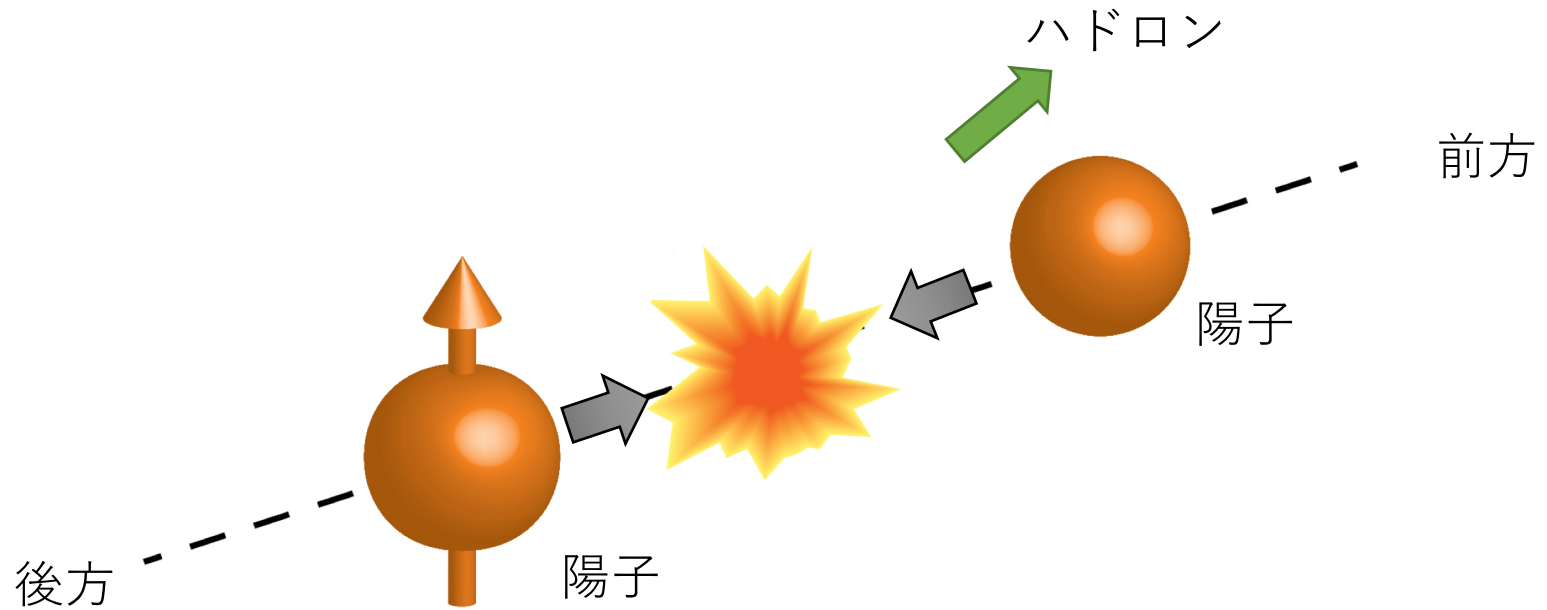


# ALICE FoCAL for RHICf-II Experiment

RIKEN/RBRC

Itaru Nakagawa



Transverse Single Spin Asymmetry

# 横偏極単スピンの非対称性

横偏極した高エネルギー陽子 + 陽子衝突で、前方に生成されるハドロンに左右非対称性が観測される

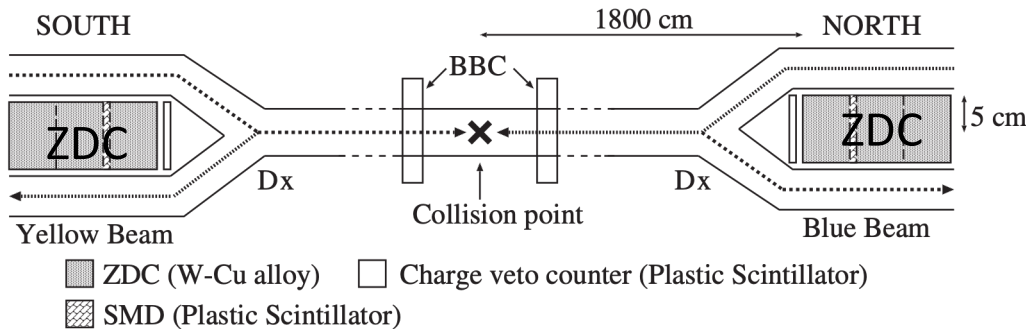
# 超前方中性子非対称性の観測

PHYSICAL REVIEW D **88**, 032006 (2013)

## Inclusive cross section and single transverse spin asymmetry for very forward neutron production in polarized $p + p$ collisions at $\sqrt{s} = 200$ GeV

A. Adare,<sup>13</sup> S. Afanasiev,<sup>29</sup> C. Aidala,<sup>40,41</sup> N. N. Ajitanand,<sup>59</sup> Y. Akiba,<sup>53,54</sup> H. Al-Bataineh,<sup>47</sup> J. Alexander,<sup>59</sup> K. Aoki,<sup>33,53</sup> L. Aphecetche,<sup>61</sup> J. Asai,<sup>53</sup> E. T. Atomssa,<sup>34</sup> R. Averbeck,<sup>60</sup> T. C. Awes,<sup>49</sup> B. Azmoun,<sup>8</sup> V. Babintsev,<sup>23</sup> M. Bai,<sup>7</sup> G. Baksay,<sup>19</sup> L. Baksay,<sup>19</sup> A. Baldisseri,<sup>16</sup> K. N. Barish,<sup>9</sup> P. D. Barnes,<sup>37,\*</sup> B. Bassalleck,<sup>46</sup> A. T. Basye,<sup>1</sup> S. Bathe,<sup>6,9</sup> S. Batsouli,<sup>49</sup> V. Baublis,<sup>52</sup> C. Baumann,<sup>42</sup> A. Bazilevsky,<sup>8</sup> S. Belikov,<sup>8,\*</sup> R. Bennett,<sup>60</sup> A. Berdnikov,<sup>56</sup> Y. Berdnikov,<sup>56</sup> A. A. Bickley,<sup>13</sup> J. G. Boissevain,<sup>37</sup> H. Borel,<sup>16</sup> K. Boyle,<sup>60</sup> M. L. Brooks,<sup>37</sup> H. Buesching,<sup>8</sup> V. Bumazhnov,<sup>23</sup> G. Bunce,<sup>8,54</sup> S. Butsyk,<sup>37</sup> C. M. Camacho,<sup>37</sup> S. Campbell,<sup>60</sup> B. S. Chang,<sup>69</sup> W. C. Chang,<sup>2</sup> J.-L. Charvet,<sup>16</sup> S. Chernichenko,<sup>23</sup> C. Y. Chi,<sup>14</sup> M. Chiu,<sup>24</sup> I. J. Choi,<sup>69</sup> R. K. Choudhury,<sup>5</sup> T. Chujō,<sup>64</sup> P. Chung,<sup>59</sup> A. Churyñ,<sup>23</sup> V. Cianciolo,<sup>49</sup> Z. Citron,<sup>60</sup> B. A. Cole,<sup>14</sup> P. Constantin,<sup>37</sup> M. Csanád,<sup>18</sup> T. Csörgő,<sup>68</sup> T. Dahms,<sup>60</sup> S. Dairaku,<sup>33,53</sup> K. Das,<sup>20</sup> G. David,<sup>8</sup> A. Denisov,<sup>23</sup> D. d'Enterria,<sup>34</sup> A. Deshpande,<sup>54,60</sup> E. J. Desmond,<sup>8</sup> O. Dietzsch,<sup>57</sup> A. Dion,<sup>60</sup> M. Donadelli,<sup>57</sup> O. Drapier,<sup>34</sup> A. Drees,<sup>60</sup> K. A. Drees,<sup>7</sup> A. K. Dubey,<sup>67</sup> A. Durum,<sup>23</sup> D. Dutta,<sup>5</sup> V. Dzhordzhadze,<sup>9</sup> Y. V. Efremenko,<sup>49</sup> F. Ellinghaus,<sup>13</sup> T. Engelmöre,<sup>14</sup> A. Enokizono,<sup>36</sup> H. En'yo,<sup>53,54</sup> S. Esumi,<sup>64</sup> K. O. Eyster,<sup>9</sup> B. Fadem,<sup>43</sup> D. E. Fields,<sup>46,54</sup> M. Finger,<sup>10</sup>

Primary Author : Manabu Togawa



INCLUSIVE CROSS SECTION AND SINGLE TRANSVERSE . .

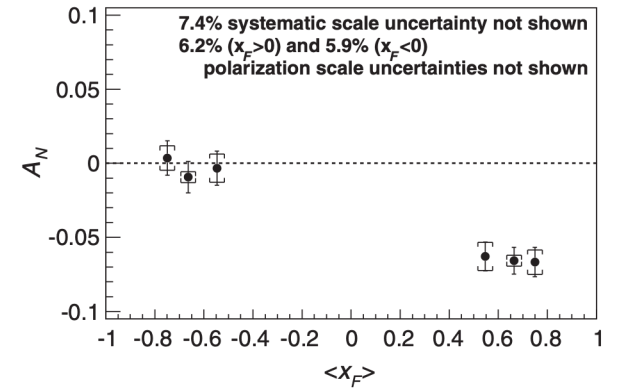
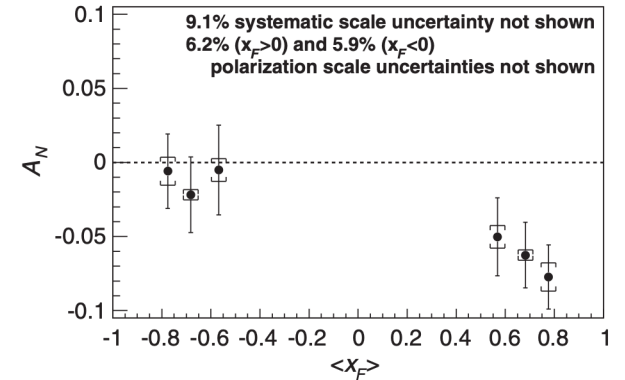
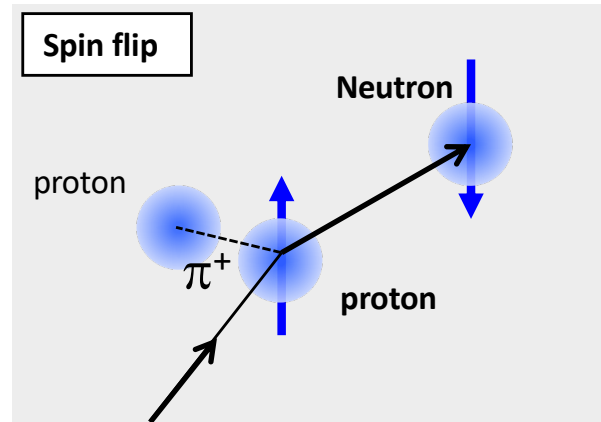
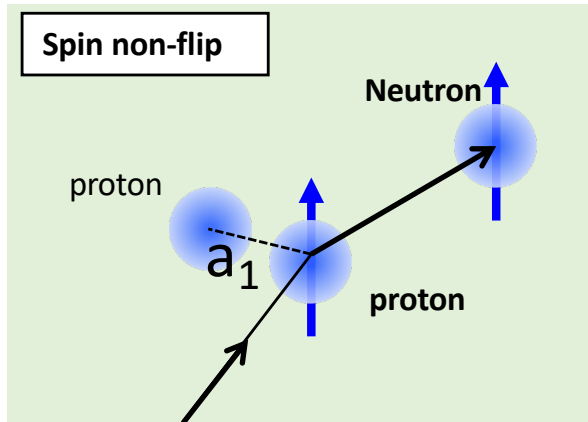


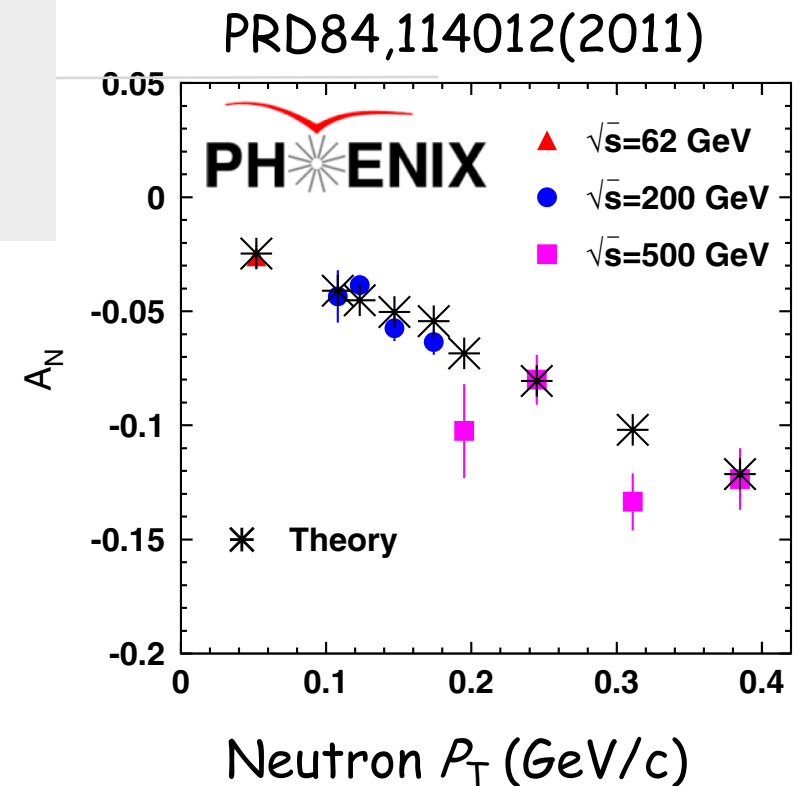
FIG. 18. The  $x_F$  dependence of  $A_N$  for neutron production in the (upper) ZDC trigger sample and for the (lower) ZDC @ BBC trigger sample. The error bars show statistical uncertainties, and brackets show  $p_T$ -correlated systematic uncertainties. Systematic scale uncertainties listed in Table IV and polarization scale uncertainties are not included.

