New Λp Cross Sections and it's Implication for Neutron Star EOS

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Introduction

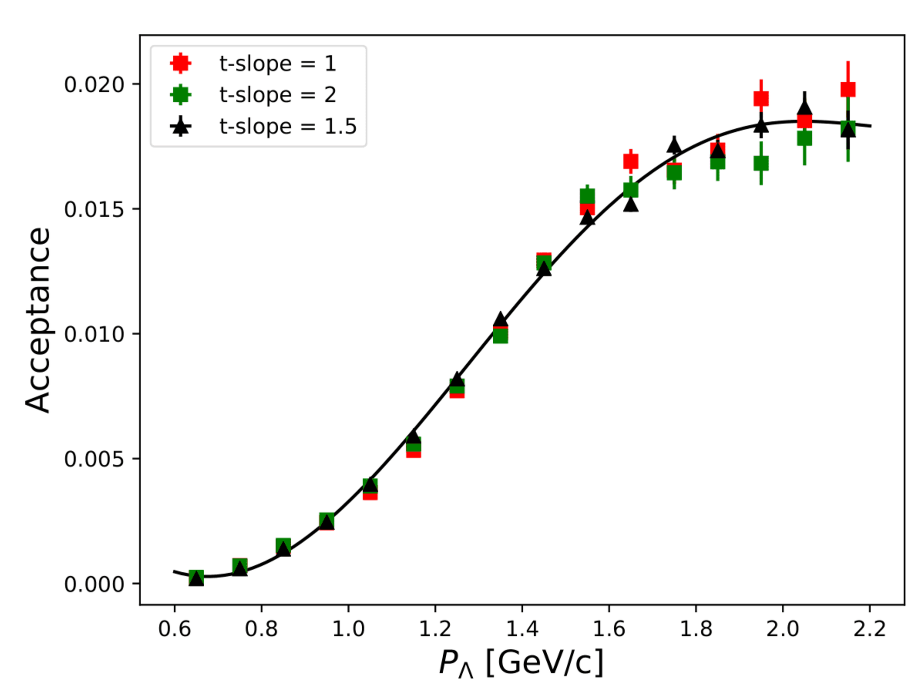
Previous data for the elastic scattering of Lambda hyperons from the nucleon date back to the bubble chamber era of the 1970s [1]. Data for Λ-N scattering are very limited in comparison with other elastic scattering processes, such as N-N, K-N and π-N. This reaction is important in the study of Neutron Star (NS) Equation of State (EOS). The presence of strange matter in the core of the NS can have a significant impact on its EOS. Whereas the presence of hyperons in the core will soften the EOS, the stiffening of the EOS at the highest densities required to explain massive stars is added by theory without firm experimental justification. Theoretical models suggest that a combination of ΛN and ΛNN interactions can create a neutron star consistent with observation.

Acceptance

To quantize the efficiency of the detector requires a simulation. The acceptance is the ratio of the number of final state particles that get accepted by the simulation and the number of Λ generated. The software used to calculate the accepted events is Geant4 and is a common software package used at various accelerator facilities. Geant uses a Monte Carlo simulation which models the detector. Binning for the generated and accepted events must be done with the same scheme as the data.

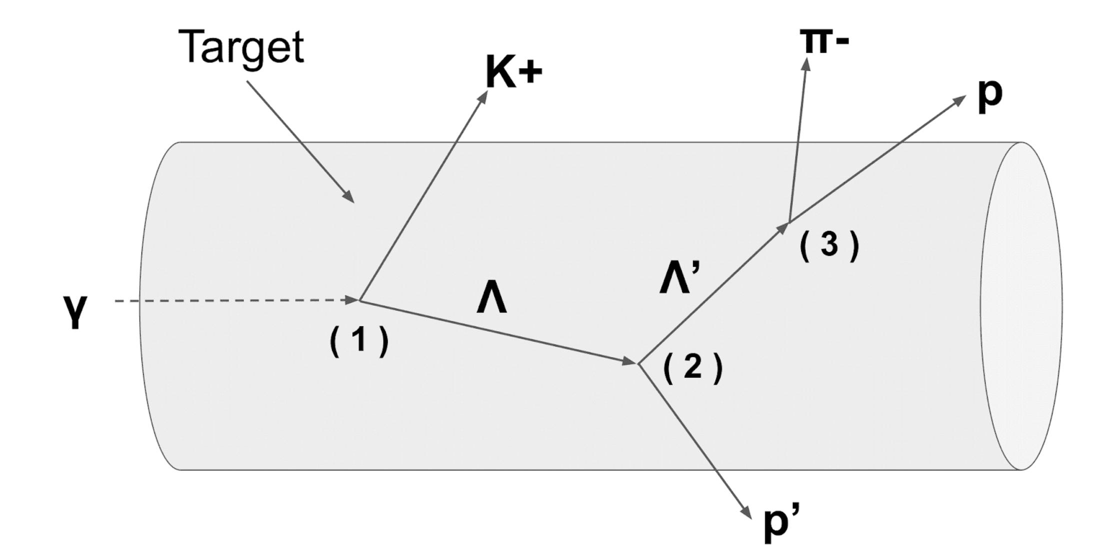
The t-slope distribution acts as an input to the generator and will affect the acceptance. Different distributions were compared and fit to a polynomial to extract the acceptance.

