EFT for New Physics Searches in Neutrino Oscillations

Joachim Kopp (JGU Mainz) • Moriond 2026

Image based on a cartoon by Charles Addams

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PRISMA++

Image based on a cartoon by Charles Addams

Neutrinos are weird.

Image based on a cartoon by Charles Addams

Neutrinos are weird.

This is true already in the SM.

Image based on a cartoon by Charles Addams

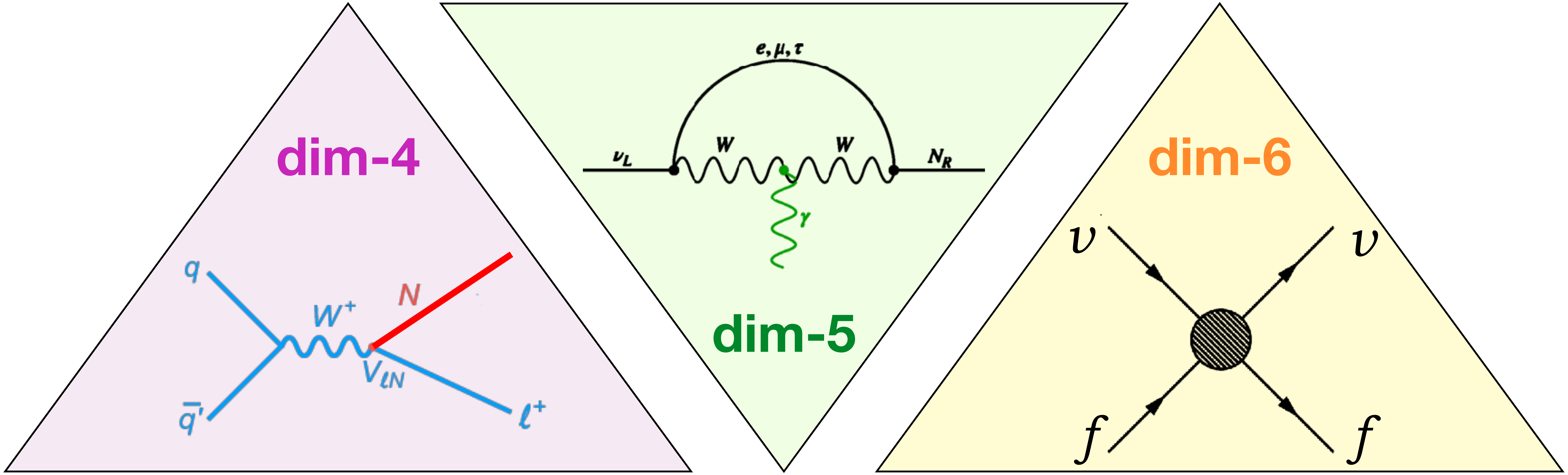
Neutrinos are weird.

This is true already in the SM.

But could they be even more weird?

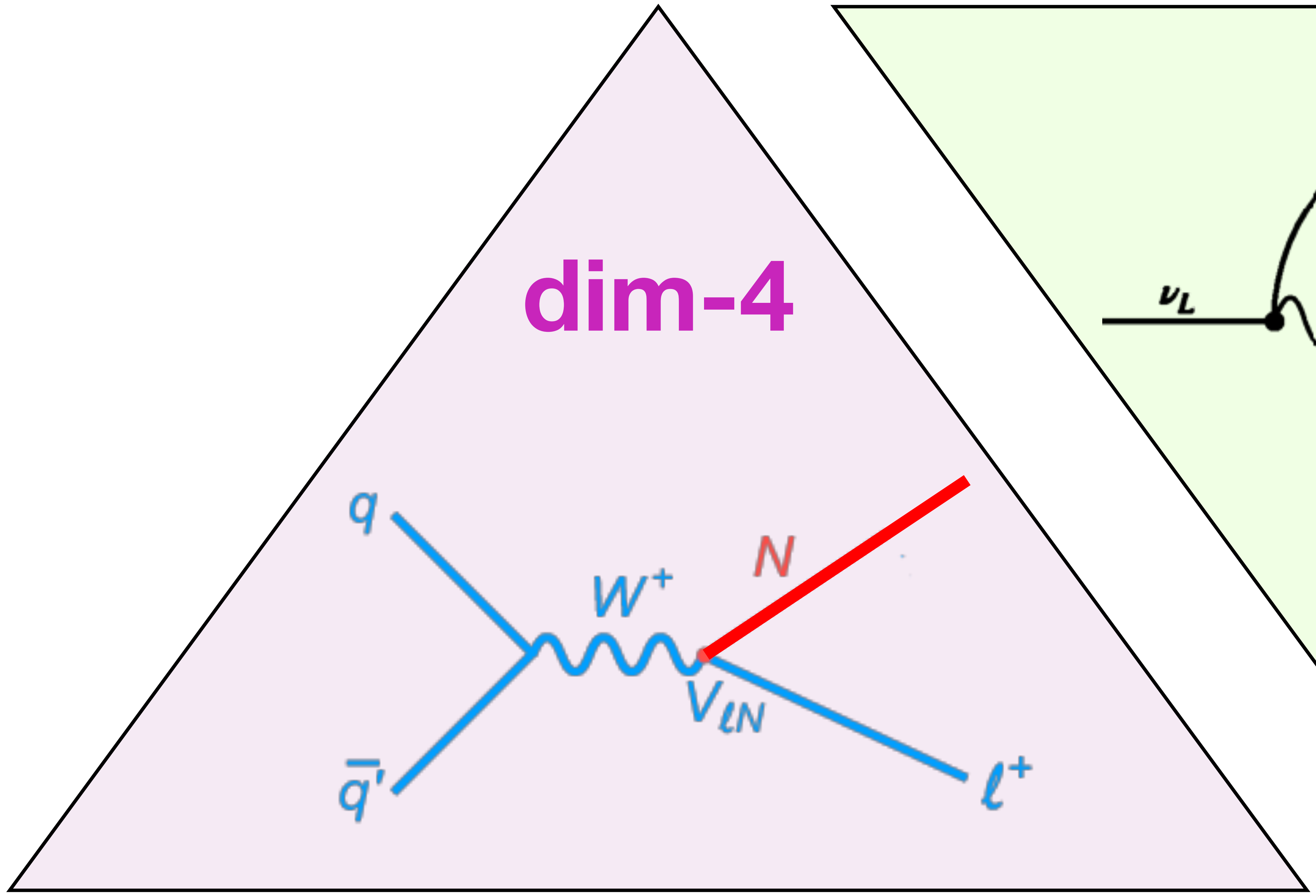
Image based on a cartoon by Charles Addams