# $p^\uparrow + p$ 超前方中性子非対称性 $A_N$



理論解釈

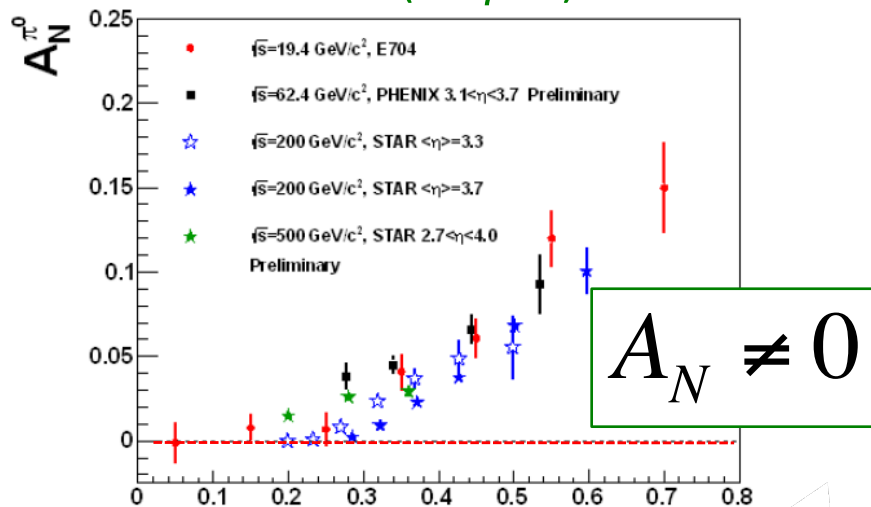
$$A_N \approx \frac{(\phi_{non-flip}^* \phi_{flip} \sin \delta)}{|\phi_{non-flip}|^2 + |\phi_{flip}|^2}$$



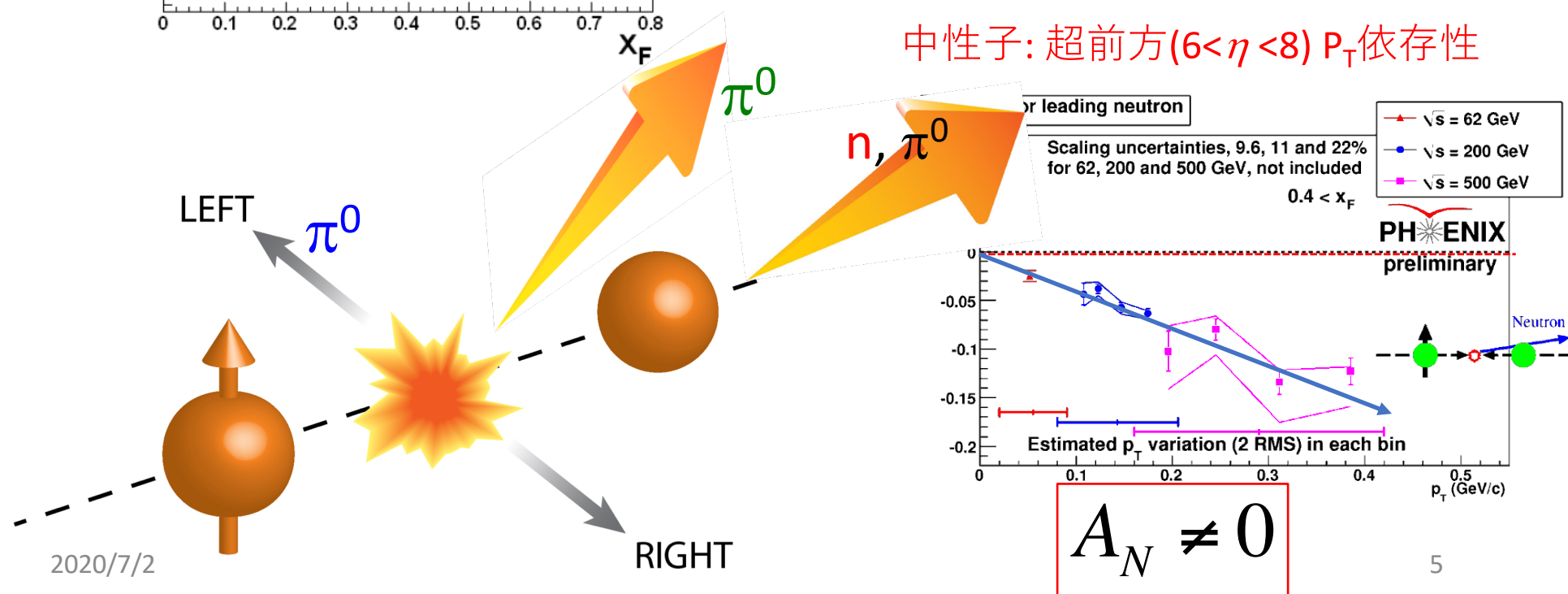
$\pi$  と  $a_1$  Reggeon の干渉でうまく説明ができた。

# 横偏極能 $A_N$ のラピディティ依存

$\pi^0$  前方 ( $2 < \eta < 4$ )



中性子: 超前方 ( $6 < \eta < 8$ )  $P_T$  依存性



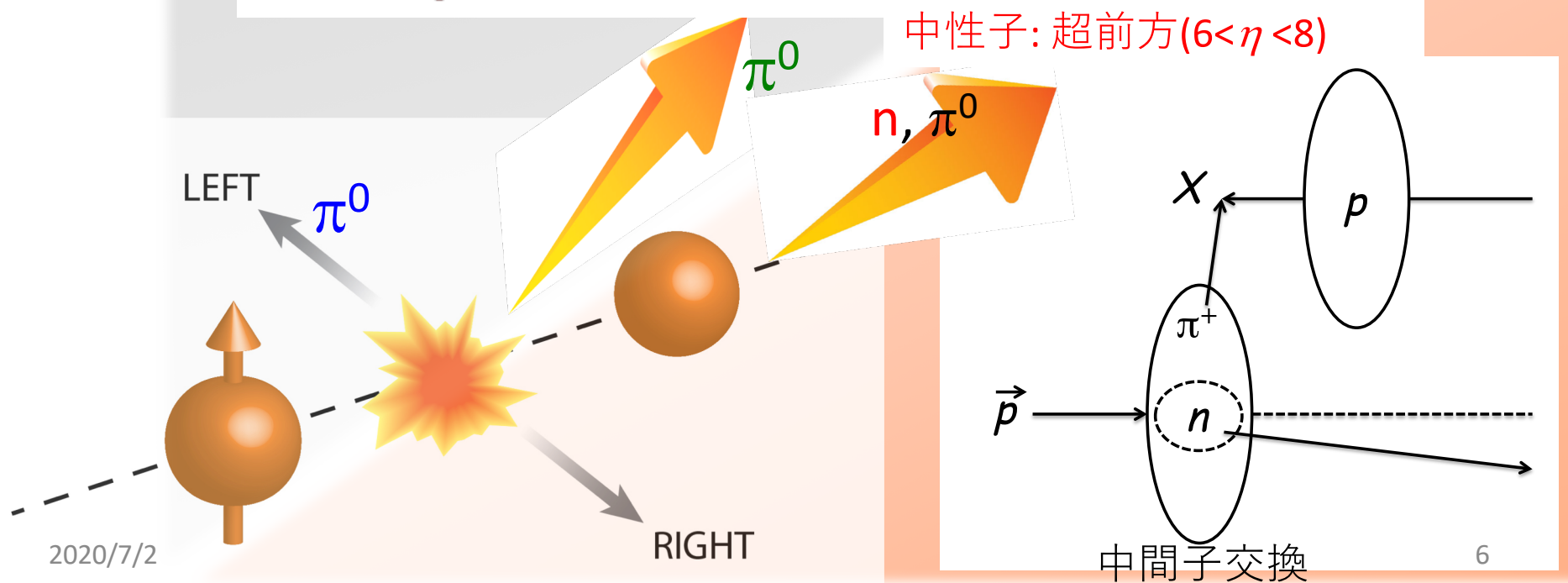
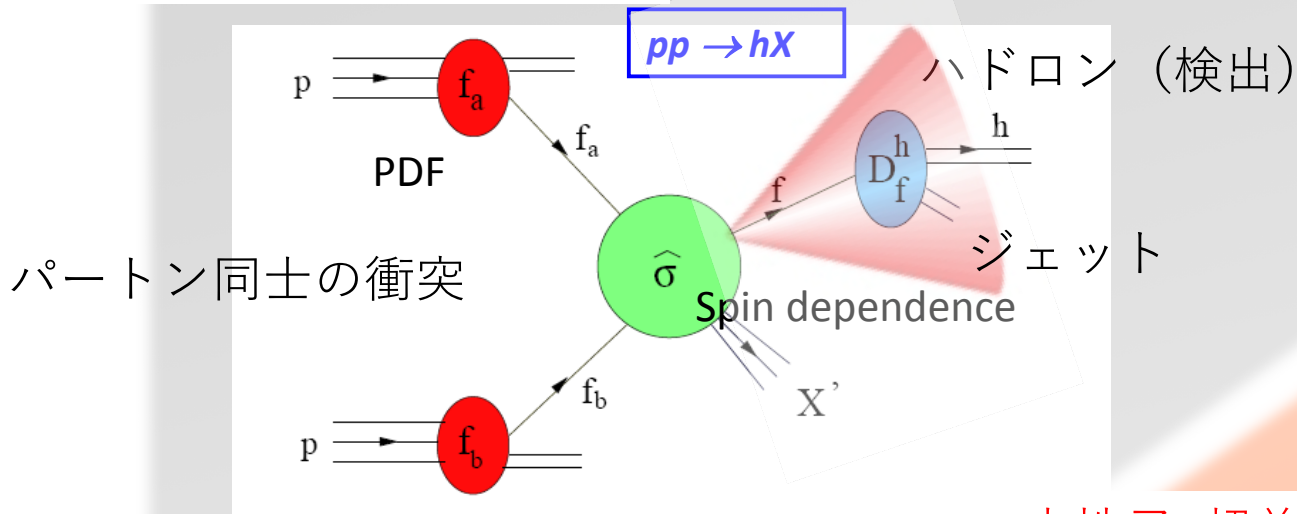
# ハドロン生成メカニズム

$\pi^0$  セントラル ( $0.35 > |\eta|$ )

$\pi^0$  前方 ( $2 < \eta < 4$ )

摂動論的

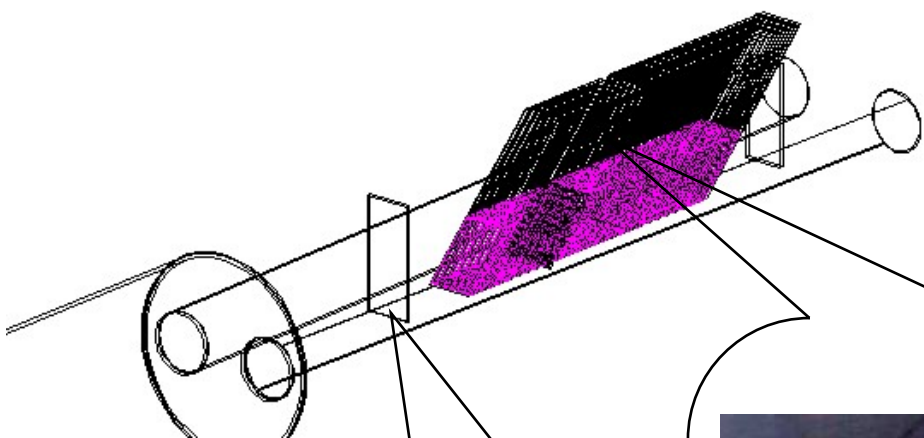
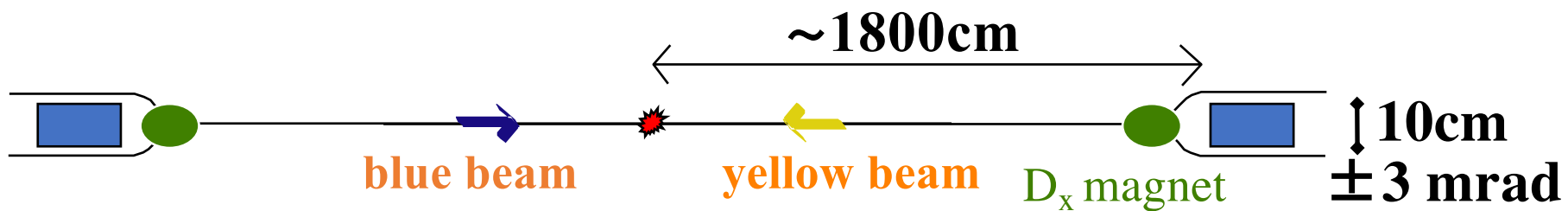
非摂動論的  
(diffractive)



