AstroHEP-PPCC24

Adventures in neutrino physics

Luis Alvarez Ruso

IFIC Institut de Física Corpuscular

CSIC Consejo Superior de Investigaciones Científicas

Vniversitat de València

Financiado por la Unión Europea NextGenerationEU

Gobierno de España Ministerio de Ciencia, Innovación y Universidades

Plan de Recuperación, Transformación y Resiliencia

Generalitat Valenciana Conselleria de Educación, Universidades y Empleo

GVANEXT Fondos Next Generation en la Comunitat Valenciana

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(with AstroHEP-PPCC money)

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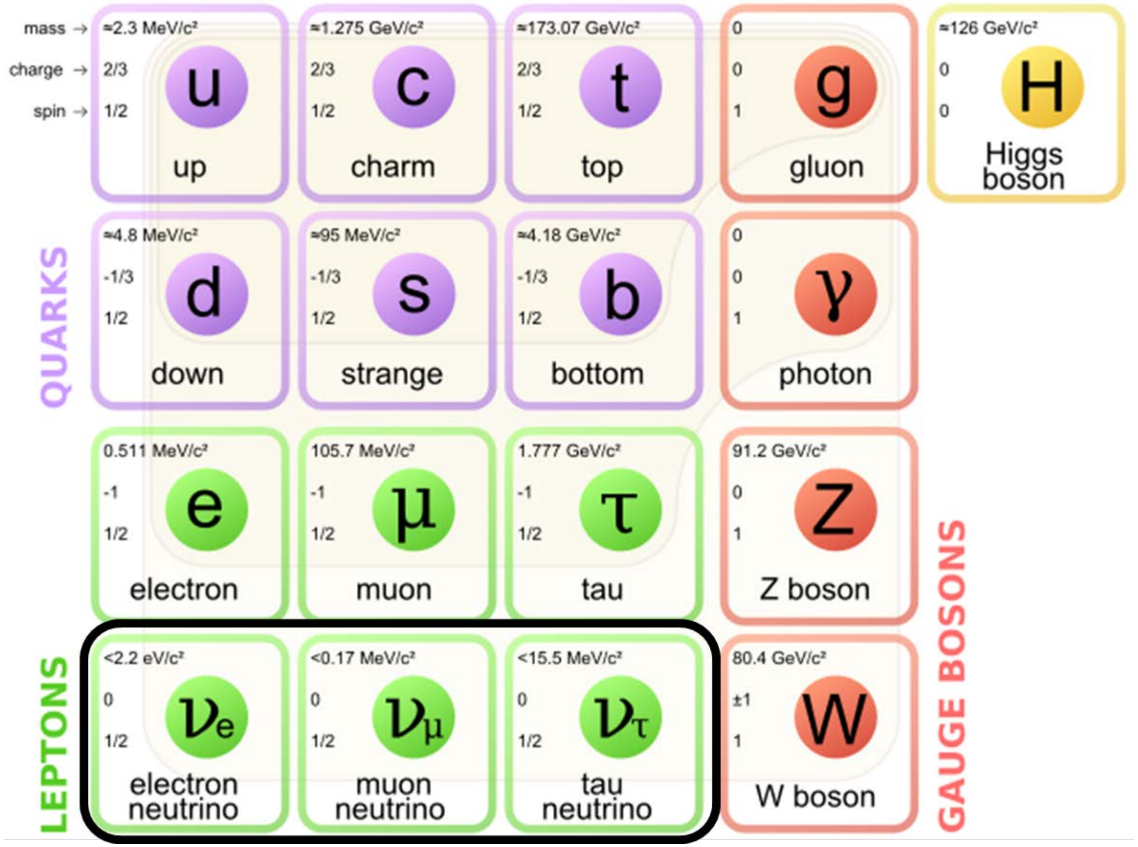
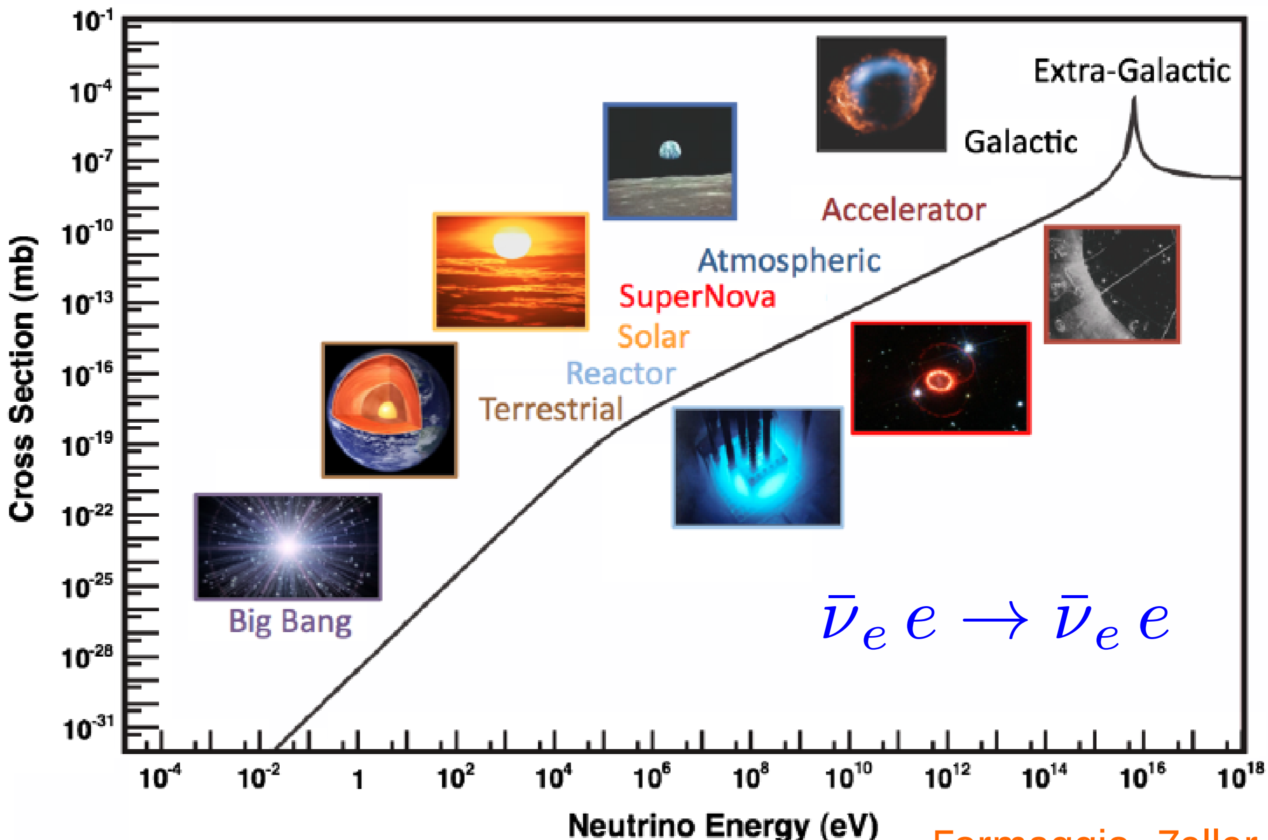
Neutrinos



