CLAS Collaboration Meeting 2023 (11/7 – 11/10)

Lambda-D scattering from g10

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2023/11/09 (Thu) 16:25 – 16:50

Index

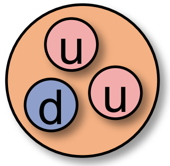
- Introduction (Physics motivation)
- 1st-level skimming (PID)
- Λd event selection
- Efficiency
- Luminosity
- Cross-sections
- Summary

Introduction (Physics motivation)

From Quark to Neutron Star

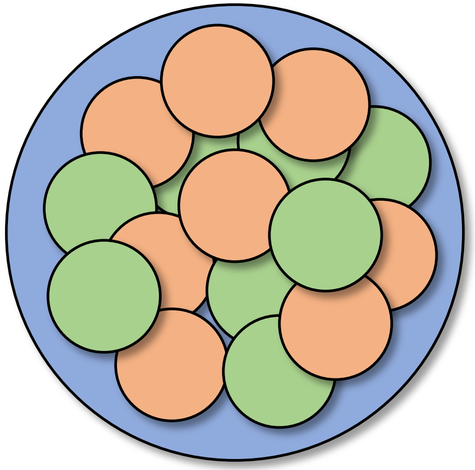
Bound systems, interacting by strong interaction with different scales

Hadron



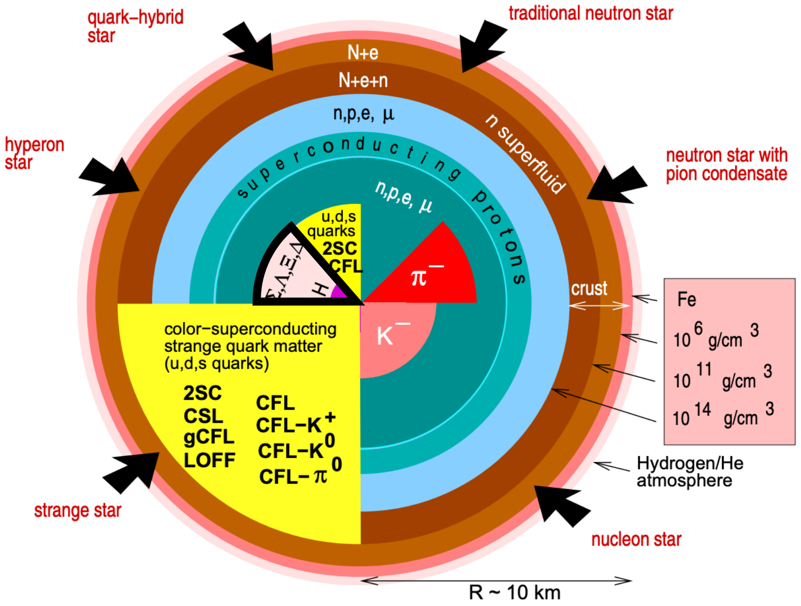
10^{-15} m

Nucleus, Hypernucleus

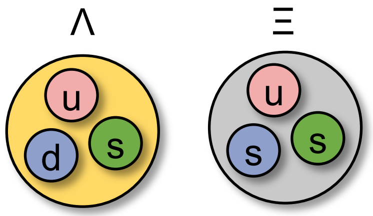


10^{-14} m

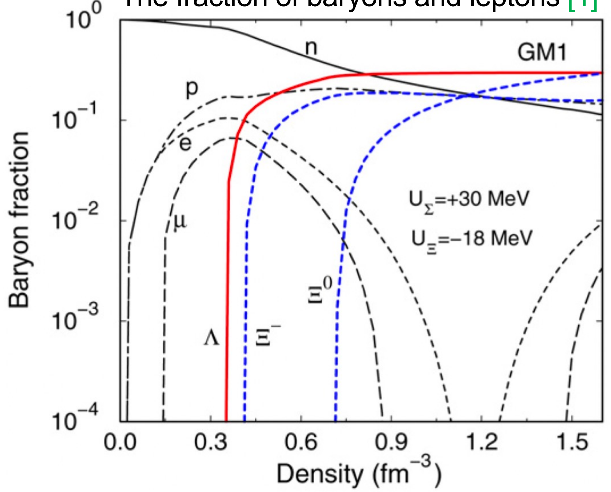
Neutron star [2]



Strange hadronic matter?



The fraction of baryons and leptons [1]

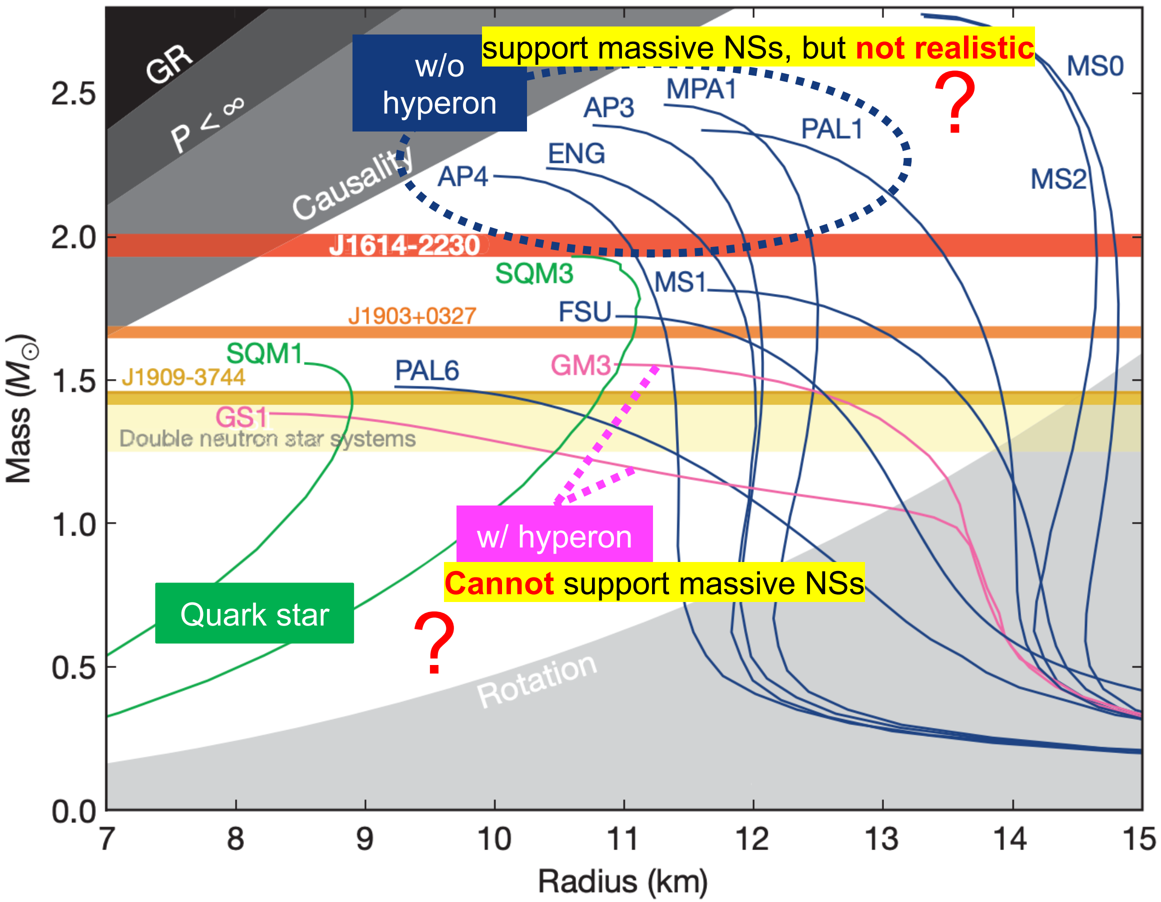


- They should be understood in the same framework based on the microscopic picture.
- Studying the mechanism of the Neutron Star would lead construction of realistic BB interactions.

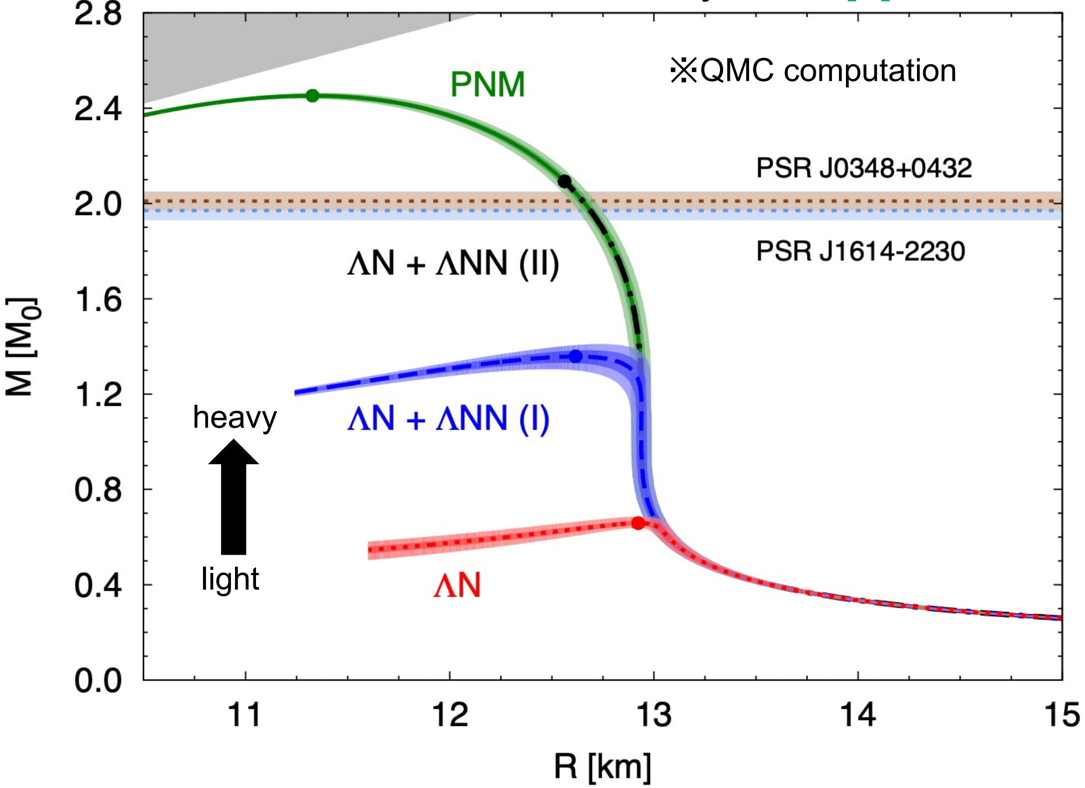
[1] J. Schaffner-Bielich, Nucl. Phys. A 804, 309 (2008)   [2] F. Weber., Prog.Part.Nucl.Phys.54 (2005)

Hyperon Puzzle of Neutron Stars (NSs)

Radius vs. Mass of Neutron Star [1]



Effect of ΛNN 3BF by QMC [2]



- Hyperon-nucleon (YN) interaction is repulsive in the short range (by the Quark Cluster Model).
- Λ is the first candidate of the hyperon appearance in Neutron Stars.

→ **ΛNN three-body forces (3BF)** could support massive NSs by making the EoS stiffer.

