29 January, 2026

The 5th Workshop on JUNO-related
Theory and Phenomenology

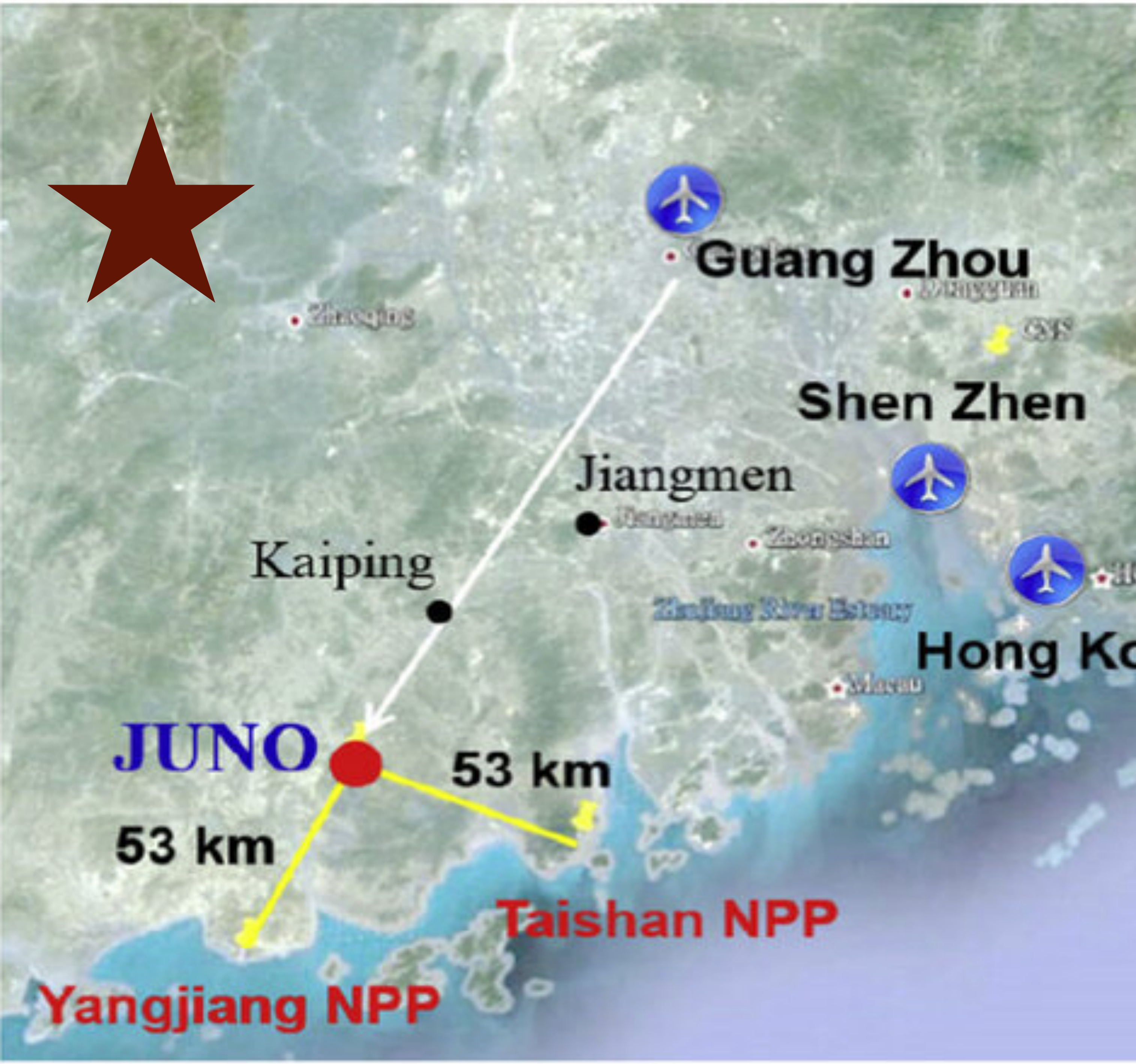
Radiative corrections to inverse beta decay at low energies

O.T., arXiv:2512.07956
arXiv:2512.07957

托马拉克
Sasha Tomalak

CP violation and mass hierarchy@laboratory

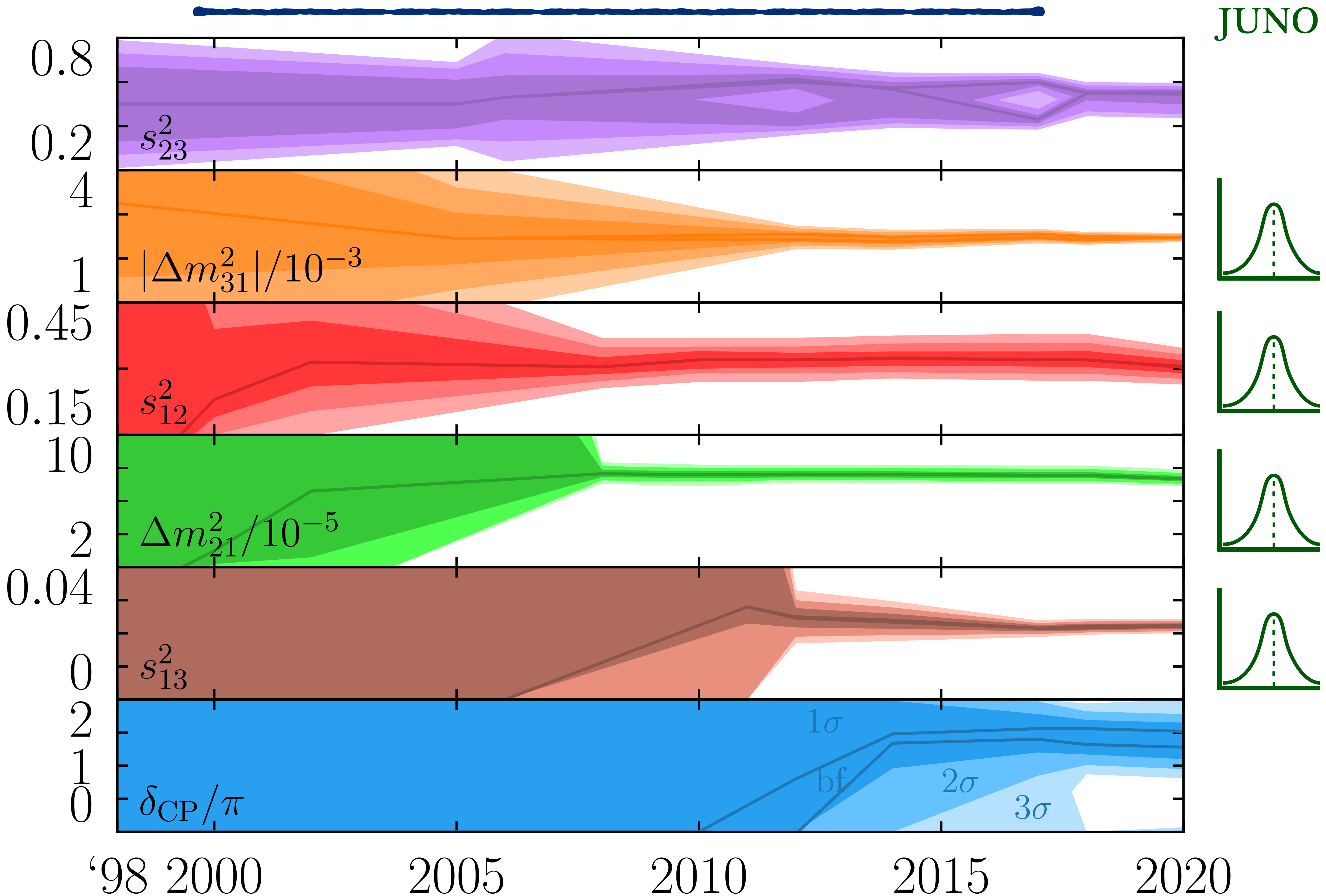
3σ determination of mass hierarchy



- 4 precise oscillation parameters from JUNO !!!

35 m, 20000 t

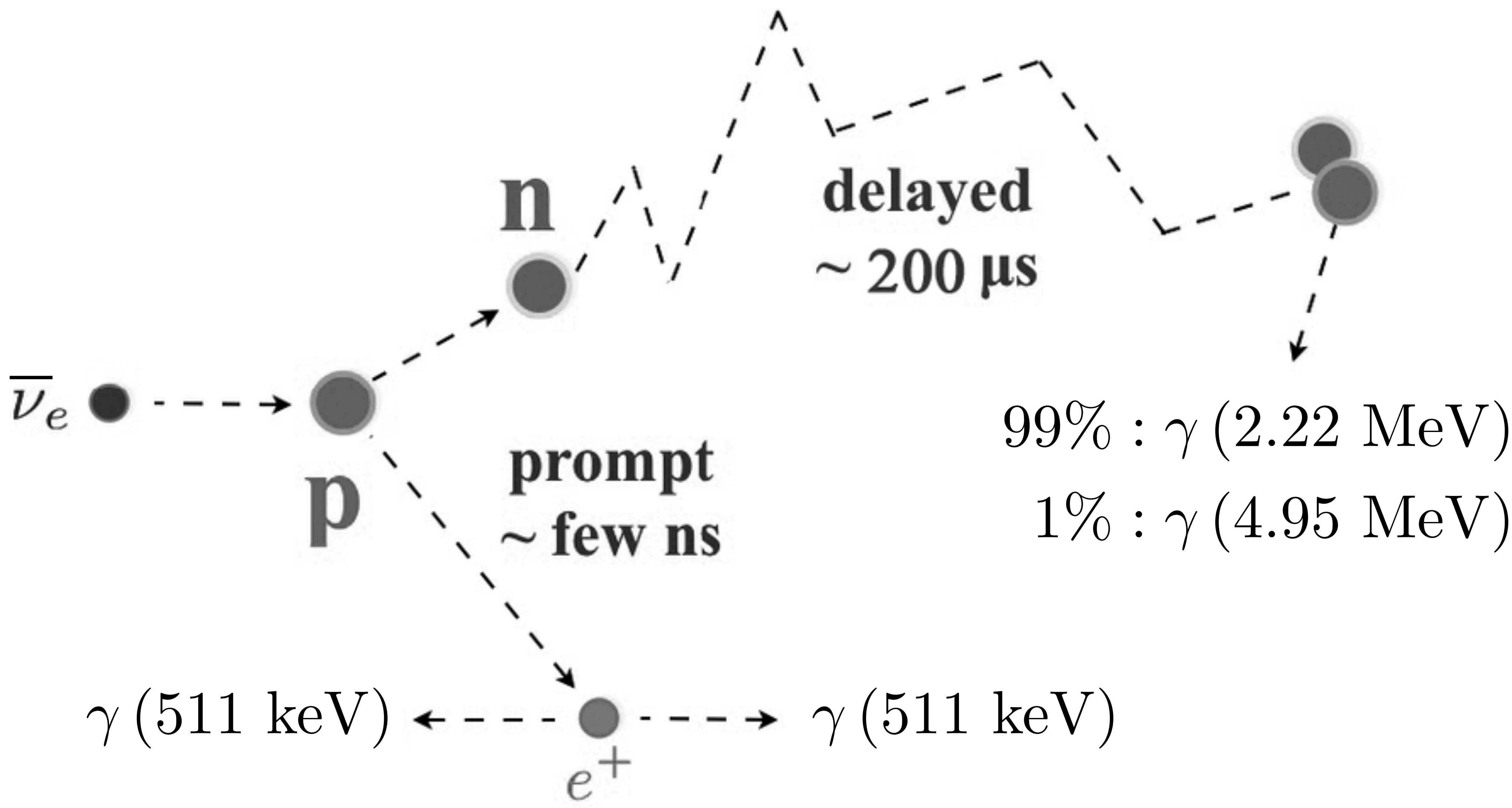
PMNS oscillation matrix



Snowmass 2021 NF01 group report

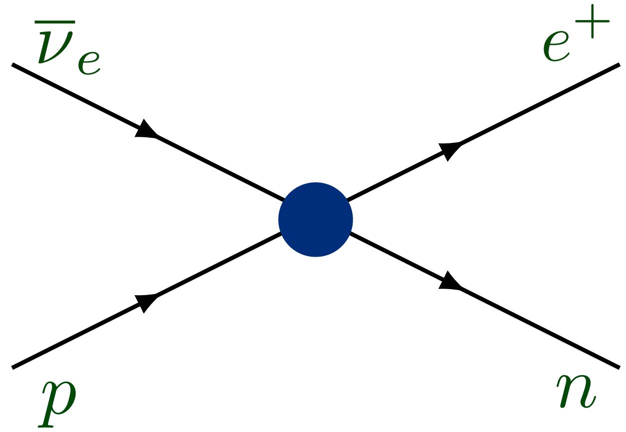
- tremendous progress in our lifetime

JUNO detection channel



Teng Li et al., Chin. Phys. C (2017)