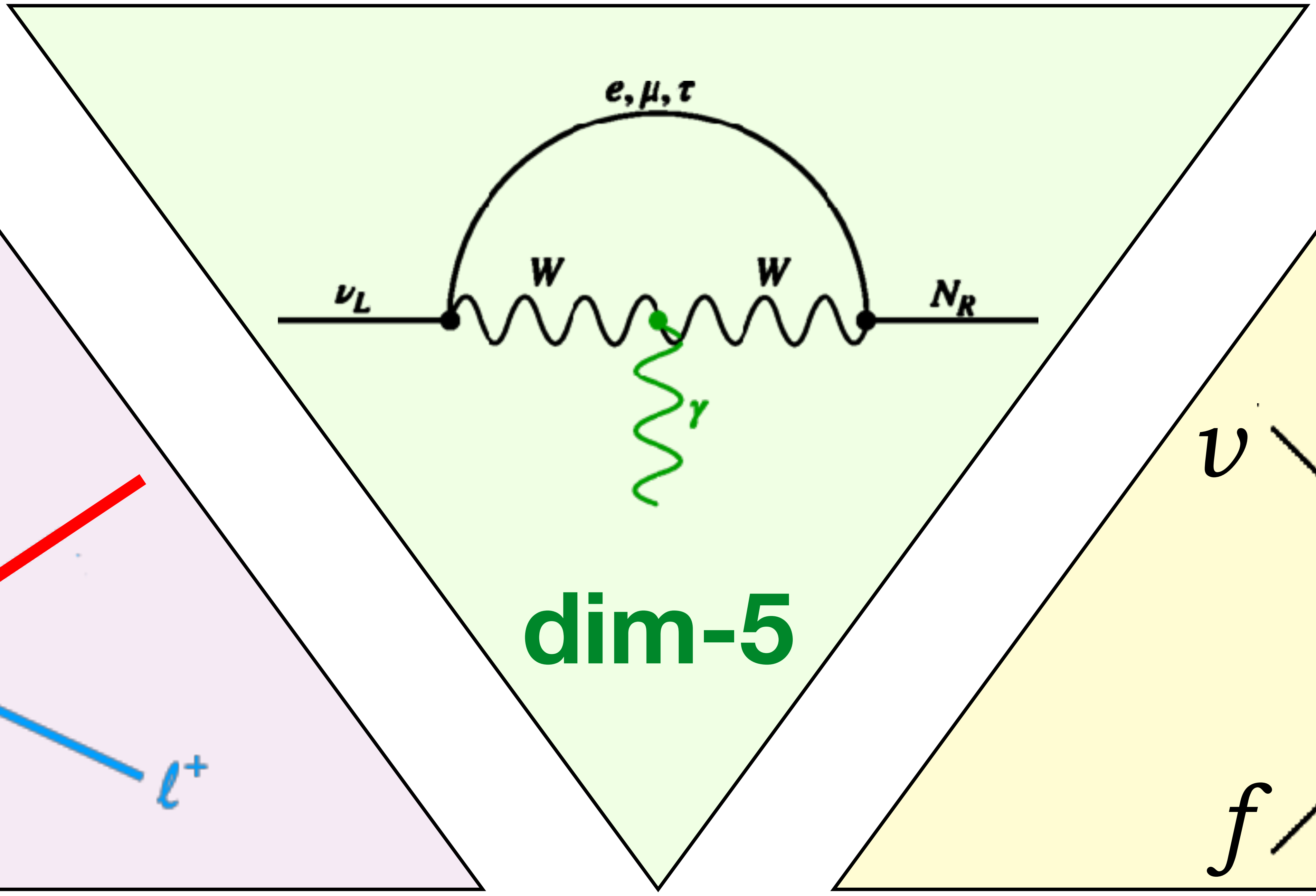
Neutrino Physics Beyond the Standard Model

