Nonperturbative QCD effects in neutrino-nucleon interactions and sigma terms.

Lorenzo Barca,
DESY Zeuthen Particle Physics Theory

Astroparticle and Particle Physics Workshop
DESY Zeuthen, 06-08/10/2025

A timeline of neutrino physics discoveries

Nobel Prize *

(ν_e) neutrino flux originated from the sun (pp-chain) and flux detected on earth are in discrepancy.

1930 — Prediction of an undetected particle ($\bar{\nu}_e$) in β-decay

W. Pauli

1956 — Discovery of ν_e *

F. Reines and C. Cowan *

1957 — Prediction of neutrino oscillations

B. Pontecorvo (Z. Maki, M. Nakagawa, S. Sakata)

1962 — Discovery of ν_μ *

L. Lederman *

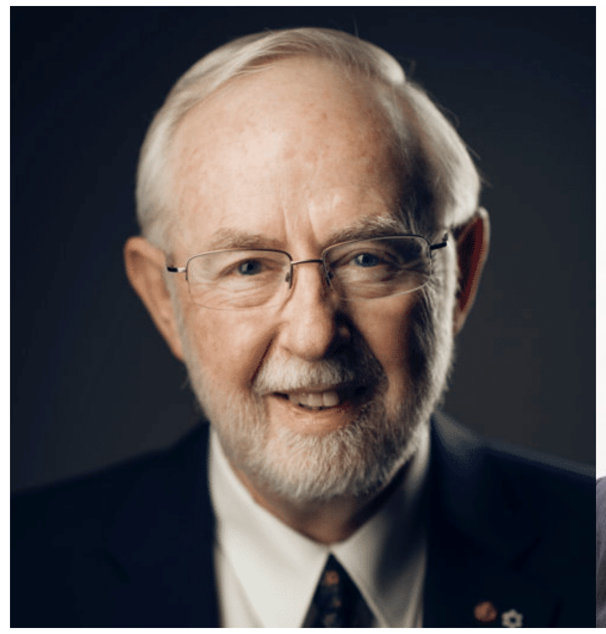
1960' — **solar neutrino puzzle** *

Homestake Experiment *

2000 — Discovery of ν_τ

DONUT Experiment

2015 — (1998/2001) Clear observation of neutrino oscillations *



A. McDonald *
SNO Experiment

T. Kajita *
Super-Kamiokande

Neutrino oscillations in the vacuum

$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i} |\nu_i\rangle$$

$$|\nu_i(t)\rangle = e^{-i(E_i t - \mathbf{p}_i \cdot \mathbf{x})} |\nu_i\rangle$$

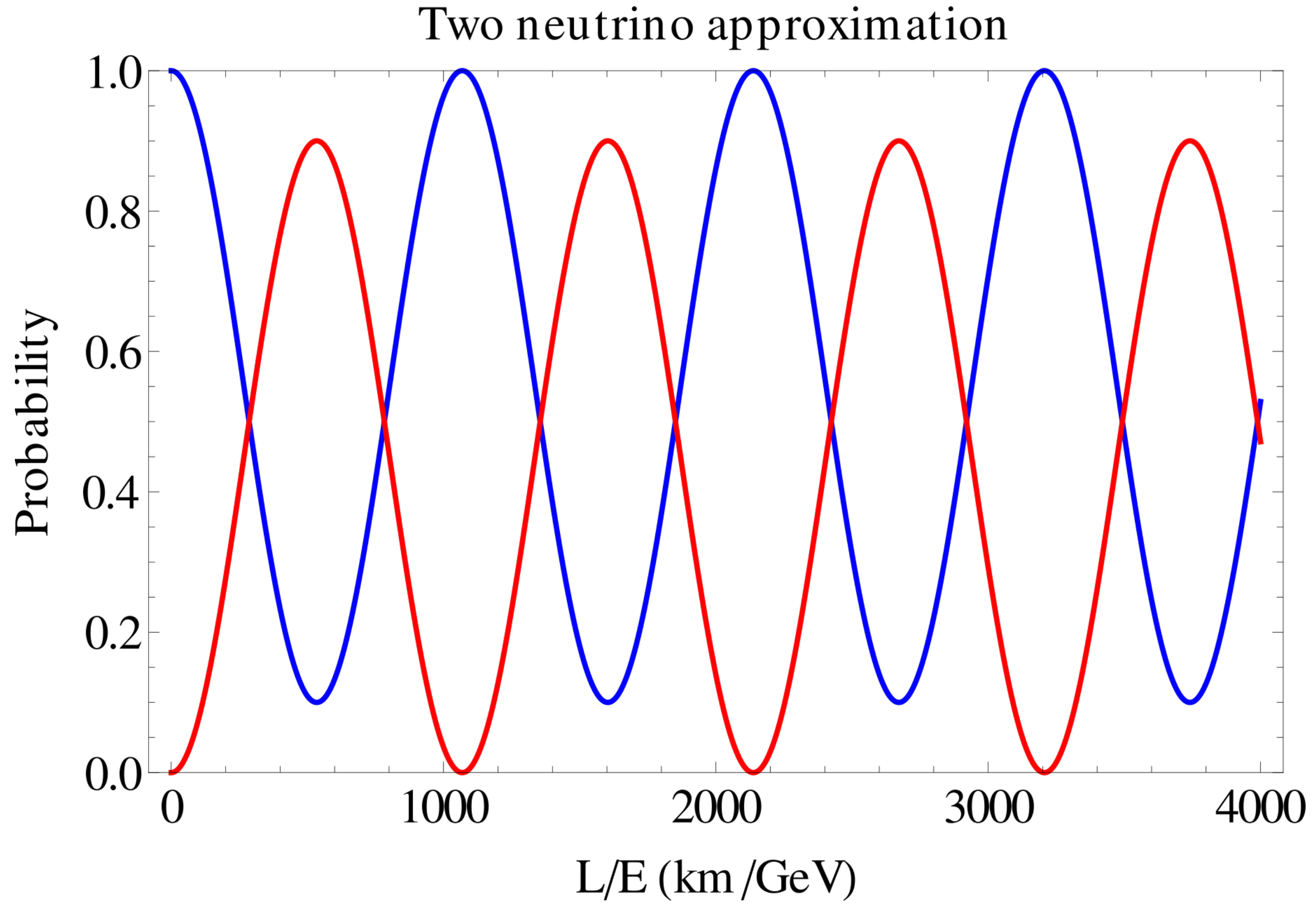
2-flavour case

Ultrarelativistic limit $t \approx L = |\mathbf{x}|$

$$P_{\alpha\to\beta} = |\langle \nu_\beta(L) | \nu_\alpha(0)\rangle|^2 = \sin^2\left(\frac{\Delta m^2 L}{4E}\right)\sin^2\theta$$

$$\Delta m^2 = m_1^2 - m_2^2$$

Neutrinos cannot be massless!



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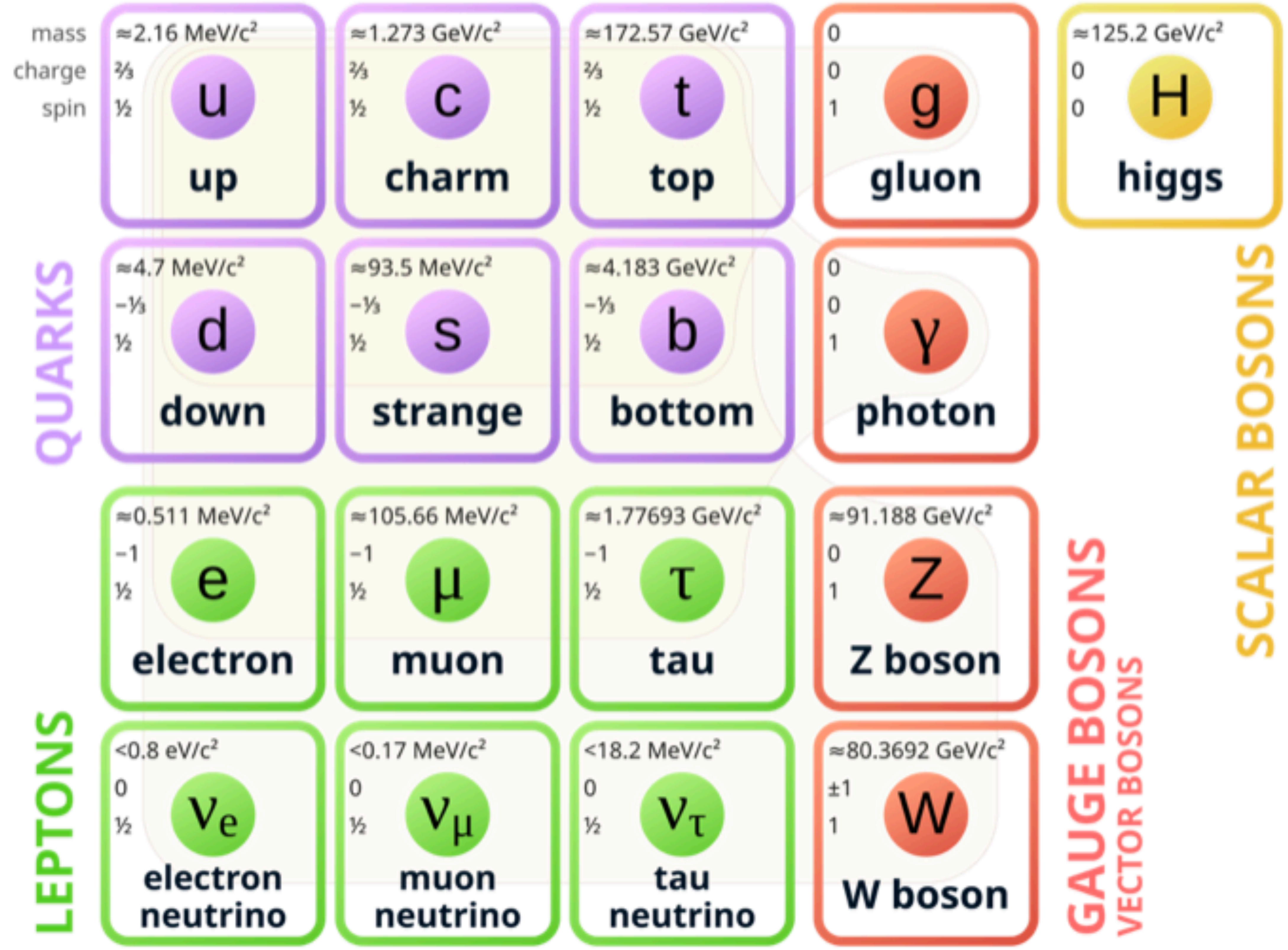

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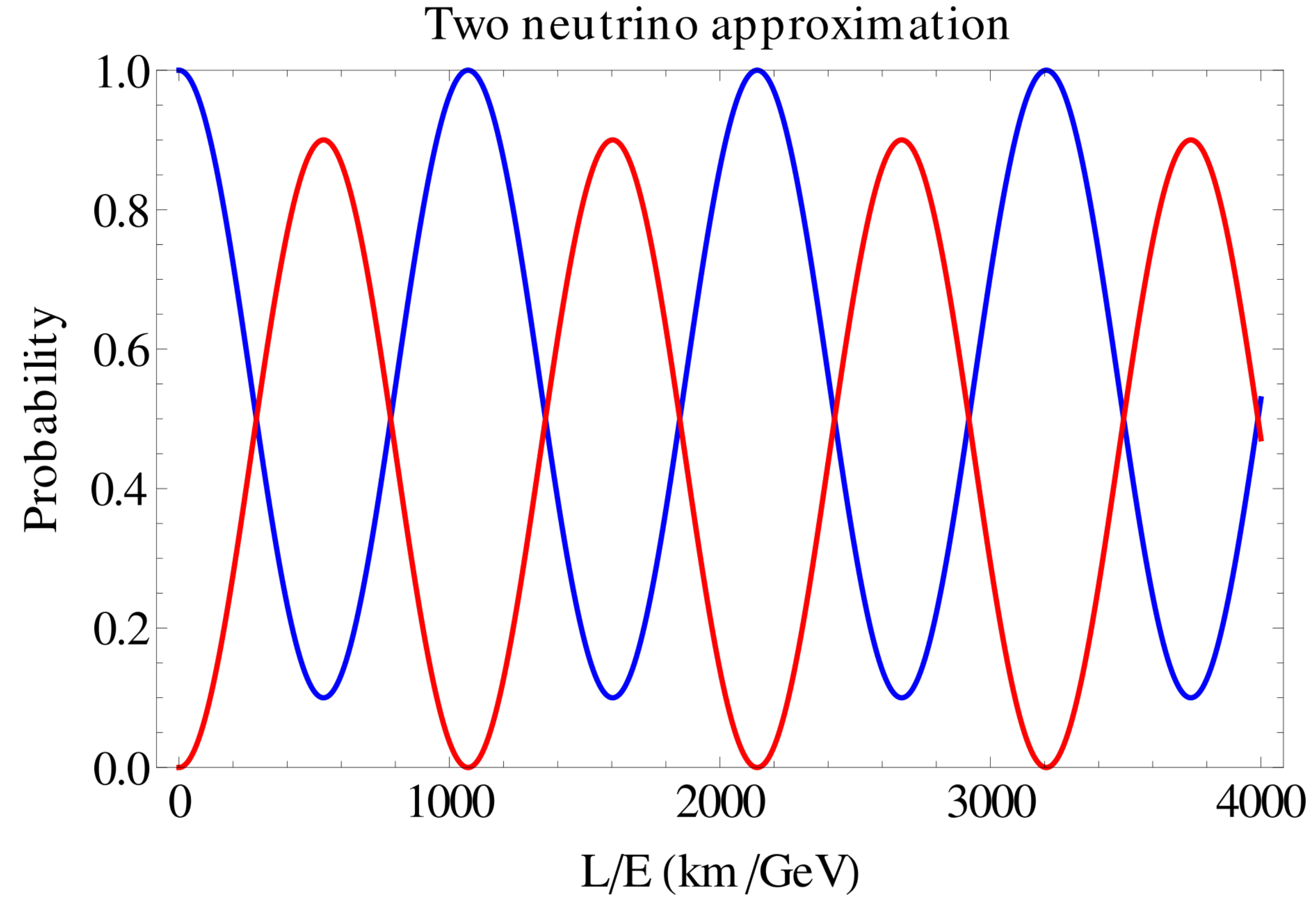