- Neutral leptons

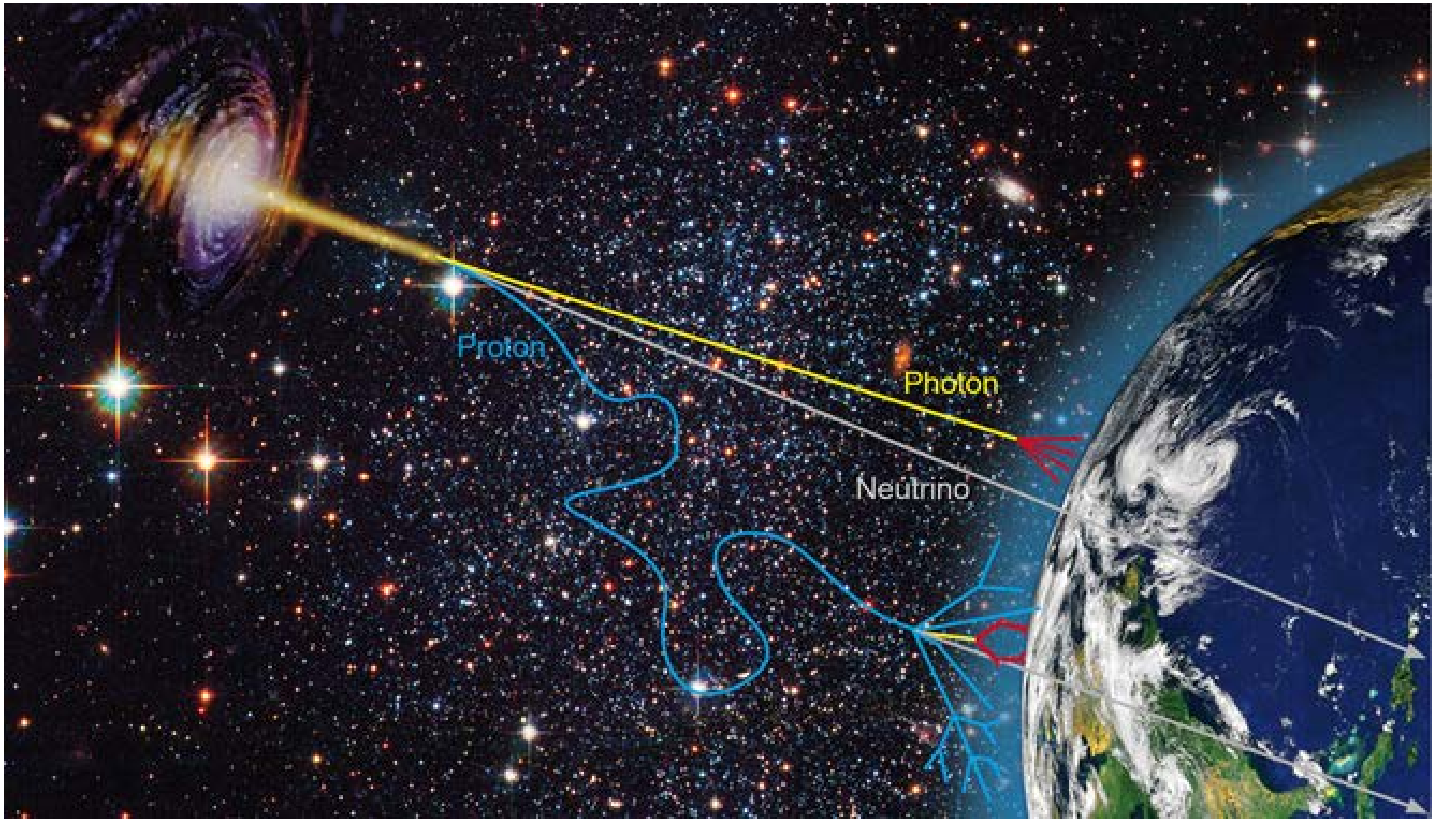
Neutrinos



Formaggio, Zeller, Rev. Mod. Phys. 84 (2012)

