# Strangeness Production

Christopher Thorpe

Lancaster University

# Contents

# Where Do Strange Particles Come From?

# Strangeness Production Processes

Interactions can be broadly separated into four categories:

1. CCQE-like hyperon production.
2. Renonant hyperon/kaon production, with non resonant background.
3. Deep inelastic scattering.
4. Coherent kaon production.

# CCQE-like Hyperon Production

- $\Delta S = 1$ counterpart to CCQE. Three processes for free nucleons:

$$\bar{\nu}_l + p \rightarrow l^+ + \Lambda^0 \tag{1}$$
$$\bar{\nu}_l + p \rightarrow l^+ + \Sigma^0 \tag{2}$$
$$\bar{\nu}_l + n \rightarrow l^+ + \Sigma^- \tag{3}$$

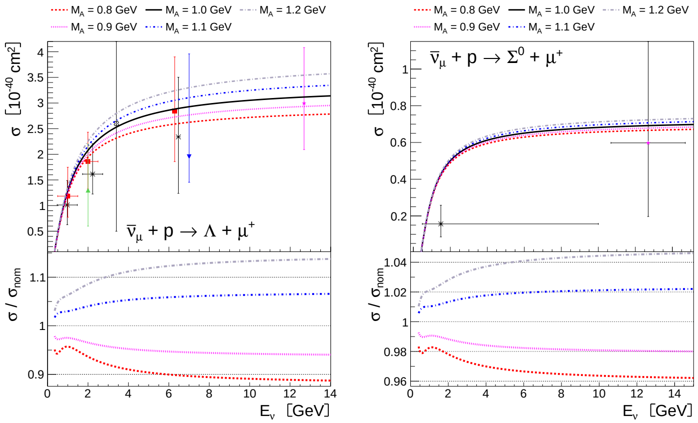
- **Anti-neutrinos only.**

- Llewelyn-Smith formalism, with different form factors obtained through SU(3) flavour relations.

- Generic notation: $N$ is a nucleon, $Y$ is a hyperon, eg.

$$\bar{\nu}_l + N \rightarrow l^+ + Y \tag{4}$$

# CCQE-like Hyperon Production and $M_A$

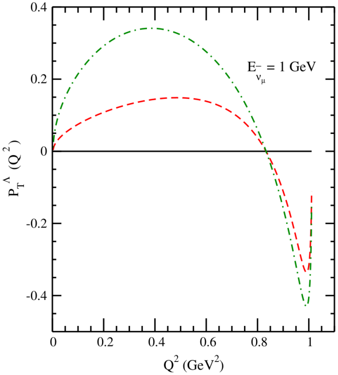



NuWro calculations of total cross sections from [1].

- Interesting observation: Λ and Σ cross sections have different dependencies on $M_A$.
- Measuring multiple channels helps disambiguate $M_A$ from other effects.

# CCQE-like Hyperon Production and SCC

- Possible non-zero second class current in some $\beta$ decays [2], and decays of $\Xi$ baryons [3].
- Polarisation of hyperons extremely sensitive to T violating currents.

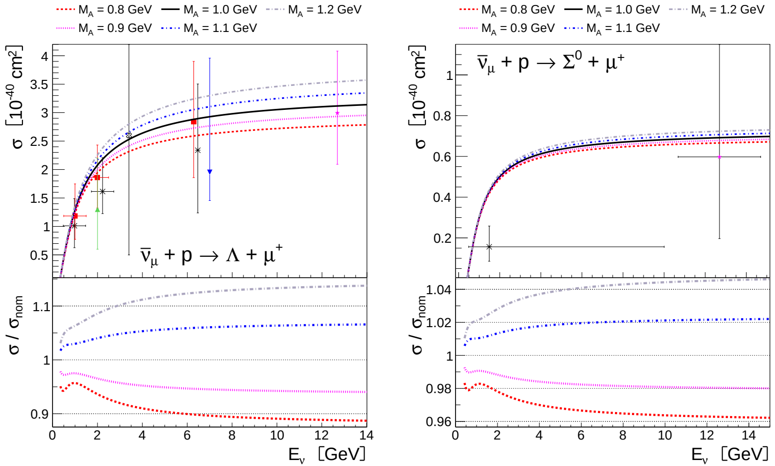



Transverse polariation of $\Lambda$ for different T-violating SCC calculated in [4]. Solid line is without SCC, dashed lines with SCC.

