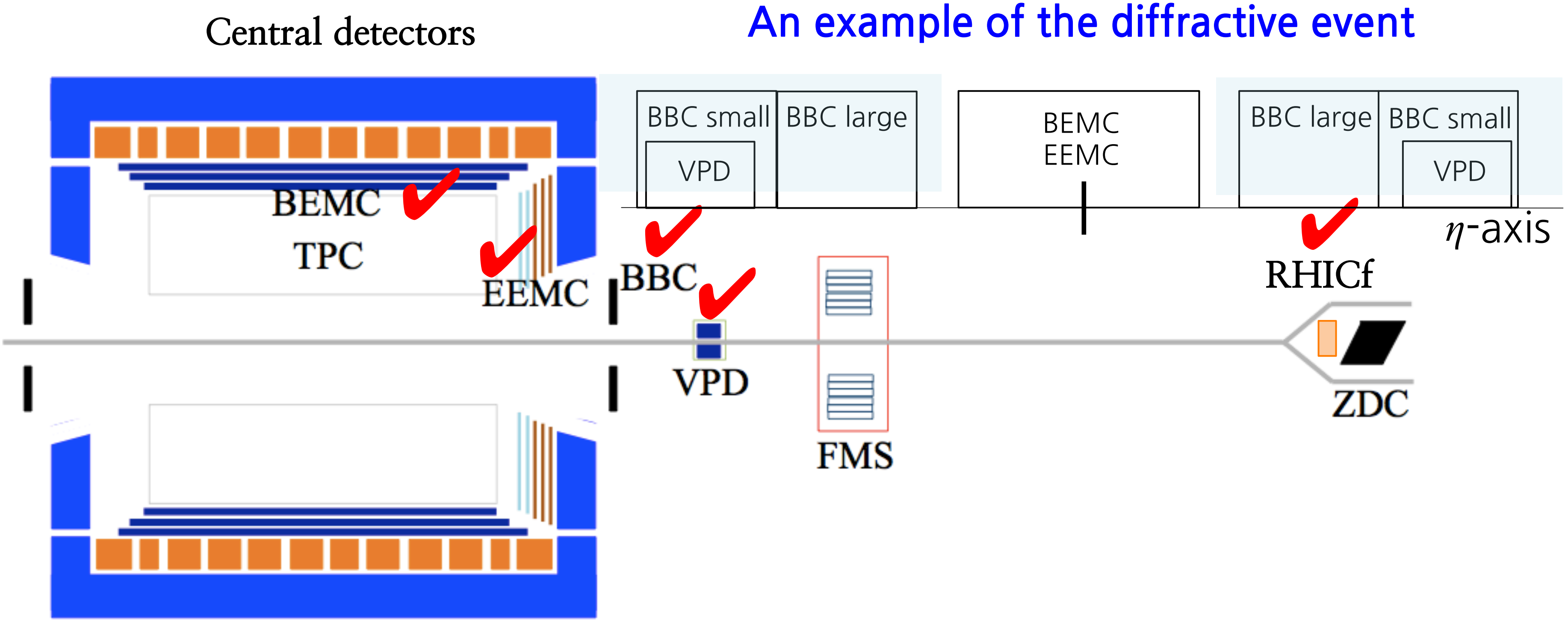
RHICf-STAR combined analysis



RHICf-STAR combined analysis



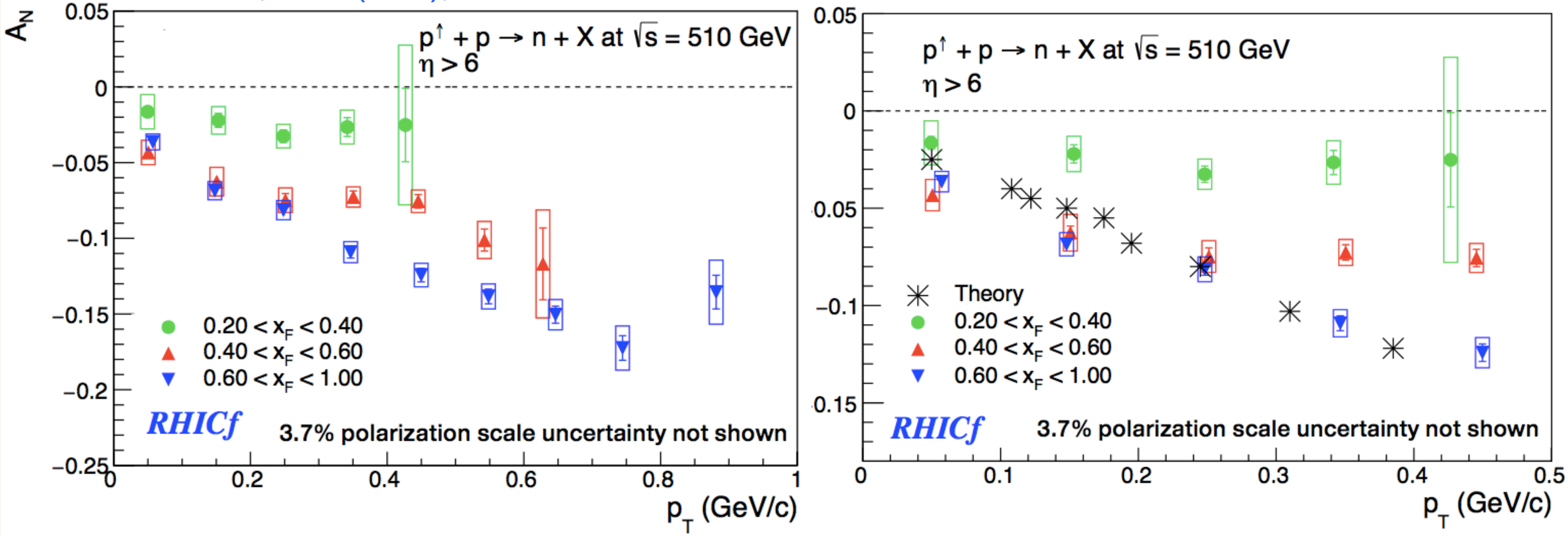
RHICf-STAR combined analysis



- We're extending the RHICf standalone analysis to a combined analysis with STAR detectors to study the origin of the RHICf π^0 results.
- If we use the STAR detectors, we could identify the diffractive and non-diffractive events.

A_N of very forward neutron

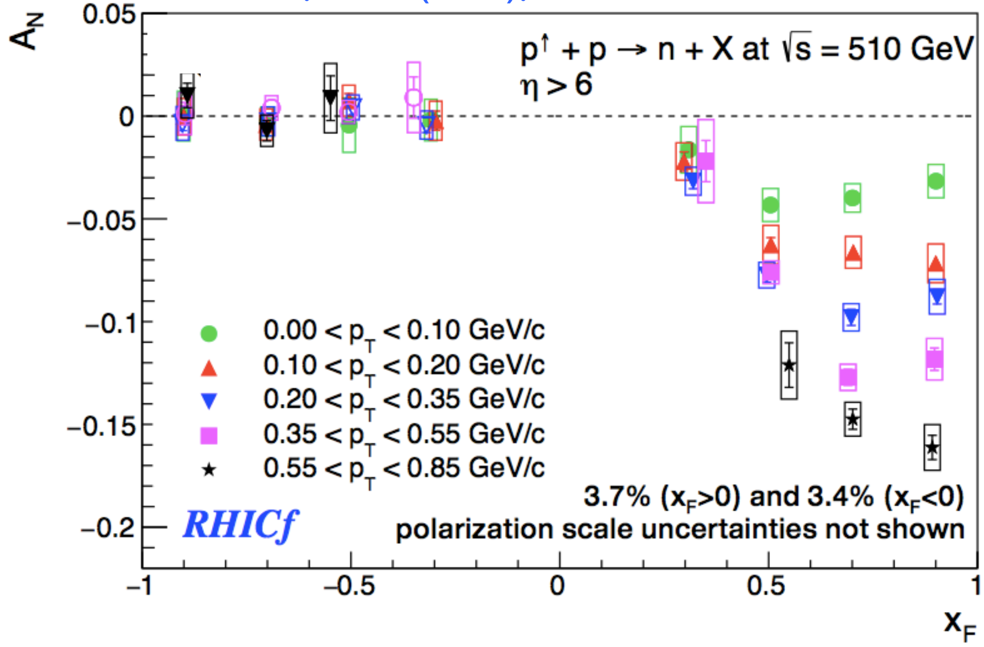
arXiv:2310.09807 (2023).



- In the low x_F range, the neutron A_N reaches a plateau at low p_T.
- In the high x_F range, the A_N doesn't seem to reach the plateau yet, but we can confirm that the A_N explicitly increases in magnitude with p_T.
- The current theoretical calculation only reproduces the A_N in the high x_F range.

