CERN Neutrino Platform Pheno Week 2023

Neutrino Interactions and Strangeness

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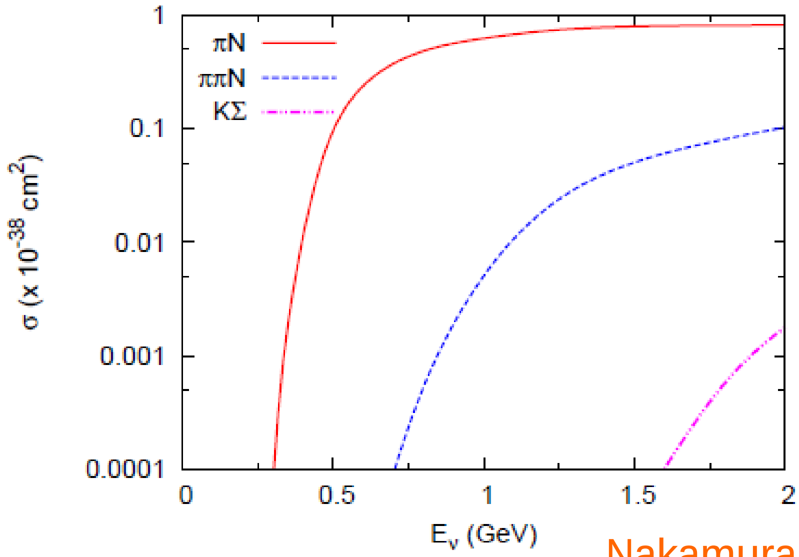
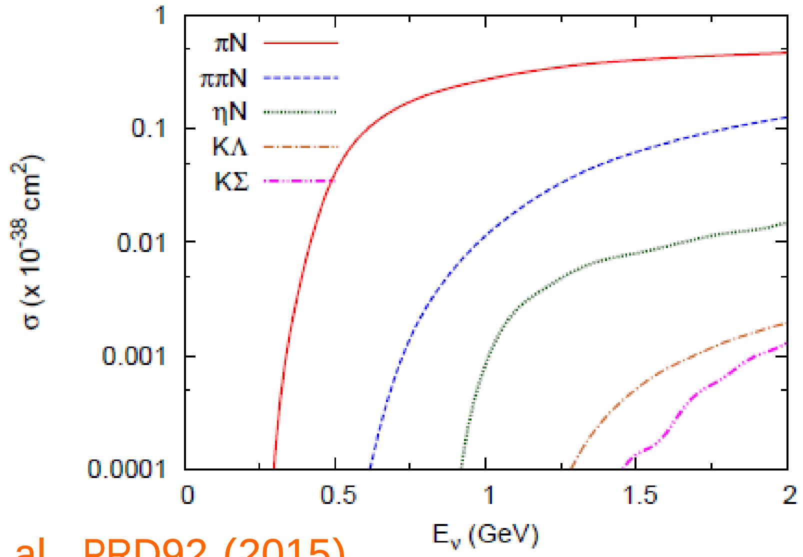
Weak Strangeness production

- $\Delta S = 0$: $\bar{s}s$ production
  - CC but also NC and EM processes
    - e.g. $\nu_l\, p(n) \to l^-\, K^+\, \Sigma^+(\Lambda)$
  - High threshold: W ≥ 1.6 GeV ⇔ $E_\nu \geq 0.9$ GeV





Nakamura et al., PRD92 (2015)

- Predominantly through Δ, N* excitation
- Unitarization in coupled channels required
  - e.g. ANL-Osaka Dynamical Coupled Channel (DCC) Model

Weak Strangeness production

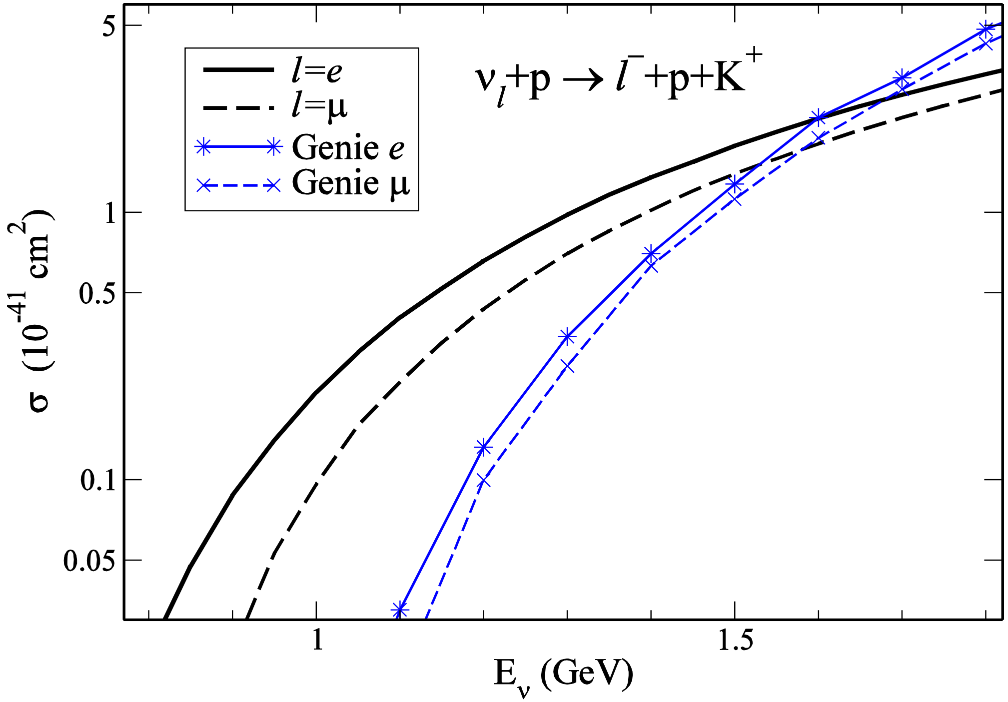
- $\Delta S = \pm 1$
  - CC; FCNC are suppressed in the **SM**
  - Cabibbo reduced ($V_{us} = 0.23$) but with lower thresholds vs $\Delta S = 0$

Weak Strangeness production

- $\Delta S = 1$: $W^+ \bar{u} \rightarrow \bar{s}$
  - Low threshold: W ≥ 1.4 GeV ⇔ $\boldsymbol{E_\nu} \geq$ 0.6 GeV
  - K: $\nu_l\, p \rightarrow l^-\, K^+\, p$

$$\nu_l\, n \rightarrow l^-\, K^0\, p$$

$$\nu_l\, n \rightarrow l^-\, K^+\, n$$



vs $\Delta S = 0$ from GENIE

Rafi Alam et al., PRD82

Weak Strangeness production

- $\Delta S = 1$: $W^+\bar{u} \to \bar{s}$
  - Low threshold: W $\geq$ 1.4 GeV $\Leftrightarrow$ $\boldsymbol{E_v}$ $\geq$ 0.6 GeV
  - K: $$\begin{aligned} \nu_l\, p &\to l^-\, K^+\, p \\ \nu_l\, n &\to l^-\, K^0\, p \\ \nu_l\, n &\to l^-\, K^+\, n \end{aligned}$$
  - No baryon resonances $\Leftrightarrow$ weak K FSI in nuclei

Weak Strangeness production

- ΔS = -1: $W^- u \to s$
- Quasielastic:
  - Lowest threshold: W $\geq$ 1.1 GeV $\Leftrightarrow$ $\boldsymbol{E_v}$ $\geq$ 0.2 GeV
  - Y: $\bar{\nu}_l \, p \rightarrow l^+ \, \Sigma^0 (\Lambda)$

    $\bar{\nu}_l \, n \rightarrow l^+ \, \Sigma^-$

Weak Strangeness production

- ΔS = -1: $W^- u \to s$
- Inelastic:
  - $\bar{K}$:
$$\bar{\nu}_l\, p \rightarrow l^+\, K^-\, p$$
$$\bar{\nu}_l\, p \rightarrow l^+\, \bar{K}^0\, n$$
$$\bar{\nu}_l\, n \rightarrow l^+\, K^-\, n$$
  - Low threshold: W ≥ 1.4 GeV ⇔ $\boldsymbol{E_v}$ ≥ 0.6 GeV
  - Yπ:
$$\bar{\nu}_l\, p \rightarrow l^+\, \Sigma^0 (\Lambda)\, \pi^0 \qquad \bar{\nu}_l\, n \rightarrow l^+\, \Sigma^0 (\Lambda)\, \pi^-$$
$$\bar{\nu}_l\, p \rightarrow l^+\, \Sigma^+\, \pi^- \qquad \bar{\nu}_l\, n \rightarrow l^+\, \Sigma^-\, \pi^0$$
$$\bar{\nu}_l\, p \rightarrow l^+\, \Sigma^-\, \pi^+$$
  - Lower threshold: W ≥ 1.3 GeV ⇔ $\boldsymbol{E_v}$ ≥ 0.4 GeV
  - can proceed through the excitation of Λ or Σ resonances
    - in particular: Σ^*(1385), Λ(1405)

