

28 August, 2026

第十五届“新物理研讨会

Weihai, China

Radiative corrections to inverse beta decay and neutron decay

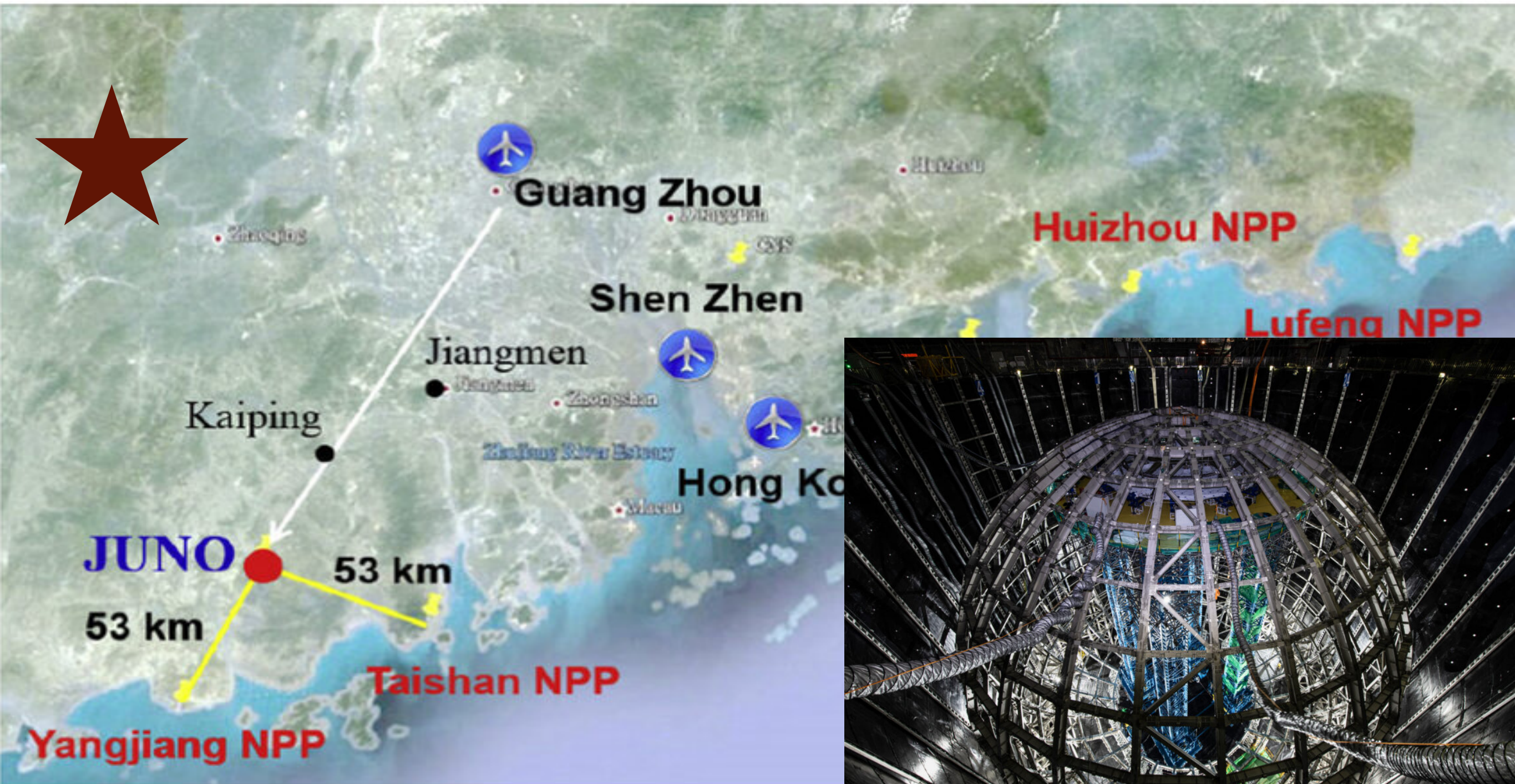


托马拉克

Sasha Tomalak

CP violation and mass hierarchy@laboratory

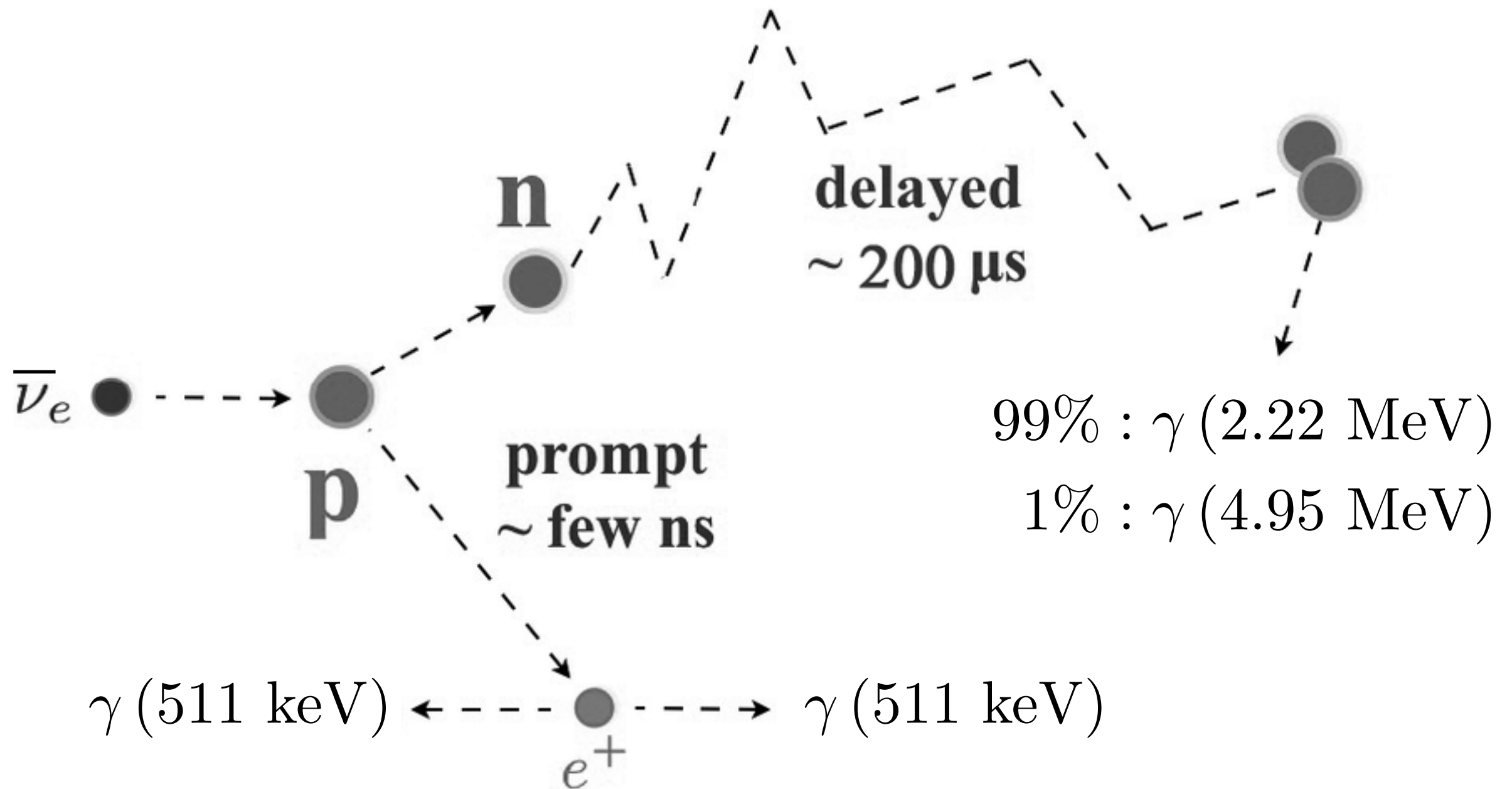
3σ determination of mass hierarchy



- 4 precise oscillation parameters from **JUNO** !!!

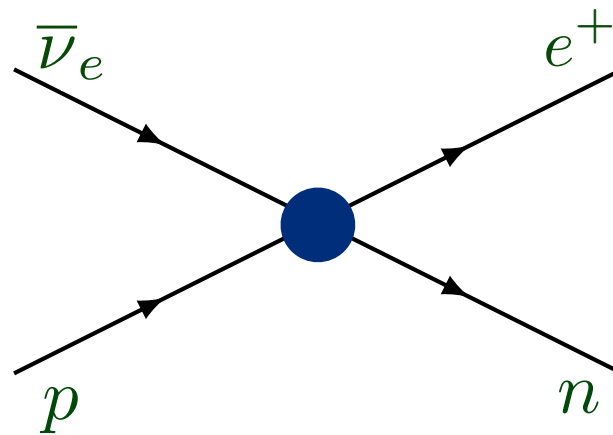
35 m, 20000 t

JUNO detection channel



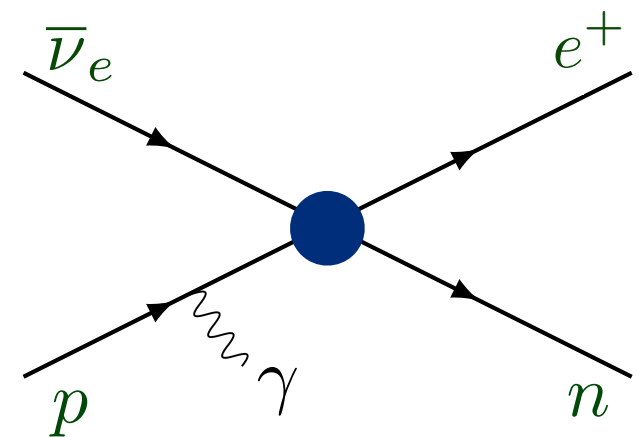
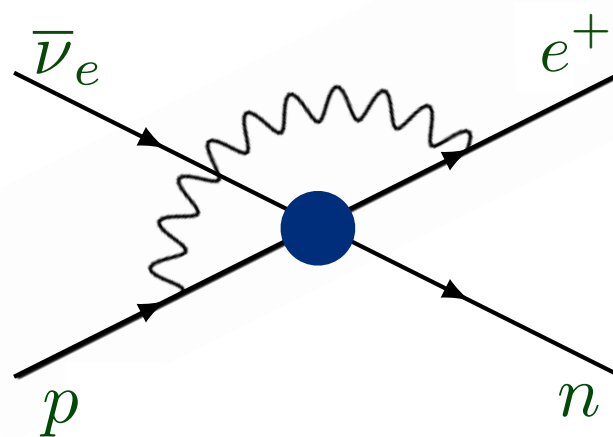
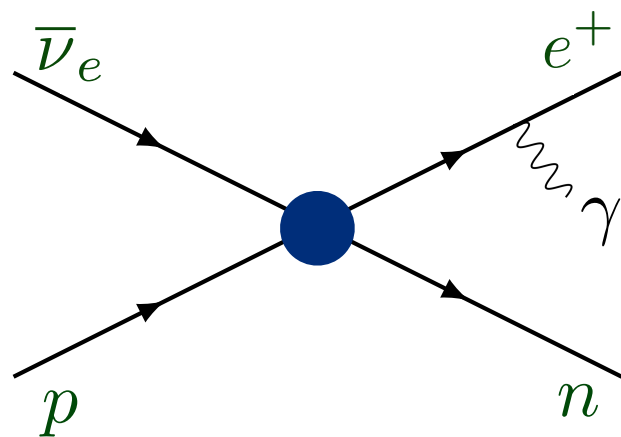
Teng Li et al., ChPC (2017)

- prompt-delayed time signature: background discrimination



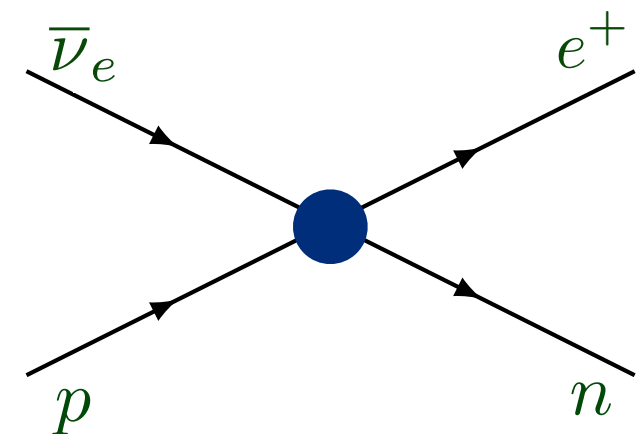
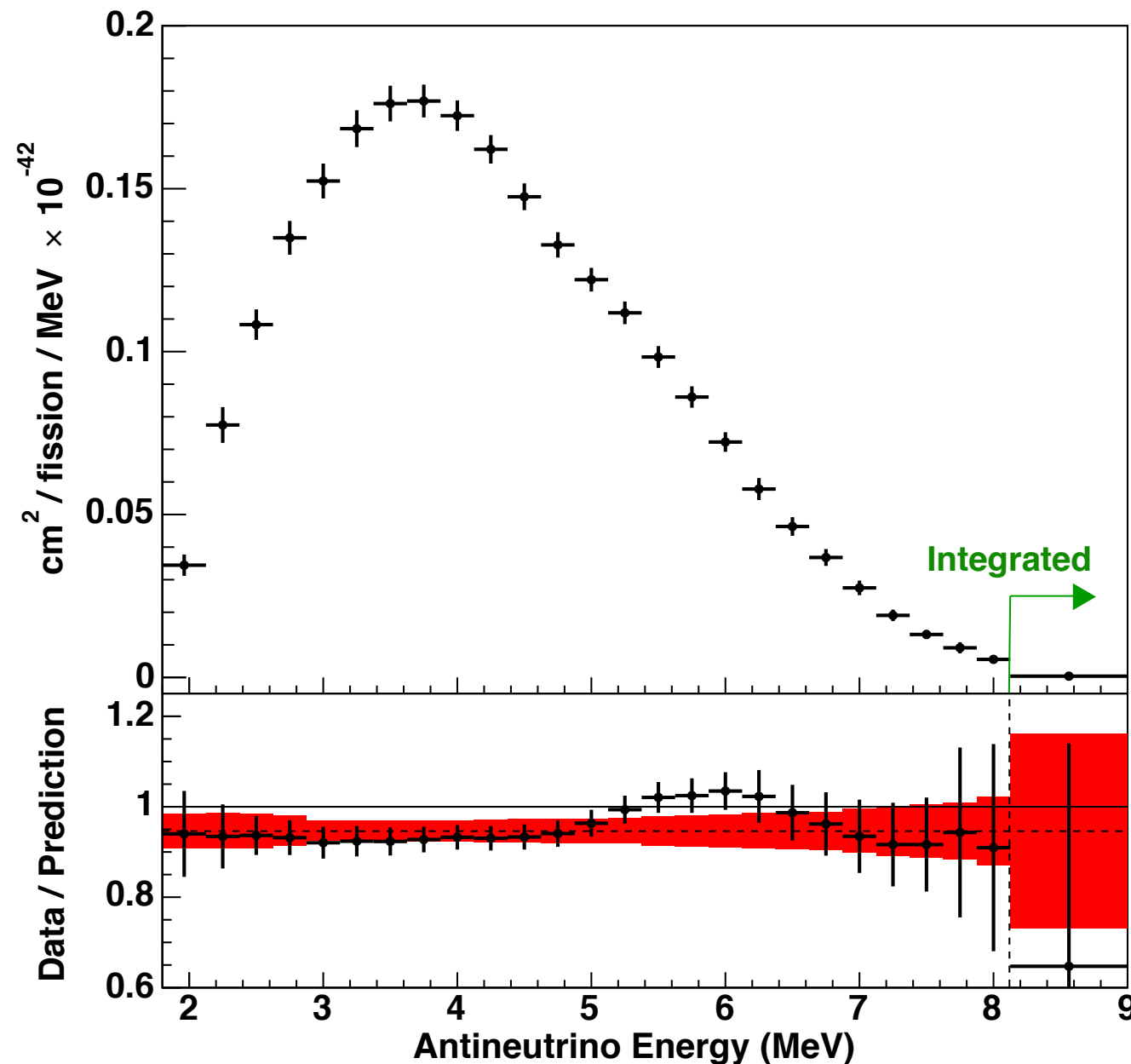
O.T., PRL (2026)

Theory of inverse beta decay for reactor antineutrinos



IBD with reactor antineutrinos

- neutron is heavier than proton by 1.3 MeV

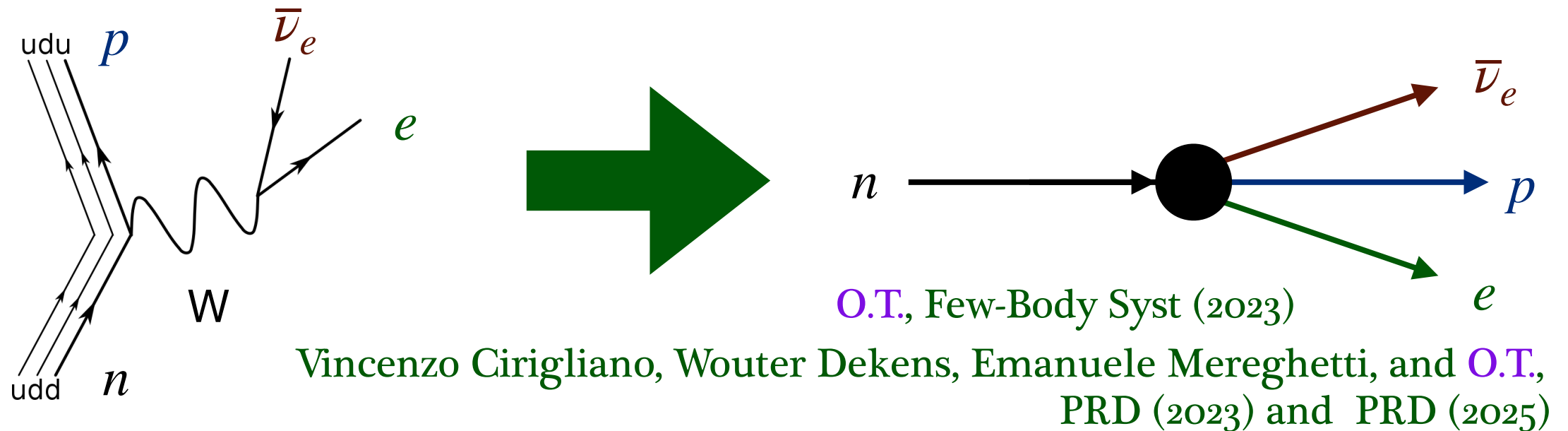


Daya Bay, PRL (2016)

