The apparatus
for next hypernuclear experiments at JLab

Graduate School of Science, Kyoto University

Toshiyuki Gogami

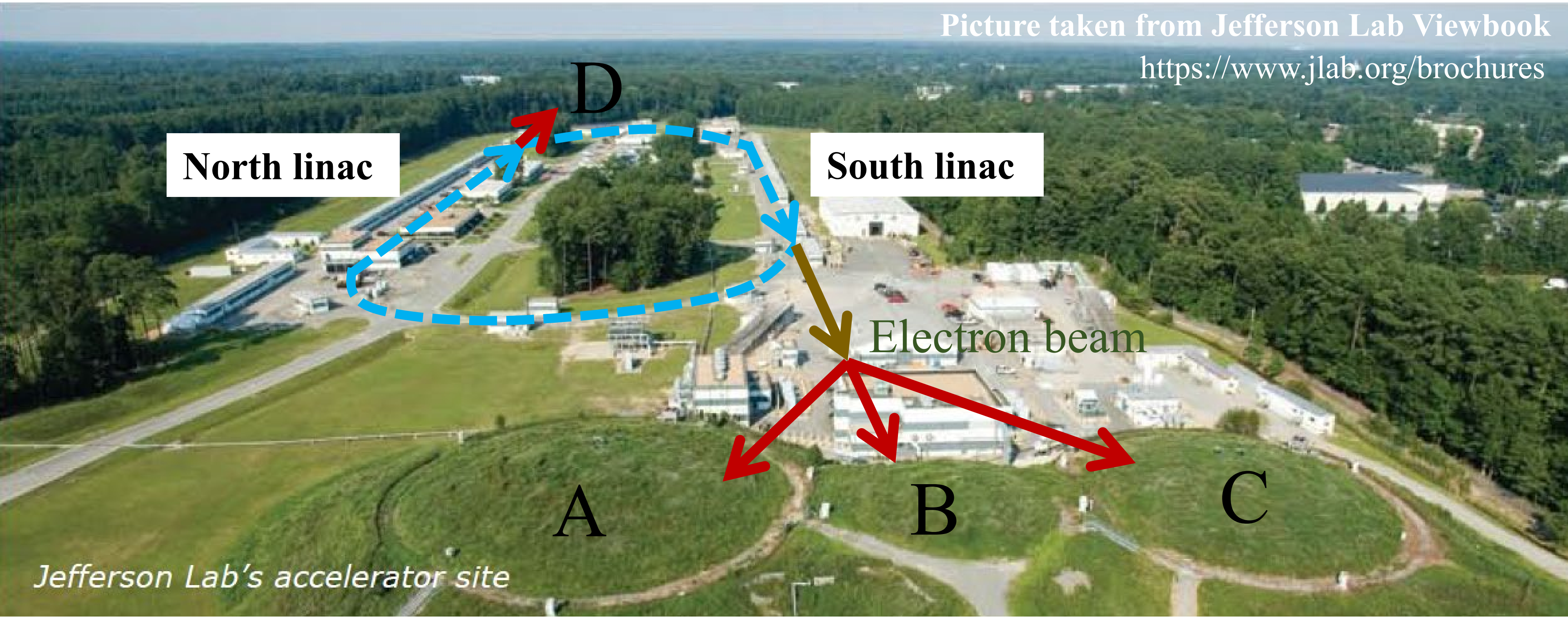
May 11, 2020

科研費
KAKENHI

SPIRITS
SUPPORTING PROGRAM FOR INTERACTION-BASED INITIATIVE TEAM STUDIES

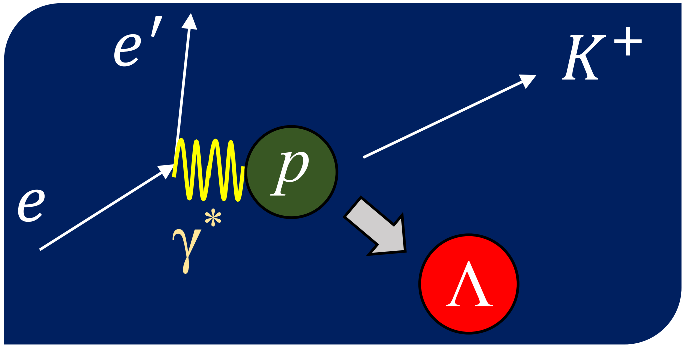
京都大学
KYOTO UNIVERSITY

CEBAF at Newport News, VA, US



Continuous electron beam facility (CEBAF)

- ✓ 12 GeV at maximum (at Hall D)
- ✓ 150 μA (> 900 THz)
- ✓ 2 or 4-ns interval bunches
- ✓ Emittance of 2 μm·mrad
- ✓ Energy spread ($^{\Delta E}/_{E} < 5 \times 10^{-5}$ rms)



$(e, e'K^+)$ experiments at JLab Hall A

<u>$^{40,48}_{\Lambda}\mathrm{K}$ (E12-15-008)</u>

➔ΛNN isospin dependence

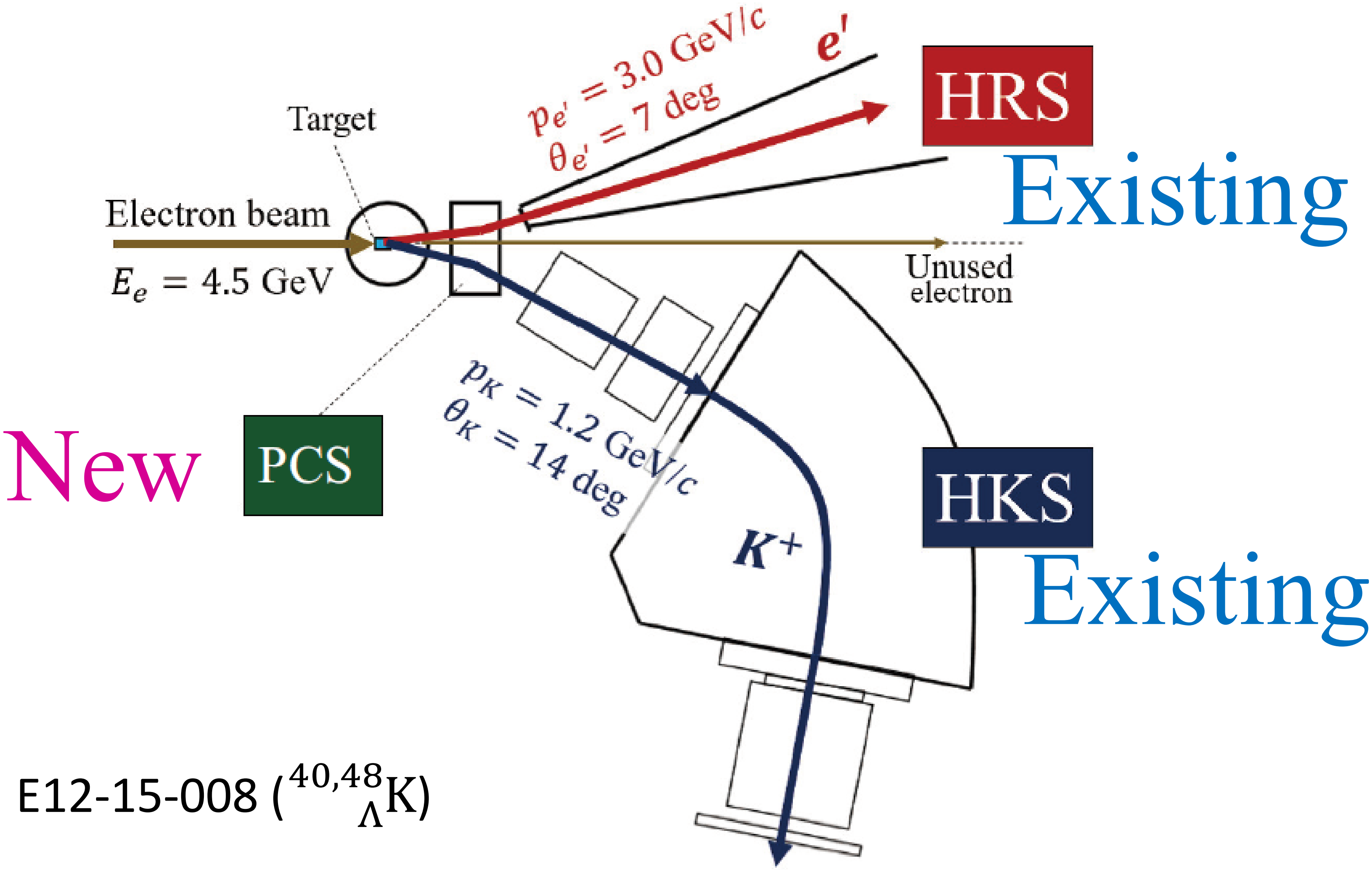
<u>$^{3,4}_{\Lambda}\mathrm{H}$ (C12-19-002)</u>

