

The 7th Joint Workshop on the Standard Model and Beyond

Nanjing Normal University, Nanjing, China

Radiative corrections to neutron and inverse beta decay at low energies



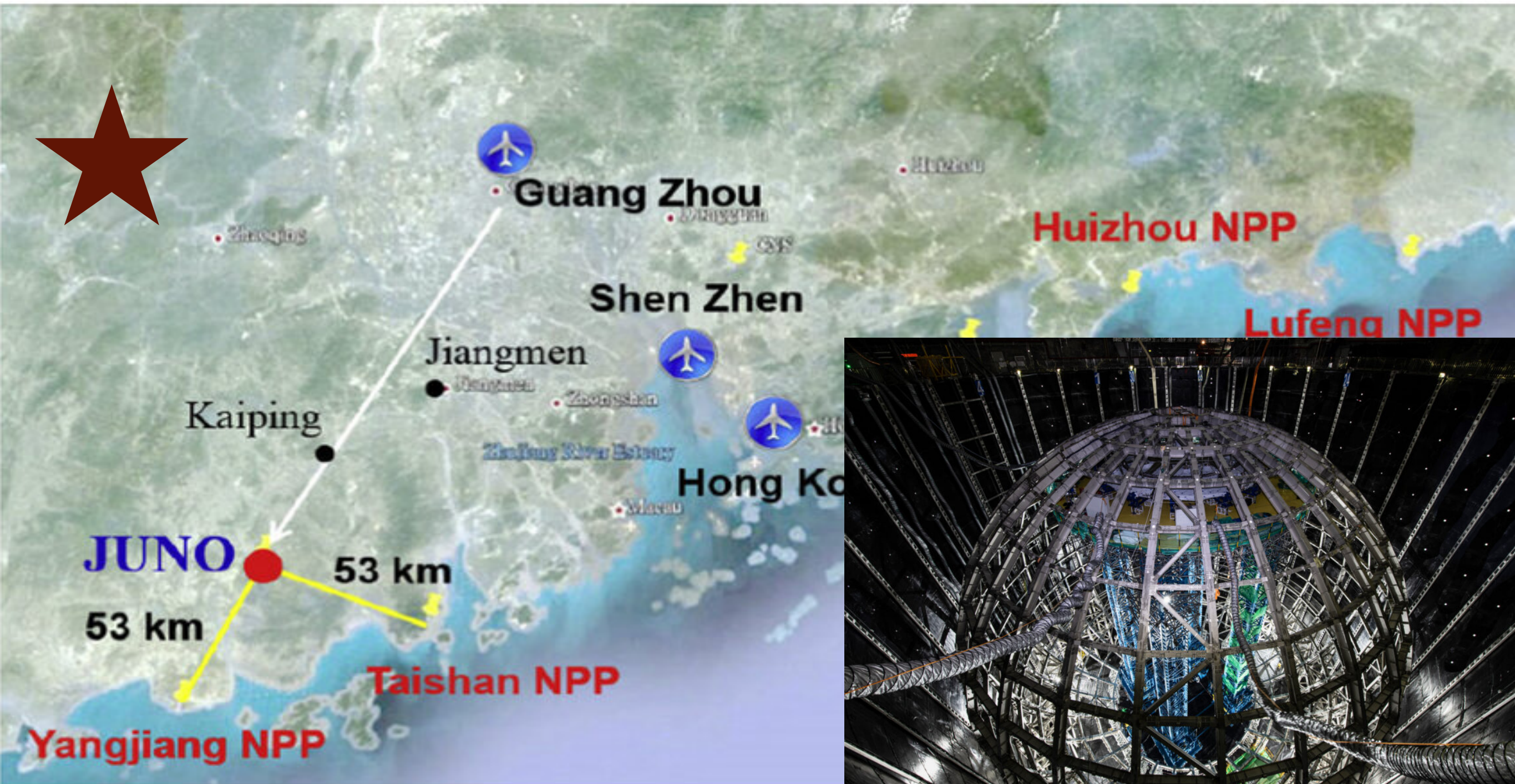
托马拉克

Sasha Tomalak

01 November, 2026

CP violation and mass hierarchy@laboratory

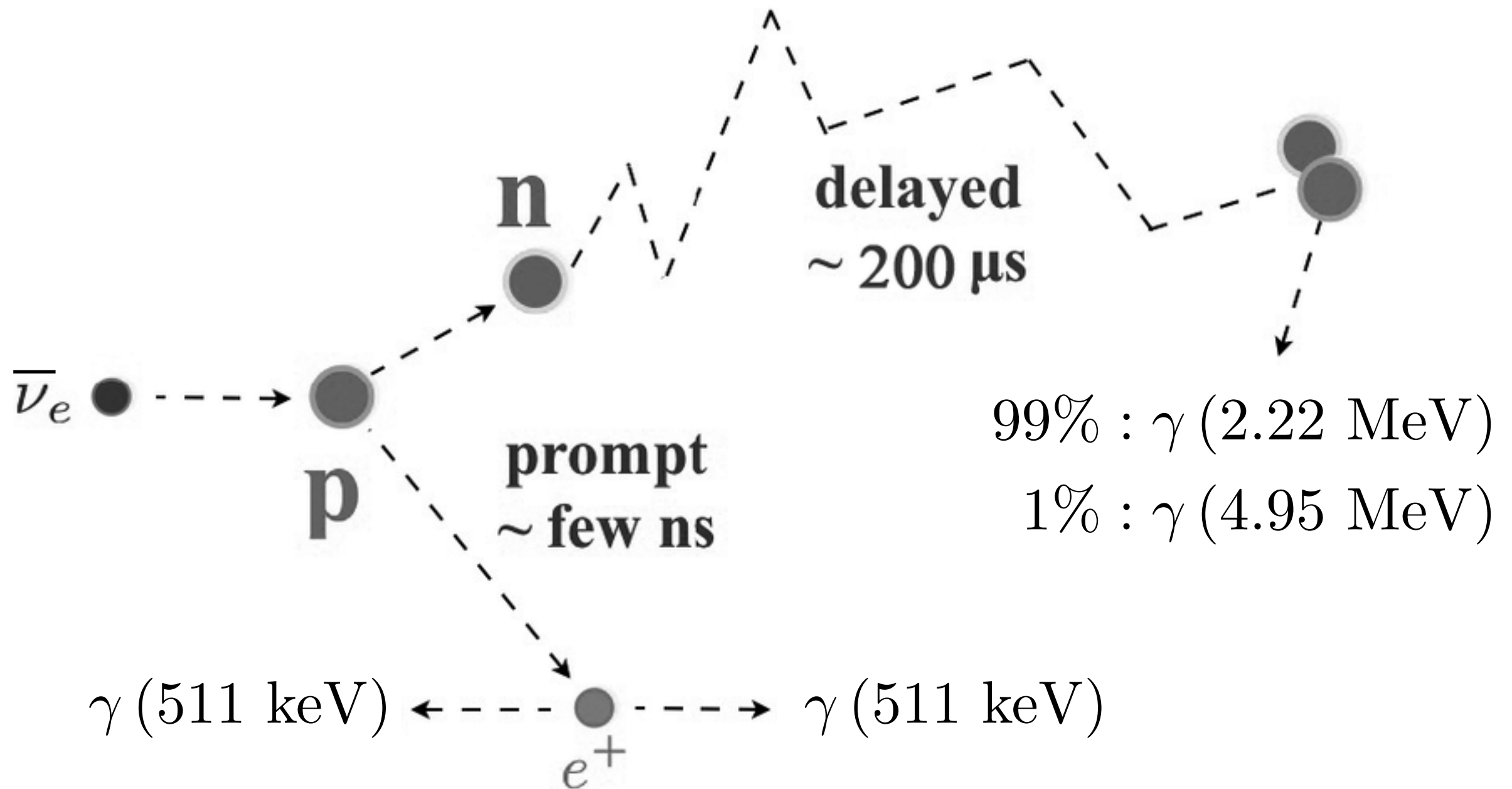
3σ determination of mass hierarchy



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

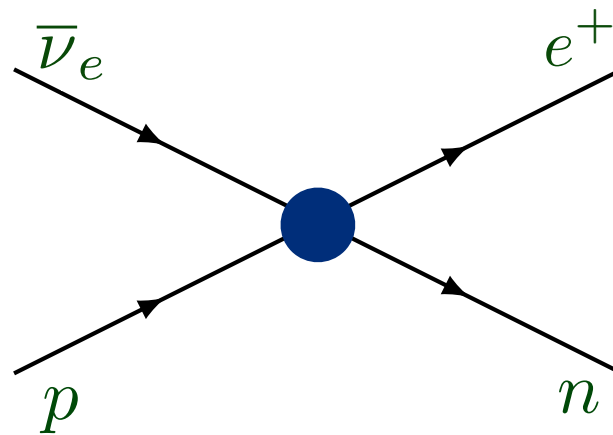
35 m, 20000 t

JUNO detection channel



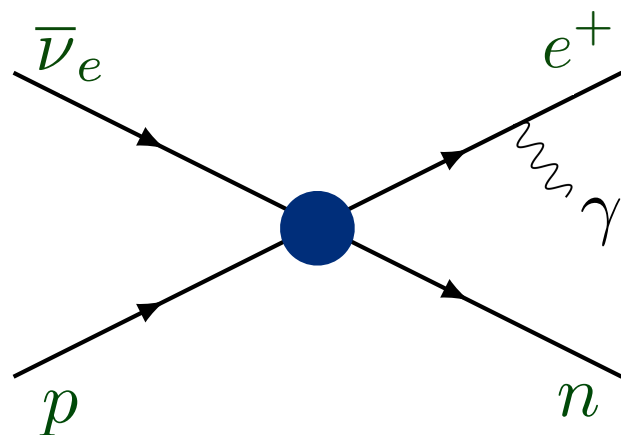
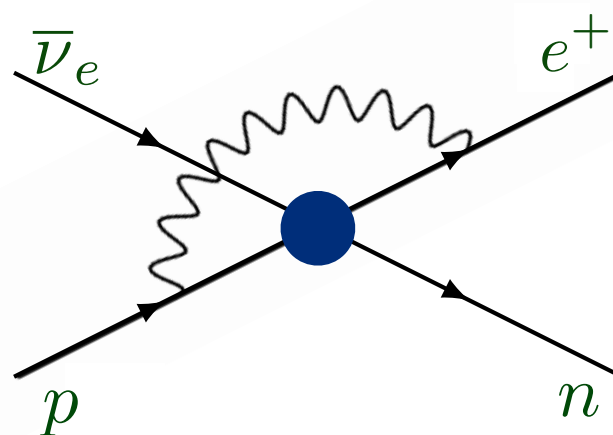
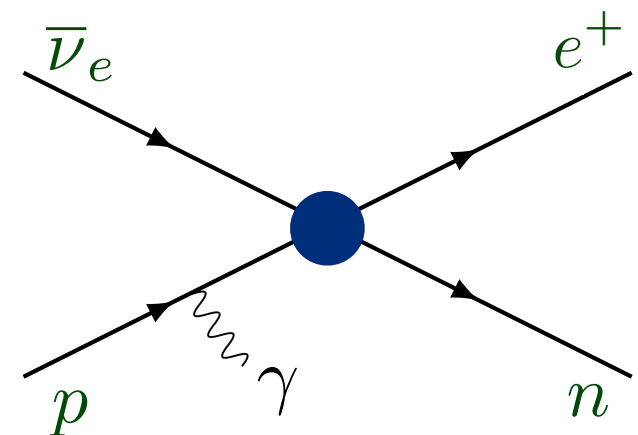
Teng Li et al., ChPC (2017)

- prompt-delayed time signature: background discrimination



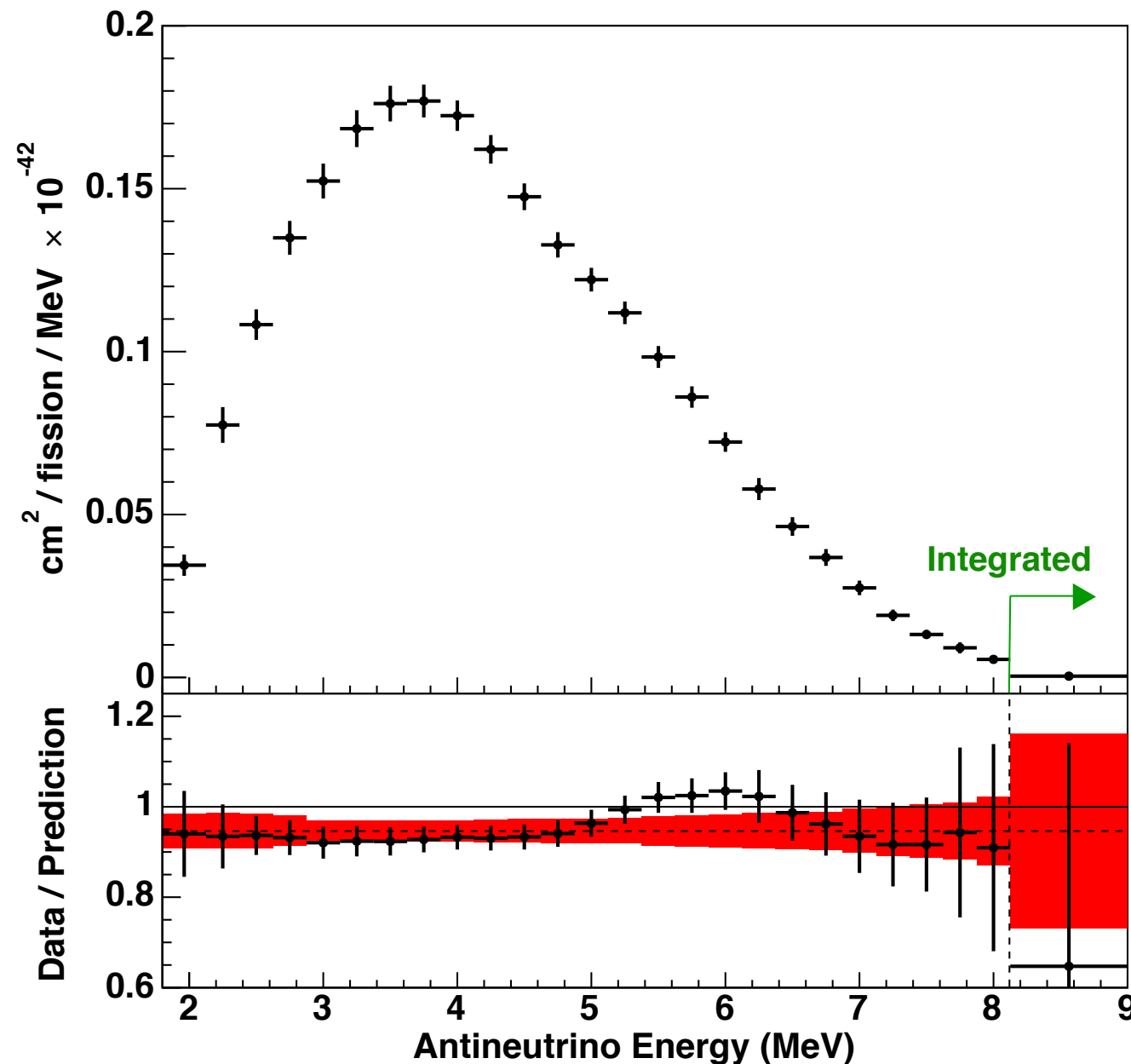
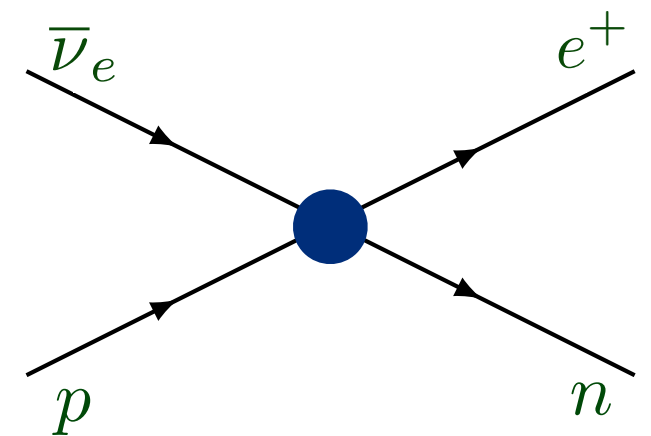
O.T., PRL (2026)

Theory of inverse beta decay for reactor antineutrinos



IBD with reactor antineutrinos

- neutron is heavier than proton by 1.3 MeV

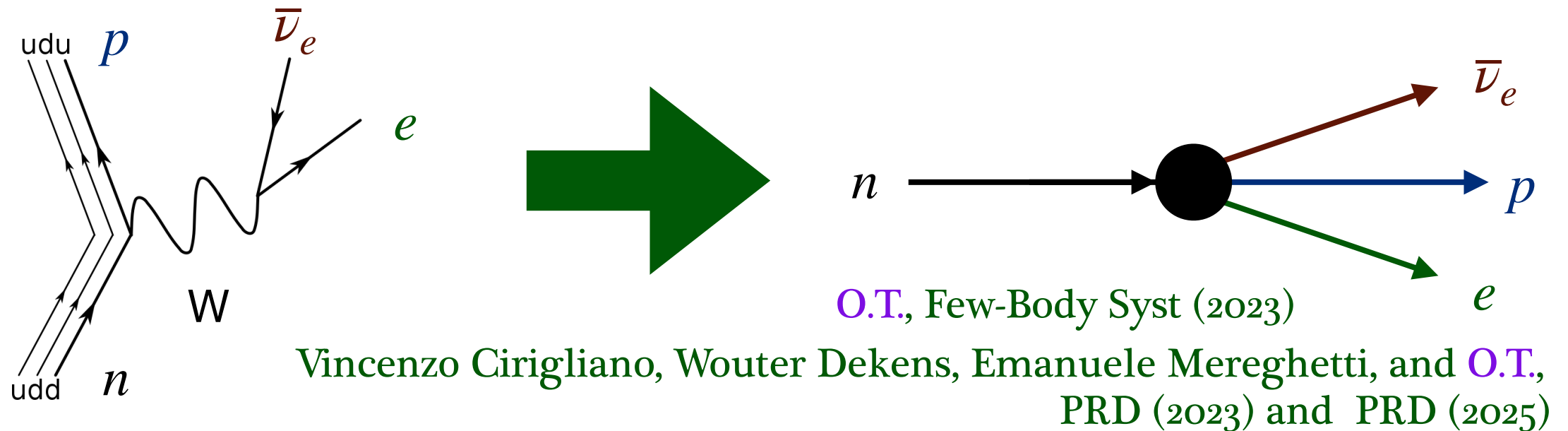


Daya Bay, PRL (2016)

