12 April, 2026

第十八届粒子物理、
核物理和宇宙学交叉学科前沿问题研讨
桂林市

Radiative corrections to inverse beta decay

O.T., arXiv:2512.07956, arXiv:2512.07957, arXiv:2604.07113

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托马拉克
Sasha Tomalak

PMNS oscillation matrix

neutrinos produced and detected in flavor basis

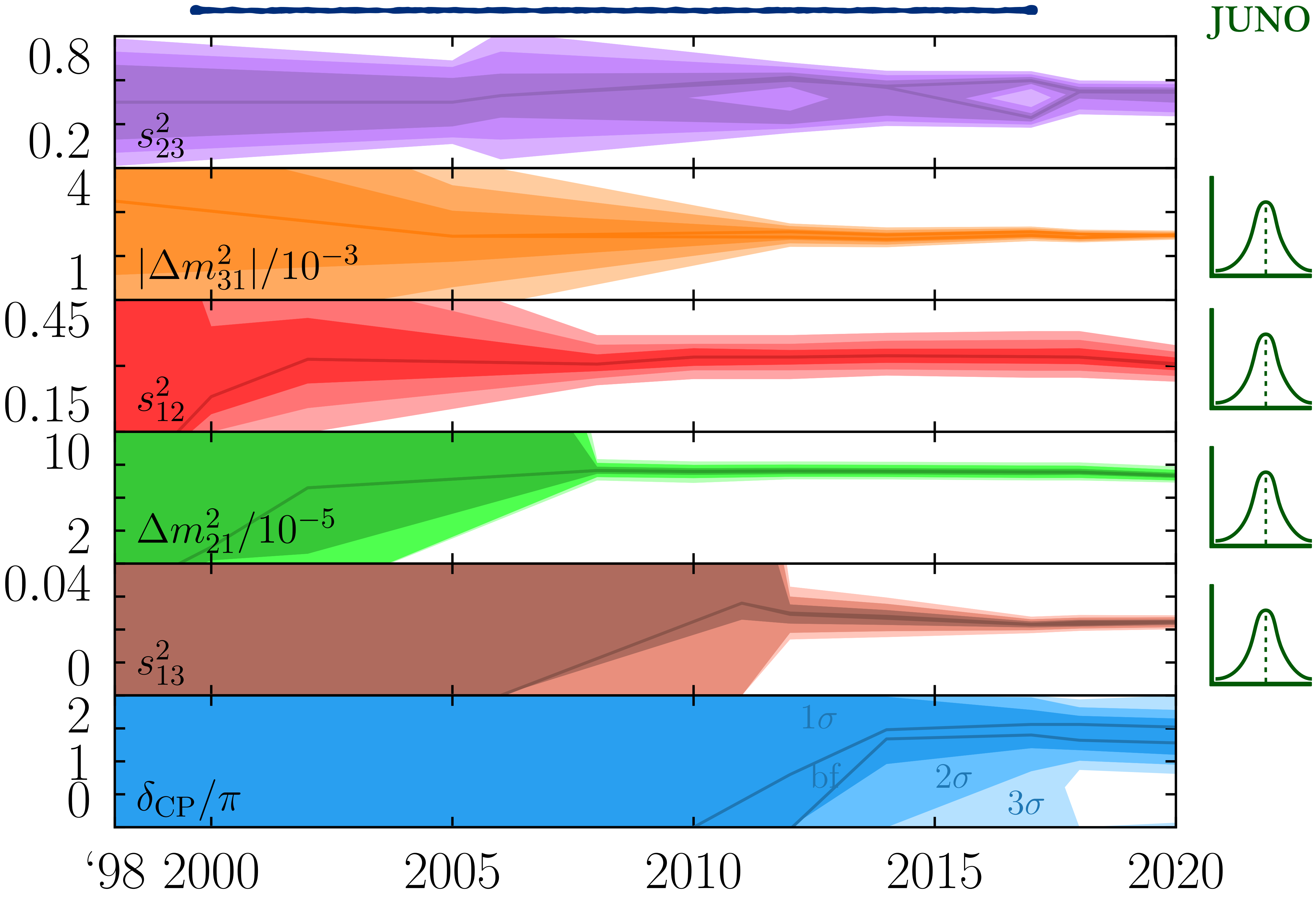
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

neutrinos propagate in mass basis

Pontecorvo-Maki-Nakagawa-Sakata matrix relates two bases

- oscillations are described by PMNS mixing matrix

PMNS oscillation matrix

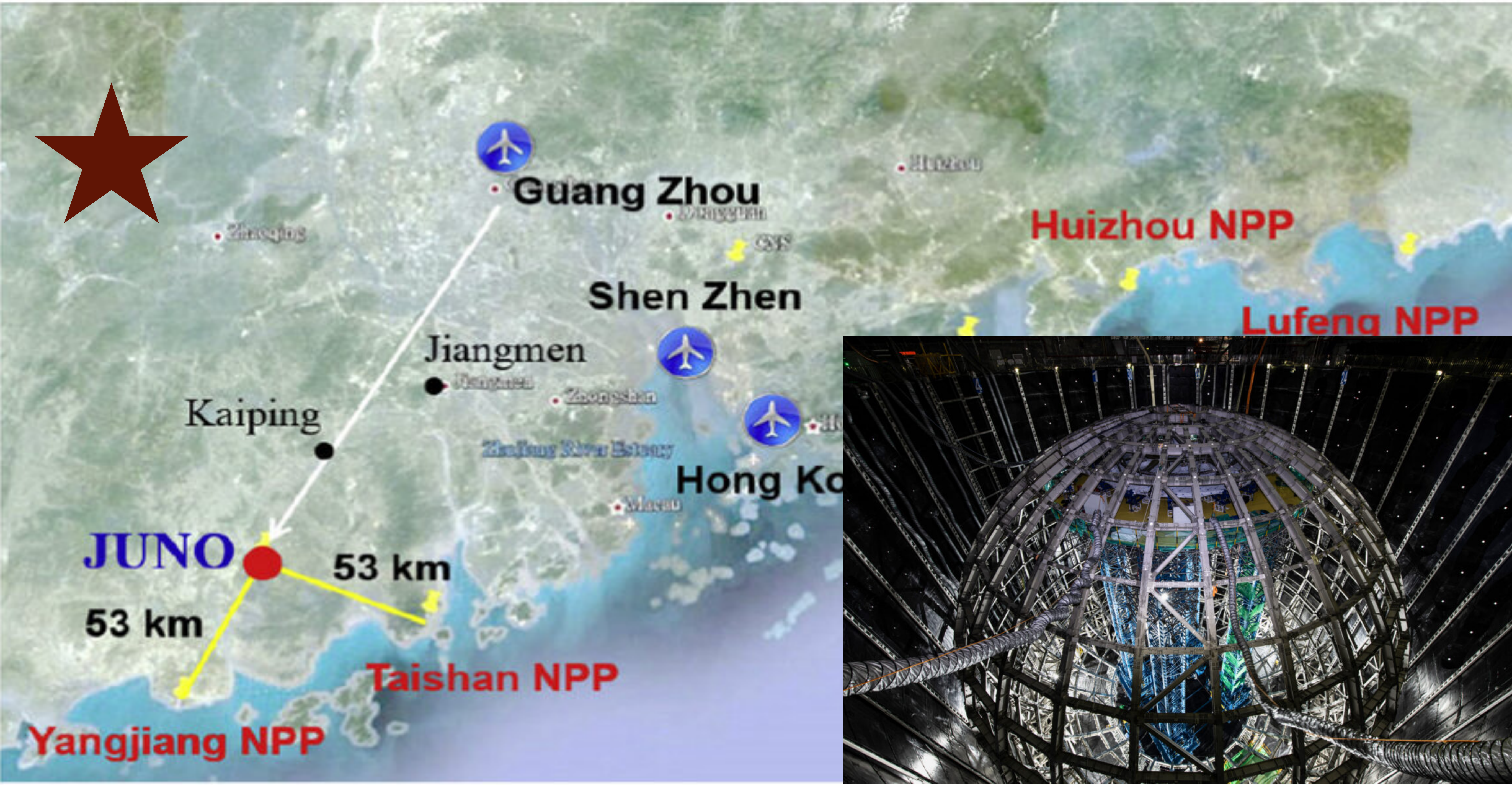


Snowmass 2021 NF01 group report

- tremendous progress in our lifetime

CP violation and mass hierarchy@laboratory

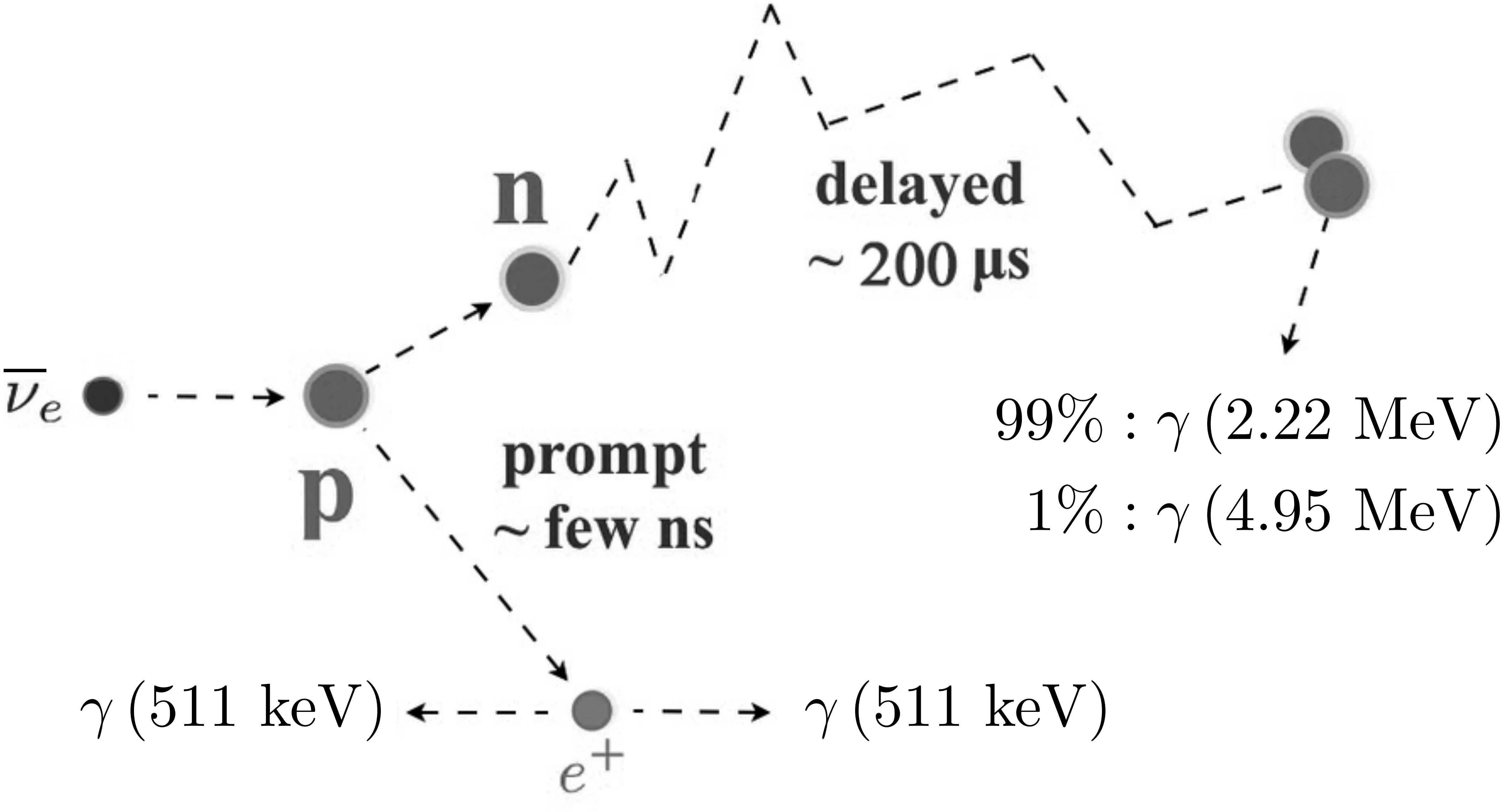
3σ determination of mass hierarchy



- 4 precise oscillation parameters from JUNO !!!

35 m, 20000 t

JUNO detection channel



$99\% : \gamma\,(2.22\ \mathrm{MeV})$

$1\% : \gamma\,(4.95\ \mathrm{MeV})$

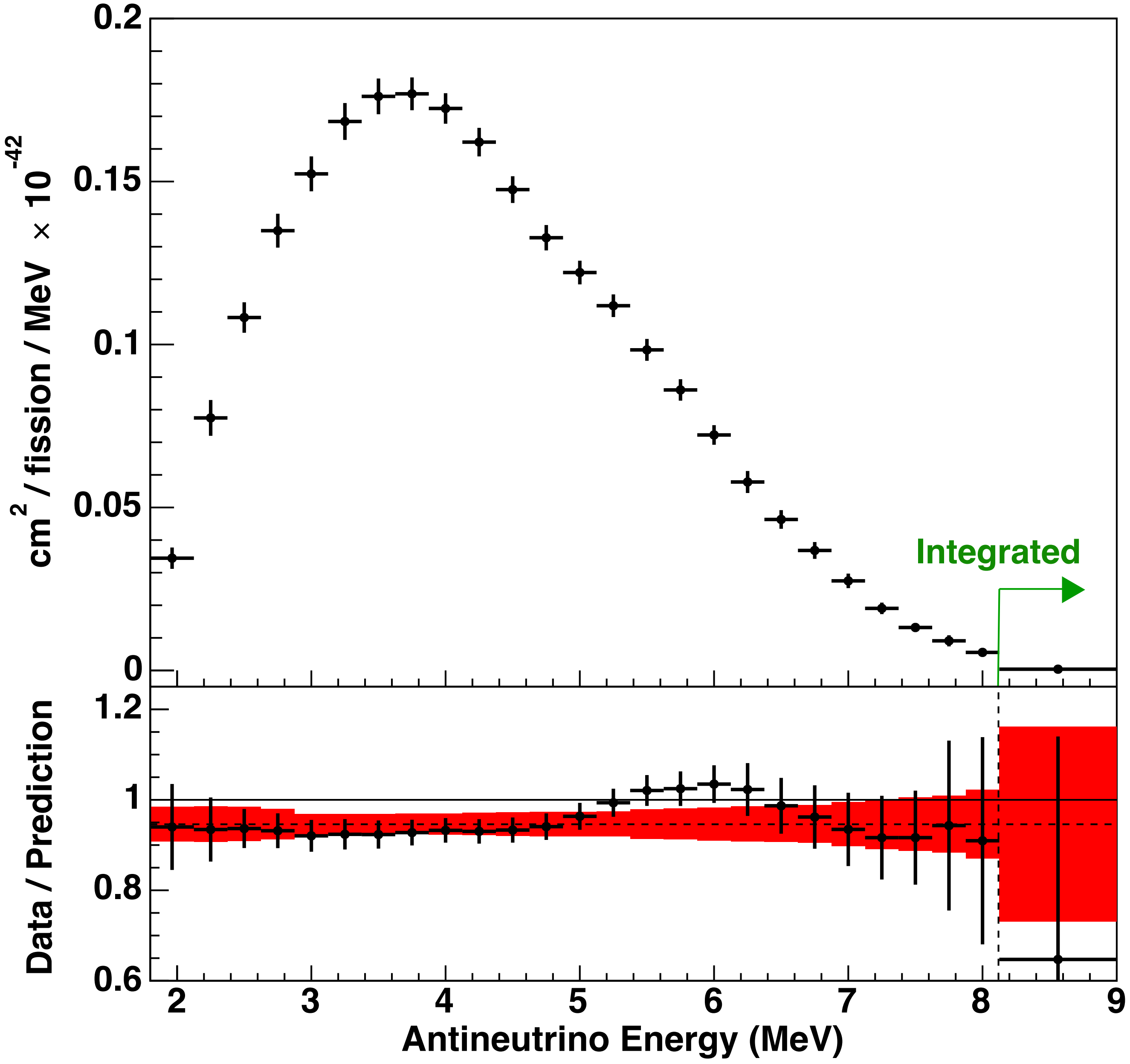
$\gamma\,(511\ \mathrm{keV})$ $\gamma\,(511\ \mathrm{keV})$

