New physics in neutrino scattering

Luis Alvarez-Ruso

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Content

- NSI in (anti)neutrino-nucleon elastic scattering
- FCNC searches by means of hyperon production at MicroBooNE & SBND

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ν interactions and BSM physics

- Non-standard/generalized ν interactions can be (potentially) accessed in:
  - τ, β, (heavy) hadron semi-leptonic decays
  - Oscillations (matter effects)
  - Cosmology (N_{eff})
  - ν scattering (@ detection):
    - Anomalies (MiniBooNE, LSND)
    - ν-e
    - CEνNS
    - DIS

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TABLE 2 | Bounds on flavor diagonal NC NSI couplings.

	90% C.L. range	Origin
NSI WITH QUARKS		
ϵ_{ee}^{dL}	[−0.3, 0.3]	CHARM
ϵ_{ee}^{dR}	[−0.6, 0.5]	CHARM
ϵ_{ee}^{dV}	[0.030, 0.55]	Oscillation data + COHERENT
ϵ_{ee}^{uV}	[0.028, 0.60]	Oscillation data + COHERENT
$\epsilon_{\mu\mu}^{dV}$	[−0.042, 0.042]	Atmospheric + accelerator
$\epsilon_{\mu\mu}^{uV}$	[−0.044, 0.044]	Atmospheric + accelerator
$\epsilon_{\mu\mu}^{dA}$	[−0.072, 0.057]	Atmospheric + accelerator
$\epsilon_{\mu\mu}^{uA}$	[−0.094, 0.14]	Atmospheric + accelerator
$\epsilon_{\tau\tau}^{dV}$	[−0.075, 0.33]	Oscillation data + COHERENT
$\epsilon_{\tau\tau}^{uV}$	[−0.09, 0.38]	Oscillation data + COHERENT
$\epsilon_{\tau\tau}^{qV}$	[−0.037, 0.037]	Atmospheric
NSI WITH ELECTRONS		
ϵ_{ee}^{eL}	[−0.021, 0.052]	Solar + KamLAND
ϵ_{ee}^{eR}	[−0.07, 0.08]	TEXONO
$\epsilon_{\mu\mu}^{eL}$, $\epsilon_{\mu\mu}^{eR}$	[−0.03, 0.03]	Reactor + accelerator
$\epsilon_{\tau\tau}^{eL}$	[−0.12, 0.06]	Solar + KamLAND
$\epsilon_{\tau\tau}^{eR}$	[−0.98, 0.23]	Solar + KamLAND and Borexino
	[−0.25, 0.43]	Reactor + accelerator
$\epsilon_{\tau\tau}^{eV}$	[−0.11, 0.11]	Atmospheric

accelerator=NuTeV, CHARM, CDHS

Farzan,Tórtola, Front.in Phys. (2018)

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  - **Our suggestion**:
    - $\upsilon/\bar{\upsilon}\, N \rightarrow \upsilon/\bar{\upsilon}\, N$
      - with LQCD input

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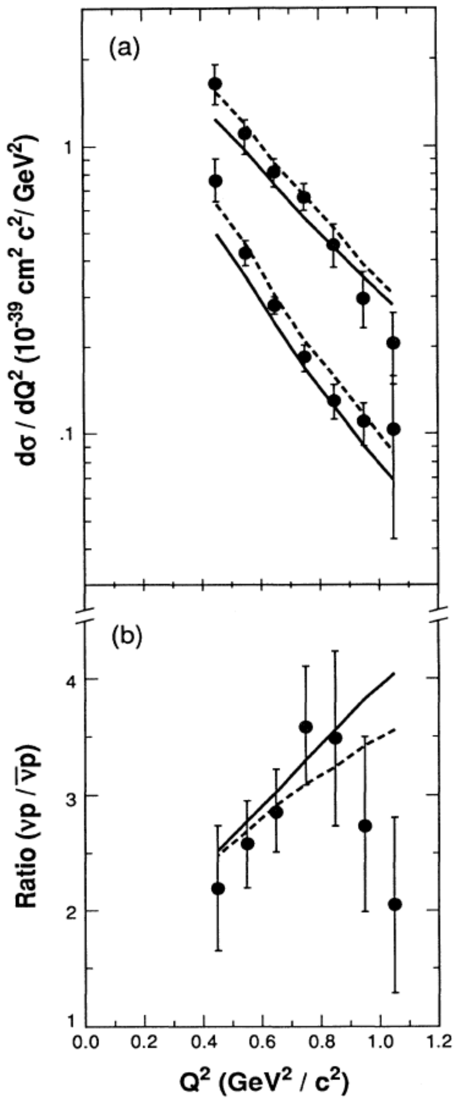

$\nu/\bar{\nu}\, p \;\rightarrow \nu/\bar{\nu}\, p$

BNL, Ahrens et al. PRD 35 (1987)

ν interactions and BSM physics

- Non-standard/generalized ν interactions can be (potentially) accessed in:
  - **Our suggestion**:
    - $\upsilon/\bar{\upsilon}\, N \to \upsilon/\bar{\upsilon}\, N$
      - with LQCD input
    - Modern measurements of $\upsilon/\bar{\upsilon}\, N$ scattering are needed:
    - directly: on H/D

    or
    - indirectly: H-enriched targets + kinematic subtraction
      - High pressure TPC (CH_4)
      - CH_2 and C solid targets (solid H)

    - LQCD results (for nucleon properties) are continuously improving

Elastic $\nu/\bar{\nu}\, p$ scattering with NSI

- $\nu/\bar{\nu}(k)\, N(p) \to \nu/\bar{\nu}(k')\, N(p')$
- Standard NSI Lagrangian: $\mathcal{L}_{\rm NSI}^{\rm NC} = -2\sqrt{2} G_F \epsilon_{ij}^{fX} \bar{\nu}^i \gamma_\mu P_L \nu^j \bar{f} \gamma^\mu P_X f$
- SM + NSI effective Lagrangian: $\mathcal{L}_{\rm SM+NSI}^{\rm NC} = -\frac{G_F}{\sqrt{2}} L_\mu^{ij} J_{ij}^\mu$