- MeV-scale physics like in neutron decay

Complete EFT approach

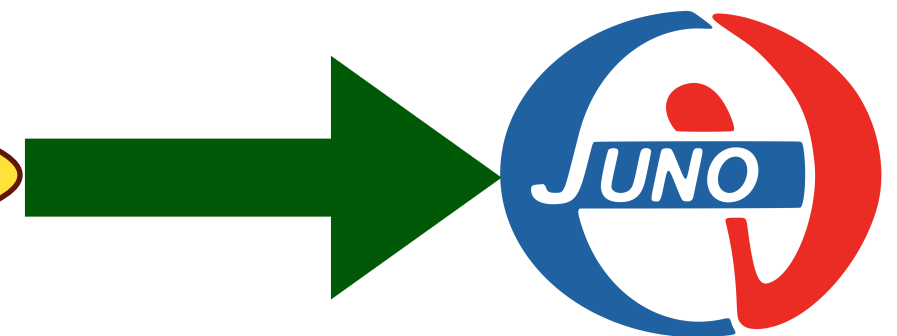
- neutron is heavier than proton by 1.3 MeV and can decay



- four-fermion interaction between leptons and heavy nucleons

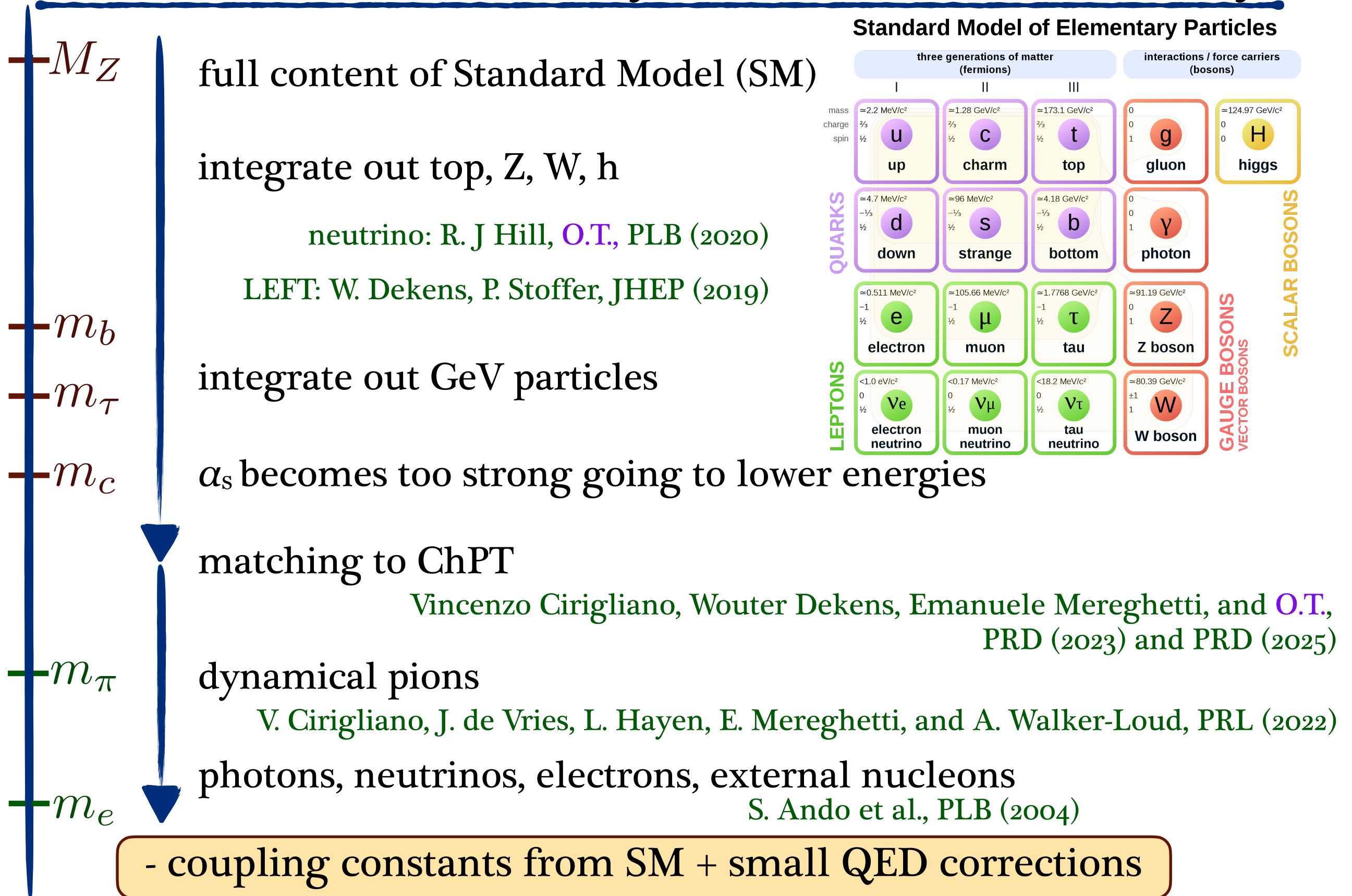
$$\mathcal{L}_{\text{eff}} = -\sqrt{2}G_F V_{ud} \bar{e} \gamma_\mu P_L \nu_e \cdot \bar{N} (g_V v^\mu - 2g_A S^\mu) \tau^+ N$$

Standard Model → 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



One-loop result

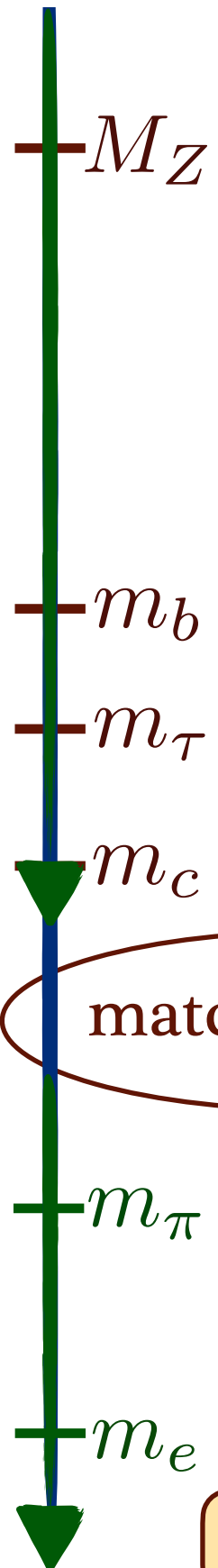
- clear illustration of leading logarithms

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

- 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

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

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

- 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

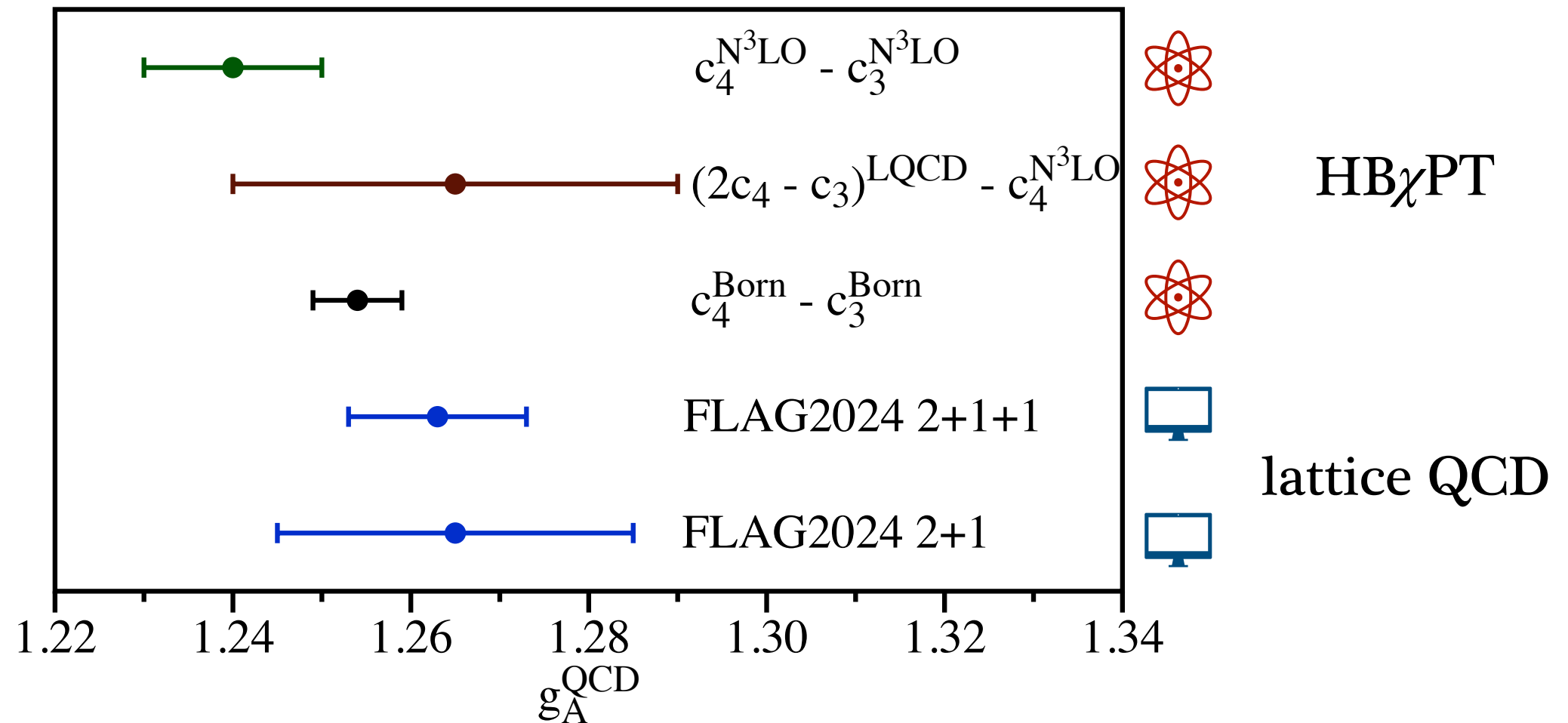
$$g_V^{1\text{-loop}}(\mu_\chi = m_e) - 1 = (2.430 \pm 0.012) \%$$

- 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)

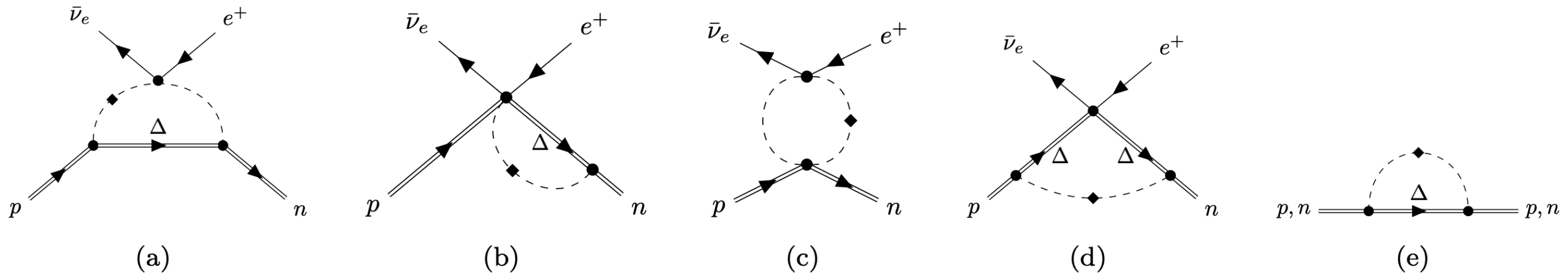
Vincenzo Cirigliano, Wouter Dekens, Emanuele Mereghetti, and O.T., PRD (2024) and PRD (2025)

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)

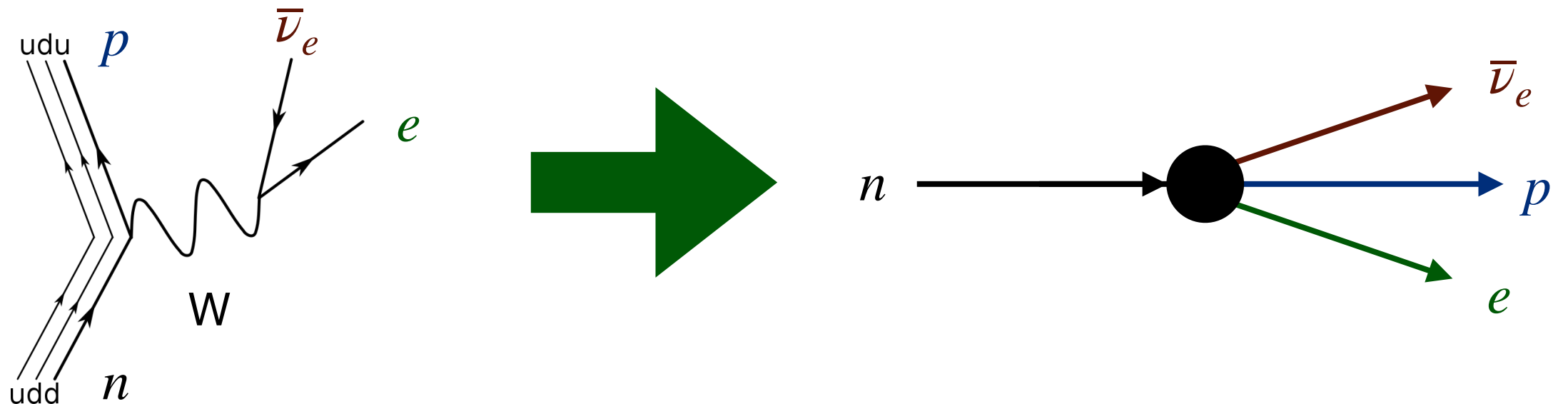
%	HBChPT pions	HBChPT pions and delta	Wilson coefficients
pion LO	0.99 (0.18)	0.99 (0.18)	
pion NLO	1.4	0.4	c3, c4
delta LO	-	0.3	h, g1
delta NLO	-	0.7	b4, b5
extra	0.16 (0.30)	0.16 (0.30)	
total	2.6 (0.4)	2.5 (0.4)	

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

- Δ resonance improves power counting and reduces QED

Complete EFT approach

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



- four-fermion interaction between leptons and heavy nucleons

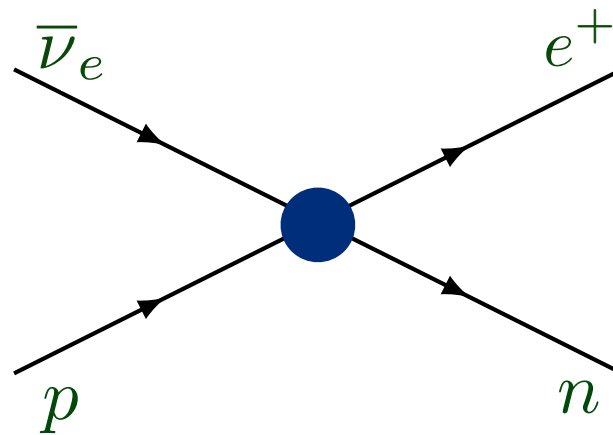
$$\mathcal{L}_{\text{eff}} = -\sqrt{2}G_F V_{ud} \bar{e} \gamma_\mu P_L \nu_e \cdot \bar{N} (g_V v^\mu - 2g_A S^\mu) \tau^+ N$$

g_V : theoretical prediction from Standard Model

g_A : beta asymmetry in polarized neutron decay

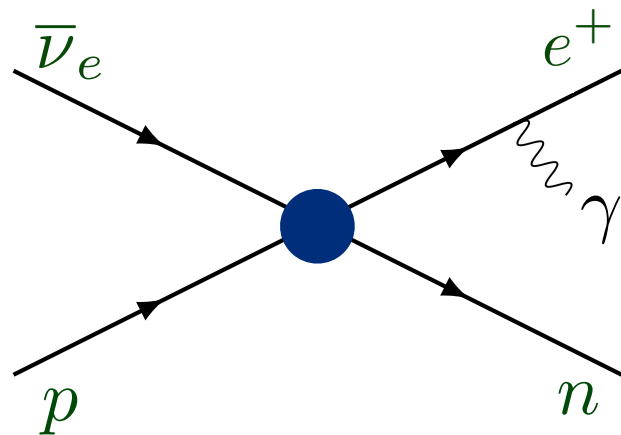
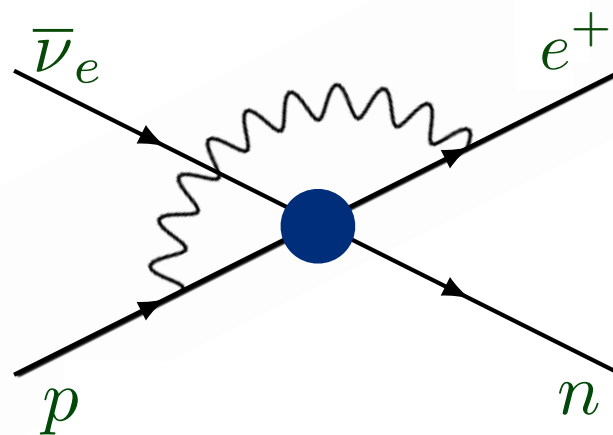
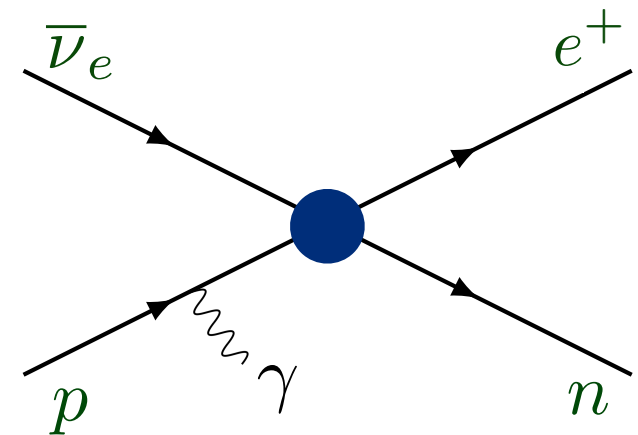
V_{ud} : superallowed transitions