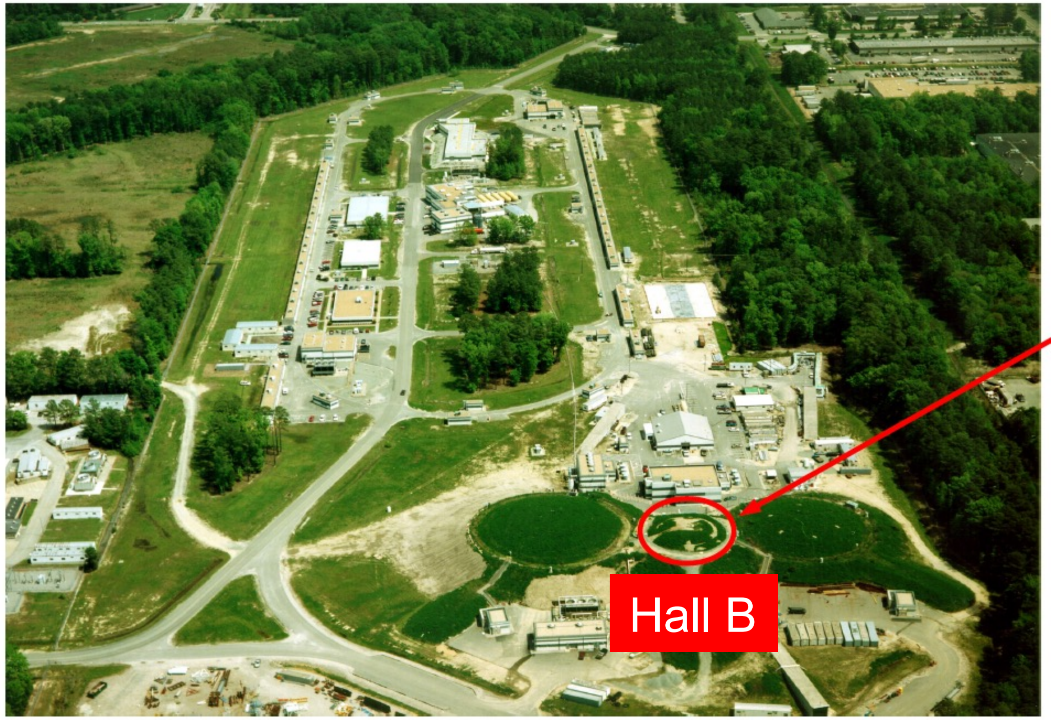
[1] P.B. Demorest *et al.*, Nature. 467., 2010
[2] Diego Lonardoni *et al.*, Phys. Rev. Lett. (2015)

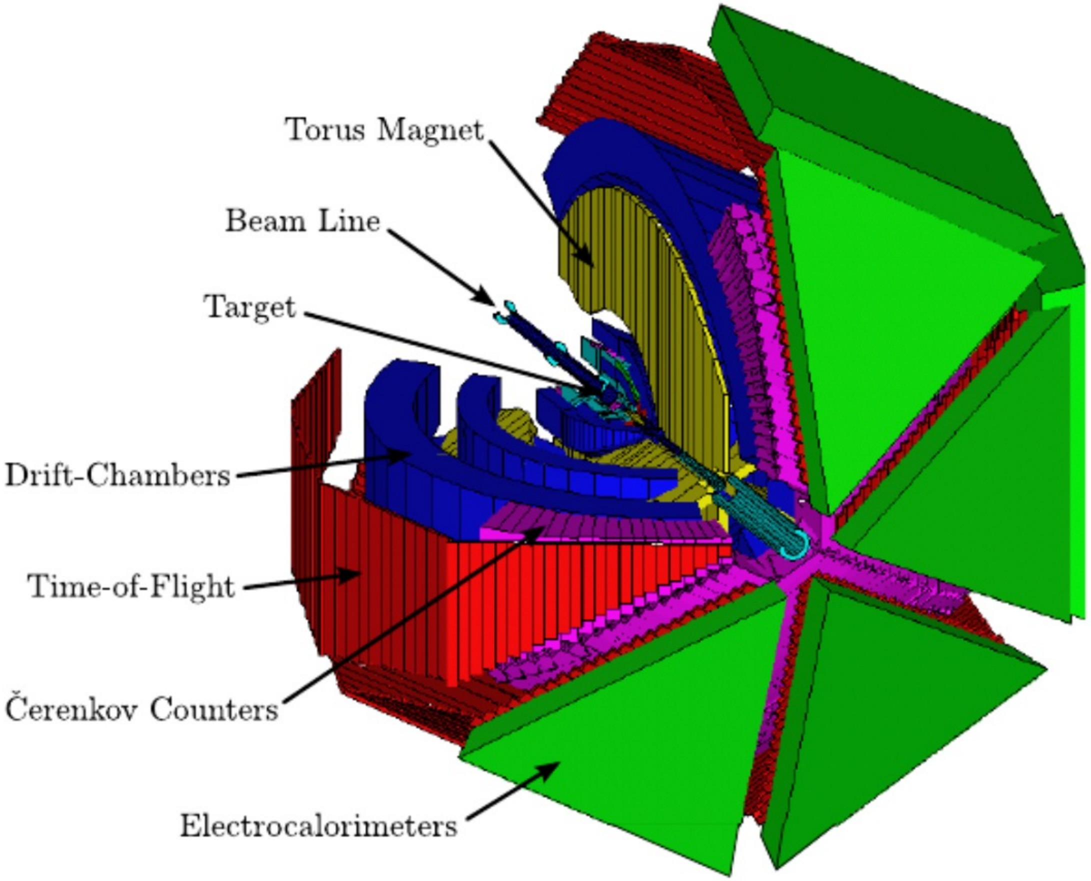
CLAS

- Λd differential & integrated cross-sections measurement by CLAS g10 dataset.
  - Analysis from Oct 2021 ~

CEBAF Large Acceptance Spectrometer (CLAS)

J-Lab
Continuous Electron Beam Accelerator Facility (CEBAF)





1^{st}-level Skimming (PID)

Number of Photon

Photon selection

$$t_{track} = t_{ST} - \frac{d}{c\beta_{\gamma\ calc}},$$

d: distance from the beam vertex to the SC

$$\beta_{\gamma\ calc} = \sqrt{\frac{p_{DC}^2}{m^2c^2 + p_{DC}^2}},$$

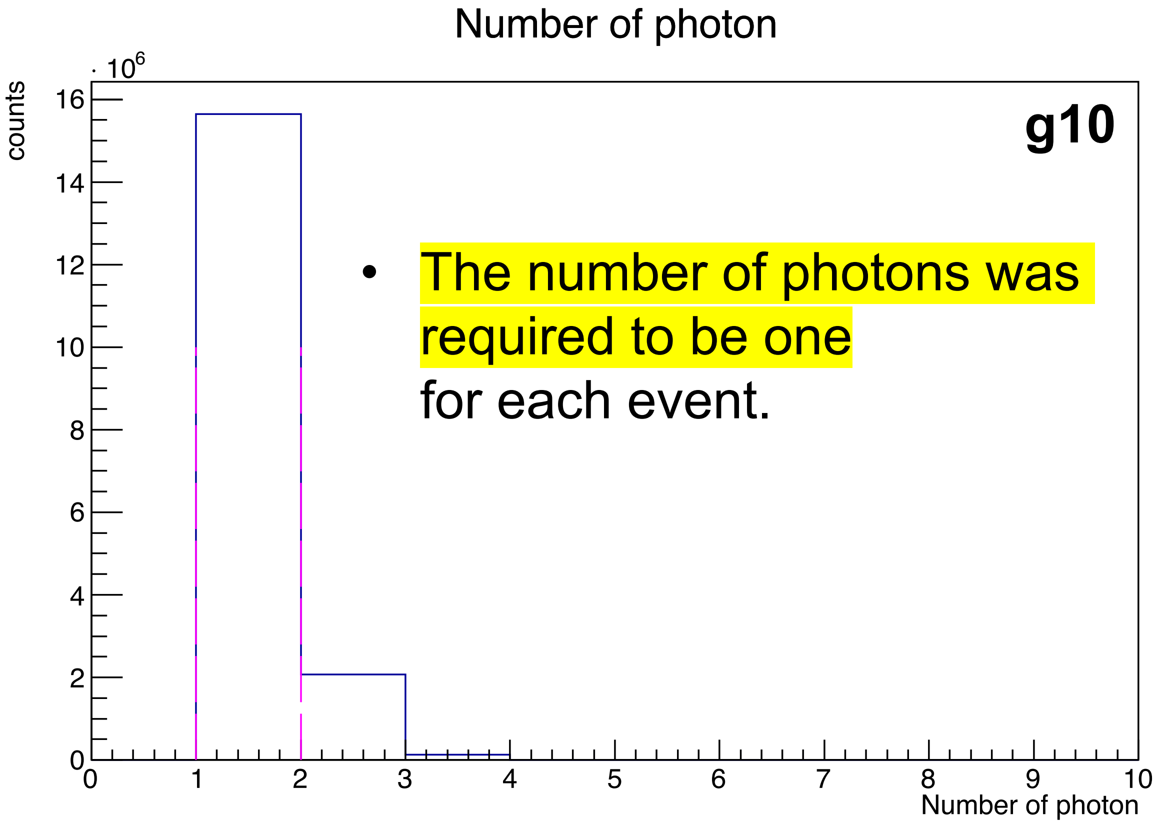
t_{event} was obtained by averaging t_{track} for each track to select photon beam

d': distance from the target center to event vertex

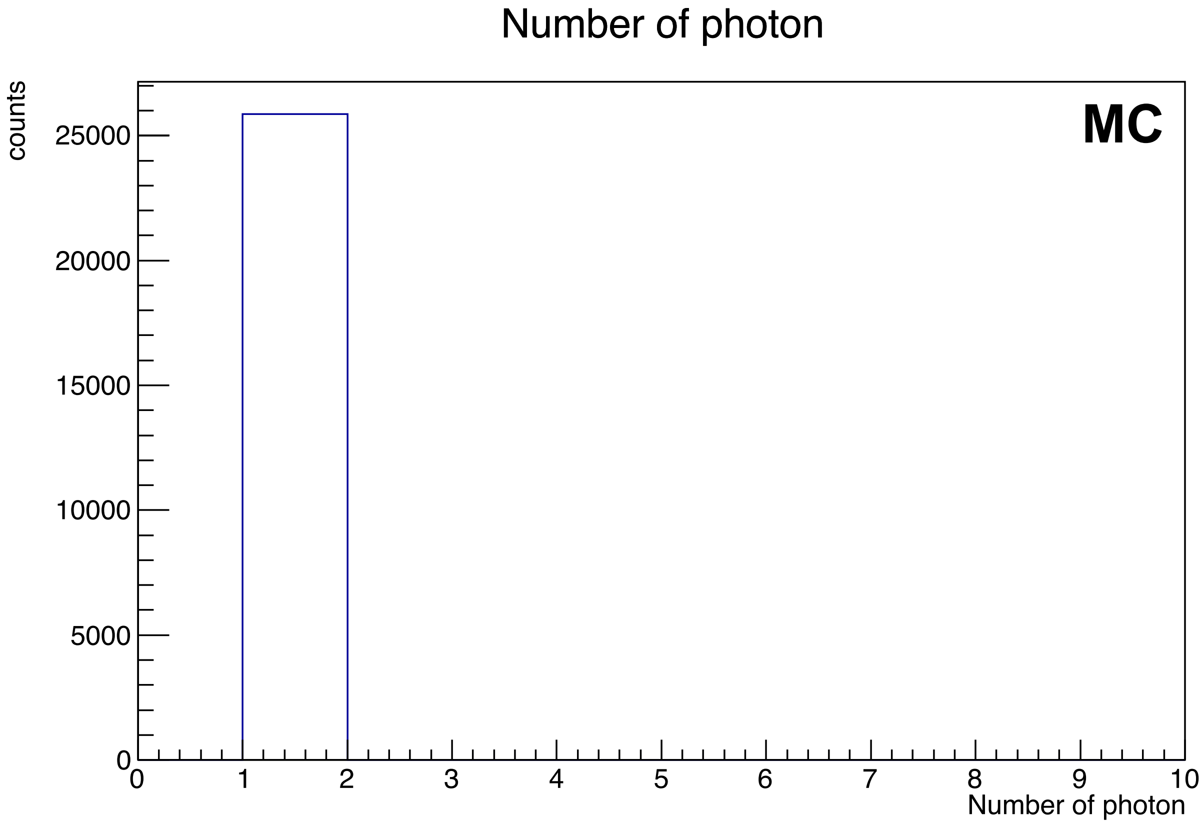
$$t_\gamma = t_{center} + \frac{d'}{c},$$

→ Compare with trigger time (t_r)

→ $\Delta t = |t_\gamma - t_r| < 20$ ns (wide gate)



- The number of photons was required to be one for each event.



