21 October, 2026

14th ITP/CAS-BLTP/JINR

Nanjing, China

Radiative corrections to neutron and inverse beta decay at low energies

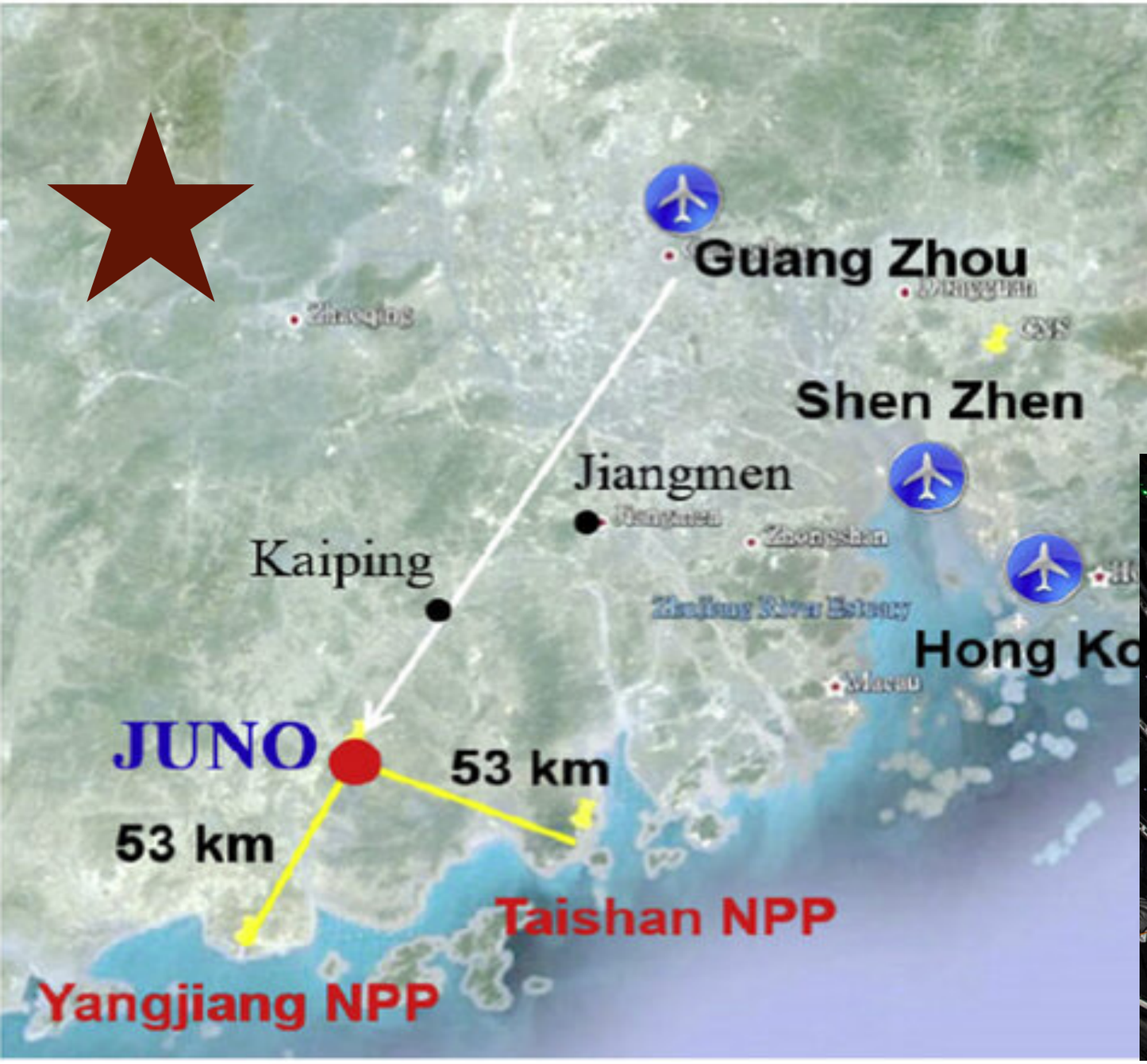


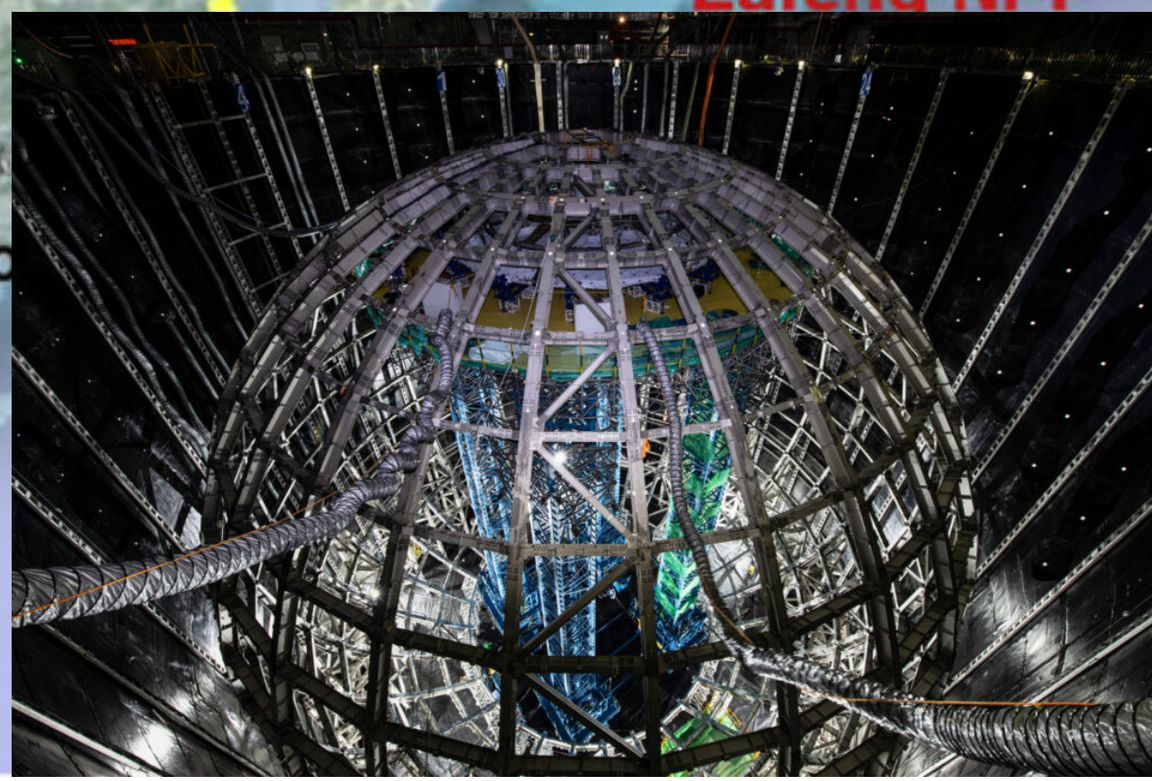
托马拉克

Sasha Tomalak

CP violation and mass hierarchy@laboratory

3σ determination of mass hierarchy

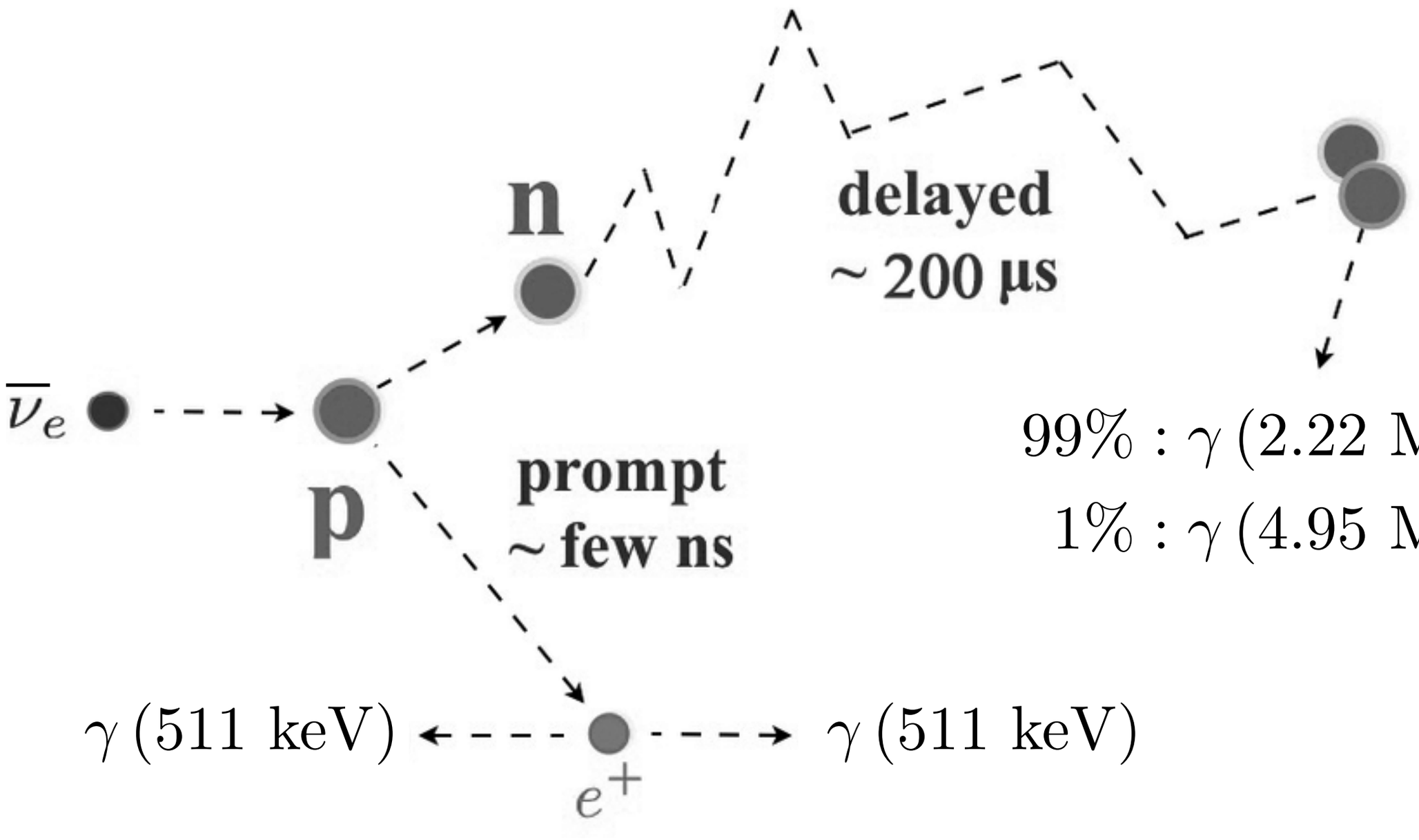




- 4 precise oscillation parameters from JUNO !!!

35 m, 20000 t

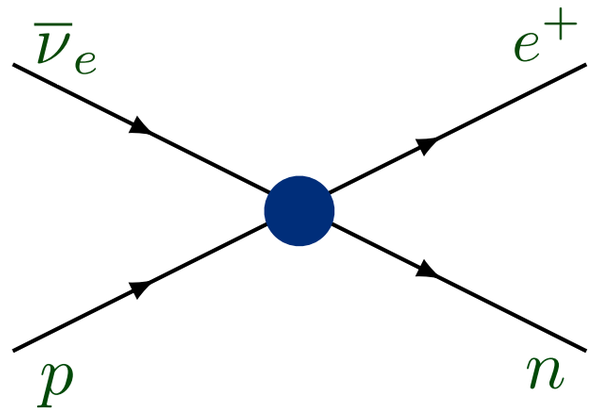
JUNO detection channel



$$99\% : \gamma\,(2.22\ \mathrm{MeV})$$
$$1\% : \gamma\,(4.95\ \mathrm{MeV})$$

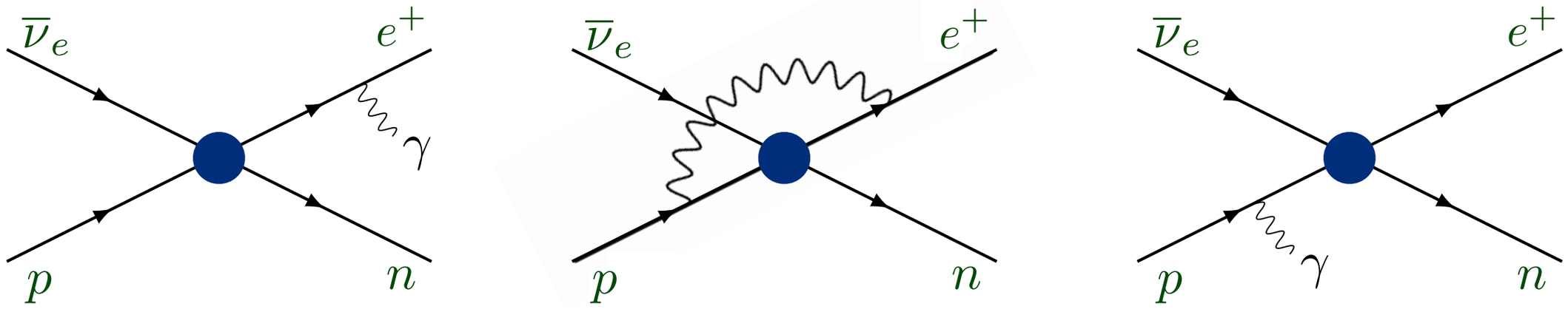
Teng Li et al., ChPC (2017)

- prompt-delayed time signature: background discrimination



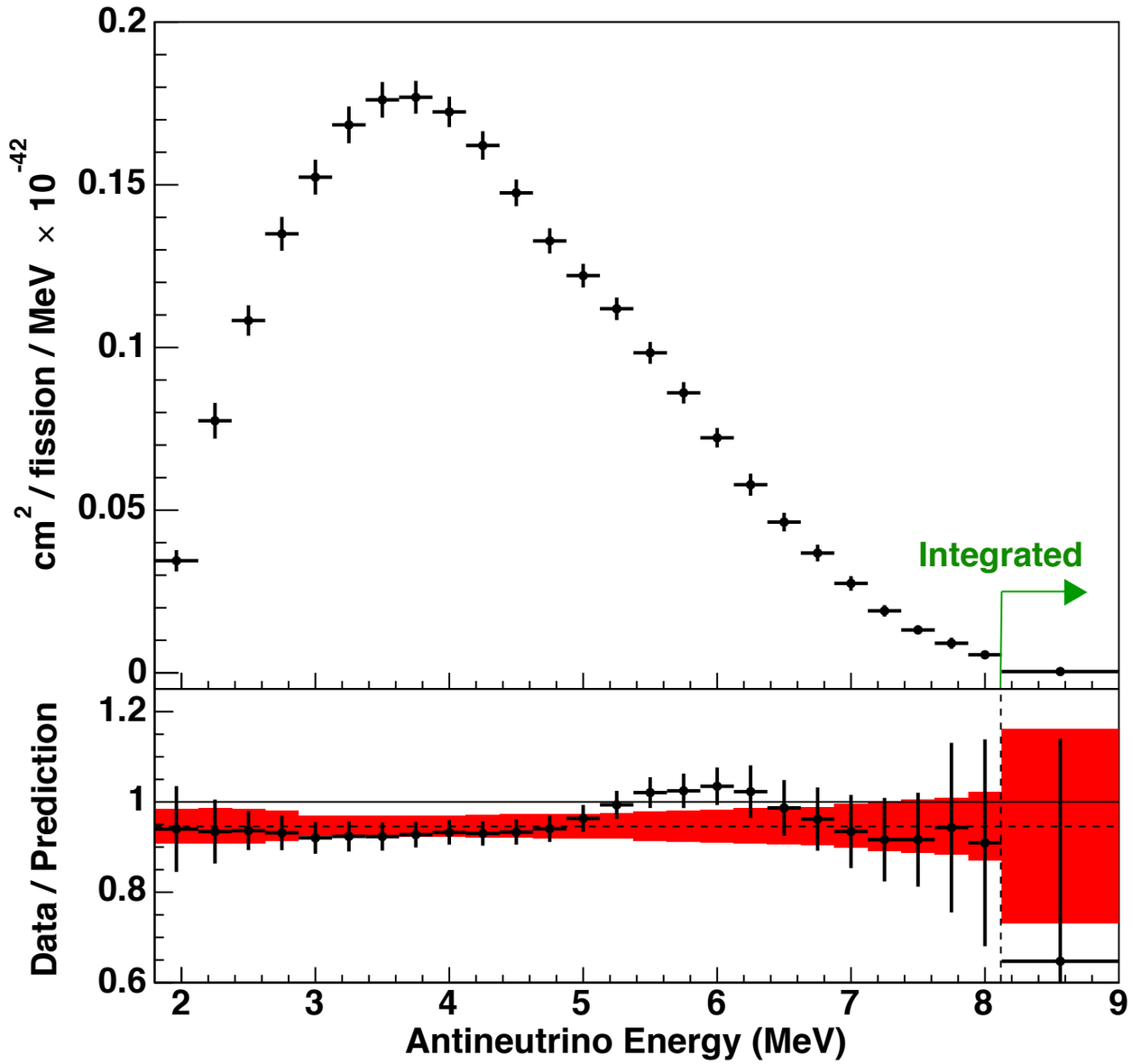
O.T., PRL (2026)