# Existing Measurements

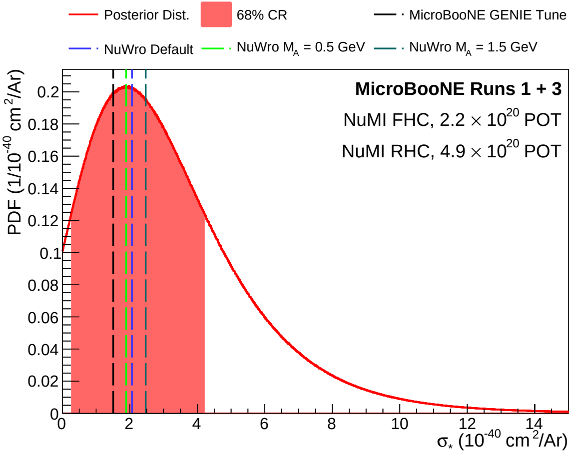
- I can summarize the entire dataset with the following three plots...

# Bubble Chamber Cross Sections




Entire set of published measurements of CCQE-like Λ and $\Sigma^0$ production, all from bubble chambers.
Data from [5-10]. Figs. from [1]

# The MicroBooNE Measurement




Partial phase space cross section for $\bar{\nu}_\mu + \mathrm{Ar} \rightarrow \Lambda + \mu^+$ measured by MicroBooNE [11]. First hyperon cross section from a modern detector. Limited by statistics. More on this later.

# RES Hyperon Production

- Excite a resonance that decays into some strange particles. If $W > M_\Lambda + M_K$ the associated channels become available, eg:

$$\nu_l + N \rightarrow l^- + N^* \rightarrow l^- + \Lambda + K^+ \tag{5}$$

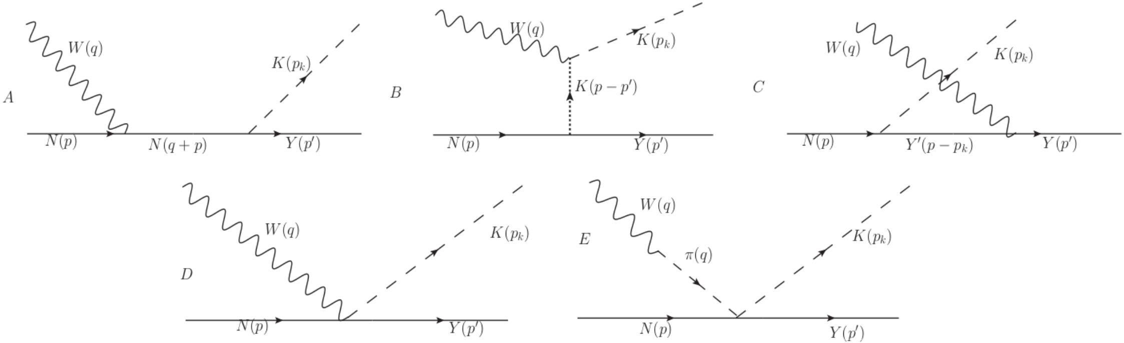
- Or, through a $\Delta S = 1$ process such as:

$$\bar{\nu}_l + N \rightarrow l^+ + \Sigma^{0*} \rightarrow l^+ + \Lambda + \pi^0 \tag{6}$$

- GENIE models these with the Rein-Sehgal/Berger-Sehgal models.
- Like CCQE hyperon production, get cross section through symmetries.

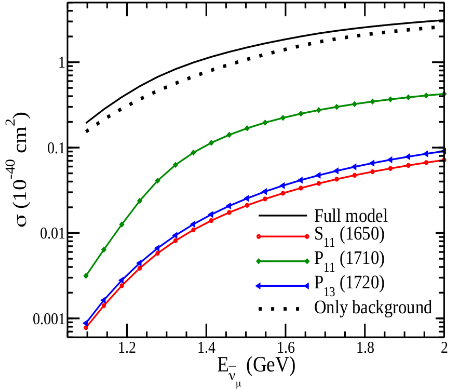
# Non-RES Background

- Can get the same final states through non-resonant diagrams such as these [12]:



# Non-RES Background

- GENIE modeling approach is to extrapolate the DIS model to lower invariant masses, and fit the combined RES + extended DIS to data.
- No hyperon/kaon DIS data to tune to.
- Some other calculations, such as [12] by Fatima, Sajjad Athar, and Singh, use analytical treatment. Non-res contribution is very large.
- $M_\Lambda + M_K \sim 1.6$ GeV. Probe the RES/DIS boundary with a final state that's hard to mimic with other channels.