1st & 2nd PID

$$v = \frac{d}{t},$$

- *t*: time the particle traveled from the event vertex to the TOF detector
- *d*: known path length the particle traveled in the Drift Chamber (DC)

$$\beta_{meas}.$$

← **Beta measurement**

$$m^2 = \frac{p^2(1-\beta_{meas}^2)}{\beta_{meas}^2},$$

← **1st Particle ID**

The particle whose textbook reference value of the mass best matches the calculated mass value is identified as the detected particle

$$\delta t = t_{meas} - t_{calc},$$

← **2nd Particle ID (p vs. δt plot)**

A difference between measured & calculated timing is ideally should be 0.

$$\boxed{t_{meas} = t_{SC} - t_{trig}}$$

$$\boxed{t_{calc} = d/(\beta_{calc} \cdot c)}$$

$$\beta_{calc} = \sqrt{\frac{p^2}{m^2c^2 + p^2}},$$

p: momentum by DC

Δβ measurement

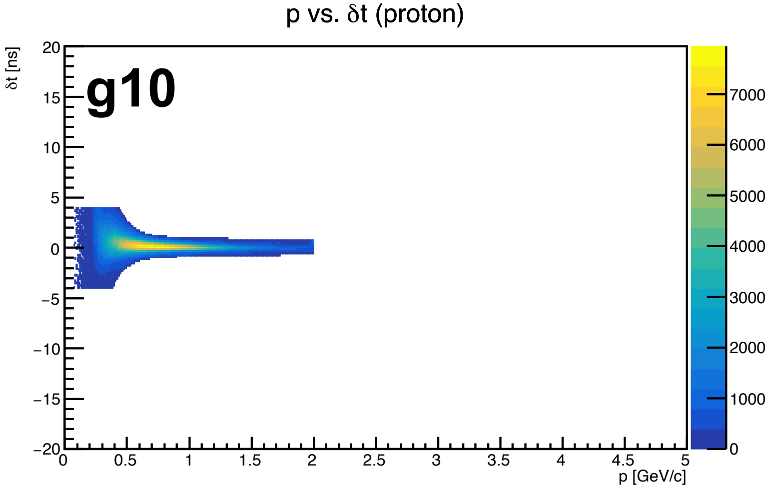
- To make PID better, a difference between measured & calculated β was obtained.

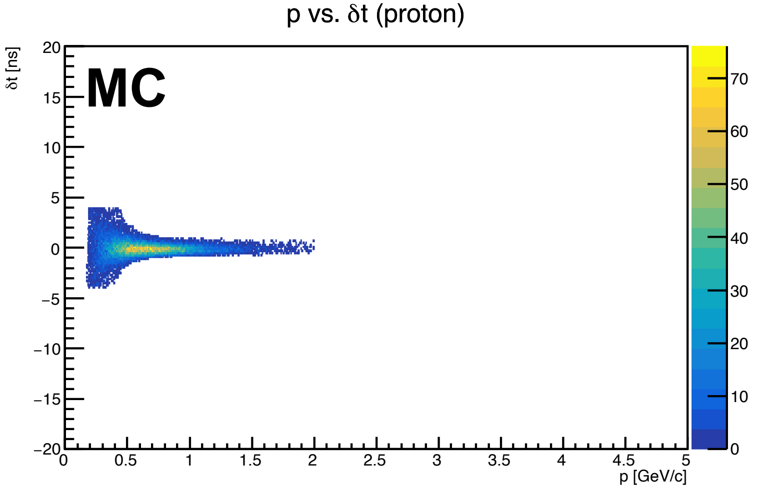
$$\Delta\beta = \beta_{calc} - \beta_{meas}.$$

2^{nd} PID (p vs. δt plot) & Δβ Measurement

2^{nd} PID (p vs. δt plot)

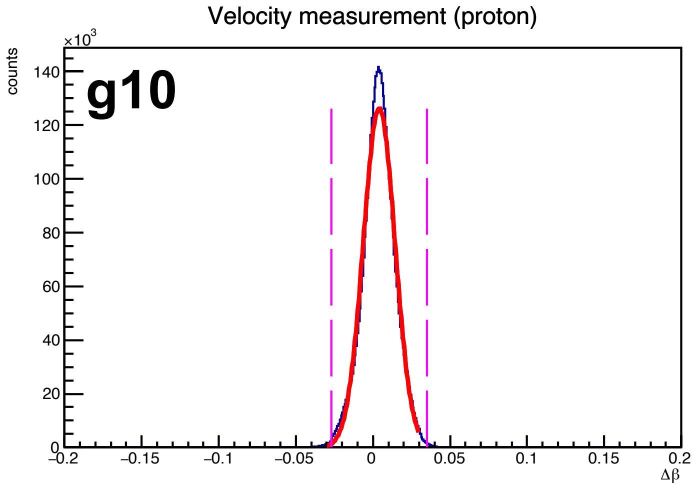
- Proper cut parameters were applied.

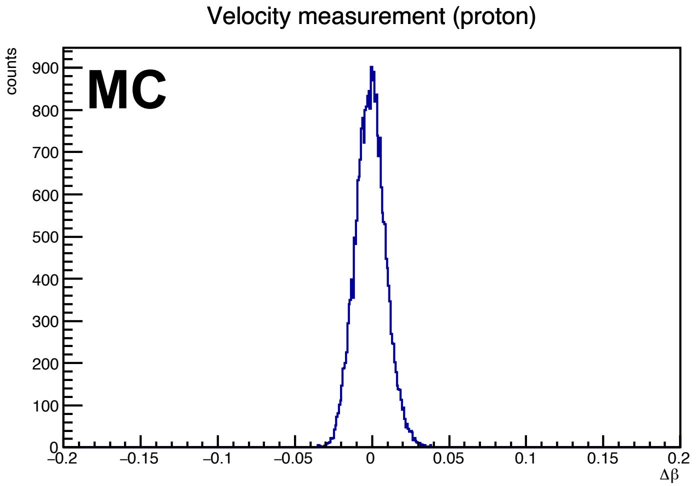




Δβ measurement

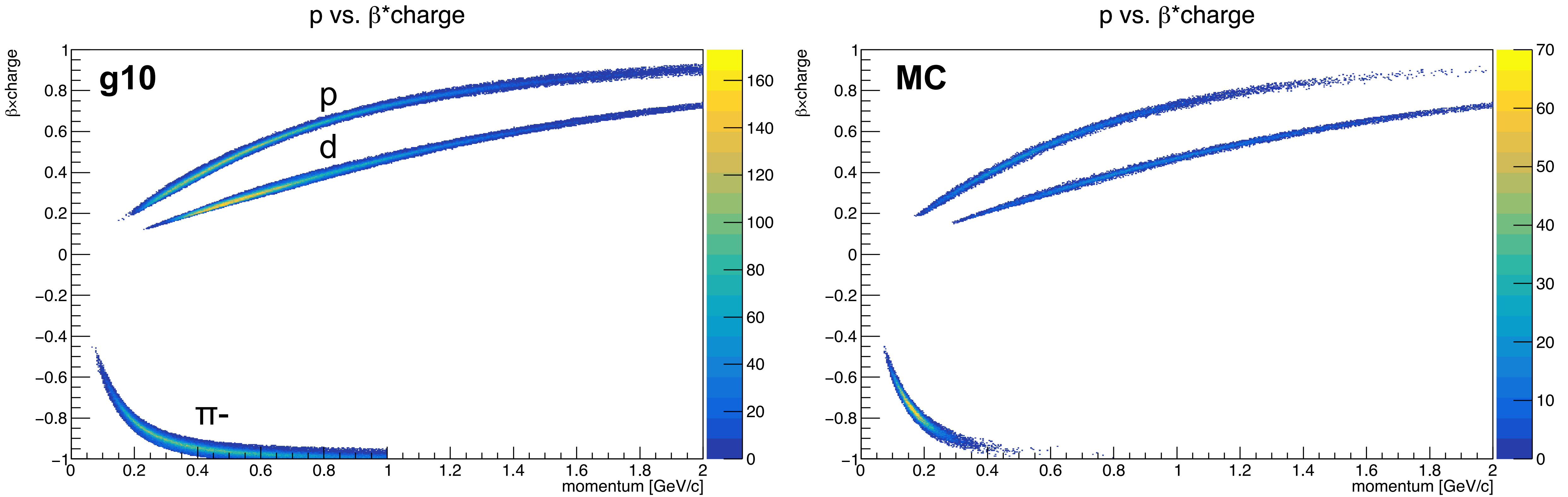
- The Δβ spectrum was fitted with Gaussian, and events within +-3σ were selected.



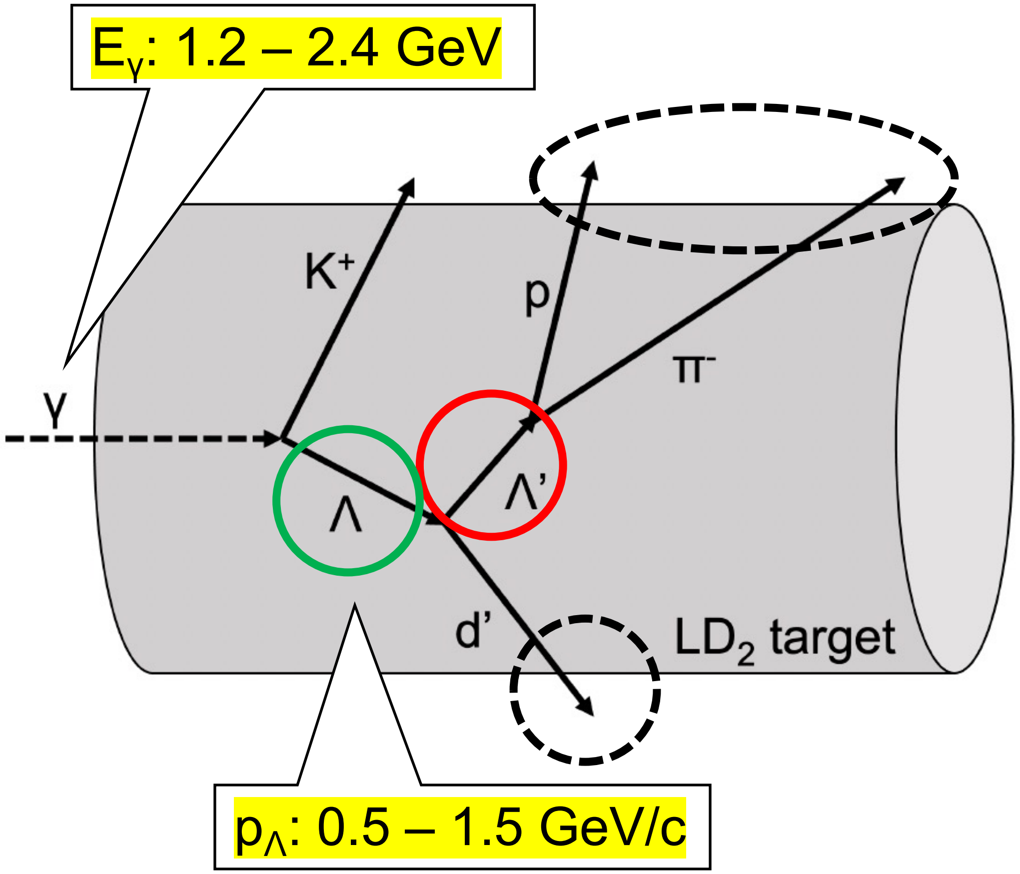


Final p vs. β*charge Plot

- Through the above PID analysis, we could clearly identify protons, deuterons, and π-.
- We used these particles for the physics analysis of Λd scattering.