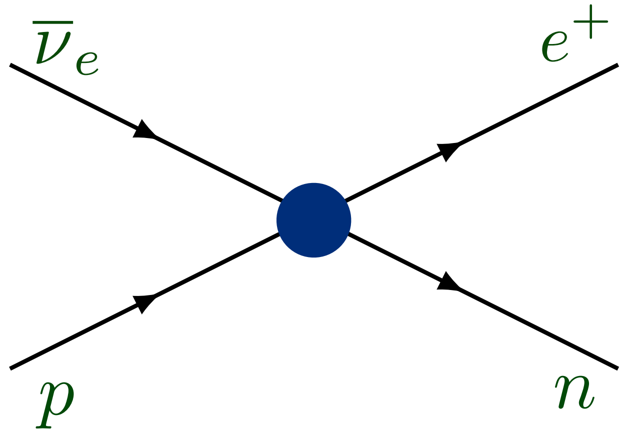
Teng Li et al., ChPC (2017)

- prompt-delayed time signature: background discrimination

IBD with reactor antineutrinos

- neutron is heavier than proton by 1.3 MeV



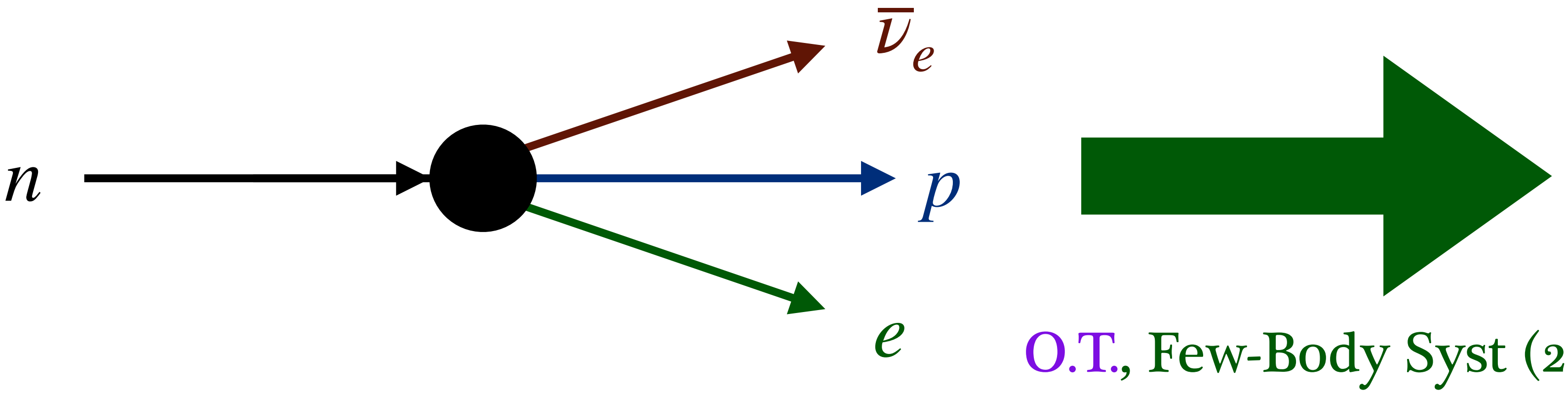


Daya Bay, PRL (2016)

- MeV-scale physics like in neutron decay

Complete EFT approach

- neutron measurements for inverse beta decay



O.T., Few-Body Syst (2023)

Vincenzo Cirigliano, Wouter Dekens, Emanuele Mereghetti, and O.T., PRD (2023) and PRD (2025)

- four-fermion interaction between leptons and heavy nucleons

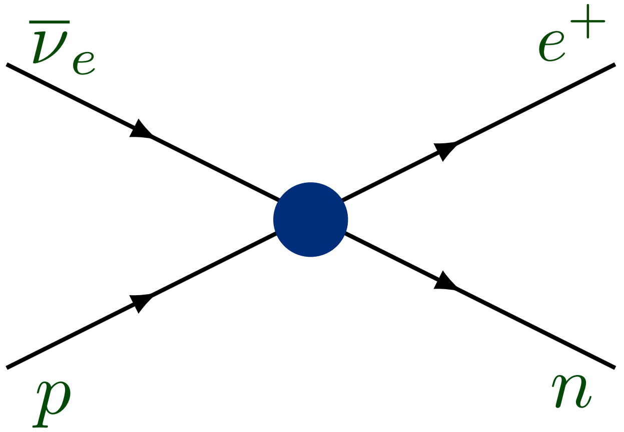
$$\mathcal{L}_{\text{eff}} = -\sqrt{2} \mathrm{G_F} V_{ud} \bar{e} \gamma_\mu \mathrm{P_L} \nu_e \cdot \overline{N} \left(g_V v^\mu - 2 g_A S^\mu \right) \tau^+ N$$

