Analysis Update on the E12-17-003 Experiment

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Jefferson Lab Experiment: E12-17-003
Data Taken: November 2018

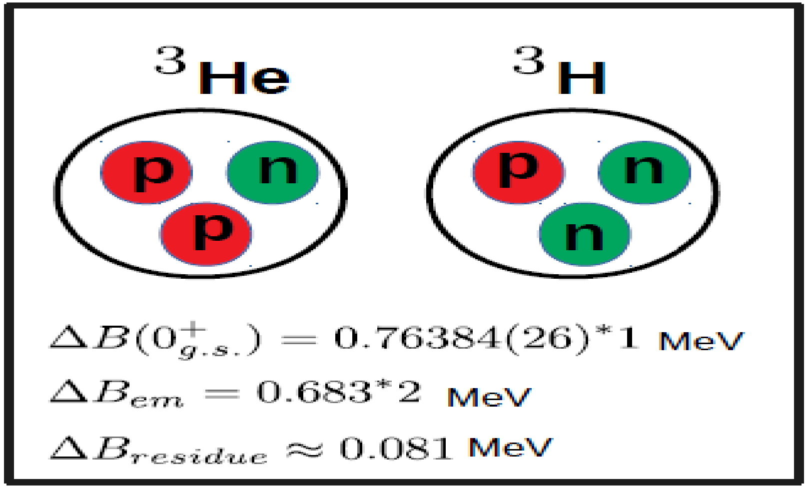
Outlines:

- Physics Motivation
- System optimization
- Analysis result
- Conclusions
- Acknowledgments

Physics Motivation:

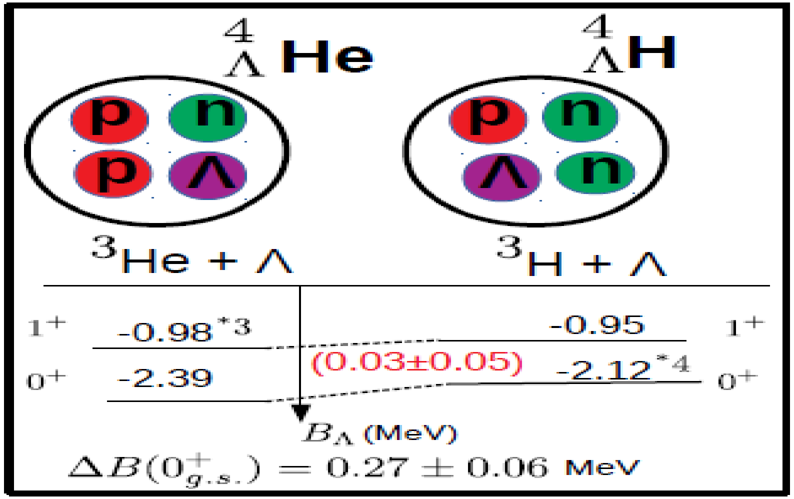
- The addition of the strangeness degree of freedom to the nuclear medium provide opportunities to study the unknown properties of the baryonic interactions in a practical way which may not be possible from the investigation of the ordinary NN interaction.
- However, limited data exists for the YN or YY interactions.
- The Λp scattering data exist but the data is poor with low statistics and high error bars.
- The Λn interaction data does not exist.
- The Λn interaction has been considered as identical with Λp interaction.

Charge Symmetry Breaking Puzzle:



*1. J.H.E. Mattauch et.al., Nucl. Phys. **67**, 1(1965)
*2. R.A. Brandenburg et.al., NPA. **294**, 305(1978)

(a) N-N Interaction



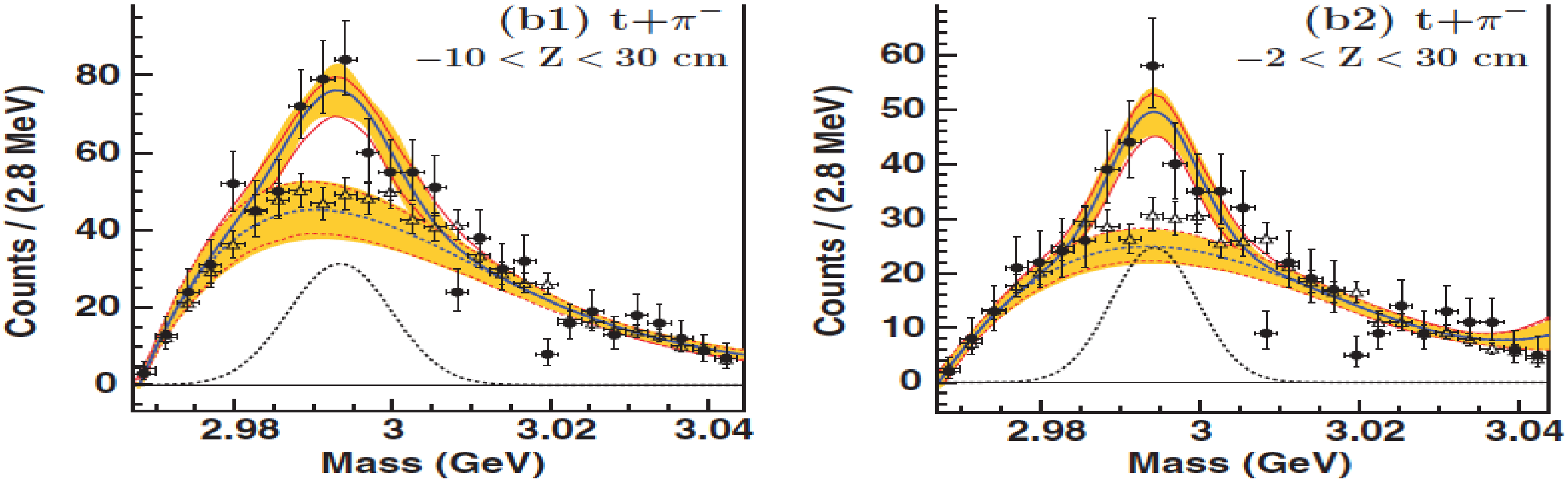
*3. T.O. Yamamoto et.al., Phys. Rev. Lett. **115**, 222501 (2015)
*4. A. Ester et.al., Phys. Rev. Lett. **114**, 232501 (2015).

(b) Y-N Interaction

- For A = 3 non-strange mirror pair of nuclei, ignoring the Columb interaction between the protons, the binding energy difference is ~ 80 KeV.
- For A = 4 isospin mirror pair of hypernuclei, the charge symmetry breaking (CSB) is more than 3 times larger than that observed in A = 3 mirror pair of nuclei.
- This strongly suggested that the Λn interaction need to be measured experimentally.

Approach to Access Λ-n Interaction:

^{6}Li (2A GeV) on ^{12}C target and study the invariant mass of final state particles



*C. Rappold et al., Phys. Rev. C **88**, 041001(R) (2013)*

- It was claimed to be a bound state.
- All theoretical studies ruled it out.
- However, some theoretical studies indicated that the Λnn resonance may likely exist and by measuring the binding energy and the natural width of such state, it is possible to extract the Λ-n interaction.

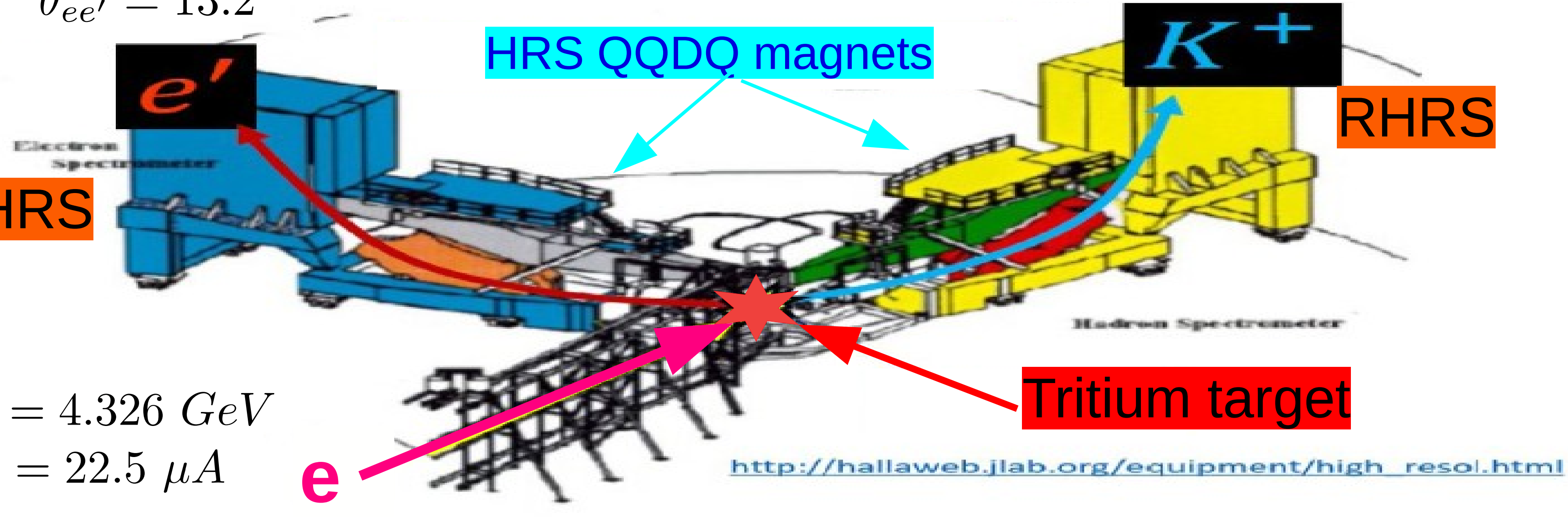
Experimental Setup for the E12-17-003 Experiment:

1. H kinematics
Target: H
p_e = 2.1 GeV/c

2. T kinematics
Target: H, He, T
p_e = 2.218 GeV/c

$$p_{e'} = 2.218\ GeV/c \pm 4.5$$
$$\theta_{ee'} = 13.2^\circ$$

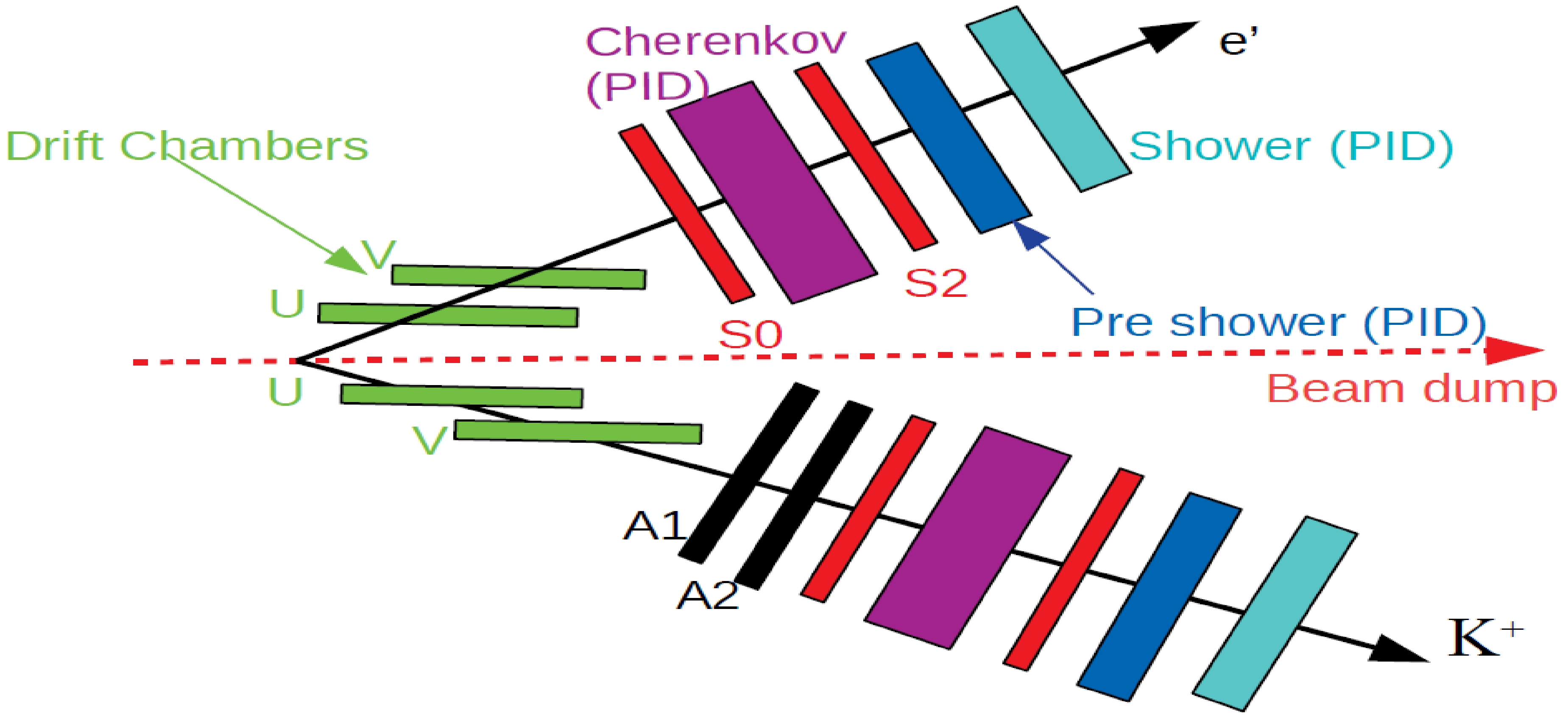
$$p_{K^+} = 1.823\ GeV/c \pm 4.5$$
$$\theta_{eK^+} = 13.2^\circ$$



$$E_e = 4.326\ GeV$$
$$I_e = 22.5\ \mu A$$

- The experimental Hall A with tritium target was aimed to search for the resonance or the bound state as indicated by the HypHI experiment.