$$Acceptance = \frac{Accepted\ pp\pi^-}{Generated\ \Lambda p\ scattering}$$



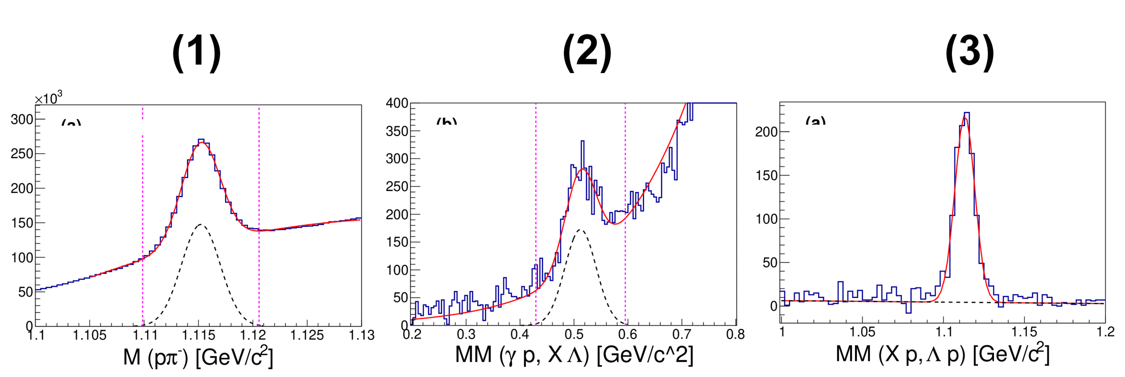
The acceptance ranges between 0.1% and 2.0% and the error bars are purely from the statistical uncertainty.