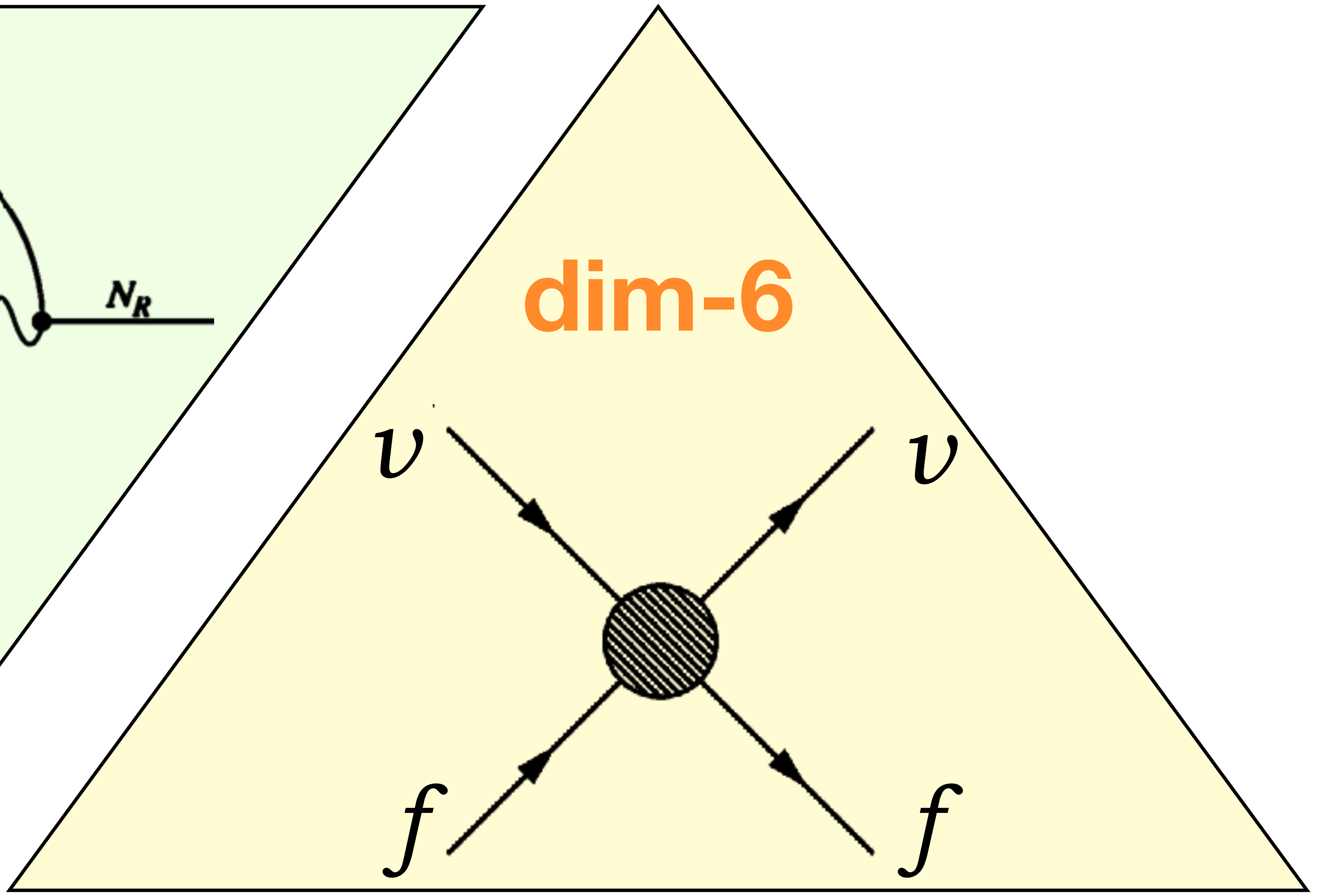


Neutrino Physics Beyond the Standard Model

e.g. neutrino magnetic moments



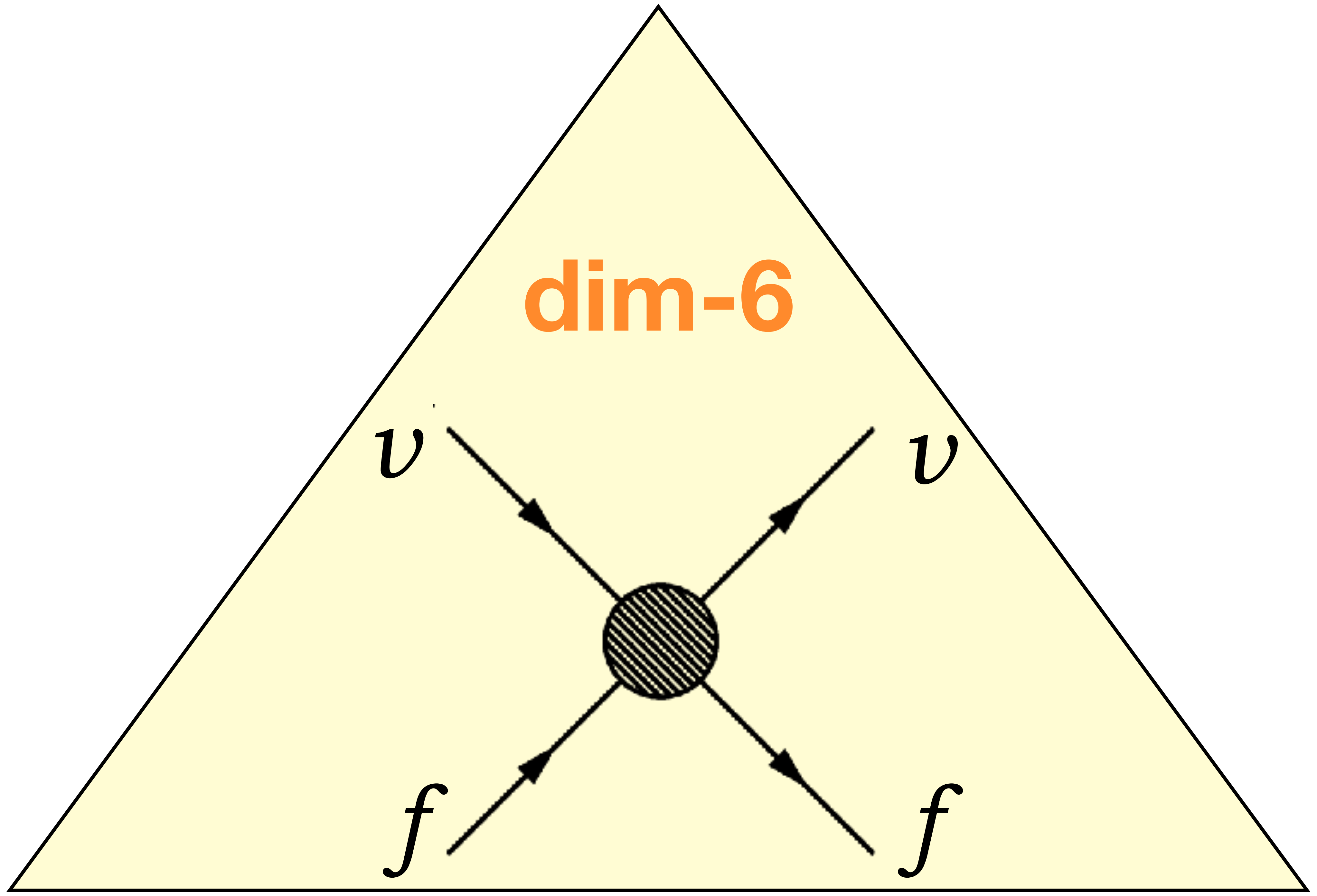




e.g. sterile neutrinos

e.g. non-standard interactions

Neutrino Physics Beyond the Standard Model



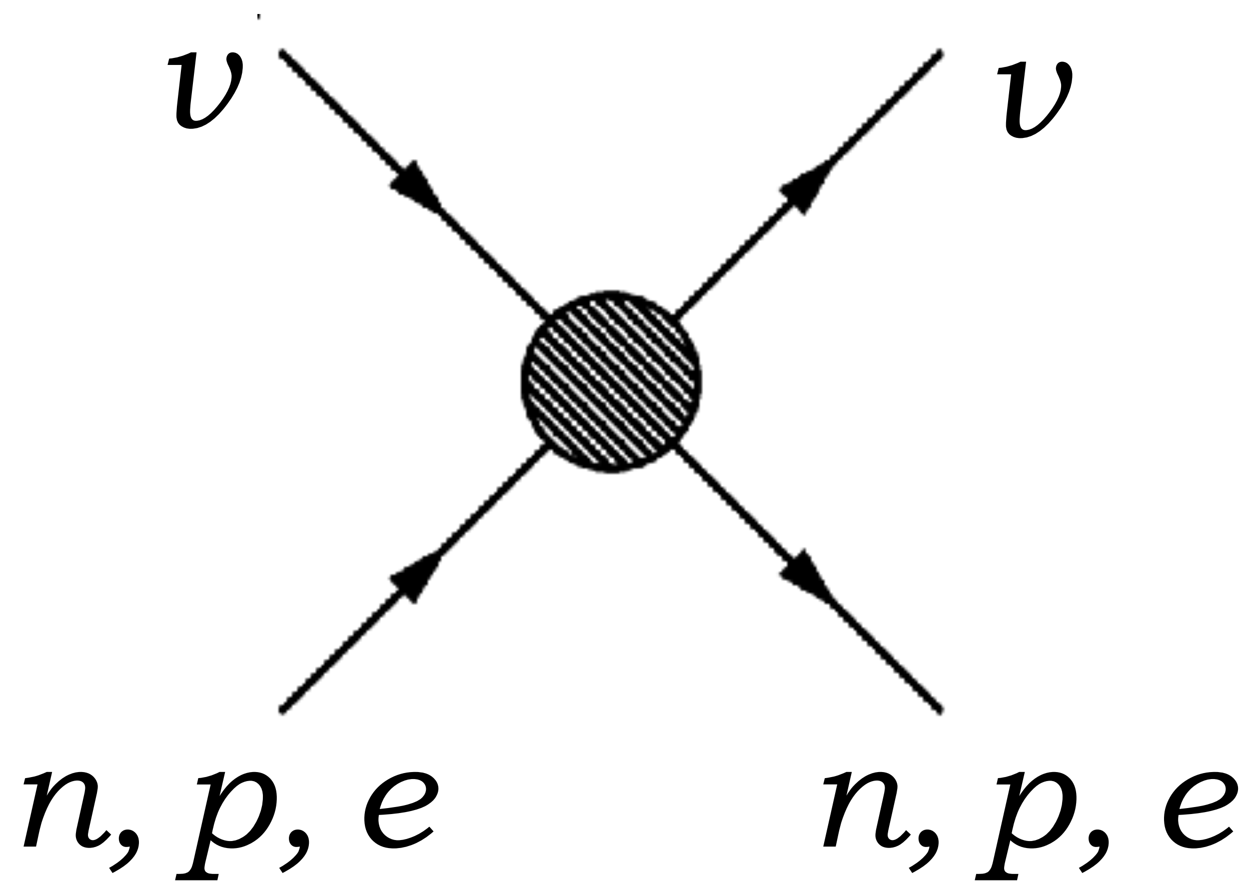
e.g. non-standard interactions

SMEFT

- SMEFT (**S**tandard **M**odel **E**ffective **F**ield **T**heory)
  = most general parameterisation of UV-scale new physics
  - the most general set of higher-dimensional operators consistent with the SU(3) x SU(2) x U(1) symmetry of the SM
  - order new operators by power of new physics scale Λ
- dim-5
  - Weinberg operator ➠ Majorana neutrino masses
- dim-6
  - 2 499 operators

Buchmüller Wyler 1985
Grzadkowski Iskrzynski Misiak Rosiek 2010
Contino Ghezzi Grojean Mühlleitner Spira 2013

Weak Effective Field Theory



- For low-energy experiments (like neutrino experiments): map SMEFT onto Weak Effective Field Theory (WEFT) (EFT valid below the electroweak scale – SU(3) x U(1) symmetry)
  - RGE running to 100 GeV
  - SMEFT → WEFT matching
  - RGE running 100 GeV → desired low-energy scale (typically 2 GeV)

- Nomenclature:
  - WEFT = LEFT ("low-energy effective field theory")
  - WEFT ≃ "non-standard neutrino interactions" (though typically not a full EFT treatment)