➔$^{3}_{\Lambda}\mathrm{H}$ puzzle, ΛN CSB

<u>$^{208}_{\Lambda}\mathrm{Tl}$</u>

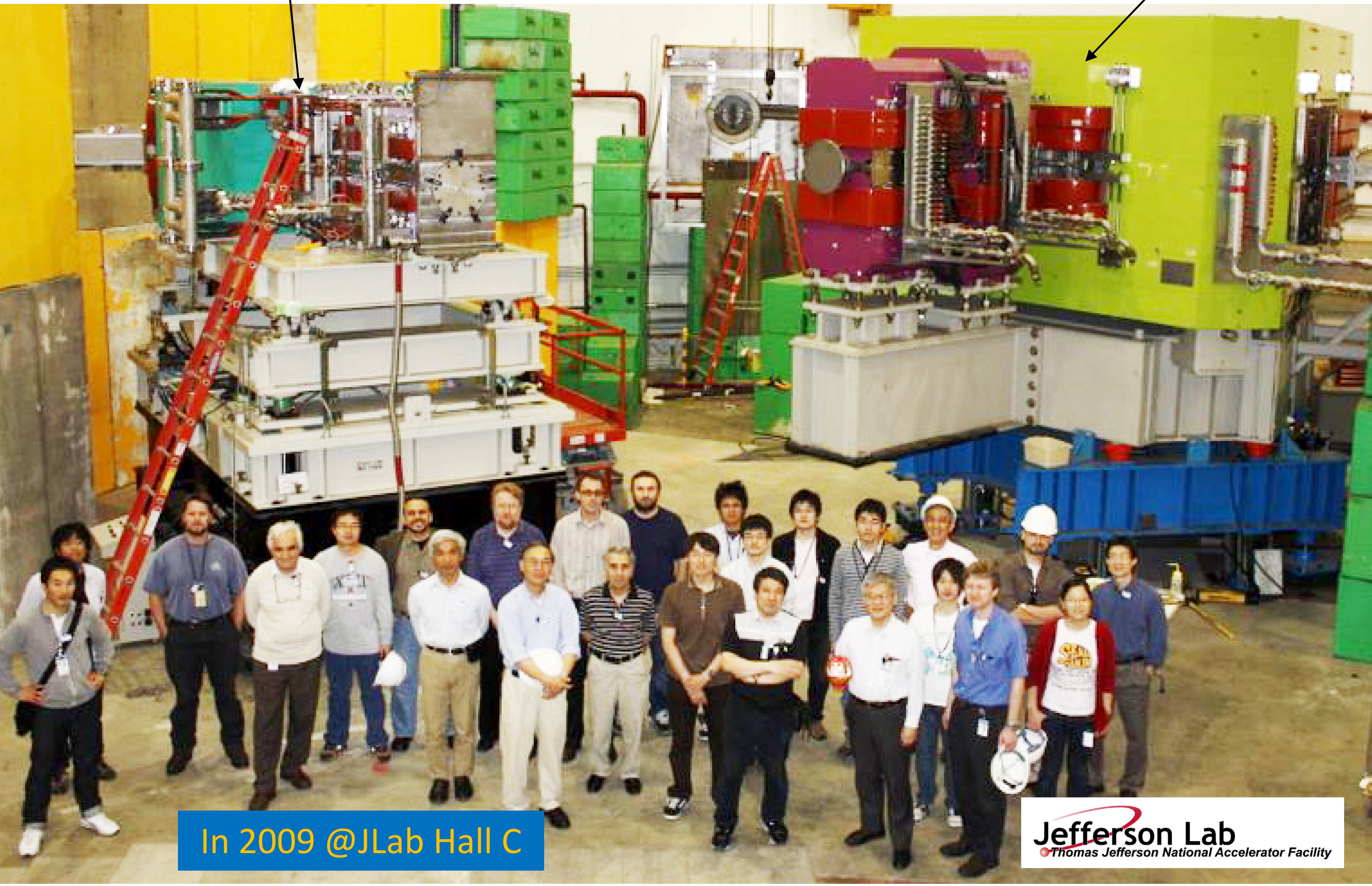
To be discussed in this WS

Experimental setup at JLab Hall A



E12-15-008 ($^{40,48}_{\Lambda}$K)

HES **HKS**


In 2009 @JLab Hall C
Jefferson Lab
Thomas Jefferson National Accelerator Facility

LHRS

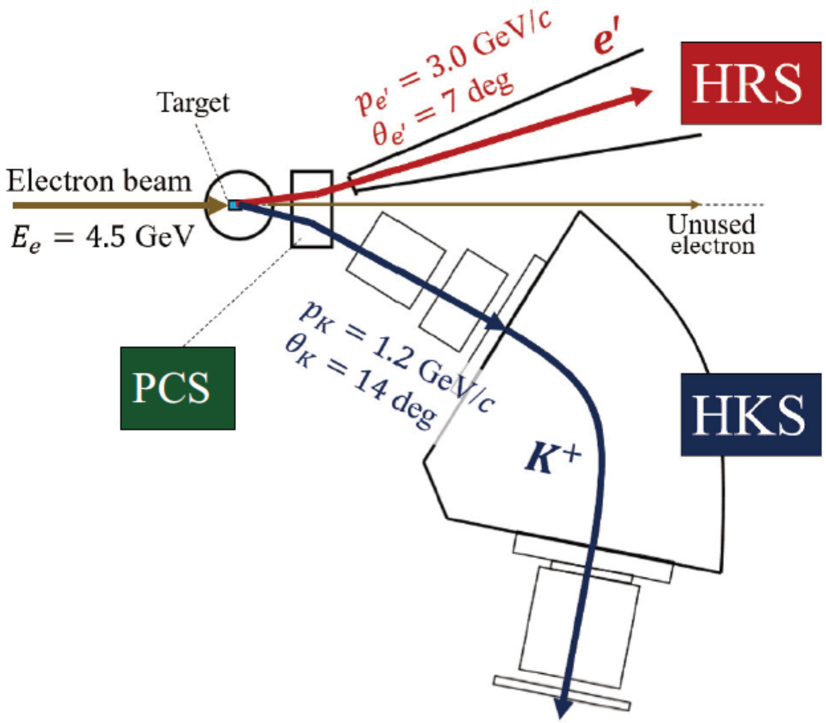

RHRS
April 2019 @JLab Hall A
Jefferson Lab
Thomas Jefferson National Accelerator Facility

PCS (Pair of Charge Separation dipole magnets)

Constructions of PCS-E and PCS-K were done in March 2020.

➔ Will be ready soon to be transported to JLab.

Spectrometer specification



Beam	$\Delta p/p$	$< 1 \times 10^{-4}$ FWHM
	E_e	4.5 GeV
PCS + HRS (e')	D(PCS) + QQDQ	
	$\Delta p/p$	$\simeq 2 \times 10^{-4}$ FWHM
	$p_{e'}$	3.0 GeV/$c \pm 4.5\%$
	$\theta_{ee'}$	7.0 ± 1.5 deg
	Solid angle $\Omega_{e'}$	5 msr
PCS + HKS (K^+)	D(PCS) + QQD	
	$\Delta p/p$	$\simeq 2 \times 10^{-4}$ FWHM
	p_K	1.2 GeV/$c \pm 10\%$
	θ_{eK}	14.0 ± 4.5 deg
	Solid angle Ω_K	3 msr
	Optical length	12 m
	K^+ survival ratio	26%

Sharing setup and calibration with E12-15-008 (+C12-19-002)
➔ Saving a lot of time and energy

Parameter difference from previous experiment

Worse resolution, but **better S/N** (➔ it allows for $^{40,48}_{\Lambda}\mathrm{K}$ measurement)

	E_{beam} (GeV)	$p_{e'}$ (GeV/c)	ω (GeV)	$p_{e'}$ (GeV/c)	S/N	ΔM_{HY}
Previous (E05-115)	2.3	0.8	1.5	1.2	△	◎
New (E12-15-008) (C12-19-002)	**4.5**	**3.0**	1.5	1.2	◎	△