$L_\mu^{ij} = \bar{\nu}^i \gamma_\mu (1-\gamma_5) \nu^j$ ← Non-diag. in flavor (in general)

$$J_{ij}^\mu = \delta_{ij}\, J_{\rm SM}^\mu + \left(J_{ij}^\mu\right)_{\rm NSI}$$

$$\begin{aligned} J_{\rm SM}^\mu &= \bar{u}\gamma^\mu \left[\frac{1}{2} - \left(\frac{2}{3}\right) 2 s_w^2 - \frac{1}{2}\gamma_5\right] u \\ &+ \bar{d}\gamma^\mu \left[-\frac{1}{2} - \left(-\frac{1}{3}\right) 2 s_w^2 + \frac{1}{2}\gamma_5\right] d \\ &+ \bar{s}\gamma^\mu \left[-\frac{1}{2} - \left(-\frac{1}{3}\right) 2 s_w^2 + \frac{1}{2}\gamma_5\right] s \end{aligned}$$

$$\begin{aligned} \left(J_{ij}^\mu\right)_{\rm NSI} &= \bar{u}\gamma^\mu \left(\epsilon_{ij}^{uV} - \epsilon_{ij}^{uA}\gamma_5\right) u \\ &+ \bar{d}\gamma^\mu \left(\epsilon_{ij}^{dV} - \epsilon_{ij}^{dA}\gamma_5\right) d \\ &+ \bar{s}\gamma^\mu \left(\epsilon_{ij}^{sV} - \epsilon_{ij}^{sA}\gamma_5\right) s \end{aligned}$$

$$\mathcal{M} = \frac{G_F}{\sqrt{2}} l_\mu^{ij} < N | J_{ij}^\mu | N >$$

Elastic $\upsilon/\bar{\upsilon}\,p$ scattering with NSI

- $\upsilon/\bar{\upsilon}(k)\,N(p) \rightarrow \upsilon/\bar{\upsilon}(k')\,N(p')$

$$\mathcal{M} = \frac{G_F}{\sqrt{2}} l^{ij}_{\mu} \langle N | J^{\mu}_{ij} | N \rangle$$

$$\langle N | J^{\mu} | N \rangle = \bar{u}(p') \Gamma^{\mu} u(p)$$

$$\Gamma^{\mu} = \gamma^{\mu} \tilde{F}_1^{(p)} + \frac{i}{2M} \sigma^{\mu\nu} q_{\nu} \tilde{F}_2^{(p)} - \gamma^{\mu}\gamma_5 \tilde{F}_A^{(p)}$$

$$\tilde{F}_{1,2}^{(p,n)} = \left(\frac{1}{2} - 2s_W^2 + 2\epsilon^{uV} + \epsilon^{dV}\right) F_{1,2}^{(p,n)} + \left(-\frac{1}{2} + 2\epsilon^{dV} + \epsilon^{uV}\right) F_{1,2}^{(n,p)} - \frac{1}{2} F_{1,2}^{(s)}$$

$$2\tilde{F}_A^{(p,n)} = \left(1 + \epsilon^{uA} - \epsilon^{dA}\right) F_A^{iv} + \left(\epsilon^{uA} + \epsilon^{dA}\right) F_A^{is} - F_A^{(s)}$$

- $F_{1,2}^{(p,n)} \leftarrow$ EM form factors
- $F_{1,2,A}^{(s)} \leftarrow$ strange EM & axial form factors

Elastic $\upsilon/\bar{\upsilon}\, p$ scattering with NSI

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- Isovector axial form factors:

$$\langle p,n| \left(\bar{u}\gamma^\mu\gamma_5 u - \bar{d}\gamma^\mu\gamma_5 d\right) |p,n\rangle \equiv \pm\bar{u}(p') \left[F_A^{iv}(Q^2)\gamma^\mu\gamma_5 + \frac{F_P^{iv}(Q^2)}{M} q^\mu\gamma_5\right] u(p)$$

- Isoscalar axial form factors:

$$\langle p,n| \left(\bar{u}\gamma^\mu\gamma_5 u + \bar{d}\gamma^\mu\gamma_5 d\right) |p,n\rangle \equiv \bar{u}(p') \left[F_A^{is}(Q^2)\gamma^\mu\gamma_5 + \frac{F_P^{is}(Q^2)}{M} q^\mu\gamma_5\right] u(p)$$

  - not probed by SM weak interactions

Elastic $\nu/\bar{\nu}\, p$ scattering with NSI

- $\nu/\bar{\nu}(k)\, N(p) \to \nu/\bar{\nu}(k')\, N(p')$

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- One relies on the flavor decomposition of the axial current from LQCD

$$\langle N| \bar{q}\gamma^\mu\gamma_5 q |N\rangle \equiv \bar{u}(p')\left[F_A^q(Q^2)\gamma^\mu\gamma_5 + \frac{F_P^q(Q^2)}{M} q^\mu\gamma_5\right] u(p)$$

  - q=u, d, s
  - Alexandrou et al., PRD 101 (2020); PRD 104 (2021)

Elastic $\upsilon/\bar{\upsilon}\, p$ scattering with NSI

- NSI couplings:
  - real
  - flavor diagonal $i = j = \mu$
  - ϵ^S neglected
  - 90% CL intervals obtained from atmospheric oscillations at SK and high energy scattering at NuTeV Escrihuela et al., PRD 83 (2011)

NSI Couplings	90% CL interval	NSI Couplings	90% CL interval
$\epsilon_{\mu\mu}^{uV}$	[−0.044,0.044]	$\epsilon_{\mu\mu}^{uA}$	[−0.094,0.14]
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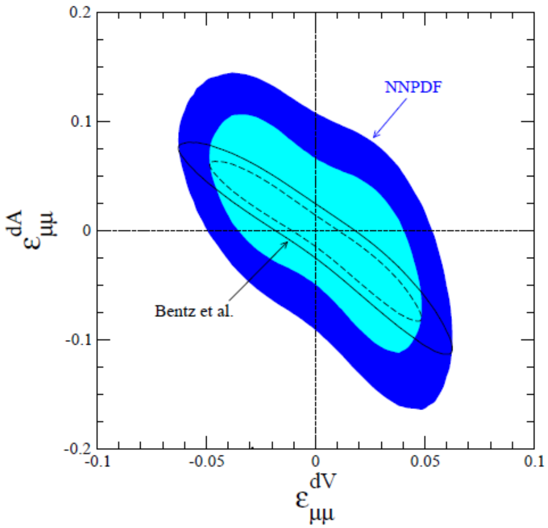