- prompt-delayed time signature: background discrimination



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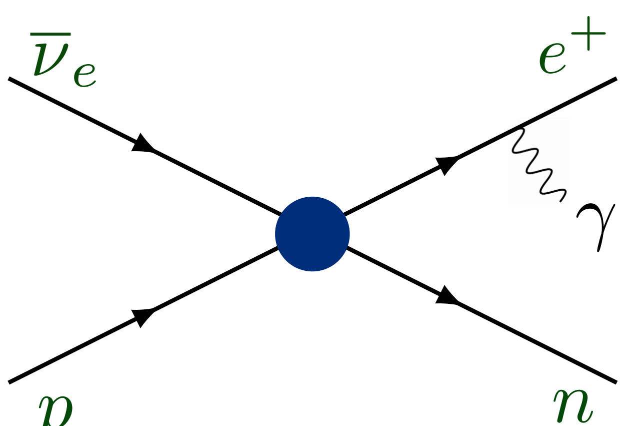
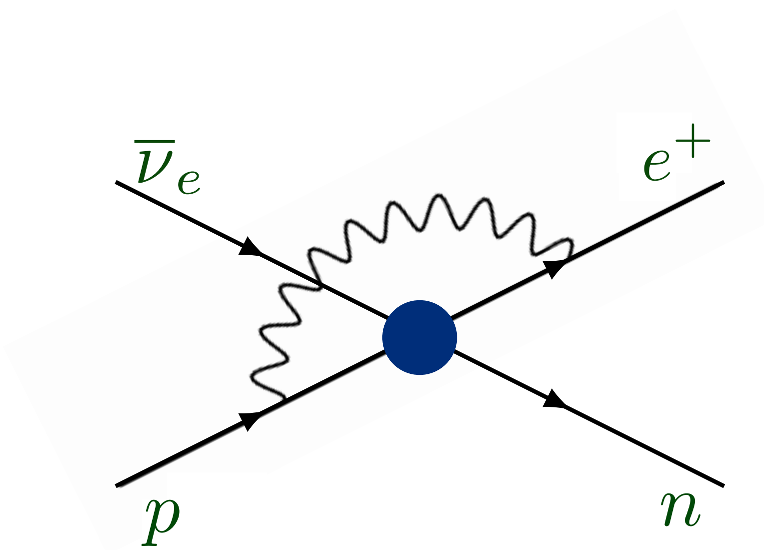
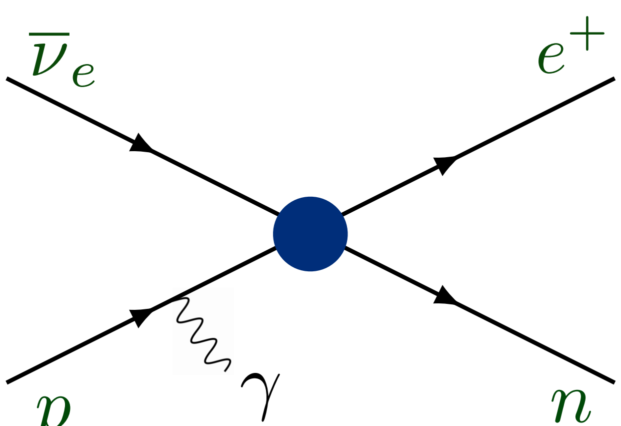
Theory of inverse beta decay for reactor antineutrinos

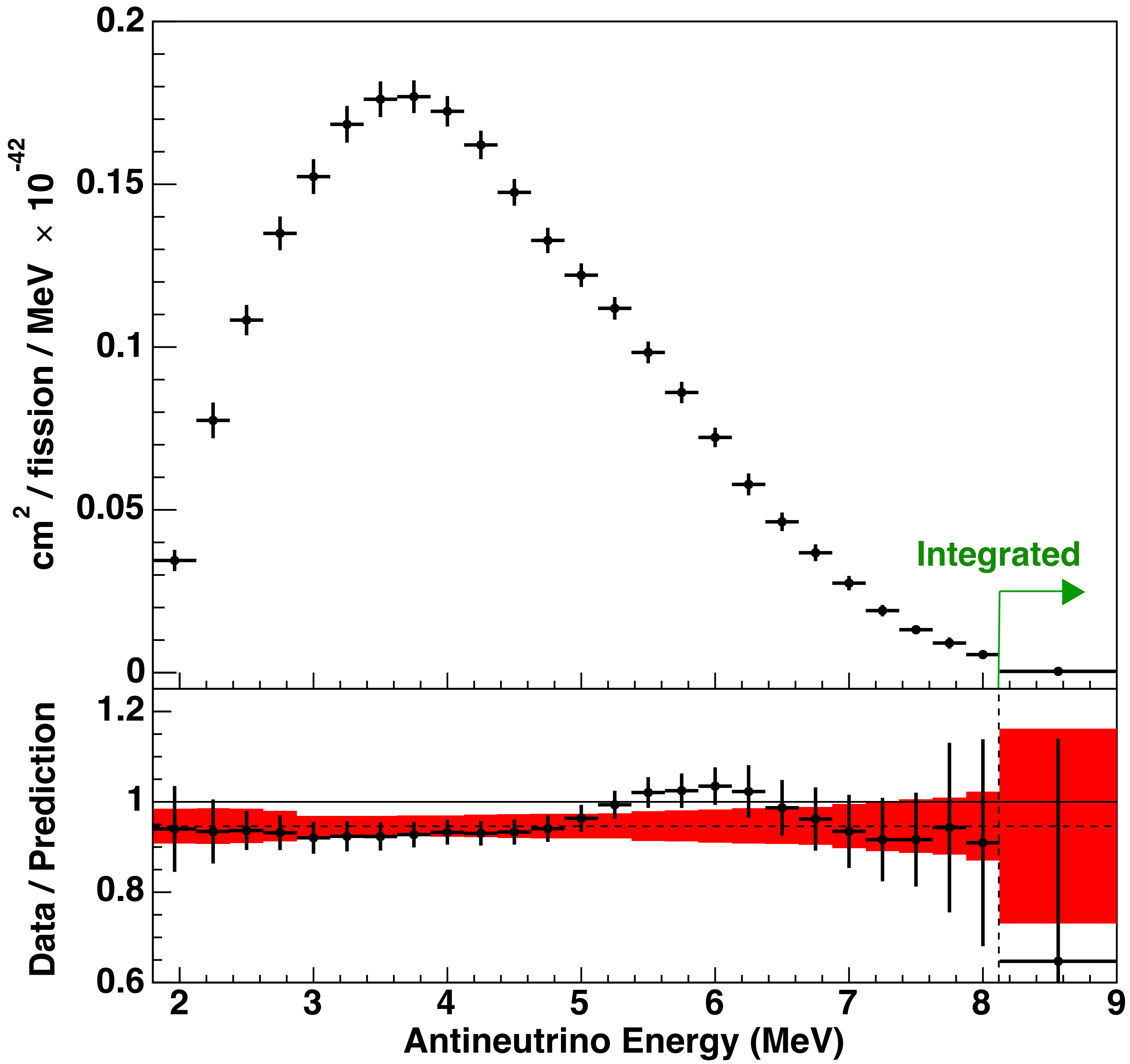


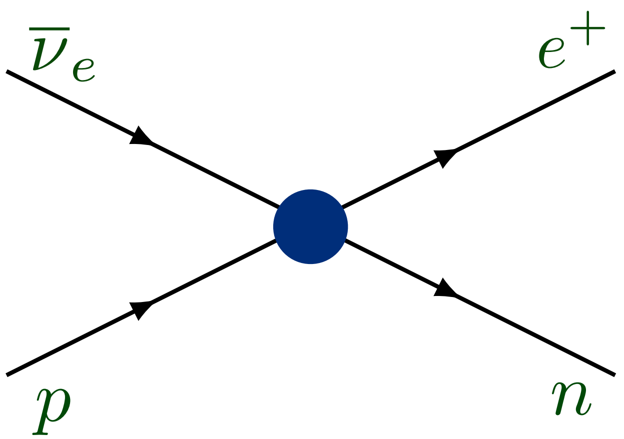




IBD with reactor antineutrinos

- neutron is heavier than proton by 1.3 MeV



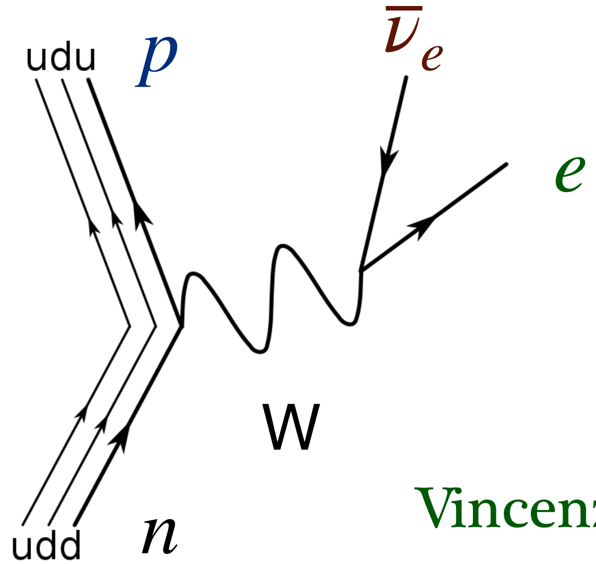


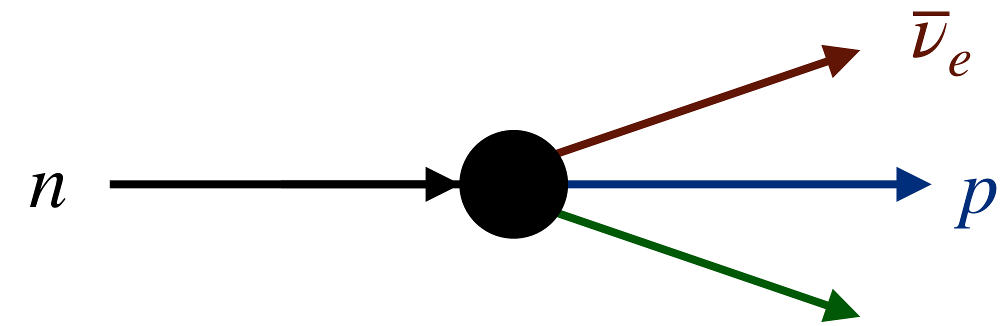
Daya Bay, PRL (2016)

- 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

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

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

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

Low-energy description

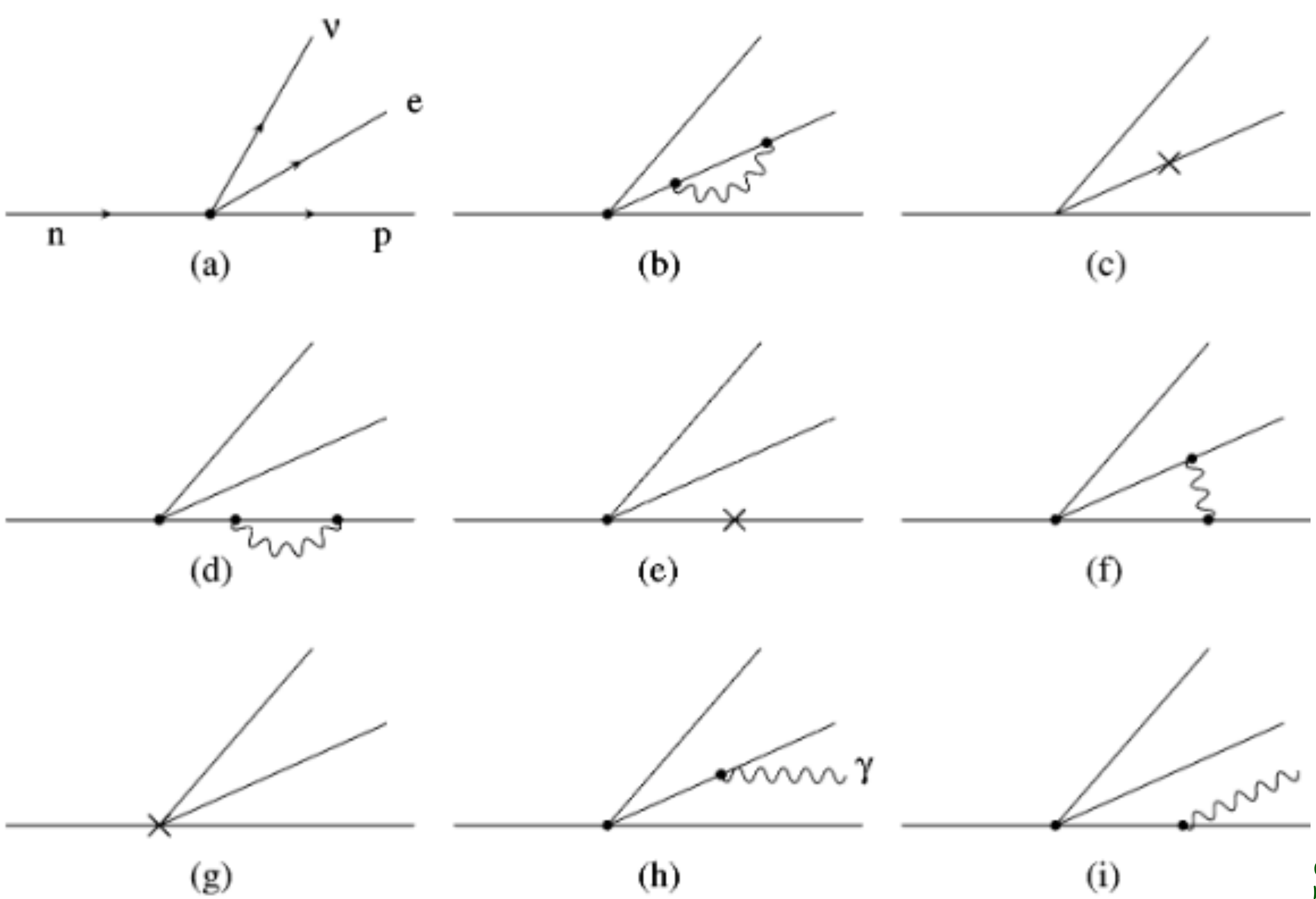
- four-fermion interaction between leptons and heavy nucleons