- first consistent at 0.1%-level QED radiative corrections

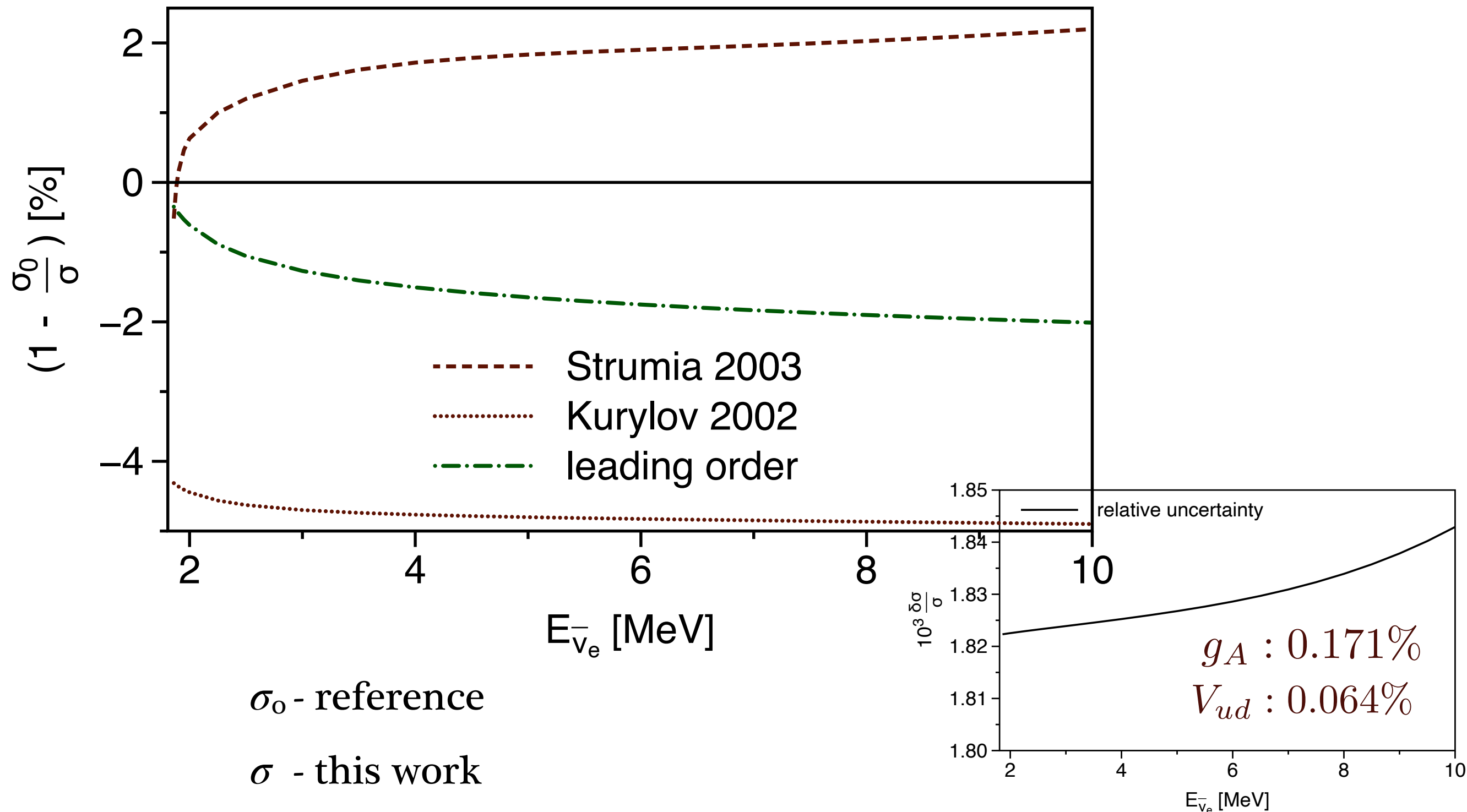


O.T, PRL (2026)

Theory of inverse beta decay for reactor antineutrinos

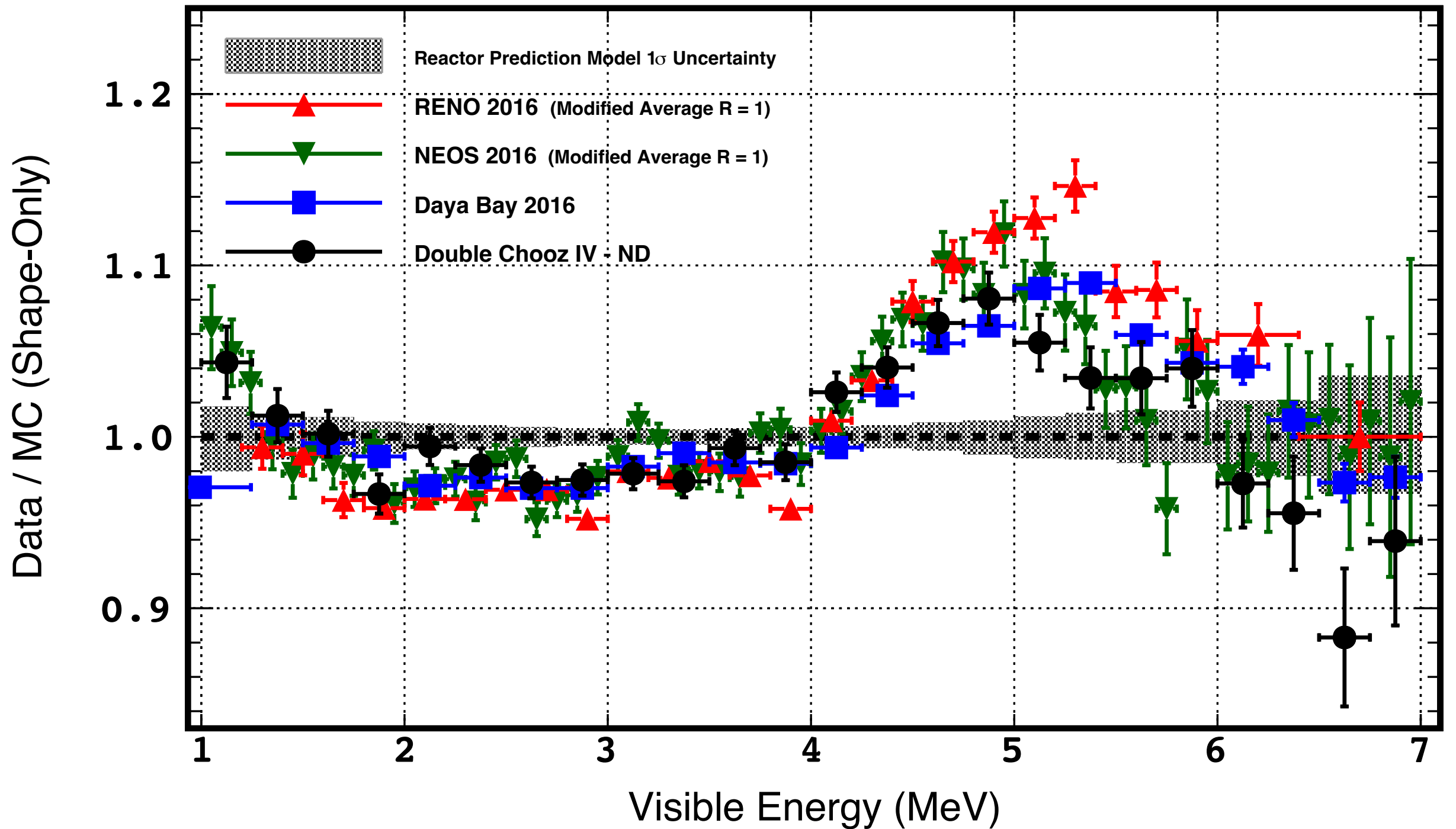


Total cross section



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

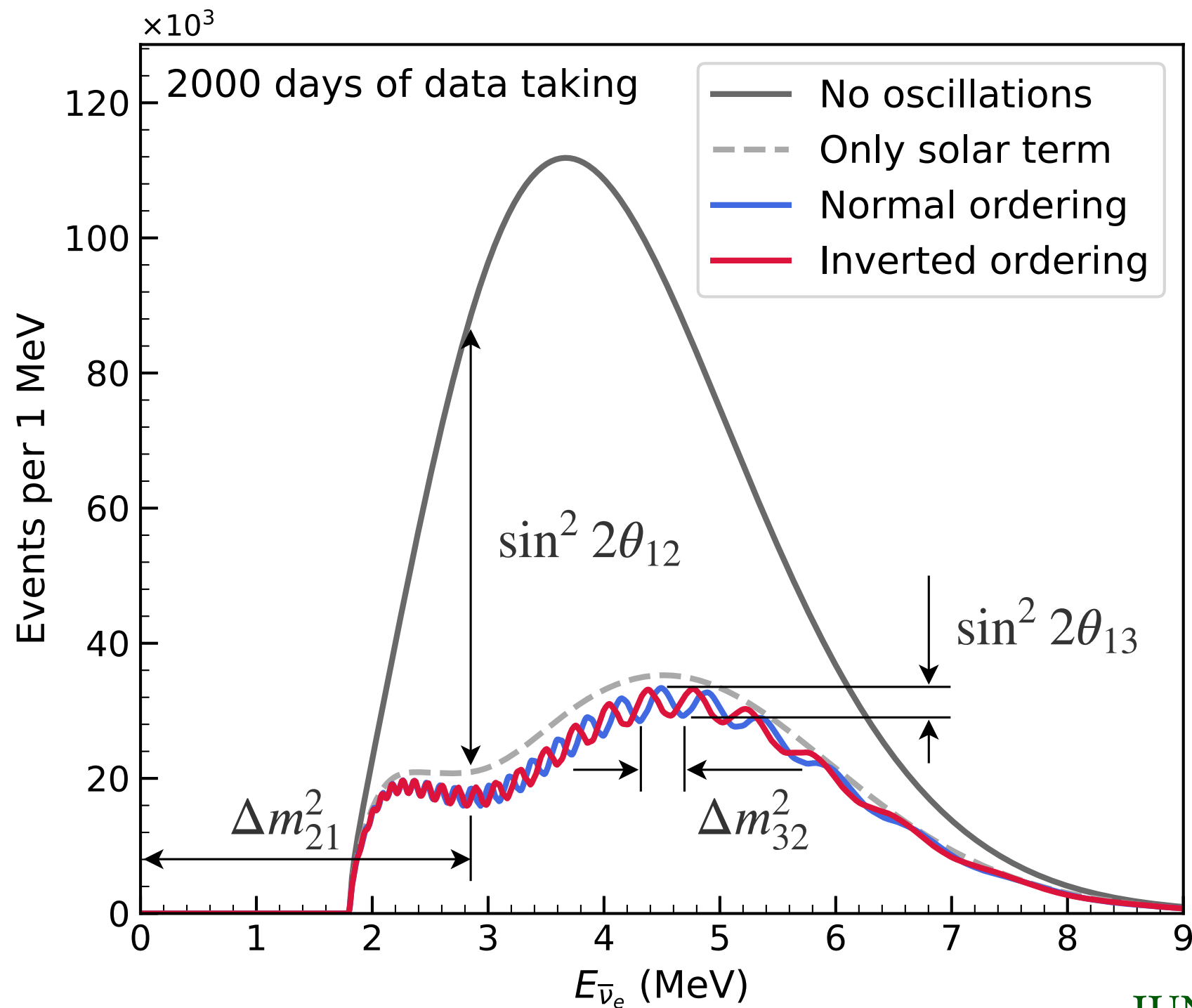
5-MeV flux excess



Double Chooz, Nature Phys (2019)

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

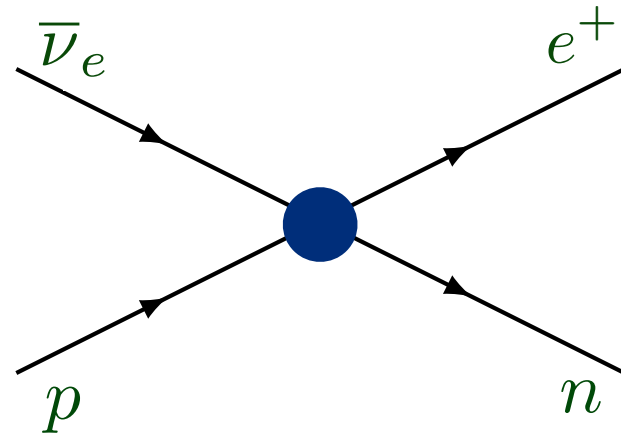
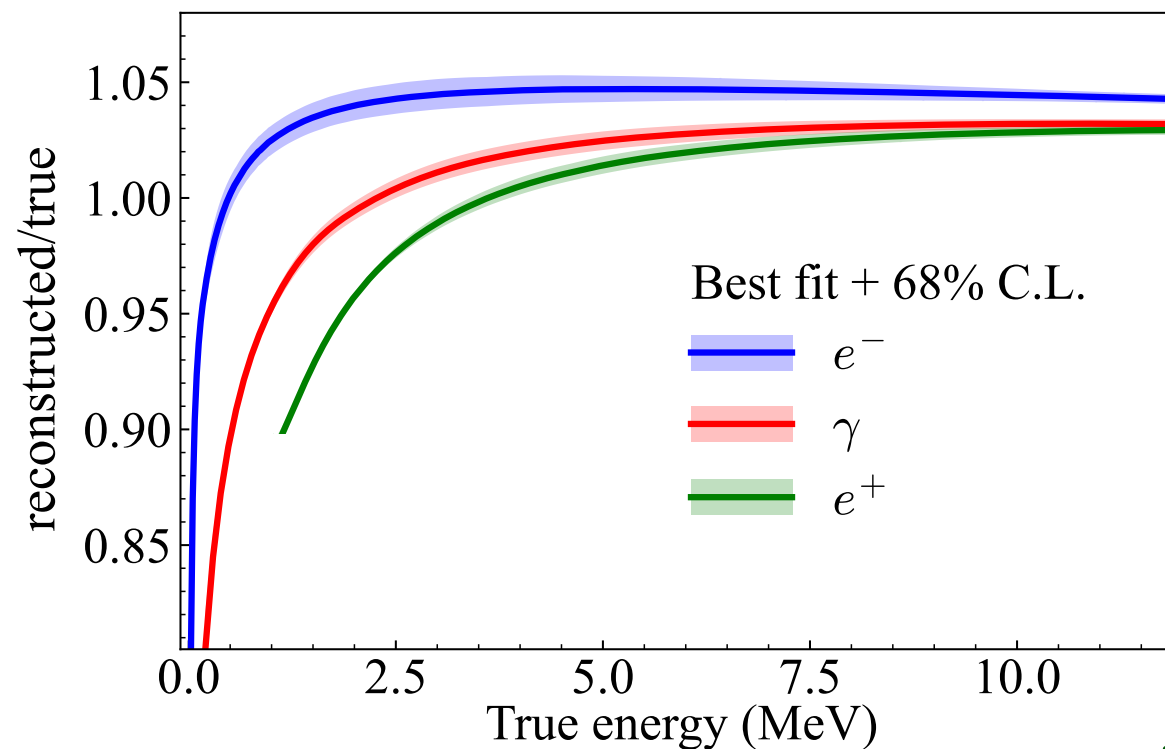
Energy reconstruction is key



JUNO, PPNP (2021)