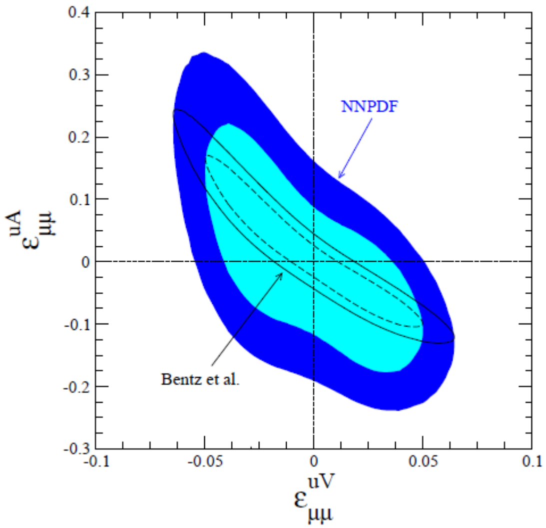

Cross section

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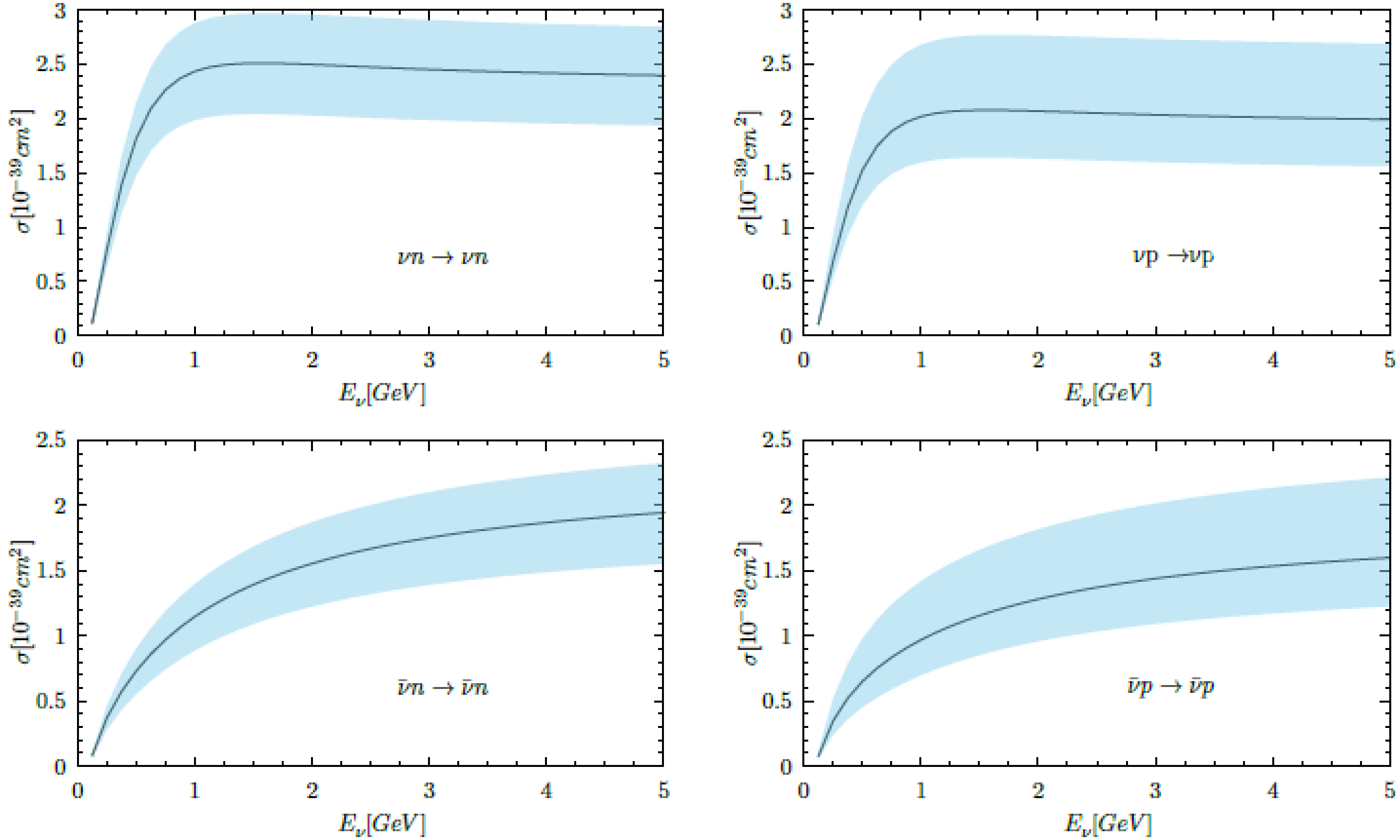
Escrihuela et al., PRD 83 (2011)

- Neglecting correlations:



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Escrihuela et al., PRD 83 (2011)

- Future:
  - joint fit SK + NuTeV + BNL (+ current LQCD input)
  - joint fit SK + NuTeV + future H data (+ future LQCD input)
  - helpful to break degeneracies.