Falkowski González-Alonso Tabrizi 2019


SCUOLA SCI
LA THUILE

The EFT Ladder

The EFT Ladder

The EFT Ladder

≫ 100 GeV	➠	SM Effective Field Theory (6 quarks, W+Z bosons, Higgs)
~ GeV	➠	Weak Effective Field Theory (5 quarks, Fermi interaction)
MeV–GeV	➠	Chiral EFT (nucleons, pions)
< MeV	➠	pionless EFT (atomic nuclei)

running+ matching

running+ matching

running+ matching

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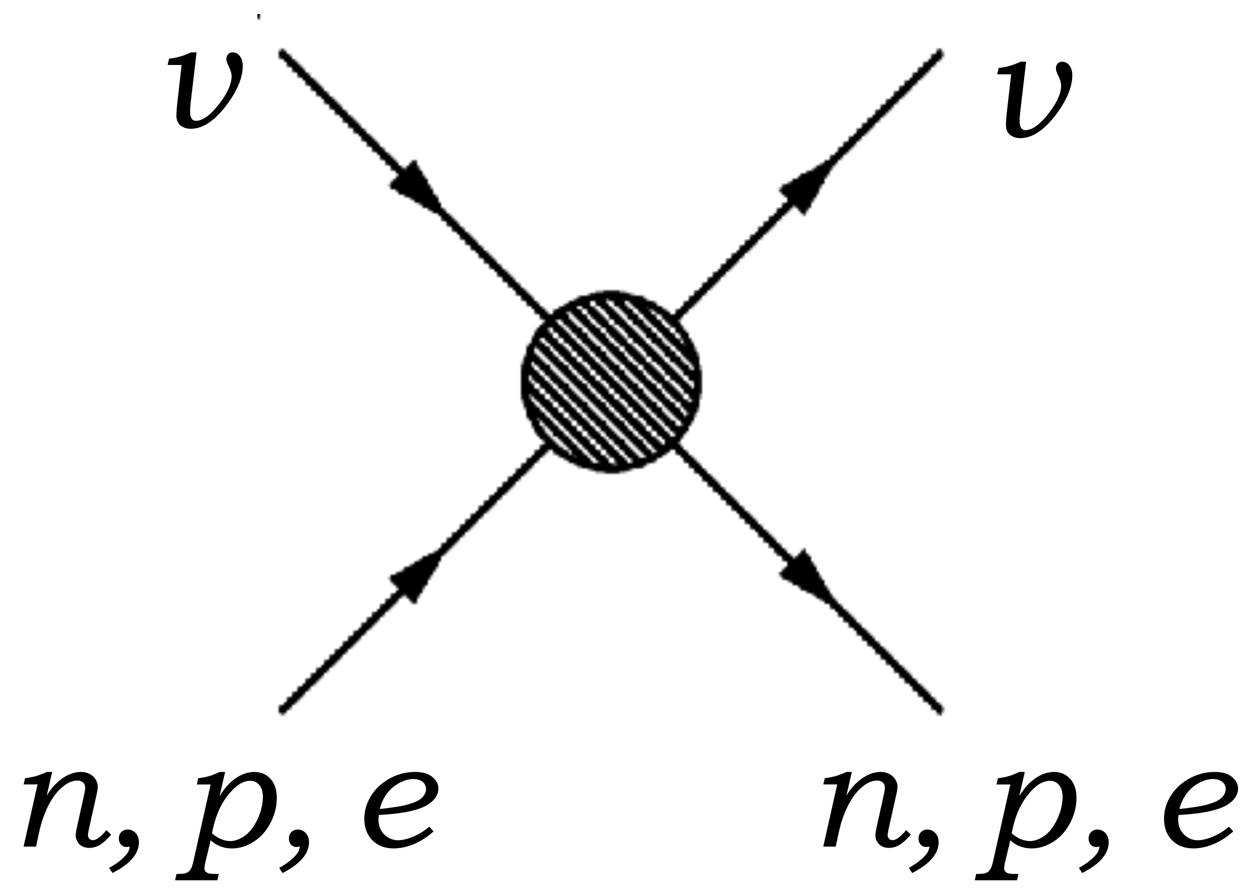
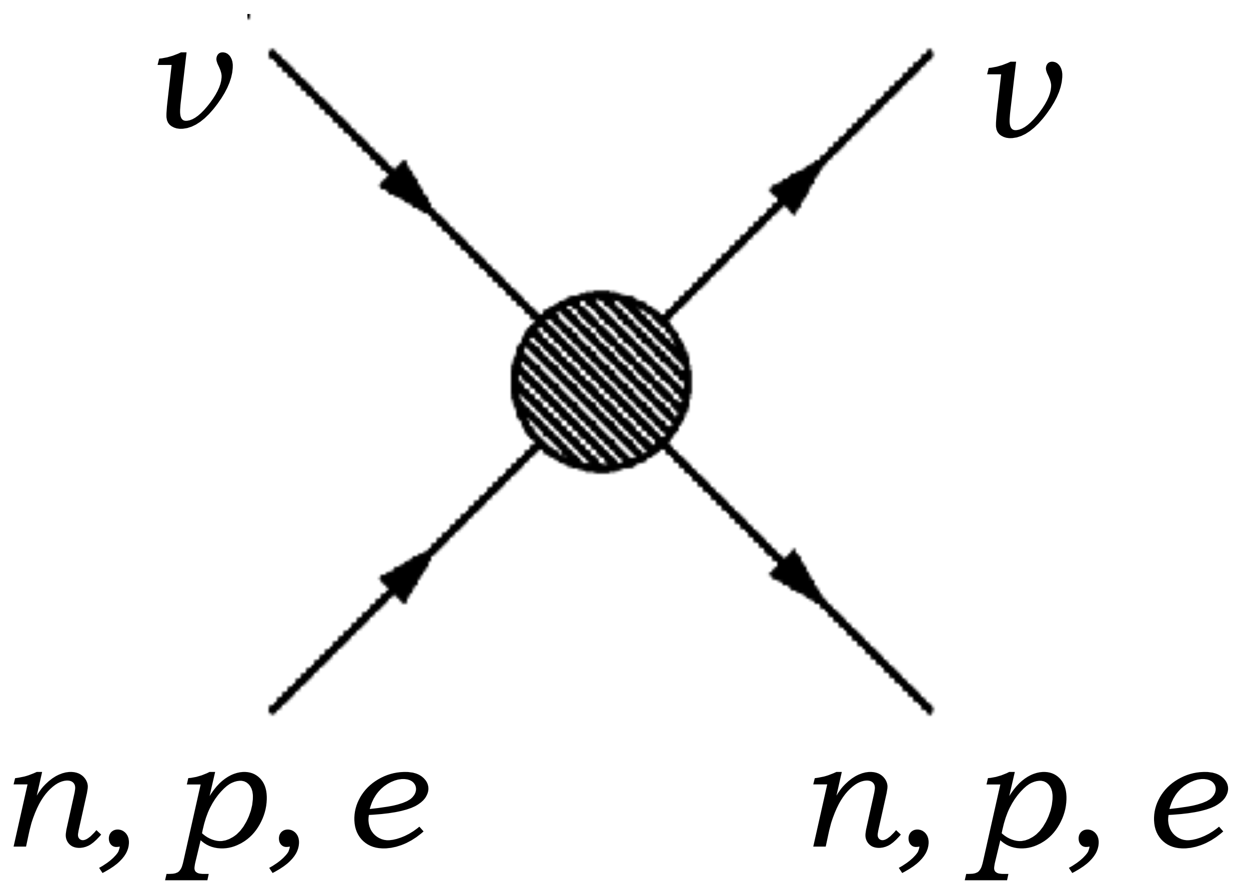
Weak Effective Field Theory



$$\mathcal{L}_{\rm NC} = \sum 2\sqrt{2} G_F \epsilon^{q,XY}_{\alpha\beta} \left(\bar\nu_\alpha \Gamma_X P_L \nu_\beta\right)\left(\bar q \Gamma_Y q\right)$$

$$\mathcal{L}_{\rm CC} = \sum 2\sqrt{2} G_F \epsilon^{qq',XY}_{\alpha\beta} \left(\bar\ell_\alpha \Gamma_X P_L \nu_\beta\right)\left(\bar q' \Gamma_Y q\right)$$

Weak Effective Field Theory



dimensionless coefficients
(interaction strength
relative to SM weak interactions)