Interest

- K production by atmospheric ν is a potential background for $p \to \nu K^+$
- Via $Y \to \pi N$, Y are a source of low energy π in $\bar{\nu}$ scattering
- QE Y production could be used to constrain $\bar{\nu}$ contamination in ν beams
- YN form factors encode interesting information about:
  - 2nd class currents, T violation, SU(3) breaking corrections
- Inelastic processes can provide information about strange baryon resonances
  - Two-pole structure of the $\Lambda(1405)$ could be studied in $\bar{\nu}_l\, p \to l^+\, \Lambda(1405) \to l^+\, \Sigma\, \pi$

    without distortion due to K $\Lambda(1405)$ interactions in strong or em prod.
- Sensitivity to nuclear dynamics in the presence of strangeness
  - K-nucleus and Y nuclear potential
- $\Delta S = 1$: $W^+ \bar{u} \to \bar{s}$ and $\Delta S = -1$: $W^- u \to s$ are very different
  - Relevant for oscillations? Maybe not but insufficiently investigated

Theoretical studies

- QE Y production on nucleons and nuclei:
  - Cabibbo & Chilton, PR 137 (1965)
  - Singh and Vicente Vacas, PRD74 (2006)
  - Mintz and Wen, EPJA33 (2007)
  - Kuzmin and Naumov, Phys.Atom.Nucl. 72 (2009)
  - Sobczyk et al., PRC99 (2019)
  - Thorpe et al., PRC104 (2021)
- K, $\bar{K}$ production on nucleons and nuclei:
  - Dewan, PRD24 (1981)
  - Rafi Alam et al., PRD82 (2010); PRD85 (2012)
  - Lalakulich, K. Gallmeister, and U. Mosel, PRC86 (2012)
  - LAR et al., PRC87 (2013)
- YK production on nucleons:
  - Shrock, PRD12 (1975)
  - Adera et al. PRC82 (2010)
- Yπ production on nucleons:
  - Dewan, PRD24 (1981)
  - Ren, Oset, LAR, Vicente Vacas, PRC91 (2015)
  - Benitez Galan, Rafi Alam, Ruiz Simo, PRD 104 (2021)

Experiments

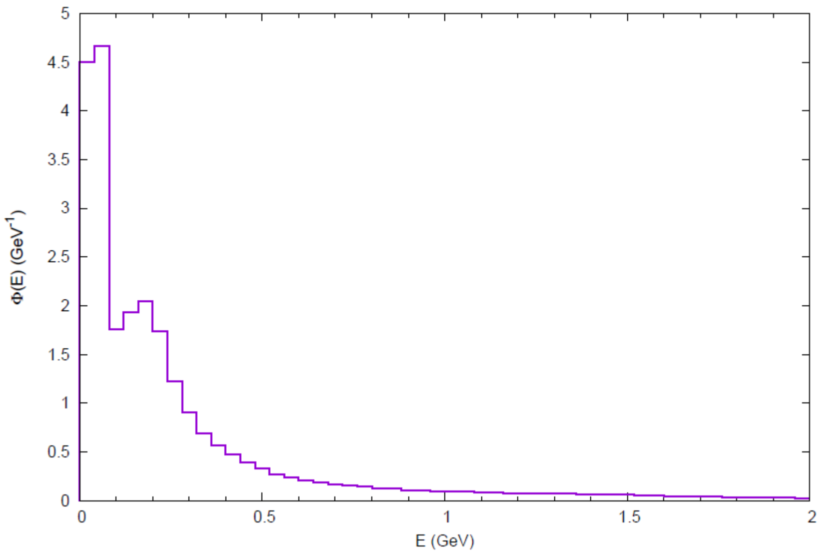
- XX Century:
  - Fermilab 15', SKAT, Gargamelle, BNL 7' bubble chambers
  - broad band high energy beams
  - observation strange particle production, yields, multiplicites, ratios,...
  - a few low statistics cross section measurements: Y and YK
- XXI Century:
  - NOMAD: Naumov et al., NPB (2004); Chukanov et al., EPJC (2006)
    - Neutral strange hadron yields
    - $K^*(892)$ yields and spin alignments
    - Λ polarizations
  - MINERvA:
    - K^+ production on CH using NUMI low-energy ν beam

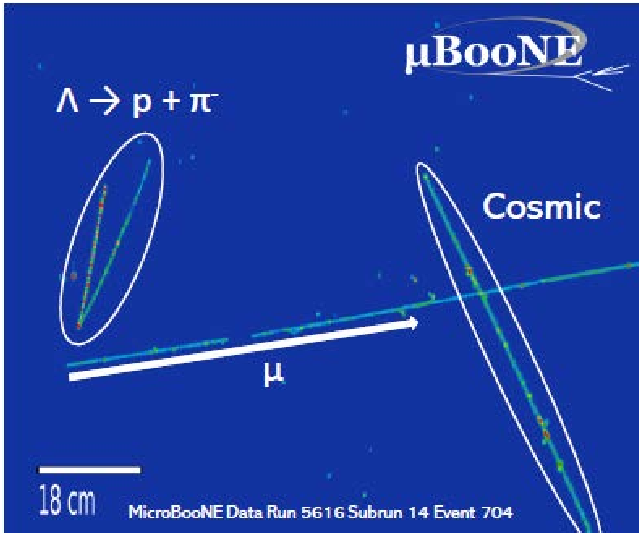
      Marshall et al., PRD92 (2016)
    - Observation of coherent K^+ production

      Wang et al., PRL 117 (2016)

MicroBooNE measurement

- First (modern) measurement of $\bar{\nu}\,\mathrm{Ar} \to \mu^+ \Lambda\; X$ arXiv:2212.07888
  - X=additional final state particles with no strangeness





Area-normalized accumulated off-axis NUMI flux.
Courtesy of C. Thorpe.

- 5 events, but more to come...
- Phase-space restricted averaged cross section:

$$\sigma_* = 2.0^{+2.1}_{-1.6} \times 10^{-40}\ \mathrm{cm}^2/\mathrm{Ar}$$

QE Y production

$$\bar{\nu}_l\, p \;\rightarrow\; l^+\, \Sigma^0(\Lambda)$$
$$\bar{\nu}_l\, n \;\rightarrow\; l^+\, \Sigma^-$$

- Following Cabibbo & Chilton, PR 137 (1965)