Nucleon polarization

- Formalism
  - Bilenky, Christova, J. Phys. G 40 (2013); Phys. Part. Nucl. Lett. 10 (2013)

$$\zeta^\tau = \frac{\mathbf{Tr}[\gamma^\tau\gamma_5\rho_f(p')]}{\mathbf{Tr}[\rho_f(p')]} = \frac{\mathcal{L}^{\alpha\beta}\mathbf{Tr}[\gamma^\tau\gamma_5\Lambda(p')\Gamma_\alpha\Lambda(p)\tilde{\Gamma}_\beta\Lambda(p')]}{\mathcal{L}^{\alpha\beta}\mathbf{Tr}[\Lambda(p')\Gamma_\alpha\Lambda(p)\tilde{\Gamma}_\beta\Lambda(p')]}$$

$$\rho_f(p') = \mathcal{L}^{\mu\nu}\Lambda(p')\Gamma_\mu\,\rho(p)\,\tilde{\Gamma}_\nu\Lambda(p')$$ $\leftarrow$ spin density matrix

$$\mathcal{L}^{\mu\nu} = \mathbf{Tr}[\gamma^\mu(1\mp\gamma_5)\not{k}\gamma^\nu(1\mp\gamma_5)\not{k}']$$ $\leftarrow$ lepton tensor

$$\Lambda(p) \equiv \not{p} + M \qquad \tilde{\Gamma}_\nu = \gamma^0\Gamma_\nu^\dagger\gamma^0$$

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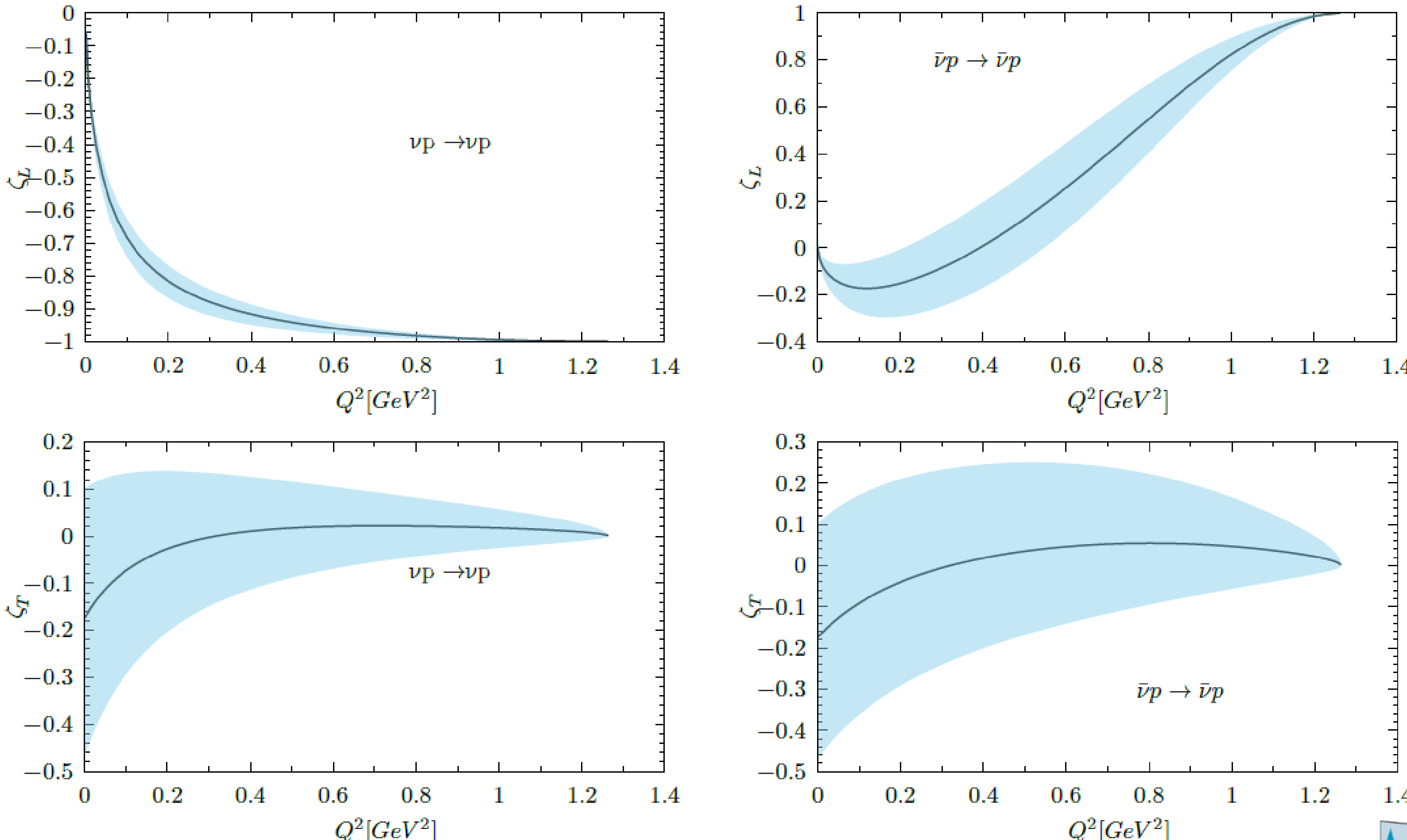
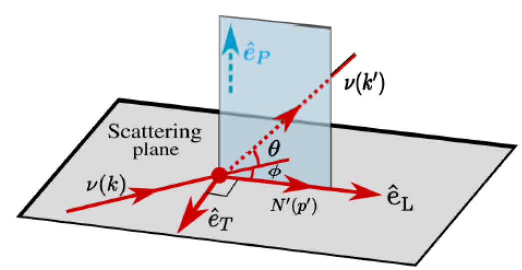


$E_\upsilon = 1$ GeV

- Ratios: partial cancellation of uncertainties
- Magnetic fields are needed for experimental study...
- Alternative: polarized target



Weak hyperon production

- ΔS = -1: $W^- u \to s$
- Cabibbo reduced ($V_{us} = 0.23$)
- Quasielastic:
  - Lowest threshold: W $\geq$ 1.1 GeV $\Leftrightarrow$ $\boldsymbol{E_v} \geq$ 0.2 GeV
  - Y: $\bar{\nu}_l \, p \quad \rightarrow \quad l^+ \, \Sigma^0 (\Lambda)$