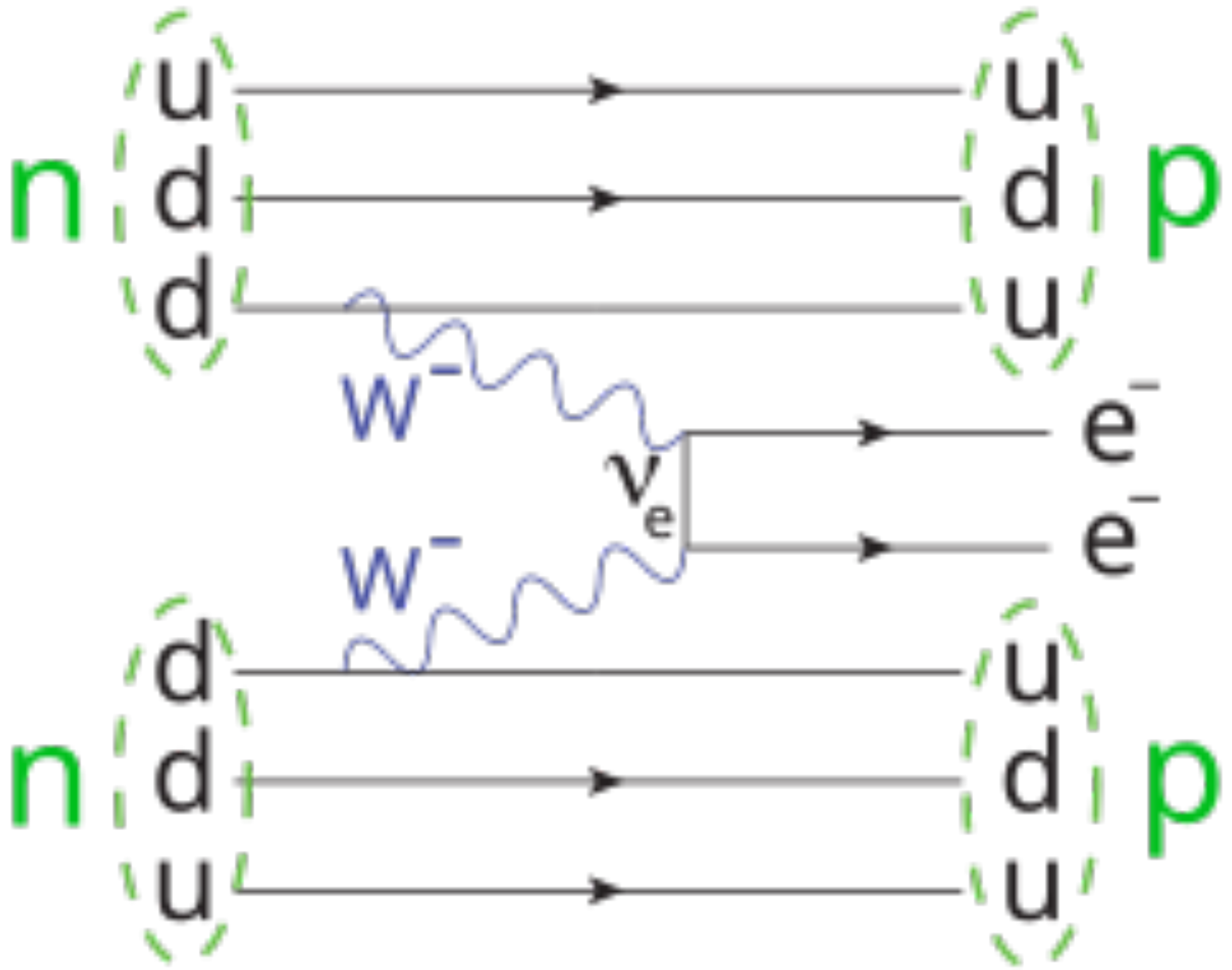
Need to revisit SM to account for massive neutrinos

Some open questions

✦ **How do neutrinos acquire their masses?** Fine tuning of Yukawa coupling? See-saw mechanism?

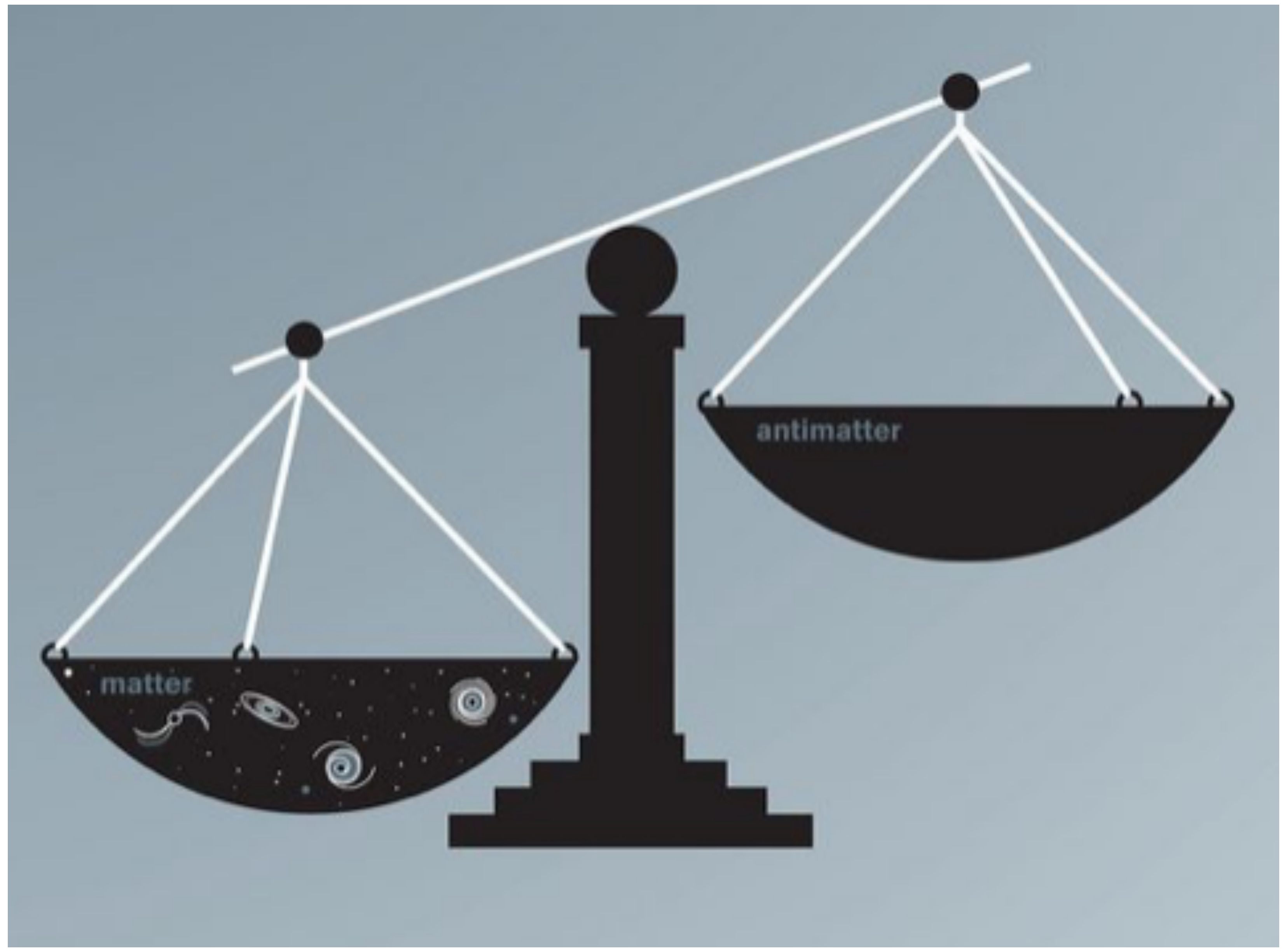
✦ **Are they Majorana particles? ($\nu_\ell = \bar{\nu}_\ell$)**

addressed by $0\nu\beta\beta$ experiments



✦ **Do $\bar{\nu}_\ell$ oscillate differently than ν_ℓ?** → CP violation

Leptogenesis —Spharelons→ Matter-Antimatter Asymmetry



(Sakharov conditions)

[Talk by G. Zaharijas 06/10]

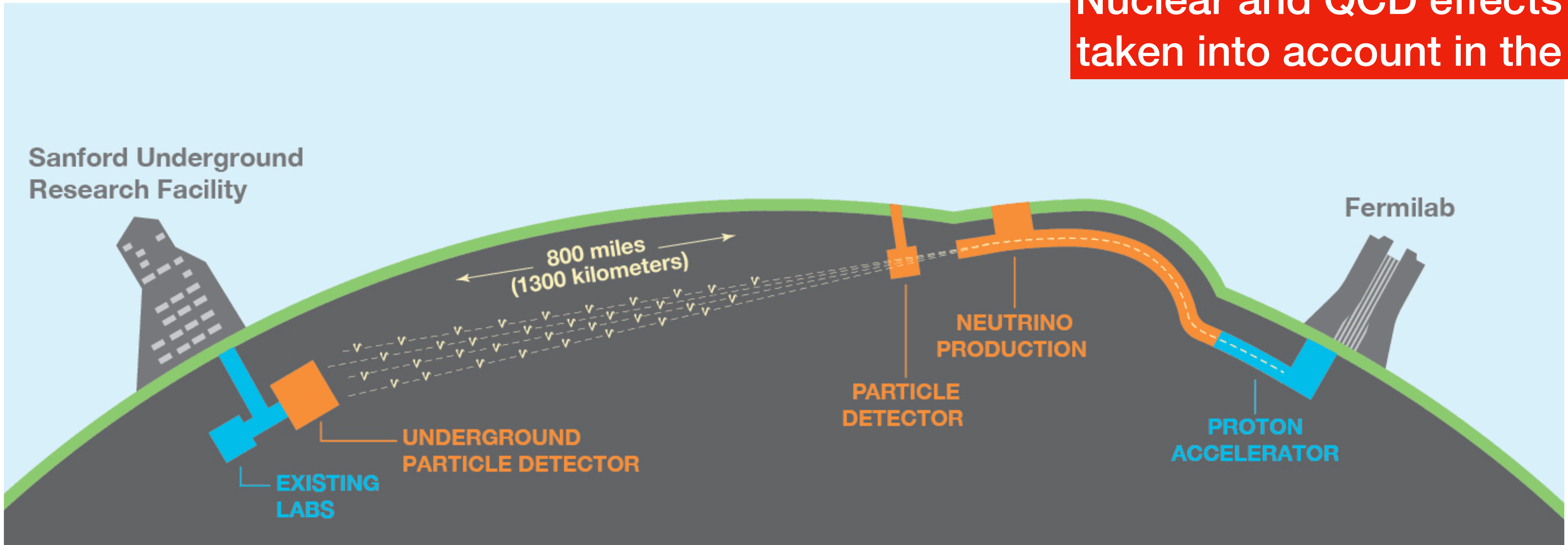
Next-generation neutrino oscillation experiments: DUNE