Reaction

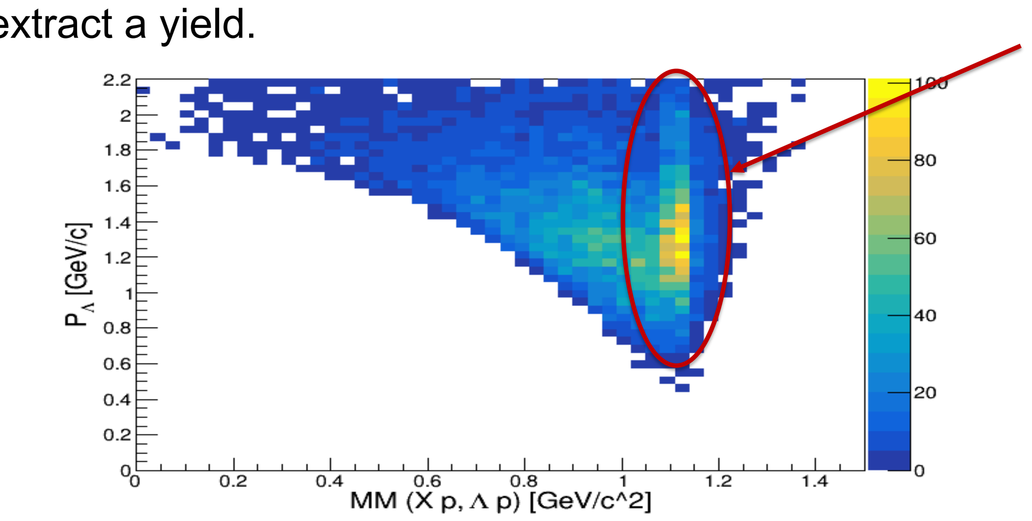


Yield

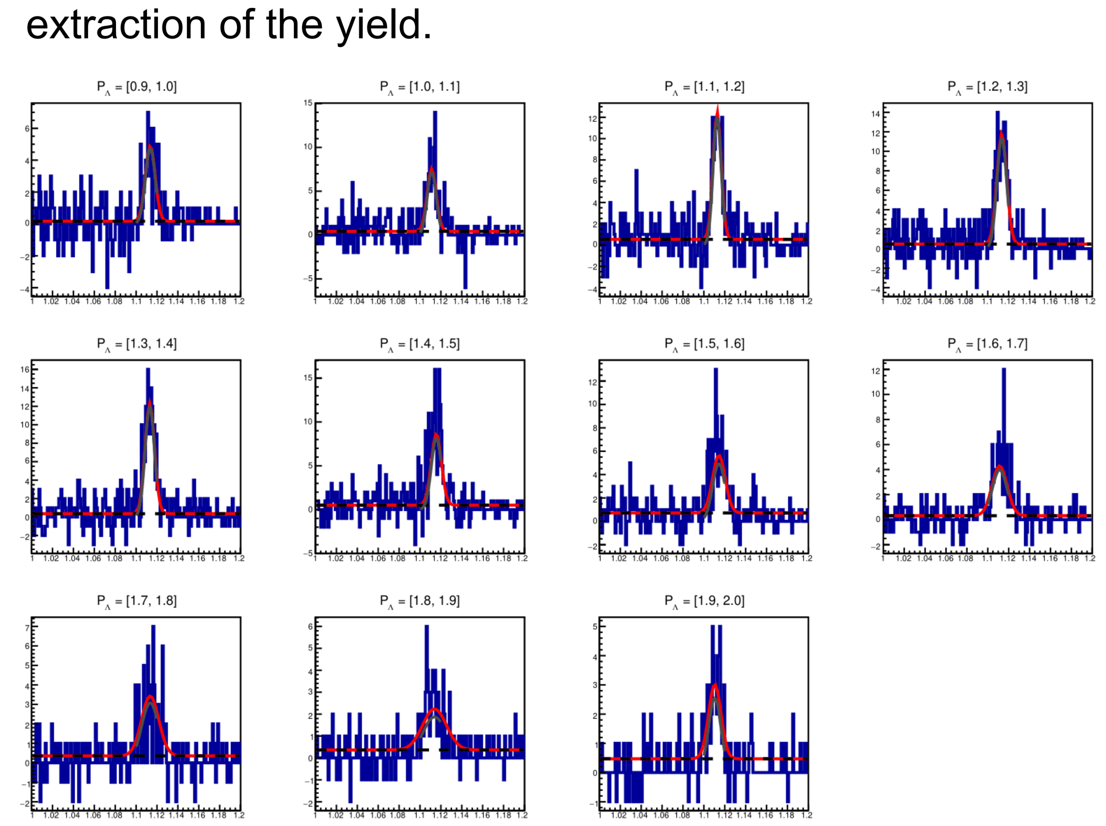
From the final state particles detected, the scattered Λ can be reconstructed from the four-momenta of its decay products ($\Lambda \to p\,\pi^-$) **(1)**. Using missing mass calculations, the Kaon can be identified from $\gamma p\ \to \mathrm{X}\,\Lambda$ **(2)**. The incident Λ is reconstructed from the incident Λ and the scattered proton **(3)**. This isolated the $\gamma p\ \to K^+\Lambda$.



To extract the yields, the data is binned in incident Λ momentum. The global spectrum of the missing mass vs. Λ momentum gives an idea of the data available to extract a yield.



Binning the data in appropriate Λ momentum bins allows extraction of the yield.



Cross Section

To measure a cross section, three values are required:

$$\sigma = \frac{\boldsymbol{Yield}}{\boldsymbol{A \times \mathcal{L} \times \Gamma}}$$

where the yield is the number of detected events, A is the acceptance of the reaction in the detector, $\mathcal{L}$ is the luminosity of the Λ beam, and Γ is the branching ratio (which for the $\Lambda \to p\,\pi^-$ decay is is 0.64) [2].