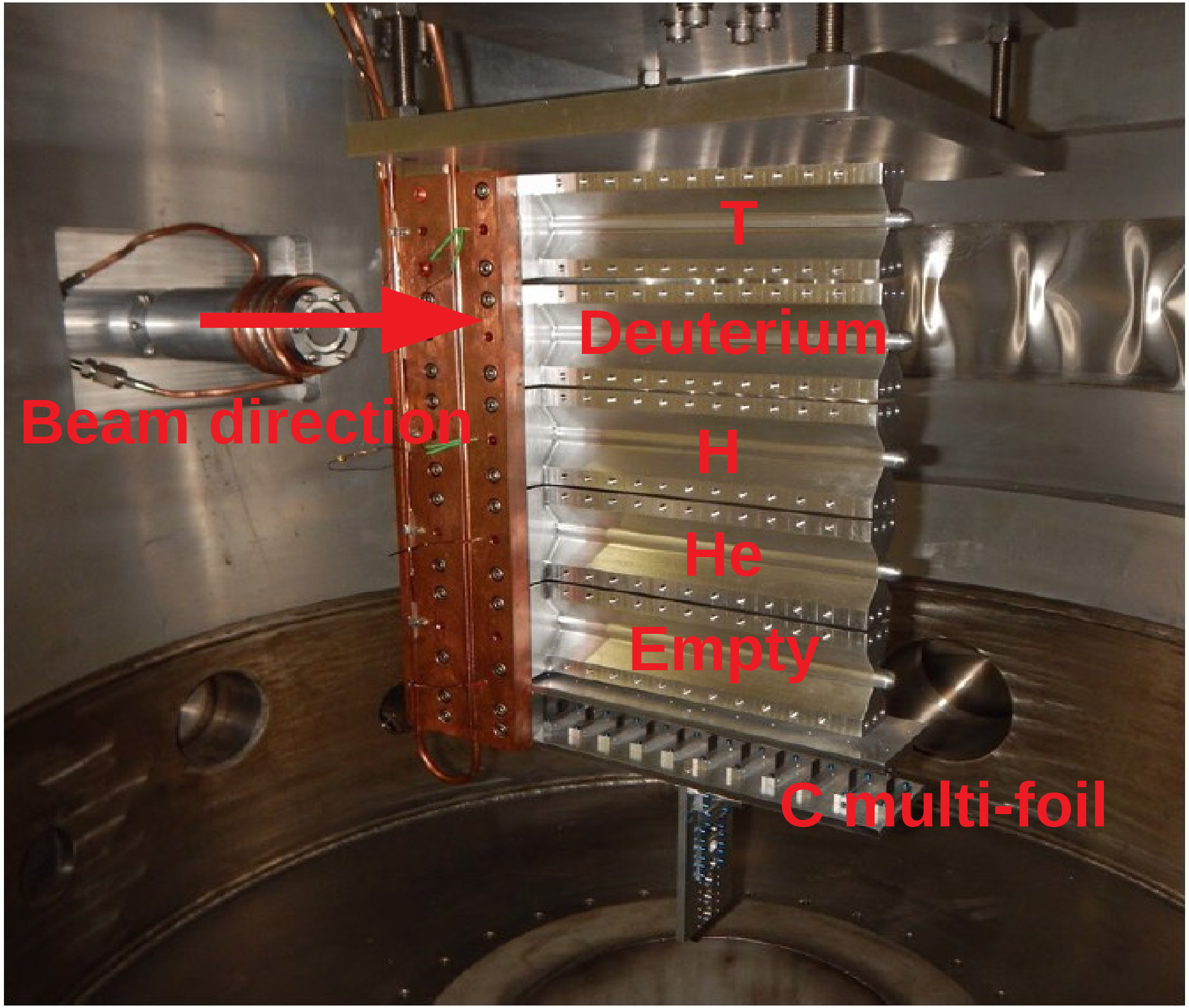
Hall A Detector System for the E12-17-003 Experiment:



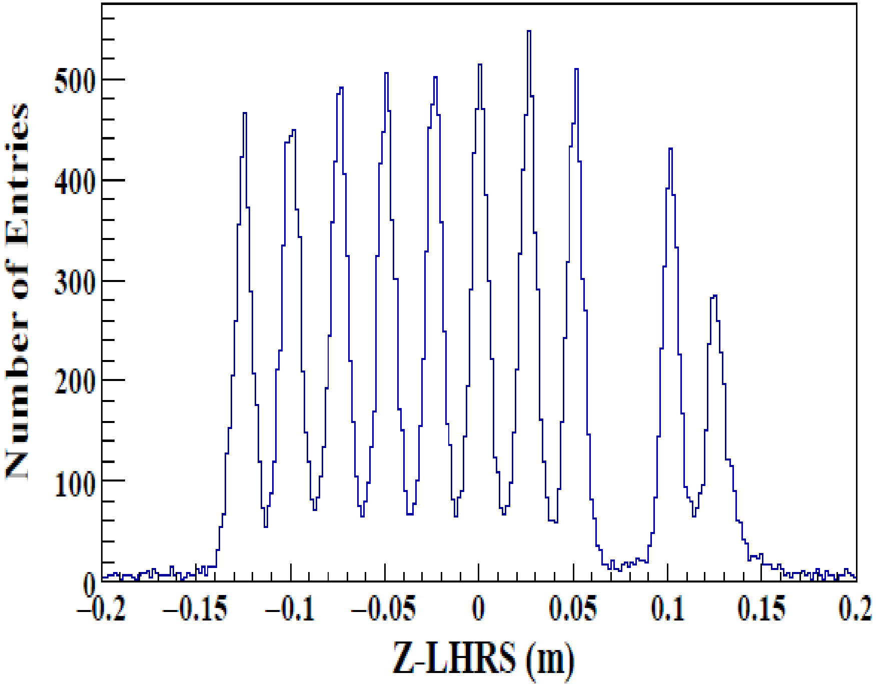
- The HRS detector system is capable to provide the particle tracking, timing, identification and the triggering information.
- At RHRS, two additional Aerogel Cherenkov detectors were installed as the KID detectors.

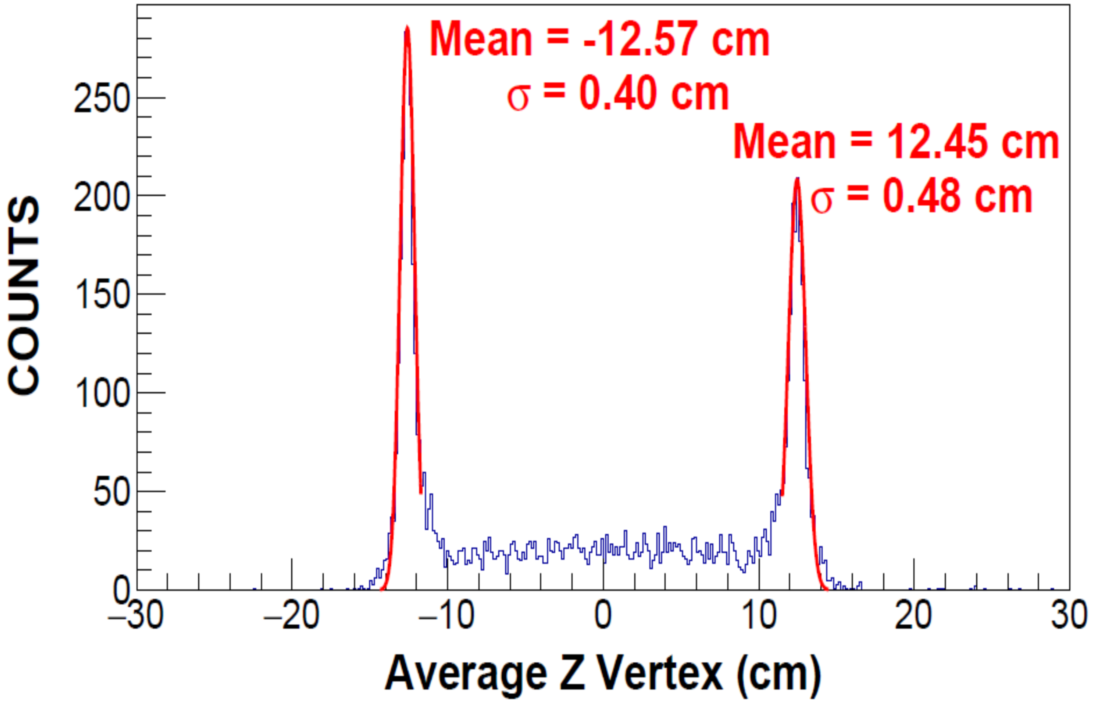
The Gas Target System:

- The gas was filled in a cylinder made of 7075 aluminum alloy.
- The length of the cylinder was ~25 cm and diameter ~12.7 mm.
- The target cell has a modular design.
- Since the tritium is radioactive, to minimize the safety hazards associated with the tritium target, a special target system with three layers of confinement was designed during the operation.



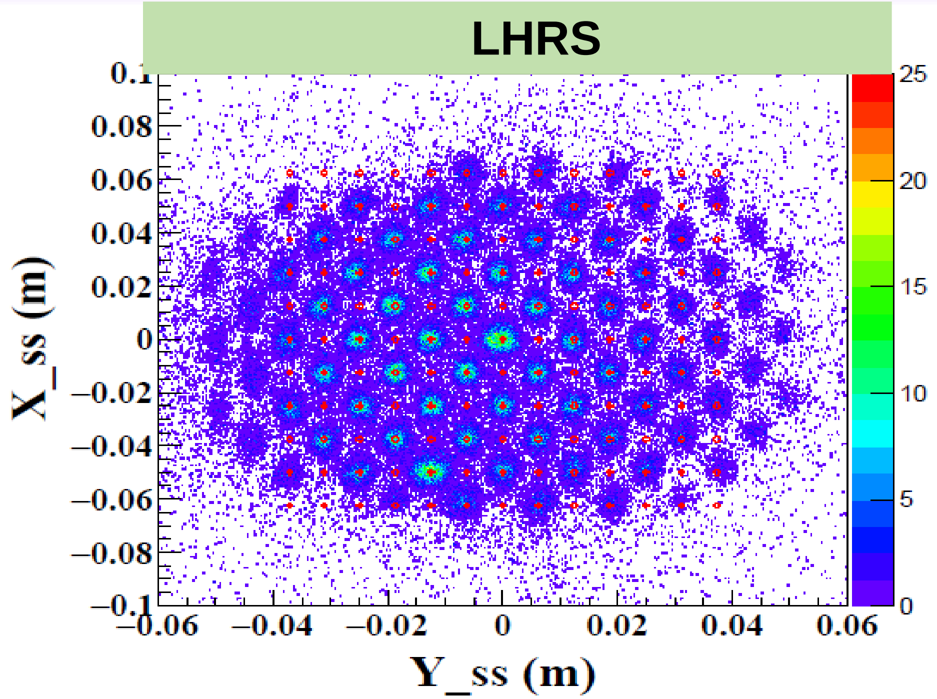
Z-vertex with Optimized Matrix:

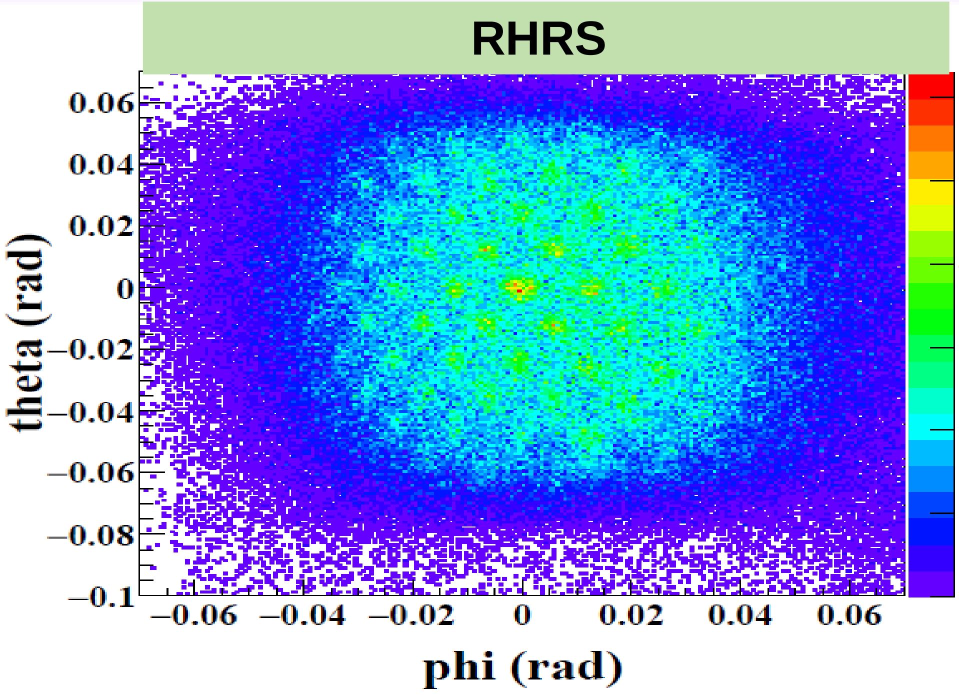




- Each *z*-vertex was optimized separately with the single arm trigger data.
- For the e’ and K^+ coincidence data, the average of the two independently reconstructed *z*’s from LHRS and RHRS was used as average *z*.
- A *z*-vertex resolution of about σ = 4.5 mm was achieved.
- For physics analysis, the average *z*-vertex ranging from -10 cm to 10 cm was used.