Cross section for $\nu_\mu + n \to \mu^- + \Lambda + K$ from [12].

# DIS Hyperon Production

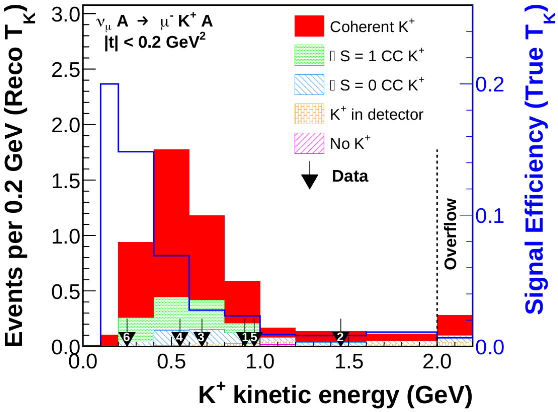
- $\Delta S = 0$ process: promote an $s\bar{s}$ pair from the quark sea. These hadronise into hyperon and kaon.
- $\Delta S = 1$ process: convert a $u$ quark to an $s$ quark. Produces a hyperon or kaon. Again, anti-neutrinos only.

- Cross sections calculated in the same manner a other DIS processes: parton distribution functions and hardronisation routines.
- Main generators outsource the hadronisation to Pythia.

- NOMAD [13, 14] looked at $\Lambda$ polarisation; no cross section measurements.

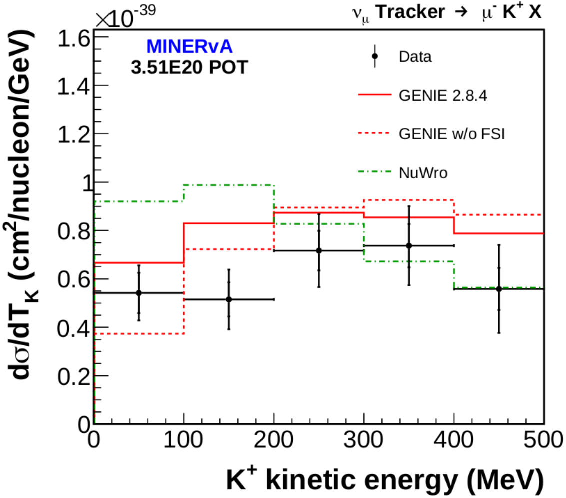
# Coherent Kaon Production

- Observed by MINERvA a few years ago [15]. Found 6 candidates.
- **Dangerous background in nucleon decay measurements.**
- Kaon KE from proton decay peaks $\sim$ 100 MeV, below MINERvA predicted events to be. Observed one event around here.



# Kaon Production in MINERvA

- Only kaon production measurement is from MINERvA.
- Inclusive $K^+$ production.
- Found good shape agreement with MC, but small tension in normalisation [16], approx 15%.

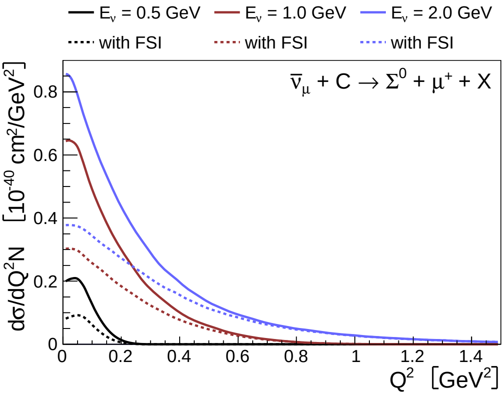


# Final State Interactions (FSI)

- A lot of the interesting effects in hyperon production appear when FSI gets involved.
- GENIE hA/hN modes provide FSI for Kaons, but not hyperons. NuWro has FSI for hyperons but not kaons.
- The Geant Bertini cascade, which can now be run as an FSI simulation in GENIE, can do both.
- Understanding the propagation of kaons through nuclear matter is important in proton decay.

# Hyperons and FSI

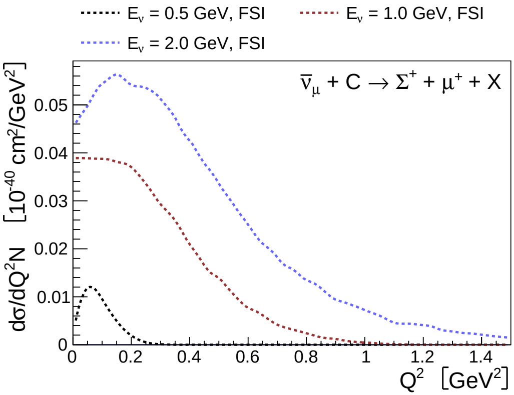
- Several calculations predict FSI to have a **very** large impact on the hyperon cross sections, especially at low energies.
- Some $N + Y \to N + Y$ data available, FSI cross sections fitted to this.
- Little data available on pion production $N + Y \to N + Y + \pi$ or kaon production $N + Y \to N + N + K$. Generators don't simulate these.