A_N of very forward neutron

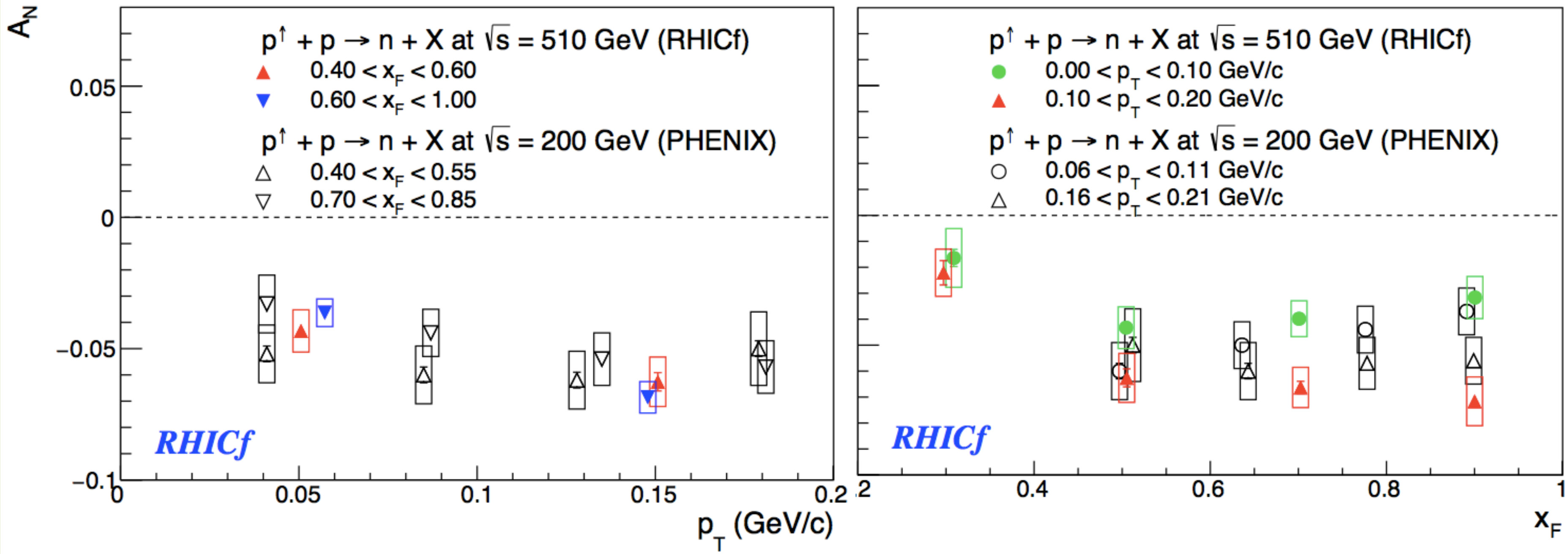
arXiv:2310.09807 (2023).



- In the low p_T range, the A_N reaches a plateau at low x_F with little x_F dependence.
- In the high p_T range, the A_N reaches a higher plateau at higher x_F with **a clear x_F dependence**.
- More comprehensive theoretical consideration is necessary to explain the present results.

Comparison with the PHENIX measurements

arXiv:2310.09807 (2023).

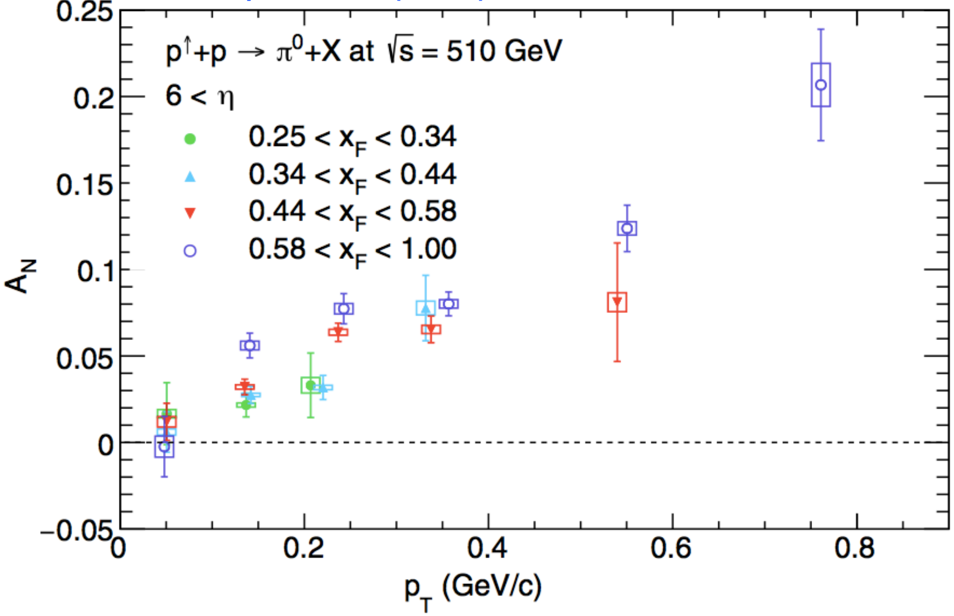


- The RHICf results are consistent with of those of PHENIX.
- In the range of $x_F > 0.4$ and $p_T < 0.2$ GeV/c, this consistency suggests that there is **no $\sqrt{s}$ dependence** in the neutron A_N.

A_Ns of very forward π^0 and neutron

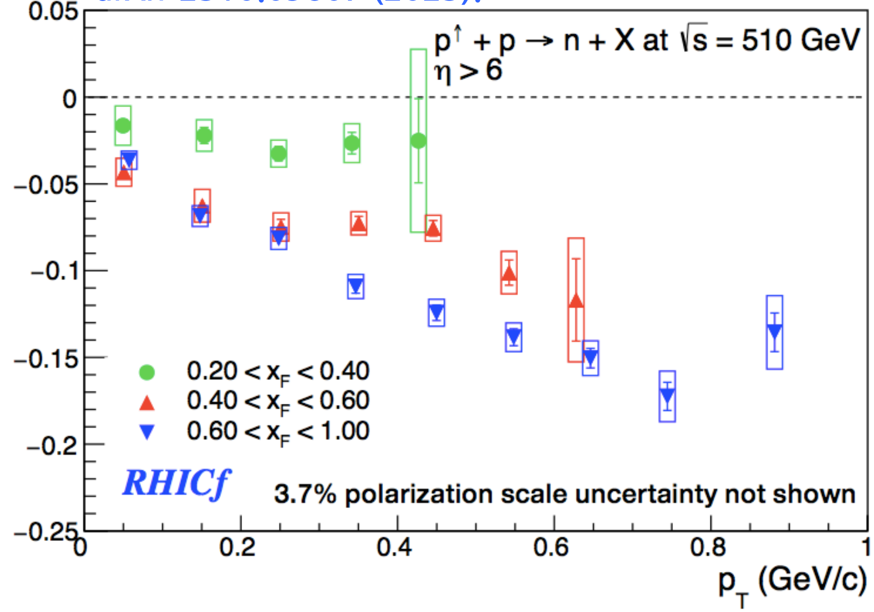
π^0

PRL 124, 252501 (2020).



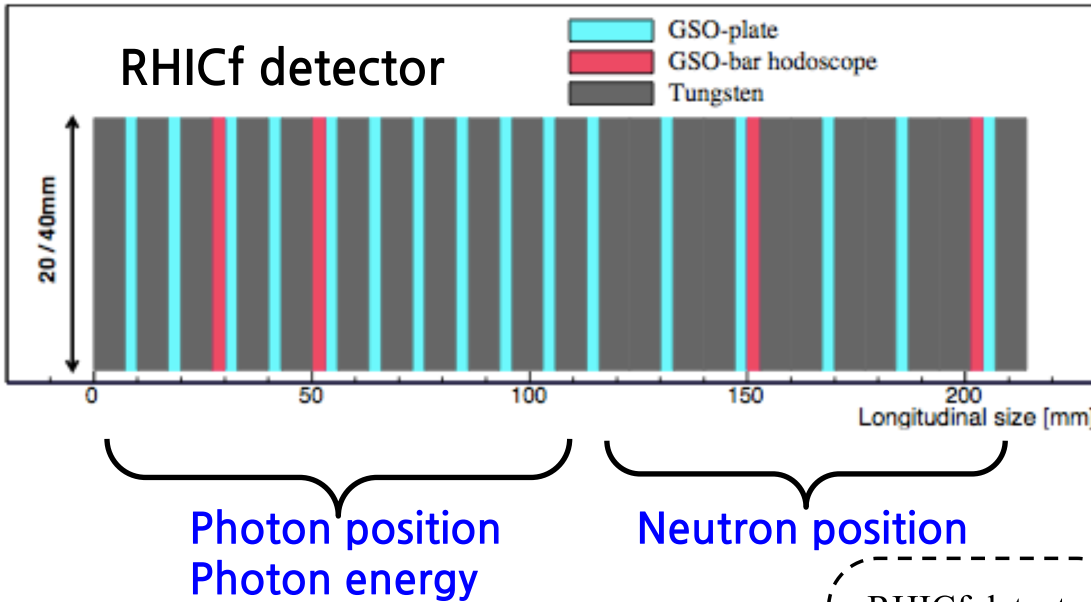
Neutron

arXiv:2310.09807 (2023).