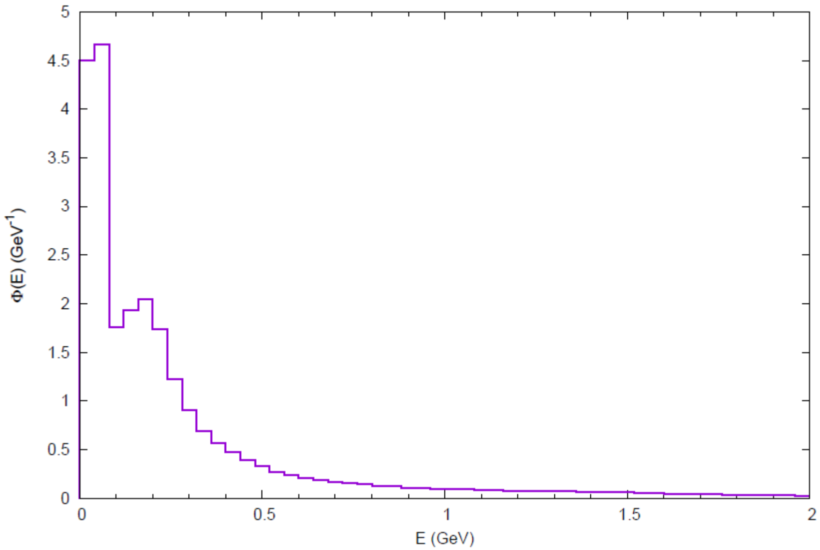
$$\bar{\nu}_l \, n \quad \rightarrow \quad l^+ \, \Sigma^-$$

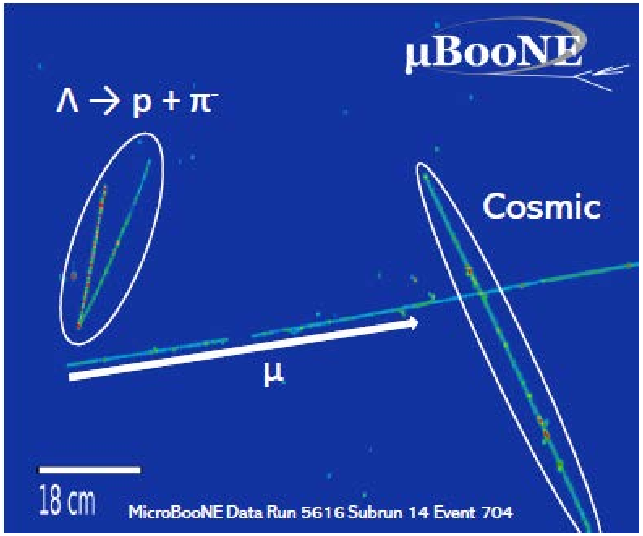
- Hyperon polarization:
  - Akbar et al., PRD 94 (2016); Fatima et al., PRD 98 (2018)
  - $\Rightarrow$ asymmetry in the decay
  - eg $\Lambda \to N \, \pi$

$$W(\theta) = 1 + \alpha \, \zeta_\Lambda \cdot \hat{p}_N$$ $\leftarrow$ in the Λ rest frame

MicroBooNE measurement

- First measurement of $\bar{\nu}\,\mathrm{Ar} \to \mu^{+}\,\Lambda\,X$ PRL 130 (2023)
  - X=additional final state particles with no strangeness





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

- 5 events, but (~ 4 times) more to come...
- Phase-space restricted flux-averaged cross section:

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

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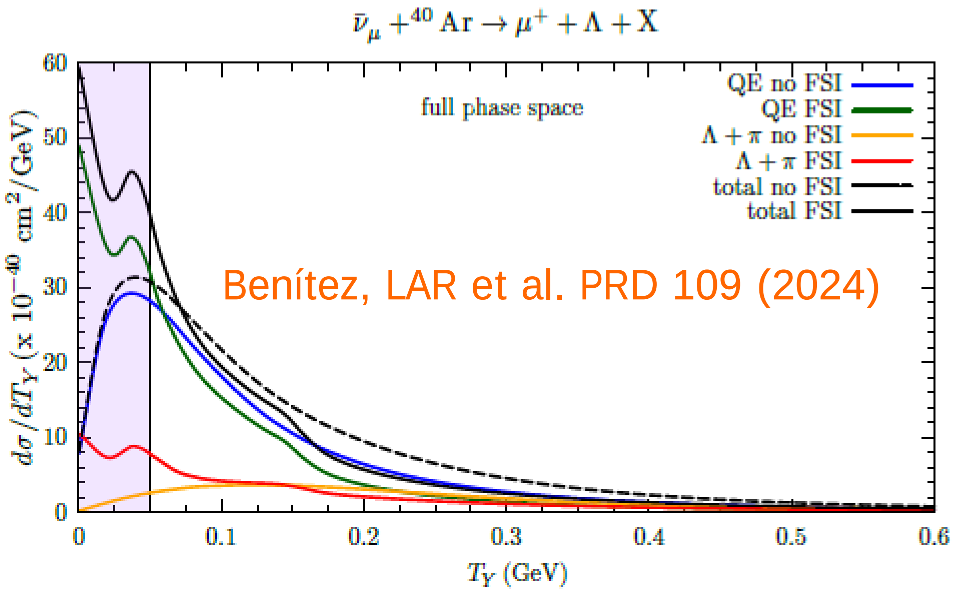
- Inelastic:
  - Yπ: $$\bar{\nu}_l\, p \to l^+\, \Sigma^0 (\Lambda)\, \pi^0 \qquad \bar{\nu}_l\, n \to l^+\, \Sigma^0 (\Lambda)\, \pi^-$$ $$\bar{\nu}_l\, p \to l^+\, \Sigma^+\, \pi^- \qquad \bar{\nu}_l\, n \to l^+\, \Sigma^-\, \pi^0$$ $$\bar{\nu}_l\, p \to l^+\, \Sigma^-\, \pi^+$$
  - Higher threshold: W $\geq$ 1.3 GeV $\Leftrightarrow$ $\boldsymbol{E_v} \geq$ 0.4 GeV
  - can proceed through the excitation of Λ or Σ resonances
    - in particular: Σ^*(1385), Λ(1405)