2020/7/2

中間子交換

# RHICのZDC検出器

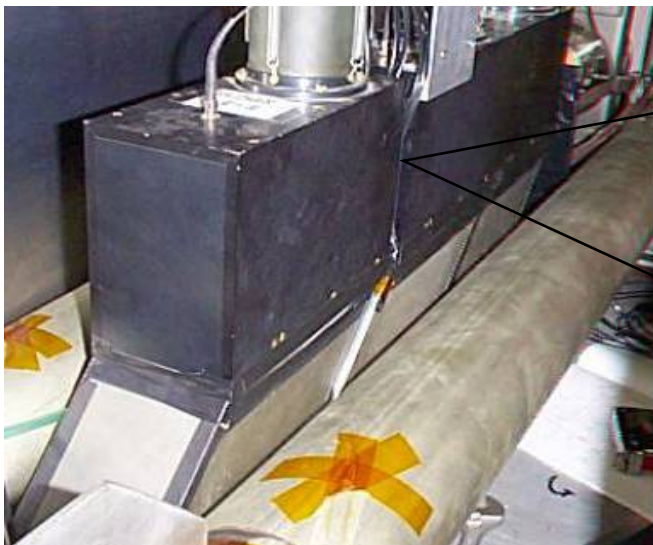


ZDC

Forward counter

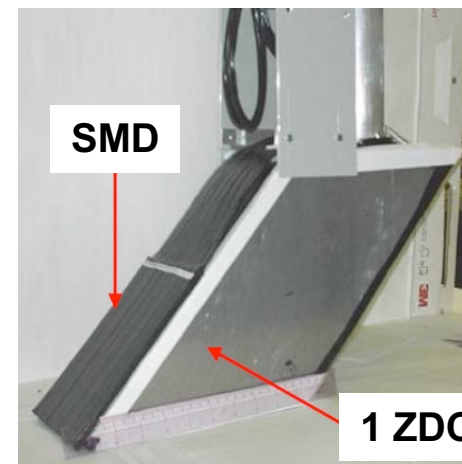


Charge veto



3 modules:  $150X_0$   $5.1\lambda_1$

SMD



position measurement  
with scintillators

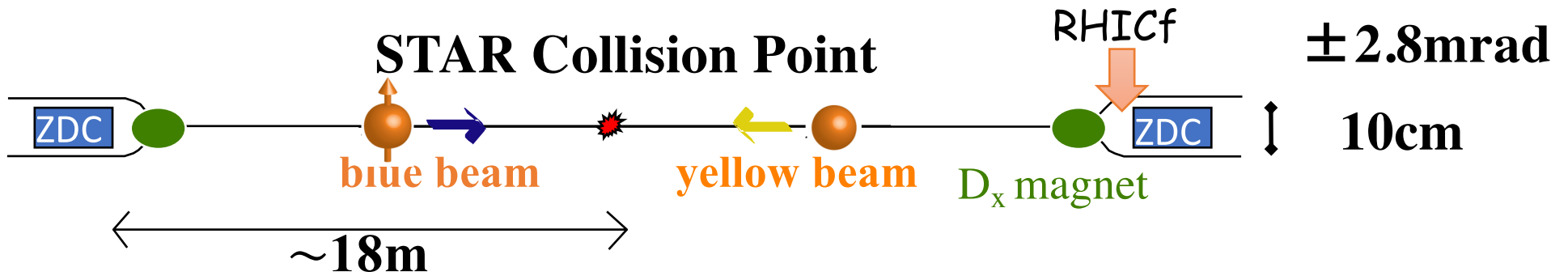
$5.1\lambda_T$   $149X_0$  (3 ZDCs),  
 $\delta E/E \sim 20\%$  @ 100GeV

# RHICf実験@STAR (2017)

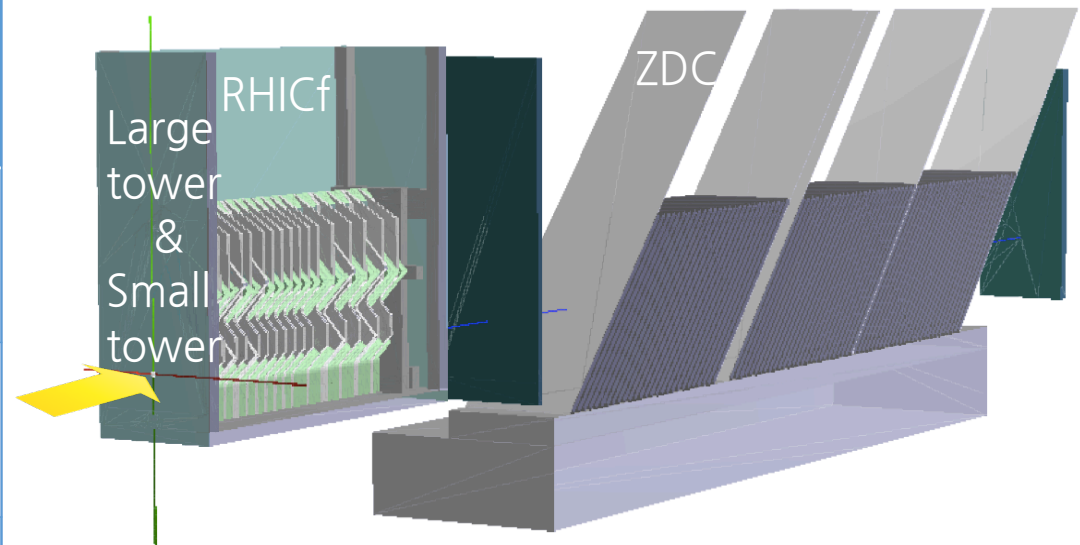
- 中性子
- $\pi^0$
- ZDCにEMカロリメータを追加し高度化



# RHICf 実験(2017)



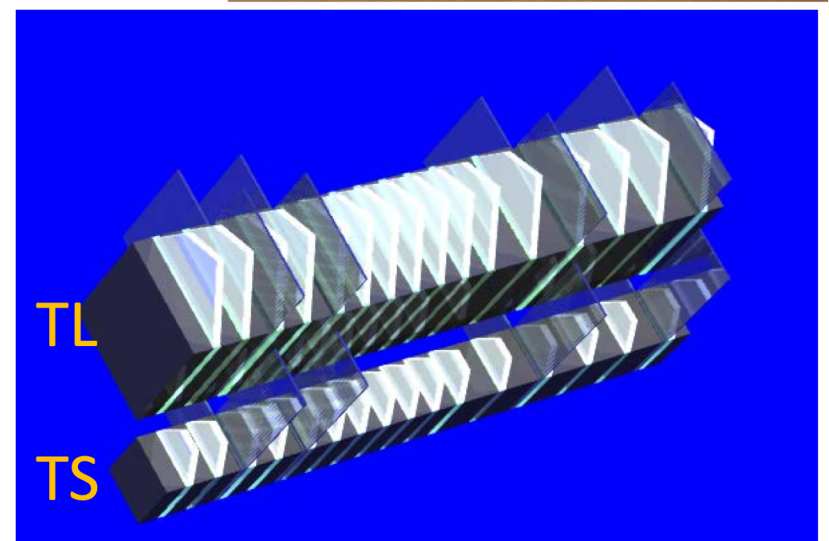
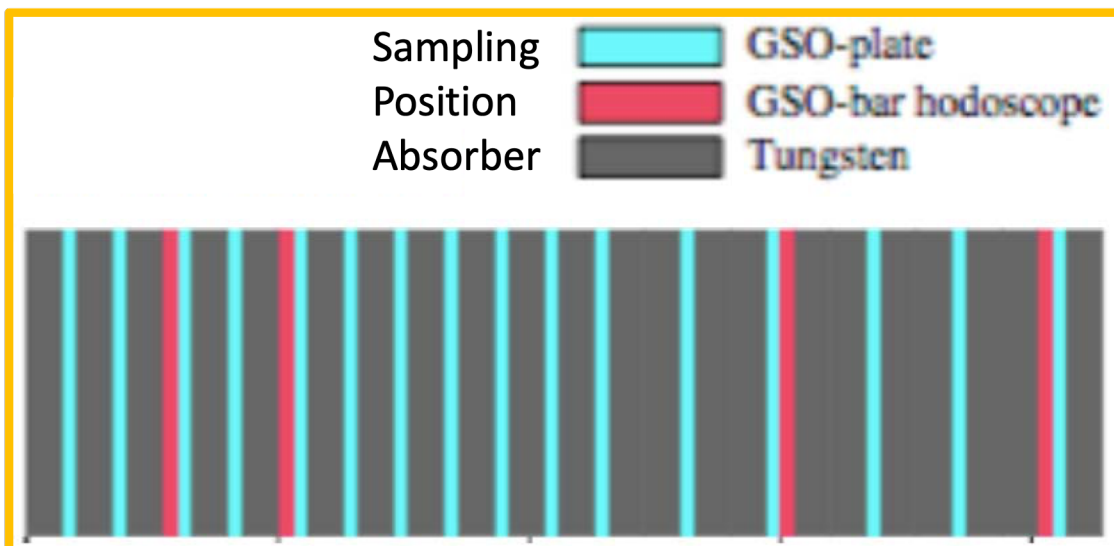
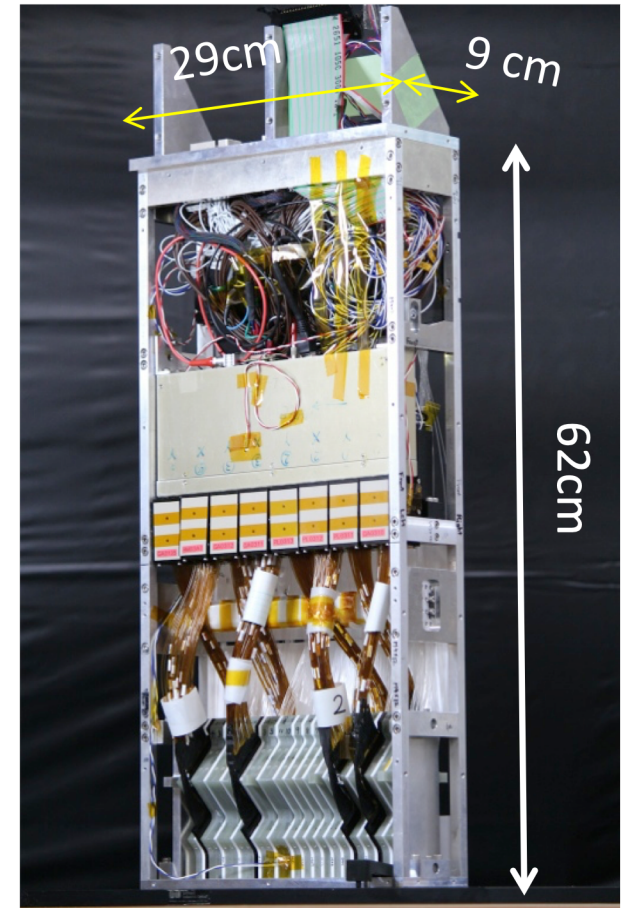
RHICf	ZDC+SMD
Sampling ( $\lambda_I=1.7$ )	Total Absorption ( $\lambda_I=5.1$ )
$S=4\text{cm} \times 4\text{cm}$ + $2\text{cm} \times 2\text{cm}$	$S=10\text{cm} \times 10\text{cm}$
$\Delta E_n \sim 35\%$	$\Delta E_n \sim 18\%$
$\Delta x_n \sim 0.1\text{cm}$	$\Delta x_n \sim 1\text{cm}$



Installed new sampling calorimeter RHICf in front of existing neutron calorimeter, ZDC.

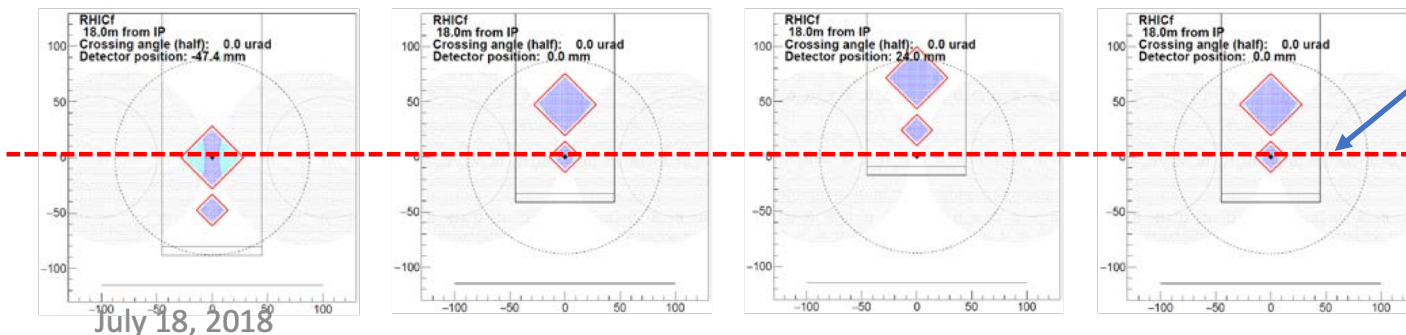
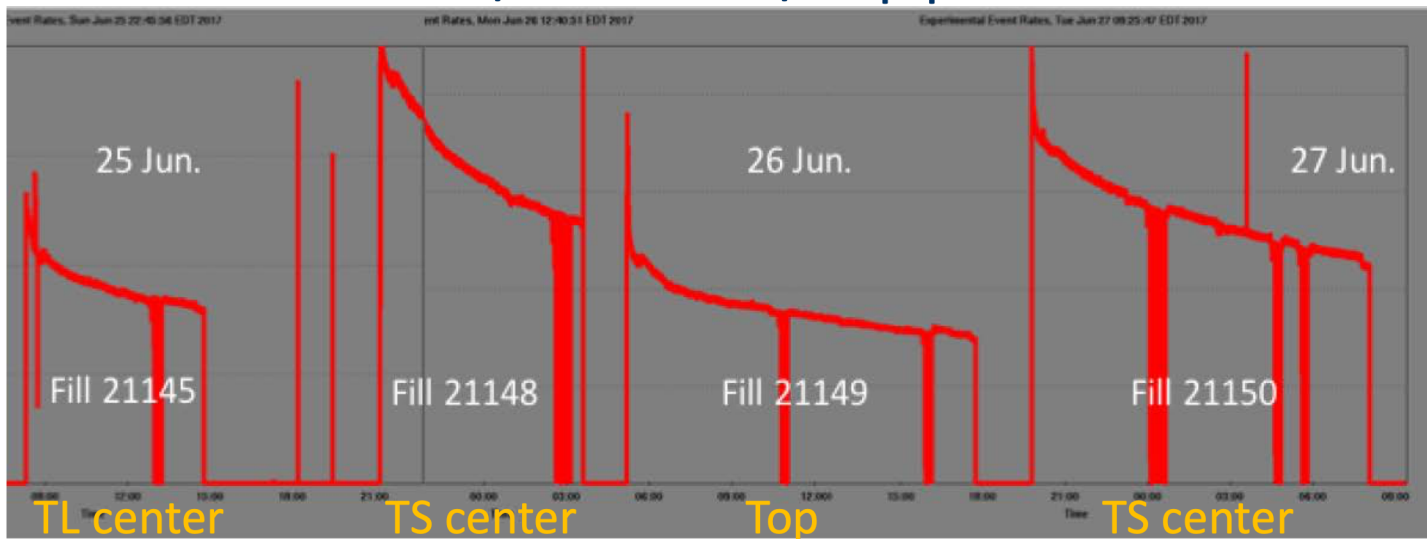
# ***RHICf detector***