- MeV-scale physics like in neutron decay

Complete EFT approach

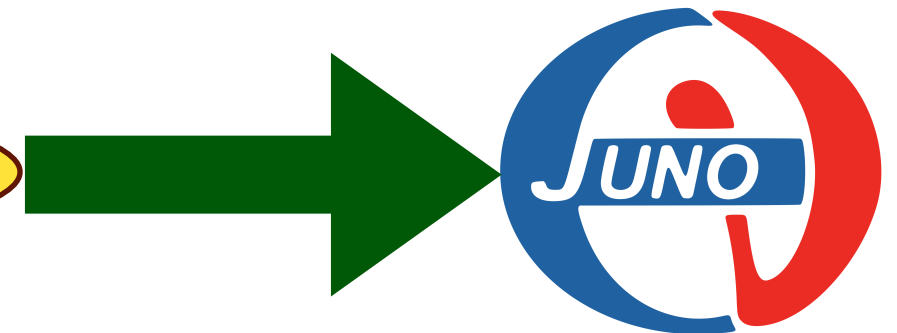
- neutron is heavier than proton by 1.3 MeV and can decay



- four-fermion interaction between leptons and heavy nucleons

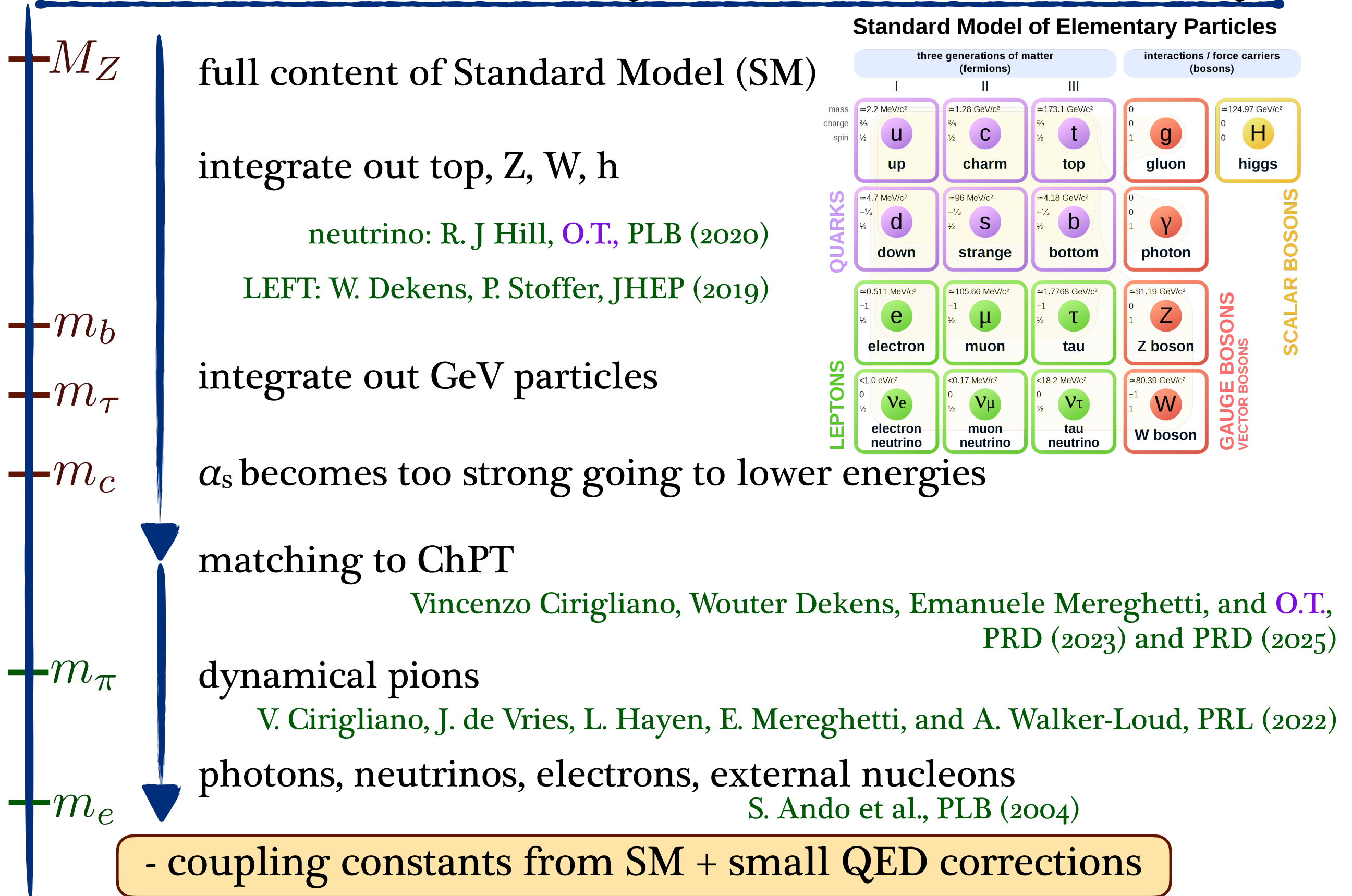
$$\mathcal{L}_{\text{eff}} = -\sqrt{2}G_F V_{ud} \bar{e} \gamma_\mu P_L \nu_e \cdot \bar{N} (g_V v^\mu - 2g_A S^\mu) \tau^+ N$$

Standard Model $\rightarrow$ LEFT $\rightarrow$ HB χ PT $\rightarrow$ $\not{E}$ 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



One-loop result

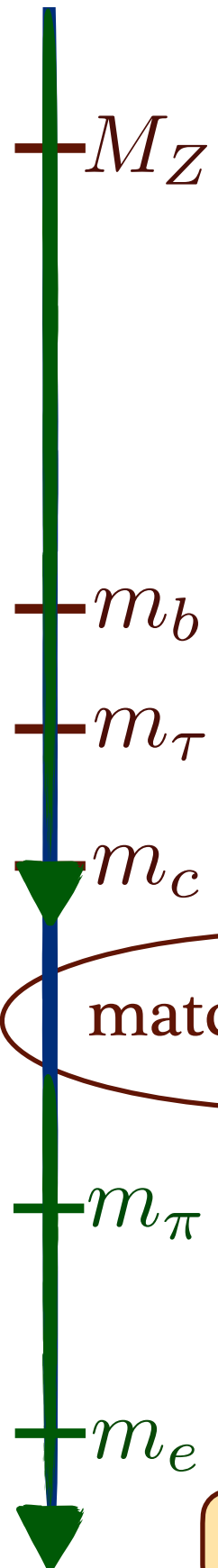
- clear illustration of leading logarithms

$$g_V(\mu_\chi) = 1 - \frac{\alpha}{2\pi} \left[\frac{5}{8} + \frac{3}{4} \ln \frac{\mu_\chi^2}{\mu_0^2} + \ln \frac{\mu_0^2}{M_Z^2} \right] \\ - e^2 \int \frac{i d^4 q}{(2\pi)^4} \frac{\nu^2 + Q^2}{Q^4} \left[\frac{T_3(\nu, Q^2)}{2\nu} - \frac{2}{3} \frac{1}{Q^2 + \mu_0^2} \right]$$

- 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



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

- renormalization group equations

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

m_b

m_τ

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

m_c

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

matching scale

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

m_π

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

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

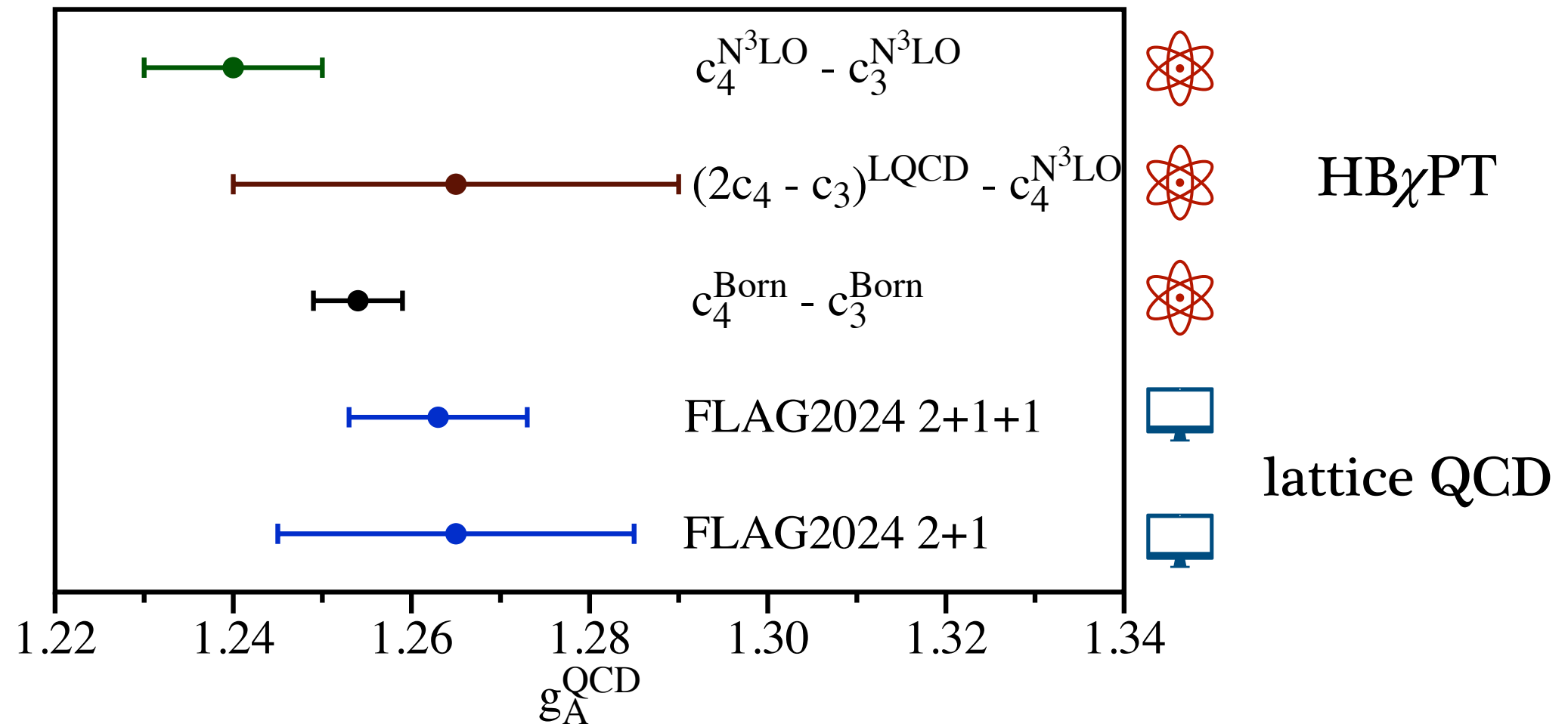
m_e

- cancellation of various contributions -> 0.07 % effect

Nucleon axial-vector charge

- effective field theory approach to low-energy charged currents

Standard Model $\rightarrow$ LEFT $\rightarrow$ HB χ PT $\rightarrow$ π EFT



O.T. and Yi-Bo Yang, Universe (2026)

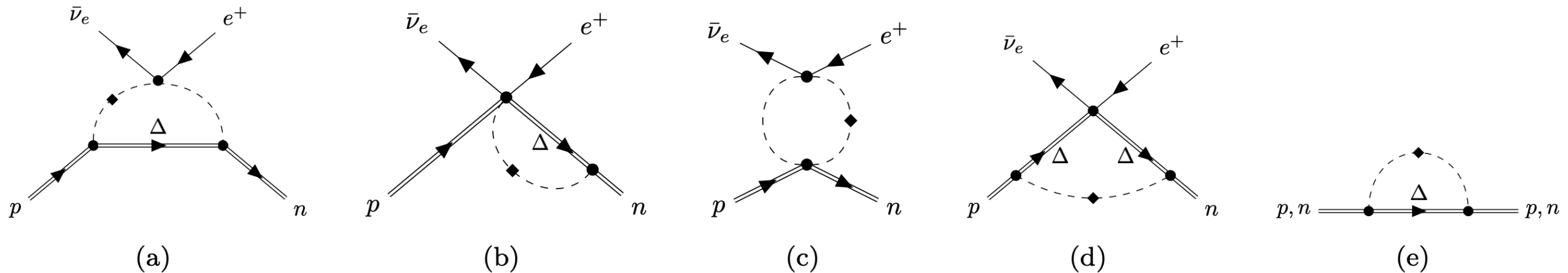
Vincenzo Cirigliano, Wouter Dekens, Emanuele Mereghetti, and O.T., PRD (2024) and PRD (2025)

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)

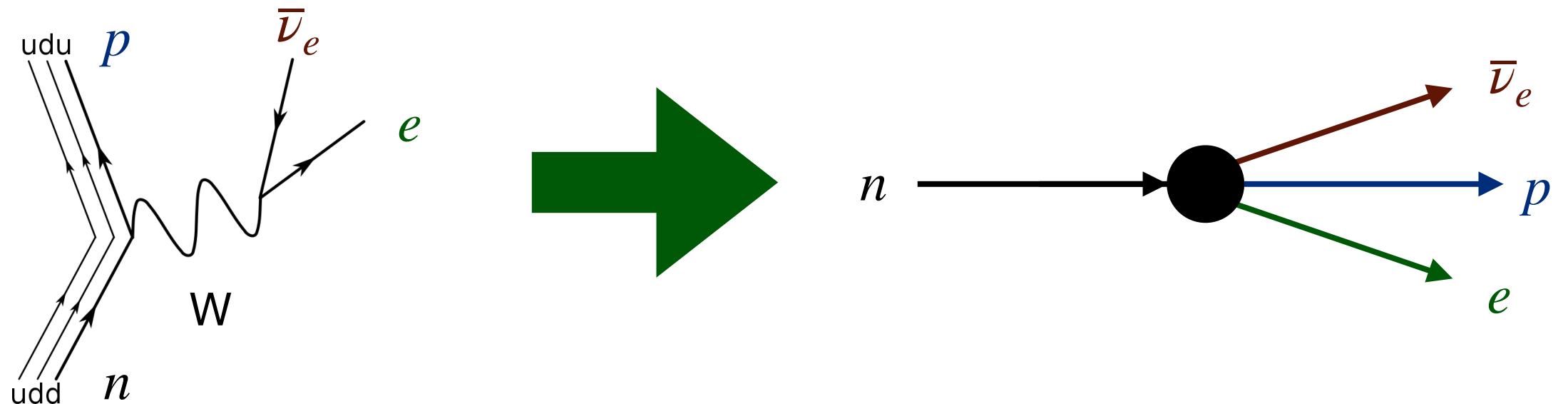
%	HBChPT pions	HBChPT pions and delta	Wilson coefficients
pion LO	0.99 (0.18)	0.99 (0.18)	
pion NLO	1.4	0.3	c3, c4
delta LO	-	-1.5	h, g1
delta NLO	-	0.3	b4, b5
extra	0.16 (0.30)	0.16 (0.30)	
total	2.6 (0.4)	0.3 (0.4)	

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

- Δ resonance restores power counting and nullifies QED

Complete EFT approach

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



- four-fermion interaction between leptons and heavy nucleons

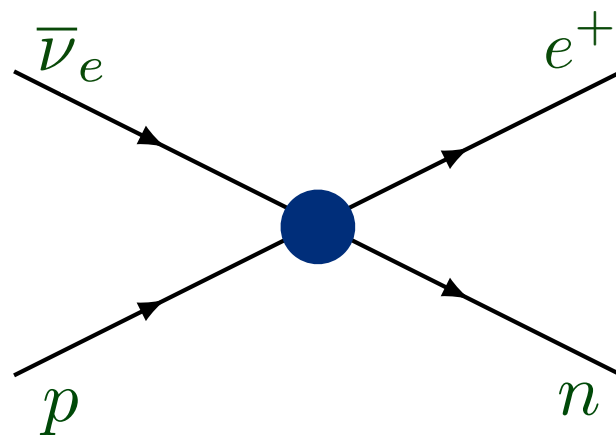
$$\mathcal{L}_{\text{eff}} = -\sqrt{2}G_F V_{ud} \bar{e} \gamma_\mu P_L \nu_e \cdot \bar{N} (g_V v^\mu - 2g_A S^\mu) \tau^+ N$$

g_V : theoretical prediction from Standard Model

g_A : beta asymmetry in polarized neutron decay

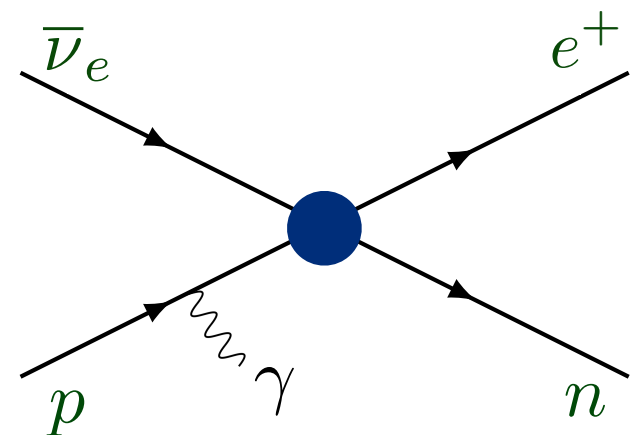
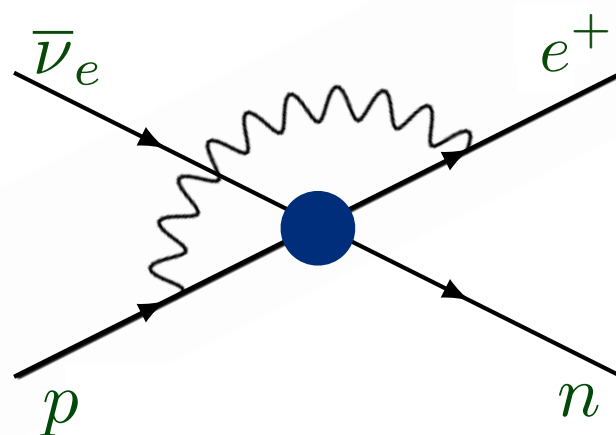
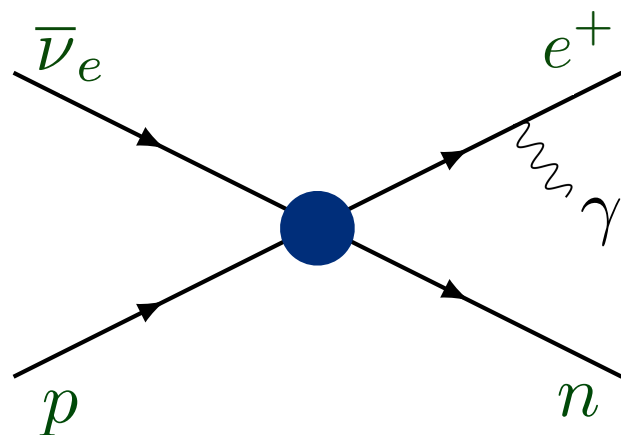
V_{ud} : superallowed transitions