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

$$m_e \sim M_p - M_n$$

A. Sirlin, Phys. Rev. (1967)

- radiative corrections formulated in modern EFT language



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

data

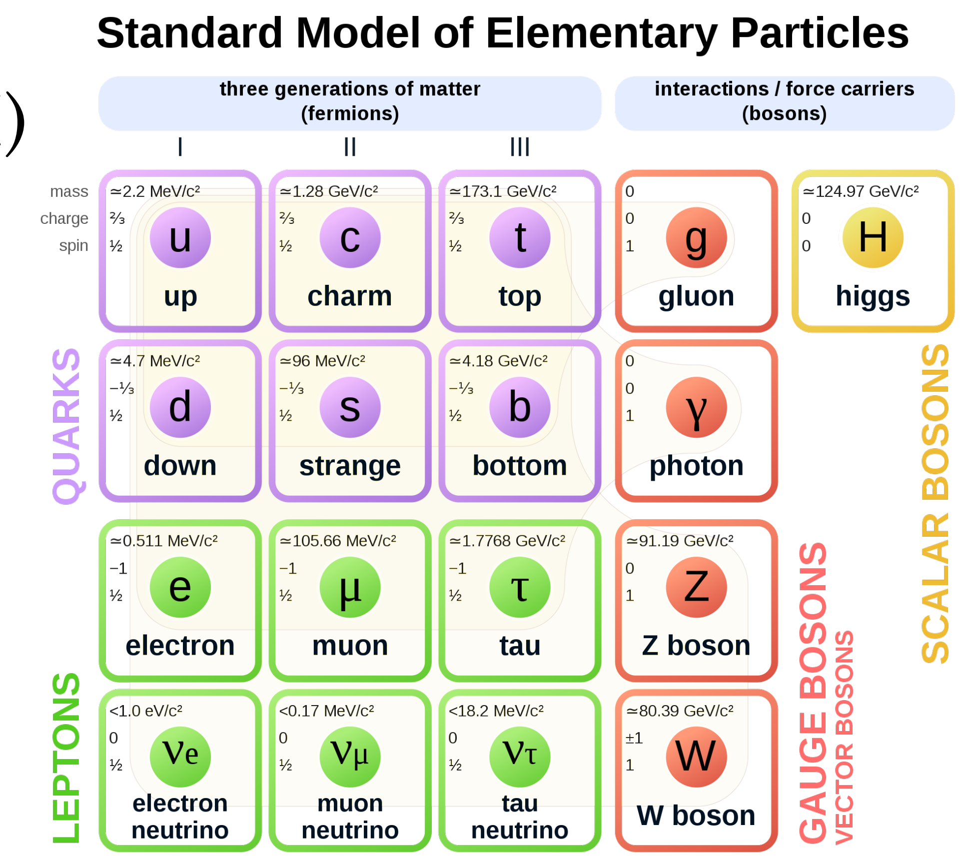
Standard Model

S. Ando et al., PLB (2004)

- two coupling constants predict all observables

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

m_τ integrate out GeV particles

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

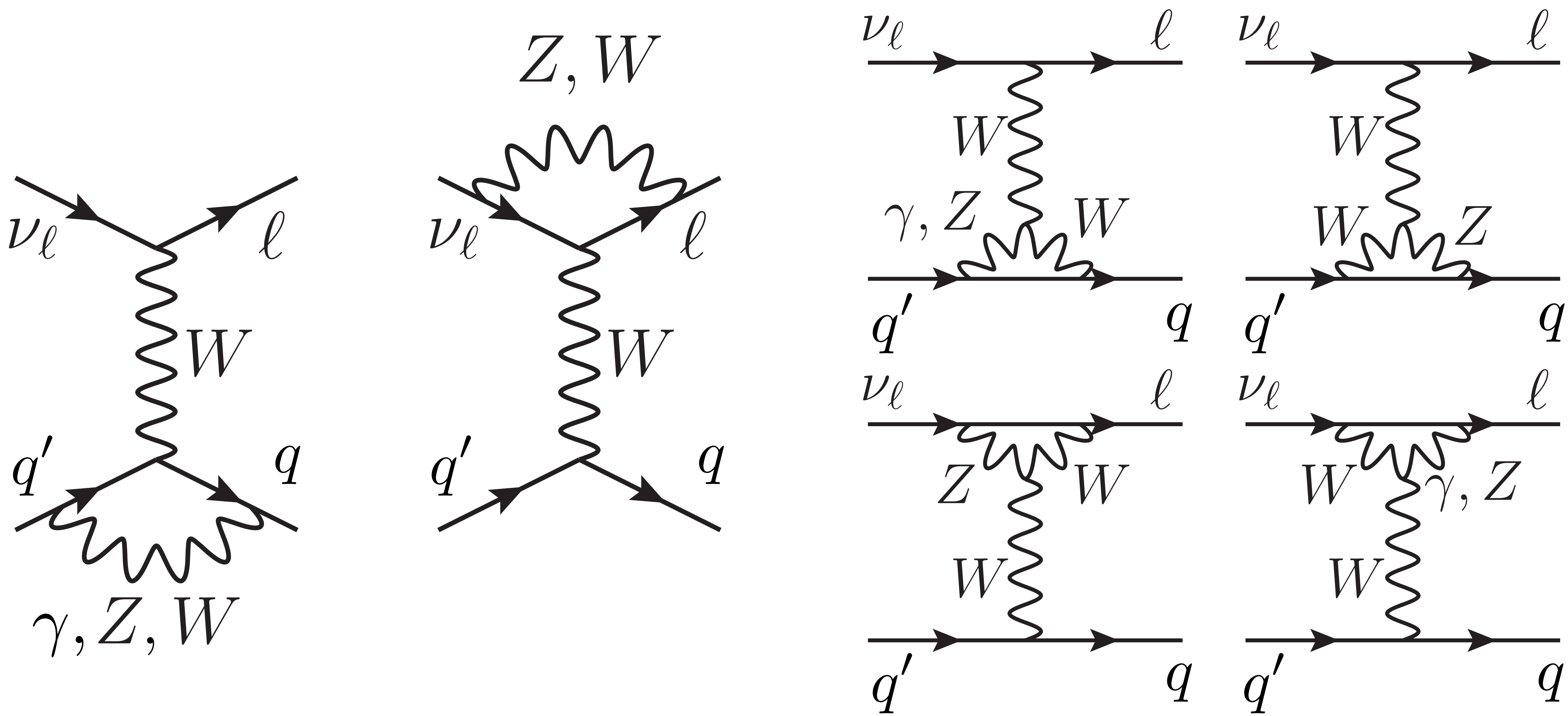
V. Cirigliano, J. de Vries, L. Hayen, E. Mereghetti, and A. Walker-Loud, PRL (2022)

m_e photons, neutrinos, electrons, external nucleons

S. Ando et al., PLB (2004)

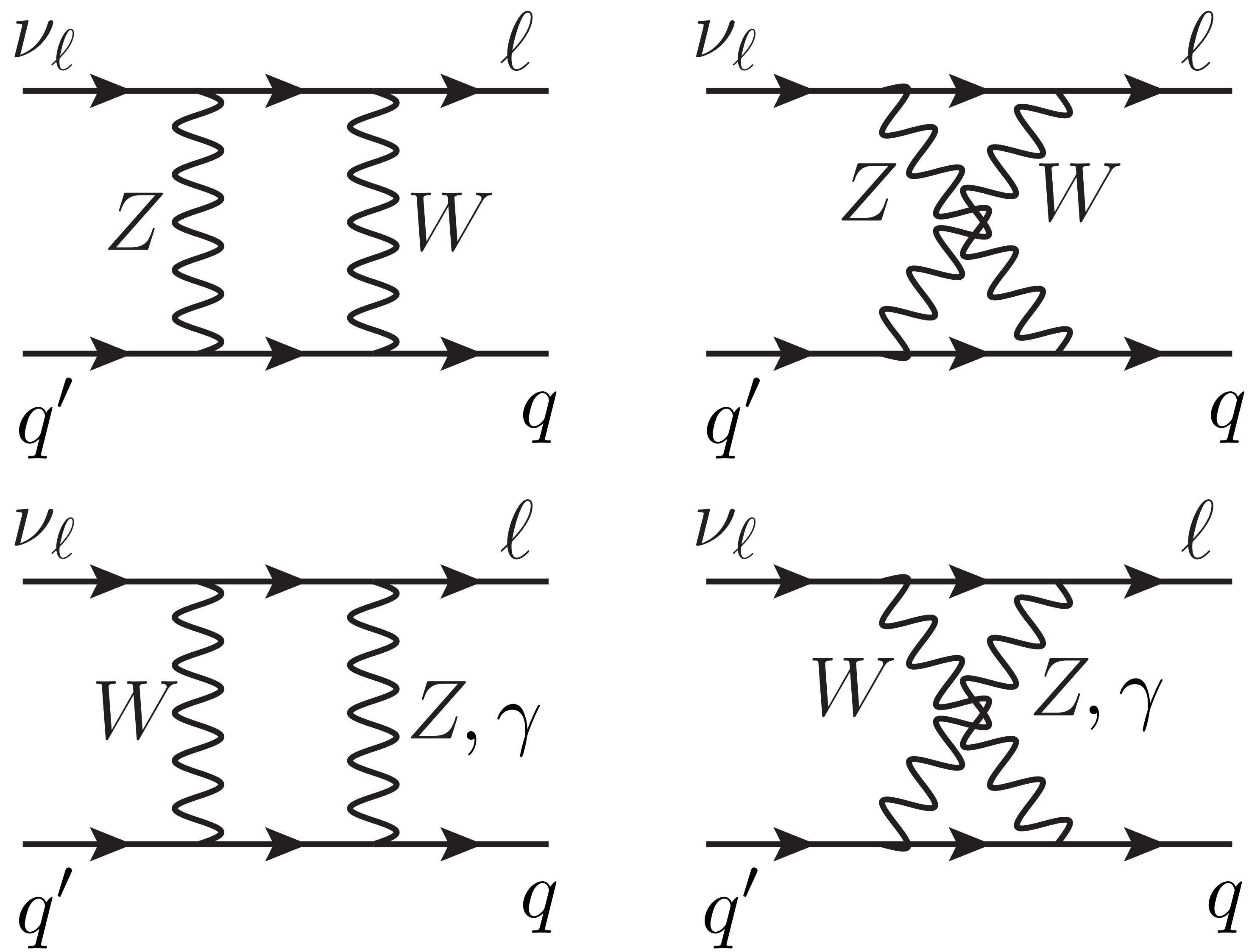
- coupling constants from SM + small QED corrections

Charged current in SM. Vertexes



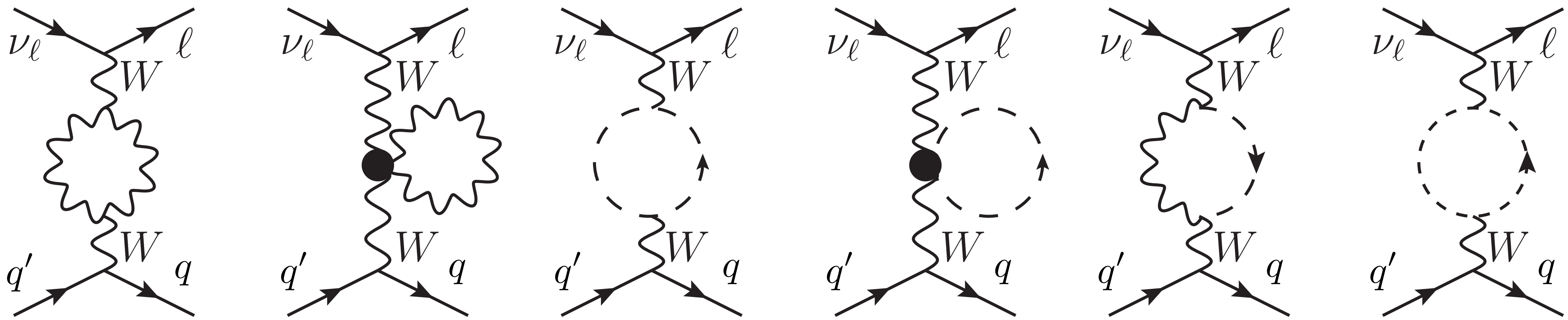
- contribution to effective couplings

Charged current in SM. Boxes

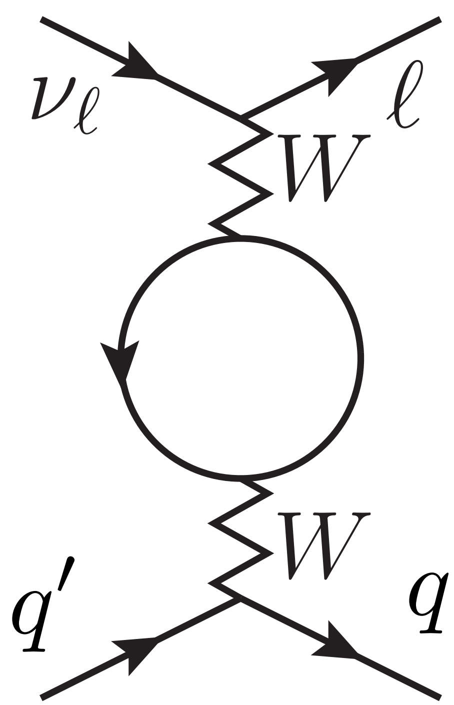


- contribution to effective couplings

W self energy



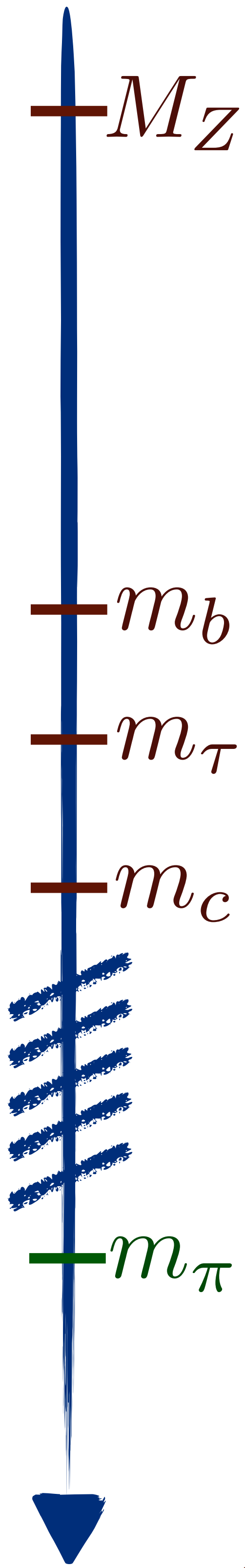
ZW,γW | WW,ZZ,$\gamma\gamma$ | hφ,χφ,χ | φφ,$\chi\chi$,hh | Wh,Zφ,γφ | cc