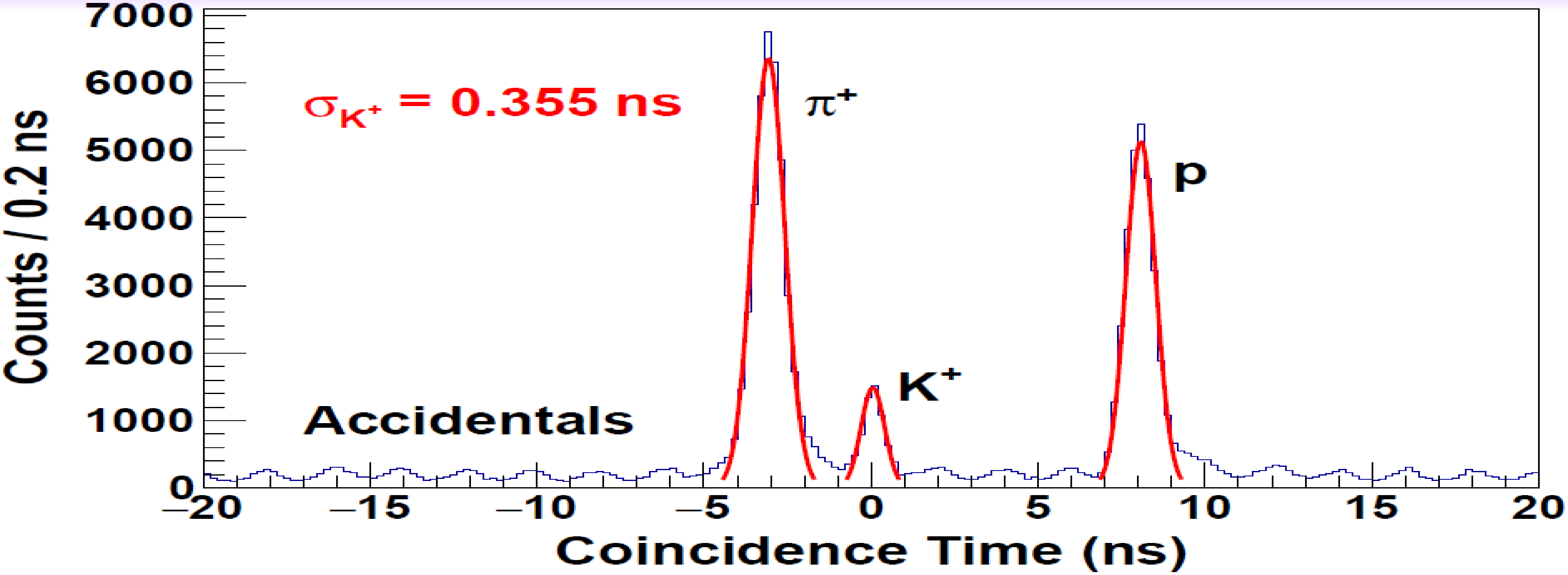
Reconstructed angles with Optimized Matrices:





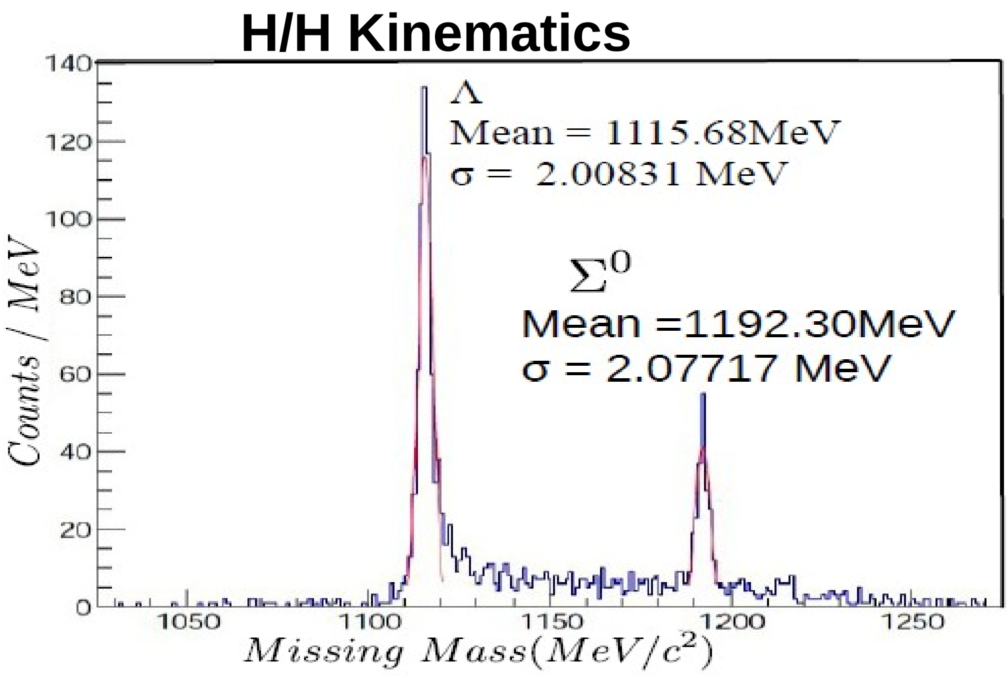
- For the LHRS, the thickness of the SS plate was sufficient to stop the electrons that did not pass through the SS holes.
- For the RHRS, the thickness of the SS plate was unable to prevent the heavy particles (such as π^+'s and protons) that did not pass through the SS holes.
- A large number of hadrons punching through the SS plate and could reach to the focal plane.
- Therefore, a huge background can be seen between the RHRS SS holes.

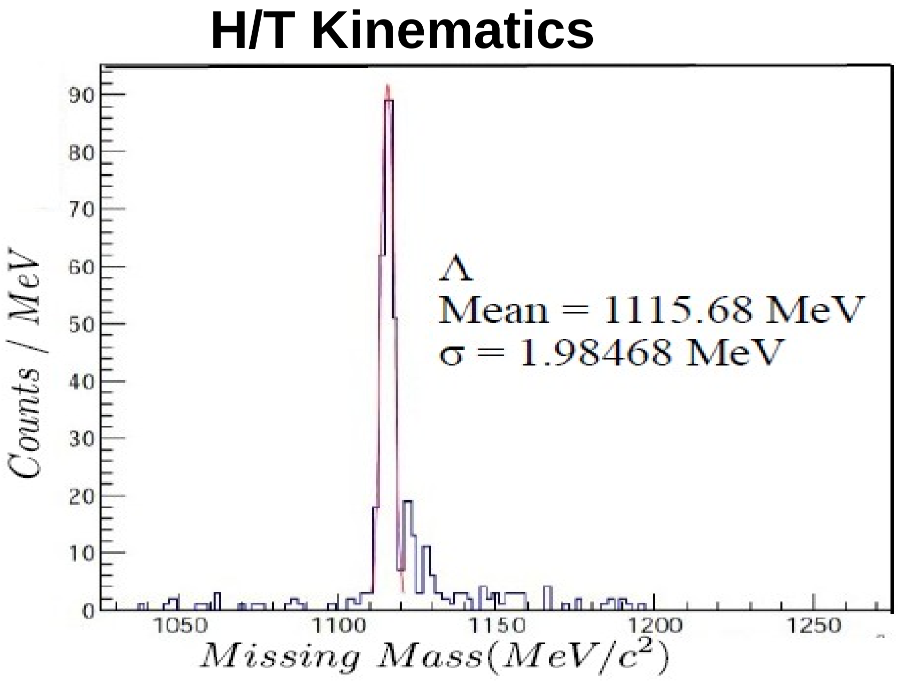
Coincidence Time Spectrum:



- Different hadrons have different CT, therefore CT can be used as a powerful tool to remove the unnecessary hadrons in the RHRS.
- For physics analysis a coincidence time gate of ± 1 ns was used to select the coincidental K^+'s.
- The small accidental peaks were formed by the accidental coincident events from π^+'s & protons.
- The accidental events within the ± 1 ns coincidence time window cannot be identified and removed. These events will form a background distribution in the physical mass spectroscopy.

Momentum Optimization:

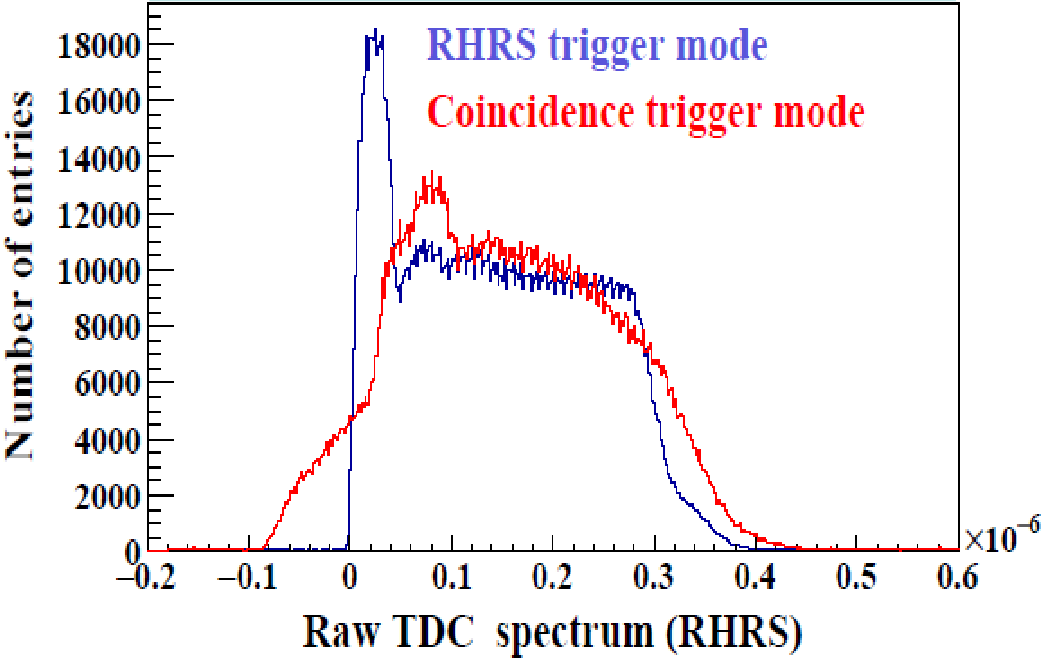




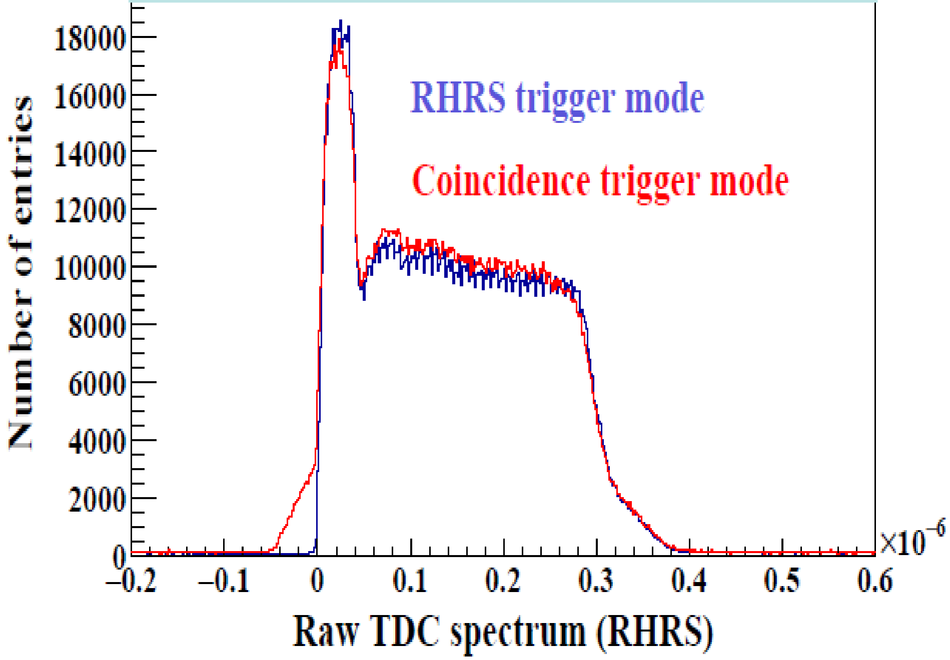
- The events from the free Λ and Σ^0 produced by the (e, e'K^+) reaction were used to optimize the HRS momentum matrices.
- With the optimized system, the resolution of Λ and Σ^0 was achieved about 2 MeV (σ).
- Further tune did not improve the optics quality.
- Two problems were recognized: (i) the time jitter for the RHRS VDC and (ii) the dependence on the residual angular uncertainties.