g_V : theoretical prediction from Standard Model

g_A : beta asymmetry in polarized neutron decay

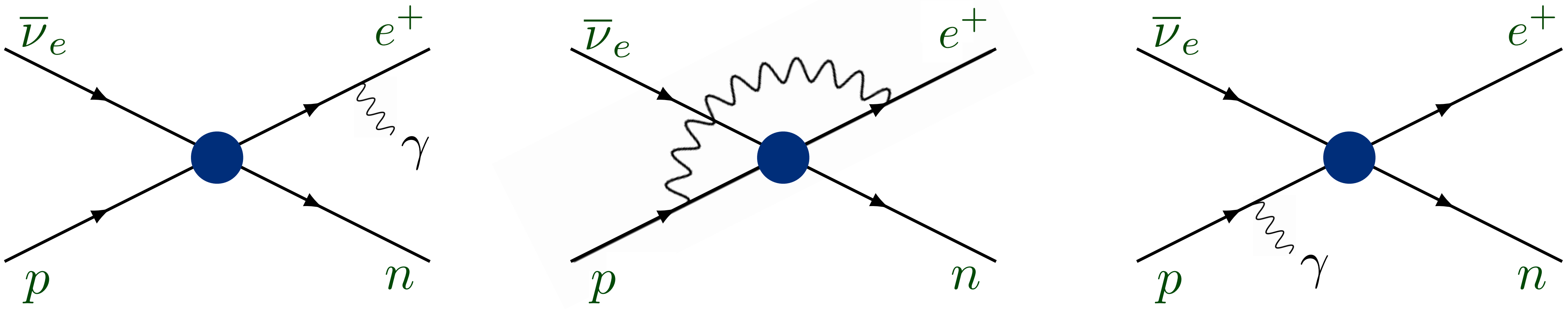
V_{ud}: superallowed transitions

- first consistent at 0.1%-level QED radiative corrections

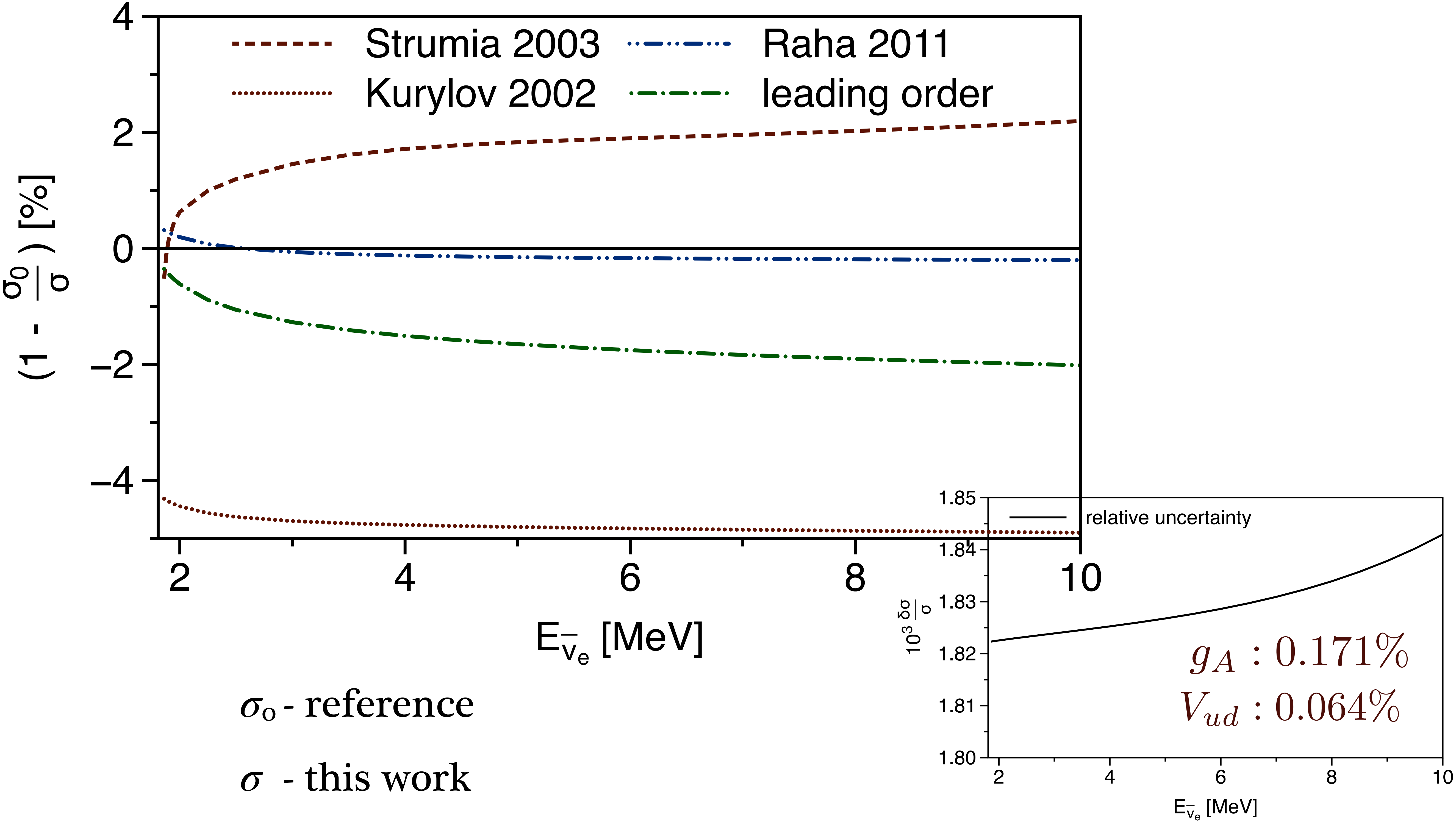


O.T., arXiv:2512.07956
arXiv:2512.07957

Theory of inverse beta decay for reactor antineutrinos



Total cross section



g_A : 0.171%

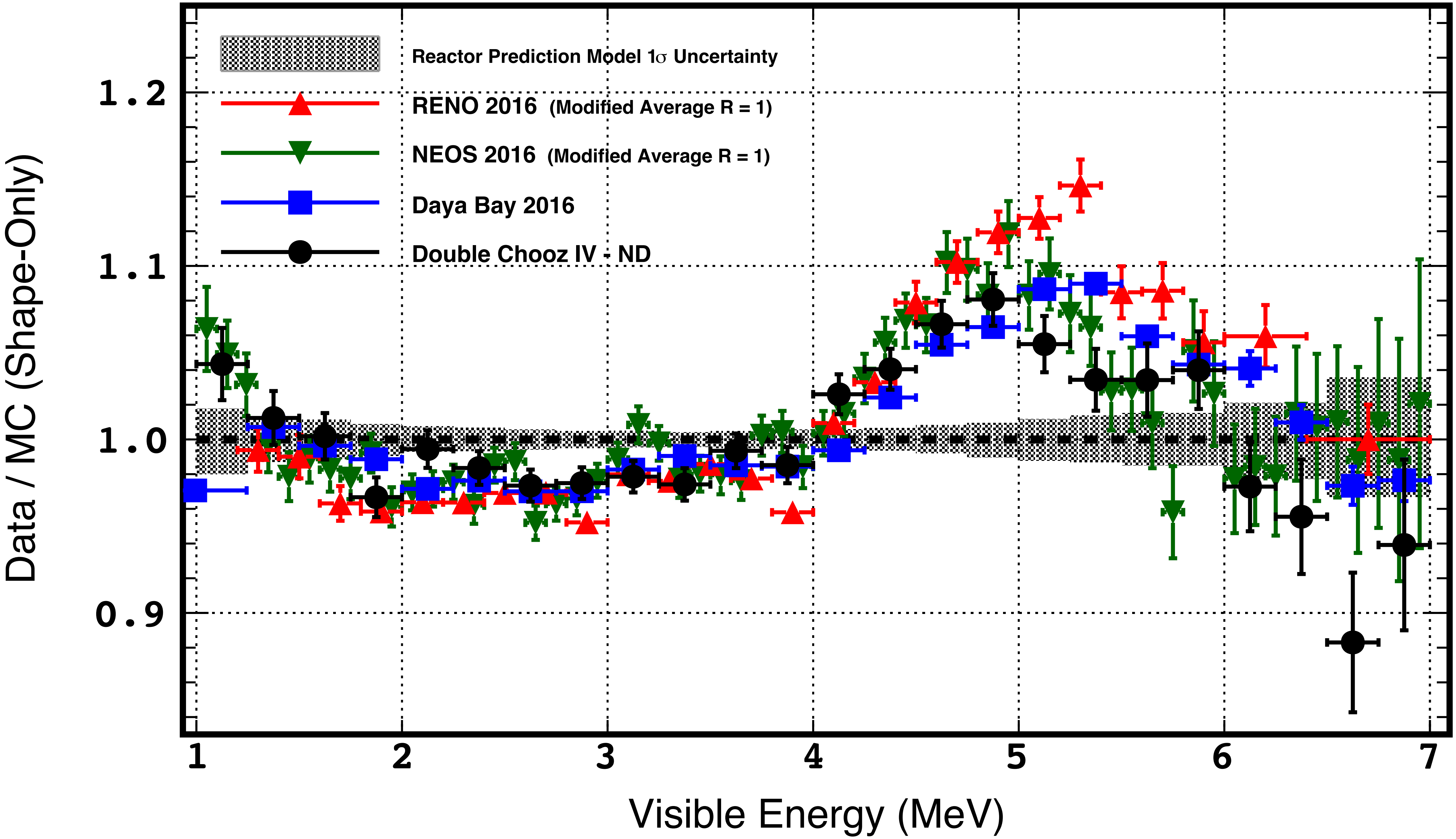
V_{ud} : 0.064%

σ_0 - reference

σ - this work

- %-level improvement to previous results; 0.18% uncertainty

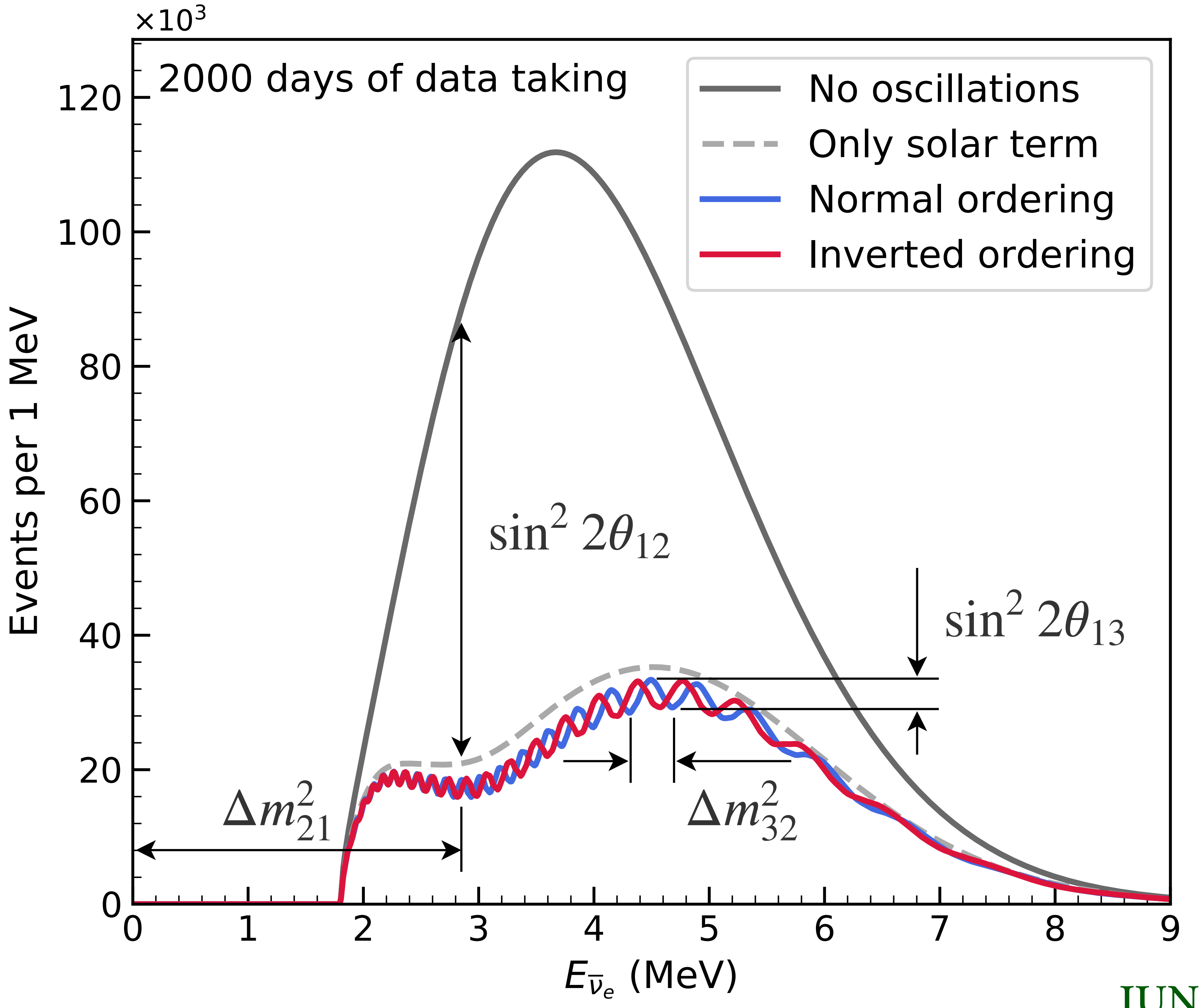
5-MEV flux excess



Double Chooz, Nature Phys (2019)

- update in cross section at 4-6 MeV: shift by 15-20% of bump

Energy reconstruction is key



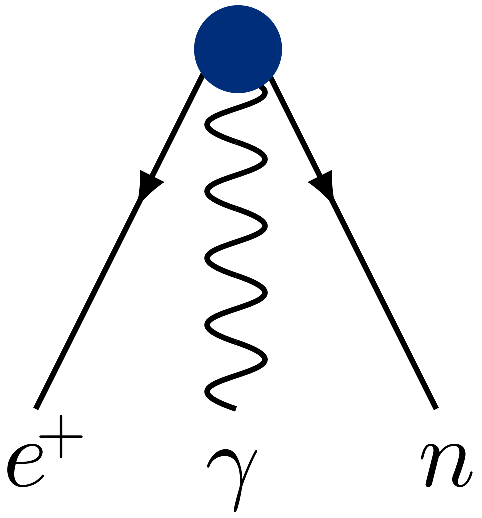
JUNO, PPNP (2021)

- JUNO: 3% energy reconstruction for precision goals

Bremsstrahlung

- new distributions beyond E_{EM} spectrum

$$\begin{tikzcd}
E_n, E_\gamma, \theta_n \arrow[d] & & E_e, E_\gamma, \theta_e \arrow[d] \\
E_n, \theta_n \arrow[d] & & E_e, \theta_e \arrow[d] \\
E_n, E_{\text{EM}} \arrow[dr] & & E_e \arrow[dl] \\
& \text{total cross section} &
\end{tikzcd}$$



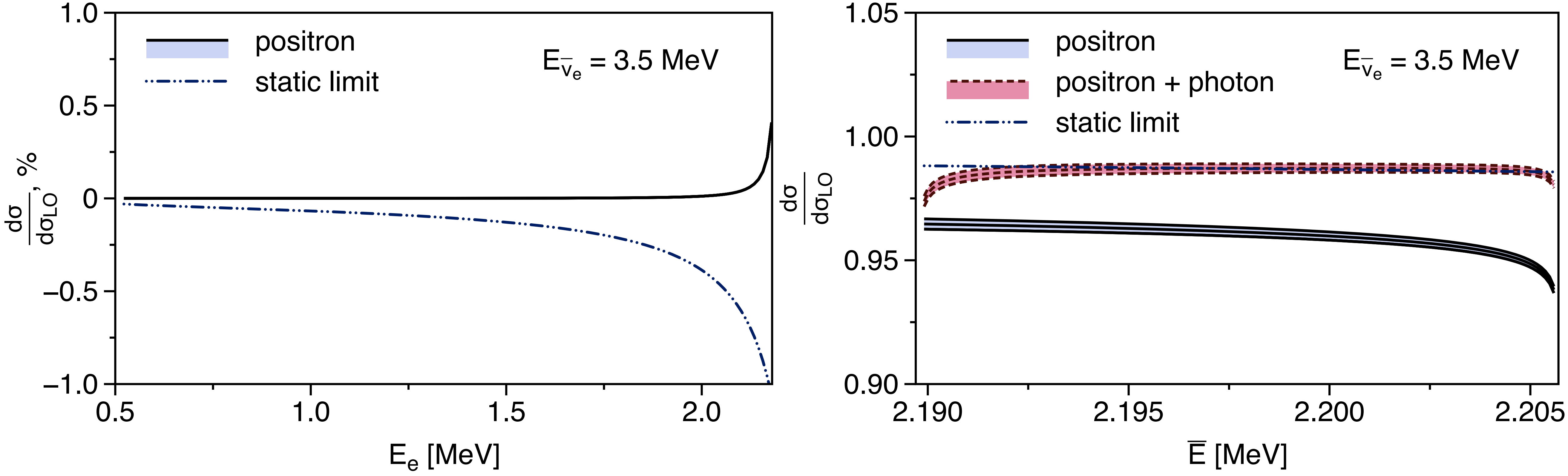
$$E_{\text{EM}} = E_e + E_\gamma$$

consistency at
cross-section level

- analytical positron energy spectrum, 2D/3D distributions

Access each particle kinematics

- evaluate radiative process w/o no-recoil approximation

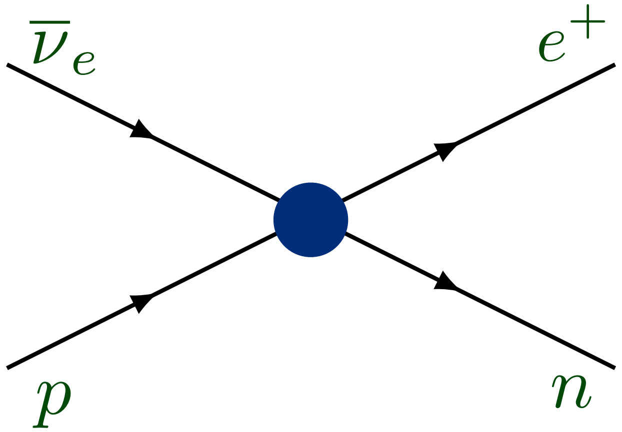


- 1st analytic expression for positron energy spectrum

$$E_{\overline{\nu}_e} \approx m_n - m_p + E_{e^+} + E_\gamma + O\left(\frac{1}{M}\right)$$

- control over each particle is necessary to achieve precision

Conclusions



radiative corrections
in EFT framework
+ scheme-dependence

Standard Model -> LEFT -> HBχPT -> $\not\pi$EFT

- 1st consistent inclusion of all QCD/EW effects at 0.1% level
- total cross section, energy spectra, 2D/3D distributions in IBD
- precision physics: important to control γ and e^+ kinematics in calibration of energy response in liquid scintillators

$$\nu e^- \to \nu e^- \, (\gamma)$$

$\pi^+ \to \mu^+ \nu_\mu (\gamma)$ $K^+ \to \mu^+ \nu_\mu (\gamma)$ $\mu^+ \to e^+ \nu_e \bar{\nu}_\mu (\gamma)$

Thanks for your attention !!!

$\bar{\nu}_\ell p \to \ell^+ n \, (\gamma)$ **谢谢** $\nu_\ell n \to \ell^- p \, (\gamma)$

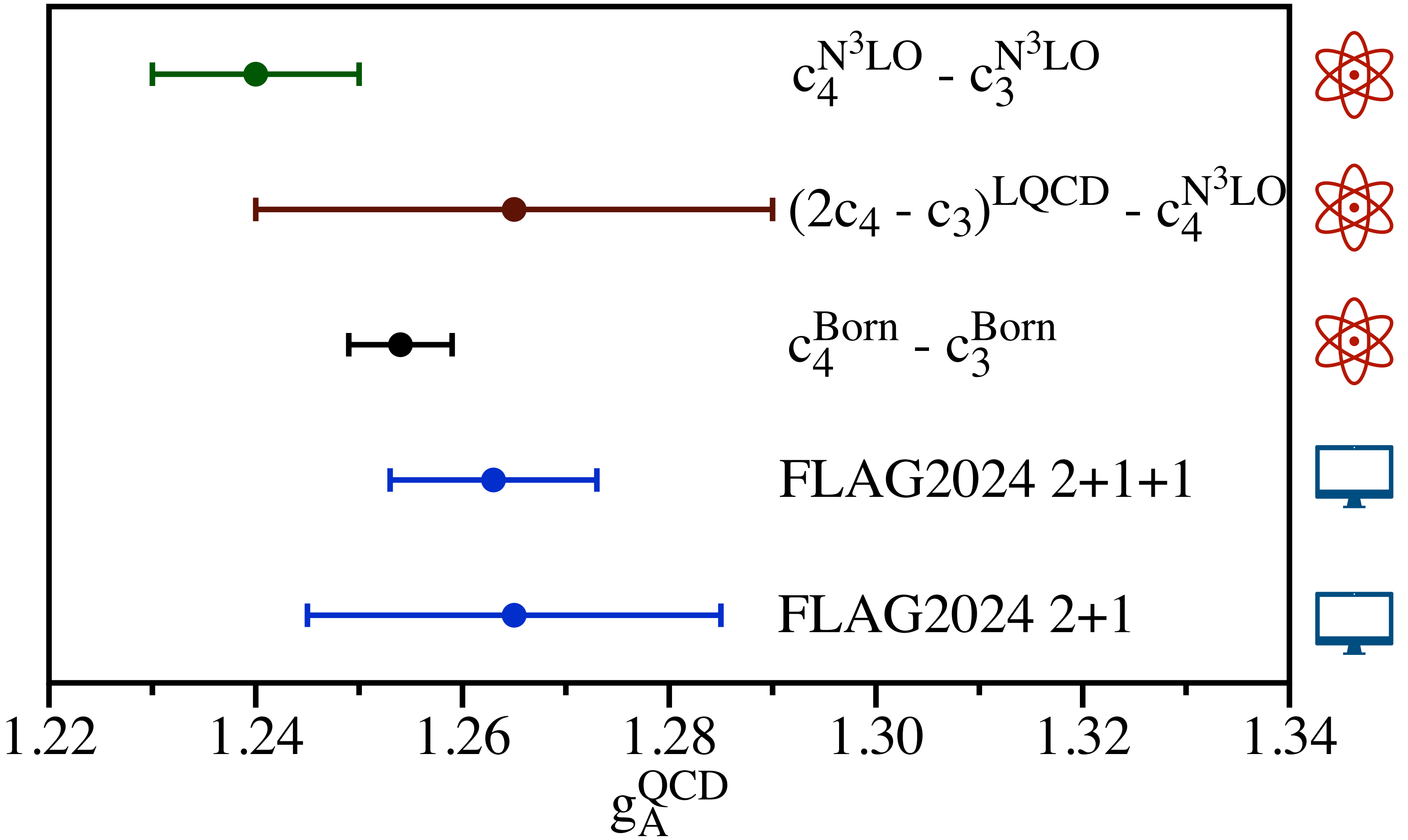
$$n \to p e^- \overline{\nu}_e$$

$$\nu \, {}^{40}\mathrm{Ar} \to \nu \, {}^{40}\mathrm{Ar} \, (\gamma)$$

Nucleon axial-vector charge

- effective field theory approach to low-energy charged currents

Standard Model -> LEFT -> HBχPT -> $\not\pi$EFT



HBχPT

lattice QCD

O.T. and Yi-Bo Yang, Universe (2026)
Vincenzo Cirigliano, Wouter Dekens, Emanuele Mereghetti, and O.T., PRD (2024) and PRD (2025)
V. Cirigliano, J. de Vries, L. Hayen, E. Mereghetti, and A. Walker-Loud, PRL (2022)

