

HETH-Forum

01 April, 2026

Institute of High Energy Physics

Chinese Academy of Sciences

Low-energy electroweak physics with neutrinos and nucleons



托马拉克

Sasha Tomalak

PMNS oscillation matrix

neutrinos produced and detected in flavor basis

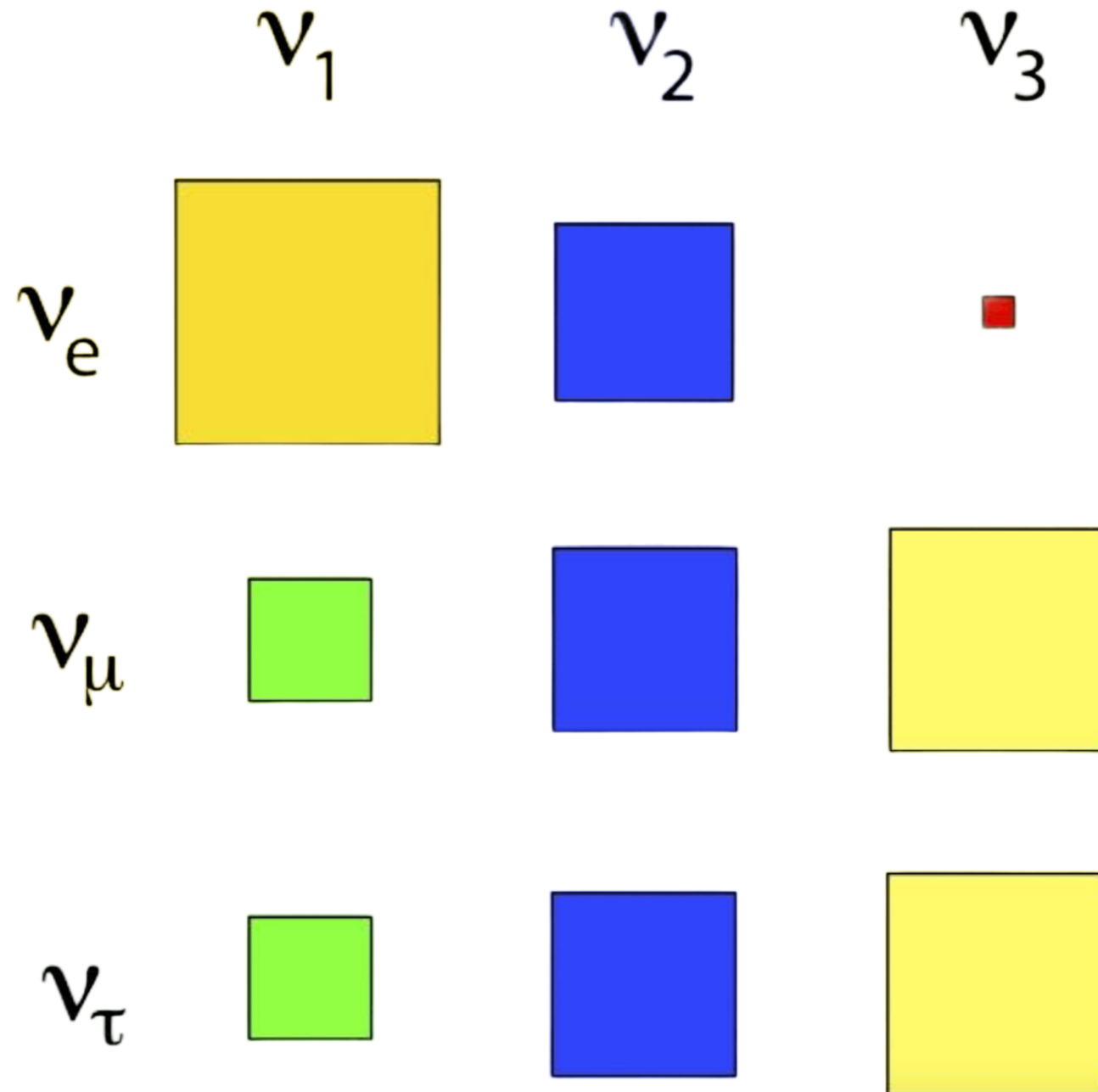
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{bmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

neutrinos propagate in mass basis

Pontecorvo-Maki-Nakagawa-Sakata matrix relates two bases

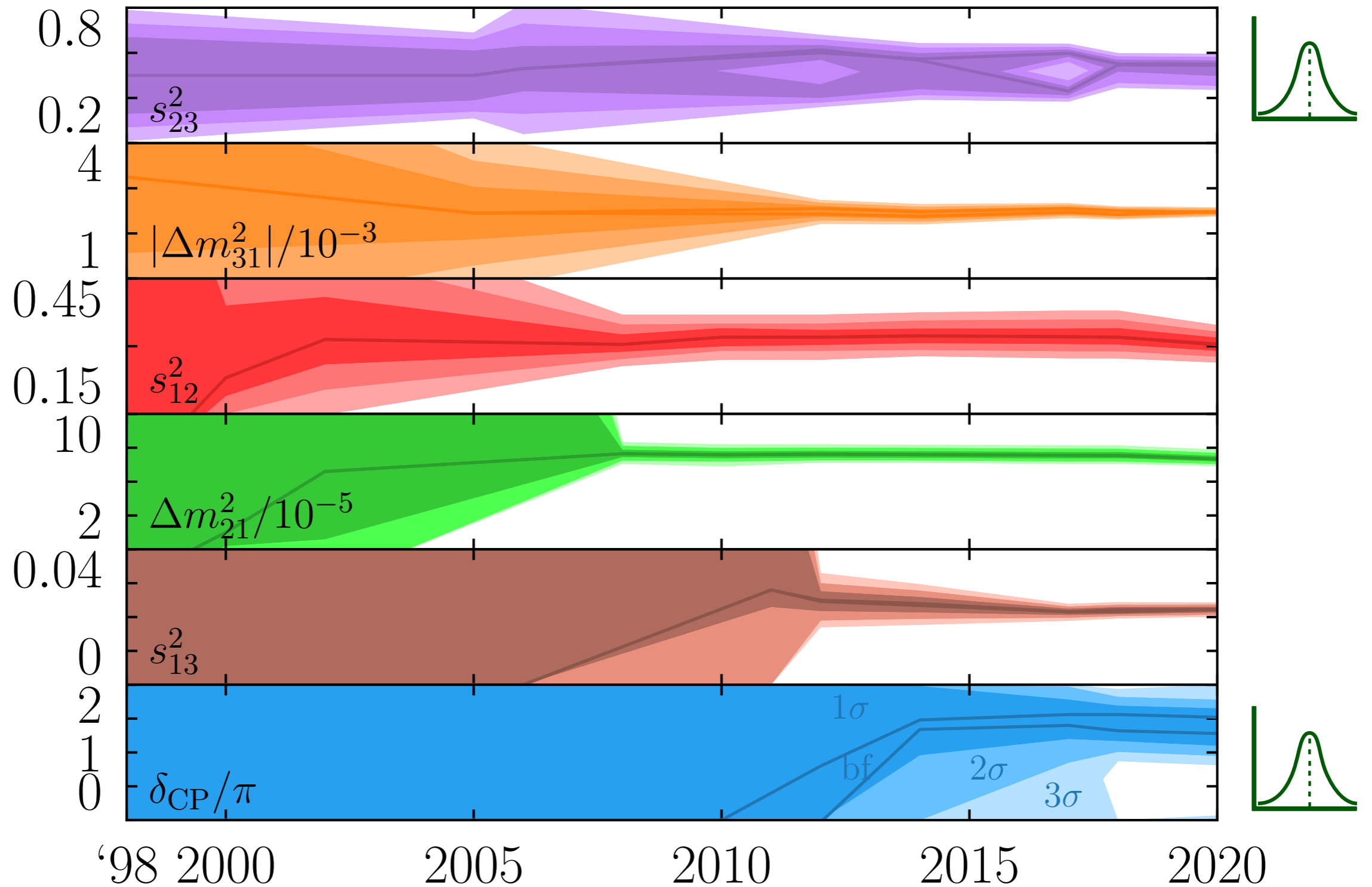
- oscillations are described by **PMNS** mixing matrix

PMNS oscillation matrix



- off-diagonal component of PMNS large besides U_{e3}

PMNS oscillation matrix

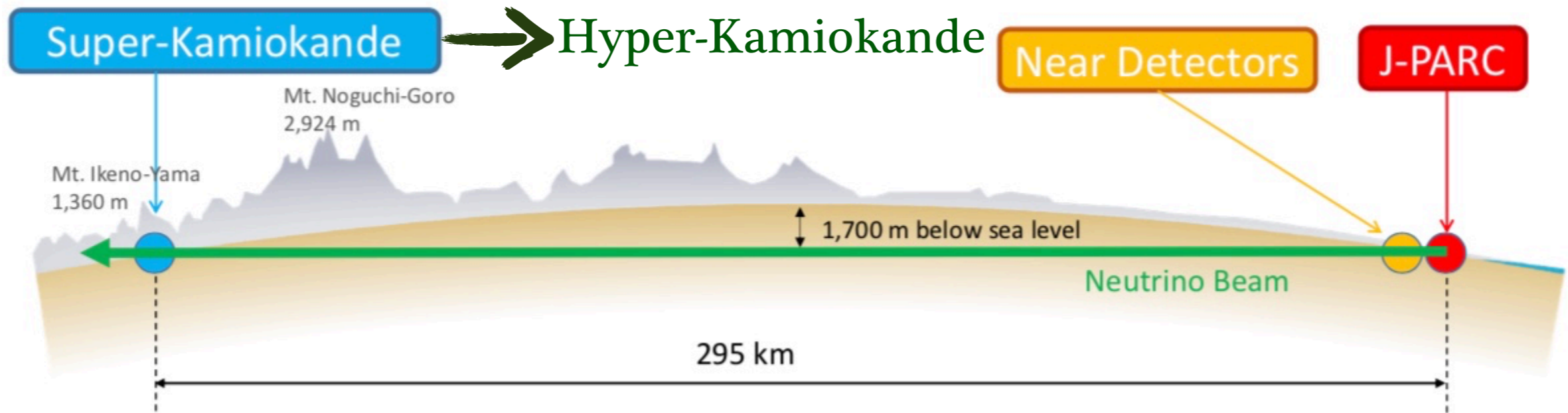


- tremendous progress in our lifetime

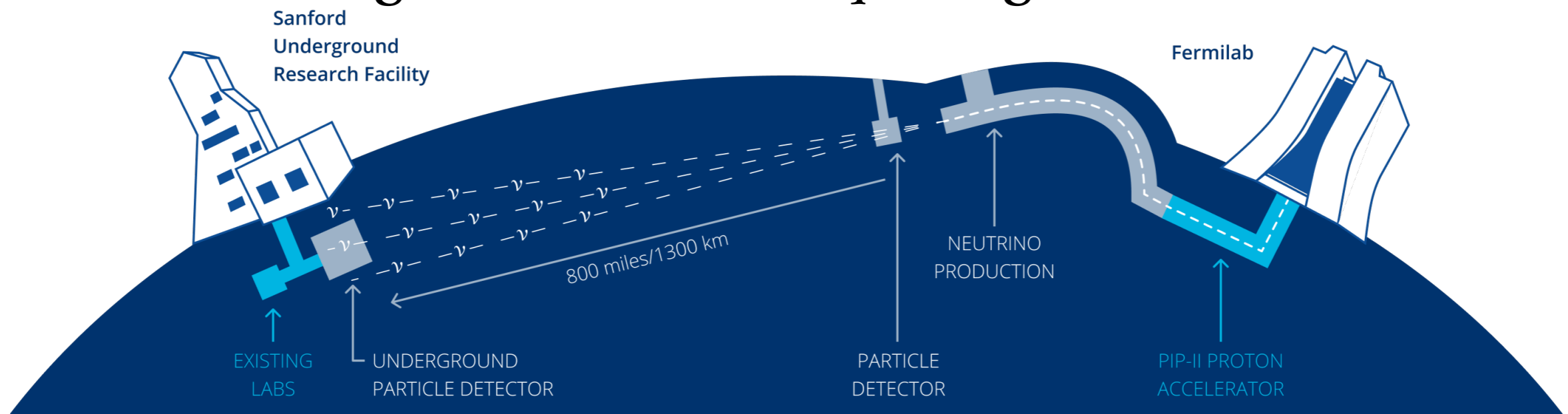
Snowmass 2021 NFO1 group report

CP violation and mass hierarchy@laboratory

650 m under rocks in mountain, 260000t of pure water



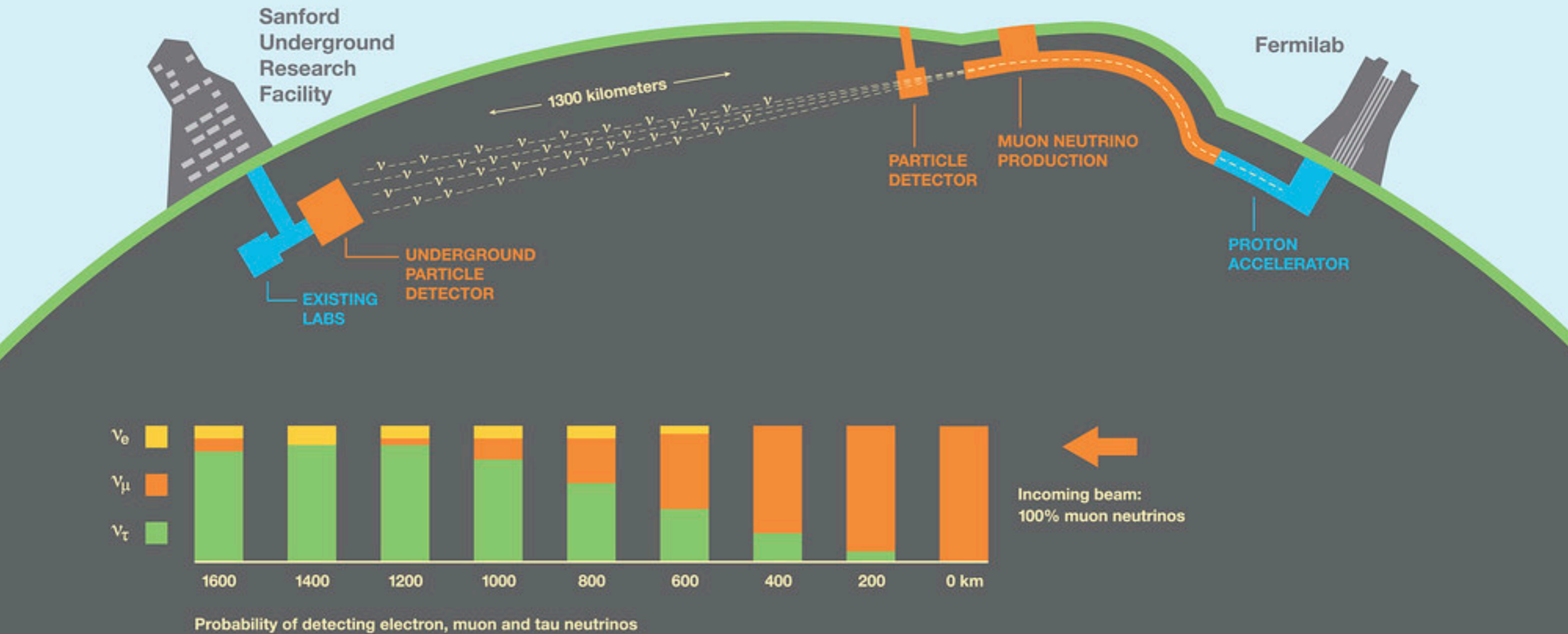
1.5 km underground, 70000t of liquid argon



- CP violation in PMNS and mass hierarchy in next 10-20 years !!!

Neutrino experiments

Deep Underground Neutrino Experiment

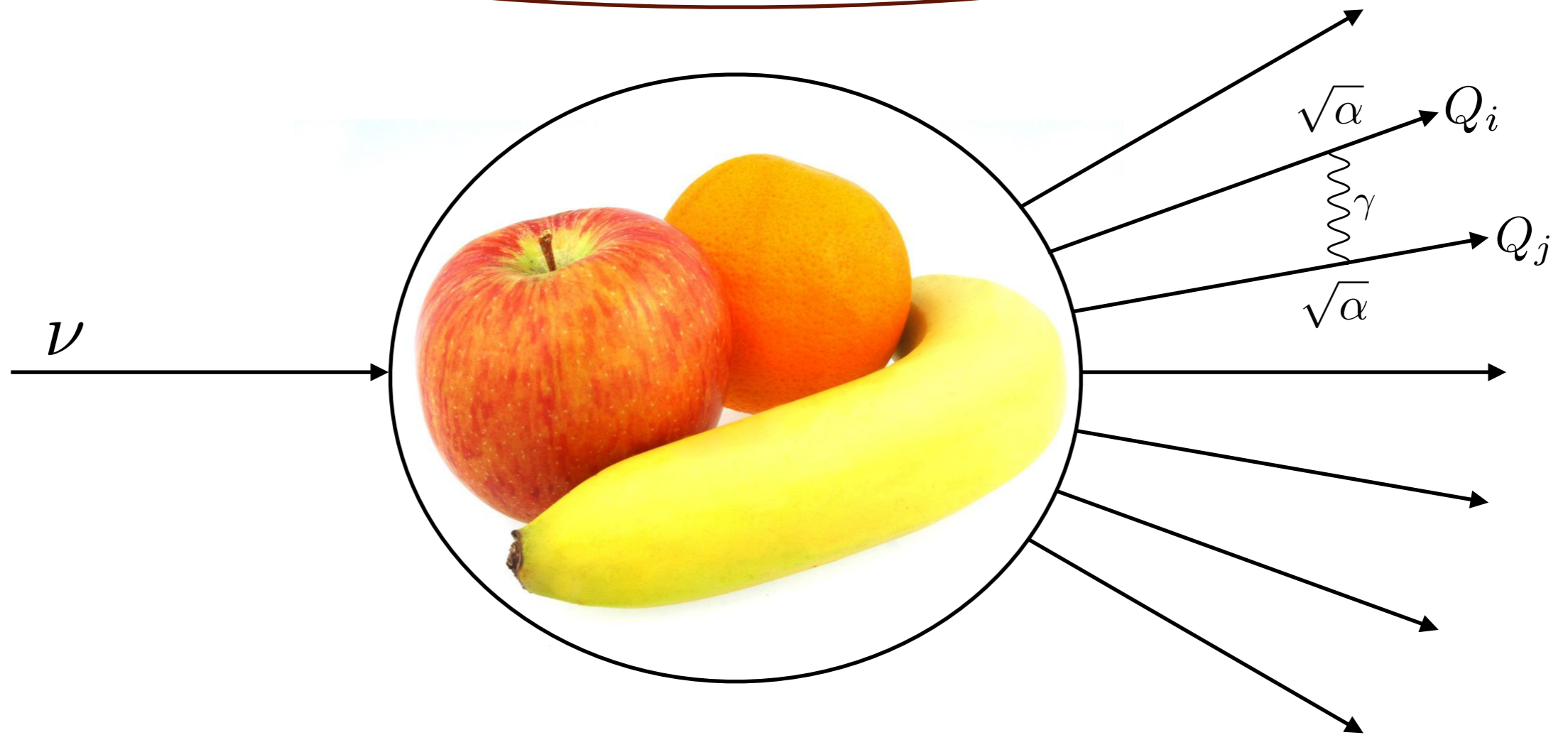


$$N_\nu \sim \int dE_\nu \Phi_\nu (E_\nu) \times \sigma (E_\nu) \times R (E_\nu, E_\nu^{\text{rec}})$$

- near detector: determine flux and cross sections

Electroweak corrections

$$m_e, m_\mu, M, E_\nu \ll M_W, M_Z, m_t, m_H$$



$$\frac{\alpha}{\pi} \sim 0.2 \% \text{ multiplied by } \frac{1}{\sin^2 \theta_W}, \ln \frac{M_Z}{M}, \ln \frac{M_t}{M}, \dots$$

- electroweak corrections can be included in low-energy interactions

couplings of **effective Lagrangian** are precisely determined

$$\mathcal{L}_{\text{eff}}^{\text{NC}} = -\bar{\nu}_l \gamma_\mu P_L \nu_l \cdot \bar{f} \gamma^\mu (c_L^{\nu_l f} P_L + c_R^{\nu_l f} P_R) f$$

$$\mathcal{L}_{\text{eff}}^{\text{CC}} = -2\sqrt{2}G_F \sum_{l \neq l'} \bar{\nu}_{l'} \gamma^\mu P_L \nu_l \bar{l} \gamma_\mu P_L l' - c^{qq'} \sum_{q \neq q'} \bar{l} \gamma^\mu P_L \nu_l \bar{q} \gamma_\mu P_L q'$$

Neutrino-lepton, neutrino-quark scattering

O.T. and Richard J Hill, PLB (2020)

known at permille level

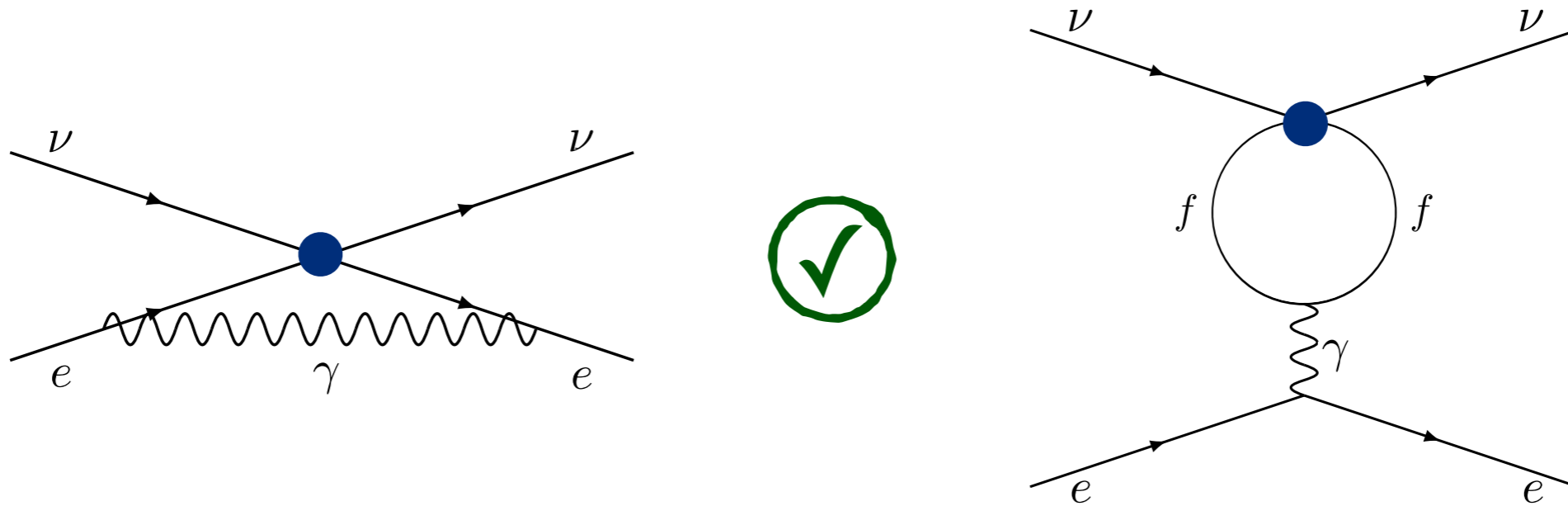


leading in G_F terms with loop expansion in α, α_s within Standard Model

poster at Neutrino 2020:

<https://youtu.be/mrW4aYjP57w>

Leptonic probes: “Standard Candles” for flux constraints

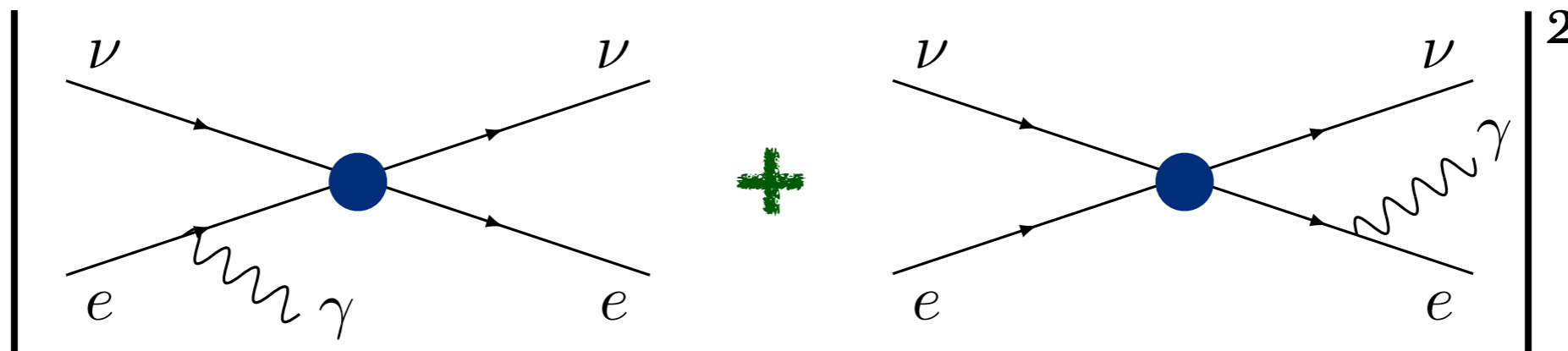


Neutrino-electron scattering

O.T. and Richard J Hill, PRD (2020)

percent-level predictions for MINERvA

known analytically at permille level for NOvA and DUNE, solar ν @JUNO



O.T., Kaushik Borah, Richard J. Hill, Kevin S. McFarland, Daniel Ruterbories, PRD (2023)

Leptonic probes: “Standard Candles” for flux constraints

process of interest at **IHEP**

V. Brdar and X.J. Xu, PLB (2023)

V. Brdar, L.J. Ferreira Leite, G.A. Parker, and X.J. Xu, PRD (2024)

J. Huang and Sh. Zhou, PRD (2025)

J. Huang, T. Ohlsson, S. Vihonen, and Sh. Zhou, PRD (2025)

L.A. Delgadillo, Q. Liu, R. Singh, arXiv:2603.20061

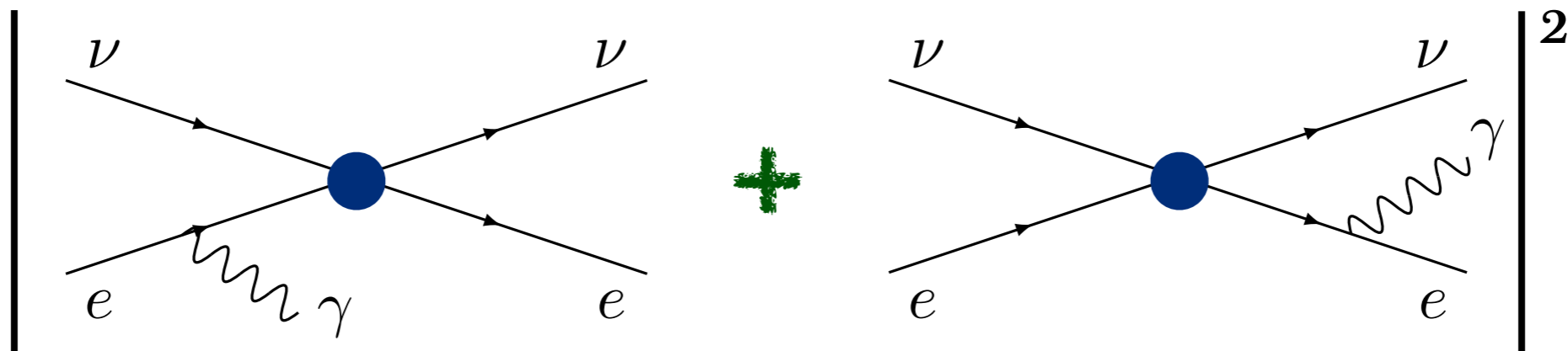
G.-E. Cao, X. Chen, L.A. Delgadillo, M. Gonchar, Y.-F. Li, and V. Zavadskyi, arXiv:2603.20061

Neutrino-electron scattering

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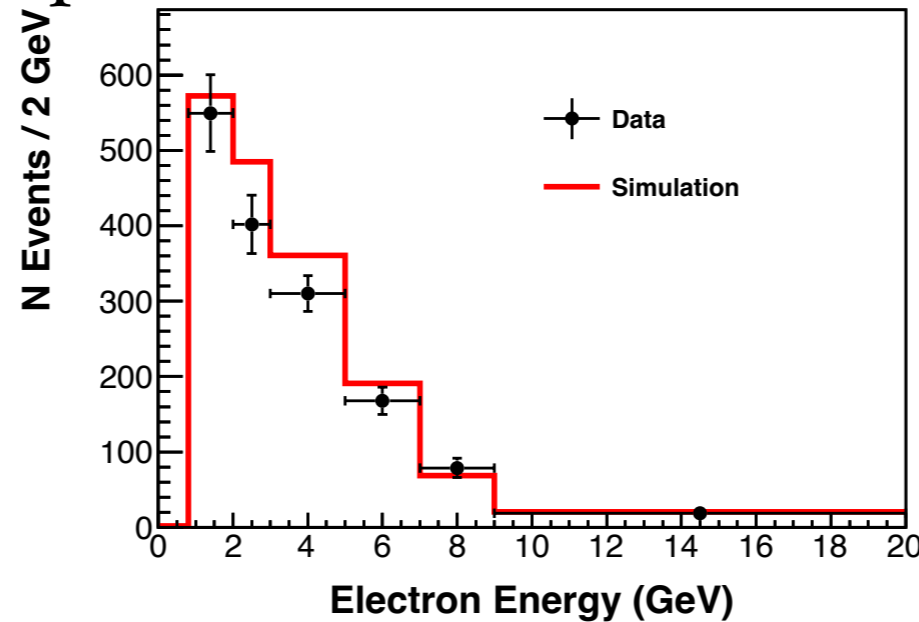


O.T., Kaushik Borah, Richard J. Hill, Kevin S. McFarland, Daniel Ruterbories, PRD (2023)

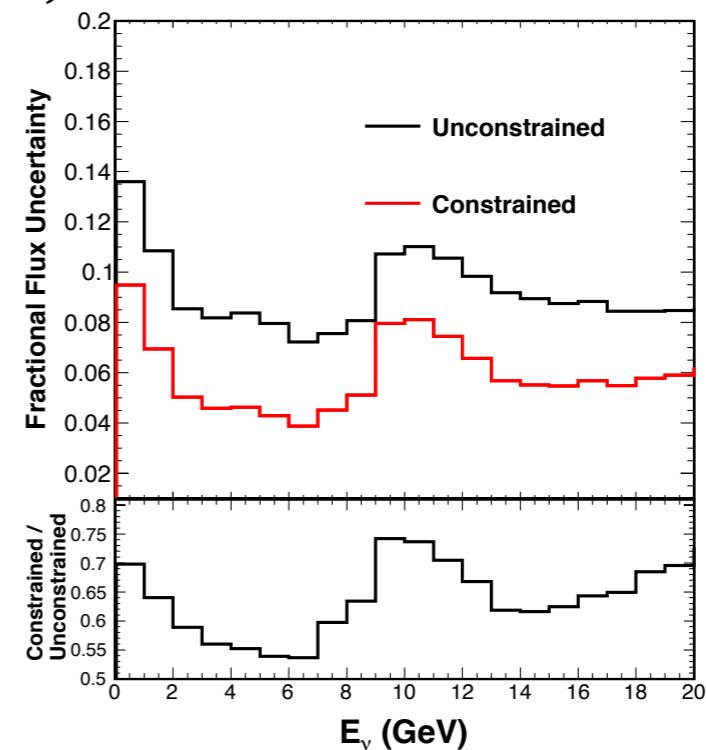
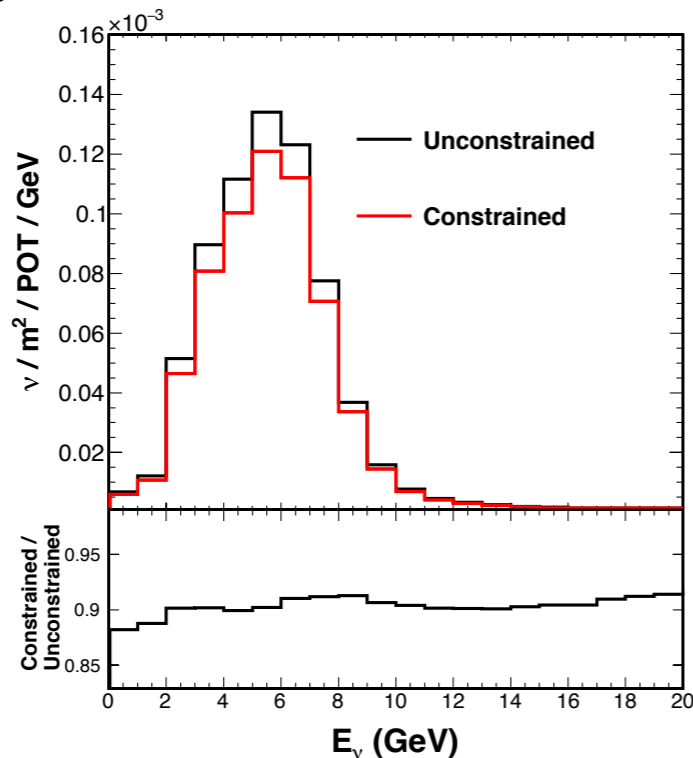
MINERvA constraint