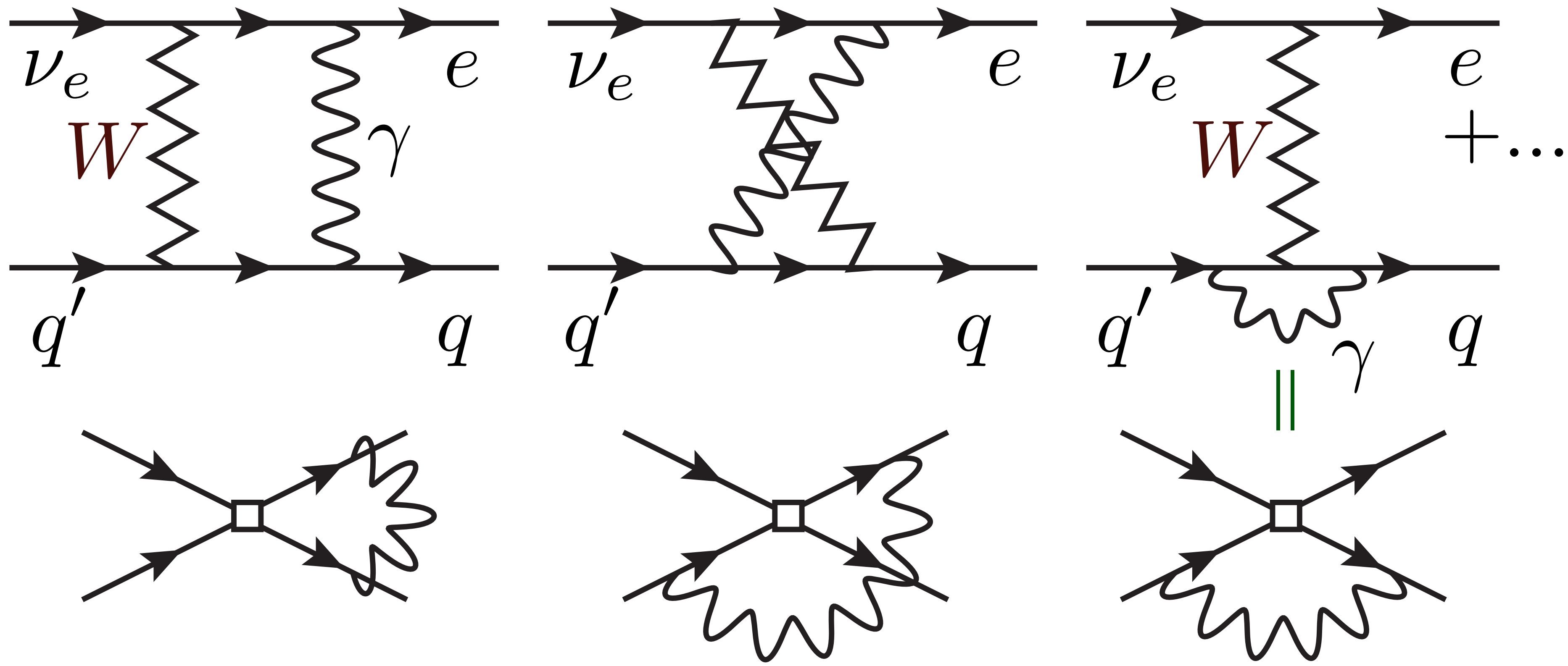
- vanishing contribution to matching besides loops with t quark

- contribution to effective couplings

LEFT Lagrangian



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



scheme independent

scheme dependent for quarks

- NDR scheme for γ_5 for evanescent operators E

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

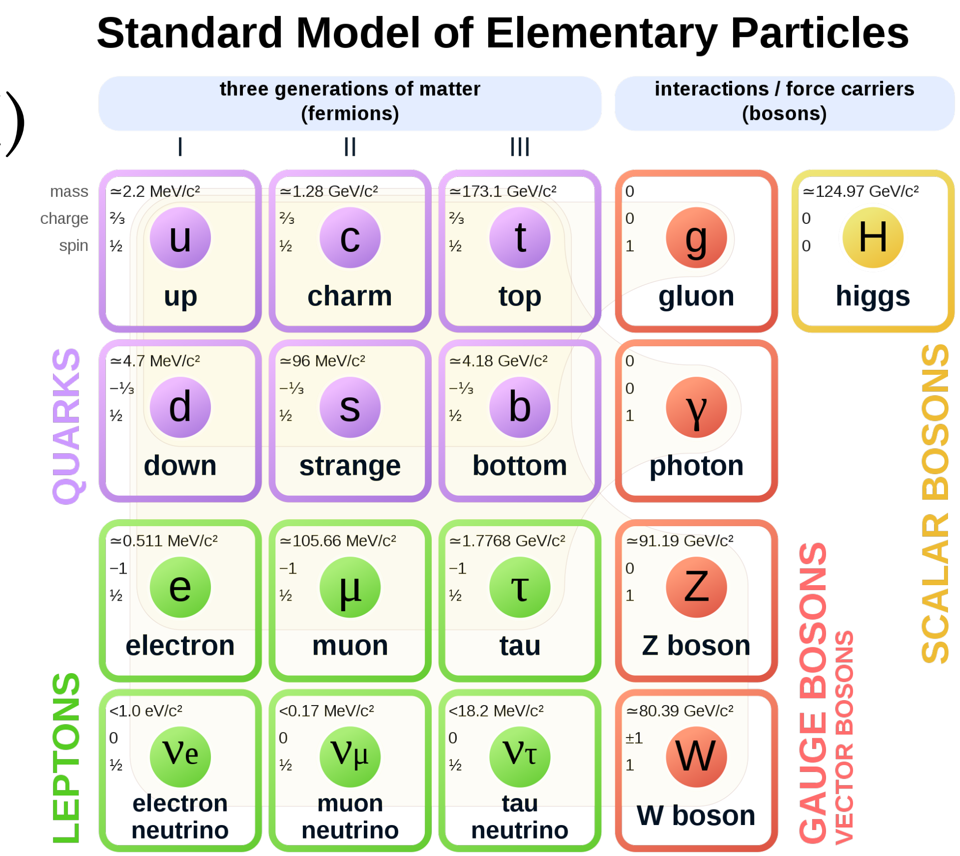
Buras and Weisz (1990)

- 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

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

- $\not\pi$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

One-loop result

- clear illustration of leading logarithms

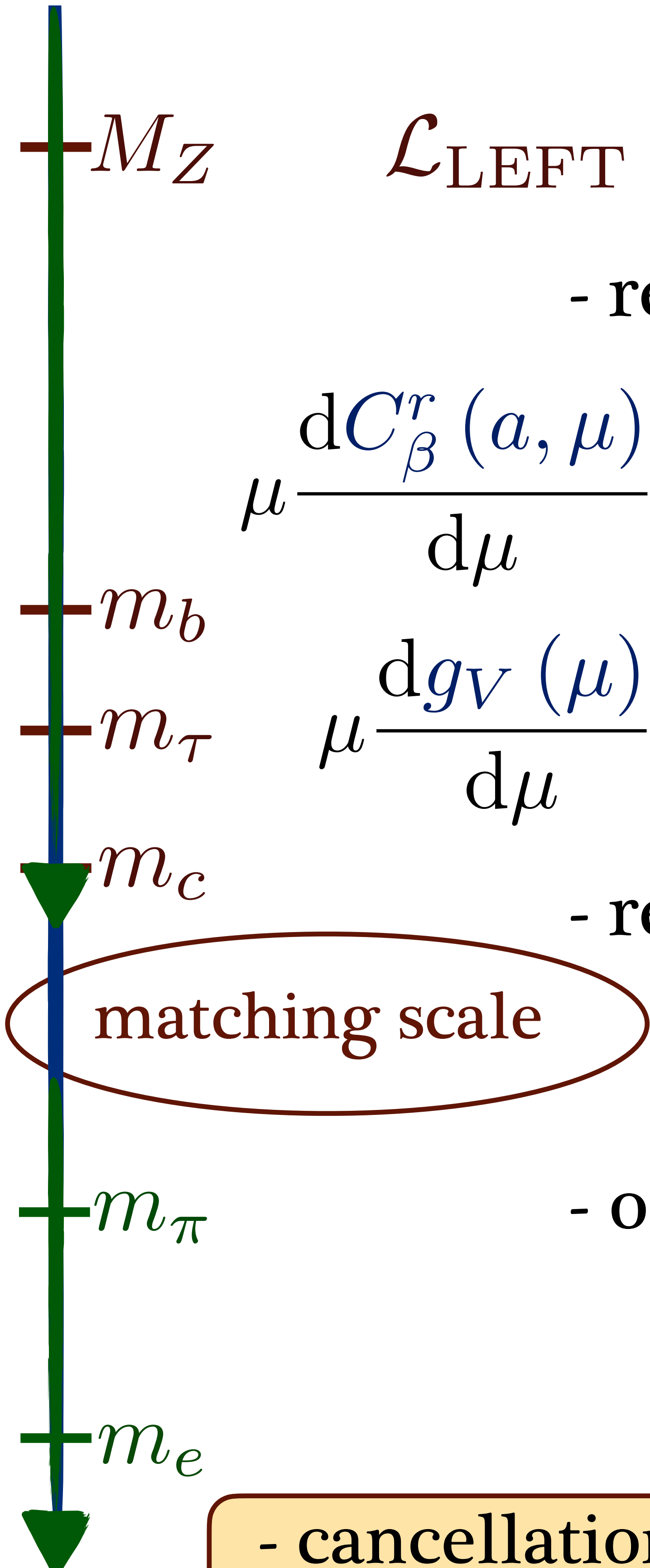
$$g_{\mathrm{V}}\left(\mu_\chi\right) = 1 - \frac{\alpha}{2\pi}\left[\frac{5}{8} + \frac{3}{4}\ln\frac{\mu_\chi^2}{\mu_0^2} + \ln\frac{\mu_0^2}{M_Z^2}\right] - e^2 \int \frac{i\mathrm{d}^4 q}{(2\pi)^4}\frac{\nu^2+Q^2}{Q^4}\left[\frac{\mathrm{T}_3(\nu,Q^2)}{2\nu} - \frac{2}{3}\frac{1}{Q^2+\mu_0^2}\right]$$

- 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



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

- 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

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

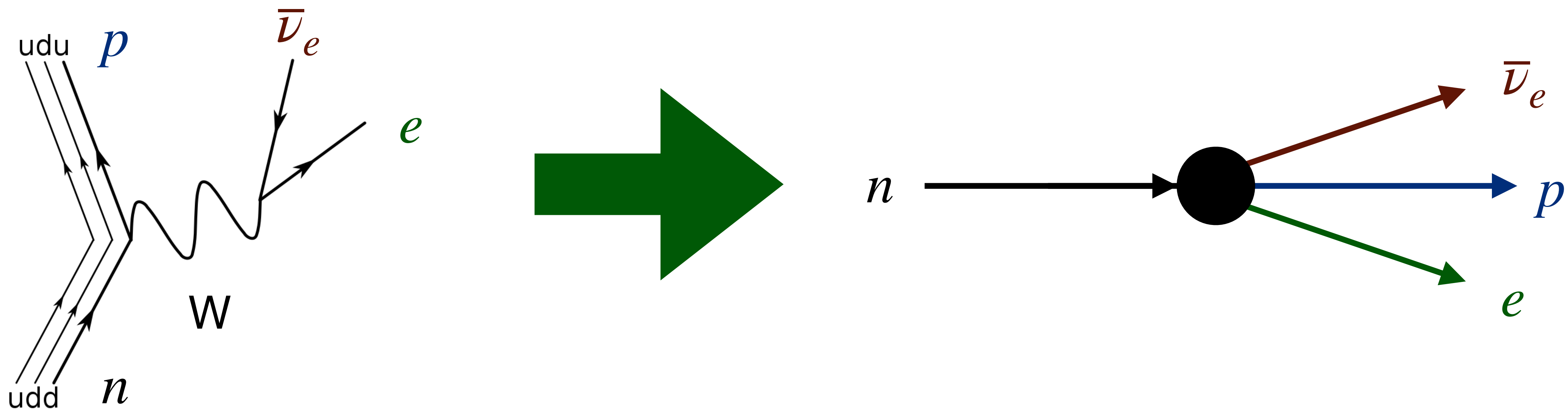
- one-loop result without $\alpha\alpha_s$ contributions