- first consistent at 0.1%-level QED radiative corrections

Update in nuclear/neutron decay

- evaluate radiative process w/o no-recoil approximation

$$m_n = m_p + E_e + E_\gamma + E_\nu + O\left(\frac{1}{M}\right)$$

- V_{ud} from superallowed transitions and neutron decay

$$V_{ud}^{0^+\to 0^+} = 0.97373(31) \longrightarrow V_{ud}^{0^+\to 0^+} = 0.97361(31)$$

Hardy and Towner, PRC (2020)

changes by 1 uncertainty of radiative corrections

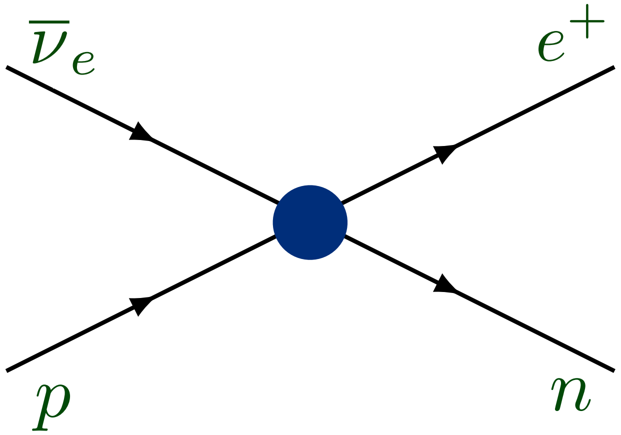
- g_A from beta asymmetry in polarized neutron decay

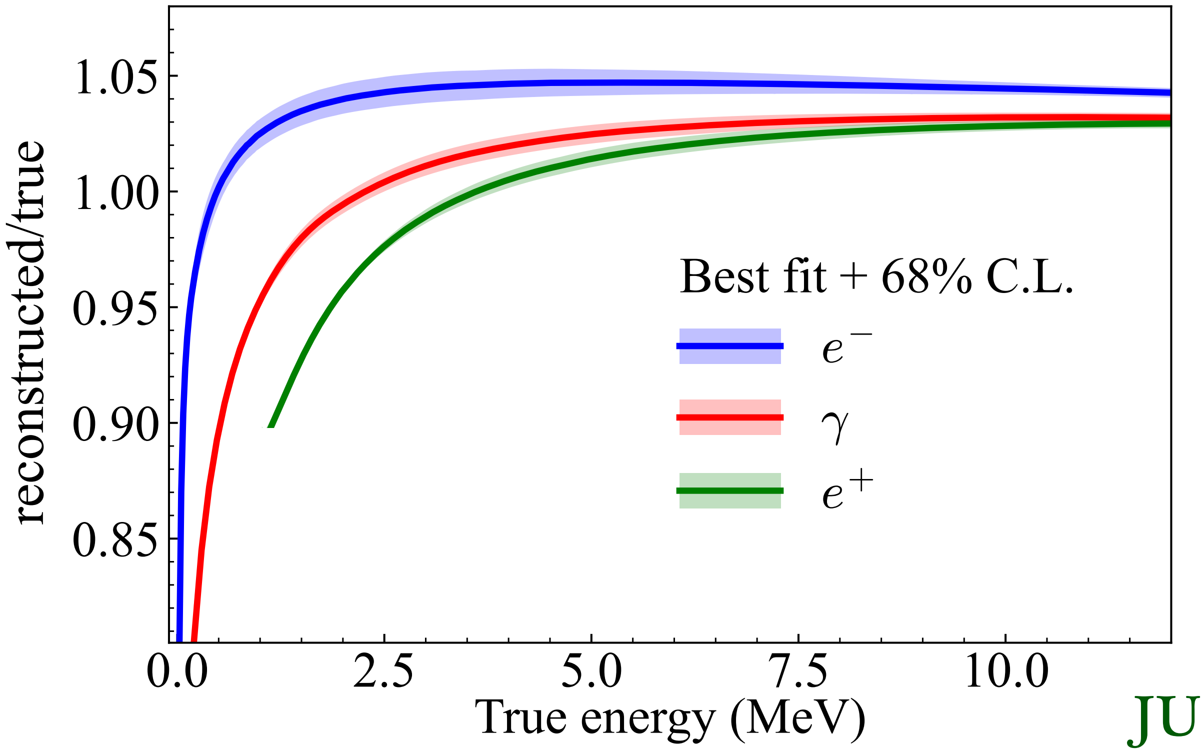
$$A = \frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow}$$

changes by 1/3 of PERKEO-III experimental uncertainty

- numerically quantified shifts in V_{ud} and g_A $\lesssim 1\sigma$

Energy reconstruction is key



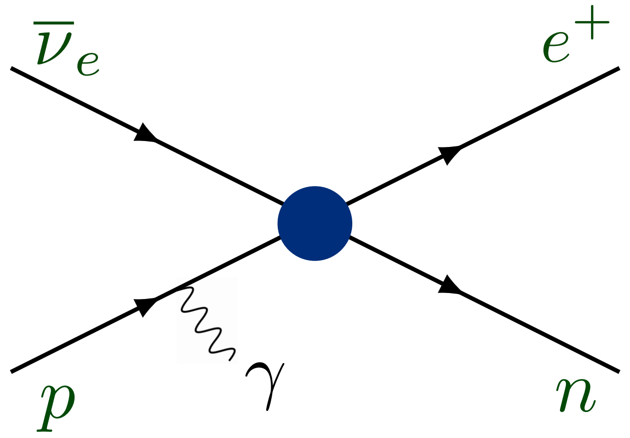


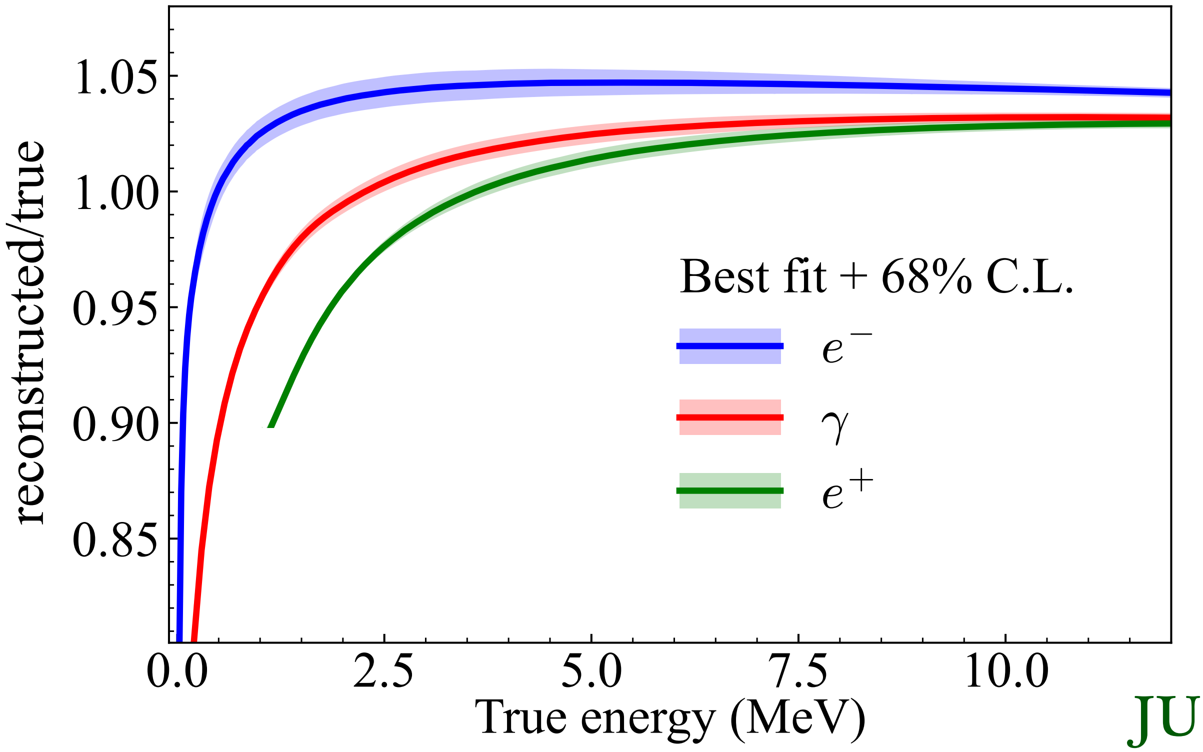
JUNO, arXiv:2511.14590

$$E_{\overline{\nu}_e} \approx m_n - m_p + E_{e^+} + O\left(\frac{1}{M}\right)$$

- control over each particle is necessary to achieve precision

Energy reconstruction is key





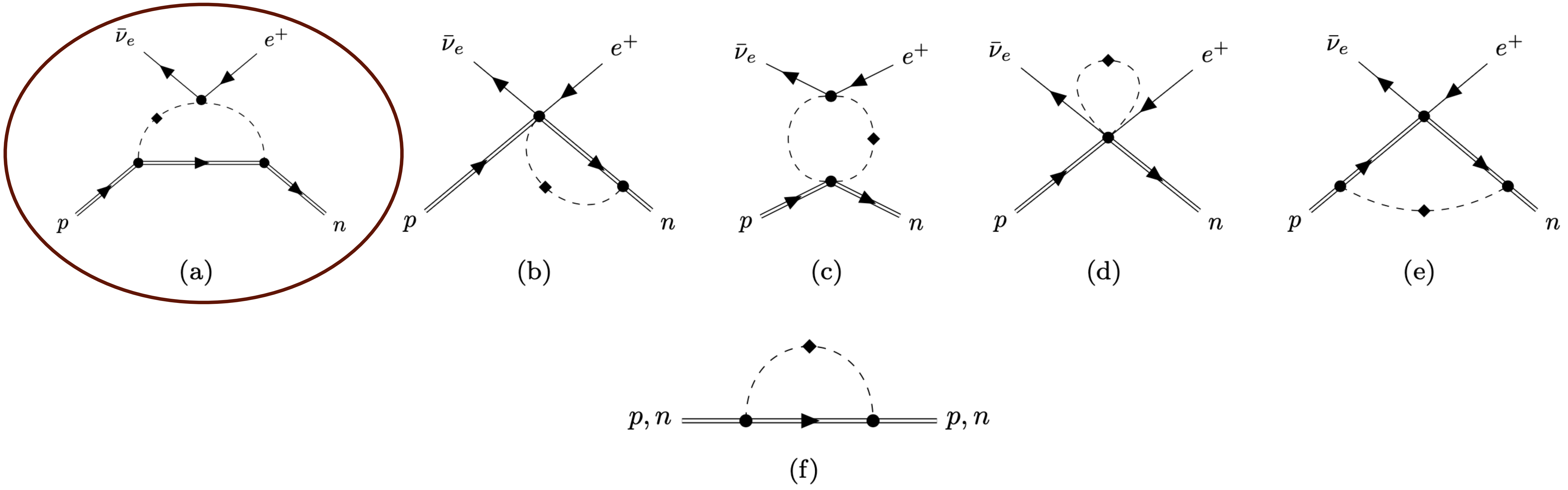
JUNO, arXiv:2511.14590

$$E_{\overline{\nu}_e} \approx m_n - m_p + E_{e^+} + E_\gamma + O\left(\frac{1}{M}\right)$$

- control over each particle is necessary to achieve precision

Supernova and πDAR energies

- include pion degrees of freedom to inverse beta decay



(a) (b) (c) (d) (e)

(f)