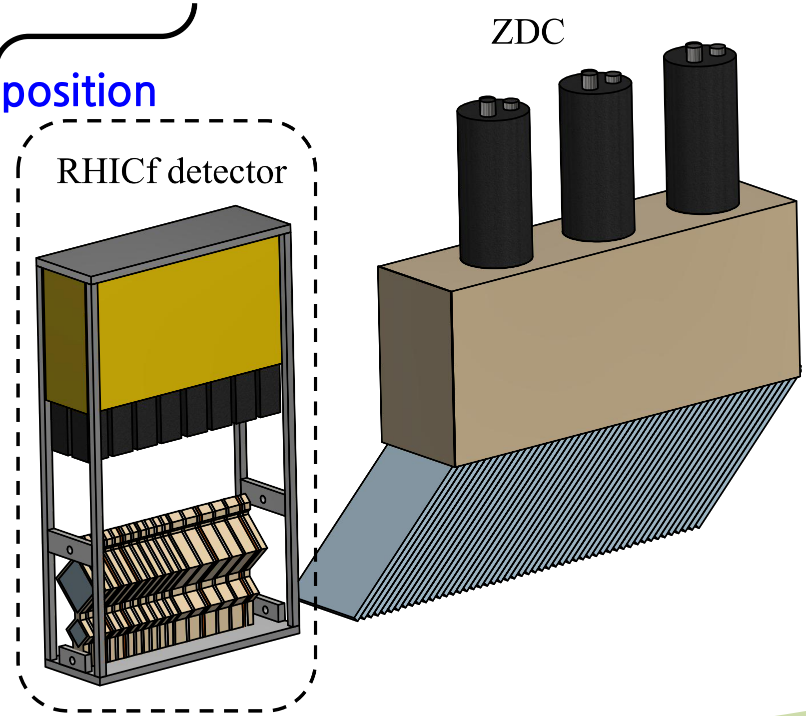


- In the very forward region, the **neutron A_N** is expected to come from the **πa_1 interference** and the **π^0 A_N** is expected come from **NN^* and $\Delta\Delta^*$ interferences**.
- Although the A_Ns of π^0 and neutron are expected to come from different production mechanisms, they show a couple of common behaviors.
- We may be able to study a correlation between the π^0 and neutron A_Ns via that of Λ.

Λ reconstruction



- A_N of Λ may provide us a correlation between the π^0 and neutron A_Ns.
- The Λ can be reconstructed using the RHICf detector and ZDC together.

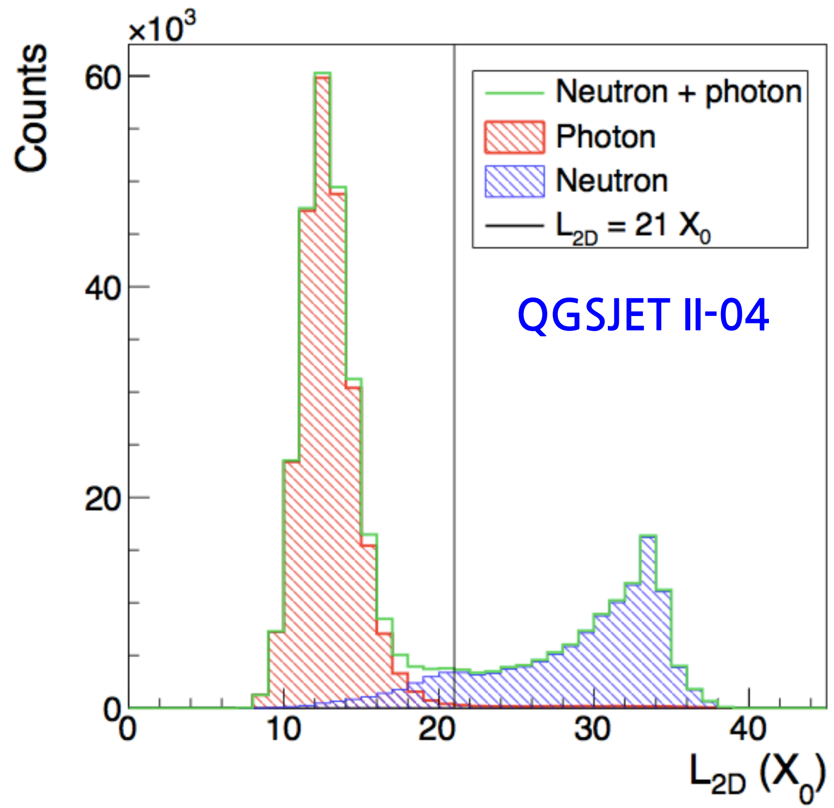


Summary

- The RHICf experiment has measured A_Ns for very forward π^0 and neutron productions in polarized p+p collisions at $\sqrt{s}$ = 510 GeV.
- Non-zero A_Ns were observed even in the p_T range lower than 1 GeV/c for very forward π^0 production.
- To understand the origin of the A_N for very forward π^0 production, we've started the RHICf-STAR combined analysis.
- In the x_F range higher than 0.6, the neutron A_N increased in magnitude with p_T as the model predicted.
- A clear x_F dependence was observed in the neutron A_N that has not been predicted by the π and a_1 exchange model.
- There was no $\sqrt{s}$ dependence in the neutron A_N.
- We're also reconstructing the Λ to study a possible correlation between the π^0 and neutron A_Ns.