- electron energy spectrum:

MINERvA, PRD (2019)



- 10% correction on flux normalization, reduced error

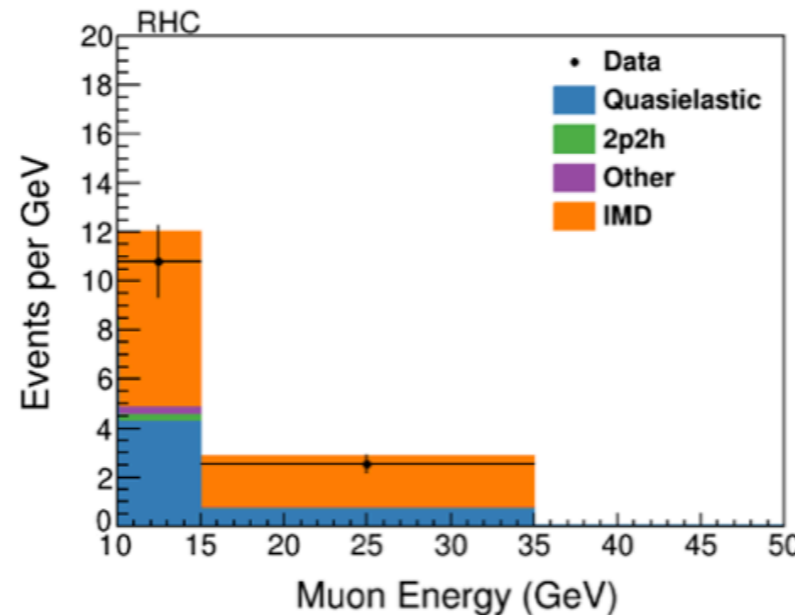
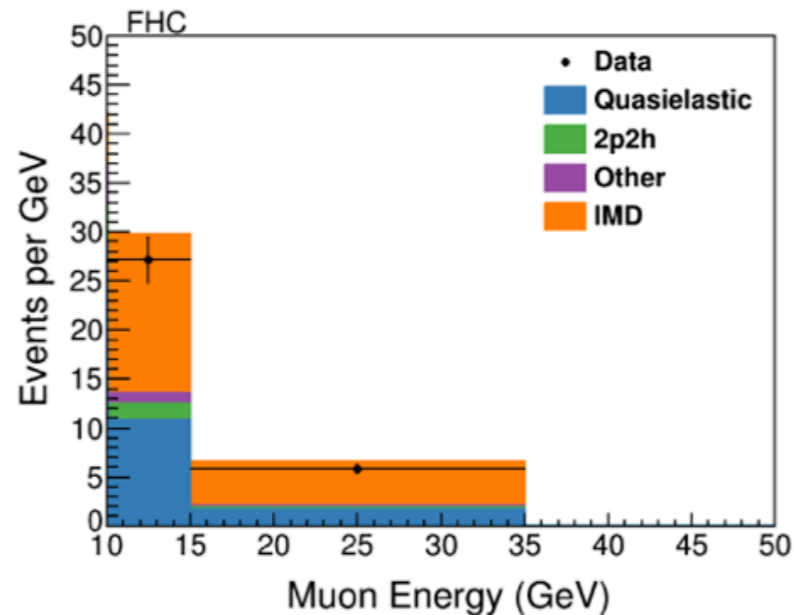


- successful implementation by MINERvA collaboration

MINERvA constraint by inverse muon decay

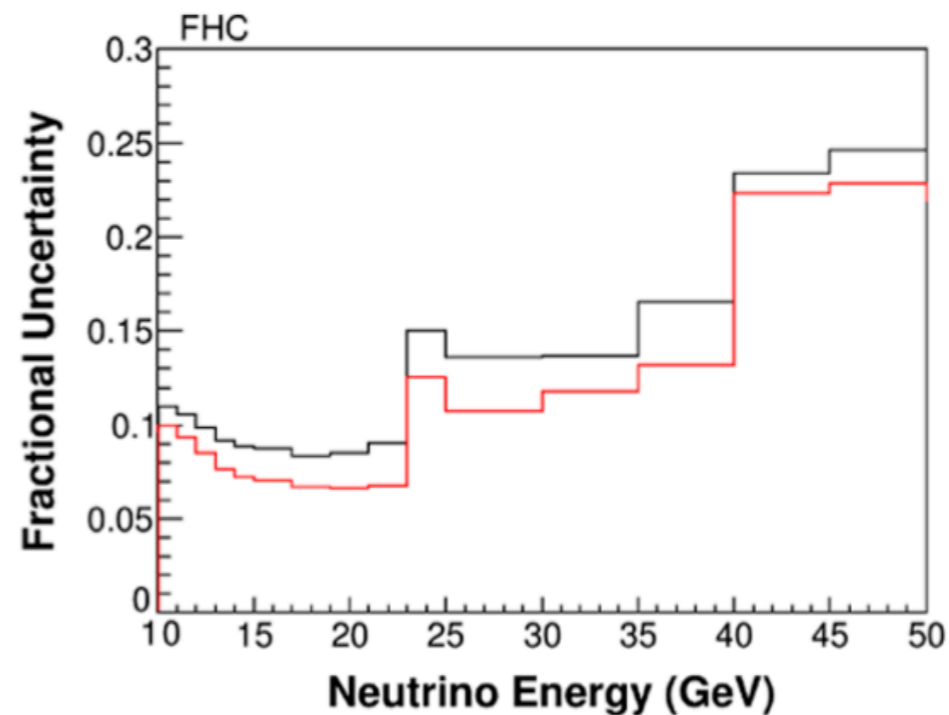
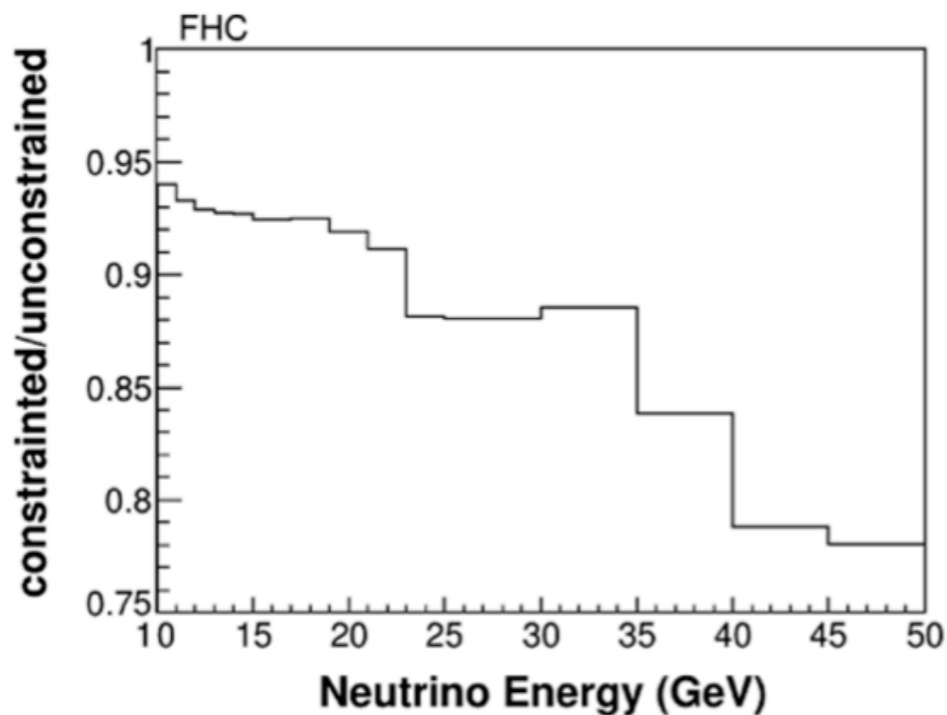
MINERvA, PRD (2021)

- muon energy spectrum:



$$E_{\nu}^{\text{thr}} \gtrsim 10.9 \text{ GeV}$$

- 10-20% correction on flux normalization, reduced error



- successful implementation by MINERvA collaboration

Light-quark contribution

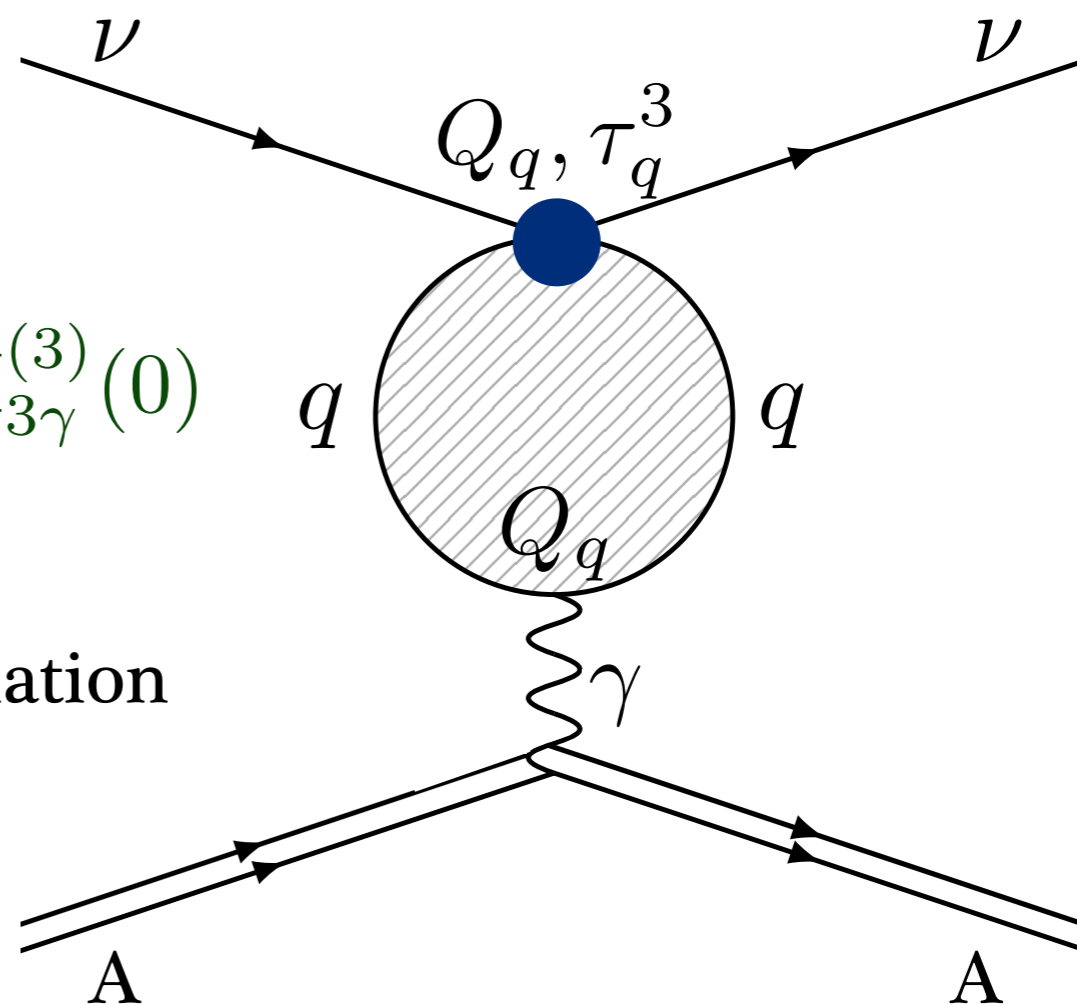
- description in terms of quarks is invalid

$$Q^2 \ll \Lambda_{\text{QCD}}^2$$

O.T. and Richard J Hill, PLB (2020)

- light quarks

$$\delta^{\text{QCD}} = 4\Pi_{\gamma\gamma}^{(3)}(0) \sin^2 \theta_W - 2\Pi_{3\gamma}^{(3)}(0)$$



- SU(3) chiral symmetry approximation

- flavor independent

O.T., Pedro Machado, Vishvas Pandey, and Ryan Plestid, JHEP (2021)

- non-perturbative light-quark contribution: error at low energy

Light-quark contribution

- charge-charge $\Pi_{\gamma\gamma}$ and charge-isospin $\Pi_{3\gamma}$ correlators:

$$(q^\mu q^\nu - q^2 g^{\mu\nu}) \Pi_{\gamma\gamma}(q^2) = 4i\pi^2 \int d^d x e^{iq \cdot x} \langle 0 | T [J_\gamma^\mu(x) J_\gamma^\nu(0)] | 0 \rangle$$

$$(q^\mu q^\nu - q^2 g^{\mu\nu}) \Pi_{3\gamma}(q^2) = 4i\pi^2 \int d^d x e^{iq \cdot x} \langle 0 | T [J_3^\mu(x) J_\gamma^\nu(0)] | 0 \rangle$$

- **spurion** technique in ChPT

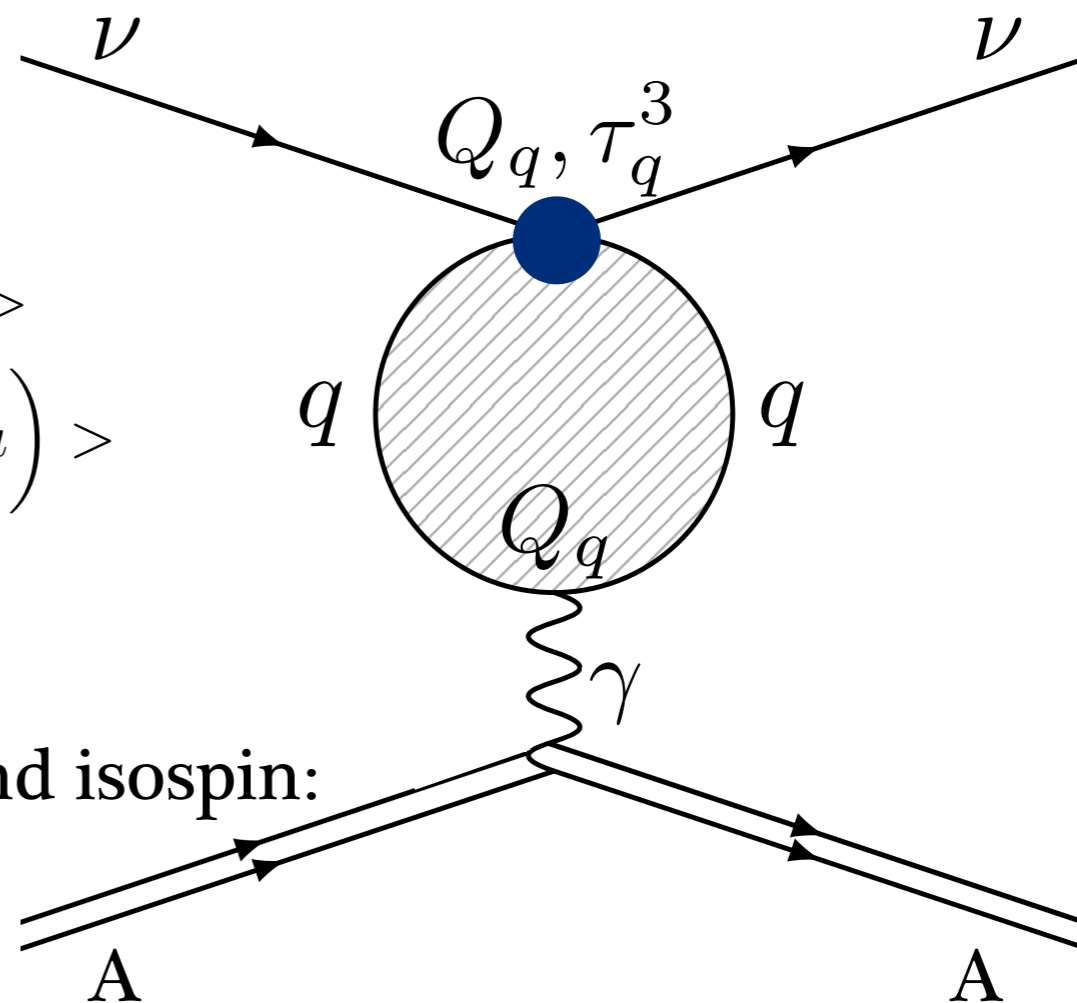
$$J_\gamma \sim \langle (u^\dagger \partial_\mu u - u \partial_\mu u^\dagger) (u Q u^\dagger - u^\dagger Q u) \rangle$$

$$J_3 \sim \langle (u^\dagger \partial_\mu u - u \partial_\mu u^\dagger) \left(u \frac{\tau^3}{2} u^\dagger - u^\dagger \frac{\tau^3}{2} u \right) \rangle$$

chiral field u

- **SU(2)** relation between charge and isospin:

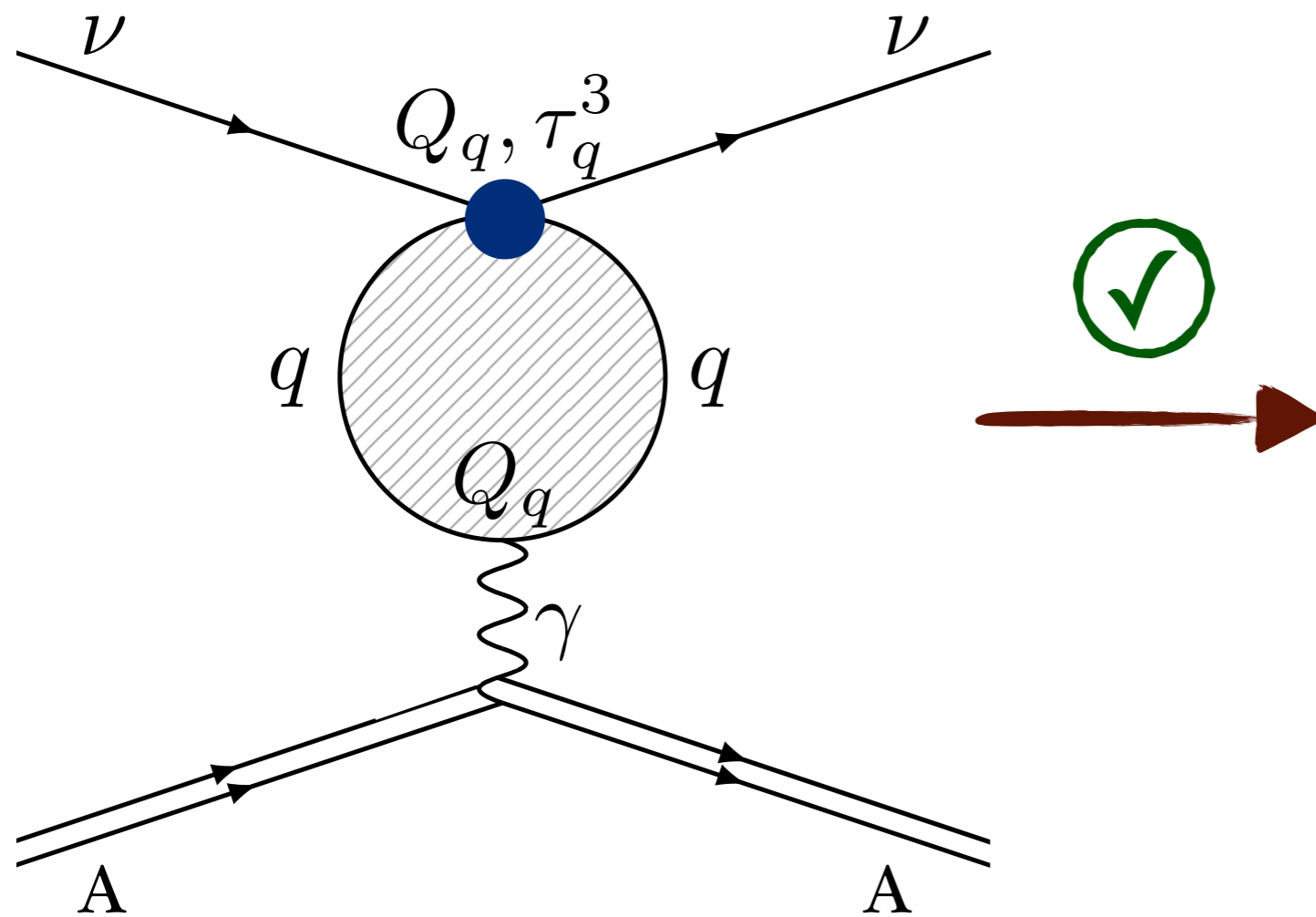
$$Q = \frac{1}{2} + \frac{\tau^3}{2}$$



O.T., PLB (2026)

- exact relation within validity of ChPT: $\Pi_{\gamma\gamma} = \Pi_{3\gamma}$

Light-quark contribution



first ChPT analysis
of charge-isospin correlator

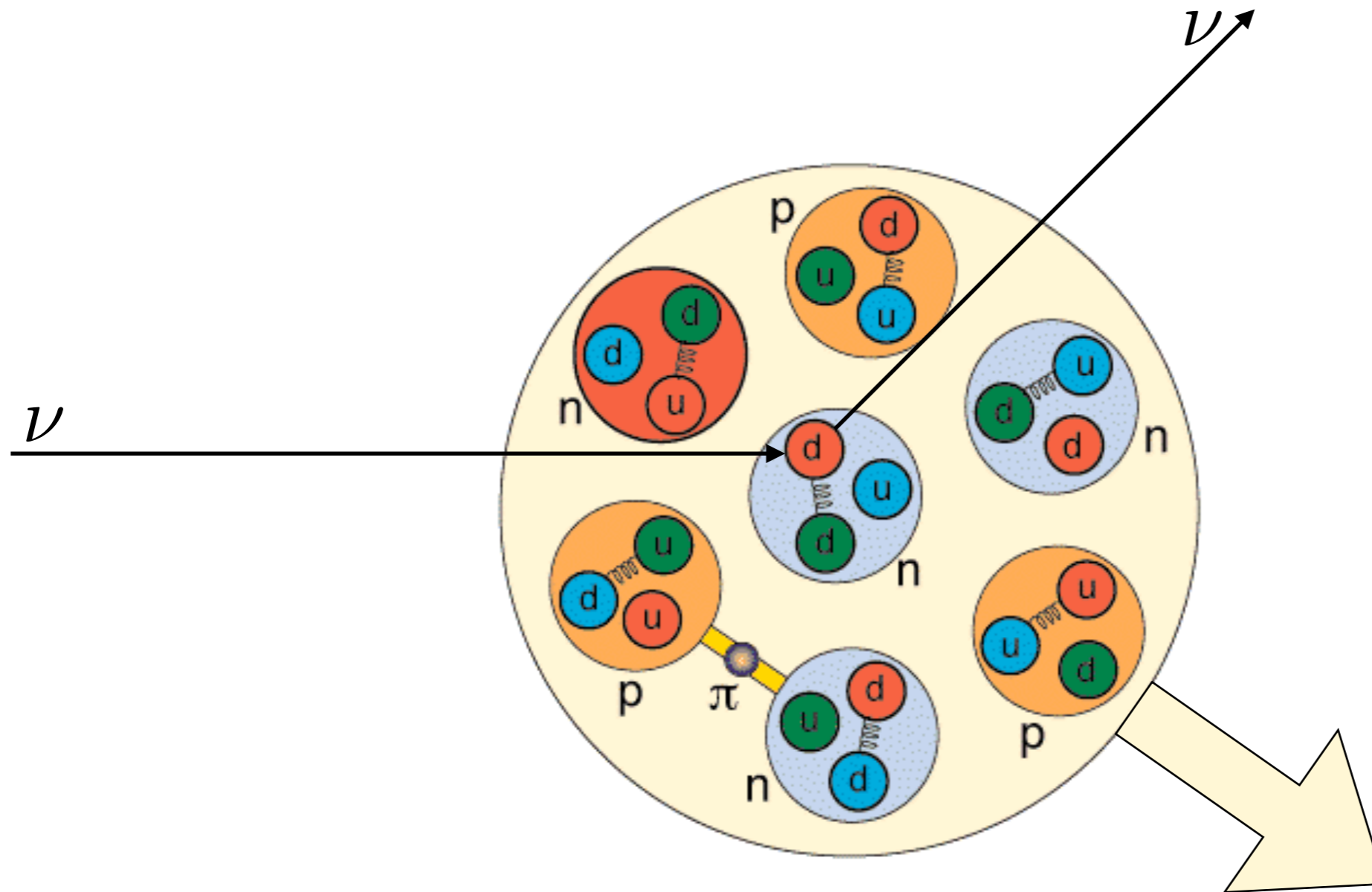


neutral currents

reduction of uncertainty
by a factor ~ 35

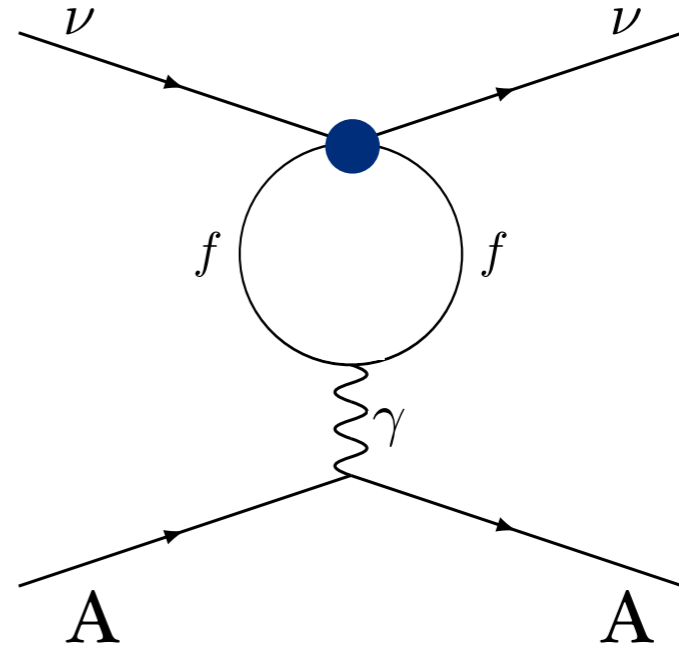
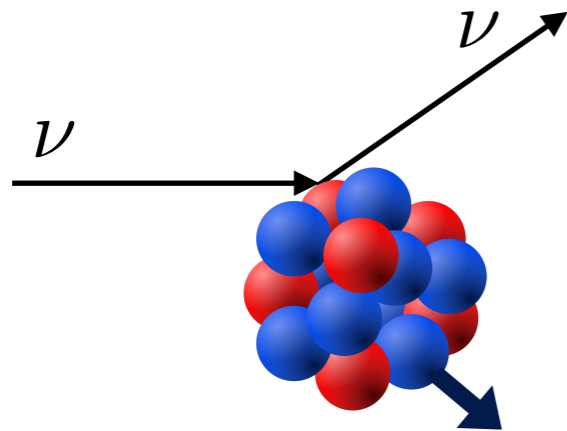
O.T., PLB (2026)

From quarks to nuclei



fafnir.phyast.pitt.edu

- scattering on quarks in nucleons in nucleus



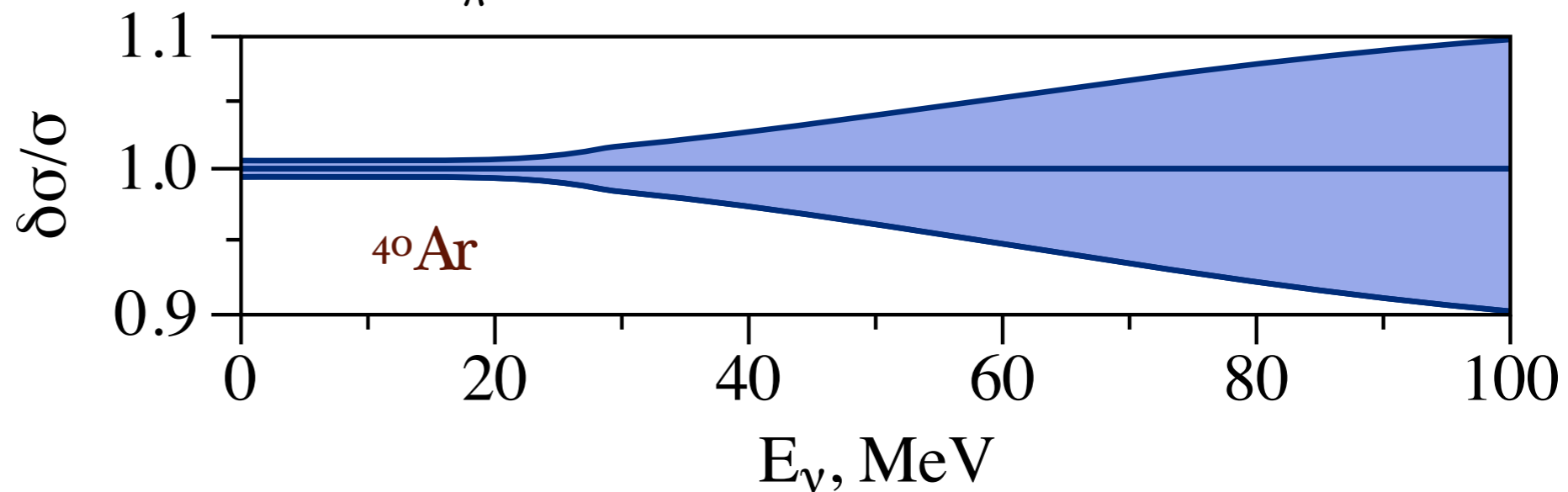
Coherent elastic neutrino-nucleus scattering

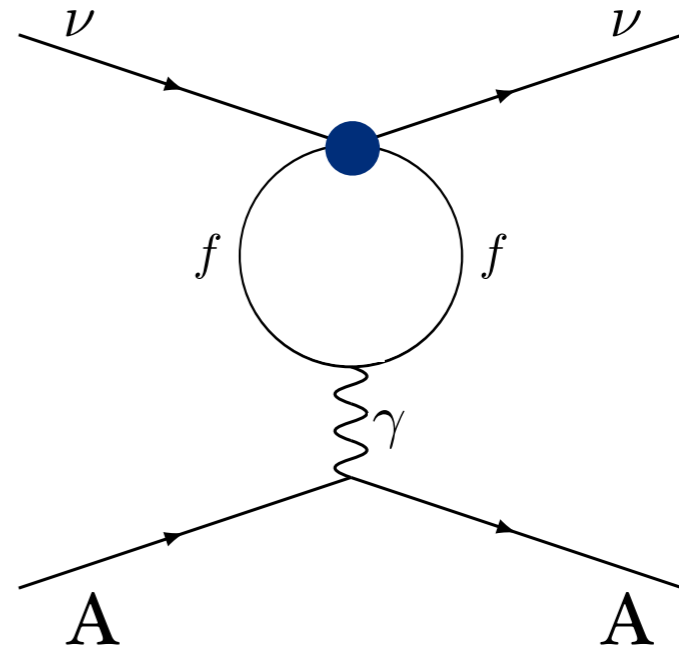
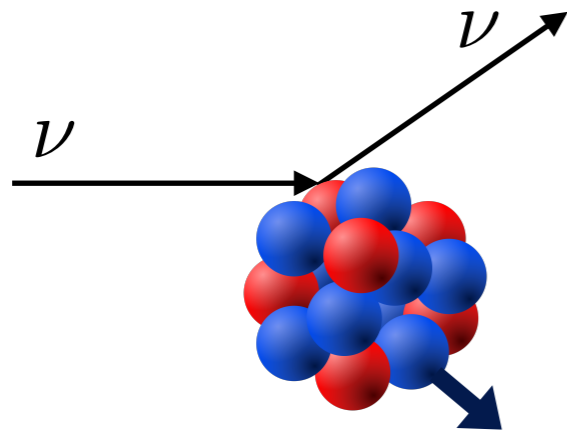
O.T., Pedro Machado, Vishvas Pandey and Ryan Plestid, JHEP (2021)

$$F_W(Q^2) \rightarrow F_W(Q^2) + \frac{\alpha}{\pi} [\delta^{\nu e} + \delta^{\text{QCD}}] F_{\text{ch}}(Q^2)$$

flavor-dependent
at percent level

for Coherent and CCM





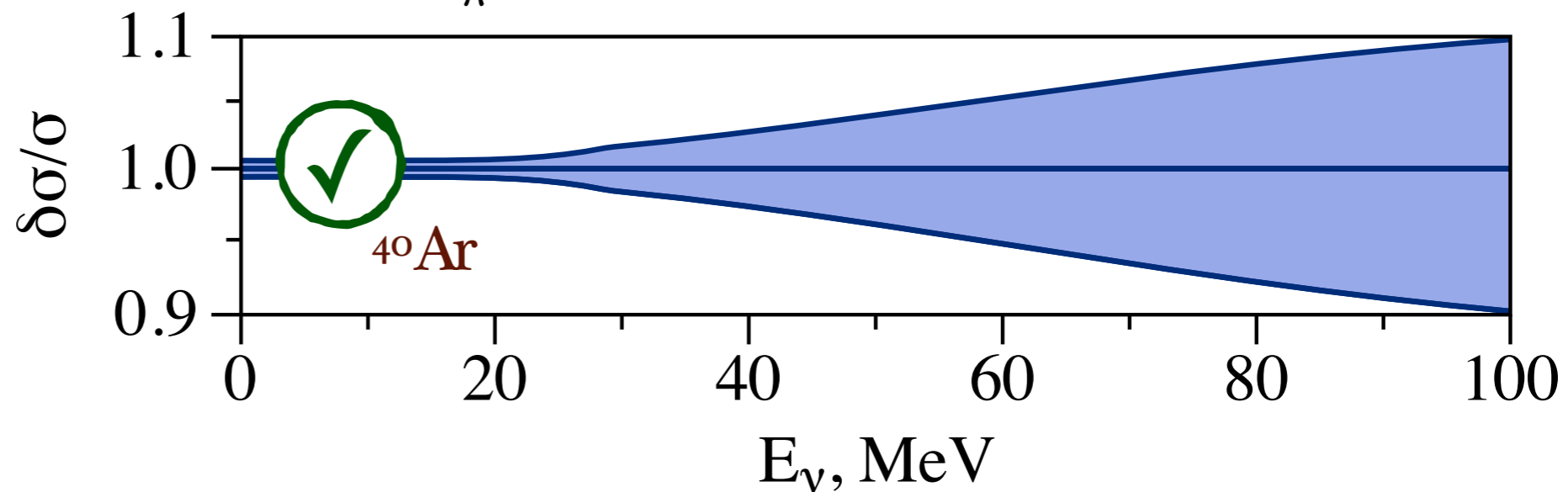
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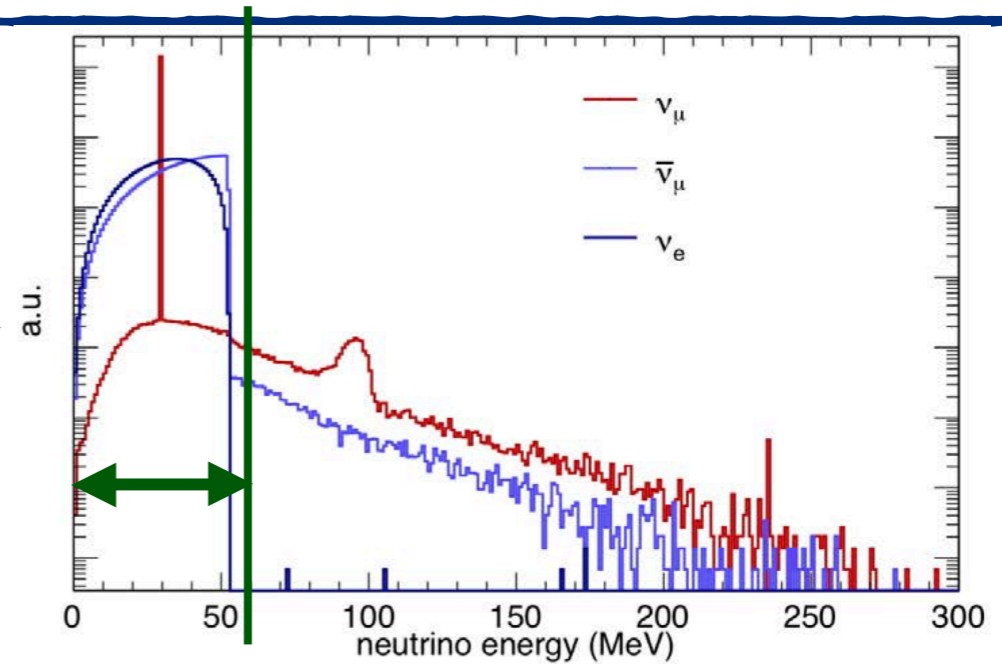


flavor-dependence at tree-level

energy spectra from π DAR \rightarrow

$$\pi^+ \rightarrow \mu^+ \nu_\mu$$

$$\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$$



Akimov et al., Science (2017)