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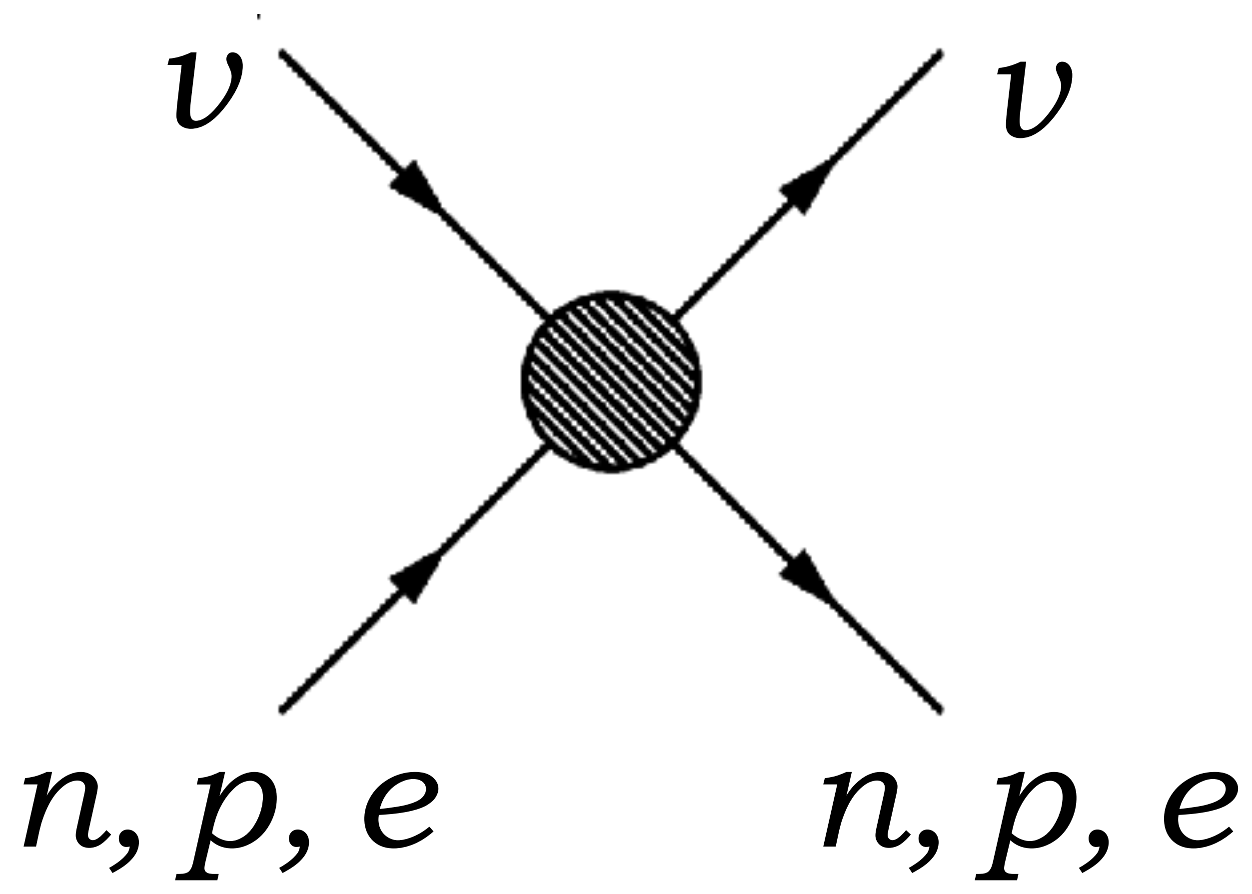
dim-6 operators
with different Lorentz structures

Weak Effective Field Theory



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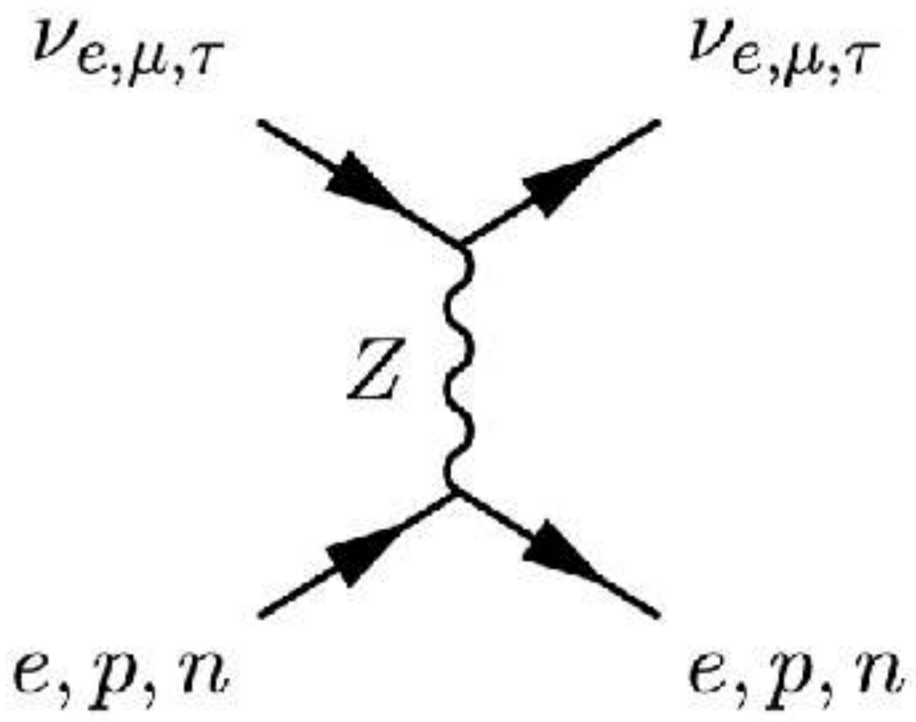
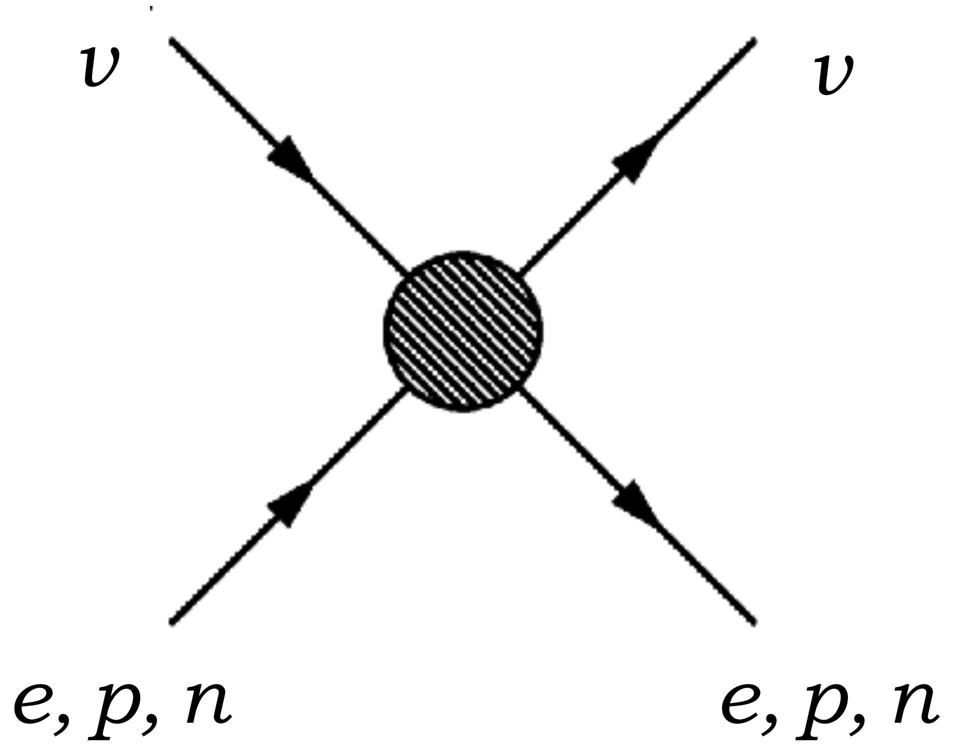
Lorentz structure
S=1, P=γ^5, V=γ^μ, A=$\gamma^\mu \gamma^5$, T=$\sigma^{\mu\nu}$