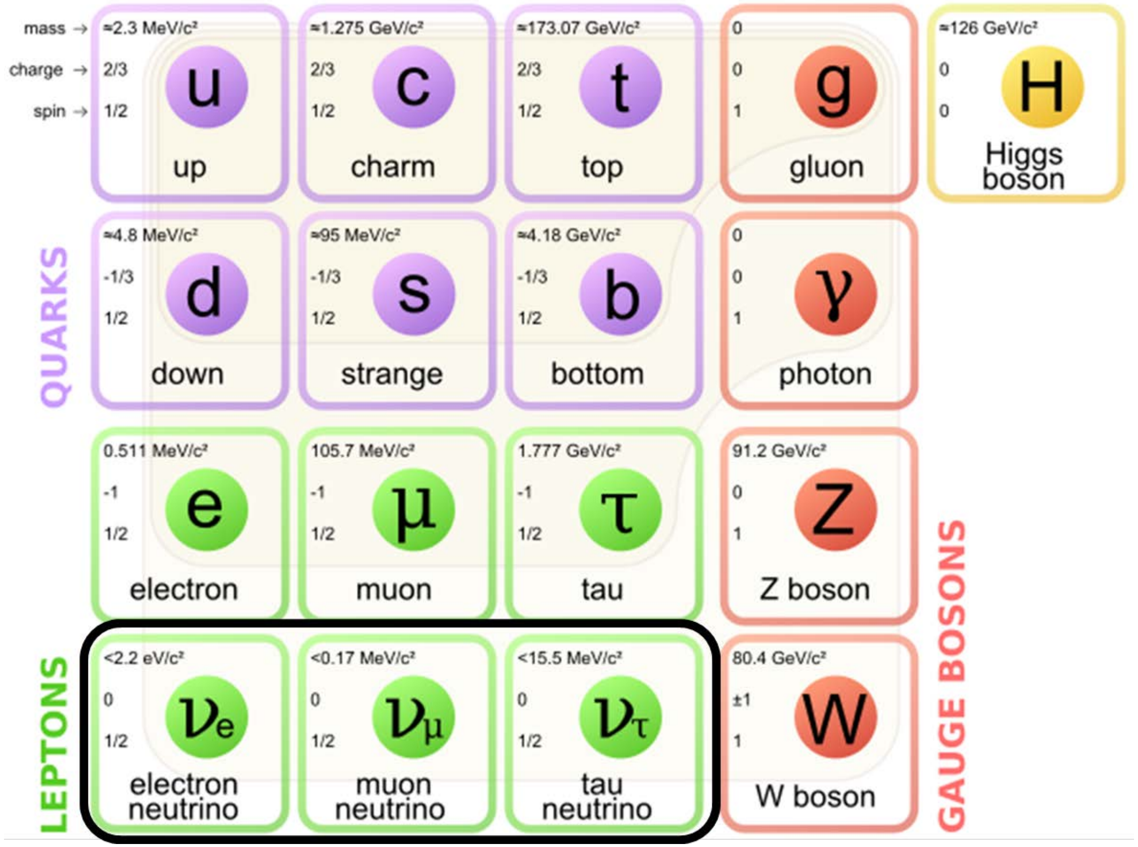
- Neutral leptons
- Weakly interacting

Neutrinos



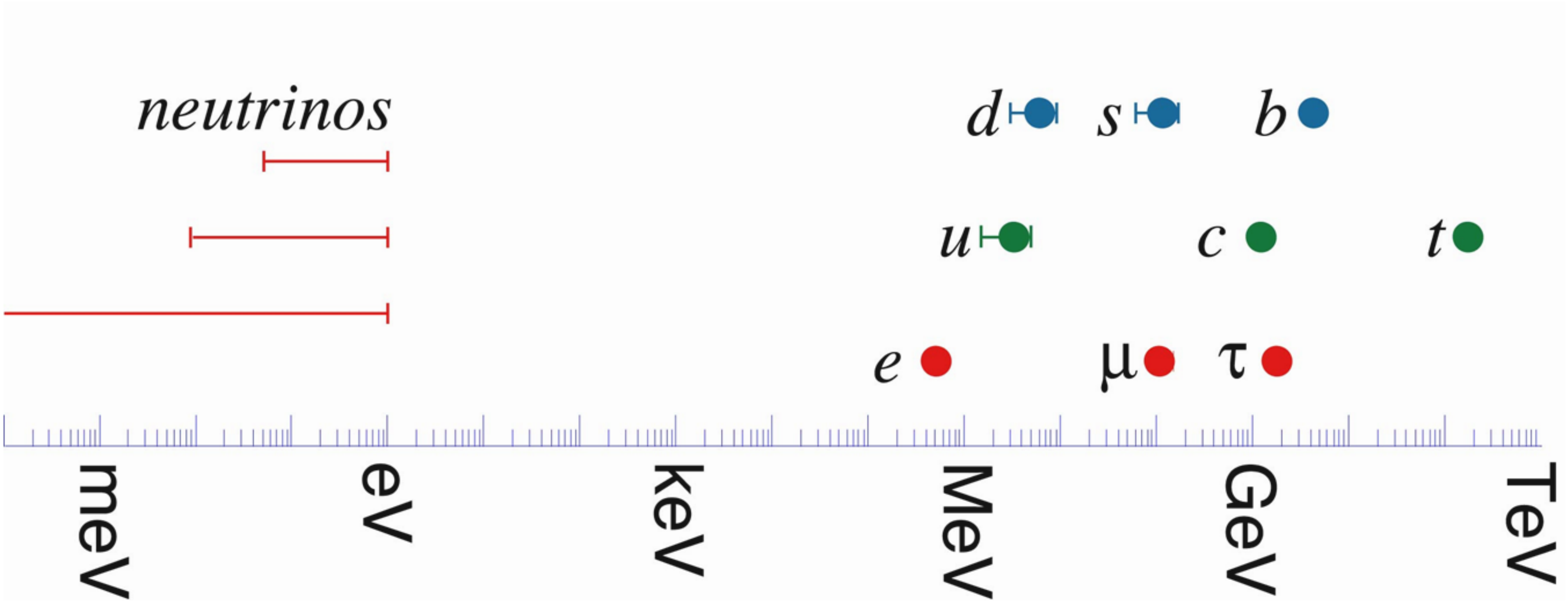
- Neutral leptons
- Weakly interacting
  - Neutrino/multi-messenger astronomy
  - hard to detect...

Neutrinos



- Neutral leptons
- Weakly interacting
- Massless in the Standard Model but...

Neutrinos



- Neutral leptons
- Weakly interacting
- Massless in the Standard Model but $m_\nu < 1\text{eV}$
  - $m_{1,2,3} \neq m_{e,\mu,\tau}$

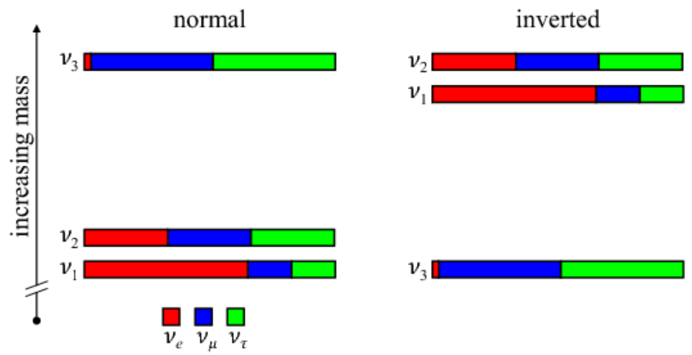
Neutrino Oscillations

- $m_{1,2,3} \neq m_{e,\mu,\tau}$
- Precise measurement of oscillation parameters

$$P_{\alpha\beta} = \delta_{\alpha\beta} - 4\sum_{i<j}^{n} \mathrm{Re}[U_{\alpha i}U^*_{\beta i}U^*_{\alpha j}U_{\beta j}] \sin^2 X_{ij}$$
$$+ 2\sum_{i<j}^{n} \mathrm{Im}[U_{\alpha i}U^*_{\beta i}U^*_{\alpha j}U_{\beta j}] \sin 2X_{ij} \,,$$

$$X_{ij} = \frac{(m_i^2 - m_j^2)L}{4E}$$

- ν mass hierarchy, CP violation



- Experimental study with reactor, atmospheric and accelerator ν
  - Requires ν detection: efforts in detector development

Experiments

- Accelerator ν

T2K

NOvA

MINERvA

μBooNE

SHORT-BASELINE SBND NEAR DETECTOR

- Future:

Hyper-K

DUNE
DEEP UNDERGROUND NEUTRINO EXPERIMENT

essνsb+
ESS neutrino Super Beam plus

Experiments

- Accelerator ν

T2K

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μBooNE

SBND — SHORT-BASELINE NEAR DETECTOR

- Future:

Hyper-K

DUNE — DEEP UNDERGROUND NEUTRINO EXPERIMENT

essνsb+ — ESS neutrino Super Beam plus

talk by M. Sorel

Neutrino telescopes

- Atmospheric and cosmic ν

KM3NeT

IceCube Neutrino Observatory

  - ARCA: cosmic ν flux
  - ORCA: ν properties

Neutrino telescopes

- Atmospheric and cosmic ν

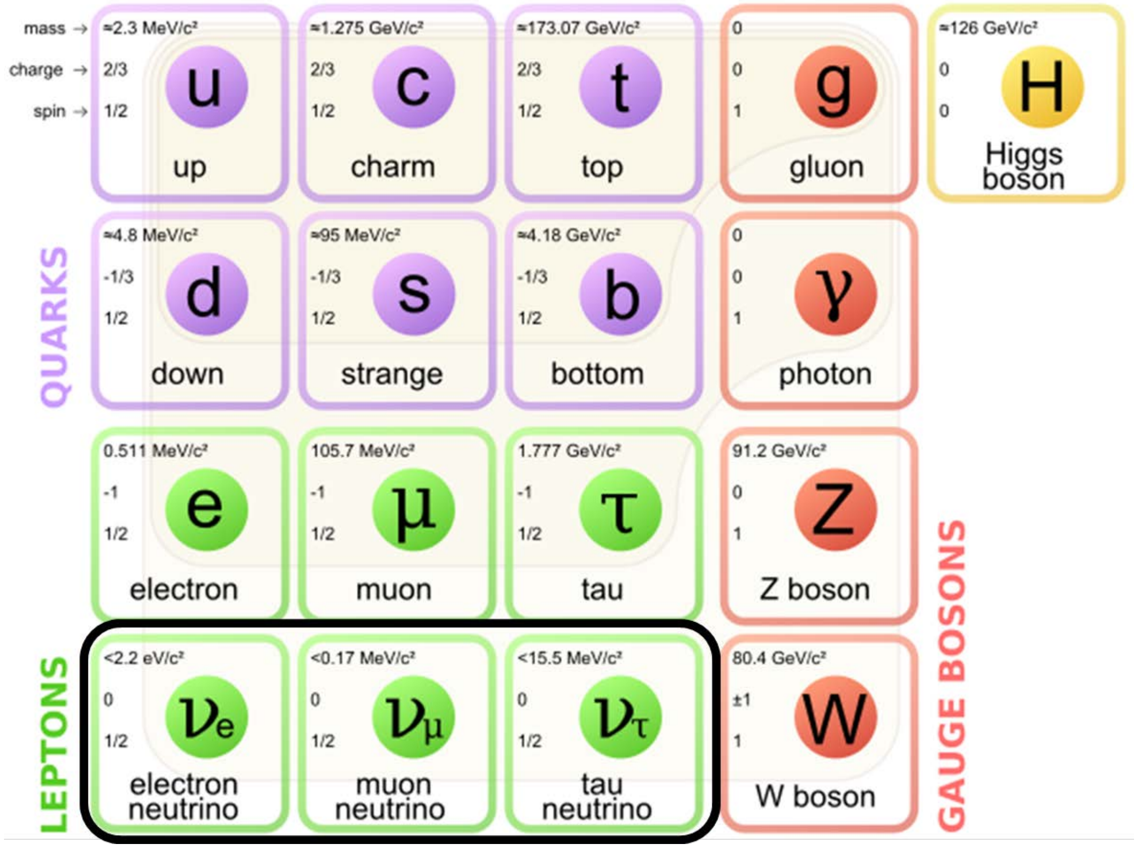
KM3NeT

ICECUBE NEUTRINO OBSERVATORY

- Hardware and software development
- Multi-messenger astronomy
- Oscillation analyses

talk by F. Salesa

Neutrinos



- Neutral leptons
- Weakly interacting
- Massless in the Standard Model but $m_\nu < 1\mathrm{eV}$
- $\nu = \bar{\nu}$? ⇔ Dirac or Majorana particles: big open question

Dirac or Majorana?

- Big open question with implications for
  - the origin of the small neutrino masses
  - Matter/antimater asymmetry

Dirac or Majorana?

- Big open question with implications for
  - the origin of the small neutrino masses
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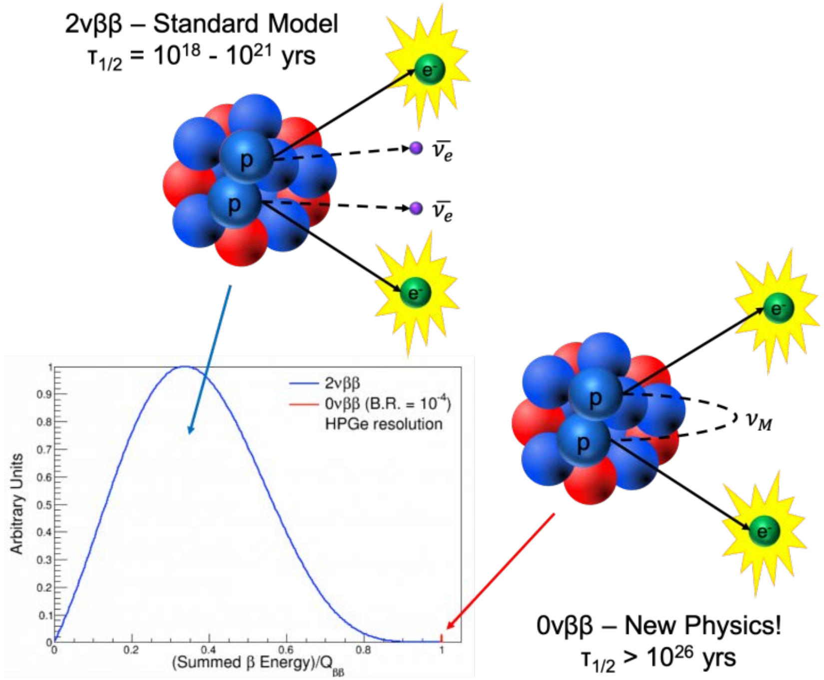
- $0\nu\beta\beta$ decay