Time Jitter Correction:

Before time jitter correction

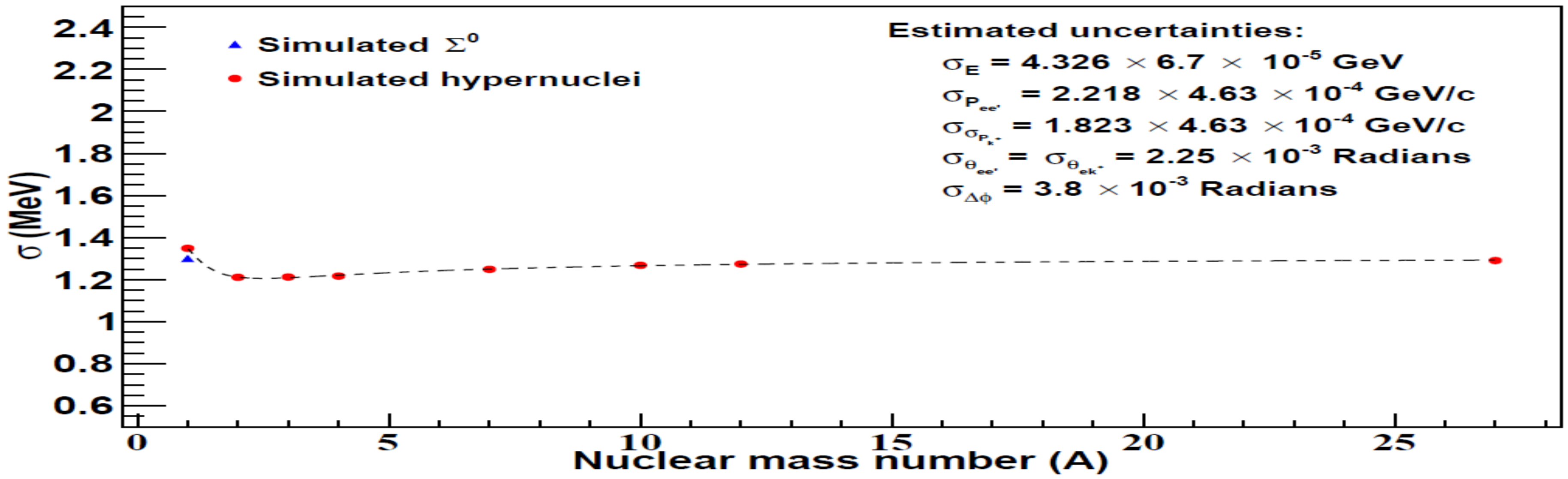


After time jitter correction



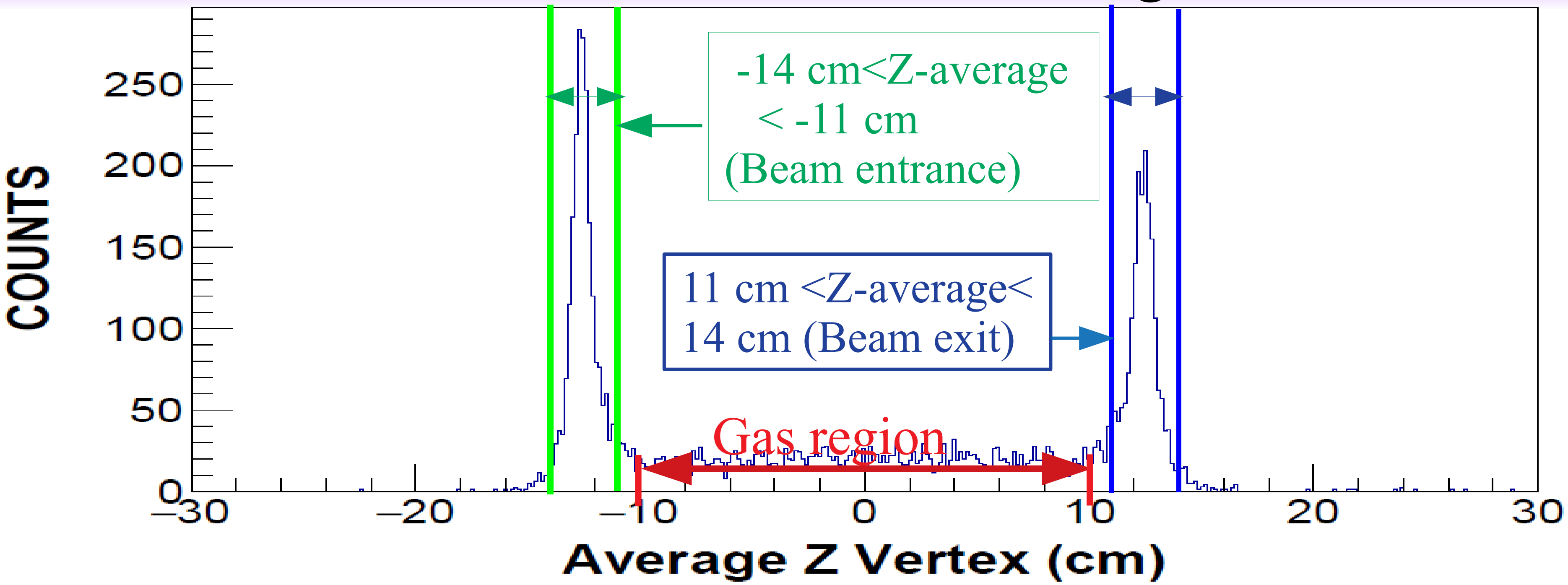
- For the coincidence events at the right arm, the VDC’s drift time was found having a time jitter and affecting the momentum optimization as well as the missing mass resolution.
- This problem was minimized by applying a software correction on an event-by-event base to the raw TDC data.

Simulation of A dependence of Missing Mass Resolution:



- With the estimated uncertainty contributions from beam energy, momenta from e' & K^+ and scattering angles, the A dependence of missing mass resolution was simulated.
- The scattering angle uncertainty dominated for A =1 system, while the energy and momentum uncertainties dominated for the system with A>7. For A = 3 system, all uncertainties evenly contribute.
- This suggested that to improve the momentum resolution further, a heavy mass system with negligible angular dependence needs to be involved in the matrix tune along with the Λ and Σ^0 masses.

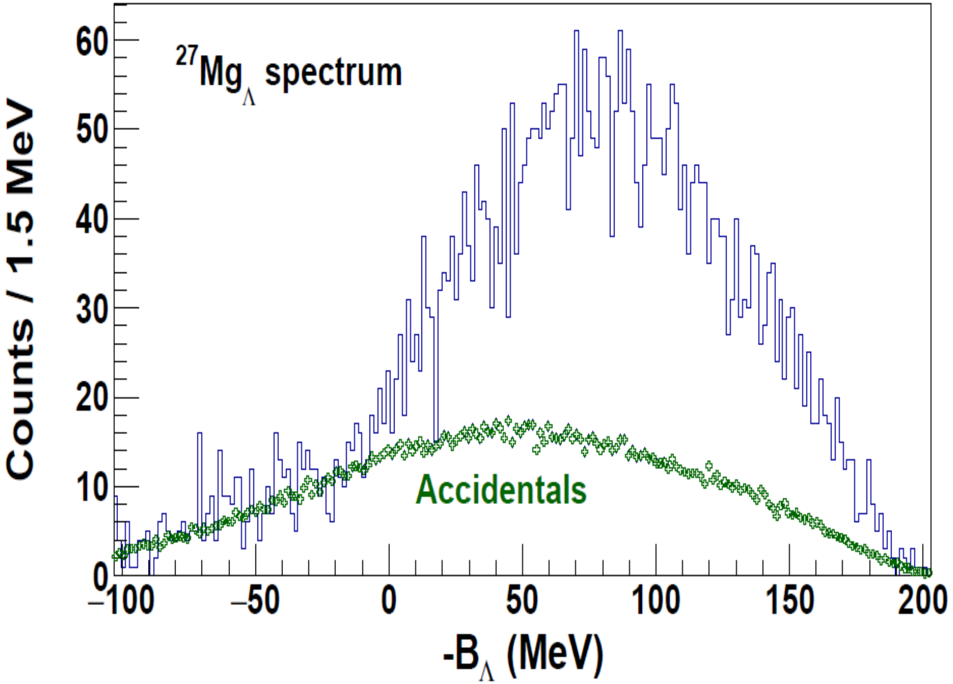
Al is Considered as a Target:



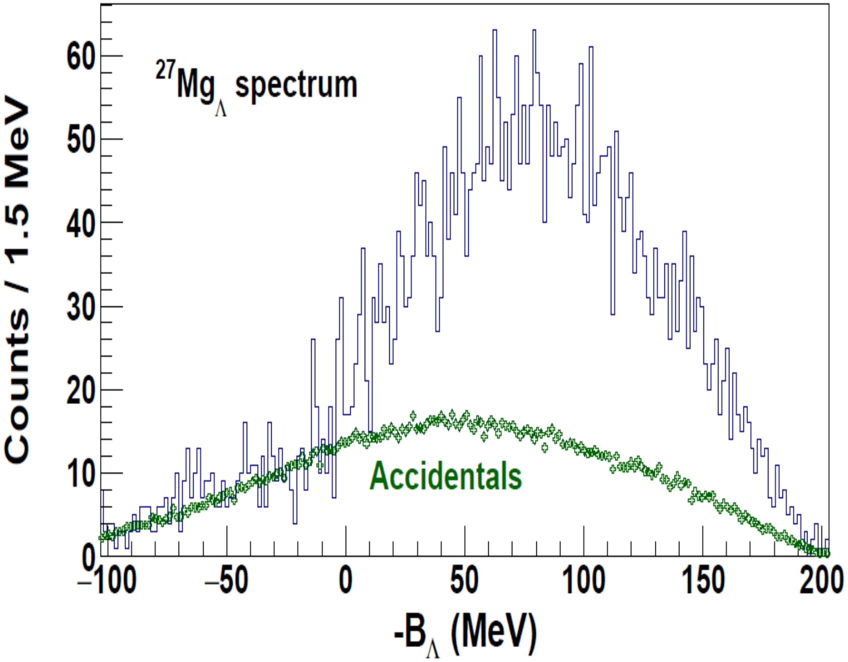
- The target cell was made of 7075 aluminum alloy (~ 90% ^{27}Al, ~5.6 % Zn, ~2.5% Mg, ~1.6% Cu and ~ 0.3% other metals) in which ^{27}Al was dominant.
- The main role of the ^{27}Al was try to find the best possible state which is sufficiently heavy so that momentum Matrix will not be suffered from the angular uncertainty and the Λ and Σ^0 will play the role of boundary conditions.
- The events from the beam entrance and beam exit Al windows were selected and combined together to produce the $^{27}{}_{\Lambda}$Mg hypernuclei.

Al Data Involved in Matrix tune Along with Λ and Σ^0 Masses:

Before Al data involve in Tune

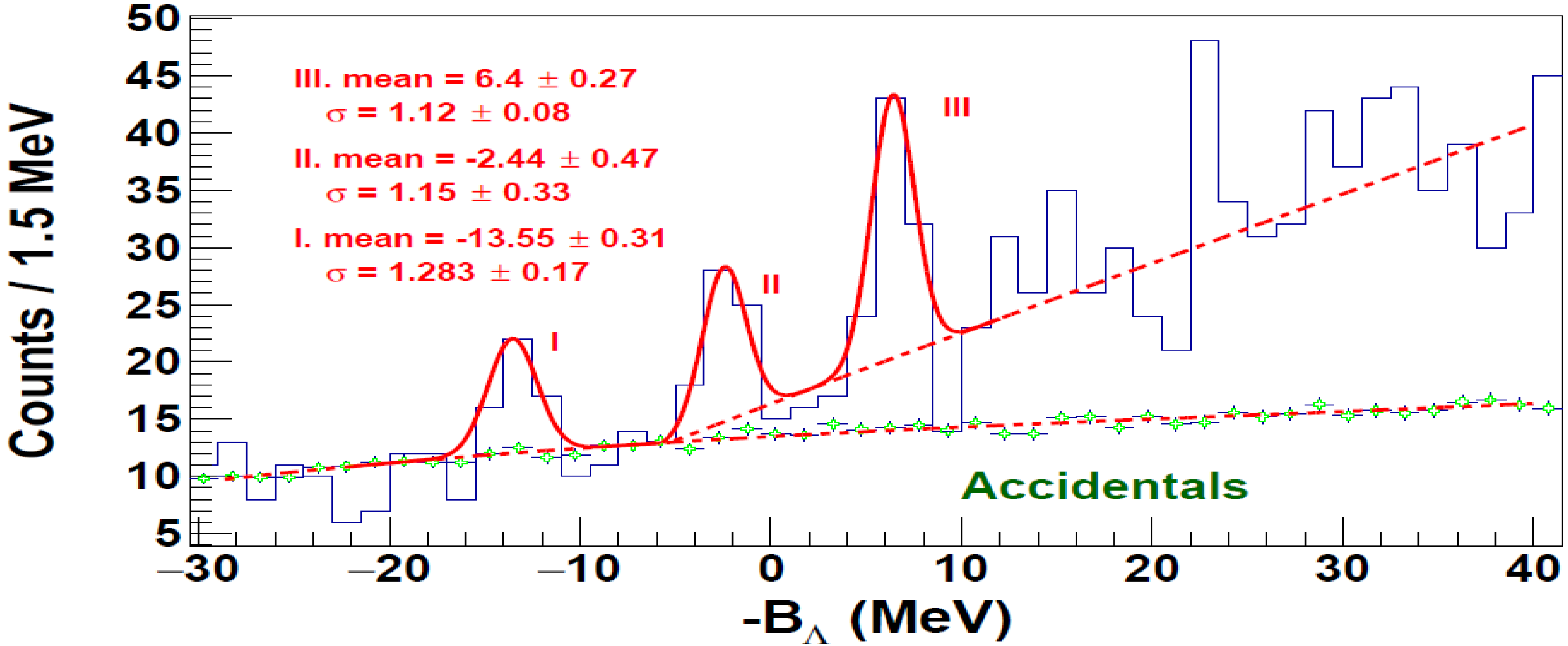


After Al data involve in Tune



- To involve the Al data in the matrix tune, a peak search test was performed to find the events from the possible single particle state.
- Initially events were gated within the wide region (-20 to -10 MeV, -10 to 0 MeV and 0 to +10 MeV).
- After involving the Al data, 3 peak structures are appeared, 2 of which are in a bound region.
- The resolution of the Al peaks agreed well with the simulation.