Nuclear Final State Interactions

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

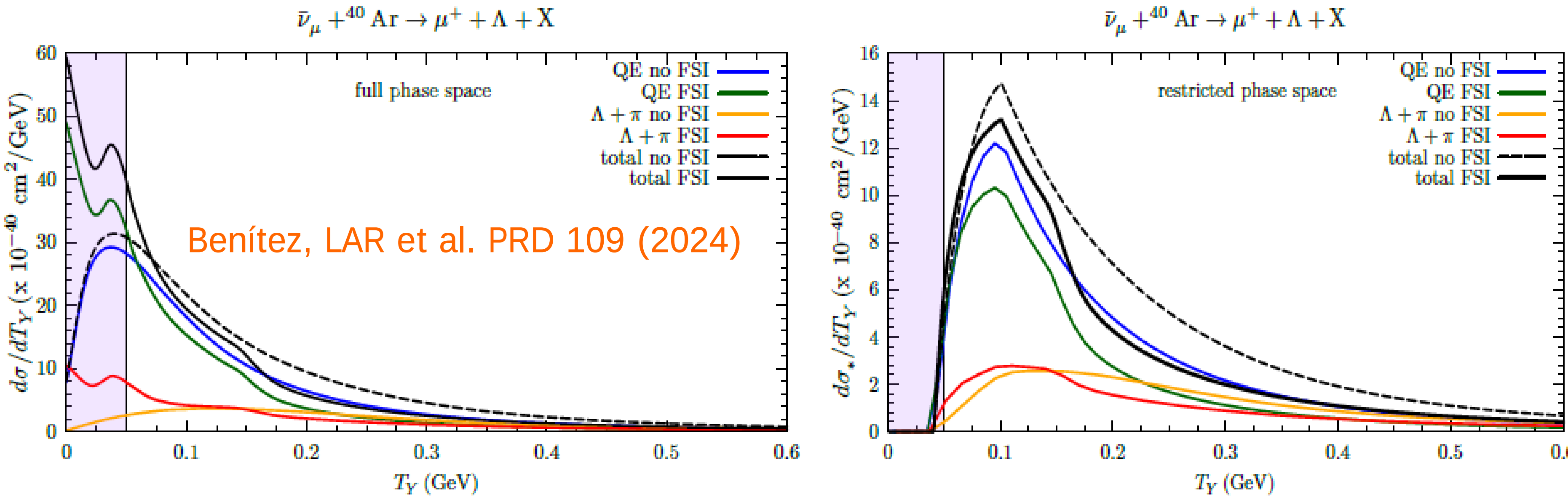
Comparison to MicroBooNE



- Large enhancement at $T_\Lambda < 50$ MeV due to FSI : $\Sigma \to \Lambda$ conversion
- ~ 15% contribution from $\Lambda\pi$
- Detection thresholds for $\Lambda \to N\,\pi$ decay products @ MicroBooNE
  - proton momentum < 300 MeV/c
  - pion momentum < 100 MeV/c
  - $\Rightarrow$ phase space restrictions

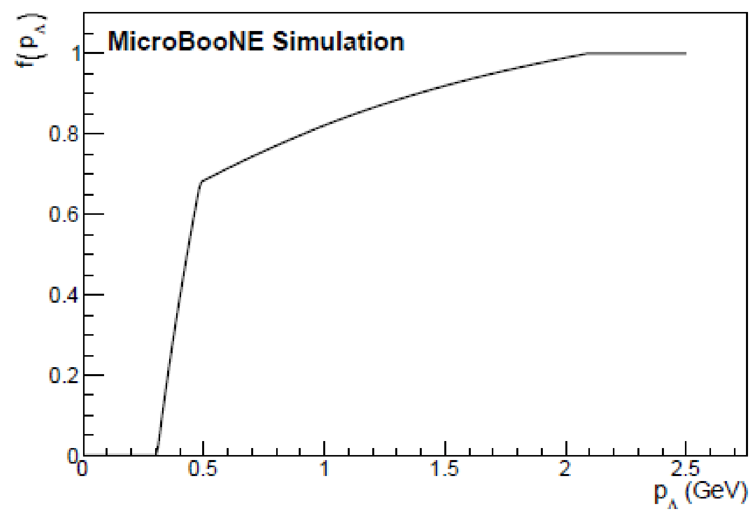
MicroBooNE, PRL 130 (2023)

Comparison to MicroBooNE



- After phase space restrictions:
- Large c. s. reduction; smaller impact of FSI
- ~ 33% contribution from $\Lambda\pi$

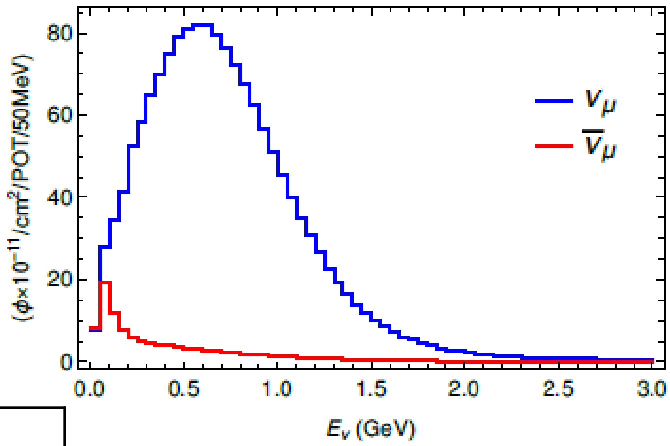
	σ_* ($\times 10^{-40}$ cm^2/Ar)
MicroBooNE	$2.0^{+2.1}_{-1.6}$
QE + $Y\pi$, full model	2.13
QE	1.44
$Y\pi$	0.69



MicroBooNE, PRL 130 (2023)

SBND

- 10-13 $\times$ 10^{20} POT (3 years)
- Detection thresholds @ SBND (priv. com.)
  - proton momentum < 197 MeV/c
  - pion momentum < 48 MeV/c
- Predicted events:



N_Λ	No Thr.	μBooNE Thr.	SBND Thr.
QE	1300 – 1700	300 – 400	960 – 1250
$\Lambda\pi$	240 – 300	60 – 70	180 – 220