- JUNO: 3% energy reconstruction for precision goals

Energy reconstruction is key

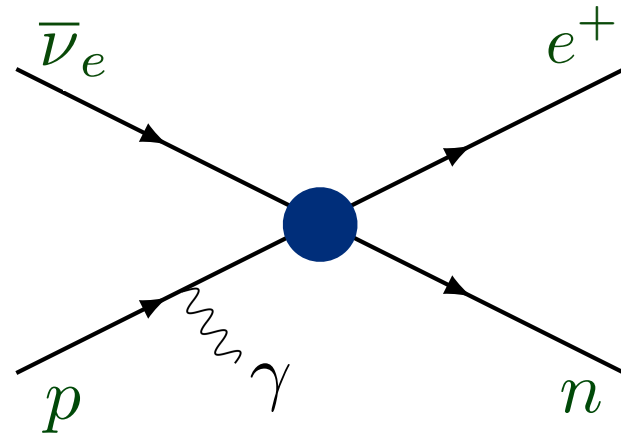
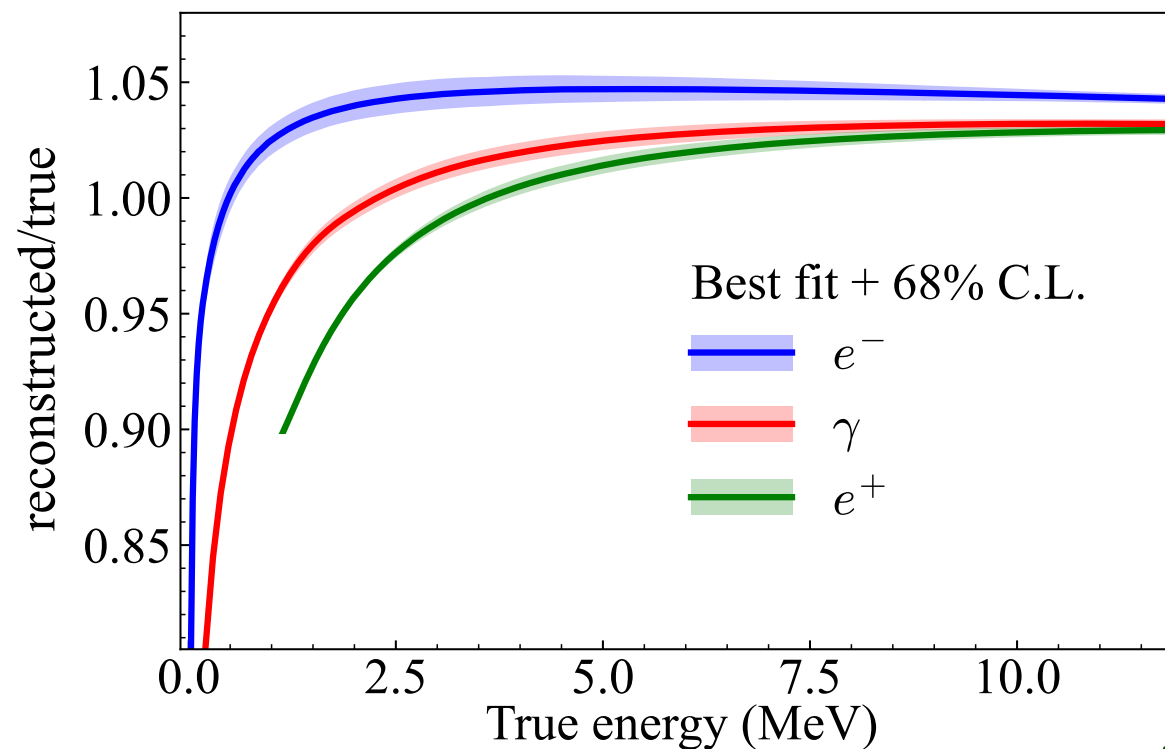


JUNO, Nature (2026)

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

- 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

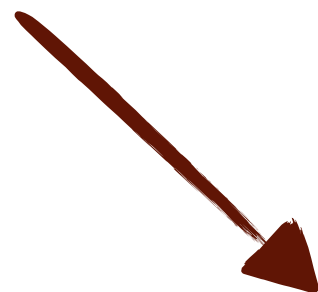
$$E_n, E_\gamma, \theta_n$$



$$E_n, \theta_n$$



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



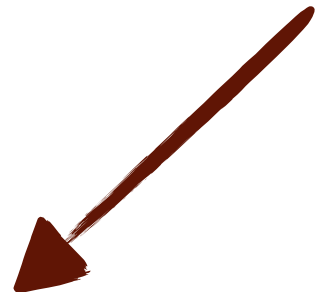
$$E_e, E_\gamma, \theta_e$$



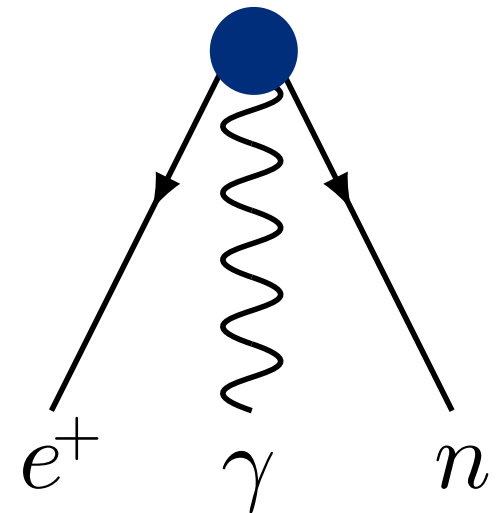
$$E_e, \theta_e$$



$$E_e$$



total cross section



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

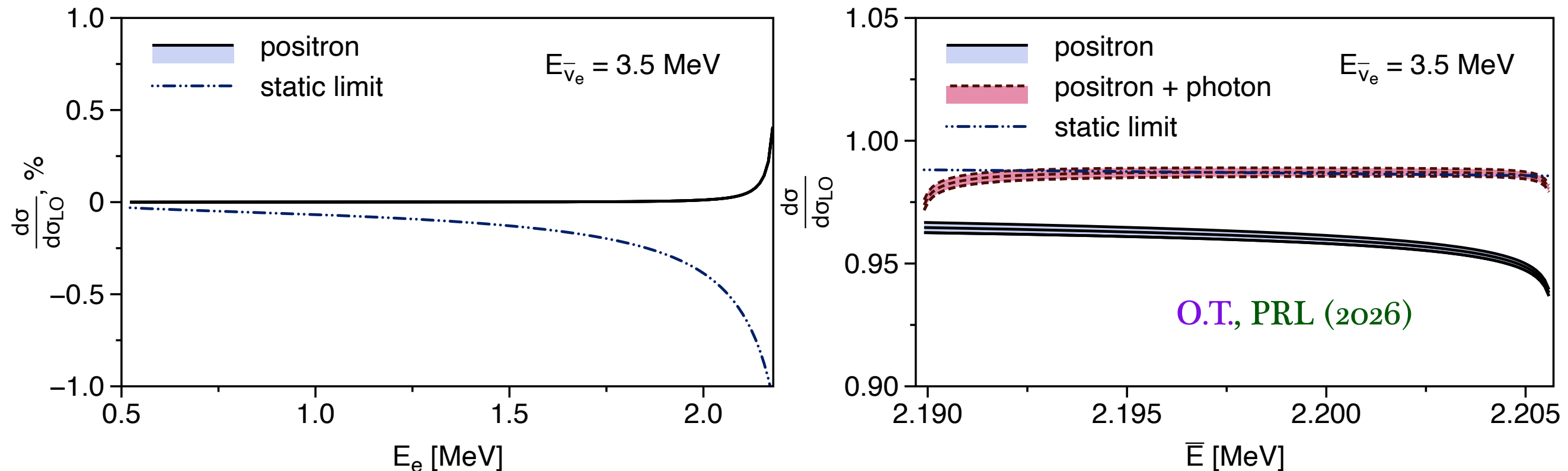
consistency at
cross-section level

O.T., PRL (2026)

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

Access each particle kinematics

- evaluate radiative process w/o no-recoil approximation

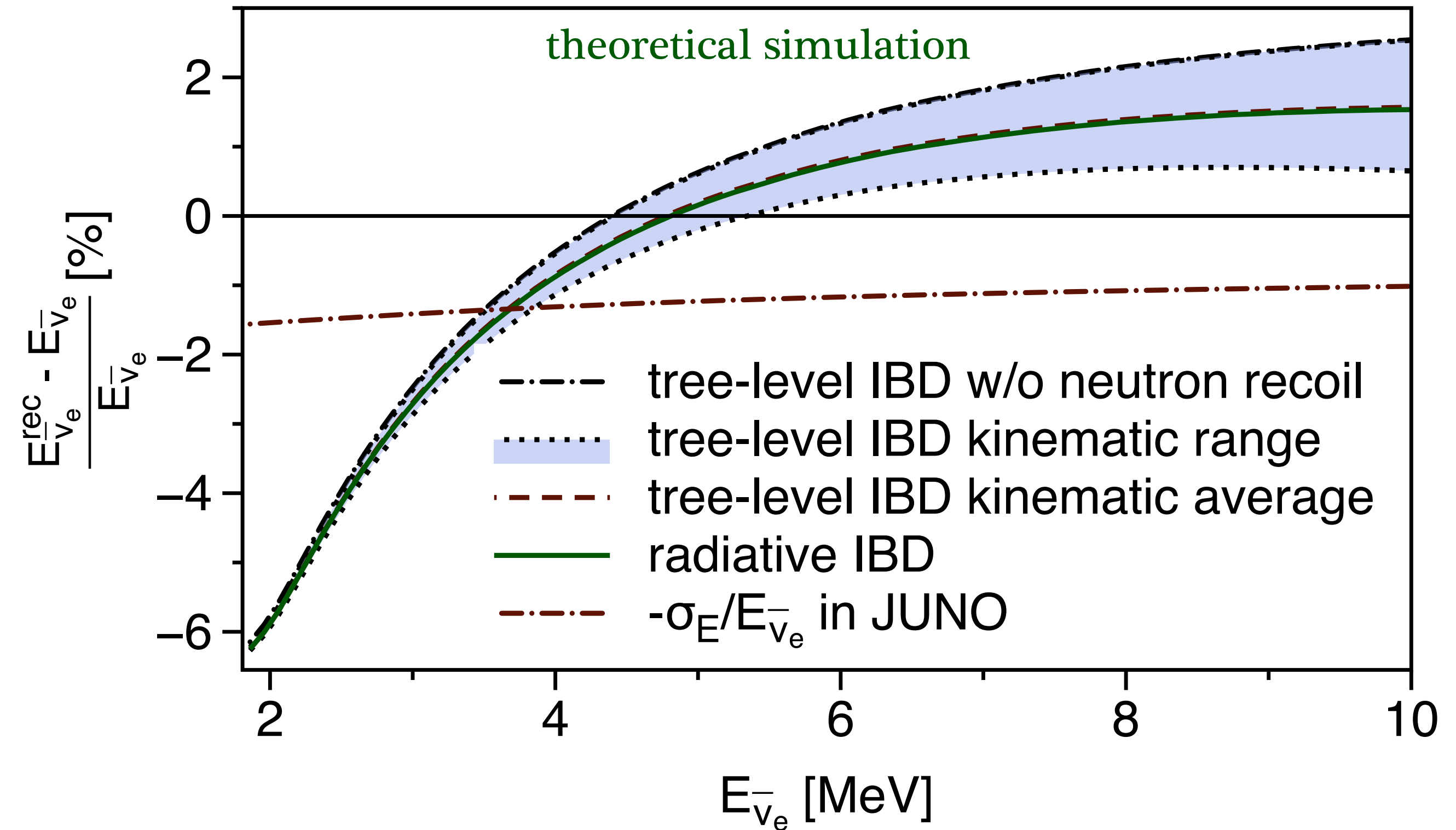


- 1st analytic expression for **positron** energy spectrum

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

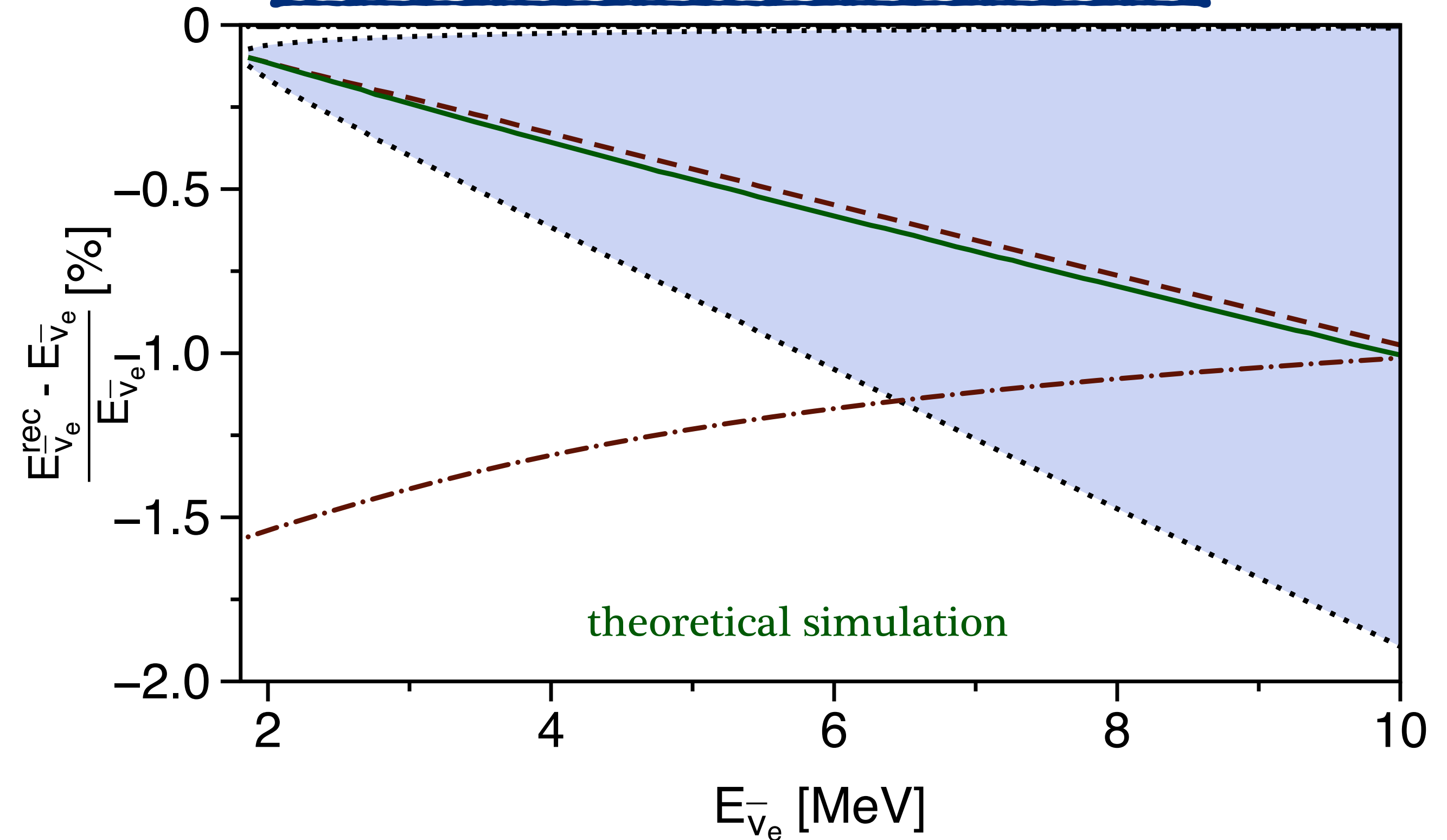
- control over each particle is necessary to achieve precision