Neutrinos from muon, pion and kaon decays

O.T., PLB (2022)

$$\pi^+ \rightarrow \mu^+ \nu_\mu \gamma$$

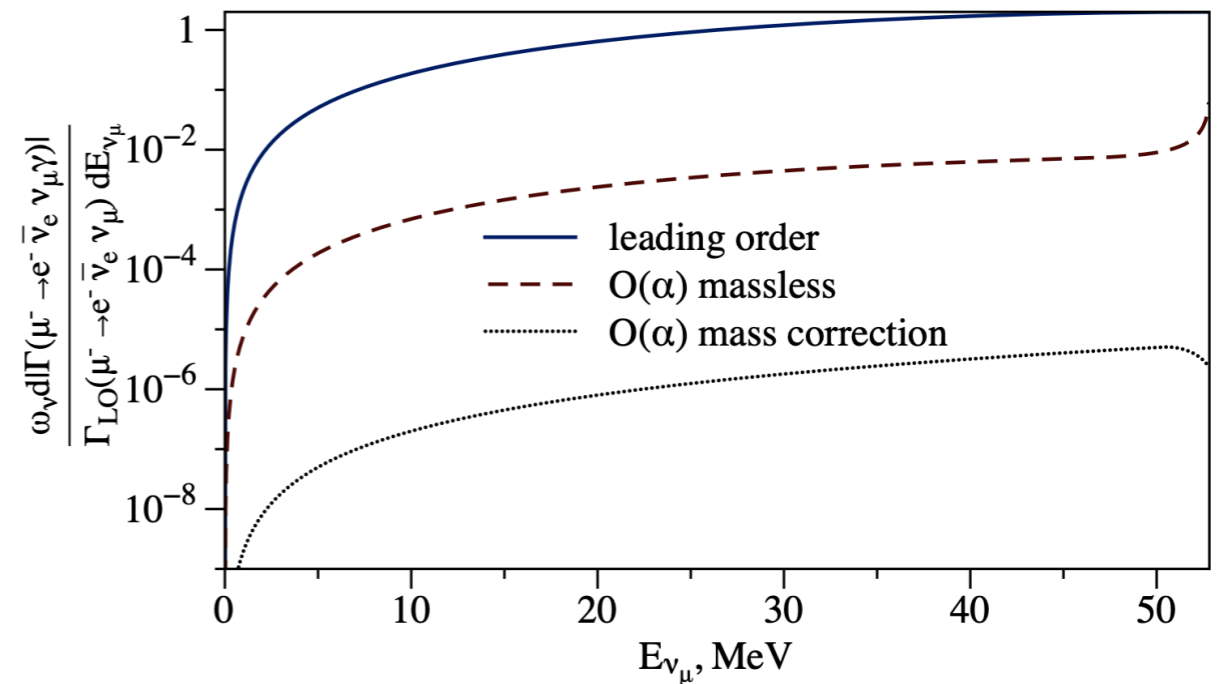
< 0.1 ‰

$$K^+ \rightarrow \mu^+ \nu_\mu \gamma$$

flavor-dependence is clarified to permille level analytically



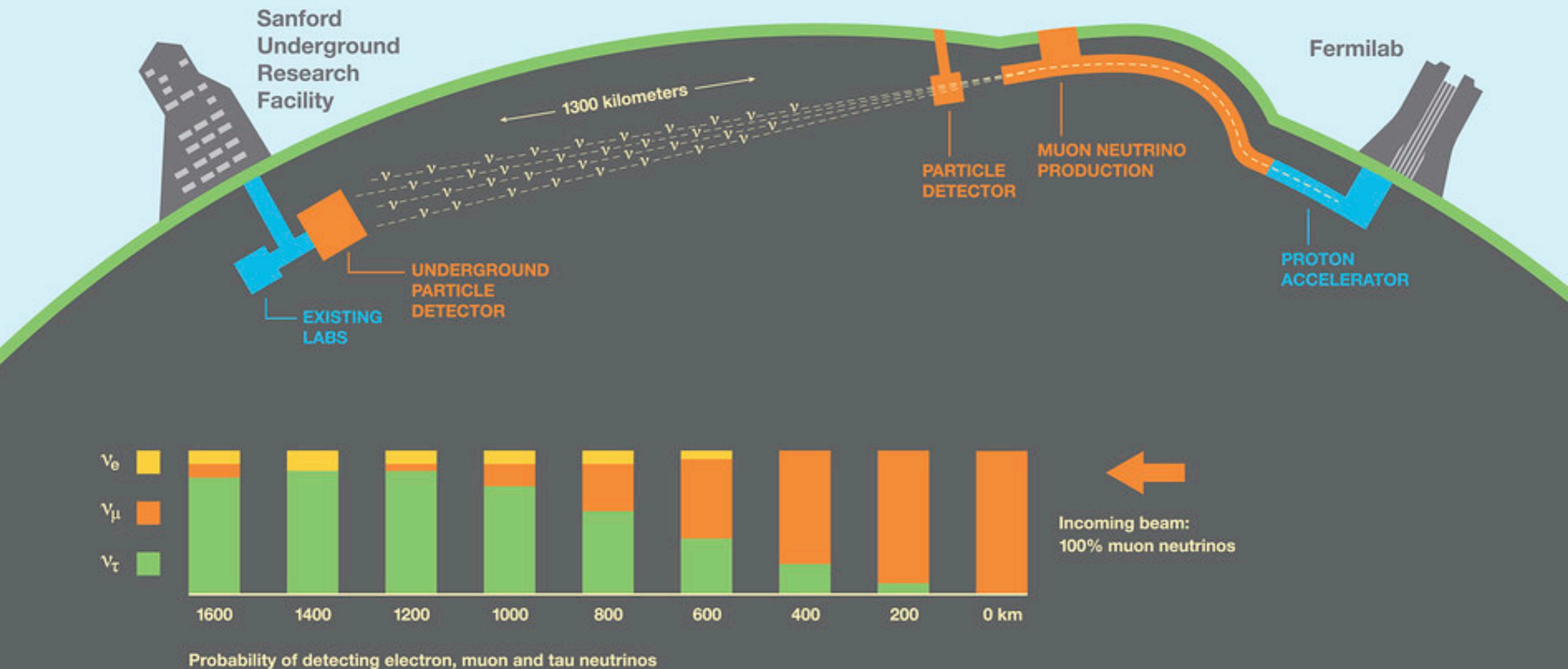
$$\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu \gamma \quad 3-4 \text{ ‰}$$



first QED/EW form factors with different mass

DUNE

Deep Underground Neutrino Experiment




- muon neutrinos oscillate to tau and electron flavors

Ideal case: monochromatic beam

oscillation parameters extracted from event rates

$$P(\nu_\mu \rightarrow \nu_\mu) \simeq \frac{N_\mu(E_\nu, L)}{N_\mu(E_\nu, L=0)}$$

far detector
near detector



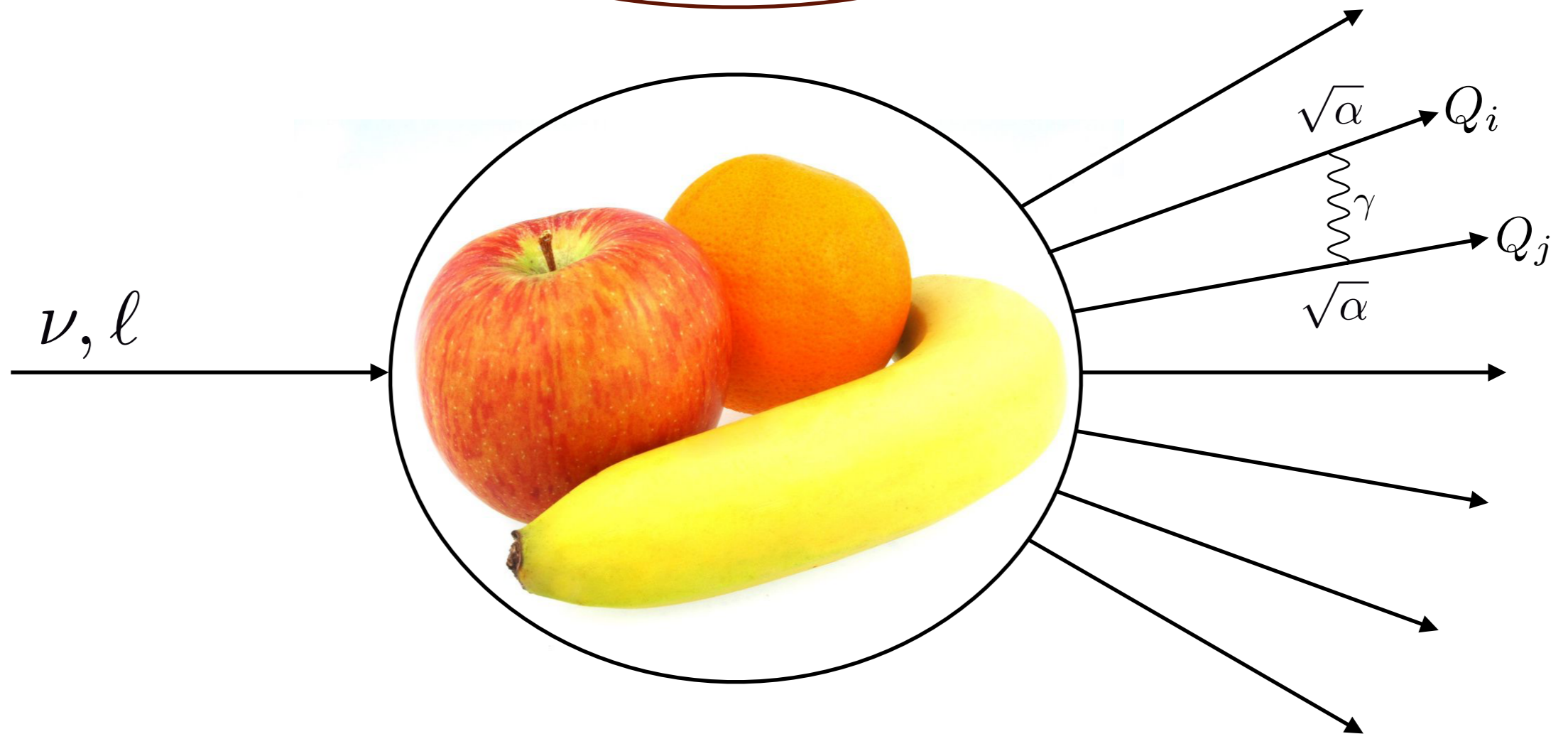
flavor-dependence of cross sections is crucial

$$P(\nu_\mu \rightarrow \nu_e) \simeq \frac{N_e(E_\nu, L)}{N_\mu(E_\nu, L=0)} \frac{\sigma_\mu(E_\nu)}{\sigma_e(E_\nu)}$$

- disappearance is given by event rates for monochromatic beams
- appearance is given by event rates and cross-section ratios

QED corrections

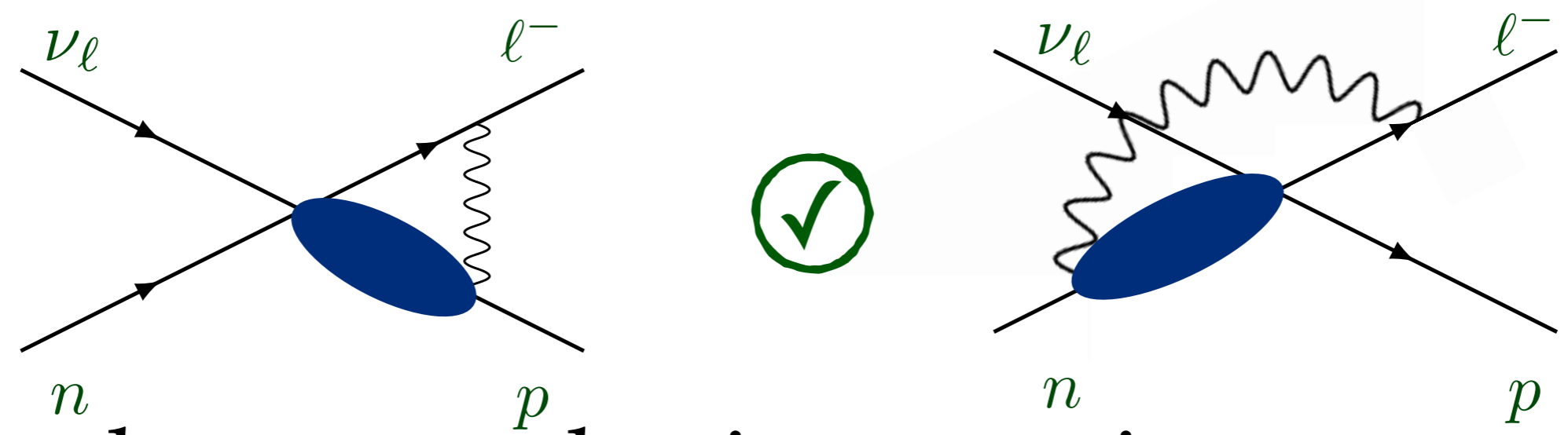
$$m_e \ll m_\mu \ll E$$



$$\frac{\alpha}{\pi} \sim 0.2 \% \text{ multiplied by } \ln \frac{E}{m_e} \sim 6 - 10 \text{ or } \ln^2 \frac{E}{m_e} \sim 36 - 100$$

- scale separation introduces large flavor-dependent QED logarithms

factorization for radiative corrections with model for hard function

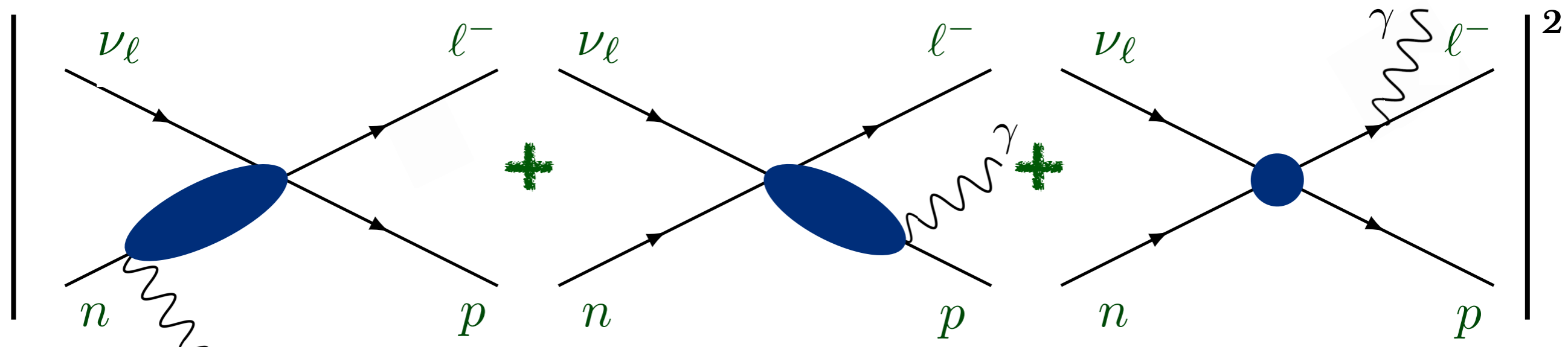


Charged-current elastic scattering on nucleons

O.T., Qing Chen, Richard J. Hill and Kevin S. McFarland, Nature Commun. (2022)

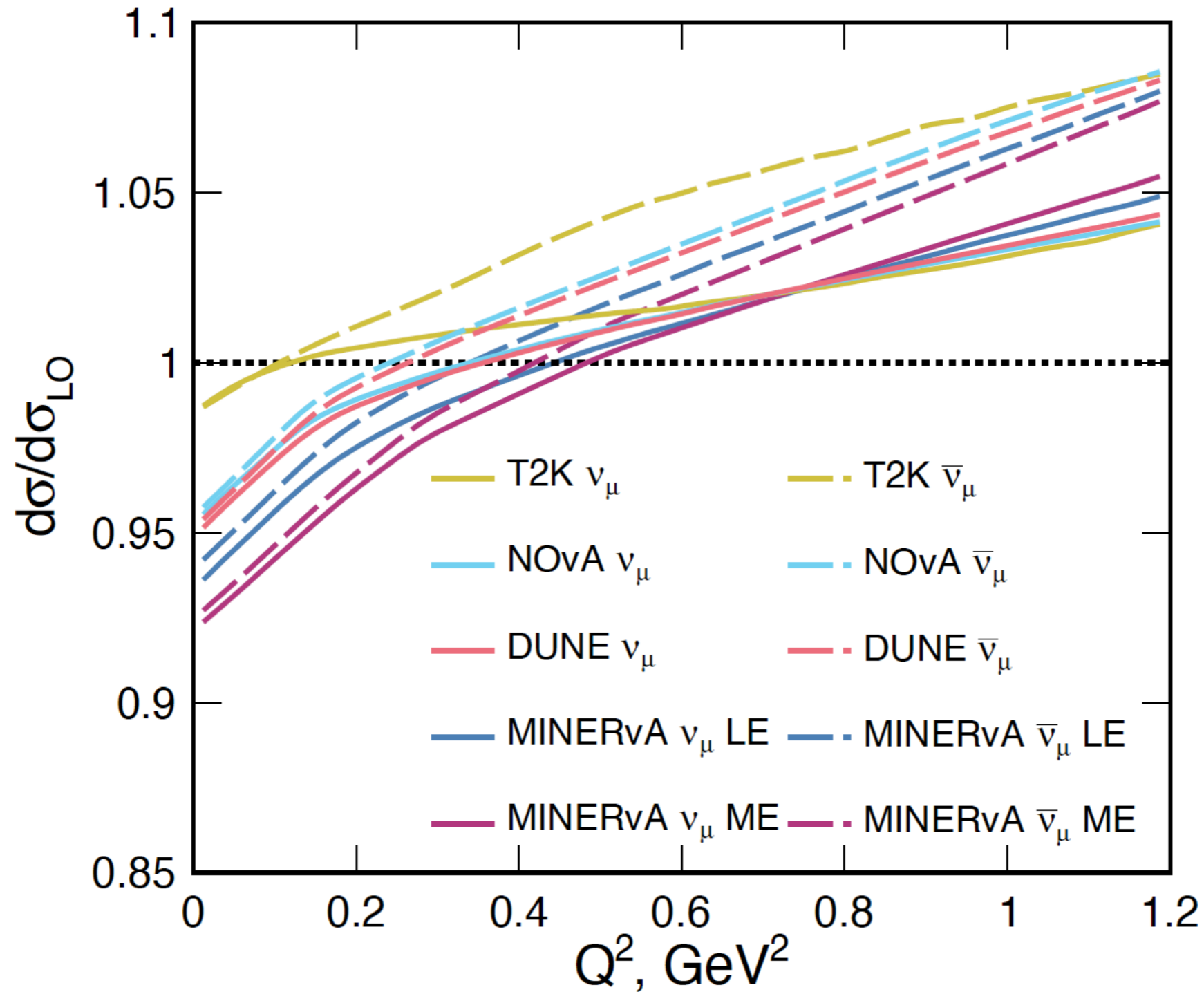
precise predictions for flavor ratios and radiative corrections

in exclusive and inclusive observables with GeV neutrino beams



O.T., Qing Chen, Richard J. Hill, Kevin S. McFarland and Clarence Wret
 editors suggestion in PRD (2022)

Comparison to data



- lepton energy spectra with lepton kinematics
- NEUT generator + flux averaging

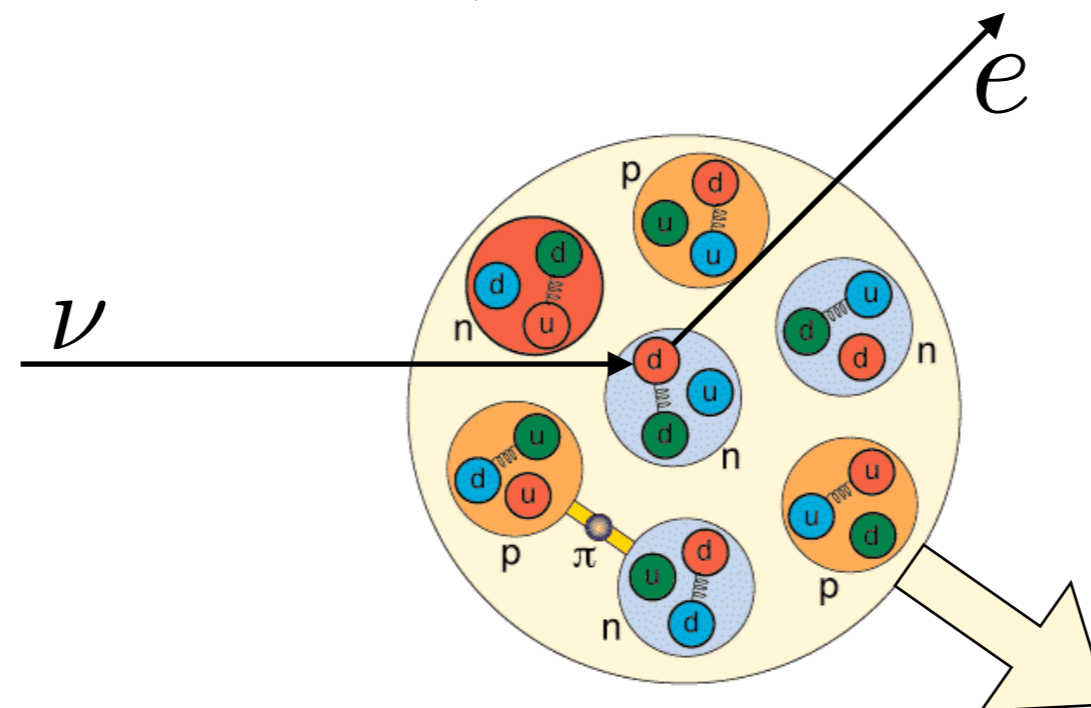
Vector and axial-vector interactions

weak interaction upon left-handed fermions

matrix elements of tree-level interaction at quark level

$$J^\mu = \bar{q} (\underbrace{\gamma^\mu}_V - \underbrace{\gamma^\mu \gamma_5}_A) q$$

induce vector and axial-vector contributions



V: electron scattering

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- vector and axial-vector matrix elements determine ν cross sections

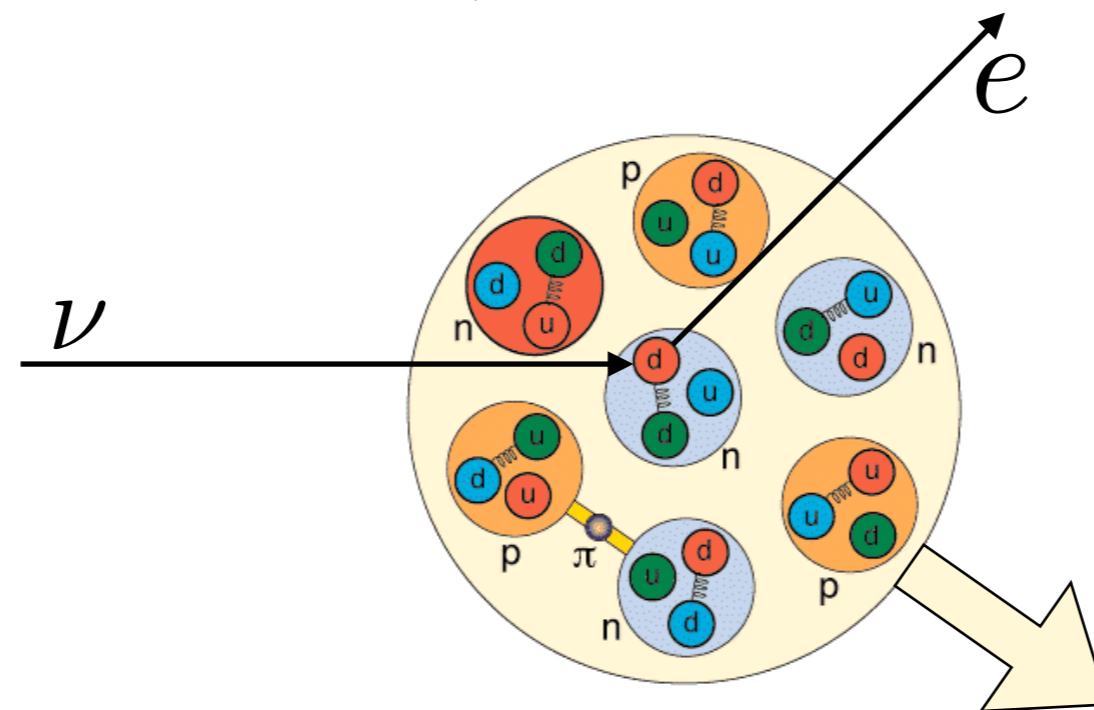
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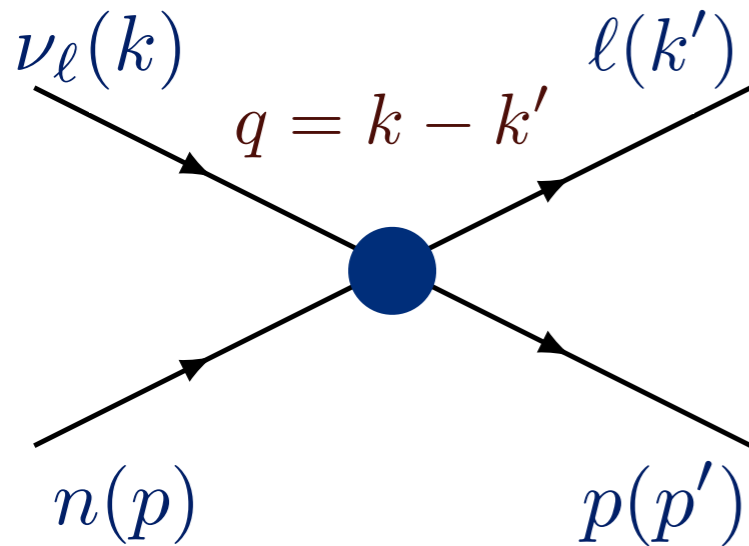
V : electron scattering

A : neutrino scattering

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- vector and axial-vector matrix elements determine ν cross sections

Elastic scattering on free nucleon



neutrino energy

$$E_\nu$$

momentum transfer

$$Q^2 = -q^2$$

contact interaction at GeV energies

- assuming isospin symmetry, nucleon current:

$$\Gamma^\mu(Q^2) = \langle p | \bar{u} (\gamma^\mu - \gamma^\mu \gamma_5) d | n \rangle$$

$$\Gamma^\mu(Q^2) = \gamma^\mu F_D^V(Q^2) + \frac{i\sigma^{\mu\nu} q_\nu}{2M} F_P^V(Q^2) + \gamma^\mu \gamma_5 F_A(Q^2) + \frac{q^\mu}{M} \gamma_5 F_P(Q^2)$$

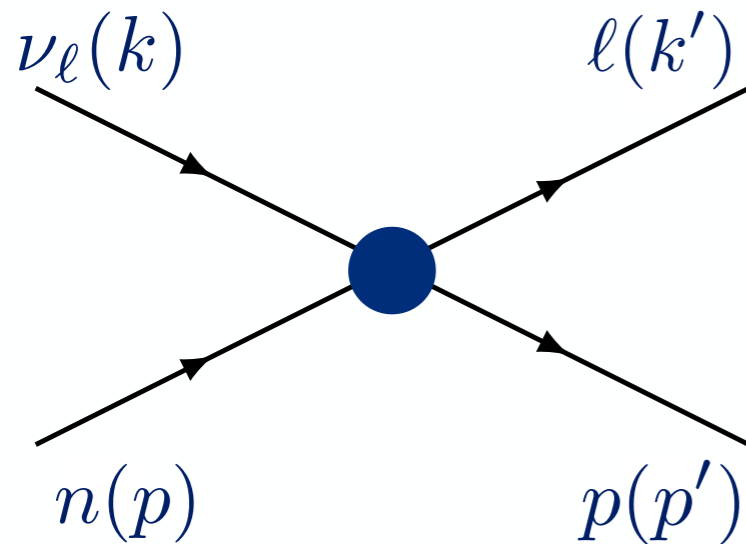
form factors: isovector Dirac and Pauli axial and pseudoscalar

$$F_{D,P}^V = F_{D,P}^p - F_{D,P}^n$$

tree-level amplitude

$$T = \frac{G_F V_{ud}}{\sqrt{2}} (\bar{\ell}(k') \gamma_\mu (1 - \gamma_5) \nu_\ell(k)) (\bar{p}(p') \Gamma^\mu(Q^2) n(p))$$

Elastic scattering on free nucleon



$$\nu = E_\nu/M - \tau - r^2$$

$$r = \frac{m_\ell}{2M} \quad \tau = \frac{Q^2}{4M^2}$$

unpolarized cross section

$$\frac{d\sigma}{dQ^2} \sim \frac{M^2}{E_\nu^2} \left((\tau + r^2) A(Q^2) - \nu B(Q^2) + \frac{\nu^2}{1 + \tau} C(Q^2) \right)$$

Llewellyn Smith (1972)

- structure-dependent functions

$$A = \tau (G_M^V)^2 - (G_E^V)^2 + (1 + \tau) F_A^2 - r^2 \left((G_M^V)^2 + F_A^2 - \underline{4\tau F_P^2 + 4F_A F_P} \right)$$

$$B = \pm 4\tau F_A G_M^V$$

$$C = \tau (G_M^V)^2 + (G_E^V)^2 + (1 + \tau) F_A^2$$

- **pseudoscalar** form factor contribution is suppressed by lepton mass
- cross section is sensitive to both **vector** and **axial** contributions

Elastic scattering on free nucleon

- only 3 experiments performed with deuterium bubble chamber
- direct access to form-factor shape

ANL 1982: 1737 events

BNL 1981: 1138 events

FNAL 1983: 362 events

world data: ~3200 events



Fermilab bubble chamber, Richard Drew

- axial form factor extracted based on electromagnetic structure

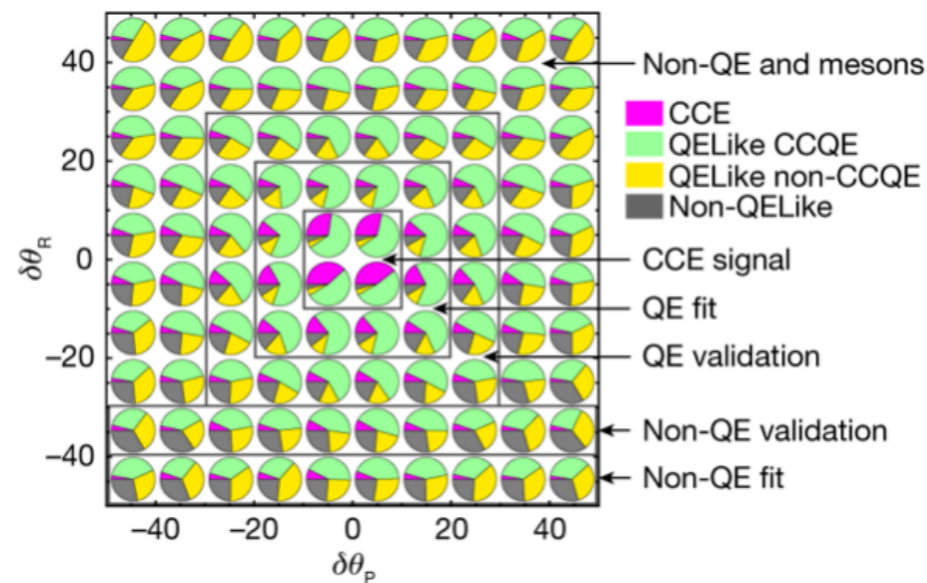
A.S. Meyer, M. Betancourt, R. Gran and R.J. Hill, PRD (2016)

MINERvA result with free protons

- idea of scattering on molecular hydrogen realized !!!