- Two position-sensitive sampling calorimeters
  - TS (small tower): 20mm x 20mm
  - TL (large tower): 40mm x 40mm
  - Tungsten absorber ( $44 X_0$ ,  $1.6 \lambda_{\text{int}}$ )
  - 16 GSO sampling layers
  - 4 XY pairs of GSO-bar position layers (MAPMT readout)



# 2017 operation

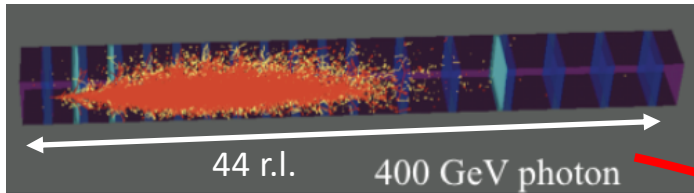
- June 23 commissioning of polarized proton collisions, detector installation at the final position, detector commissioning
- June 24 – 27 physics data acquisition
  - 27.7hours, ~110M events
- 3 detector positions
  - TL center / TS center / Top position



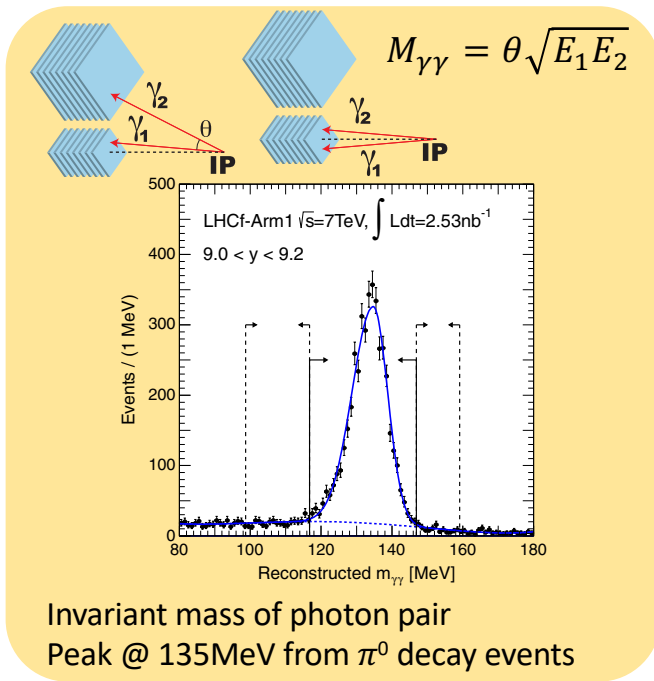
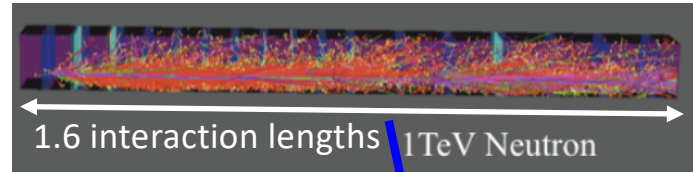
Beam Pipe  
Beam Center

# PID

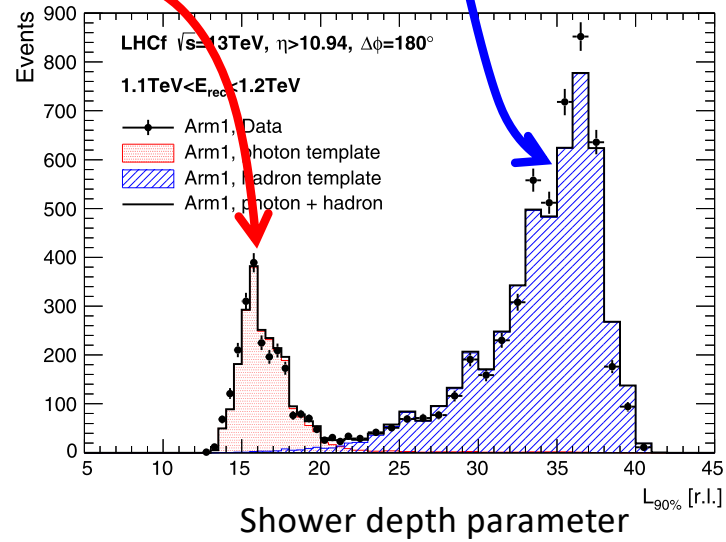
## Photon event



## Neutron event



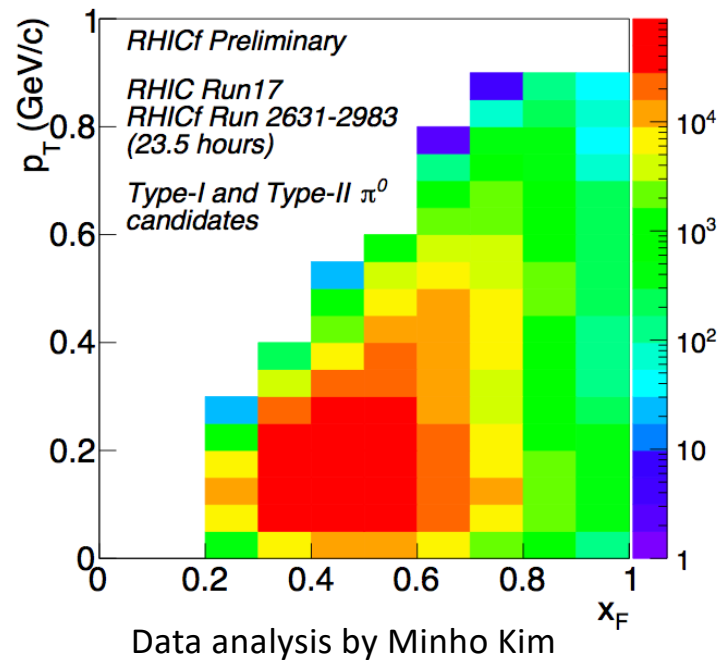
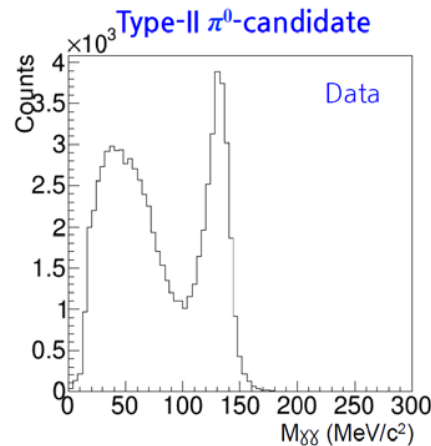
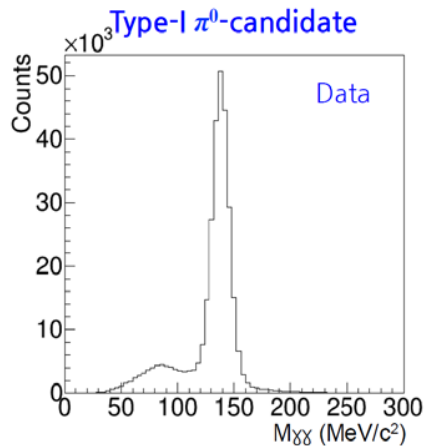
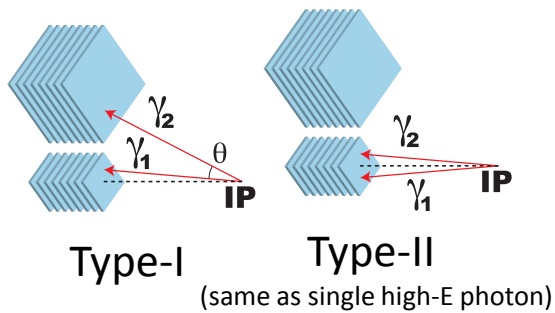
(Adriani et al., PRD, 2012)



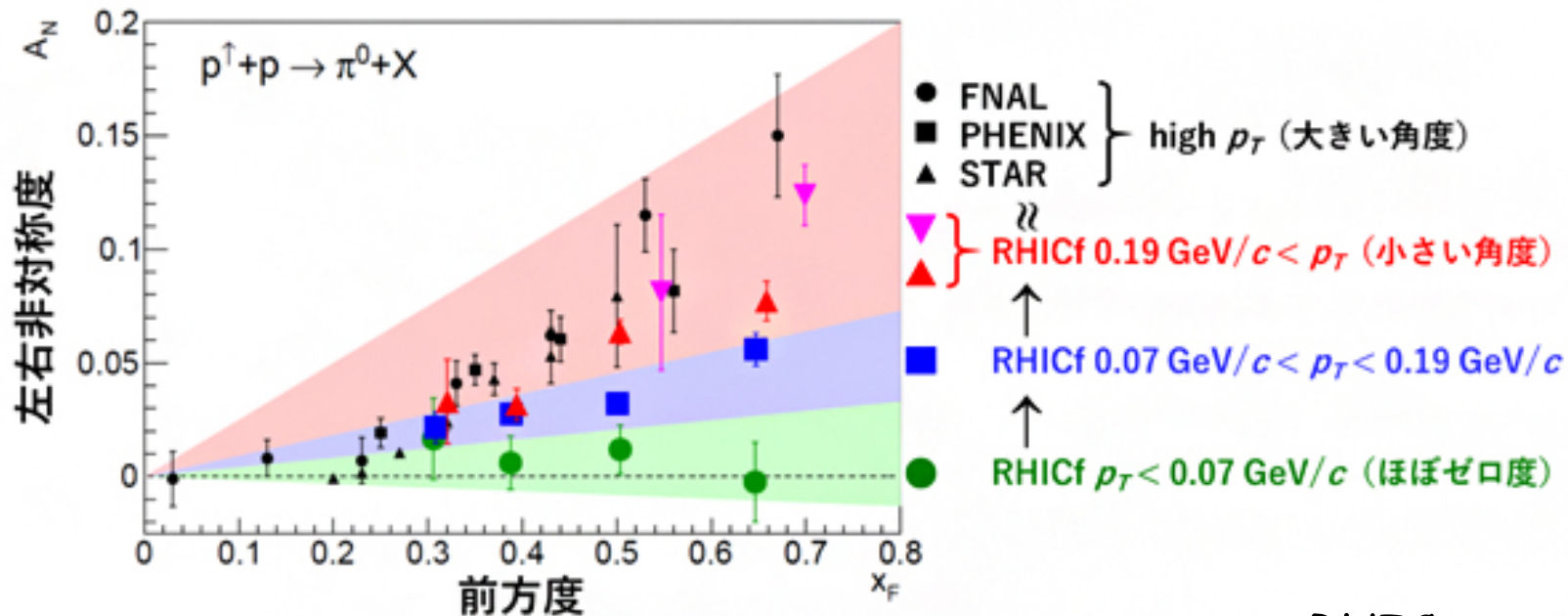
(Adriani et al., PLB, 2018)

# $\pi^0$ Performance

- $\pi^0$  peak with  $\sim 10 \text{ MeV}/c^2$  width
  - $3\sigma$  region selected as  $\pi^0$  candidates
- $p_T < 1.0 \text{ GeV}/c$
- $0.2 < x_F < 1.0$