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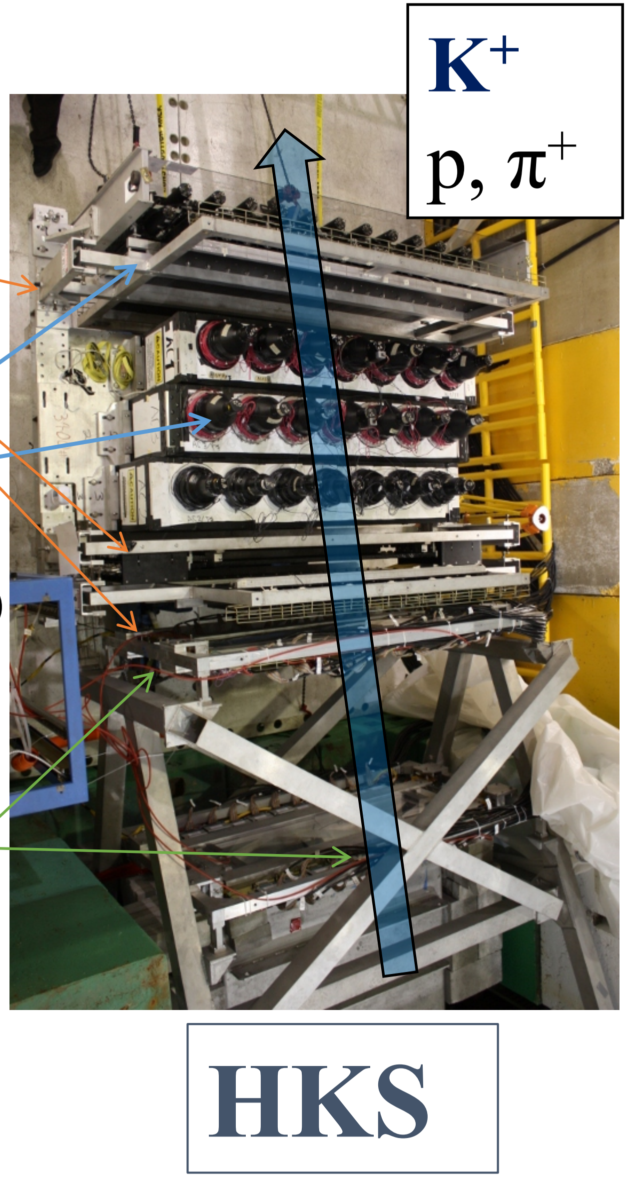
Kaon identification in HKS

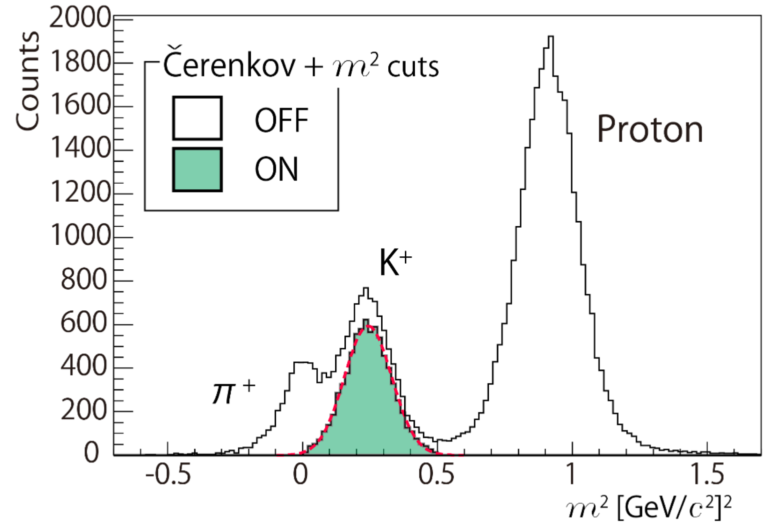
TOF walls
(Plastic scintillators)

Cerenkov detectors
- **Aerogel (n=1.05)**
- **Water (n=1.33)**

Drift chambers



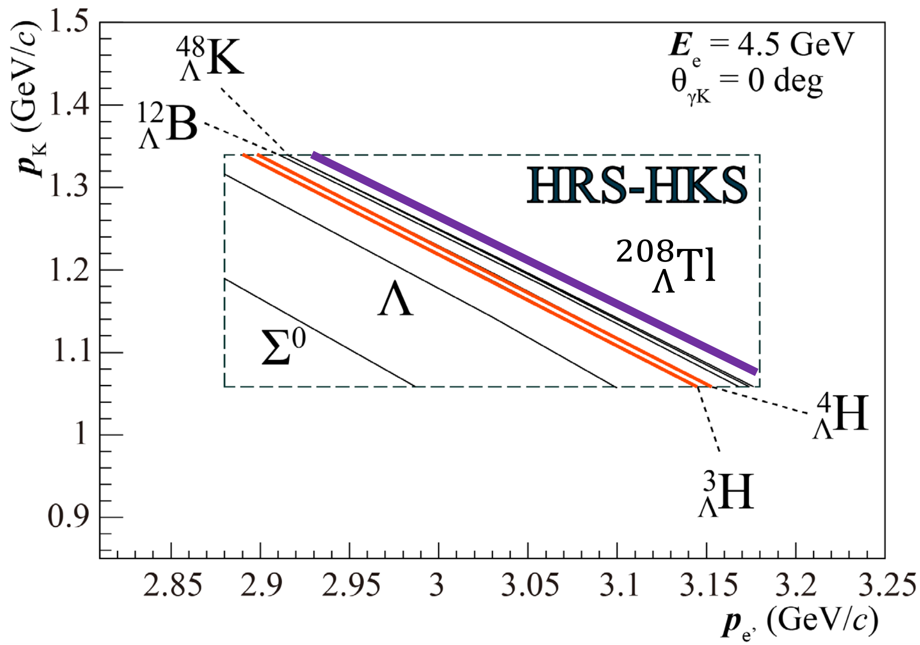
TG *et al.*, NIMA **729** (2013) 816–824



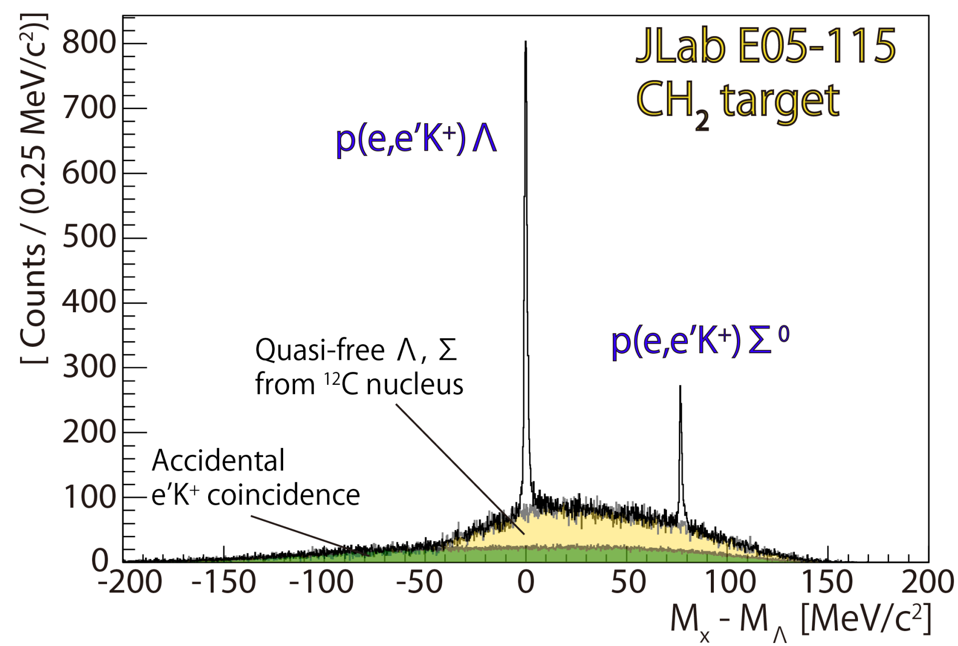
Survival ratios (on- and off-lines)