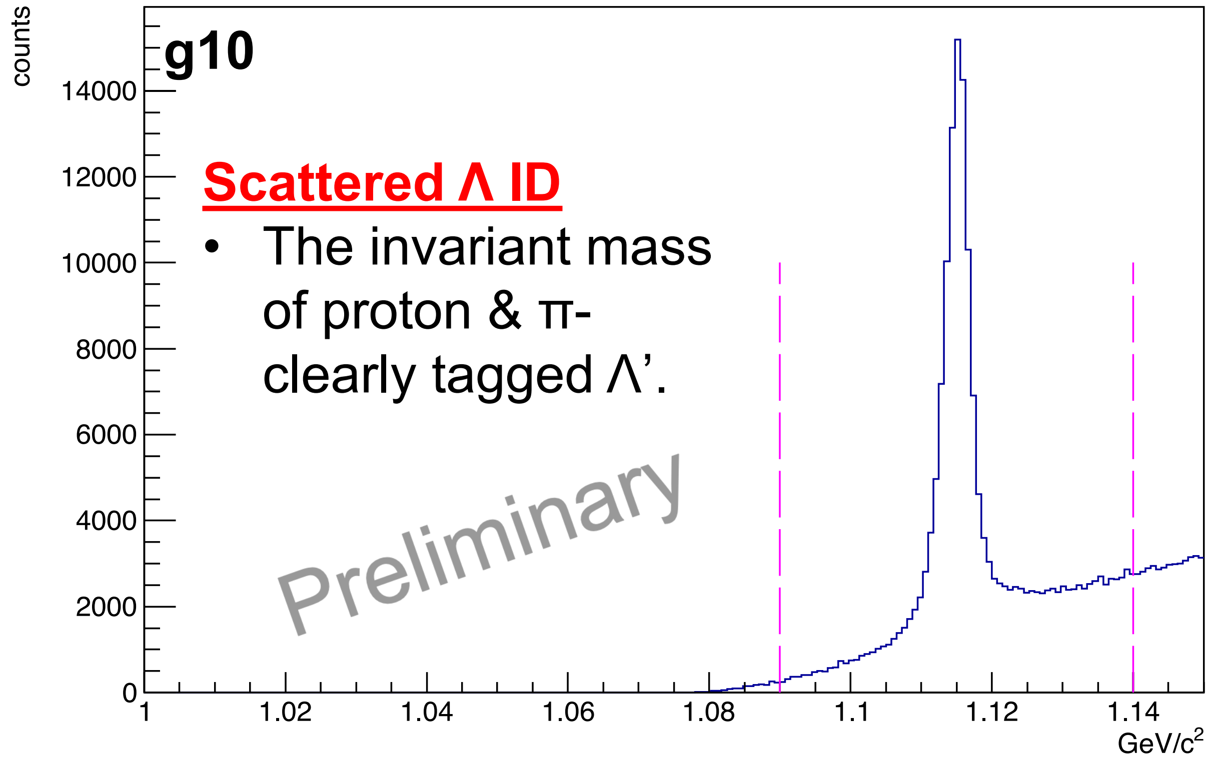


Λd Event Selection



$$M_{\Lambda'} = \sqrt{(E_p + E_{\pi^-})^2 - |\boldsymbol{p_p} + \boldsymbol{p_{\pi^-}}|^2}$$

Invariant mass (p & π^-)



Scattered Λ ID

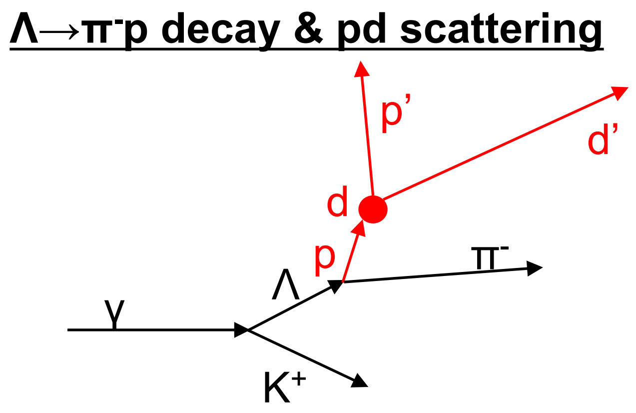
- The invariant mass of proton & π- clearly tagged Λ’.

$$M_X = \sqrt{(m_d - E_{d'} - E_{\Lambda'})^2 - (p_{d'}^2 + p_{\Lambda'}^2 + 2p_{d'}p_{\Lambda'}, \cos\theta_{d'\Lambda'})},$$

Beam Λ ID

- The missing mass of Xd→Λd was required to be >0 GeV/c^2.

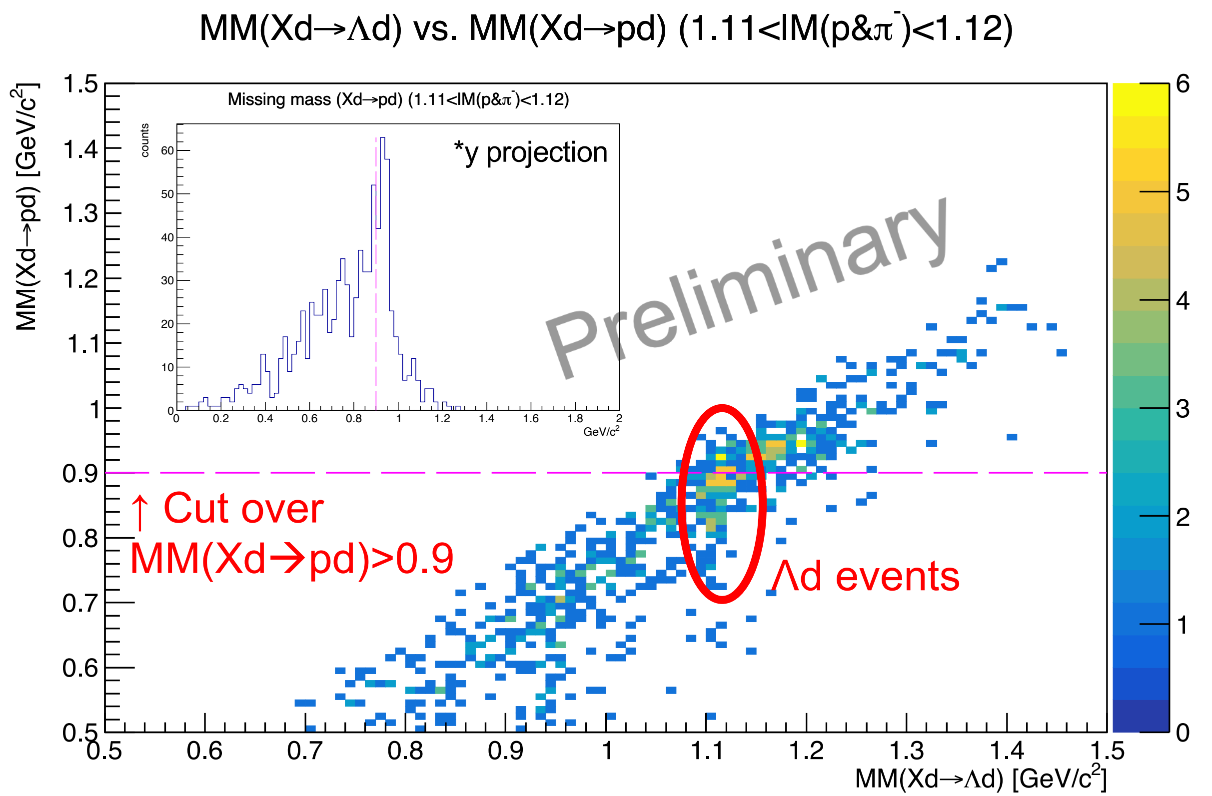
Main BG (pd scattering) Removal

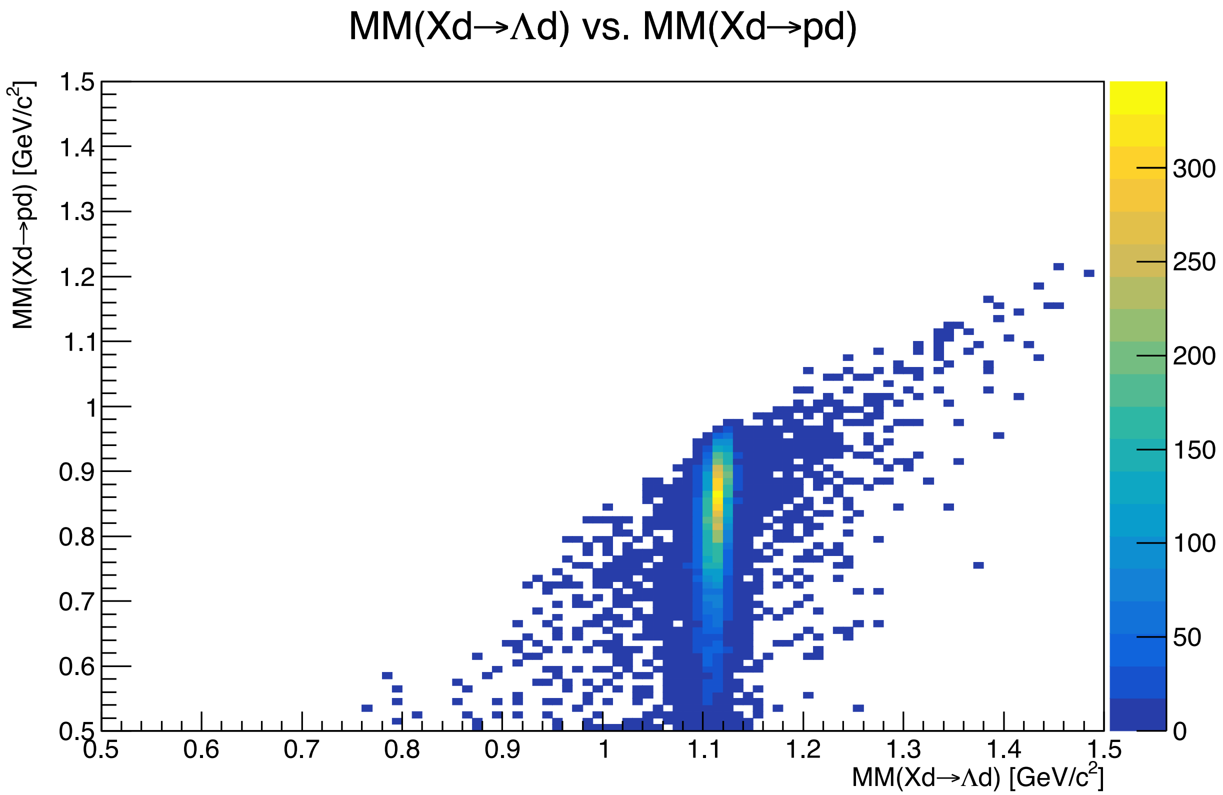


- The main background in Λd analysis is pd scattering
  - Kinematically mixed in the MM(Xd→Λd)

→ Cut the events over MM(Xd→pd)>0.9

although some Λd events were removed.



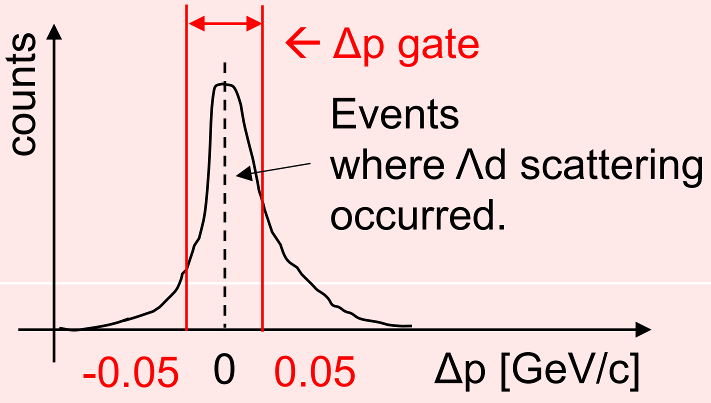


Yield of Λd Scattering Events

Scattered Λ momentum index (Δp)

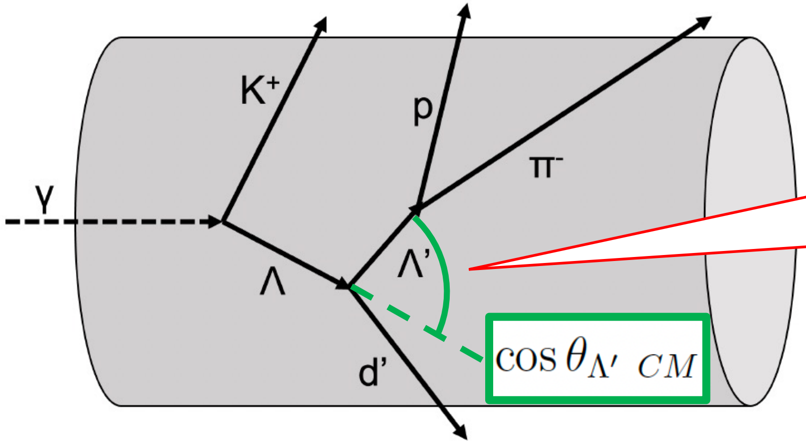
※ Equivalent to the missing mass method

- When calculating Λ' momentum ($p_{\Lambda'\ calc}$), we assumed Λd→Λ'd' kinematics.
- $p_{\Lambda'\ calc}$ was compared to the measured momentum ($p_{\Lambda'\ meas}$).
- The difference between $p_{\Lambda'\ meas}$ & $p_{\Lambda'\ calc}$ is "Δp."
- Events in the Δp gate (|Δp|<0.05 GeV/c) → Integrated cross-section