$$J^\alpha = \bar{u}_Y(p')\Gamma^\alpha u(p) = V^\alpha - A^\alpha$$

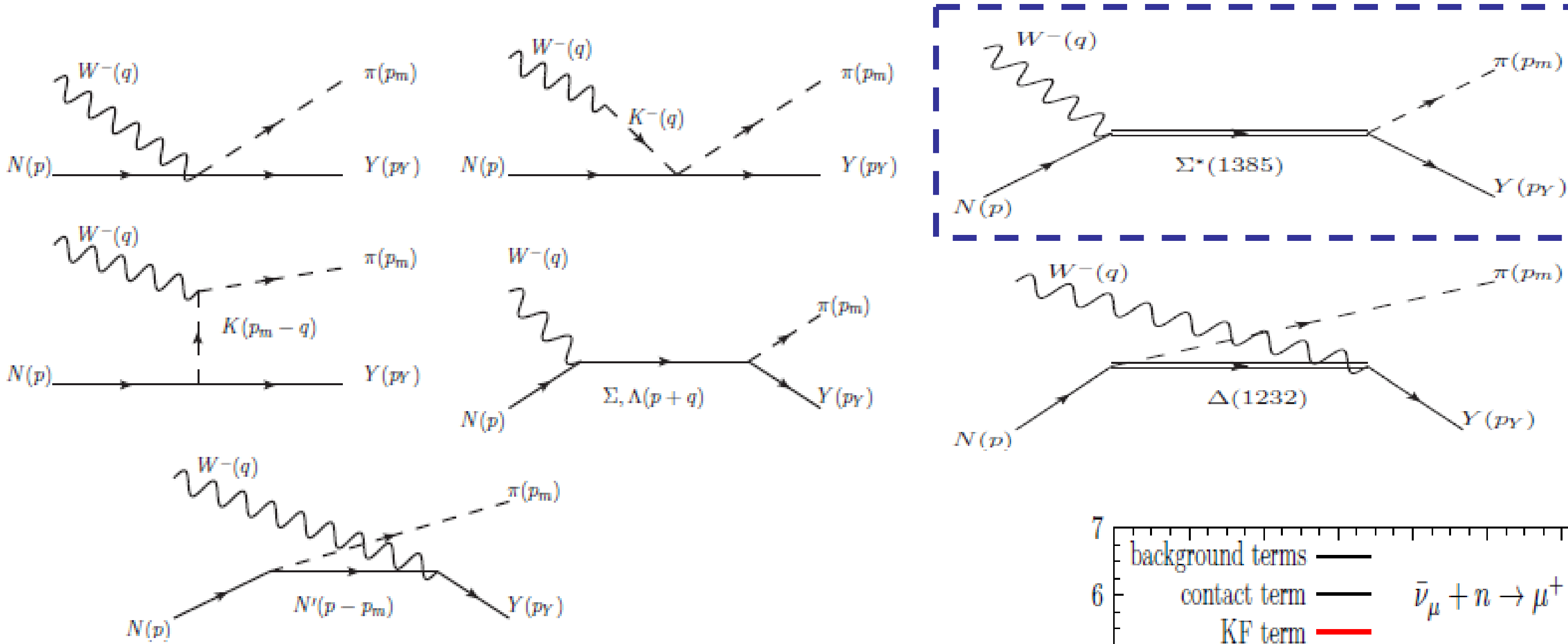
$$V^\alpha = \bar{u}_Y(p')\left[\gamma^\alpha f_1(q^2) + i\sigma^{\alpha\beta}\frac{q_\beta}{M+M_Y}f_2(q^2) + \frac{q^\alpha}{M_Y}f_3(q^2)\right]u(p)$$

$$A^\alpha = \bar{u}_Y(p')\left[\gamma^\alpha g_1(q^2) + i\sigma^{\alpha\beta}\frac{q_\beta}{M+M_Y}g_2(q^2) + \frac{q^\alpha}{M_Y}g_3(q^2)\right]\gamma_5\, u(p)$$

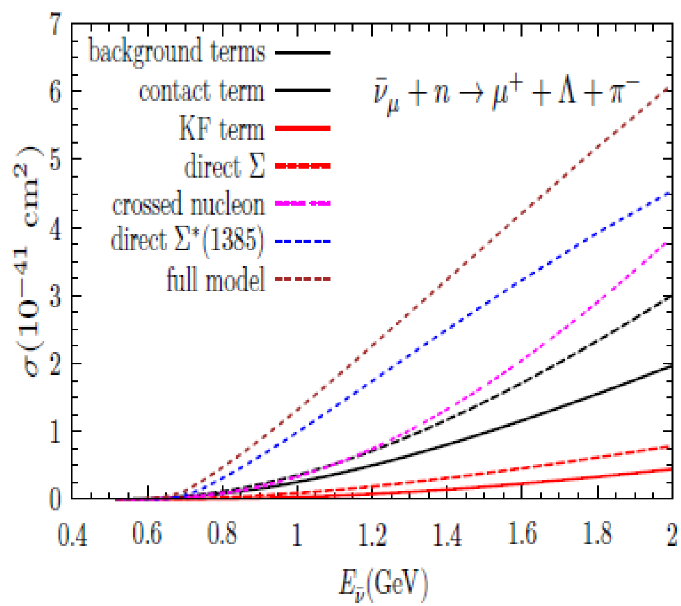
- SU(3) flavor symmetry: NY transition form factors can be related to the em and axial nucleon counterparts
- G parity invariance: $f_3 = g_2 = 0$

Yπ production

- Benitez Galan, Rafi Alam, Ruiz Simo, PRD 104 (2021)



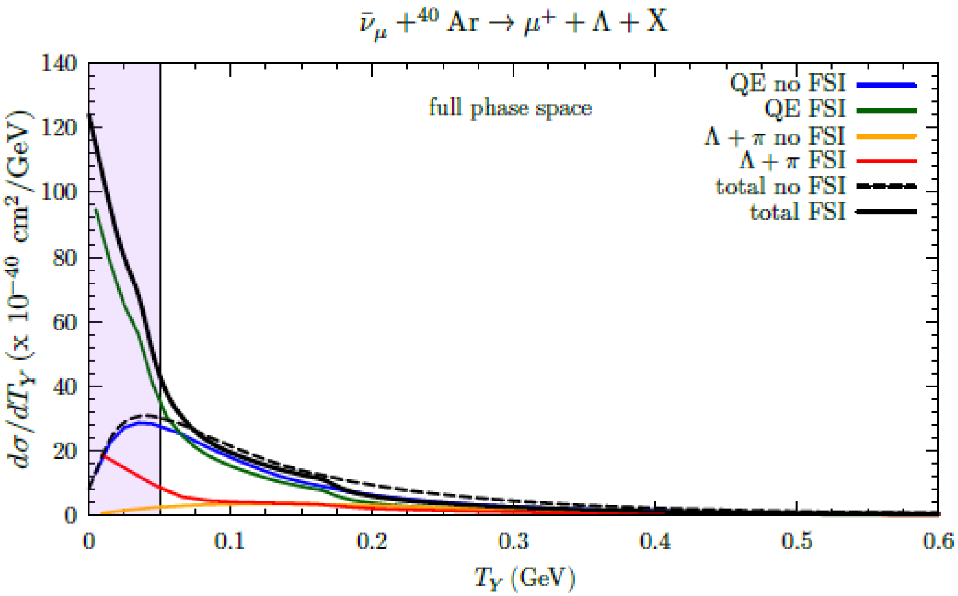
- Born terms at threshold determined by chiral symmetry
- SU(3) symmetry used to relate form factors to measured quantities



FSI

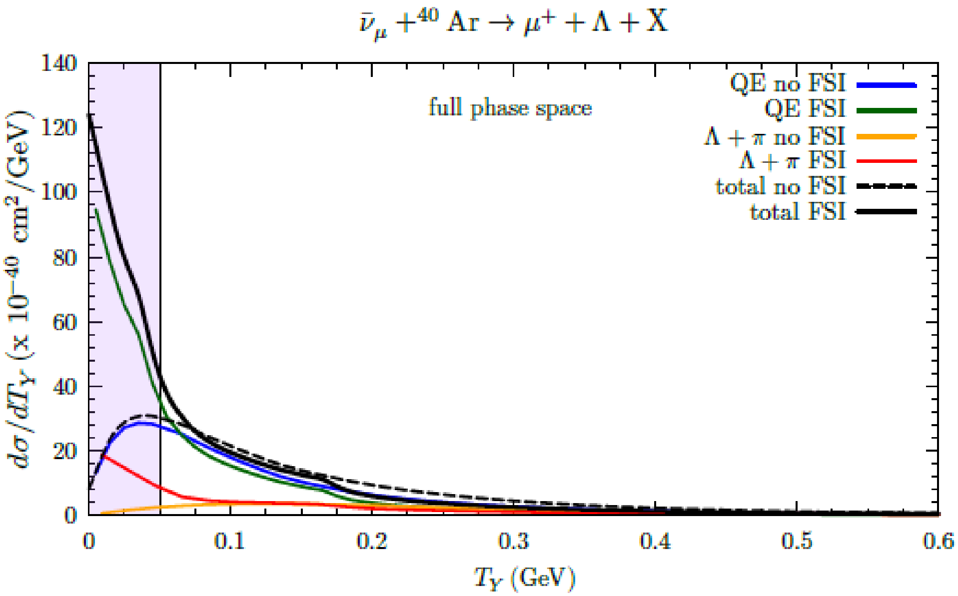
- Intranuclear cascade: semiclassical Monte-Carlo simulation
  - Experimental input for Y N $\rightarrow$ Y' N' cross sections (poorly known)
  - Isotropic angular distributions in the CM frame
  - Pauli blocking
  - Real part of the Y nuclear potential neglected
    - Typically assumed to be $V(r) \approx -30 \, \frac{\rho(r)}{\rho(0)}$ MeV
  - Enhancement of $\Sigma \rightarrow \Lambda$ conversion