- ✓ K^+ : 83%
- ✓ π^+: 4.7×10^{-4}
- ✓ p : 1.9×10^{-4}

Energy Calibration



TG et al., NIMA 900 (2018) 69—83



Λ and Σ^0 from p target + Elastic scattering

→ Systematic error $\left|\Delta B_{\Lambda}^{sys.}\right| \leq 100$ keV

Preparation status

Item	Main task (current progress)	Progress
Spectrometer	PCS (70%) HKS base Collimator/SS	40—60%
Target	Ladder (20%) Cryo-target (20%) Target chamber	20—40%
Trigger	FPGA (30%)	20—40%
Detector	KDC1, 2 (10%) WC (50%) AC (50%) KTOF (80%)	40—60%
Software	Simulator (70%) Analyzer (30%)	20—40%

Goal of preparation in JFY2020 (~Mar 2021)

Item	Main task (current progress)	Progress
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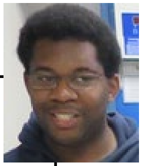
We aim to be ready for installation in 2021


T. Toyoda (Kyoto)
➔ Master's thesis

K. Katayama (Kyoto)
➔ Master's thesis




- N. Lashley (Hampton)
- T. Akiyama (Tohoku)
  ➔ Master thesis
- K. Okuyama (Tohoku)



- Y.R. Nakamura (Tohoku)
- K.N. Suzuki (Kyoto)

Japanese (running) grants to support the present work

- **KAKENHI (JSPS)**
  - ✓17H01121 (JFY2017—2020), PI = S.N. Nakamura
  - ✓18H05459 (JFY2018—2022), PI = S.N. Nakamura
  - ✓18H01219 (JFY2018—2022), PI = T. Gogami
- **SPIRITS 2020 (Kyoto Univ.)**
  - ✓JFY2020—2021, PI = T. Gogami

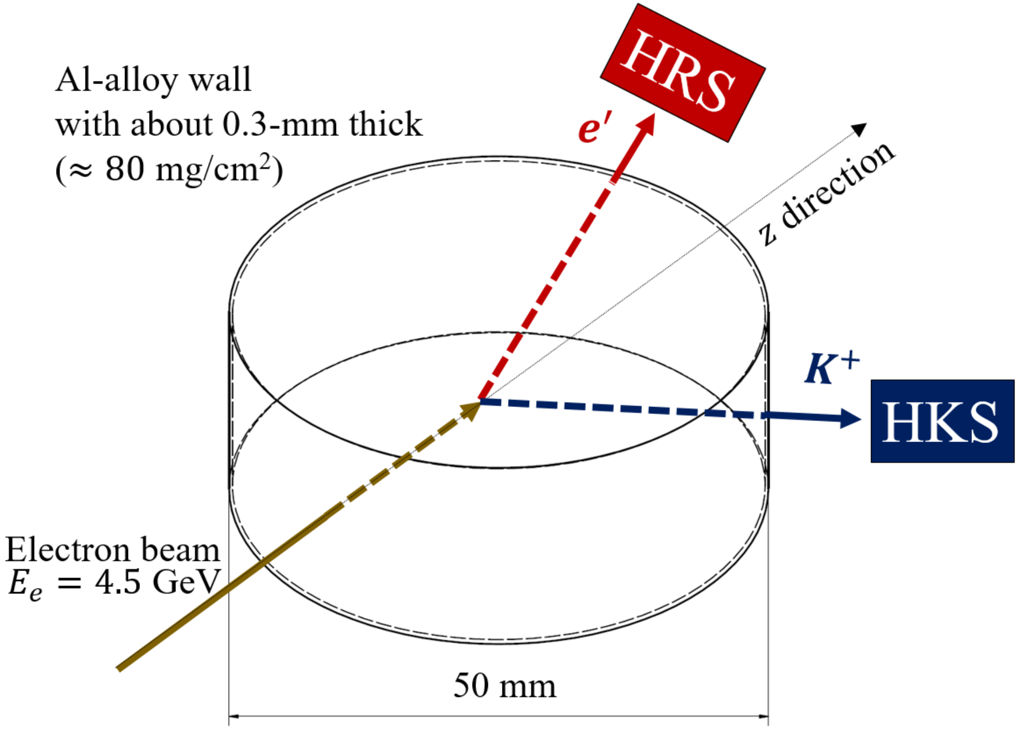
Backup

^{3,4}He target

Assumed spec of cryogenic targets:
J. Alcorn et al., NIMA 522 (2004) 294—346

Proposed measurements

- ☐ Cryogenic targets
  - ✓ LH_2
  - ✓ ^{3}He and ^{4}He (gas)
- ☐ Multi foil target



Solid targets and cryogenic targets can be on the same ladder
(Target design is underway: T. Toyoda (M student, Kyoto Univ.))

Missing-mass reconstruction and calibration with Λ and Σ^0

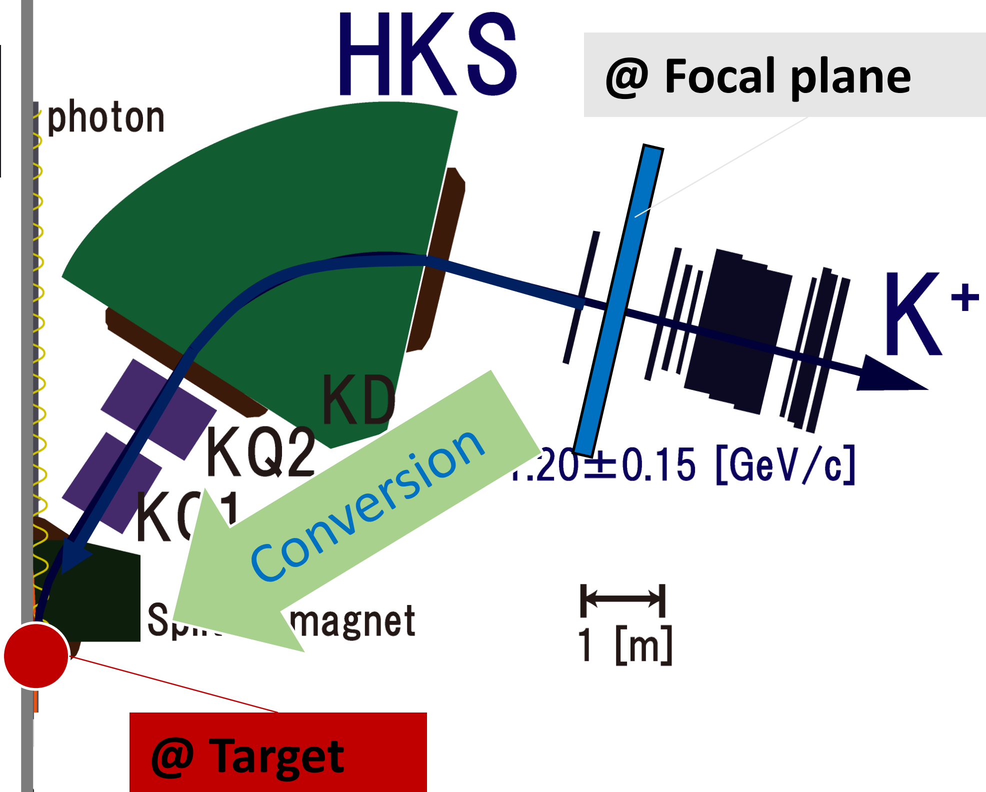
BTM

$$\begin{pmatrix} x_T \\ x'_T \\ y_T \\ y'_T \\ p \end{pmatrix} = M^{R2T} \begin{pmatrix} x_{RP} \\ x'_{RP} \\ y_{RP} \\ y'_{RP} \\ x^2_{RP} \\ x_{RP} x'_{RP} \\ \vdots \end{pmatrix}$$

x,x',y,y'

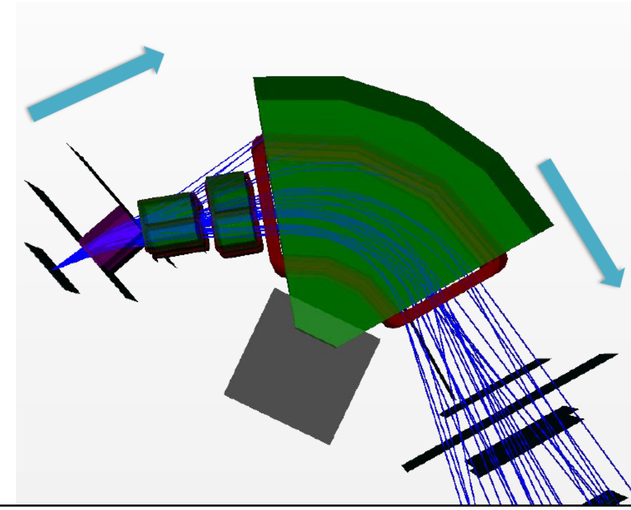
Conversion

$\vec{p}$



Momentum resolutions with long z target

$$\begin{pmatrix} x' \\ y' \\ p \end{pmatrix}_T = M^{R2T} \begin{pmatrix} x_{RP} \\ x'_{RP} \\ y_{RP} \\ y'_{RP} \end{pmatrix}$$