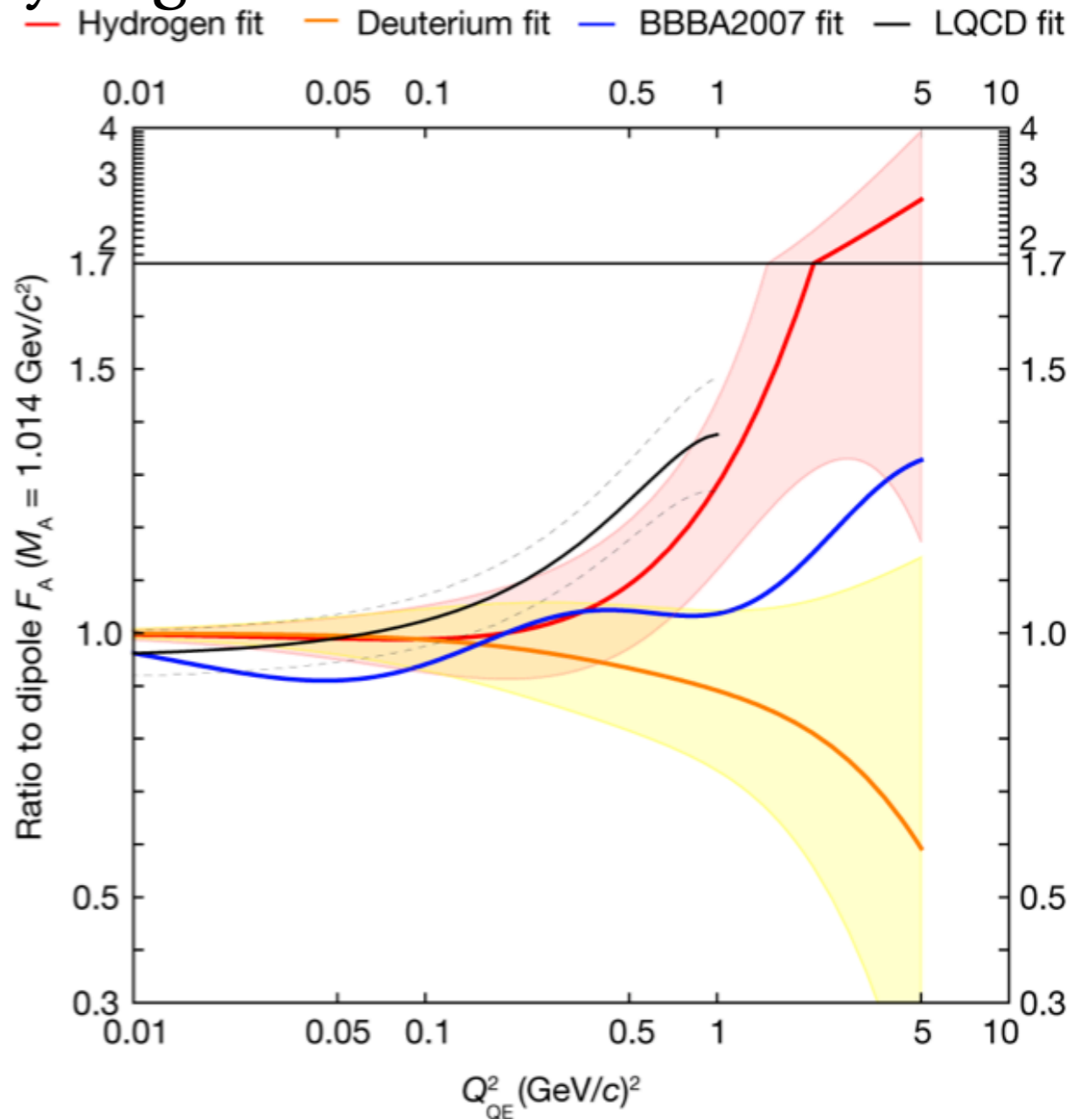


kinematic selection



5580 events over
12500 background

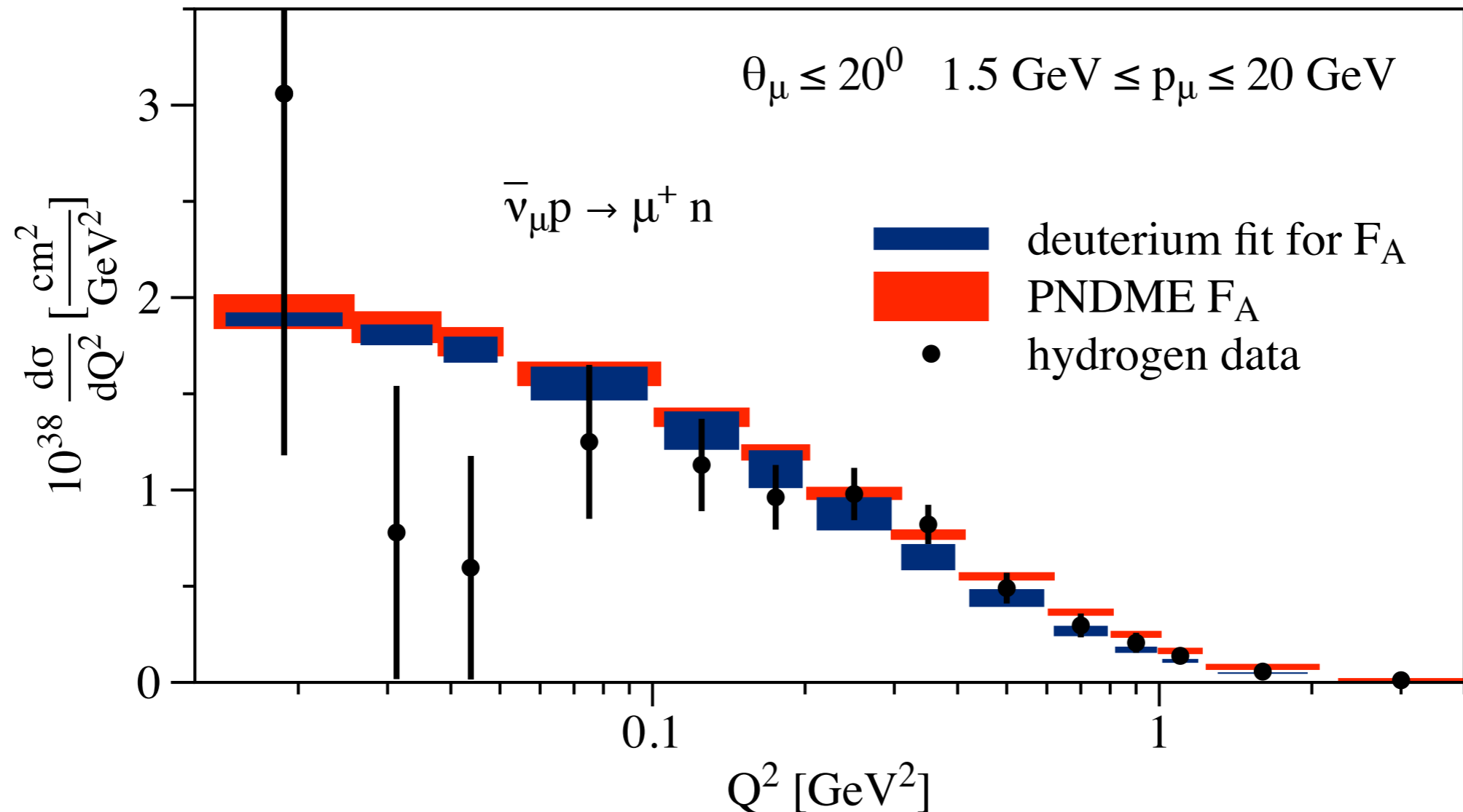
background nuclear events
constrained by scattering of ν



- 1st measurement of axial form factor on “free” protons $\bar{\nu}_\mu p \rightarrow \mu^+ n$

Lattice QCD vs MINERvA

- PNDME 2023 axial-vector form factor as representative of lattice QCD



- $\lesssim 1\sigma$ agreement for each bin besides two at small Q^2

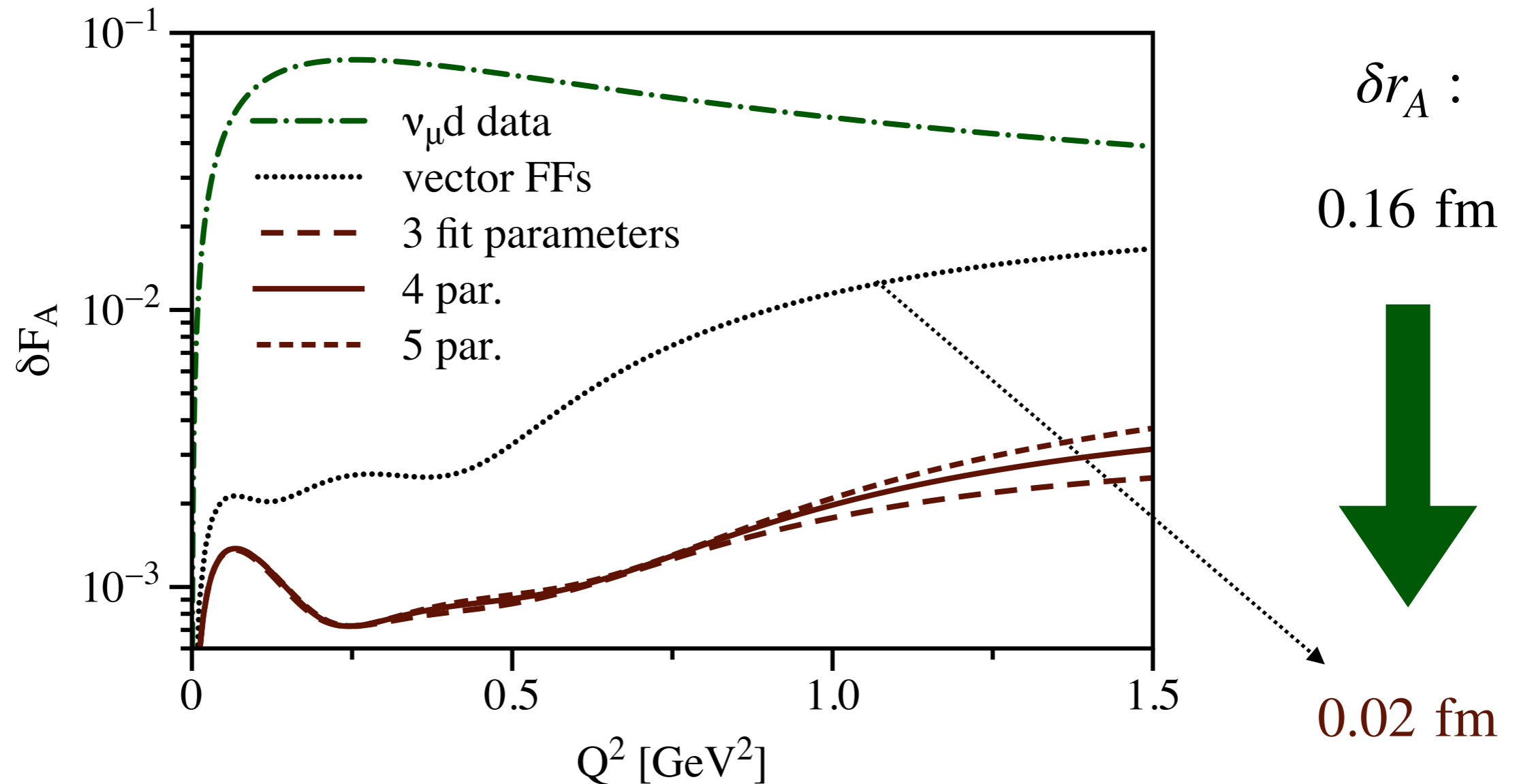
- 2-3 σ tension between lattice QCD and deuterium data
- MINERvA hydrogen data consistent with LQCD and deuterium

O.T., Rajan Gupta, and Tanmoy Bhattacharya, PRD (2023)

DUNE projections

- estimates for 700 kg of H in Straw Tube Tracker at near detector

H. Duyang, B. Guo, S. R. Mishra, and R. Petti, PLB (2019)



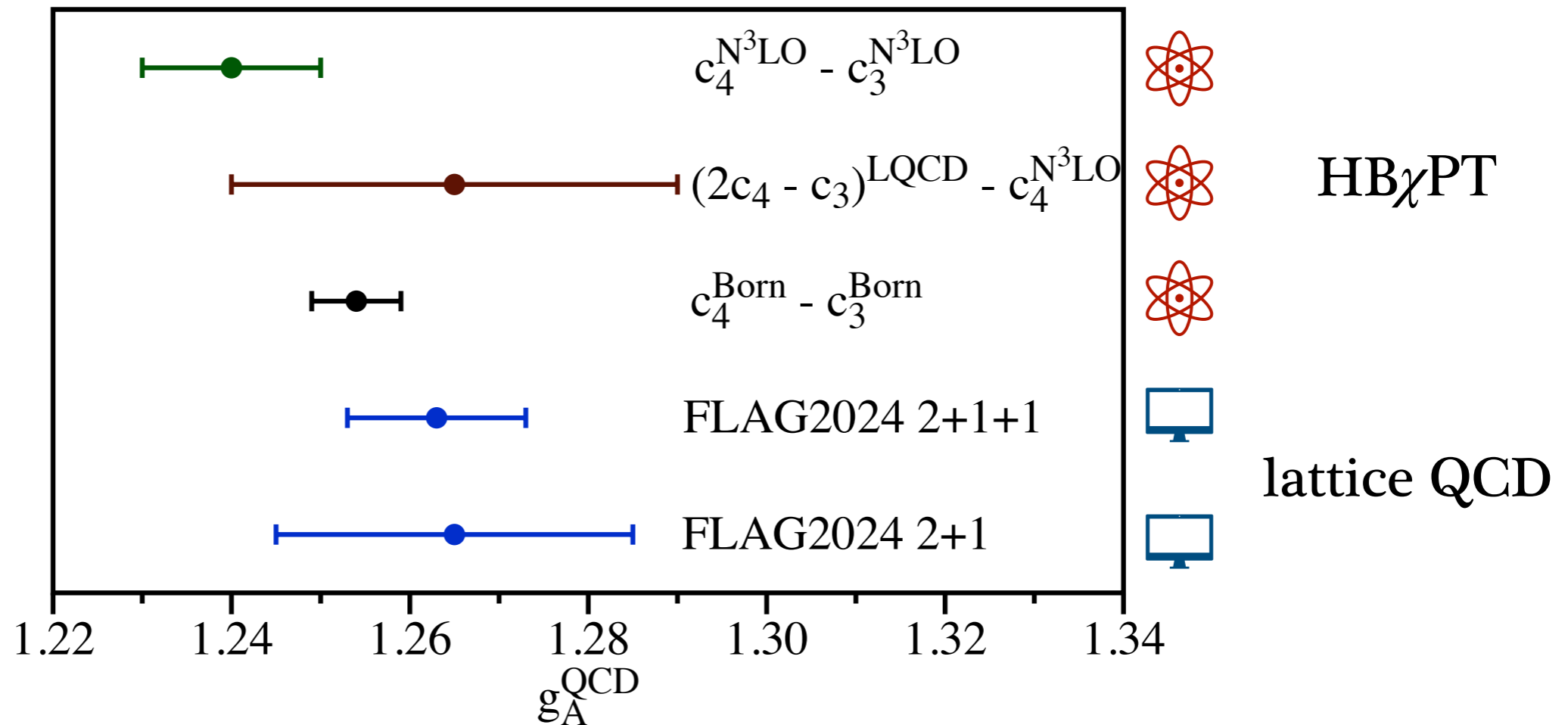
- order of magnitude improvement in axial form factor and radius
- DUNE will probe vector form factors and isospin symmetry

Roberto Petti, O.T., and Richard J. Hill, letter in PRD (2024)

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, arXiv:2603.08596

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

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

- first consistent at 0.1%-level QED radiative corrections

Factorization approach

- cross section is given by **factorization formula**

$$d\sigma \sim S \left(\frac{\Delta E}{\mu} \right) J \left(\frac{m_\ell}{\mu} \right) H \left(\frac{M}{\mu} \right)$$

- determine **hard function** at hard scale by matching experiment or **hadronic model** to the theory with heavy nucleon

- **soft and collinear functions** are evaluated **perturbatively**

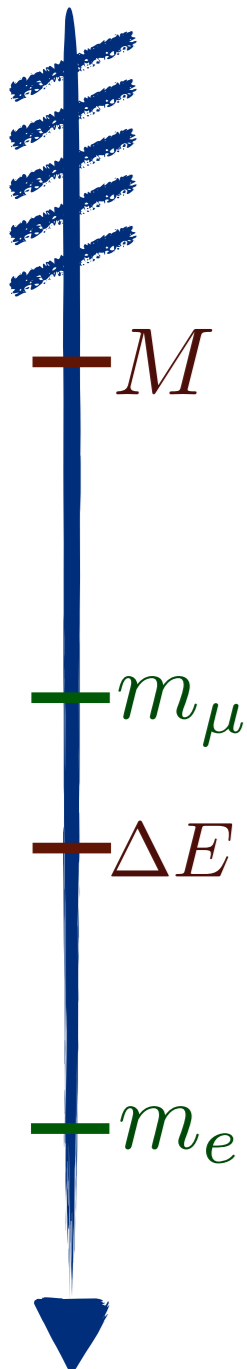
SCET power expansion parameter

$$\lambda \sim \frac{m_\mu^2}{E_\nu^2} \sim (\Delta\theta)^2 \sim \frac{\Delta E}{E_\nu}$$

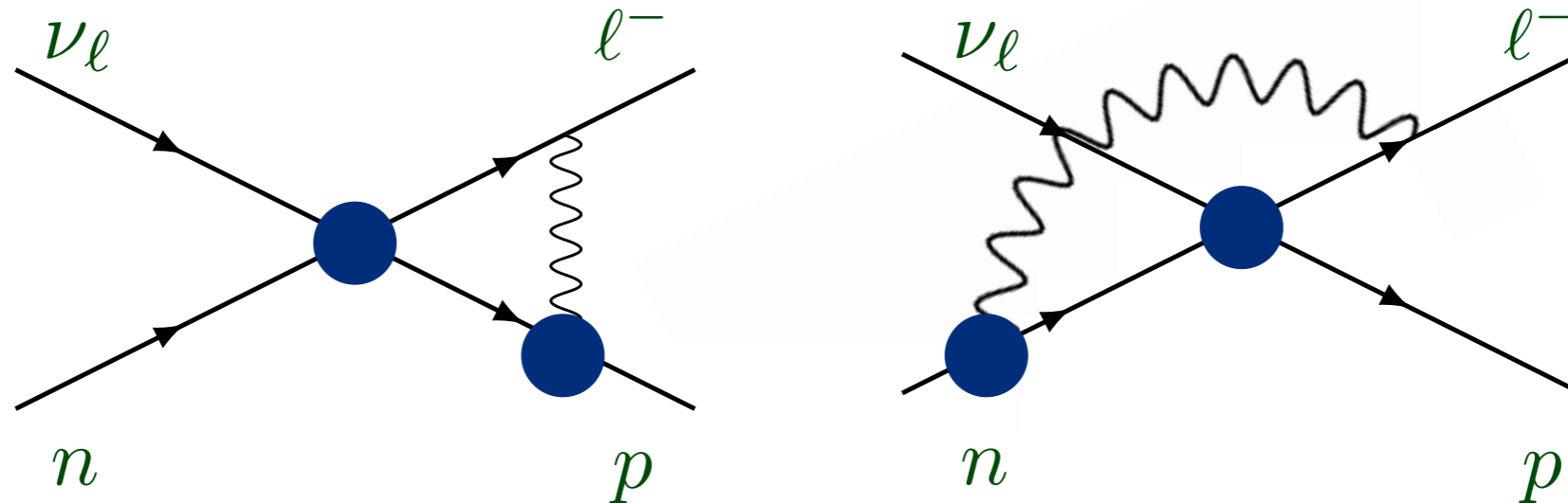
In λ enhancements

O.T, Qing Chen, Richard J. Hill and Kevin S. McFarland, Nature Commun. (2022)

O.T, Qing Chen, Richard J. Hill, Kevin S. McFarland and Clarence Wret
editors suggestion in PRD (2022)



Hadronic model at GeV scale

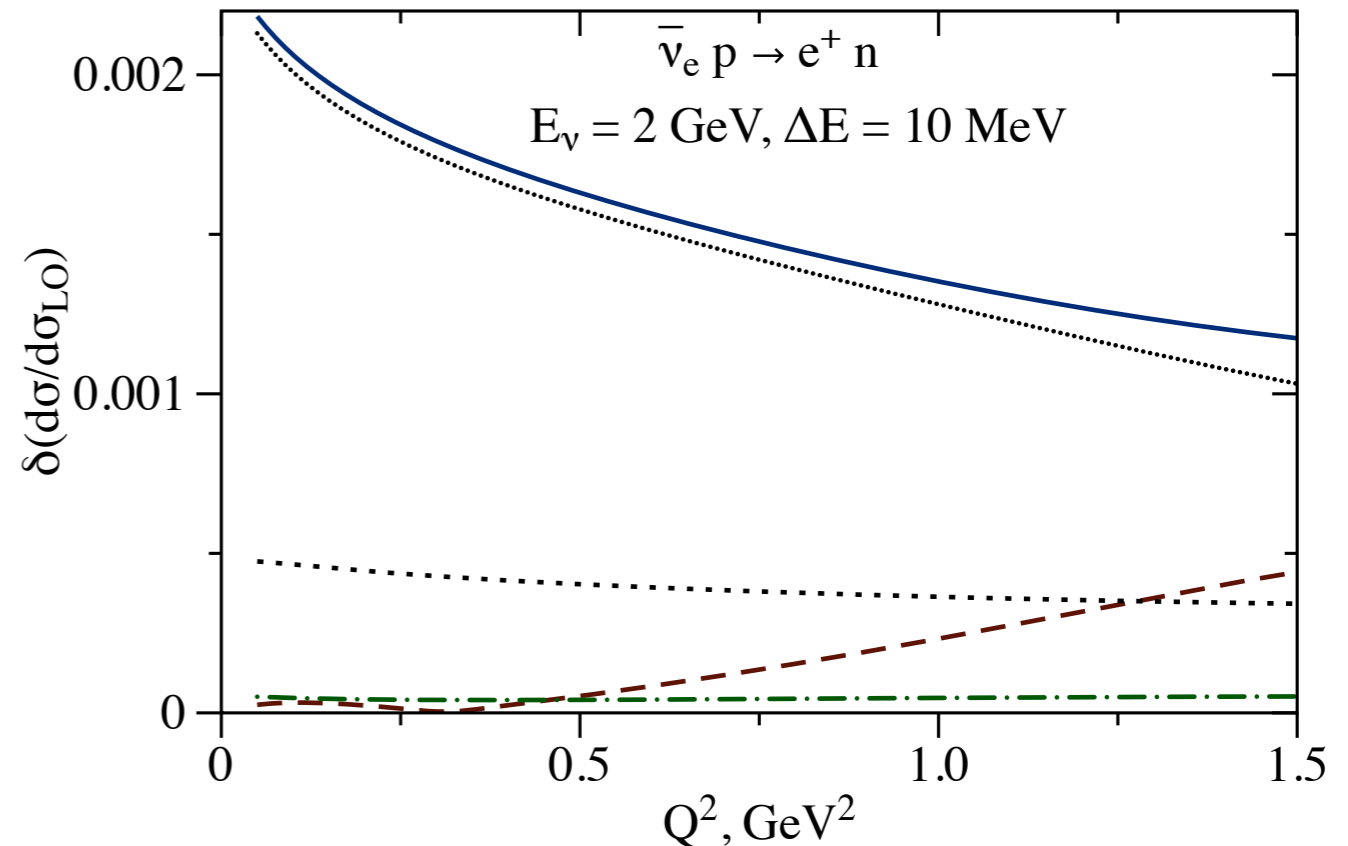
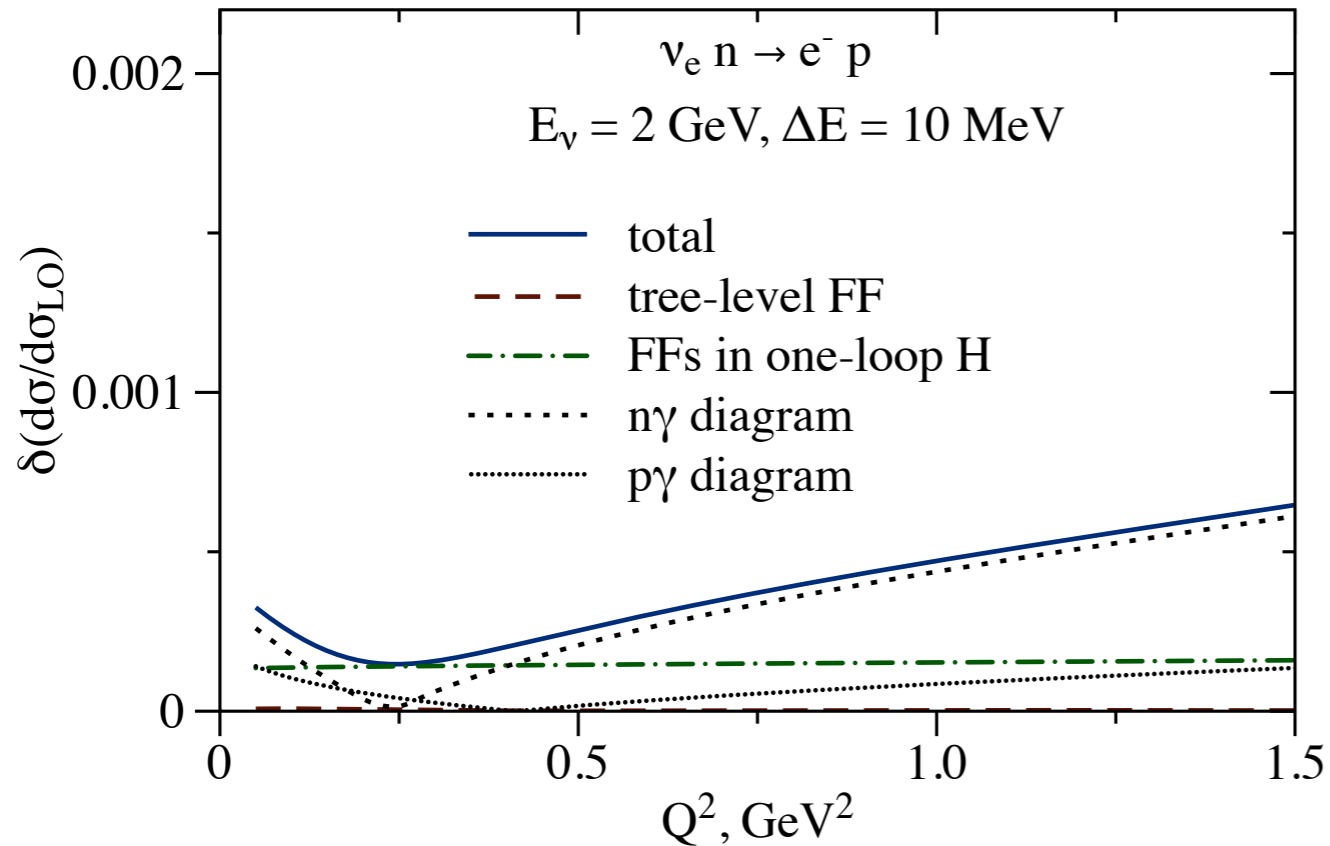


- exchange of photon between the charged lepton and nucleons
- assume **onshell form** for each interaction with dipole form factors
discussed for neutrino-nucleon scattering: Graczyk, PLB (2013)
- add **self energy** for charged particles
- reproduce soft and collinear regions of SCET

- best determination of hard function

Error budget

- uncertainties from hard function



- nucleon form factors

Meyer, Betancourt, Gran and Hill, PRD (2016)

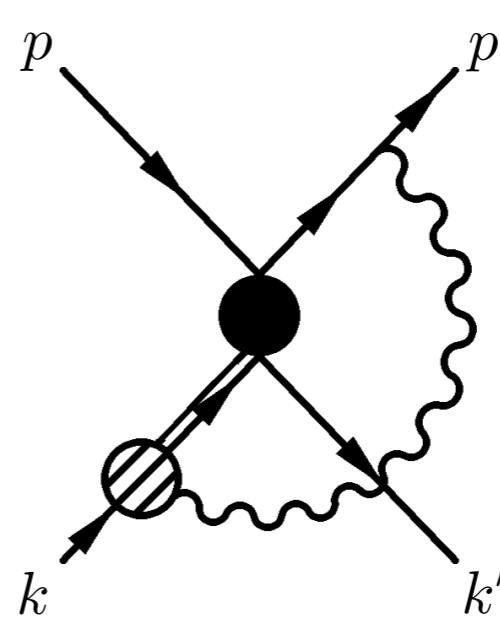
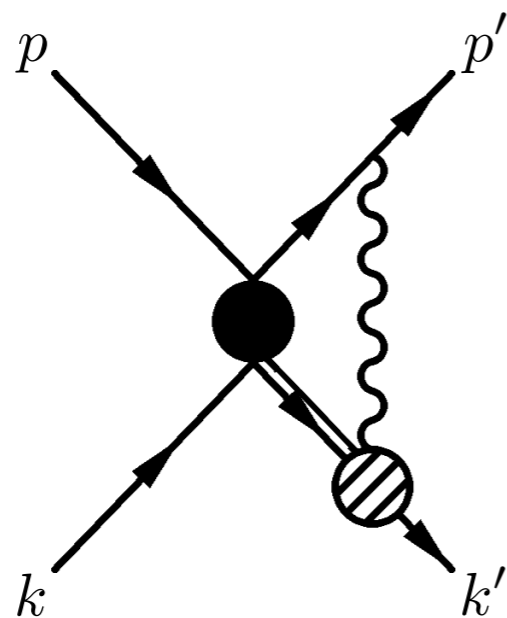
Kaushik Borah, Gabriel Lee, Richard J. Hill and O.T., PRD (2020)