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

- 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

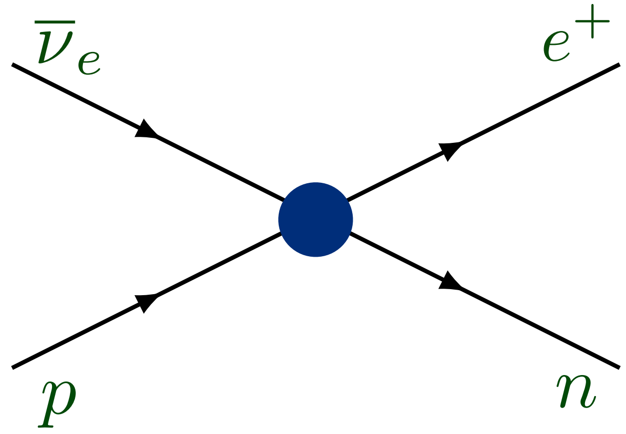
$$\mathcal{L}_{\text{eff}} = -\sqrt{2} \mathrm{G_F} V_{ud} \bar{e} \gamma_\mu \mathrm{P_L} \nu_e \cdot \overline{N} \left(g_V v^\mu - 2 g_A S^\mu \right) \tau^+ N$$

g_V : theoretical prediction from Standard Model

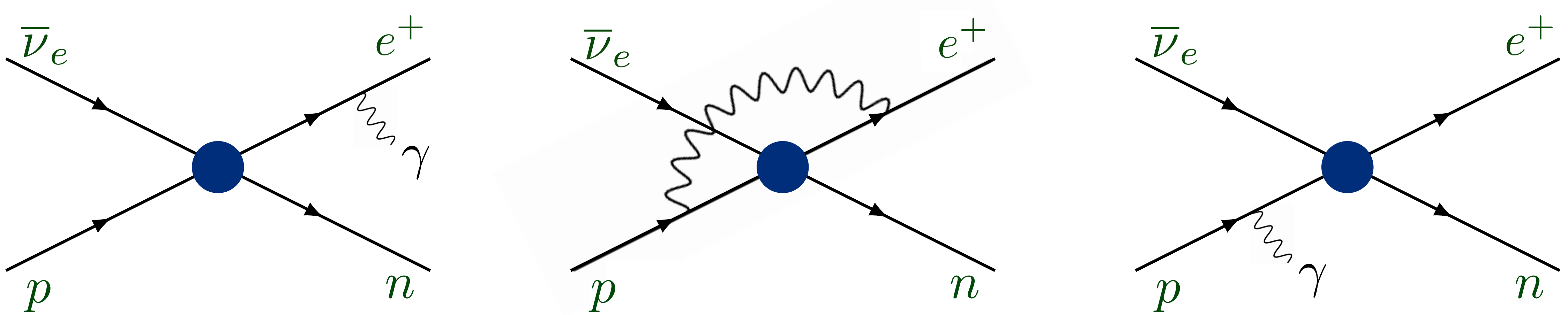
g_A : beta asymmetry in polarized neutron decay

