Experimental design for future hypernuclear experiment at JLab based on Monte Carlo simulation

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Contents

- Geant4 simulation for the next JLab Hypernuclear experiments
  - **SPL**+**HKS**+**HES** / **PCS**+**HKS**+**HES**

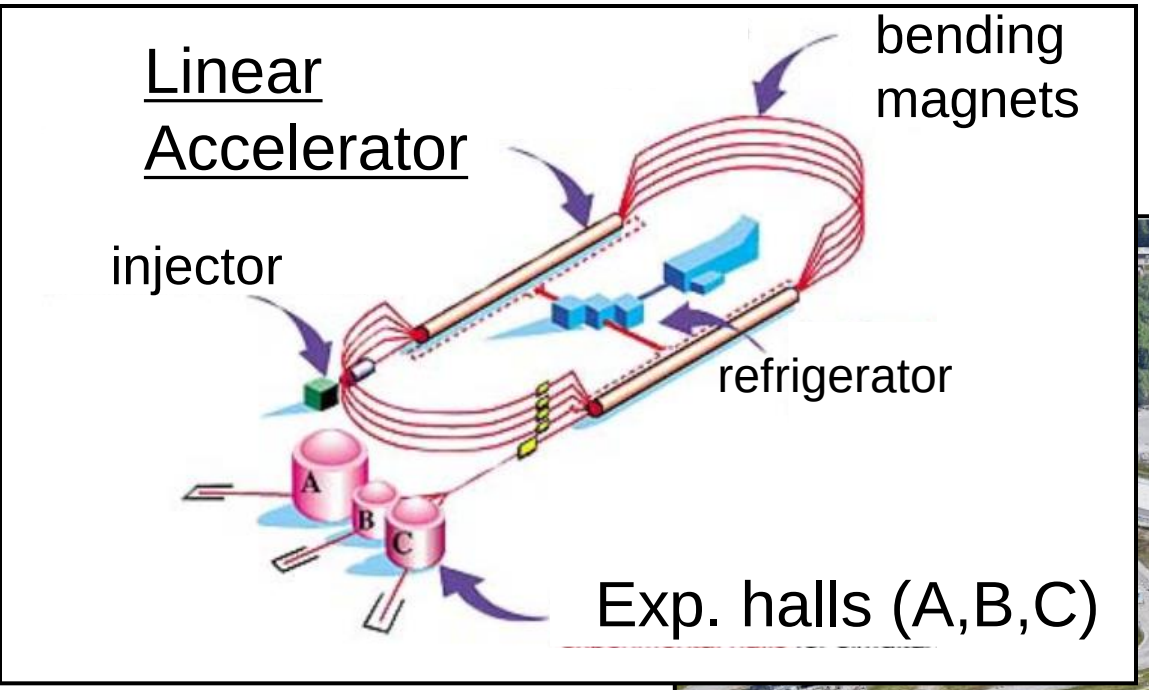
    E05-115: our latest experiment at JLab Hall-C

    → **SPL** + **HKS**(horizontal) + **HES**(horizontal)

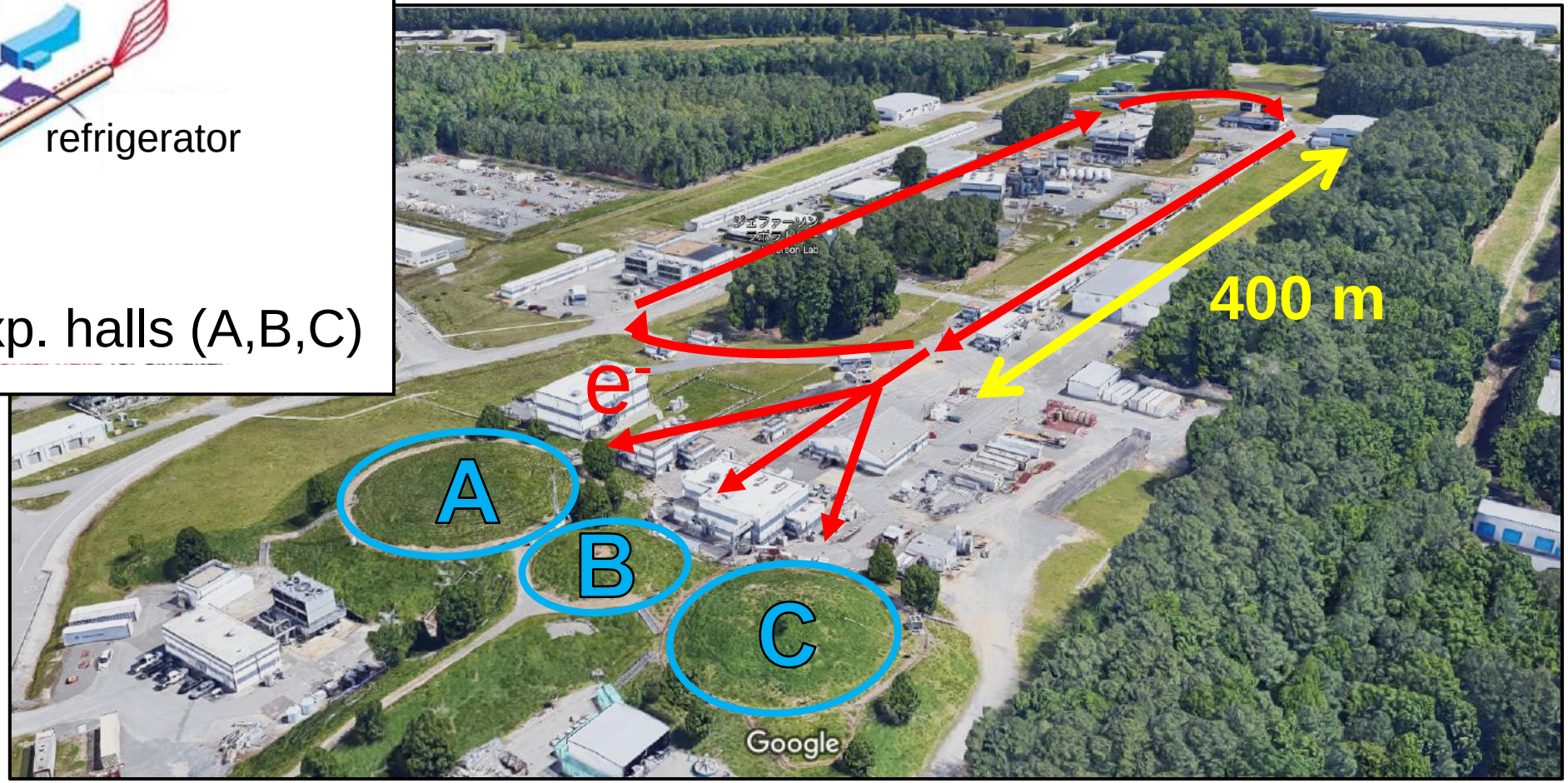
- Vertical bending spectrometer is essential to reconstruct Z-vertex
  - **HKS**: horizontal → vertical
  - **HES**: horizontal → vertical
    - Z-vertex Resolution
    - Momentum Resolution
    - Acceptance

Jefferson Lab

Jefferson Lab (JLab)



Continuous Electron Beam Accelerator Facility (CEBAF)



Campaign of our next experiments

1 PAC day = 2 days

Exp. No.	Beamtime [PAC days]	Target
E12-15-008 *approved*	28	CH_2, ^{6}Li, ^{7}Li, ^{9}Be, ^{10}B, ^{12}C, ^{27}Al, **^{40}Ca**, **^{48}Ca**
E12-20-013 *approved*	20	**^{208}Pb**
E12-19-002 *approved*	14.5	^{12}C, **H_2(gas)**, **$^{3,4}He$(gas)**, ^{27}Al(cell)

Physics Motivation [related talks in the past]:

$^{40,48}Ca(e,e'K^+)^{40,48}_{\Lambda}K$ → isospin dependence of ΛNN int. [JPS2021 Autumn, 15aV1-1, T. Akiyama]

$^{208}Pb(e,e'K^+)^{208}_{\Lambda}Tl$ → heavy hypernucleus [JPS2021 Autumn, 14aV1-1, Y.R. Nakamura]

$^{3,4}He(e,e'K^+)^{3,4}_{\Lambda}H$ → hypertriton puzzle, CSB [JPS2020 Autumn, 17aSJ-4, T. Gogami]