- add perturbative uncertainty by variation of scale

- uncertainty of permille level for the ratio to LO result

Δ resonance contribution

- vector part with **magnetic transition** only; **pQCD** for axial-vector



$$C_5^A(Q^2) \lesssim \frac{\ln Q^2}{Q^6}$$

- **free from soft singularities** \longrightarrow **flavor-independent**

- **expected collinear limit**

$$g_M, g_E, f_A, f_{A3} \sim \text{const}$$

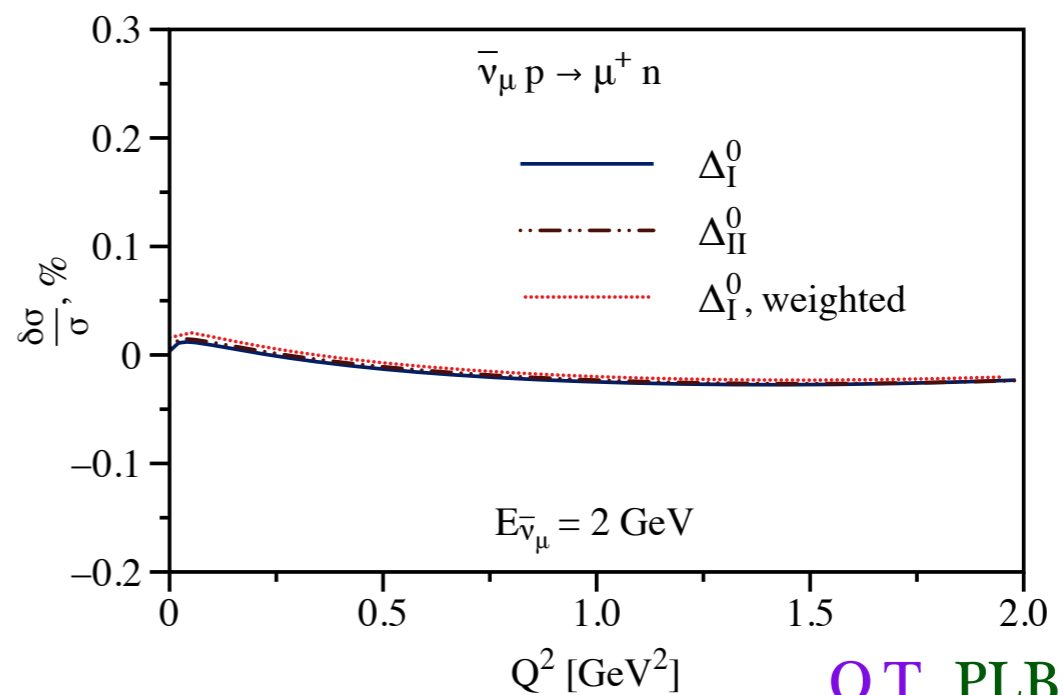
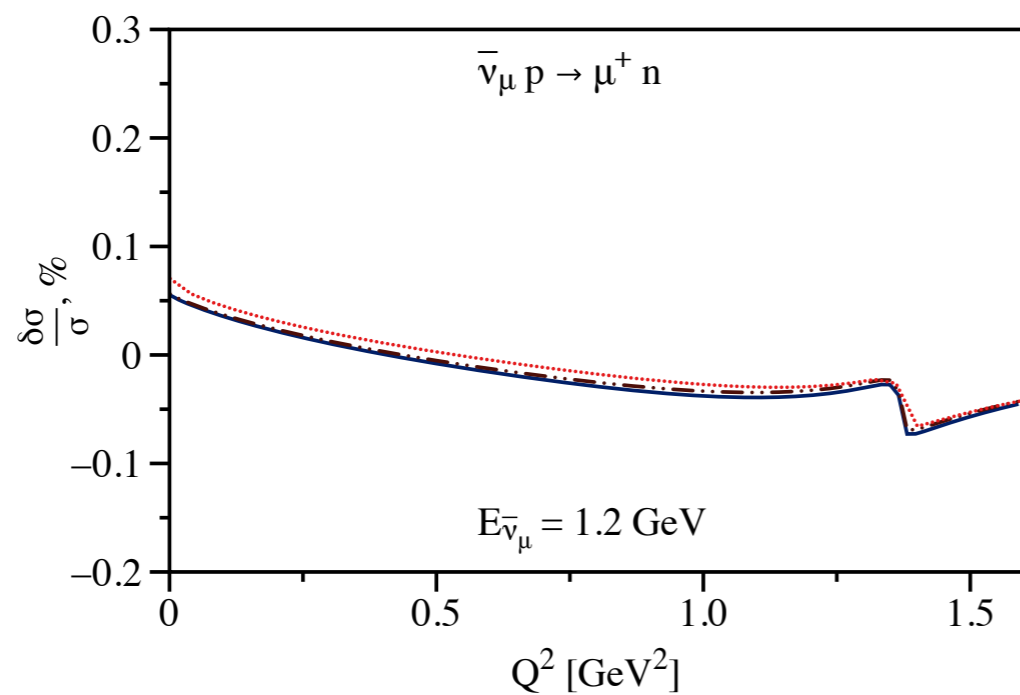
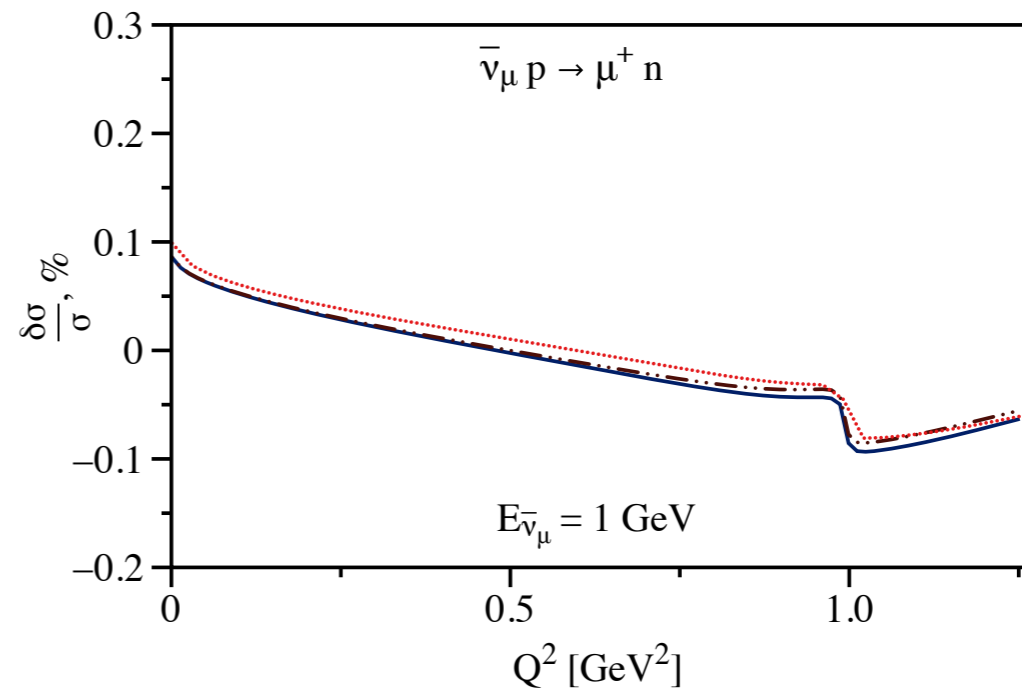
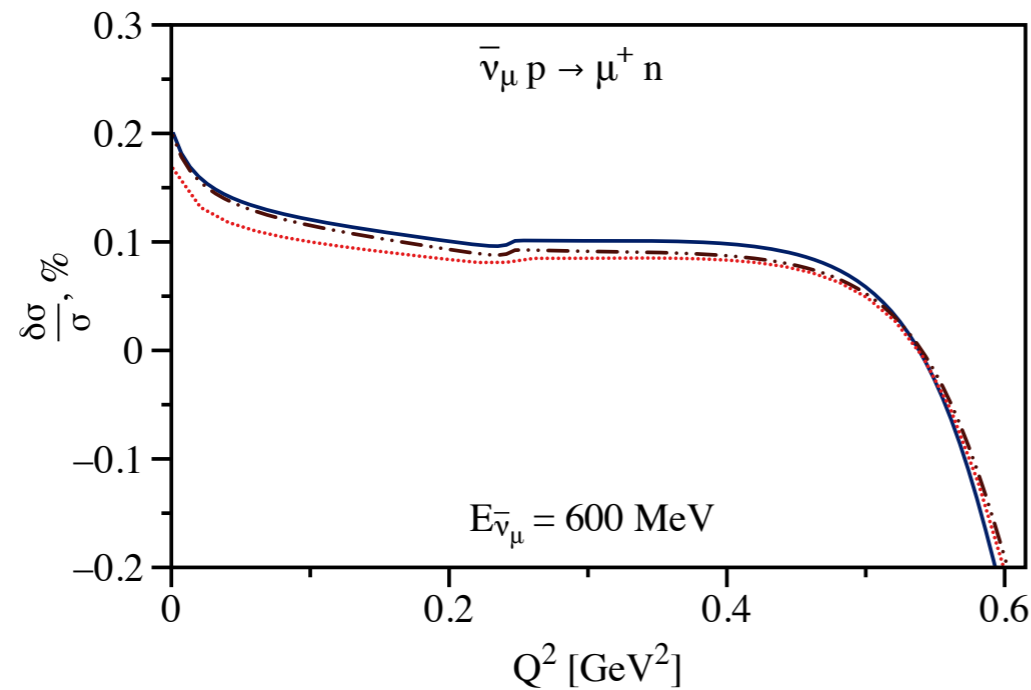
$$f_P, f_3, f_R, f_T \sim \ln m$$

O.T., PLB (2026)

- **expected infrared behavior**

Δ resonance contribution

- width of Δ resonance included

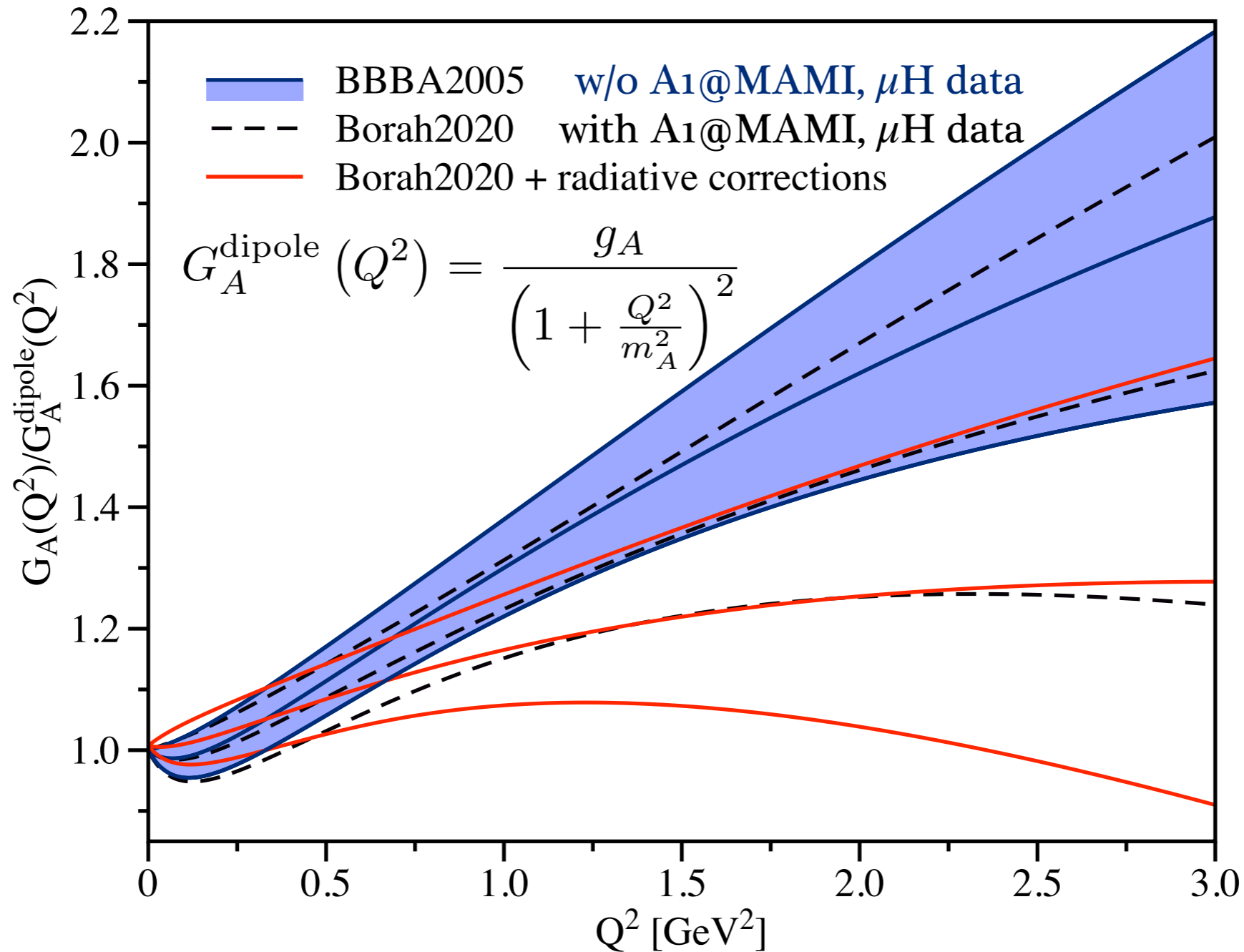


O.T., PLB (2026)

- in agreement with conservative error estimates of inelastic states

Nucleon axial-vector form factor

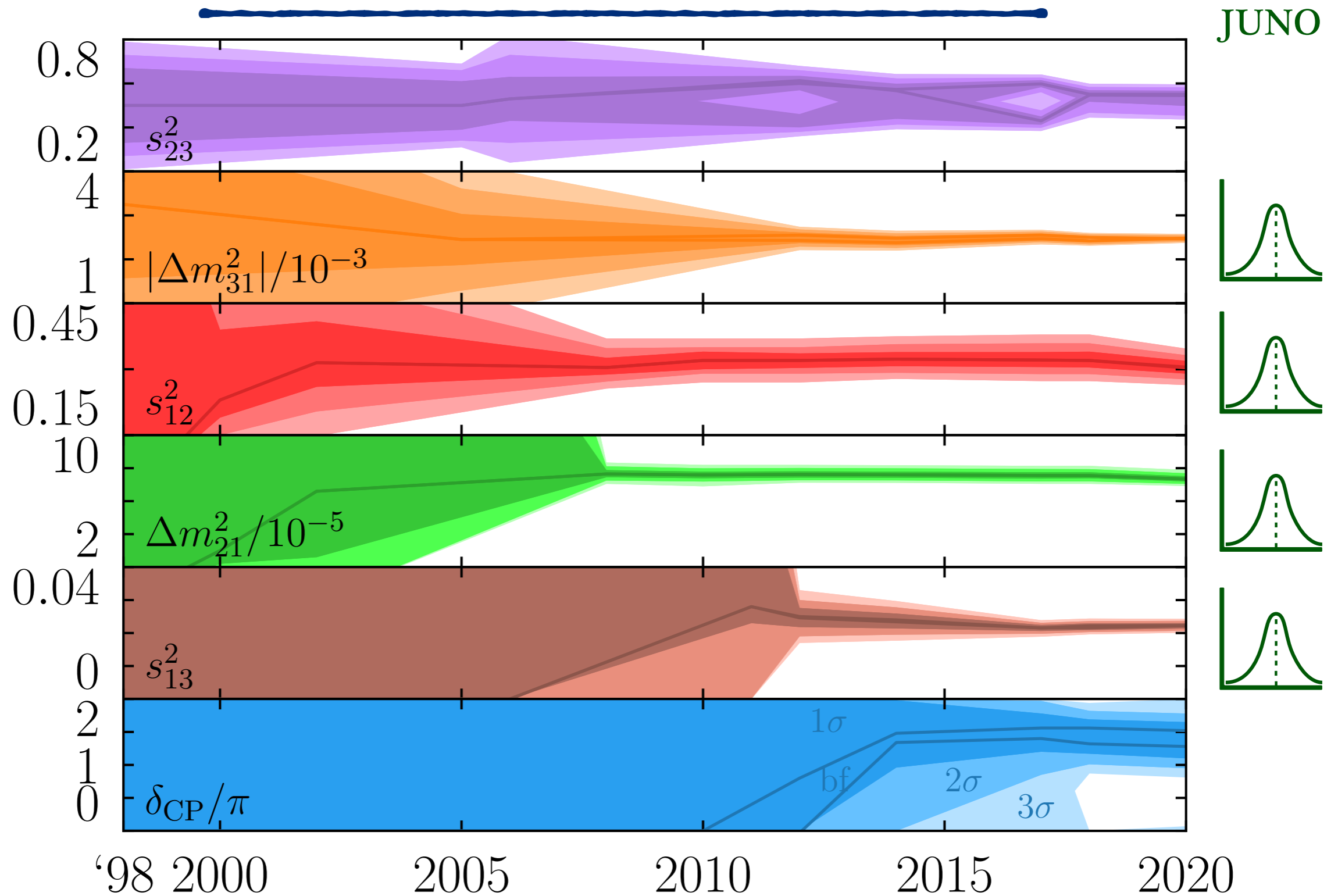
- first extraction of axial-vector form factor with QED



O.T., Aaron S. Meyer, Clarence Wret, Tejin Cai, Richard J. Hill, Kevin S. McFarland, PRD (2026)

- first consistent at 1%-level QED radiative corrections

PMNS oscillation matrix



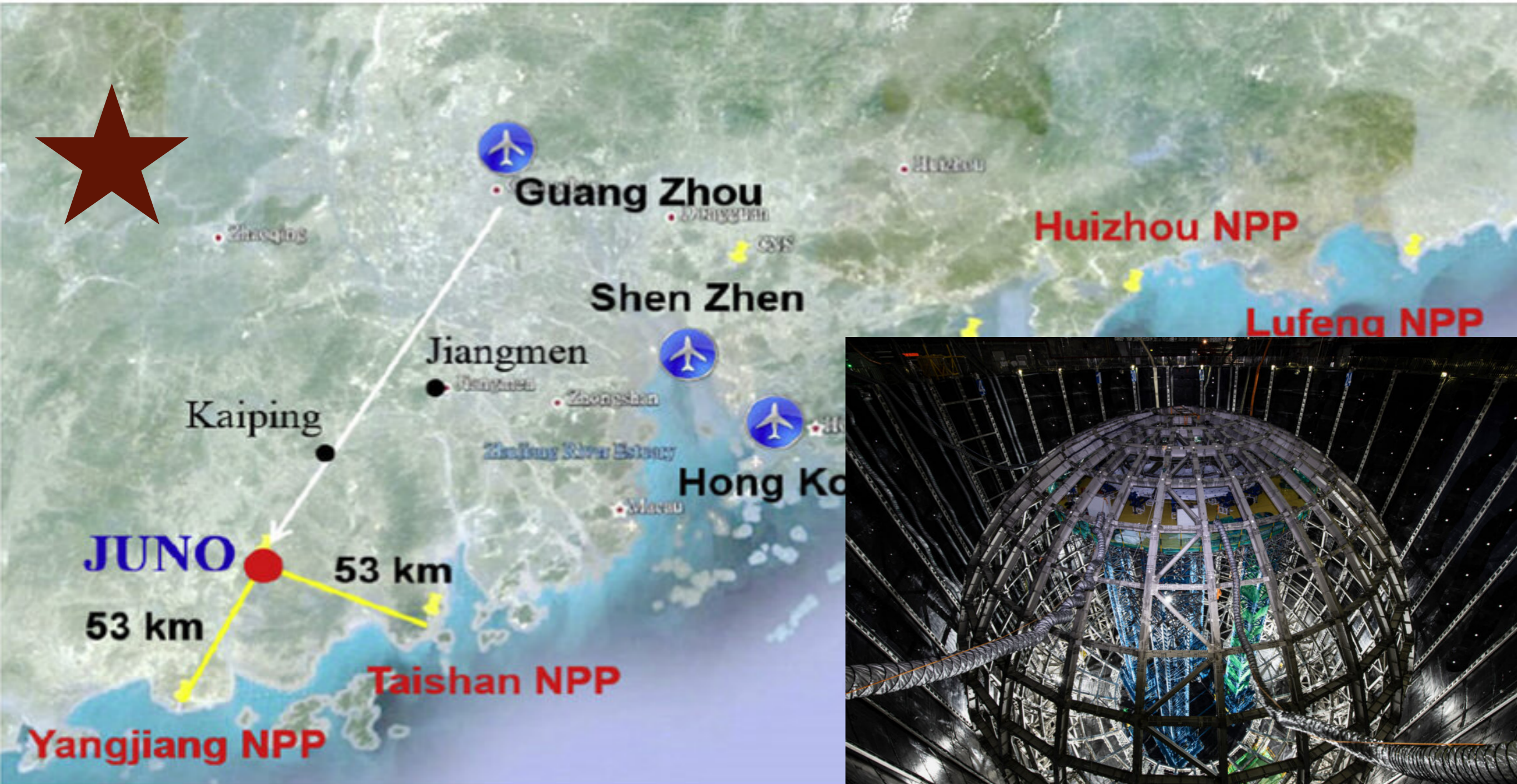
JUNO

Snowmass 2021 NFO1 group report

- tremendous progress in our lifetime

CP violation and mass hierarchy@laboratory

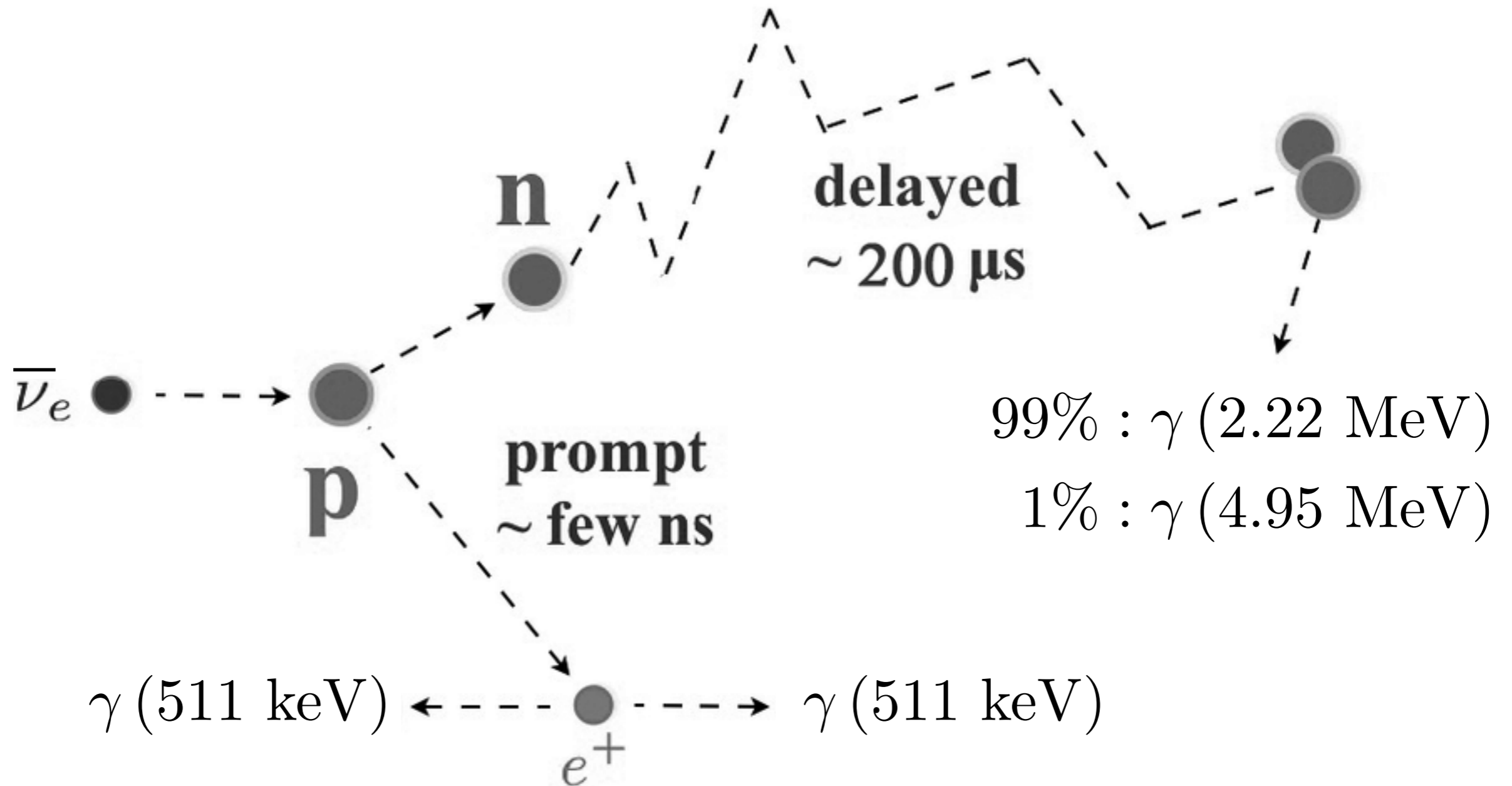
3σ determination of mass hierarchy



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

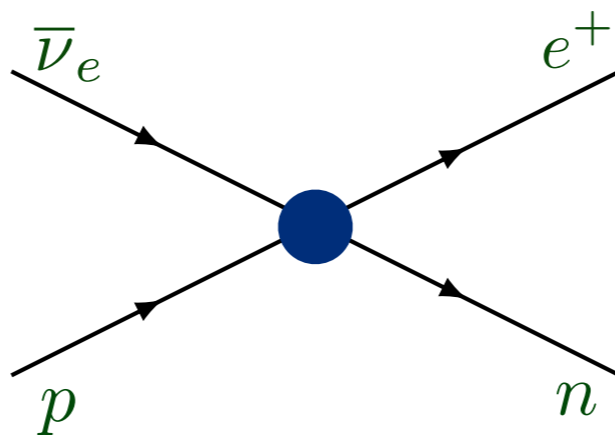
35 m, 20000 t

JUNO detection channel



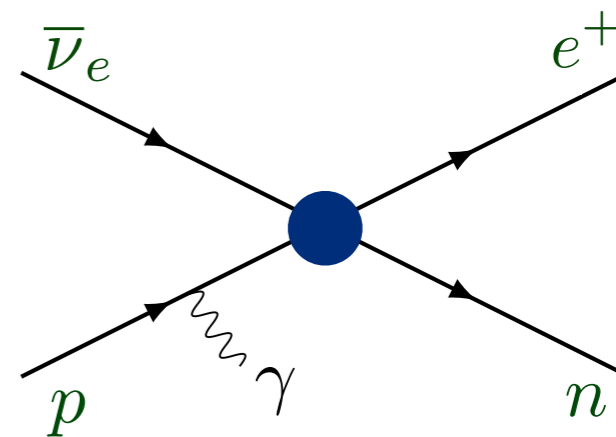
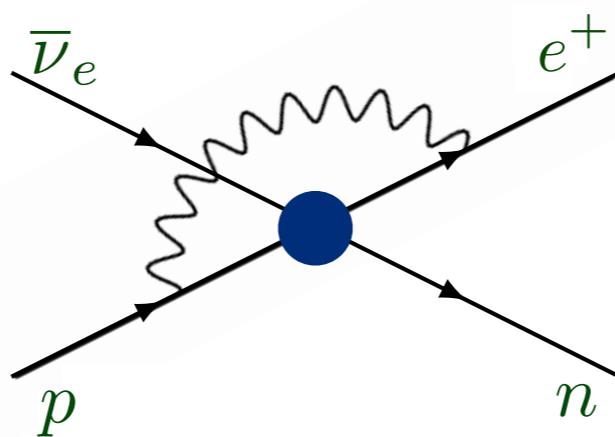
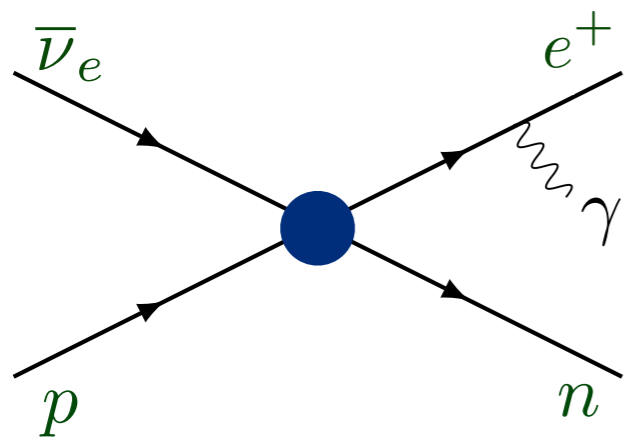
Teng Li et al., ChPC (2017)

- prompt-delayed time signature: background discrimination



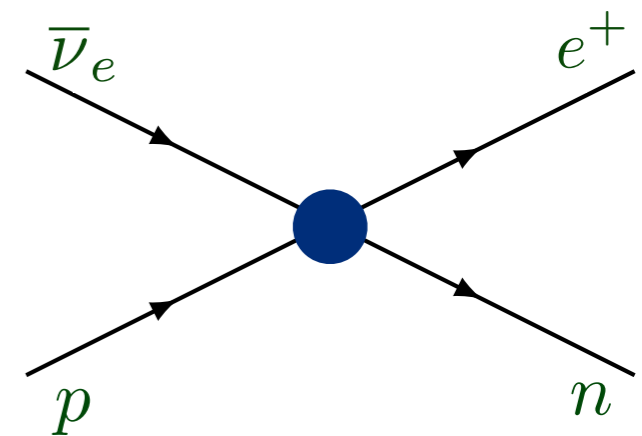
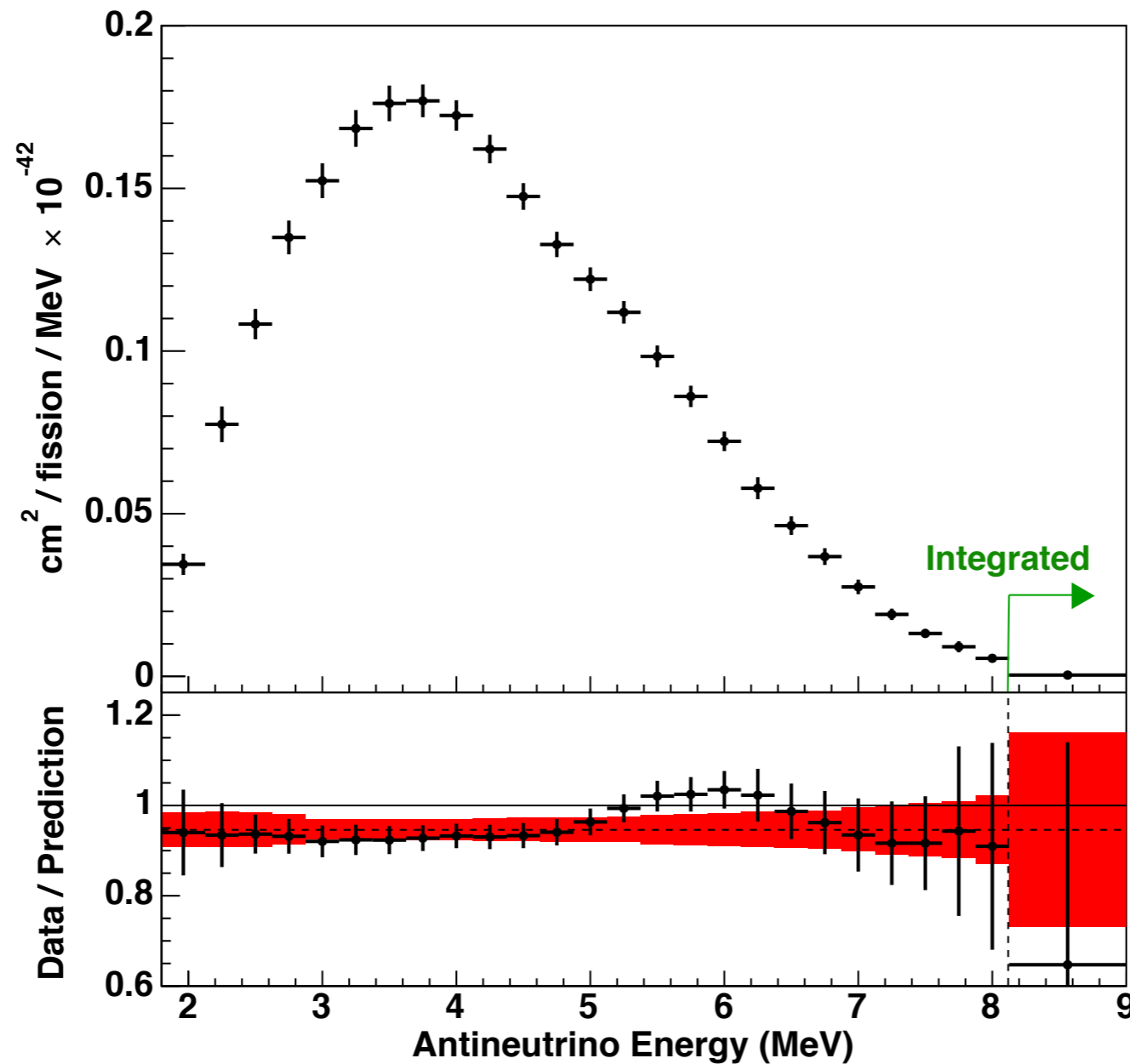
O.T., arXiv:2512.07956
arXiv:2512.07957

Theory of inverse beta decay for reactor antineutrinos



IBD with reactor antineutrinos

- neutron is heavier than proton by 1.3 MeV

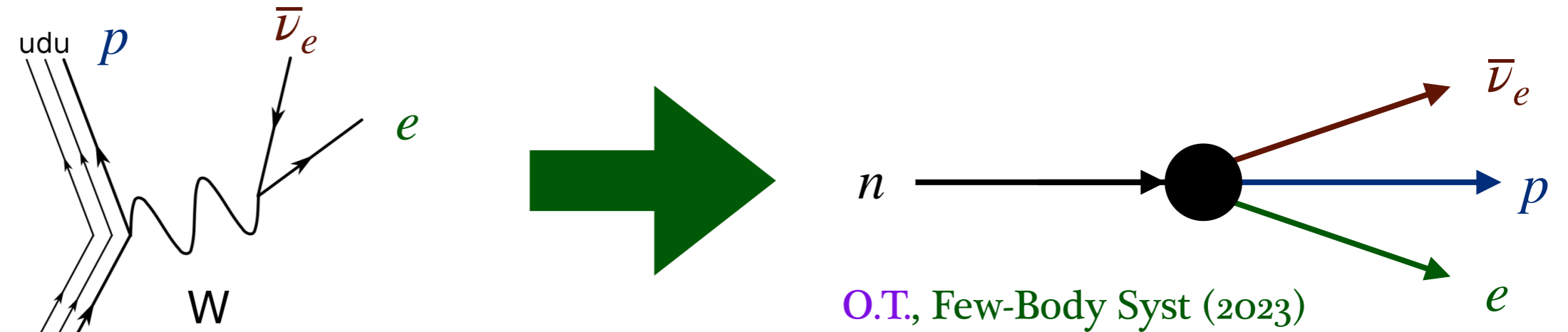


Daya Bay, PRL (2016)