Luminosity

The Λ beam needs to be parametrized. This is luminosity and can be calculated from:

$$\boldsymbol{L_\Lambda(E_\Lambda) = \frac{\rho_T \times N_A \times l}{M} \times N_\Lambda(E_\Lambda)}$$

N_A is Avogadro's number, ρ_T is the density of the target, l is the average path length of the Λ beam, and N_Λ is the number of Λ particles in the beam. Both l and N_Λ are unknown quantities. The average path length can be calculated using [2]:

$$P(z) = \exp[-\left(\frac{M}{p}\right)\left(\frac{z-z0}{c\tau}\right)]$$

Which gives the probability that a Λ will decay at a location z after being created at z0. Path lengths calculations for test cases (p=M=1.115 GeV/c):

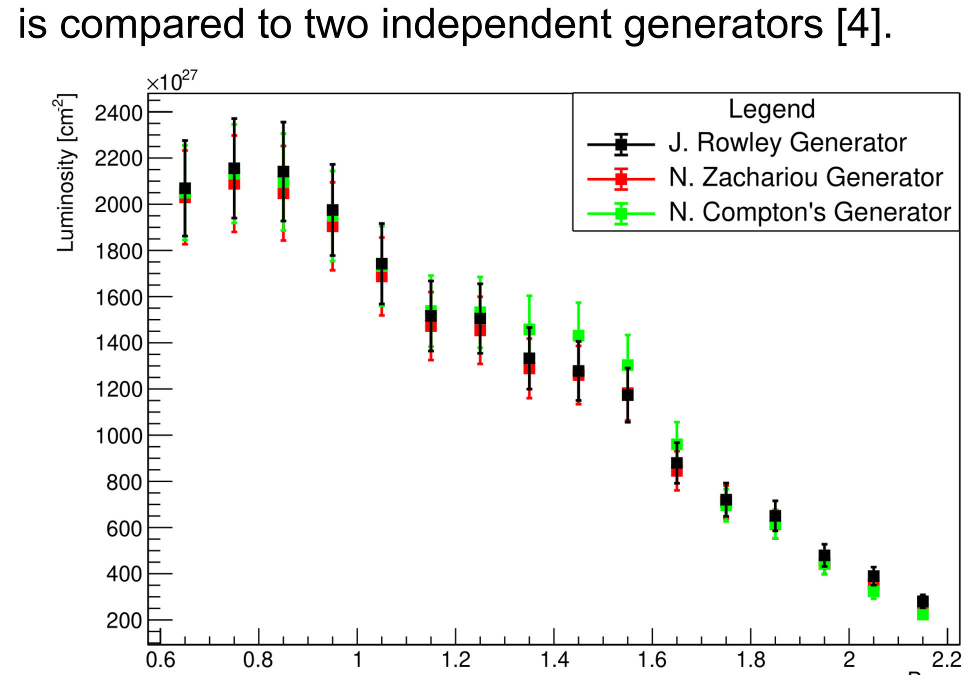
z-Vertex (cm)	cos(Θ)	Avg. Pathlength (cm)
0.0	1.0	7.8
20	1.0	7.3
20	.707	2.4
Random	Random	2.2

The first 3 rows can be solved analytically and verify the simulation.

To model a correct angular distribution, existing $K^+\Lambda$ cross sections are examined [3]. From existing cross sections, N_Λ can be found from:

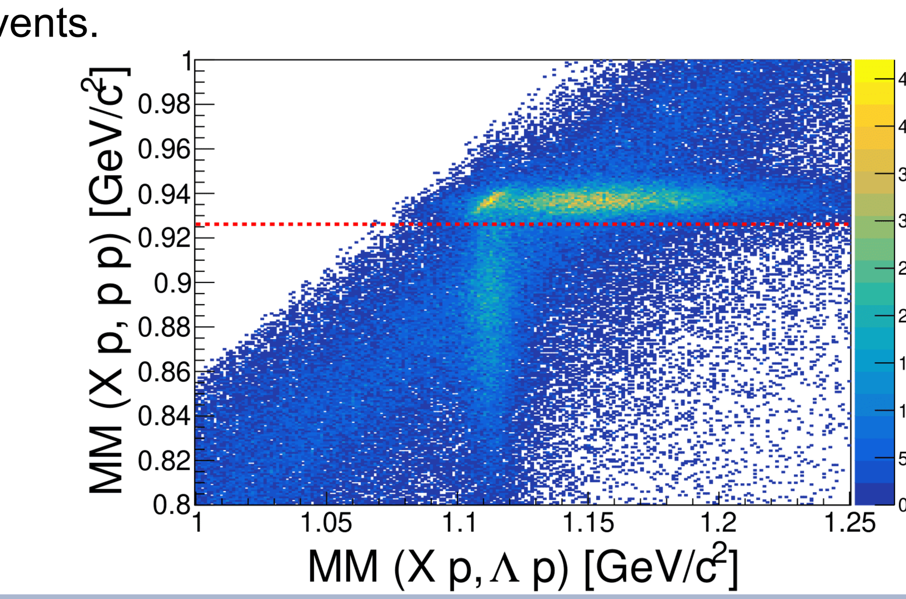
$$\frac{d\sigma}{d\Omega} = \frac{N_\Lambda}{2\pi \times L_\gamma \times \Delta\cos(\theta)}$$