- first consistent at 0.1%-level QED radiative corrections

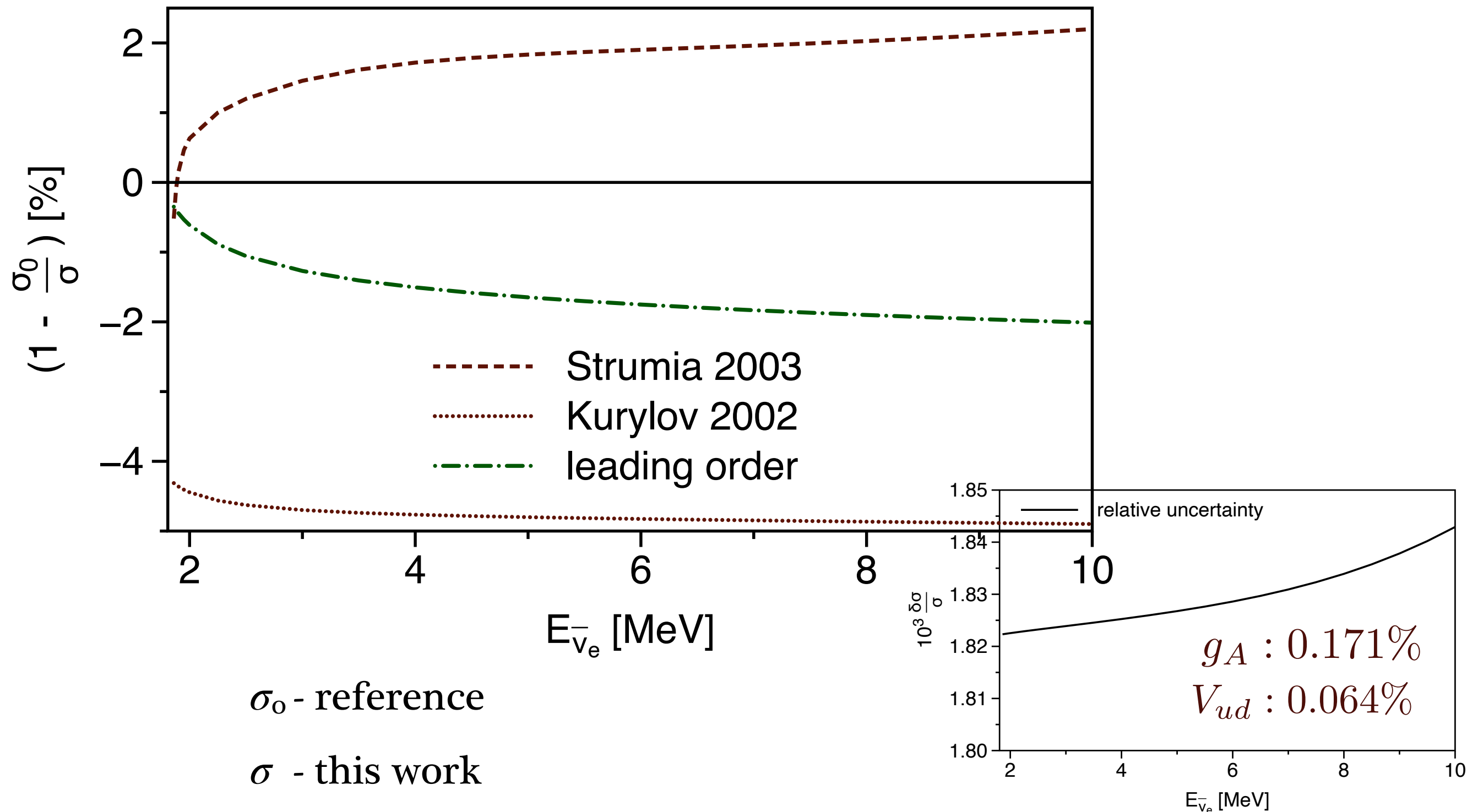


O.T., PRL (2026)

Theory of inverse beta decay for reactor antineutrinos

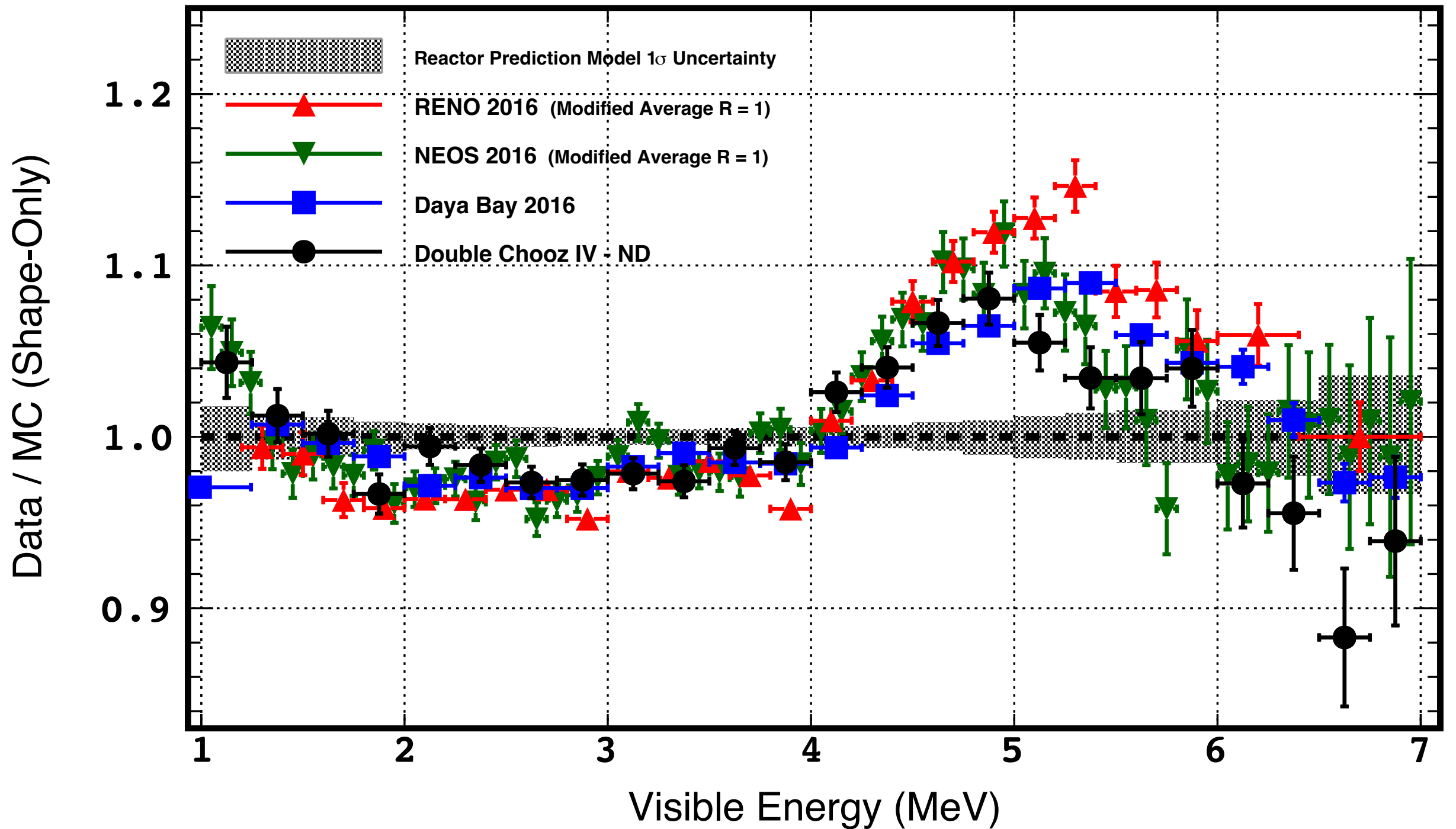


Total cross section



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

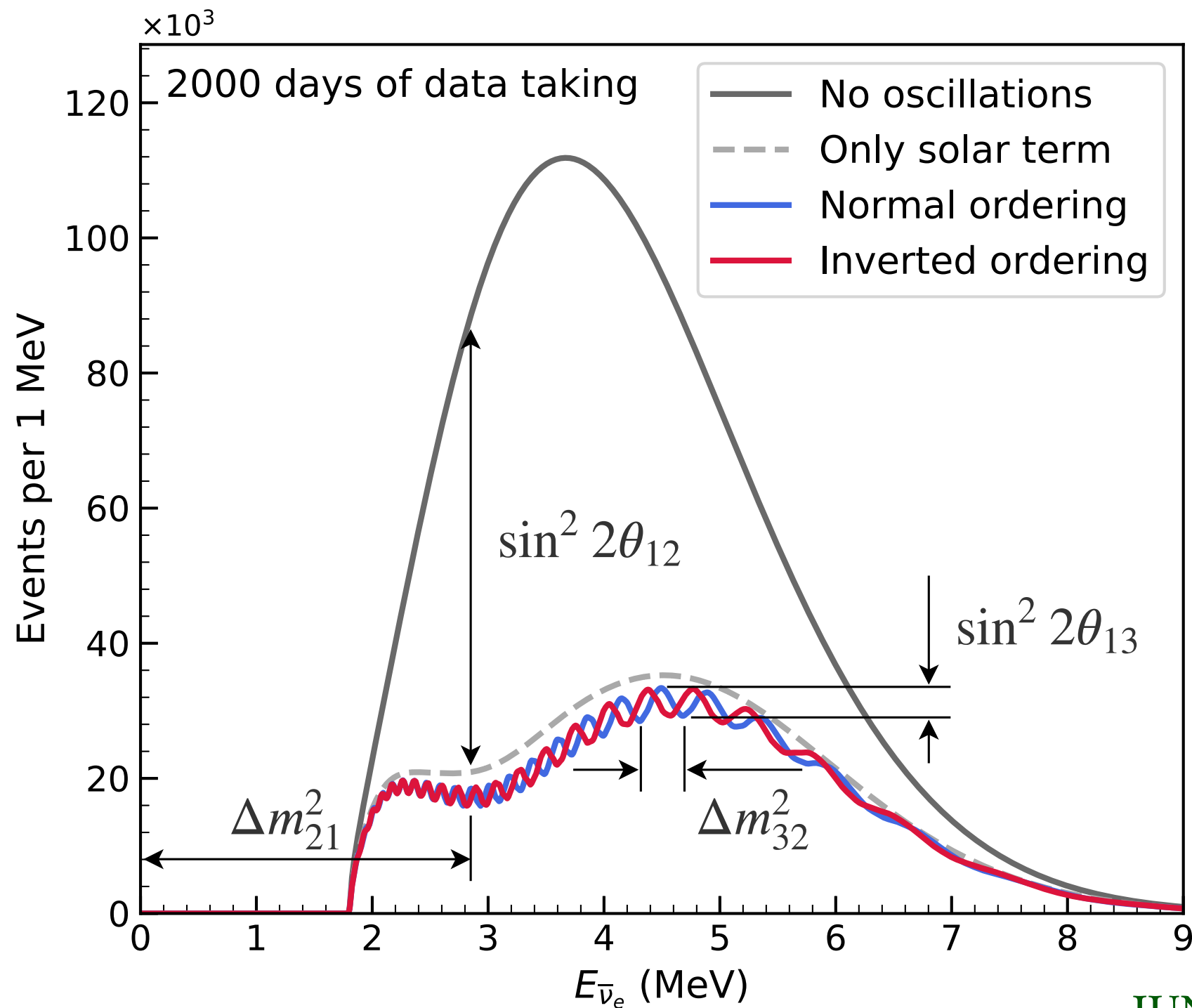
5-MEV flux excess



Double Chooz, Nature Phys (2019)

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

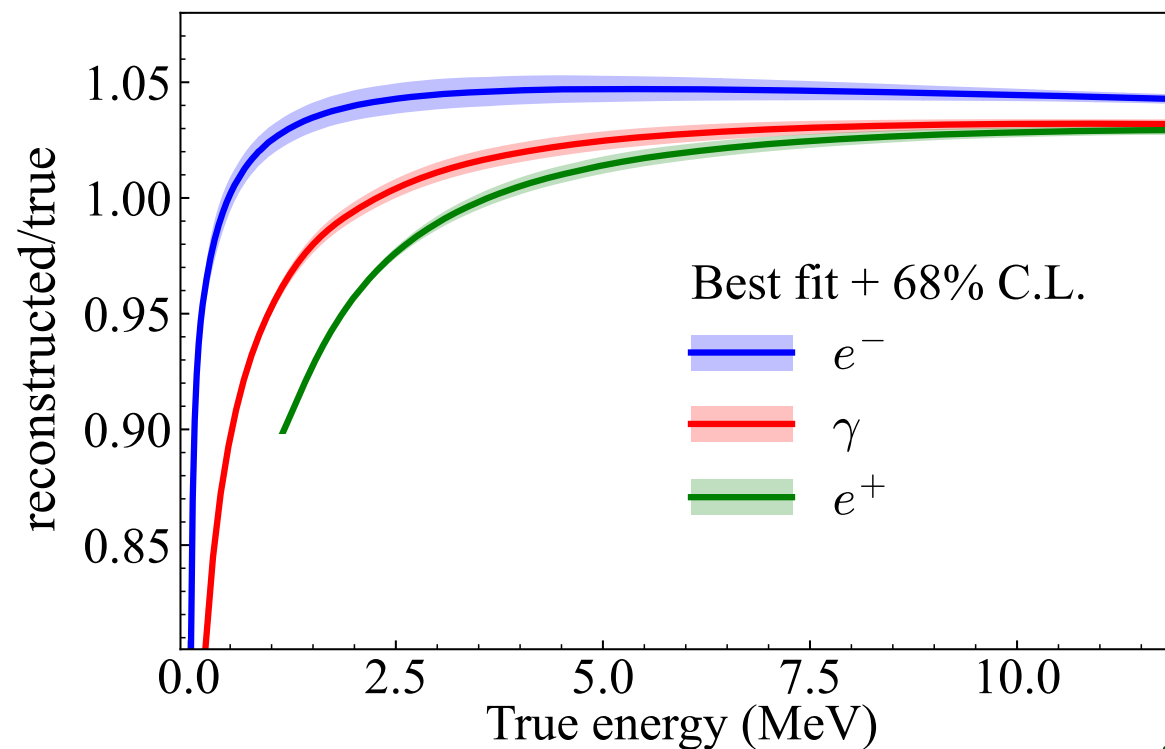
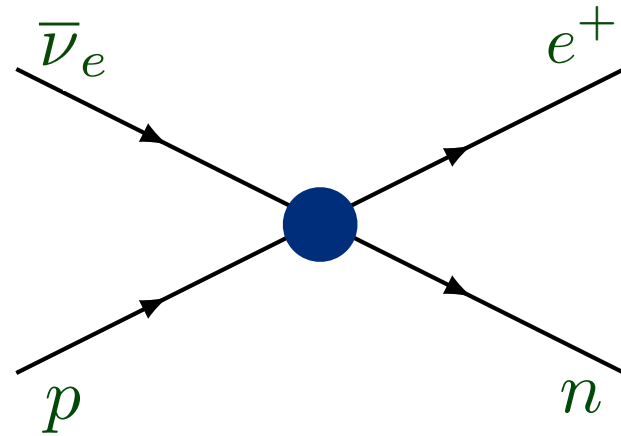
Energy reconstruction is key



JUNO, PPNP (2021)

- JUNO: 3% energy reconstruction for precision goals

Energy reconstruction is key

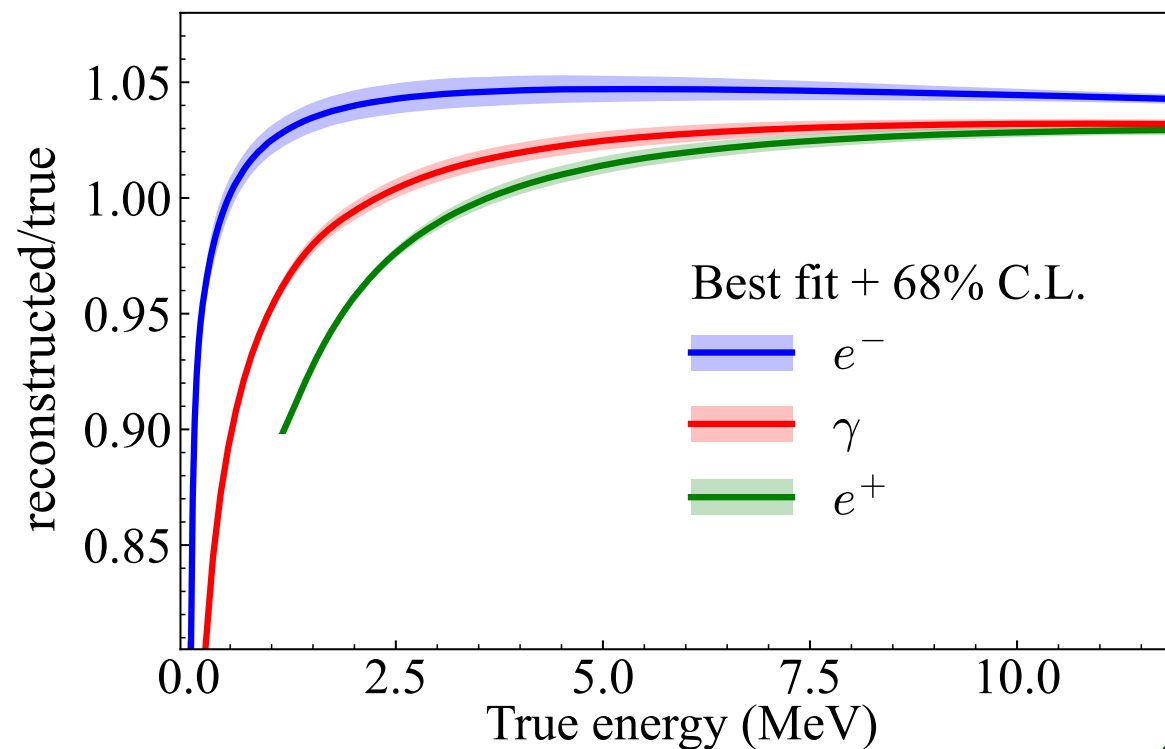
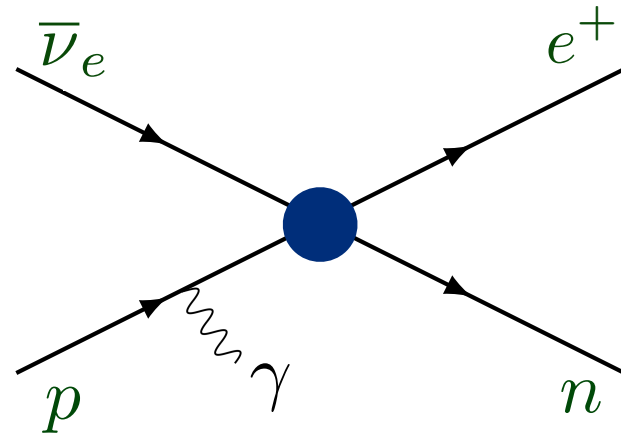