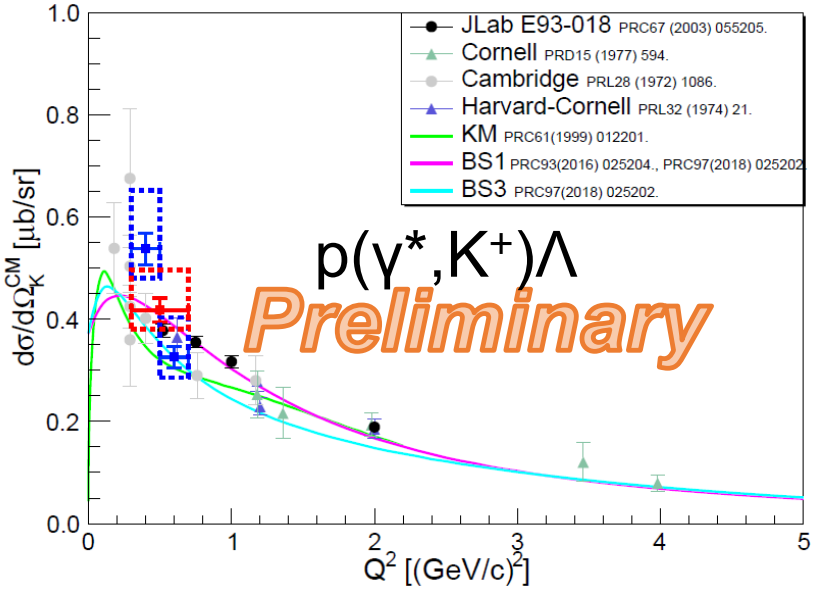
$^{27}Al(e,e'K^+)^{27}_{\Lambda}Mg$ → triaxial deformation [JPS2021 Autumn, 15aV1-2, K. Okuyama]

$p(e,e'K^+)\Lambda/\Sigma^0$ → elementary process [JPS2021 Annual, 12pU1-5, K. Okuyama]

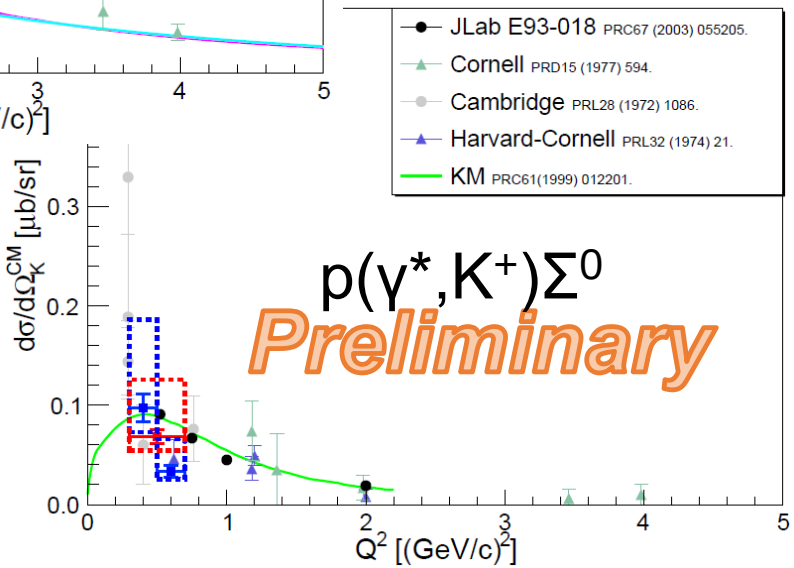
and more…

elementary process

$p(e,e'K^+)\Lambda/\Sigma^0$



E12-17-003 (2018)
θ_{γ^*K} ~ 0 (forward)
Q^2 ~ 0.5 (GeV/c)^2



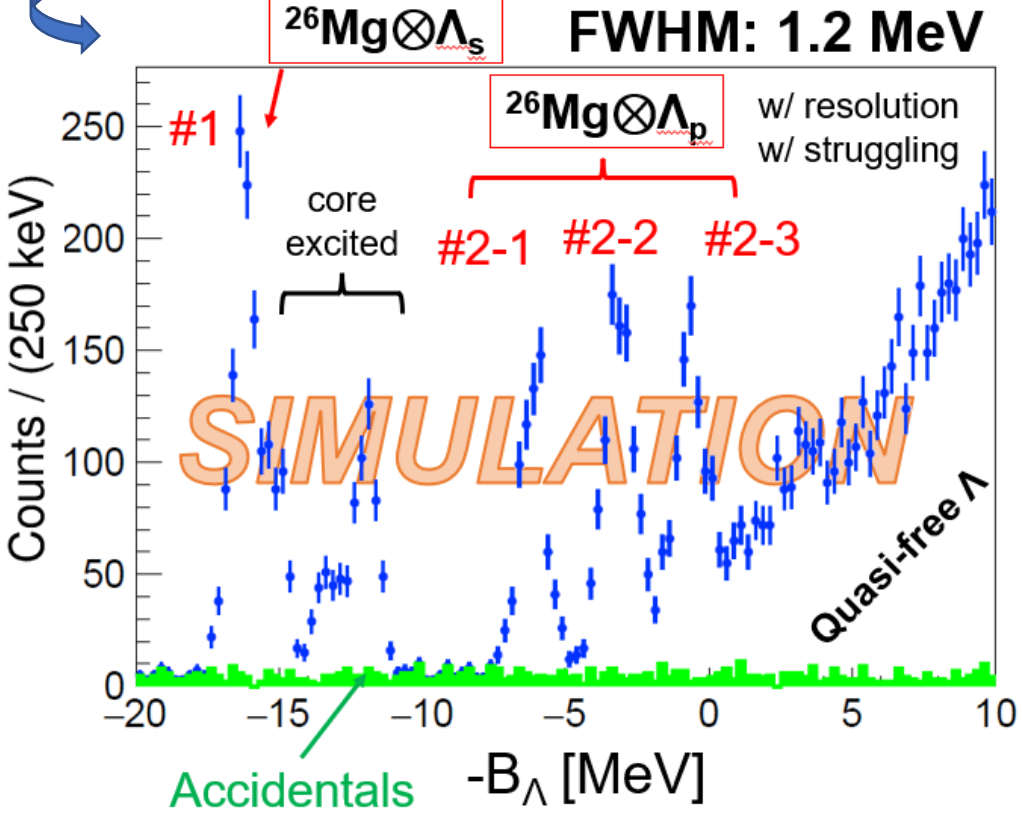
JPS2021 Autumn, 15aV1-2, K. Okuyama

triaxial deformation

$^{27}Al(e,e'K^+)^{27}{}_{\Lambda}Mg$

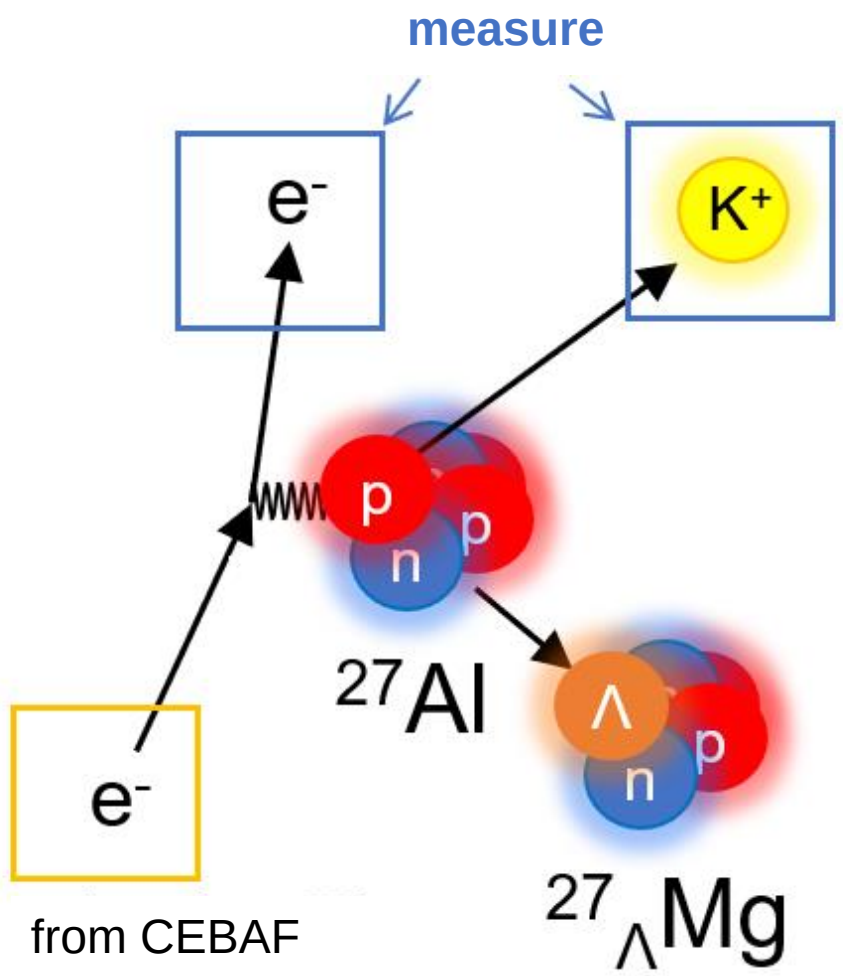
for the future experiments
(E12-15-008, E12-19-002)