SBND

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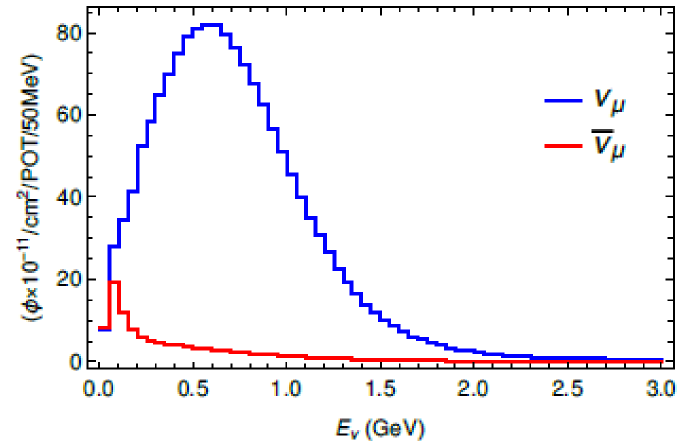
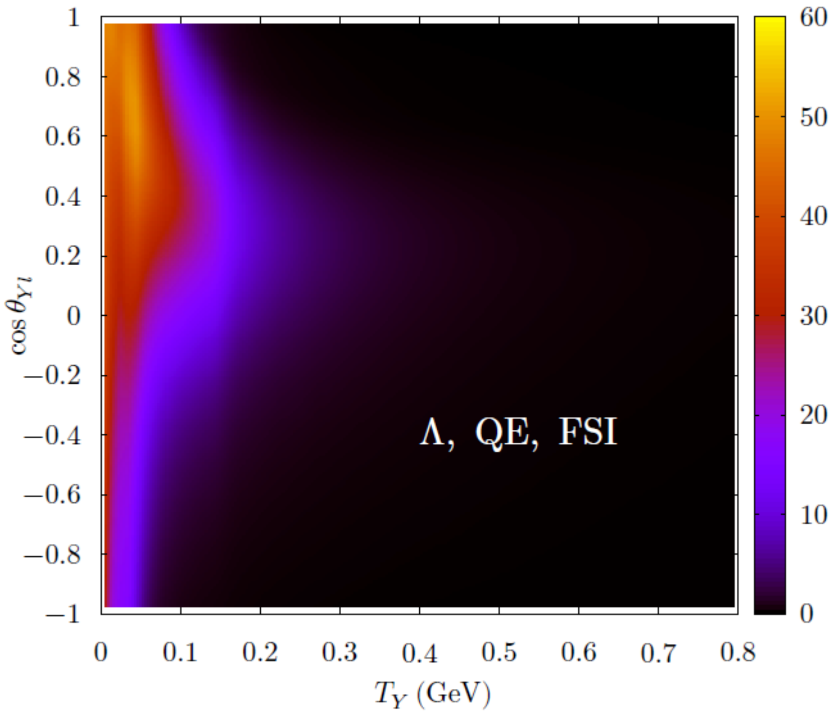
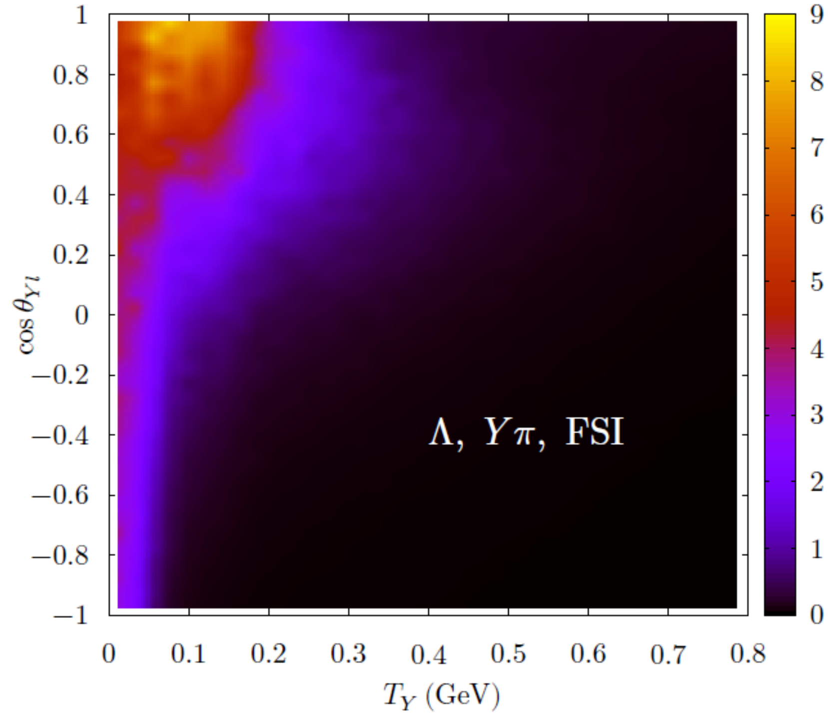






Flavor Changing Neutral Currents

- Suppressed in the **SM**
- $d \to s$ using $$\begin{aligned} \nu_l\, n &\to \nu_l\, \Sigma_0(\Lambda) \\ \nu_l\, p &\to \nu_l\, \Sigma^+ \end{aligned}$$
- Effective Hamiltonian:

$$\mathcal{H} = \frac{G_F}{\sqrt{2}} \left\{ \epsilon_V^l \left[\bar{s}\gamma_\mu d \right] + \epsilon_A^l \left[\bar{s}\gamma_\mu\gamma_5 d \right] \right\} \left[\bar{\nu}_l \gamma_\mu (1-\gamma_5) \nu_l \right]$$

  - Only left handed ν
  - Lepton flavor diagonal
  - Real $\epsilon_{V,A}$ (CP violation not considered)
- Constraints from K decays: Geng, Martin Camalich, Shi, JHEP 02 (2022) 178
  - Based on upper limits for branching ratios from KOTO and NA62
  - $K \to \pi\, \nu\bar{\nu}$ $\epsilon_V < 10^{-6} \approx 0$
  - $K \to \pi\pi\, \nu\bar{\nu}$ $|\epsilon_A| < 7.6 \times 10^{-3}$ ($\times \sqrt{3}$ if only 1ν flavor contributes)