# 観測した左右非対称性

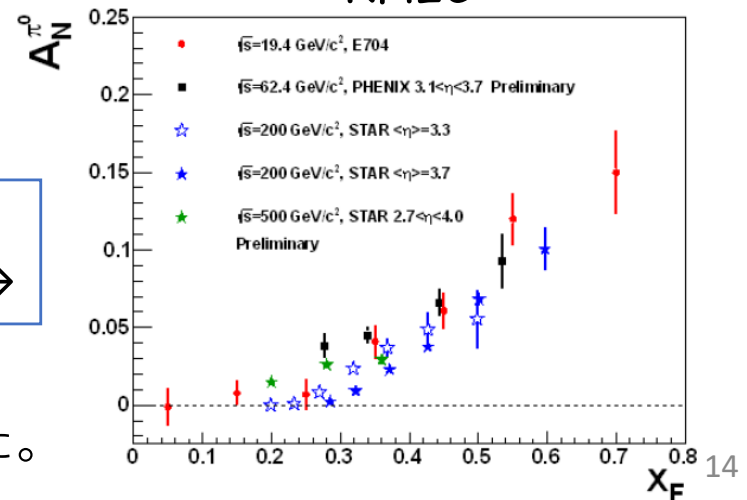


↑核子-メソン自由度が寄与すると考えられる運動学

パートンの軌道角運動量やスピンの非対称性に寄与すると考えられる運動学→

似たような非対称性が観測された。

## RHIC



2020年6月23日

理化学研究所  
東京大学宇宙線研究所  
名古屋大学  
日本原子力研究開発機構

← 前の記事 | 一覧へ戻る | 次の記事

## 陽子衝突からの左右非対称な $\pi$ 中間子生成

— 粒子生成の起源に迫る新たな発見 —

英語ページ

理化学研究所 (理研) 仁科加速器科学センター放射線研究室の後藤雄二主任研究員、キム・ミンホ国際プログラム・アソシエイト (研究当時)、東京大学宇宙線研究所のさこ隆志准教授、名古屋大学宇宙地球環境研究所・素粒子宇宙起源研究所の伊藤好孝教授、日本原子力研究開発機構先端基礎研究センターの谷田聖研究主幹らが参画する国際共同研究グループは、米国ブルックヘブン国立研究所 (BNL) の偏極陽子衝突型加速器「RHIC (リック)」<sup>[1]</sup> を使って、反対方向に運動する陽子同士の衝突により、衝突位置の超前方<sup>[2]</sup>に生成される「中性  $\pi$  (パイ) 中間子<sup>[3]</sup>」が大きな左右非対称度を持つことを発見しました。

陽子には、地球の自転に似た「スピン」と呼ばれる向きを表す性質があります。スピンの向きは人為的にそろえることができ、これを「偏極」と呼びます。偏極した陽子を何かの粒子に衝突させると、生成される  $\pi$  中間子の生成量が偏極陽子の衝突の軸方向に対して、元の陽子のスピンの向きの左側と右側で非対称になることが知られており、その起源として、クォーク<sup>[4]</sup>やグルーオン<sup>[5]</sup>の直接散乱に基づく理論「摂動QCD<sup>[6]</sup>」で説明されてきました。陽子衝突での粒子生成に対する理論・計算の構築は積年の研究課題であり、高エネルギーの宇宙線が大気中で起こす「空気シャワー<sup>[7]</sup>」の理解のためにも、その発展が望まれています。



Open Access

## Transverse Single-Spin Asymmetry for Very Forward Neutral Pion Production in Polarized $p + p$ Collisions at $\sqrt{s} = 510$ GeV

M. H. Kim, O. Adriani, E. Berti, L. Bonechi, R. D'Alessandro, Y. Goto, B. Hong, Y. Itow, K. Kasahara, J. H. Lee, T. Ljubicic, Y. Makino, H. Menjo, I. Nakagawa, A. Ogawa, J. S. Park, T. Sako, N. Sakurai, K. Sato, R. Seidl, K. Tanida, S. Torii, A. Tricomi, M. Ueno, and Q. D. Zhou (RHICf Collaboration)  
Phys. Rev. Lett. **124**, 252501 – Published 22 June 2020



Article | References | No Citing Articles | PDF | HTML | Export Citation



### ABSTRACT

Transverse single-spin asymmetries of very forward neutral pions generated in polarized  $p + p$  collisions allow us to understand the production mechanism in terms of perturbative and nonperturbative strong interactions. During 2017, the RHICf Collaboration installed an electromagnetic calorimeter in the zero-degree region of the STAR detector at the Relativistic Heavy Ion Collider (RHIC) and measured neutral pions produced at pseudorapidity larger than 6 in polarized  $p + p$  collisions at  $\sqrt{s} = 510$  GeV. The large nonzero asymmetries increasing both in longitudinal momentum fraction  $x_F$

Issue  
Vol. 124, Iss. 25 — 26 June 2020



# RHICf-II実験計画(2024)

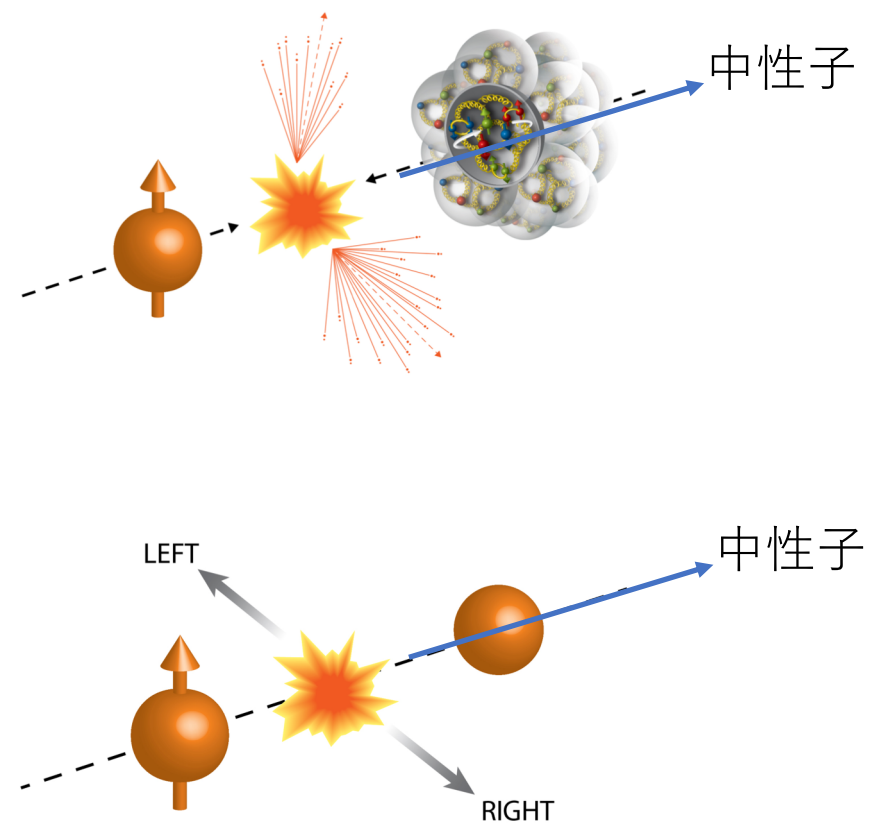
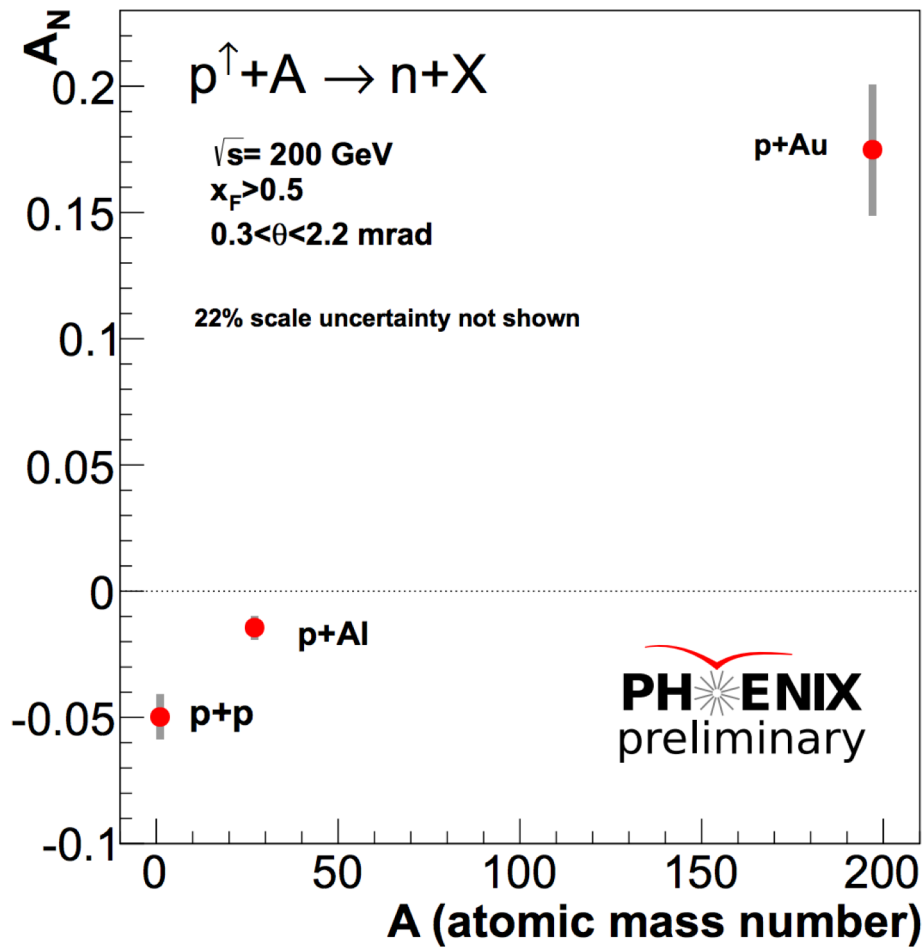
- 大立体角化
- $p^\uparrow + A$

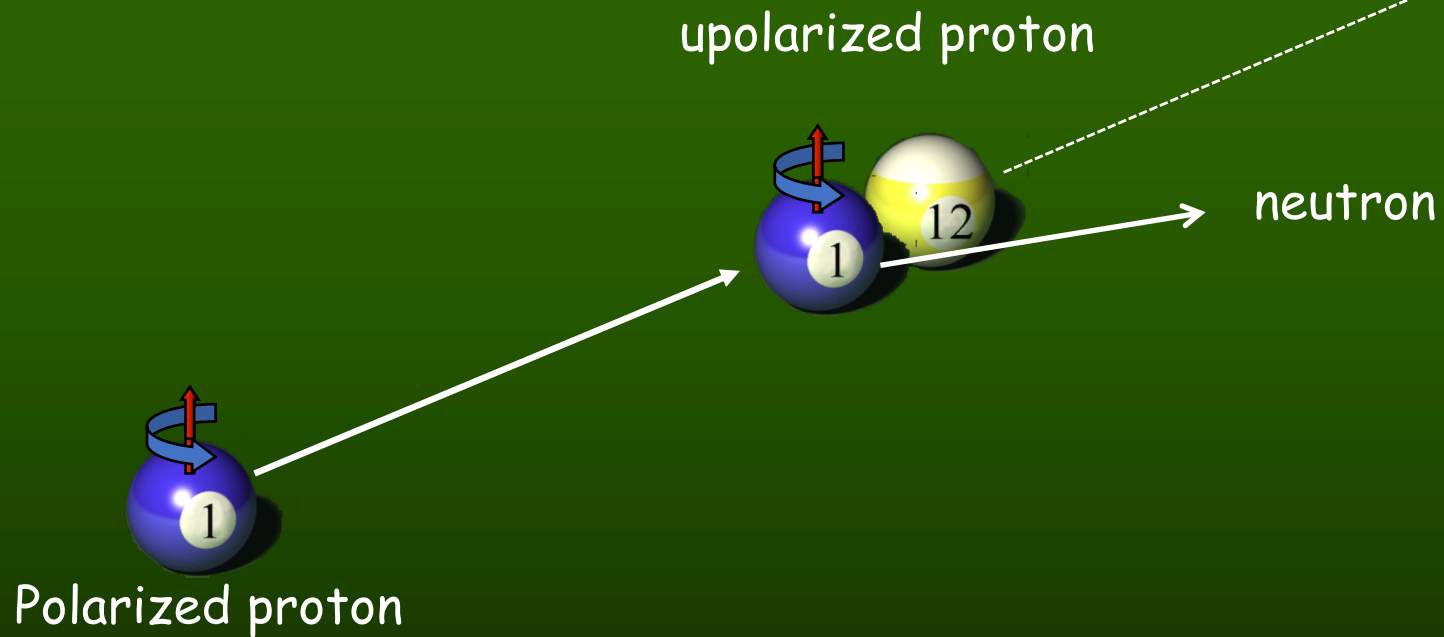
Year	Species	Energy [GeV]	Wks	Rec. L	Samp. L	Samp. L (all-z)	
2023	Year-1	Au+Au	200	16.0	7 nb <sup>-1</sup>	8.7 nb <sup>-1</sup>	34 nb <sup>-1</sup>
2024	Year-2	$p+p$	200	11.5	—	48 pb <sup>-1</sup>	267 pb <sup>-1</sup>
		$p+Au$	200	11.5	—	0.33 pb <sup>-1</sup>	1.46 pb <sup>-1</sup>
	Year-3	Au+Au	200	23.5	14 nb <sup>-1</sup>	26 nb <sup>-1</sup>	88 nb <sup>-1</sup>
	Year-4	$p+p$	200	23.5	—	149 pb <sup>-1</sup>	783 pb <sup>-1</sup>
	Year-5	Au+Au	200	23.5	14 nb <sup>-1</sup>	48 nb <sup>-1</sup>	92 nb <sup>-1</sup>