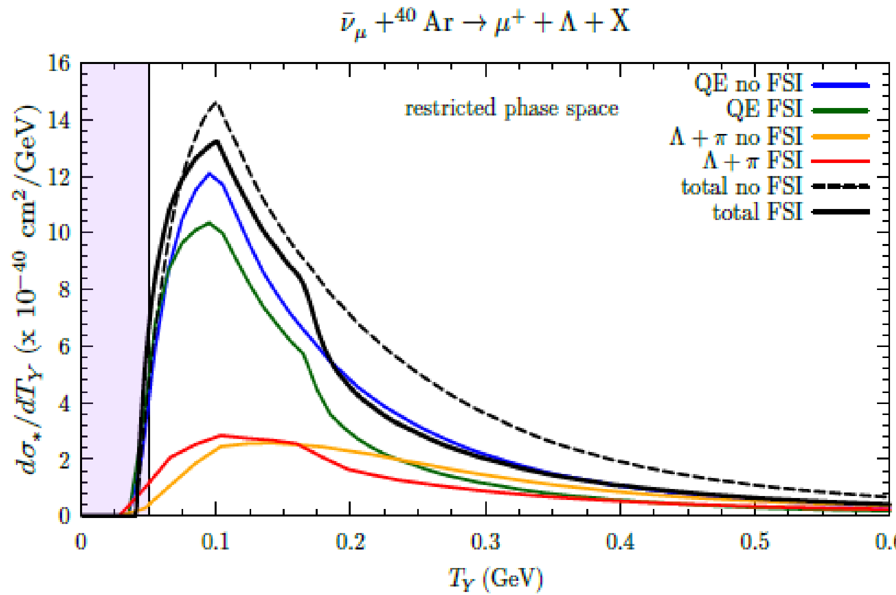
Comparison to MicroBooNE



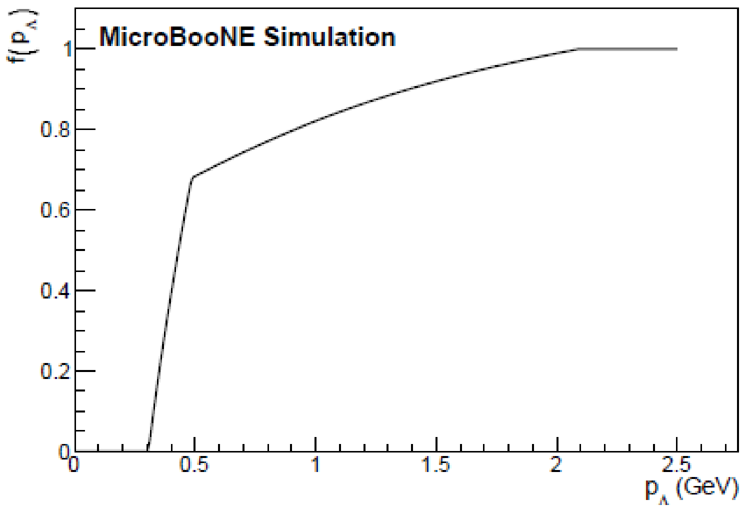
- Before phase space restrictions:
- Large enhancement at $T_\Lambda < 50$ MeV due to FSI (absent in GENIE but present in NuWro)
- ~ 15% contribution from $\Lambda\pi$

Comparison to MicroBooNE



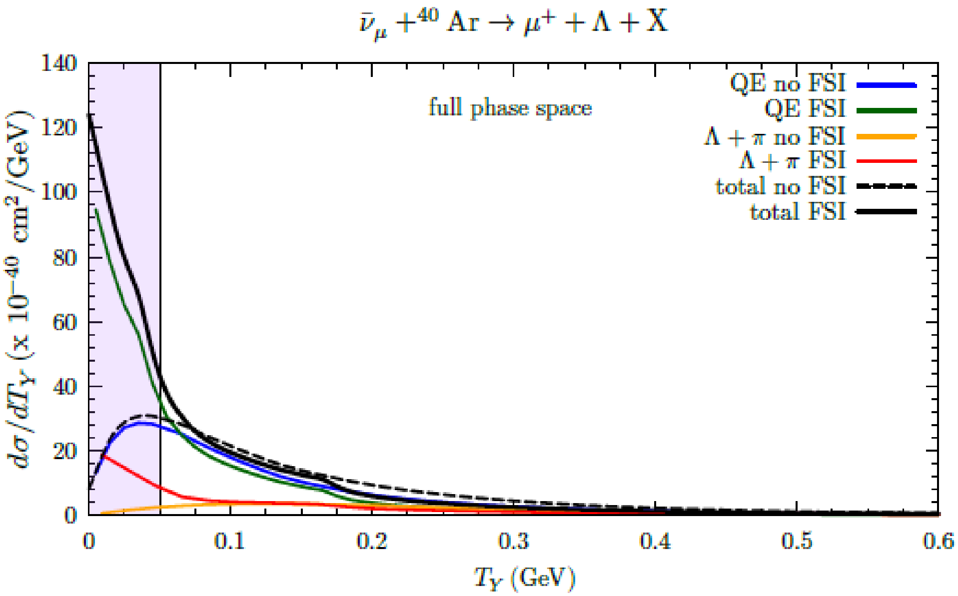


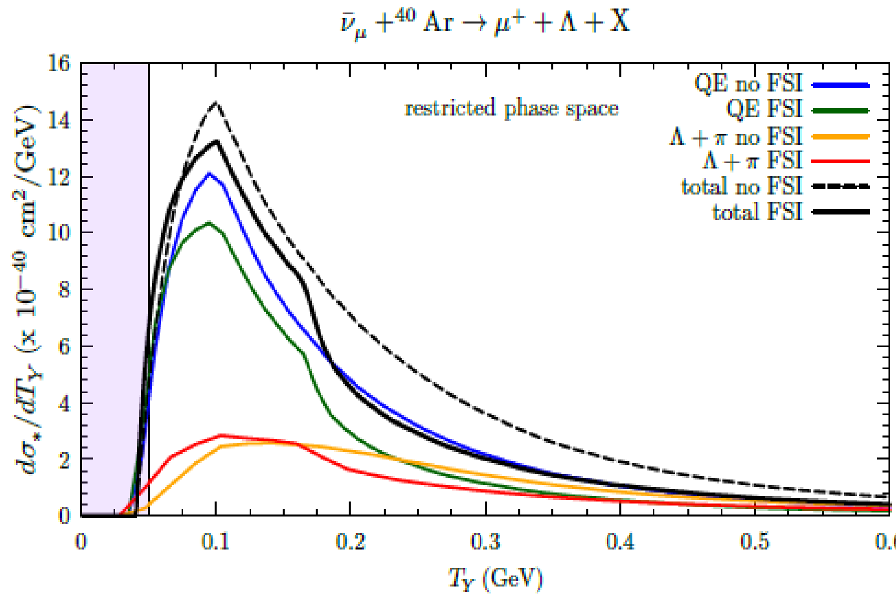
- After phase space restrictions:
- Large c. s. reduction
- Small impact of FSI



MicroBooNE, arXiv:2212.07888

Comparison to MicroBooNE

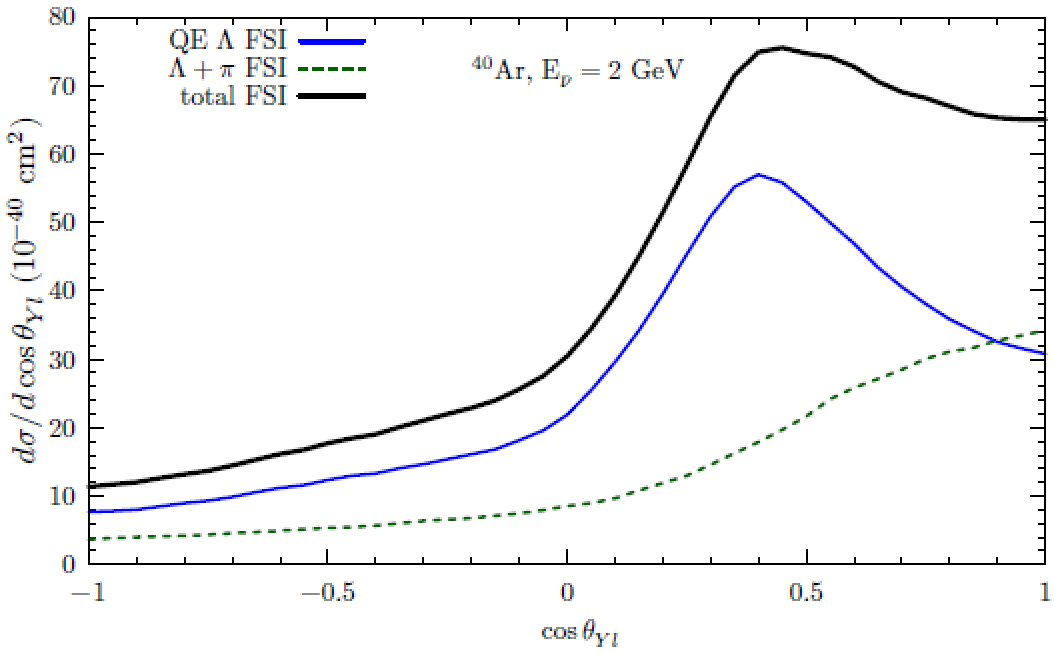




- After phase space restrictions:
- Large c. s. reduction
- Small impact of FSI
- ~ 33% contribution from $\Lambda\pi$
  - dominated by Σ^*(1385)
  - absent in GENIE & NuWro