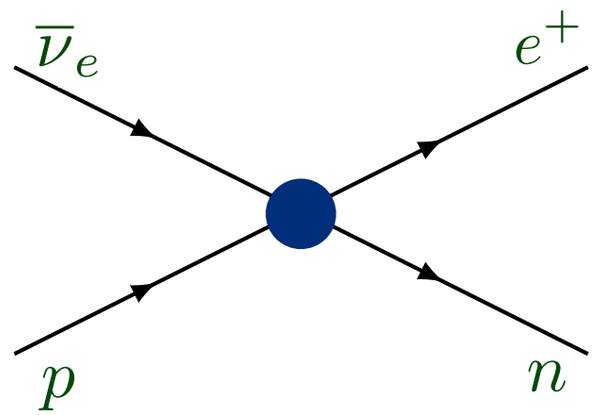
Theory of inverse beta decay for reactor antineutrinos



IBD with reactor antineutrinos

- neutron is heavier than proton by 1.3 MeV



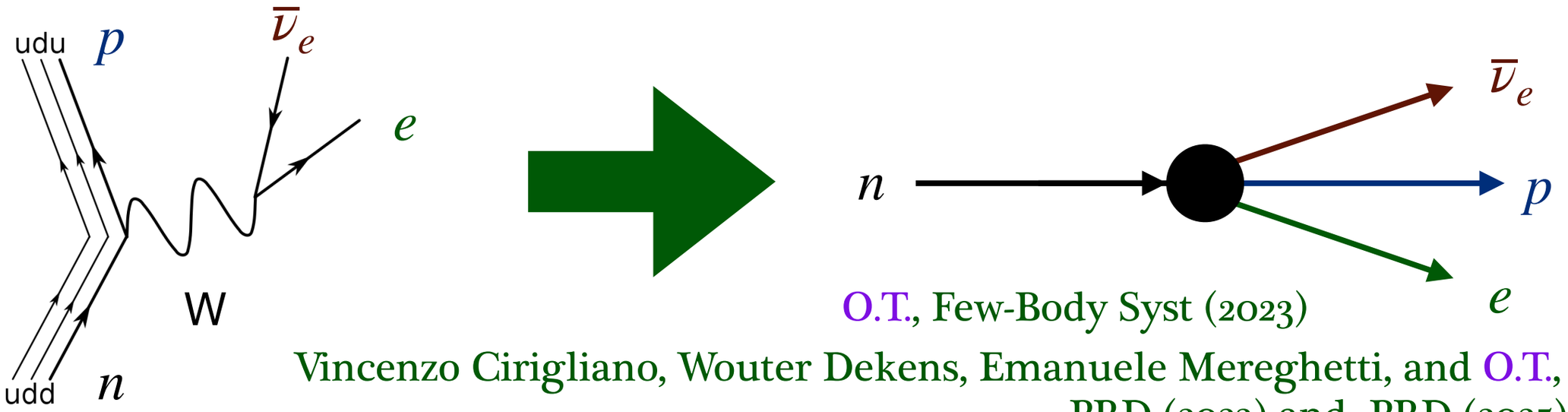


Daya Bay, PRL (2016)

- MeV-scale physics like in neutron decay

Complete EFT approach

- neutron is heavier than proton by 1.3 MeV and can 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

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

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

- systematic approach: determine low-energy coupling constants
- first consistent at 0.1%-level QED radiative corrections

Effective field theory for IBD and β decay

M_Z

full content of Standard Model (SM)

integrate out top, Z, W, h

neutrino: R. J Hill, O.T., PLB (2020)

LEFT: W. Dekens, P. Stoffer, JHEP (2019)

m_b

integrate out GeV particles

m_τ

m_c

α_s becomes too strong going to lower energies

matching to ChPT

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

m_π

dynamical pions

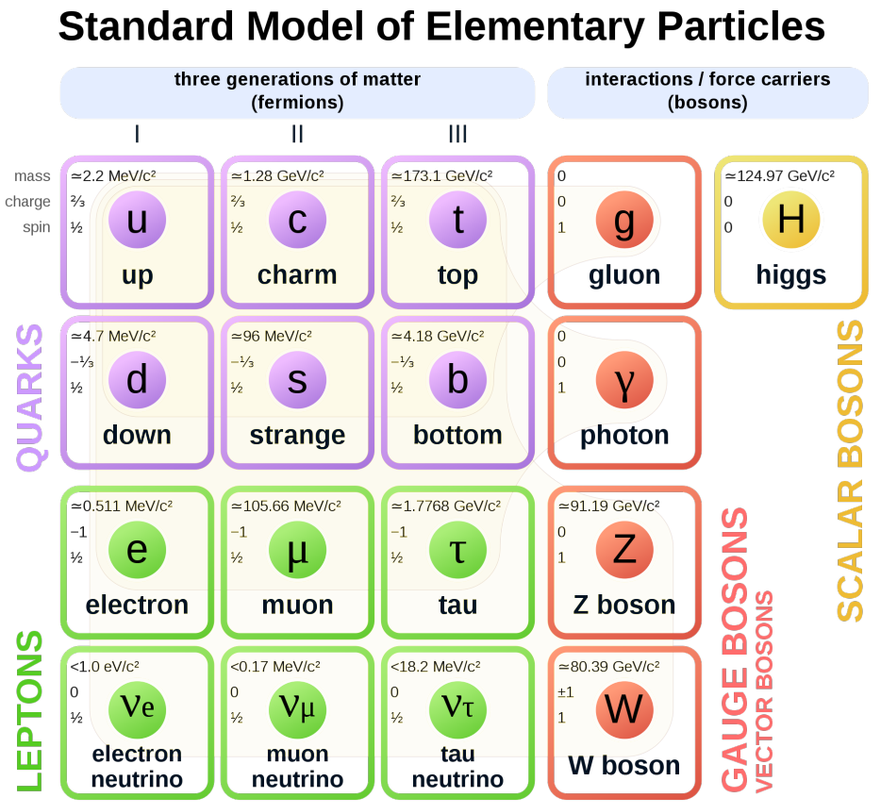
V. Cirigliano, J. de Vries, L. Hayen, E. Mereghetti, and A. Walker-Loud, PRL (2022)

photons, neutrinos, electrons, external nucleons

m_e

S. Ando et al., PLB (2004)

- coupling constants from SM + small QED corrections



One-loop result

- clear illustration of leading logarithms

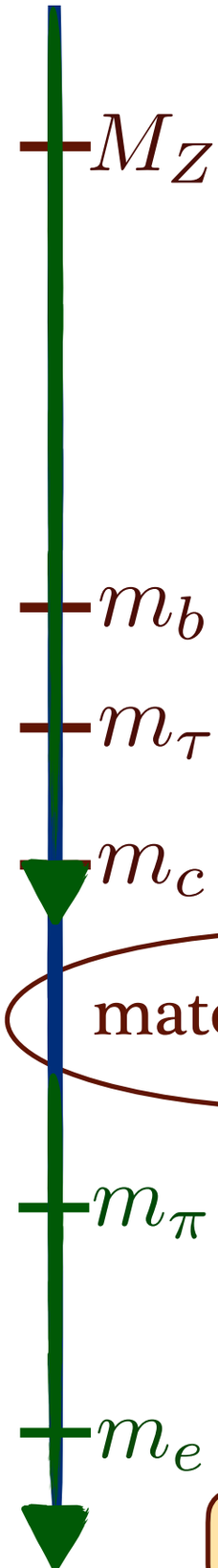
$$g_{\mathrm{V}}\left(\mu_\chi\right) = 1 - \frac{\alpha}{2\pi}\left[\frac{5}{8} + \frac{3}{4}\ln\frac{\mu_\chi^2}{\mu_0^2} + \ln\frac{\mu_0^2}{M_Z^2}\right]$$
$$- e^2\int\frac{i\mathrm{d}^4q}{(2\pi)^4}\frac{\nu^2+Q^2}{Q^4}\left[\frac{\mathrm{T}_3(\nu,Q^2)}{2\nu} - \frac{2}{3}\frac{1}{Q^2+\mu_0^2}\right]$$

- same Regge and resonance inputs as in traditional approach

- updates in elastic; DIS is part of running in LEFT

- agreement with current algebra evaluation

Effect of running



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

- 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

$$g_V(\mu_\chi = m_e) - 1 = (2.499 \pm 0.012)\,\%$$

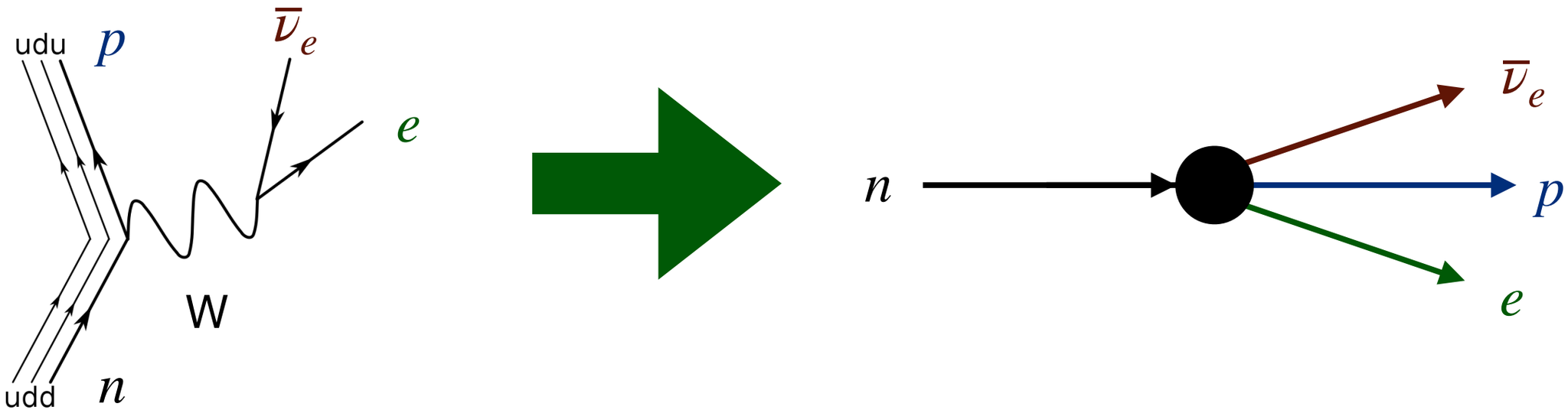
- one-loop result without $\alpha\alpha_s$ contributions

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

- cancellation of various contributions -> 0.07 % effect

Complete EFT approach

- neutron is heavier than proton by 1.3 MeV and can decay



- four-fermion interaction between leptons and heavy nucleons

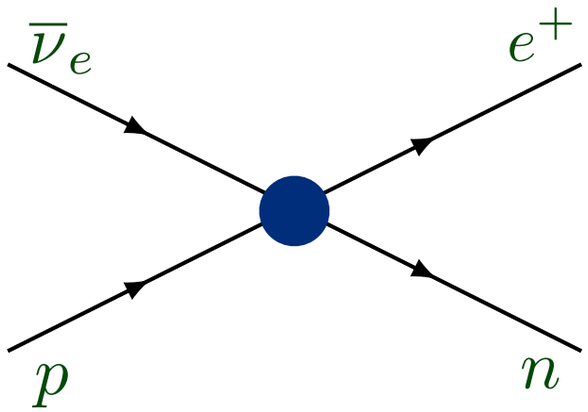
$$\mathcal{L}_{\text{eff}} = -\sqrt{2}\mathrm{G_F} V_{ud} \bar{e}\gamma_\mu \mathrm{P_L}\nu_e \cdot \overline{N}\left(g_V v^\mu - 2 g_A S^\mu\right)\tau^+ N$$