35 countries, ~200 institutions involved

> $3B investment

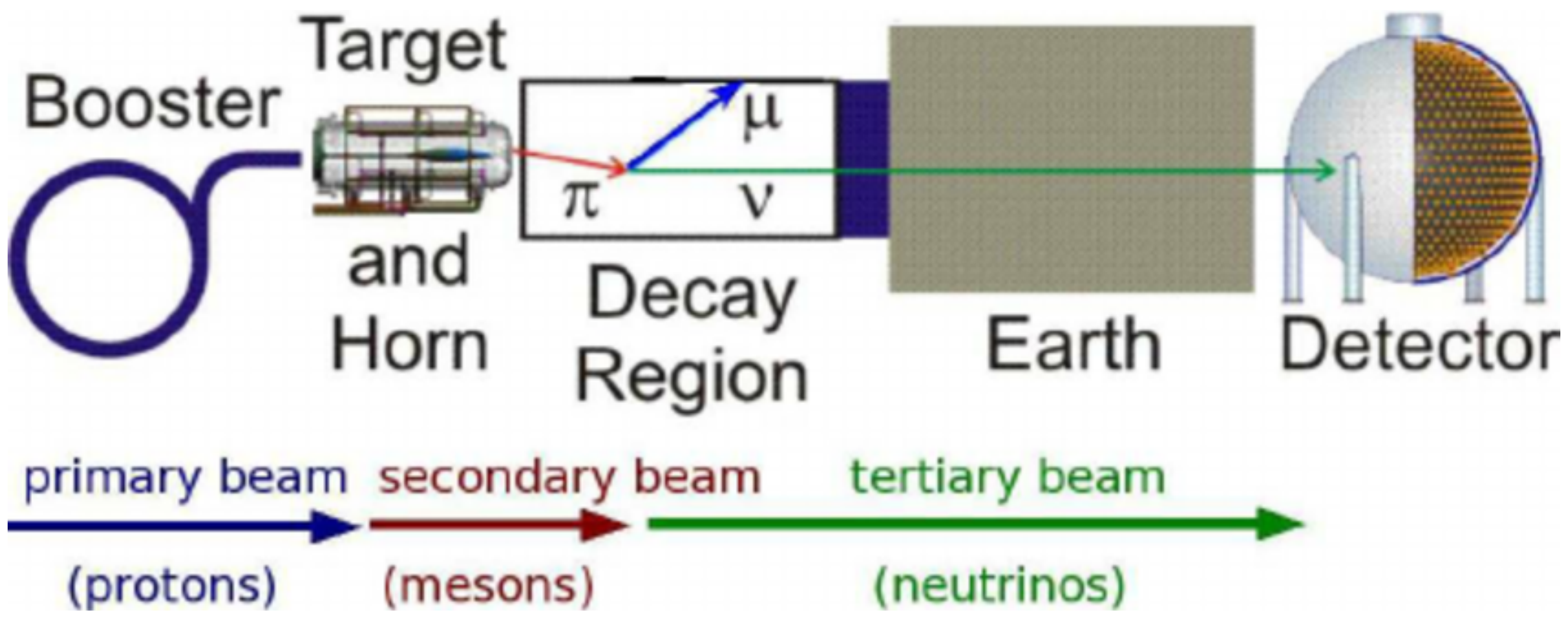
Next-generation experiments aim to improve the accuracy of the neutrino mixing parameters and observe any asymmetry in how neutrinos and antineutrinos oscillate

Nuclear and QCD effects must be taken into account in the analysis



Liquid Argon Time Projection Chamber

Neutrino-nucleon interactions in neutrino oscillation experiments: MiniBooNE

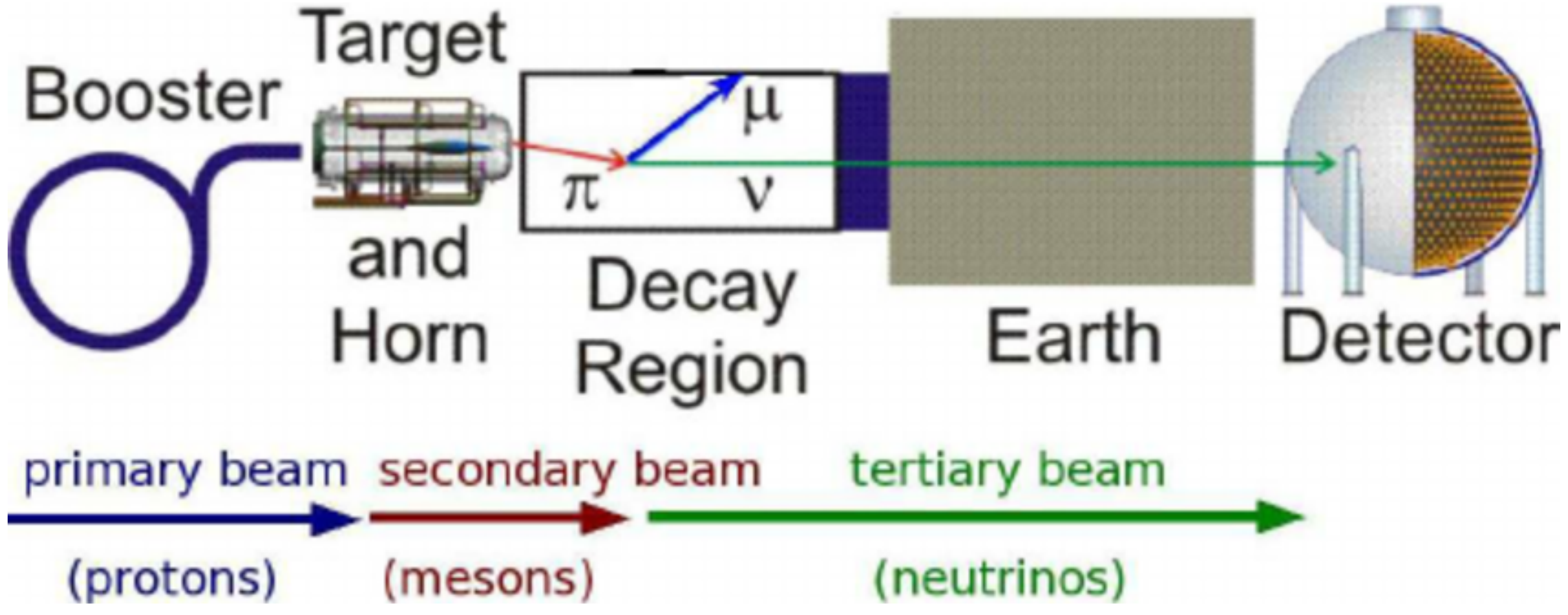


ν_μ flux is artificially produced and then detected after a travel length L

$$\nu_\mu\, n \xrightarrow{\mathcal{J}^-} \mu^- p \qquad \frac{d\sigma^{(\nu N)}}{dQ^2} \propto |\langle N|\mathcal{J}^-|N\rangle|^2$$

$\mathcal{J}^-$ is the weak current

Neutrino-nucleon interactions in neutrino oscillation experiments: MiniBooNE



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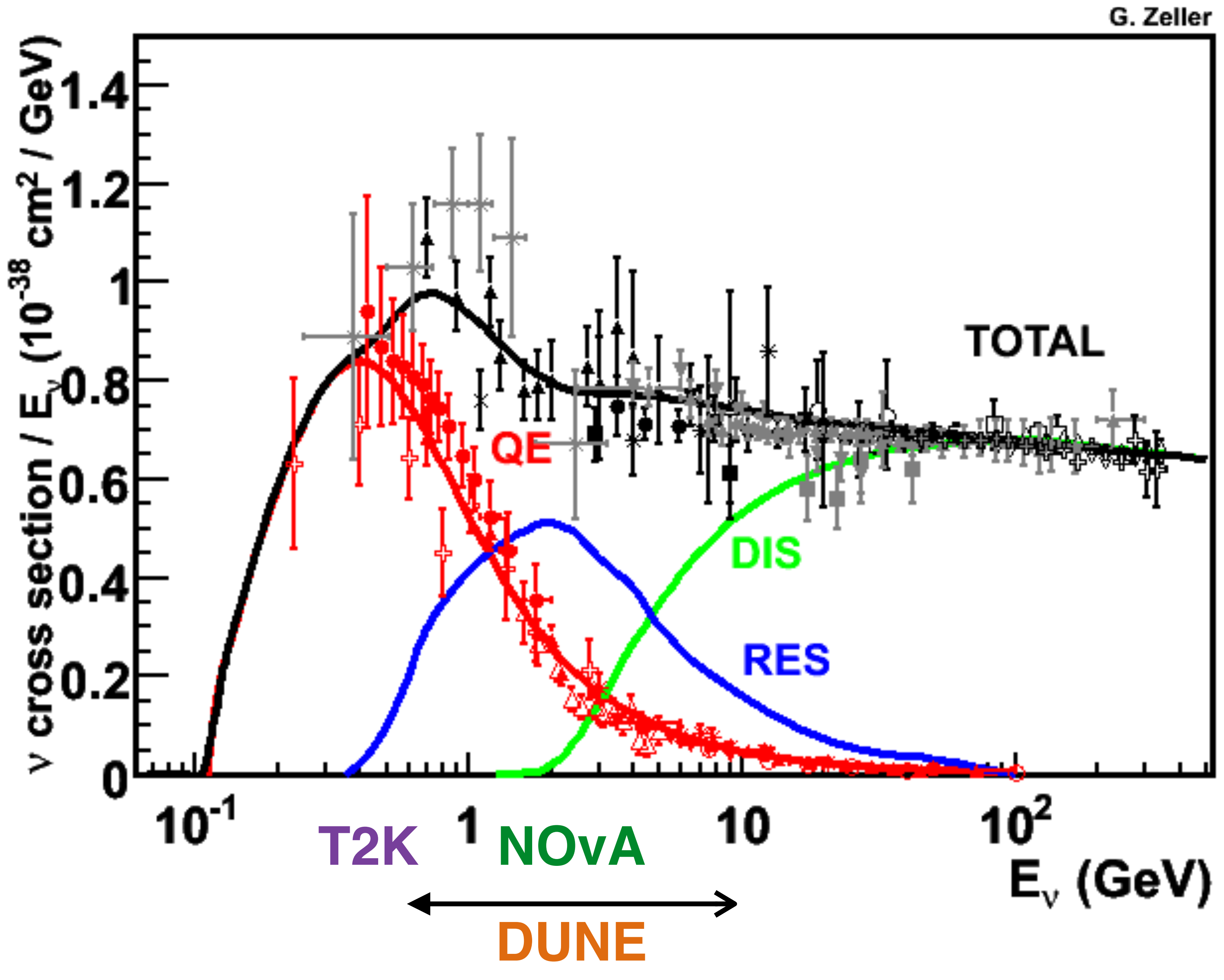


[J. A. Formaggio, G. Zeller, RMP.84.1307]

Main challenges

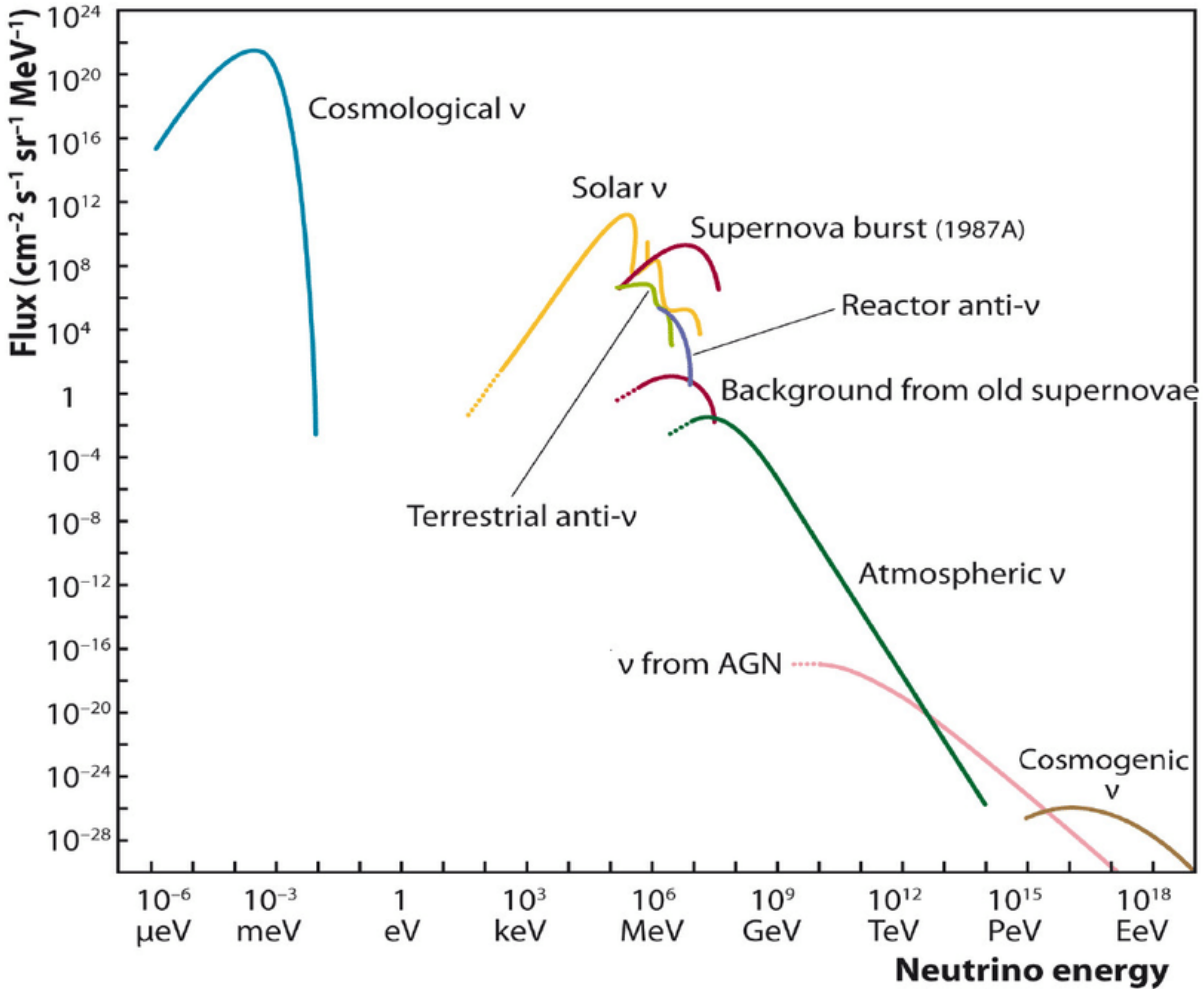
- **Nuclear model to factorise neutrino-nuclei scattering into neutrino-nucleon scattering (known from theory);**
- **Q^2 in a range where excited nucleons are produced!**