Sigma production suppressed by FSI at low $Q^2$. NuWro calculation from [1].

# Hyperons and FSI

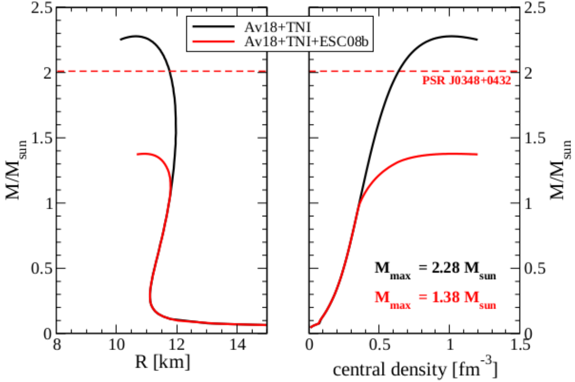
- The $\Sigma^+$ only gets produced in the CCQE-like interaction if FSI is involved.
- Predicted cross section $\sim 1/10$ that of other channels.




From [1].

# The Hyperon Puzzle

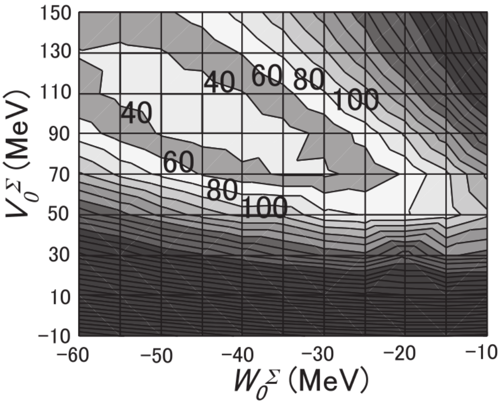
- Attempts to model the creation of hyperons in large neutron stars obtain an upper limit on their masses of 1.4 $M_{\odot}$.
- This conflicts with astronomical data.
- Density at which they appear depends on strength of their interaction with the nuclear medium.




Predicted masses of neutron star with and without hyperons from [17].

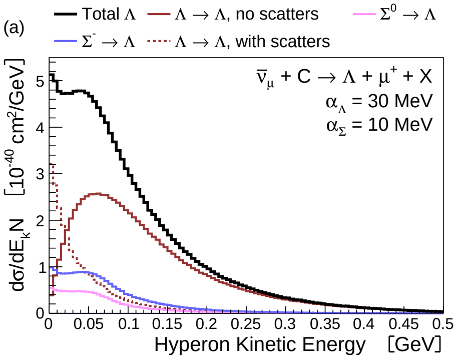
# Hypernuclear Potentials

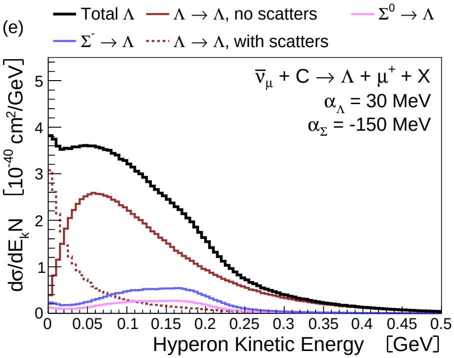
- Some calculations include hyperon-nucleus potentials [18].
- Only major generator to include them is NuWro.
- Σ-nucleus potential from K(A,A')Σ scattering data yields very large range of strengths, both attractive and repulsive.
- Calculations of the Λ potential are a little better.




Fit of Σ-nucleus potential strength ($V_0^\Sigma$) from [19].