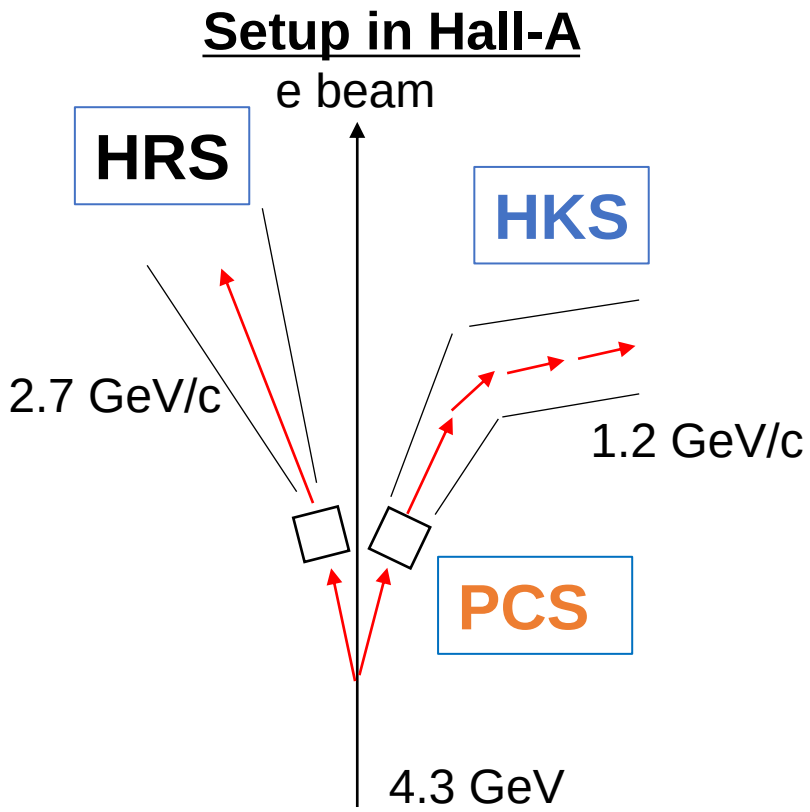
based on Isaka-san's calculation

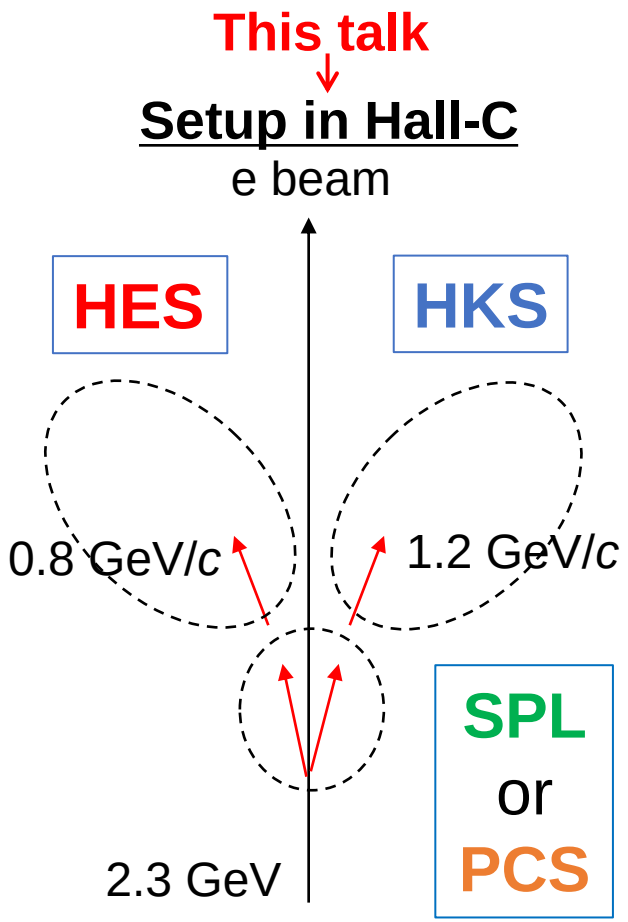


JPS2021 Annual, 12pU1-5, K. Okuyama

Experimental method and setup





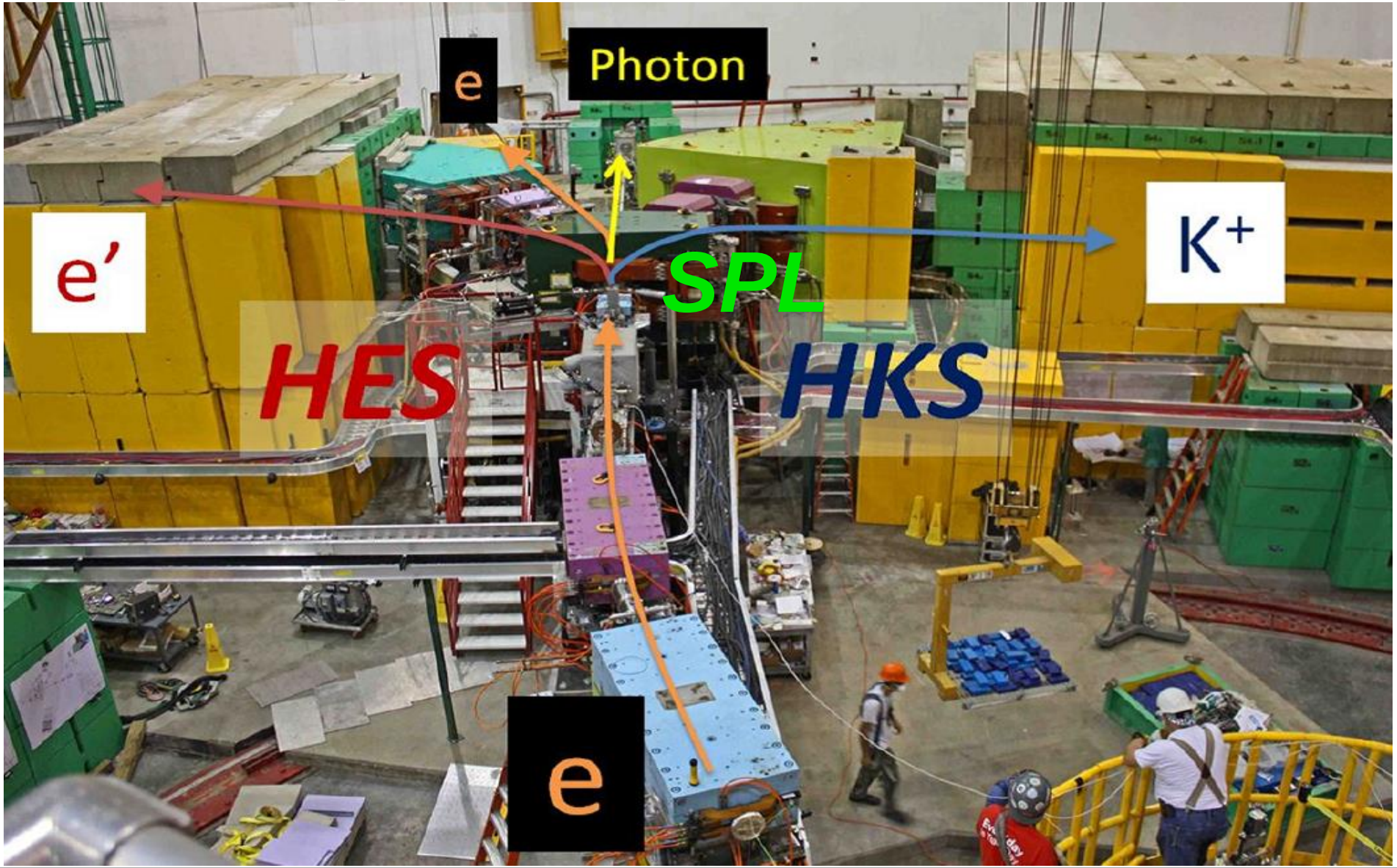


Missing Mass

$$M(^{27}_{\Lambda}\mathrm{Mg}) = \sqrt{\{(E_e - E_{e'}) + M(^{27}\mathrm{Al}) - E_K\}^2 - \{(\boldsymbol{P}_e - \boldsymbol{P}_{e'}) - \boldsymbol{P}_K\}^2}$$