USQCD Collaboration *[arXiv:2203.09030, 2207.07641]*

Required also knowledge of $\langle N^* | \mathcal{J}^- | N \rangle$, $\langle \Delta | \mathcal{J}^- | N \rangle$ and $\langle N\pi | \mathcal{J}^- | N \rangle$

I am the first to investigate $\langle N\pi | \mathcal{J}^- | N \rangle$ with LQCD [**LB**, et al., *Phys.Rev.D* 107 (2023) 5, L051505, *arXiv:2110.11908*]

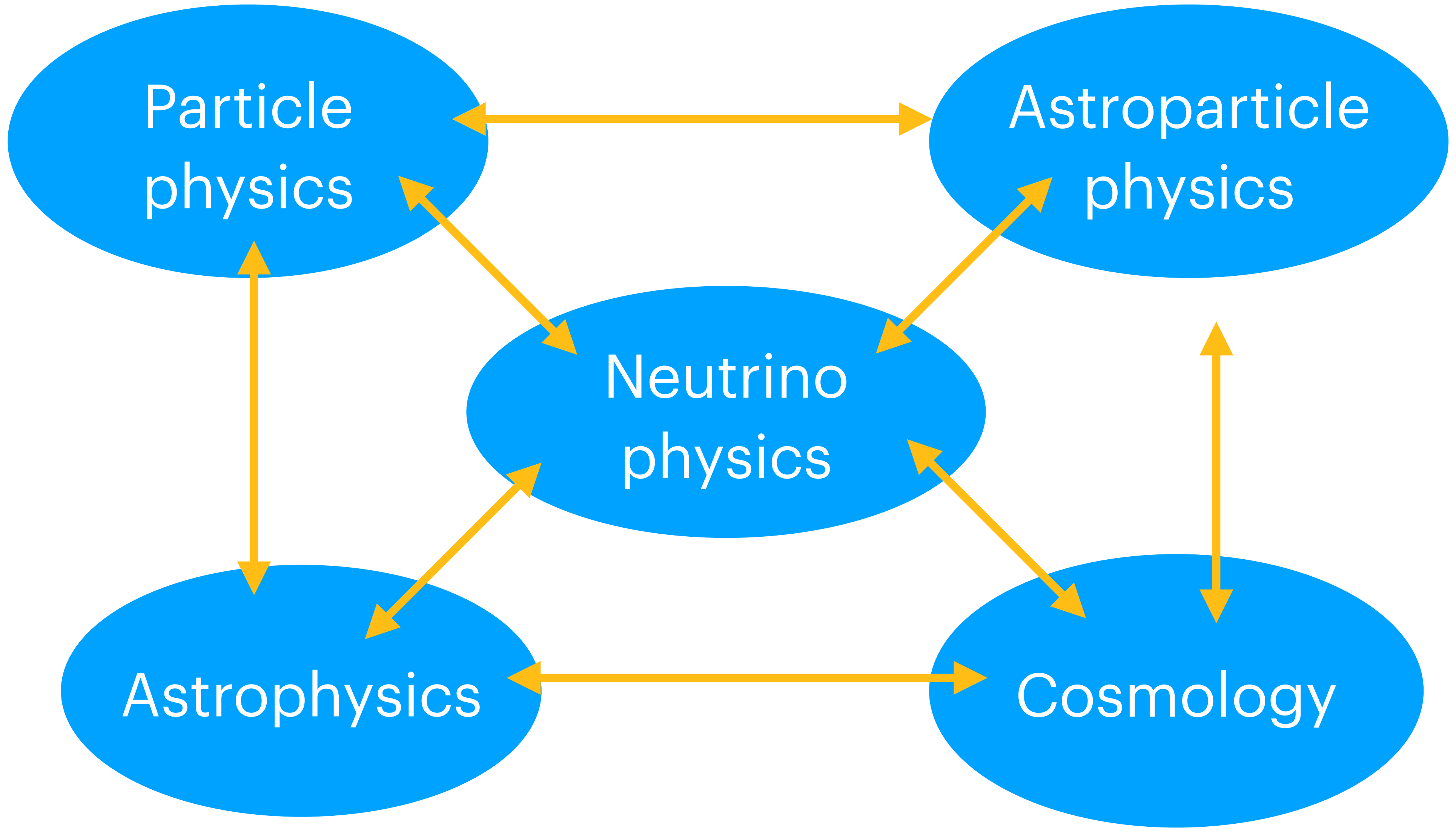
Neutrino flux from different sources



Caveat

Similar nonperturbative effects may occur in other analysis involving "low-energy" neutrinos

Neutrino physics: a truly multidisciplinary field



Nucleon sigma terms: QCD confinement & dark matter searches

Defined as $\sigma_{fN} = m_f \langle N | \bar{q}_f q_f | N \rangle$ they enter in:

- Nucleon mass decomposition: $$m_N = \langle \frac{\beta}{2g} F^2 + \sum_{f=u,d,s,c,b,t} (1+\gamma_m)\, m_f\, \bar{q}_f q_f \rangle_N$$

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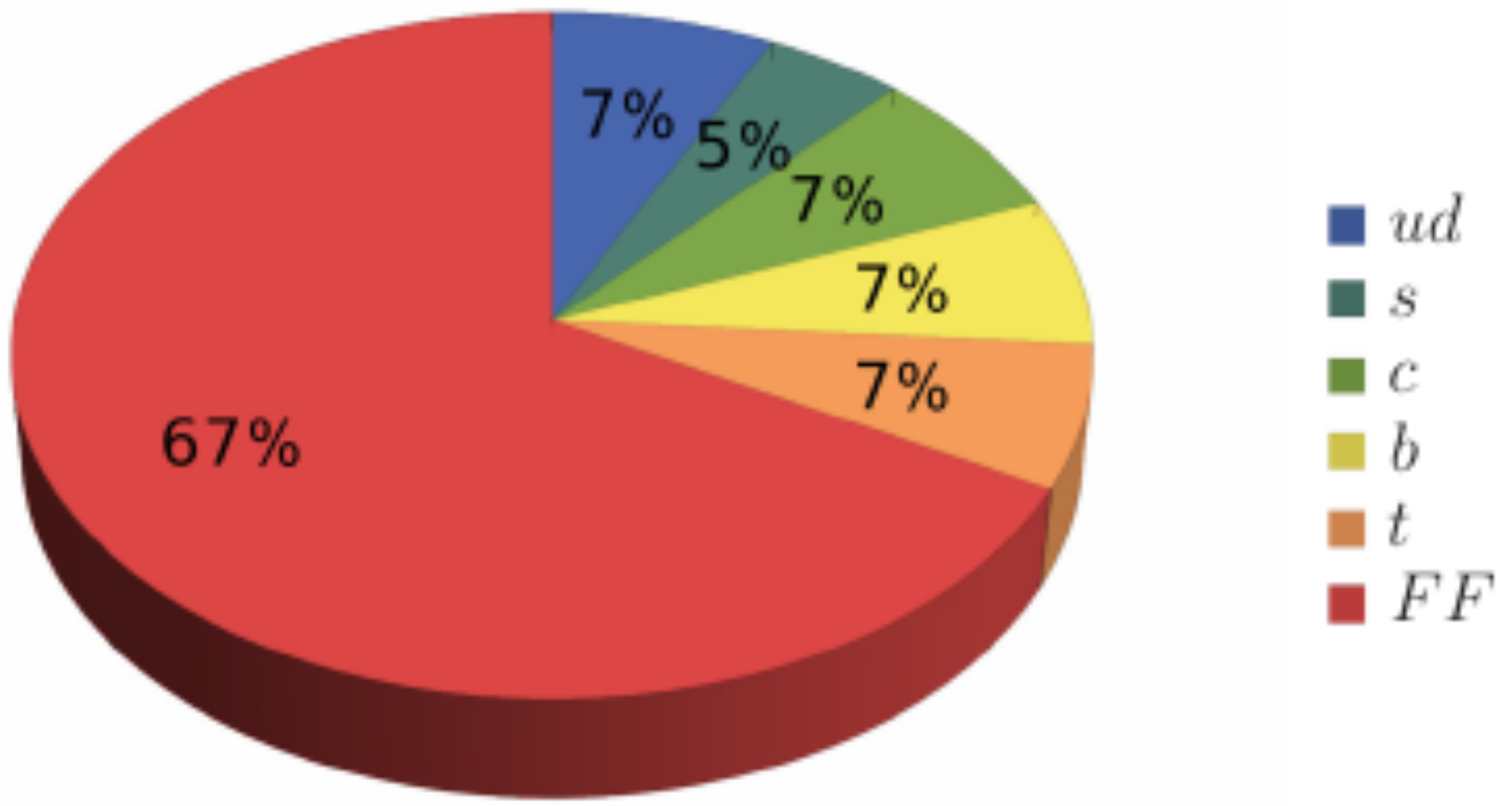
"Trace Anomaly" contribution

due to gluon dynamics

(67% of the total nucleon mass)



Nucleon mass decomposition

[M. Hoferichter, J. Ruiz de Elvira Encyclopedia of Particle Physics]

"Quark mass" contribution

(33% of the total nucleon mass)

Fun Fact

In the chiral limit ($m_f \rightarrow 0$)

Nucleons are still heavy

Nucleon sigma terms: QCD confinement & dark matter searches

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- BSM scenarios: WIMP, SUSY, …

$$\mathscr{L}_{\text{eff}} \supset \sum_q \frac{g_\chi g_q}{m_h^2} (\bar{\chi}\chi)(\bar{q}q)$$

Many dark-matter candidates (e.g. χ) interact with nucleons via the exchange of a scalar particle (e.g. H)