K. Suzuki (Ph.D. student, Kyoto Univ.)

Geant4 simulation with TOSCA magnetic field →

Spectrometer	PCSM+HRS	PCSM+HKS
Δp/p FWHM	3×10^{-4}	12×10^{-4}

Our goal is to achieve an order of 10^{-4}

Momentum resolutions with long z target

$$\begin{pmatrix} x' \\ y' \\ p \end{pmatrix}_{\mathrm{T}} = M^{R2T} \begin{pmatrix} x_{RP} \\ x'_{RP} \\ y_{RP} \\ y'_{RP} \end{pmatrix}$$

Vertex z largely affects horizontal bending spectrometer

Geant4 simulation with TOSCA magnetic field

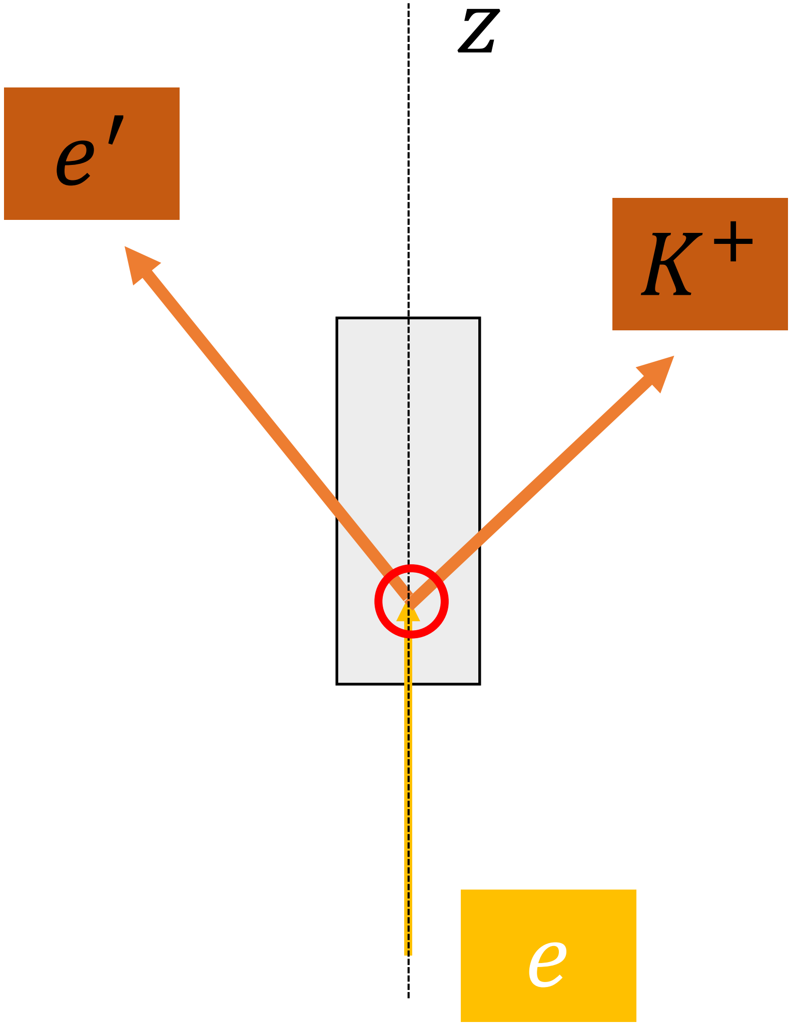
Spectrometer	PCSM+HRS	PCSM+HKS
Δp/p FWHM	3×10^{-4}	12×10^{-4}

Our goal is to achieve an order of 10^{-4}

Matrix space expansion

$$\begin{pmatrix} x' \\ y' \\ p \end{pmatrix}_{\mathrm{T}} = M^{R2T} \begin{pmatrix} x_{RP} \\ x'_{RP} \\ y_{RP} \\ y'_{RP} \end{pmatrix}$$

$$\begin{pmatrix} x' \\ y' \\ p \end{pmatrix}_{\mathrm{T}} = M^{R2T} \begin{pmatrix} x_{RP} \\ x'_{RP} \\ y_{RP} \\ y'_{RP} \\ \boldsymbol{z_T} \end{pmatrix}$$



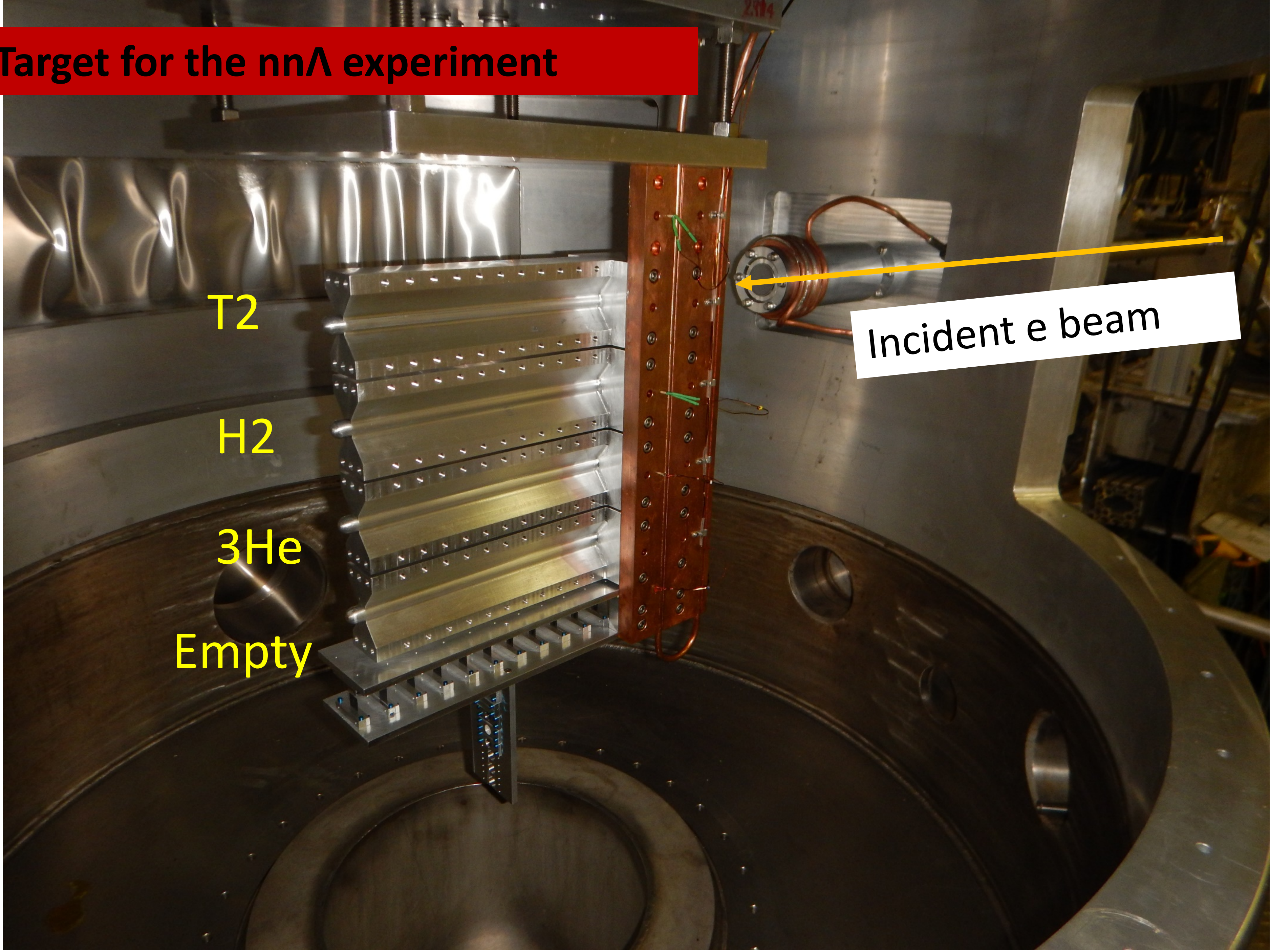
Parameter optimization

$$\begin{pmatrix} x' \\ y' \\ p \end{pmatrix}_T = \begin{pmatrix} p_1^{x'} & p_2^{x'} & p_3^{x'} & p_4^{x'} & \cdots \\ p_1^{y'} & p_2^{y'} & p_3^{y'} & p_4^{y'} & \cdots \\ p_1^{p} & p_2^{p} & p_3^{p} & p_4^{p} & \cdots \end{pmatrix} \begin{pmatrix} x_{RP} \\ x'_{RP} \\ y_{RP} \\ y'_{RP} \\ \cdots \\ z_T \end{pmatrix}$$