With $\boldsymbol{l}$ and $\boldsymbol{N_A}$, $\boldsymbol{L_A(E_A)}$ can be calculated. This simulation is compared to two independent generators [4].



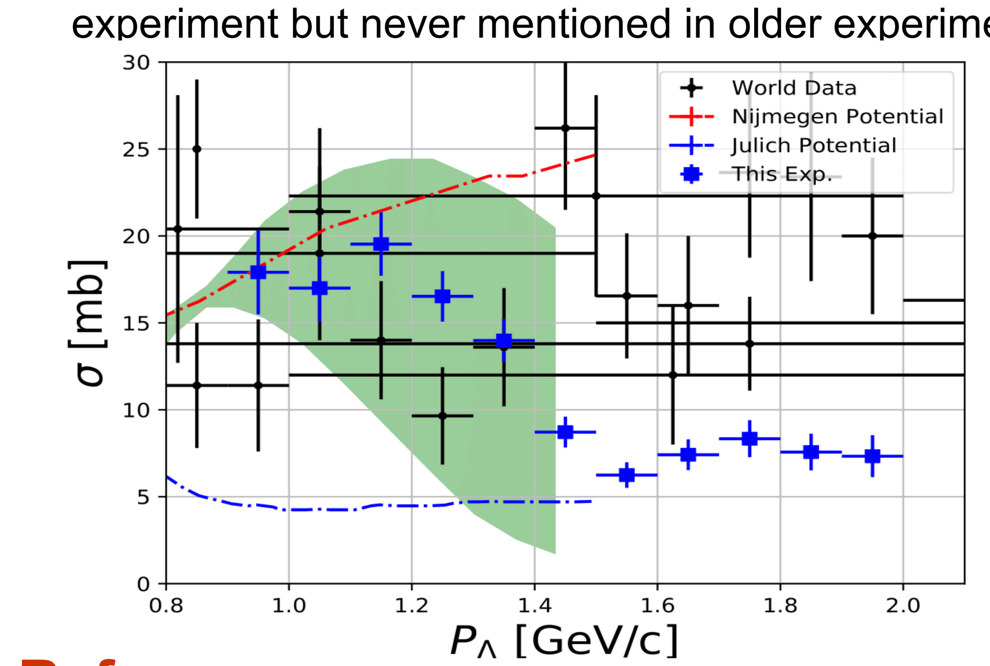
pp → *pp* Scattering

Additional analysis was also required to remove background from the *pp* → *pp* elastic scattering reaction. This reaction can happen when the Λ decays, followed by an elastic scattering of the decay proton. This leads to the same final-state which can be misidentified as Λp → Λ'p' events. Kinematic calculations are used to remove these events. There are prominent bands at the mass of the Λ (vertical band) and the mass of the proton (horizontal band). At the intersection of these bands there is significant overlap. This region represents *pp* elastic scattering events which must be removed. The band to the right of the overlap are *pp* inelastic scattering events. Data above the dashed line are rejected. The Λ band remains mostly intact. The same cut is applied to the MC events.



Results

- The cross sections from this experiment follow close to the center of the NLO EFT (green band) calculation [5] up to 1.4 GeV/c.
- Data for low Λ momentum are consistent with existing world data, with increased precision.
- Data for high Λ momentum fall off from the existing world data. A possible explanation for this is the presence of *pp* → *pp* which were removed from this experiment but never mentioned in older experiments.



References

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[3] McCracken, M.C. (2010). *Phys Rev C*. 81, 025201

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[5] J. Haidenbauer, U.-G. Meißner, and A. Nogga, Eur. Phys. J. A 114, 91 (2020)