WIMP- nucleon scalar cross section

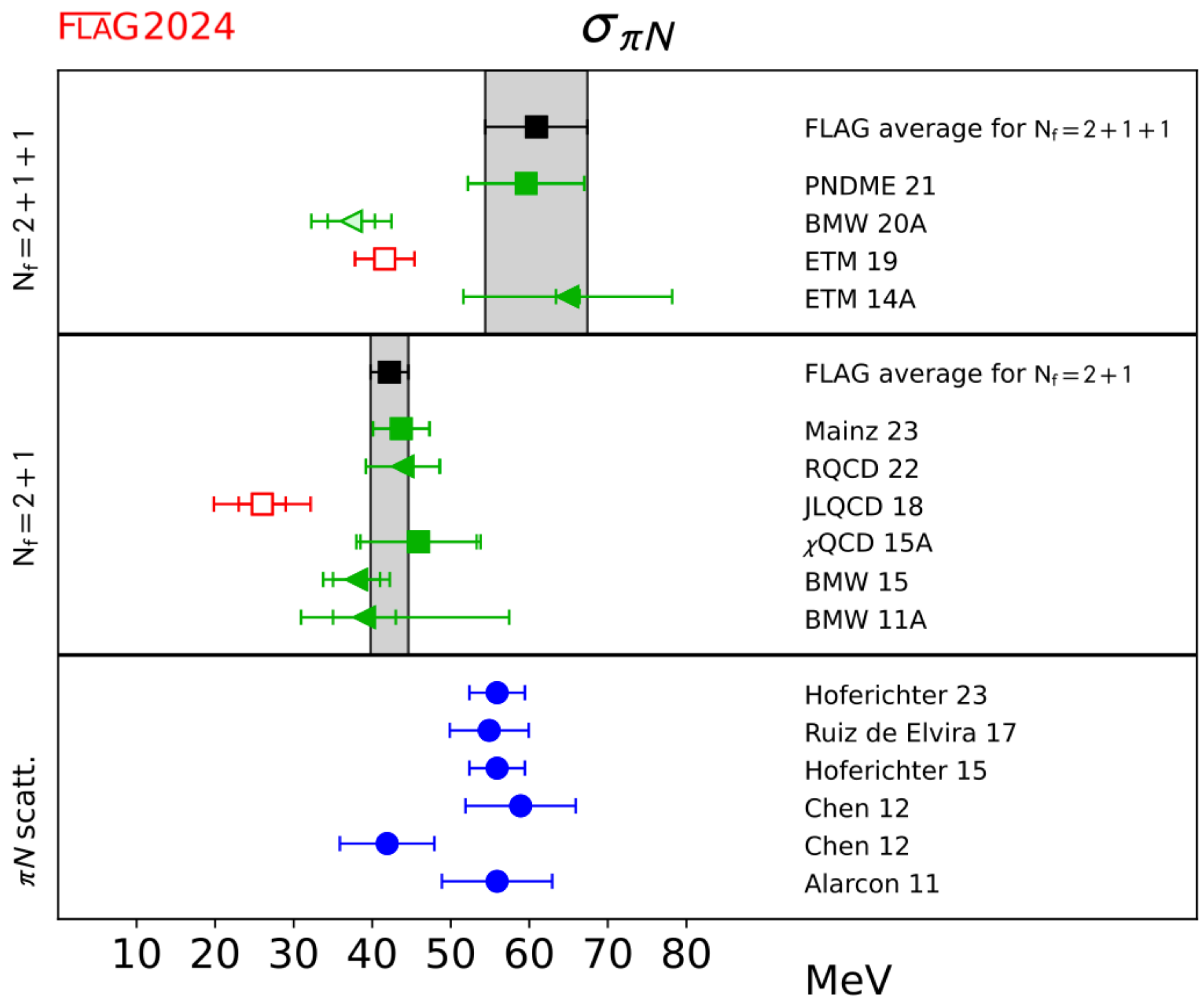
$\sigma^{SI} \propto |f_N|^2$ $\qquad f_N \propto \sigma_{fN}$

particle physics

$$\text{Flux } (\gamma, \nu) = \frac{1}{4\pi} \frac{(\sigma_{\text{ann}} v)}{2\, m_\chi^2} \times \sum_i \text{BR}_i \frac{dN_\gamma^i}{dE_\gamma} \times \text{cosmology}$$

[Talk by G. Zaharijas 06/10]

Nucleon sigma terms: QCD confinement & dark matter searches



$$\sigma_{fN} = m_f \langle N | \bar{q}_f q_f | N \rangle$$

$$\sigma_{\pi N} = \sigma_{uN} + \sigma_{dN}$$

Possible sources of uncontrolled systematic effects (lattice):

- Finite volume → Infinite Volume, continuum limit
- Physical quark mass extrapolation (arXiv:2508.11435)

(Need good EFT)

- Uncontrolled excited state effects

*[**LB**, et al., Phys.Rev.D 111 (2025) 3, L031505]*

*[**LB**, arXiv:2508.09006 (Letter to PRD)]*

Need to correctly account for excited state effects for reliable extraction of matrix elements.

Lattice QCD Hadron Structure Calculations: Basics

$$\langle \mathrm{O}'_N(t)\ \mathcal{J}(\tau)\ \bar{\mathrm{O}}_N(0)\rangle \ = \int [dU][dq][d\bar{q}]\frac{e^{-S_{QCD}}}{\mathcal{Z}_{QCD}}\ \mathrm{O}'_N(t)\ \mathcal{J}(\tau)\ \bar{\mathrm{O}}_N(0)$$

(Spectral decomposition) $$= \langle N'|\mathcal{J}|N\rangle\ A'_N A_N\ e^{-E'_N(t-\tau)}\ e^{-E_N\tau}$$

$$+ \sum_{i,f\neq N} \langle i|\mathcal{J}|f\rangle\ A'_f A_i\ e^{-E'_f(t-\tau)}\ e^{-E_i\tau}$$

High-dimensional integral
estimated via Monte Carlo sampling
using HPC on supercomputers

$\langle N'|\mathcal{J}|N\rangle$ can be extracted

For $t \gg \tau \gg 0$ $\ (E'_f, E_i > E'_N, E_N)$

Excited states are suppressed.

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$\langle N'|\mathcal{J}|N\rangle$ can be extracted

For $t \gg \tau \gg 0$ $(E'_f, E_i > E'_N, E_N)$

Excited states are suppressed.

At large t, τ, the statistical error grows (Lepage-Parisi)

Analysis is thus restricted to short t, τ

→

Contribution from excited states is large

And must be carefully accounted for.

Lattice QCD Hadron Structure Calculations: Variational method (GEVP)

Instead of using a single nucleon operator O_N $\quad \mathrm{O}_N|0\rangle = c_N|N\rangle + c_{N\pi}|N\pi\rangle + \ldots \quad \langle \mathrm{O}'_N(t)\ \mathcal{J}(\tau)\ \bar{\mathrm{O}}_N(0)\rangle$

construct a basis of operators with nucleon quantum numbers: $\mathrm{O}_i = \mathrm{O}_N, \mathrm{O}_{N\pi}, \ldots \quad \langle \mathrm{O}'_i(t)\ \mathcal{J}(\tau)\ \bar{\mathrm{O}}_j(0)\rangle$

diagonalise the system, and construct improved operators Ω_N s.t.

$$\langle \Omega'_N(t)\ \mathcal{J}(\tau)\ \bar{\Omega}_N(0)\rangle \;=\; \langle N'|\mathcal{J}|N\rangle\, A'_N A_N\, e^{-E'_N(t-\tau)}\, e^{-E_N\tau}$$

The variational approach allows us to extract also transition matrix elements like

$$\langle N\pi|\mathcal{J}|N\rangle, \qquad \langle \Delta(1232)|\mathcal{J}|N\rangle, \qquad \langle N^*(1440)|\mathcal{J}|N\rangle, \ldots$$

GEVP commonly used to study spectroscopy: *[J. Green talk 06/07, A. Stump poster]*

Lattice QCD Hadron Structure Calculations: Variational method (GEVP)

Applied successfully for different nucleon structure quantities: (Pilot studies at $m_\pi = 430$ MeV)

- [**LB**, et al., *PRD* 107 (2023) 5, L051505 (letter)] $O_N,\ O_{N\pi}$ $\langle N|\mathscr{A}_\mu|N\rangle,\ \langle N\pi|\mathscr{A}_\mu|N\rangle$
- [**LB**, et al., *PRD* 111 (2025) 3, L031505 (letter)] $O_N,\ O_{N\sigma}$ $\langle N|\mathscr{S}|N\rangle,$
- [**LB**, arXiv:2508.09006 (letter to PRD)] $O_N,\ O_{N\rho}$ $\langle N|\mathscr{V}_\mu|N\rangle$
- [**ETMc**, *PRD* 110 (2024) 9, 094514]

Found a **pattern** of current-enhanced excited states

- [**LB**, arXiv:2508.09006 (letter to PRD)]

and a formalism to explain such current-enhanced excited states with broad applications

→ Plenary talk at Lattice Conference 2025, TIFR, Mumbai, 2-8 November

Lattice QCD Hadron Structure Calculations: Plans for the future

Reliable physical point extrapolation of

- $\sigma_{\pi N}$ with O_N, $O_{N\sigma}$ ~3 years (very soon results at 220 MeV)
- $\langle N | \mathcal{J}_W | N \rangle$, $\langle N\pi | \mathcal{J}_W | N \rangle$, $\langle \Delta(1232) | \mathcal{J}_W | N \rangle$ with O_N, $O_{N\pi}$, O_Δ 5 - 7 years

Working in collaboration with researchers from U. Regensburg

Fermilab, Berkeley, Los Alamos

Many US institutions are very interested in this research (→DUNE, DM experiments)

Currently writing competitive grant applications for continuing this work.

More and more lattice groups will start using variational approach for hadron structure.

Conclusions.

What is the relevance of your research within your research field?

Very relevant. It has important implications in hadron structure calculations.

What is the relevance of your research for other fields?

Understanding the low-energy structure of nucleons is of high relevance for particle physics, astroparticle physics (DM searches, e.g. LUX-ZEPLIN, XENONnt, ...) and cosmology (matter-antimatter).

What methods are you using or developing that could be useful for others?

HPC on supercomputers, Monte Carlo sampling and variational analysis
for faster ground state convergence

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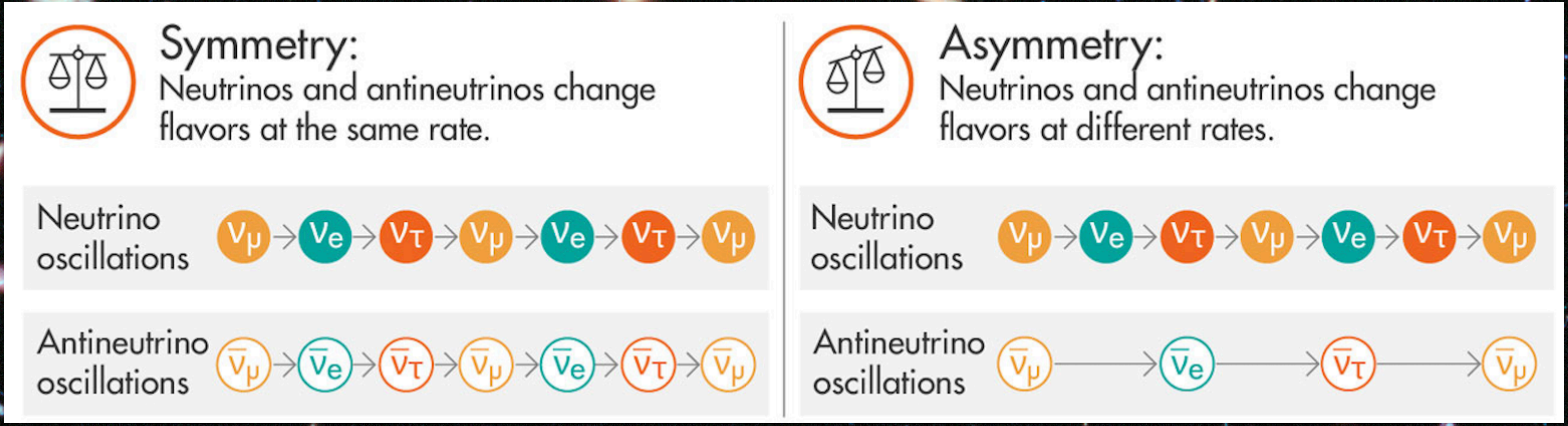
Thank you!

FOR 5269

Backup slides

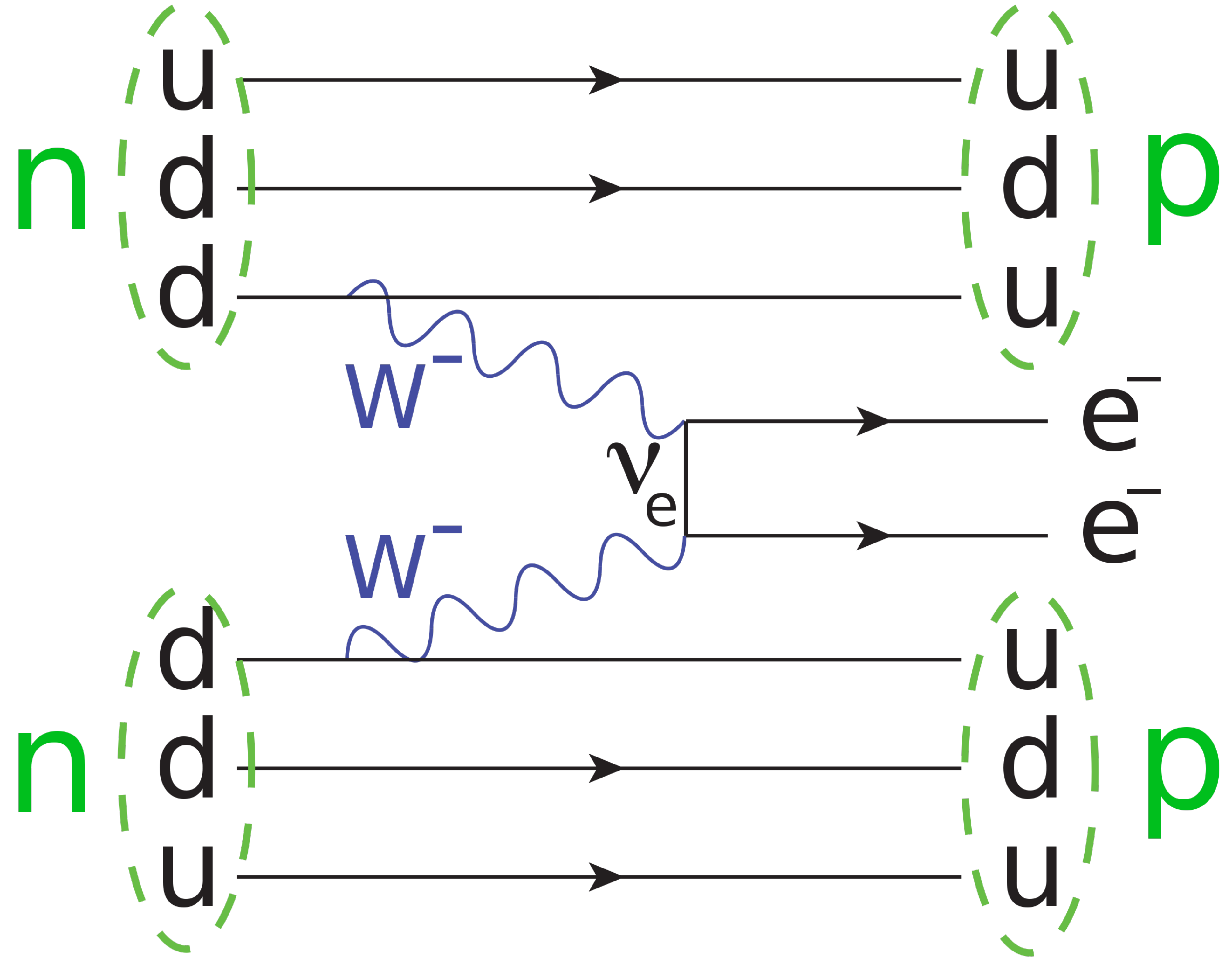
Imprints of baryon asymmetry in neutrino physics