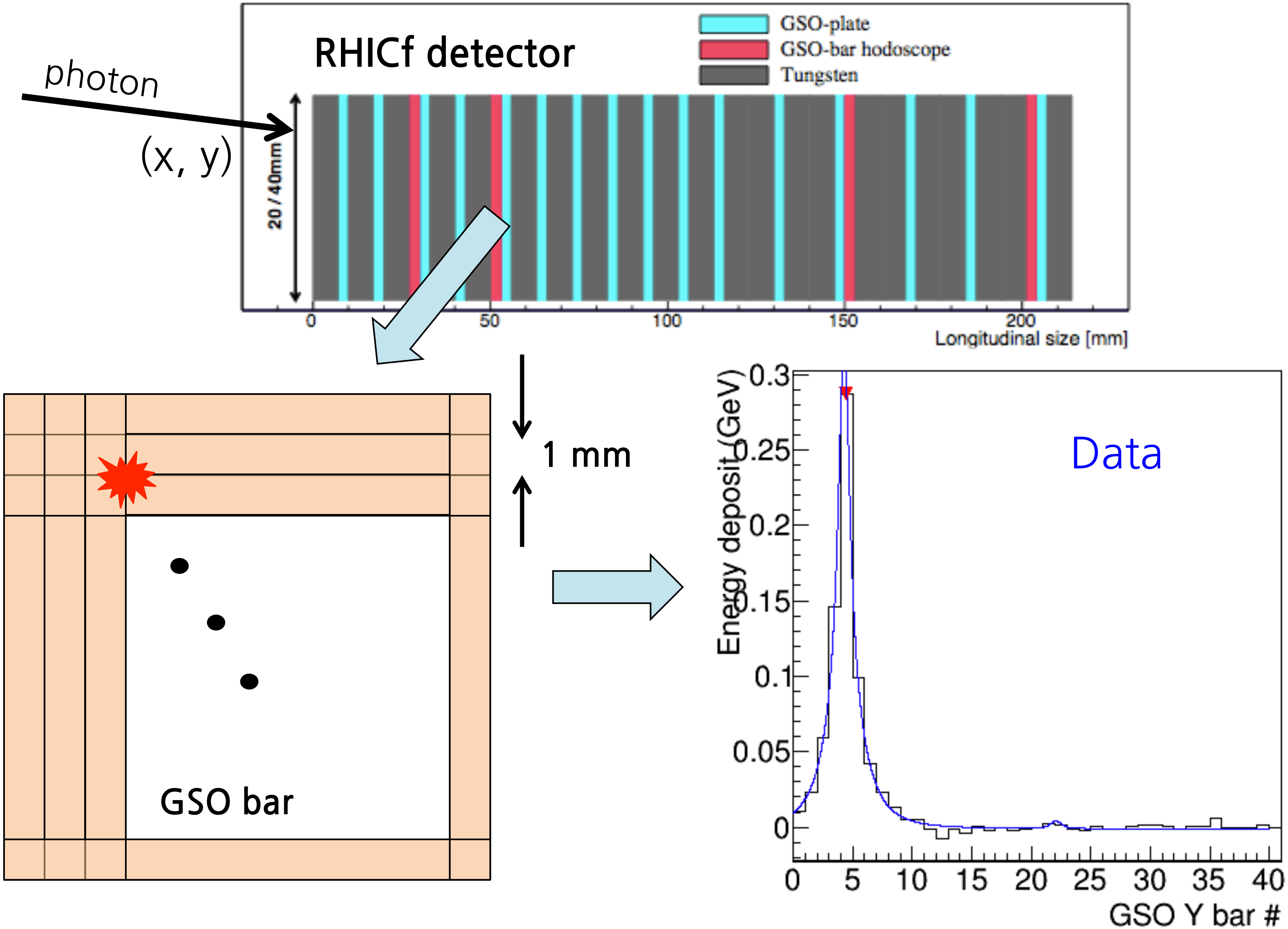
Backup

Neutron photon separation

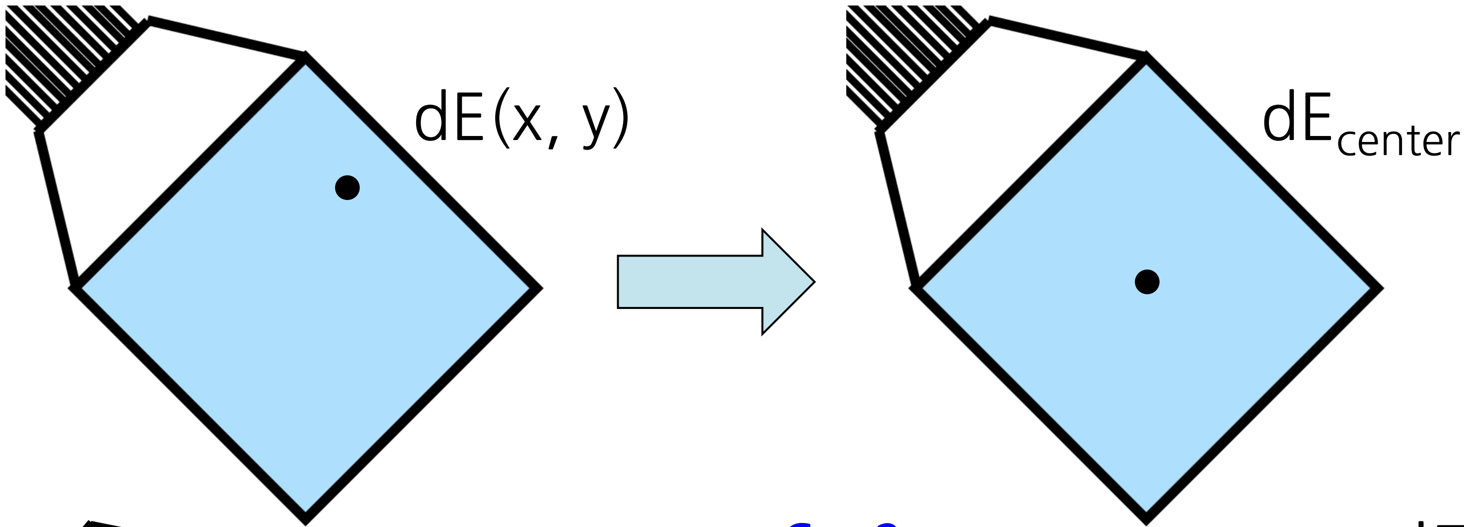


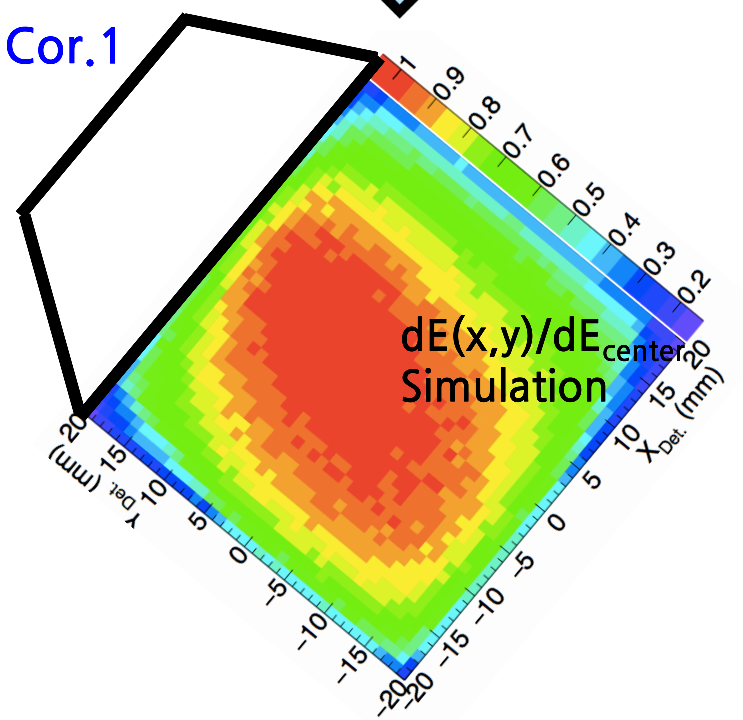
- We used a variable called L_{2D} for neutron photon separation, which described how early a particle shower was developed in the detector.
- We optimized a L_{2D} threshold taking into account the particle purity and efficiency.