Energy reconstruction is key



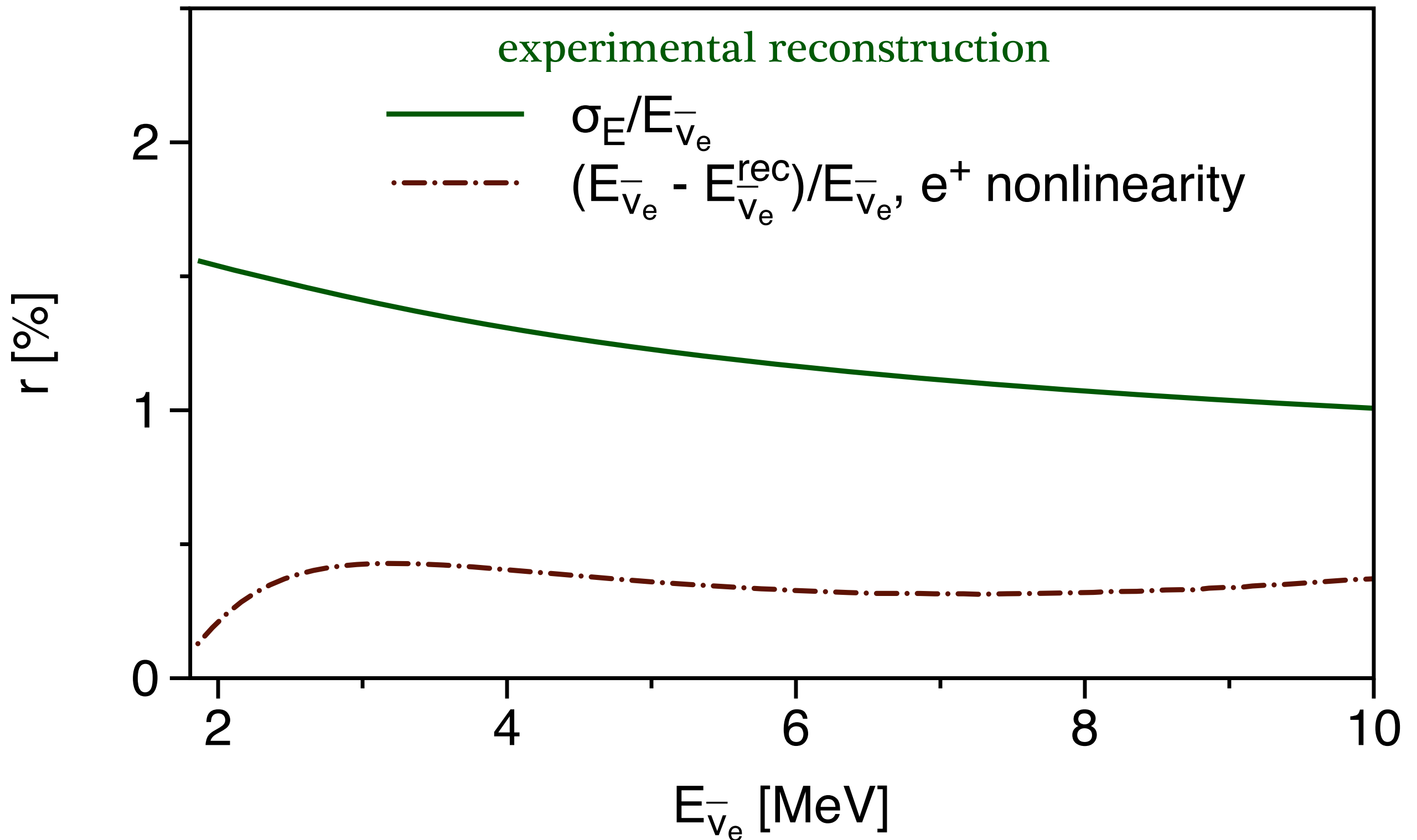
- tree-level recoil effects are sizable

Energy reconstruction is key



- tree-level recoil effects are sizable

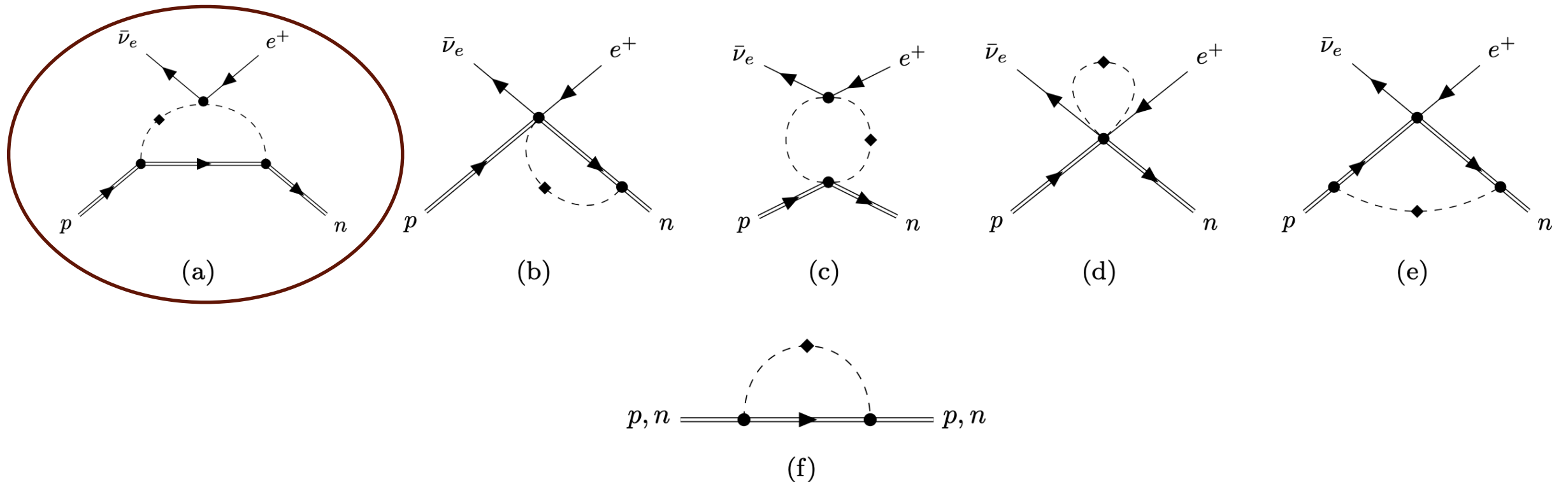
Energy reconstruction is key



- 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)

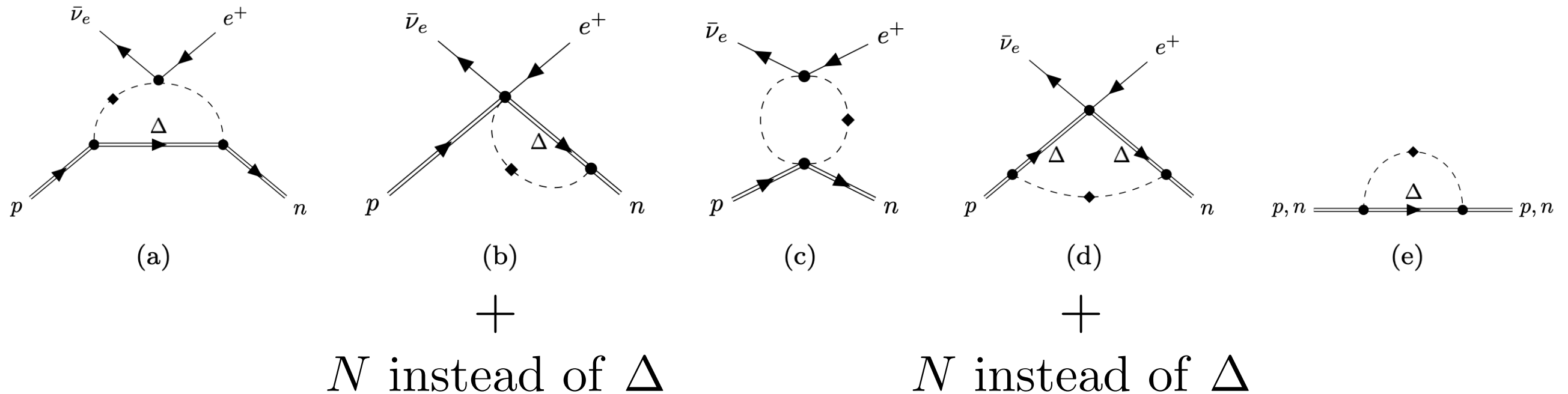
- neglect recoil diagrams without pions

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

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

Supernova and π DAR energies

- include Δ degrees of freedom to inverse beta decay



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

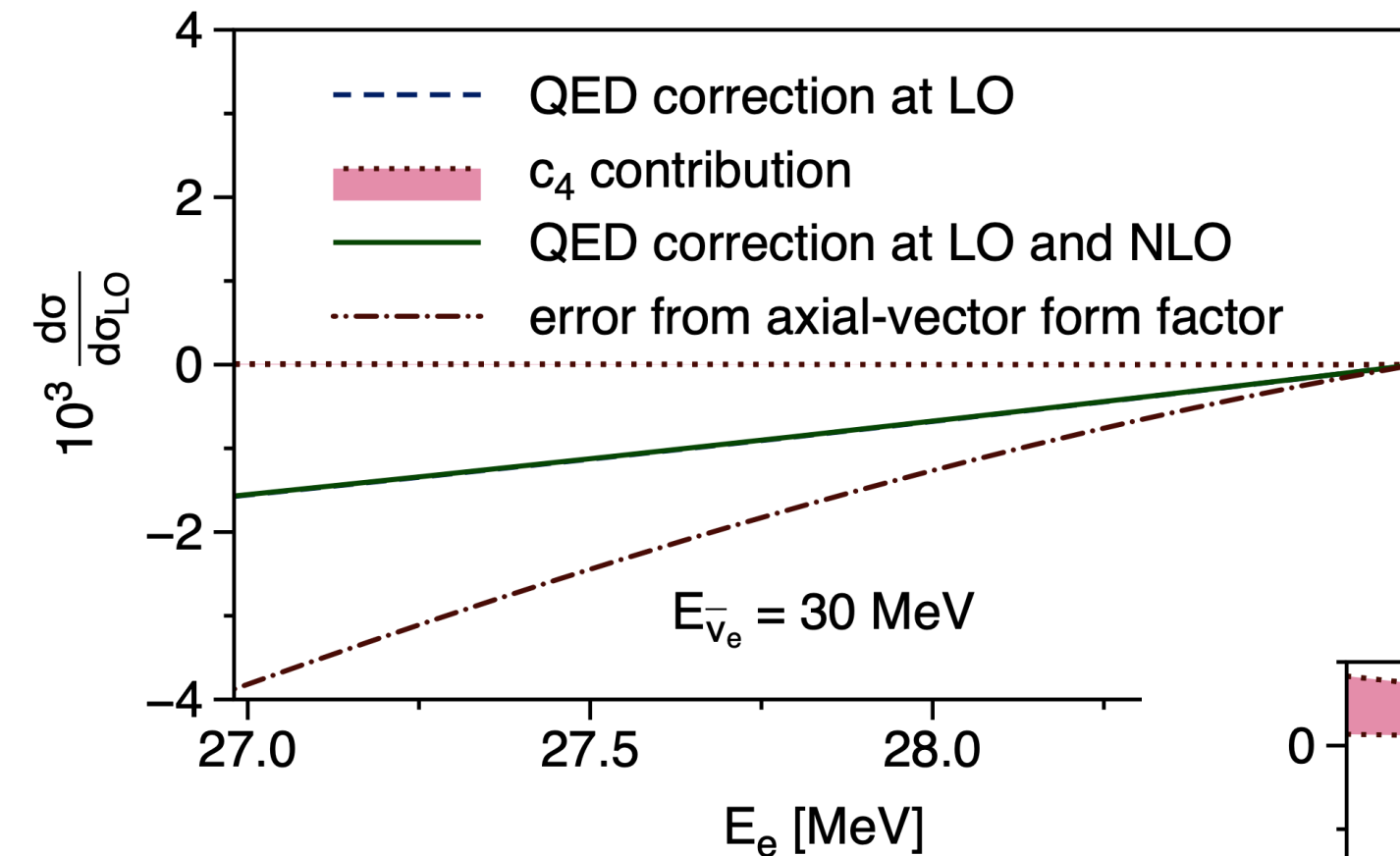
O.T. and Yi-Bo Yang, arXiv: 2608.22845

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

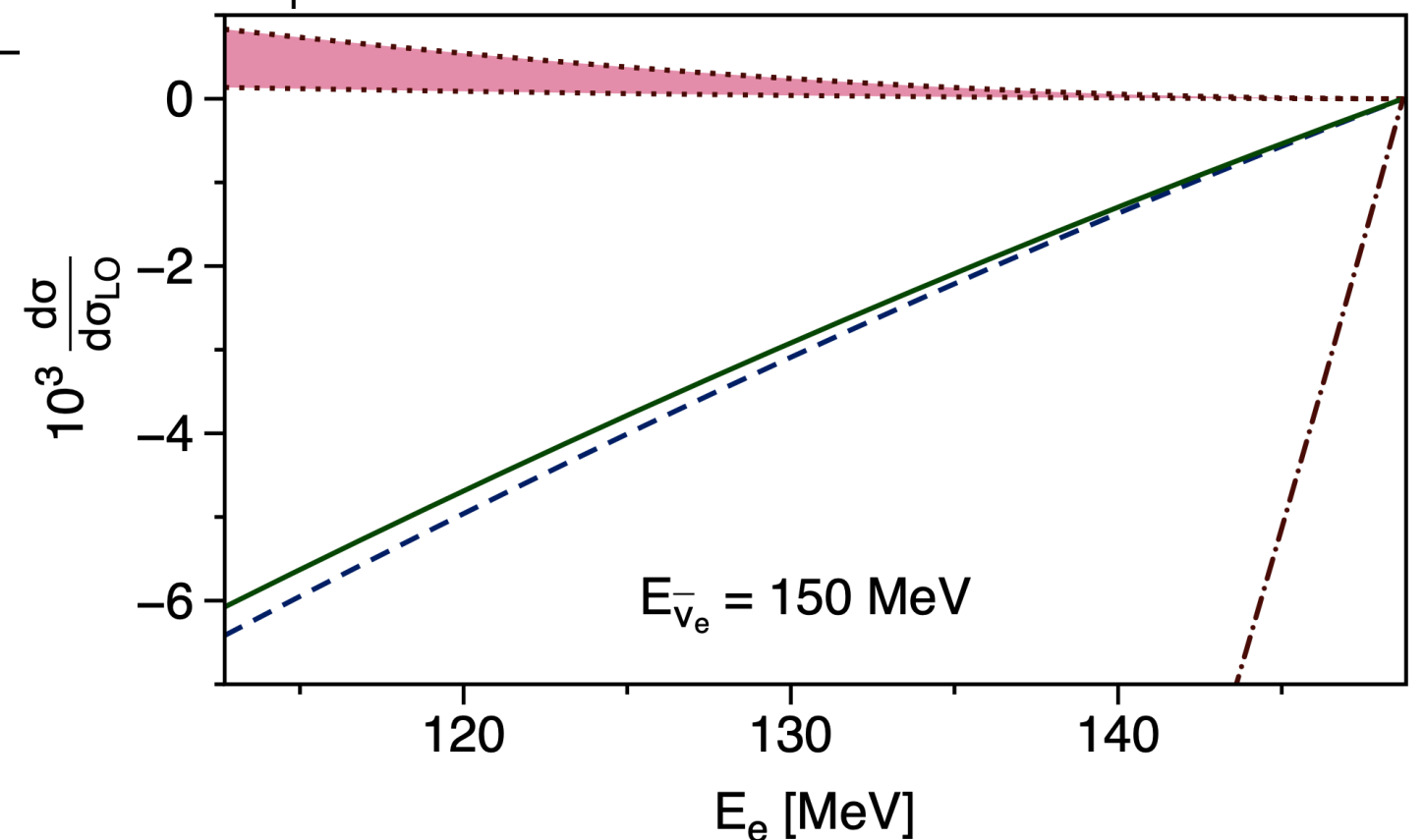
- extending **0.1%-level** predictions to energies above **10 MeV**

Supernova and π DAR energies



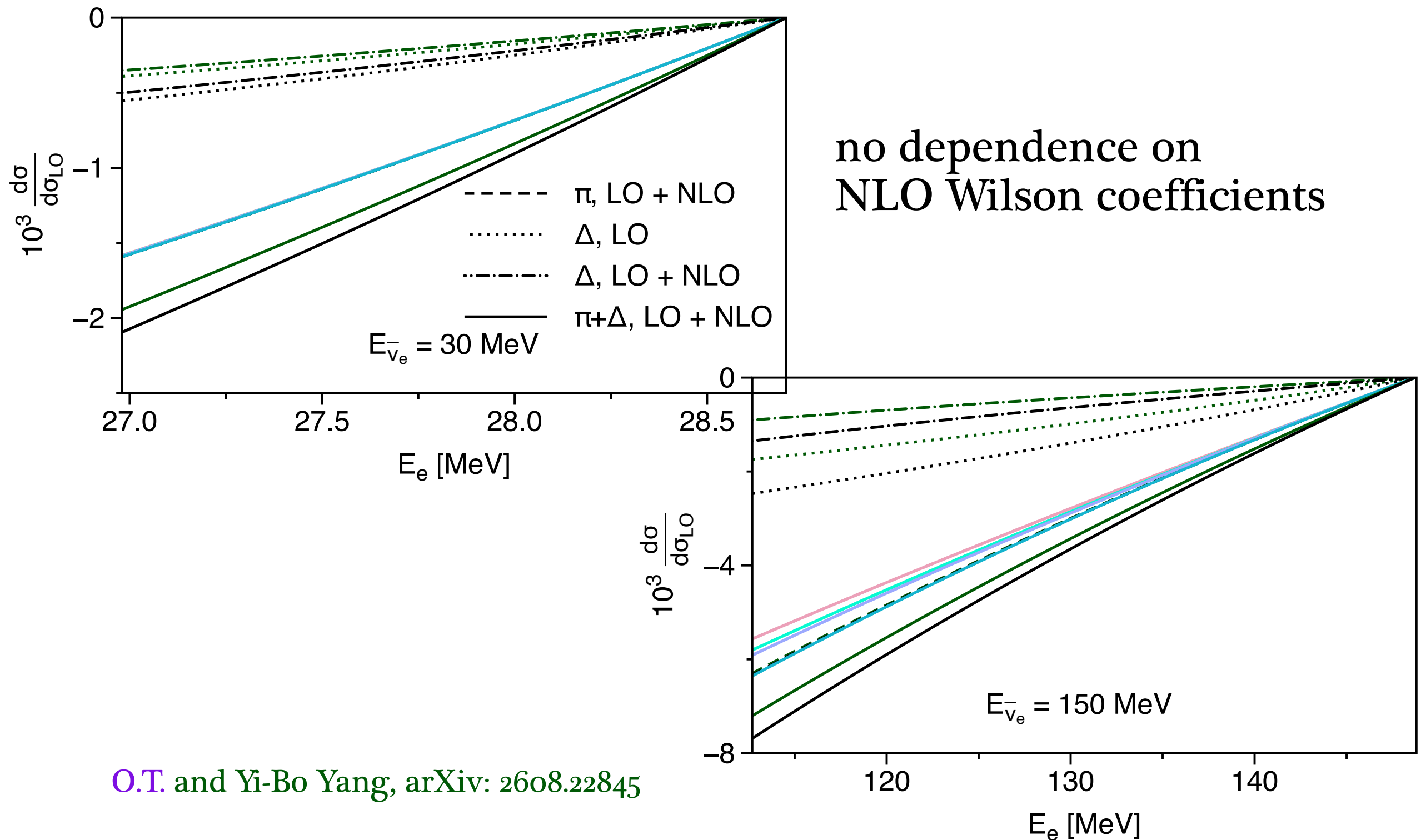
Wilson coefficient c_4 enters at higher energies

O.T., JHEP (2026)