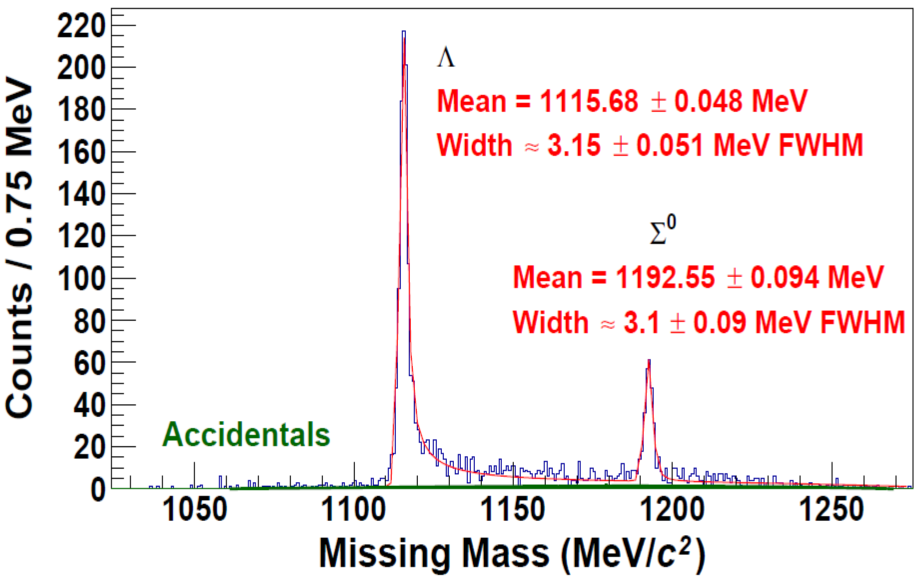
Closer view of 27Mg_L spectrum



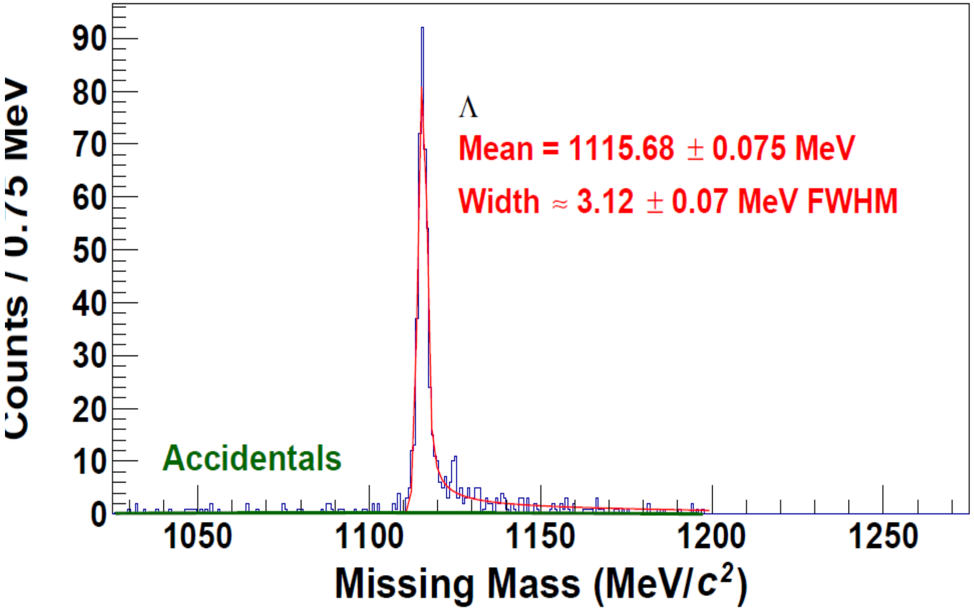
- To make the clear view of the 27Mg_L spectrum, the spectrum is plotted from -30 to 40 MeV.
- The three peak structures are observed which are located at -13.55, -2.44 and 6.4 MeV respectively.
- The statistical significance of the 1st, 2nd and 3rd peaks are 2.7,3.57, and 4.18 respectively.

Missing Mass Spectrum:

H/H Kinematics

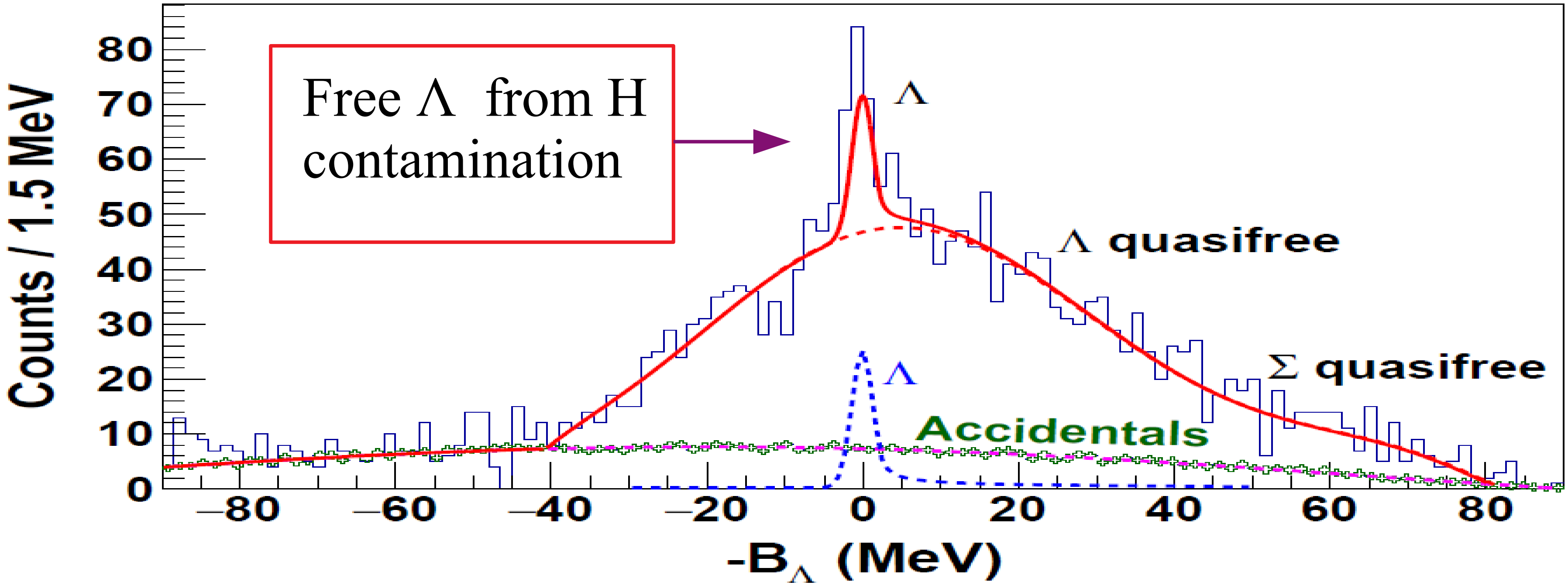


H/T Kinematics



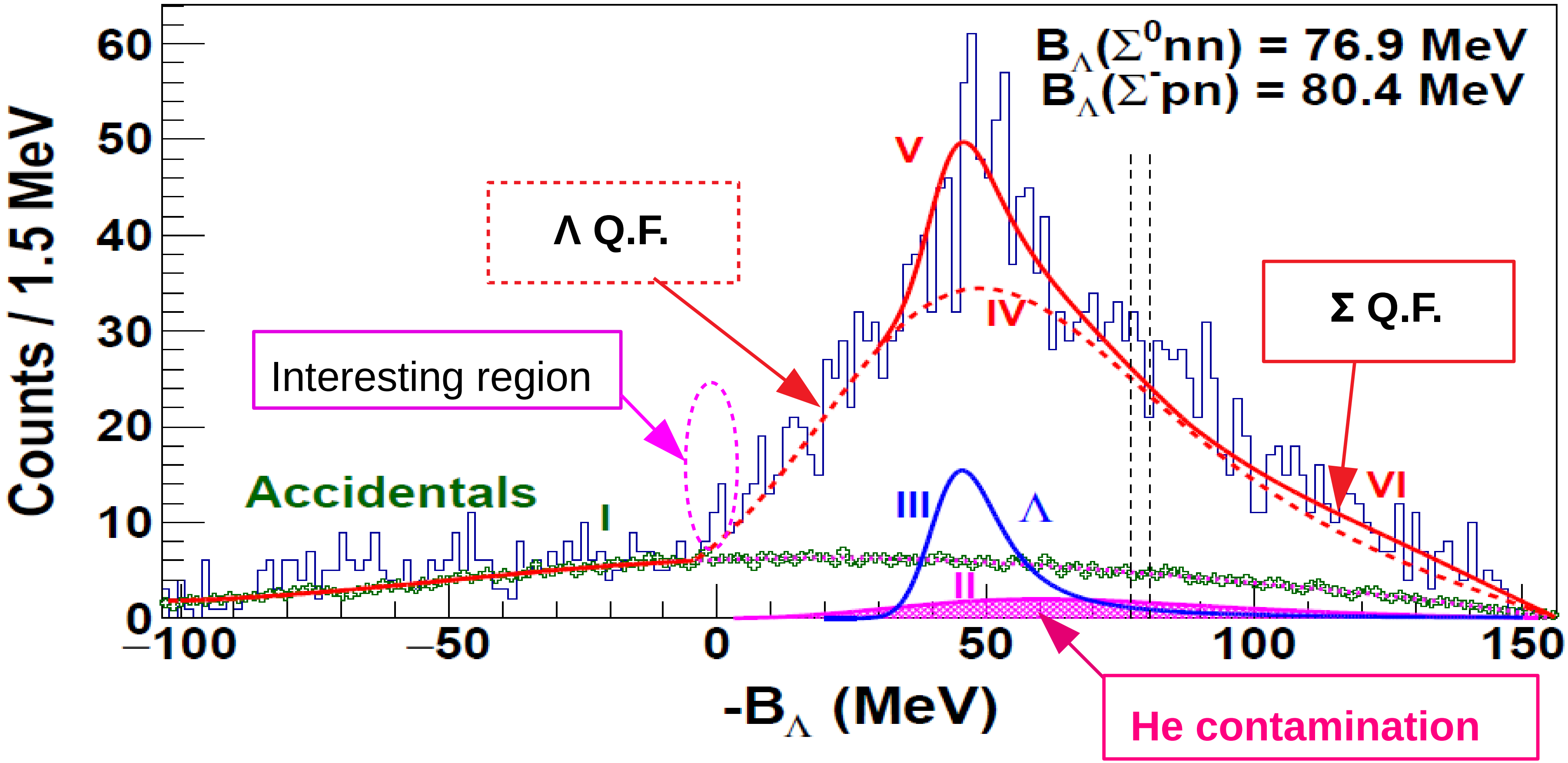
- These are the important data sets used for the absolute missing mass calibration.
- The Λ and Σ^0 landed at their known masses with a separation of 76.87 MeV/c² (Nominal separation = 76.96 MeV/c²).
- Achieved resolution of Λ and Σ^0 agreed with the simulation.
- Systematic uncertainty for the missing mass (binding energy) found ~ 108 keV.

Hydrogen Contamination Test:



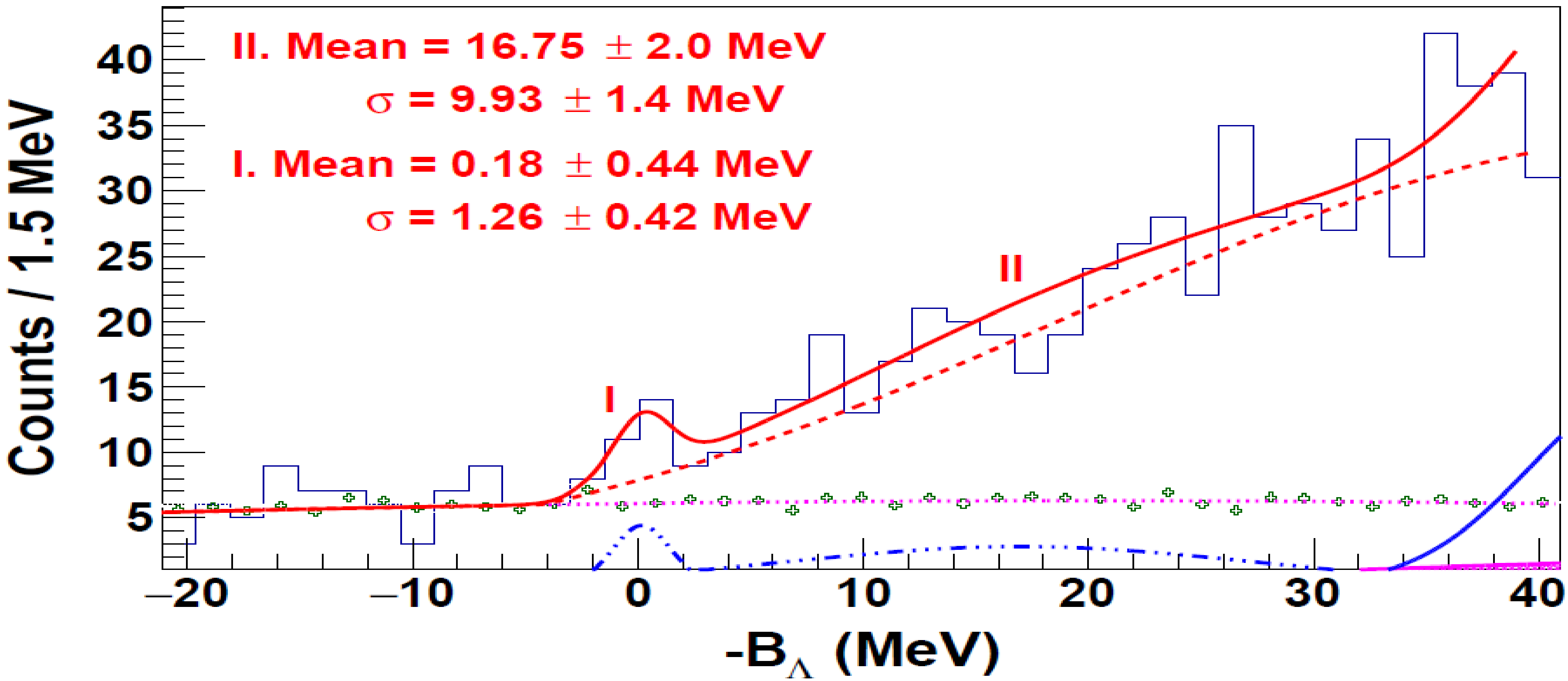
- The previous tritium experiment (E12-11-112) reported that about 2% of H was present in the tritium gas.
- To confirm this, the tritium data were then analyzed by H kinematics, the clear peak at $B_\Lambda = 0$ MeV verifies the presence of H in the tritium gas.
- A similar peak is expected in the Λnn spectrum with the broader width.