- MeV-scale physics like in neutron decay

Complete EFT approach

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



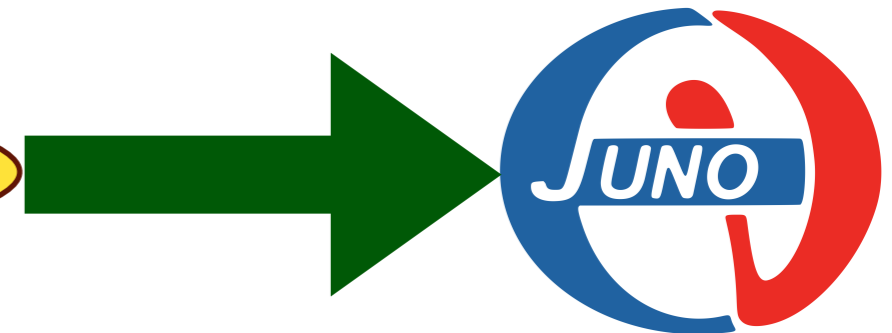
O.T., Few-Body Syst (2023)

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

- four-fermion interaction between leptons and heavy nucleons

$$\mathcal{L}_{\text{eff}} = -\sqrt{2}G_{\text{F}}V_{ud}\bar{e}\gamma_{\mu}P_{\text{L}}\nu_e \cdot \bar{N} (g_{\text{V}}v^{\mu} - 2g_{\text{A}}S^{\mu}) \tau^{+} N$$

Standard Model \rightarrow LEFT \rightarrow HB χ PT \rightarrow \not{n} EFT



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

Low-energy description

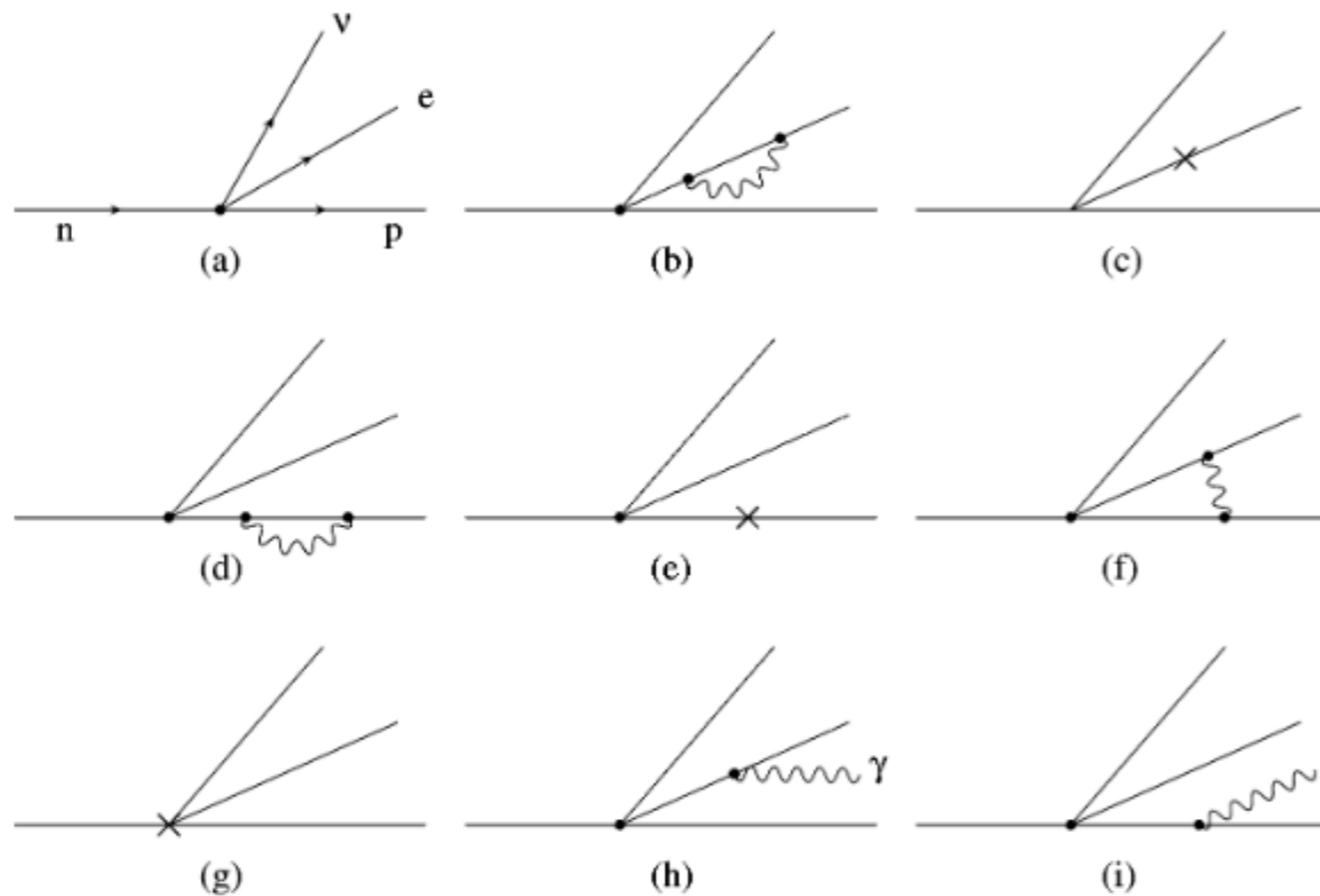
- four-fermion interaction between leptons and heavy nucleons

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

$$m_e \sim M_p - M_n$$

A. Sirlin, Phys. Rev. (1967)

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



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

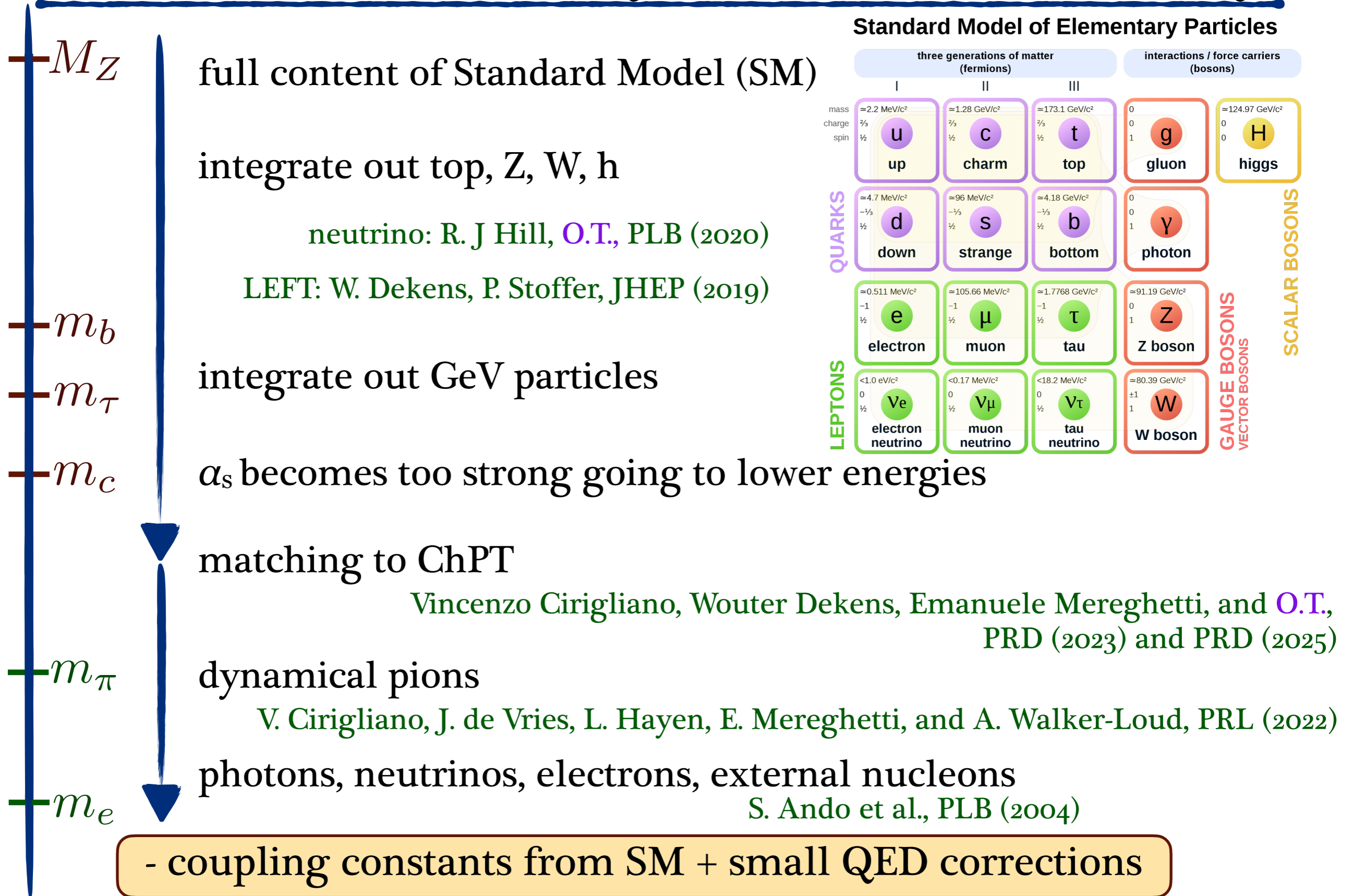
data

Standard Model

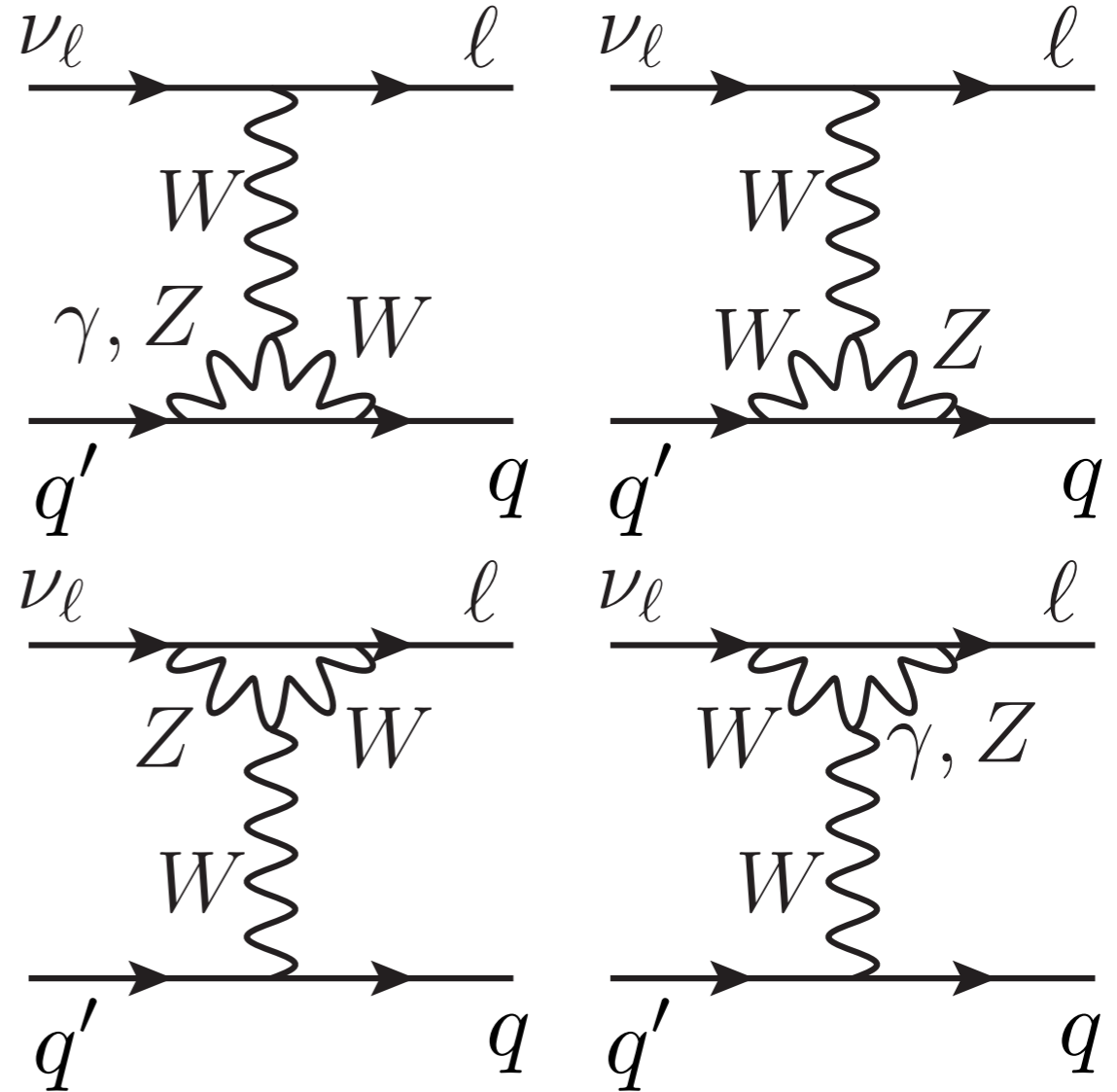
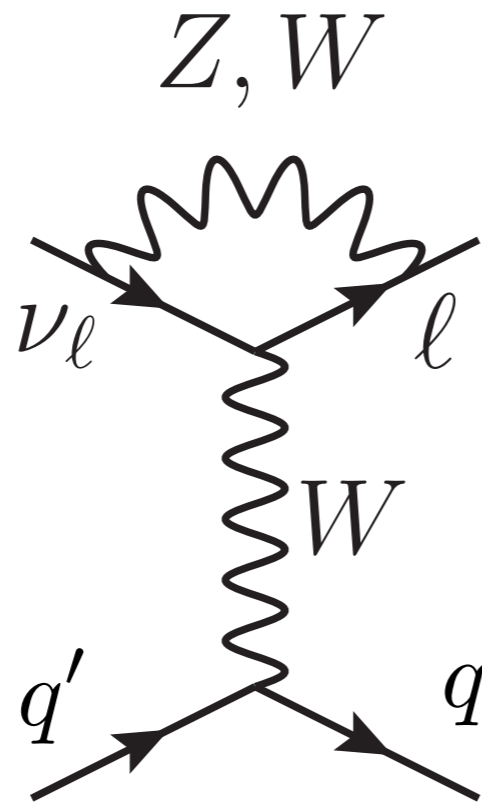
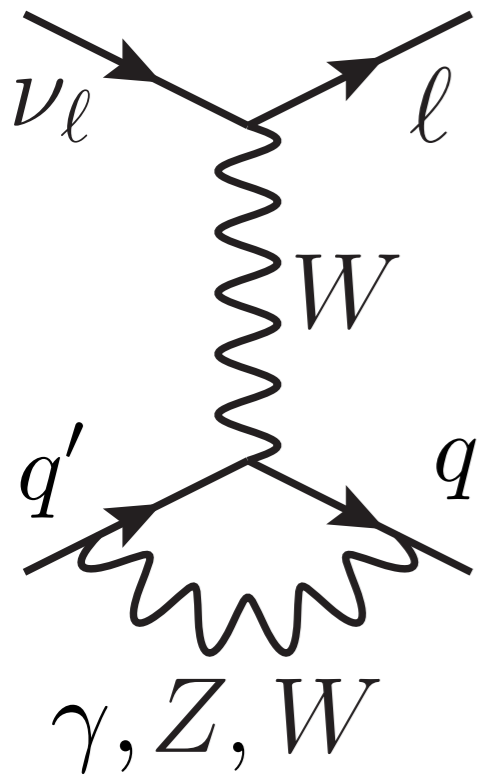
S. Ando et al., PLB (2004)

- two coupling constants predict all observables

Effective field theory for IBD and β decay

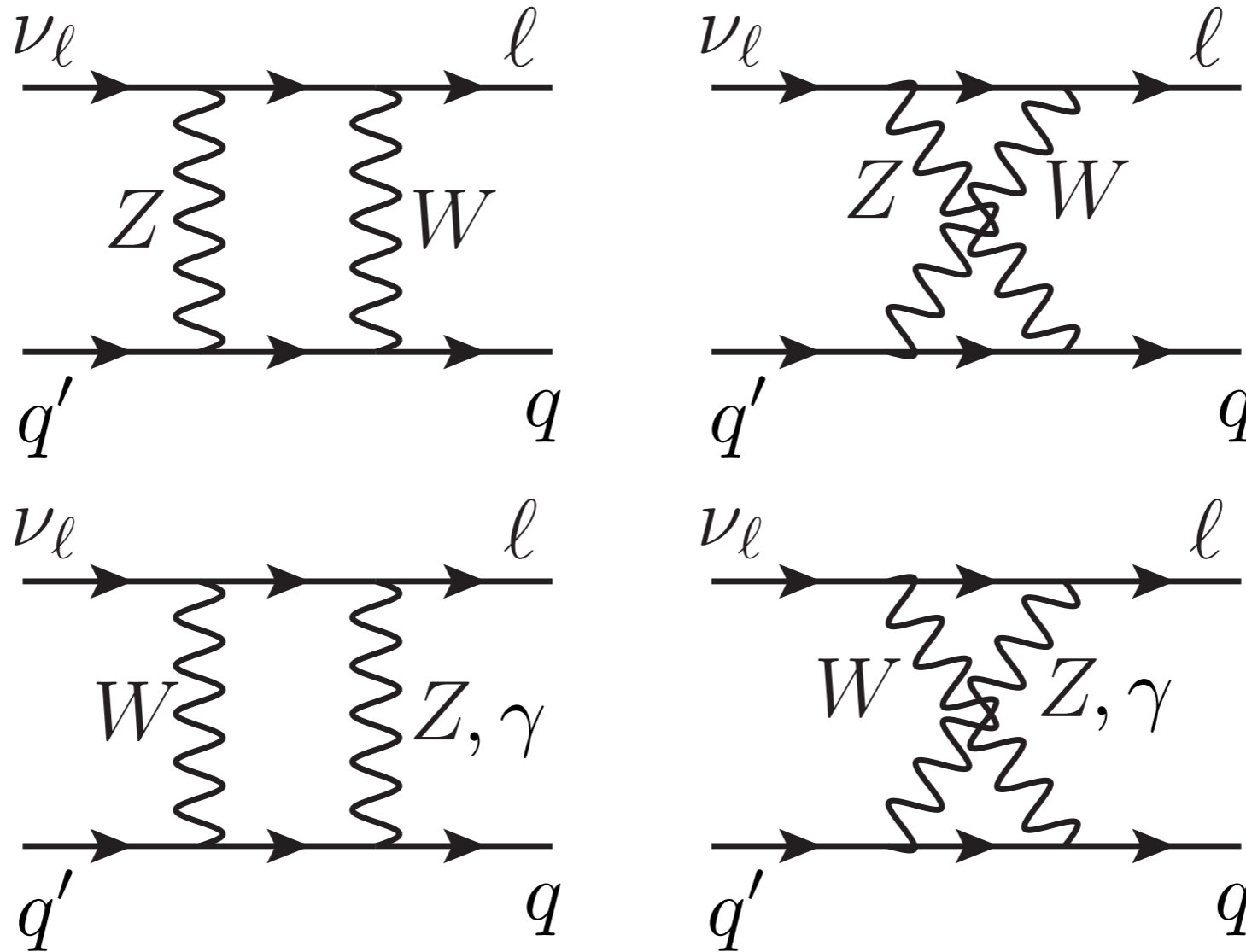


Charged current in SM. Vertexes



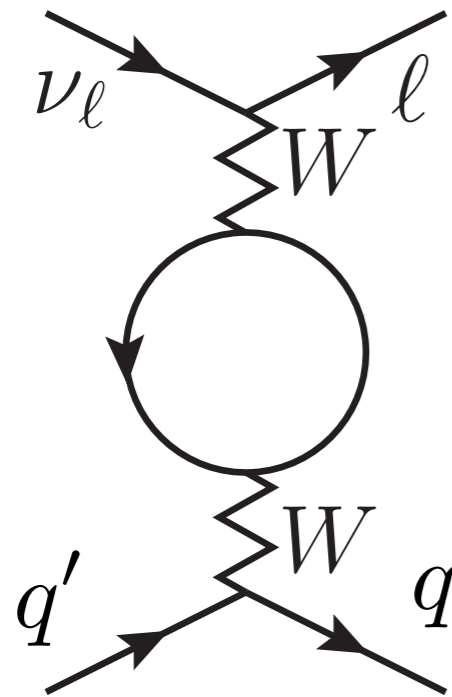
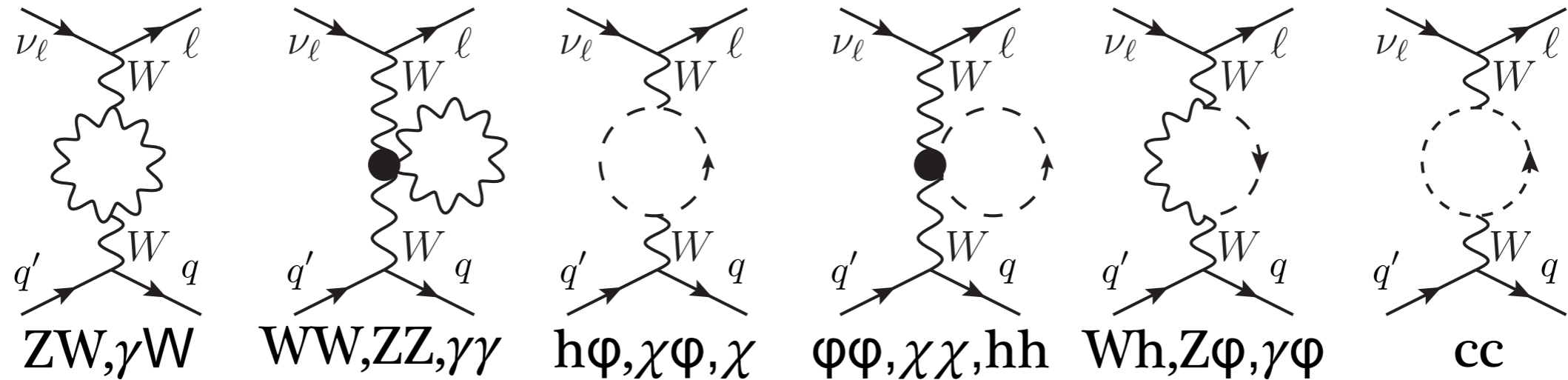
- contribution to effective couplings

Charged current in SM. Boxes



- contribution to effective couplings

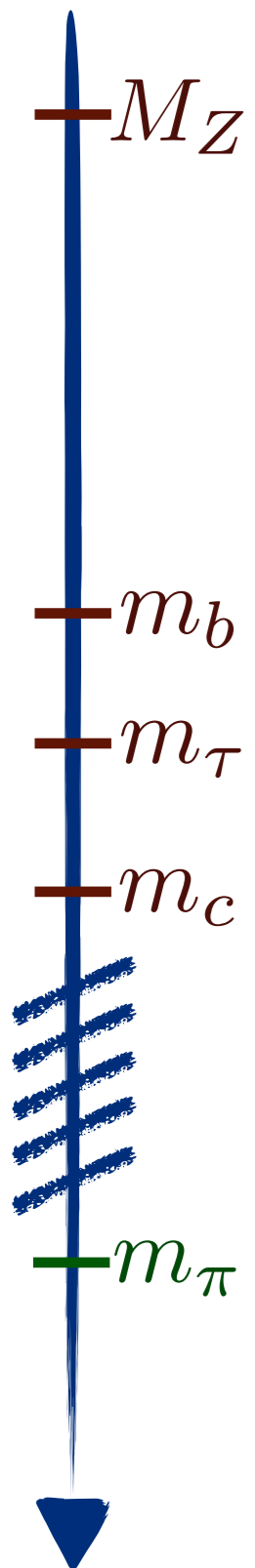
W self energy



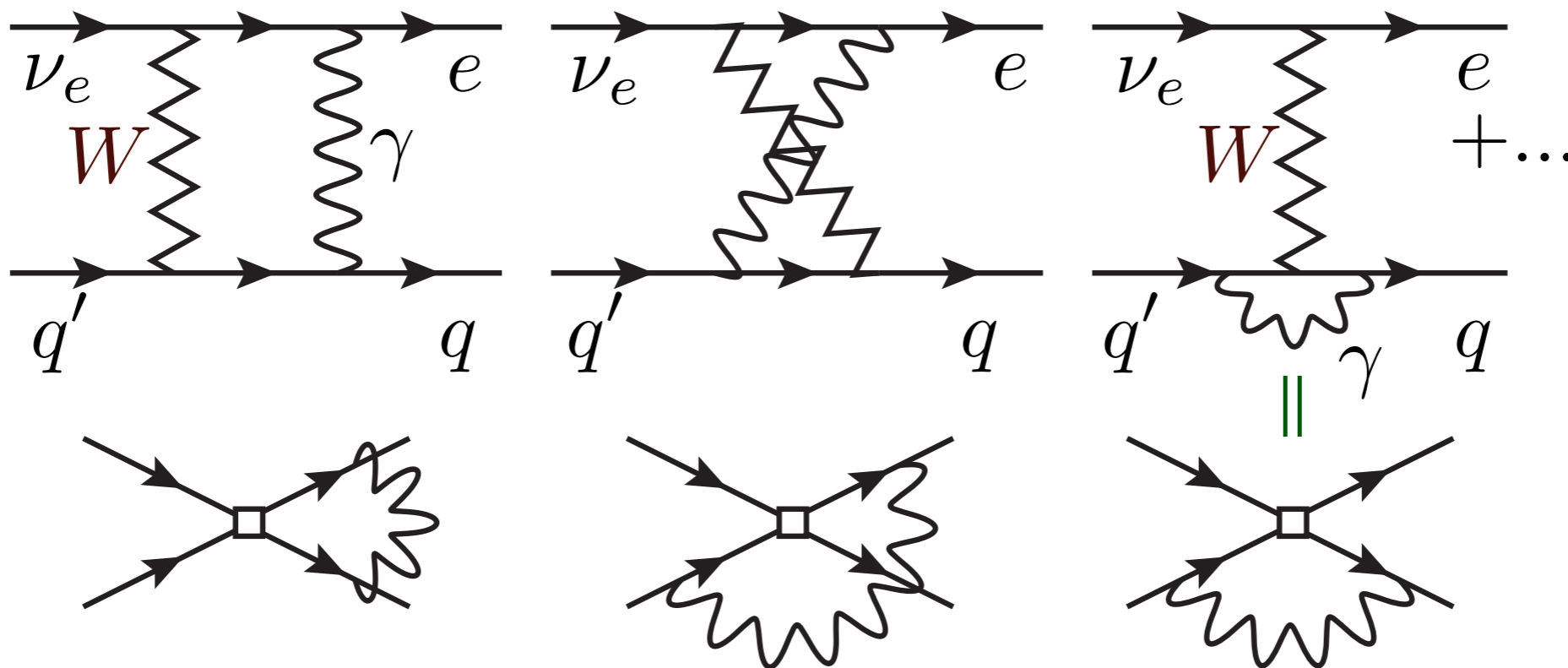
- vanishing contribution to matching besides loops with t quark

- 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

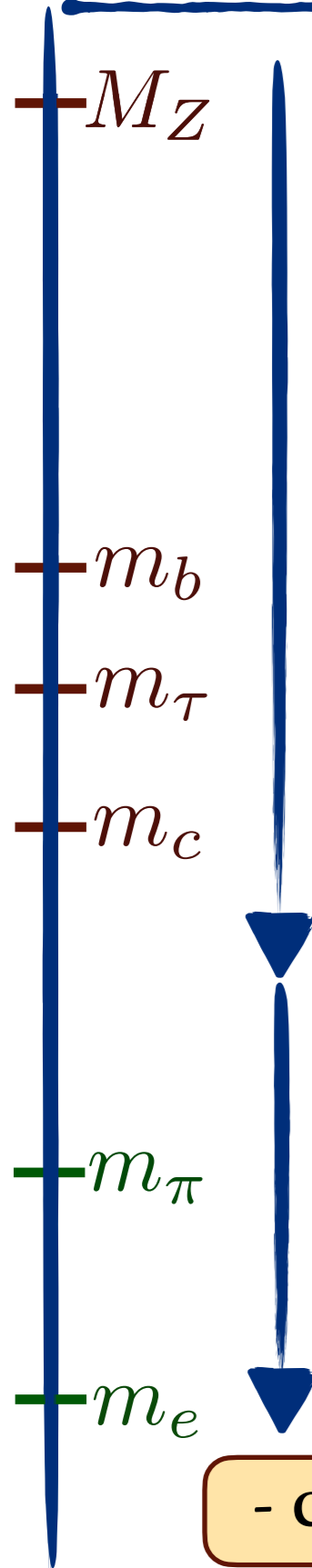
- NDR scheme for γ_5 for evanescent operators E

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

Buras and Weisz, NPB (1990)

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

Effective field theory for IBD and β decay



full content of Standard Model (SM)

integrate out top, Z, W, h

integrate out GeV particles

α_s becomes too strong going to lower energies

matching to ChPT hadron physics

dynamical pions

photons, neutrinos, electrons, external nucleons

- coupling constants from SM + small QED corrections

Standard Model of Elementary Particles

three generations of matter (fermions)			interactions / force carriers (bosons)		
I	II	III			
mass $\approx 2.2 \text{ MeV}/c^2$ charge $\frac{2}{3}$ spin $\frac{1}{2}$ u up	mass $\approx 1.28 \text{ GeV}/c^2$ charge $\frac{2}{3}$ spin $\frac{1}{2}$ c charm	mass $\approx 173.1 \text{ GeV}/c^2$ charge $\frac{2}{3}$ spin $\frac{1}{2}$ t top	0 0 1 g gluon	mass $\approx 124.97 \text{ GeV}/c^2$ 0 0 H higgs	
mass $\approx 4.7 \text{ MeV}/c^2$ charge $-\frac{1}{3}$ spin $\frac{1}{2}$ d down	mass $\approx 96 \text{ MeV}/c^2$ charge $-\frac{1}{3}$ spin $\frac{1}{2}$ s strange	mass $\approx 4.18 \text{ GeV}/c^2$ charge $-\frac{1}{3}$ spin $\frac{1}{2}$ b bottom	0 0 1 γ photon	SCALAR BOSONS	
mass $\approx 0.511 \text{ MeV}/c^2$ charge -1 spin $\frac{1}{2}$ e electron	mass $\approx 105.66 \text{ MeV}/c^2$ charge -1 spin $\frac{1}{2}$ μ muon	mass $\approx 1.7768 \text{ GeV}/c^2$ charge -1 spin $\frac{1}{2}$ τ tau	mass $\approx 91.19 \text{ GeV}/c^2$ 0 1 Z Z boson		GAUGE BOSONS VECTOR BOSONS
mass $< 1.0 \text{ eV}/c^2$ 0 spin $\frac{1}{2}$ ν_e electron neutrino	mass $< 0.17 \text{ MeV}/c^2$ 0 spin $\frac{1}{2}$ ν_μ muon neutrino	mass $< 18.2 \text{ MeV}/c^2$ 0 spin $\frac{1}{2}$ ν_τ tau neutrino	mass $\approx 80.39 \text{ GeV}/c^2$ ± 1 1 W W boson		



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

One-loop result

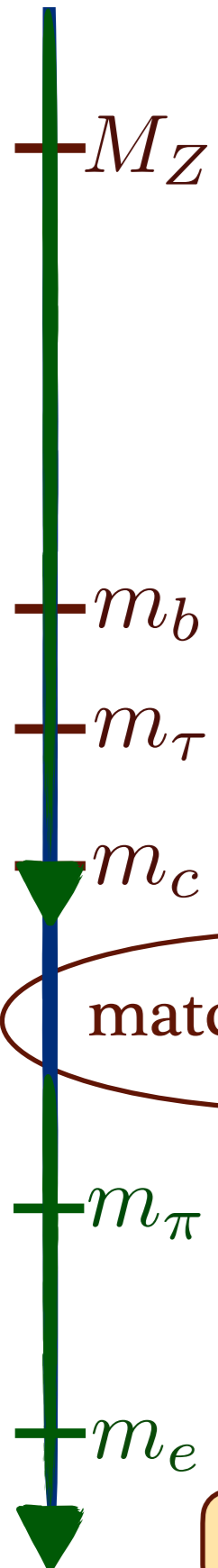
- clear illustration of leading logarithms

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

- 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 \rightarrow 0.07 % effect