- work at leading and next-to-leading order in HBChPT

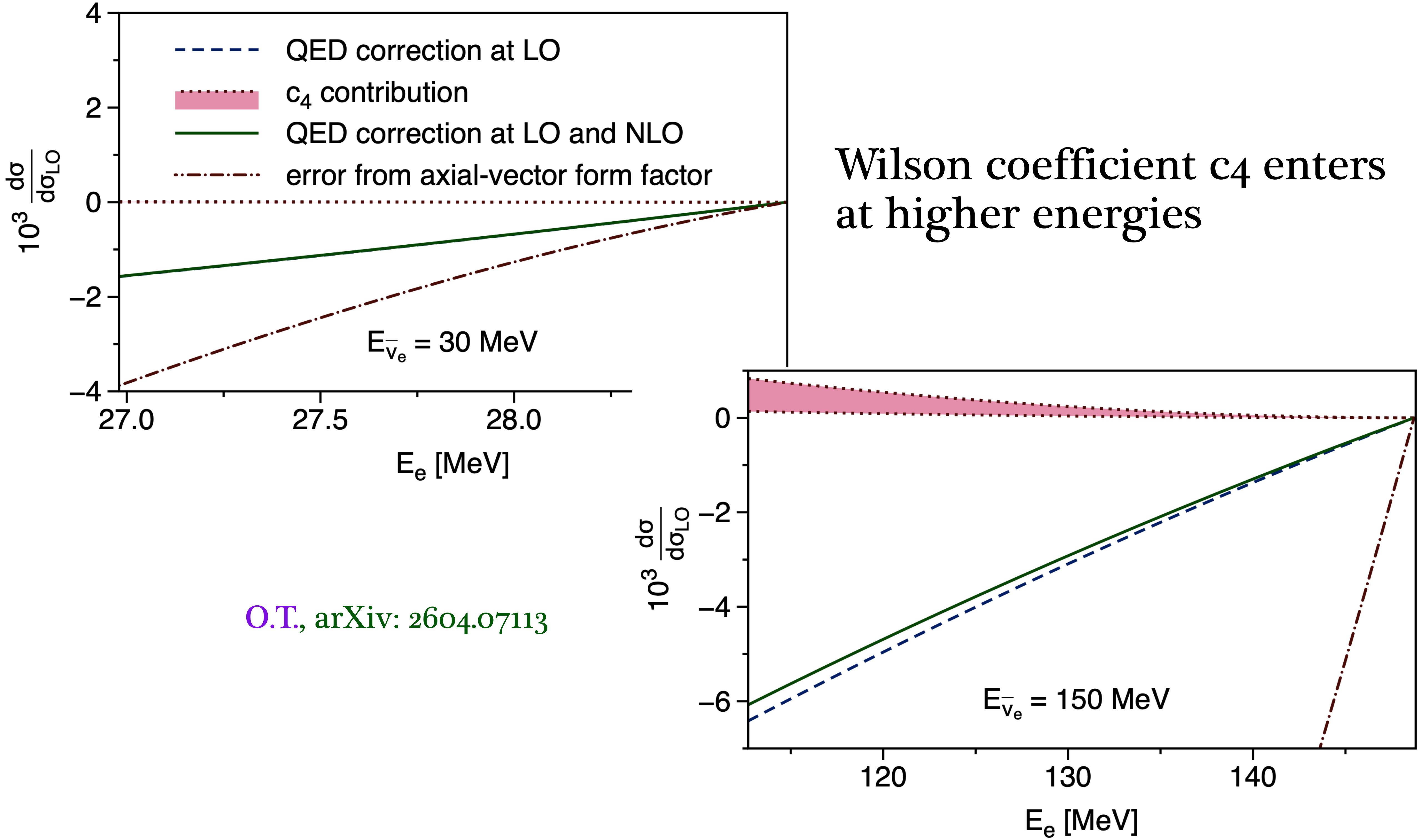
O.T., arXiv:2604.07113

- neglect recoil diagrams without pions

$$\frac{m_e^2}{m_\pi^2} \sim \frac{\alpha}{\pi}\frac{m_e}{m_\pi} << \frac{\alpha}{\pi}\frac{m_e}{E_{\overline{\nu}_e}} \lesssim \frac{\alpha}{\pi}\frac{E_{\overline{\nu}_e}}{m_n} \lesssim \frac{\alpha}{\pi}\frac{E_{\overline{\nu}_e}^2}{m_\pi^2} << \frac{\alpha}{\pi}\frac{m_\pi}{m_n} \lesssim \frac{\alpha}{\pi}\frac{E_{\overline{\nu}_e}}{m_\pi}$$

- extends 0.1%-level predictions to energies above 10 MeV

Supernova and πDAR energies

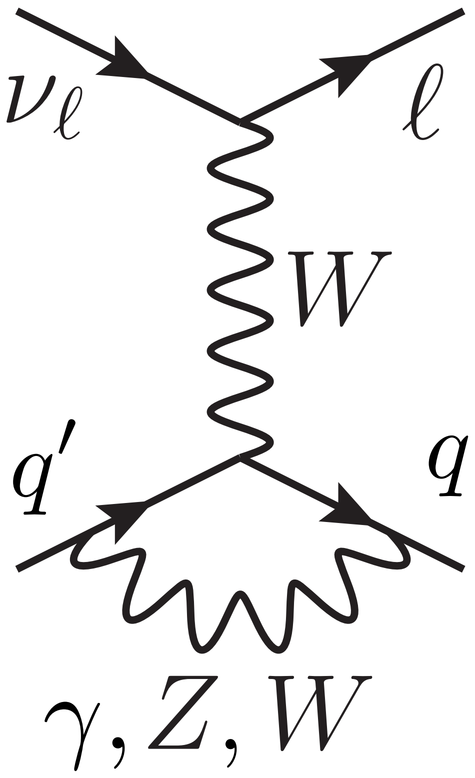


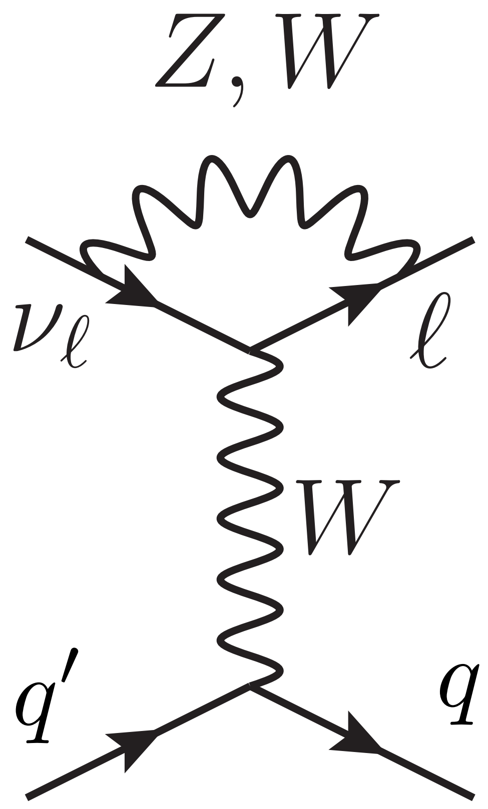
Wilson coefficient c4 enters at higher energies

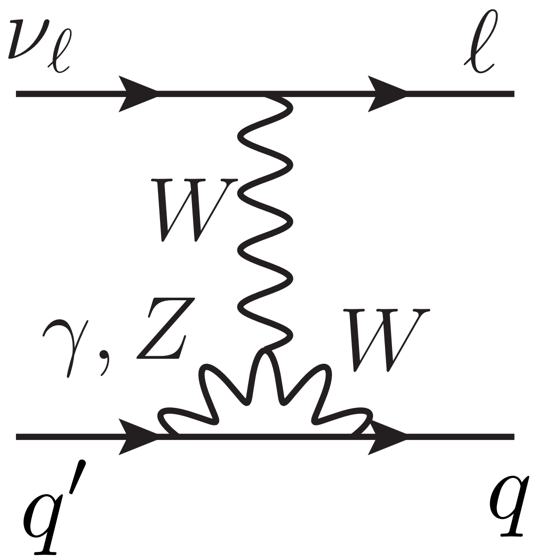
O.T., arXiv: 2604.07113

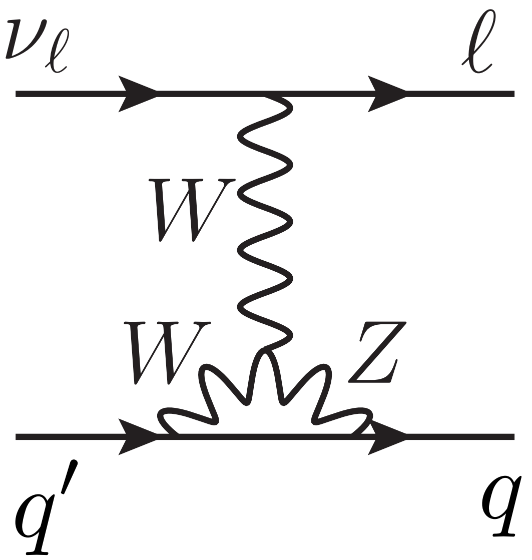
- extends 0.1%-level predictions to energies above 10 MeV