Λnn Spectrum



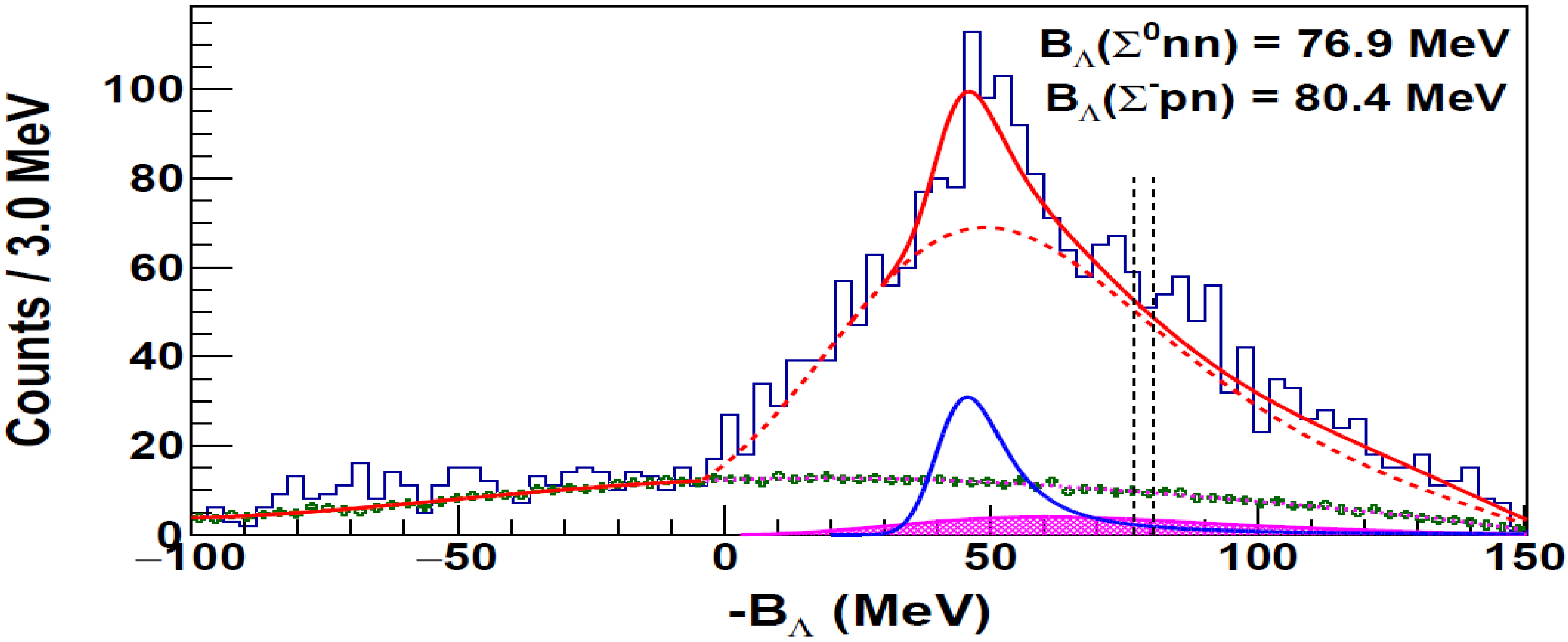
- The Λ/Σ QF shape is obtained by fitting the SIM A simulated data.
- The free Λ curve is obtained by fitting the H data in T kinematics and considering Tritium as target and Λnn as threshold mass.

Closer view of Λnn Spectrum



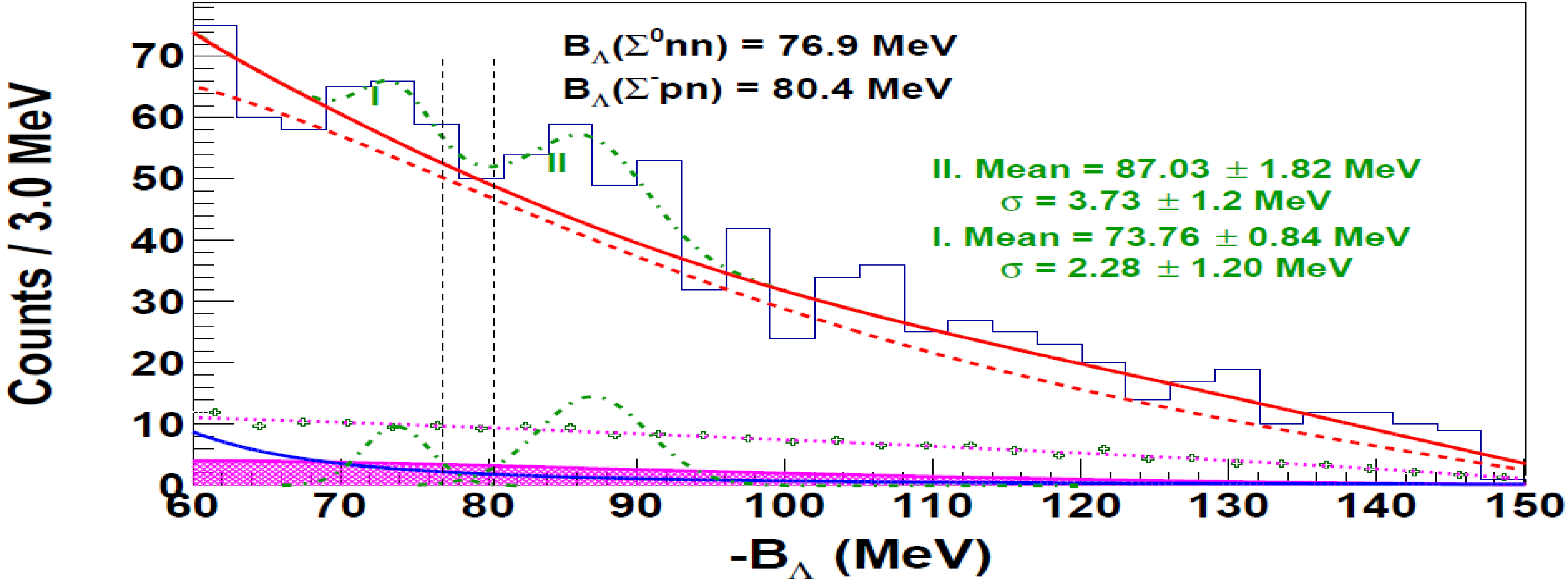
- To make the clear view of the Lnn spectrum, the spectrum is plotted from -20 to 40 MeV.
- The 1st peak is possible to be the expected resonance. However, the statistics is very low.
- The statistical significance of the 1st peak is found about 2.7.
- To make a definite conclusion, higher statistics are needed.

Mass Spectroscopy with Widerer Bins:



- In order t o reduce statistical fluctuation (especially near the ΣNN threshold region) the same Λnn spectroscopy is plotted with the wider bins.

Mass Spectroscopy of $^{3}_{n}\Lambda$:



- To make the clear observation, the wider bin spectrum is plotted from 60 to 150 meV.
- It looks like near the ΣNN threshold lines there are two enhancements.
- The enhancement might be the signature of the ΣNN hypernuclei which has been predicted long ago. However the statistics is not enough to make a solid conclsion.
- The statistical significance of these peak is studied and found about 2.4 and 5.0 respectively.

Conclusions:

- The experiment demonstrated that by using the tritium target and $(e,e'K^+)$ reaction, it is possible to observe the 3-body neutral Λ and Σ hypernuclei. However, Hall A system need to be optimized for higher statistics.
- From this experiment one small enhancement near the Λnn thresholds and two enhancements near the ΣNN thresholds are observed. However, to make a definite identification, higher statistics are required.
- A simulation predicted the intrinsic missing mass resolution of A = 3 resonance to be σ = 1.21 MeV. Thus, the natural width is about 0.35 MeV.
- However, due to low statistics the precision does not permit sufficient constrain in determination of the Λ-n Interaction.

Future Suggestions:

- The electron arm was at very large angle $\theta_{e'}$ = 13.2°, produces large Q^2 = 0.5 $(GeV/c)^2$ which results low production yield.
- The path length for the hadron arm was too large (~ 26 m) which limits the K^+ survival rate ~ 10 %.
- The $\vec{q}(\Lambda)$ is too high ~ 400 MeV/c which gives very small value of $d\sigma/d\Omega$.
- The K^+ efficiency of the Aerogel detector was very low.
- The RHRS SS plate can not stop the hadrons that do not pass through the SS holes, therefore for any future measurement, the SS plate need to be replaced.

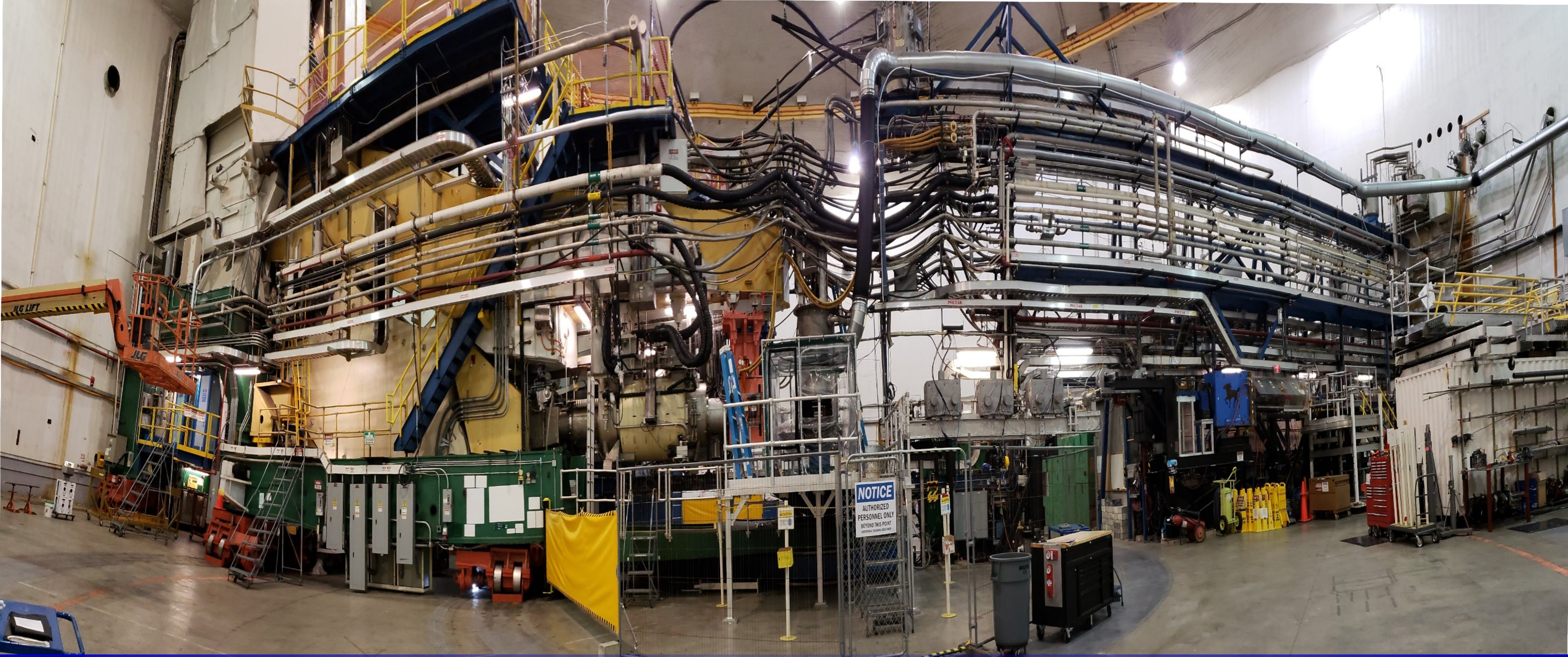
Acknowledgements:

Financial Support:

- This work is supported by US-DOE grant DE-FG02-97ER41047 and Japan-JSPS KAKENHI Grants No. 18H05459 and 17H01121.