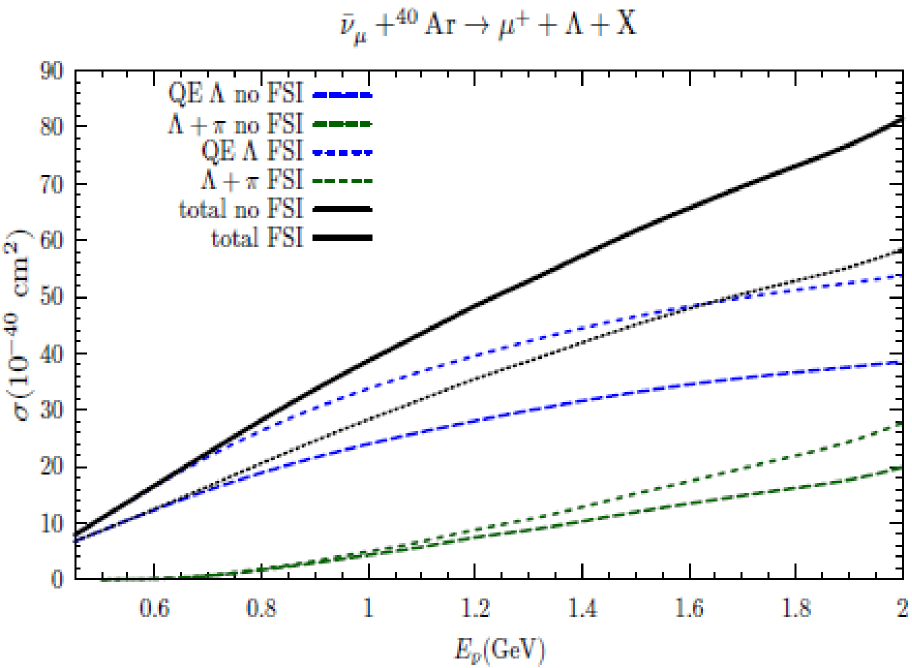
	σ_* $(\times 10^{40} cm^2/Ar)$
MicroBooNE	$2.0^{+2.1}_{-1.6}$
QE + $Y\pi$, full model	2.21
QE contr.	1.49
$Y\pi$ contr.	0.72

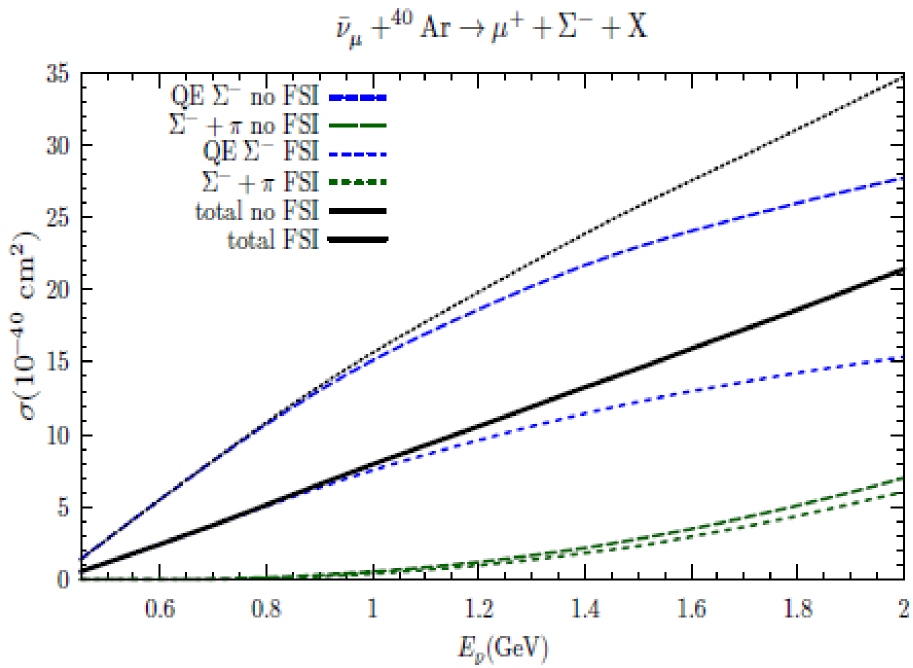
Angular distributions



- Distinctive hyperon-lepton angular distributions for QE and $\Lambda\pi$
- Can help to experimentally disentangle the two processes

Σ production





- σ(Σ) smaller than σ(Λ) before FSI
- σ(Σ) even smaller than σ(Λ) after FSI

Inelastic Σ production

- $\Sigma\,\pi$: $\bar{\nu}_l\, p \rightarrow l^+\,\Sigma^0\,\pi^0$ $\quad$ $\bar{\nu}_l\, n \rightarrow l^+\,\Sigma^0\,\pi^-$

$$\bar{\nu}_l\, p \rightarrow l^+\,\Sigma^+\,\pi^- \qquad \bar{\nu}_l\, n \rightarrow l^+\,\Sigma^-\,\pi^0$$

$$\bar{\nu}_l\, p \rightarrow l^+\,\Sigma^-\,\pi^+$$

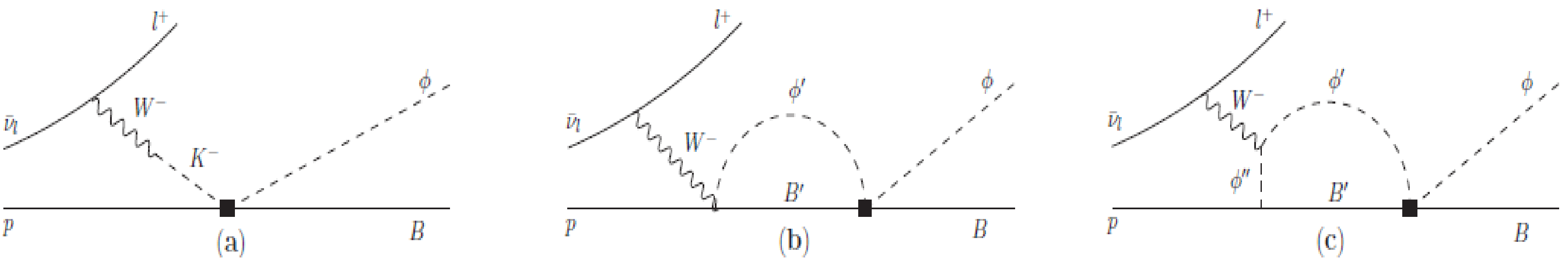
  - can proceed through the excitation of Λ(1405)

$\Lambda(1405)$

- $\bar{\nu}_l \, p \to l^+ \, \phi \, B$ Ren, Oset, LAR, Vicente Vacas, PRC91 (2015)

$$\phi \, B = K^- p, \, \bar{K}^0 n, \, \pi^0 \Lambda, \, \pi^0 \Sigma^0, \, \eta \Lambda, \, \eta \Sigma^0, \, \pi^+ \Sigma^-, \, \pi^- \Sigma^+, \, K^+ \Xi^-, \, K^0 \Xi^0$$