Scattering angle distribution of Λ' ($\cos\theta_{CM}$)

- After applying the Δp gate, $\cos\theta_{CM}$ spectra were obtained.
  - Events where $|\cos\theta_{CM}|<0.6$ → Differential cross-section



$$p_{\Lambda'\ calc} = \frac{A\ p_\Lambda \cos\theta_{\Lambda'} + (E_\Lambda + m_d)\sqrt{B}}{2((E_\Lambda + m_d)^2 - p_\Lambda^2 \cos\theta_{\Lambda'})},$$

$$A = m_\Lambda^2 + m_d^2 + m_{\Lambda'}^2 - m_{d'} + 2E_\Lambda m_d$$

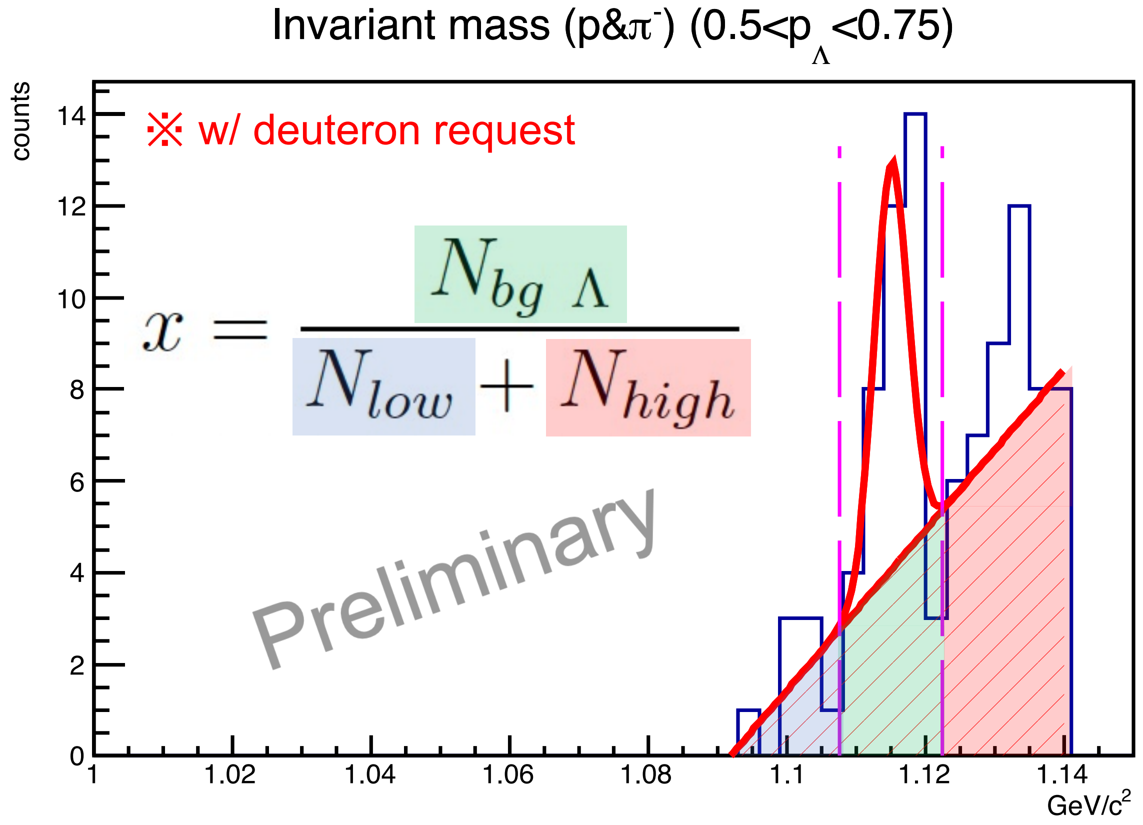
$$B = 4m_{\Lambda'}^2(p_\Lambda^2 \cos\theta_{\Lambda'} - (E_\Lambda + m_d)^2) + A^2.$$

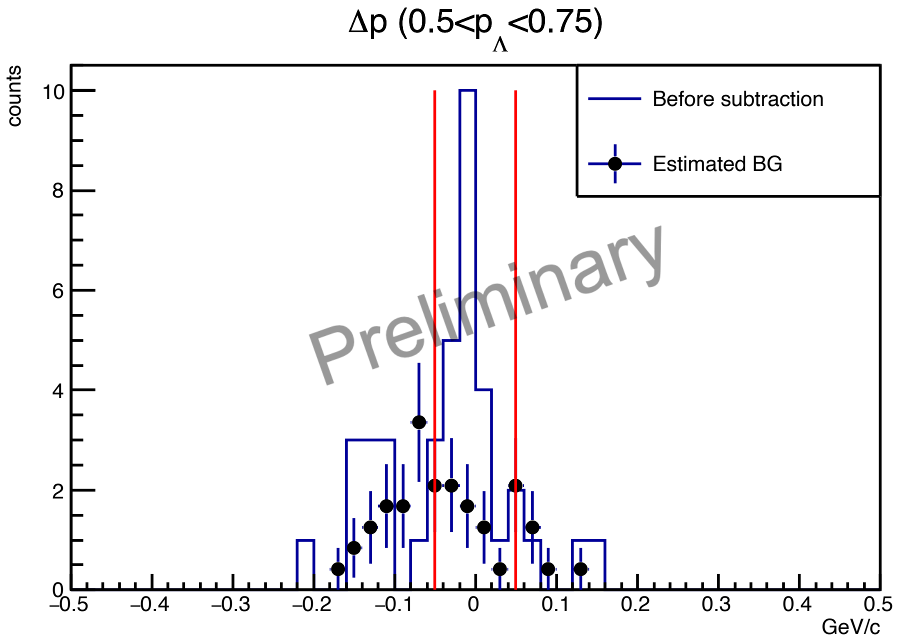
$$\boxed{\Delta p_{\Lambda'} = p_{\Lambda'\ meas} - p_{\Lambda'\ calc},}$$

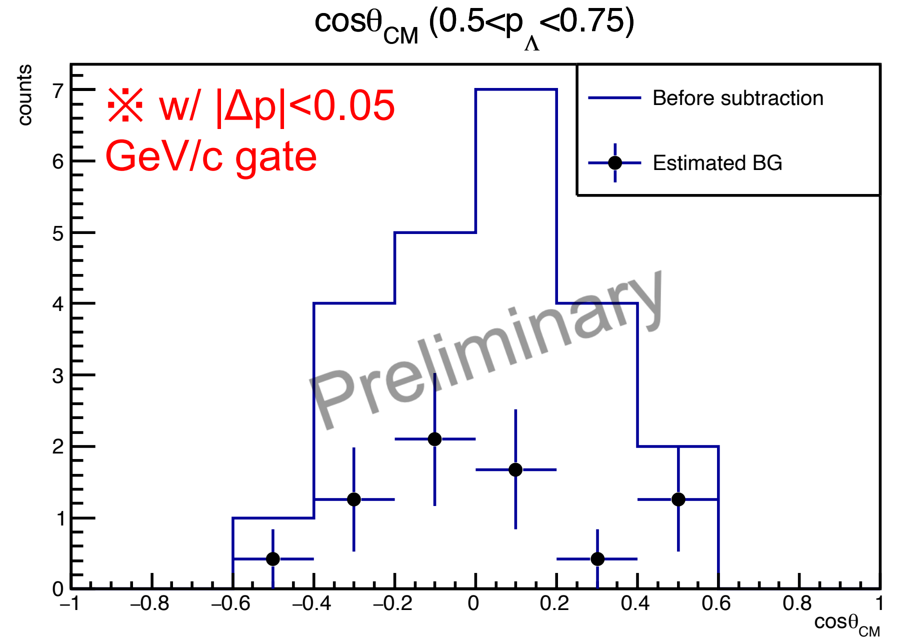
BG Subtraction before Cross-section Calculation

BG estimation

- Using the sidebands of the Λ peak in the invariant mass of proton and π-.
- The scaling factor (x) to estimate the BG ratio under the Λ peak was calculated by fitting the invariant mass with linear and Gaussian functions.