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

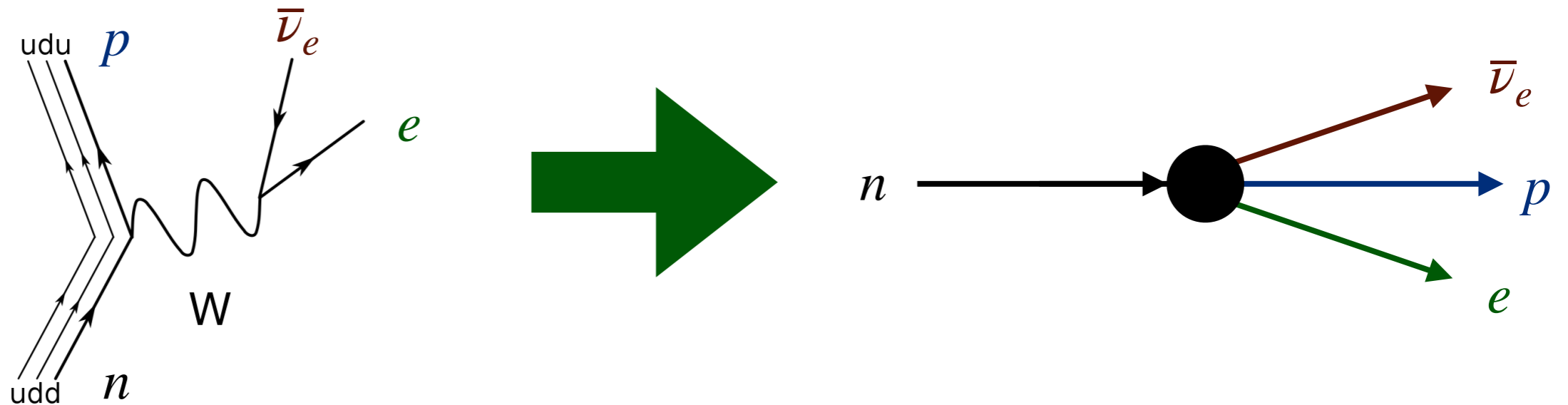
$$|V_{ud}^{0^+ \rightarrow 0^+}| = 0.97373(31)$$

Hardy and Towner, PRC (2020)

- clean neutron lifetime extraction vs superallowed β decays

Complete EFT approach

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



- four-fermion interaction between leptons and heavy nucleons

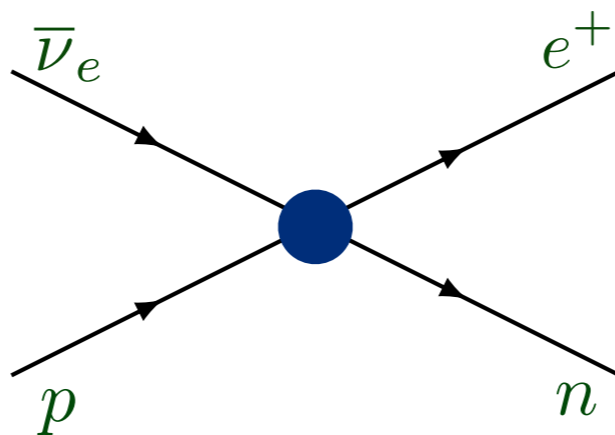
$$\mathcal{L}_{\text{eff}} = -\sqrt{2}G_{\text{F}}V_{ud}\bar{e}\gamma_{\mu}P_{\text{L}}\nu_e \cdot \bar{N} (g_{\text{V}}v^{\mu} - 2g_{\text{A}}S^{\mu}) \tau^{+} N$$

g_{V} : theoretical prediction from Standard Model

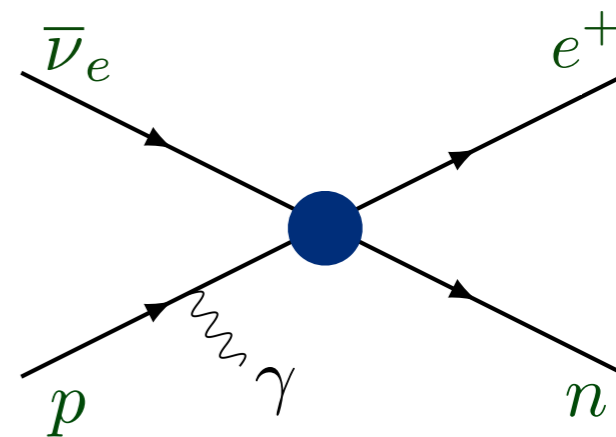
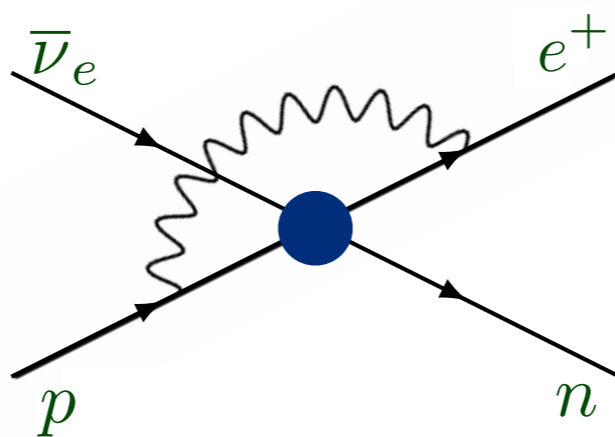
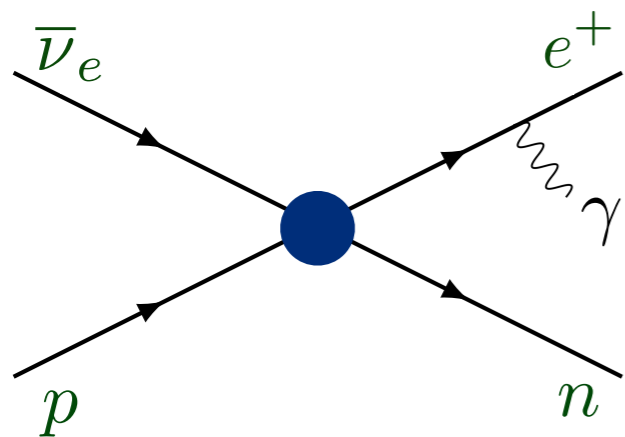
g_{A} : beta asymmetry in polarized neutron decay

V_{ud} : superallowed transitions

- first consistent at 0.1%-level QED radiative corrections



Theory of inverse beta decay for reactor antineutrinos



Bremsstrahlung

- new distributions beyond E_{EM} spectrum

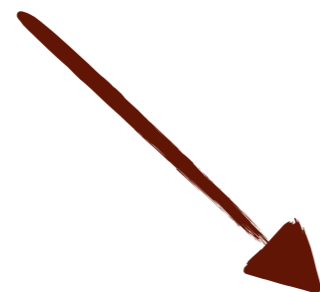
$$E_n, E_\gamma, \theta_n$$



$$E_n, \theta_n$$



$$E_n, E_{EM}$$



total cross section

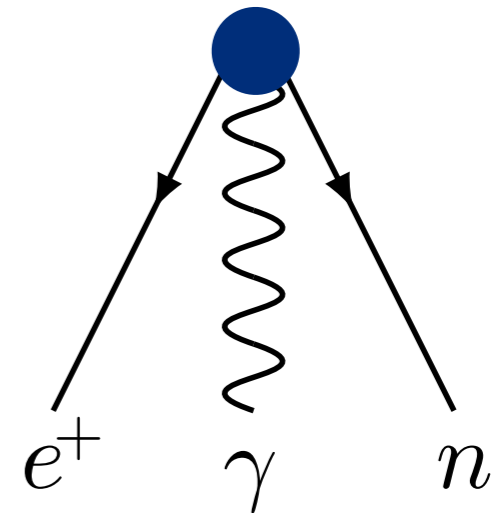
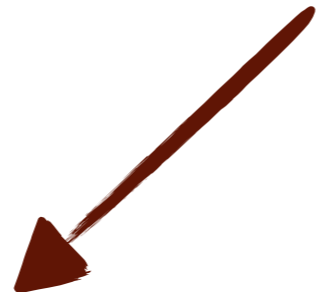
$$E_e, E_\gamma, \theta_e$$



$$E_e, \theta_e$$



$$E_e$$



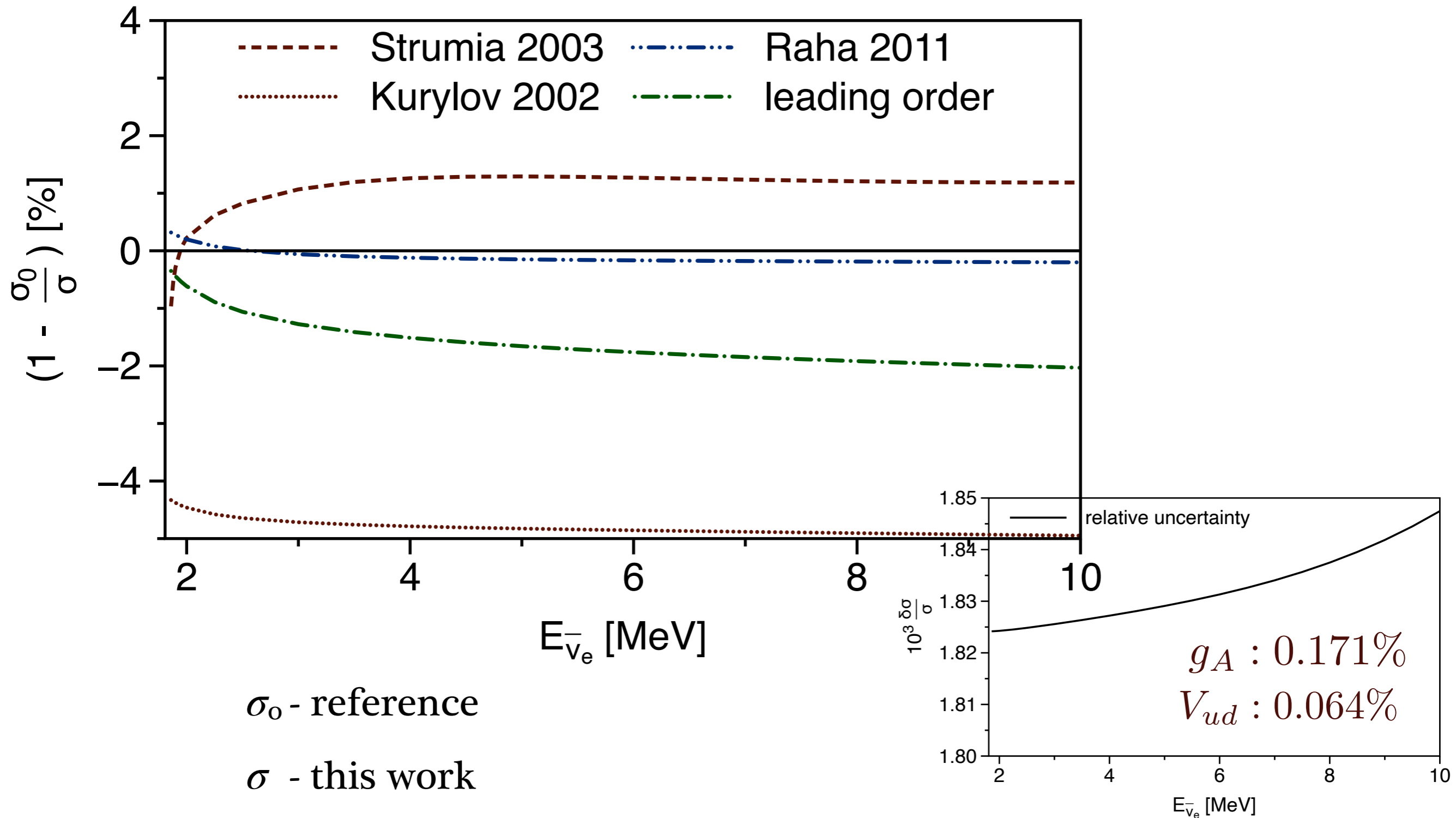
$$E_{EM} = E_e + E_\gamma$$

consistency at
cross-section level

O.T., arXiv:2512.07956
arXiv:2512.07957

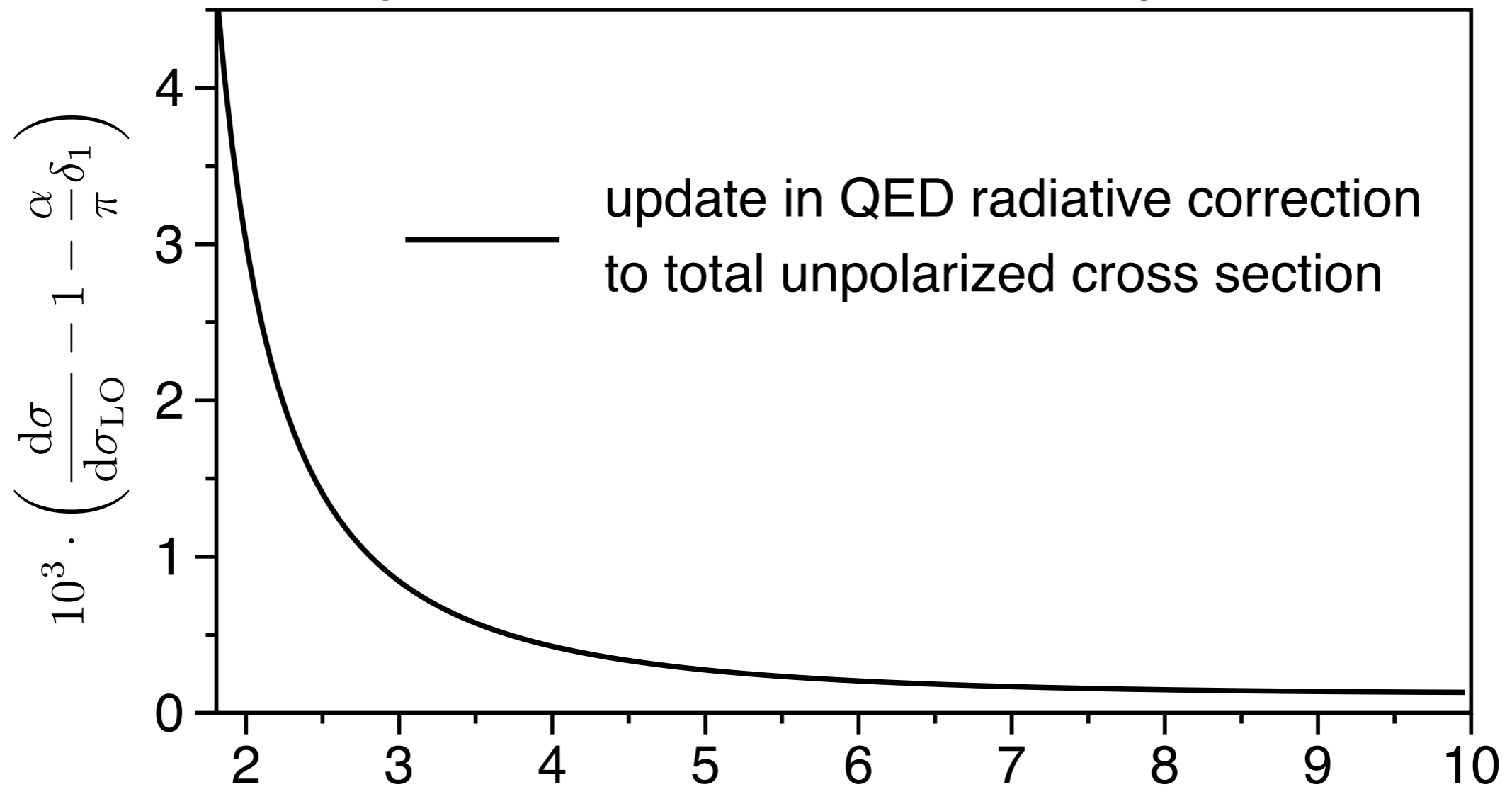
- analytical positron energy spectrum, 2D/3D distributions

Total cross section



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

Total cross section



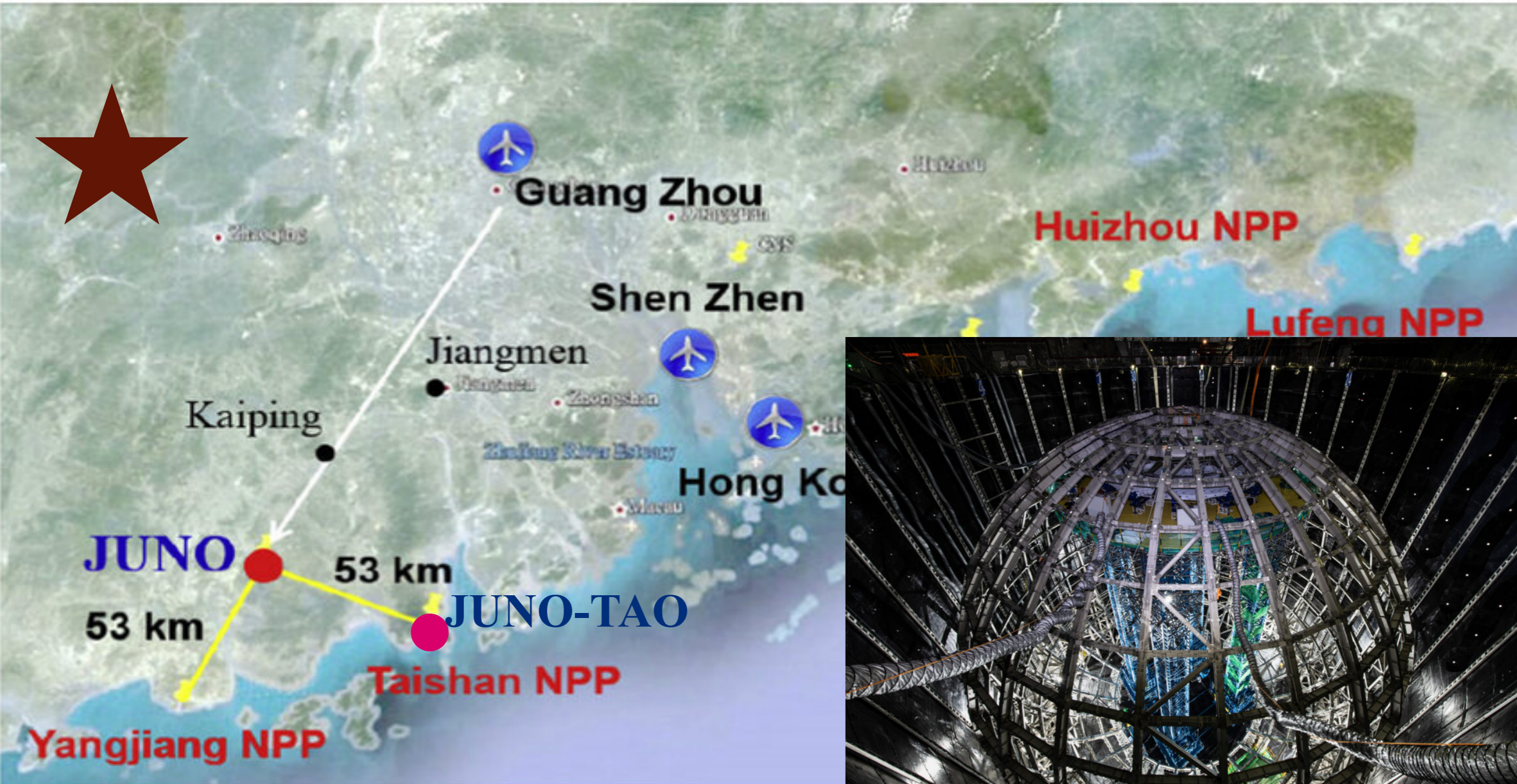
$$E_{\bar{\nu}_e} \approx m_n - m_p + E_{e^+} + E_\gamma + O\left(\frac{1}{M}\right)$$

$E_{\bar{\nu}_e}$ [MeV] 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

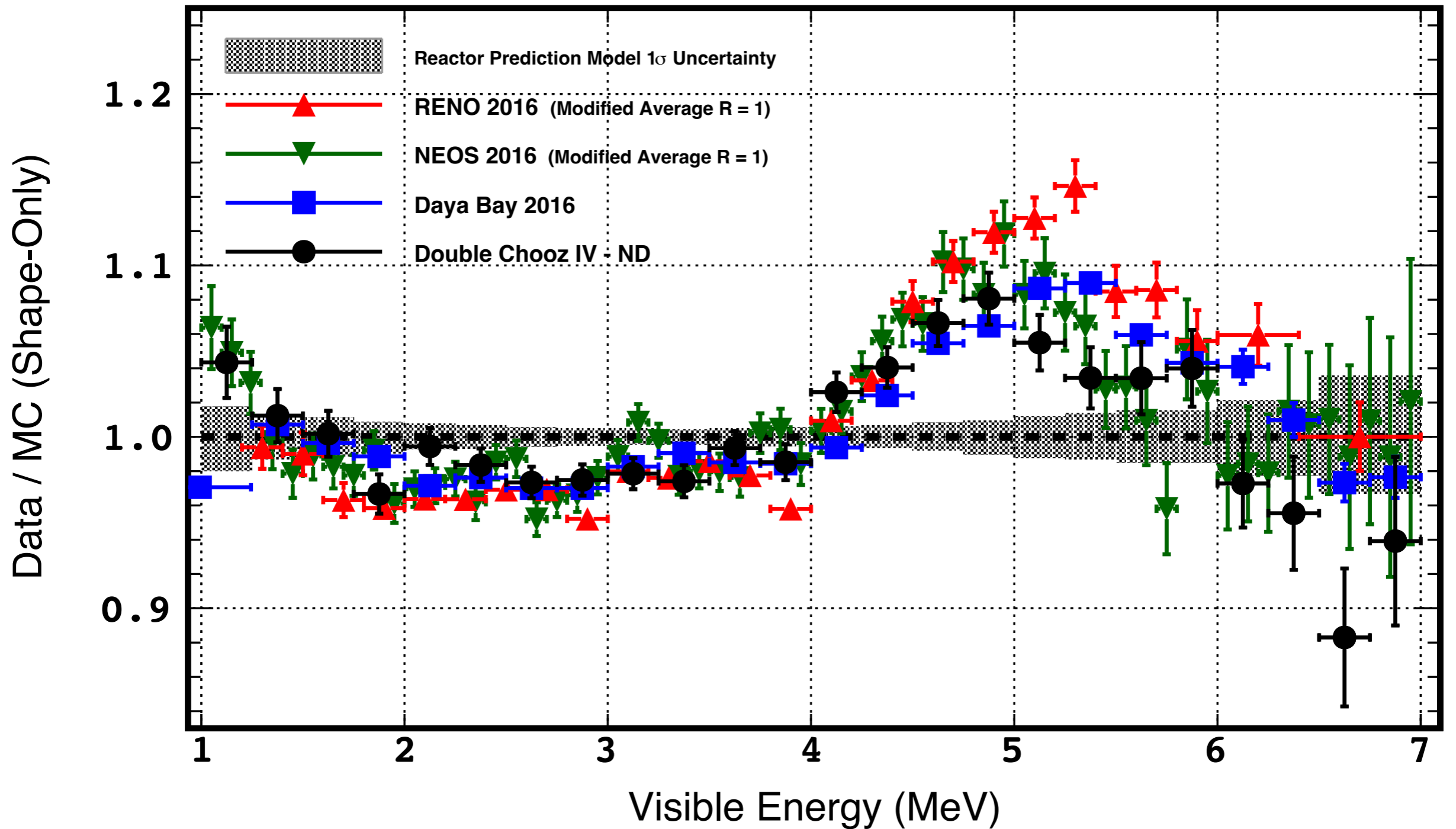
CP violation and mass hierarchy@laboratory

3σ determination of mass hierarchy



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

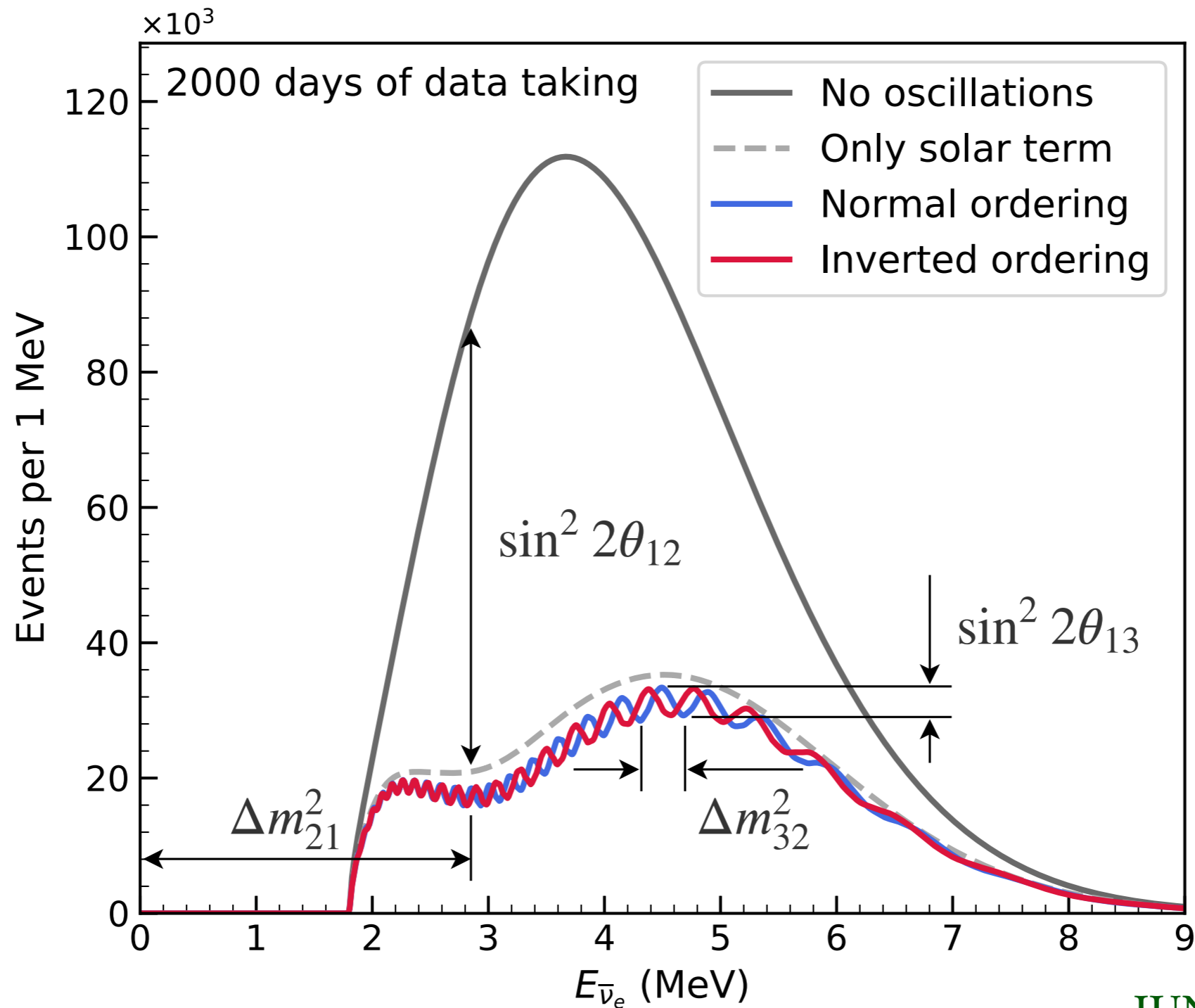
5-MeV flux excess



Double Chooz, Nature Phys (2019)

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

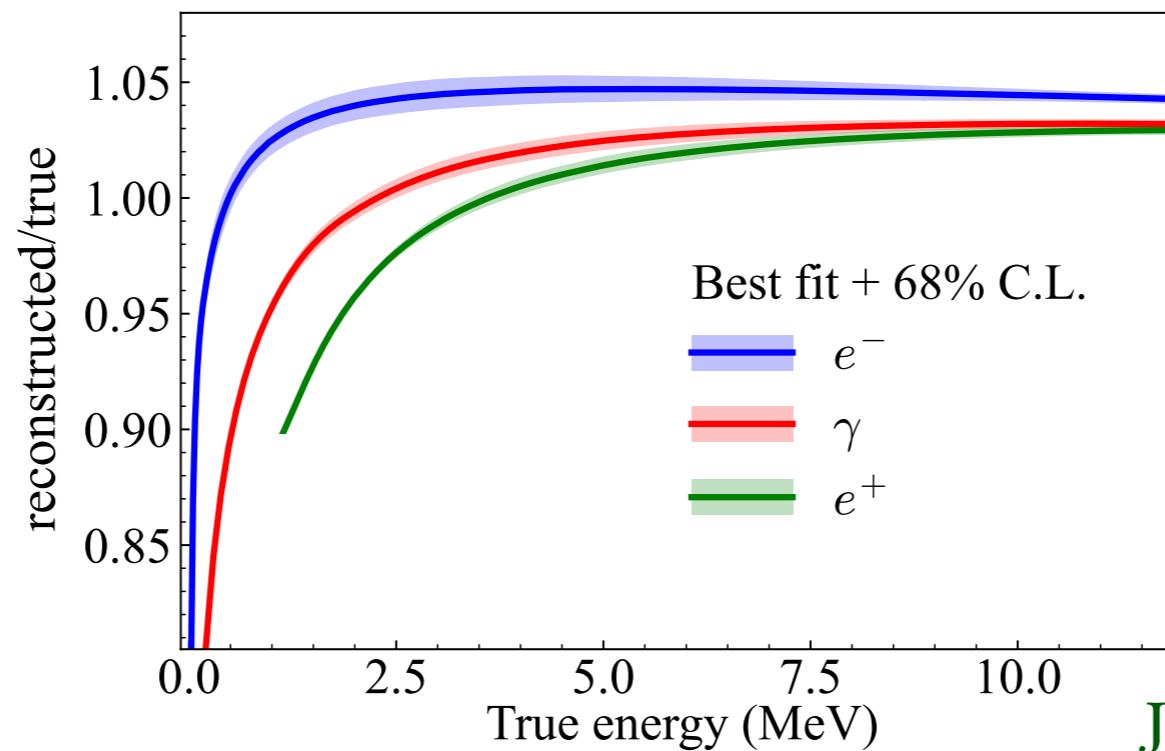
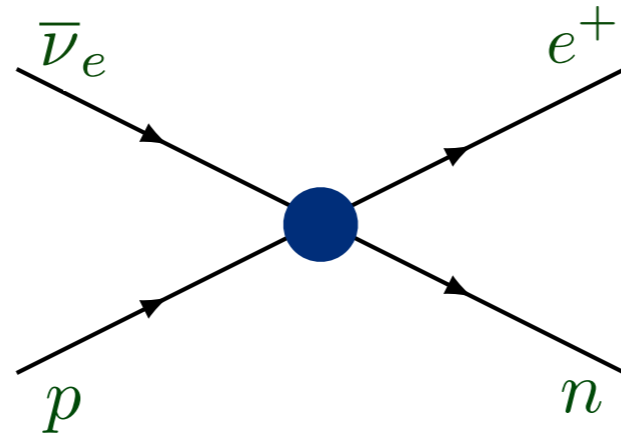
Energy reconstruction is key



JUNO, PPNP (2021)

- JUNO: 3% energy reconstruction for precision goals

Energy reconstruction is key

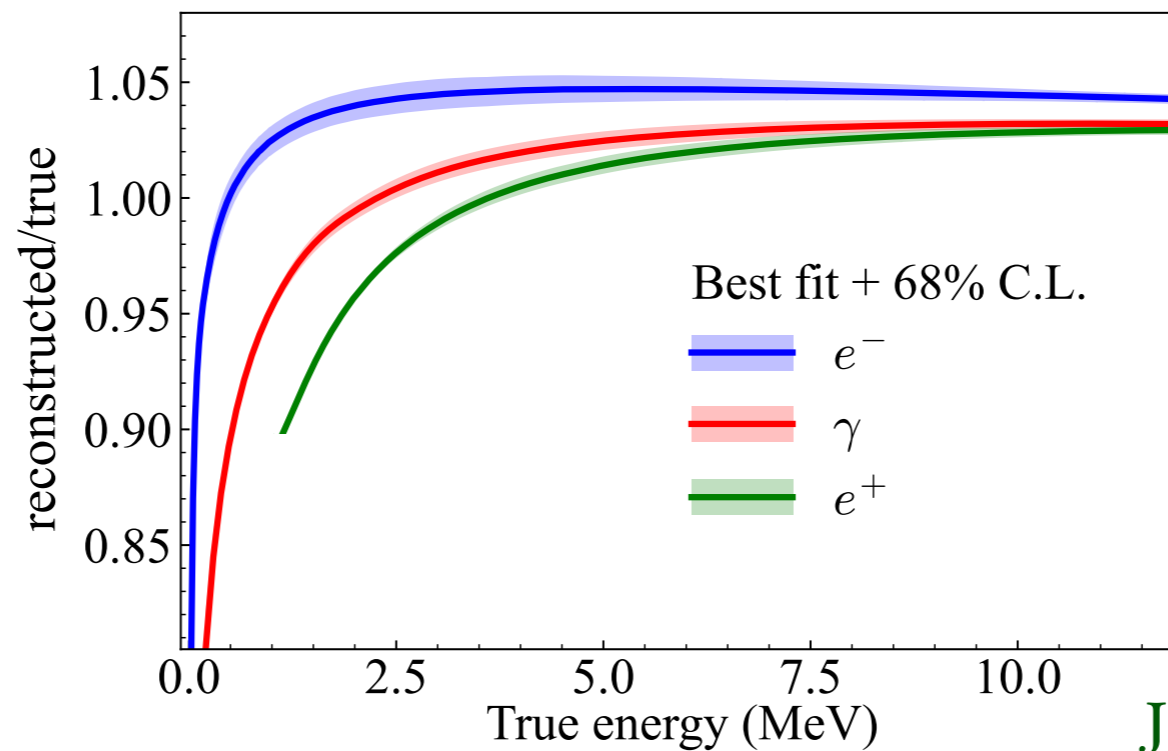
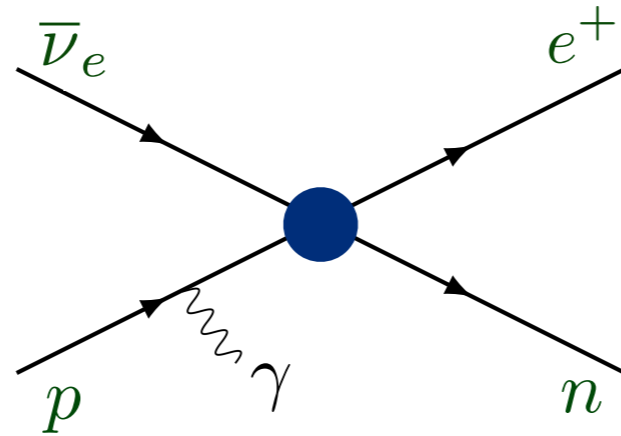