$$-B_\Lambda = M(^{27}_{\Lambda}\mathrm{Mg}) - M_\Lambda - M(^{26}\mathrm{Mg})$$

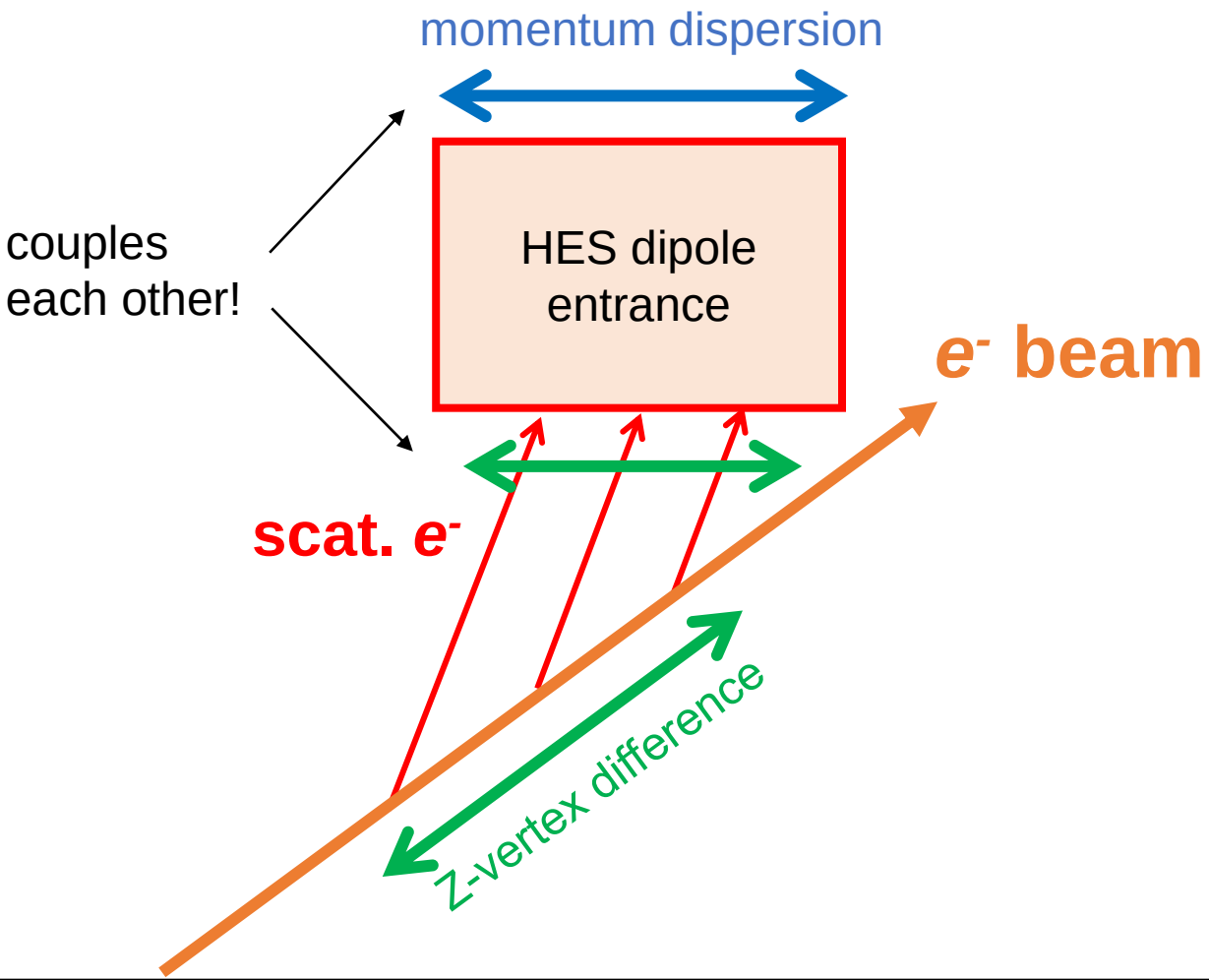
E05-115 experiment in 2009



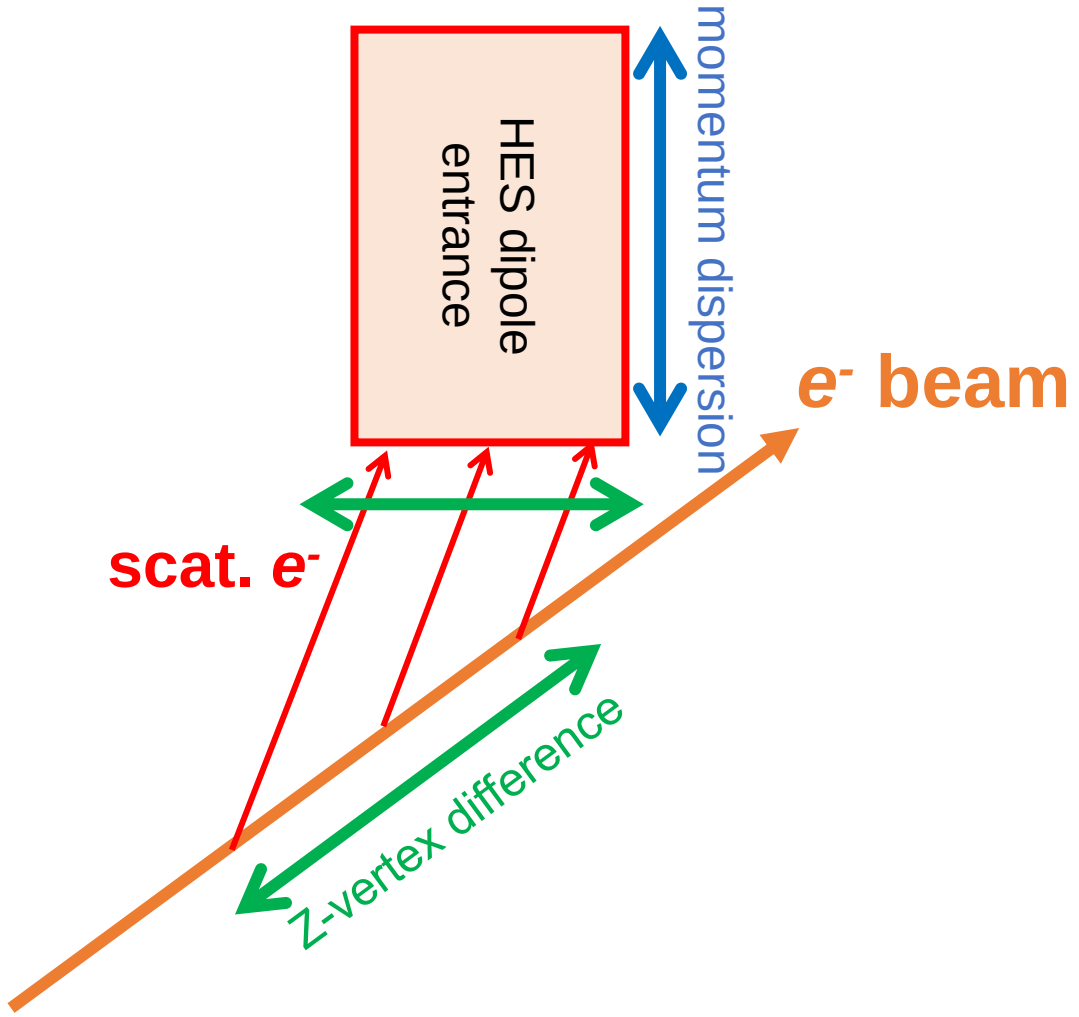
Vertical bending spectrometer is essential

especially, for multi-foil target system (E12-15-008) and cryo-gas target (E12-19-002)