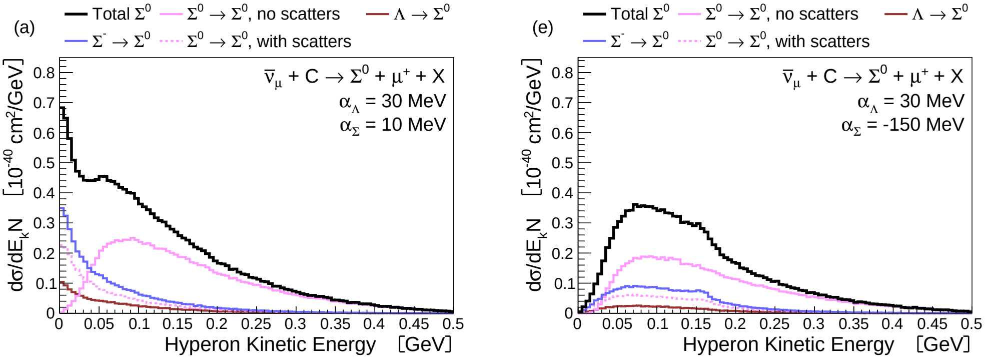
# Hypernuclear Potentials



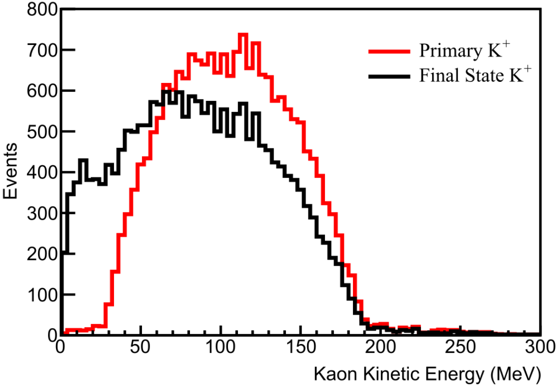

NuWro calculation of cross section at extremes of allowed values shows significant variation in size and shape of cross sections. Figs. from [1]. Sign convention opposite to previous slide - $\alpha < 0$ is repulsive.

# Hypernuclear Potentials




NuWro calculation of cross section at extremes of allowed values shows significant variation in size and shape of cross sections. Figs. from Ref. [1].

# Kaon FSI




Kinetic energies of kaons from $p \to \nu + K$, with kaon rescattering simulated with hA2018 [20].

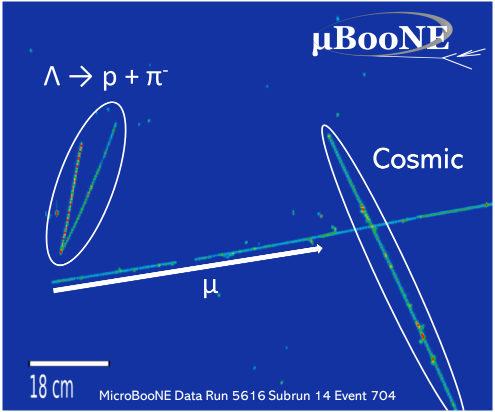
- Predicted to shift kaons to lower energies without affecting normalisation.
- GENIE simulates FSI with one of two models: hA and hN, both data driven.

# Models/Measurements Summary

- **Almost no data to go on, much of it from decades ago. All very statistics limited**.
- Unique nuclear and nucleon cross section effects.
- Can compliment measurements outside strange sector.
- Multiple channels: use to disambiguate different physics effects.
- New probe or RES/DIS transition that's harder for other interactions such as CCQE to mimic.

# The MicroBooNE Measurement

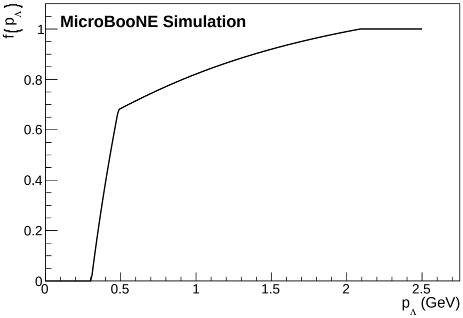
- Measure CCQE-like $\Lambda$ channel.
- Flux averaged total cross section, with NuMI flux.
- Combine $\nu$ and $\bar{\nu}$ mode data.
- Look for $\Lambda \rightarrow p + \pi^-$. BF = 68%.
- Signature is displaced V. **Any future measurements will require a detector with tracking with $\sim$ cm level resolution.**




One of the $\Lambda$ candidates found in MicroBooNE's data.