g_V : theoretical prediction from Standard Model

g_A : beta asymmetry in polarized neutron decay

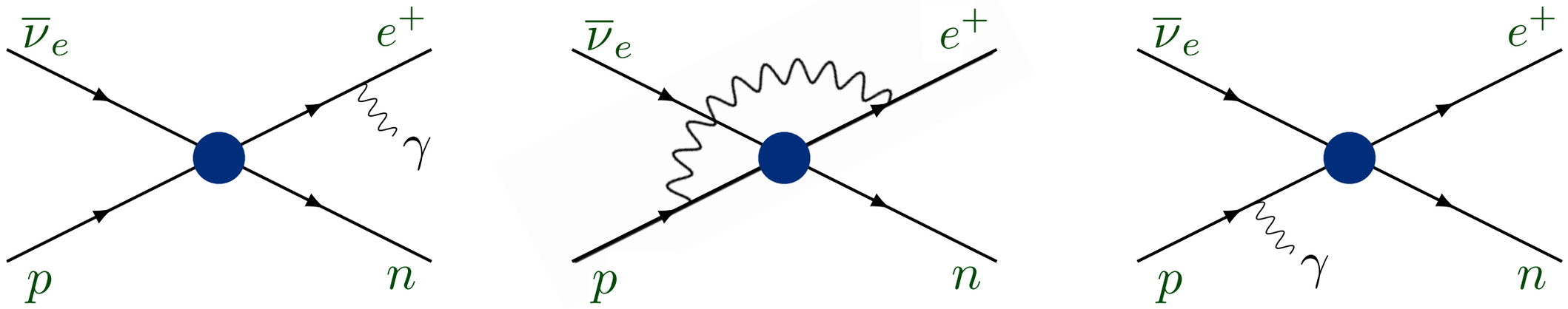
V_{ud}: superallowed transitions

- first consistent at 0.1%-level QED radiative corrections

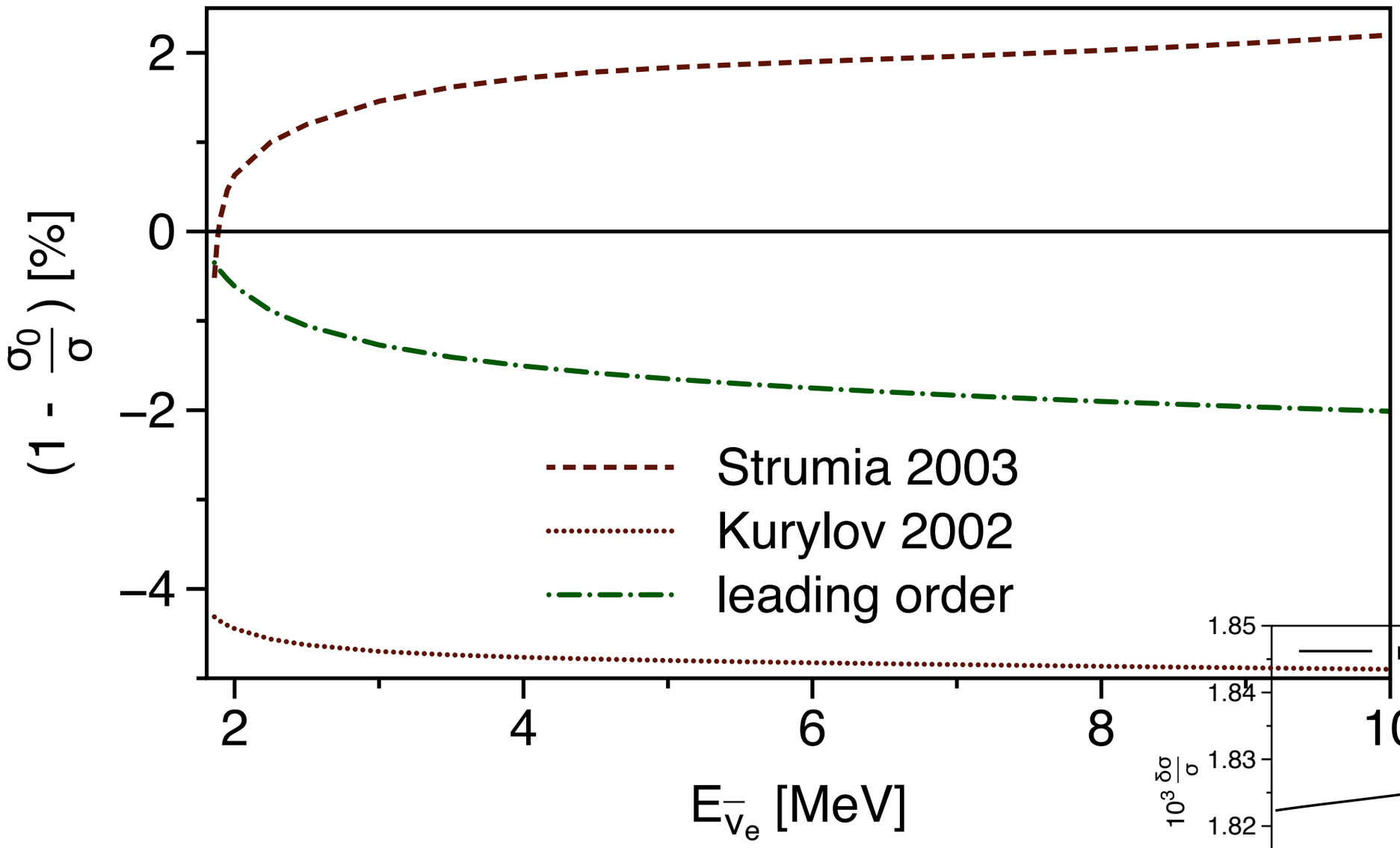


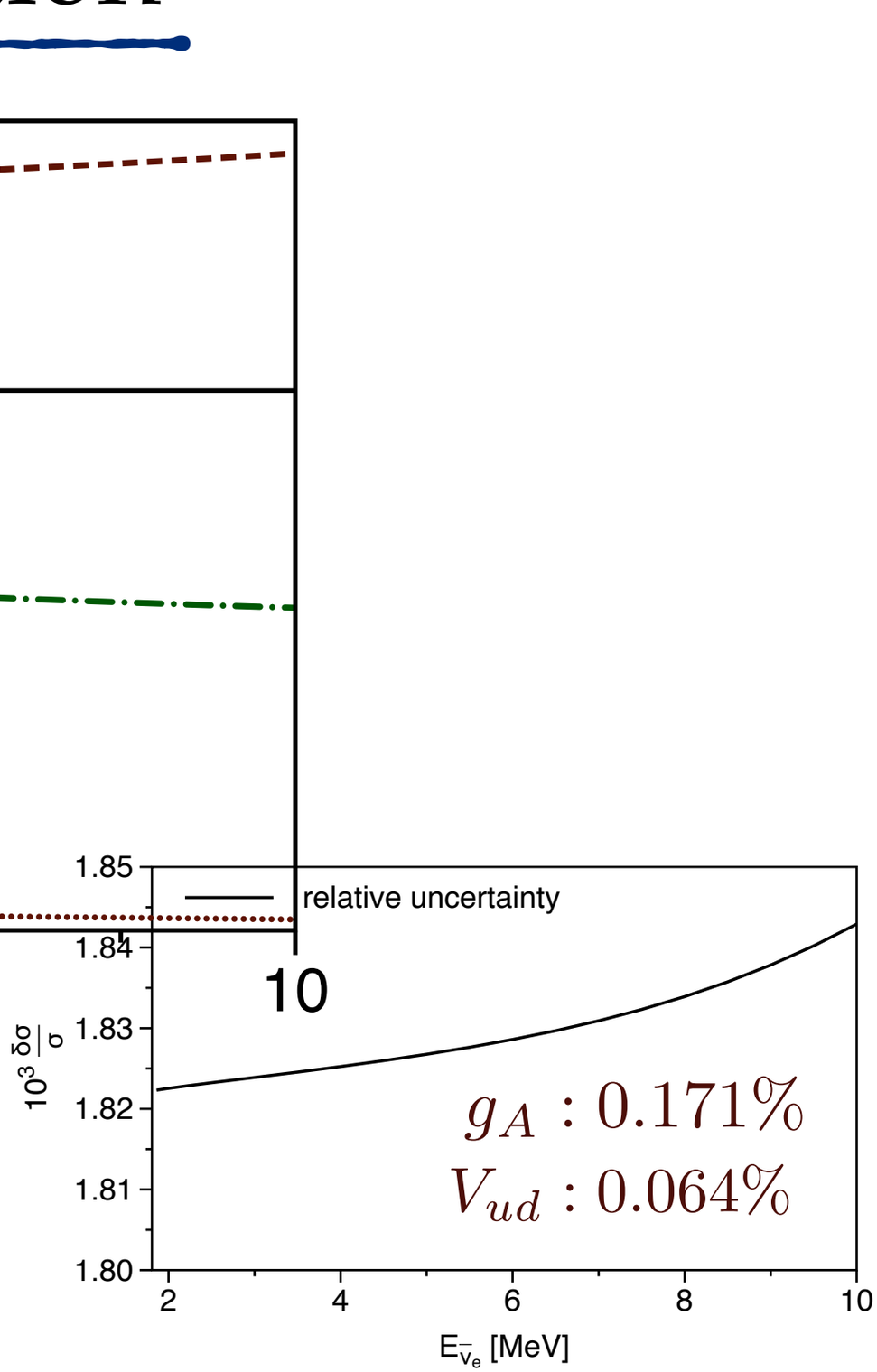
O.T., PRL (2026)

Theory of inverse beta decay for reactor antineutrinos



Total cross section



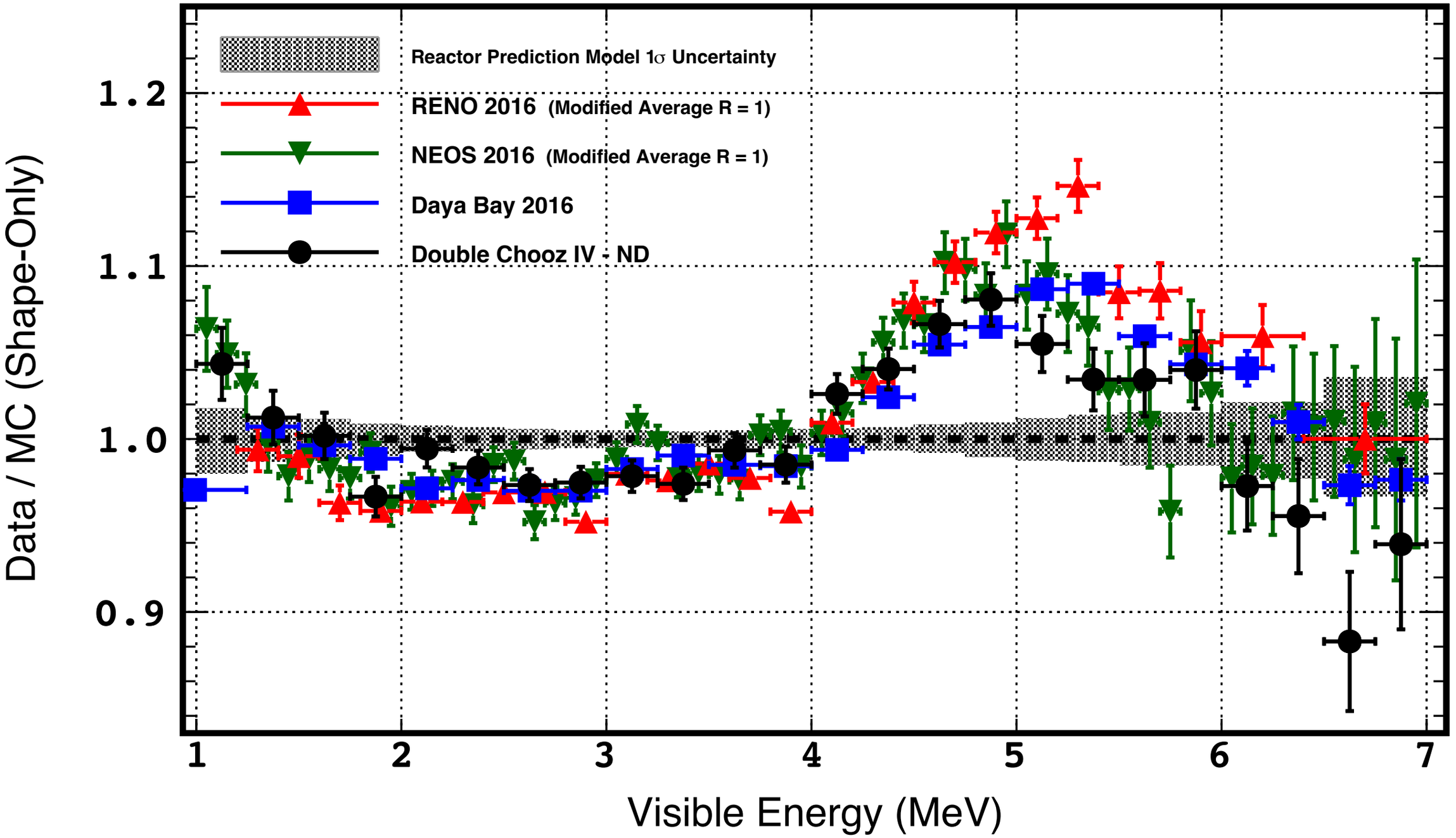


σ_0 - reference

σ - this work

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

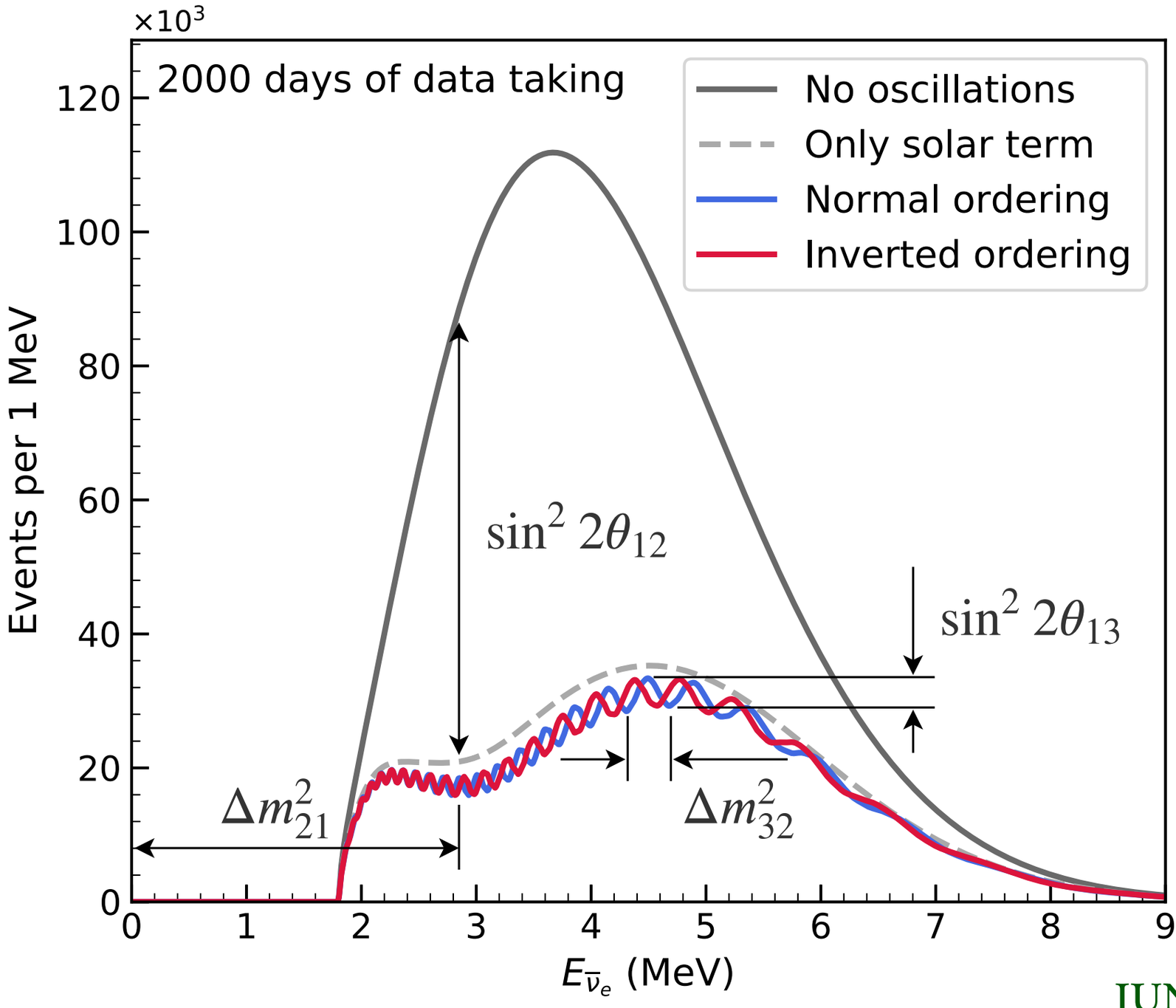
5-MEV flux excess



Double Chooz, Nature Phys (2019)

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

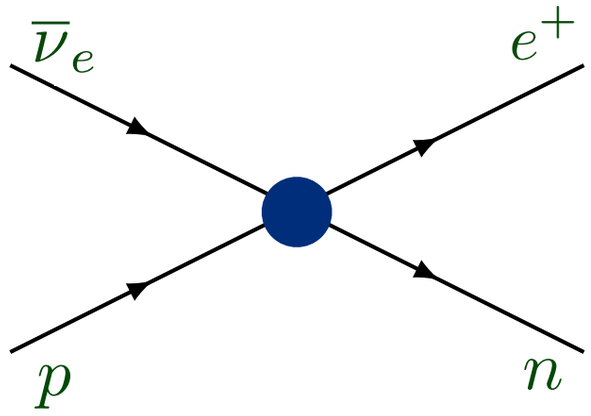
Energy reconstruction is key

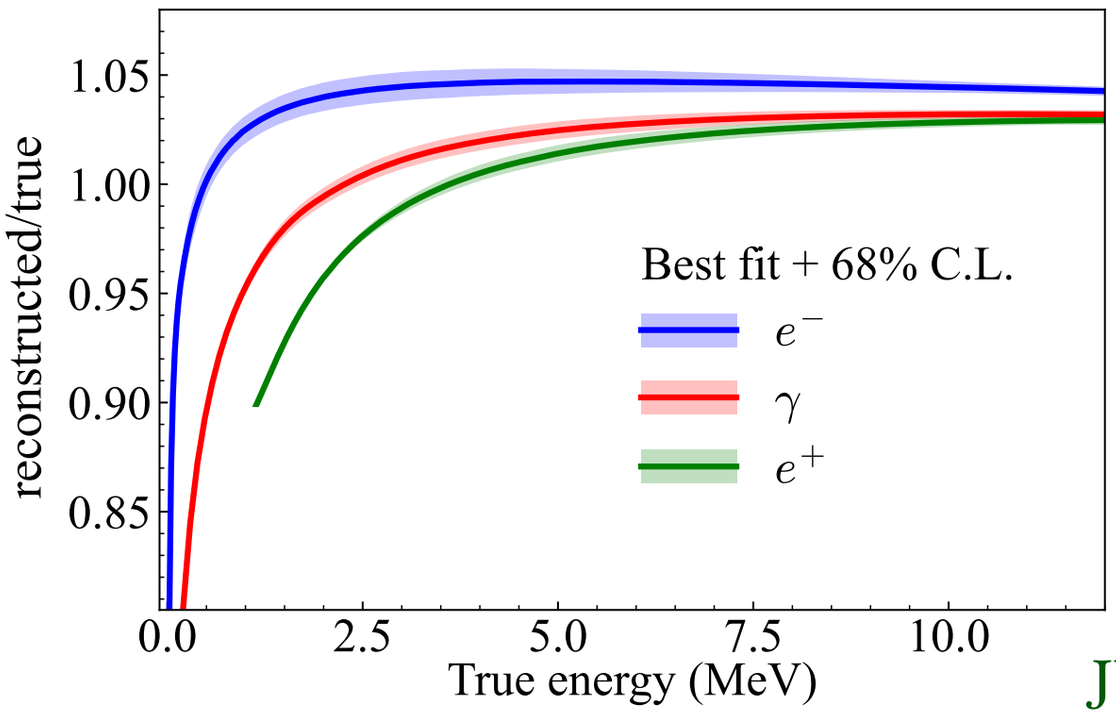


JUNO, PPNP (2021)

- JUNO: 3% energy reconstruction for precision goals

Energy reconstruction is key



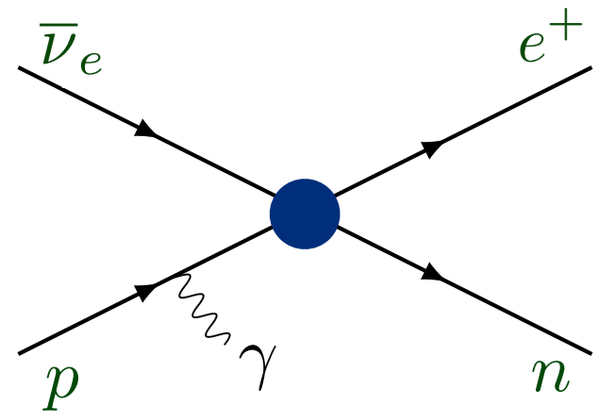


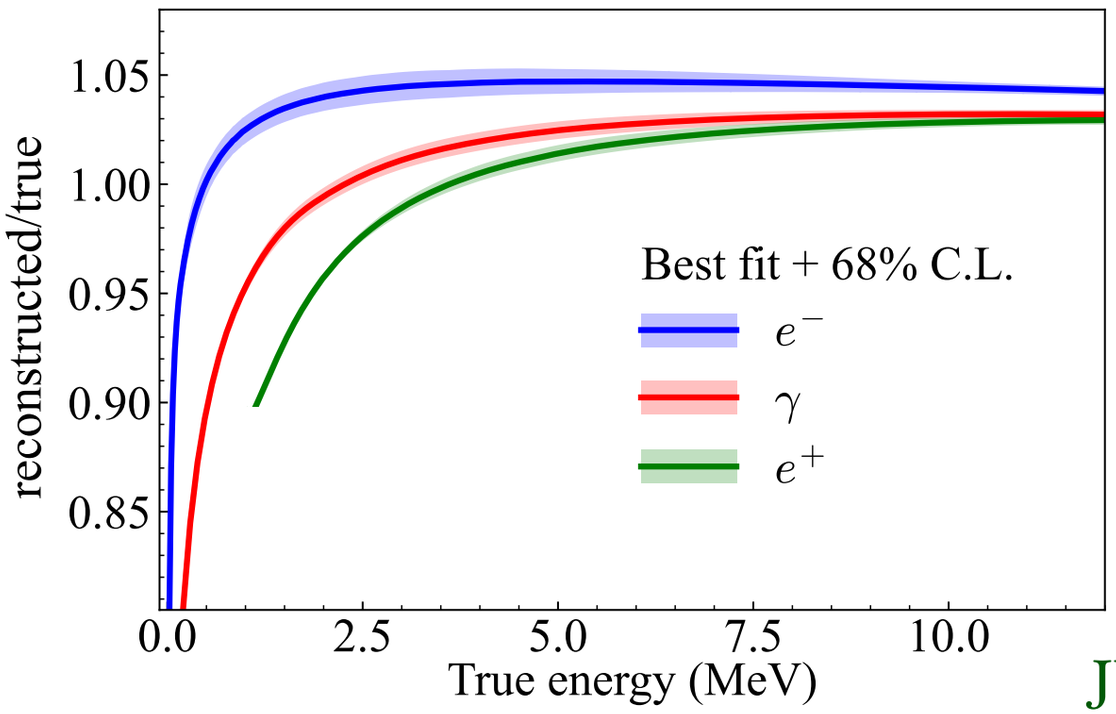
JUNO, Nature (2026)