JUNO, Nature (2026)

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

- control over each particle is necessary to achieve precision

Energy reconstruction is key



JUNO, Nature (2026)

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

- control over each particle is necessary to achieve precision

Bremsstrahlung

- new distributions beyond E_{EM} spectrum

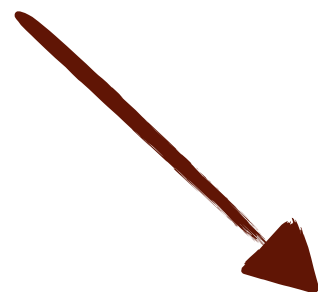
$$E_n, E_\gamma, \theta_n$$



$$E_n, \theta_n$$



$$E_n, E_{\text{EM}}$$



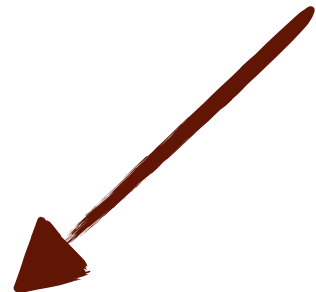
$$E_e, E_\gamma, \theta_e$$



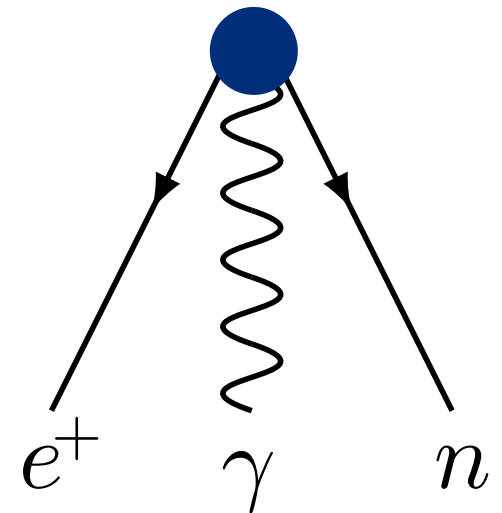
$$E_e, \theta_e$$



$$E_e$$



total cross section



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

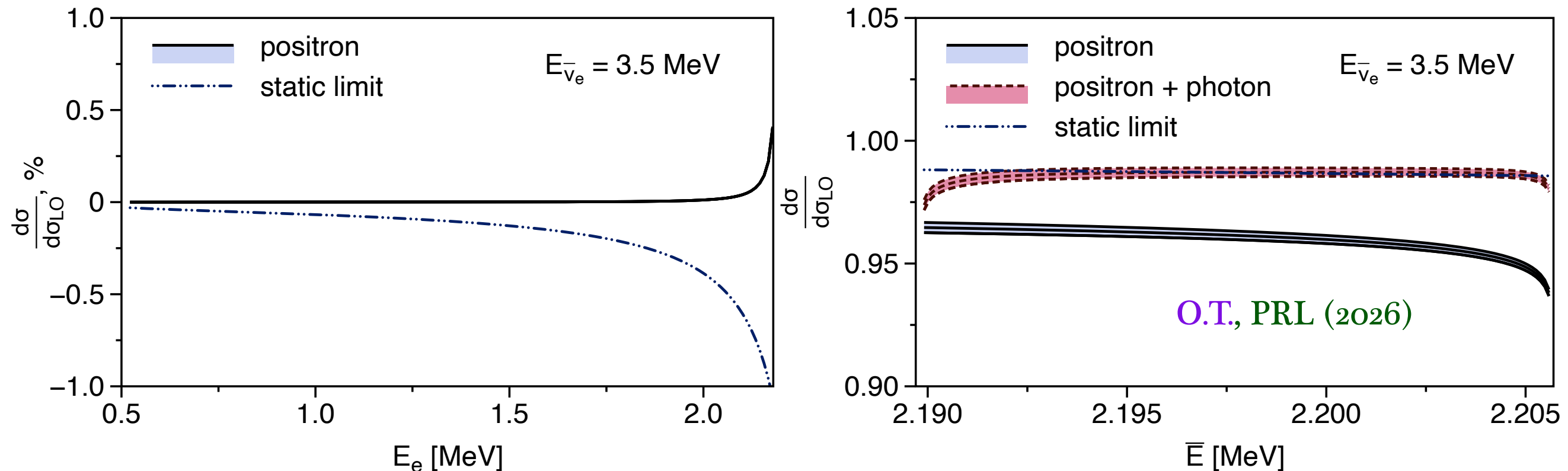
consistency at
cross-section level

O.T., PRL (2026)

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

Access each particle kinematics

- evaluate radiative process w/o no-recoil approximation

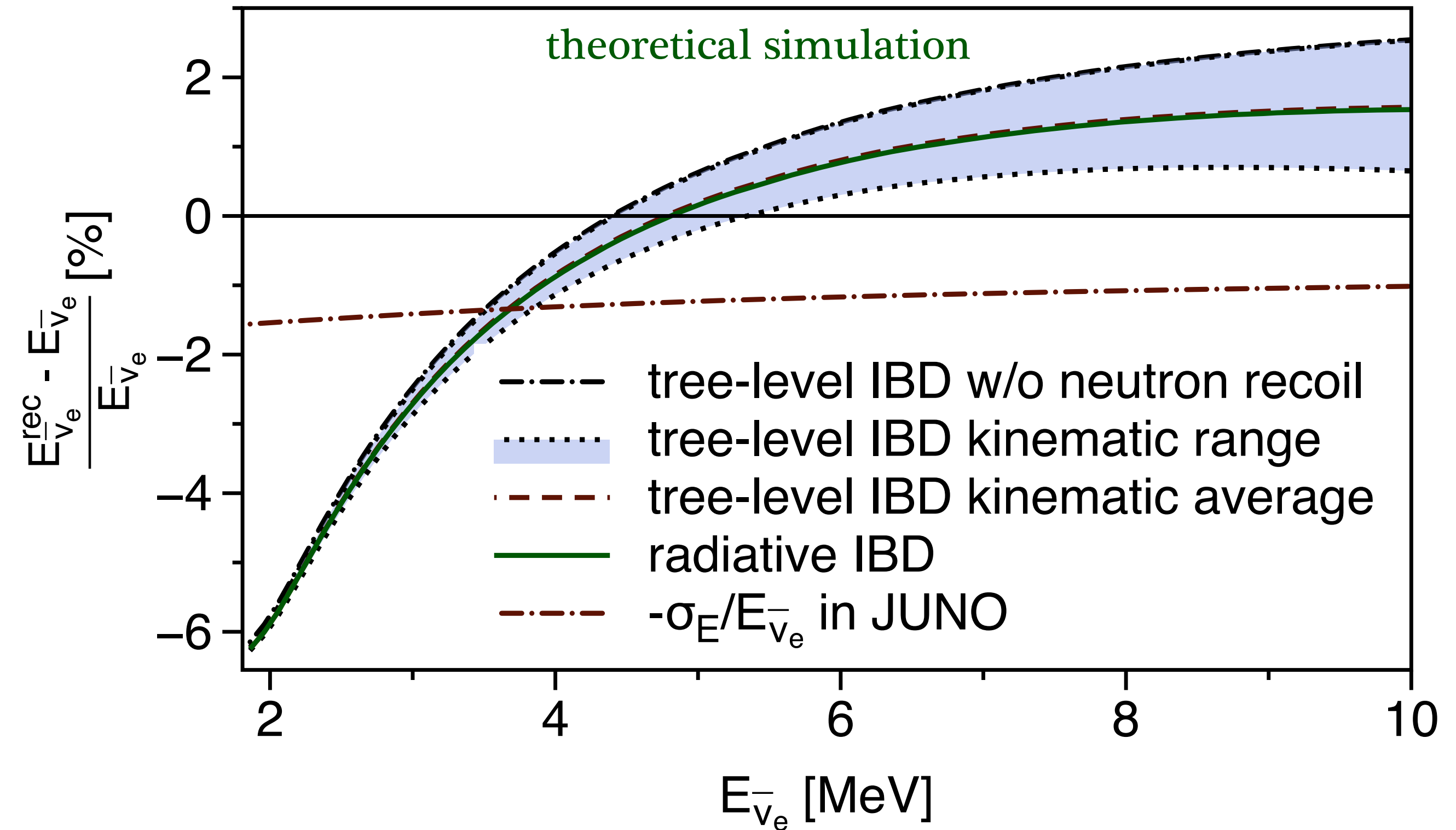


- 1st analytic expression for **positron** energy spectrum

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

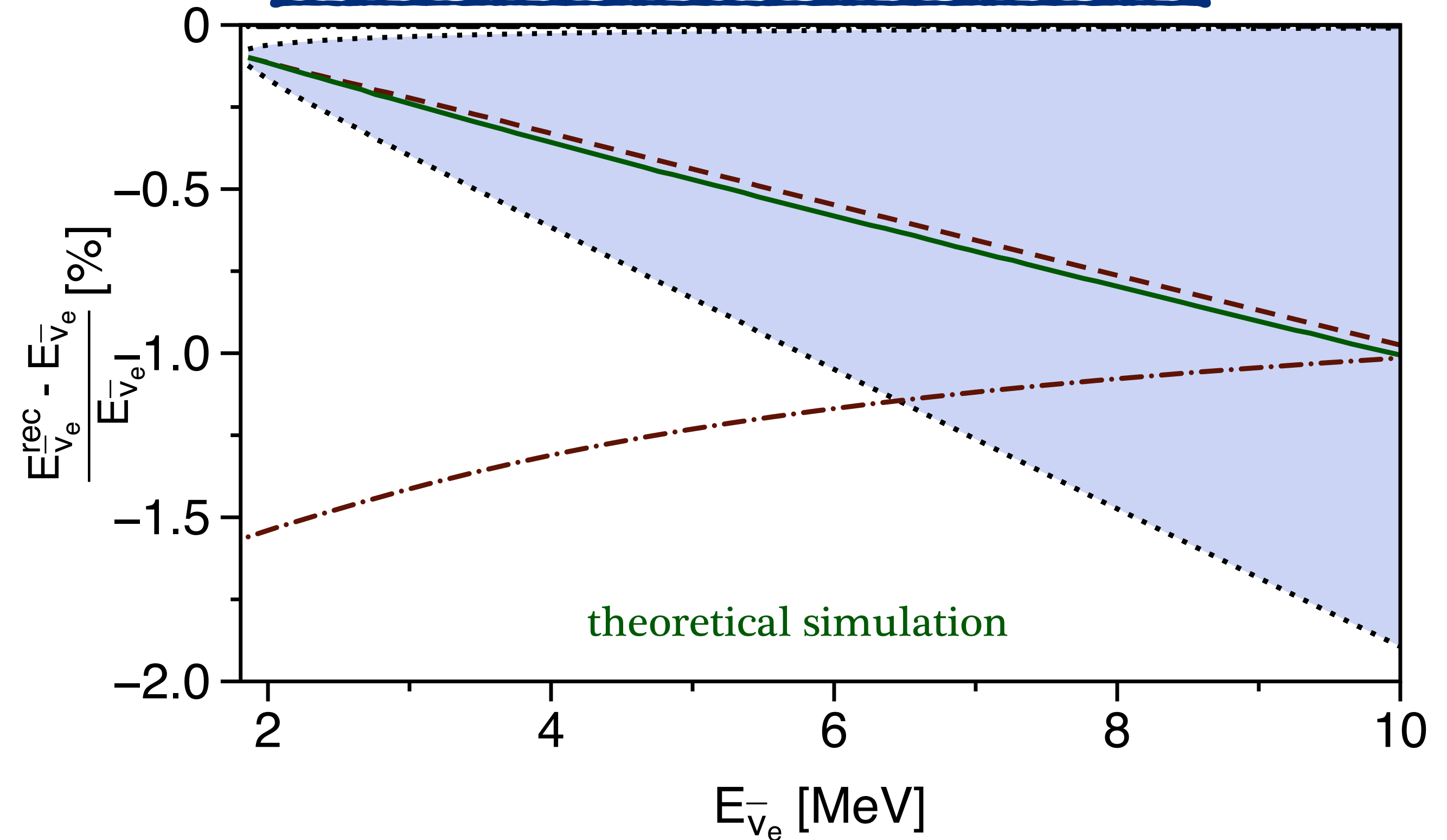
- control over each particle is necessary to achieve precision