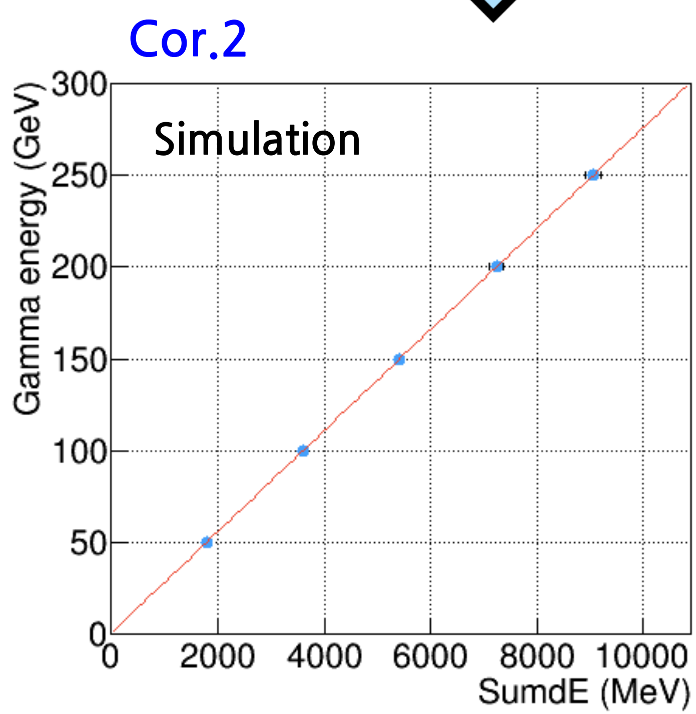
Position reconstruction



Energy reconstruction







$dE(x, y)$

↓ Cor.1

dE_{center}

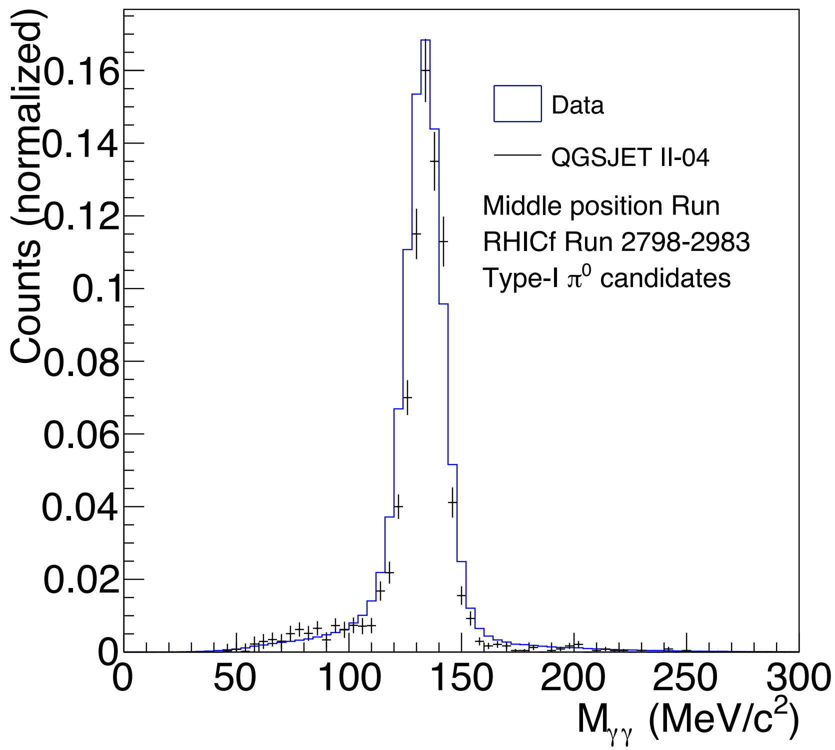
↓

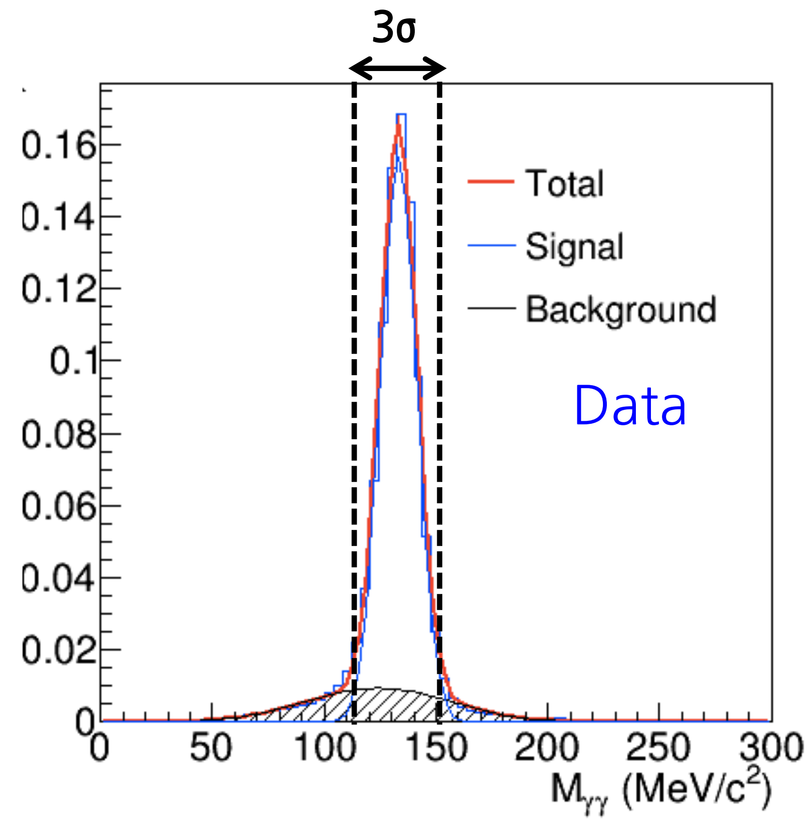
SumdE

↓ Cor.2

$E_{particle}$

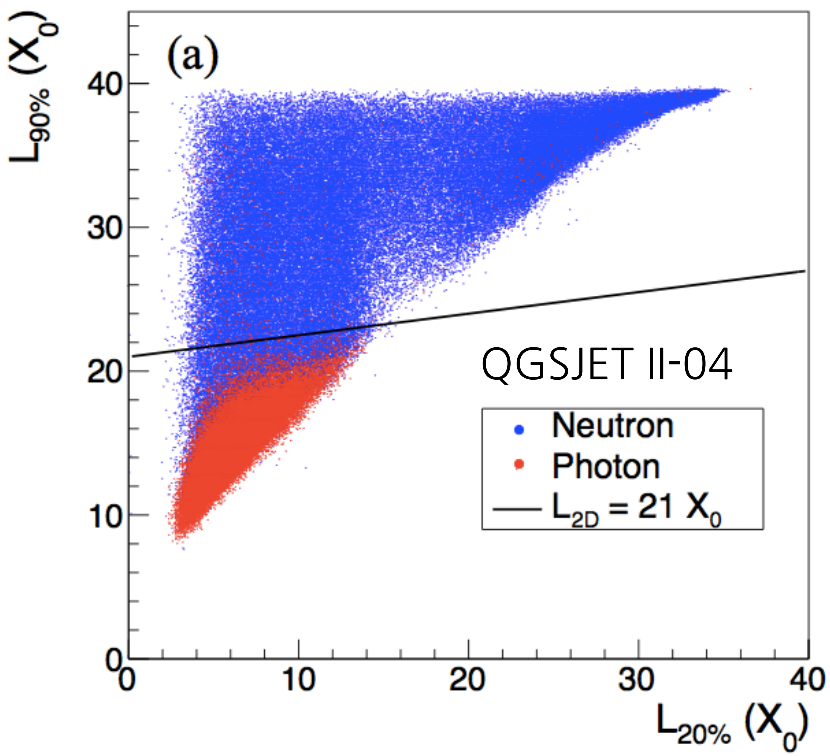
π^0 reconstruction

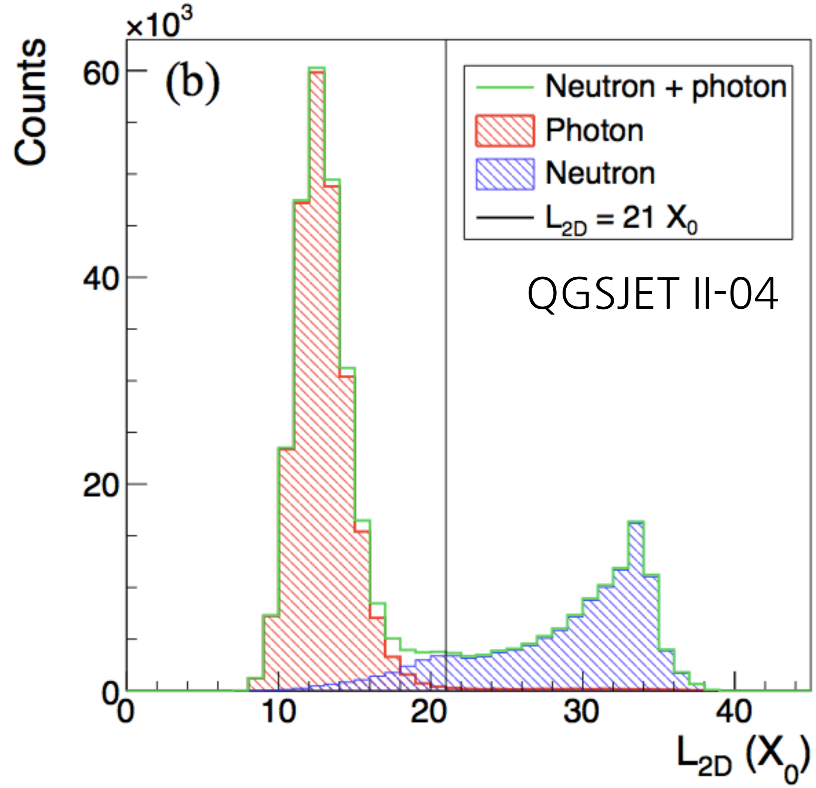




- Data is well matched with simulation showing a clear π^0 peak at 135 MeV/c^2.
- Invariant mass was fitted by a superposition of polynomial and Gaussian functions, and π^0 candidates were selected within 3σ tolerance.