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

- control over each particle is necessary to achieve precision

Energy reconstruction is key





JUNO, Nature (2026)

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

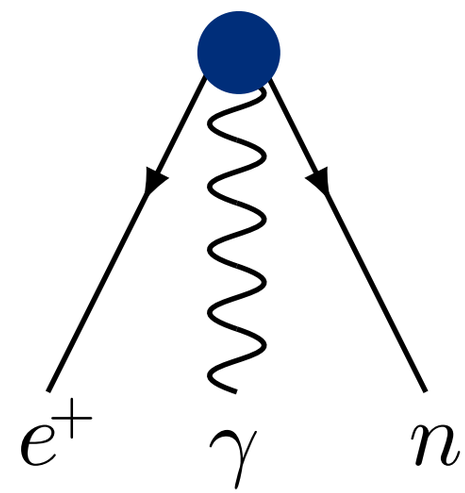
- control over each particle is necessary to achieve precision

Bremsstrahlung

- new distributions beyond E_{EM} spectrum

E_n, E_γ, θ_n → E_n, θ_n → E_n, E_{EM}

E_e, E_γ, θ_e → E_e, θ_e → E_e



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

consistency at cross-section level

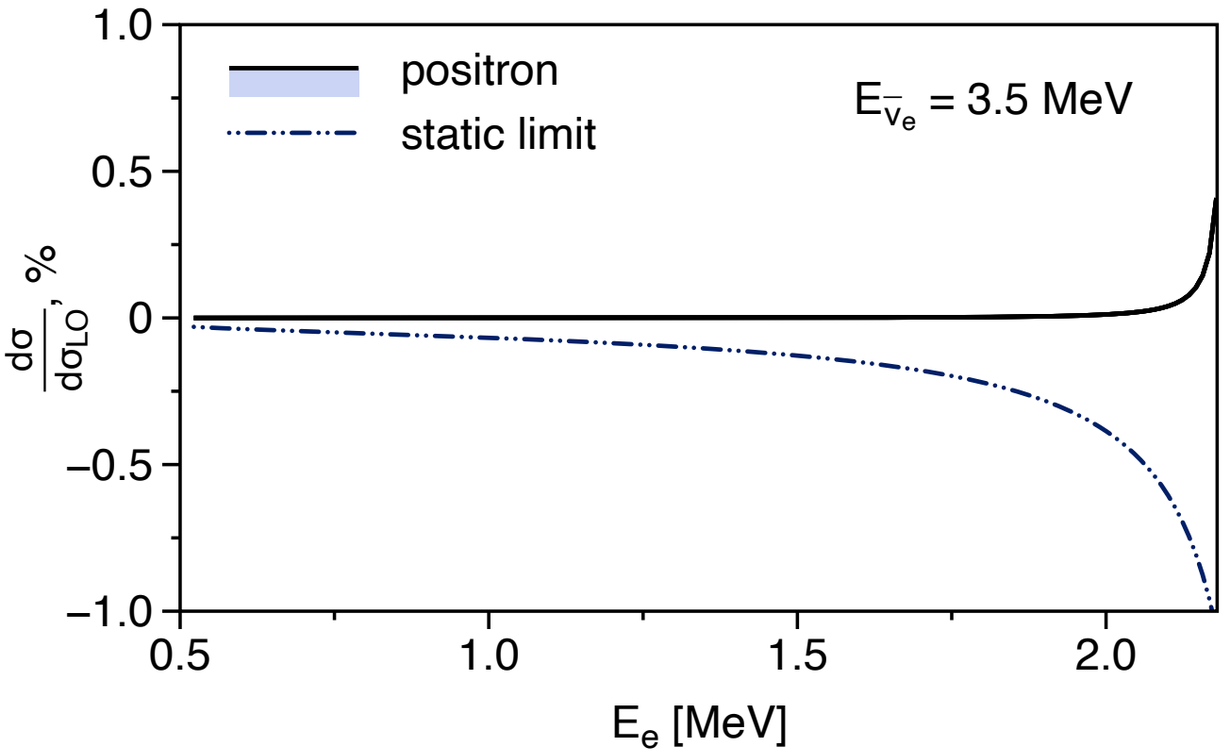
O.T., PRL (2026)

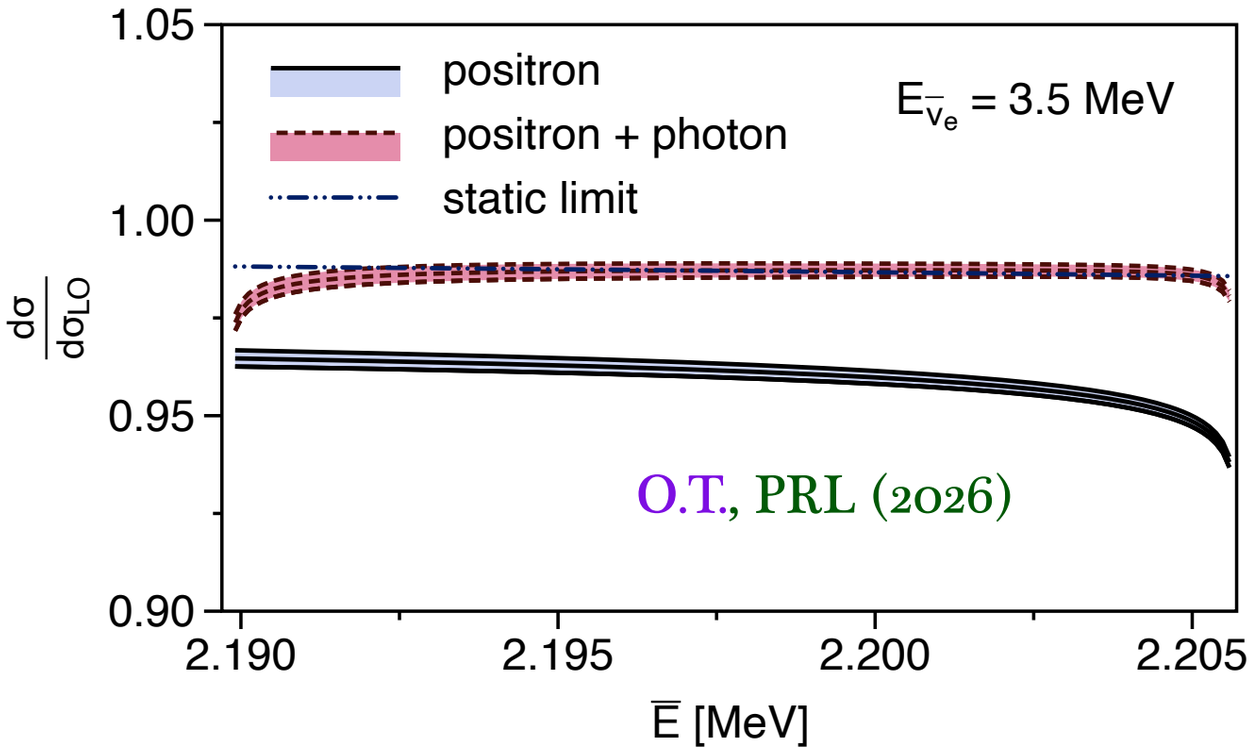
total cross section

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

Access each particle kinematics

- evaluate radiative process w/o no-recoil approximation



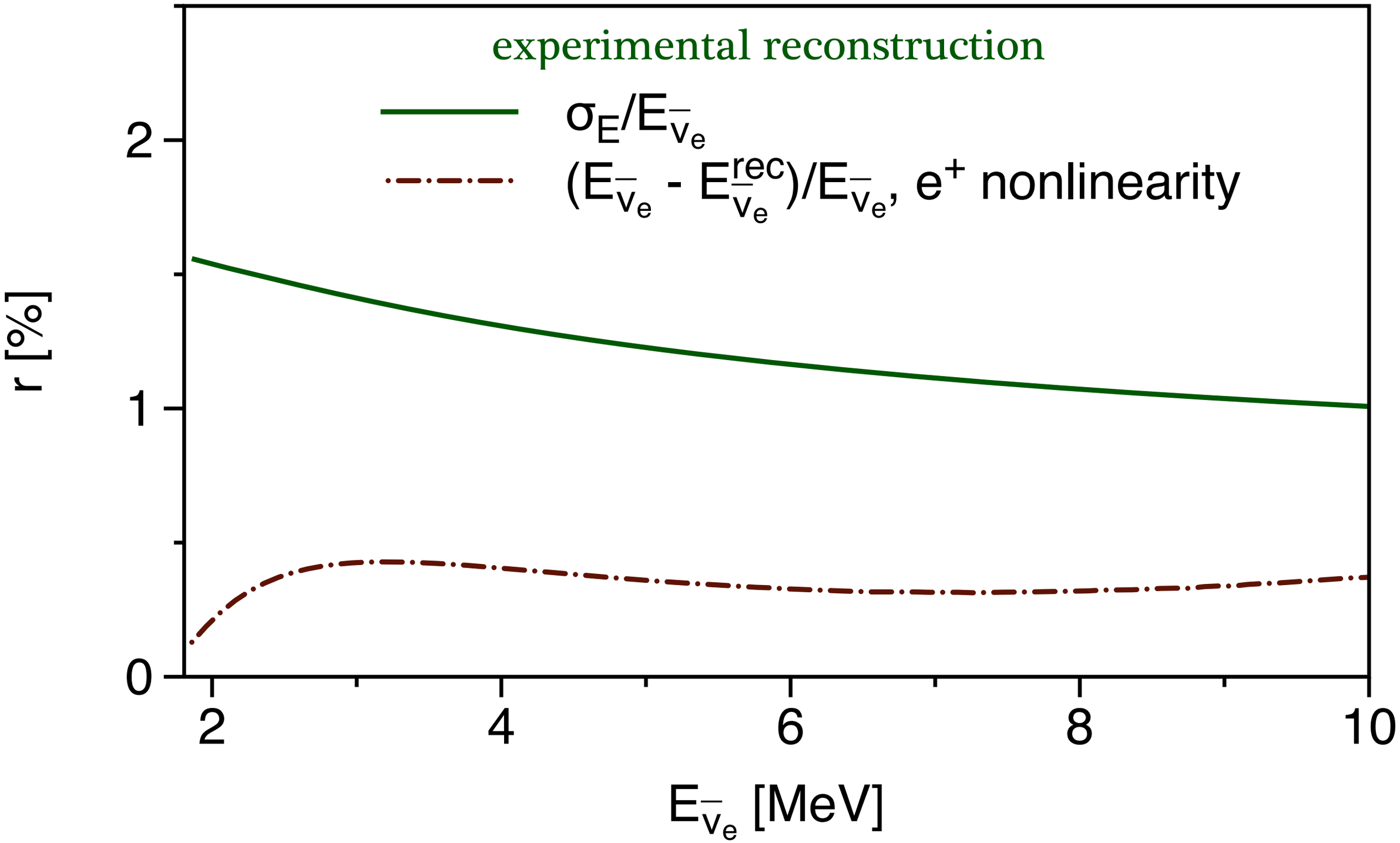


- 1st analytic expression for positron energy spectrum

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

- control over each particle is necessary to achieve precision

Energy reconstruction is key

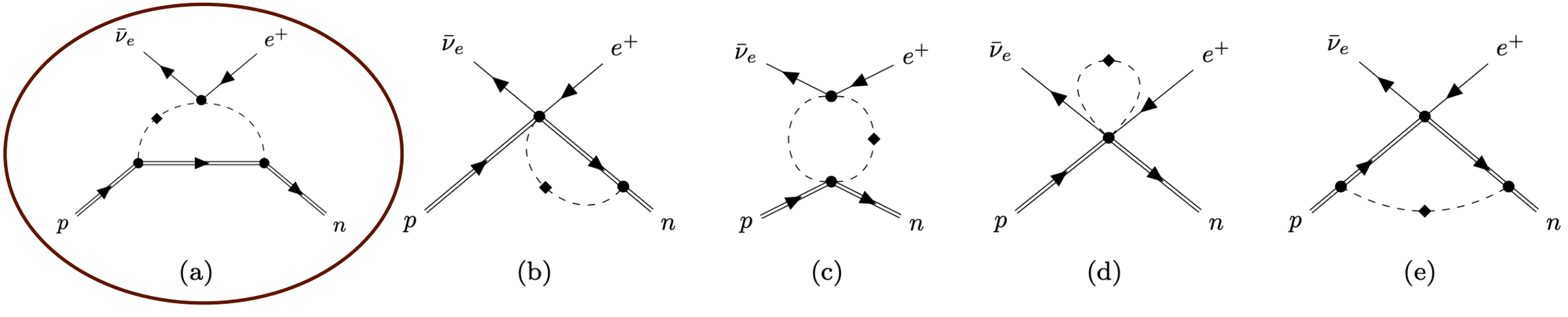


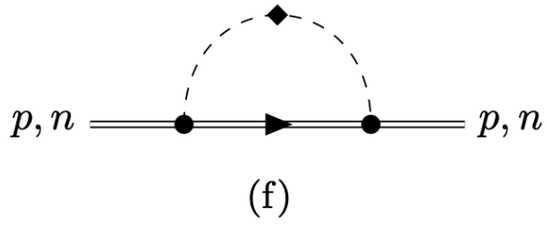
- radiative effects ~ 1/3 of expected resolution

O.T., Qishan Liu, Yu-Feng Li, PRD (2026)

Supernova and πDAR energies

- include pion degrees of freedom to inverse beta decay





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

O.T., JHEP (2026)