- Unitarization in coupled channels



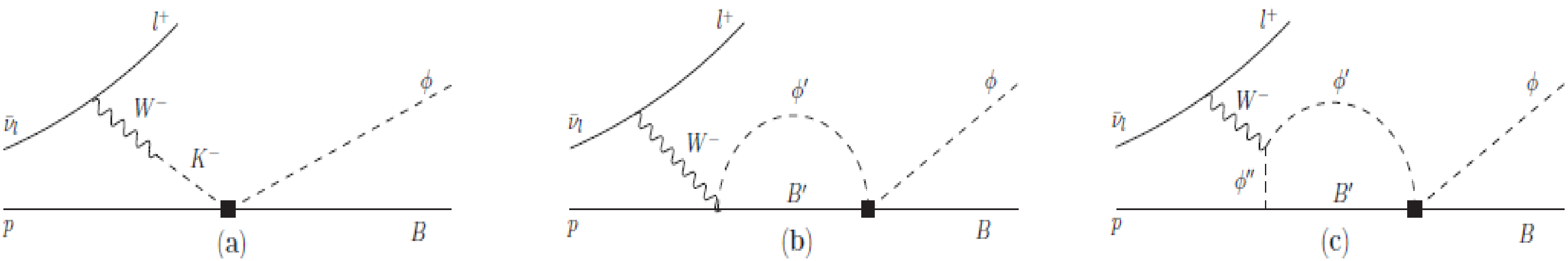
- $\Lambda(1405)$ dynamically generated
- Two poles: M$\approx$ 1385 MeV, $\Gamma \approx$ 150 MeV
  M$\approx$ 1420 MeV, $\Gamma \approx$ 40 MeV
- Suggested by Dalitz et al.(60ies) and obtained in many theoretical studies
- Consistent with data:
  $K^- p \to \phi B$, $K^- p \to \pi^0 \pi^0 \Sigma^0$, $p \, p \to p \, K^- \Lambda(1405)$, $\gamma \, p \to K^+ \pi \Sigma$, $e \, p \to e' K^+ \Lambda(1405)$

$\Lambda(1405)$

- $\bar{\nu}_l \, p \to l^+ \, \phi \, B$ Ren, Oset, LAR, Vicente Vacas, PRC91 (2015)

$$\phi \, B = K^- \, p, \, \bar{K}^0 \, n, \, \pi^0 \, \Lambda, \, \pi^0 \, \Sigma^0, \, \eta \, \Lambda, \, \eta \, \Sigma^0, \, \pi^+ \, \Sigma^-, \, \pi^- \, \Sigma^+, \, K^+ \, \Xi^-, \, K^0 \, \Xi^0$$

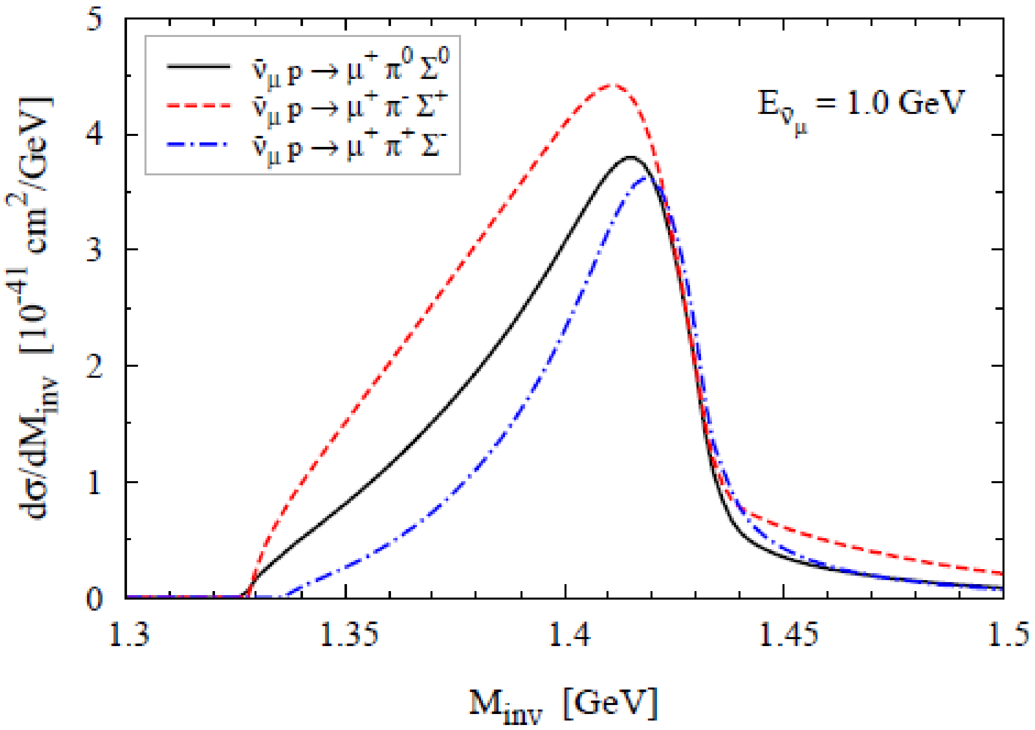
- Unitarization in coupled channels



- $\Lambda(1405)$ dynamically generated
- Two poles: M≈ 1385 MeV, $\Gamma \approx$ 150 MeV
  M≈ 1420 MeV, $\Gamma \approx$ 40 MeV
- $\bar{\nu}_l \, p \to l^+ \, \Lambda(1405)$ vs $\gamma \, p \to K^+ \, \pi \, \Sigma$, $e \, p \to e' \, K^+ \, \Lambda(1405)$, etc
  - no lineshape distortion due to $K^+ \Lambda(1405)$ interactions
  - but weak and Cabibbo suppressed

Λ(1405)

- $\bar{\nu}_l \, p \to l^+ \, \Sigma \, \pi$ Ren, Oset, LAR, Vicente Vacas, PRC91 (2015)

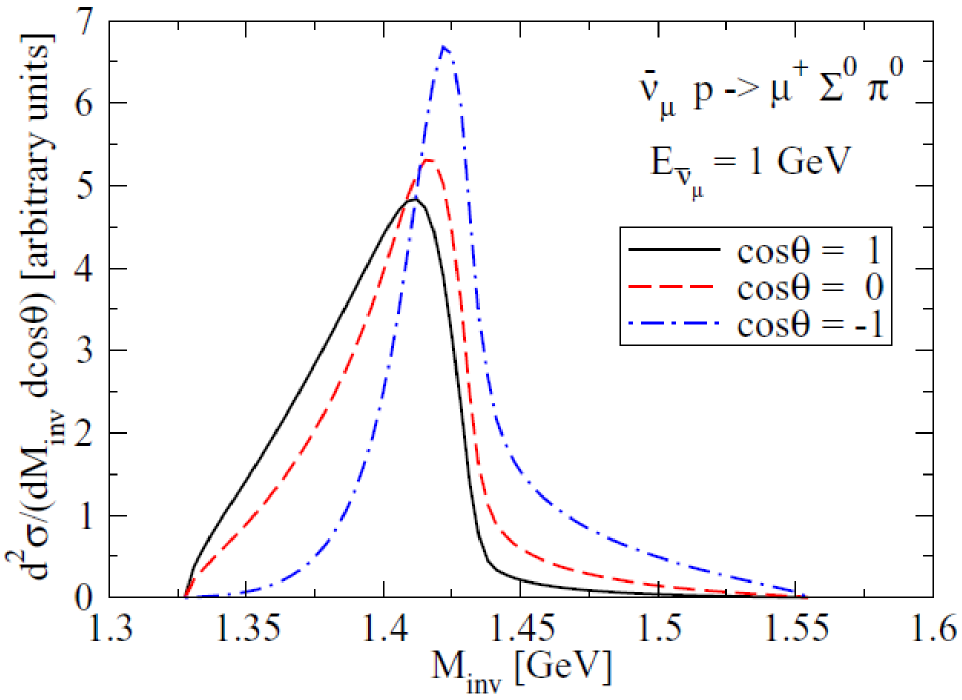


- Two poles: M≈ 1385 MeV, $\Gamma \approx$ 150 MeV
  M≈ 1420 MeV, $\Gamma \approx$ 40 MeV

- Single asymmetric peak with more weight from the 1420 MeV pole

$\Lambda(1405)$

- $\bar{\nu}_l \, p \to l^+ \, \Sigma \, \pi$ Ren, Oset, LAR, Vicente Vacas, PRC91 (2015)

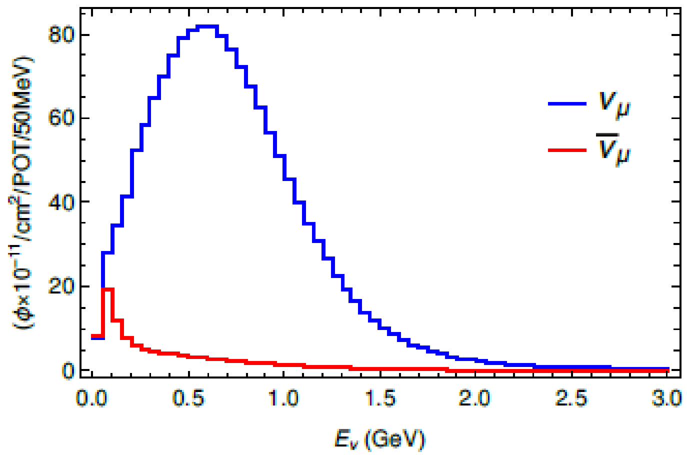


- Single asymmetric peak with more weight from the 1420 MeV pole
- Backwards: ~ Breit-Wigner resonance with M ≈ 1420 MeV, $\Gamma \approx$ 40 MeV
- Although $d^2\sigma(\cos\theta = -1) \sim d^2\sigma(\cos\theta = 1)/14$