Anomalous Neutral Currents

Anomalous Neutral Currents

- Contribute to neutrino matter effects





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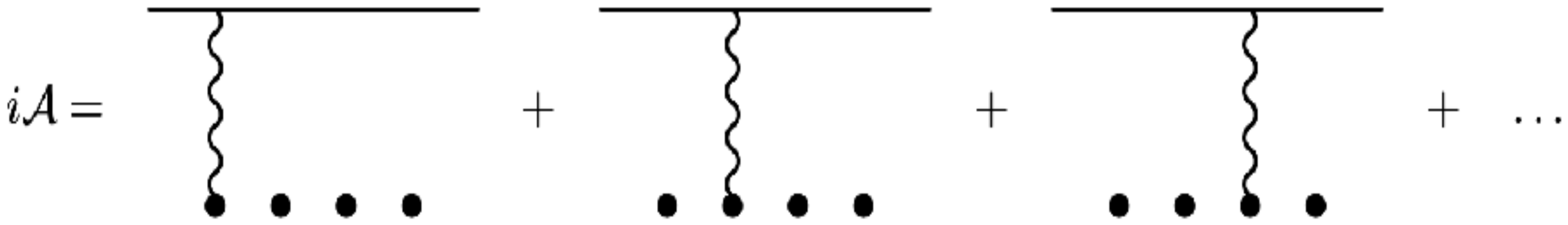

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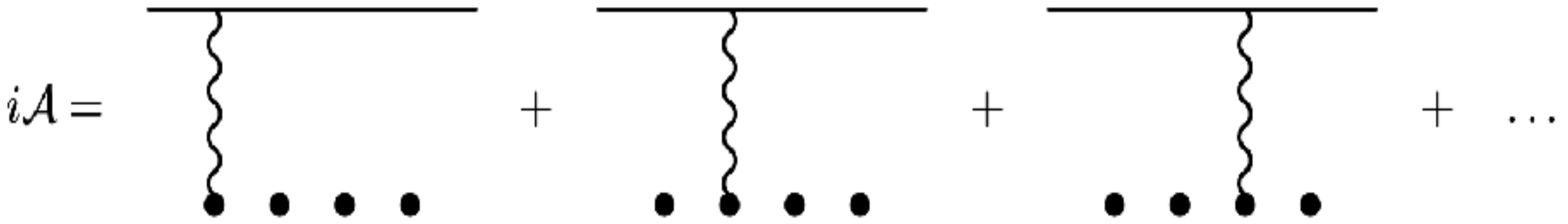

$$\mathcal{H}_{\text{eff}} \supset \frac{G_F}{\sqrt{2}} \langle \bar{e}\gamma^\mu(1-\gamma^5)e \rangle \, [\overline{\nu_e}\gamma^\mu(1-\gamma^5)\nu_e]$$

$$H_{\alpha\beta} = \frac{1}{2E}\left[U_{\alpha j} \begin{pmatrix} 0 & & \\ & \Delta m_{21}^2 & \\ & & \Delta m_{31}^2 \end{pmatrix}_{jk} (U^\dagger)_{k\beta} + (\tilde{V}_{\text{MSW}})_{\alpha\beta} \right]$$

Anomalous Neutral Currents

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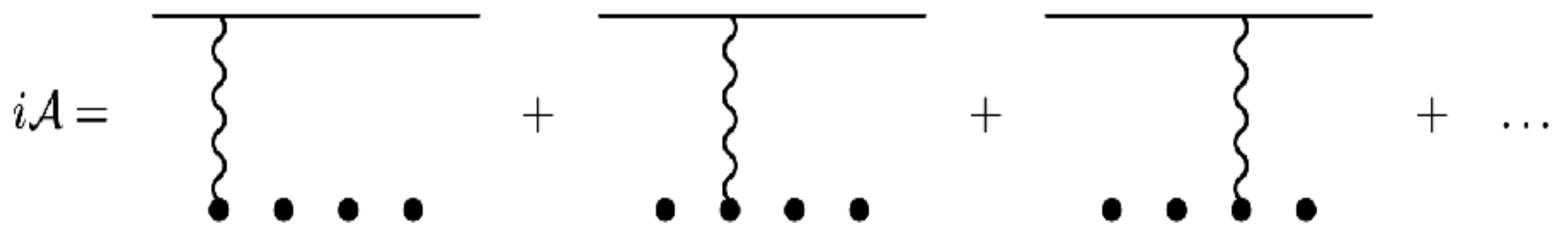

neutrino current

background matter
described as classical field

$$\mathcal{H}_{\text{eff}} \supset \frac{G_F}{\sqrt{2}} \langle \bar{e}\gamma^\mu(1-\gamma^5)e\rangle [\overline{\nu_e}\gamma^\mu(1-\gamma^5)\nu_e]$$