Neutron photon separation

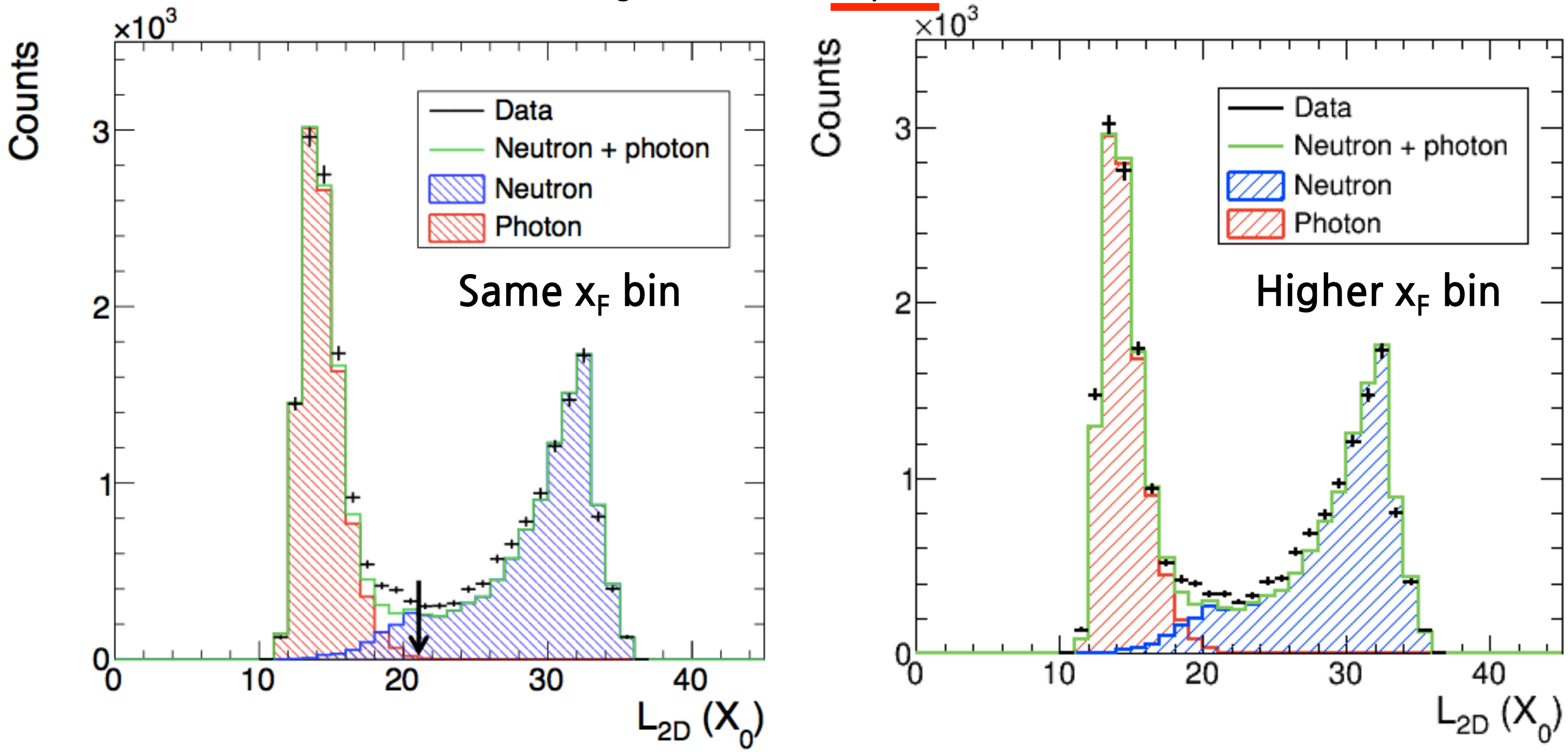




- An event was considered as a neutron if $L_{90\%} > aL_{20\%} + b\ X_0$.
- Among "a" and "b" values that made the neutron purity higher than 99%, they were optimized so that (purity) x (efficiency) had a maximum value.
- The optimized "a" and "b" are 0.15 and 21, respectively, thereby the L_{2D} was defined as $L_{90\%}$ - $0.15L_{20\%}$.

Photon background subtraction

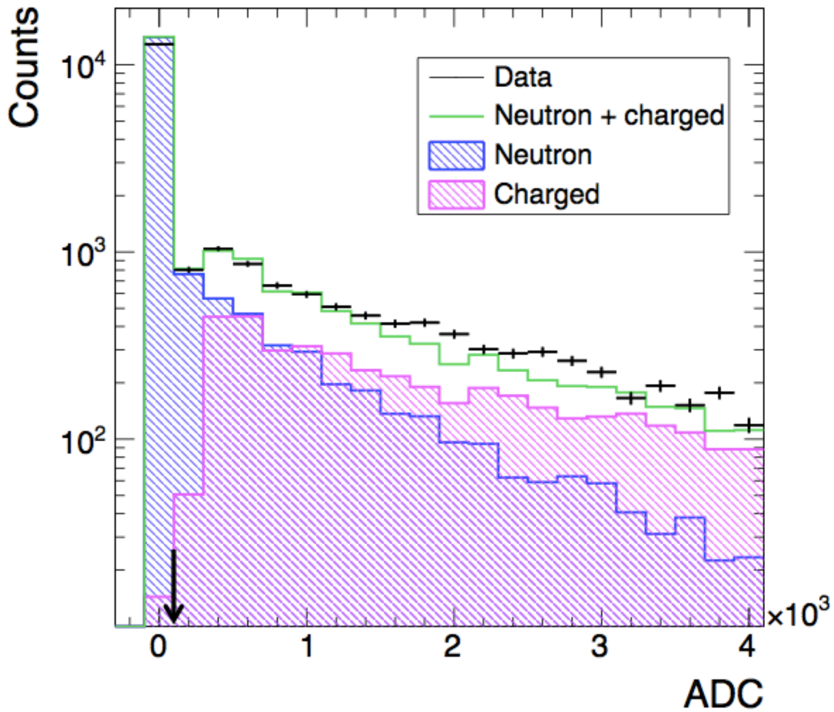
$N_{trig} = N_{neu} + N_{pho} + N_{cha}$



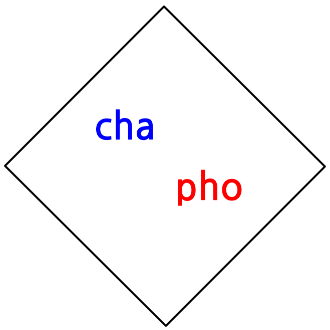
- To estimate and subtract the photon contamination, a template fit was performed to the L_{2D} distribution.
- To study effect of the discrepancy between the MC and data, the template fit was performed again using the template of the higher x_F bin.
- A_N difference after unfolding between the two methods was negligible, which was less than 0.0007. → No systematic uncertainty was assigned.

Charged background subtraction

$N_{trig} = N_{neu} + N_{pho} + N_{cha}$



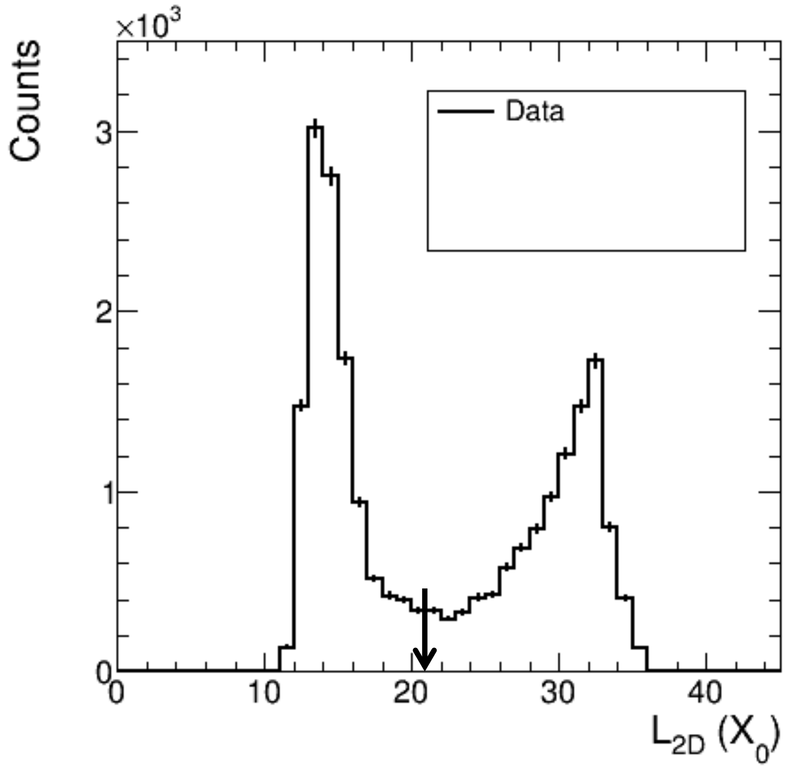
If every charged hadron event includes at least one photon on the detector,

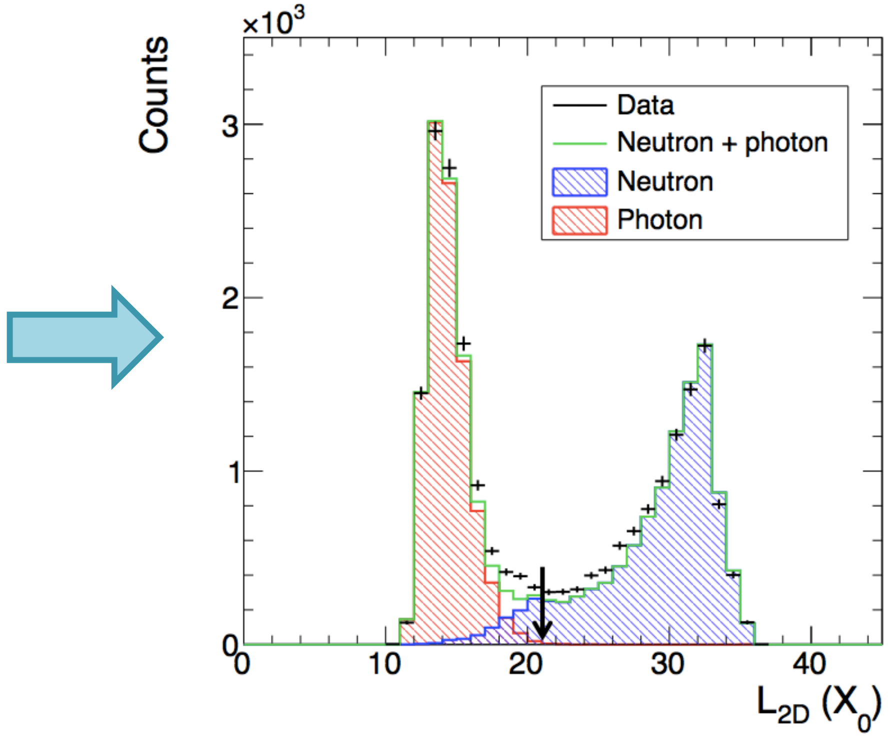


only the photon contamination needs to be subtracted because $N_{cha} < N_{pho}$.