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

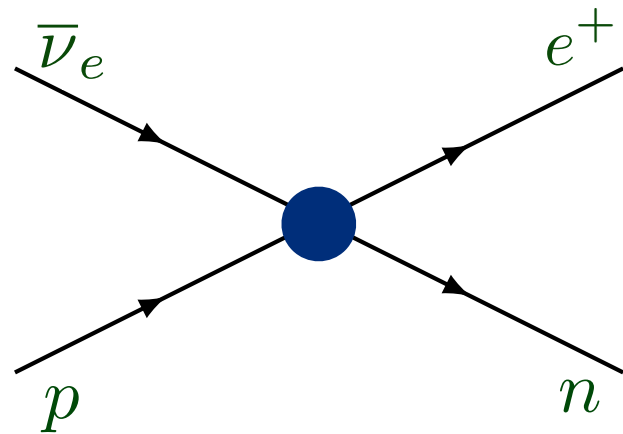
Supernova and π DAR energies



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

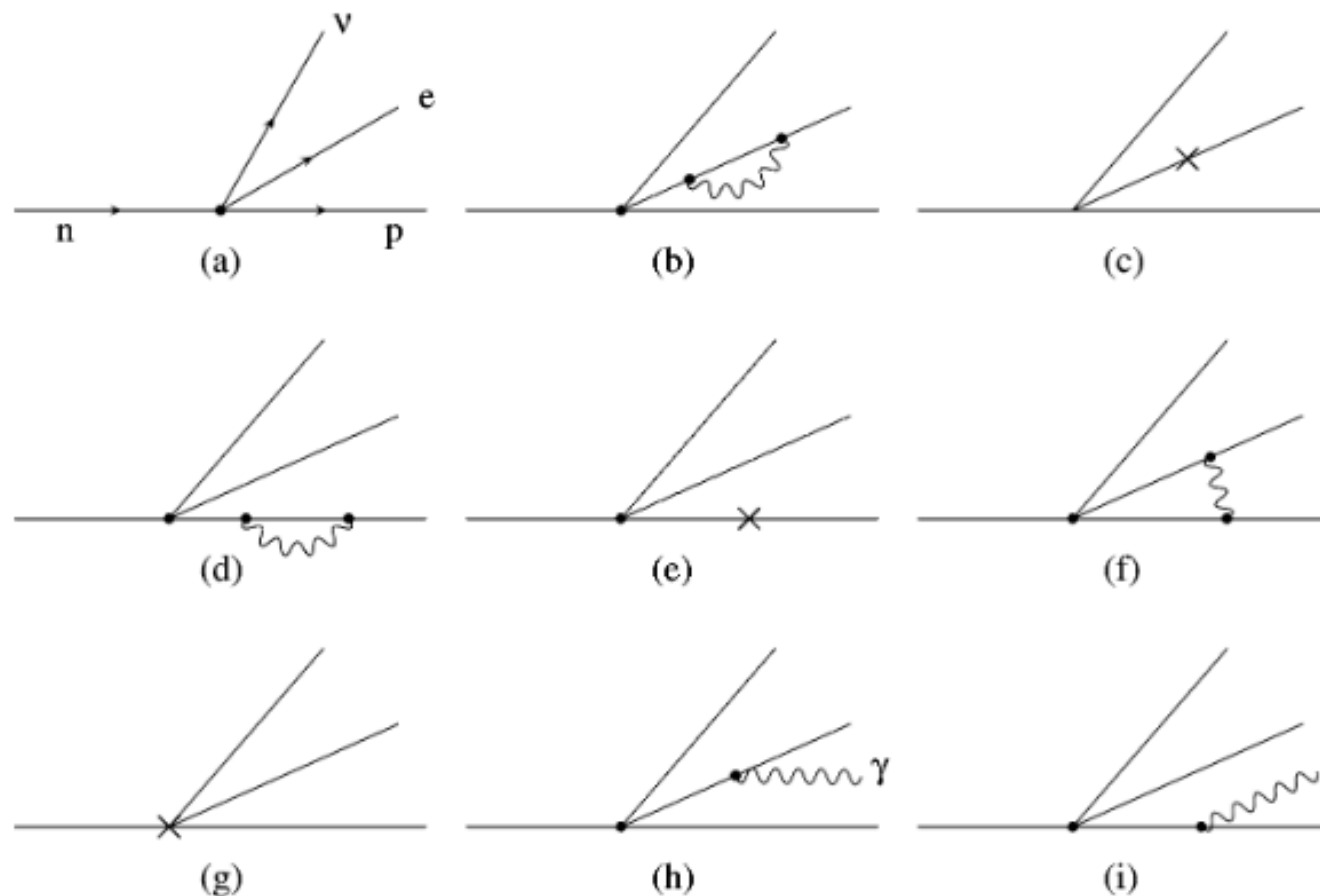
- four-fermion interaction between leptons and heavy nucleons

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

$$m_e \sim M_p - M_n$$

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


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

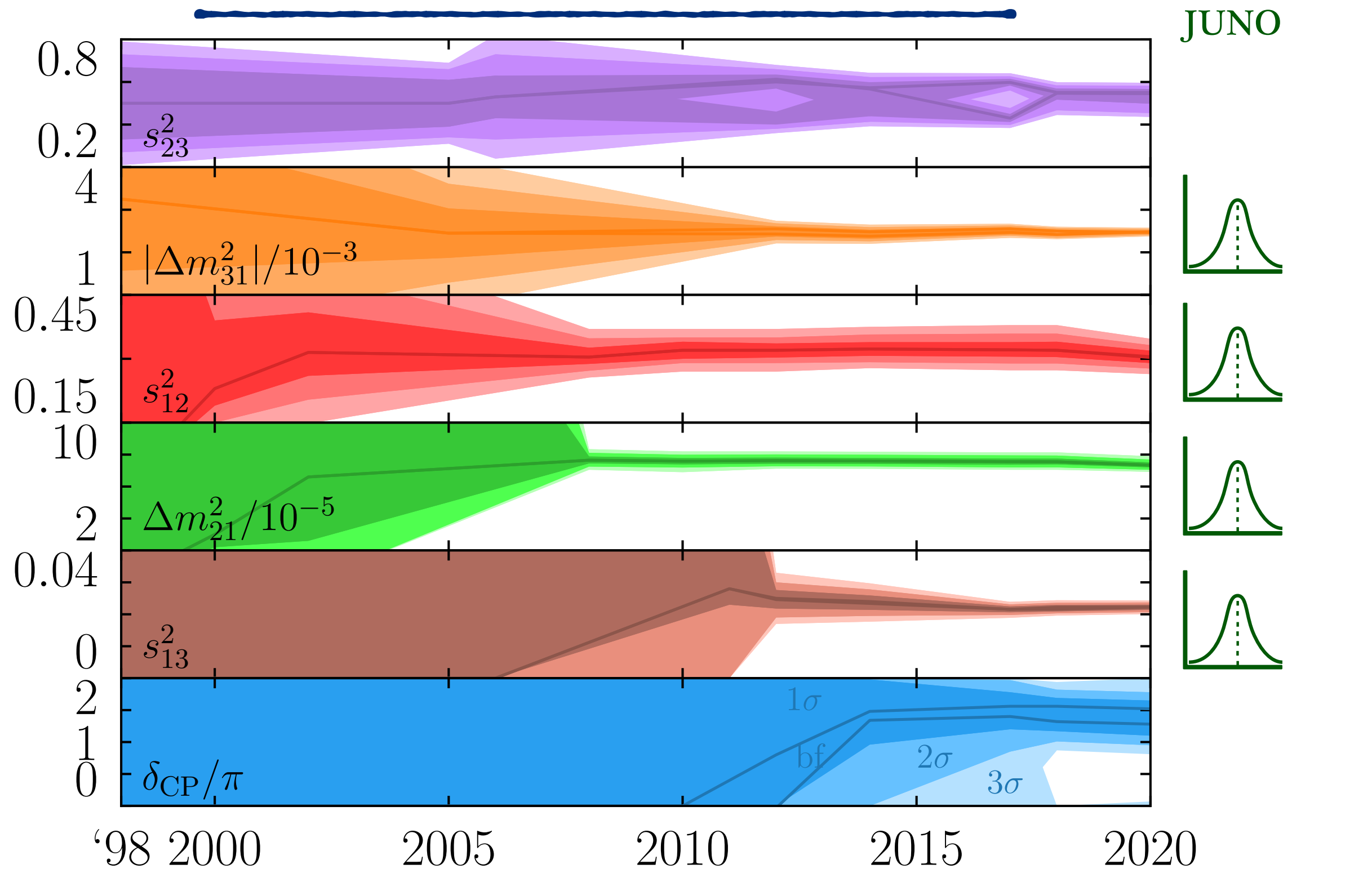
neutrinos propagate in mass basis



Pontecorvo-Maki-Nakagawa-Sakata matrix relates two bases

- oscillations are described by **PMNS** mixing matrix

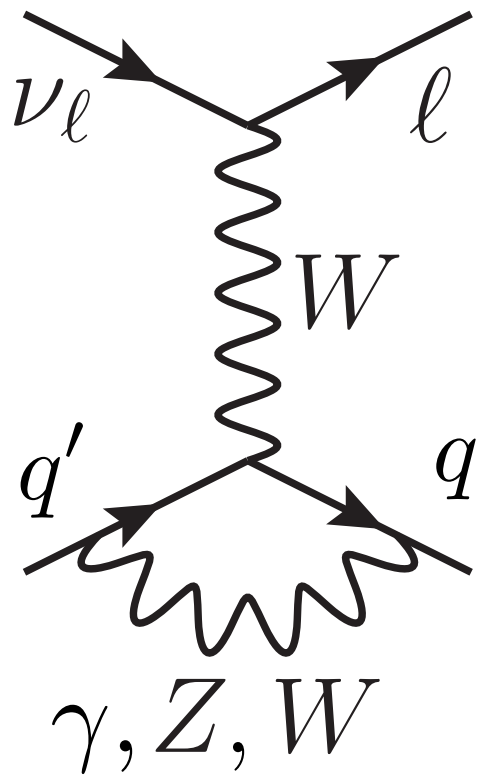
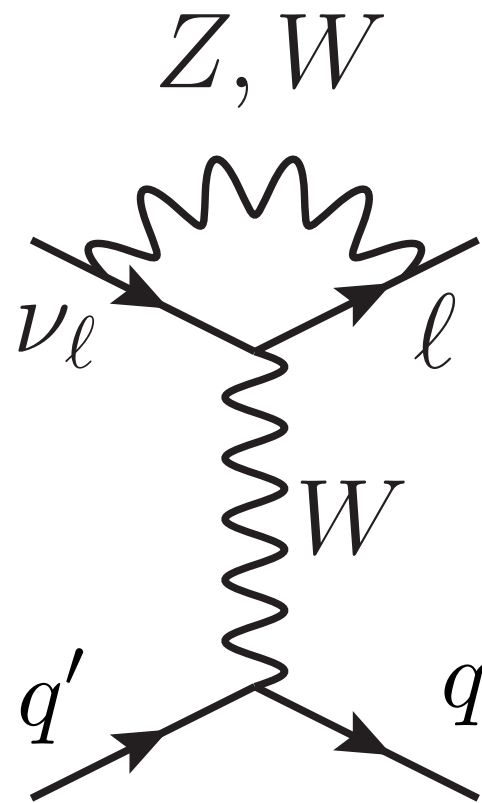
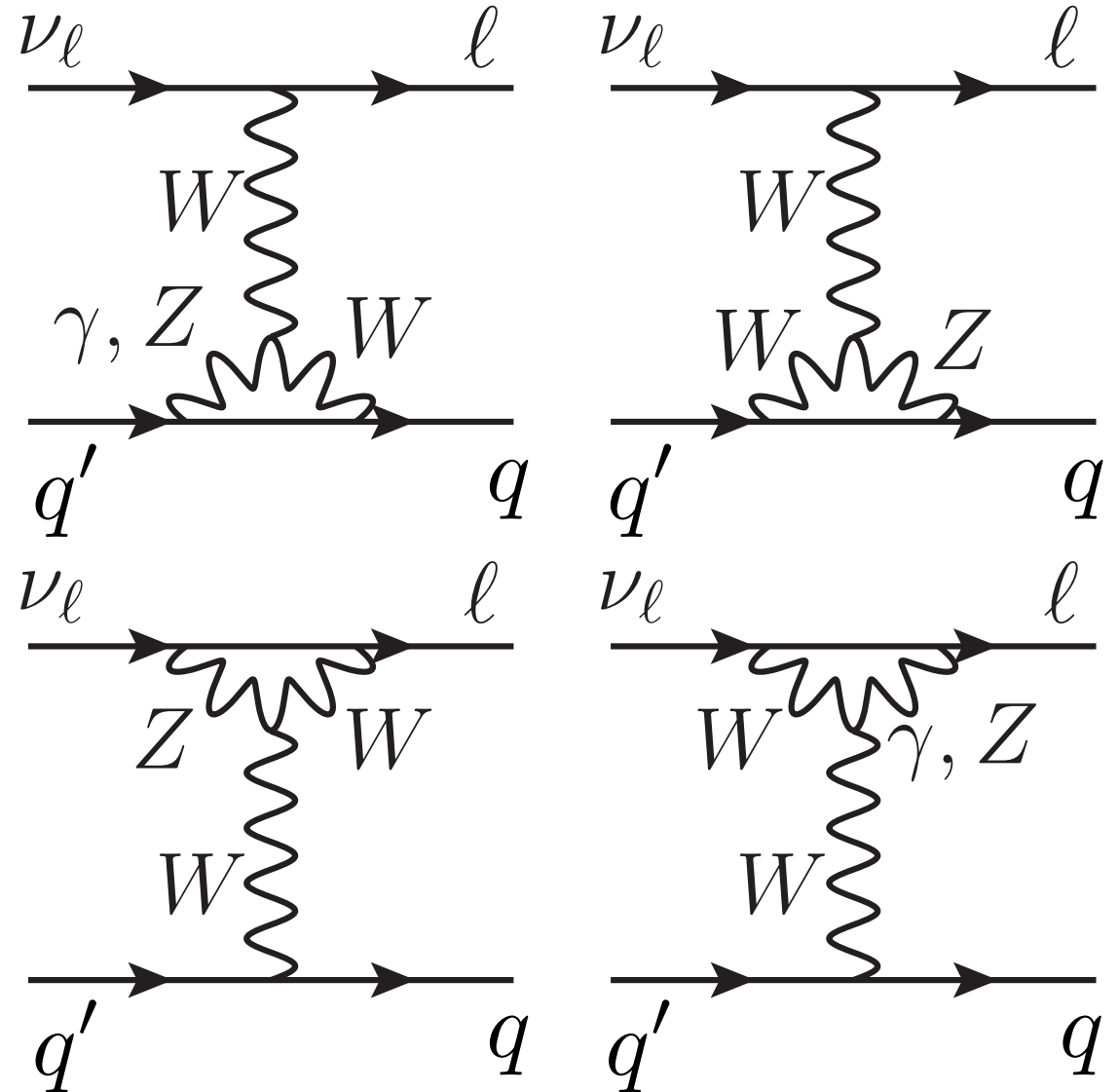
PMNS oscillation matrix