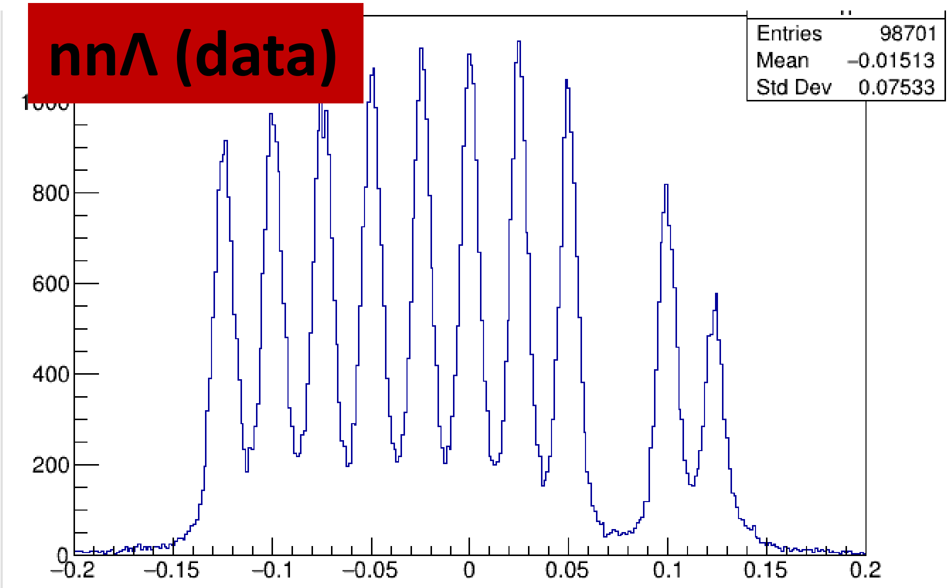
$$z_T = \begin{pmatrix} \boldsymbol{p_1^z} & \boldsymbol{p_2^z} & \boldsymbol{p_3^z} & \boldsymbol{p_4^z} & \cdots \end{pmatrix} \begin{pmatrix} x_{RP} \\ x'_{RP} \\ y_{RP} \\ y'_{RP} \\ x_{RP}^2 \\ \cdots \end{pmatrix}$$

Need to be optimized first

Target for the nnΛ experiment



Particle vertex z (Left HRS)



vertex z (m)

3rd order:
35 parameters

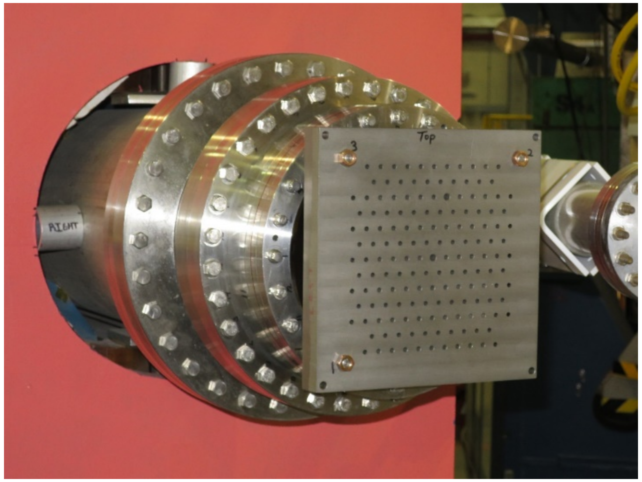
$$z_T^{L,R} = \begin{pmatrix} p_1^z & p_2^z & p_3^z & p_4^z & \cdots \end{pmatrix} \begin{pmatrix} x_{RP} \\ x'_{RP} \\ y_{RP} \\ y'_{RP} \\ x_{RP}^2 \\ \cdots \end{pmatrix}$$

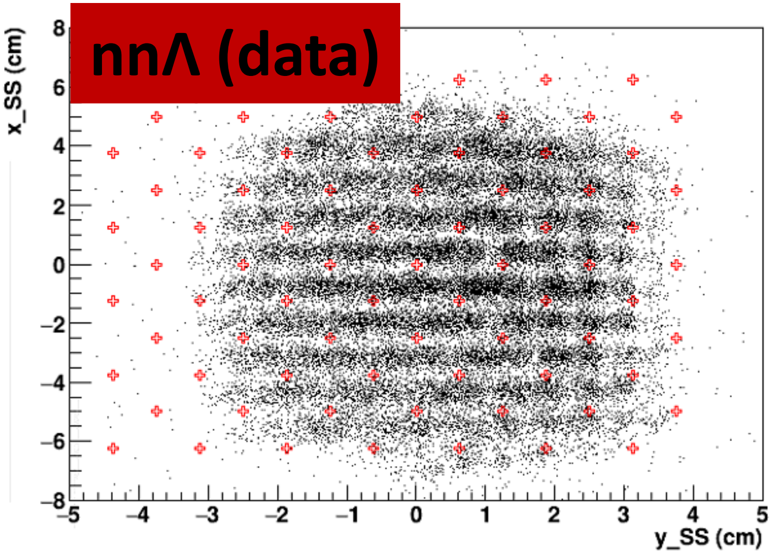
$$z_T = (z_T^L + z_T^R)/2$$

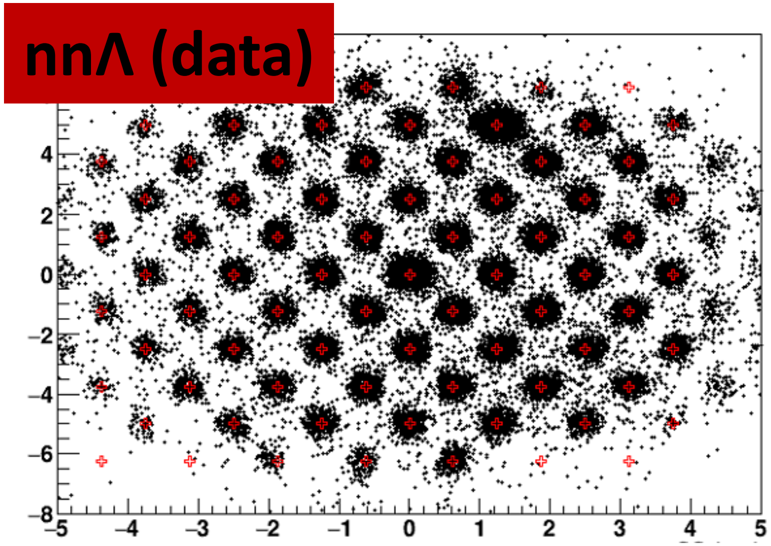
Angle calibration

Sieve slit data

$$\begin{pmatrix} x' \\ y' \\ p \end{pmatrix}_T = \begin{pmatrix} p_1^{x'} & p_2^{x'} & p_3^{x'} & p_4^{x'} & \cdots \\ p_1^{y'} & p_2^{y'} & p_3^{y'} & p_4^{y'} & \cdots \\ p_1^{p} & p_2^{p} & p_3^{p} & p_4^{p} & \cdots \end{pmatrix} \begin{pmatrix} x_{RP} \\ x'_{RP} \\ y_{RP} \\ y'_{RP} \\ \cdots \\ z_T \end{pmatrix}$$