- To estimate and subtract the charged contamination, another template fit was performed to the front counter ADC distribution.
- According to QGSJET II-04, less than 5% of the charged hadron event has photon.
  → Photon and charged contaminations were subtracted separately.
- There is almost no difference in the resulting A_N (< 0.0004) even if only one contamination was subtracted. → No systematic uncertainty was assigned.

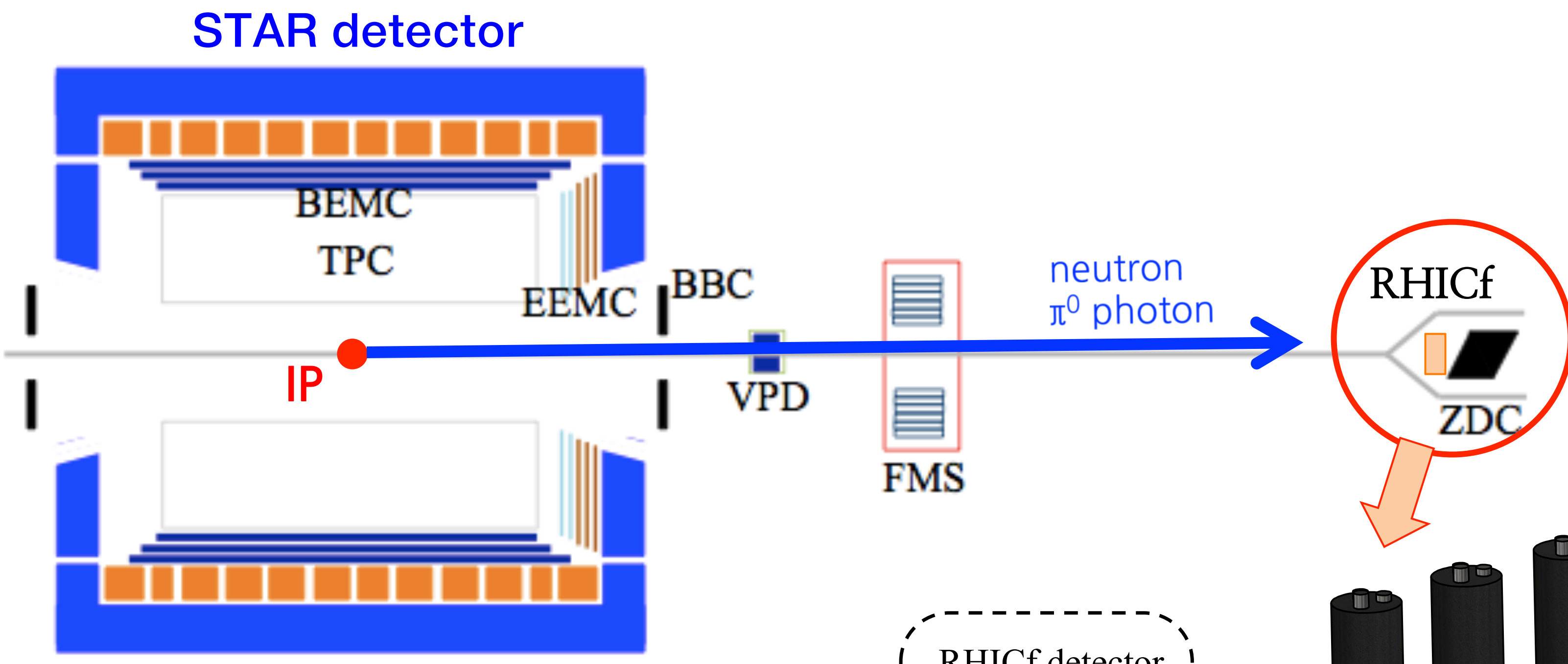
Photon background



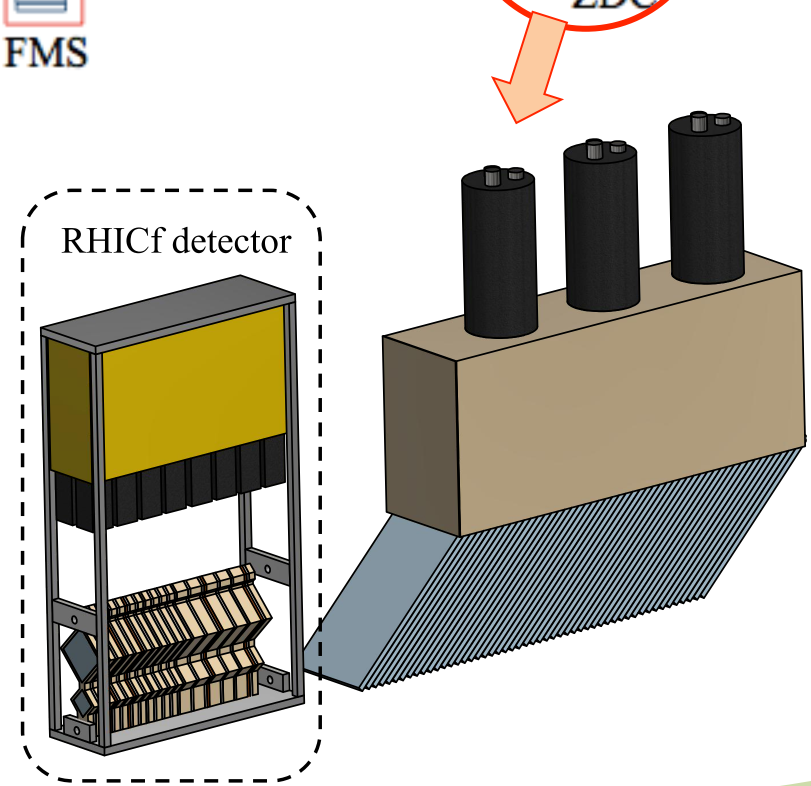


- We performed a template of the L_{2D} distribution using those of the neutron and photon events obtained from QGSJET II-04 MC sample.
- Photon contamination above the threshold was estimated and subtracted.

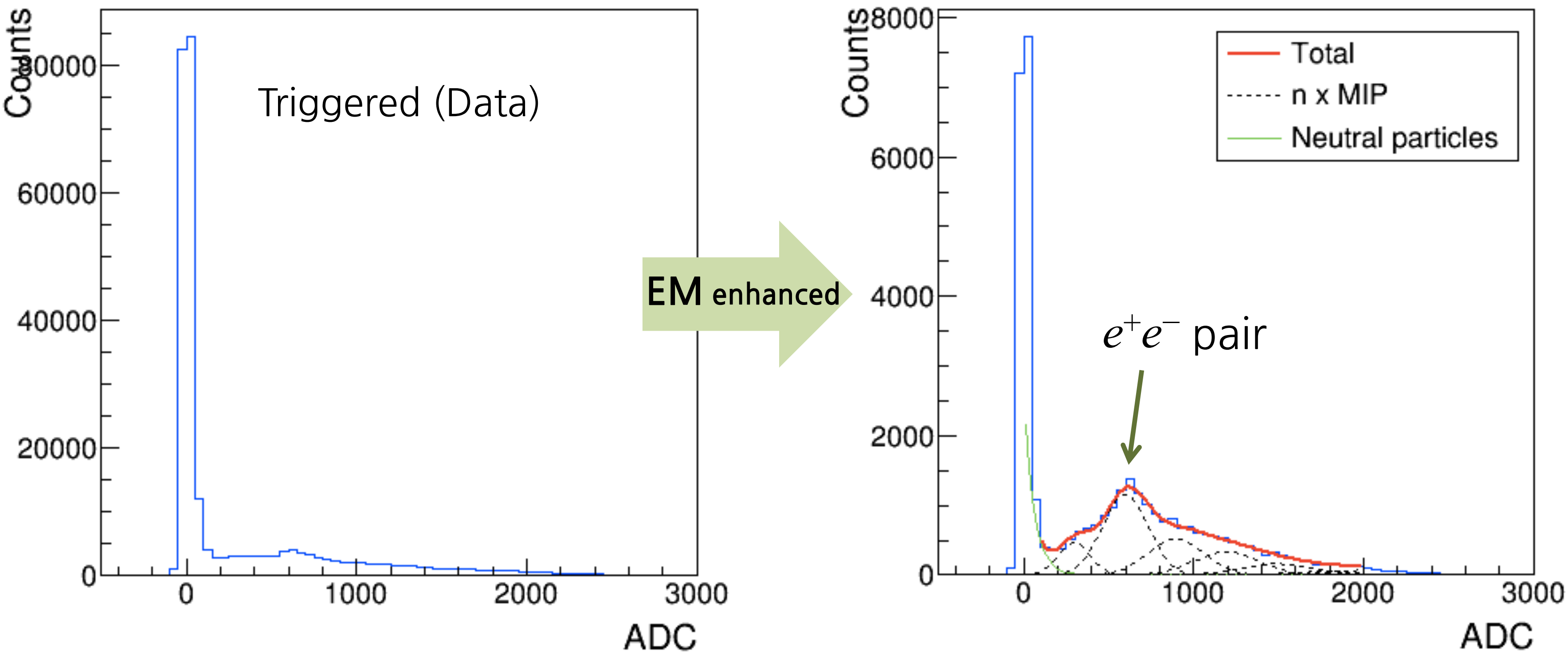
RHIC forward (RHICf) experiment



- In June 2017, the RHICf experiment was operated at STAR in polarized p+p collisions at $\sqrt{s}$ = 510 GeV.
- We installed the RHICf detector in front of the ZDC.