# Threshold Effects

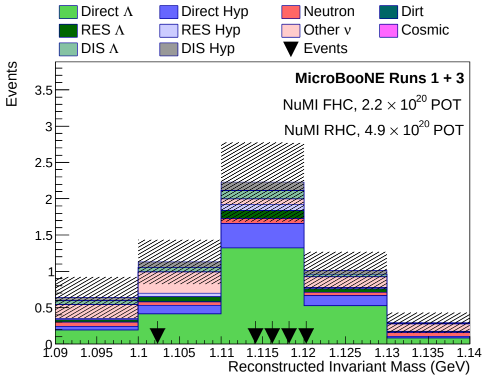
- MicroBooNE cannot see protons and pions with momentum $< 0.3$ GeV and $< 0.1$ GeV respectively.
- In MicroBooNE we calculated the fraction of $\Lambda$s that could decay this way.
- $\Lambda$s below 0.3 GeV invisible.
- Dedicated reconstruction algorithm remains on the wishlist.




Fraction of $\Lambda \rightarrow p + \pi^{-}$ decays visible in MicroBooNE.

# Background

- Event selection targets CCQE channel, with some contamination from other Λ sources such as RES/DIS.
- These sources of background can be eliminated with better control of flux shape, demonstrate in a few slides...




Invariant mass distribution predicted by MC. Green is CCQE-like Λ signal.

# Rudimentary Studies with the NuTORM Fluxes

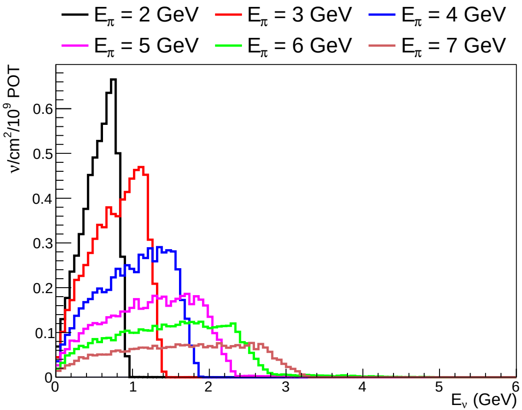
- Paul Kyberd very kindly provided me with the fluxes.
- Disclaimer: I am not a NuSTORM collaborator, these are studies I decided to perform on my own using the fluxes.
- Nothing on the following slides is official NuSTORM material in any capacity.

# Rudimentary Studies with the NuSTORM Fluxes

- These are some early studies I have performed with NuWro, this is the generator I am the most familiar with.
- I wasn't able to prepare GENIE samples of sufficient statistics in time.
- **I think a comparison of the two generators would be interesting given their radically different approaches to RES/DIS modeling.**

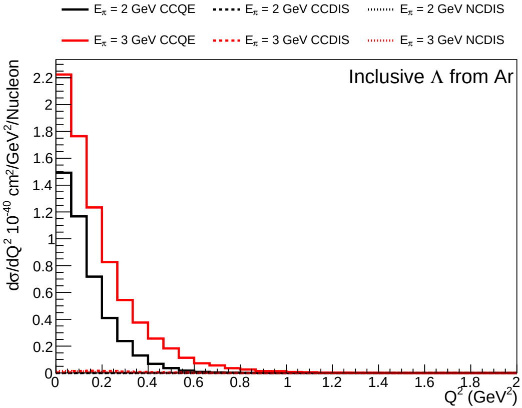
# Which Flux?

- We can produce different flux shape by tuning the energy of the pions.
- CCQE/RES/DIS processes will dominate at different energies.



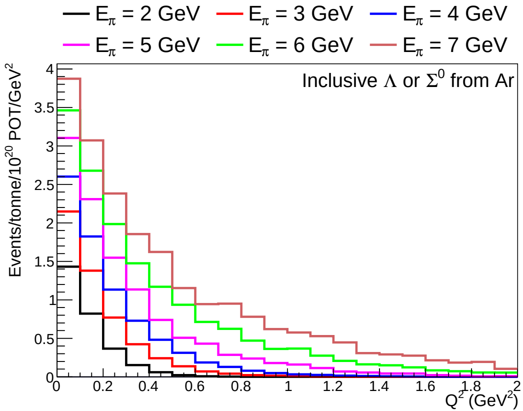
# $\pi$ Energy Dependence

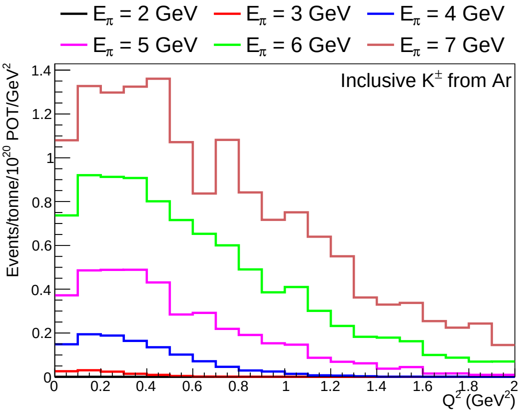
- Associated $\Lambda + K$ cross section very small when $E_\pi = 2$ GeV.
- **Clean place to study the CCQE-like hyperon production channels.**




Simulating $\nu_\mu$ and $\bar{\nu}_\mu$ on argon with NuWro.