Collaborators:

- The whole HKS collaboration and spokes persons of the experiment
- Hall A collaboration, tritium group students and postdocs
- Hall A technical staffs, target group, and accelerator staffs



Thank you

Statistical Significance:

For the observed peaks in the spectrum, their statistical significance were calculated by selecting the events witin the range of ± 2.0σ from the observed mean. The statistical significance was calculated by:

$$S = \sqrt{2n_0 ln(1 + s/b) - 2s}$$

where, n0 is the total number of events, s is the number of real events and b is the number of background events.

Missing Mass:

- The electro-production of Λ (Σ^0) from a proton target is expressed as:

$$e + p = e' + K^+ + \Lambda\ (hyp)$$

- The e' and K^+ can be detected by two spectrometers, however the Λ can not measured directly because it is a neutral particle with extremely short lifetime.

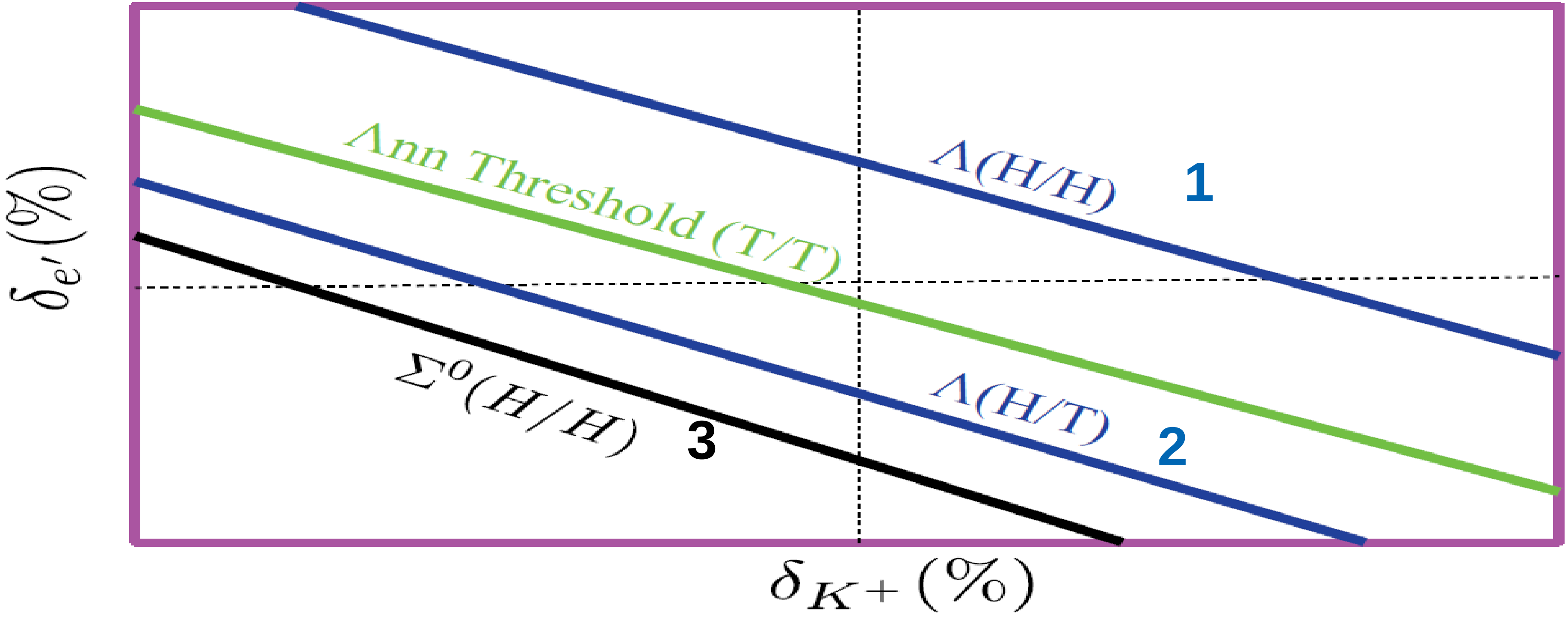
- For e' and K^+, their focal plane measured information (positions and angles) are converted into the momentum vectors at the target by using the backward transfer matrices. Then the missing mass can be calculated by using the energy and momentum conservation principles.

- From the energy conservation principle: $E_{hyp} = E_e + M_p - E_{e'} - E_{K+}$

  and from the momentum conservation principle: $\vec{p}_{hyp} = \vec{p_e} - \vec{p_{e'}} - p_{\vec{K^+}}$

- Finally, with the known value of HRS angles and momentum, the missing mass can be calculated by, $(M_{hyp})^2 = (E_{hyp})^2 - (p_{\vec{hyp}})^2$

Kinematic Space for e,e'K+ Experiment:



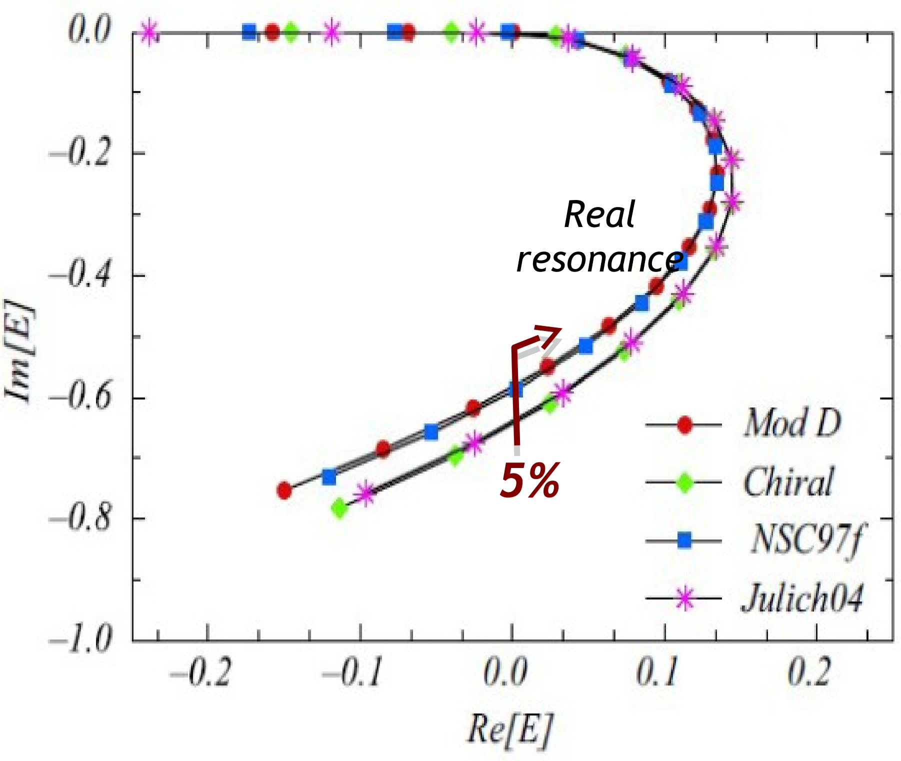
- The momentum calibration is the two dimensional correlation.
- There are only three data point to calibrate the momentum matrices.
- There is large kinematic gap between the two Λ correlation lines.
- The optics quality may not be uniform in the gap region.

Model Describing the Λnn Resonance:

- Four different baryonic potential model were used to fit for the effective range parameters of the nn and Λp interactions from the existing scattering data.

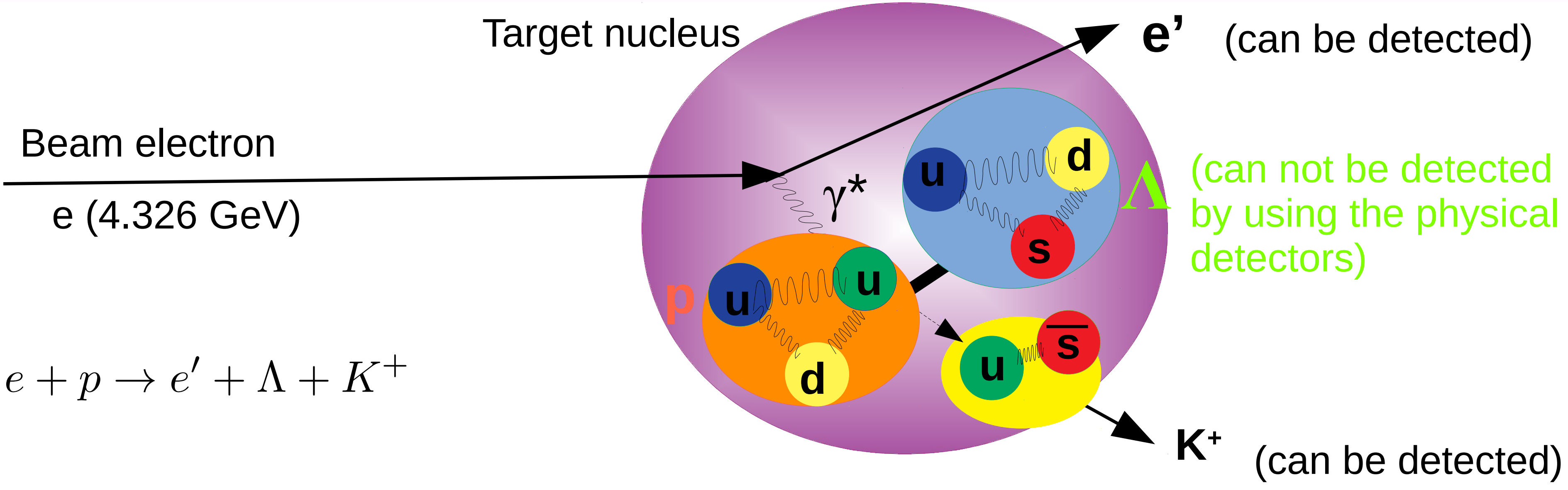
- They solved the Λnn Faddeev equations into the second complex energy (E) plane in the search of resonance.

- The Λp and Λn interactions are assumed same to begin. Continuously scaling up the Λn strength by 2.5 % in each step to obtain the eigenvalue spectrum.



Iraj R. Afnan and Benjamin F. Gibson, Phys. Rev. C 92, 054608(2015)

How to produce Hyperons at Jefferson Lab?:



$$e + p \rightarrow e' + \Lambda + K^+$$

- A high energy electron scattered of a proton target by exchanging a virtual photon.
- The virtual photon interacts with the proton resulting a Λ (uds) and a kaon (us̄).
- The hyperon (Λ) can not be measured directly, therefore to measure the hyperon missing mass (MM) method is used.

The E12-17-003 Kinematics:

The data were collected with two different kinematics.

1. Hydrogen (H) kinematics:

Target	Beam energy (GeV)	HRS angles (degree)	RHRS central momentum (GeV/c)	LHRS central momentum (GeV/c)
H	4.326	13.2	1.823	2.1

- In this kinematics, both Λ and Σ^0 were produced for the kinematics calibration.

2. Tritium (T) kinematics:

Targets	Beam energy (GeV)	HRS angles (degree)	RHRS central momentum (GeV/c)	LHRS central momentum (GeV/c)
H, He, T	4.326	13.2	1.823	2.218

- In the T kinematics, the Λ from the H/T data was also used for the kinematics calibration. In this kinematics Σ^0 was out of acceptance.
- The T data was taken to study the Λnn spectroscopy.

Took All Types of Data for the Analysis:

1. Optics data
   Target: Carbon multi-foil w/ and w/o raster and with sieve slits in.
   Target: Dummy target for background analysis.
   Purpose: To optimize the various reconstructions such as z-vertex reconstruction, raster calibration and HRS angle reconstruction.

2. Calibration data :
   Target: H (with H/H and H/T kinematics)
   Purpose: Kinematics calibration with known Λ and Σ^0 masses and for the determination of the absolute beam energy and spectrometer central momentum.

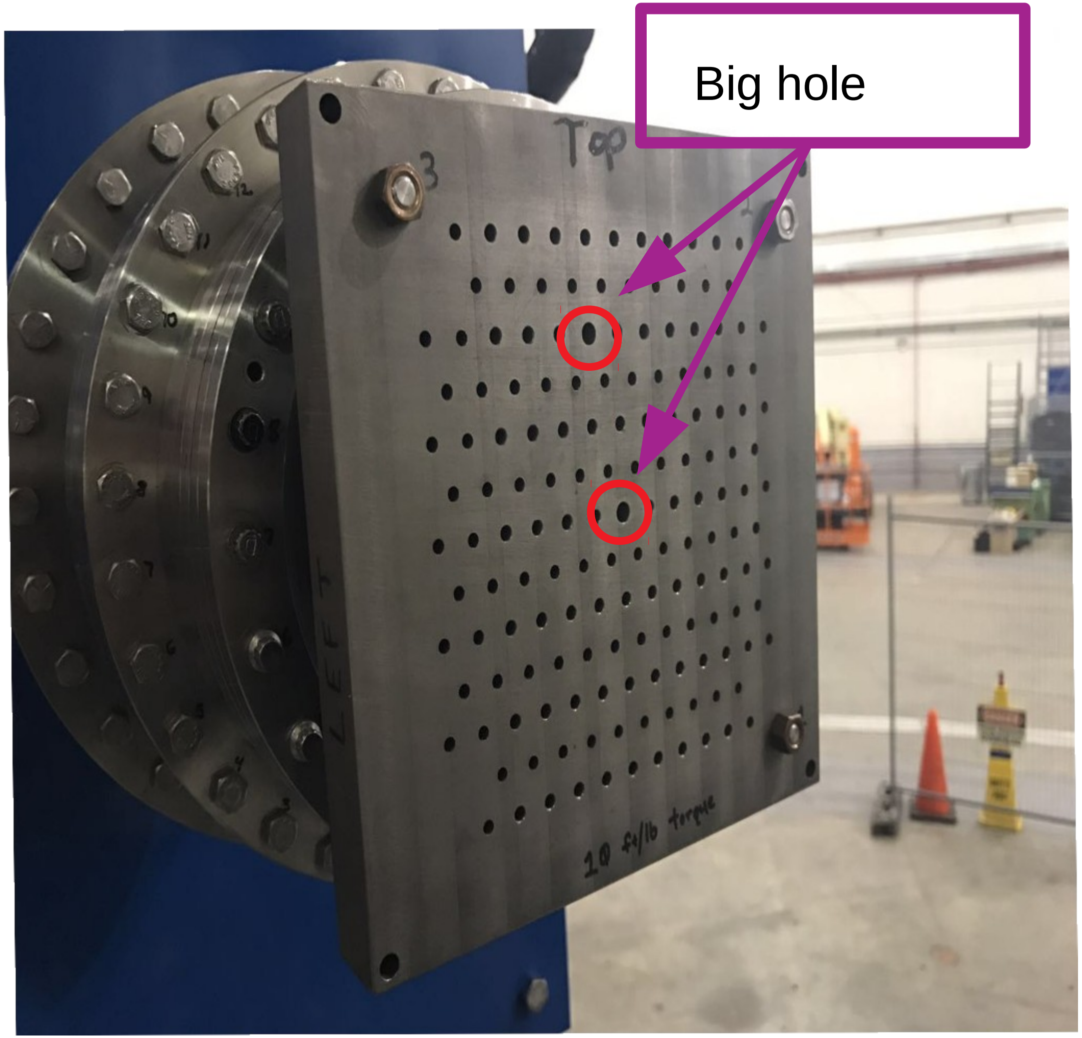
3. Production data:
   Target: T (with T kinematics)
   Purpose: physics analysis.