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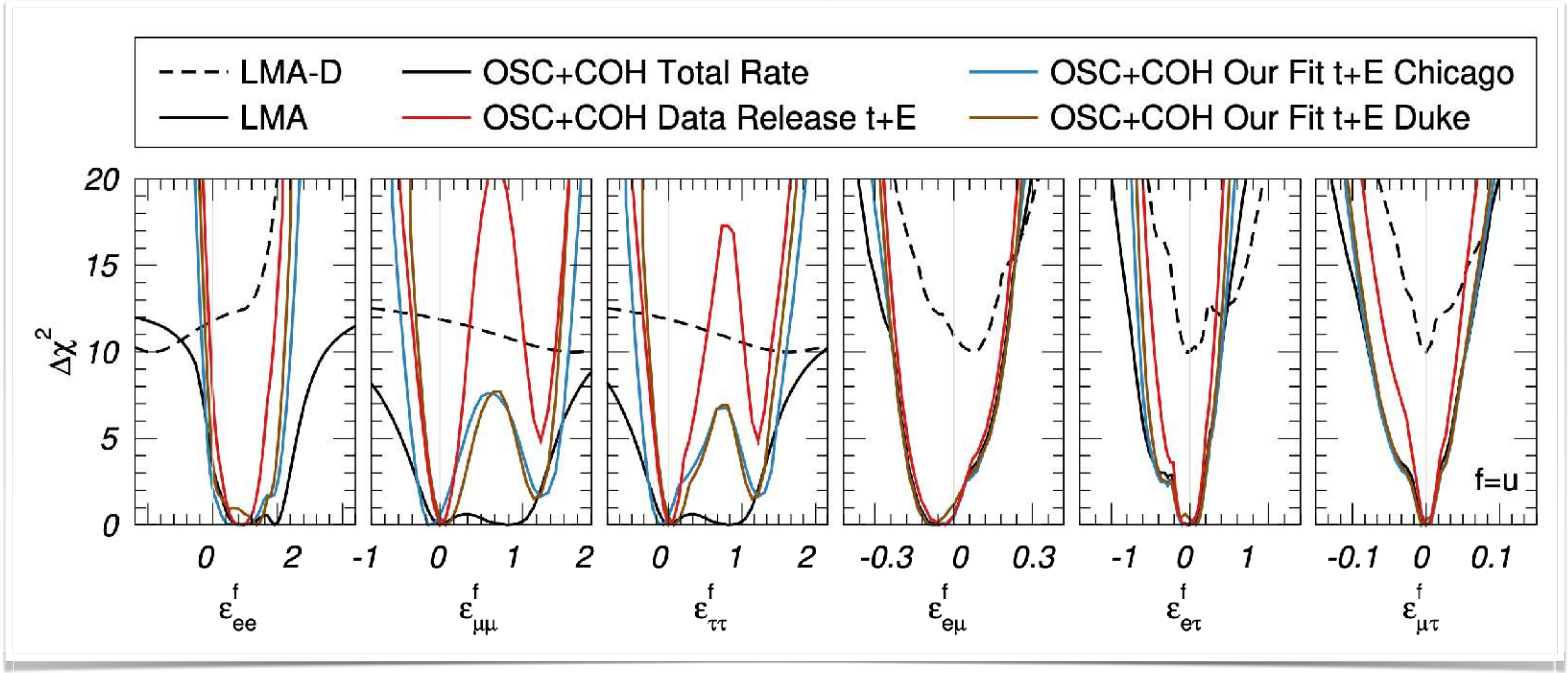
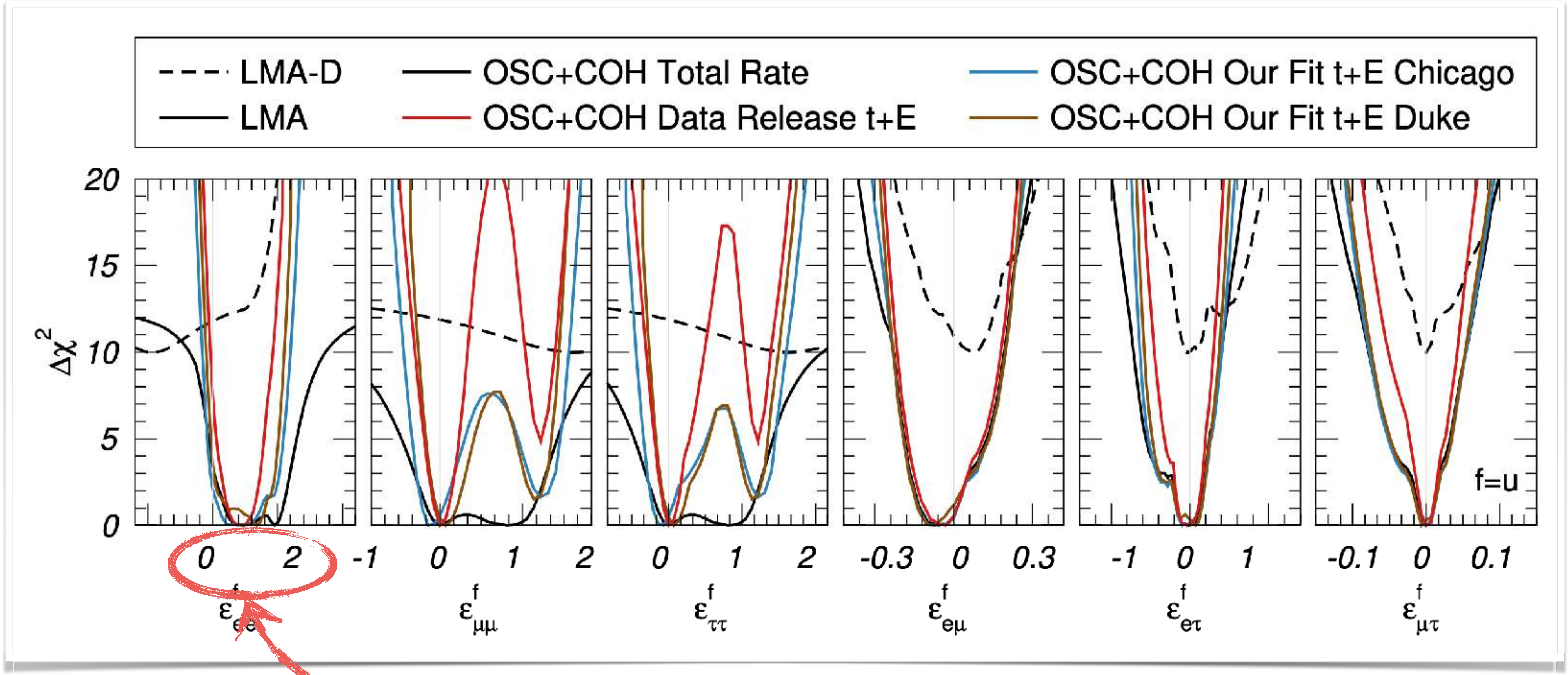
Anomalous Neutral Currents – Current Limits



Coloma Esteban Gonzalez-Garcia Maltoni 2019

Anomalous Neutral Currents – Current Limits



sensitivity to interactions
similar in strength to
SM weak interactions

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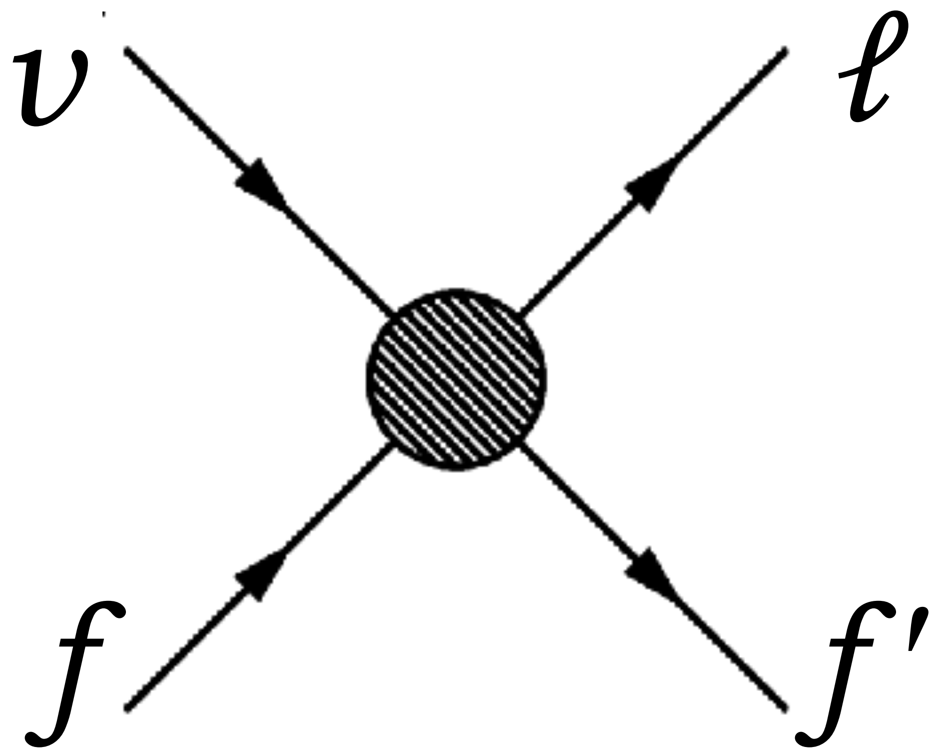
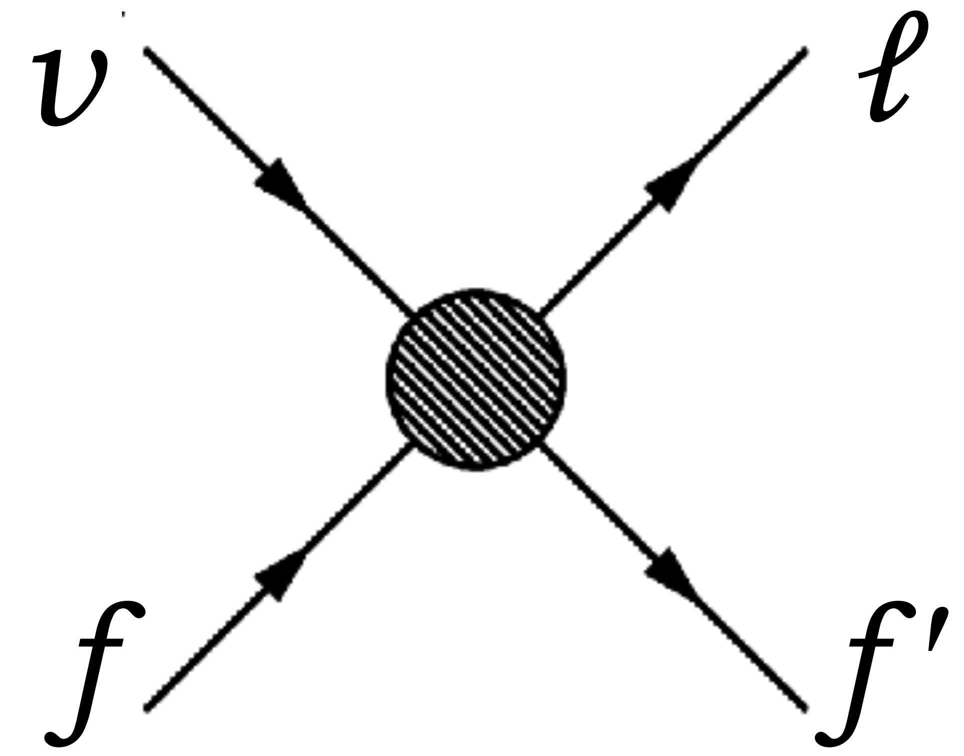
Anomalous Charged Currents