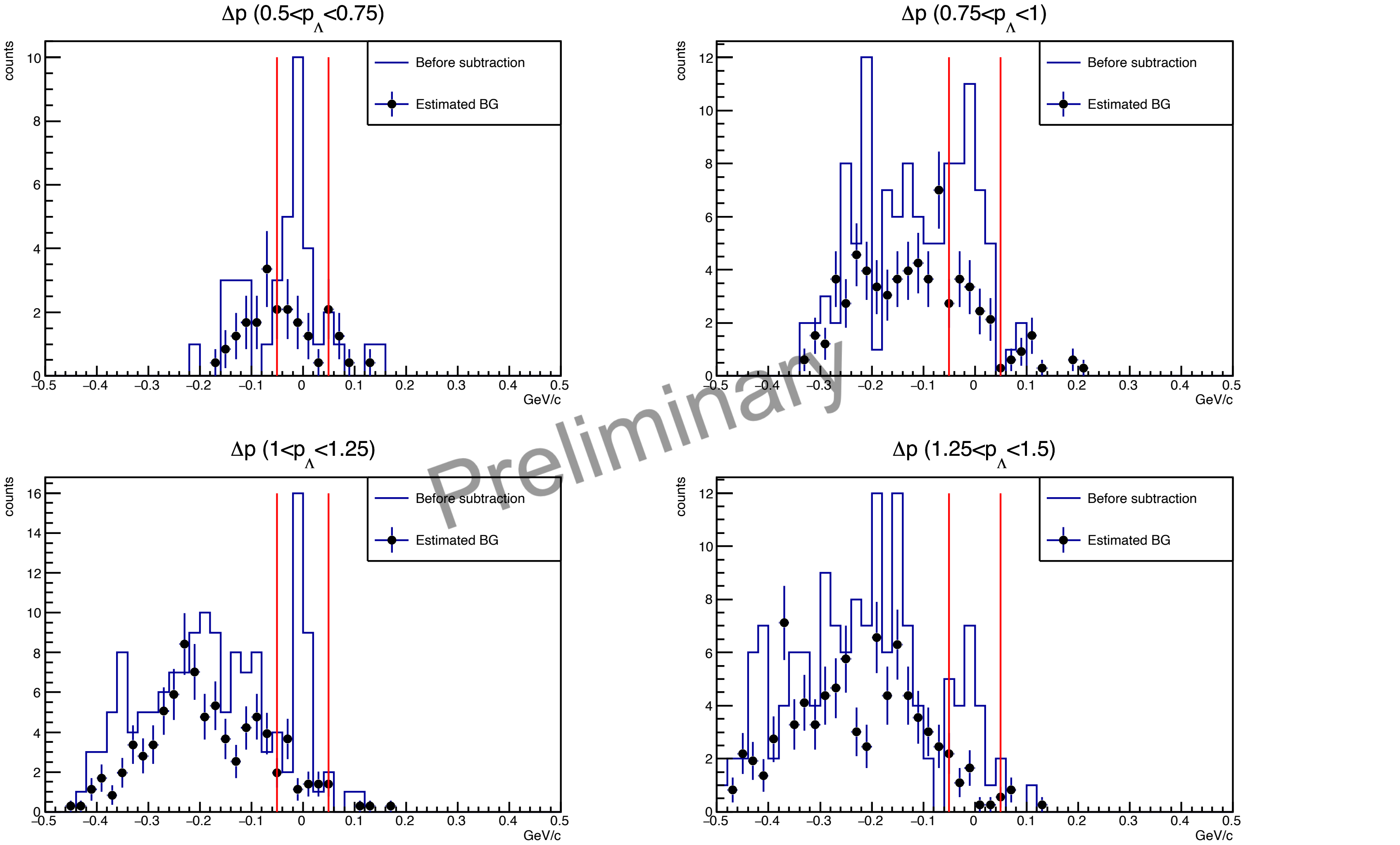




Corrected Δp soectra

Final Λd events counting

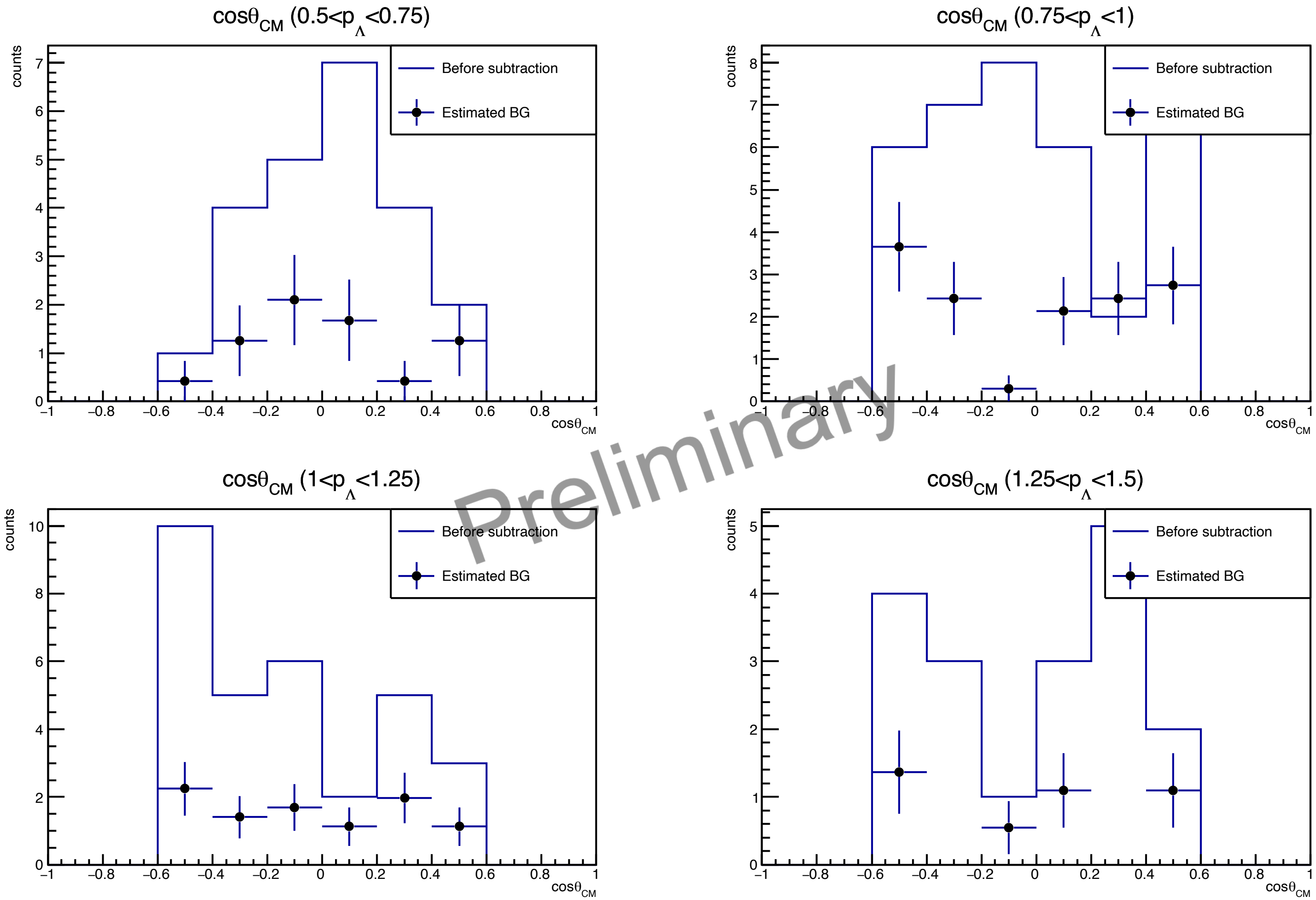
- The Δp spectra were calculated in each Λ beam momentum range (dp_{Λ} = 0.25 GeV/c)
- Then, BG structures were subtracted. Events remaining in the range of |Δp|<0.05 GeV/c were used to derive a integrated cross-section.



Corrected $\cos\theta_{CM}$ soectra

Final Λd events counting

- The $\cos\theta_{CM}$ spectra were calculated in each Λ beam momentum range (dp_Λ = 0.25 GeV/c)
- Then, BG structures were subtracted. Events remaining in the range of $|\cos\theta_{CM}|<0.6$ were used to derive a differential cross-section.



Efficiency

Efficiency for Cross-sections

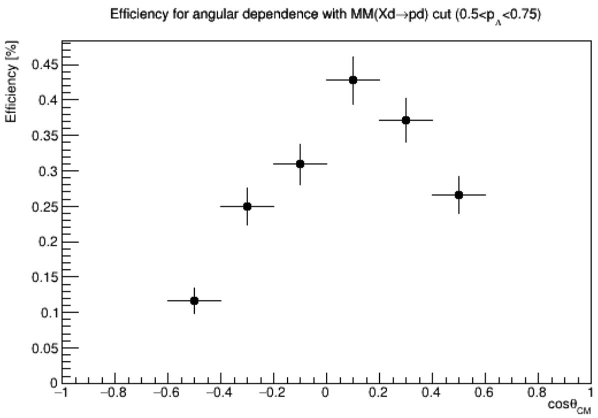
- The detection efficiency was estimated independently from CLAS Geant4 simulations.

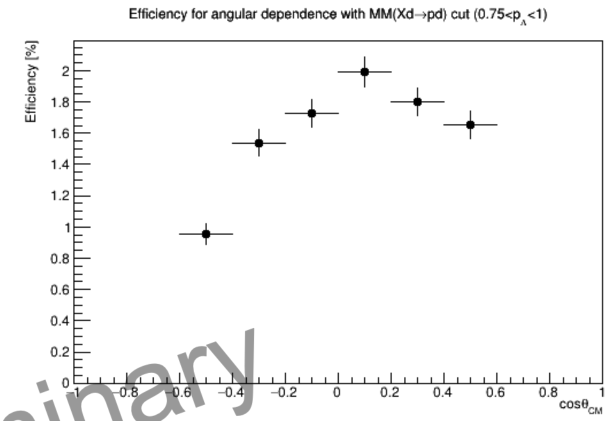
$$E_{\cos\theta_{\Lambda'},\ CM} = \left(\frac{N_{\Lambda d,\ skim}}{N_{\Lambda d,\ gen}}\right)_{\cos\theta_{\Lambda'},\ CM}$$

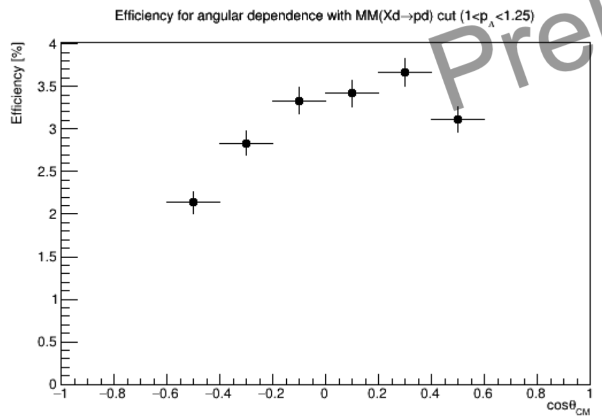
$$\sigma(E_{\cos\theta_{\Lambda'},\ CM}) = \frac{\sqrt{N_{\Lambda d,\ gen} E_{\cos\theta_{\Lambda'},\ CM}(1 - E_{\cos\theta_{\Lambda'},\ CM})}}{N_{\Lambda d,\ gen}}$$

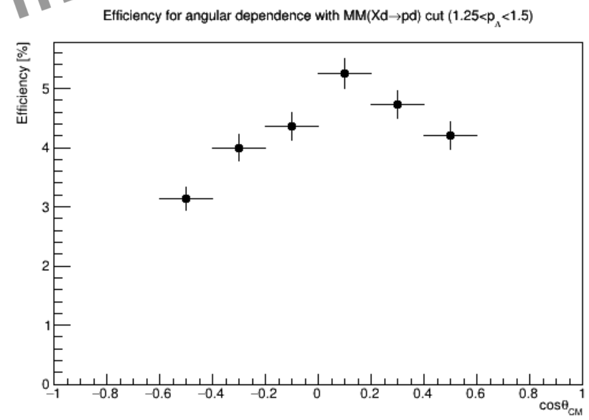
$$E_{p_\Lambda} = \left(\frac{N_{all\ \Lambda d,\ skim}}{N_{all\ \Lambda d,\ gen}}\right)_{p_\Lambda} = \left(\frac{\sum_{i=n}^{m}(N_{\Lambda d,\ skim})_i}{\sum_{i=n}^{m}(N_{\Lambda d,\ gen})_i}\right)_{p_\Lambda}$$

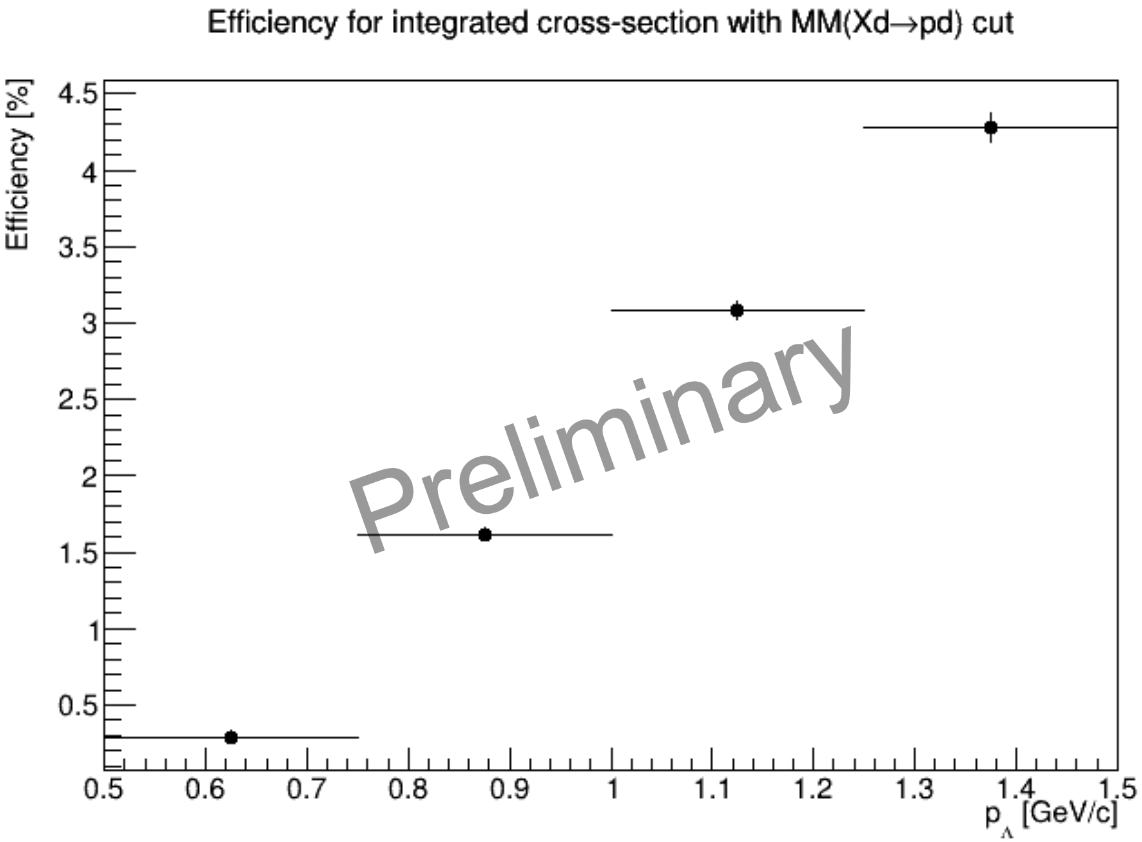
$$\sigma(E_{p_\Lambda}) = \frac{\sqrt{N_{all\ \Lambda d,\ gen} E_{p_\Lambda}(1 - E_{p_\Lambda})}}{N_{all \Lambda d,\ gen}}$$