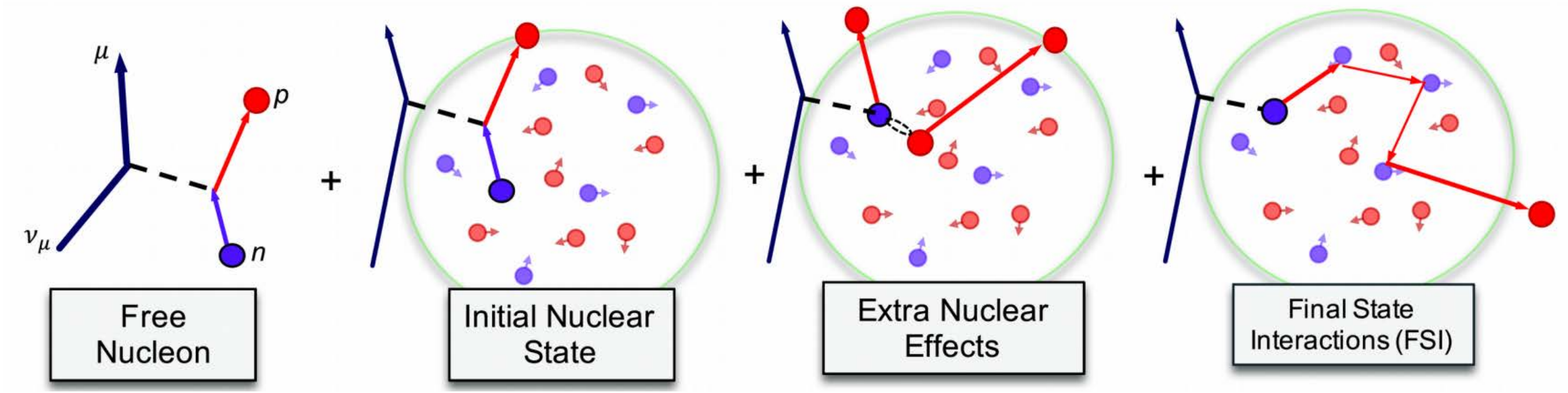


- Light detection and electronics for next

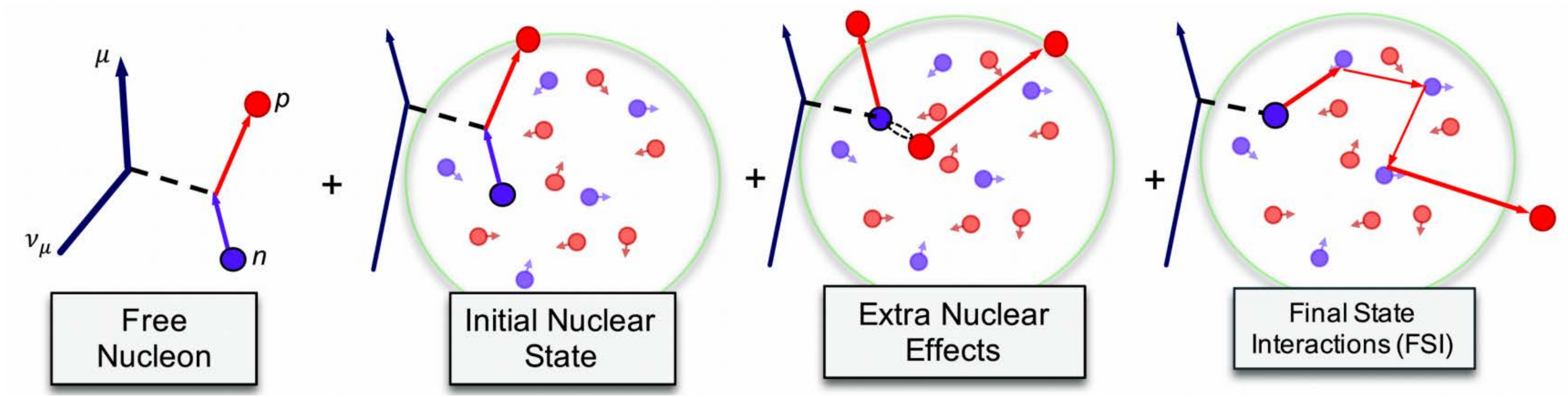
talk by M. Sorel

Neutrino Interactions

- ASFAE project: Modeling neutrino interactions with matter for current and future experiments



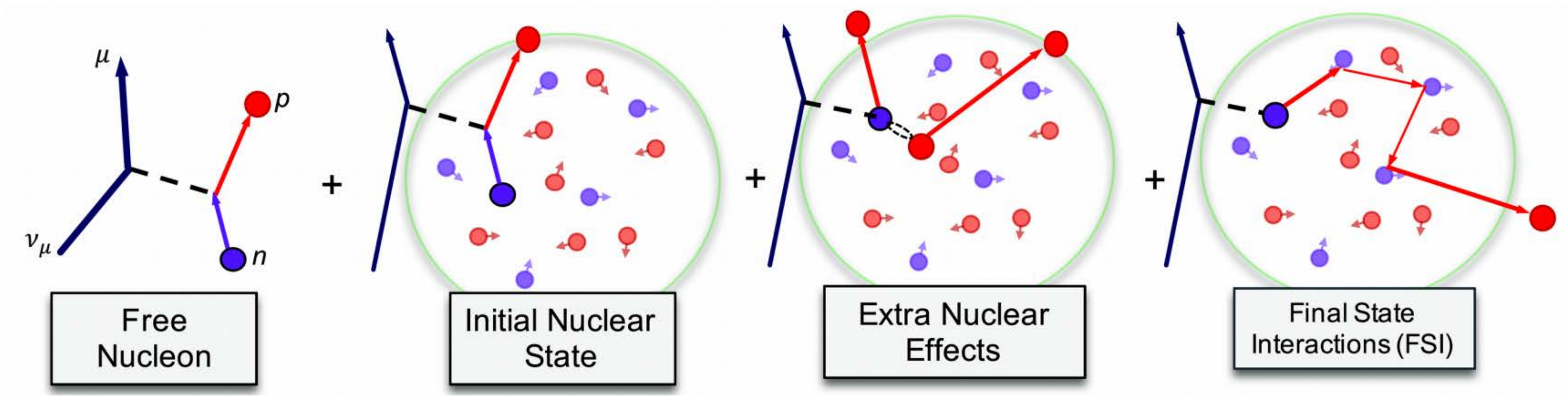
Neutrino Interactions



C. Wilkinson

- Need for neutrino interaction theory:
- Experiments (partially) rely on theory-based simulations for:
  - background subtraction
  - flux calibration
  - E_ν reconstruction (ν beams are not monochromatic)
  - efficiency and acceptance determination
  - $\sigma(\nu_\mu)$ to $\sigma(\nu_e)$, target extrapolations
  - future projections
- Mismodeling can lead to systematic errors even with the best data.

Neutrino interaction theory



C. Wilkinson

- @ IFIC: 15+ years developing advanced theoretical models and simulations of few-GeV neutrino interaction with matter:
  - Quasi-elastic scattering on nuclear targets.
  - Two-body currents.
  - Meson production on nucleons and nuclei.
  - Photon emission
  - Coherent processes
  - Strangeness production
  - Deep inelastic scattering