- tremendous progress in our lifetime

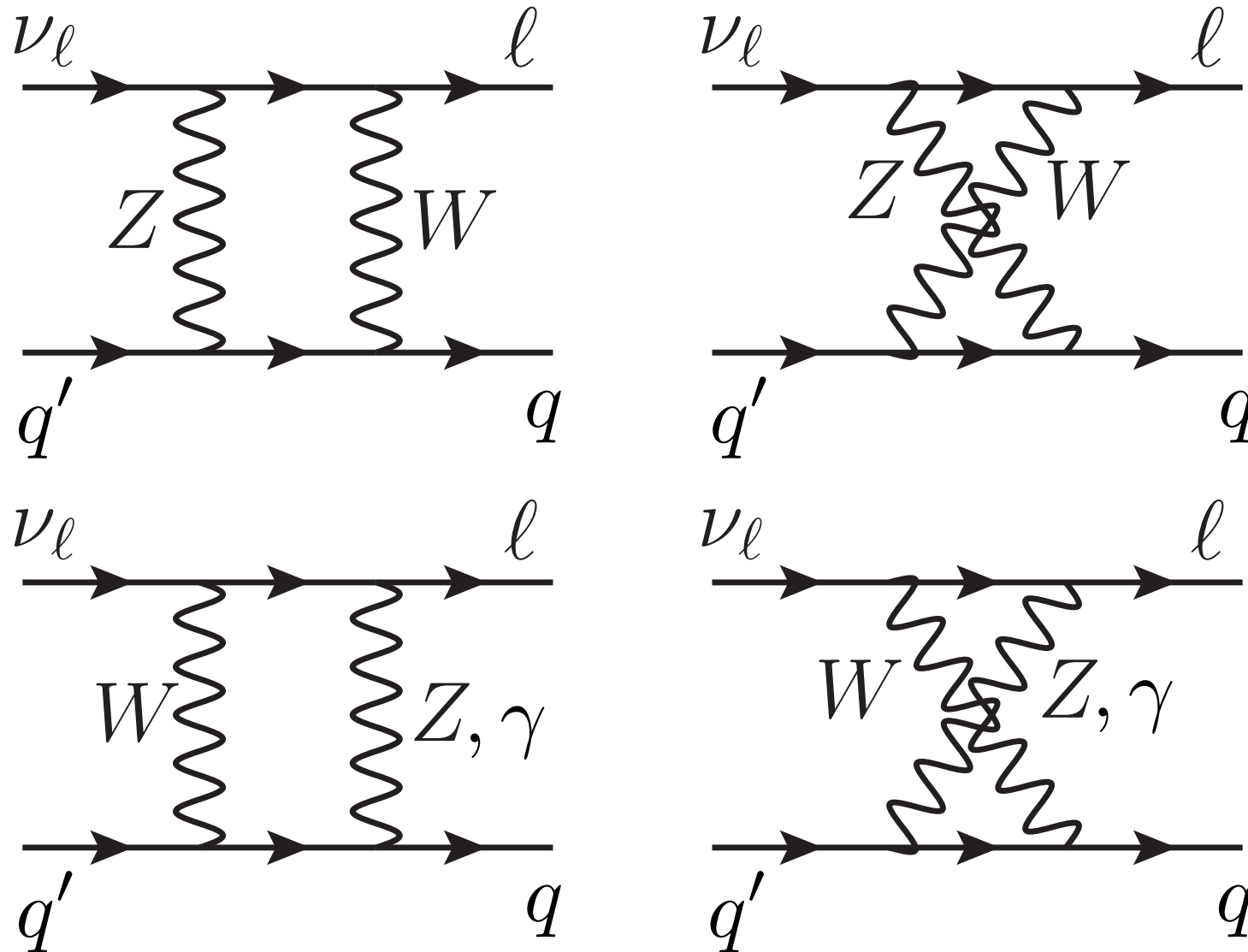
Snowmass 2021 NFO1 group report

Charged current in SM. Vertexes



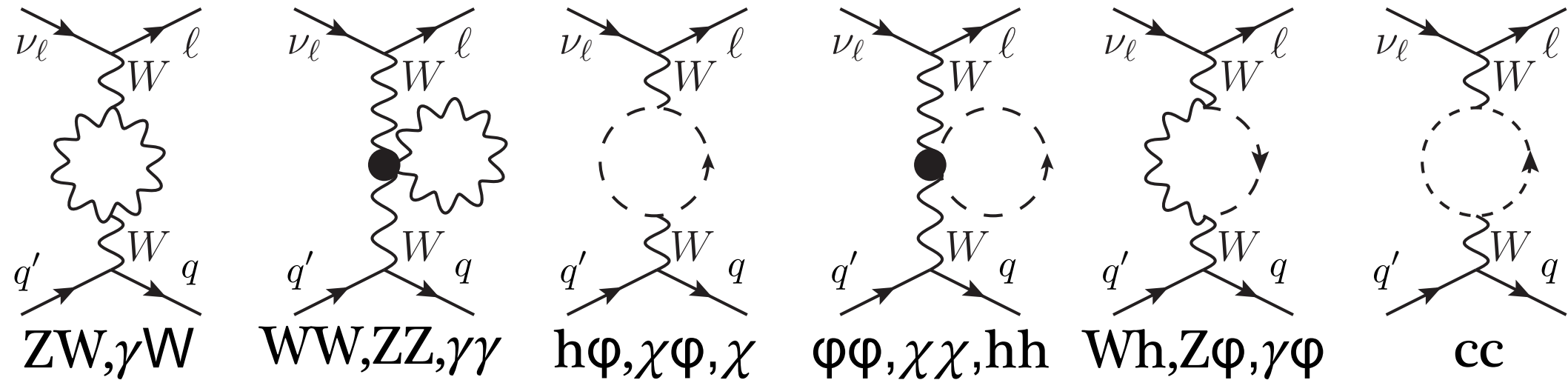
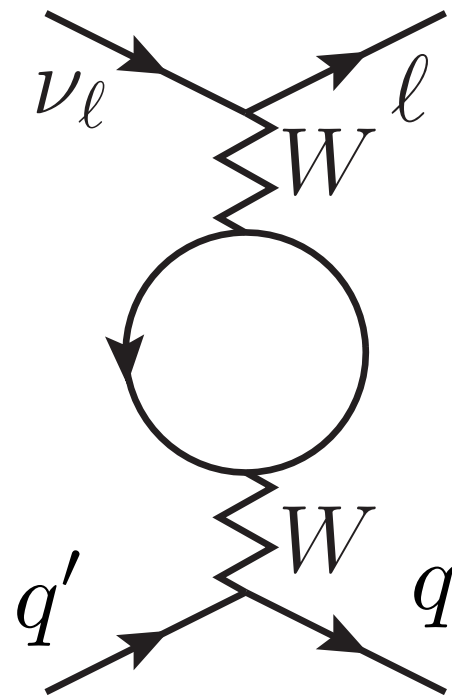
- contribution to effective couplings

Charged current in SM. Boxes



- contribution to effective couplings

W self energy

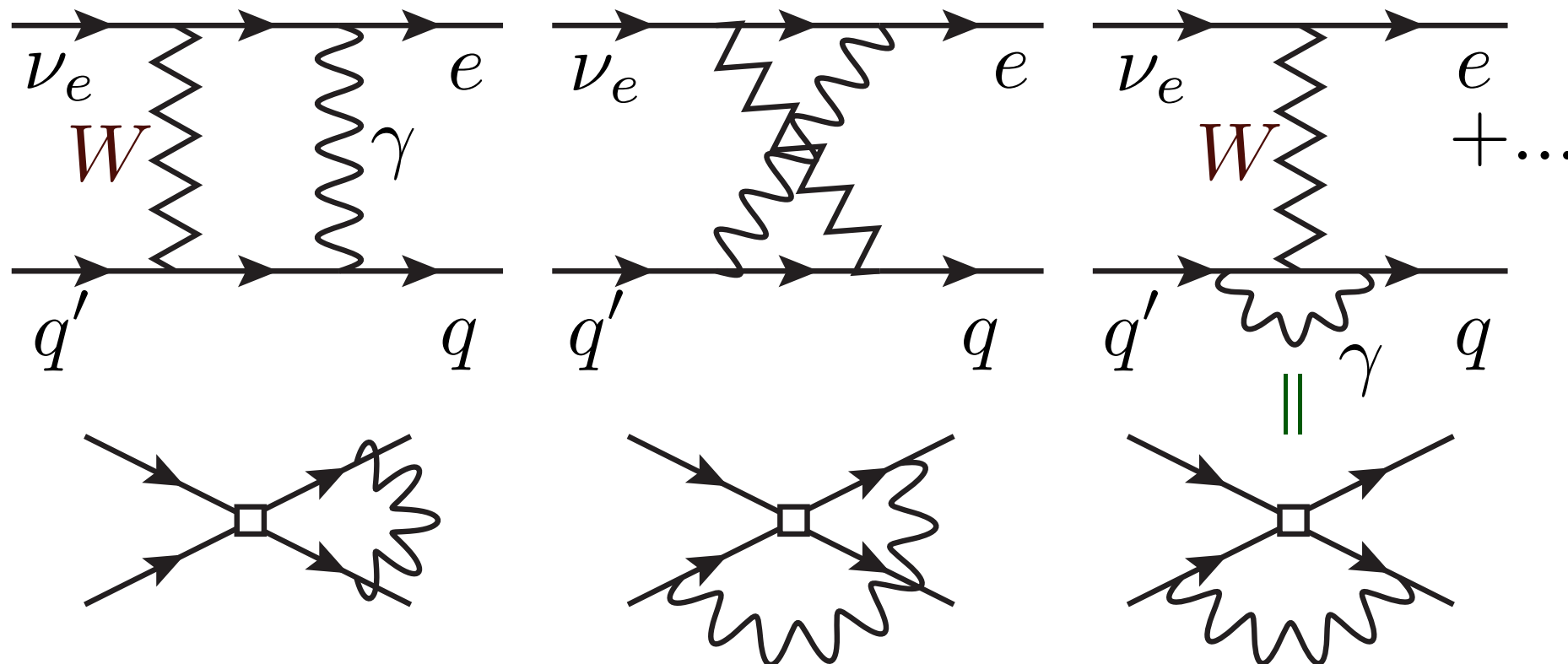


- vanishing contribution to matching besides loops with t quark

- 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

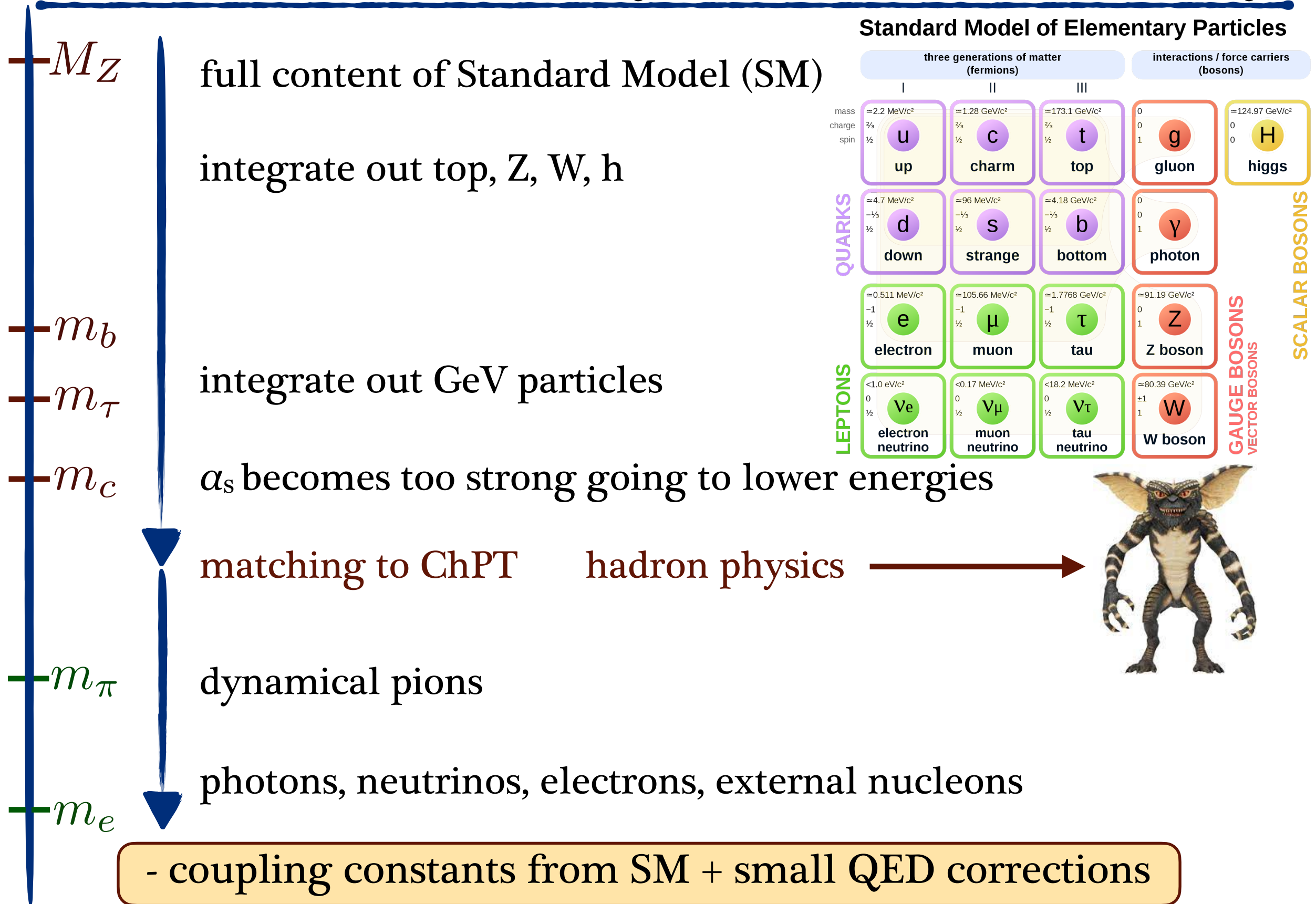
- NDR scheme for γ_5 for evanescent operators E

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

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

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

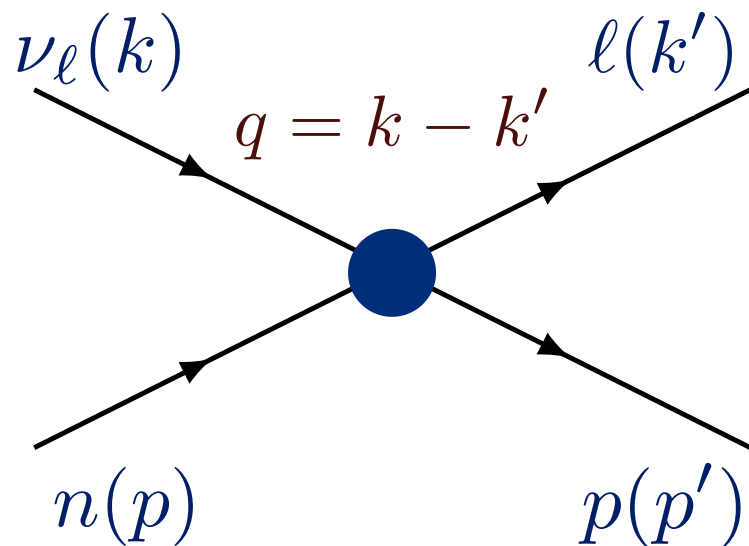
- π EFT counterterms from χ PT couplings in baryon sector

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

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

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

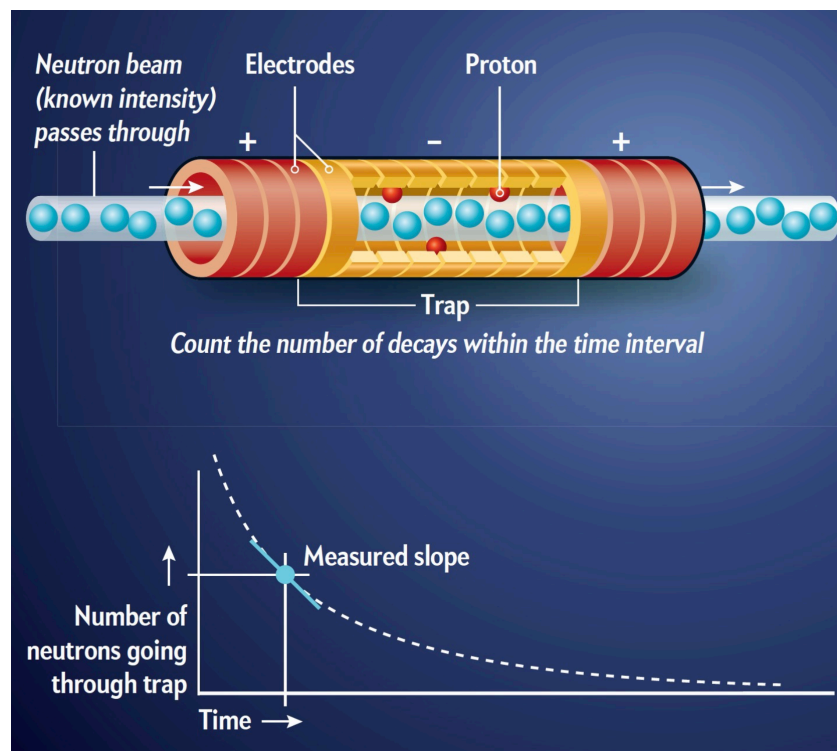
changes by 1/3 of PERKEO-III experimental uncertainty

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

Neutron lifetime measurements



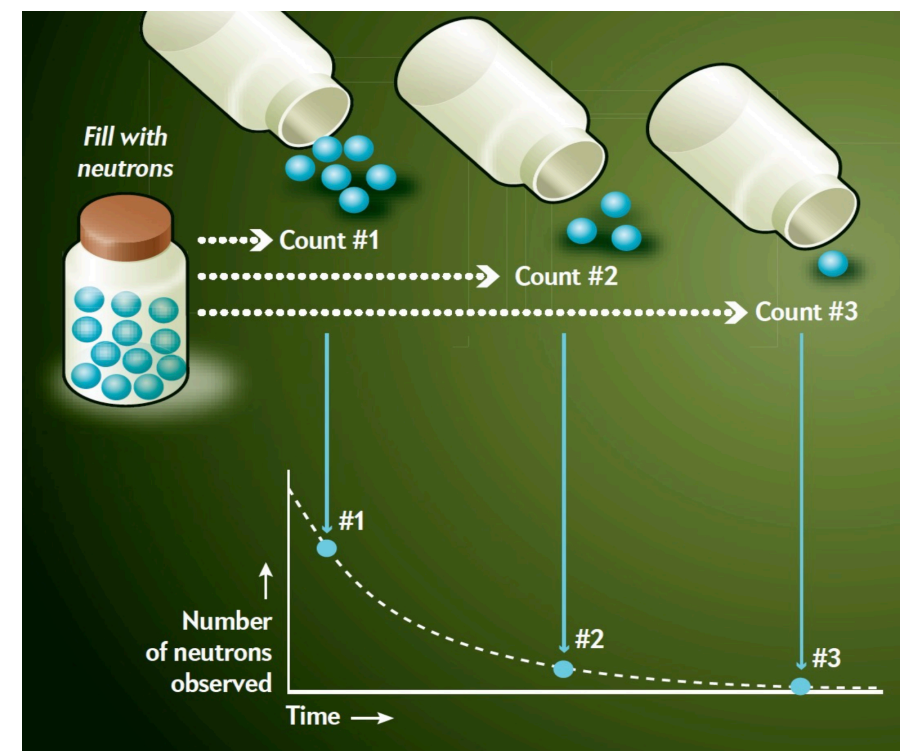
beam method



how many neutrons pass?