If extended

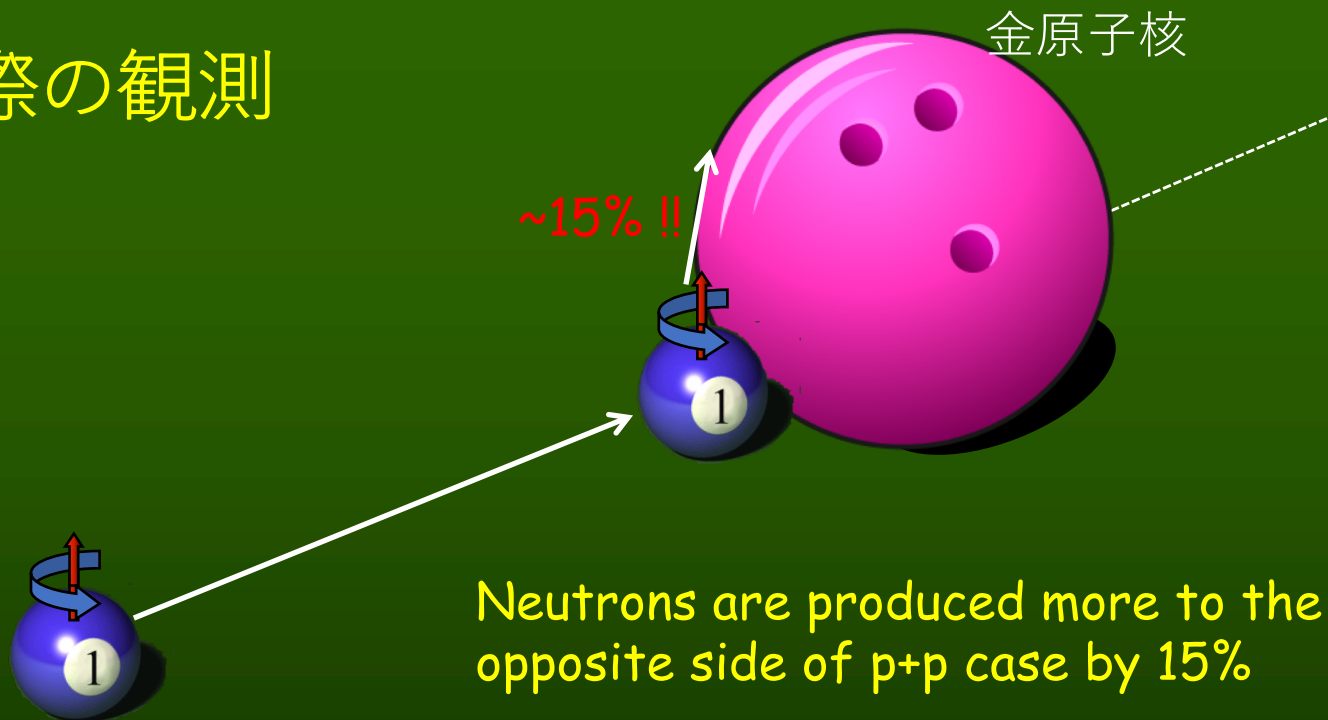


# 偏極陽子 + 原子核衝突

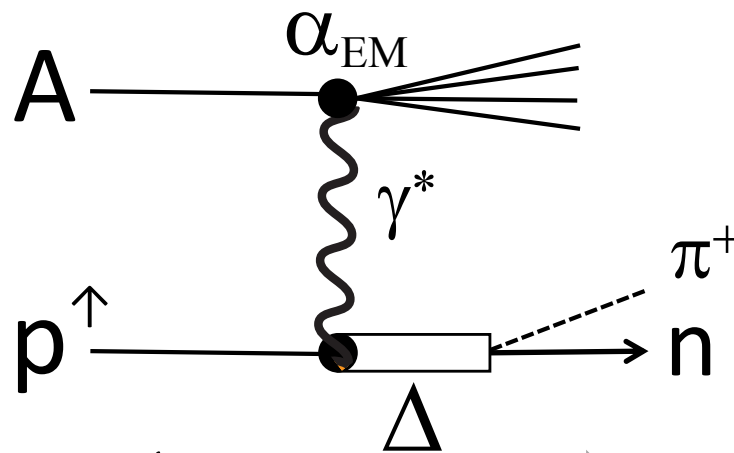
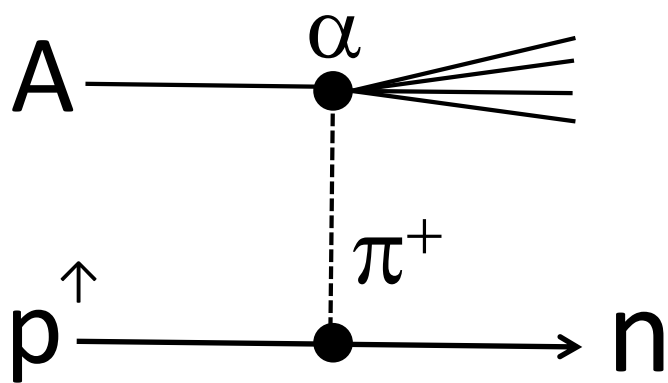
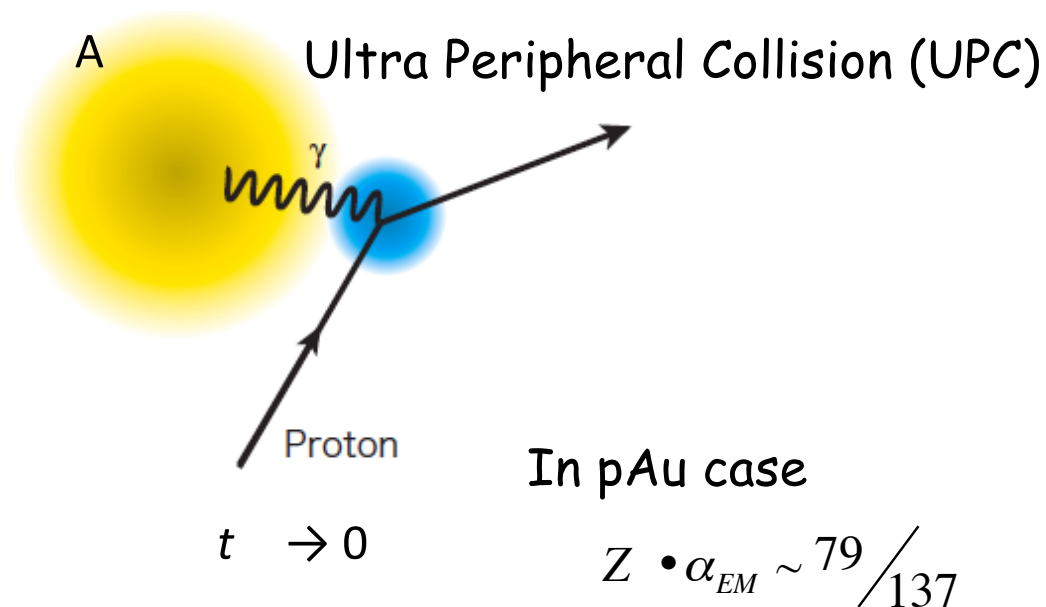
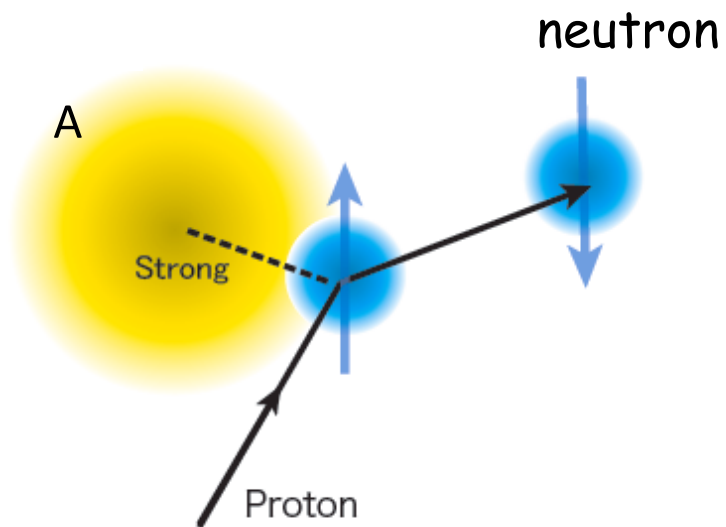




## 実際の観測



# EM 効果



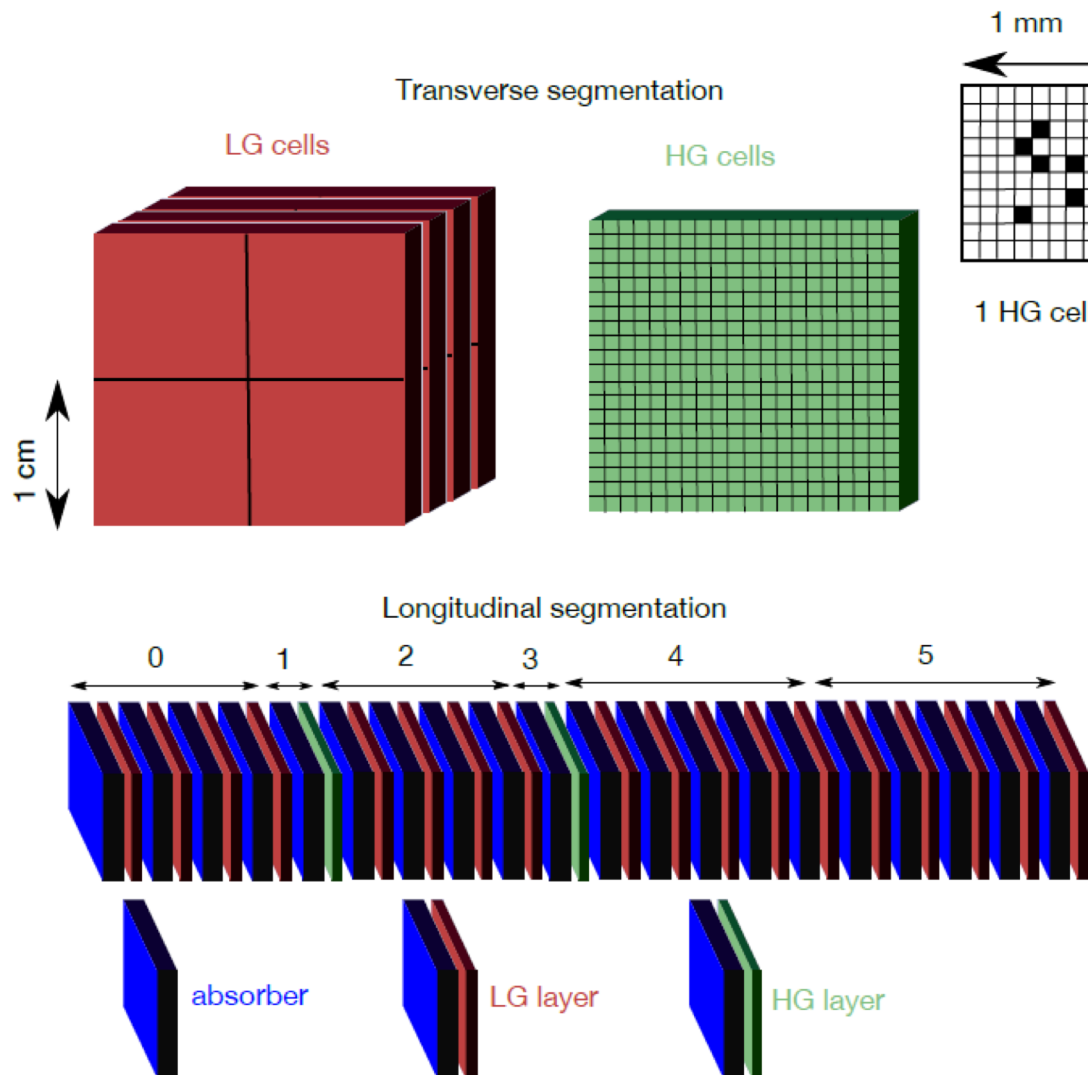
small ← Impact Parameter  $b$  → large<sup>19</sup>



# ALICE-FoCal



## FoCal-E basic design



The design of the detector:

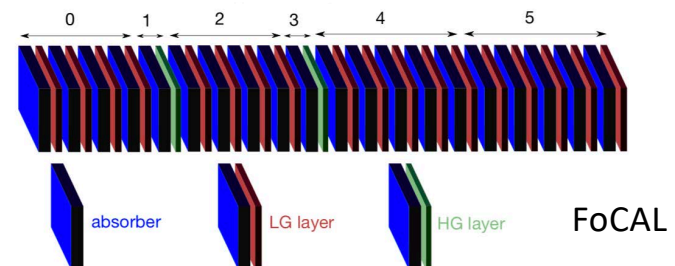
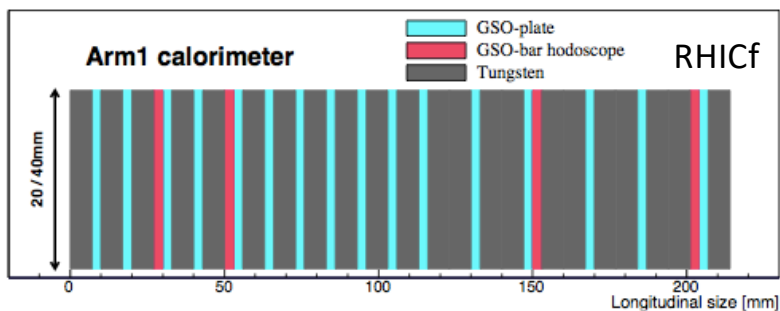
- 20 layers: W ( $3.5\text{mm} \approx 1 X_0$ ) + Si-sensors (2 types):
  - **low granularity (LG), Si-pads**
  - **high granularity (HG), pixels (e.g. CMOS-MAPS)**
- Moliere radius  $\sim 1\text{-}2\text{ cm}$