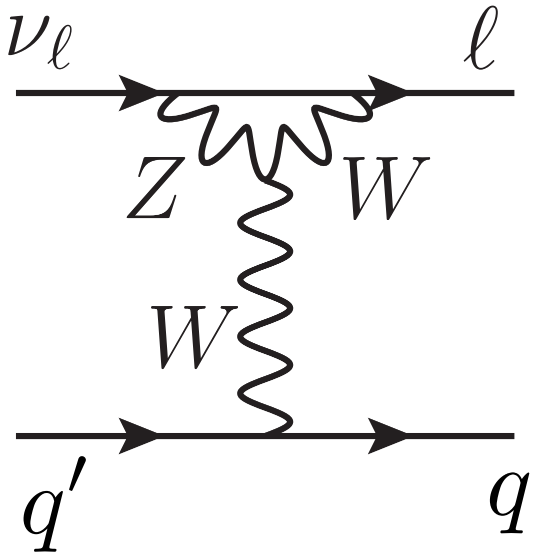
Charged current in SM. Vertexes

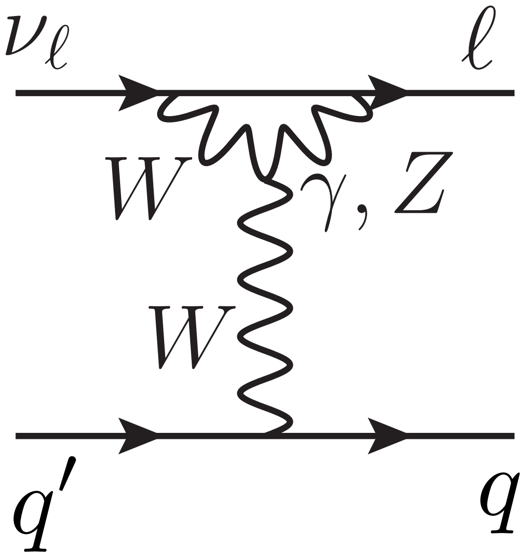






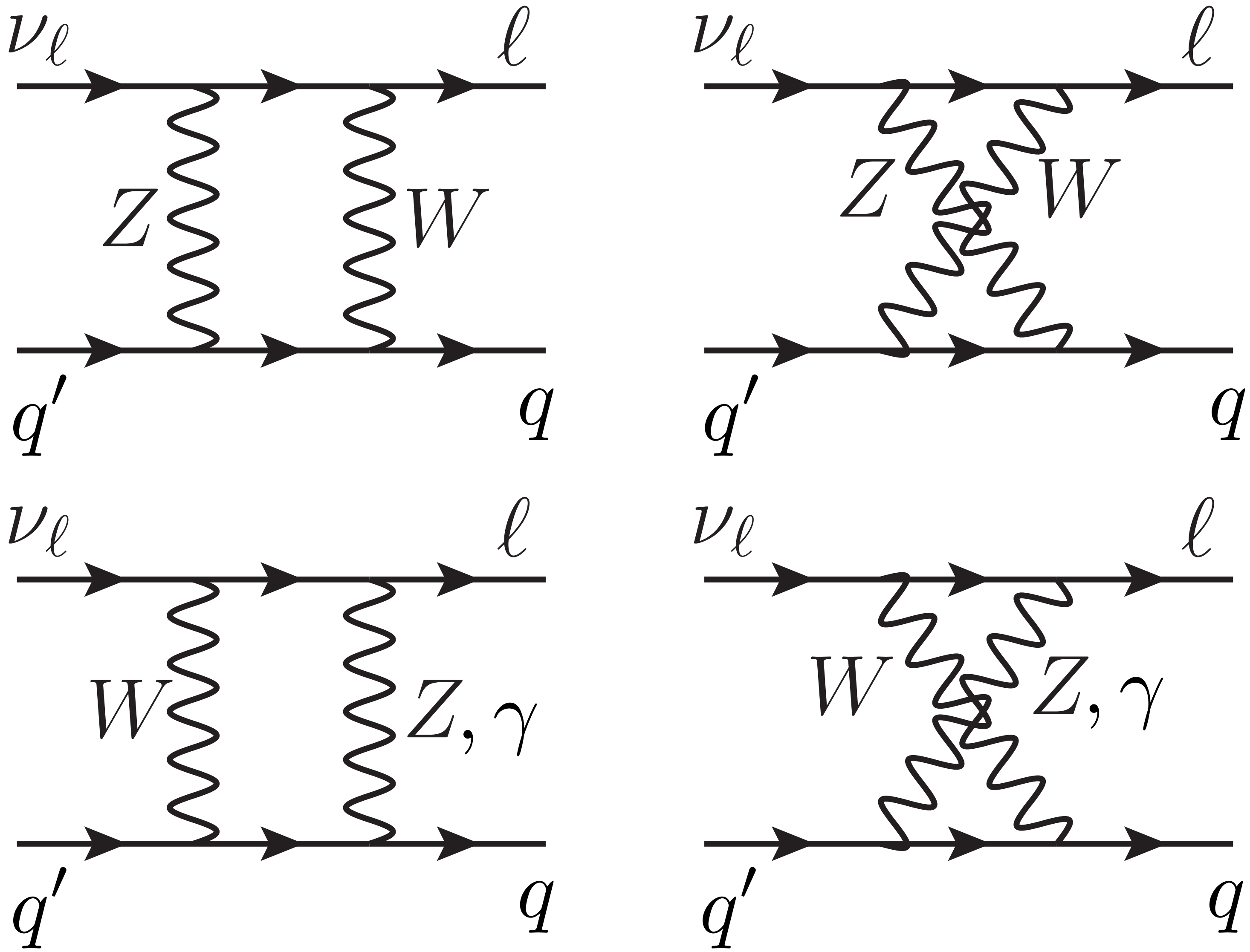






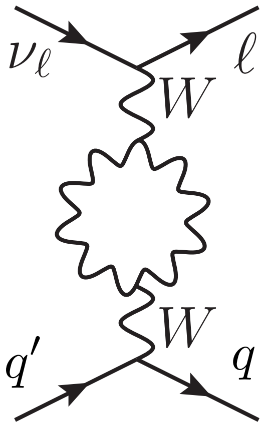
- contribution to effective couplings

Charged current in SM. Boxes

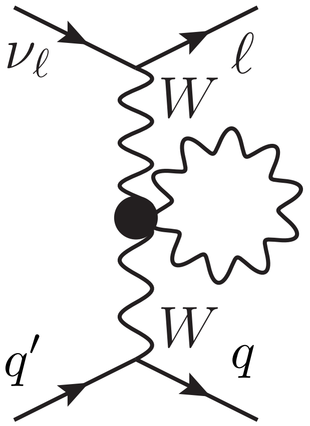


- contribution to effective couplings

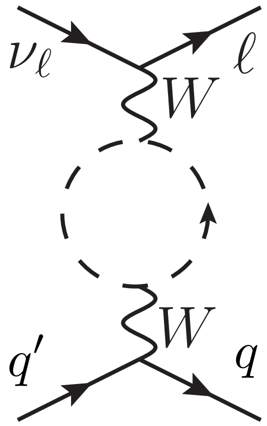
W self energy



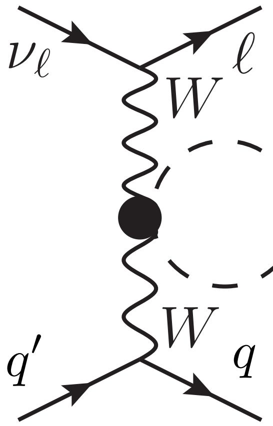
ZW,γW



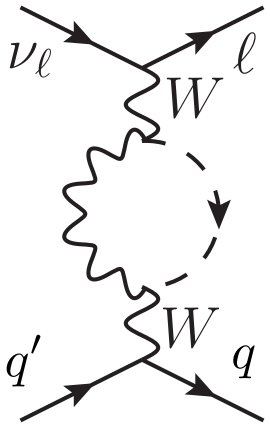
WW,ZZ,$\gamma\gamma$



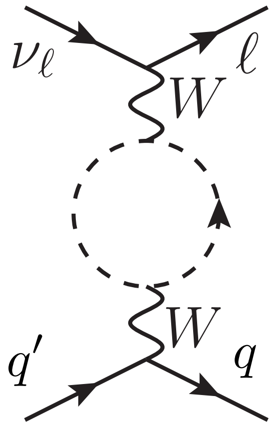
hφ,χφ,χ



φφ,$\chi\chi$,hh



Wh,Zφ,γφ



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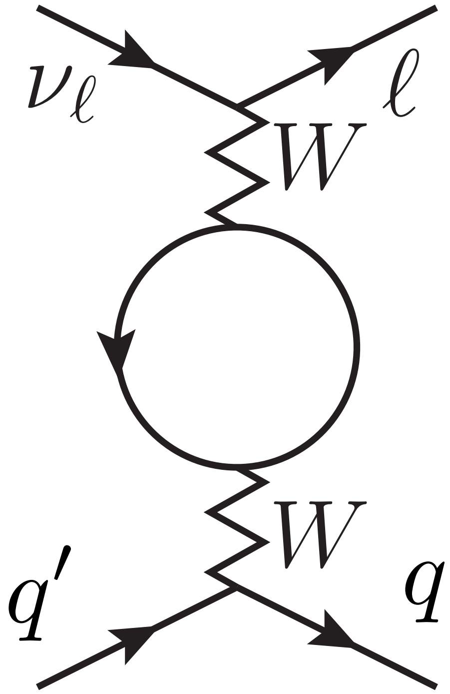
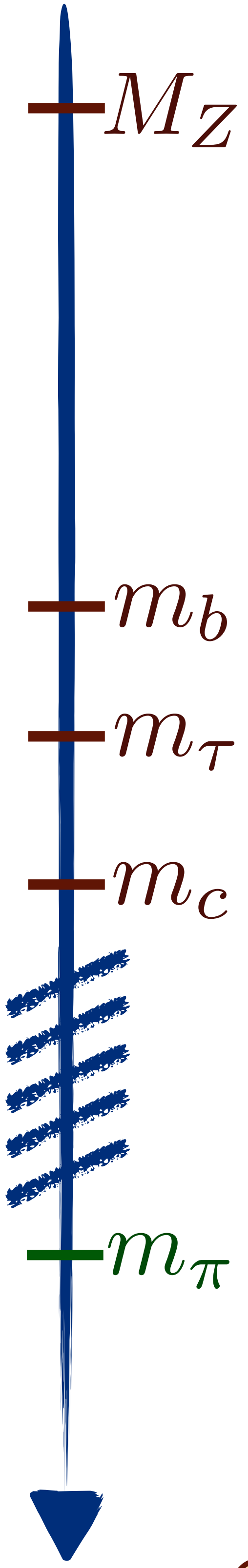


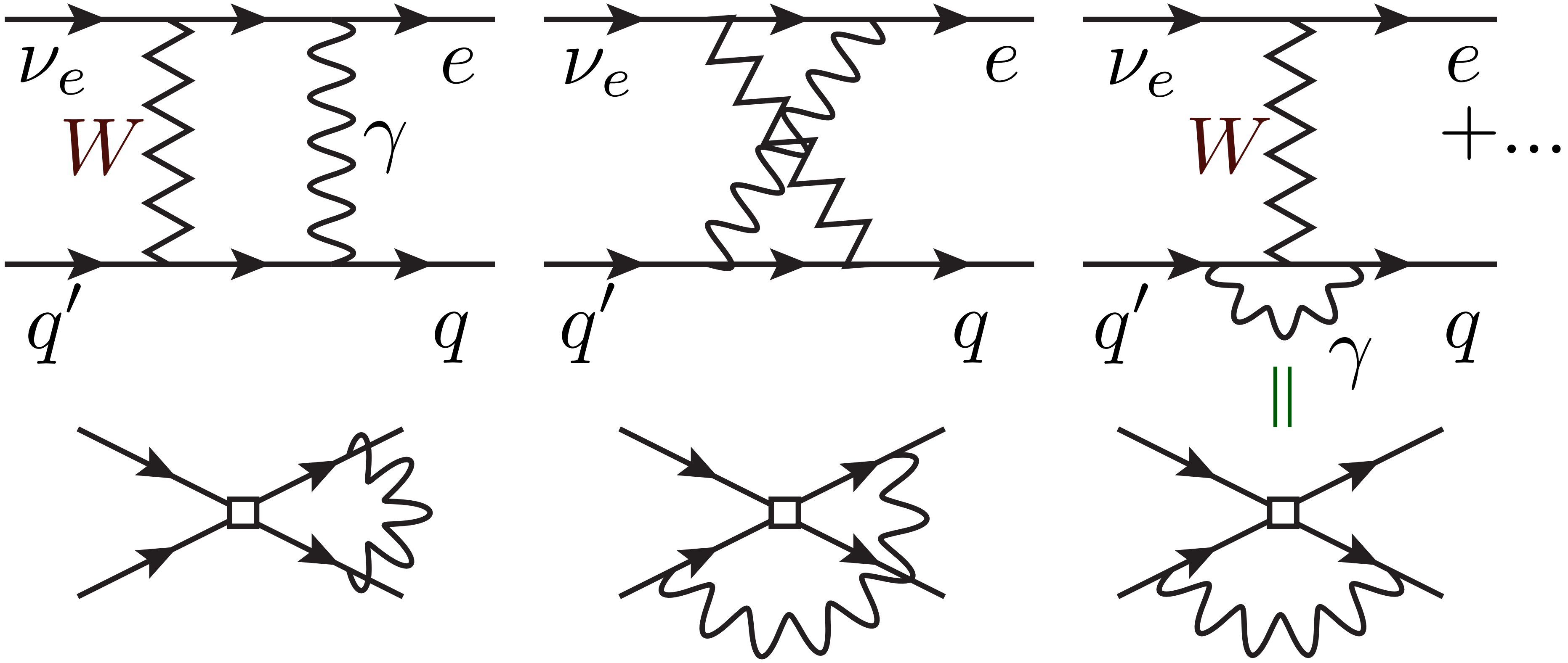
- vanishing contribution to matching besides loops with t quark

- contribution to effective couplings

LEFT Lagrangian



$$\mathcal{L}_{\mathrm{LEFT}} \sim G_F V_{ud} C^r_\beta(a,\mu)\, \bar{e}_L \gamma_\rho \nu_{eL}\, \bar{u}_L \gamma^\rho d_L$$



scheme independent

scheme dependent for quarks

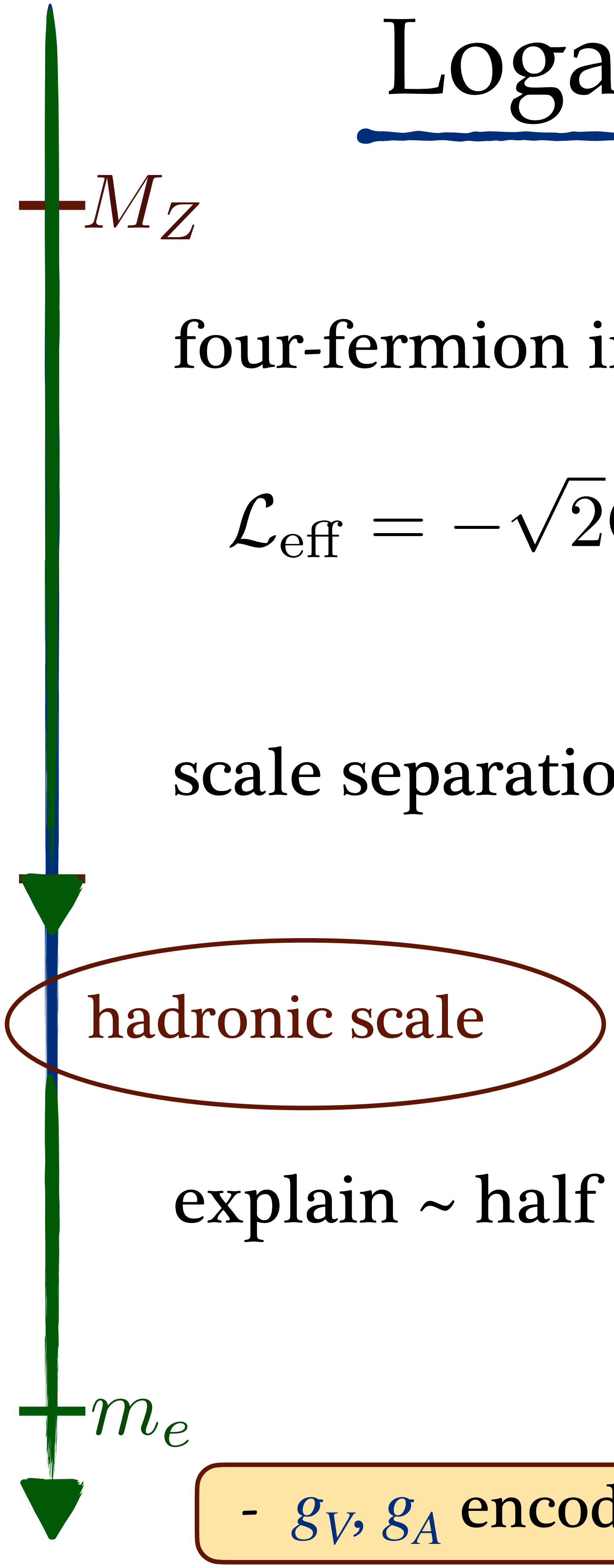
- NDR scheme for γ_5 for evanescent operators E

$$\gamma^\alpha\gamma^\beta\gamma^\mu \mathrm{P_L} \otimes \gamma_\mu\gamma_\beta\gamma_\alpha \mathrm{P_L} = 4\,(1 + a\,(4-d))\,\gamma^\mu \mathrm{P_L} \otimes \gamma_\mu \mathrm{P_L} + \mathrm{E}\,(a)$$

Buras and Weisz, NPB (1990)

- scheme dependence of 1-loop matching and 2-loop running

Logarithms in neutron decay



four-fermion interaction between leptons and heavy nucleons

$$\mathcal{L}_{\rm eff} = -\sqrt{2}\mathrm{G_F} V_{ud} \bar{e}\gamma_\mu \mathrm{P_L}\nu_e \cdot \overline{N}\left(g_V v^\mu - 2 g_A S^\mu\right)\tau^+ N$$

scale separation introduces large logarithms:

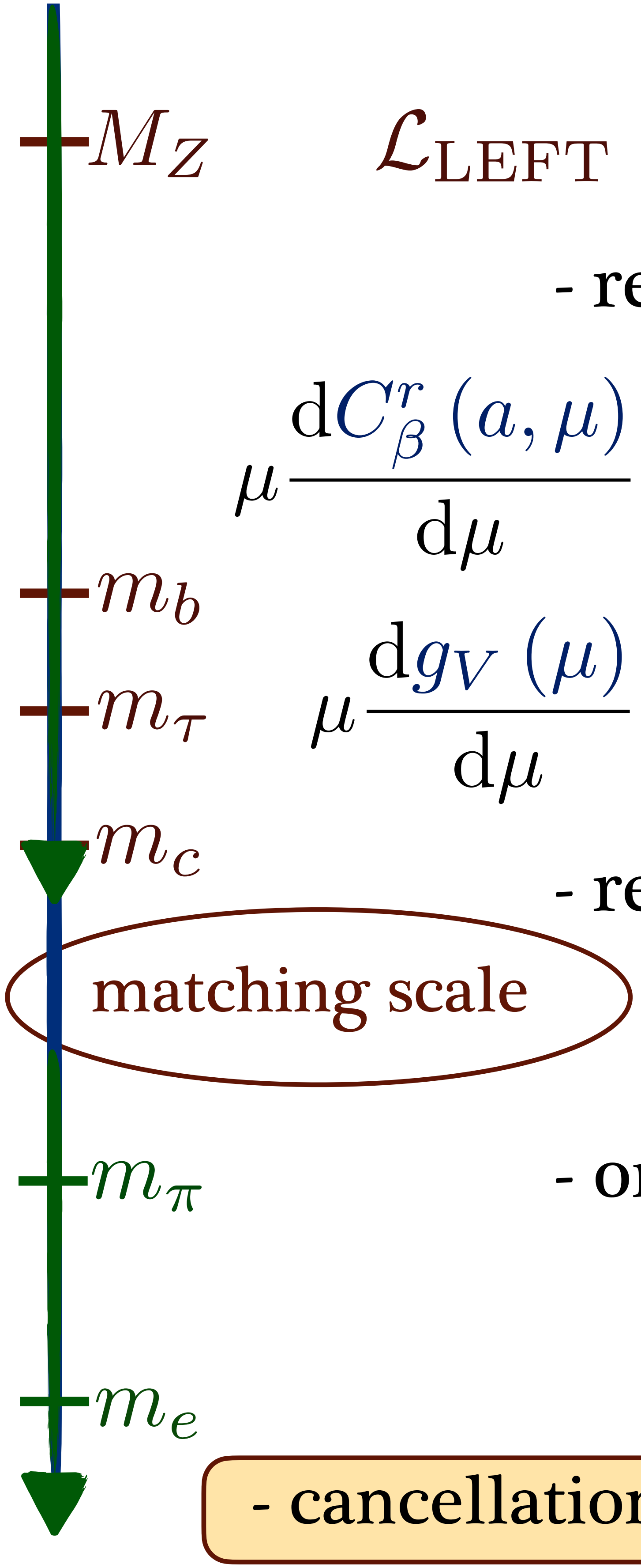
$$\ln\frac{M_Z}{\Lambda_{\rm had}} \qquad\qquad \ln\frac{\Lambda_{\rm had}}{m_e}$$

explain ~ half of radiative correction to neutron lifetime

$$\Delta = 7.756(27)\%$$

- g_V, g_A encode electroweak logarithms and hadronic corrections

Effect of running



$$\mathcal{L}_{\text{LEFT}} \sim G_F V_{ud} C_\beta^r(a,\mu) \bar{e}_L \gamma_\rho \nu_{eL}\, \bar{u}_L \gamma^\rho d_L$$