bottle method



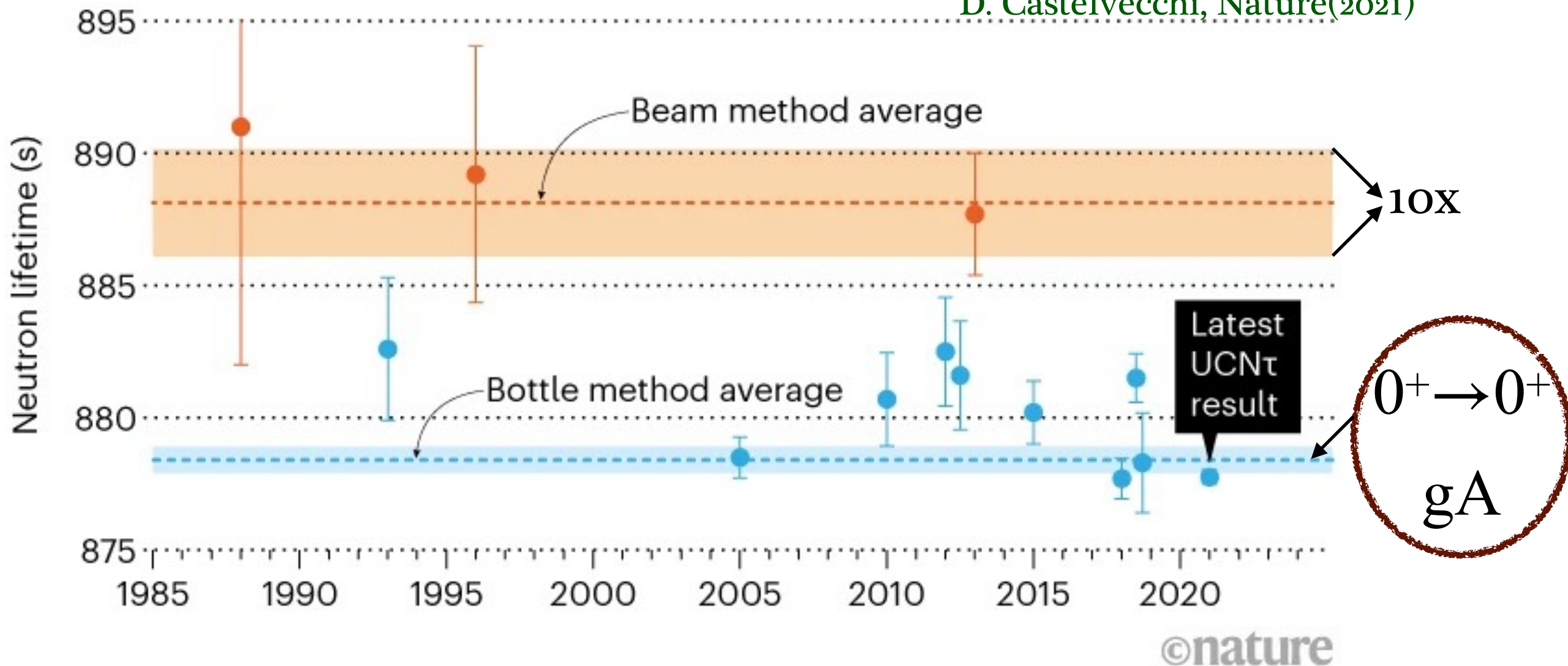
how many neutrons survive?

Neutron lifetime puzzle

● Results using beam method ● Bottle method

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

D. Castelvechi, Nature(2021)

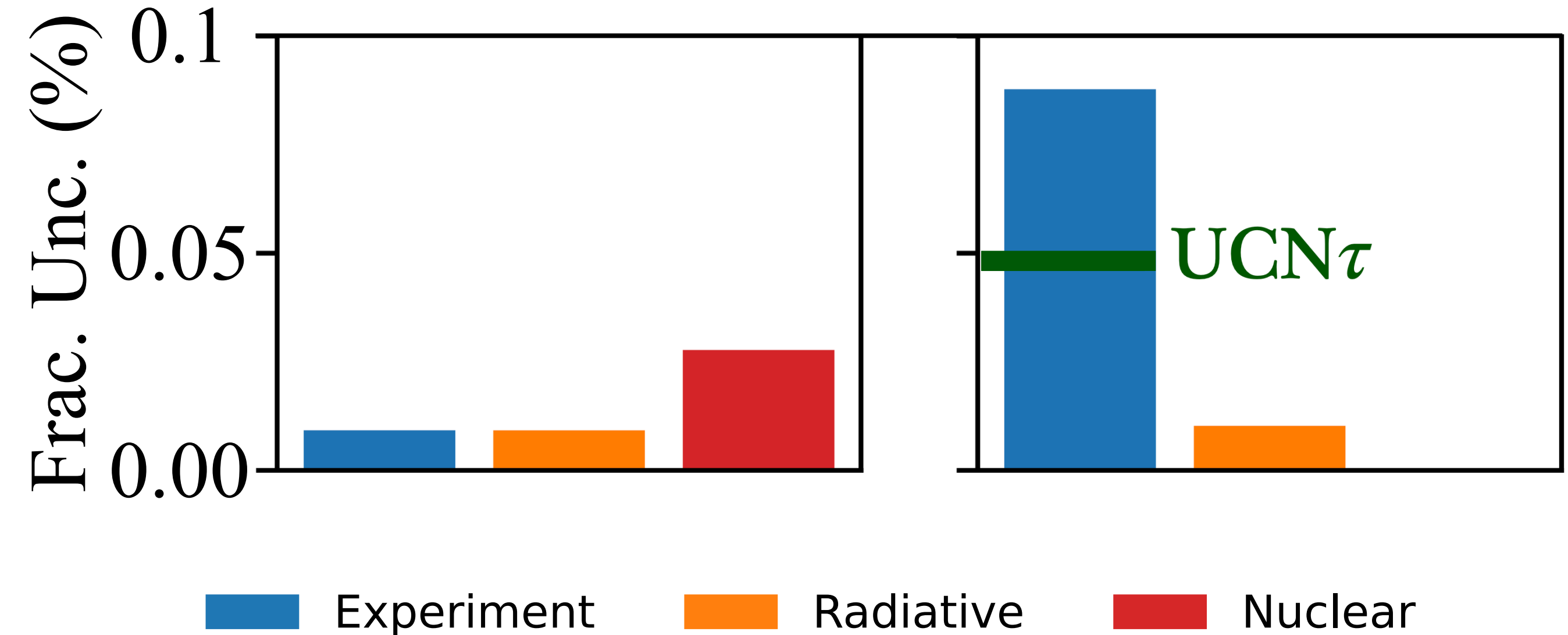


- 8-9 seconds discrepancy beam vs bottle method : $3-5\sigma$
- V_{ud} from $0^+ \rightarrow 0^+ + gA$ from β asymmetry $\equiv$ bottle
- 0.3 seconds uncertainty of UCN τ @LANL : $(3 - 4) \times 10^{-4}$

V_{ud} determinations

$0^+ \rightarrow 0^+$

Neutron

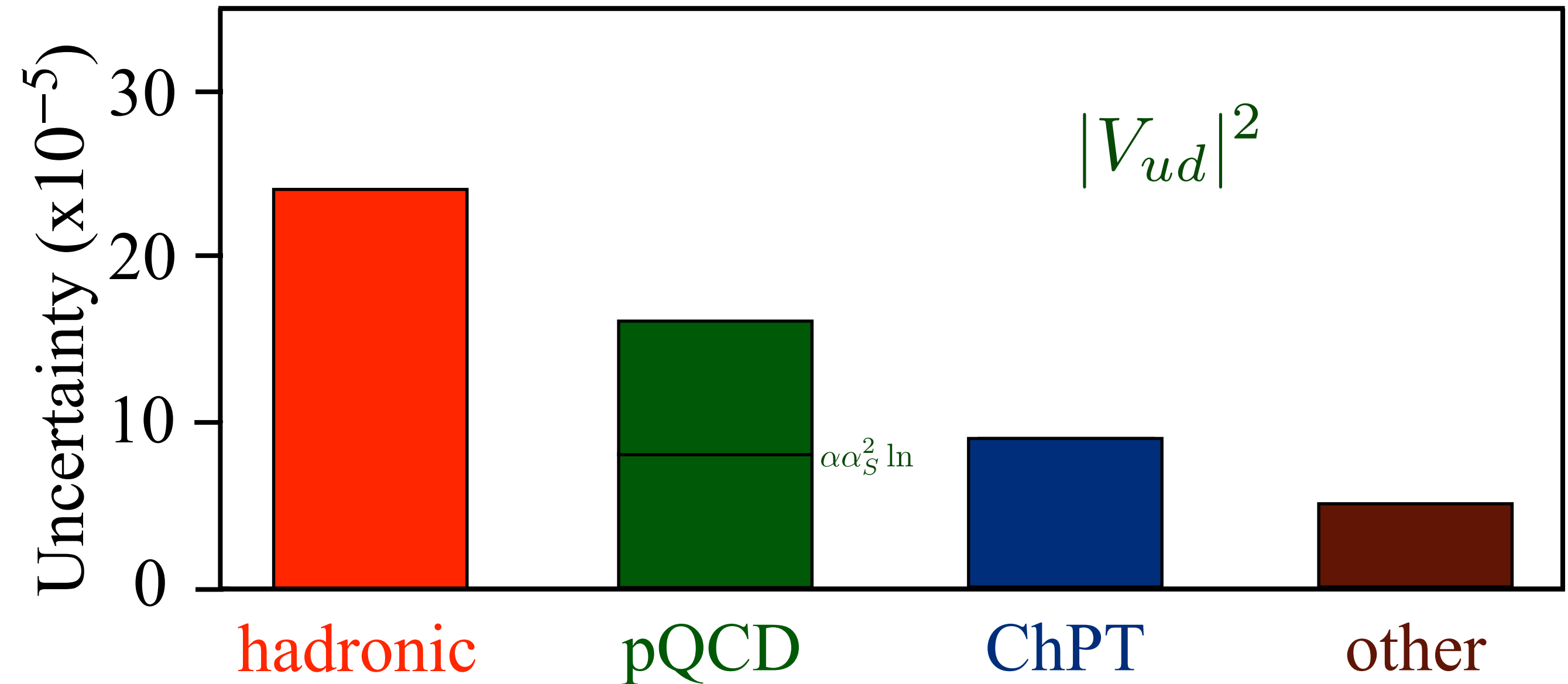


2022 Fundamental Symmetries, Neutrons, and Neutrinos (FSNN) white paper

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

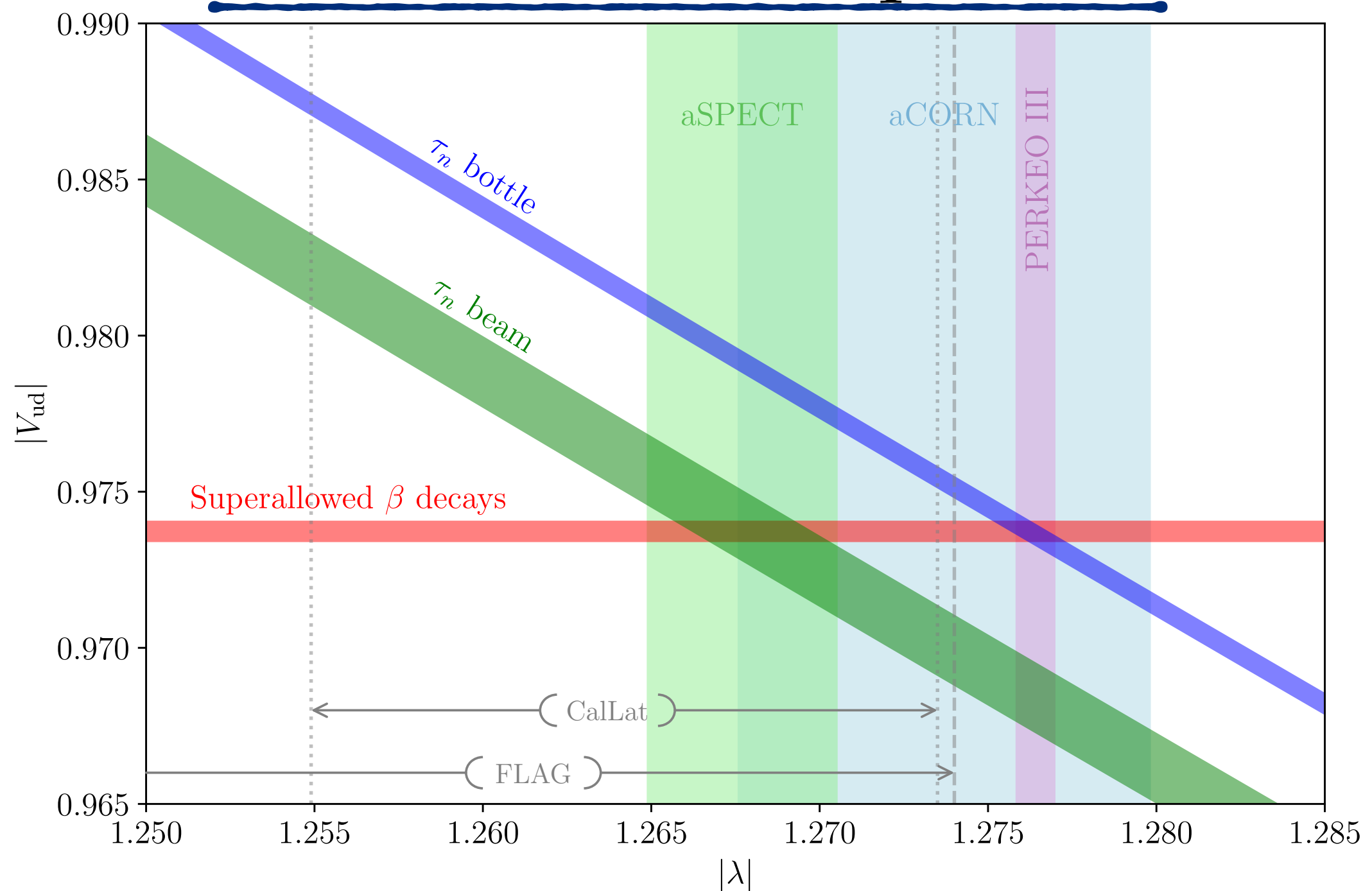
Our work

- 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

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

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

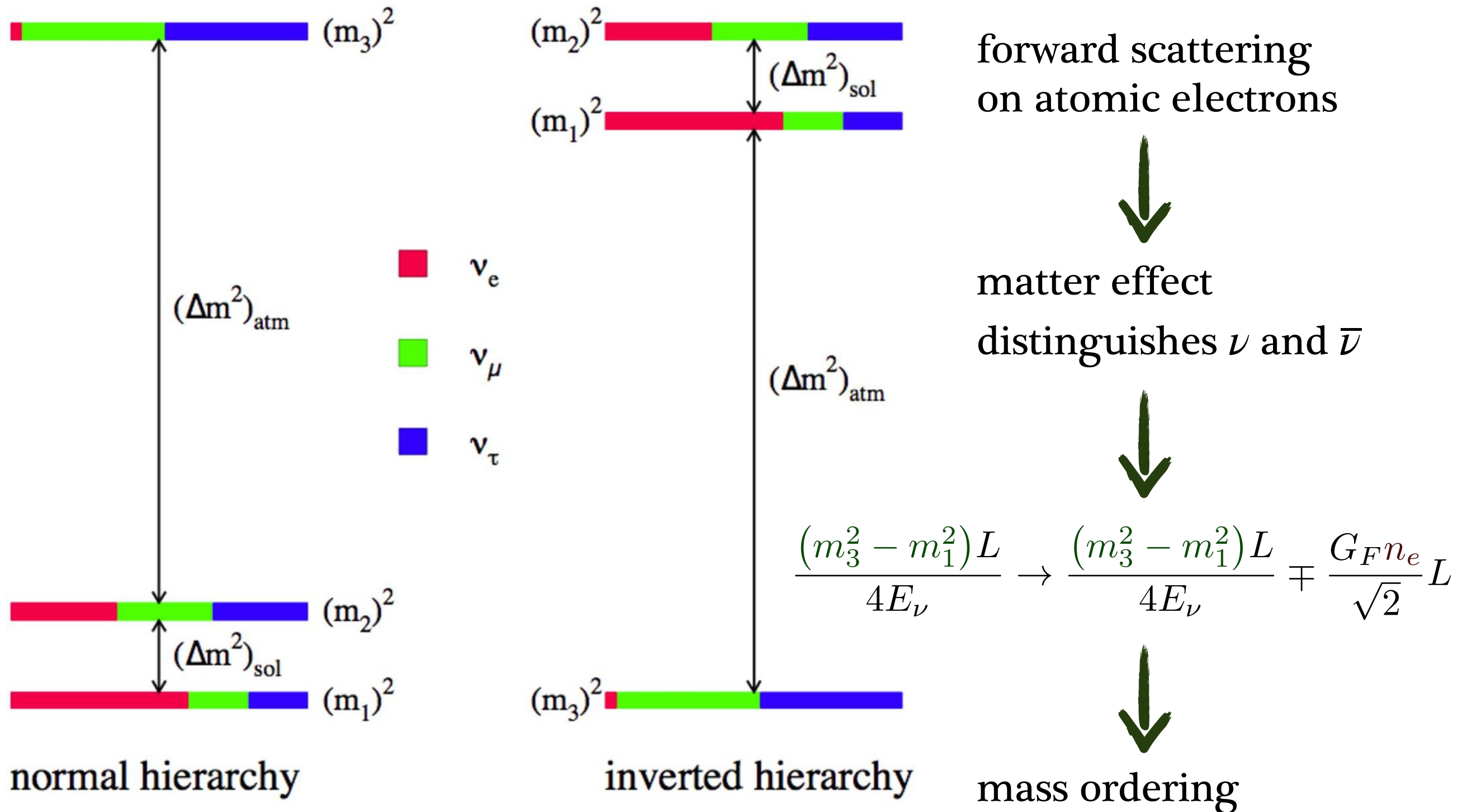
explain $\sim$ half of radiative correction to **neutron lifetime**

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

m_e

- g_V, g_A encode electroweak logarithms and hadronic corrections

Neutrino mass hierarchy



- matter effects can resolve neutrino mass hierarchy