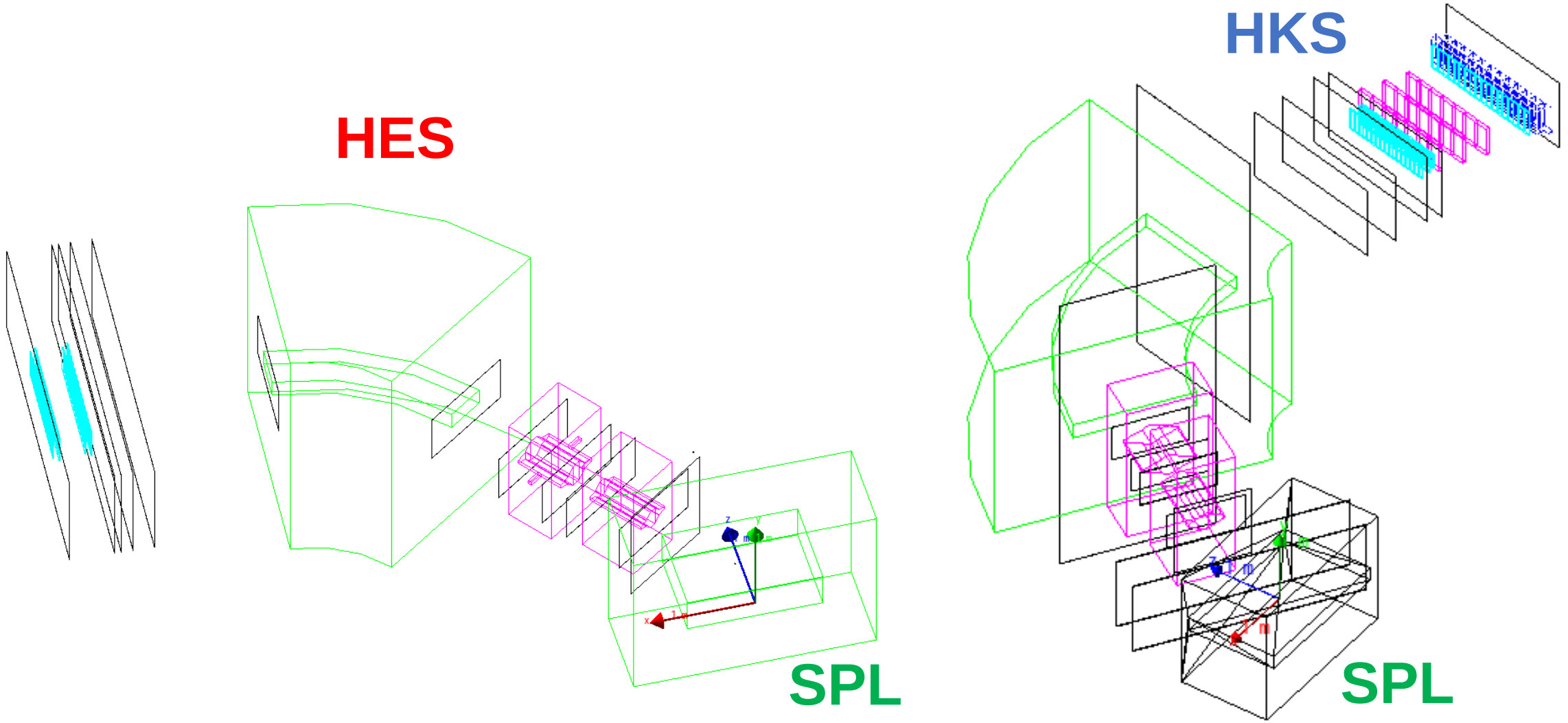
horizontal bending spectrometer



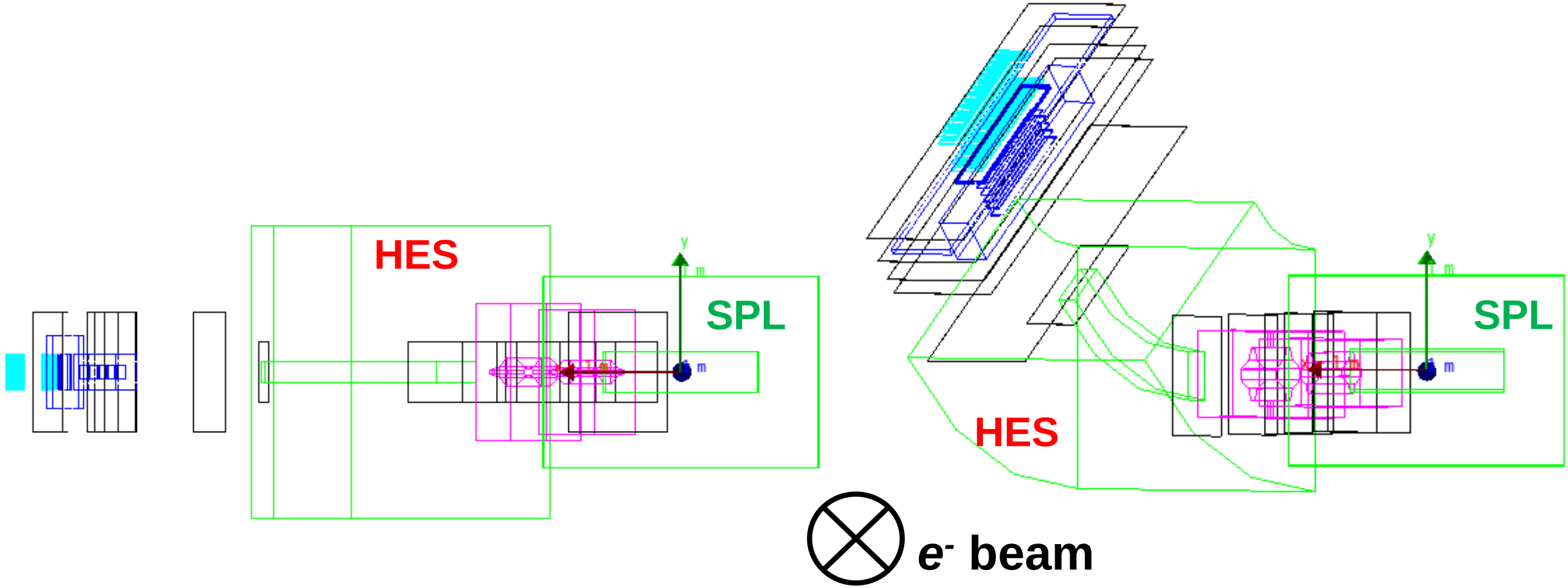
vertical bending spectrometer



SPL+HKS+HES in Geant4

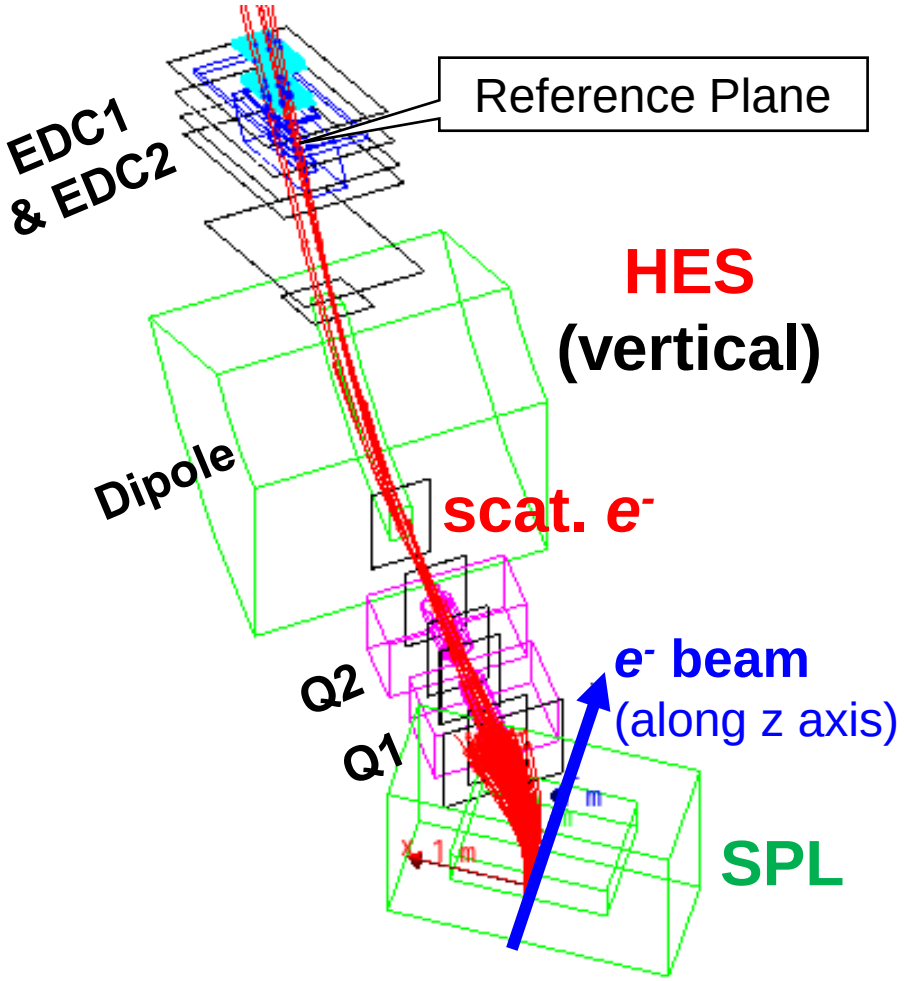


HES and/or HKS: Horizontal → Vertical bending



Geant4 Simulation

Particle transportation by Geant4 simulation



at Target — matrix element — measured at Reference Plane

$$X'_{\mathrm{T}} = \sum_{i+j+k+l=0}^{n} C_{X'}(i,j,k,l)(X_{\mathrm{RP}})^i(X'_{\mathrm{RP}})^j(Y_{\mathrm{RP}})^k(Y'_{\mathrm{RP}})^l$$

$$Y'_{\mathrm{T}} = \sum_{i+j+k+l=0}^{n} C_{Y'}(i,j,k,l)(X_{\mathrm{RP}})^i(X'_{\mathrm{RP}})^j(Y_{\mathrm{RP}})^k(Y'_{\mathrm{RP}})^l$$

$$P = \sum_{i+j+k+l=0}^{n} C_{P}(i,j,k,l)(X_{\mathrm{RP}})^i(X'_{\mathrm{RP}})^j(Y_{\mathrm{RP}})^k(Y'_{\mathrm{RP}})^l$$

$$Z_{\mathrm{T}} = \sum_{i+j+k+l=0}^{n} C_{\mathrm{Z}}(i,j,k,l)(X_{\mathrm{RP}})^i(X'_{\mathrm{RP}})^j(Y_{\mathrm{RP}})^k(Y'_{\mathrm{RP}})^l$$

Z_{T} ↓ (n = 3)　　P ↓ (n = 6)

Matrix Order (n)	0	1	2	3	4	5	6	7
Number of terms	1	5	15	35	70	126	210	330

Inverse Transfer Matrix Optimization

③ Blurred by Detector Resolution

X, X', Y, Y'
at Reference Plane

HKS (typical resolution)
σ_X=100 μm, $\sigma_{X'}$=0.2 mr, σ_Y=160 μm, $\sigma_{Y'}$=0.3 mr
HES (typical resolution)
σ_X= 97 μm, $\sigma_{X'}$=0.8 mr, σ_Y=120 μm, $\sigma_{Y'}$=1.5 mr

Ref.) T. Gogami, Doctoral Thesis, Tohoku University (2015).