V_{ud}: superallowed transitions

- first consistent at 0.1%-level QED radiative corrections



Theory of inverse beta decay for reactor antineutrinos

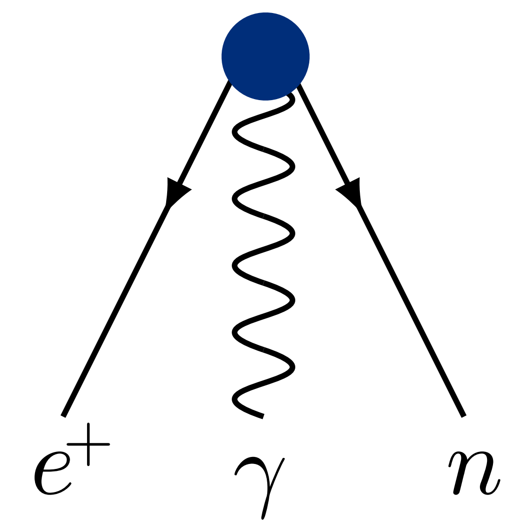


Bremsstrahlung

- new distributions beyond E_{EM} spectrum

E_n, E_γ, θ_n → E_n, θ_n → E_n, E_{EM} → total cross section

E_e, E_γ, θ_e → E_e, θ_e → E_e → total cross section



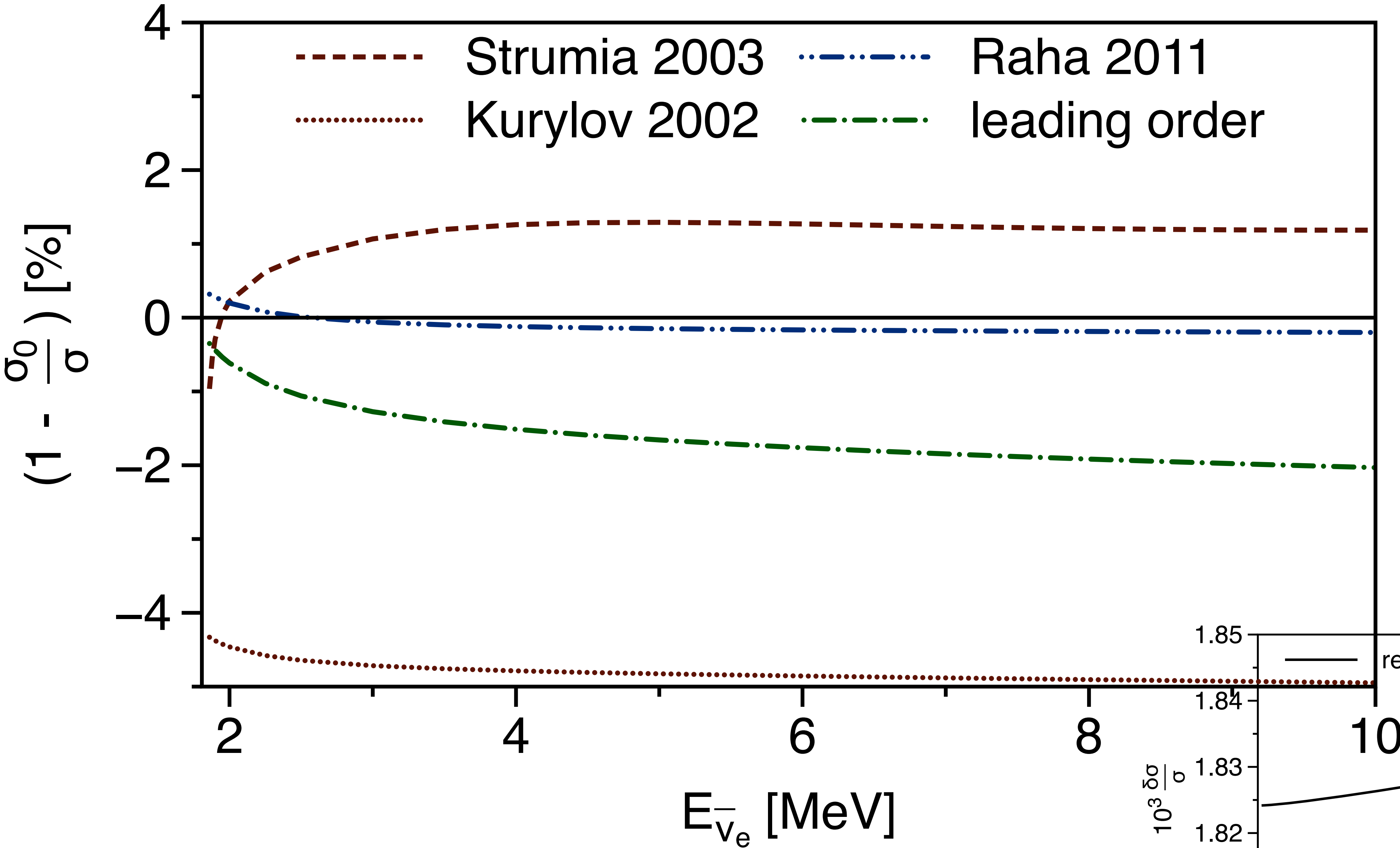
$$E_{\text{EM}} = E_e + E_\gamma$$

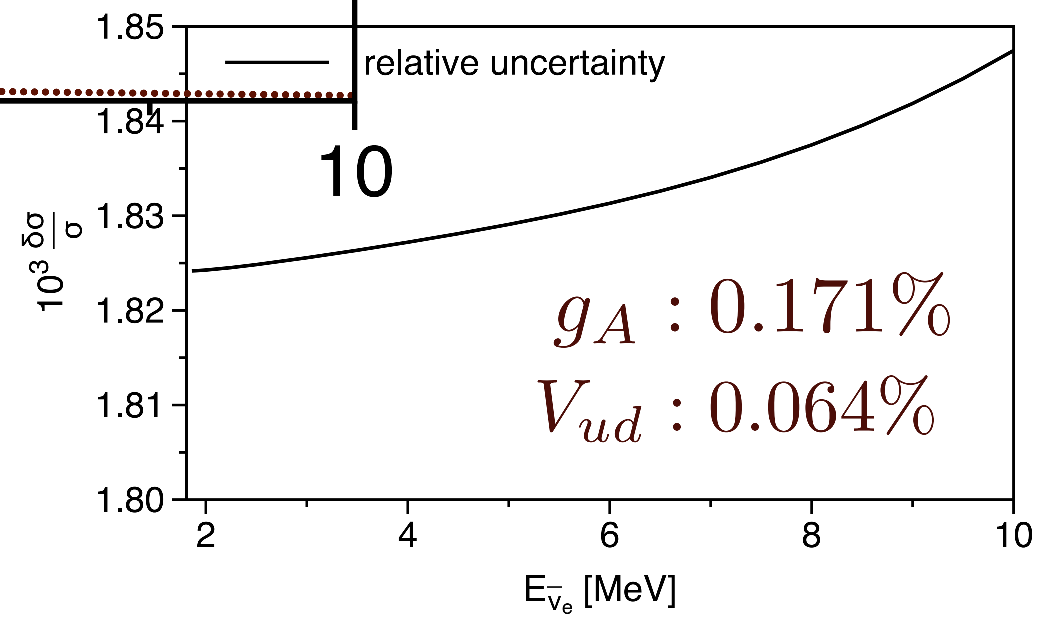
consistency at cross-section level

O.T., arXiv:2512.07956
arXiv:2512.07957

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

Total cross section



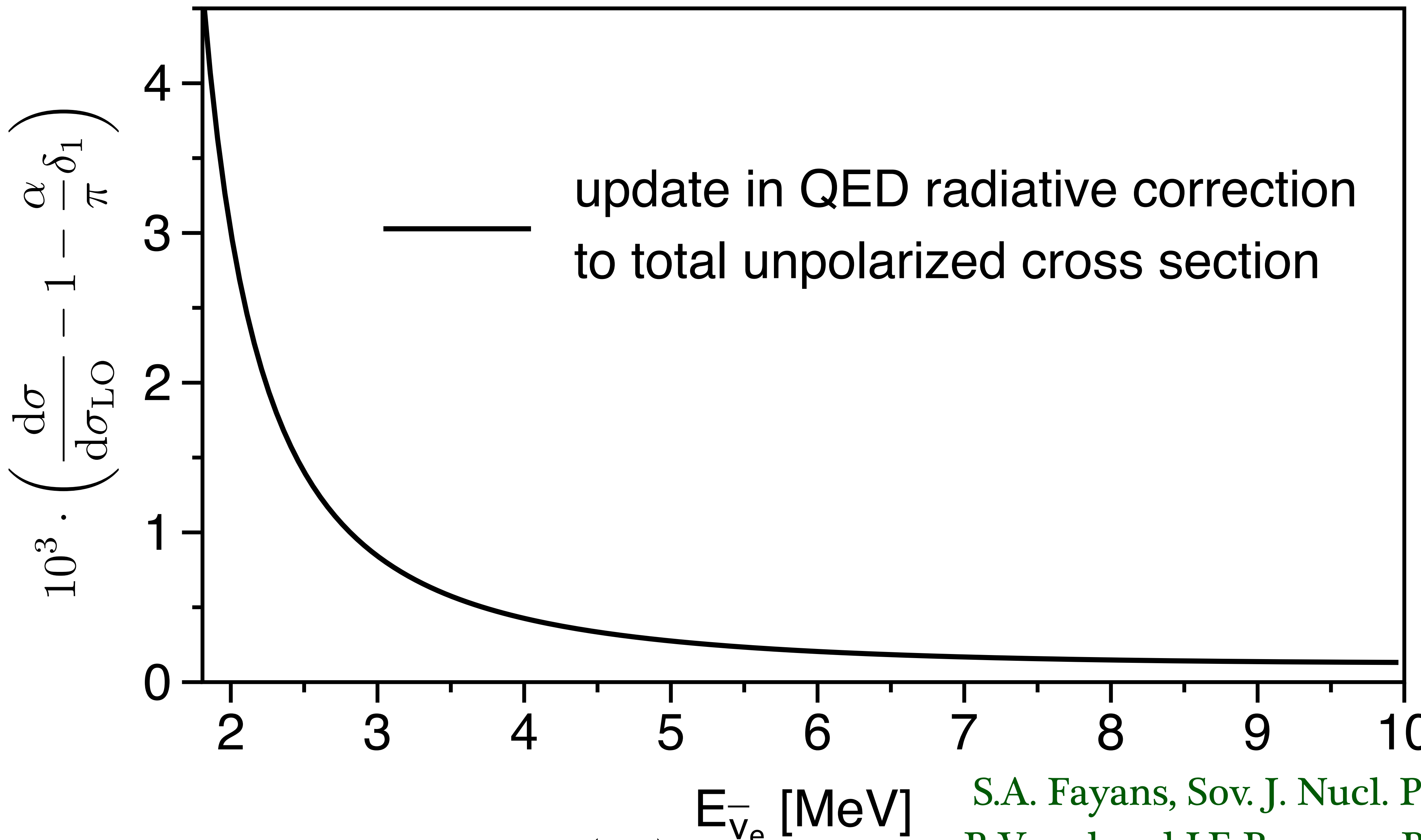


σ_0 - reference

σ - this work

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

Total cross section



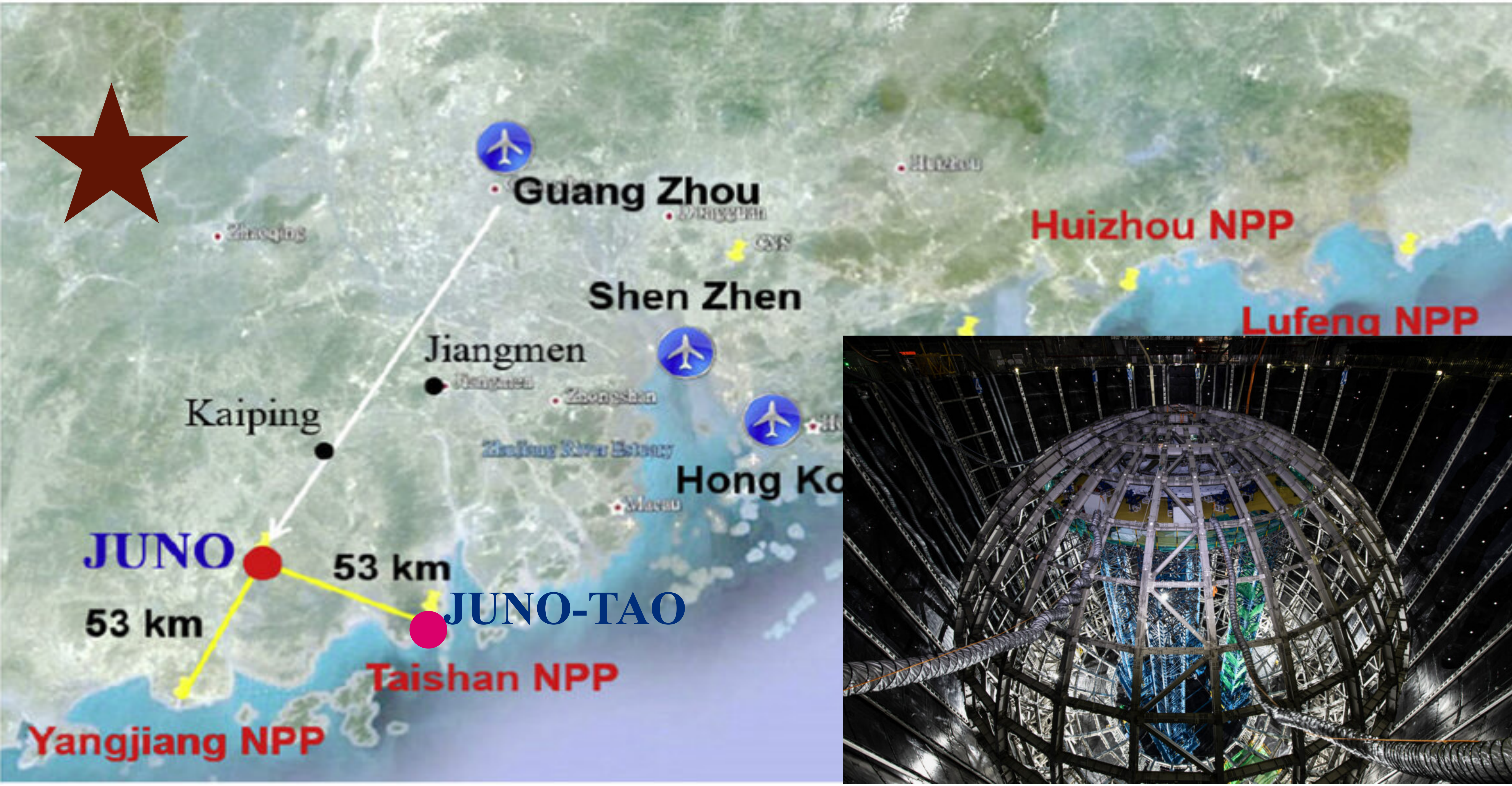
$$E_{\bar{\nu}_e} \approx m_n - m_p + E_{e^+} + E_\gamma + O\left(\frac{1}{M}\right)$$

S.A. Fayans, Sov. J. Nucl. Phys (1985)
P. Vogel and J.F. Beacom, PRD (1999)
M. Fukugita and T. Kubota, PRD (2005)
U. Raha, F. Myhrer, and K. Kubodera, PRC (2012)
O.T., Qing Chen, Richard J. Hill, Kevin S. McFarland, and Clarence Wret, PRD (2022)

- analytical expression δ_1 in static limit works at $\lesssim$0.1% level

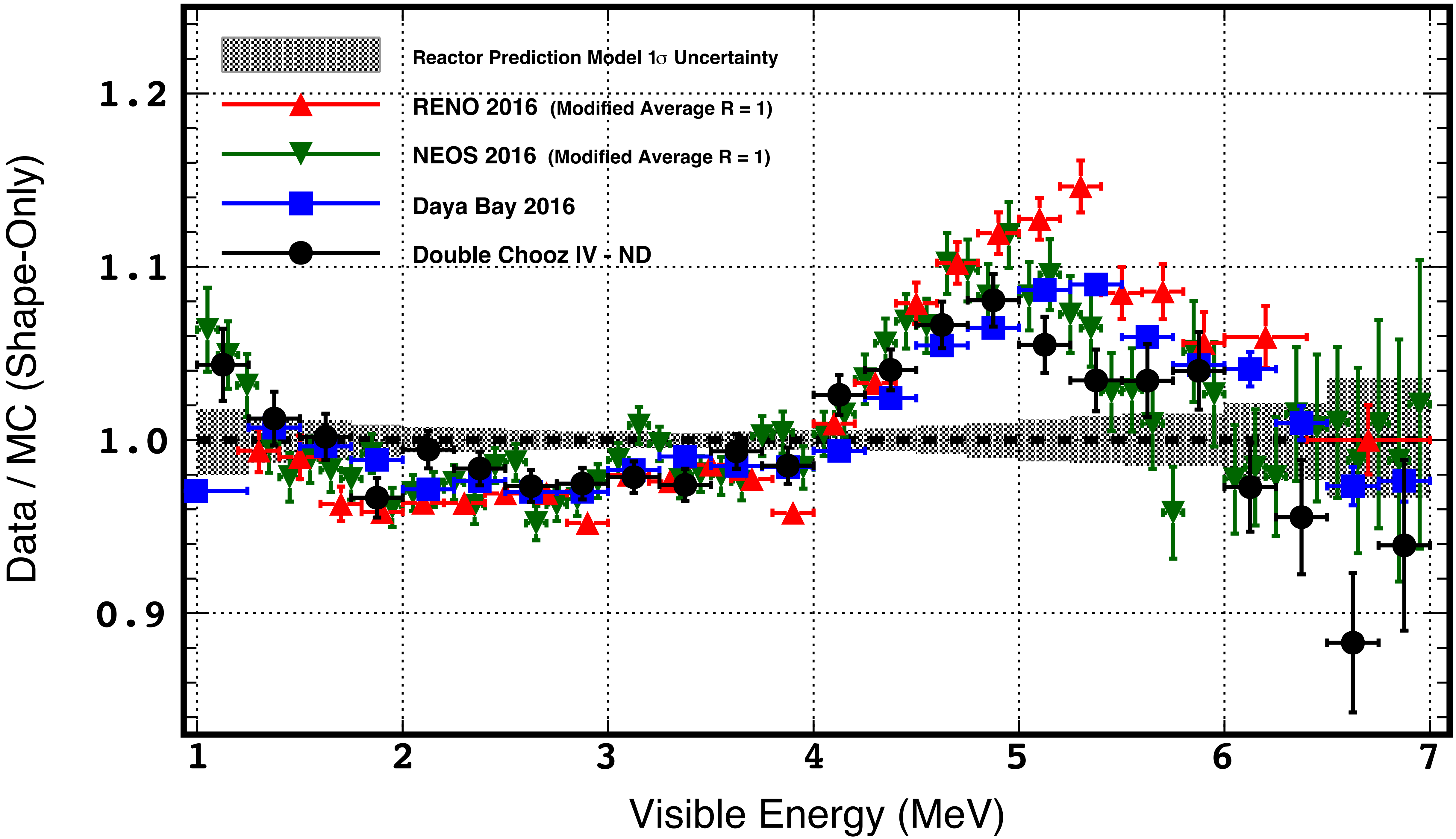
CP violation and mass hierarchy@laboratory

3σ determination of mass hierarchy



- partial reduction of cross-section uncertainty with JUNO-TAO

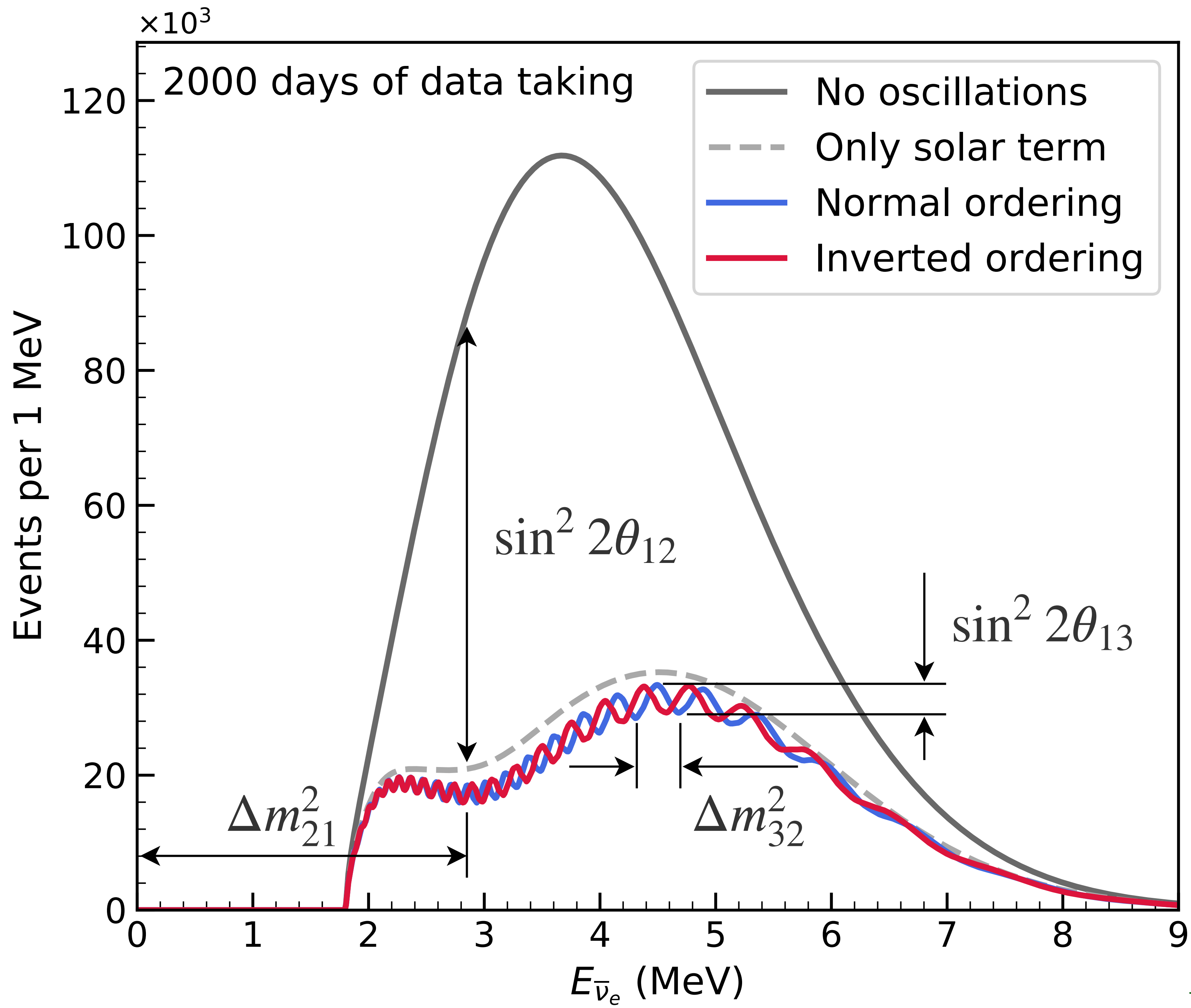
5-MEV flux excess



Double Chooz, Nature Phys (2019)