Lepton asymmetry $\xrightarrow{\text{Spharelons}}$ Baryon asymmetry



Neutrinoless double beta-decay

$$(A, Z) \rightarrow (A, Z+2) \; + \; 2e^-$$



$$\Gamma^{0\nu}_{\beta\beta} = \frac{1}{T^{0\nu}_{\beta\beta}} \propto |M^{0\nu}|^2 \langle m_{\beta\beta} \rangle^2$$

$$\langle m_{\beta\beta} \rangle = \sum_i U^2_{ei} \, m_i$$

$M^{0\nu}$ **is the nuclear matrix element**

U_{ei} **is a PMNS matrix element**

Isotope ⬍	Experiment ⬍	lifetime $T^{0\nu}_{\beta\beta}$ [years] ⬍
^{48}Ca	ELEGANT-VI	$> 1.4 \cdot 10^{22}$
^{76}Ge	Heidelberg-Moscow[14]	$> 1.9 \cdot 10^{25}$ [14]
^{76}Ge	GERDA	$> 1.8 \cdot 10^{26}$ [15]
^{82}Se	NEMO-3	$> 1.0 \cdot 10^{23}$
^{82}Se	CUPID-0	$> 4.6 \cdot 10^{24}$ [16]
^{96}Zr	NEMO-3	$> 9.2 \cdot 10^{21}$
^{100}Mo	NEMO-3	$> 2.1 \cdot 10^{25}$
^{116}Cd	Solotvina	$> 1.7 \cdot 10^{23}$
^{130}Te	CUORE	$> 2.2 \cdot 10^{25}$
^{136}Xe	EXO	$> 3.5 \cdot 10^{25}$ [17]
^{136}Xe	KamLAND-Zen	$> 1.07 \cdot 10^{26}$ [18]
^{150}Nd	NEMO-3	$> 2.1 \cdot 10^{25}$

LQCD studies

Short & Long-distance

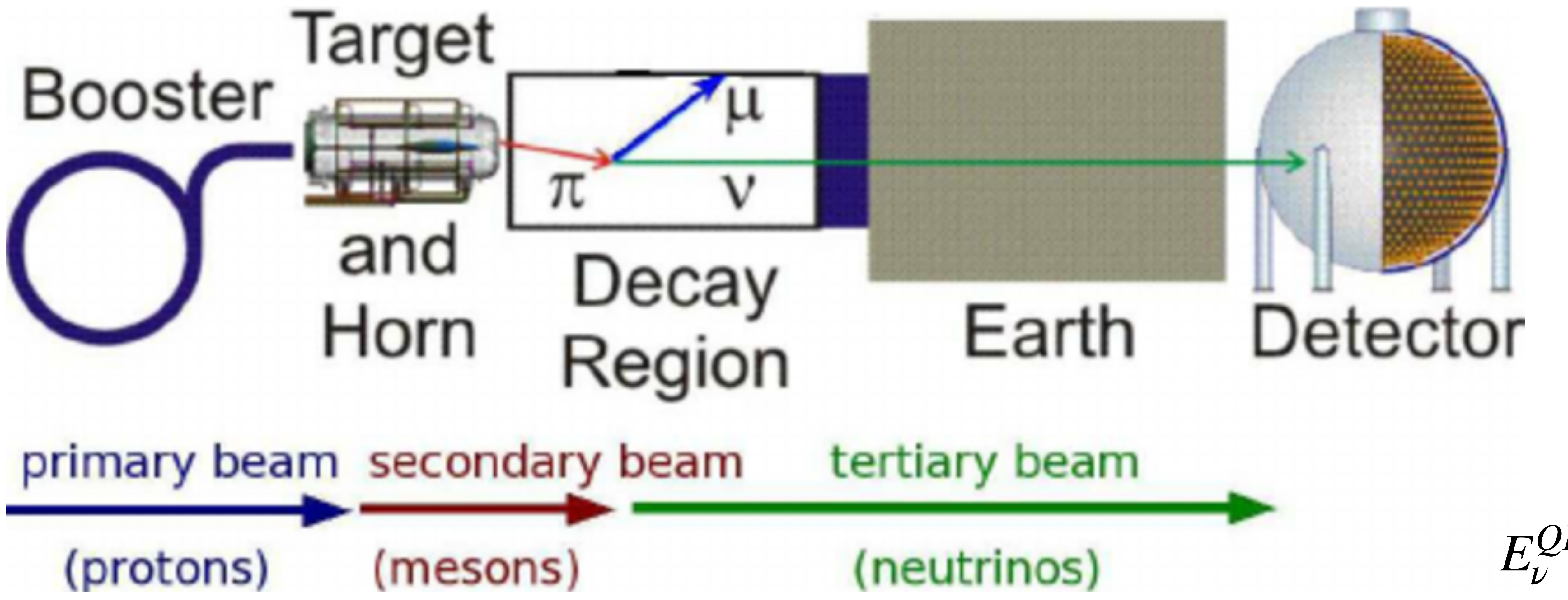
$\pi^- \rightarrow \pi^+ e^- e^-$

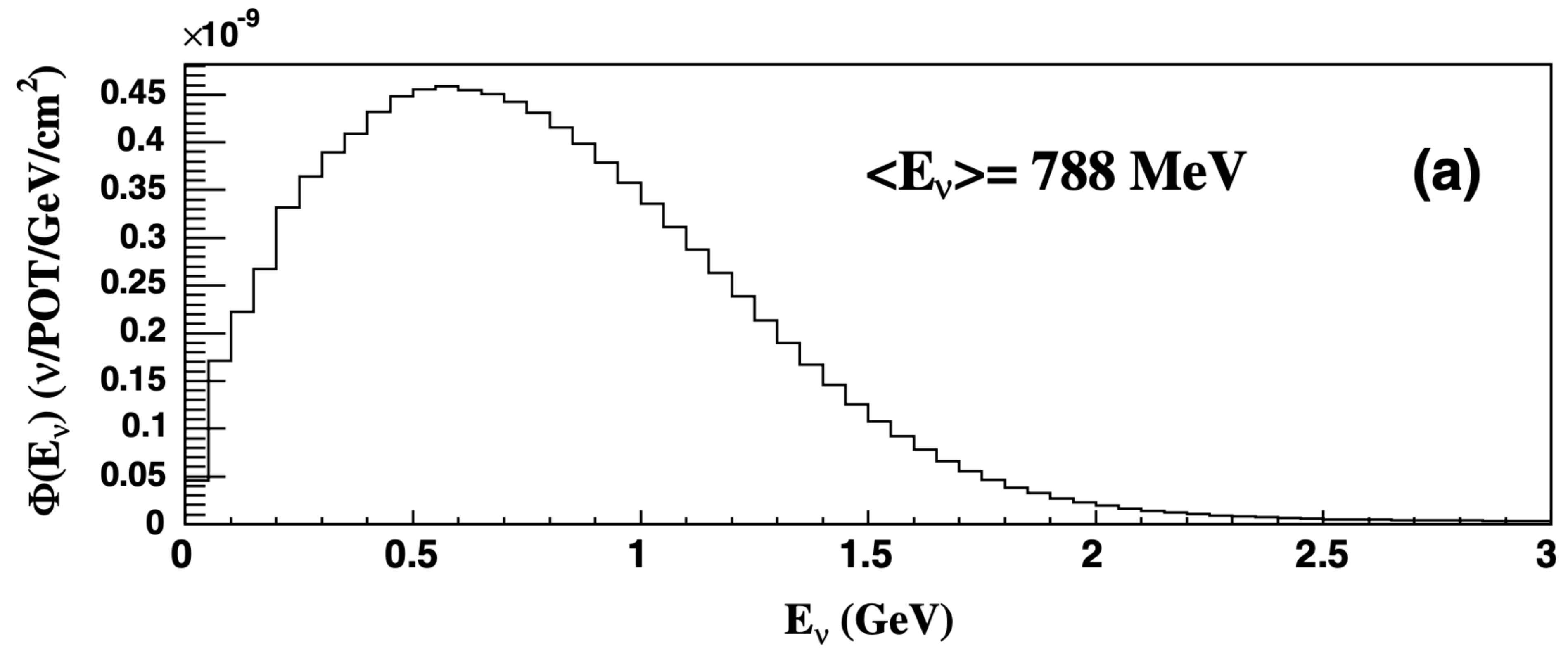
MIT, *Phys.Rev.D* 107 (2023) 9, 094501

NPLQCD Collab., *arXiv:2004.07404*

very rare process

MiniBooNE experiment





Predicted flux at the detector

$$E_\nu^{QE} = \frac{2M_N E_\mu - M_N^2 + m_\mu^2 + M_p^2}{2[M_N - E_\mu + cos\theta_\mu \sqrt{E_\mu^2 - m_\mu^2}]}$$

$M_N = M_n - E_b$ (Carbon binding energy)

Detector: spherical steel tank filled with 818 tons of mineral oil $(\mathrm{CH_2})$

Booster: proton beam is accelerated

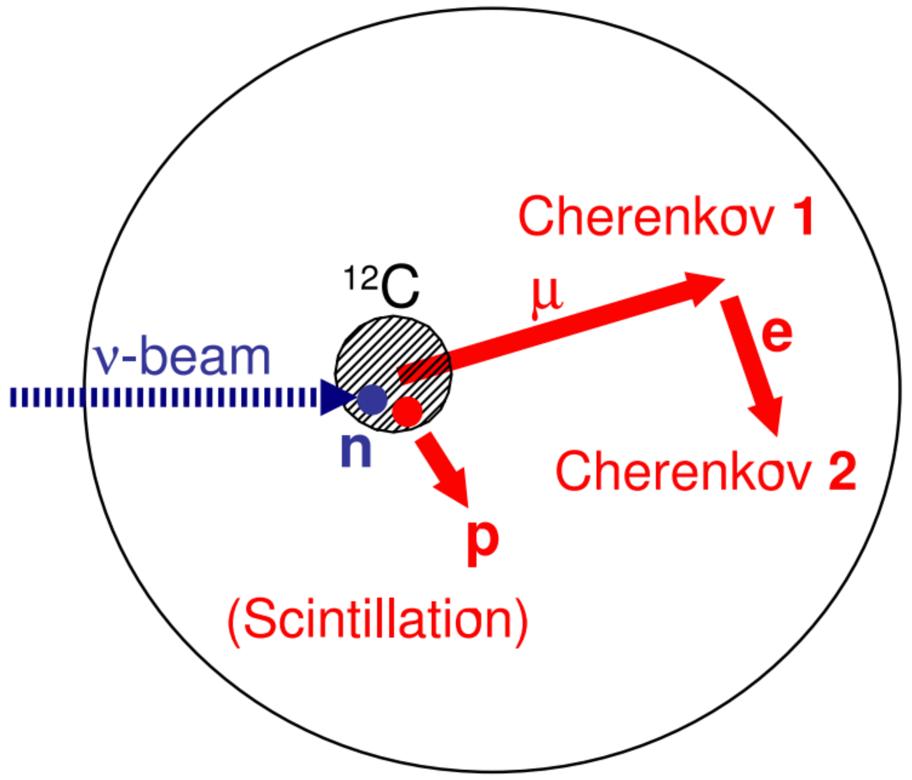
Target: proton beam scatters off a target, producing a meson beam