JUNO, arXiv:2511.14590

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

- control over each particle is necessary to achieve precision

Energy reconstruction is key



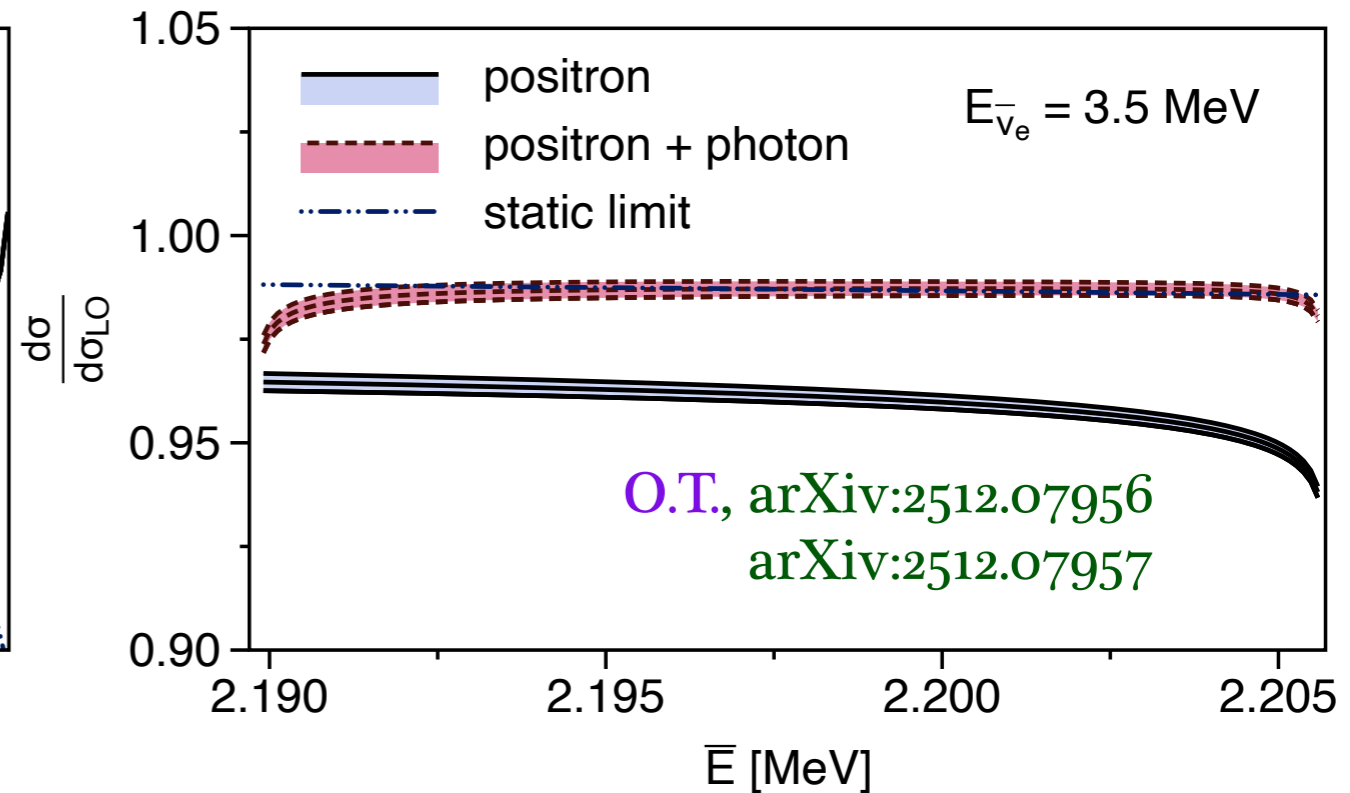
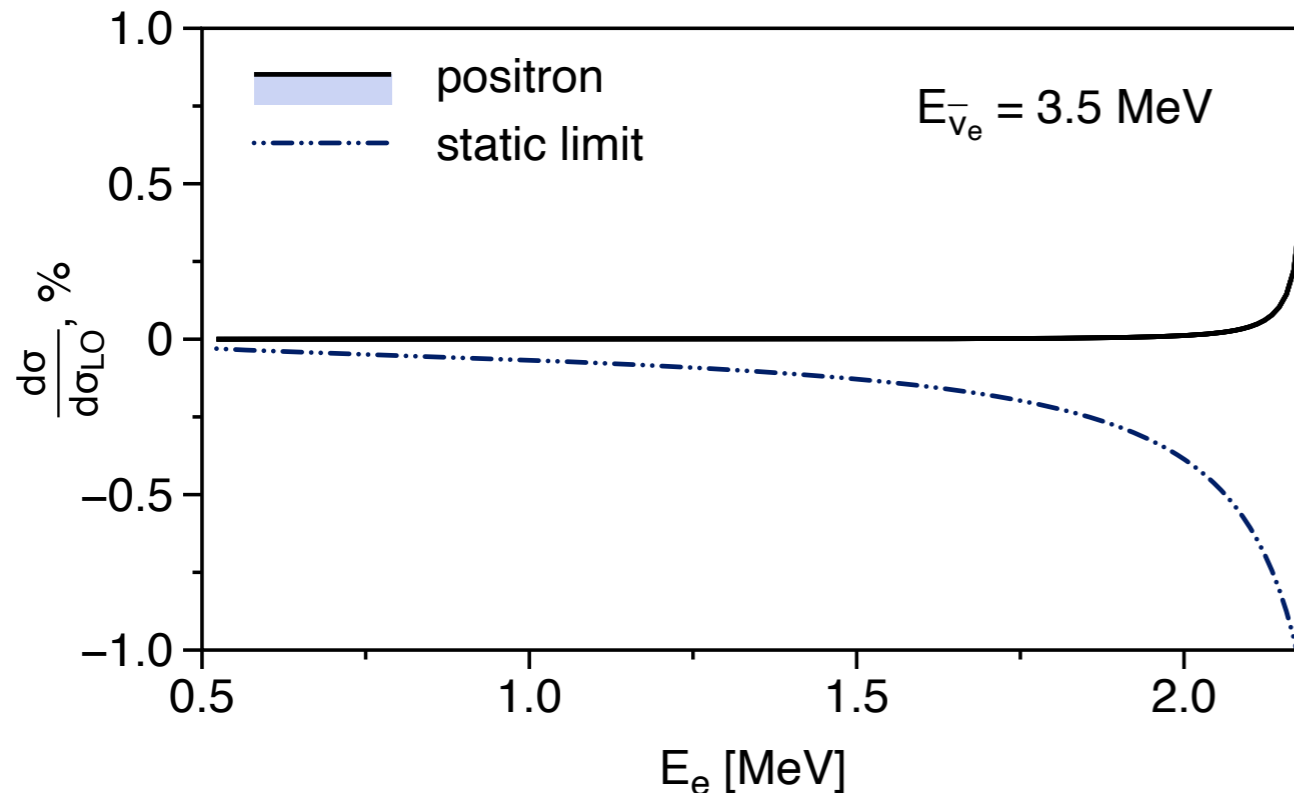
JUNO, arXiv:2511.14590

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

- control over each particle is necessary to achieve precision

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

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

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

Hardy and Towner, PRC (2020)

changes by 1 uncertainty of radiative corrections

- g_A from beta asymmetry in polarized neutron decay

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

CSNS physics!

changes by 1/3 of PERKEO-III experimental uncertainty

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

Conclusions

- radiative corrections and cross sections in EFT framework
- various production and interaction mechanisms at all energy scales
- radiative corrections (1-20%) for consistent uncertainty estimates
- radiative corrections for precise flux determinations
- total and differential $\nu e, \nu_\ell n \rightarrow \ell^- p$ and $\bar{\nu}_\ell p \rightarrow \ell^+ n$
flavor ratios evaluated from theory with rigorous error analysis
- most precise calculation of neutron lifetime with rigorous errors

$$\nu e^- \rightarrow \nu e^- (\gamma)$$

$$\pi^+ \rightarrow \mu^+ \nu_\mu (\gamma)$$

$$K^+ \rightarrow \mu^+ \nu_\mu (\gamma)$$

$$\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu (\gamma)$$

Thanks for your attention !!!

$$\bar{\nu}_\ell p \rightarrow \ell^+ n (\gamma)$$

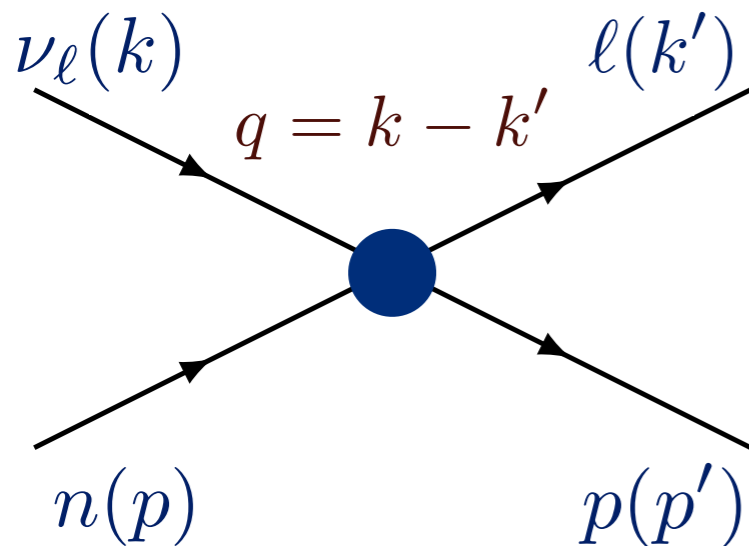
谢谢

$$\nu_\ell n \rightarrow \ell^- p (\gamma)$$

$$n \rightarrow p e^- \bar{\nu}_e$$

$$\nu \text{}^{40}\text{Ar} \rightarrow \nu \text{}^{40}\text{Ar} (\gamma)$$

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

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

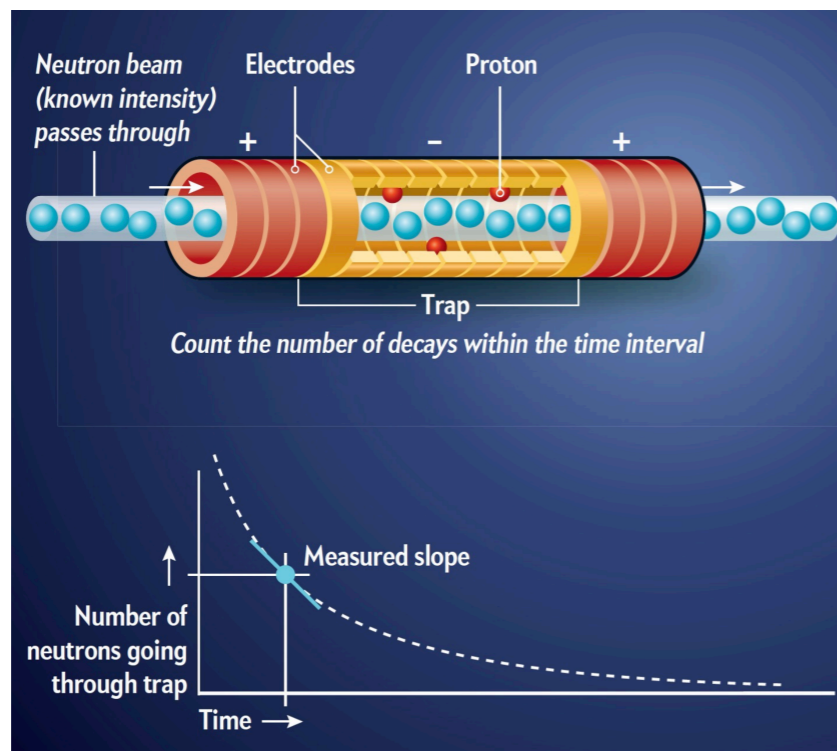
$$+ \sqrt{2}G_F V_{ud} \frac{m_\ell}{M} \frac{f_T}{4} \bar{\ell}^- \sigma^{\mu\nu} P_L \nu_\ell \bar{p} \sigma_{\mu\nu} n$$

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

Neutron lifetime measurements



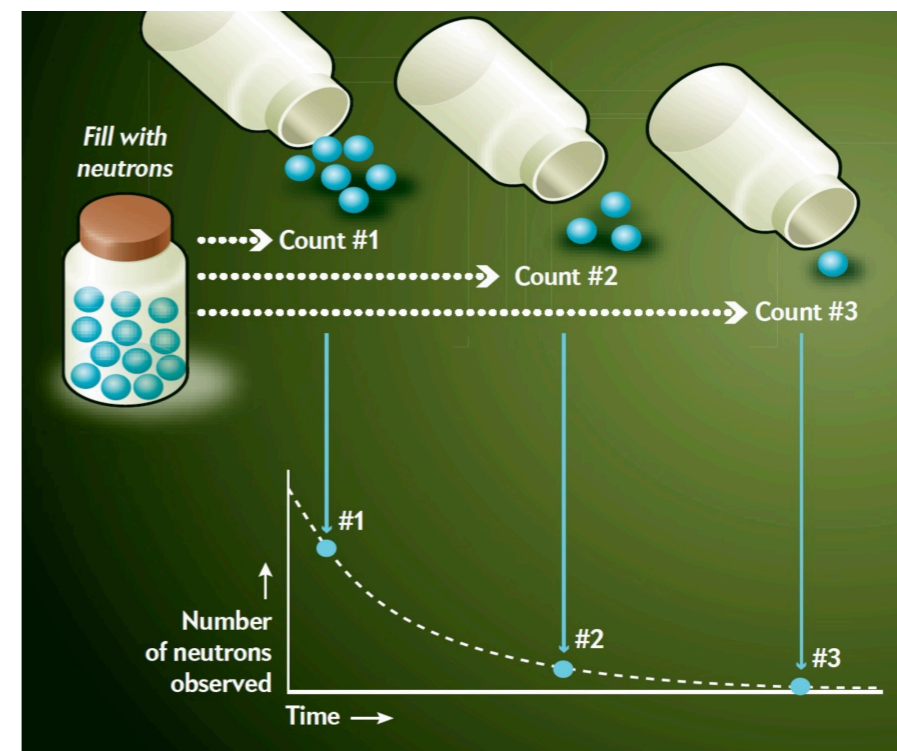
beam method



how many neutrons pass?

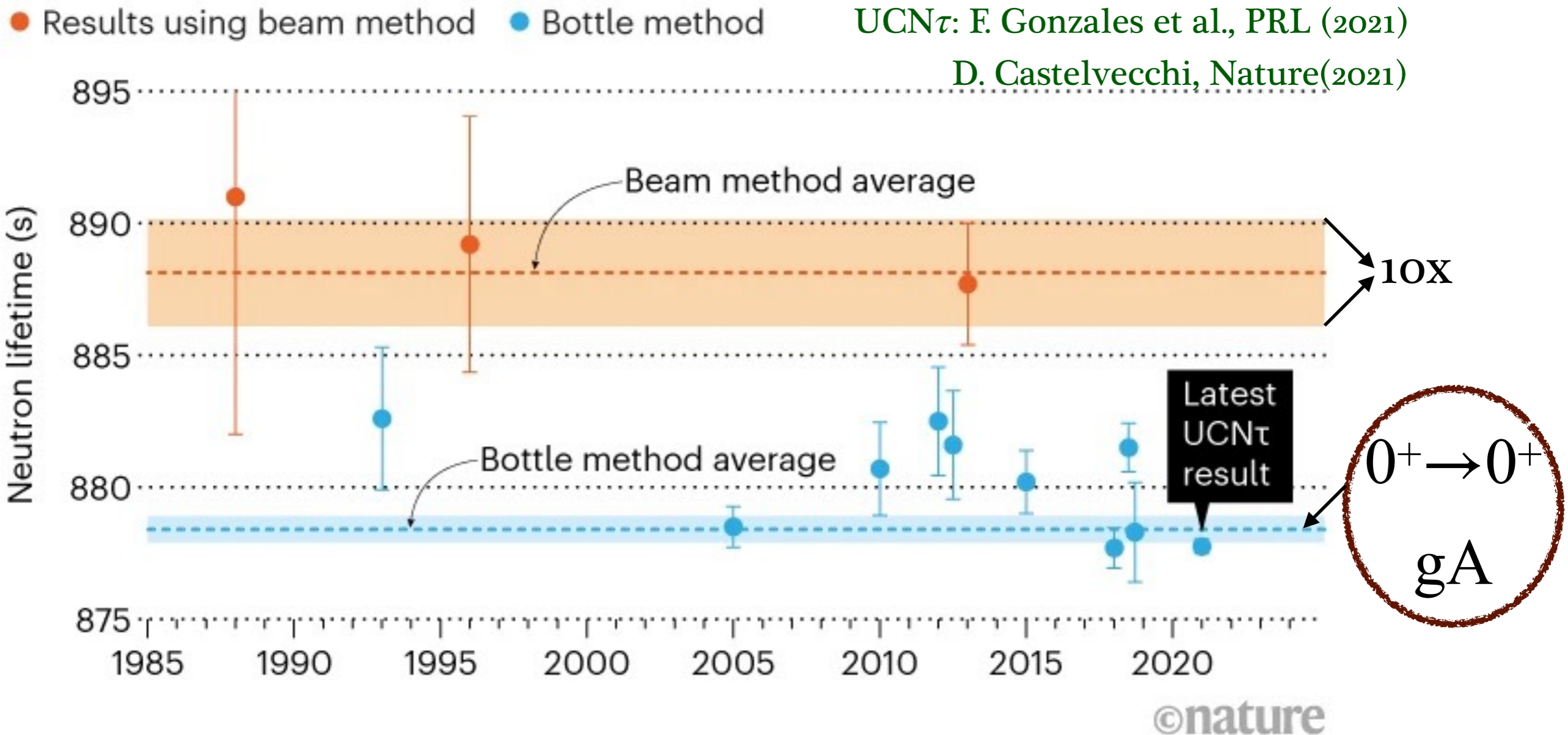


bottle method



how many neutrons survive?

Neutron lifetime puzzle

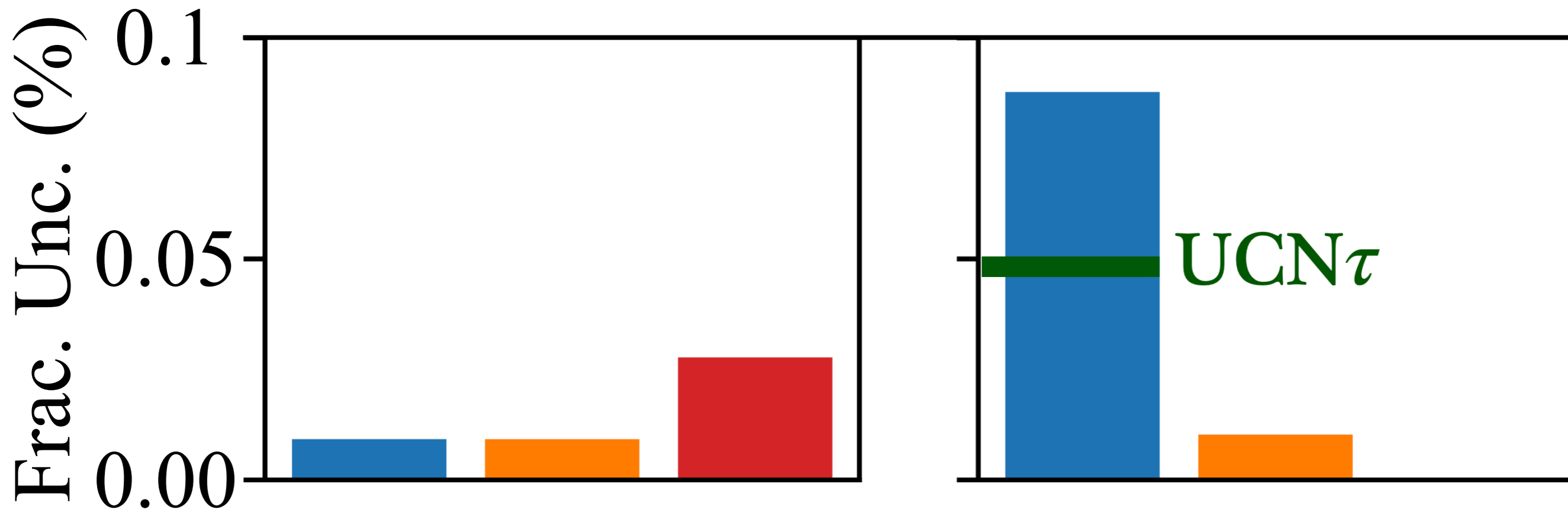


- 8-9 seconds discrepancy beam vs bottle method : $3-5\sigma$
- V_{ud} from $0^+ \rightarrow 0^+ + gA$ from β asymmetry \equiv bottle
- 0.3 seconds uncertainty of UCN τ @LANL : $(3 - 4) \times 10^{-4}$

V_{ud} determinations

$0^+ \rightarrow 0^+$

Neutron



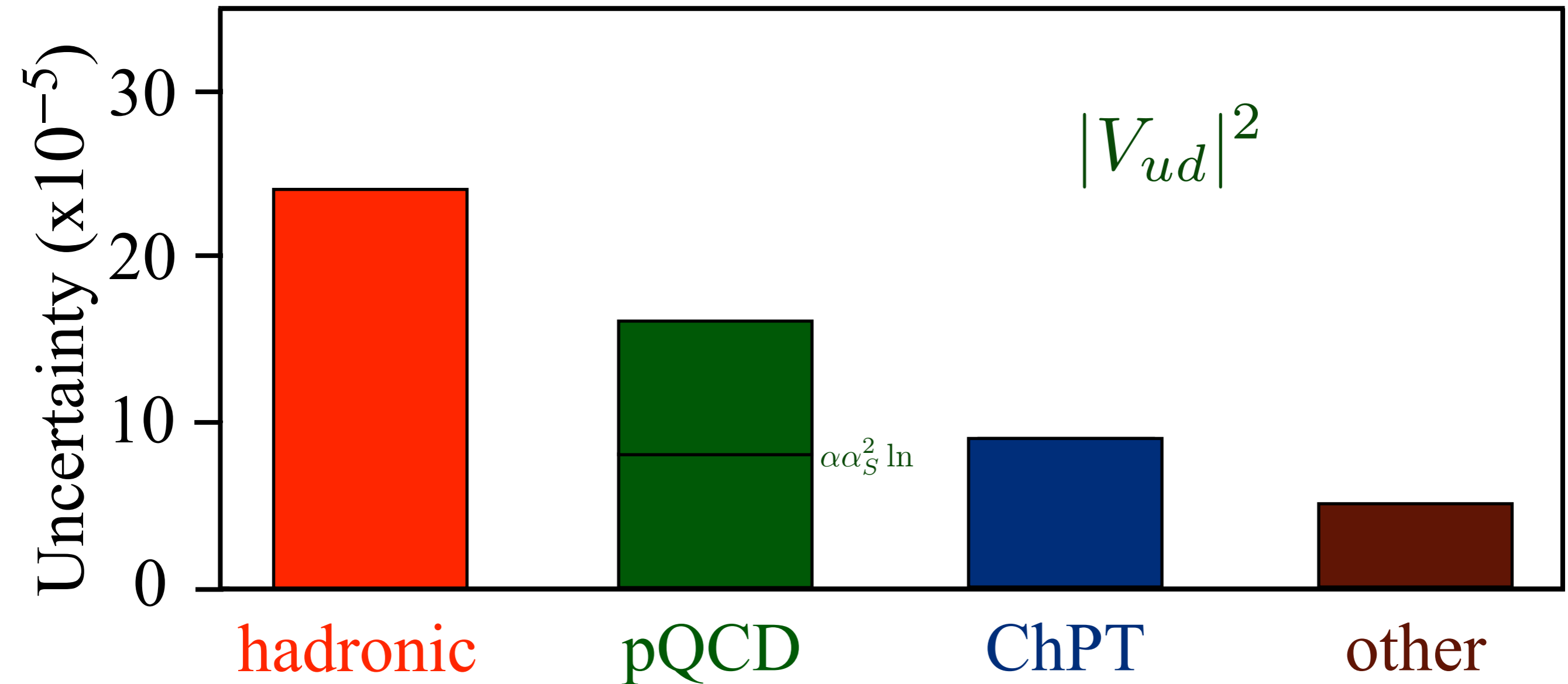
Experiment Radiative Nuclear

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

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

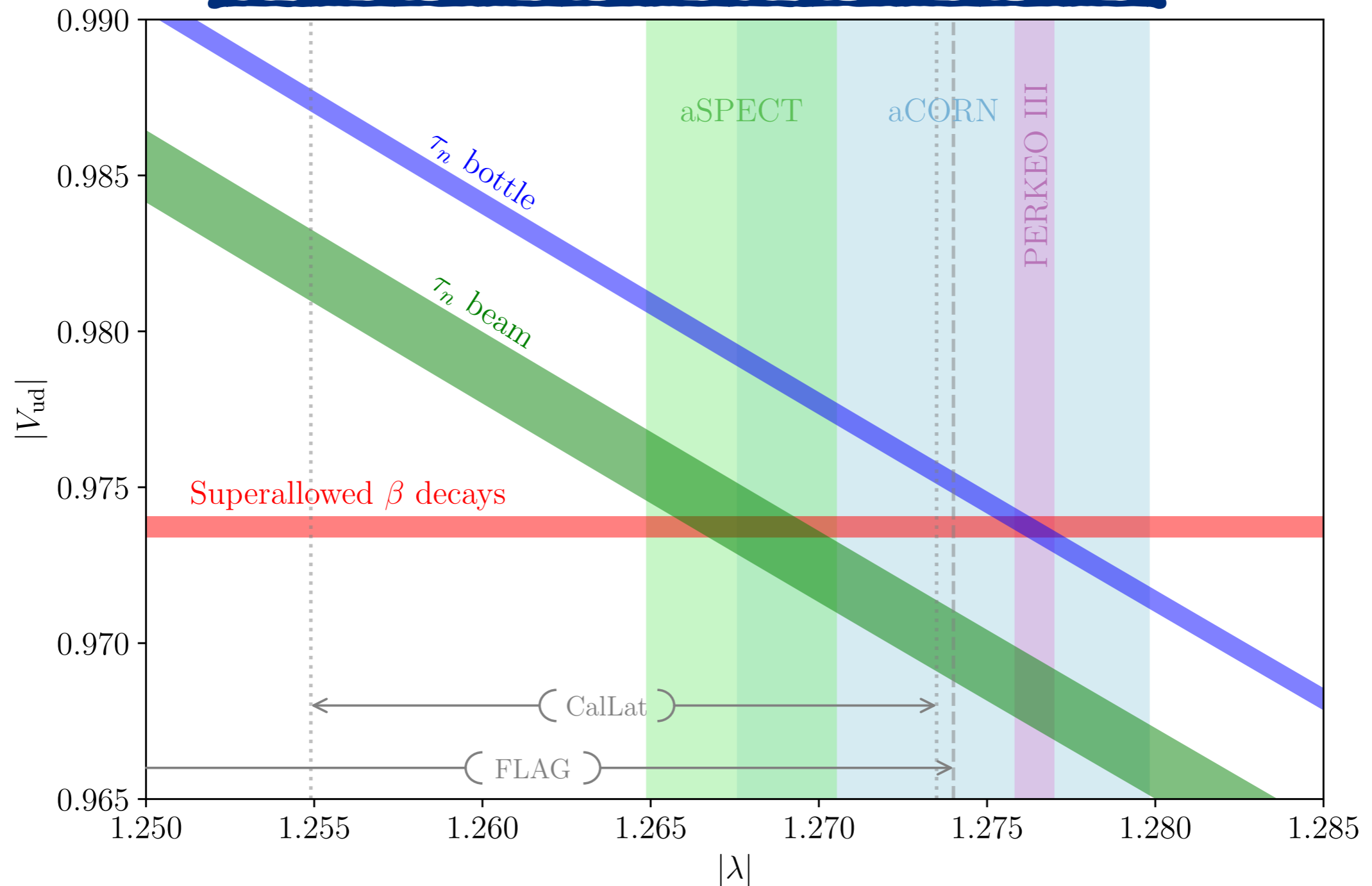
Our work

- 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 g_A 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

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

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

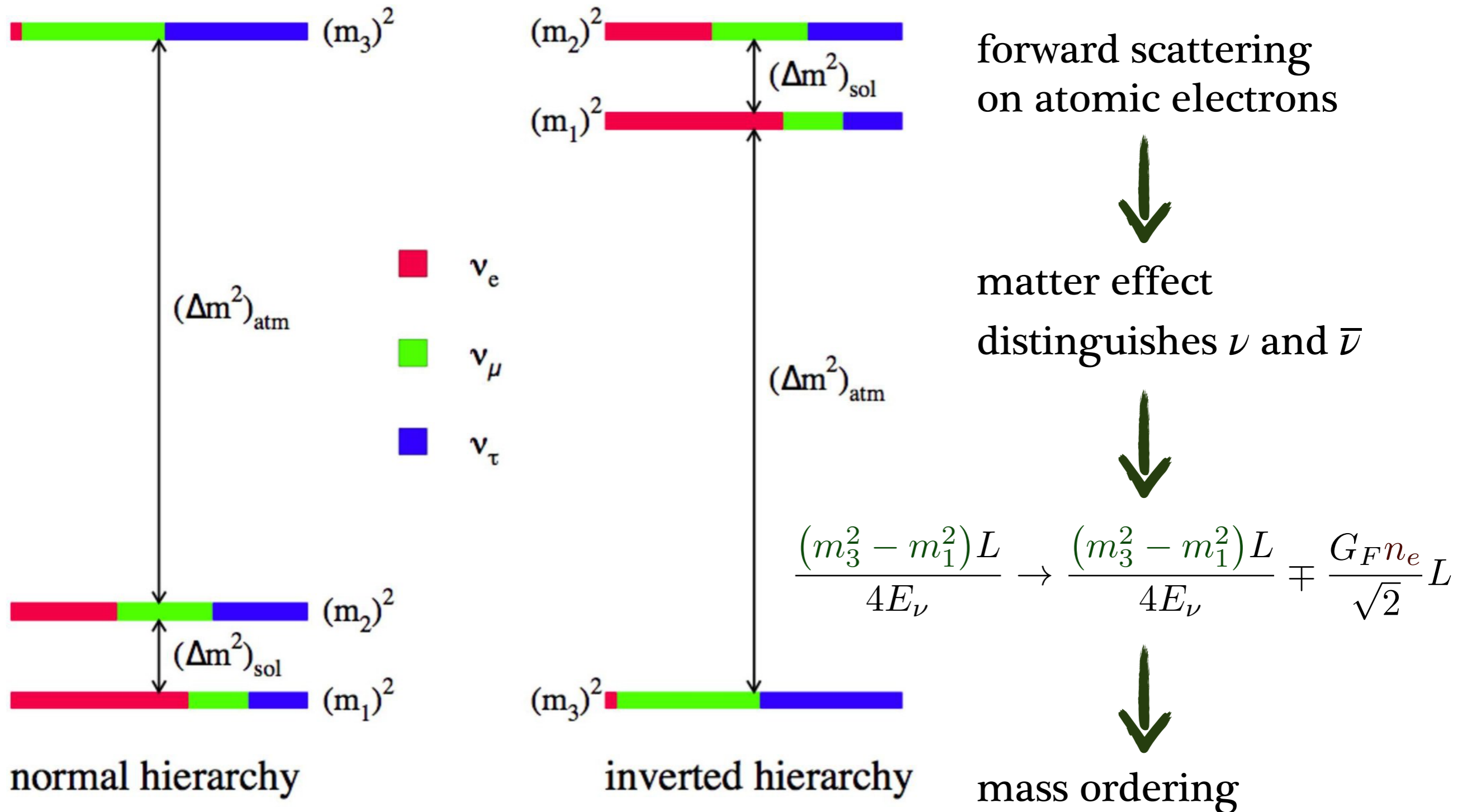
explain ~ half of radiative correction to **neutron lifetime**

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

m_e

- g_V, g_A encode electroweak logarithms and hadronic corrections

Neutrino mass hierarchy



- matter effects can resolve neutrino mass hierarchy