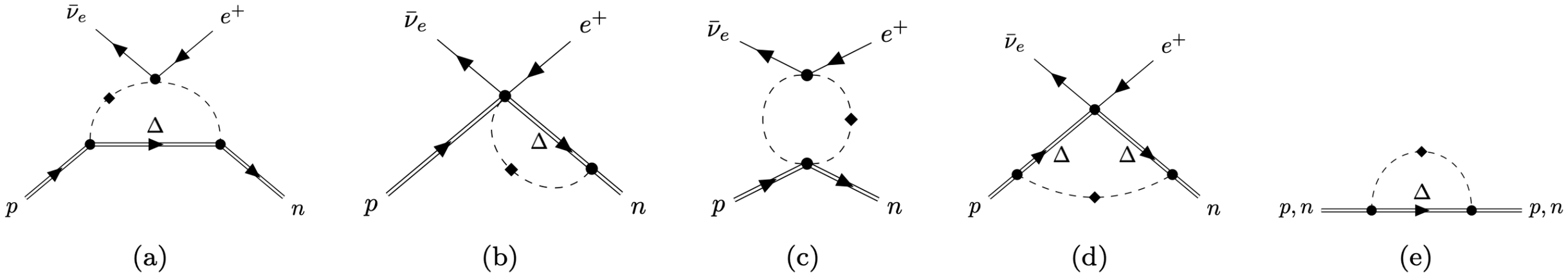
- neglect recoil diagrams without pions

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

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

Supernova and πDAR energies

- include Δ degrees of freedom to inverse beta decay



$+$ N instead of Δ $+$ N instead of Δ

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

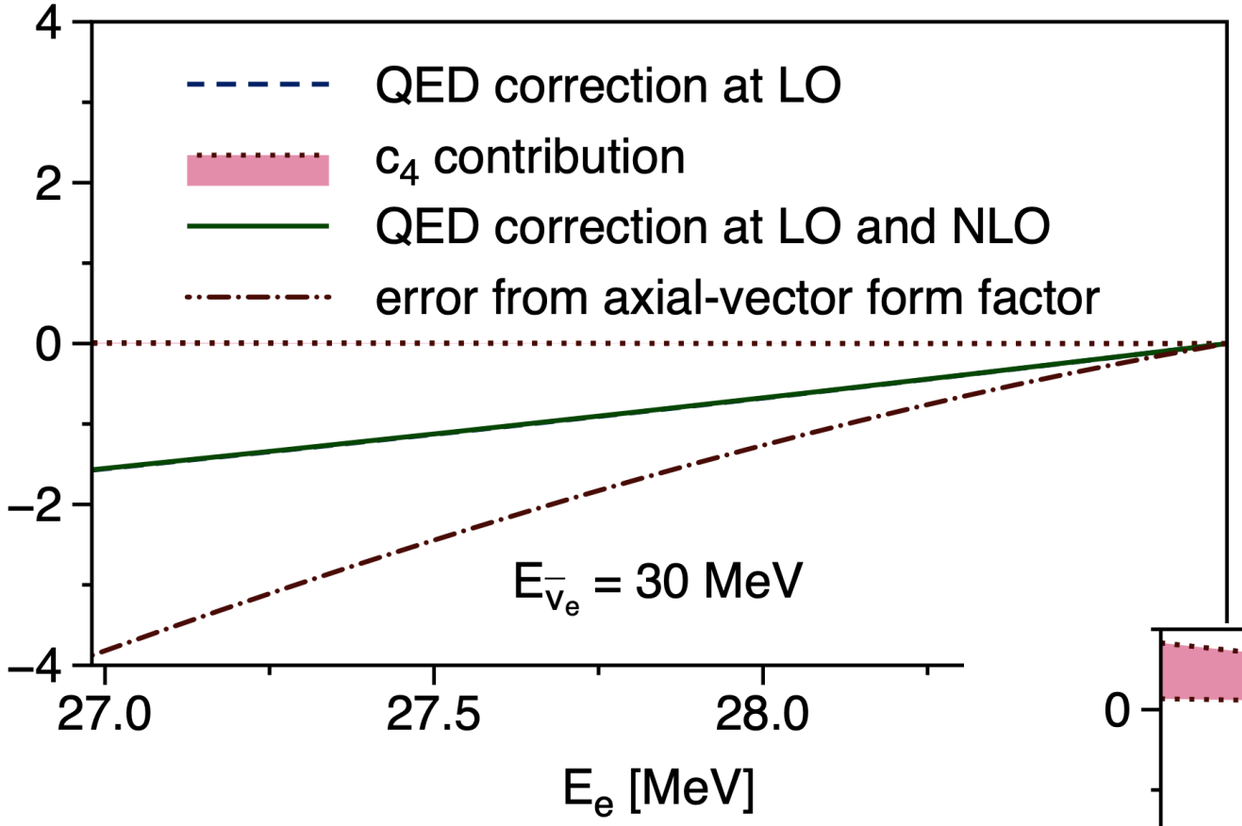
O.T. and Yi-Bo Yang, arXiv: 2608.22845

- neglect recoil diagrams without pions

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

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

Supernova and πDAR energies

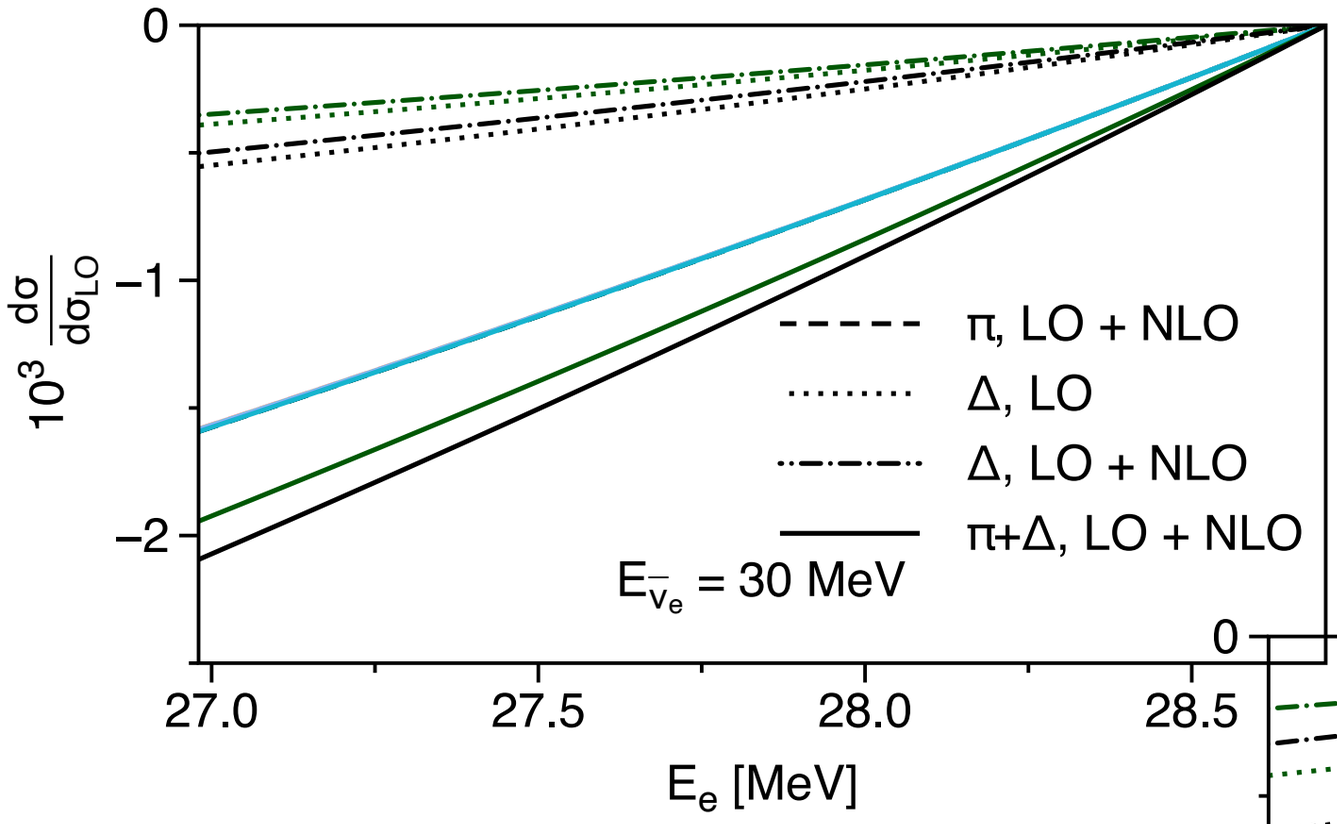


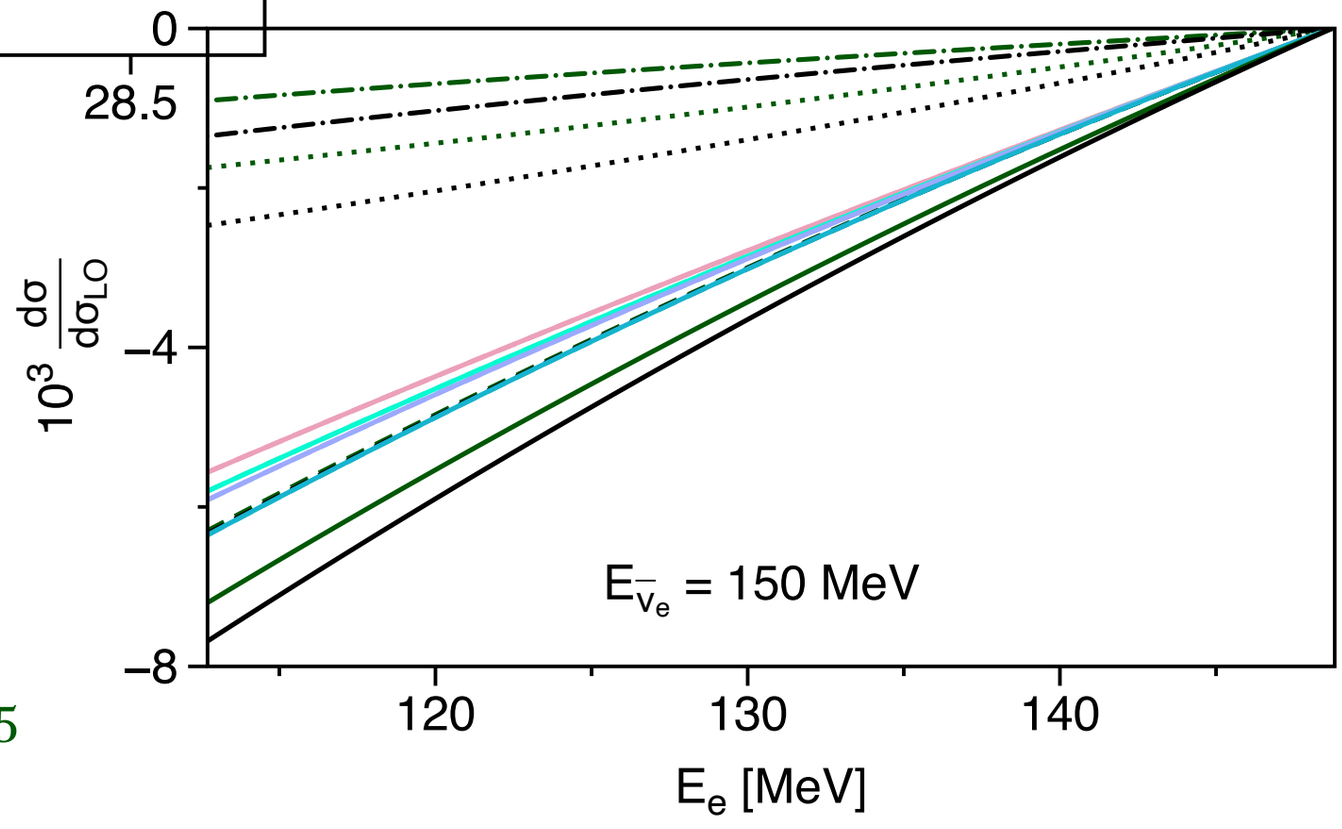
Wilson coefficient c_4 enters at higher energies

O.T., JHEP (2026)

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

Supernova and πDAR energies



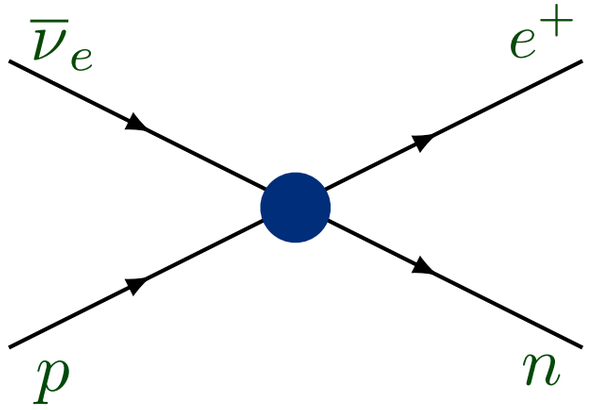


no dependence on
NLO Wilson coefficients

O.T. and Yi-Bo Yang, arXiv: 2608.22845

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

Conclusions



radiative corrections
in EFT framework
+ scheme-dependence

Standard Model -> LEFT -> HBχPT -> πEFT

- 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

- 1st evaluation of π-, Δ-induced corrections to inverse beta decay

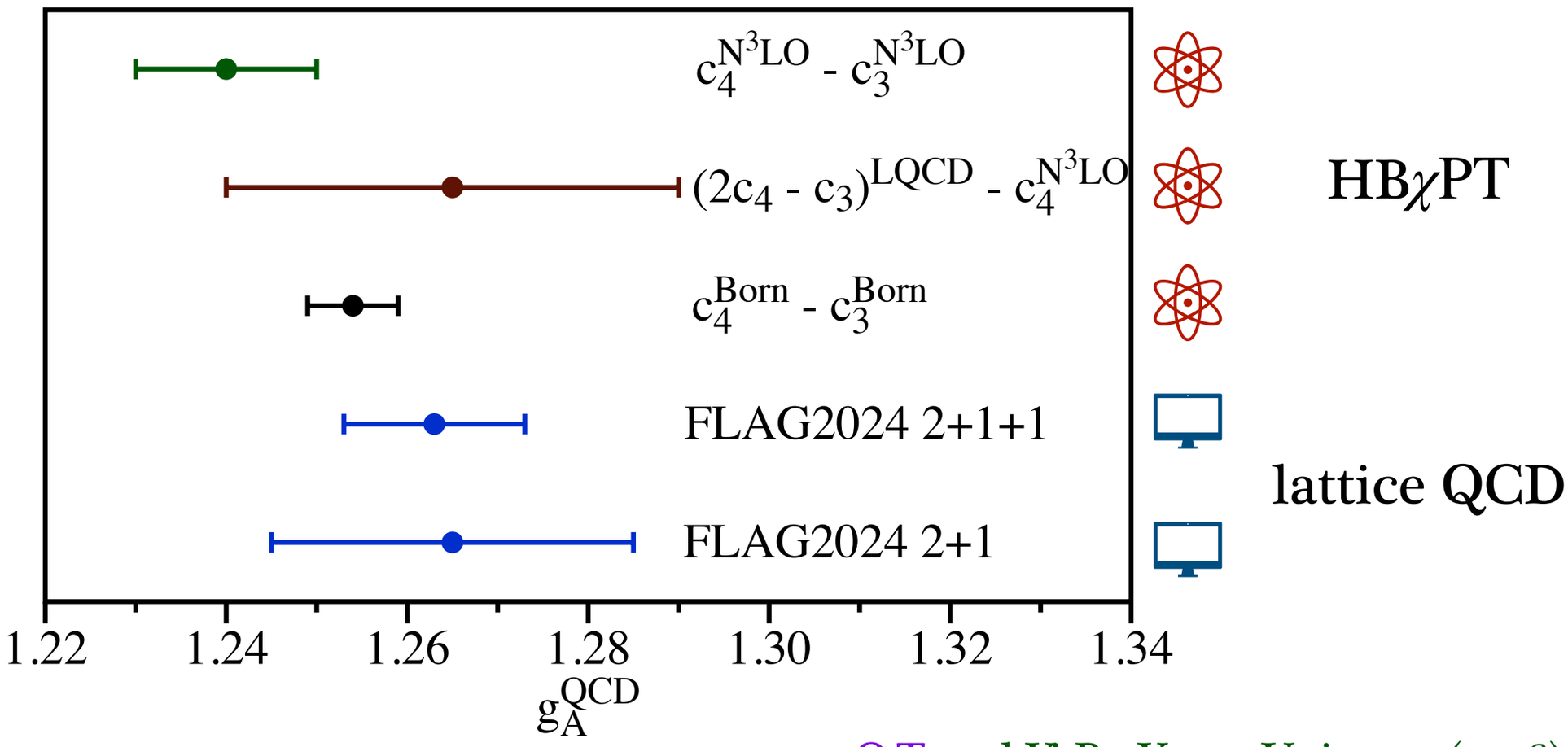
Thanks for your attention !!!

谢谢

Nucleon axial-vector charge

- effective field theory approach to low-energy charged currents

Standard Model -> LEFT -> HBχPT -> πEFT

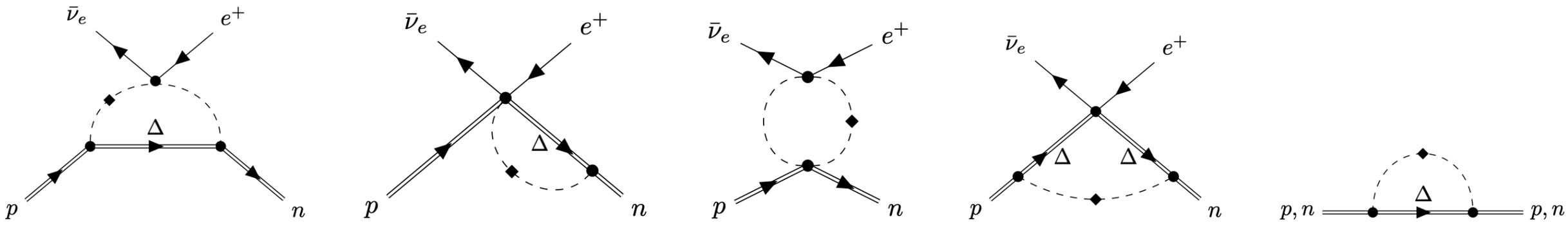


O.T. and Yi-Bo Yang, Universe (2026)
Vincenzo Cirigliano, Wouter Dekens, Emanuele Mereghetti, and O.T., PRD (2024) and PRD (2025)
V. Cirigliano, J. de Vries, L. Hayen, E. Mereghetti, and A. Walker-Loud, PRL (2022)

- first consistent framework of QED radiative corrections

Nucleon axial-vector charge

- ~1st evaluation of diagrams with Δ in HBChPT, small-scale expansion



N instead of Δ N instead of Δ

fits to πN data from

Siemens et al, PRC (2017)
Siemens, arXiv (2020)

%	HBChPT pions	HBChPT pions and delta	Wilson coefficients
pion LO	0.99 (0.18)	0.99 (0.18)	
pion NLO	1.4	0.4	c3, c4
delta LO	-	0.3	h, g1
delta NLO	-	0.7	b4, b5
extra	0.16 (0.30)	0.16 (0.30)	
total	2.6 (0.4)	2.5 (0.4)	