- renormalization group equations

$$\mu \frac{\mathrm{d}C_\beta^r(a,\mu)}{\mathrm{d}\mu} = \left(\gamma_0 \frac{\alpha}{\pi} + \gamma_1 \left(\frac{\alpha}{\pi}\right)^2 + \gamma_{se} \frac{\alpha}{\pi}\frac{\alpha_s}{4\pi}\right) C_\beta^r(a,\mu)$$

$$\mu \frac{\mathrm{d}g_V(\mu)}{\mathrm{d}\mu} = \left(\tilde{\gamma}_0 \frac{\alpha}{\pi} + \tilde{\gamma}_1 \left(\frac{\alpha}{\pi}\right)^2\right) g_V(\mu)$$

- resummed result with leading $\alpha\alpha_s$ corrections

$$g_V(\mu_\chi = m_e) - 1 = (2.499 \pm 0.013)\ \%$$

full error

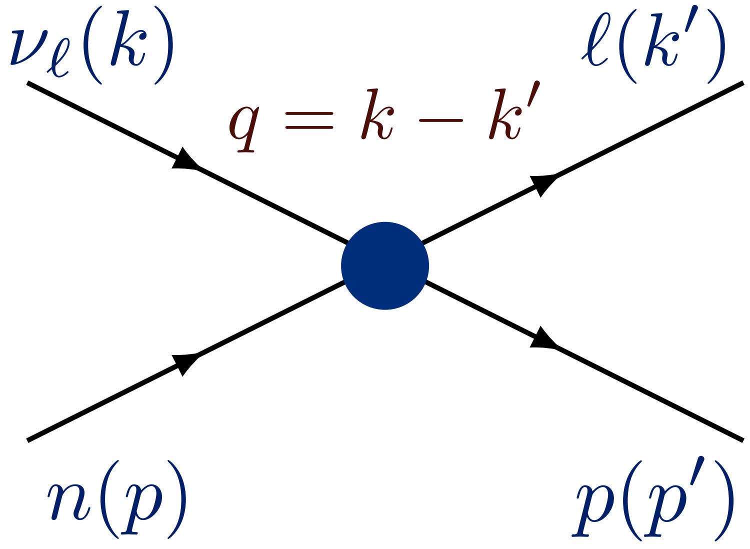
- one-loop result without $\alpha\alpha_s$ contributions

$$g_V^{1-\text{loop}}(\mu_\chi = m_e) - 1 = (2.430 \pm 0.012)\ \%$$

hadronic error

- cancellation of various contributions -> 0.07 % effect

Invariant amplitudes



averaged lepton momentum $K_\mu = \frac{k_\mu + k'_\mu}{2}$

averaged nucleon momentum $P_\mu = \frac{p_\mu + p'_\mu}{2}$

- four amplitudes for massless charged lepton

$$T^{m_\ell=0}_{\nu_\ell n\to\ell^- p} = \sqrt{2}\mathrm{G_F}V_{ud}\,\bar{\ell}^-\gamma^\mu \mathrm{P_L}\nu_\ell\,\bar{p}\left(\gamma_\mu\left(g_M + f_A\gamma_5\right) - \left(f_2 + f_A^3\gamma_5\right)\frac{K_\mu}{M}\right)n$$

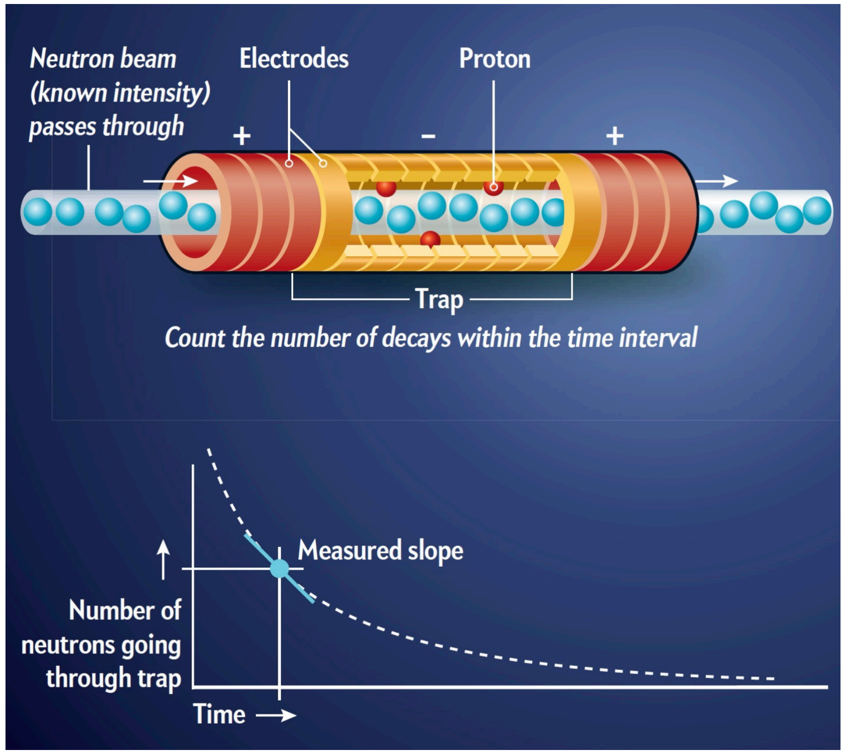
- four extra amplitudes for massive charged lepton

$$T^{m_\ell\neq0}_{\nu_\ell n\to\ell^- p} = -\sqrt{2}\mathrm{G_F}V_{ud}\frac{m_\ell}{M}\,\bar{\ell}^-\mathrm{P_L}\nu_\ell\,\bar{p}\left(f_3 + f_P\gamma_5 - \frac{f_R}{4}\frac{P_\mu}{M}\gamma^\mu\gamma_5\right)n$$
$$+ \sqrt{2}\mathrm{G_F}V_{ud}\frac{m_\ell}{M}\frac{f_T}{4}\,\bar{\ell}^-\sigma^{\mu\nu}\mathrm{P_L}\nu_\ell\,\bar{p}\sigma_{\mu\nu}n$$

- 8 invariant amplitudes for charged-current elastic scattering

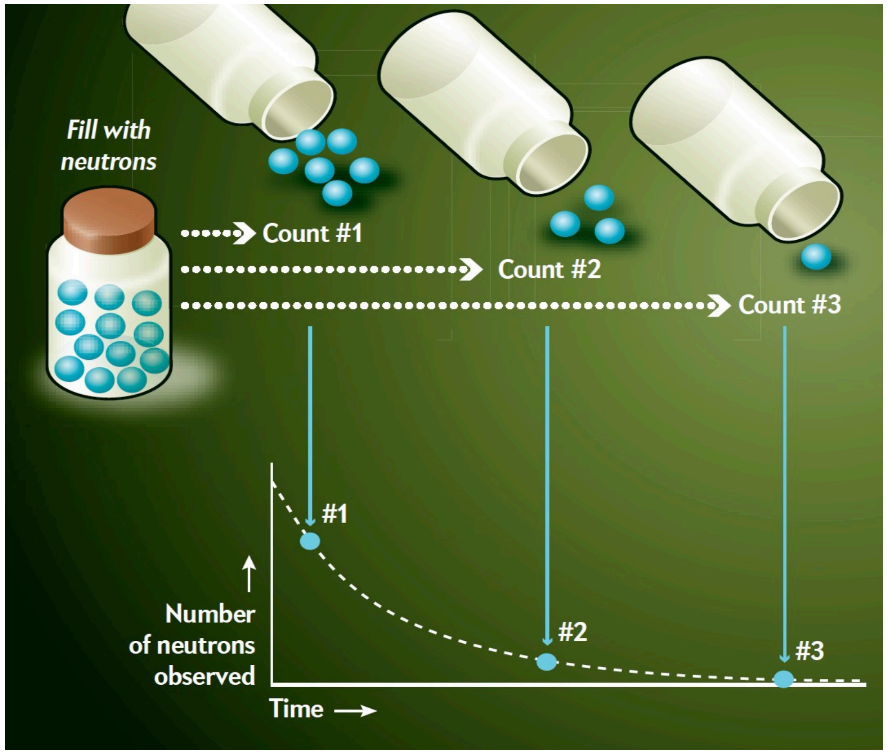
Neutron lifetime measurements

beam method



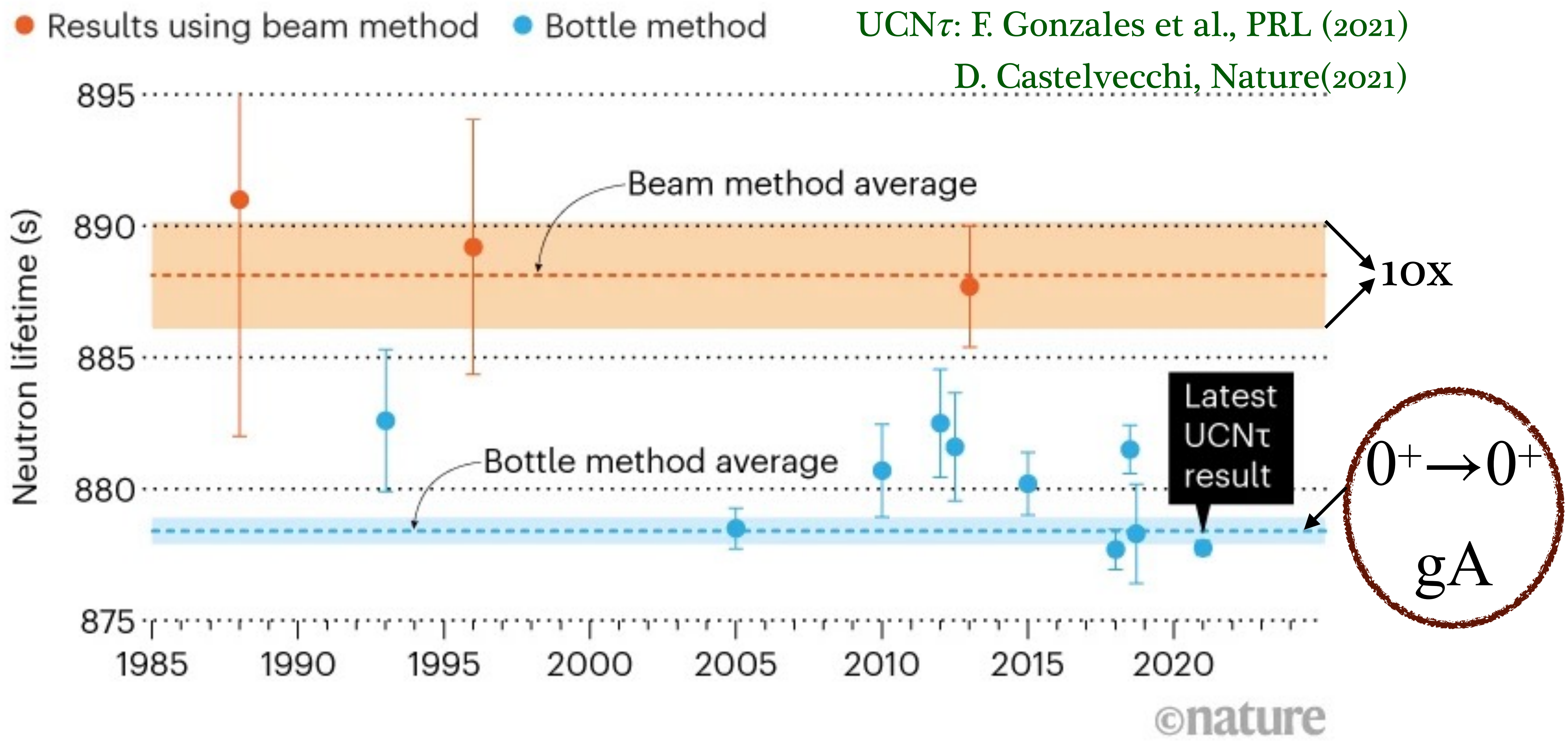
how many neutrons pass?

bottle method



how many neutrons survive?