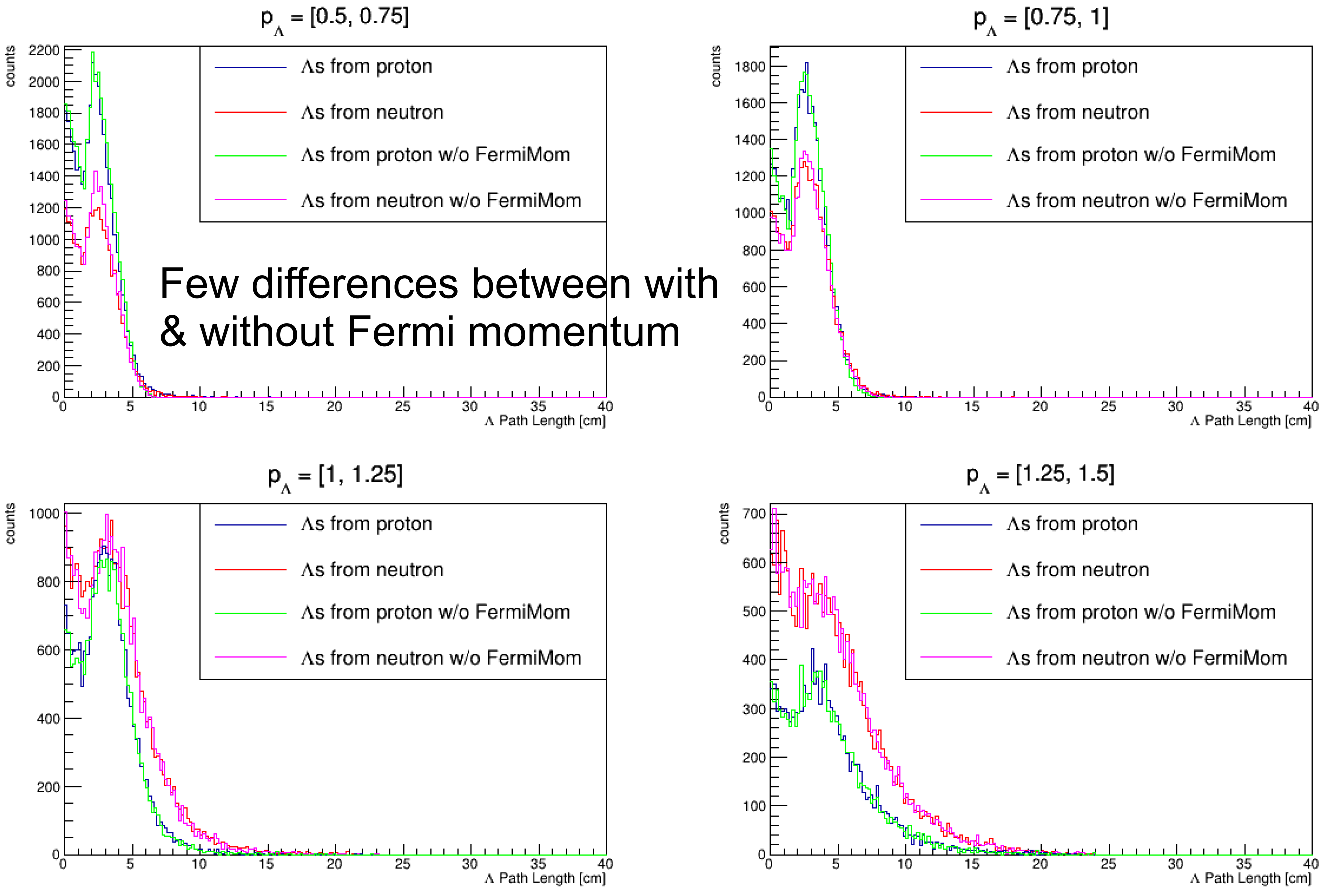


Luminosity

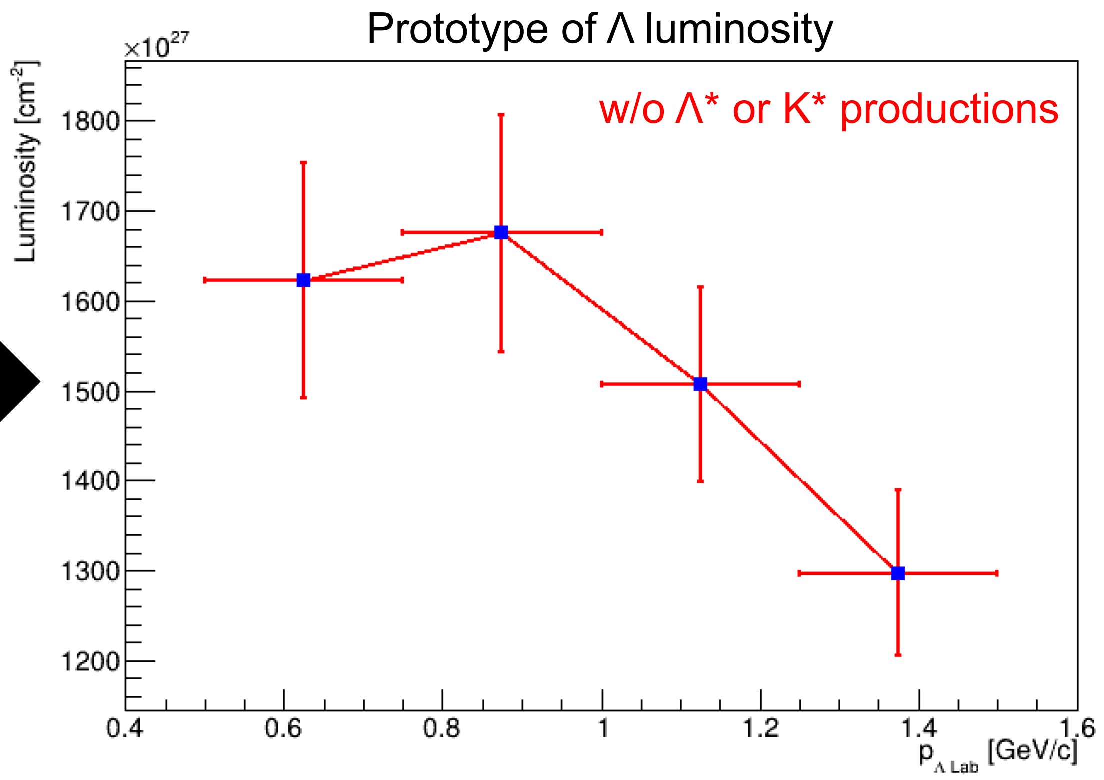
Λ path length (inside the LD_2 target)

- Λs derived from both proton & neutron should be considered.
- Path lengths were calculated with & without Fermi momentum in each p_Λ range.
- We calculated the luminosity considering the Fermi momentum of the target particle: proton or neutron.

→ **Problem**: The simulations handled by CLAS luminosity software did not include resonance events such as Λ* and K* production.

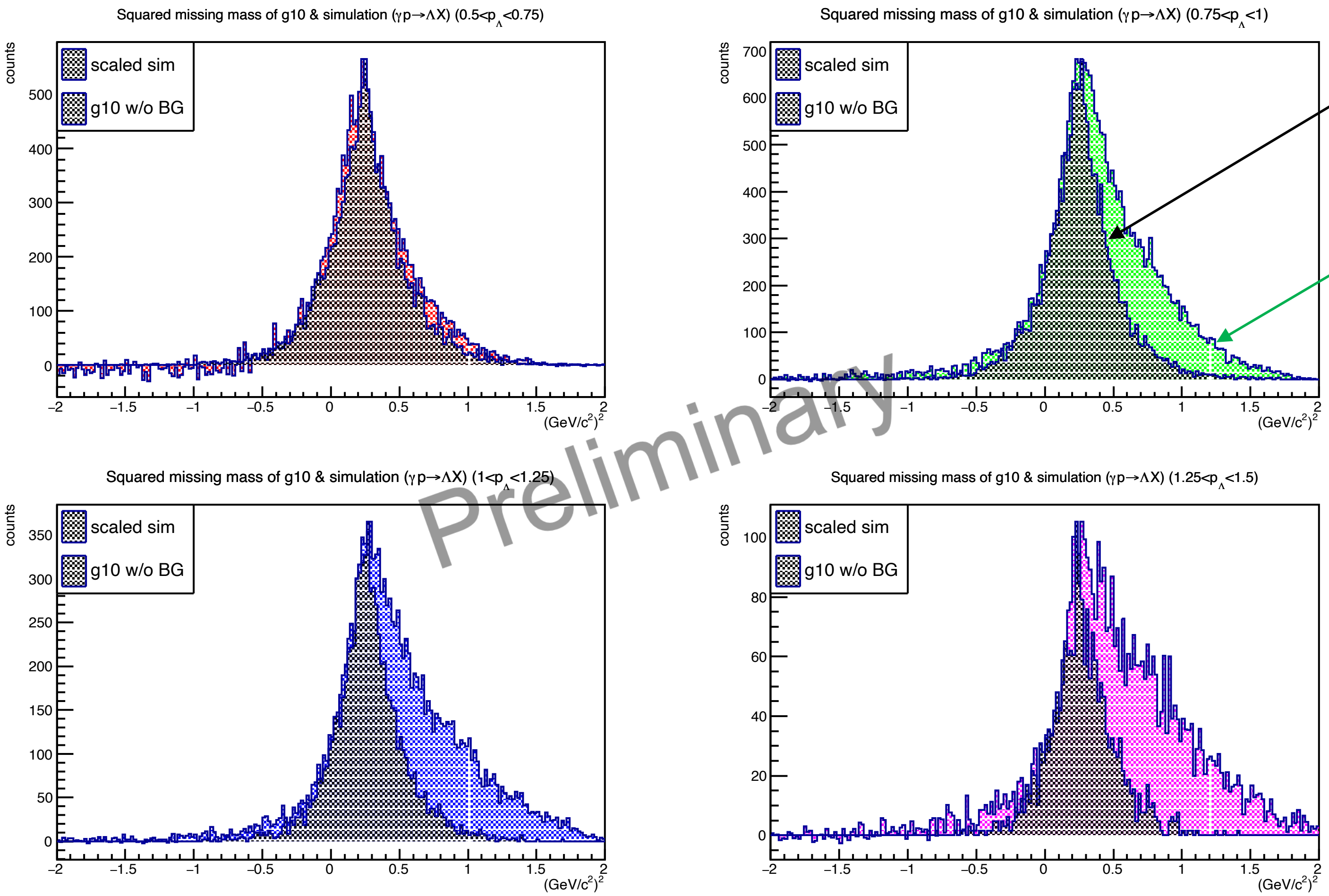


Few differences between with & without Fermi momentum



Estimation of resonance yield

- The number of resonance events included in the g10 data was estimated from the difference between the simulation result of only the elementary process (γp→K⁺Λ or γn→K⁰Λ) and the g10 data result of the squared missing mass of γp→ΛX.
- Then, scaling factors for current luminosities were calculated.



Simulation result of γp→K⁺Λ or γn→K⁰Λ reactions.