Energy reconstruction is key



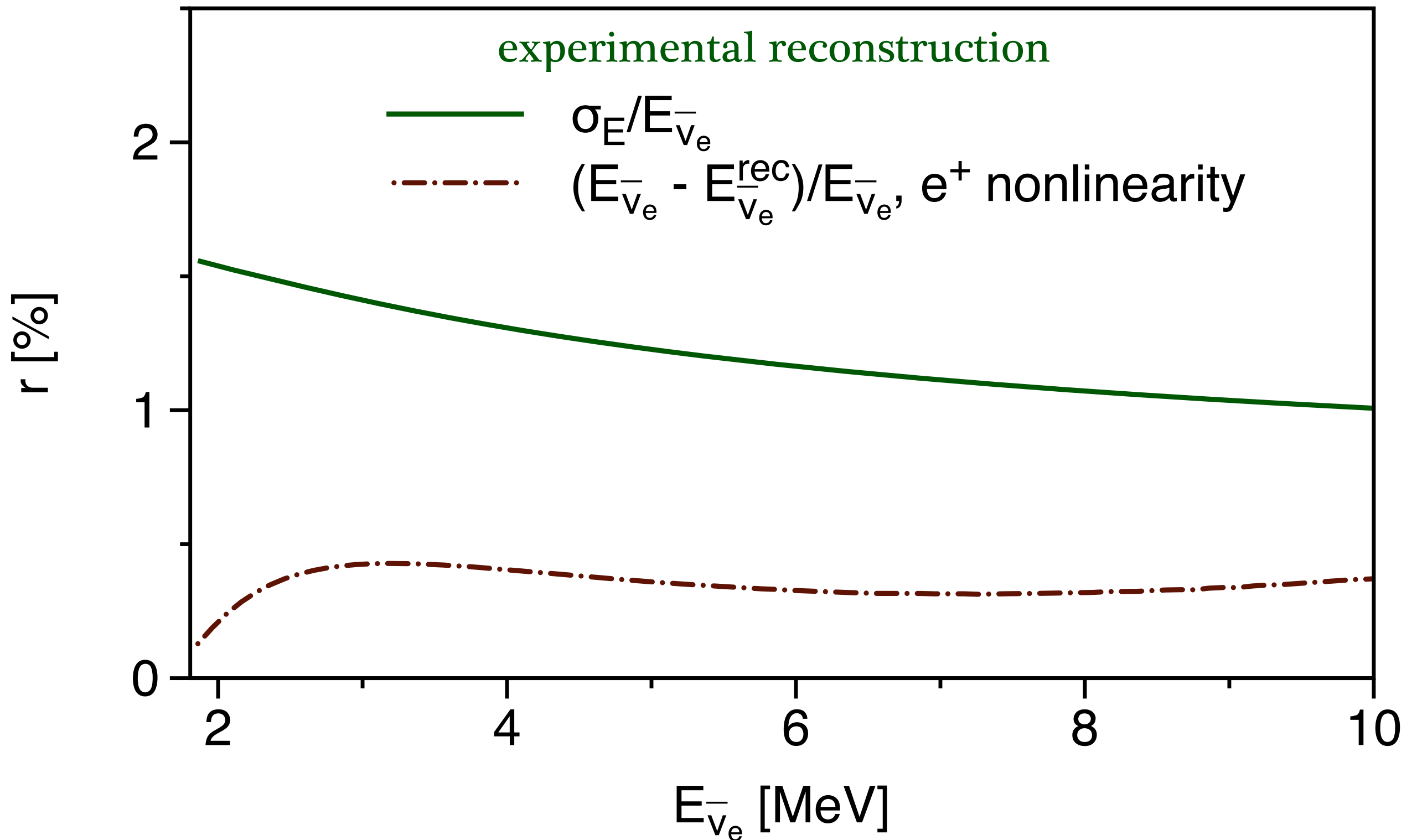
- tree-level recoil effects are sizable

Energy reconstruction is key



- tree-level recoil effects are sizable

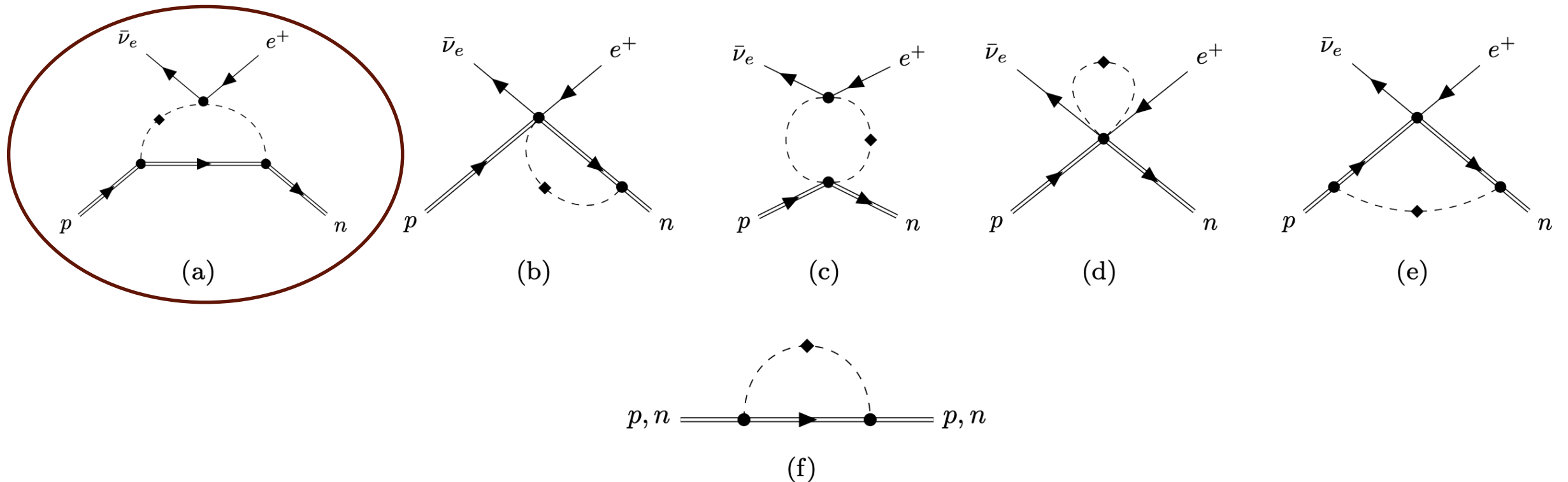
Energy reconstruction is key



- radiative effects $\sim 1/3$ of expected resolution

Supernova and π DAR energies

- include pion degrees of freedom to inverse beta decay



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

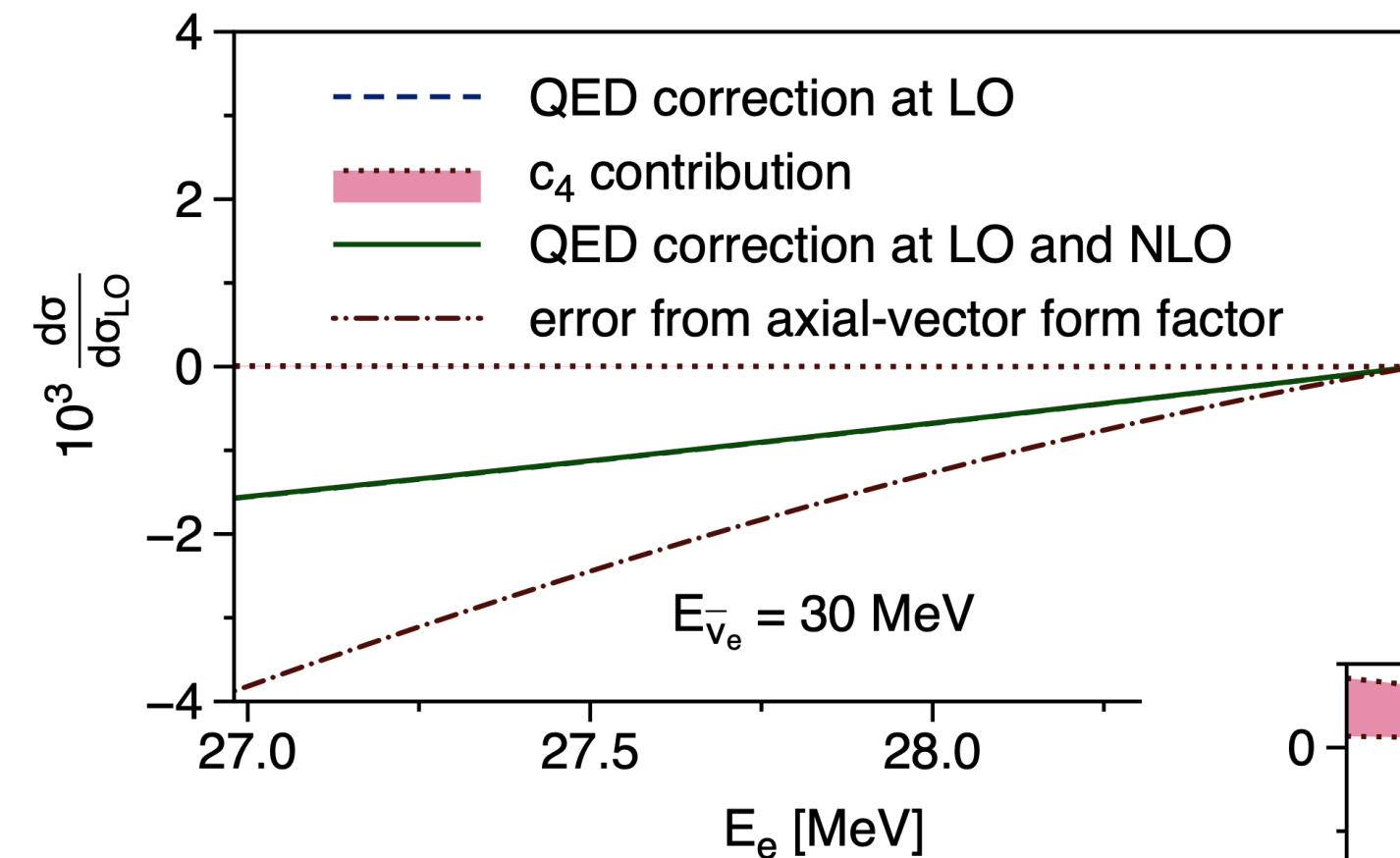
O.T., JHEP (2026)

- neglect recoil diagrams without pions

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

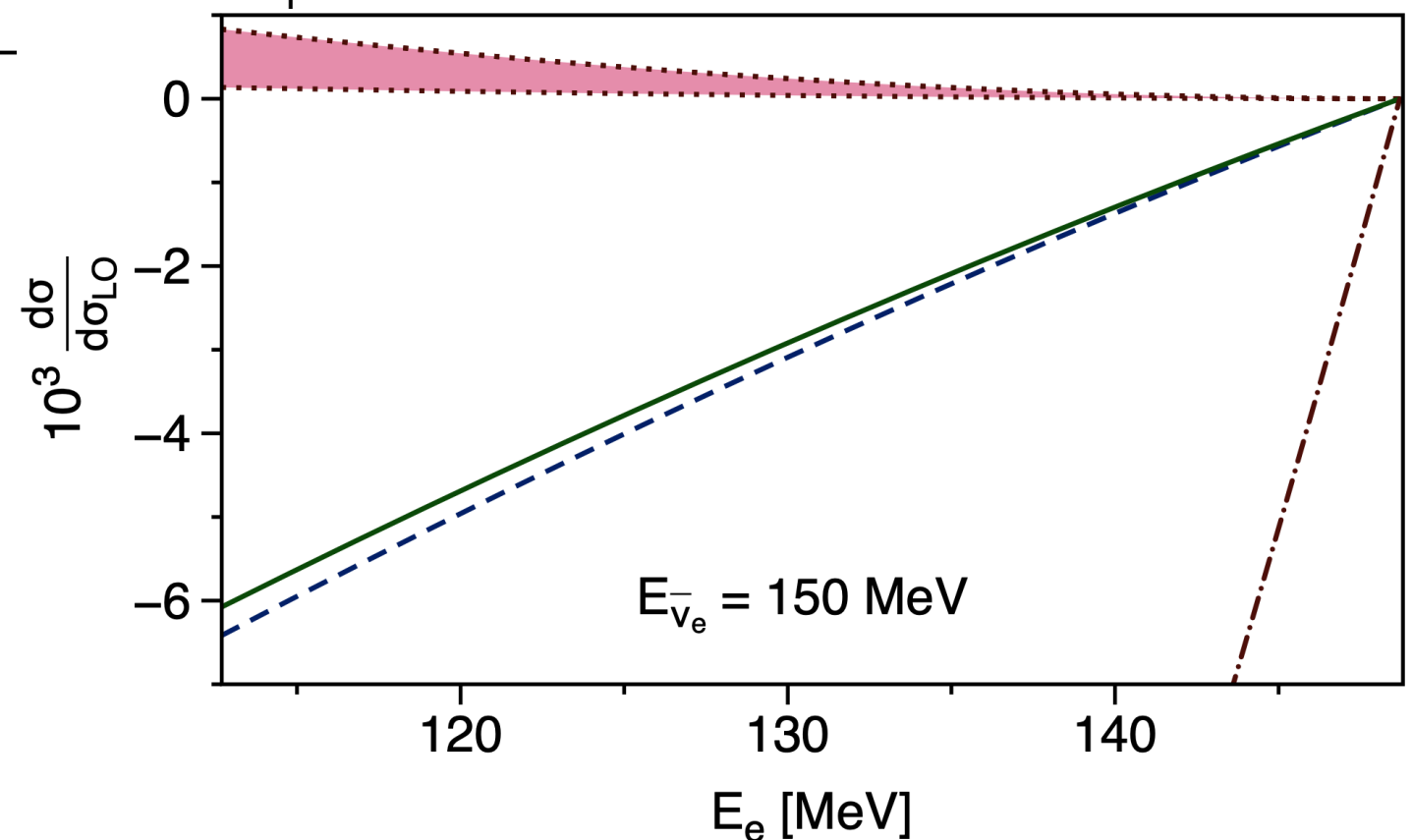
- extending **0.1%-level** predictions to energies above **10 MeV**

Supernova and π DAR energies



Wilson coefficient c_4 enters at higher energies

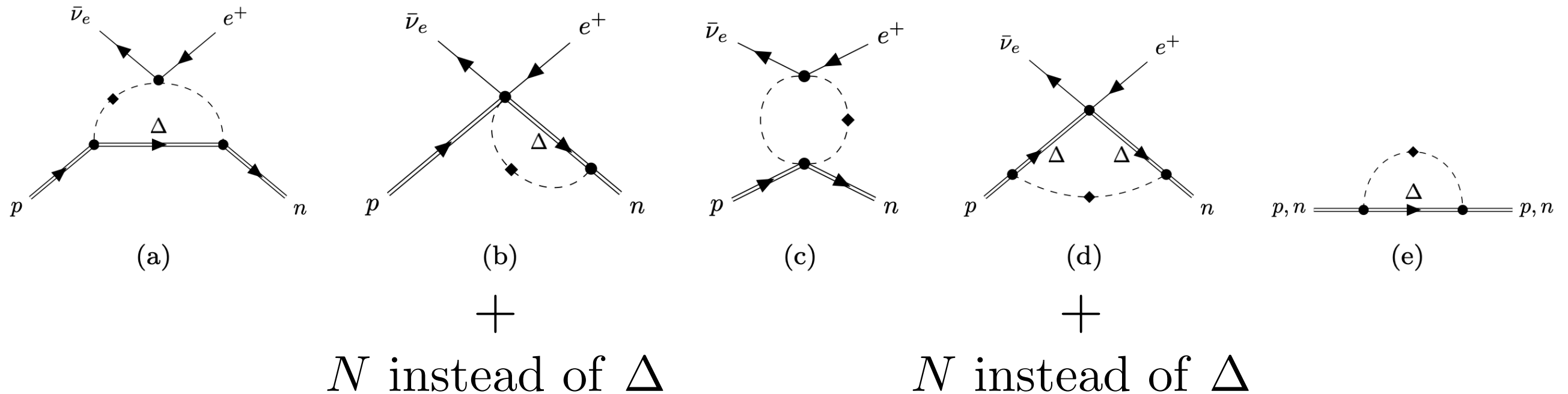
O.T., JHEP (2026)



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

Supernova and π DAR energies

- include Δ degrees of freedom to inverse beta decay



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

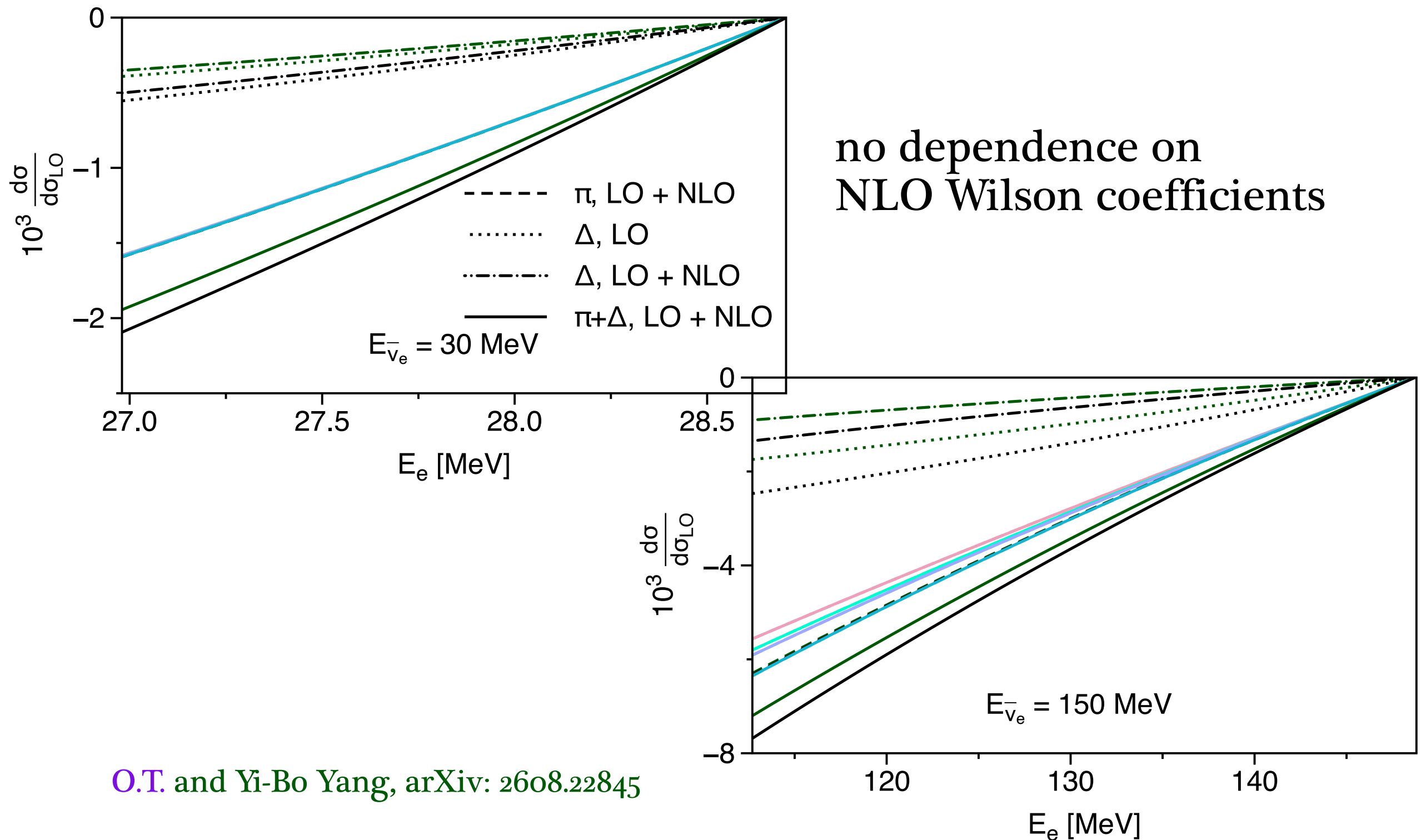
O.T. and Yi-Bo Yang, arXiv: 2608.22845

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

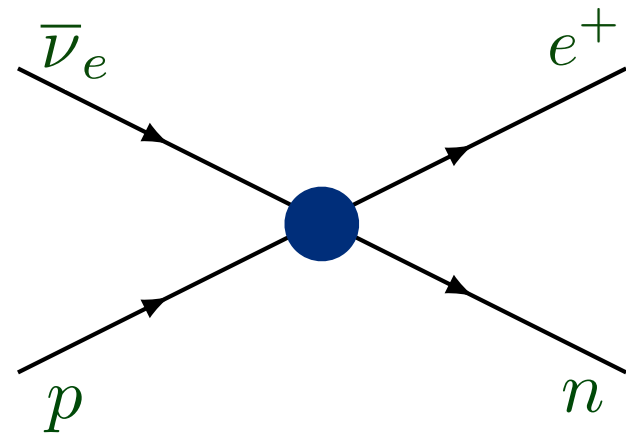
Supernova and π DAR energies



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 $\rightarrow$ LEFT $\rightarrow$ HB χ PT $\rightarrow$ π 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
- **1st** evaluation of π -, Δ -induced corrections to **inverse beta decay**

Thanks for your attention !!!