# Statistics?

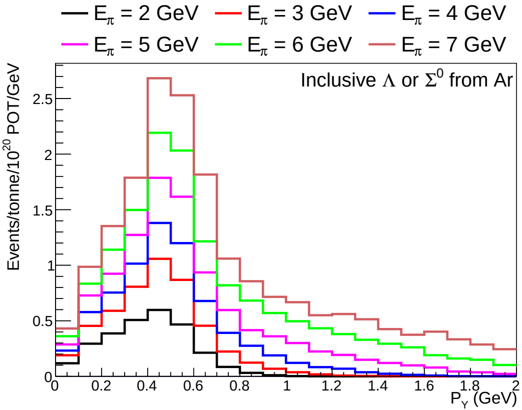



Expect a few events per tonne of active material per $10^{20}$ POT. Need to run on the higher energies to get many kaons.

# What's Visible?

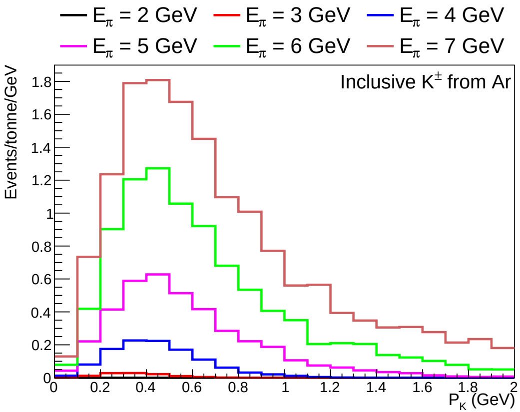
Calculate the momentum distribution of the Λs, and Λs from $\Sigma^0$ decay. Compare to LArTPC detection threshold of 0.3 GeV.




Most of the distribution is above detection threshold.

# What's Visible?

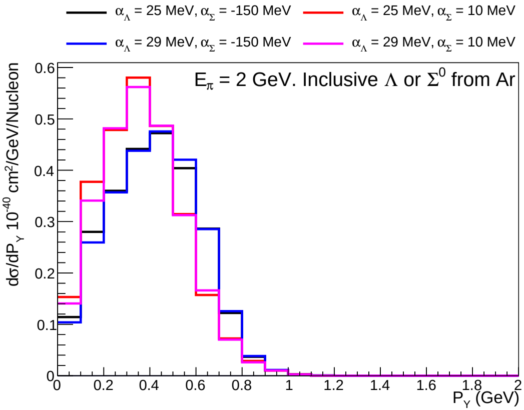
Similarly, we can look at charged kaons. Detection threshold in a LArTPC is about 0.3 GeV.




Most of the distribution is above detection threshold.

# Could We See the Σ-Nucleus Potential?

What effects do the hypernuclear potentials have?



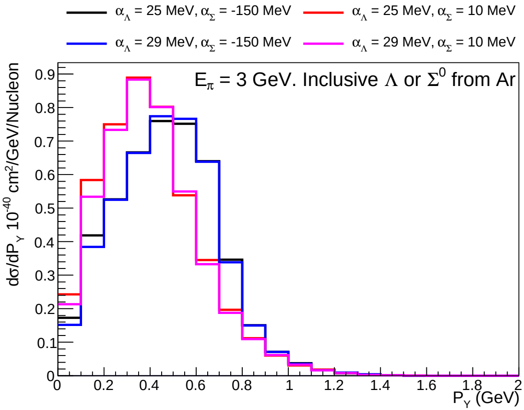
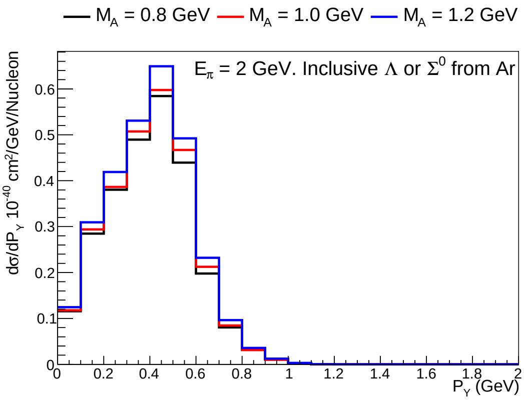
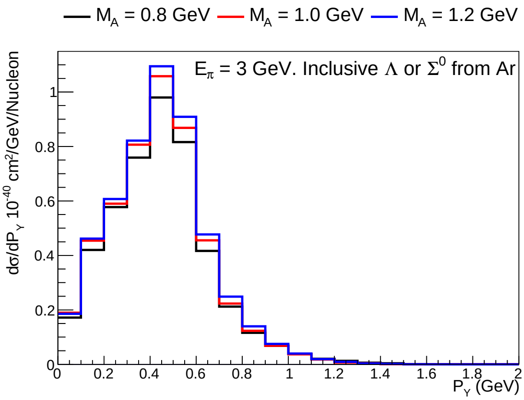