Mesons' decay: (muon) neutrino beam is produced $\pi^+ \to \mu^+ + \nu_\mu$

Earth: neutrino beam travels a length $L \approx 450\mathrm{m}$

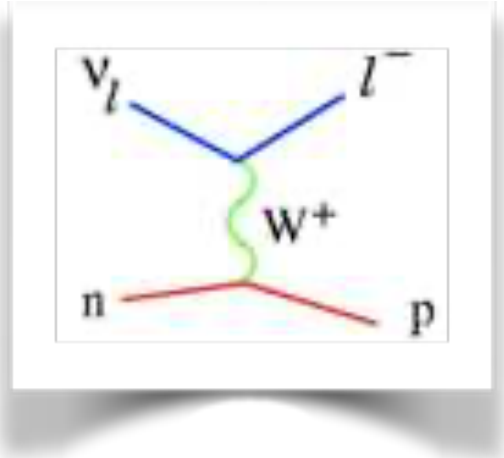
Detector: muons are produced and accelerated in matter $\nu_\mu + n \to \mu^- + p$

—> Cherenkov light (refractive index) $n = \frac{c}{v} = 1.47$ —> Cherenkov threshold: $\beta = \frac{v}{c} > 0.68$

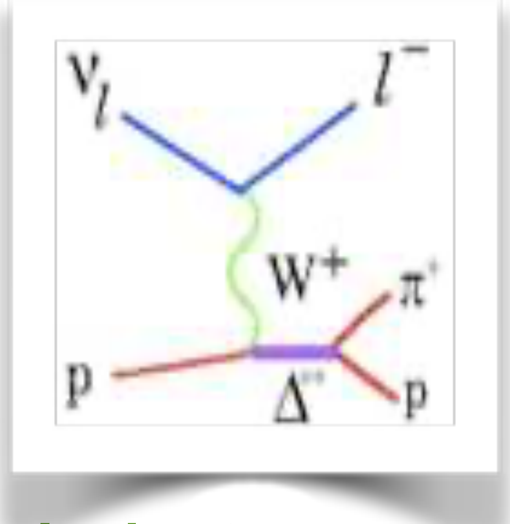


CCQE interaction at the MiniBoone detector

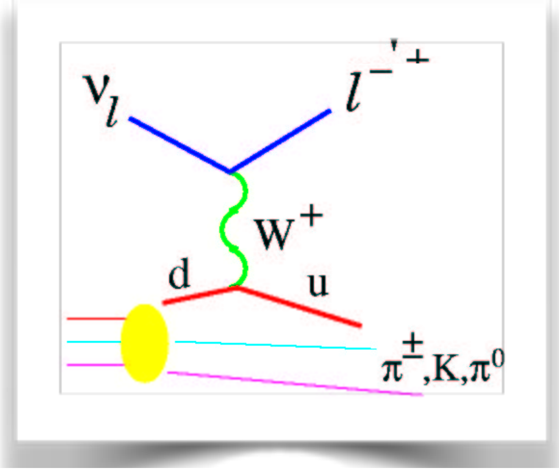
Quasi-elastic scattering (QE)

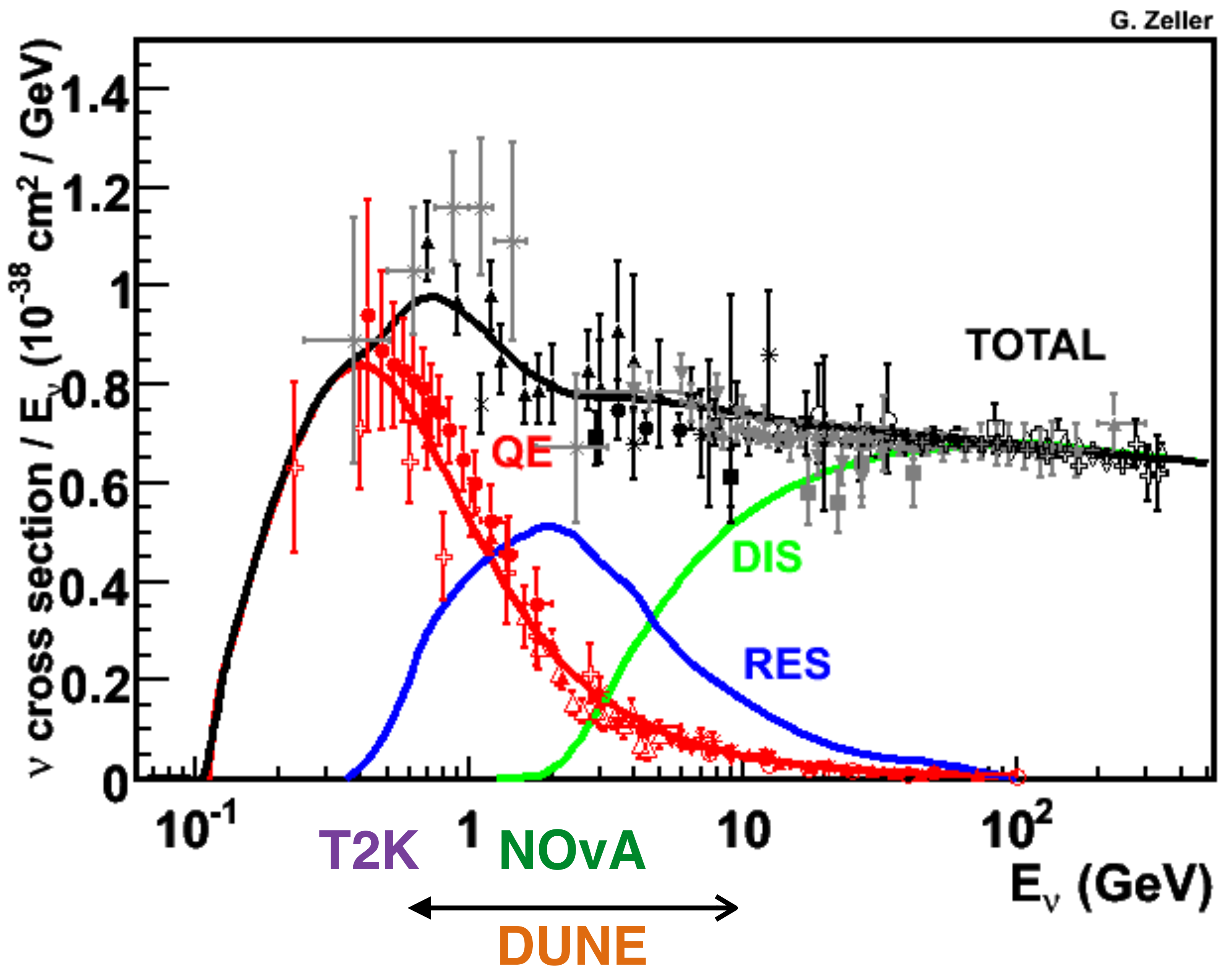


Resonance production (RES)



Deep Inelastic scattering (DIS)





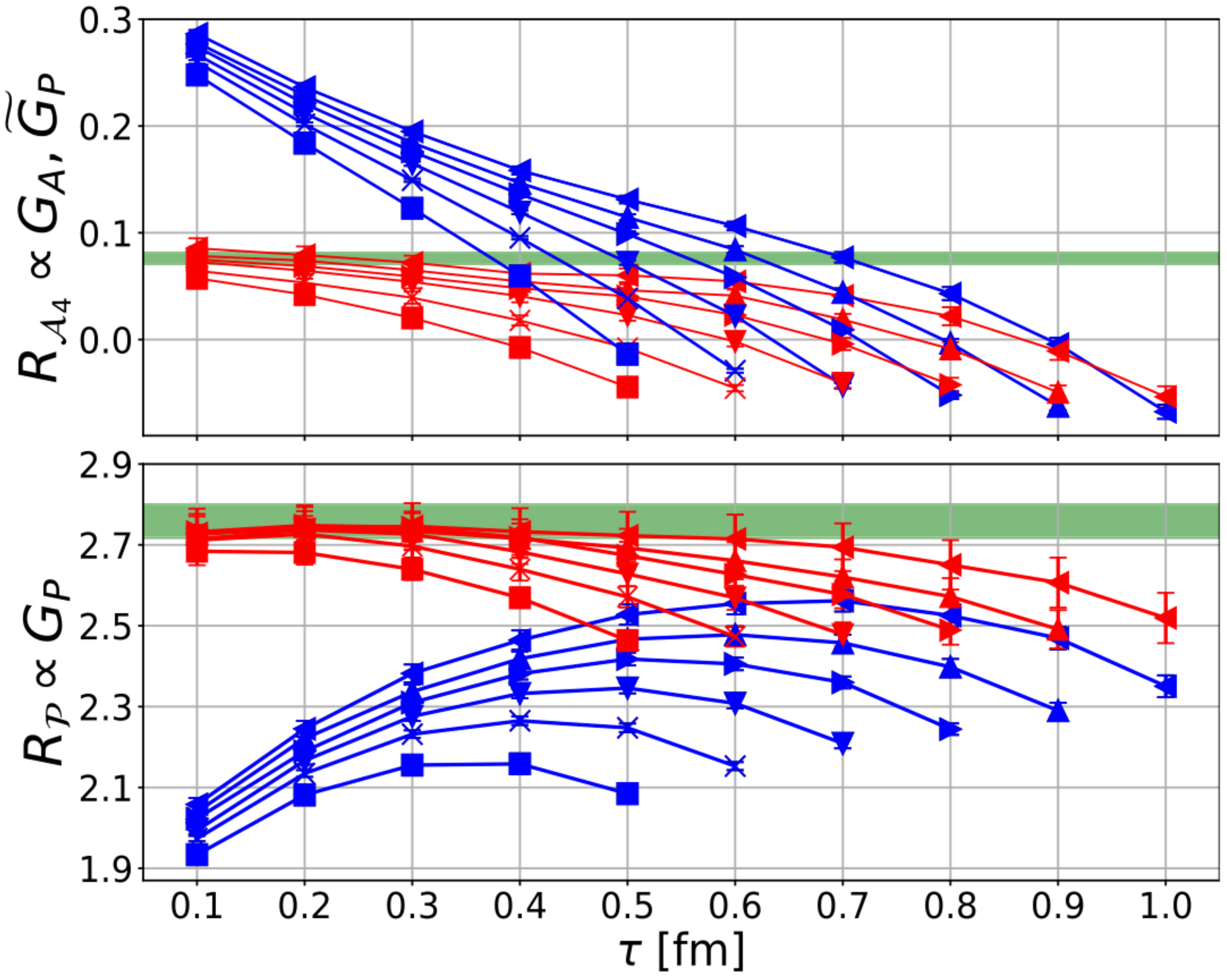
J.A. Formaggio, G. Zeller, Reviews of Modern Physics, 84 (2012)

[arXiv:2203.09030]

neutrino process	abbreviation	reaction	fraction (%)
CC quasielastic	CCQE	$\nu_\mu + n \to \mu^- + p$	39
NC elastic	NCE	$\nu_\mu + p(n) \to \nu_\mu + p(n)$	16
CC $1\pi^+$ production	CC$1\pi^+$	$\nu_\mu + p(n) \to \mu^- + \pi^+ + p(n)$	25
CC $1\pi^0$ production	CC$1\pi^0$	$\nu_\mu + n \to \mu^- + \pi^0 + p$	4
NC $1\pi^\pm$ production	NC$1\pi^\pm$	$\nu_\mu + p(n) \to \nu_\mu + \pi^+(\pi^-) + n(p)$	4
NC $1\pi^0$ production	NC$1\pi^0$	$\nu_\mu + p(n) \to \nu_\mu + \pi^0 + p(n)$	8
multi pion production, DIS, etc.	other	$\nu_\mu + p(n) \to \mu^- + N\pi^\pm + X$, etc.	4

[PRD.81.092005]