谢谢

Low-energy description

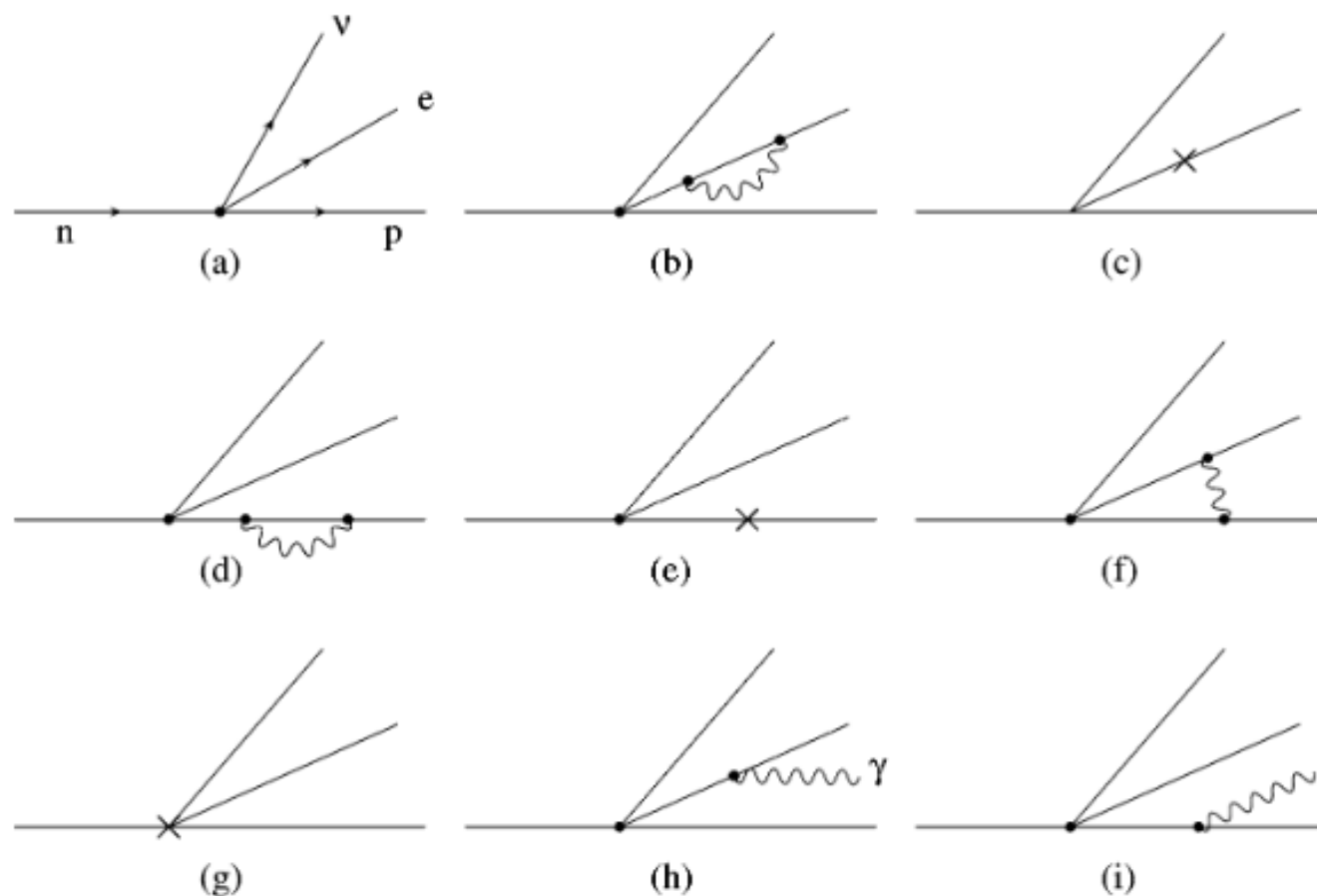
- four-fermion interaction between leptons and heavy nucleons

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$$m_e \sim M_p - M_n$$

A. Sirlin, Phys. Rev. (1967)

- radiative corrections formulated in modern **EFT language**



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

data

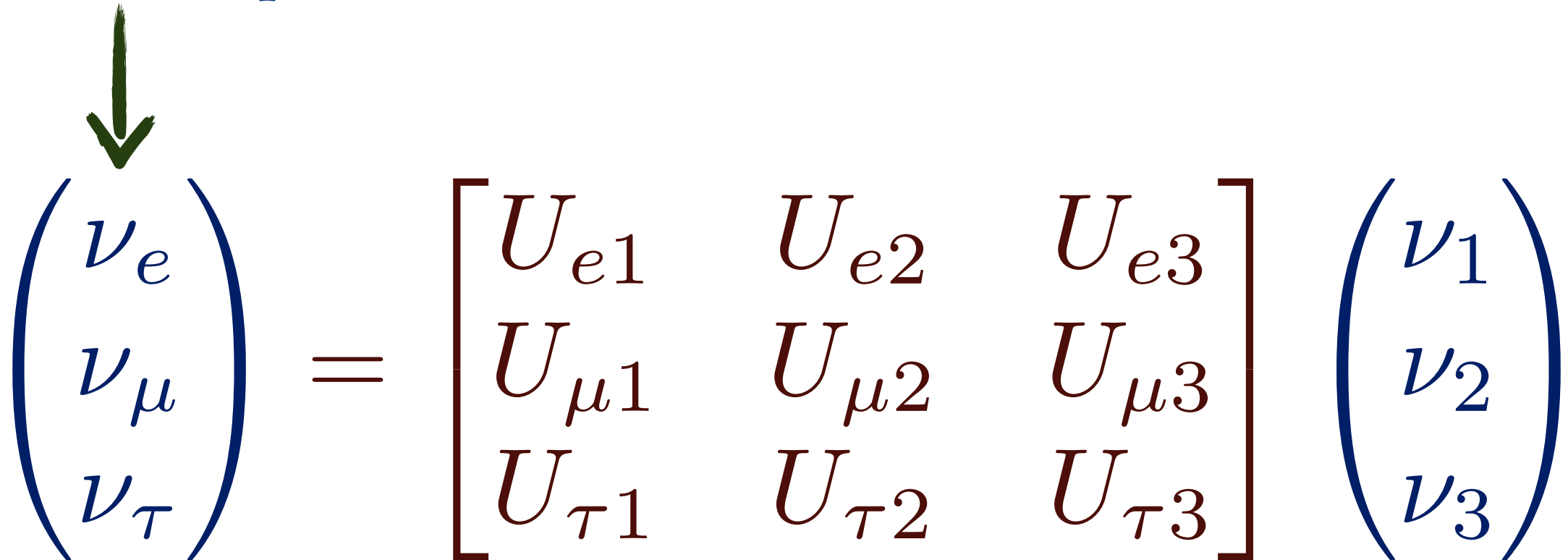
Standard Model

S. Ando et al., PLB (2004)

- **two coupling constants** predict all observables

PMNS oscillation matrix

neutrinos produced and detected in flavor basis

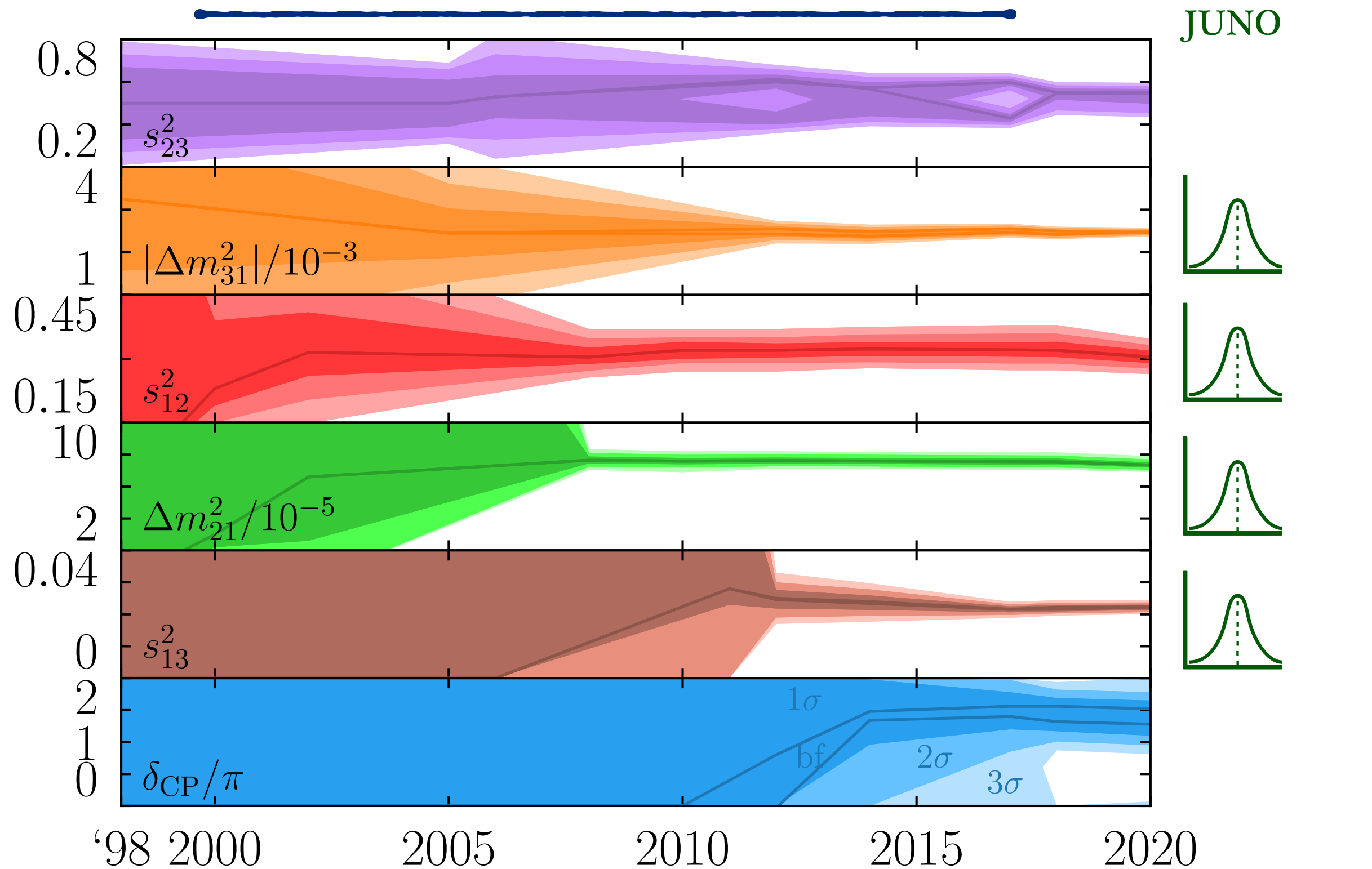

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

neutrinos propagate in mass basis

Pontecorvo-Maki-Nakagawa-Sakata matrix relates two bases

- oscillations are described by PMNS mixing matrix

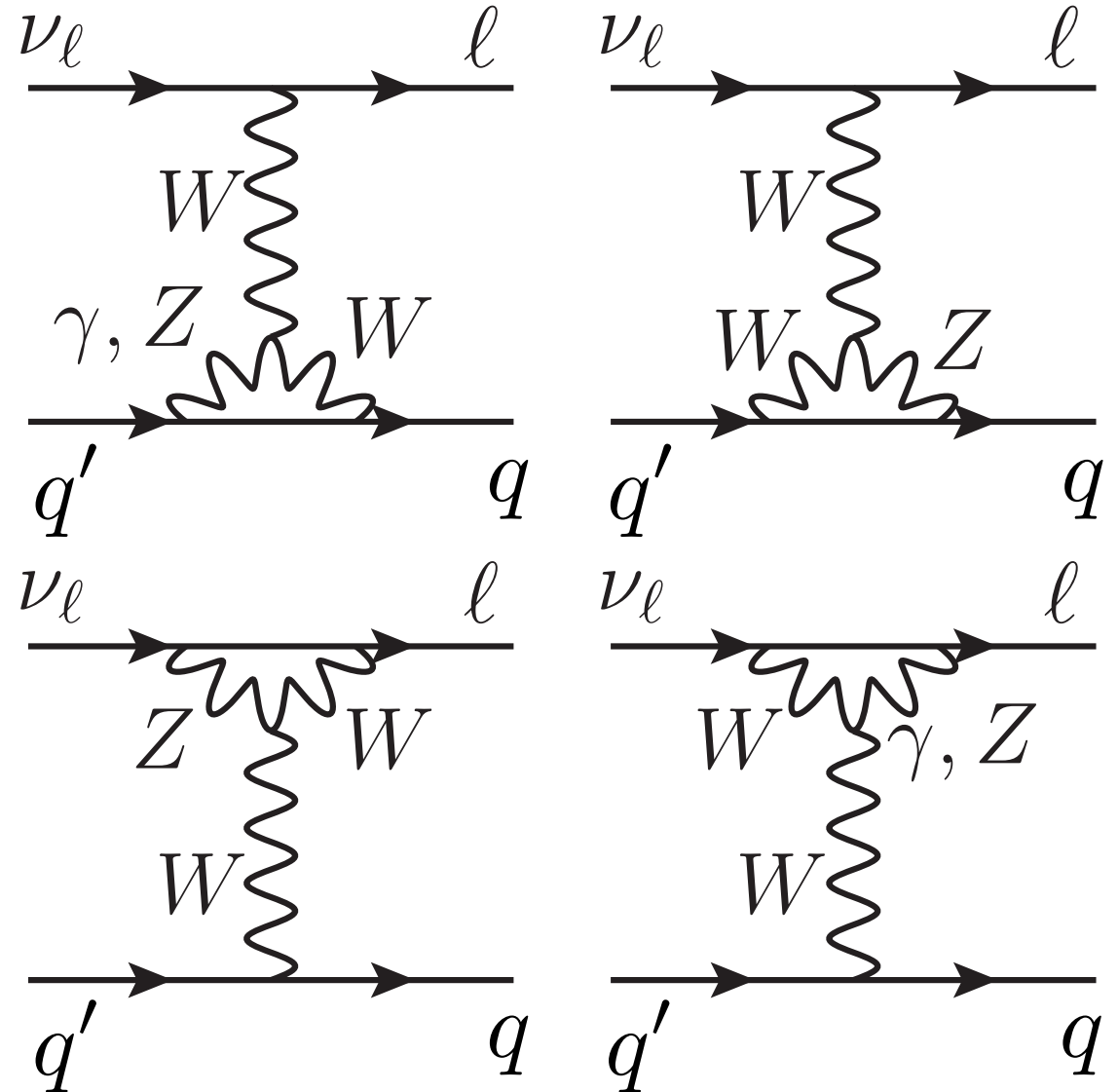
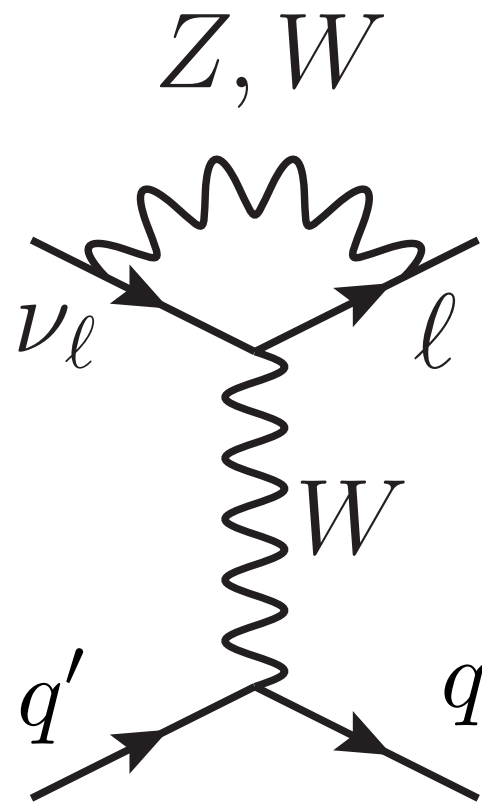
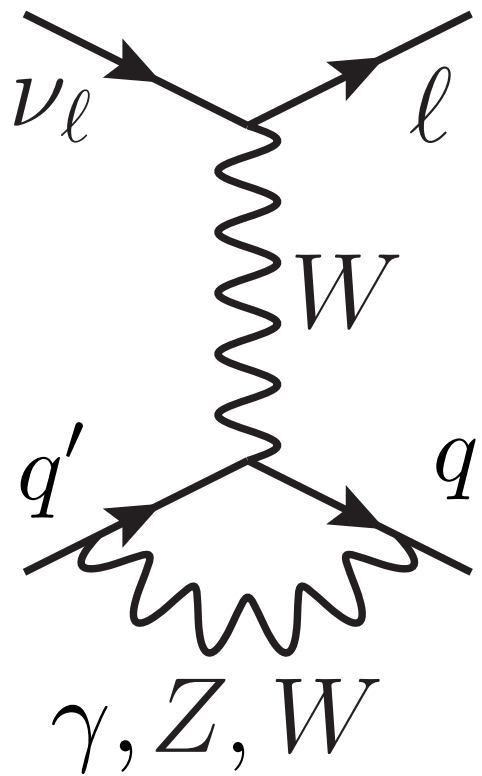
PMNS oscillation matrix