	LG	HG
pixel/pad size	$\approx 1\text{ cm}^2$	$\approx 30 \times 30\ \mu\text{m}^2$
total # of pixels/pads	$\approx 2.5 \times 10^5$	$\approx 2.5 \times 10^9$

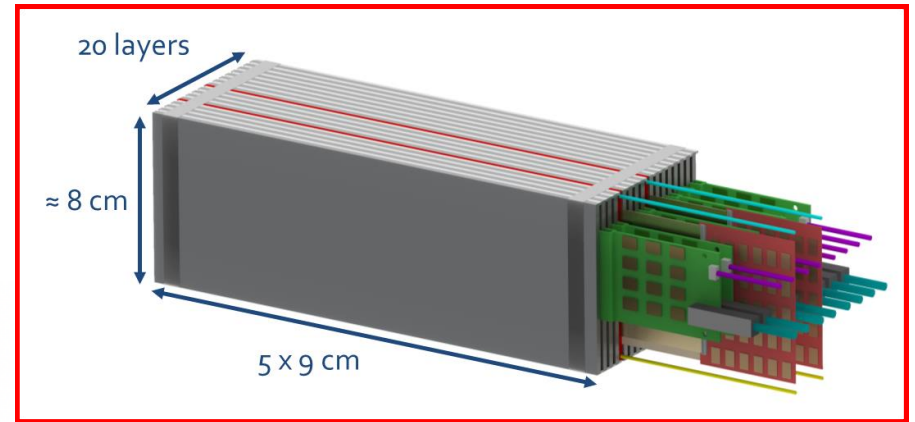
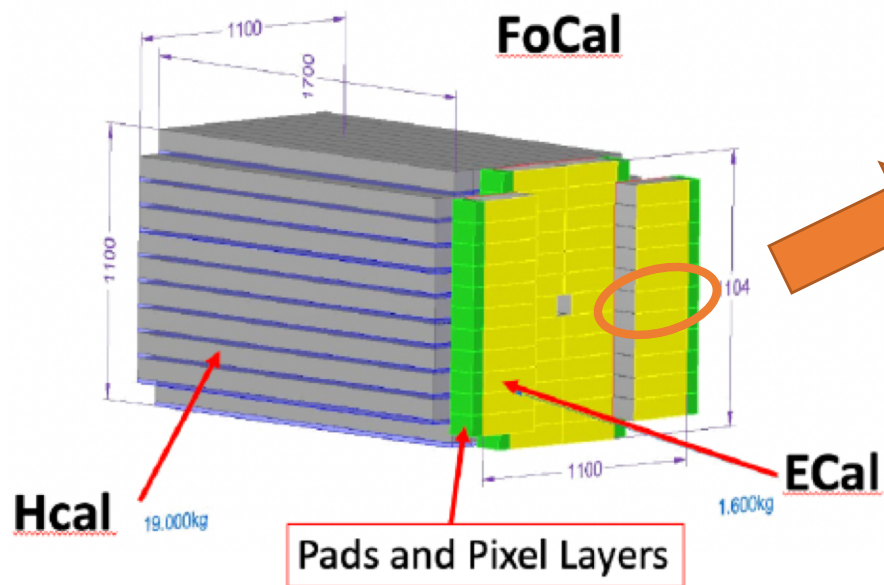
The **surface** area of the detector will be about  $1\text{ m}^2$

# RHICf vs FoCAL Performance

	RHICf	FoCAL Prototype
Acceptance	4cm x 4cm + 2cm x 2cm	8cm x 9cm x 2 units
Radiation Length	$44X_0$	$20X_0$
Interaction Length	$1.6 \lambda_{\text{int}}$	$\sim 0.8 \lambda_{\text{int}} ?$
Position Layer Resolution	$100 \mu\text{m}$	$\sim 10 \mu\text{m} ?$
Energy Resolution	$< 3\%$	3.6%
Position Detector	GSO-bar	MAPS(Under development)



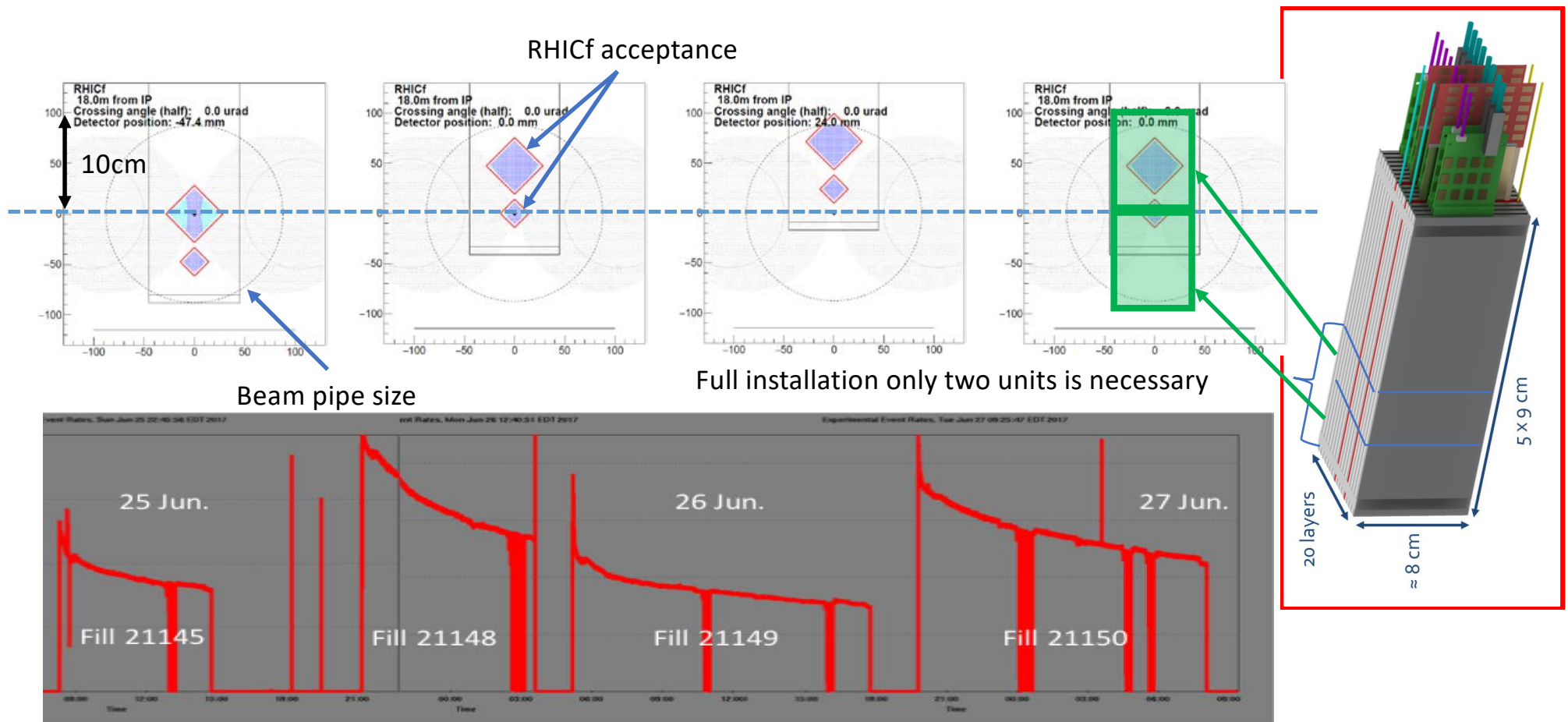
# RHICf-II 検出器



ALICE-FoCalのモジュールのコピーを  
RHICf-II検出器として理研で製作。

HCal: ~2K channels

# RHICfとRHICf-IIの立体角比較

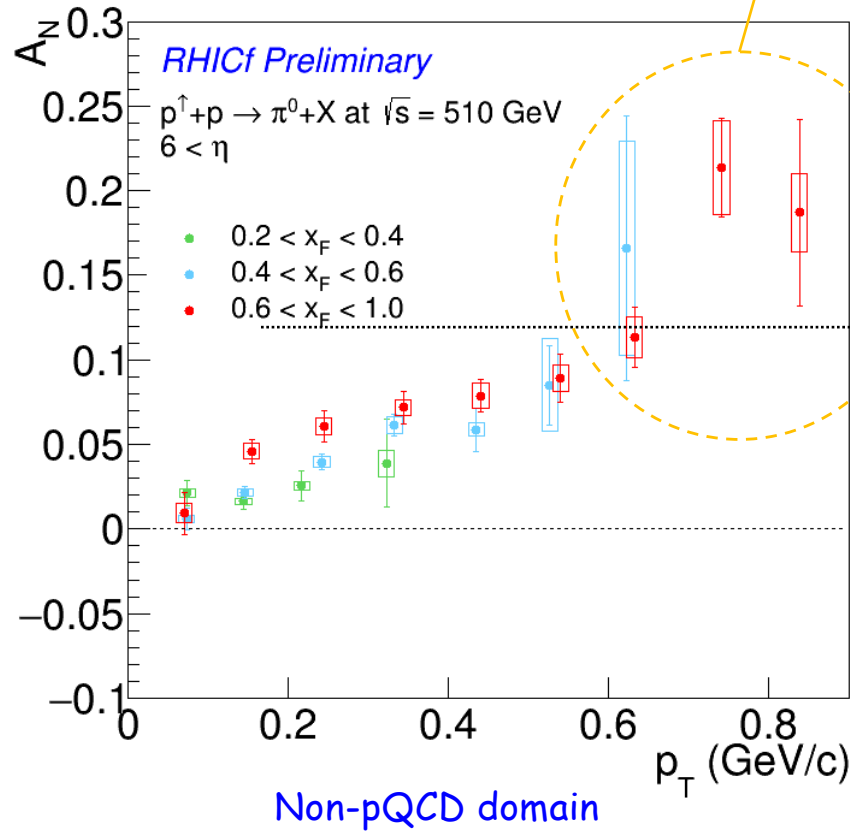


→ Series of dedicated position measurement becomes one shot measurement!

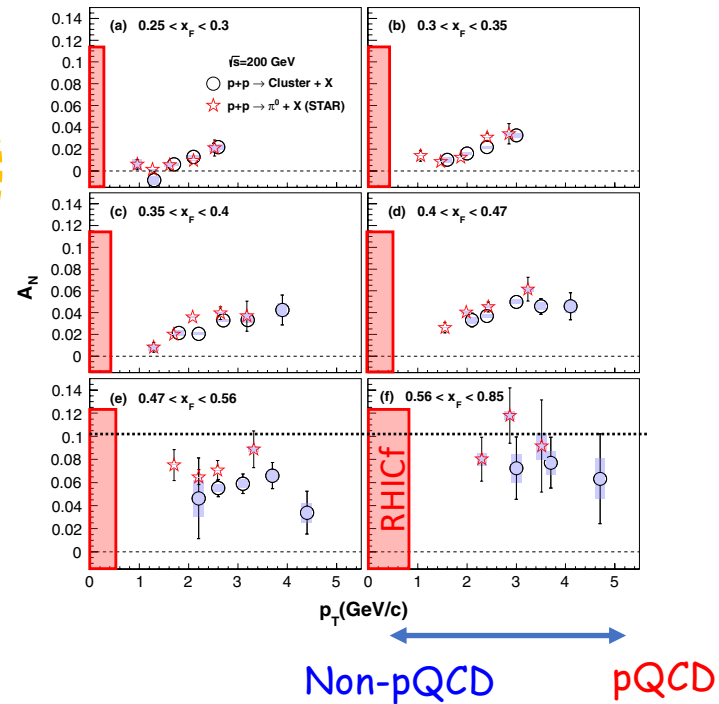


# $\pi^0$ Asymmetry Preliminary Results

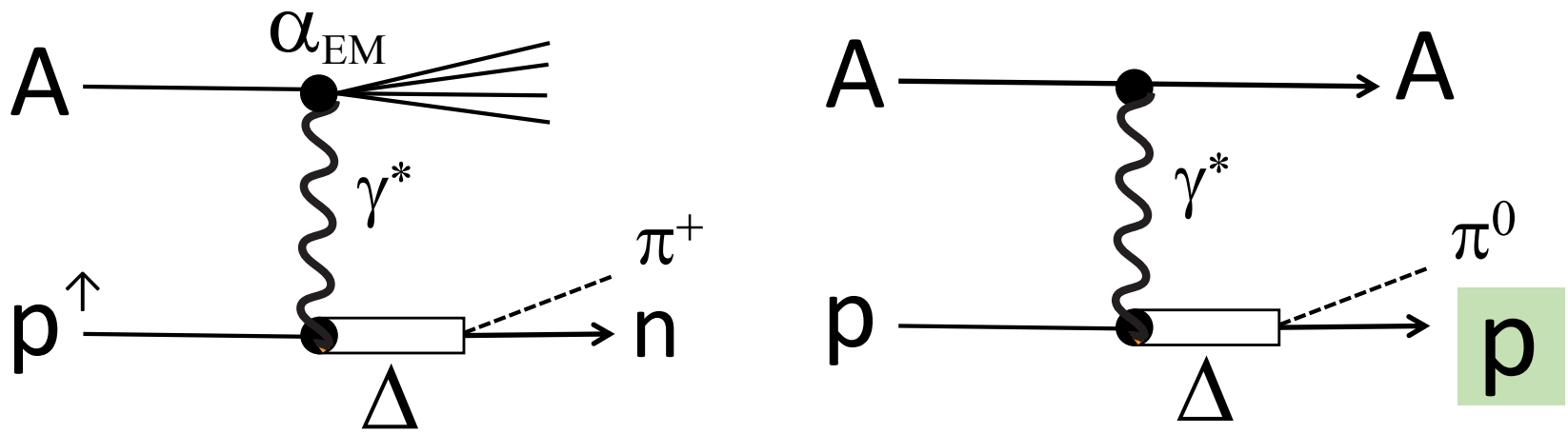
統計精度の改善



Phys. Rev. D 90, 012006



# $p^\uparrow + A$ 中性子と $\pi^0$ 非対称性



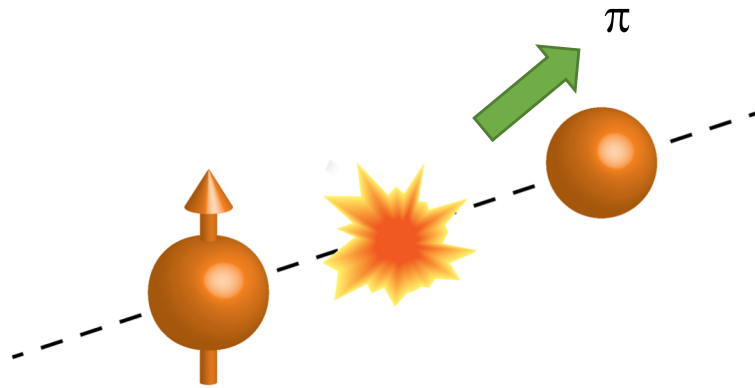
核子励起の  $\pi^0/\pi^+$  崩壊チャンネルの違いを見ることになる？