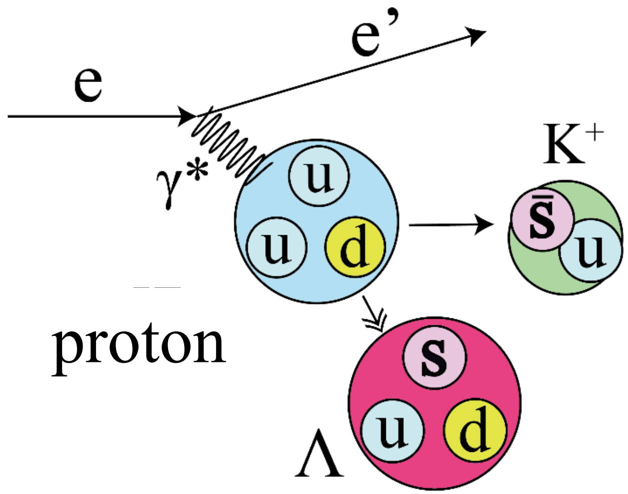


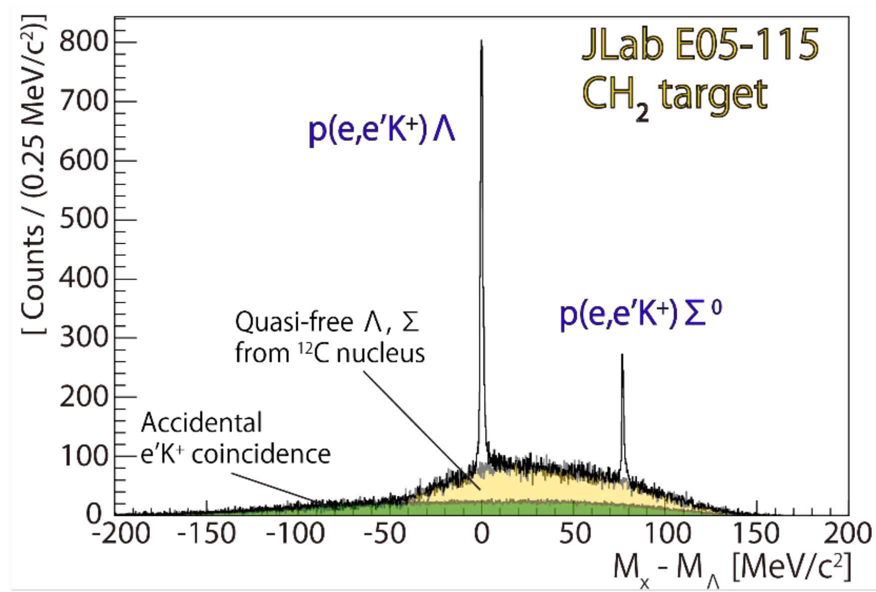


Momentum calibration

$$
\begin{pmatrix} x' \\ y' \\ p \end{pmatrix}^{\mathrm{T}} = \begin{pmatrix} p_1^{x'} & p_2^{x'} & p_3^{x'} & p_4^{x'} & \cdots \\ p_1^{y'} & p_2^{y'} & p_3^{y'} & p_4^{y'} & \cdots \\ p_1^{p} & p_2^{p} & p_3^{p} & p_4^{p} & \cdots \end{pmatrix} \begin{pmatrix} x_{RP} \\ x'_{RP} \\ y_{RP} \\ y'_{RP} \\ \cdots \\ z_T \end{pmatrix}
$$

NIMA **900**, 69–83 (2018)





Momentum resolutions

Geant4 simulation with TOSCA magnetic field

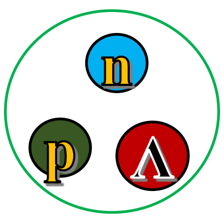
	PCS+HRS	PCS+HKS
Δz FWHM (cm)	1.5	5
Δp/p FWHM	3×10^{-4}	12×10^{-4}
Δp/p FWHM with z_T	$\mathbf{3 \times 10^{-4}}$	$\mathbf{3 \times 10^{-4}}$

The missing mass resolution is expected to achieve 0.9 MeV FWHM

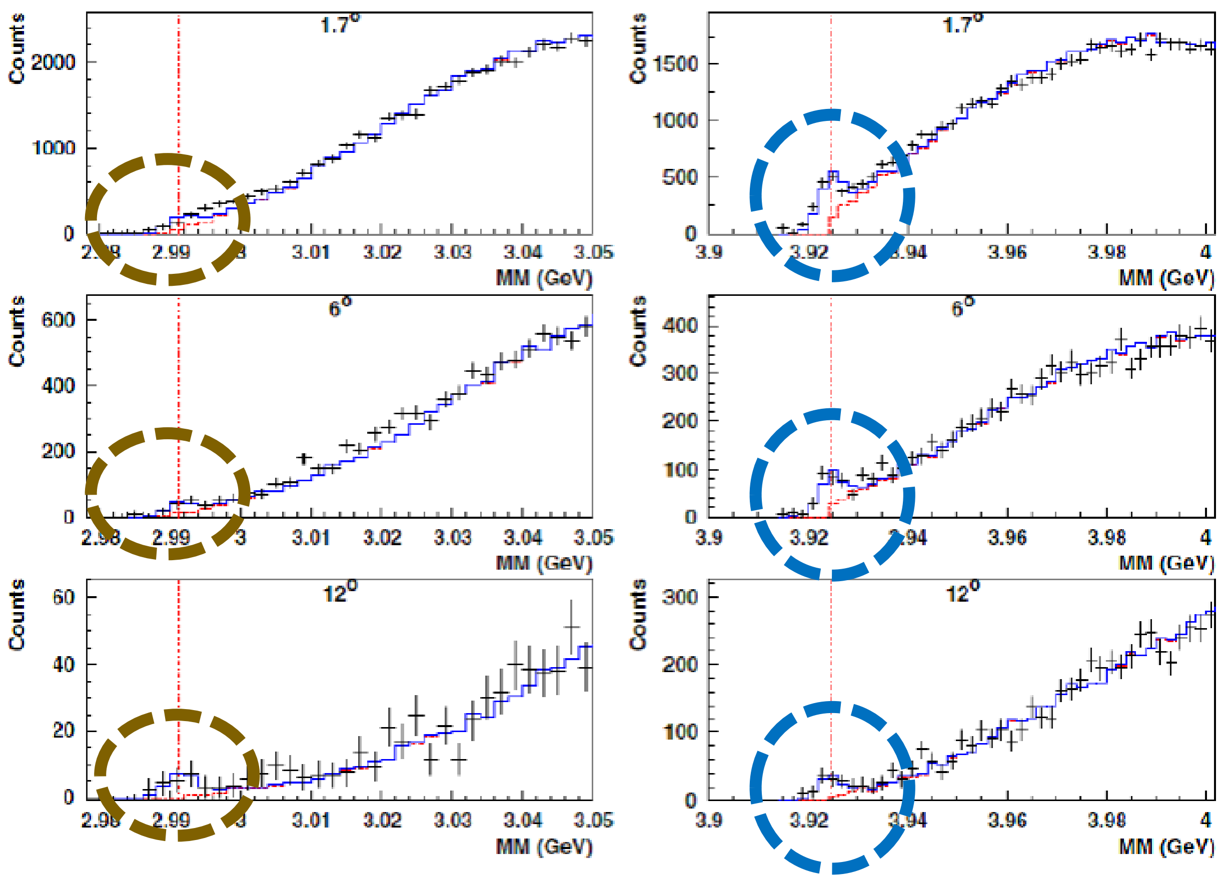
Previous experiment at Hall C

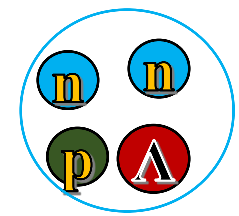
F. Dohrmann et al., *Phys. Rev. Lett.* **93**, 242501 (2004).