- tremendous progress in our lifetime

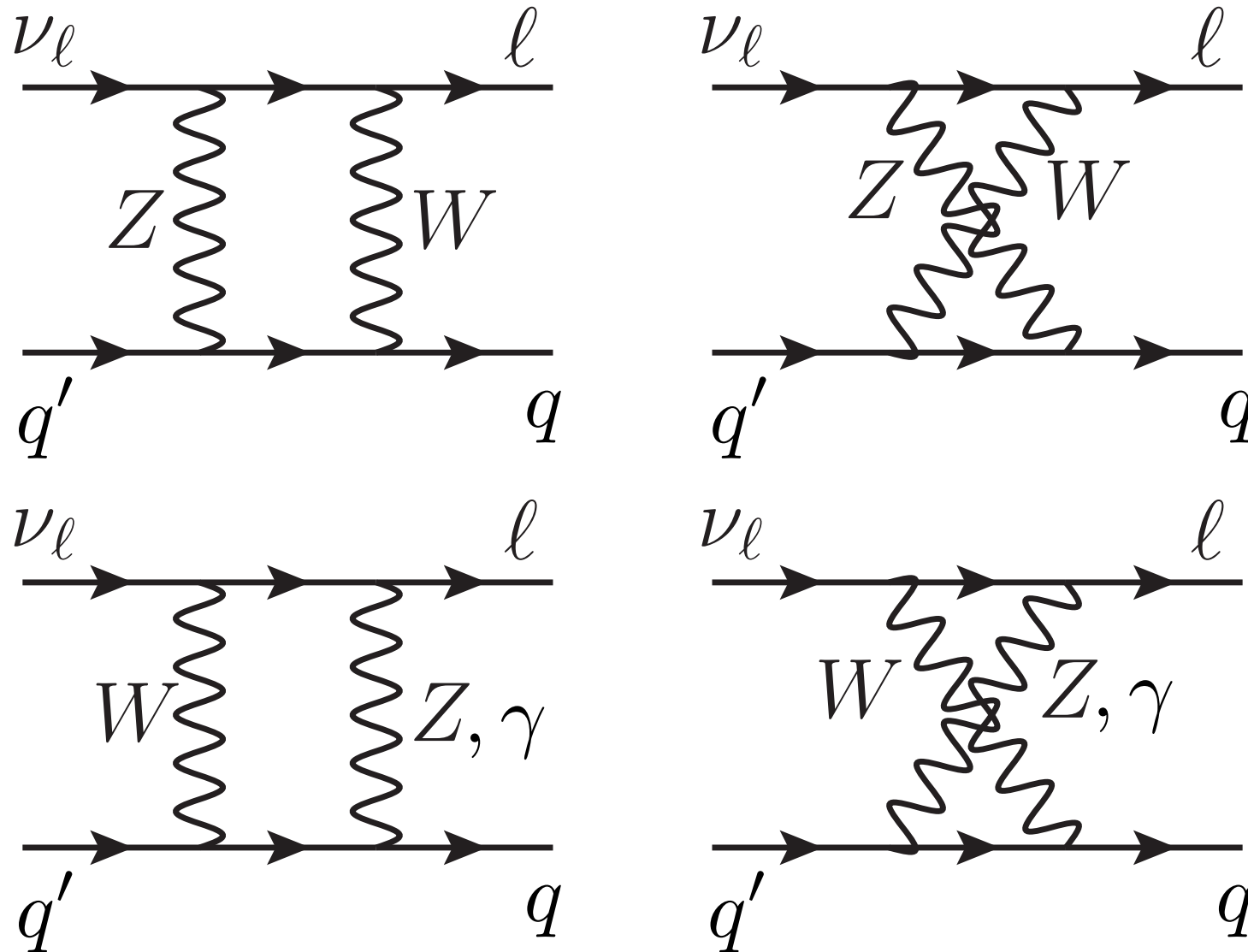
Snowmass 2021 NFOI group report

Charged current in SM. Vertexes



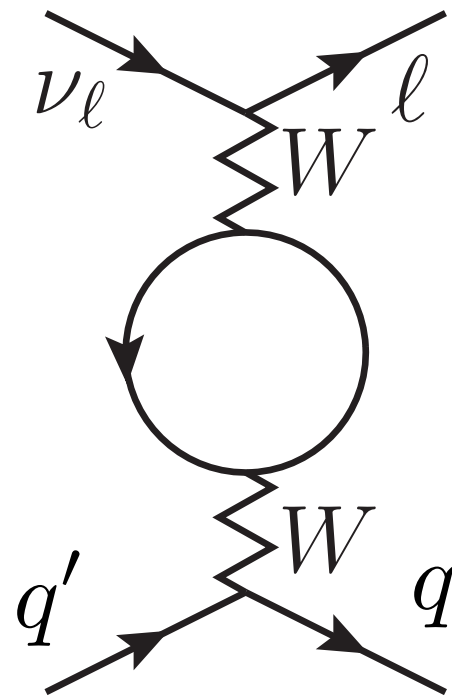
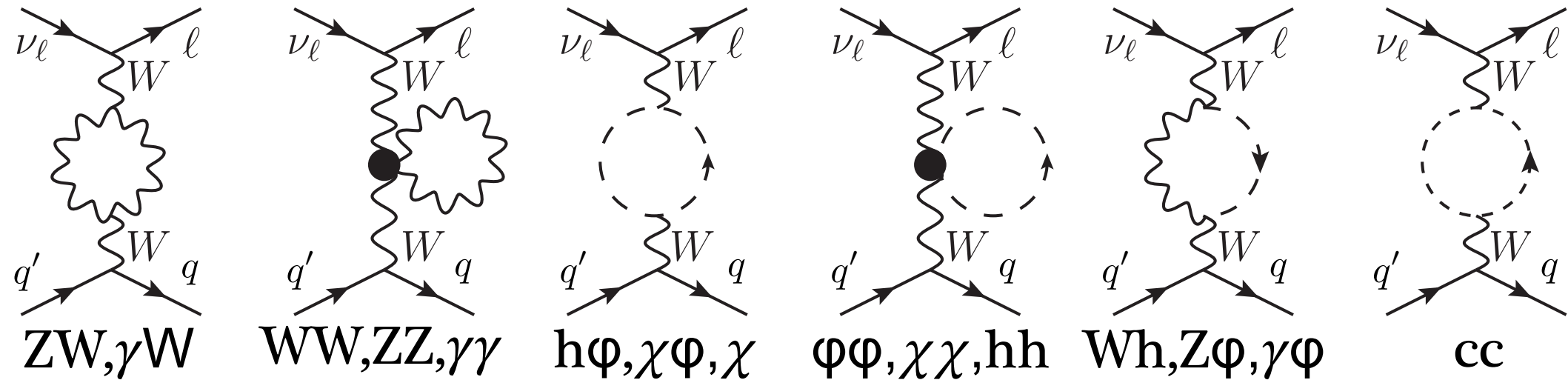
- contribution to effective couplings

Charged current in SM. Boxes



- contribution to effective couplings

W self energy

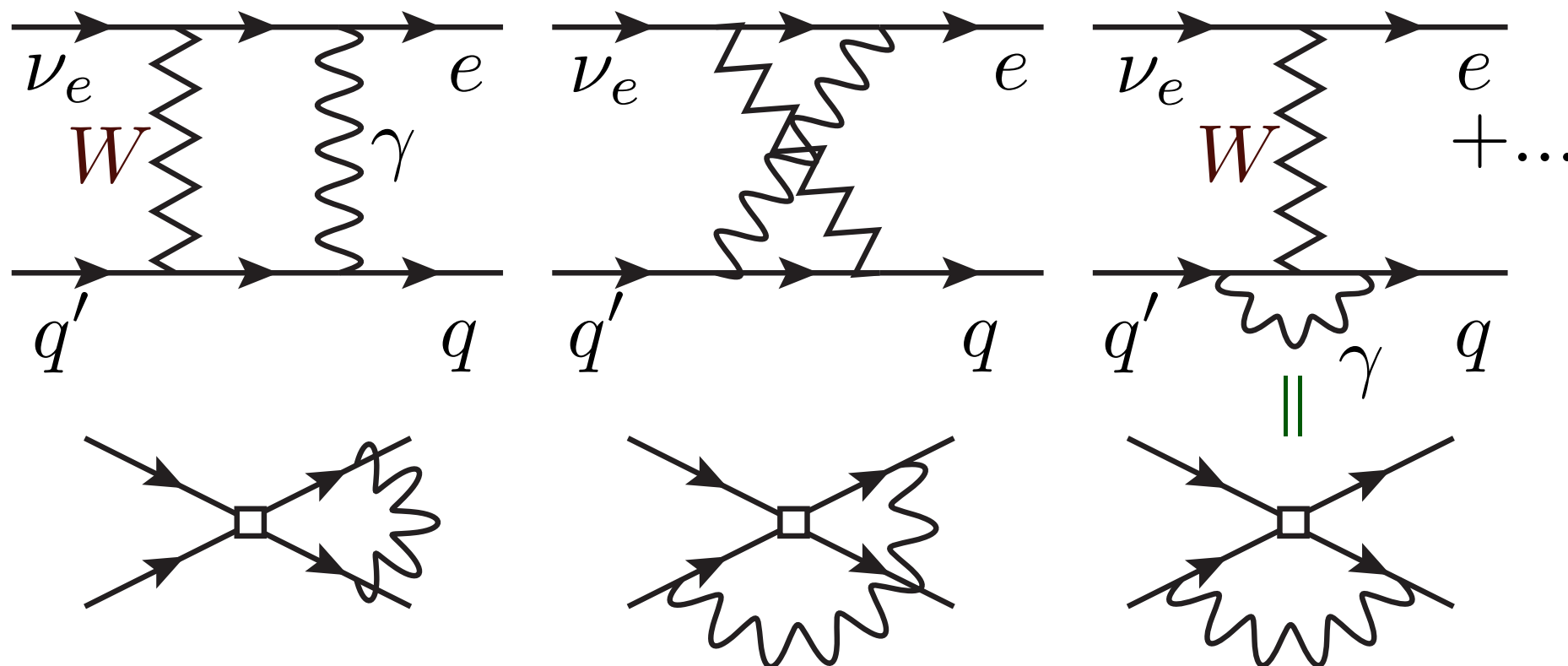


- vanishing contribution to matching besides loops with t quark

- contribution to effective couplings

LEFT Lagrangian

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



scheme independent

scheme dependent for quarks

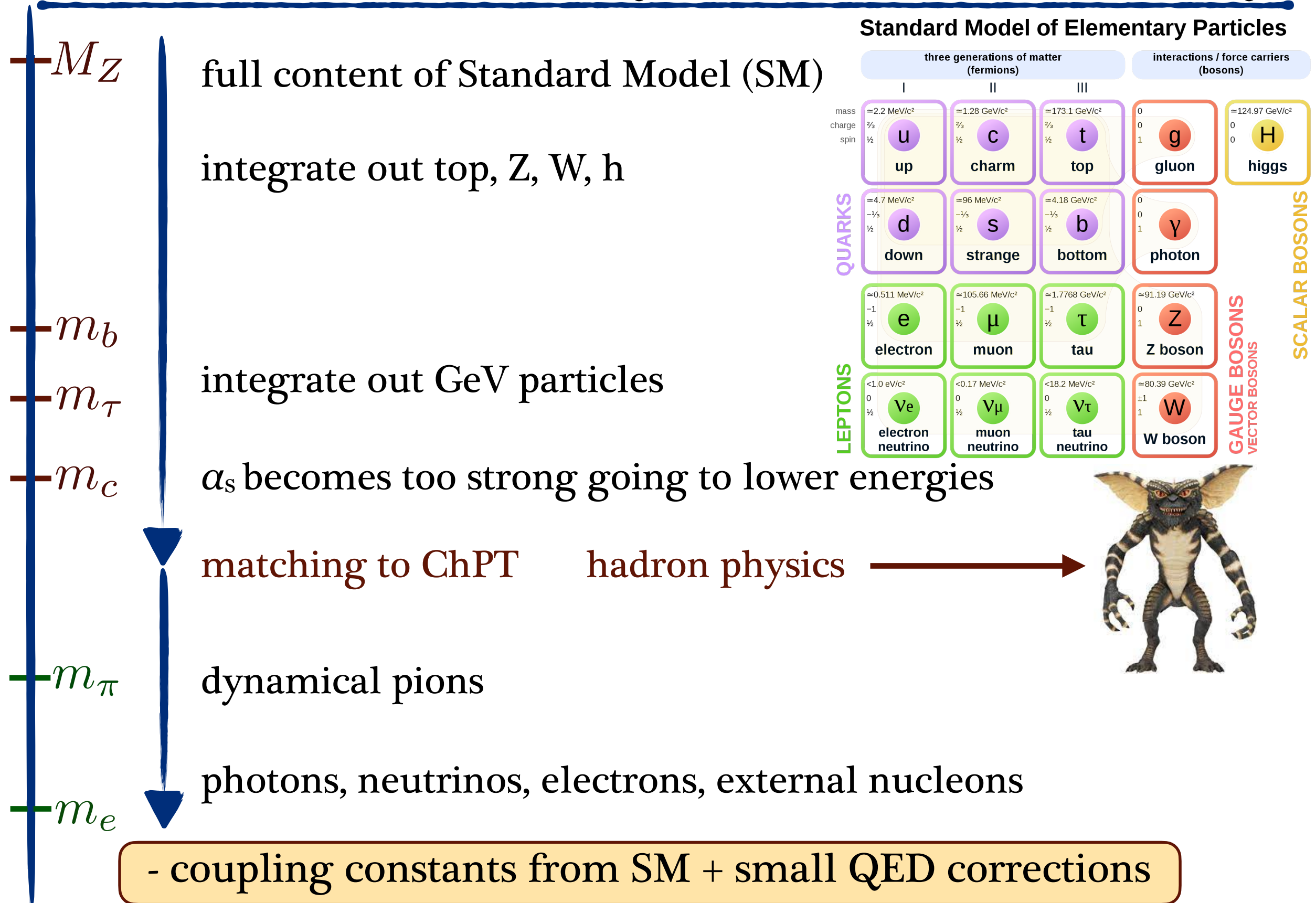
- NDR scheme for γ_5 for evanescent operators E

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

Buras and Weisz, NPB (1990)

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

Effective field theory for IBD and β decay



HB χ PT to π EFT matching

- purely leptonic counterterm

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

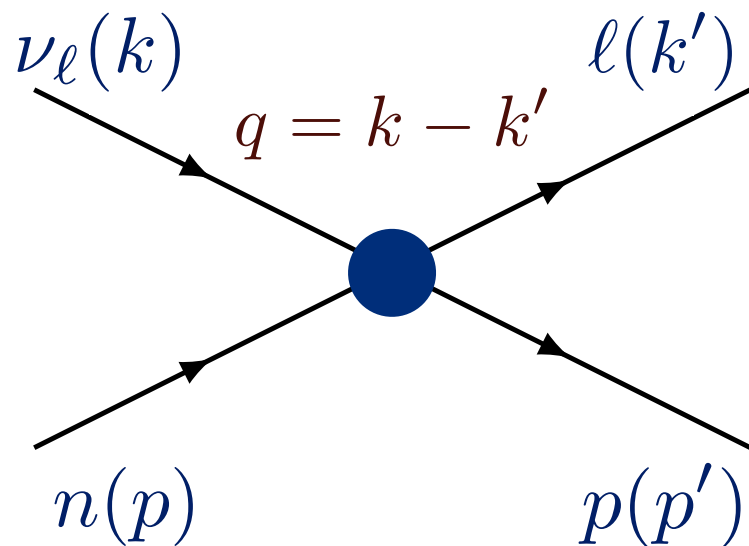
- π EFT counterterms from χ PT couplings in baryon sector

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

EW + electromagnetic

- LECs in terms of correlation functions

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

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

- **four extra amplitudes** for massive charged lepton

$$\begin{aligned} T_{\nu_\ell n \rightarrow \ell^- p}^{m_\ell \neq 0} = & -\sqrt{2}G_F V_{ud} \frac{m_\ell}{M} \bar{\ell}^- P_L \nu_\ell \bar{p} \left(f_3 + f_P \gamma_5 - \frac{f_R}{4} \frac{P_\mu}{M} \gamma^\mu \gamma_5 \right) n \\ & + \sqrt{2}G_F V_{ud} \frac{m_\ell}{M} \frac{f_T}{4} \bar{\ell}^- \sigma^{\mu\nu} P_L \nu_\ell \bar{p} \sigma_{\mu\nu} n \end{aligned}$$

- **8 invariant amplitudes** for charged-current elastic scattering

V_{ud} from neutron decay

- λ from electron spin correlation measurements

$$|V_{ud}|^2 \tau_n (1 + 3\lambda^2) \left(1 + \Delta_{\text{TOT}}\right) = 5283.321(5) \text{ s}$$
$$\Delta_{\text{TOT}}^{\text{EFT}} = 7.761(27)\% \quad \text{vs} \quad \Delta_{\text{TOT}} = 7.735(27)\% \quad \lambda = \frac{g_A}{g_V}$$

- extraction with **PDG** lifetime and λ

CSNS physics!

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

- extraction with **UCN τ** lifetime and **PERKEO-III** λ

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

- in agreement with superallowed β decays, similar error

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

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

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

- V_{ud} from superallowed transitions and neutron decay

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

Hardy and Towner, PRC (2020)

changes by 1 uncertainty of radiative corrections

- g_A from beta asymmetry in polarized neutron decay

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

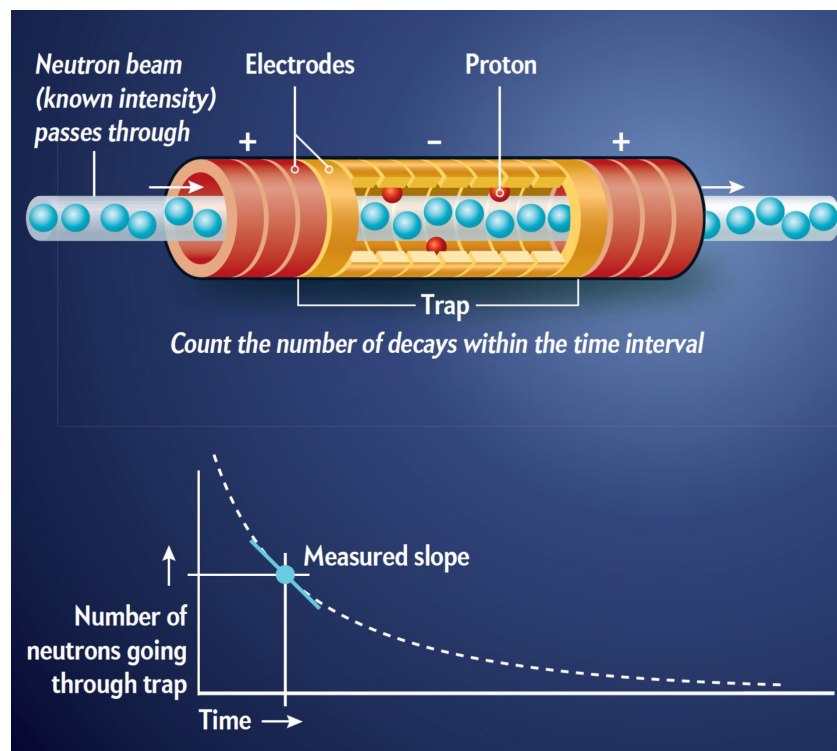
changes by 1/3 of PERKEO-III experimental uncertainty

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

Neutron lifetime measurements



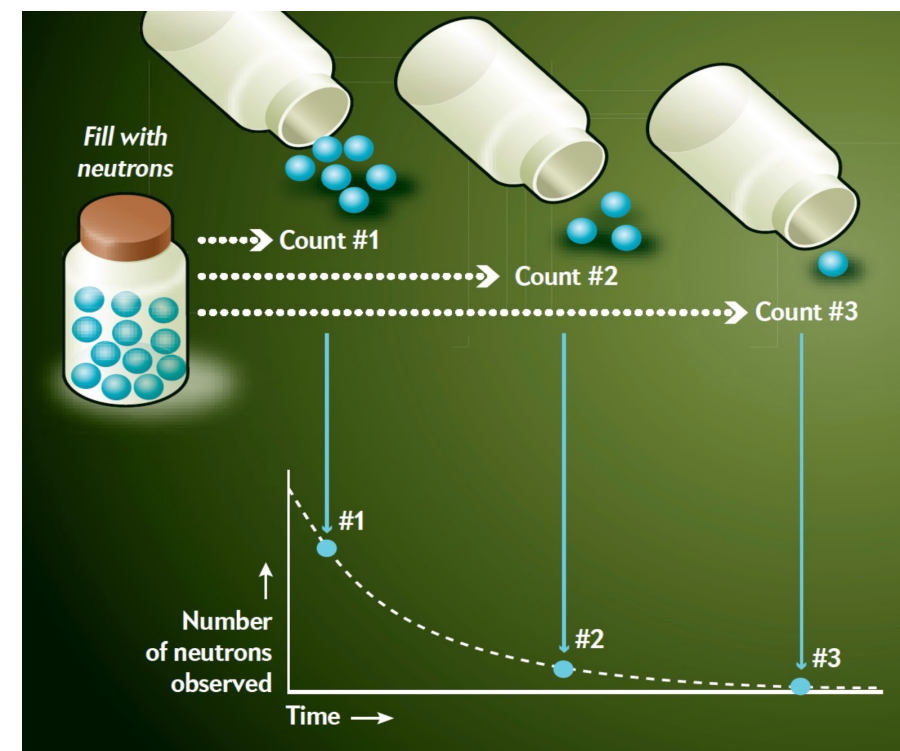
beam method



how many neutrons pass?