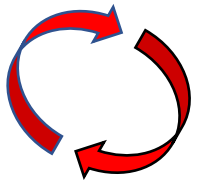
② Transport Particles by Geant4 simulation

④ Reconstruction using Matrix (we get P_{calc})

① Generate Particles at Target (we know P_{true})

P, X', Y', Z, etc.
at Target

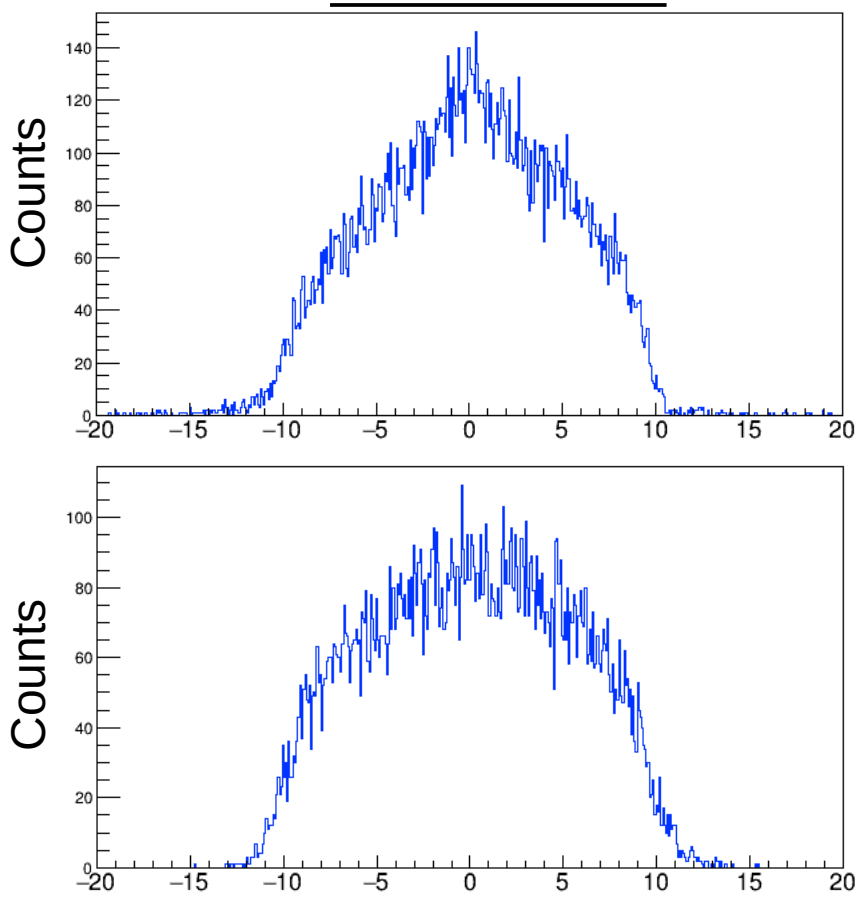
⑤ Compare P_{true} with P_{calc}



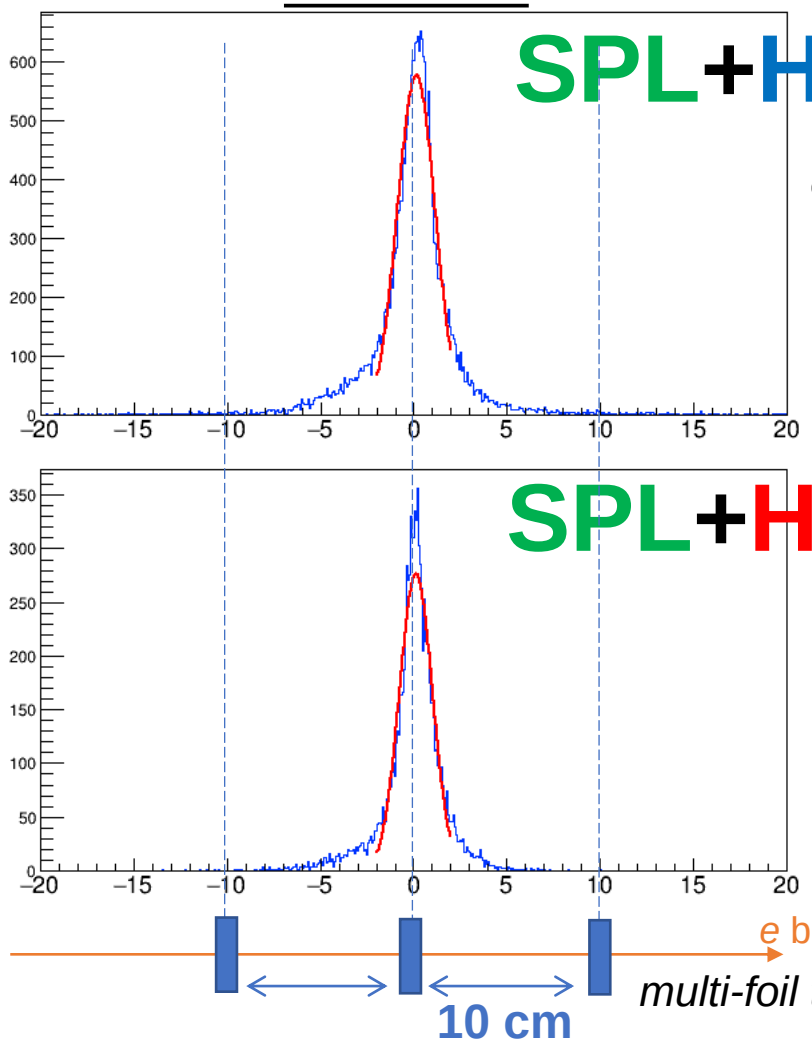
iteration
minimize the difference
→ **matrix optimization**

Z-vertex Resolution

Horizontal



Vertical



generated in Geant4

calculated using inverse transfer matrix

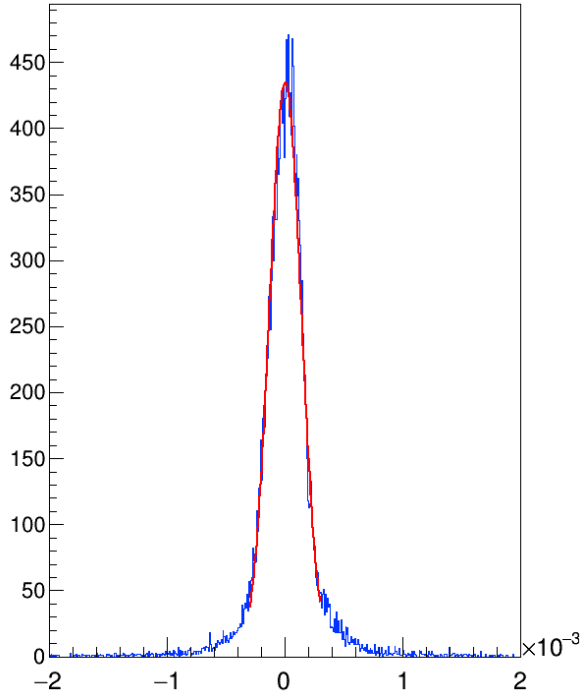
Effect on Momentum Resolution 1

HKS: horizontal → vertical

Momentum Resolution (SPL+HKS)

Horizontal

$\Delta p/p = 3.2\times10^{-4}$ (FWHM) $\rightarrow \Delta p \sim 0.3$ MeV/c



$\Delta p/p=(p_{true}-p_{calc})/p_{true}$

generated in Geant4

calculated using inverse transfer matrix

$\Delta p/p$ (FWHM) [unit = 10^{-4}]

	Horizontal	Vertical
multifoil target-like analysis		
Z = 0 (fixed)	3.2	3.6
Z = +10 cm (fixed)	3.4	3.5
Z = −10 cm (fixed)	3.5	3.8
gas target-like analysis		
Z∈[-10 cm, 10 cm]	9.3	4.5

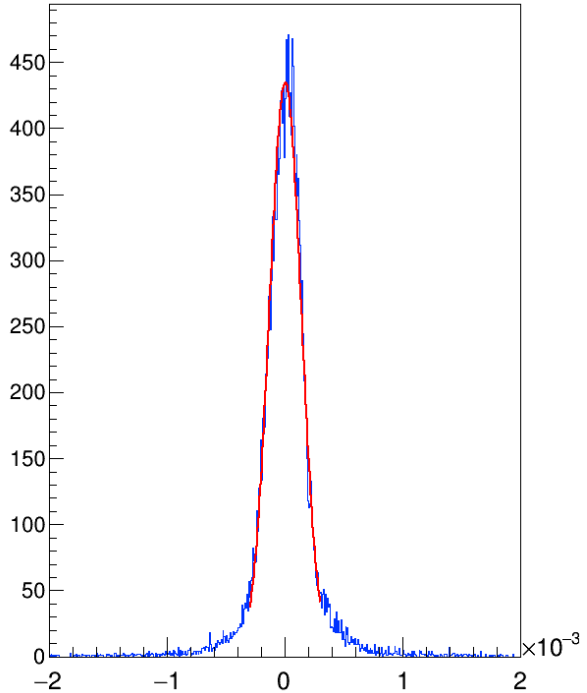
Rotation of HKS, deviation of Z do **NOT** make $\Delta p/p$ worse

If particles are randomly generated, $\Delta p/p$ get worse, however, it may be improved by adding Z-term on P-matrix explicitly.