Figure: Σ potential pushes peak to the right.
Need enough statistics to do a two bin measurement though.

# What About $M_A$?



# Other Analysis Ideas

- Use a hydrocarbon target: measure the free proton cross section in the same vein as the recent MINERvA nature paper. **Could be cleaner as the $\Lambda$ decays with predictable kinematics; don't have to rely on neutrons.**

Way too many plots to add to this talk, get in touch if you fancy a look...

# Summary

- Not much understood about strangeness production in any channel. Next to no data to go on.

- Sensitive to lots of unique nuclear effects, and can nicely compliment measurements of $M_A$ and other physics effects from the non-strange channels.

# Summary

- Expect a few events per tonne per $10^{20}$ POT with the NuSTORM fluxes with current EG modeling.
- Large benefit I can see from NuSTORM is the ability to separate the CCQE-like channel from the others thanks to better control over the shape of the flux.
- Still expecting measurements to be quite statistically limited.
- Low threshold detection technology preferable, but not essential.

# References I


[1] C. Thorpe, J. Nowak, K. Niewczas, J. T. Sobczyk and C. Juszczak, Phys. Rev. C **104** (2021) no.3, 035502

[2] K. Minanisono, T. Yamaguchi, K. Matsuta, T. Minamisono, T. Ikeda, Y. Muramoto, M. Fukuda, Y. Nojiri, A. Kitagawa and K. Koshigiri, *et al.* Nucl. Phys. A **654** (1999) no.1, 955c-960c

[3] A. Alavi-Harati *et al.* [KTeV], Phys. Rev. Lett. **87** (2001), 132001

[4] A. Fatima, M. Sajjad Athar and S. K. Singh, Phys. Rev. D **98** (2018) no.3, 033005.

[5] O. Erriquez *et al.*, Nucl. Phys. B **140** (1978) 123.

[6] O. Erriquez *et al.* Phys. Lett. B **70** (1977) 383.

[7] T. Eichten *et al.*, Phys. Lett. **40B**, 593 (1972).

[8] J. Brunner *et al.* [SKAT Collaboration], Z. Phys. C **45** (1990) 551.

# References II


[9] V. V. Ammosov *et al.*, Z. Phys. C **36**, 377 (1987).

[10] G. Fanourakis *et al.*, Phys. Rev. D **21**, 562 (1980)

[11] P. Abratenko *et al.* [MicroBooNE], [arXiv:2212.07888 [hep-ex]].

[12] M. Sajjad Athar, A. Fatima and S. K. Singh, Prog. Part. Nucl. Phys. **129** (2023), 104019

[13] D. Naumov *et al.* [NOMAD], Nucl. Phys. B **700** (2004), 51-68

[14] P. Astier *et al.* [NOMAD], Nucl. Phys. B **621** (2002), 3-34

[15] Z. Wang *et al.* [MINERvA], Phys. Rev. Lett. **117** (2016) no.6, 061802

[16] C. M. Marshall *et al.* [MINERvA], Phys. Rev. D **94** (2016) no.1, 012002

[17] I. Vidaña, EPJ Web Conf. **271** (2022), 09001

# References III

[18] J. E. Sobczyk, N. Rocco, A. Lovato and J. Nieves, Phys. Rev. C **99** (2019) no.6, 065503

[19] P. K. Saha *et al.*, Phys. Rev. C **70** (2004), 044613

[20] B. Abi *et al.* [DUNE], Eur. Phys. J. C **81** (2021) no.4, 322

[21] M. Rafi Alam *et al.*, AIP Conf. Proc. **1663** (2015) no.1, 070004