# まとめ

- スピン物理には偏極度陽子 + 陽子・原子核衝突で0度方向のハドロン生成に巨大な非対称性が出る
- またそのメカニズムはよくわかっておらず、魅力的なテーマ
- RHICfで位置分解能の高いEMカロリメータを稼働させることで、中性子に加え $\pi^0$ にも大きな非対称性があることがわかった。
- この現象をEICで見るとどう見えるのか？

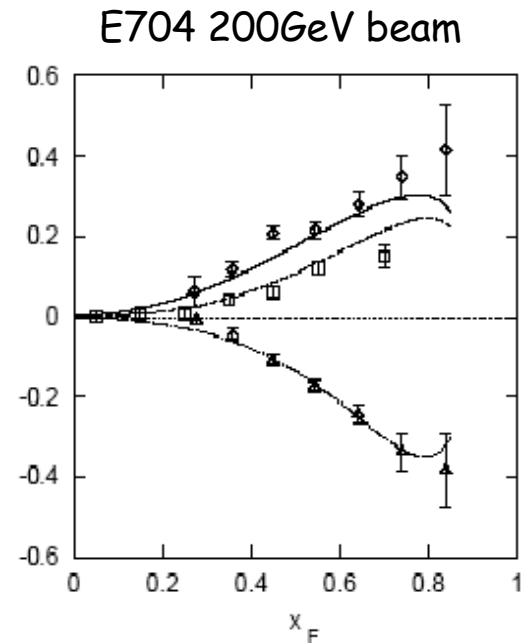
# Backup

# E704~代表的な実験



偏極能  $A_N$

$$A_N = \frac{1}{P} \frac{\sigma_L^\pi - \sigma_R^\pi}{\sigma_L^\pi + \sigma_R^\pi}$$



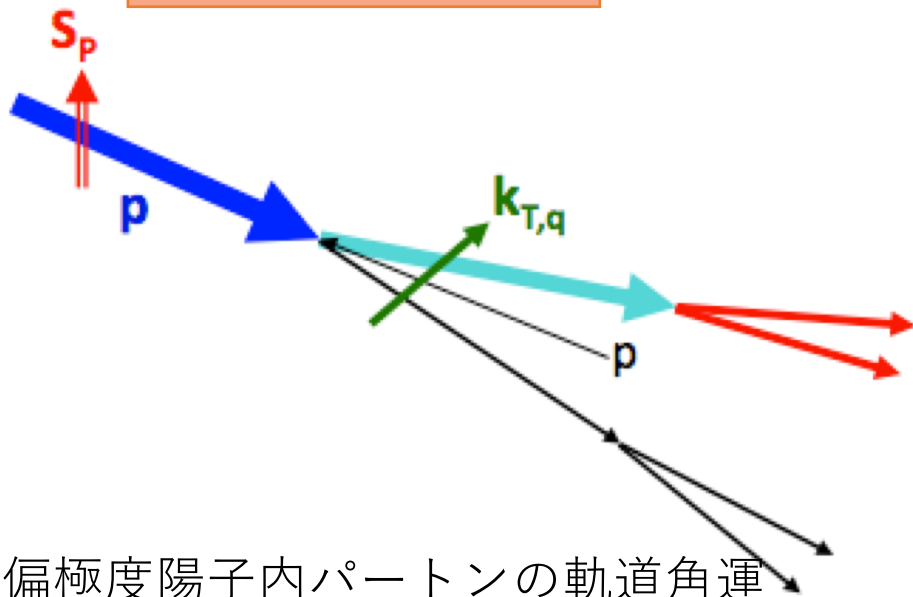
PLB261, 201 (1991)

PLB264, 462 (1991)

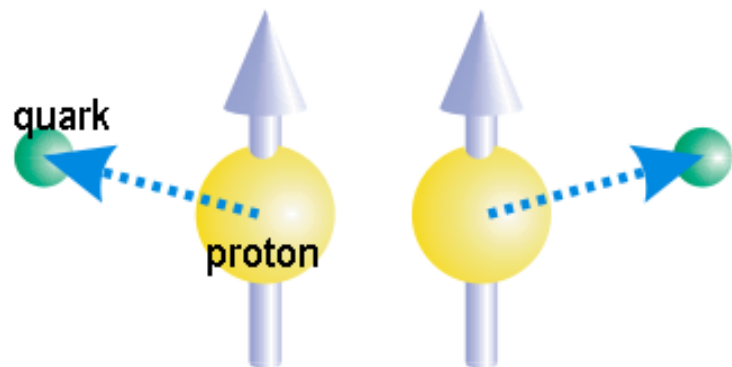
< 40%の大きな非対称性が観測された

# Initial State Effect

## Sivers Mechanism

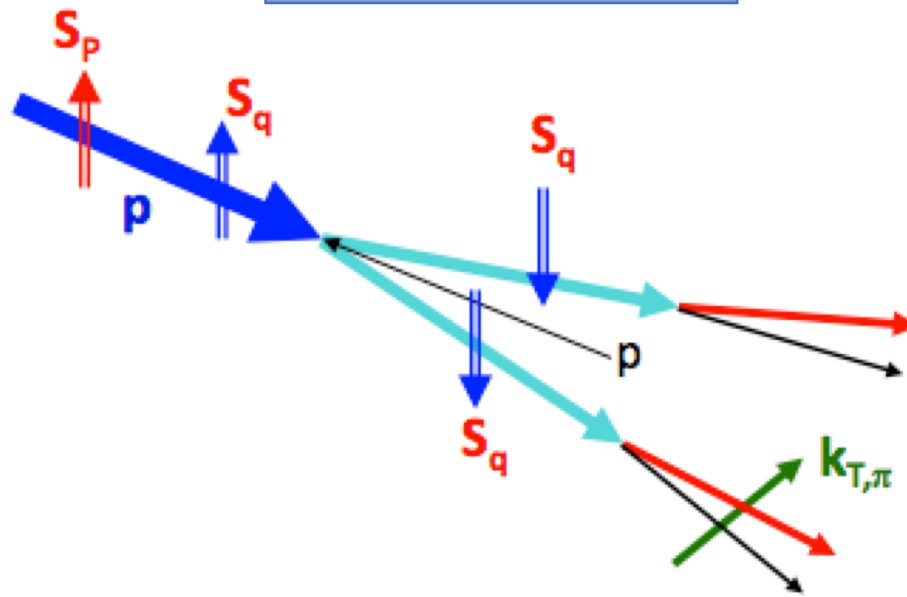


偏極度陽子内パートンの軌道角運動量が非対称を産む

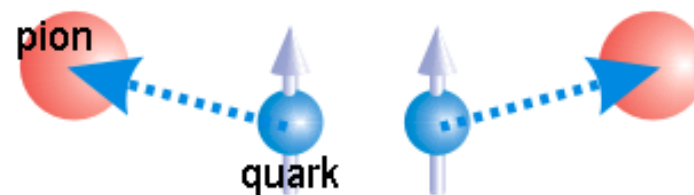


# Final State Effect

## Collins Mechanism

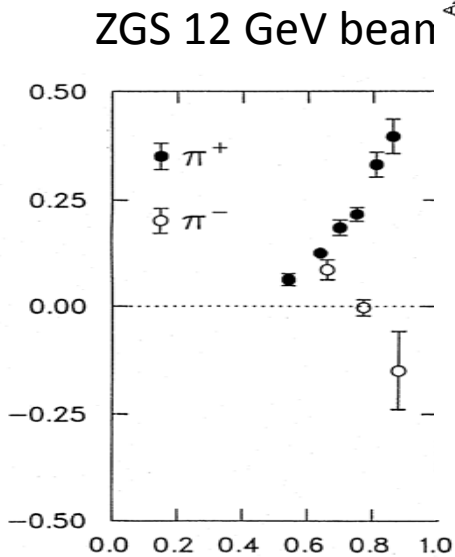


陽子内の偏極パルトンスピンのハドロン化の際に非対称を産む

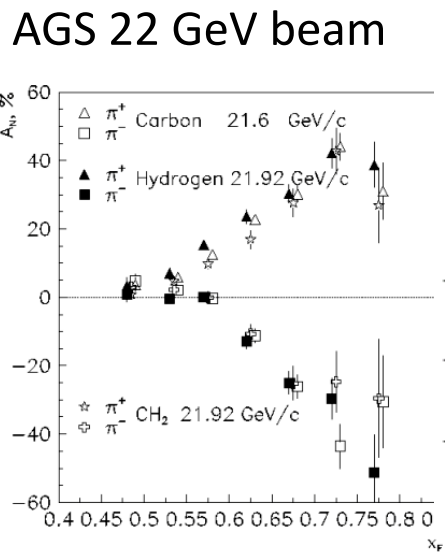


+ 高次ツイスト効果

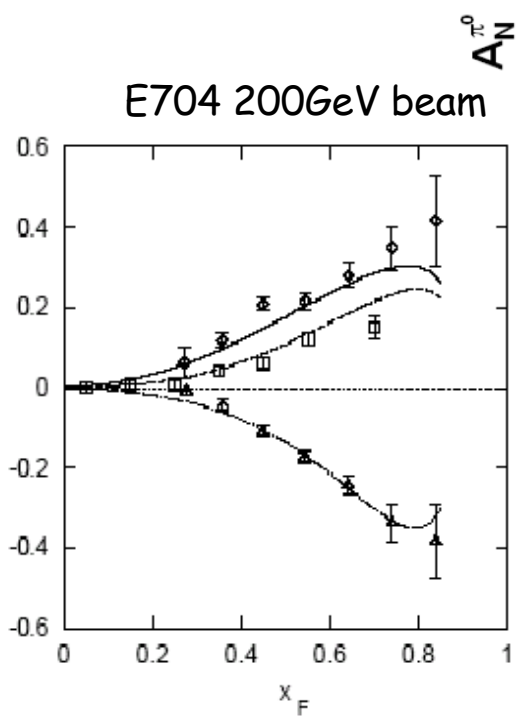
# $A_N$ のエネルギー一依存性



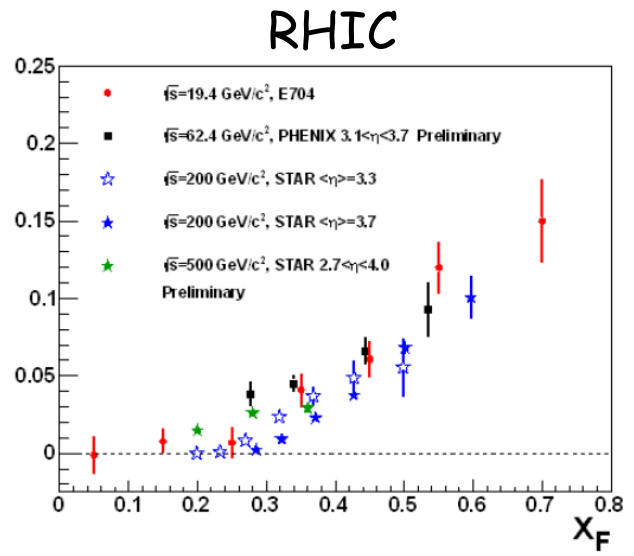
PRL36, 929 (1976)



PRD65, 092008 (2002)



PLB261, 201 (1991)  
PLB264, 462 (1991)



Asymmetry still persists even in high energy!

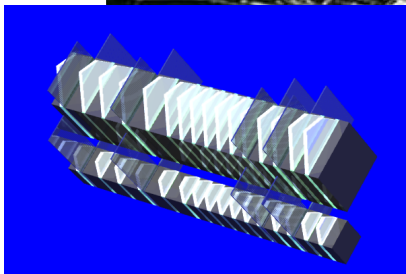
左右非対称性はエネルギーが低くても観測される。  
非摂動的QCD効果でも非対称を産むメカニズムがあるのでは？

Non-perturbative

Perturbative



# LHC forward (LHCf) Experiment



LHCf detector

## LHC ATLAS