SBND

- 8000 Λ and 4500 Σ are expected from $\bar{\nu}$

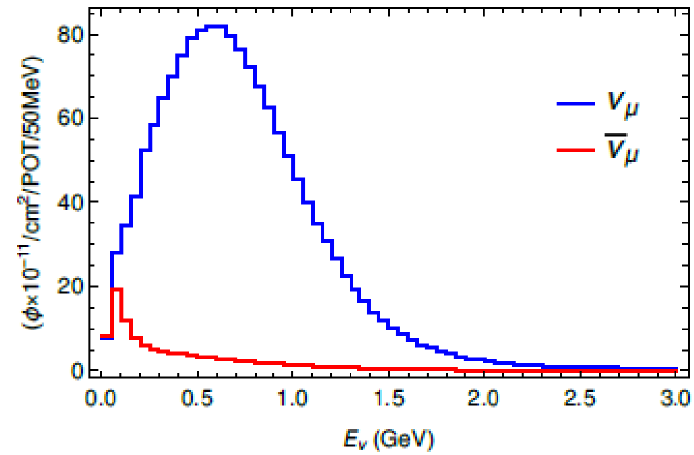
  Brailsford, Neutrino 2016 Proceedings



FCNC @ SBND?

- 8000 Λ and 4500 Σ are expected from $\bar{\nu}$

  Brailsford, Neutrino 2016 Proceedings



- $d \to s$ using
$$\nu_l\, n \to \nu_l\, \Lambda$$
$$\nu_l\, p \to \nu_l\, \Sigma^+$$

- Effective Hamiltonian:

$$\mathcal{H} = \frac{G_F}{\sqrt{2}} \{\epsilon_V\, [\bar{s}\gamma_\mu d] + \epsilon_A\, [\bar{s}\gamma_\mu\gamma_5 d]\}\; [\bar{\nu}\gamma_\mu(1-\gamma_5)\nu]$$

  - Only left handed ν ; real $\epsilon_{V/A}$

- Constraints from K decays: Geng, Martin Camalich, Shi, JHEP 02 (2022) 178
  - $K \to \pi\, \nu\bar{\nu}$ $\quad \epsilon_V \approx 0$
  - $K \to \pi\pi\, \nu\bar{\nu}$ $\quad |\epsilon_A| < 7 \times 10^{-3}$
  - $\frac{(n\to\Lambda)\text{ events}}{(p\to\Lambda)\text{ events}} \approx 0.02 \Rightarrow$ up to **180** events (preliminary, without FSI)

Summary

- Weak strangeness production encompasses several relevant but still poorly understood processes
- Experimental constrains and guidance are needed
- 8000 Λ and 4500 Σ are expected at SBND with $\bar{\nu}$
- Possibility to constrain FCNC using QE Y production with ν

Experiments

- Early low-statistics bubble-chamber measurements:
  - Fermilab 15': Ammosov et al., Z. Phys. C (1987)
    - filled with a heavy neon-hydrogen mixture
    - high energy (5-100 GeV) $\bar{\nu}$
    - observation of neutral strange particles
  - SKAT: Brunner et al., Z. Phys. C (1990)
    - filled with freon (CF_3Br)
    - 3-30 GeV beam (Serpukhov)
    - hyperon production
  - Gargamelle: Eichten et al., PLB (1972); Erriquez et al., NPA (1978)
    - filled with freon, propane
    - CERN-PS
    - hyperon and strange particle production

$\Lambda(1405)$

- $\bar{\nu}_l \, p \to l^+ \, \phi \, B$ Ren, Oset, LAR, Vicente Vacas, PRC91 (2015)

$$\phi \, B = K^- p, \, \bar{K}^0 n, \, \pi^0 \Lambda, \, \pi^0 \Sigma^0, \, \eta \Lambda, \, \eta \Sigma^0, \, \pi^+ \Sigma^-, \, \pi^- \Sigma^+, \, K^+ \Xi^-, \, K^0 \Xi^0$$

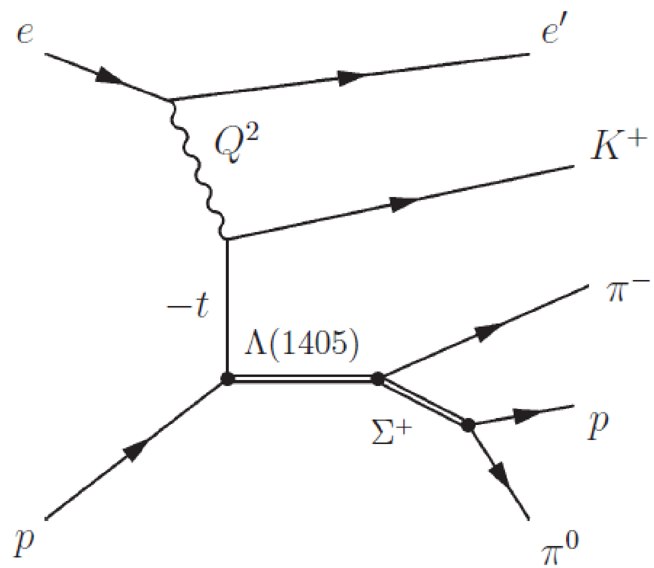
- SU(3) symmetric chiral Lagrangian
- Physical hadron masses
- Couplings depend on V_{us} and D, F, f_π $\leftarrow$ fixed by semileptonic decays
- Global dipole form factor

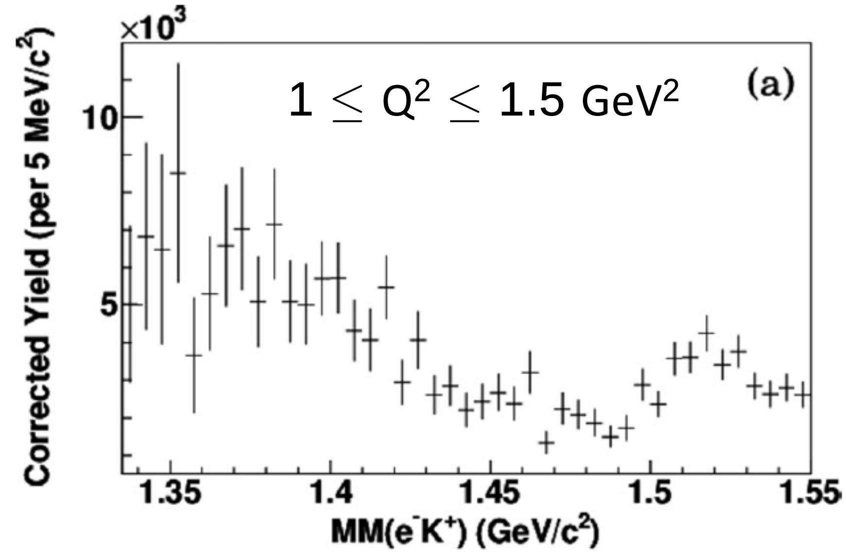
$$F(q^2) = \left(1 - \frac{q^2}{M_F^2}\right)^{-2}$$ $M_F = 1 \pm 0.1$ GeV

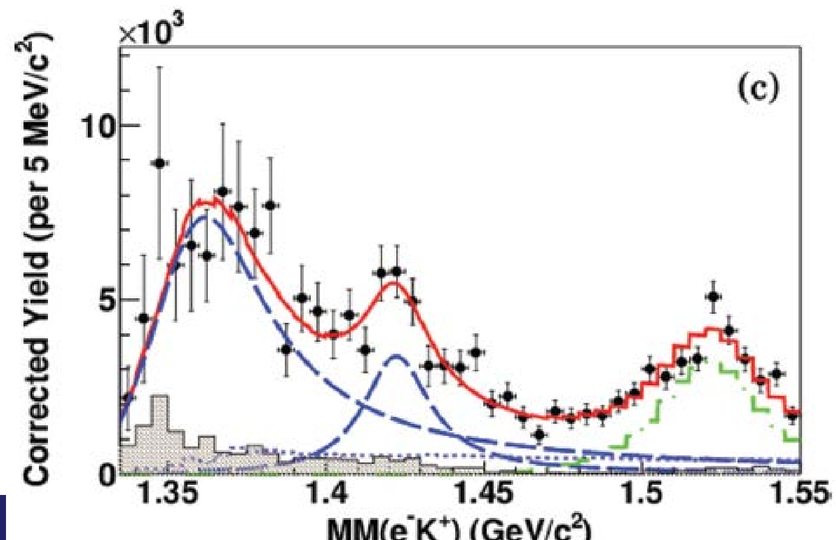
- s-wave projection
- Unitarization in coupled channels