(e,e'K$^+$) experiment at Hall C



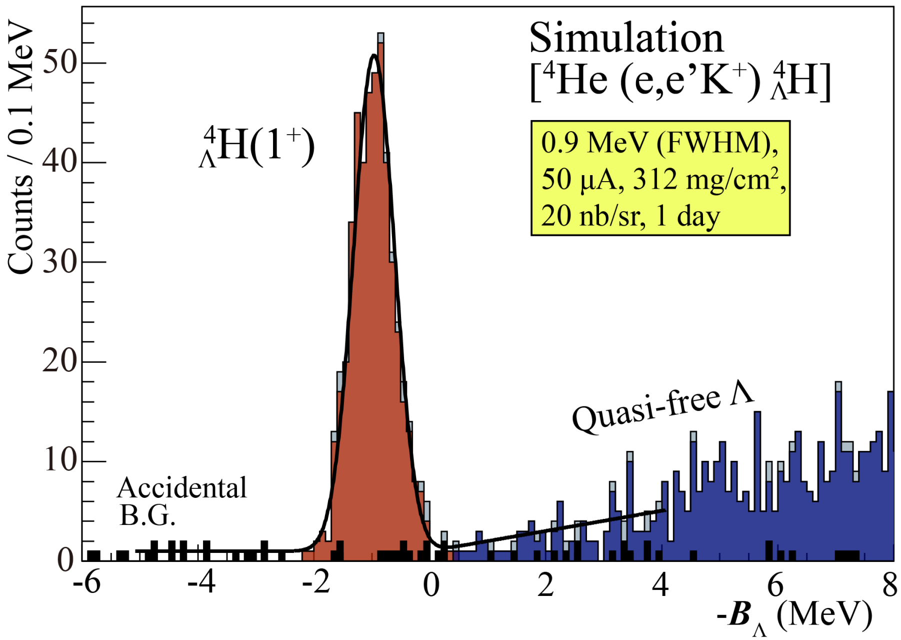
$^{3}_{\Lambda}$H



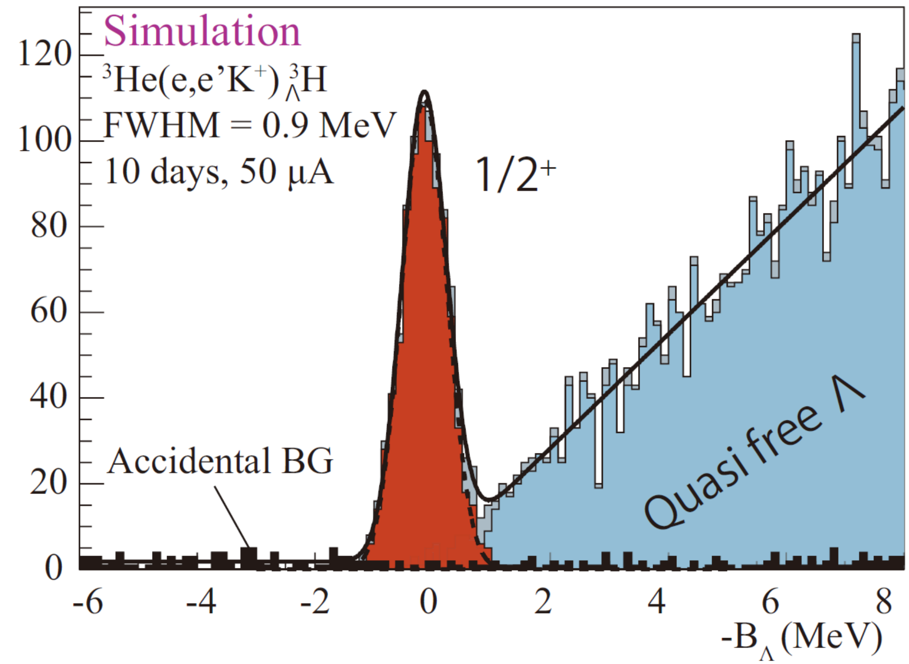


$^{4}_{\Lambda}$H

Expected spectra



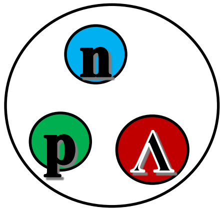
$\Delta B_{\Lambda}^{\text{stat.}} < \pm 20$ keV



$\Delta B_{\Lambda}^{\text{stat.}} < \pm 20$ keV

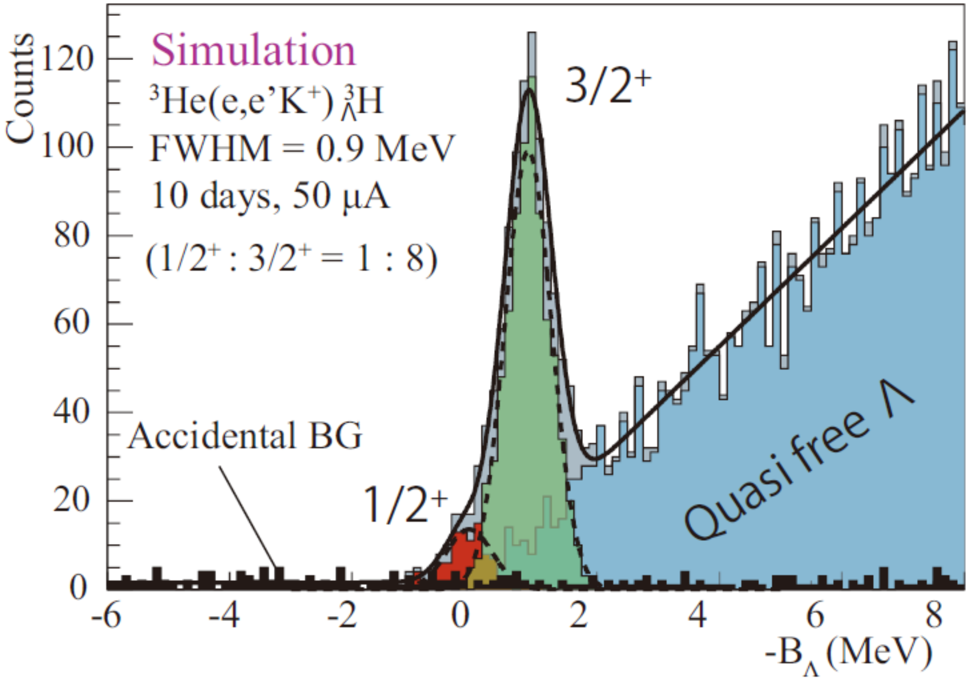
- Cross section of signals: simulated based on E91-016 results
- Distribution of quasi free Λ: E91-016
- Accidental background: E05-115
- Resolution: MC simulation assuming spectrometers' specifications

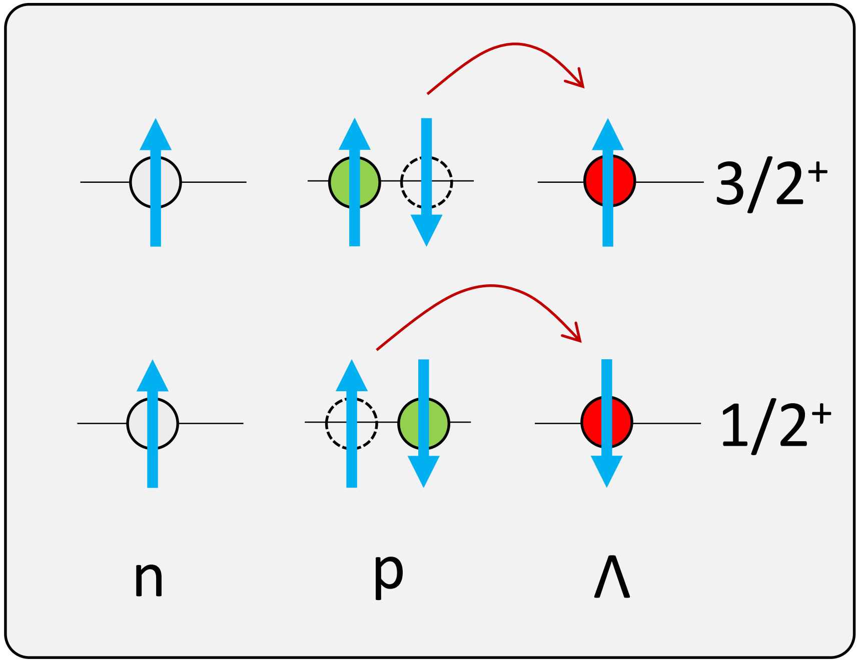
Expected ${}^{3}_{\Lambda}\mathrm{H}$ spectrum



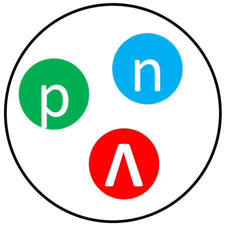
<u>1/2⁺: 3/2⁺ = 1:8</u> in the (γ,K⁺) reaction

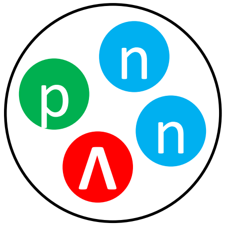
T. Mart et al., *Phys. Rev. C* **78**, 014004 (2008)





Summary (C12-19-002)





Accrate B_{Λ} measurements that are unique at JLab (2021?)

- $^{3}\mathrm{He}(e, e'K^{+})^{3}_{\Lambda}\mathbf{H}$ (1/2+, 3/2+) ➔ **Hypertriton puzzle** (10 days)
- $^{4}\mathrm{He}(e, e'K^{+})^{4}_{\Lambda}\mathbf{H}$ (1+) ➔ **ΛN CSB** (1 day)

We request additional 12 days to E12-15-008 ($^{40,48}_{\Lambda}\mathbf{K}$)

- Installation time (~0.5 year) can be shared
- Calibration data can be shared