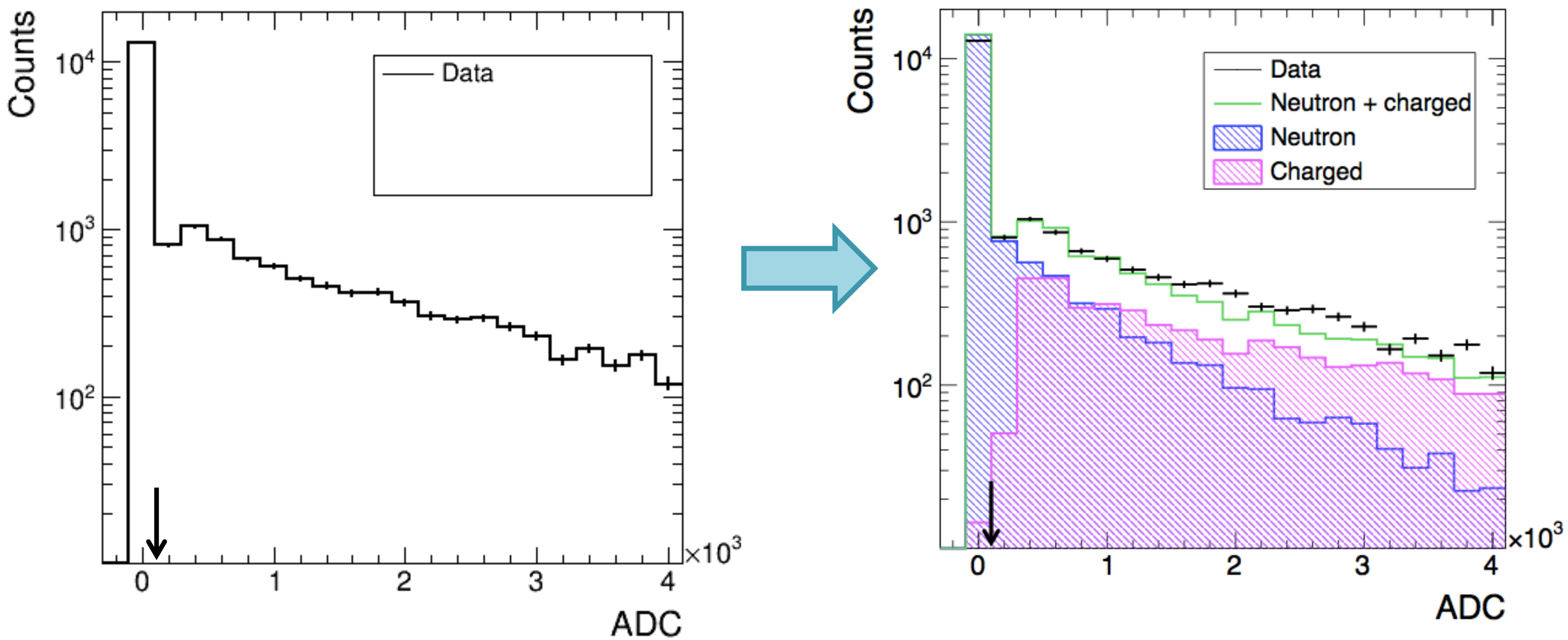


Reproduction of the front counter response



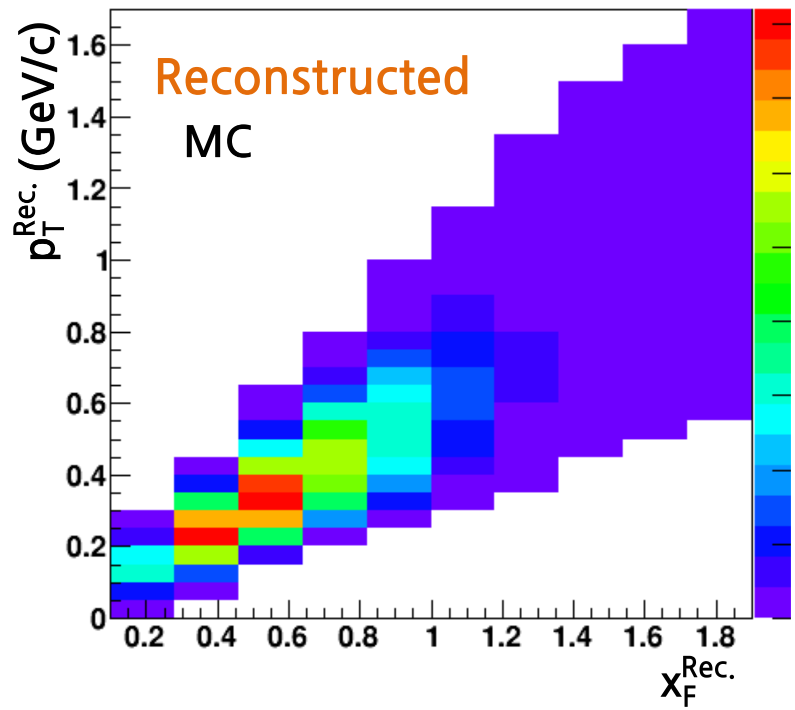
- To fit the front counter ADC distribution, EM events were enhanced.
- The ADC distribution was fitted by assigning free parameters to mean and sigma of MIP distribution, and number of events of each n x MIP distributions.

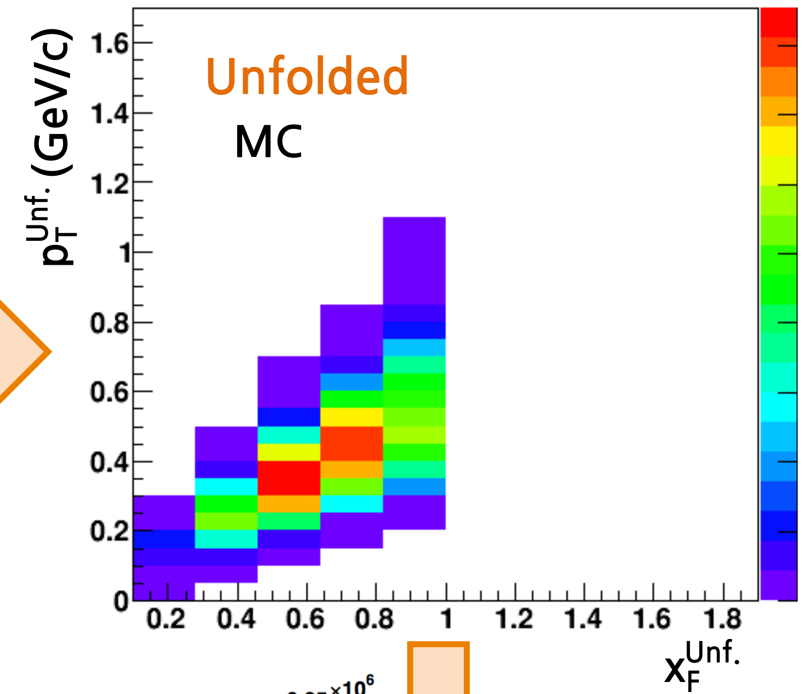
Charged background



- We applied a threshold to the front counter ADC distribution to suppress the charged hadron events.
- We performed a template of the front counter ADC distribution using those of the neutron and charged hadron events obtained from QGSJET II-04 MC sample.
- Charged hadron contamination below the threshold was estimated and subtracted.

Unfolding





- Kinematic variables of neutrons, x_F, p_T, and ϕ, were unfolded using Bayesian unfolding.
- For prior distribution, neutrons were uniformly generated to the detector.