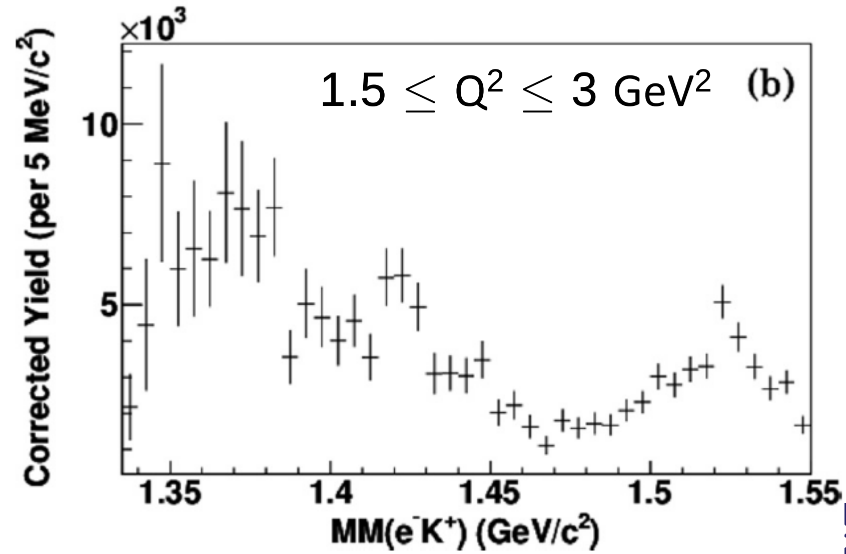
$\Lambda(1405)$

- $e\,p \to e'\,K^+\,\Lambda(1405)$ Lu et al. (CLAS), PRC88(2013)



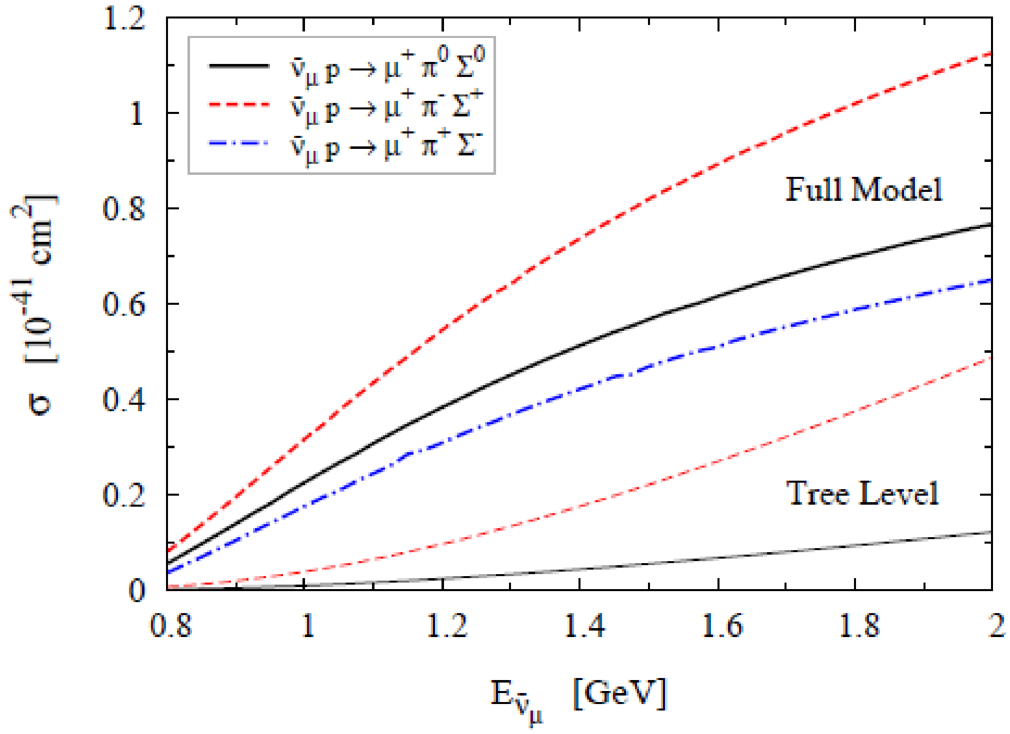






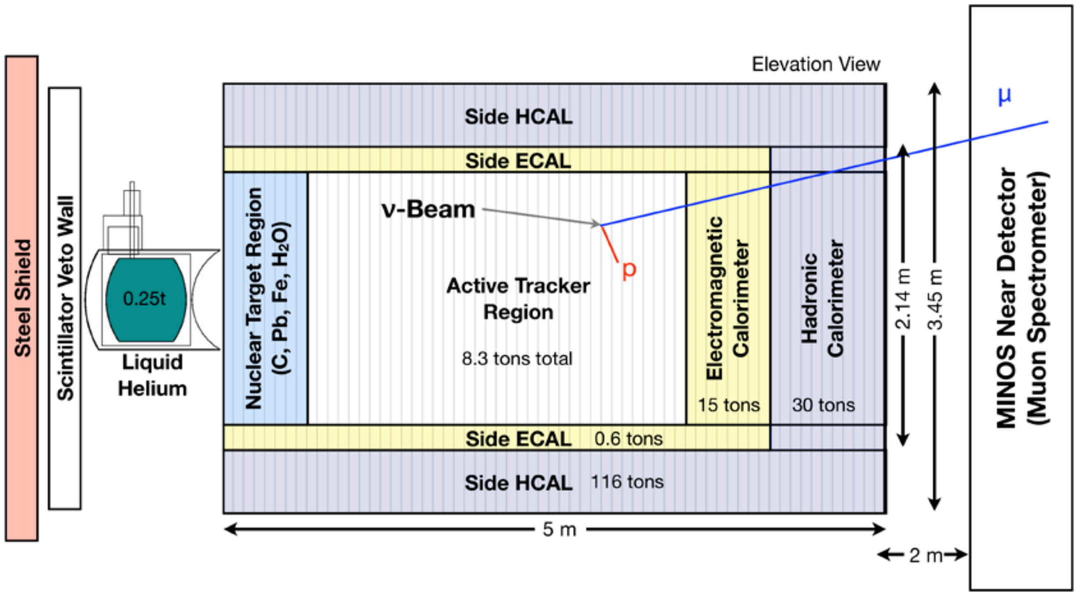
Λ(1405)

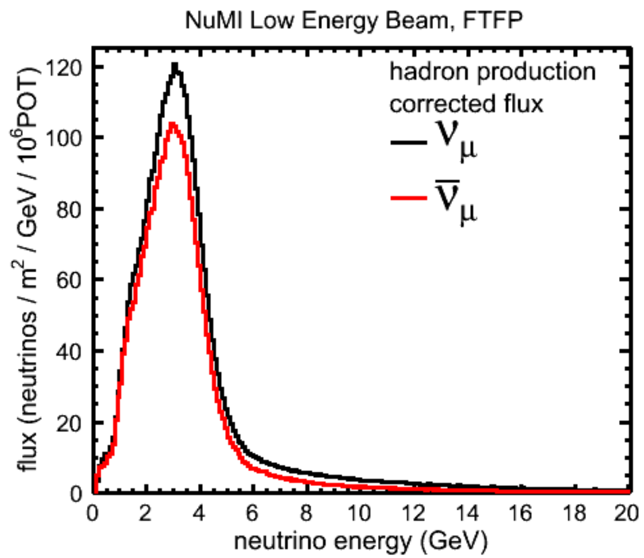
- $\bar{\nu}_l \, p \to l^+ \, \Sigma \, \pi$ Ren, Oset, LAR, Vicente Vacas, PRC91 (2015)



Λ(1405)

- $\bar{\nu}_l \, p \to l^+ \, \Sigma \, \pi$ @ MINERvA (FNAL)





- ≈ 2000 $\pi\Sigma$ pairs @ scintillator