Raster Optimization:

- To minimize the local heating by the small spot size (80 to 200 μm) electron beam, the beam was spread over the larger region of target by applying a raster to the beam.
- The matrix elements of the raster correction are: $p_{0x}, p_{0y}, p_{1x}, p_{1y}$
- Since the nominal values for the raster elements were not known, so that their optimization was done with the help of the reconstructed z-vertex.
- The z-vertex was optimized first with the help of non-rastered beam.
- Then the optimized z-vertex was plotted with the rastered beam, the peak of the carbon multi-foil were broadened because of the beam uncertainty.
- Then by using the least χ^2 method the raster parameters were optimized with the known nominal values of 11 carbon multi-foil peaks such that the peak locations and width became the same as that obtained from the non-rastered beam.
- The previous experiment (MARATHAN experiment) also optimized the raster and both optimizations were found consistent.

Sieve slit plate:

- To calibrate the HRS angles, data were taken from the carbon multi-foil target with sieve slit in.
- The center of the SS was aligned along the central ray of the spectrometer.
- Only those scattered particles whose track passes through the SS holes can reach the detector plane.



The Matrix Optimization equation is

$$\begin{bmatrix} x' \\ y' \\ p \end{bmatrix}_{tgt} = M^{R2T} \begin{bmatrix} x \\ x' \\ y \\ y' \\ Z_T \end{bmatrix}_{fp} ,$$

More explicitly,

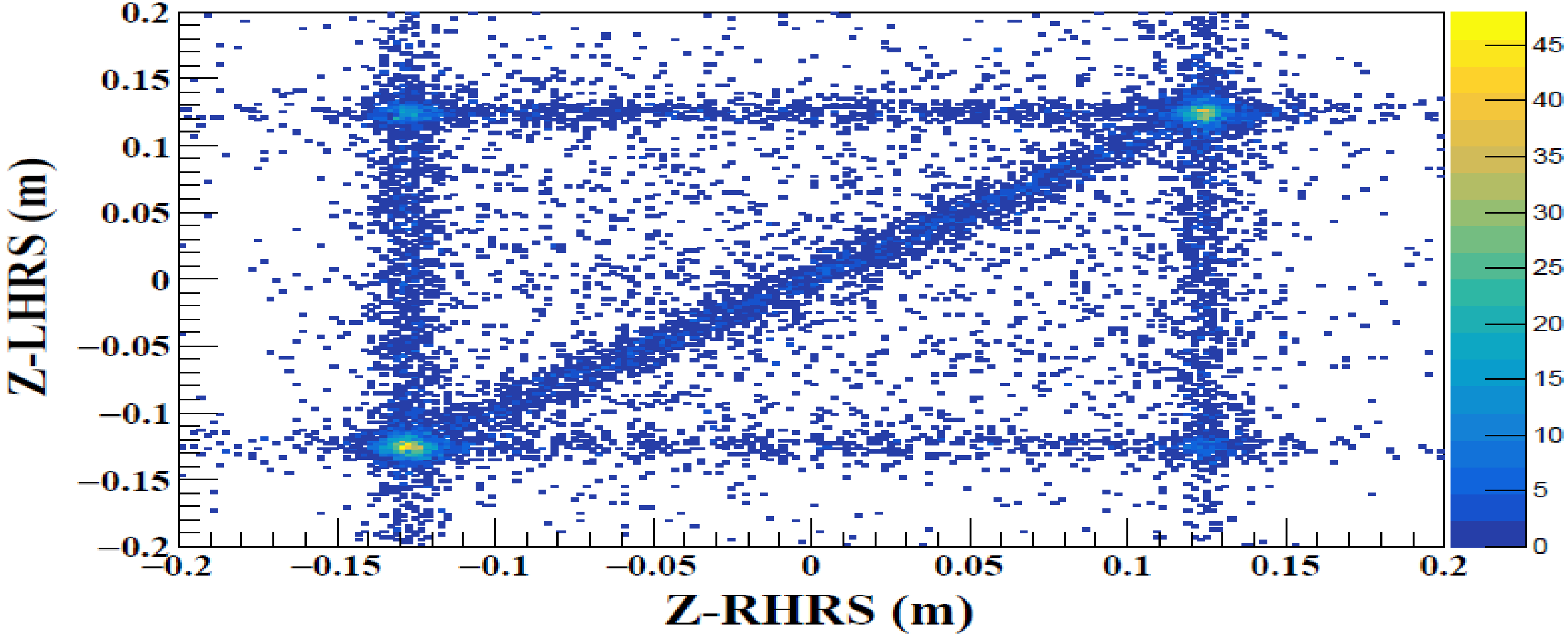
$$x' = \sum_{i+j+k+l+m=0}^{n} T_x(i,j,k,l,m)(x_{fp})^i(x'_{fp})^j(y_{fp})^k(y'_{fp})^l(Z_{tgt})^m,$$

$$y' = \sum_{i+j+k+l+m=0}^{n} T_y(i,j,k,l,m)(x_{fp})^i(x'_{fp})^j(y_{fp})^k(y'_{fp})^l(Z_{tgt})^m,$$

$$p = \sum_{i+j+k+l+m=0}^{n} T_p(i,j,k,l,m)(x_{fp})^i(x'_{fp})^j(y_{fp})^k(y'_{fp})^l(Z_{tgt})^m.$$

The matrix elements T’s in the above equations need to be optimized using the corresponding calibration data.

The Z-Vertex Correlation Cut



abs(LHRS z-vertex - RHRS z-vertex) < 0.053 m.

- The events contained in the diagonal correlation were spatially coincident events recognized by LHRS and RHRS.
- The events located outside this correlation were the spatial accidental events, in which the two particles recognized by LHRS and RHRS were not from the same spatial location

Target Energy Straggling:

- The E12-17-003 target energy straggling was studied by using a GEANT4 simulation.
- The energy loss depends on the reaction point at the target, the charge particle type, and the thickness of the material through which it passes.
- The studies were made for the three different cell thicknesses 300, 400 and 500 µm.

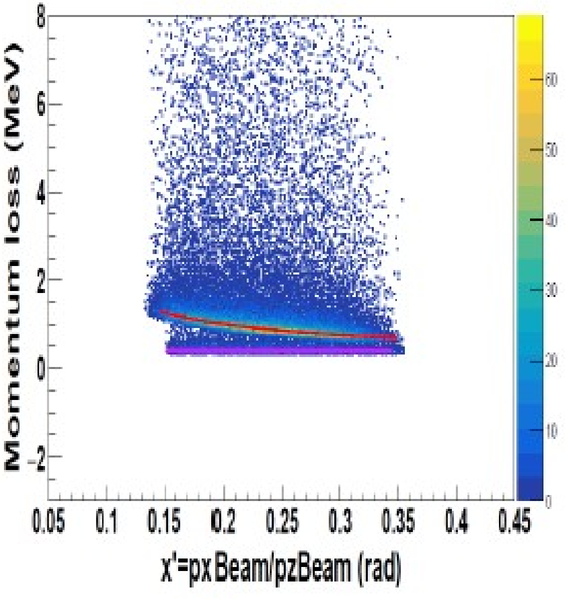
- For beam energy, the angular dependence doesn't exist.

$$p^{real}_{beam} = p^{measured}_{beam} - \Delta p$$

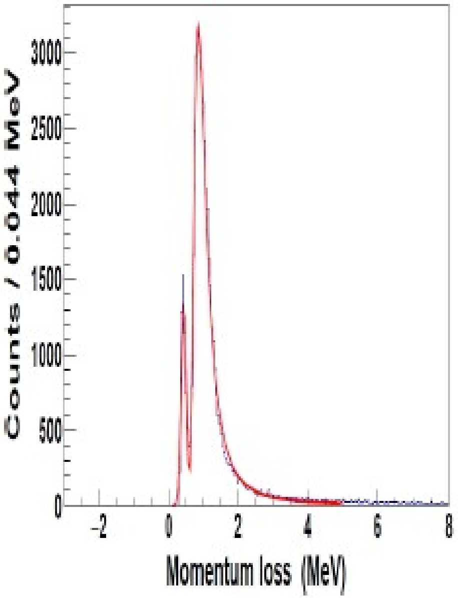
Where $p^{measured}_{beam}$ provided by CEBAF and Δp is the MPV obtained by fitting a Landau function over the momentum loss distribution.

- For the scattered particles, a strong angular dependence exist.

$$p^{real} = p^{measured} + \Delta p$$



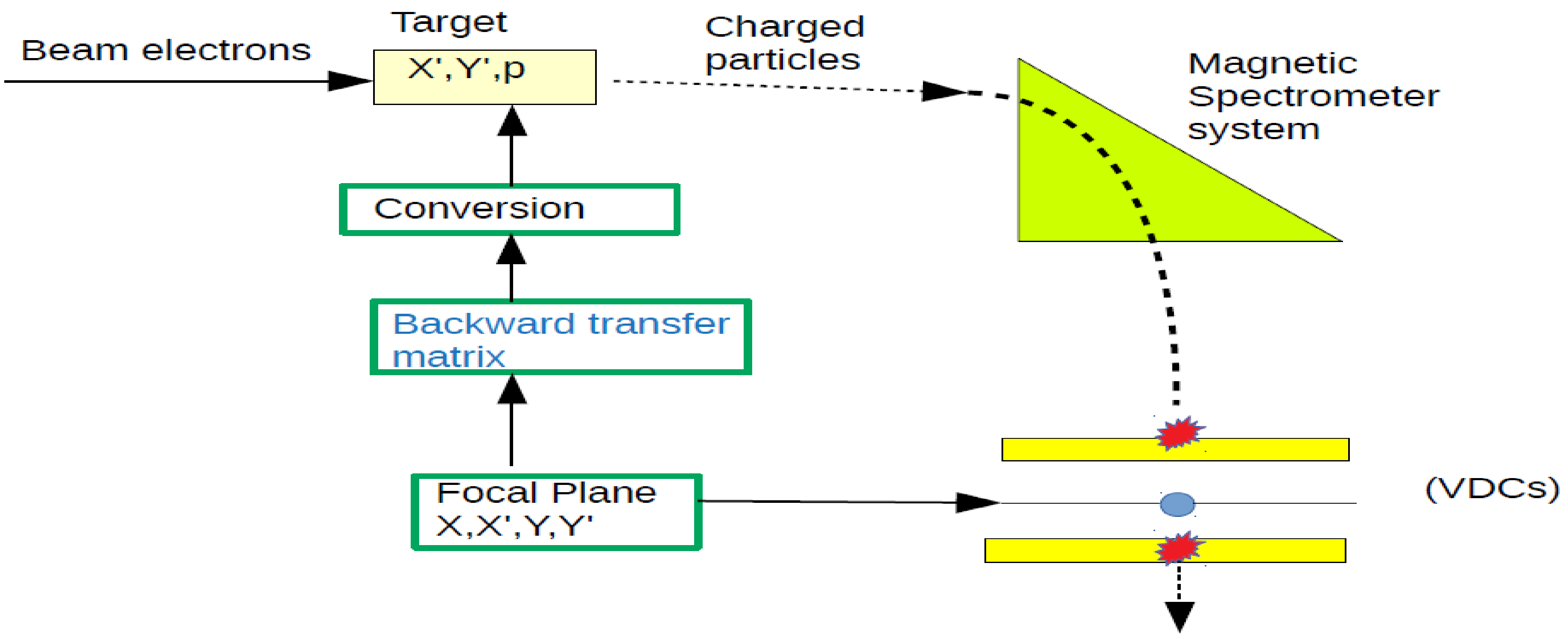
(a)



(b)

Where, $p^{measured}$ is the reconstructed momentum at the target and Δp can be obtained by fitting a function to the correlation (momentum loss vs x').

Simple Optics process:



- The focal plane obtained information is changed into the target by using the backward transfer matrix.