Momentum Resolution (SPL+HKS)

Horizontal

$\Delta p/p = 3.2\times10^{-4}$ (FWHM) $\rightarrow \Delta p \sim 0.3$ MeV/*c*



$\Delta p/p=(p_{true}-p_{calc})/p_{true}$

generated in Geant4

calculated using inverse transfer matrix

$\Delta p/p$ (FWHM) [unit = 10^{-4}]

	Horizontal	Vertical
multifoil target-like analysis		
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gas target-like analysis		
Z∈[-10 cm, 10 cm]	9.3	4.5

Rotation of HKS, deviation of Z do **NOT** make Δp/p worse

If particles are randomly generated, Δp/p get worse, however, it may be improved by adding Z-term on P-matrix explicitly.

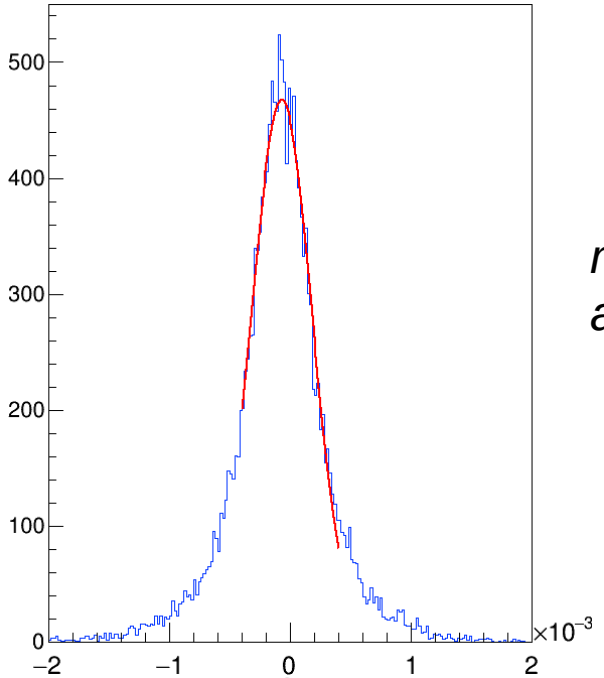
Effect on Momentum Resolution 2

HES: horizontal → vertical

Momentum Resolution (SPL+HES)

Horizontal

$\Delta p/p = 5.4\times10^{-4}$ (FWHM) $\rightarrow \Delta p \sim 0.6$ MeV/c



$\Delta p/p=(p_{true}-p_{calc})/p_{true}$

generated in Geant4

calculated using inverse transfer matrix

$\Delta p/p$ (FWHM) [unit = 10^{-4}]

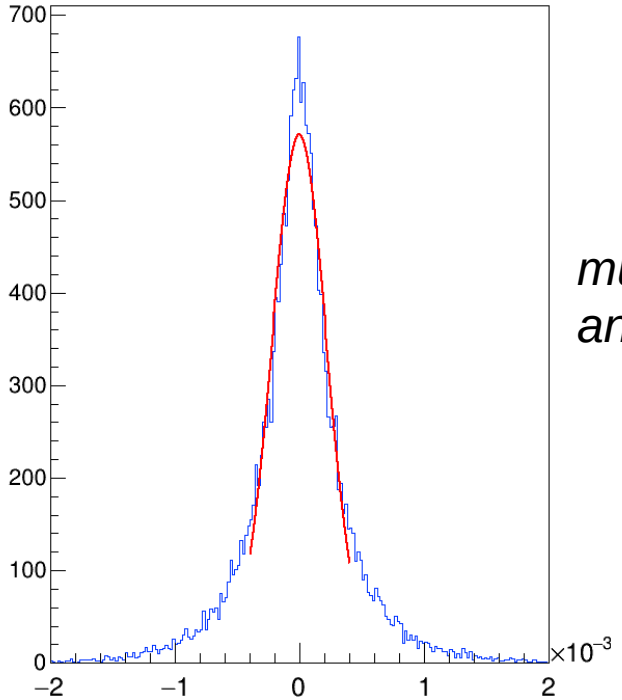
	Horizontal	Vertical
multifoil target-like analysis		
Z = 0 (fixed)	5.4	6.1
Z = +10 cm (fixed)	5.3	9.1
Z = −10 cm (fixed)	5.9	14.5
gas target-like analysis		
Z∈[-10 cm, 10 cm]	>20	9.8

Rotation of HES does **NOT** make $\Delta p/p$ worse, however, $\Delta p/p$ get worse at Z=+/-10 cm than Z=0 (vertical bending)

Momentum Resolution (PCS+HES)

Horizontal

$\Delta p/p = 5.2\times10^{-4}$ (FWHM) $\rightarrow \Delta p \sim 0.6$ MeV/c



$\Delta p/p = (p_{true} - p_{calc})/p_{true}$

generated in Geant4

calculated using inverse transfer matrix

$\Delta p/p$ (FWHM) [unit = 10^{-4}]

	Horizontal	Vertical
multifoil target-like analysis		
Z = 0 (fixed)	5.2	5.8
Z = +10 cm (fixed)	5.5	6.1
Z = −10 cm (fixed)	5.2	6.9
gas target-like analysis		
Z∈[-10 cm, 10 cm]	>20	6.6

$\Delta p/p$ get recovers at Z=+/-10 cm with PCS-magnet
← vertical HES more suitable for PCS than SPL?