O.T. and Yi-Bo Yang, arXiv: 2608.22845

- Δ resonance improves power counting and reduces QED

Low-energy description

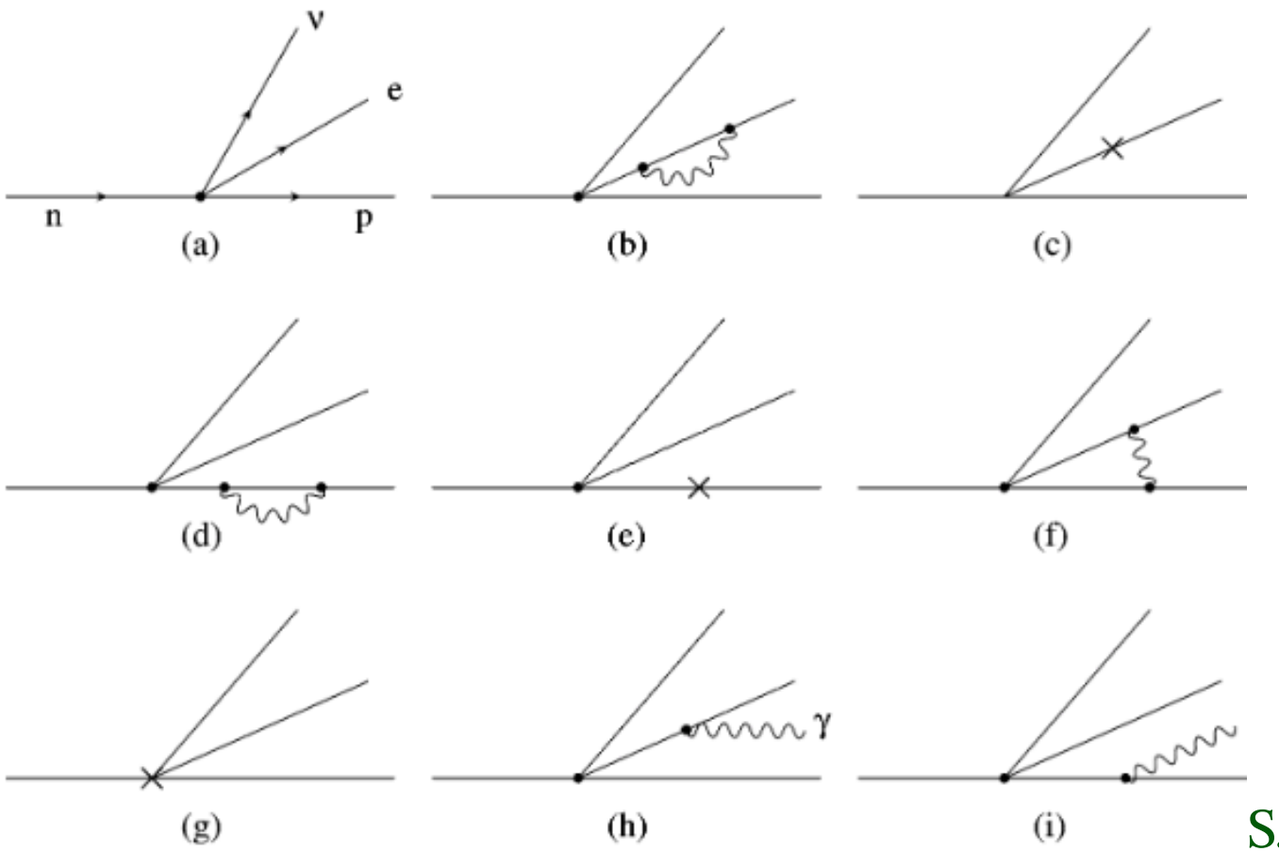
- four-fermion interaction between leptons and heavy nucleons

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

$$m_e \sim M_p - M_n$$

A. Sirlin, Phys. Rev. (1967)

- radiative corrections formulated in modern EFT language



vector and axial-vector counterterms (diagrams c, e, g)

data — Standard Model

S. Ando et al., PLB (2004)

- two coupling constants predict all observables

PMNS oscillation matrix

neutrinos produced and detected in flavor basis

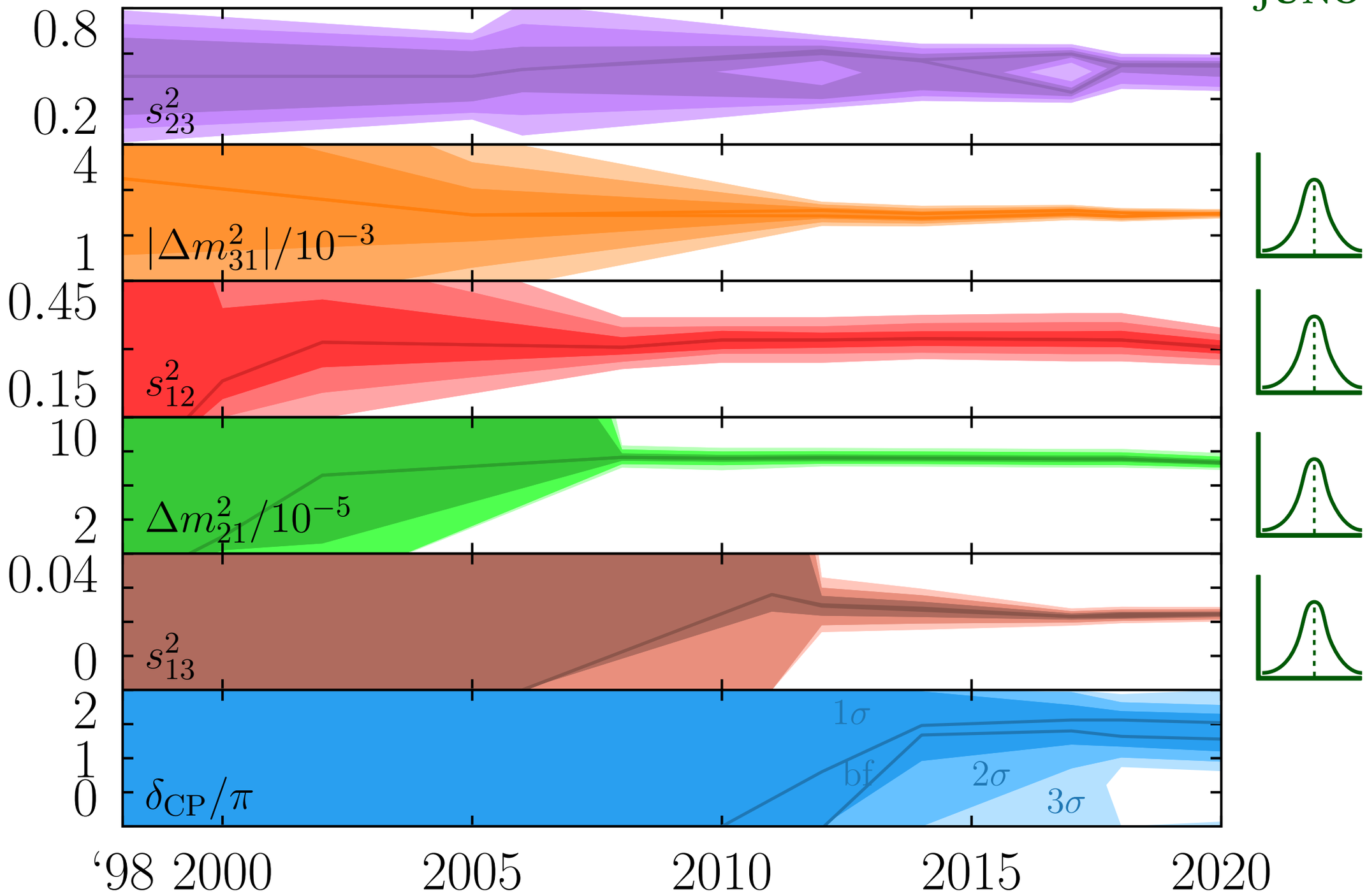
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