bottle method



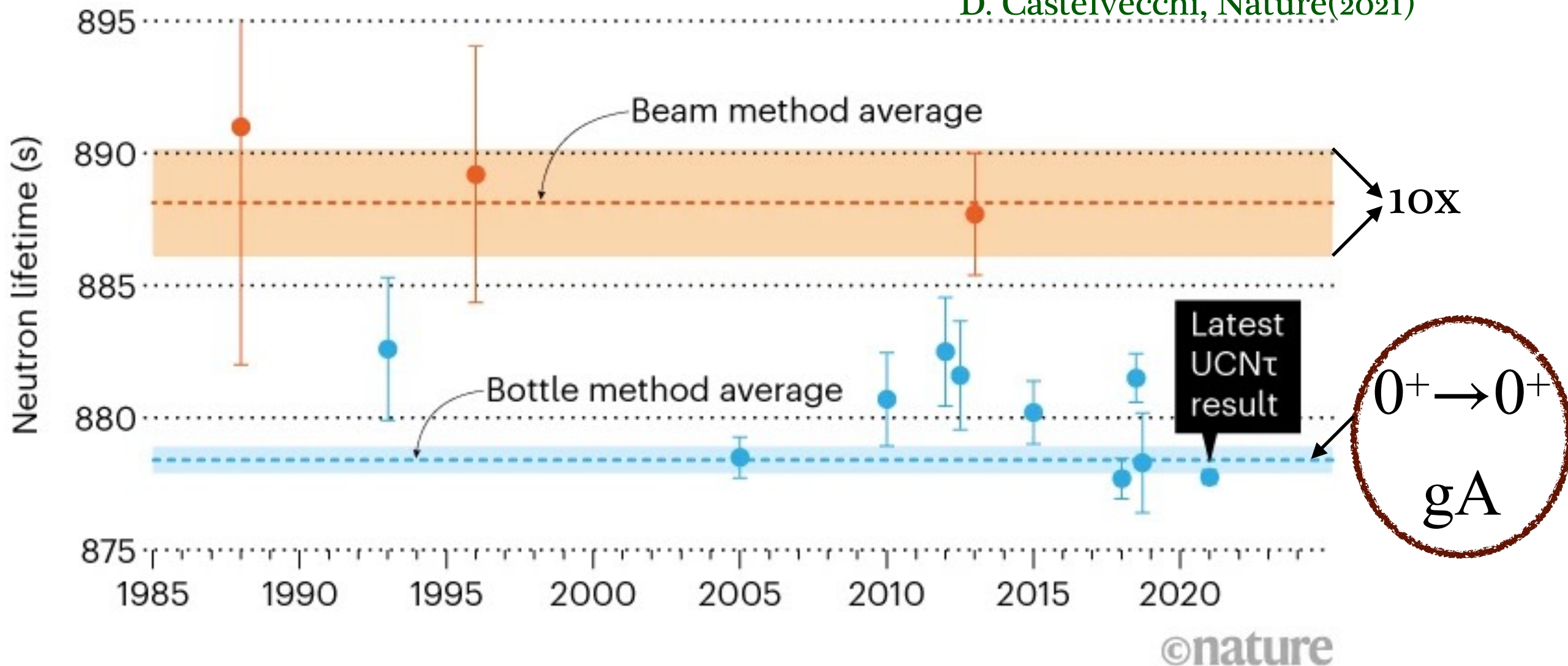
how many neutrons survive?

Neutron lifetime puzzle

● Results using beam method ● Bottle method

UCN τ : F. Gonzales et al., PRL (2021)

D. Castelvechi, Nature(2021)

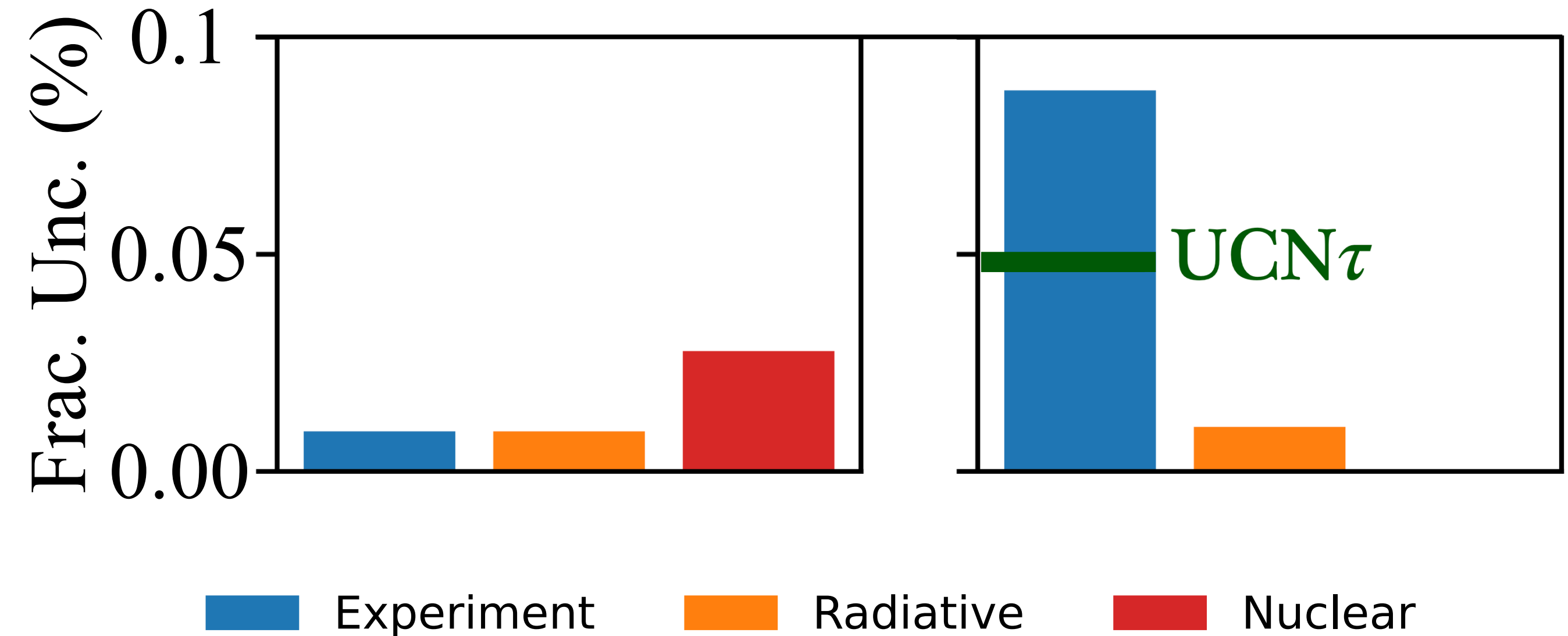


- 8-9 seconds discrepancy beam vs bottle method : $3-5\sigma$
- V_{ud} from $0^+ \rightarrow 0^+ + gA$ from β asymmetry $\equiv$ bottle
- 0.3 seconds uncertainty of UCN τ @LANL : $(3 - 4) \times 10^{-4}$

V_{ud} determinations

$0^+ \rightarrow 0^+$

Neutron

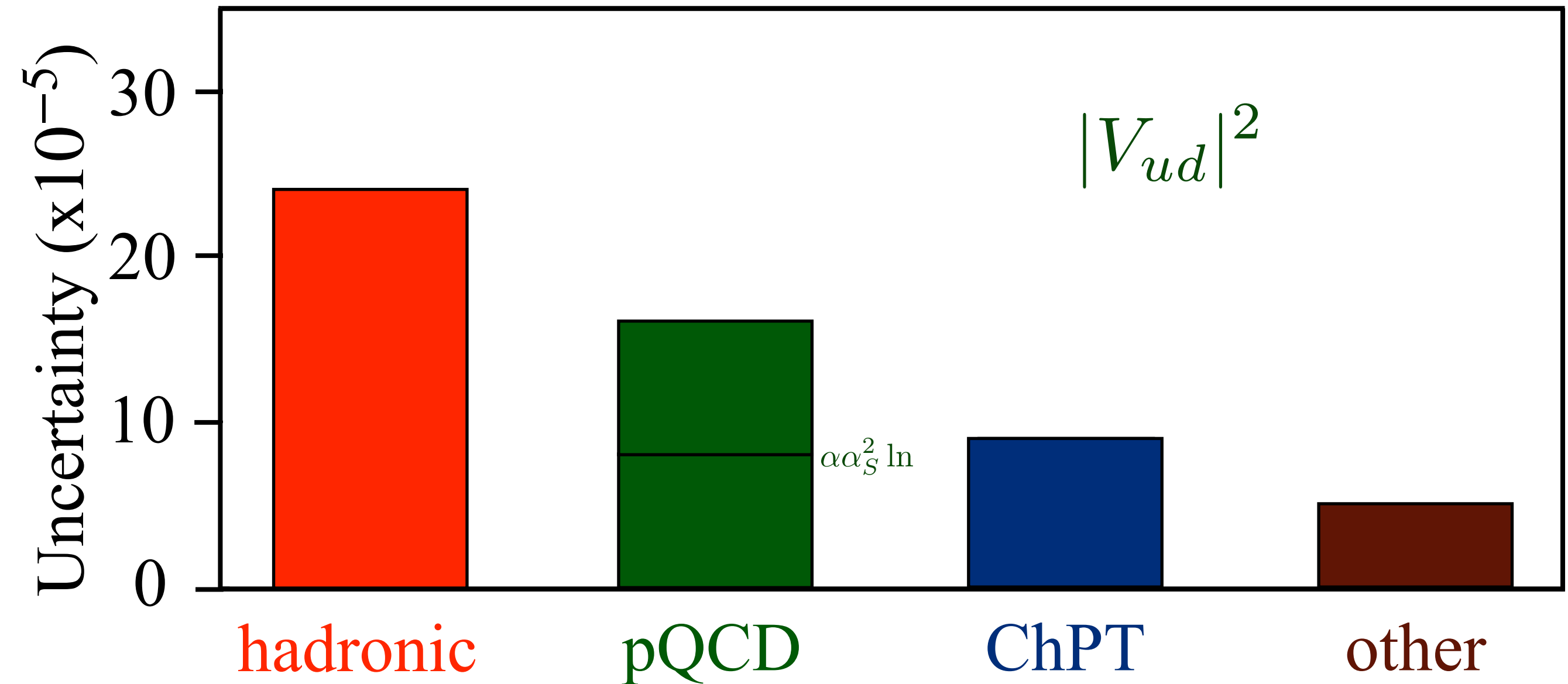


2022 Fundamental Symmetries, Neutrons, and Neutrinos (FSNN) white paper

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

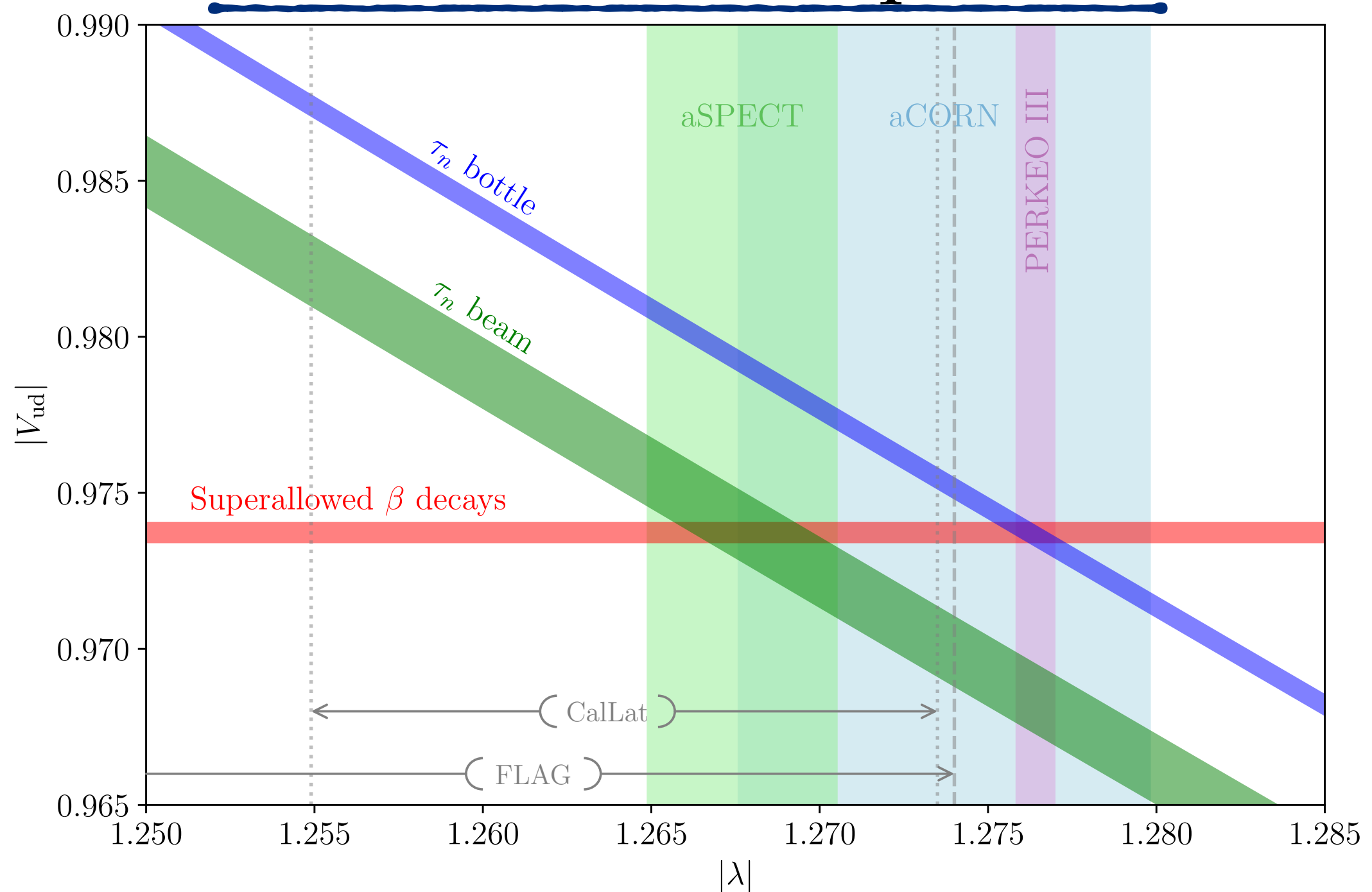
Our work

- 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

M_Z

four-fermion interaction between leptons and heavy nucleons

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

scale separation introduces large **logarithms**:

hadronic scale

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

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

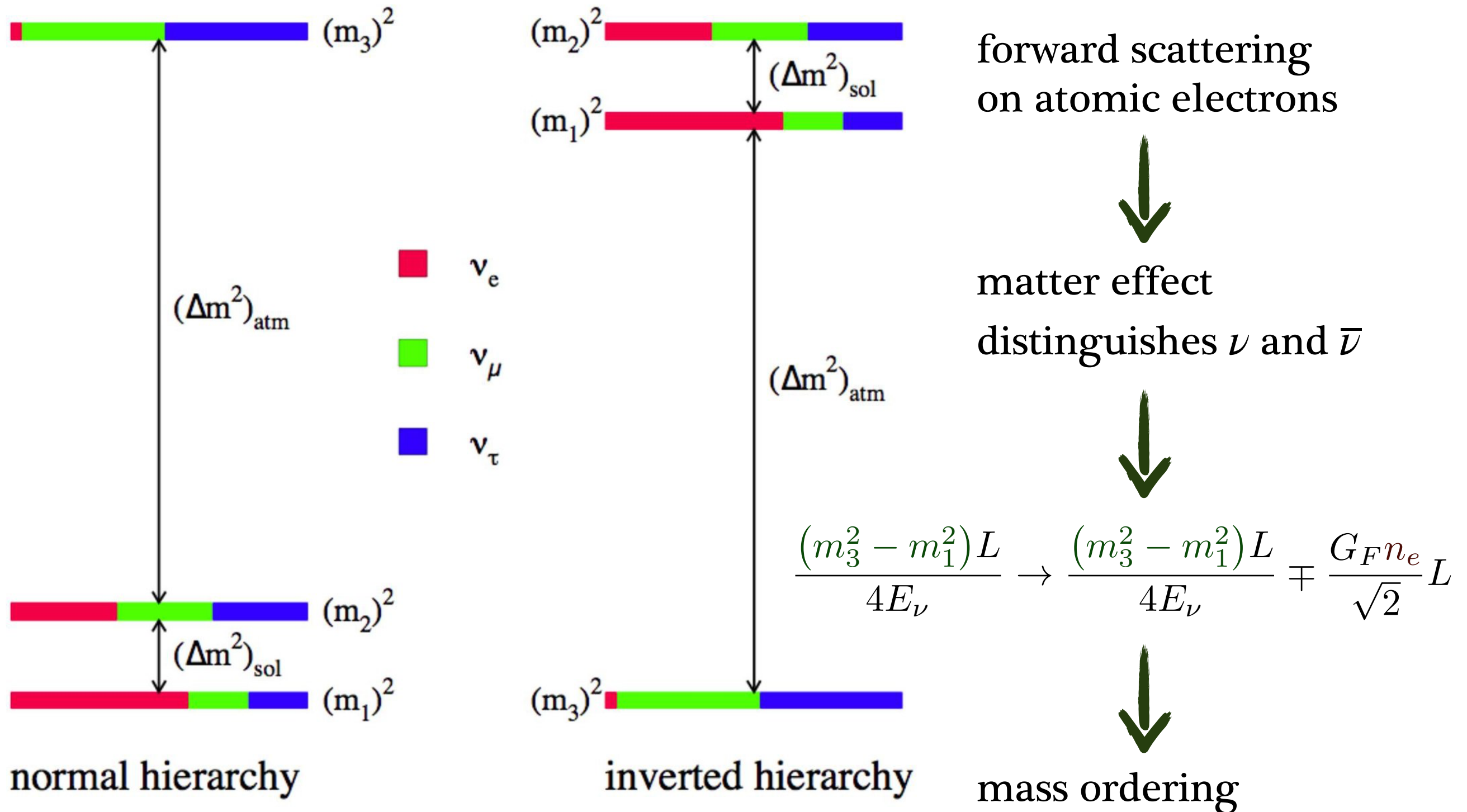
explain $\sim$ half of radiative correction to **neutron lifetime**

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

m_e

- g_V, g_A encode electroweak logarithms and hadronic corrections

Neutrino mass hierarchy



- matter effects can resolve neutrino mass hierarchy