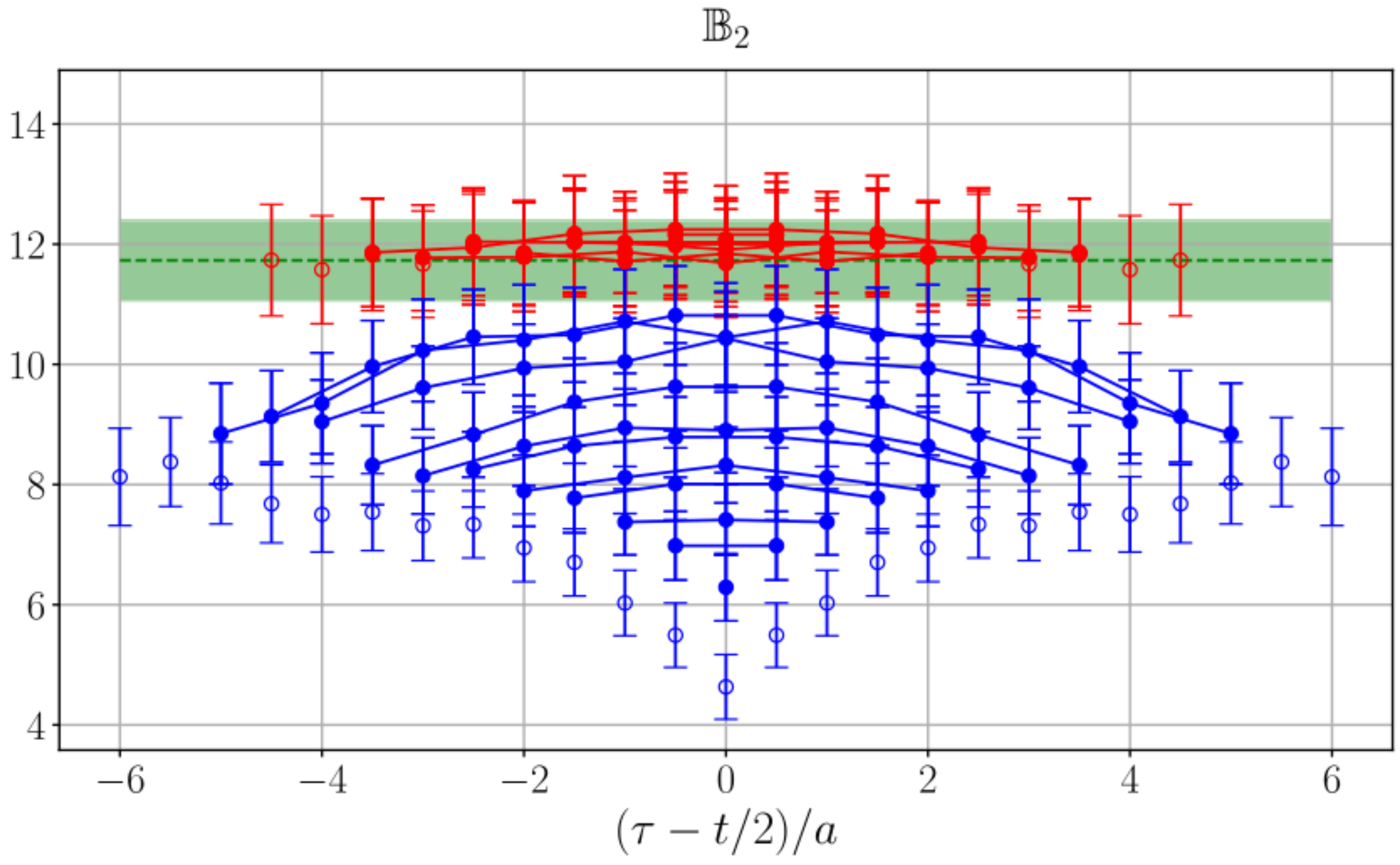
Examples: Excited states for Nucleon weak matrix elements



Data should be constant in τ if no excited states contribute

Red data are with GEVP

Examples: Excited states for Nucleon scalar matrix elements

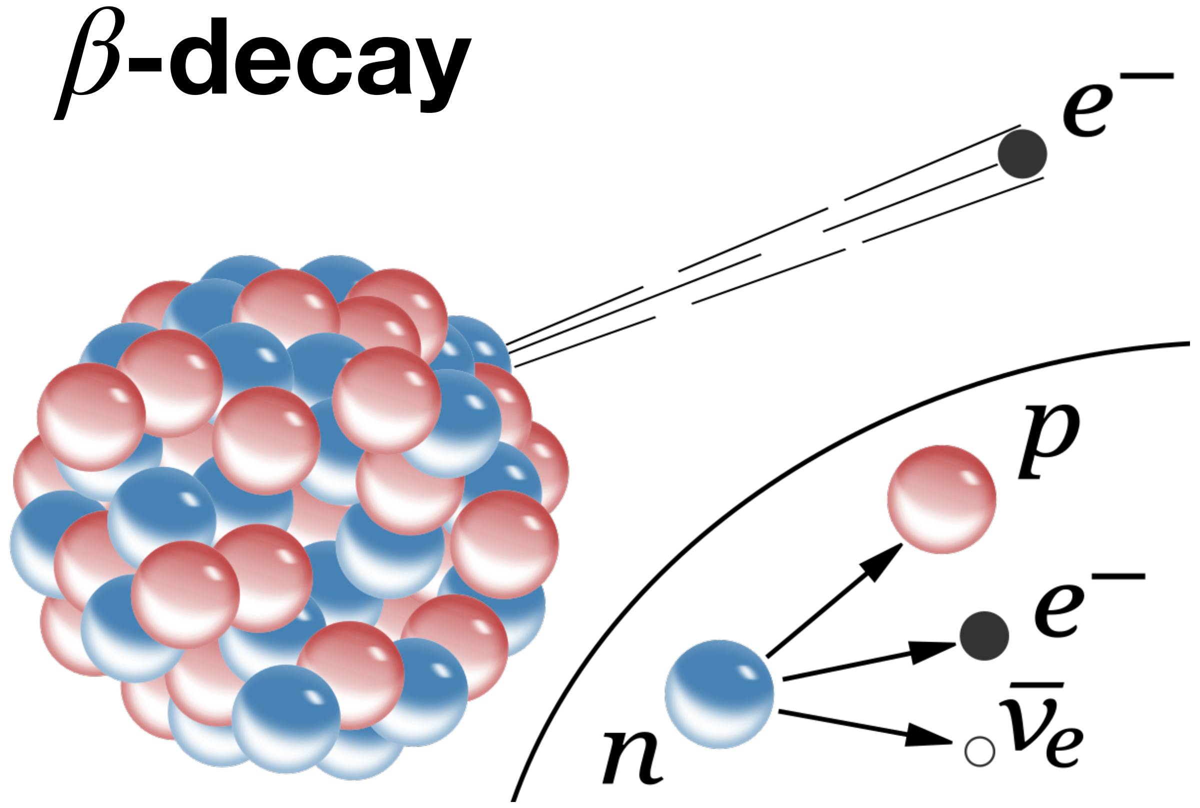


Great improvement after GEVP.

Weak Nucleon Structure

Weak Form Factors $G_A(Q^2),\ \widetilde{G}_P(Q^2),\ F_1^W(Q^2),\ F_2^W(Q^2)$

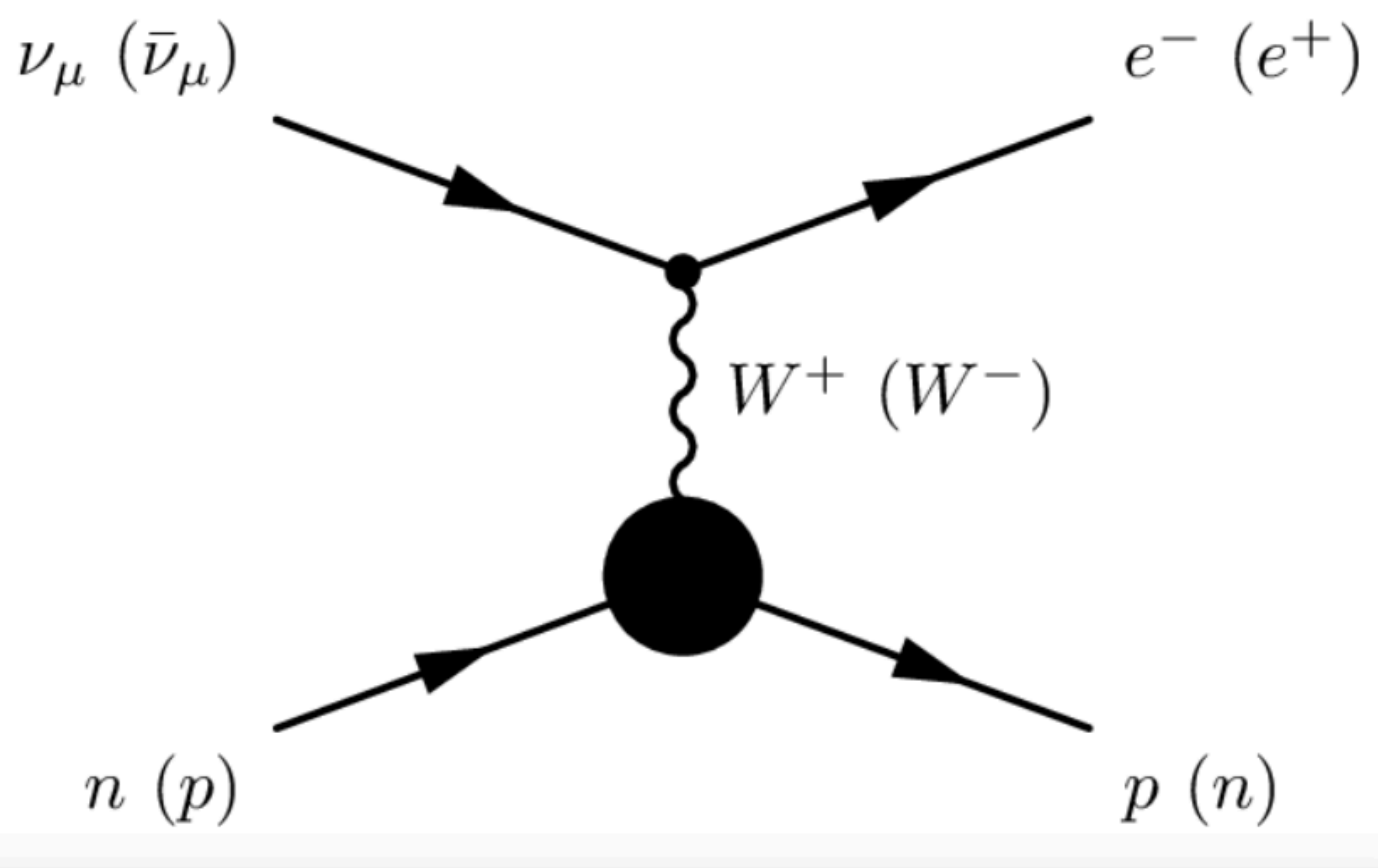
β-decay



Weak interactions mediated by Vector - Axial currents

Decay Rate : $\Gamma \propto G_A(Q^2=0),\ F_1^W(Q^2=0)$

$\nu - N$ scattering (CC)



$$\frac{d\sigma^{(\nu p,\bar{\nu}p)}}{dQ^2} = \frac{G_F m^2}{8\pi E_\nu}\left[A(Q^2) \mp B(Q^2)\frac{(s-u)}{m^2} + C(Q^2)\frac{(s-u)^2}{m^4}\right]$$

$$A(Q^2), B(Q^2), C(Q^2)\ \propto\ G_A(Q^2),\ \widetilde{G}_P(Q^2),\ F_1^W(Q^2),\ F_2^W(Q^2)$$

"Axial Structure of the Nucleon" [V. Bernard, L. Elouadrhiri, U. Meißner]

Lorentz decomposition of nucleon matrix elements

$$\langle N(\mathbf{p}') | \mathcal{J}(\mathbf{q}) | N(\mathbf{p}) \rangle = \bar{u}_{\mathbf{p}'}\, FF[\mathcal{J}]\, u_{\mathbf{p}}$$

$$\frac{d\sigma^{(\nu N)}}{dQ^2} \propto |\langle N | \mathcal{J}^- | N \rangle|^2$$

$\mathcal{J} = \bar{q}\Gamma q \qquad \Gamma \in \{\gamma_5,\, \gamma_\mu,\, \gamma_\mu\gamma_5\}$

$FF[\mathcal{J}]$ = Lorentz decomposition of the nucleon matrix element in terms of nucleon form factors $G(Q^2)$

Pseudoscalar $\quad \Gamma = \gamma_5 \;:\; \mathcal{J} = \mathcal{P}$

$$\langle N(\mathbf{p}') | \mathcal{P}(\mathbf{q}) | N(\mathbf{p}) \rangle = \bar{u}_{\mathbf{p}'}\, \gamma_5 G_P(Q^2)\, u_{\mathbf{p}}$$

Axial $\quad \Gamma = \gamma_\mu\gamma_5 \;:\; \mathcal{J} = \mathcal{A}_\mu$

$$\langle N(\mathbf{p}') | \mathcal{A}_\mu(\mathbf{q}) | N(\mathbf{p}) \rangle = \bar{u}_{\mathbf{p}'} \left[\gamma_\mu\gamma_5 G_A(Q^2) + \frac{q_\mu}{2m_N}\gamma_5 \widetilde{G}_P(Q^2) \right] u_{\mathbf{p}}$$

$g_A \equiv G_A(0)$

Axial charge

Vector $\quad \Gamma = \gamma_\mu \;:\; \mathcal{J} = \mathcal{V}_\mu$

$$\langle N(\mathbf{p}') | \mathcal{V}_\mu(\mathbf{q}) | N(\mathbf{p}) \rangle = \bar{u}_{\mathbf{p}'} \left[\gamma_\mu F_1(Q^2) + \frac{i\sigma_{\mu\nu}q_\nu}{2m_N} F_2(Q^2) \right] u_{\mathbf{p}}$$