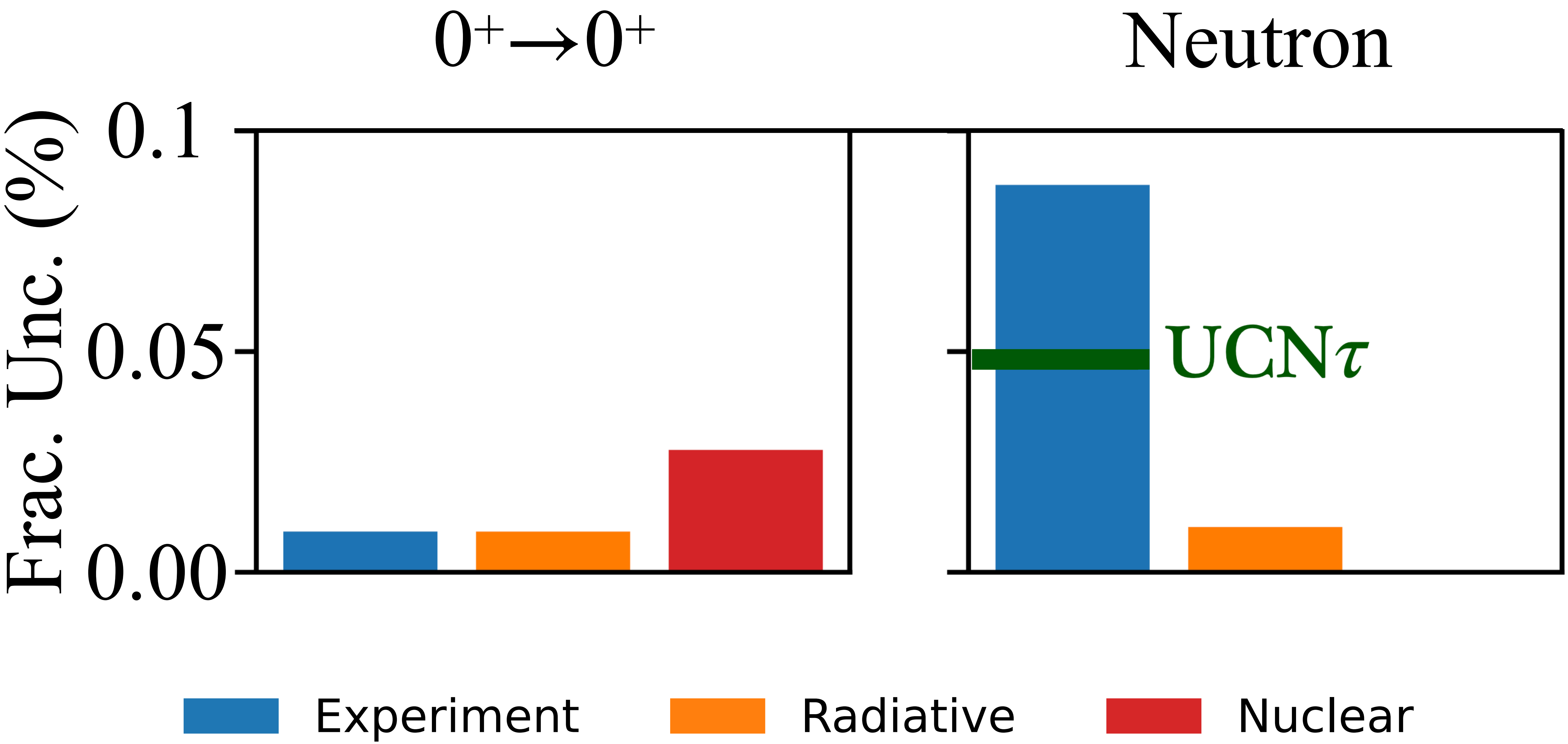
Neutron lifetime puzzle



UCNτ: F. Gonzales et al., PRL (2021)
D. Castelvecchi, Nature(2021)

- 8-9 seconds discrepancy beam vs bottle method : 3-5σ
- Vud from $0^+ \to 0^+$ + gA from β asymmetry ≡ bottle
- 0.3 seconds uncertainty of UCNτ@LANL : $(3-4)\times 10^{-4}$

V_{ud} determinations

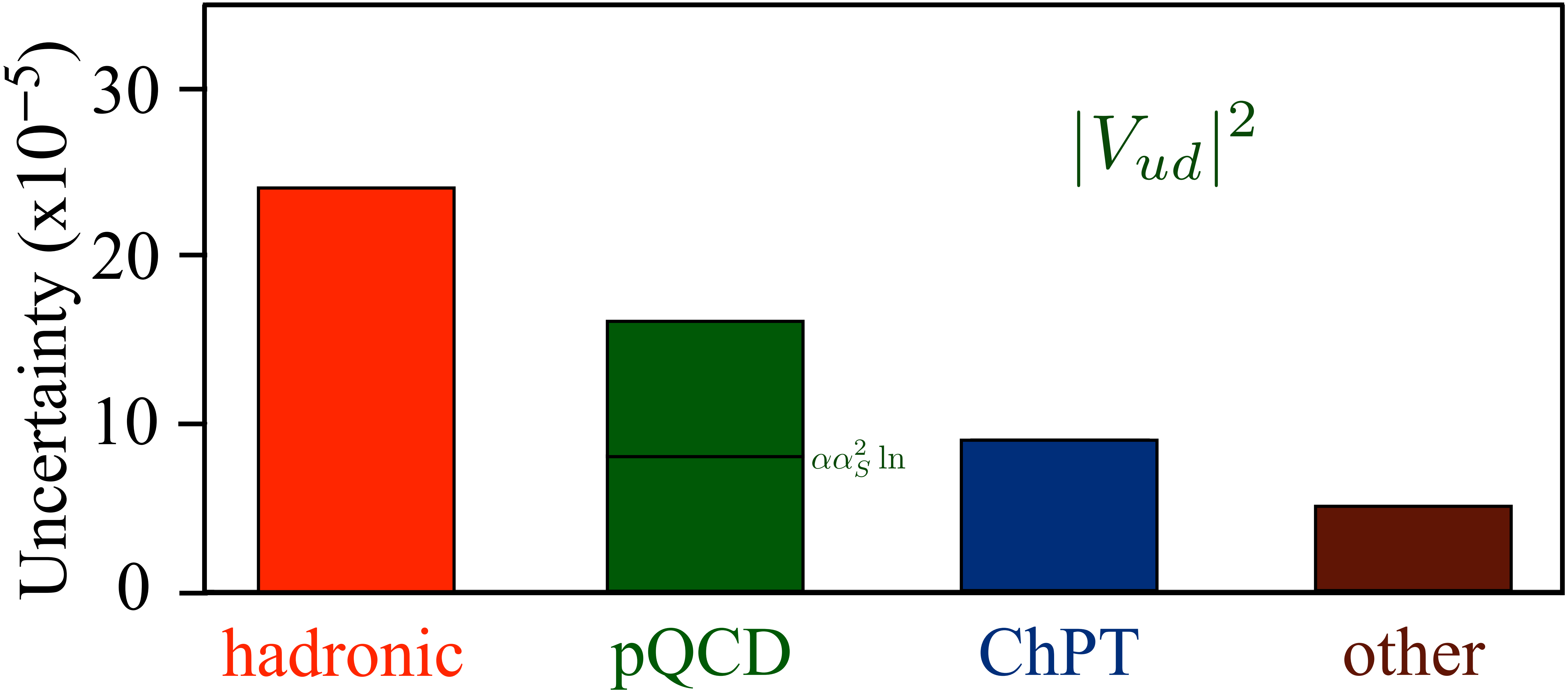


2022 Fundamental Symmetries, Neutrons, and Neutrinos (FSNN) white paper

- neutron decay becomes competitive with 0^+->0^+

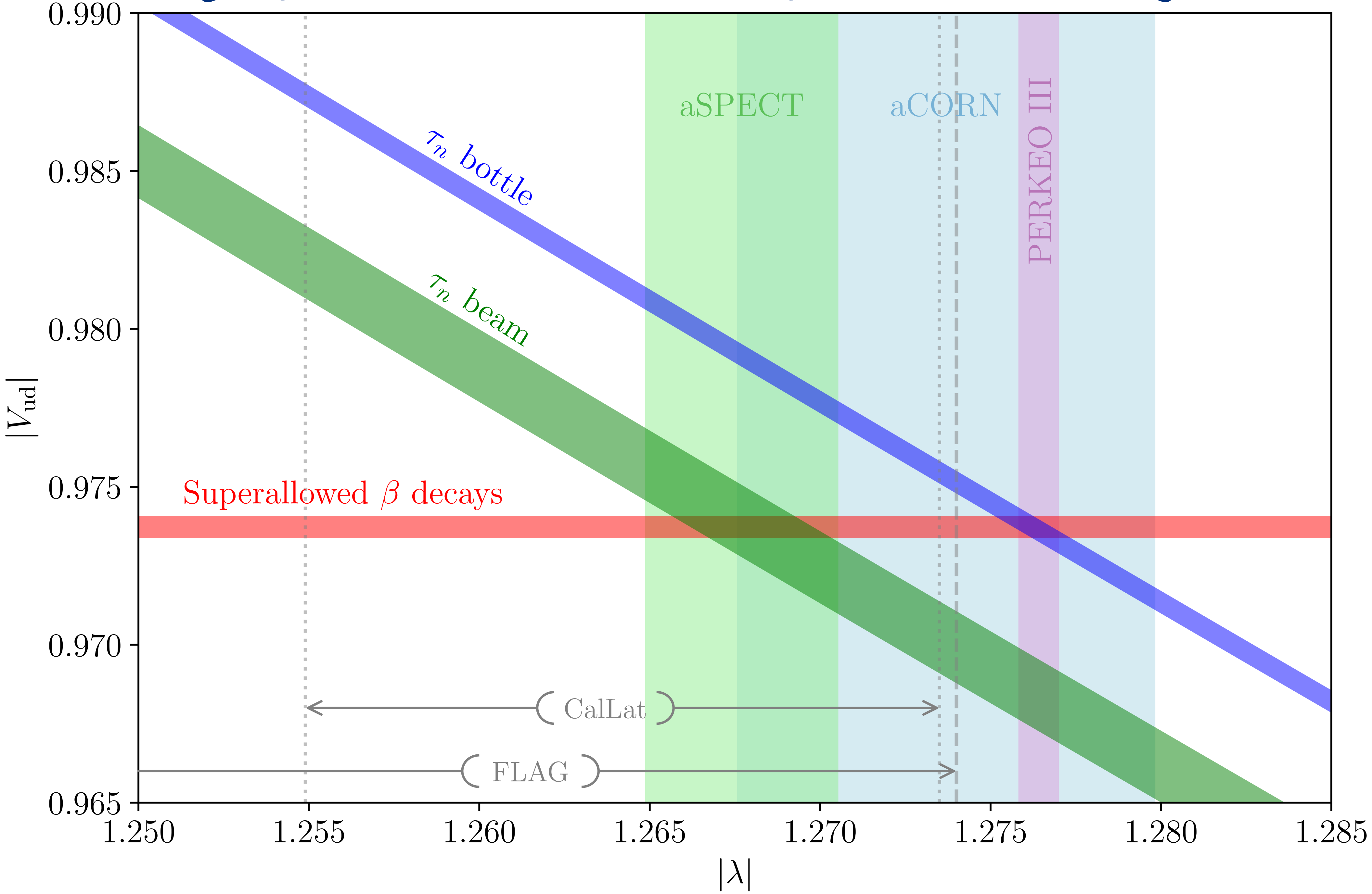
Our work

- detailed error budget and perturbative corrections



- shift of central value by ~1 error of radiative corrections
- quantification of perturbative/nonperturbative uncertainties

Neutron lifetime puzzle

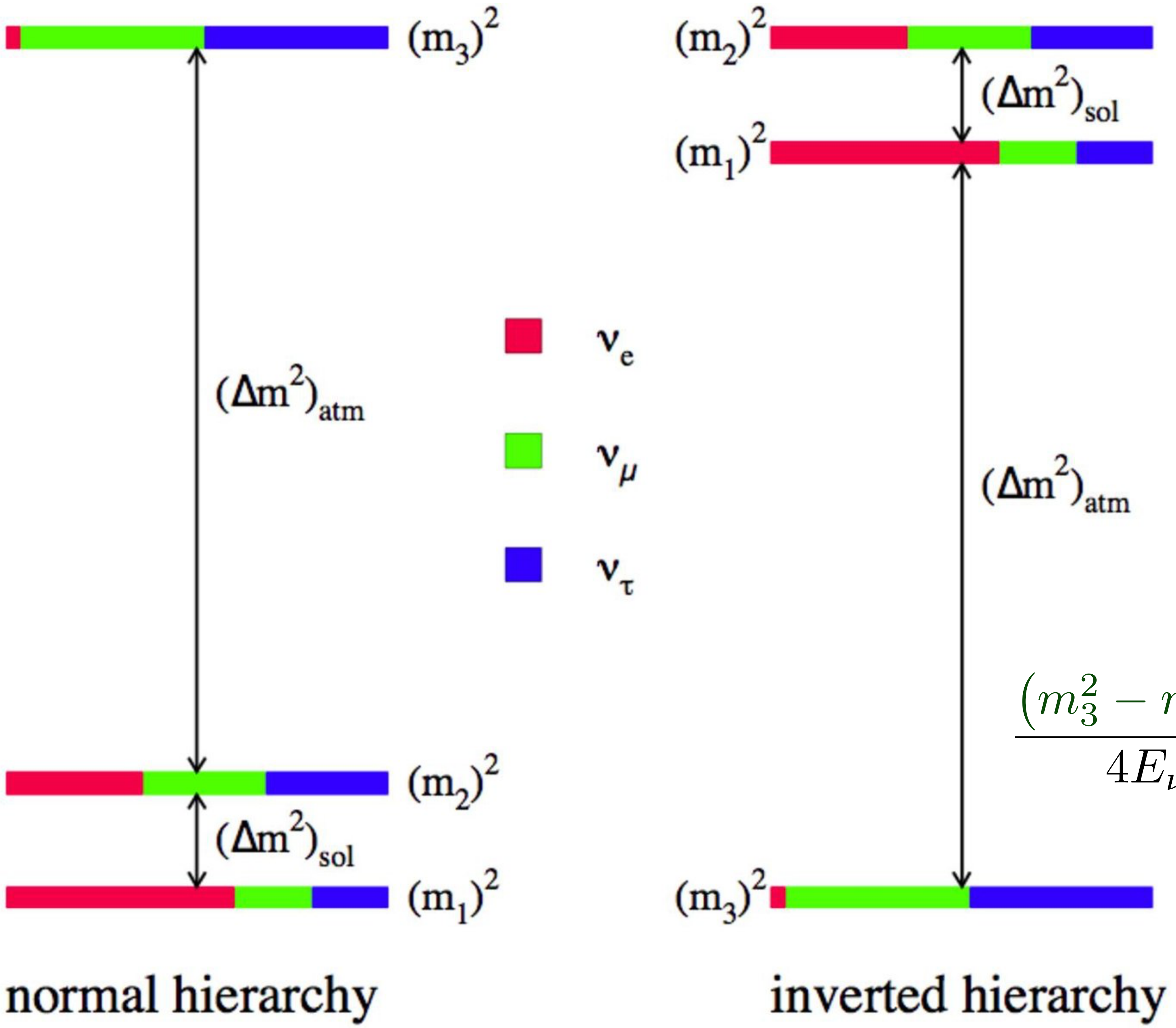


Andrzej Czarnecki, William J. Marciano, Alberto Sirlin, PRL (2018)

Susan Gardner, Mohammadreza Zakeri, Universe (2024)

- tensions in gA data: puzzle is not resolved

Neutrino mass hierarchy



forward scattering
on atomic electrons

matter effect

distinguishes ν and $\overline{\nu}$

$$\frac{(m_3^2 - m_1^2)L}{4E_\nu} \rightarrow \frac{(m_3^2 - m_1^2)L}{4E_\nu} \mp \frac{G_F n_e}{\sqrt{2}} L$$

mass ordering

- matter effects can resolve neutrino mass hierarchy