neutrinos propagate in mass basis

Pontecorvo-Maki-Nakagawa-Sakata matrix relates two bases

- oscillations are described by PMNS mixing matrix

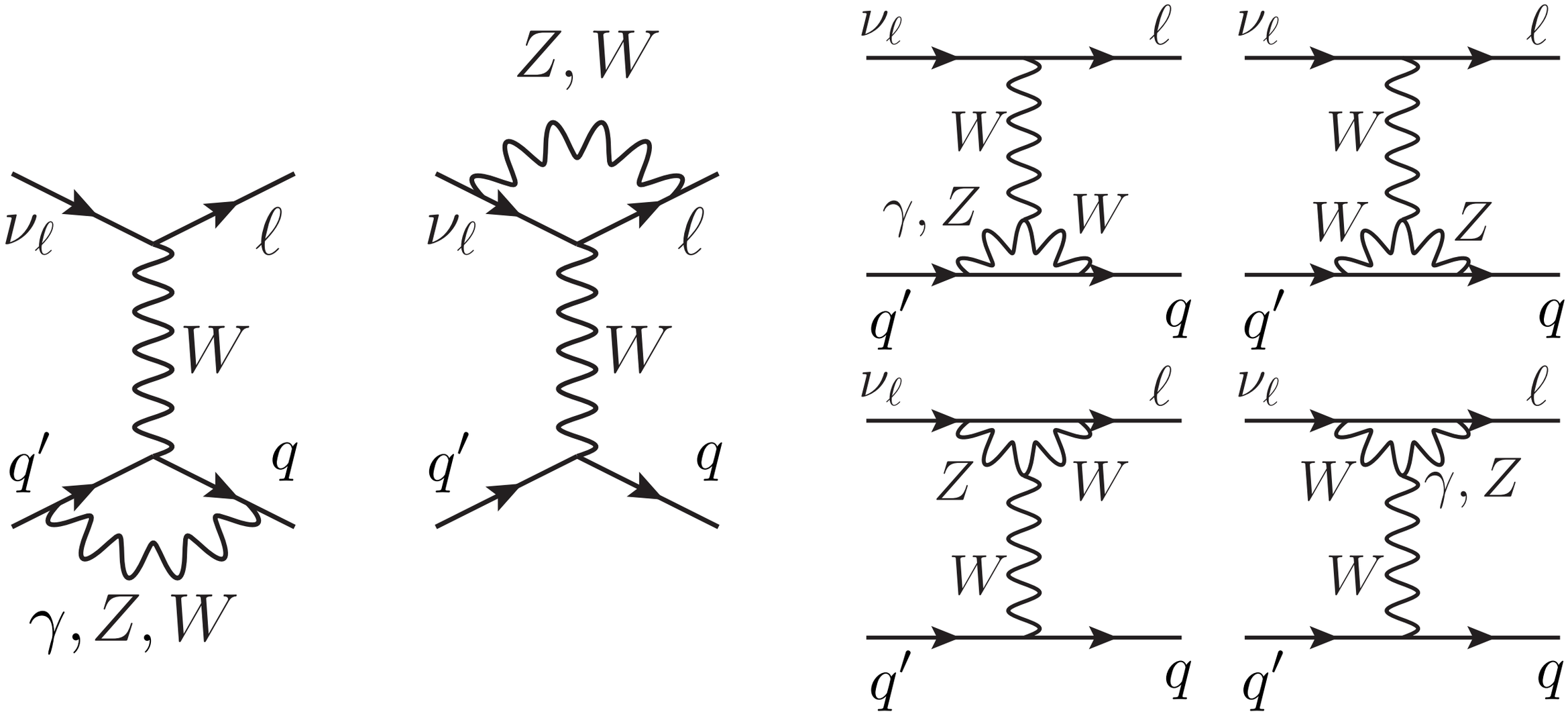
PMNS oscillation matrix



Snowmass 2021 NF01 group report

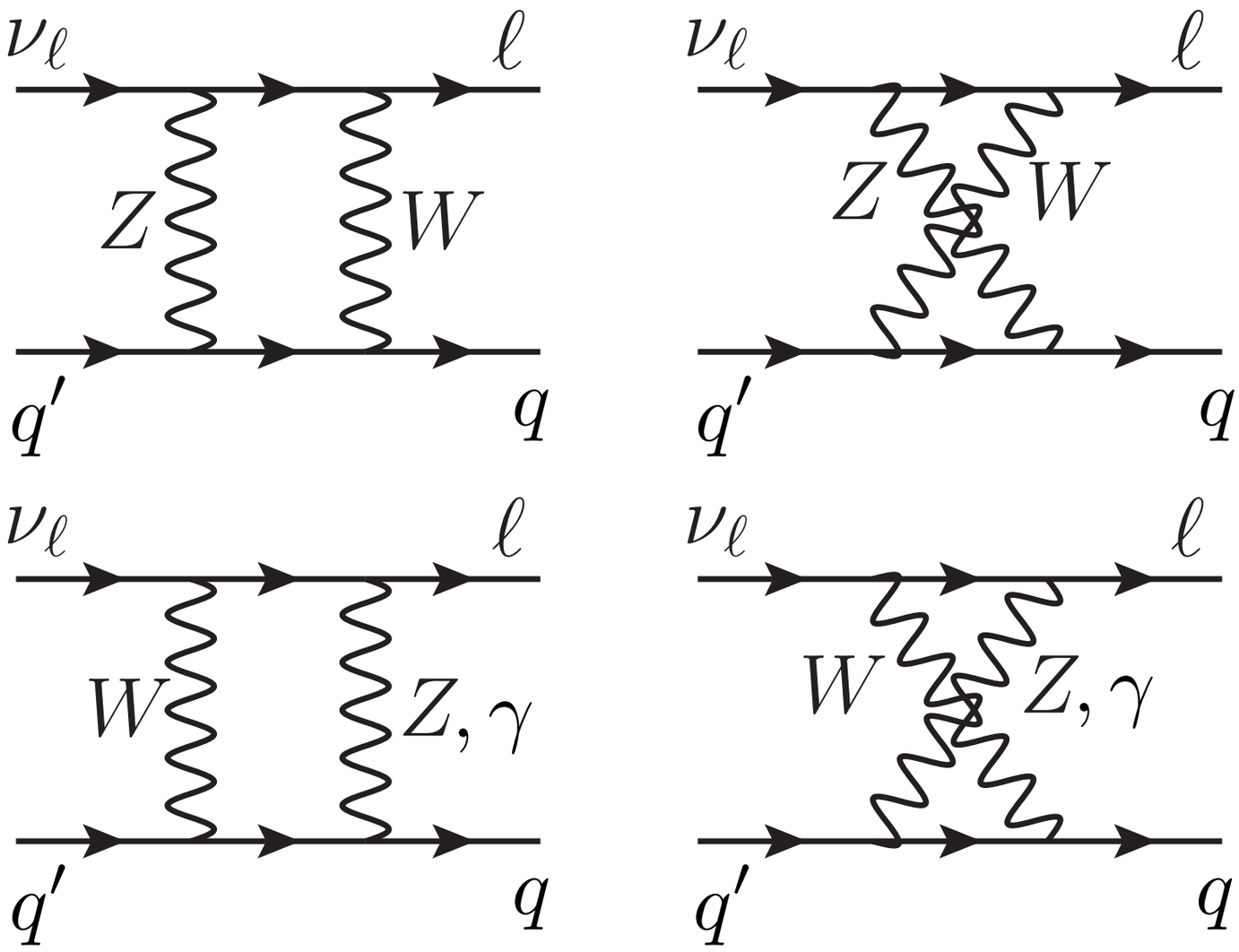
- tremendous progress in our lifetime

Charged current in SM. Vertexes



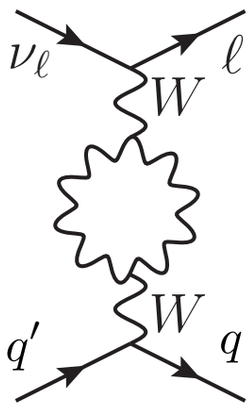
- contribution to effective couplings

Charged current in SM. Boxes

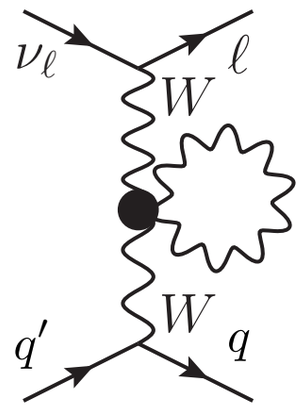


- contribution to effective couplings

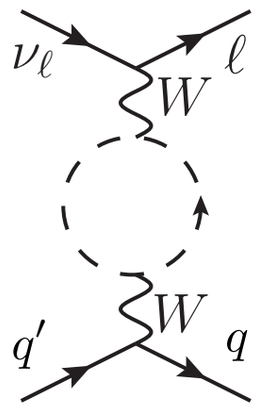
W self energy



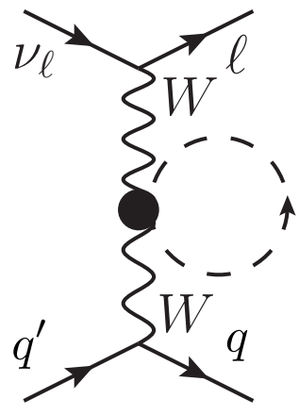
ZW,γW



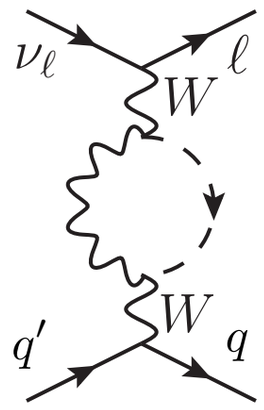
WW,ZZ,$\gamma\gamma$



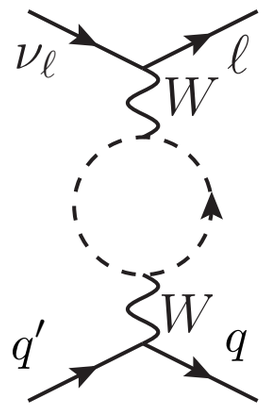
hφ,$\chi\varphi$,χ



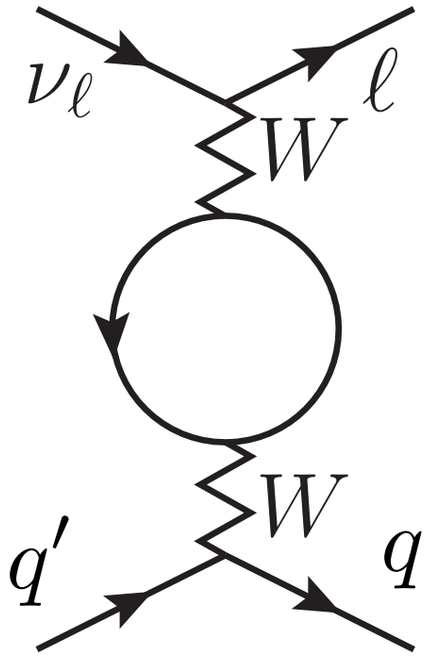
$\varphi\varphi$,$\chi\chi$,hh



Wh,Zφ,$\gamma\varphi$



cc

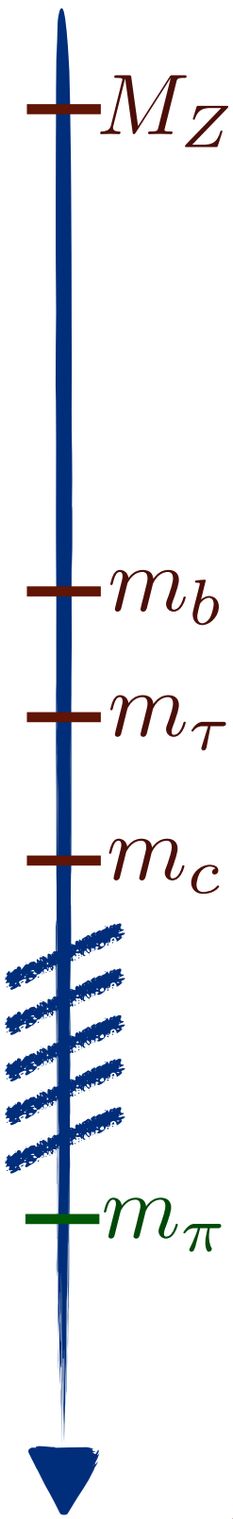


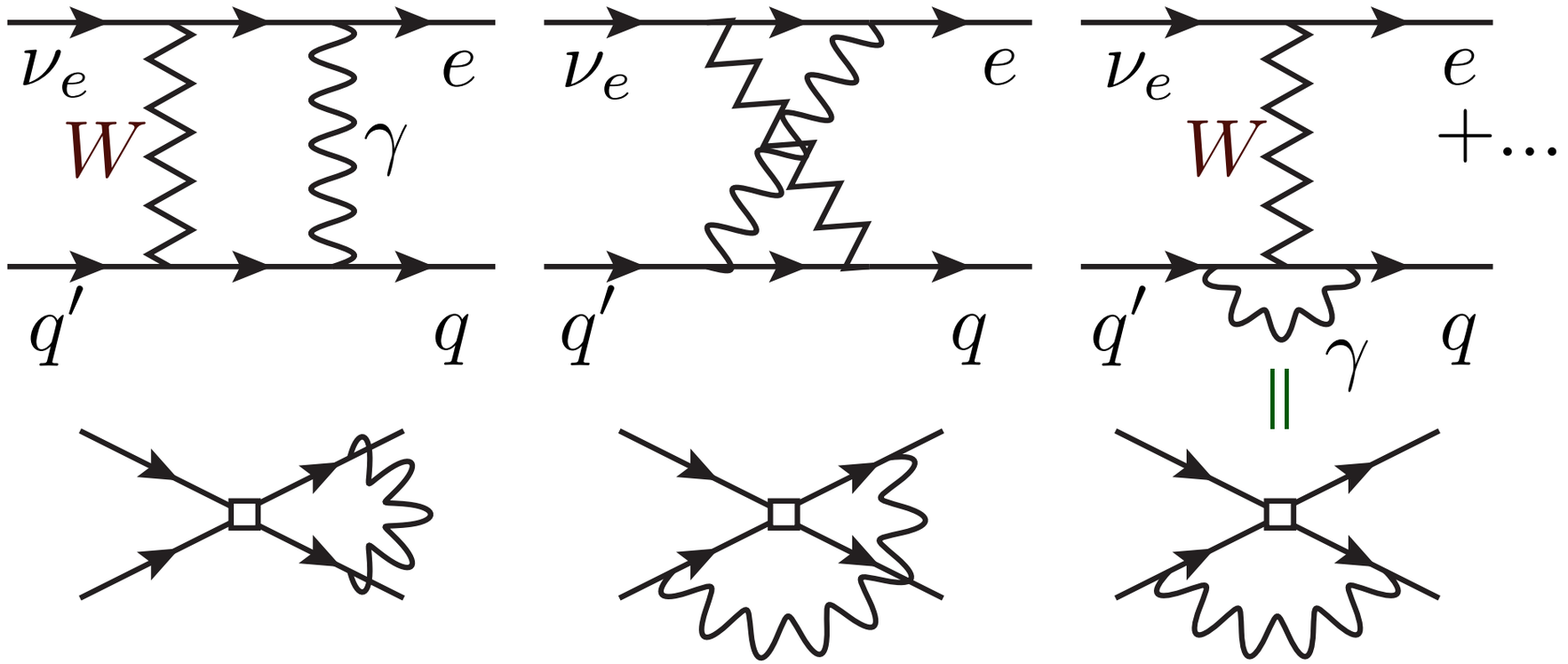
- vanishing contribution to matching besides loops with t quark

- contribution to effective couplings

LEFT Lagrangian

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





scheme independent

scheme dependent for quarks

- NDR scheme for γ_5 for evanescent operators E

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

Buras and Weisz, NPB (1990)

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

Effective field theory for IBD and β decay

M_Z

full content of Standard Model (SM)

integrate out top, Z, W, h

m_b

m_τ

integrate out GeV particles

m_c

α_s becomes too strong going to lower energies

matching to ChPT hadron physics →



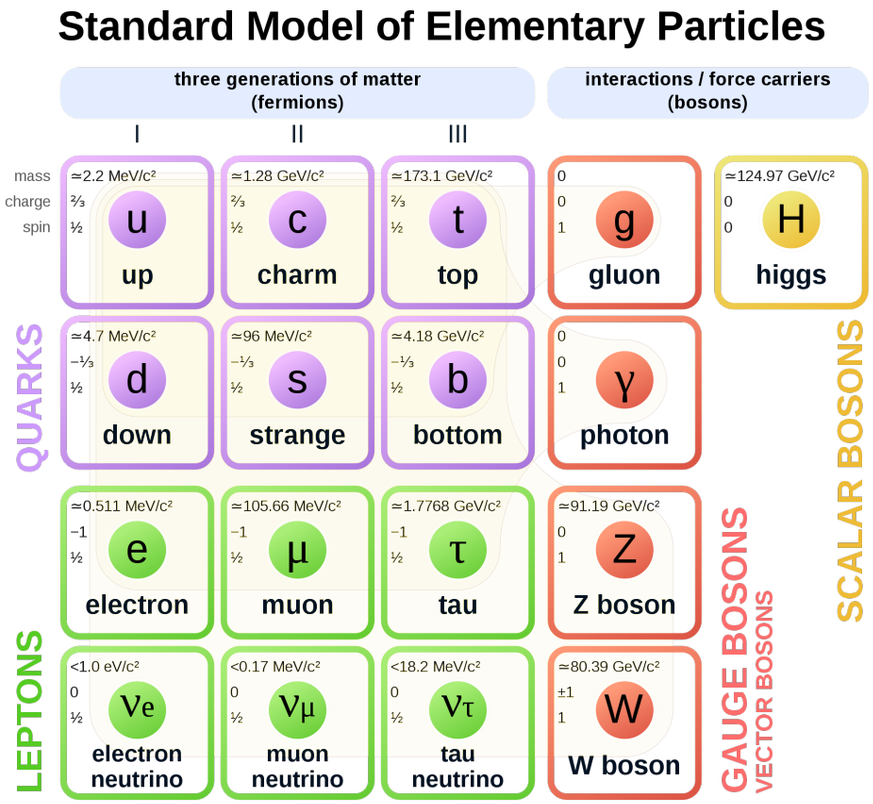
m_π

dynamical pions

m_e

photons, neutrinos, electrons, external nucleons

- coupling constants from SM + small QED corrections



HBχPT to $\not\pi$EFT matching

- purely leptonic counterterm

$$\mathcal{L}_{\text{lept}}^{\text{CT}} = e^2 X_6 \bar{e} \left(i\partial_\mu + eA_\mu\right) \gamma^\mu e$$

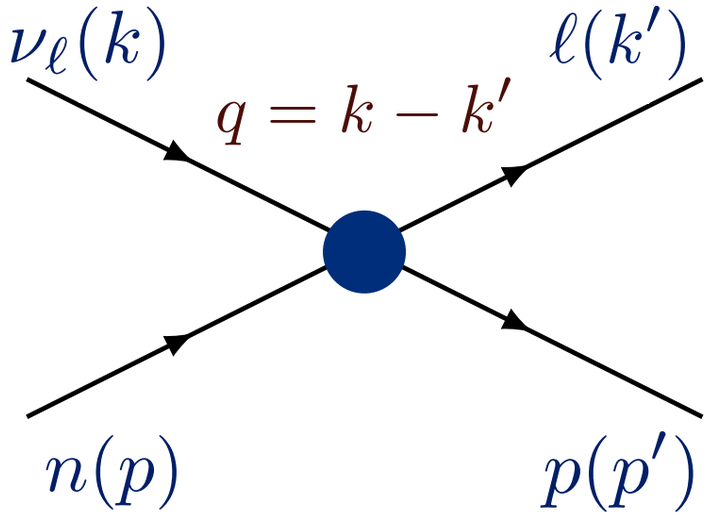
- $\not\pi$EFT counterterms from χPT couplings in baryon sector

$$g_V = C_\beta^r \left(1 + e^2 \left[-\frac{X_6}{2} + 2\left(V_1 + V_2 + V_3 + V_4\right) - g_9\right]\right)$$

EW + electromagnetic

- LECs in terms of correlation functions

Invariant amplitudes



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

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

- 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

V_{ud} from neutron decay

- λ from electron spin correlation measurements

$$|V_{ud}|^2 \tau_n \left(1+3\lambda^2\right)\left(1+\Delta_{\rm TOT}\right) = 5283.321(5)\ {\rm s}$$

$$\Delta_{\rm TOT}^{\rm EFT} = 7.761(27)\% \qquad \text{vs} \qquad \Delta_{\rm TOT} = 7.735(27)\% \qquad \lambda = \frac{g_A}{g_V}$$

- extraction with PDG lifetime and λ CSNS physics!

$$V_{ud}^{\rm n,\ PDG} = 0.97430(2)_{\Delta_f}(13)_{\Delta_R}(82)_{\lambda}(28)_{\tau_n}[88]_{\rm total}$$

- extraction with UCNτ lifetime and PERKEO-III λ

$$V_{ud}^{\rm n,\ best} = 0.97402(2)_{\Delta_f}(13)_{\Delta_R}(35)_{\lambda}(20)_{\tau_n}[42]_{\rm total}$$

- in agreement with superallowed β decays, similar error

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

Hardy and Towner, PRC (2020)

- clean neutron lifetime extraction vs superallowed β decays

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

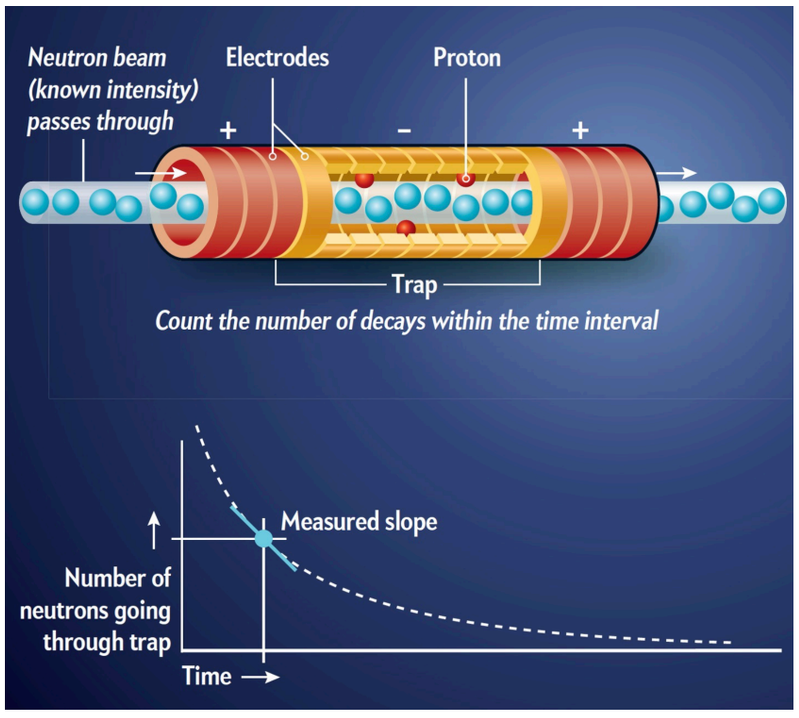
- numerically quantified shifts in V_{ud} and g_A $\lesssim 1\sigma$

Neutron lifetime measurements

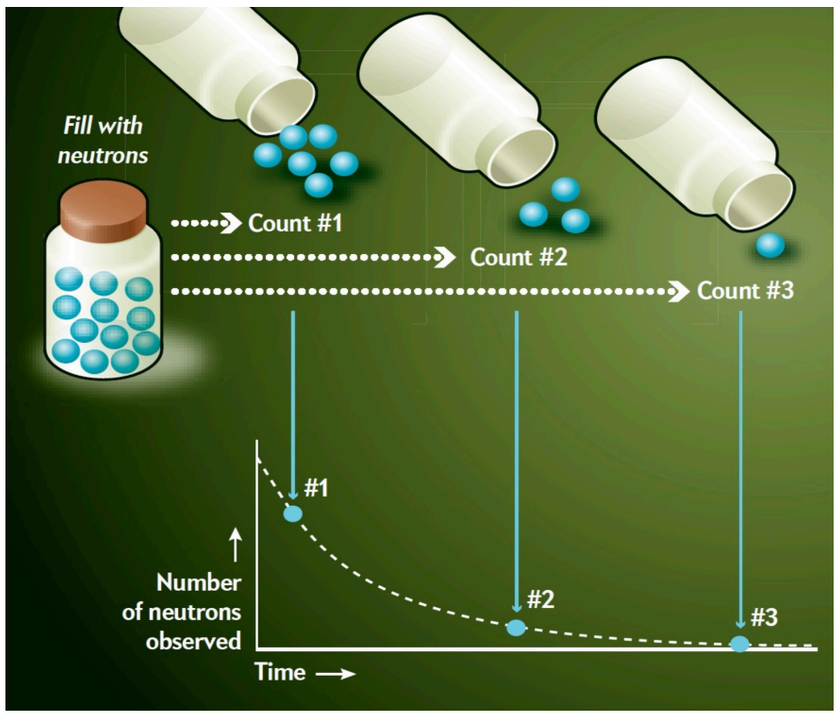




beam method



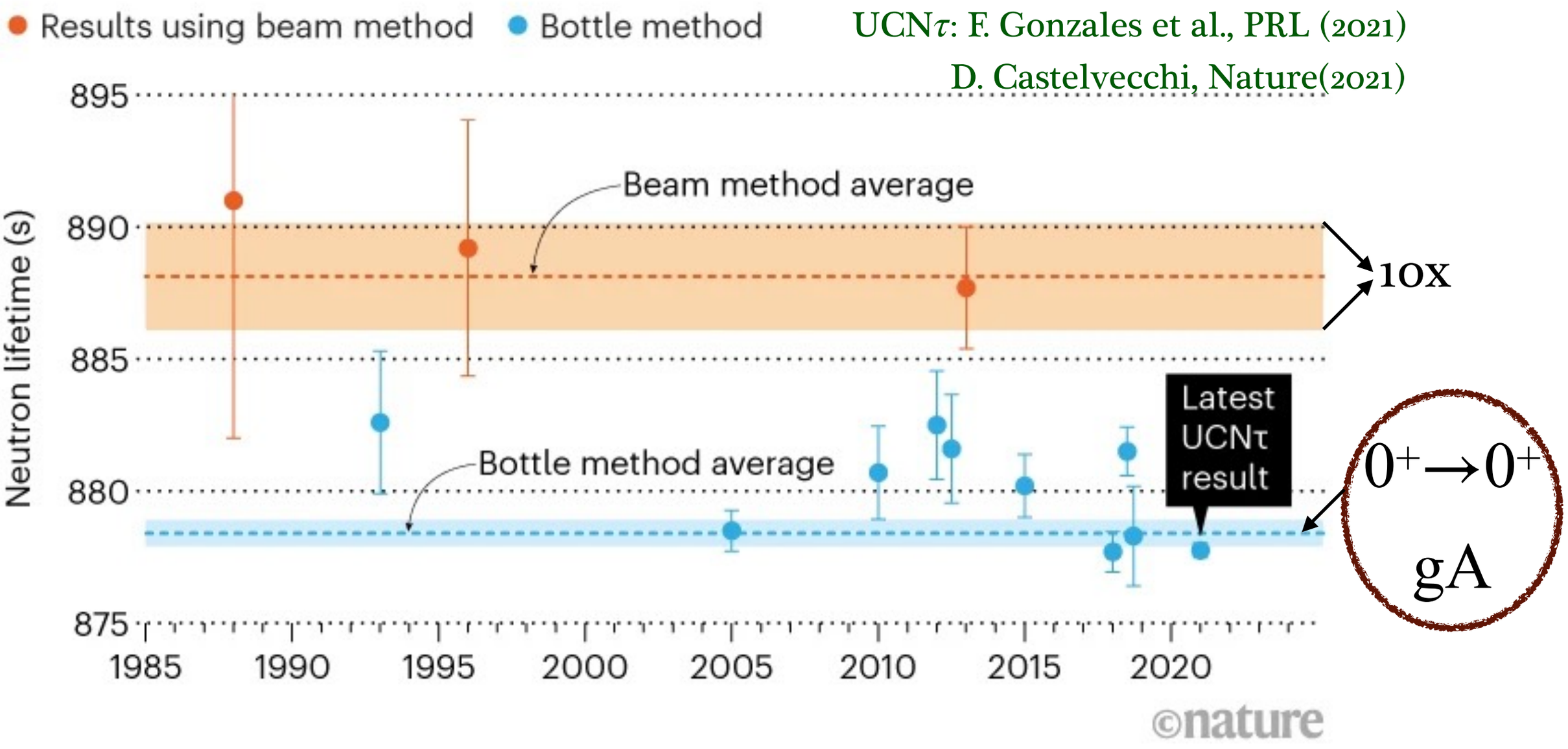
bottle method



how many neutrons pass?