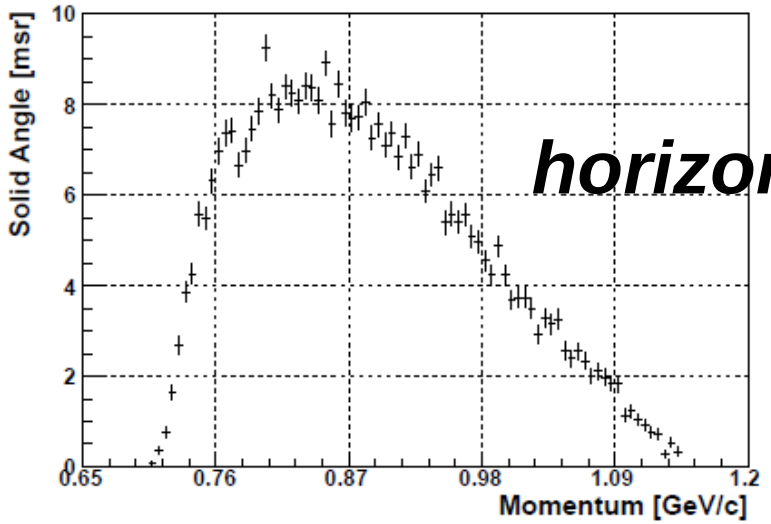
Solid Angle

HKS: horizontal → vertical

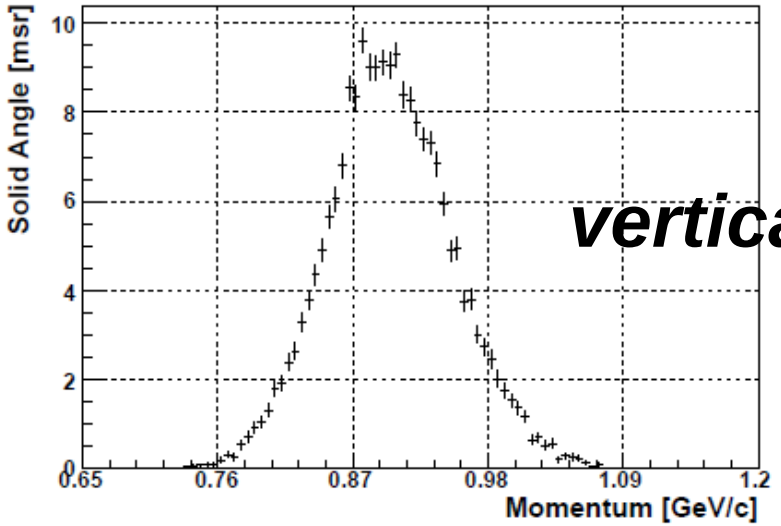
HES: horizontal → vertical

Solid Angle at Z=0

SPL+HES

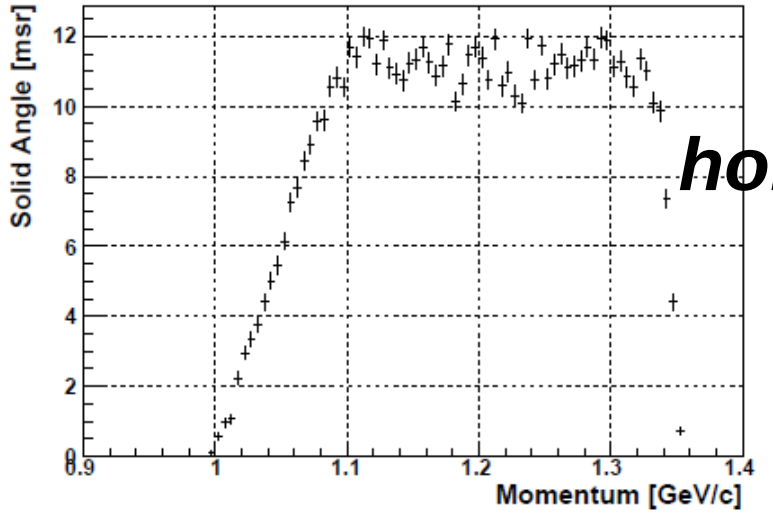


horizontal

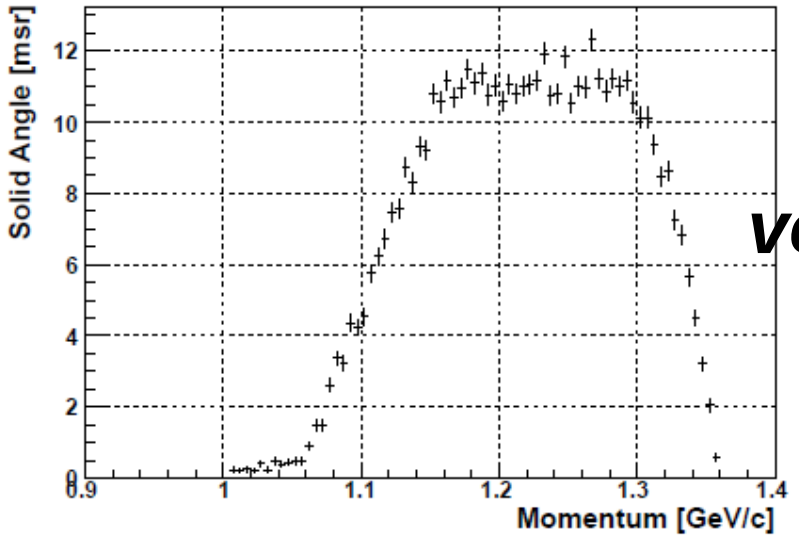


vertical

SPL+HKS



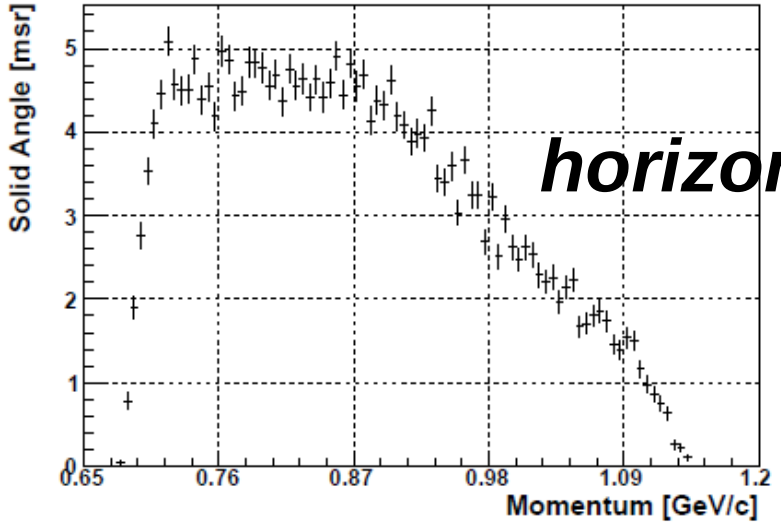
horizontal



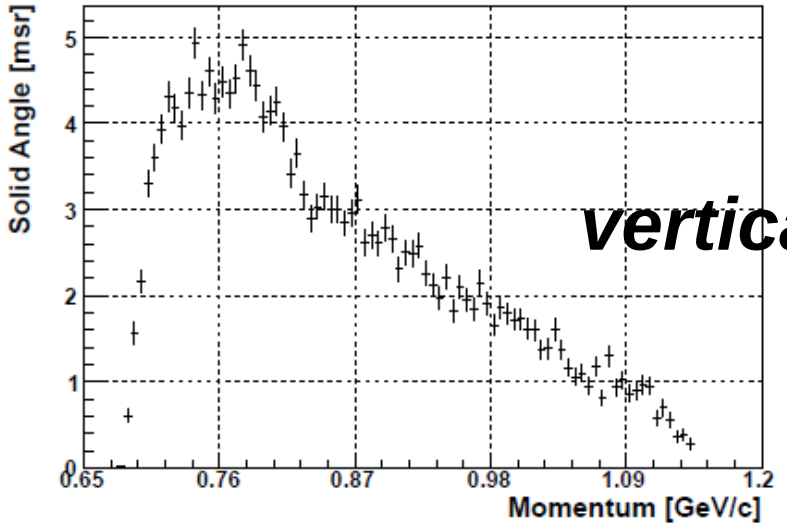
vertical

Solid Angle at Z=0

PCS+HES

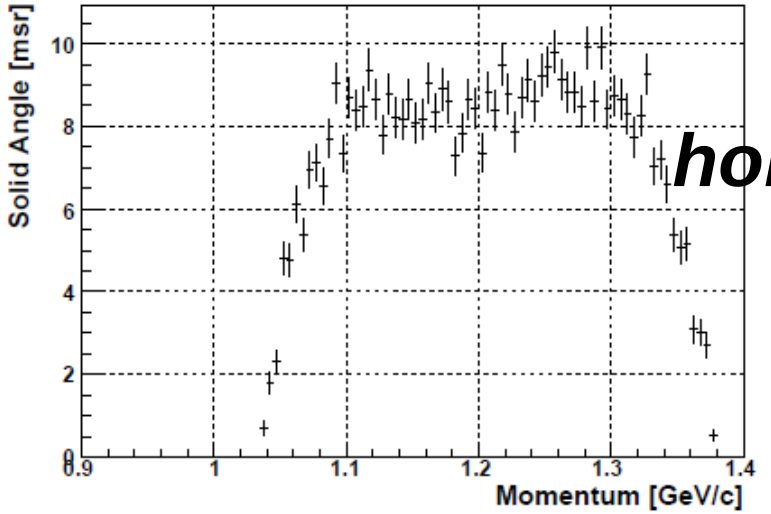


horizontal

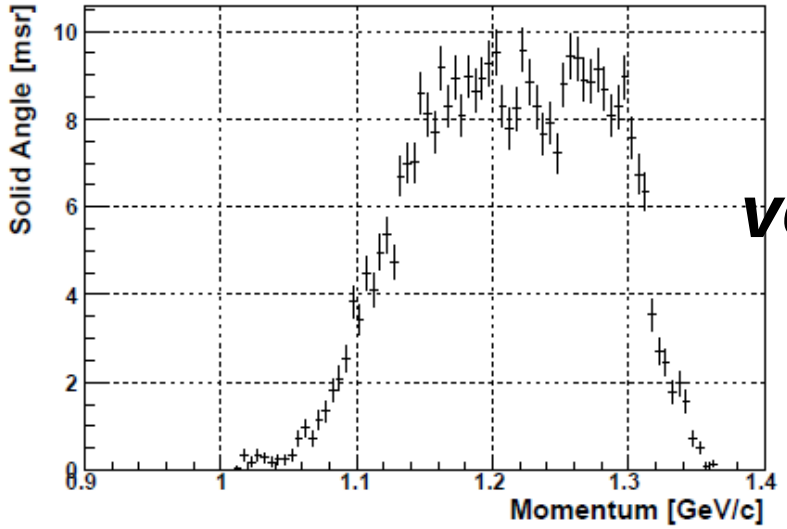


vertical

PCS+HKS



horizontal



vertical

Summary

- Geant4 simulation for the next JLab Hypernuclear experiments
  - **SPL**+**HKS**+**HES** / **PCS**+**HKS**+**HES**
    - **HKS**: horizontal → vertical
      - σ_z : ~1 cm
      - $\Delta p/p$: not changed at Z=0, ±10 cm
    - **HES**: horizontal → vertical
      - σ_z : ~1 cm
      - $\Delta p/p$: somewhat worse at Z= ±10 cm with **SPL**
      - $\Delta p/p$: not changed at Z=0, ±10 cm with **PCS**
      - Acceptance reduction should be considered

      →*further study will be done in near future*

Aiming to carry out the experiments in 2024