Neutrino interaction theory

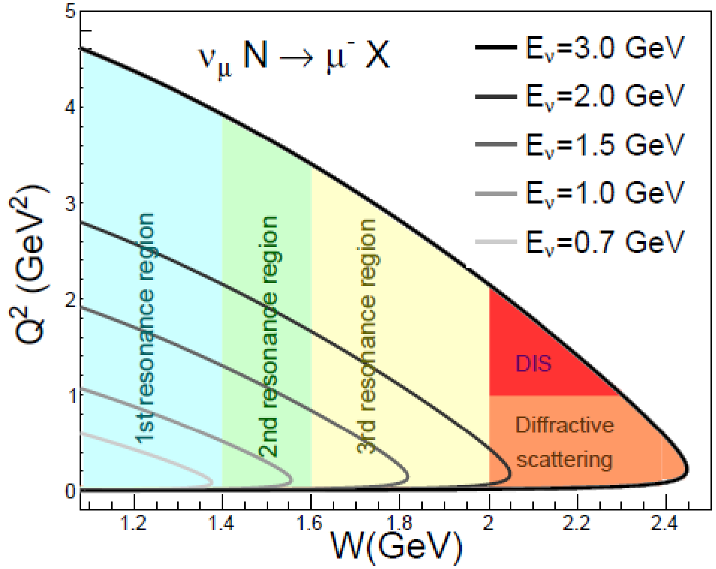
- ASFAE project: Modeling neutrino interactions with matter for current and future experiments

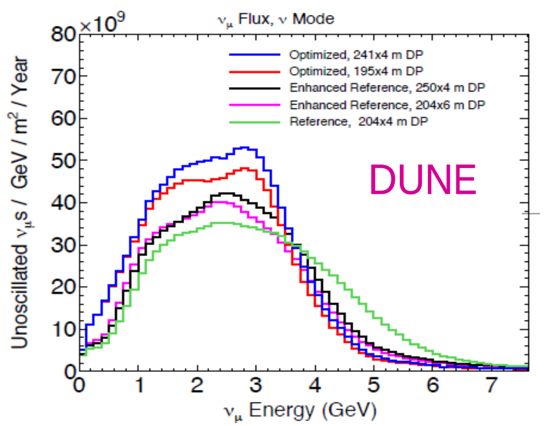
Current activity:

- Weak pion production of the nucleon over a broad kinematic range.
  Collaborator: M. Gorchtein (Mainz)
- Target mass dependence of CC coherent pion production.
- Photon emission in NC interactions with nucleon knockout.
  Collaborator: M. Benítez (Granada)
- Meson production in $\bar{\nu}\, e^-$ collisions at FASERν (CERN).
- NC neutrino-nucleon scattering in presence of non-standard interactions.
  Collaborators: Ilma, M. Rafi Alam (Aligarh), I. Ruiz Simó (Granada)
- Weak hyperon production (including FCNC searches) .
  Collaborators: M. Rafi Alam (Aligarh), M. Benítez, I. Ruiz Simó (Granada)
- New physics in charmed hyperon production by CC υ_τ interactions.
  Collaborator: J. Sobczyk (Mainz)

Modeling neutrino interactions

- Weak pion production of the nucleon over a broad kinematic range.
  Collaborator: M. Gorchtein (Mainz)
- The most important inelastic process
  - Source of background eg NCπ^0 in Cherenkov detectors
- Proceeds predominantly through the excitation of nucleon resonances

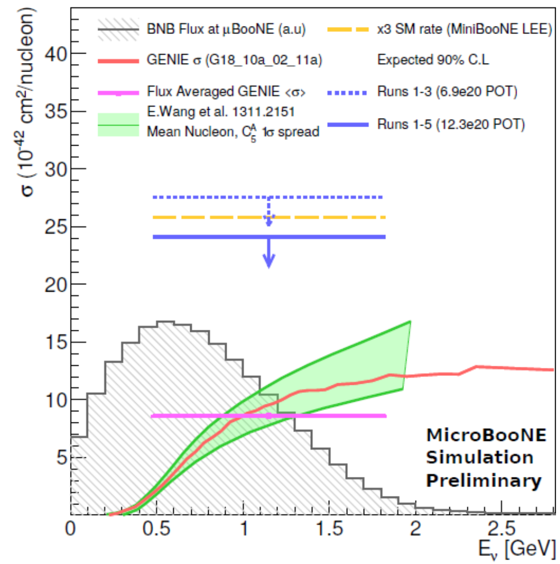




- Mainz Unitary Isobar Model for Pion Photo- and Electroproduction on the Nucleon (MAID) extended to the axial sector.
  - To be implemented in GENIE.

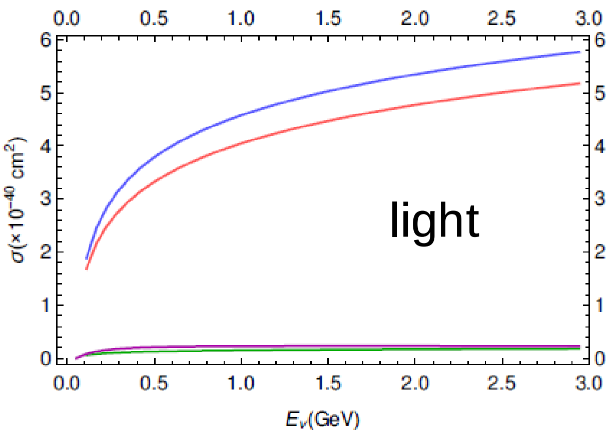
Modeling neutrino interactions

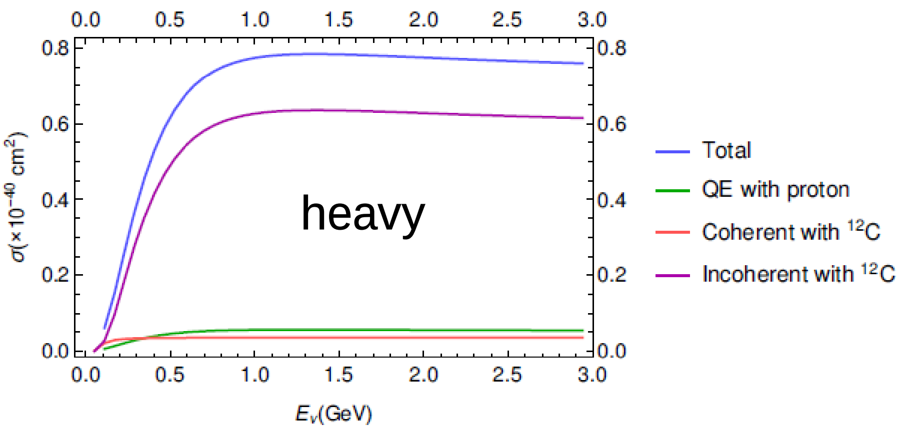
- Photon emission in NC interactions with nucleon knockout.
  Collaborator: M. Benítez (Granada)
- Electronlike background
  - Candidate to explain the MiniBooNE anomaly
    - **SM** and **BSM** mechanisms
- Upper bounds by T2K and MicroBooNE ➡



K. Sutton, PoS (NuFact 2021)

- Our task: Extend our study of $\nu(\bar{\nu})\, A \to \nu(\bar{\nu})\, \gamma\, X$ to the exclusive γ p channel
- Comparisons to MicroBooNE and SBND future data
- Test the role of heavier **BSM** mediators:



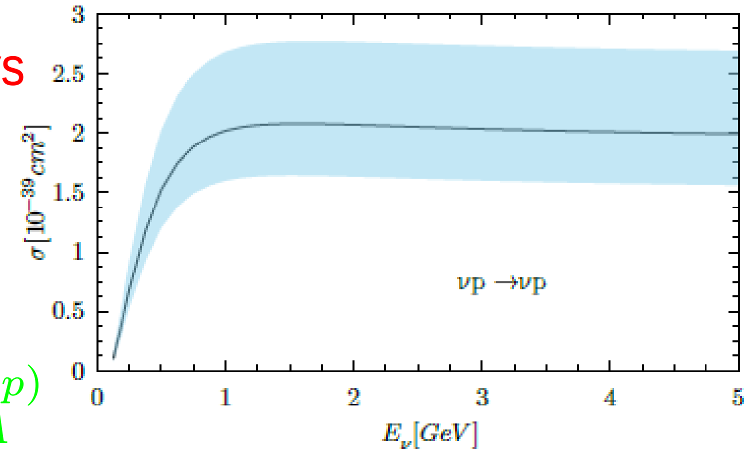


Modeling neutrino interactions

- NC neutrino-nucleon scattering in presence of non-standard interactions.
  Collaborators: Ilma, R. Alam (Aligarh), I. Ruiz Simó (Granada)
- Non-standard/generalized ν interactions can be (potentially) accessed in:
  - Oscillations (matter effects)
  - τ, β, (heavy) hadron semi-leptonic decays
  - ν scattering: ν-e , CEνNS, DIS
    - Other possibilities: eg $\nu\, p \rightarrow \nu\, p$

$$\langle p | \, J^\mu \, | p \rangle = \bar{u}(p') \Gamma^\mu u(p) = \mathcal{V}^\mu - \mathcal{A}^\mu$$

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



- In presence of NSI:

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

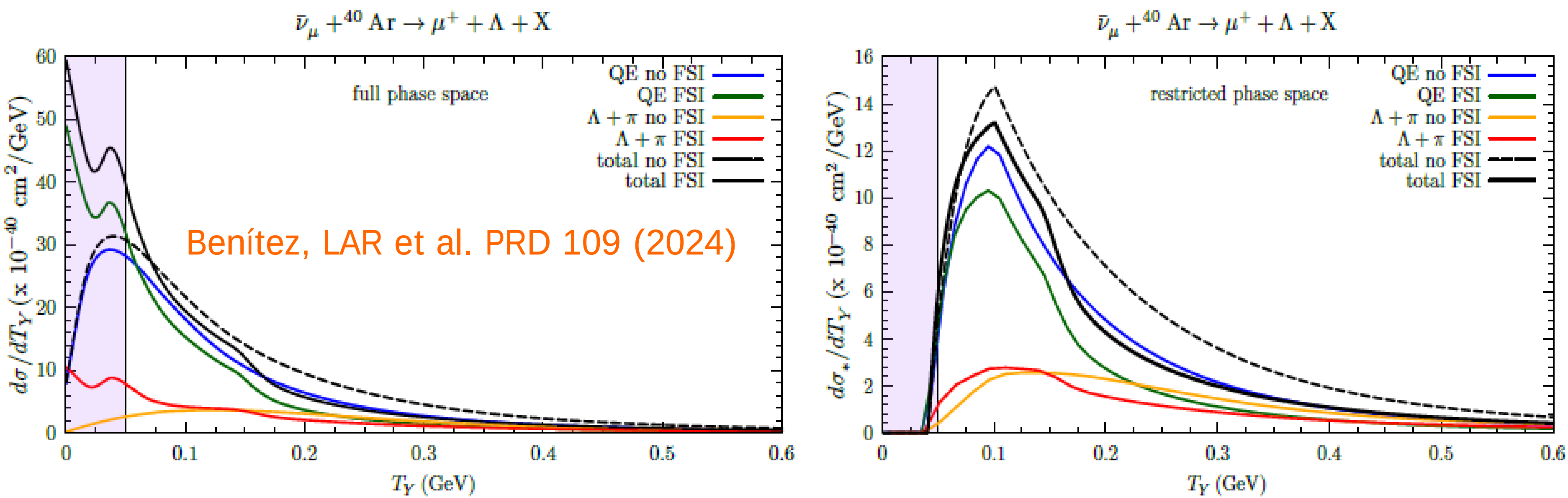
$$2\tilde{F}_A^{(p)} = \left(1 + \epsilon^{uA} - \epsilon^{dA} \right) F_A^{iv} + \left(\epsilon^{uA} + \epsilon^{dA} \right) F_A^{is} - F_A^{(s)}$$

  - Reliable (flavor decomposed) input from LQCD required
  - Complementary to DIS

Weak hyperon production

- ΔS = -1: $W^- u \to s$
- Cabibbo reduced ($V_{us} = 0.23$)
- Via Y$\to \pi$ N, Y are a source of low energy π in $\bar{\nu}$ scattering
- Y production could be used to constrain $\bar{\nu}$ contamination in ν beams

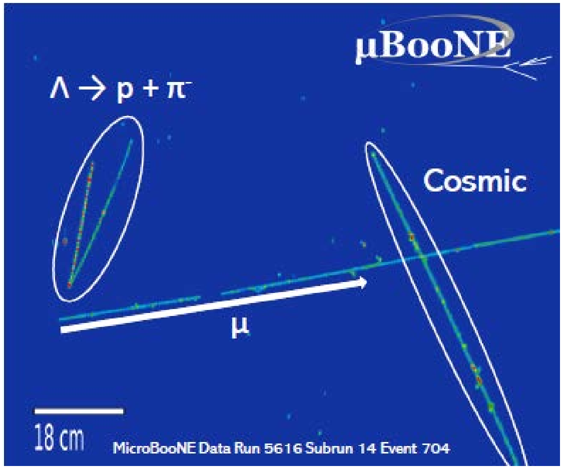
Comparison to MicroBooNE



Benítez, LAR et al. PRD 109 (2024)

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

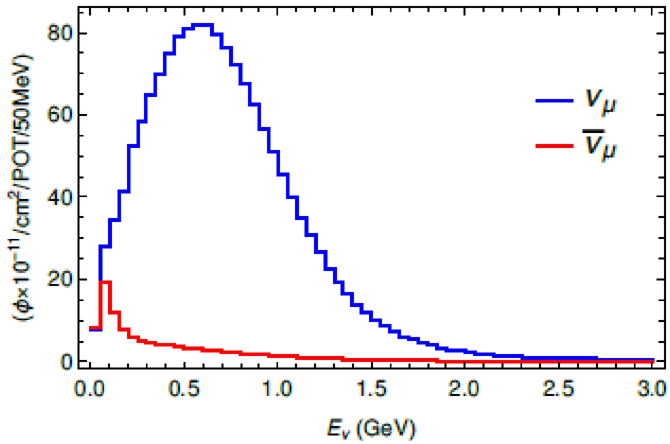
	σ_* ($\times 10^{-40}$ cm^2/Ar)
MicroBooNE	$2.0^{+2.1}_{-1.6}$
QE + $Y\pi$, full model	2.13
QE	1.44
$Y\pi$	0.69