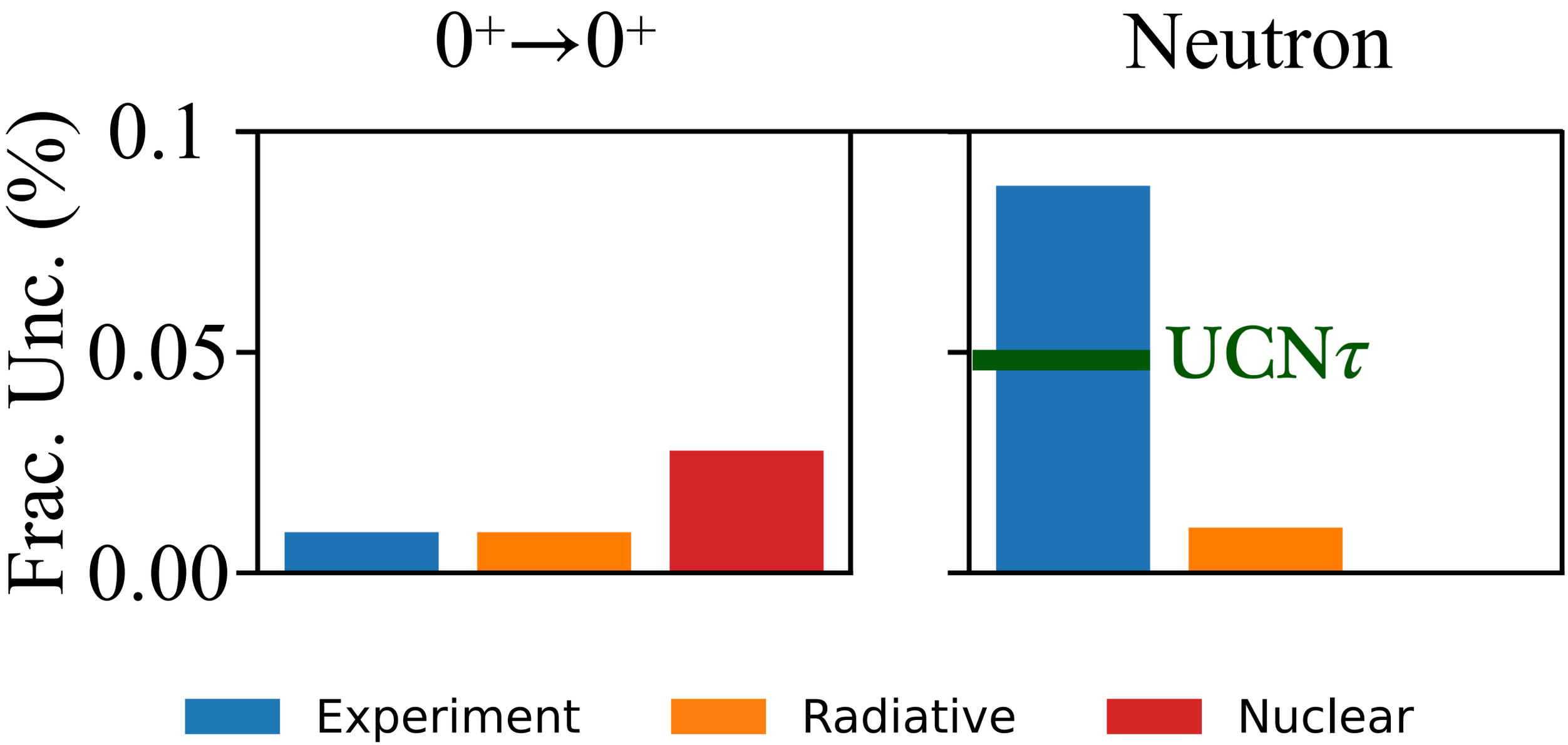
how many neutrons survive?

Neutron lifetime puzzle



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

V_{ud} determinations

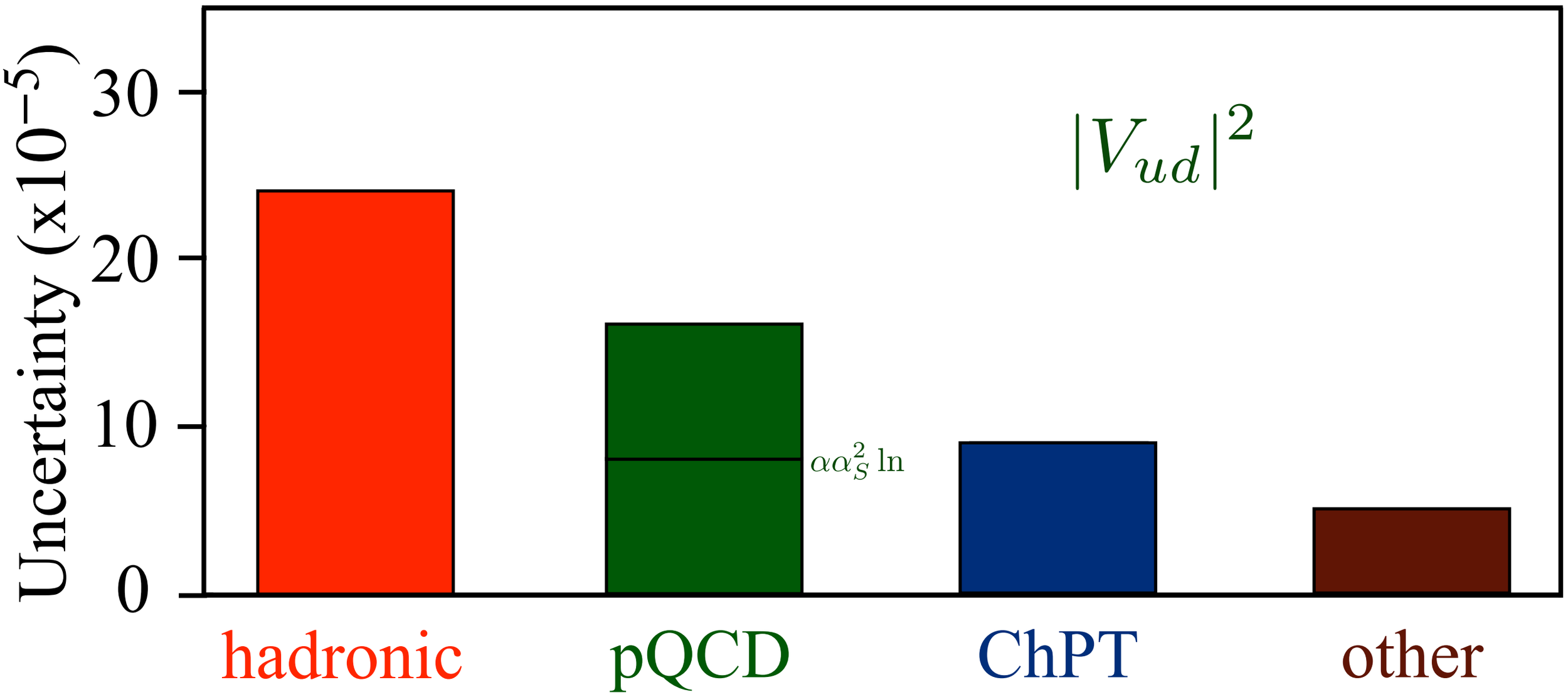


2022 Fundamental Symmetries, Neutrons, and Neutrinos (FSNN) white paper

- neutron decay becomes competitive with $0^+ \rightarrow 0^+$

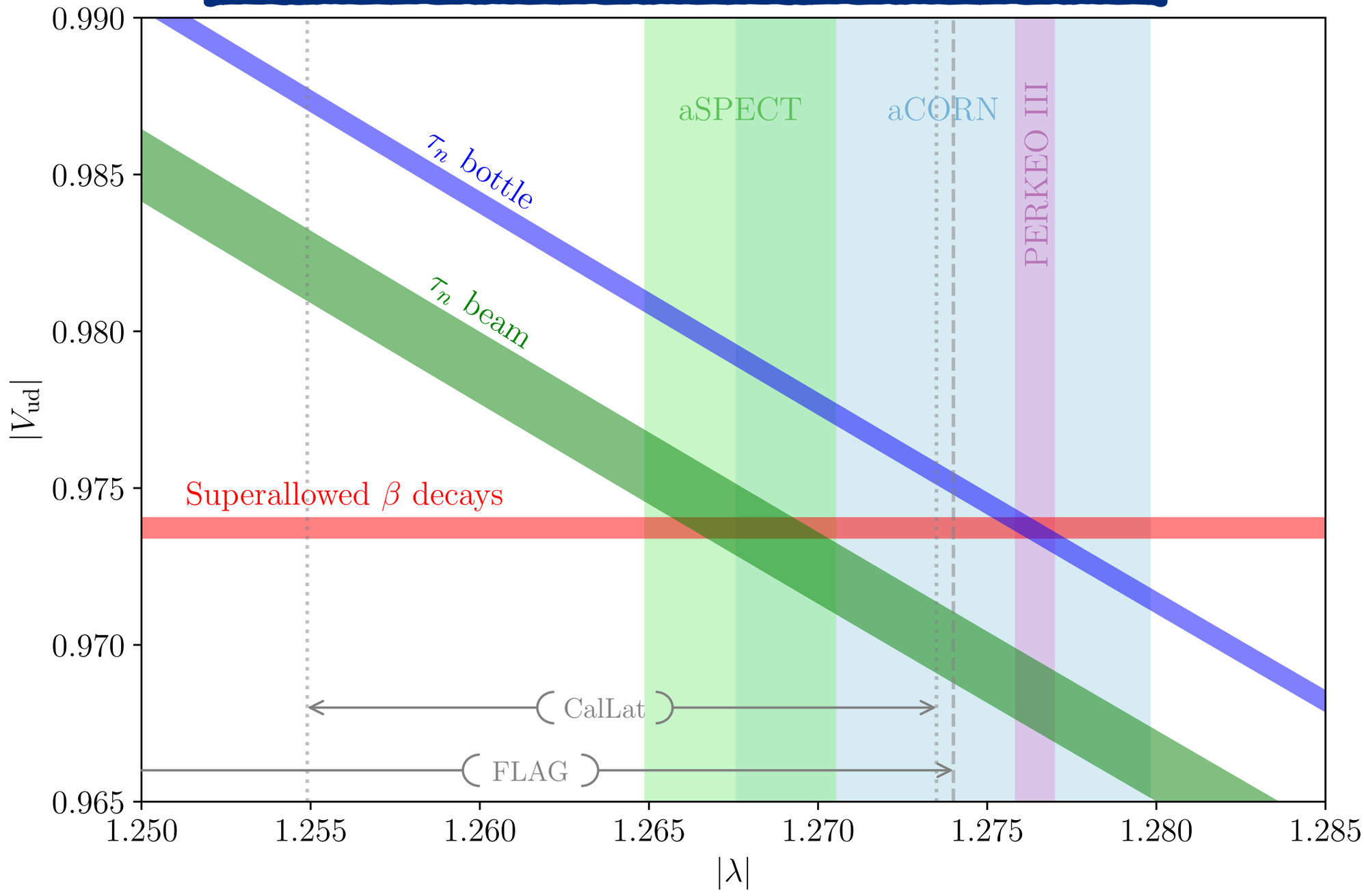
Our work

- 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

Logarithms in neutron decay



four-fermion interaction between leptons and heavy nucleons

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

scale separation introduces large logarithms:

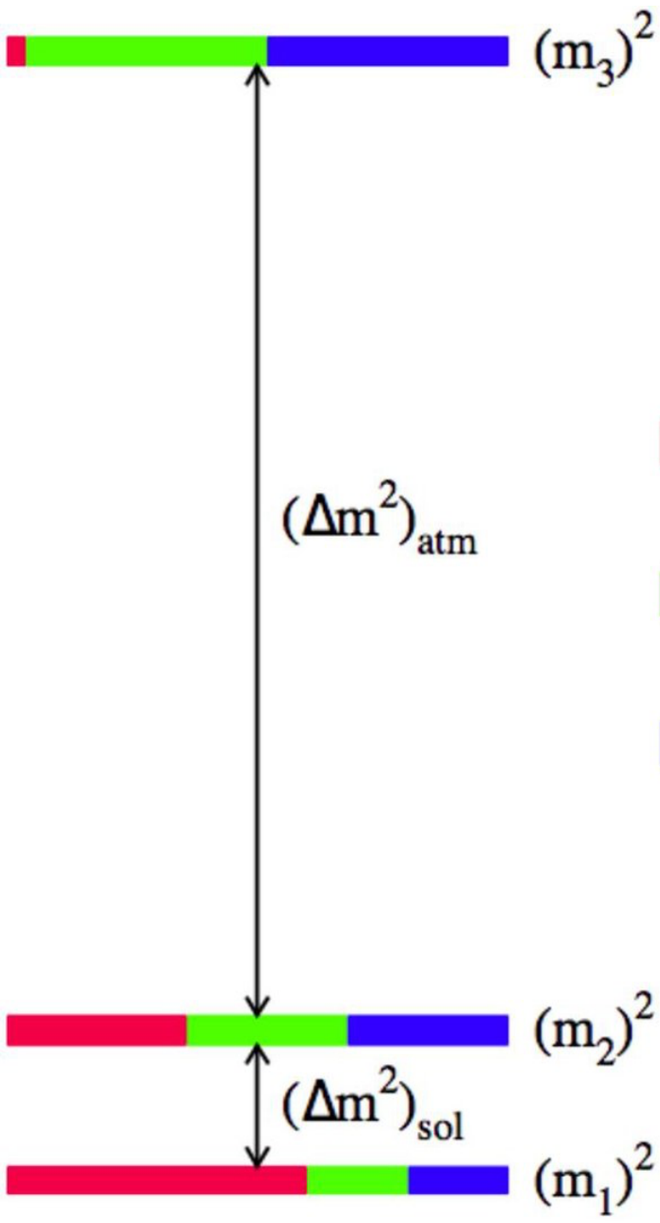
$$\ln \frac{M_Z}{\Lambda_{\text{had}}} \qquad \ln \frac{\Lambda_{\text{had}}}{m_e}$$

explain ~ half of radiative correction to neutron lifetime

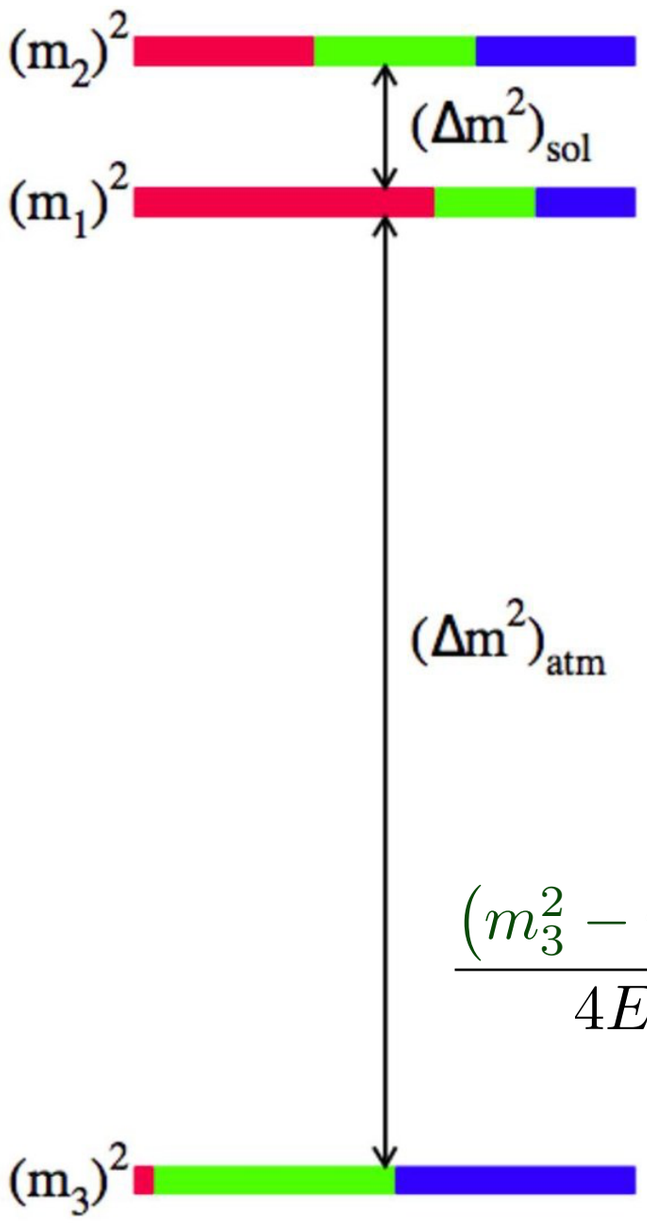
$$\Delta = 7.756(27)\%$$

- g_V, g_A encode electroweak logarithms and hadronic corrections

Neutrino mass hierarchy



normal hierarchy



inverted 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