- update in cross section at 4-6 MeV: shift by 10-15% of bump

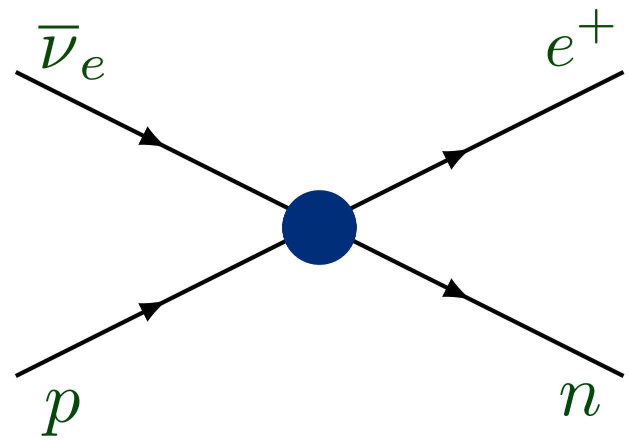
Energy reconstruction is key

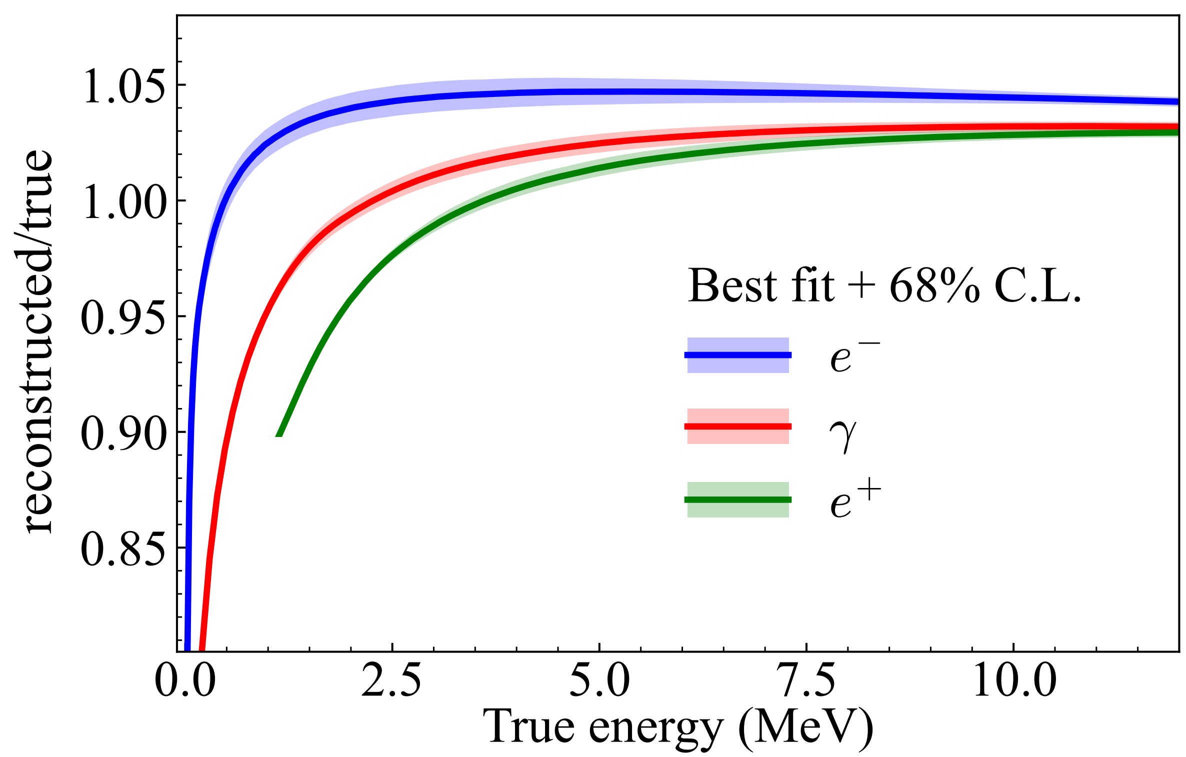


JUNO (2021)

- JUNO: 3% energy reconstruction for precision goals

Energy reconstruction is key



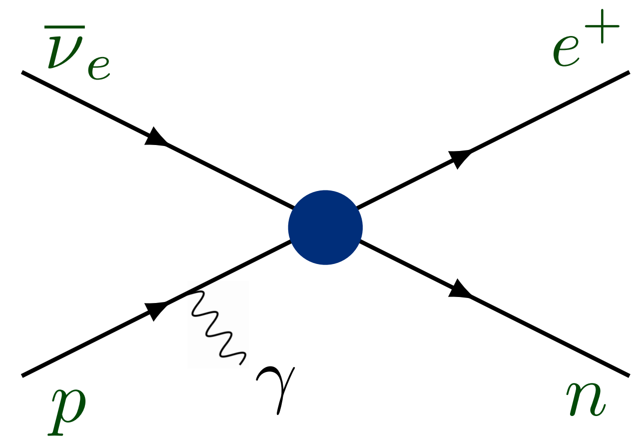


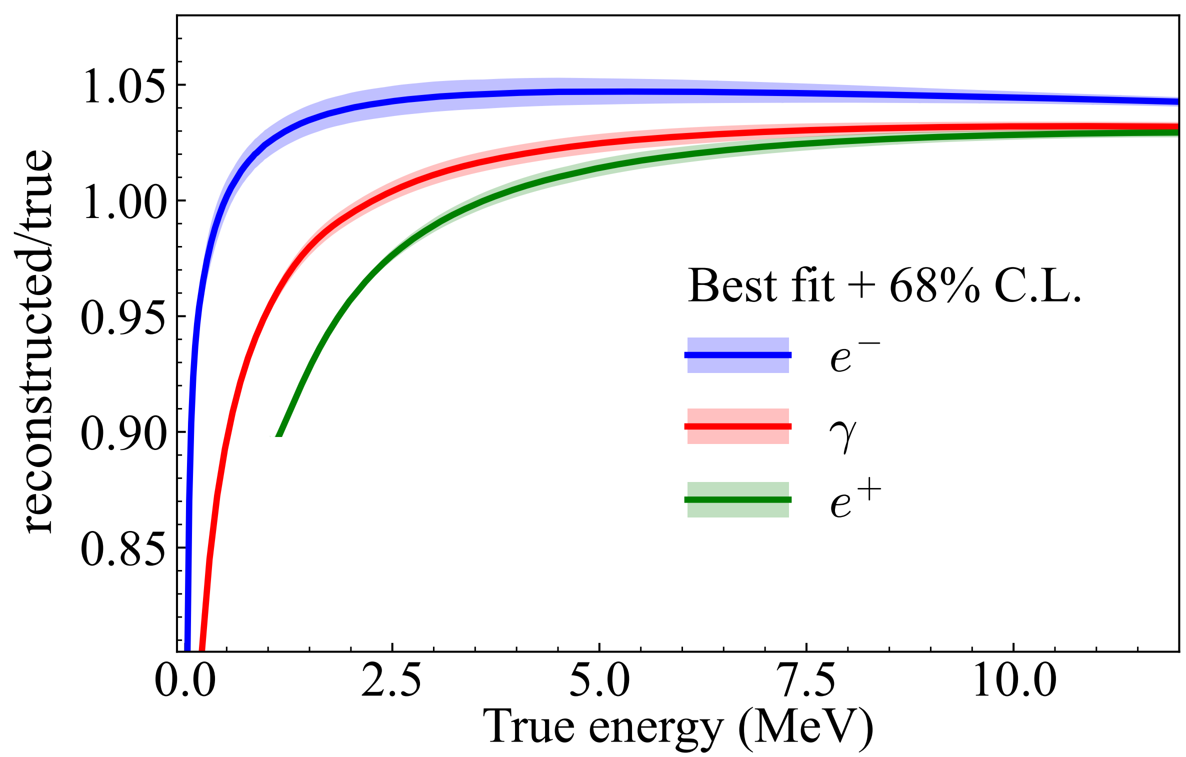
JUNO (2025)

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

- control over each particle is necessary to achieve precision

Energy reconstruction is key





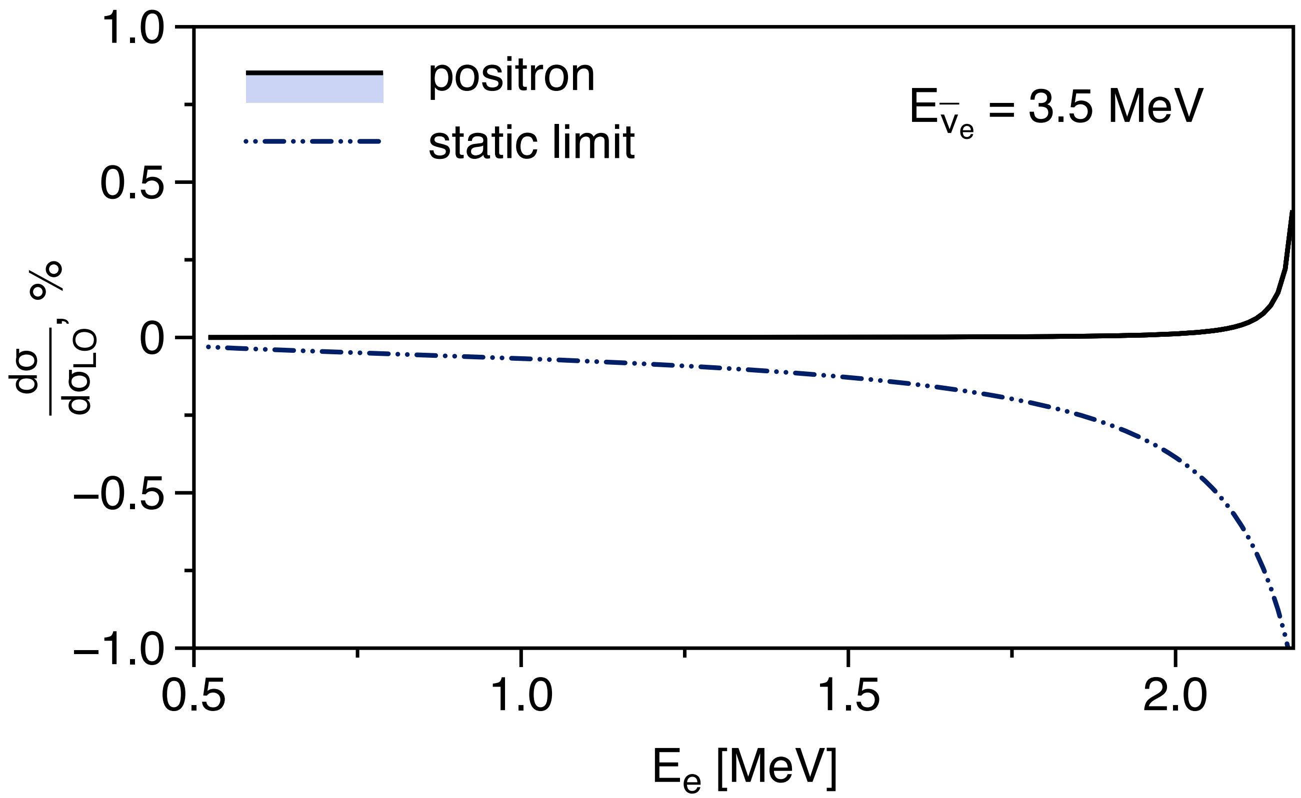
JUNO (2025)

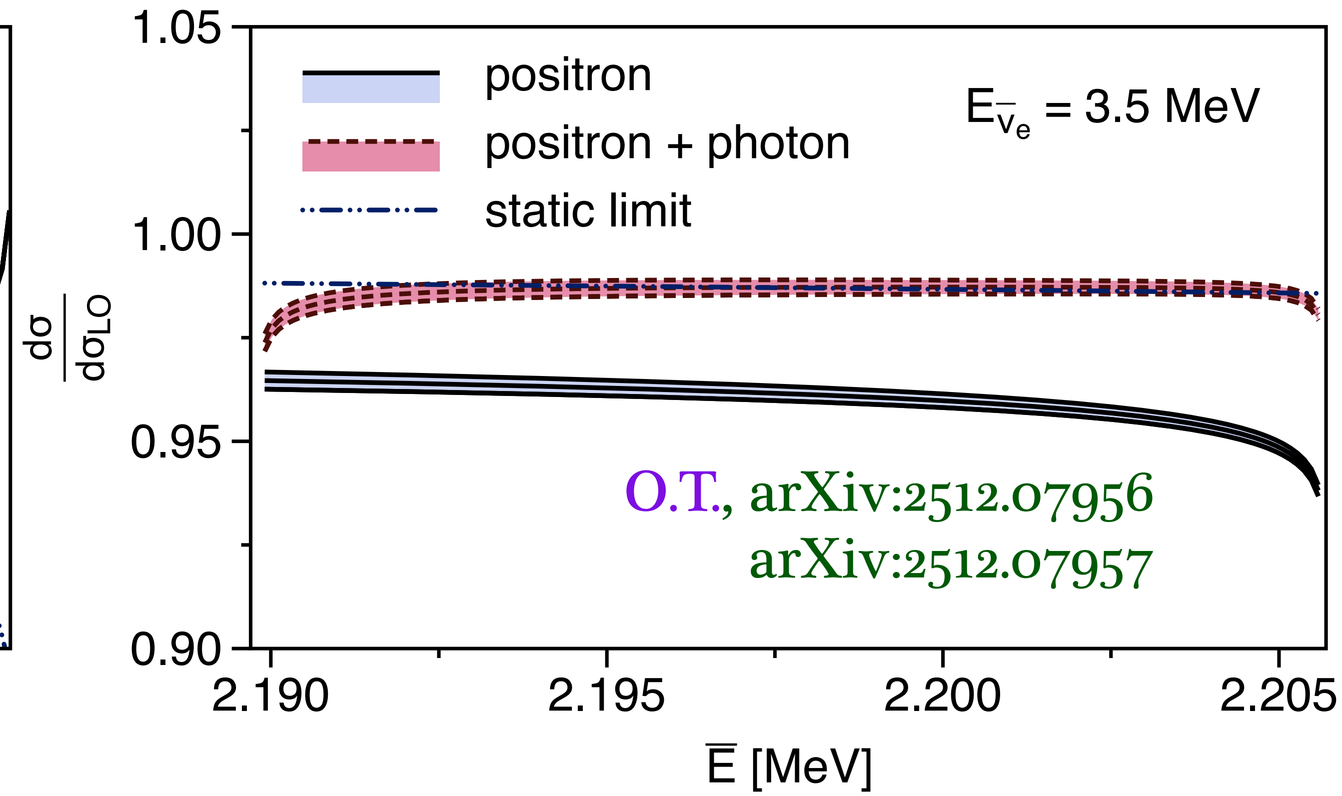
$$E_{\overline{\nu}_e} \approx m_n - m_p + E_{e^+} + E_\gamma + O\left(\frac{1}{M}\right)$$