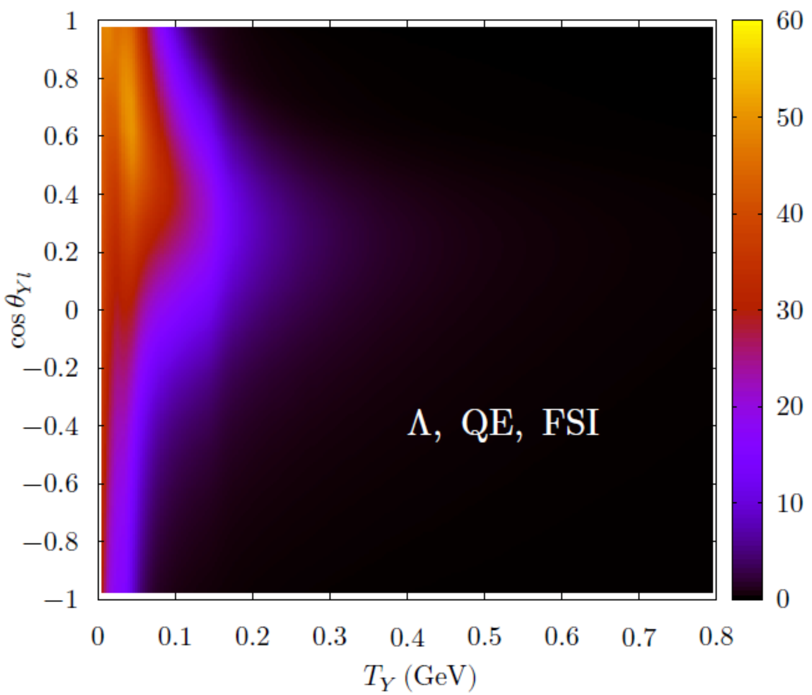


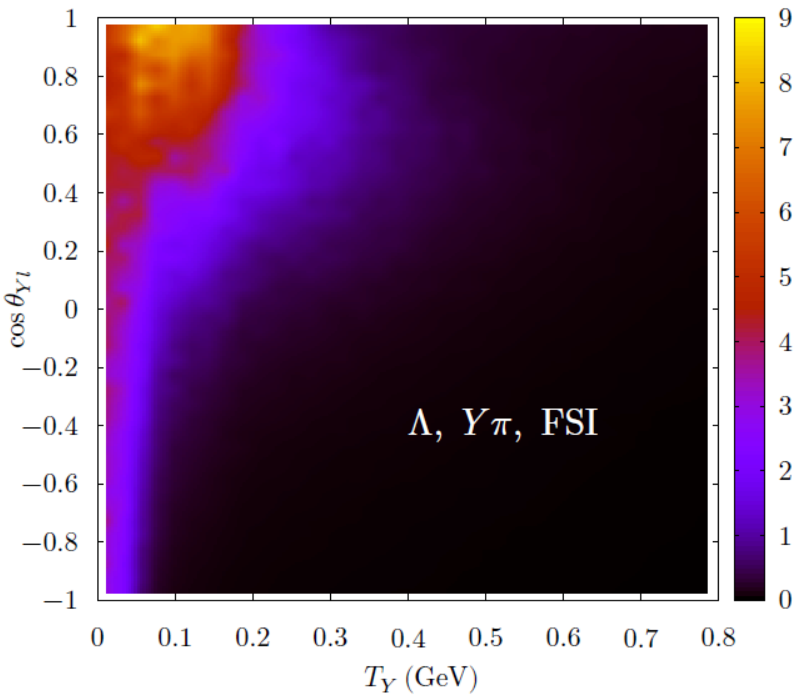
MicroBooNE, PRL 130 (2023)

SBND

- $10\text{-}13 \times 10^{20}$ POT (3 years)
- Expected events before detection thresholds:
  - N_Λ = 1300 – 1700 (QE)
  - N_Λ = 240 – 300 ($\Lambda\pi$)

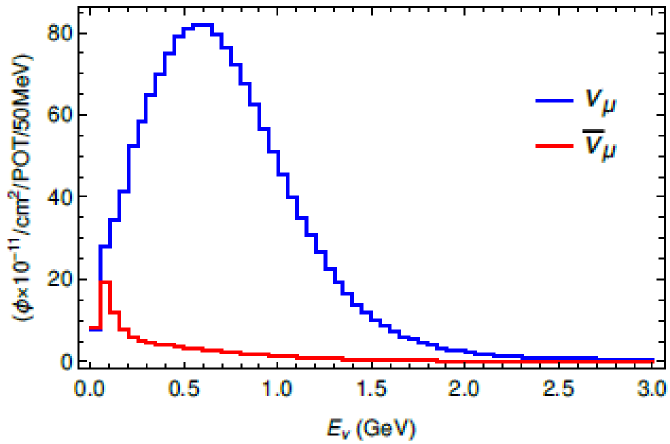






FCNC searches with neutrinos

- Suppressed in the **SM**
- Constraints from K decays:
  - $\epsilon_V < 10^{-6} \approx 0;\ |\epsilon_A| < 7.6 \times 10^{-3}$



- At SBND
- $d \to s$ using $\nu_l\, n \to \nu_l\, \Lambda$

  $\nu_l\, p \to \nu_l\, \Sigma^+$

- $N_{\mathrm{FCNC}\,\Lambda} \approx 466\, |\epsilon_A|^2 N_{\mathrm{CC}\,\Lambda}$
- With $N_{\mathrm{CC}\Lambda}$ = 1300 – 1700 ($\bar{\nu}$) and the upper bound $|\epsilon_A| < 7.6 \times 10^{-3}$
- $N_{\mathrm{FCNC}\,\Lambda}$ < 46 - 60 events (x 3)

- At DUNE
  - More possible final states: $\nu_l\, N \to \nu_l\, Y\,,\, Y\,\pi\,,\, N'\,\bar{K}\,,\, N'\,\bar{K}\,\pi$
  - More statistics (particularly with a gas TPC)
  - Background from $\nu_l\, N \to \nu_l\, Y\, K$

Outlook

- Line 6: Neutrinos
  - Sound contributions to neutrino and astroparticle physics experiments:
    - T2K, HK, DUNE, KM3NeT, NEXT
- ASFAE project: Modeling neutrino interactions with matter for current and future experiments
  - Making progress in our understanding of neutrino interactions with matter in the SM
  - Searching for processes and observables sensitive to BSM non-standard and flavor changing NC interactions