Original g10 spectrum (including Λ* or K* productions)

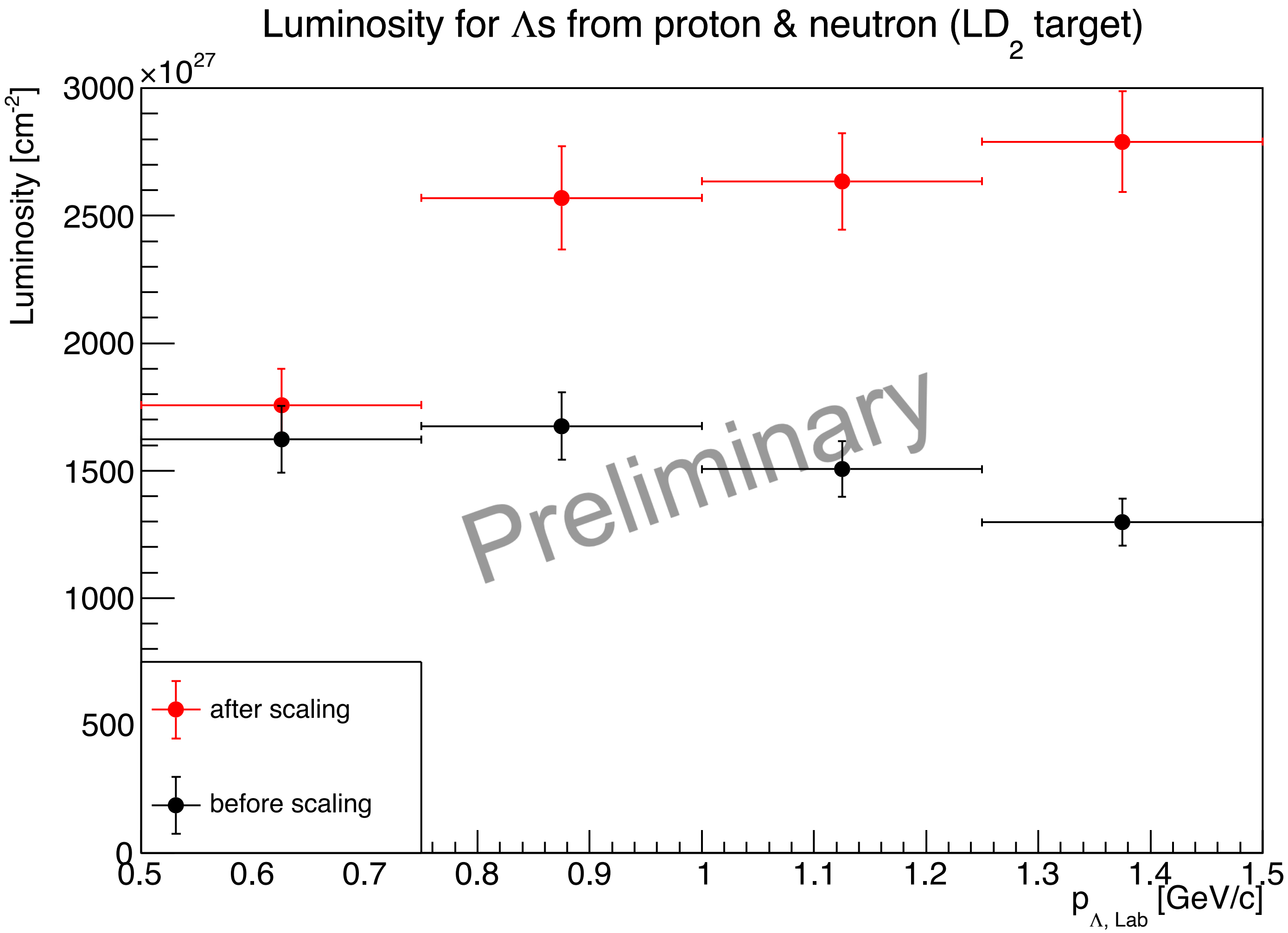
$$\boxed{x_{lum} = \frac{N_{sim\ tot} + N_{reso}}{N_{sim\ tot}} + 1}$$

Scaling factor for current Luminosity ↓

p_Λ bin (GeV/c)	$N_{sim\ tot}$	N_{reso}	x_{lum}
0.5 – 0.75	13705.6	1139.6	1.083
0.75 – 1.0	15210.0	8124.0	1.534
1.0 – 1.25	7538.4	5642.0	1.748
1.25 – 1.5	1898.9	2186.0	2.151

Estimation of resonance yield

- The luminosity of the Λ beam before and after correction is shown below.
- In this analysis, we used the corrected values represented by red dots to derive the cross-sections.



Final Luminosity ↓

p_Λ bin (GeV/c)	L_{before} ($\times 10^{30}$ cm^{-2})	L_{after} ($\times 10^{30}$ cm^{-2})
0.5 – 0.75	1.623 ± 0.131	1.758 ± 0.142
0.75 – 1.0	1.675 ± 0.132	2.570 ± 0.202
1.0 – 1.25	1.507 ± 0.108	2.634 ± 0.189
1.25 – 1.5	1.297 ± 0.921	2.790 ± 0.198

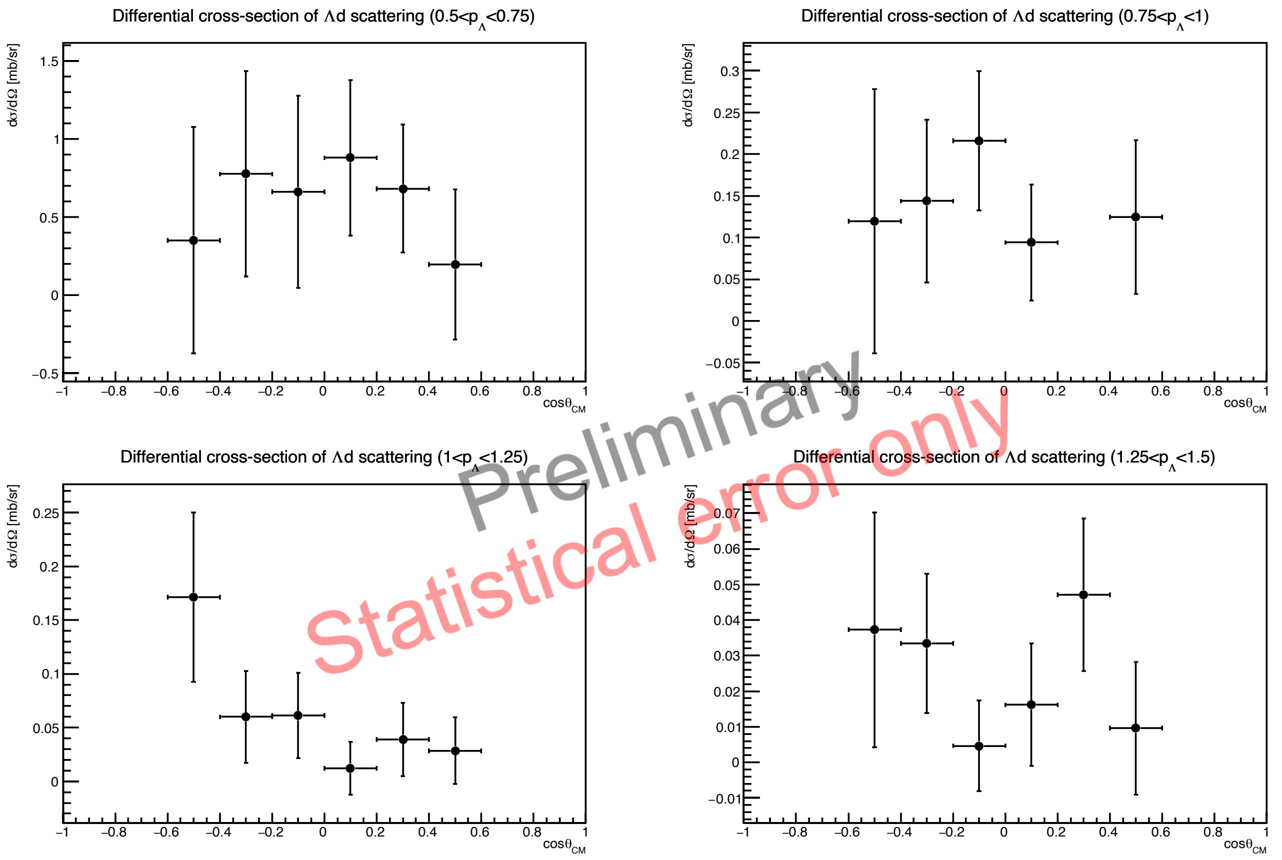
Cross-sections

Differential & Integrated cross-sections of Λd Scattering

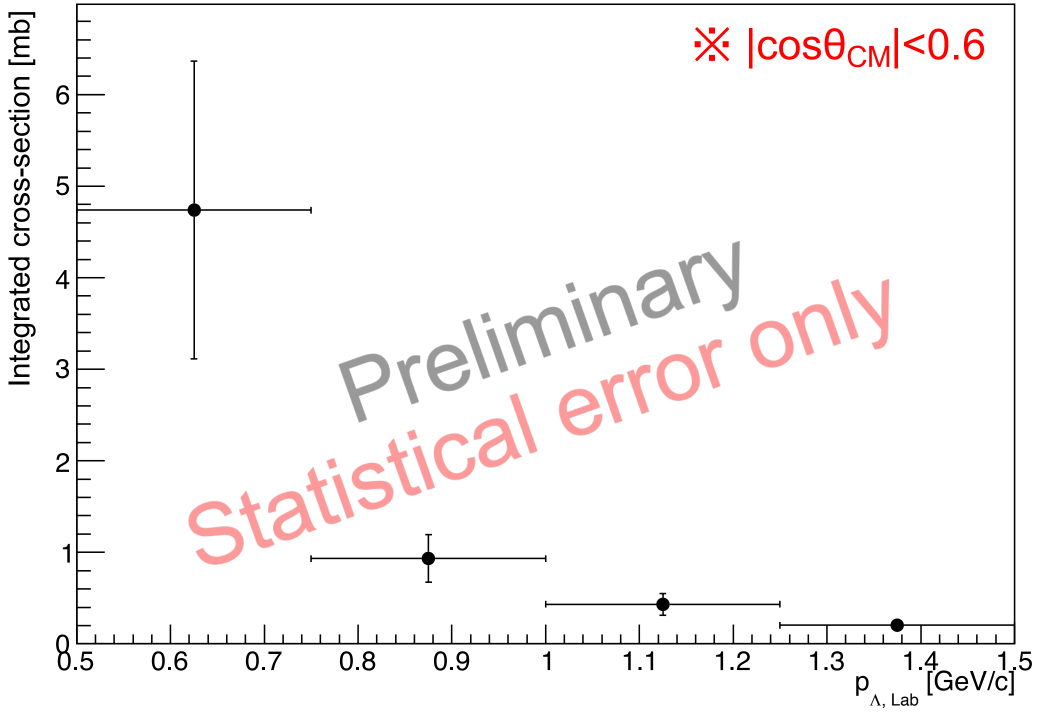
- Finally, the differential and integrated cross-sections in the $|\cos\theta_{CM}|<0.6$ range were measured (dp_Λ=0.25 GeV/c, $d\cos\theta_{CM}$=0.2).
- Systematic errors will be estimated by changing the angular distribution of Λd scattering in Geant4.
- The full analysis contents are currently summarized in a CLAS analysis note.

$$\left(\frac{d\sigma}{d\Omega}\right) = \frac{N_{\Lambda d\ \cos\theta_{\Lambda'\ CM}}}{\epsilon_{\cos\theta_{\Lambda'\ CM}}\cdot\tau\cdot L\cdot\Delta\Omega}$$

$$\sum_{\cos\theta_{CM}=-0.6}^{0.6}\frac{d\sigma}{d\Omega} = \frac{N_{\Lambda d\ \Delta p}}{\epsilon_{p_\Lambda}\cdot\tau\cdot L}$$



Integrated cross-section of Λd scattering



Summary

- As a first step in knowing many-body BB interactions to solve the “Hyperon puzzle in Neutron Star, YNN data is essential. Therefore, we measured Λd differential and integrated cross-sections.

- After 1st-level skimming (PID), Λd events were selected
  - $|\Delta p|<0.05$ GeV/c → integrated cross-section
  - $|\cos\theta_{CM}|<0.6$ → differential cross-section

- Efficiencies for differential & integrated cross-sections were estimated CLAS GSIM independently.
- Realistic Luminosity, which includes resonance events, was estimated using GSIM of elementary processes.

- The CLAS g10 dataset successfully measured Λd differential and integrated cross-sections.
  - E_γ : 1.2 – 2.4 GeV, p_Λ : 0.5 – 1.5 GeV/c
  - dp_Λ = 0.25 GeV/c, $d\cos\theta_{CM}$ = 0.2
  - Integrated cross-section = 0.1 ~ 5 mb in the scattering angular range of $|\cos\theta_{CM}|<0.6$
  - Systematic errors will be estimated soon

  - The CLAS analysis note is almost ready.