- control over each particle is necessary to achieve precision

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

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

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

Hardy and Towner, PRC (2020)

changes by 1 uncertainty of radiative corrections

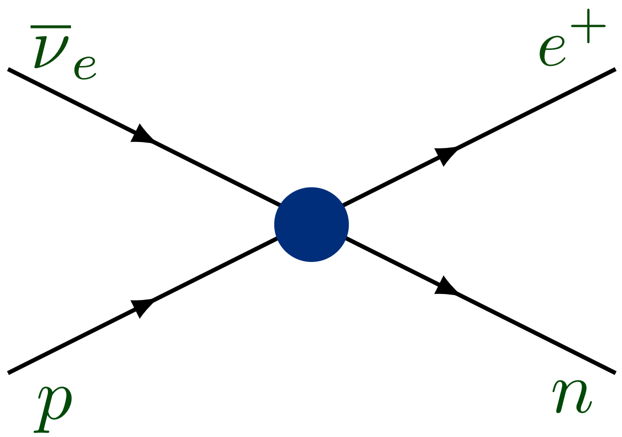
- g_A from beta asymmetry in polarized neutron decay

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

changes by 1/3 of PERKEO-III experimental uncertainty

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

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 !
- $1\sigma/0.3\sigma$ updates in V_{ud}/g_A from nuclear/neutron decay

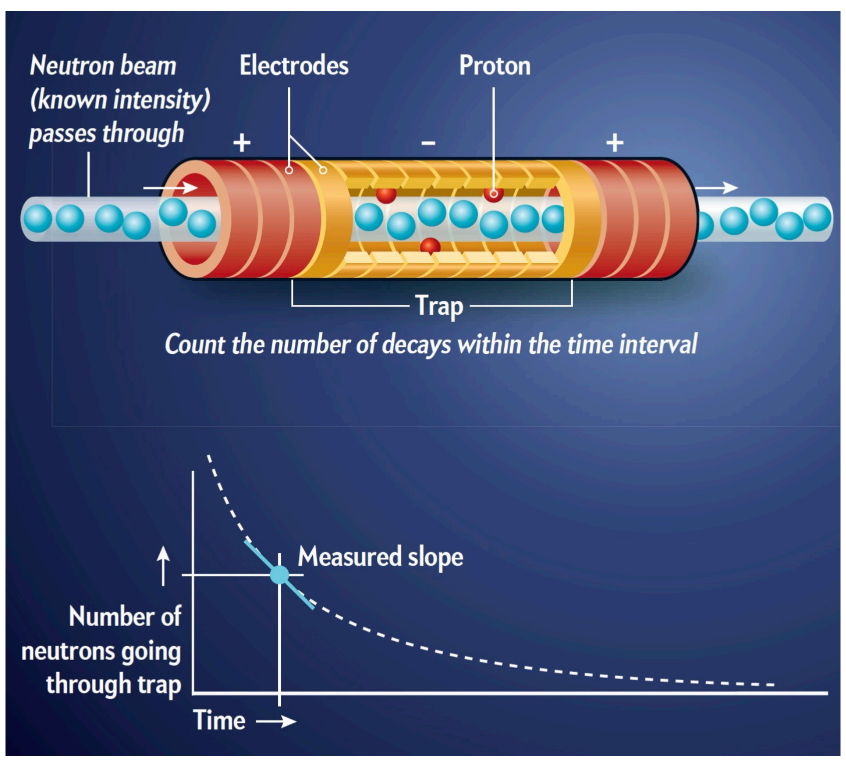
Thanks for your attention !!!

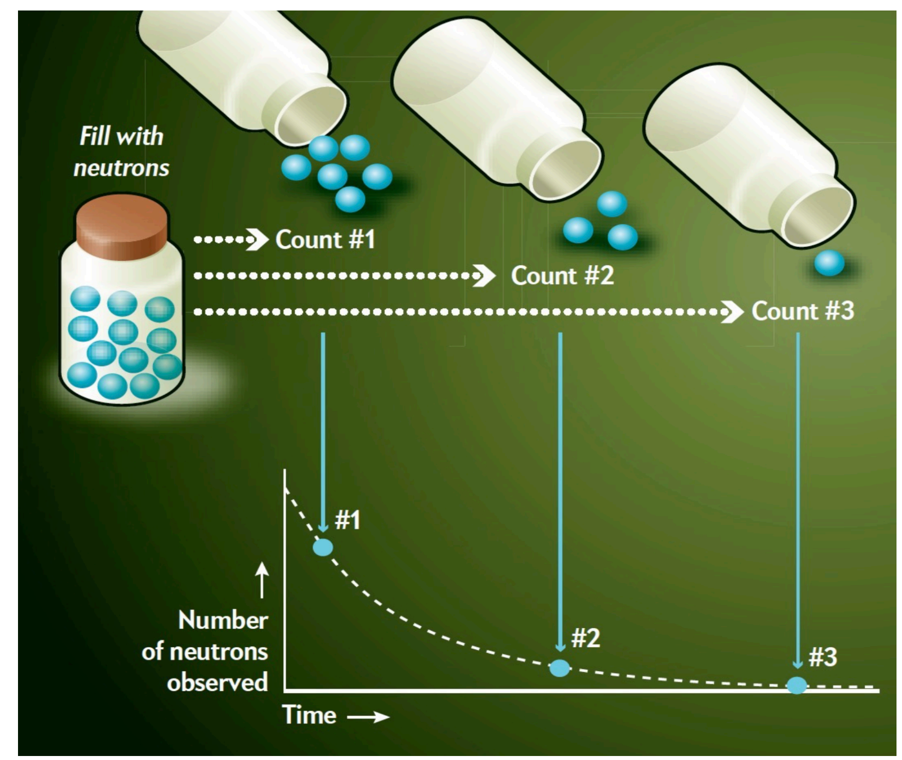
谢谢

Neutron lifetime measurements

beam method

bottle method



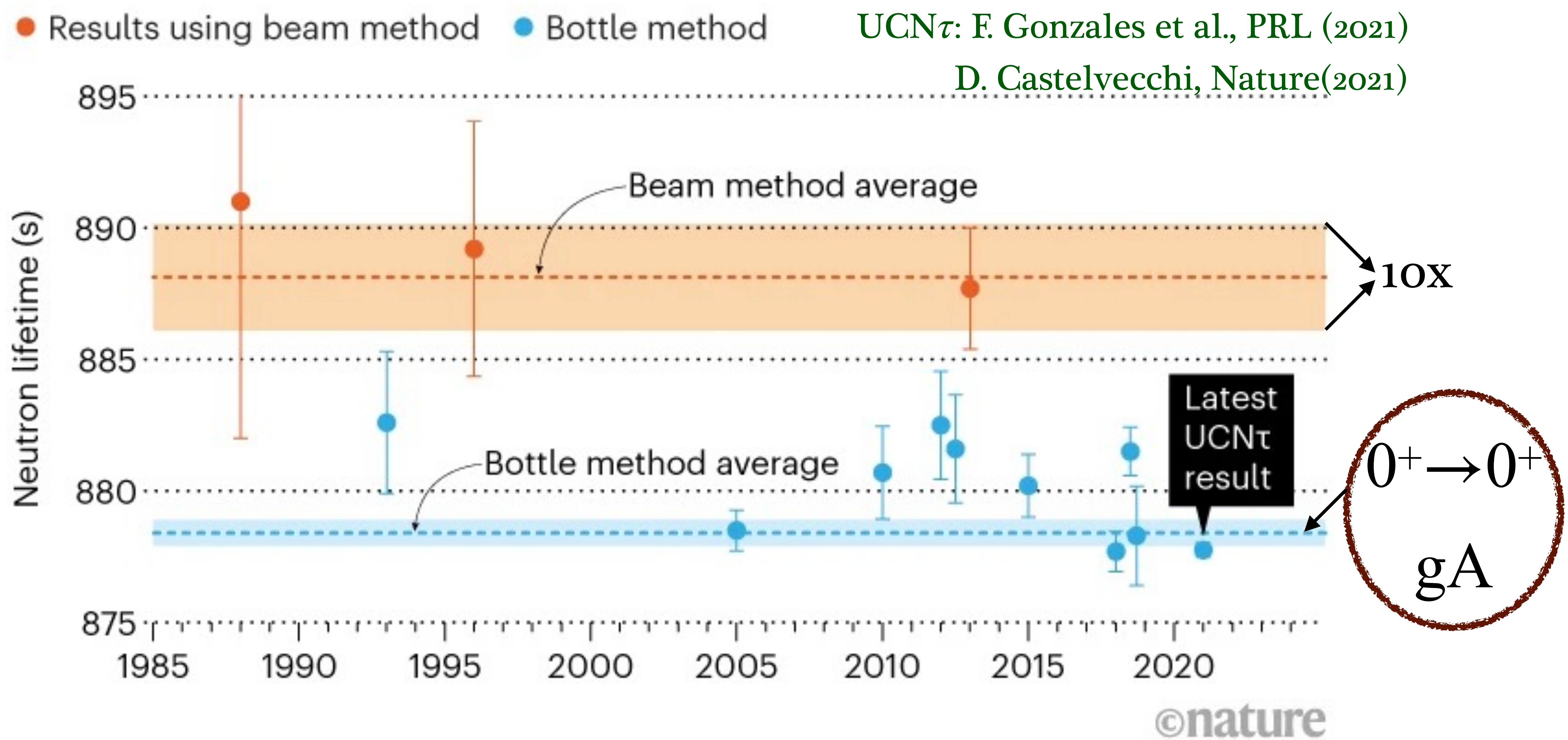


how many neutrons pass?

how many neutrons survive?

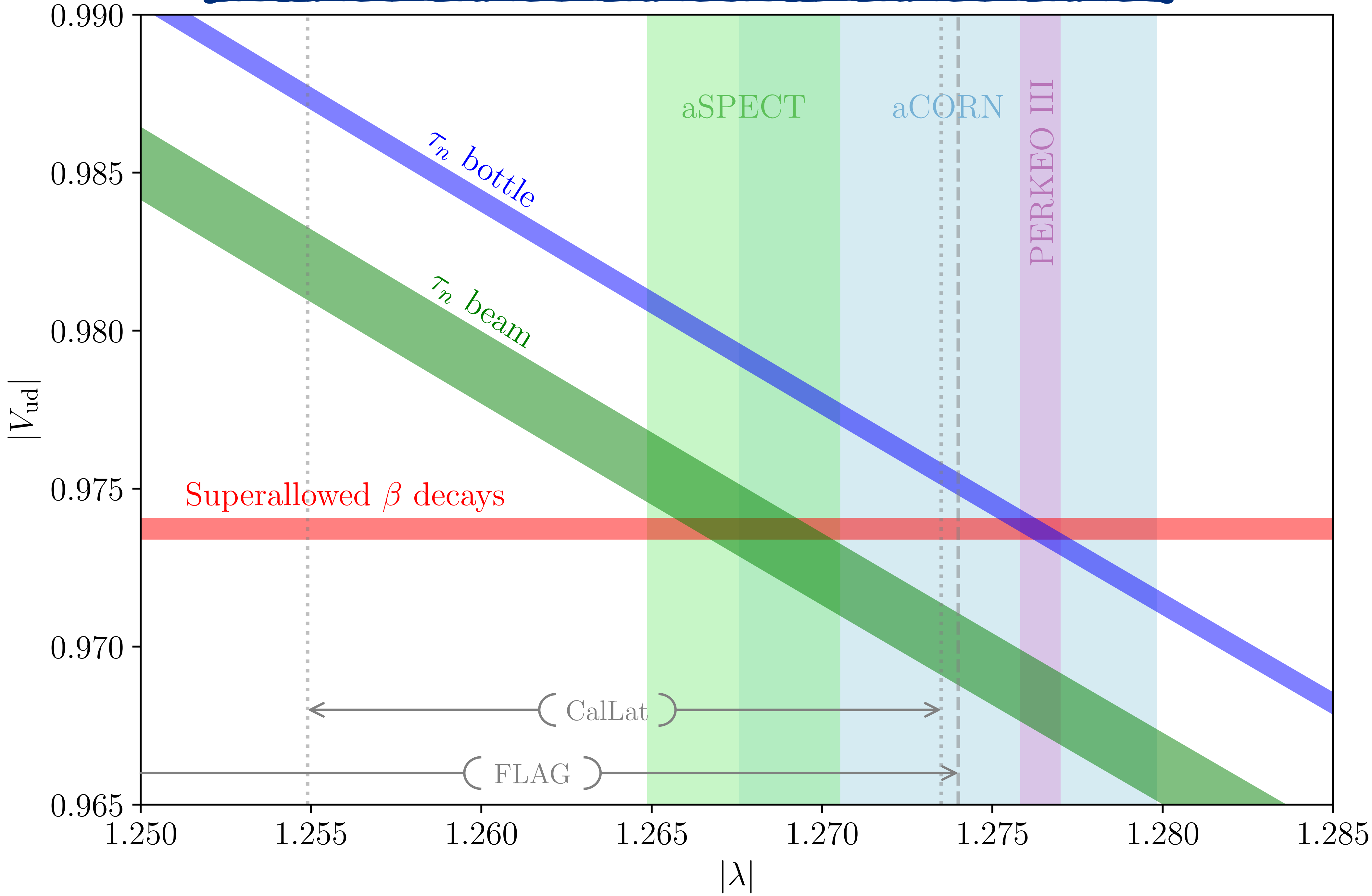
Neutron lifetime puzzle

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 : $(3-4)\times 10^{-4}$

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