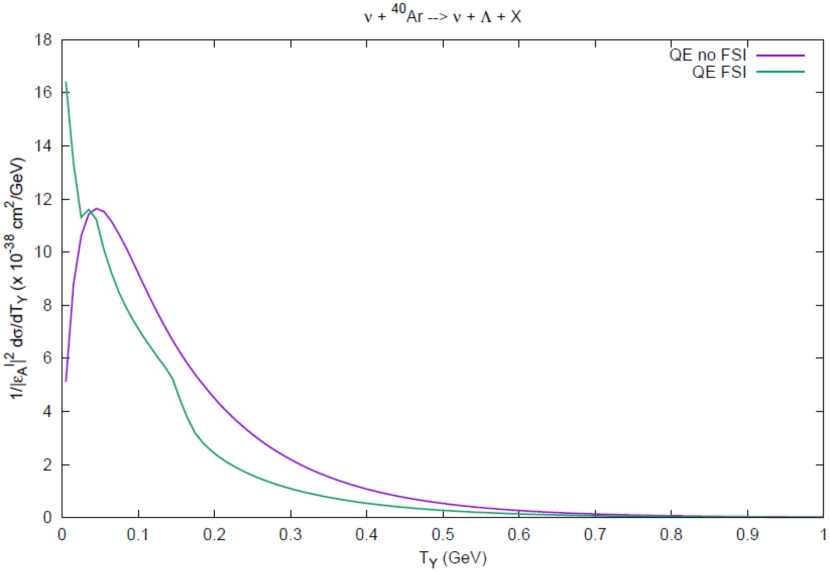
Flavor Changing Neutral Currents

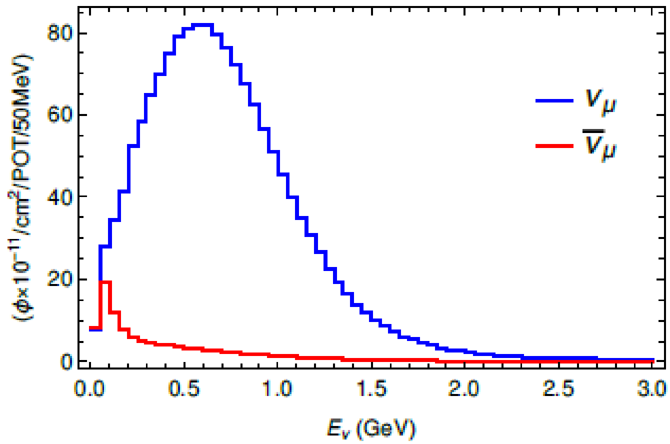
- Suppressed in the **SM**
- $d \to s$ using
$$\begin{aligned} \nu_l\, n &\to \nu_l\, \Sigma_0(\Lambda) \\ \nu_l\, p &\to \nu_l\, \Sigma^+ \end{aligned}$$
- Effective Hamiltonian:
$$\mathcal{H} = \frac{G_F}{\sqrt{2}} \left\{ \epsilon^l_V \left[\bar{s}\gamma_\mu d\right] + \epsilon^l_A \left[\bar{s}\gamma_\mu\gamma_5 d\right] \right\} \left[\bar{\nu}_l \gamma_\mu (1-\gamma_5)\nu_l\right]$$
  - Same matrix elements (up to isospin rotations) as in $W^- u \to s$
$$\begin{aligned} \langle \Lambda | \, \bar{s}\gamma^\mu(\gamma_5) d \, | n \rangle &= \langle \Lambda | \, \bar{s}\gamma^\mu(\gamma_5) u \, | p \rangle \\ \left\langle \Sigma^0 \right| \bar{s}\gamma^\mu(\gamma_5) d \, | n \rangle &= - \left\langle \Sigma^0 \right| \bar{s}\gamma^\mu(\gamma_5) u \, | p \rangle \\ \left\langle \Sigma^+ \right| \bar{s}\gamma^\mu(\gamma_5) d \, | p \rangle &= \left\langle \Sigma^- \right| \bar{s}\gamma^\mu(\gamma_5) u \, | n \rangle \end{aligned}$$

FCNC searches with neutrinos

- At SBND
- $d \to s$ using

$$\nu_l\, n \;\to\; \nu_l\, \Sigma_0(\Lambda)$$
$$\nu_l\, p \;\to\; \nu_l\, \Sigma^+$$





- Upper bounds:

N_Λ FCNC	No Thr.	μBooNE Thr.	SBND Thr.
QE	35 – 45	8 – 10	25 – 35

(× 3 if only ν_μ contributes)

FCNC searches with neutrinos

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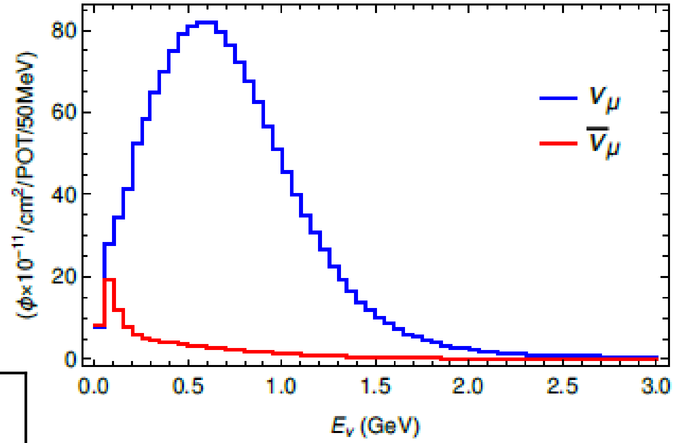

- Upper bounds:

N_Λ FCNC	No Thr.	μBooNE Thr.	SBND Thr.
QE	35 – 45	8 – 10	25 – 35

(× 3 if only υ_μ contributes)

- Other contributions to signal:
  - $\nu_l\, N \to \nu_l\, Y\, \pi$ ← important
  - $\nu_l\, N \to \nu_l\, N'\, \bar{K}\,,\, N'\, \bar{K}\, \pi$ ← suppressed
- Backgrounds:
  - $\nu_l\, N \to \nu_l\, Y\, K$ ← suppressed
  - Unidentified charged leptons from CC interactions
- There are (some) uncertainty cancellations in $N_{\mathrm{FCNC}\,\Lambda}\,/N_{\mathrm{CC}\,\Lambda}$

Outlook

- We are investigating the potential of (anti)neutrino-nucleon elastic scattering to disclose NSI and break degeneracies among parameters
- Requires
  - Reliable quark-flavor decomposition of nucleon axial form factors from LQCD
  - New data on H/D
- Polarization observables provide additional information

- We are exploring the opportunities of SBN experiments to search for FCNC in Y production (with axial vector interactions)
  - Upper limits are promising
  - Detection thresholds are important
  - Uncertainty cancellations in FCNC/CC ratios is desirable to minimize model dependence