Anomalous Charged Currents



- Modified neutrino production and detection processes
- related to NC operators due to SU(2) symmetry
  - consistent EFT is essential
  - in oscillation experiments, NC and CC need to be considered together

Anomalous Charged Currents



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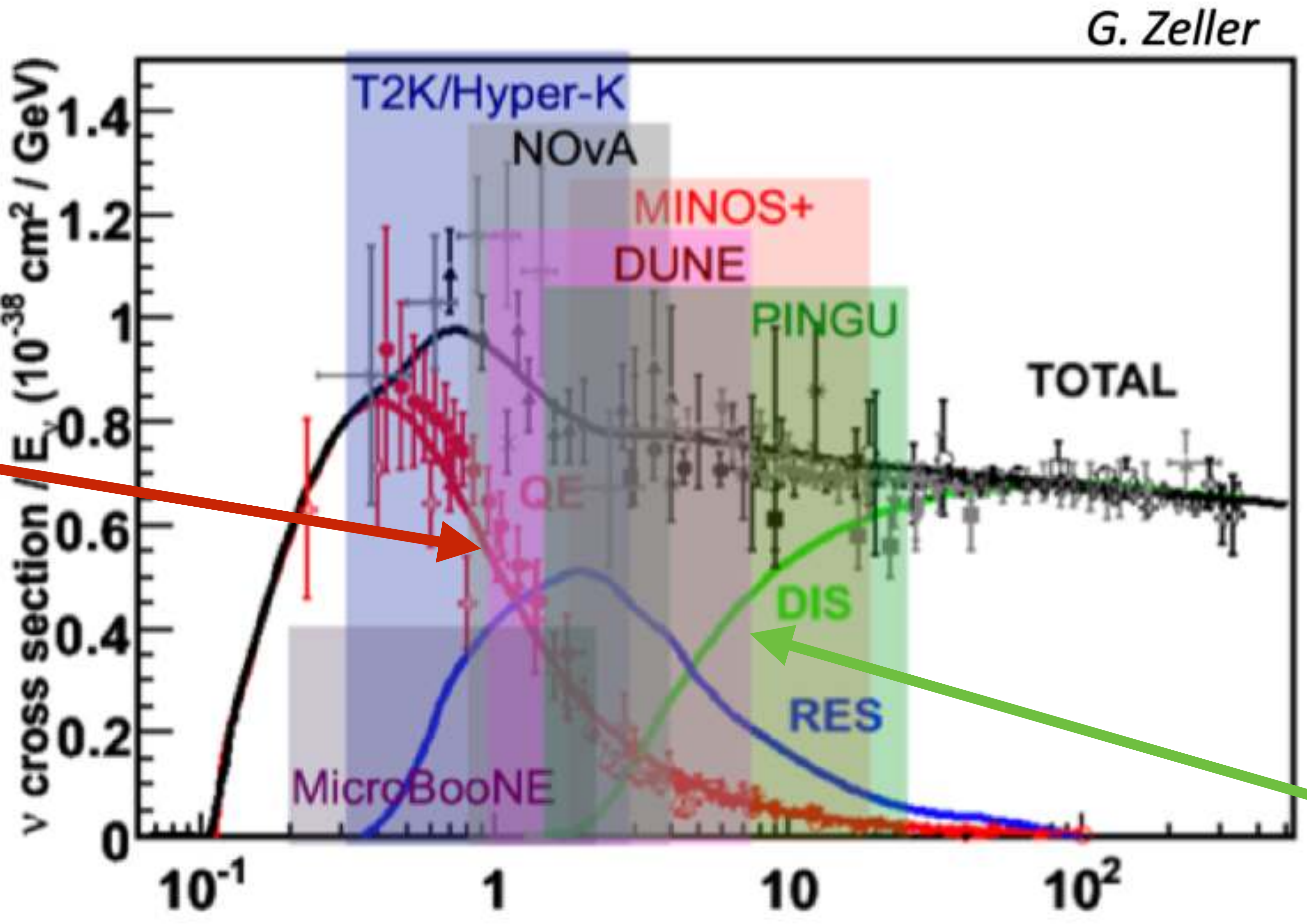
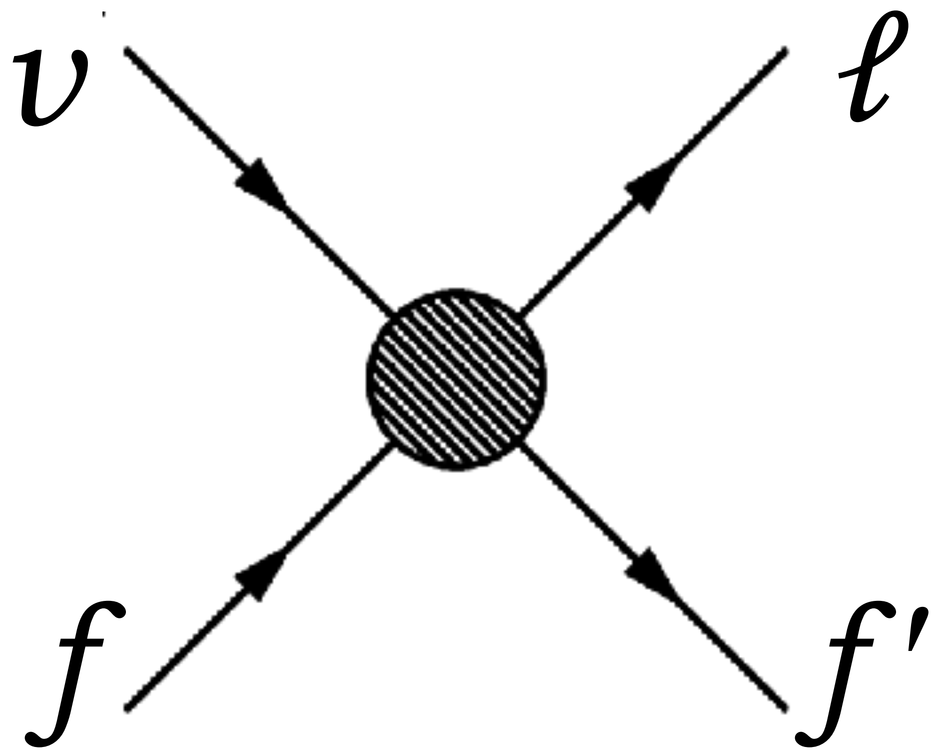
Quasi-Elastic Scattering (QES)



Deep-Inelastic Scattering (DIS)

Deep-Inelastic Scattering (> GeV)



- neutrino scattering on quarks
- admits description in terms of PDFs
- interesting opportunities at
  - short-baseline experiments
  - collider neutrino detectors

New Interactions in Quasi-Elastic Scattering (< GeV)

- neutrino scatters on nucleons
- need to map lepton–quark interactions onto lepton–nucleon interactions

$$A_{L,\alpha} = -\frac{2V_{ud}}{v^2}\left[\bar{u}_{\ell_\alpha}(p_{\ell_\alpha})\gamma^\mu P_L u_\nu(p_\nu)\right]\langle p(p_p)|\bar{q}_u\gamma_\mu P_L q_d|n(p_n)\rangle$$

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scattering amplitude

hadronic matrix element
depends on hadronic form factors

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scattering amplitude

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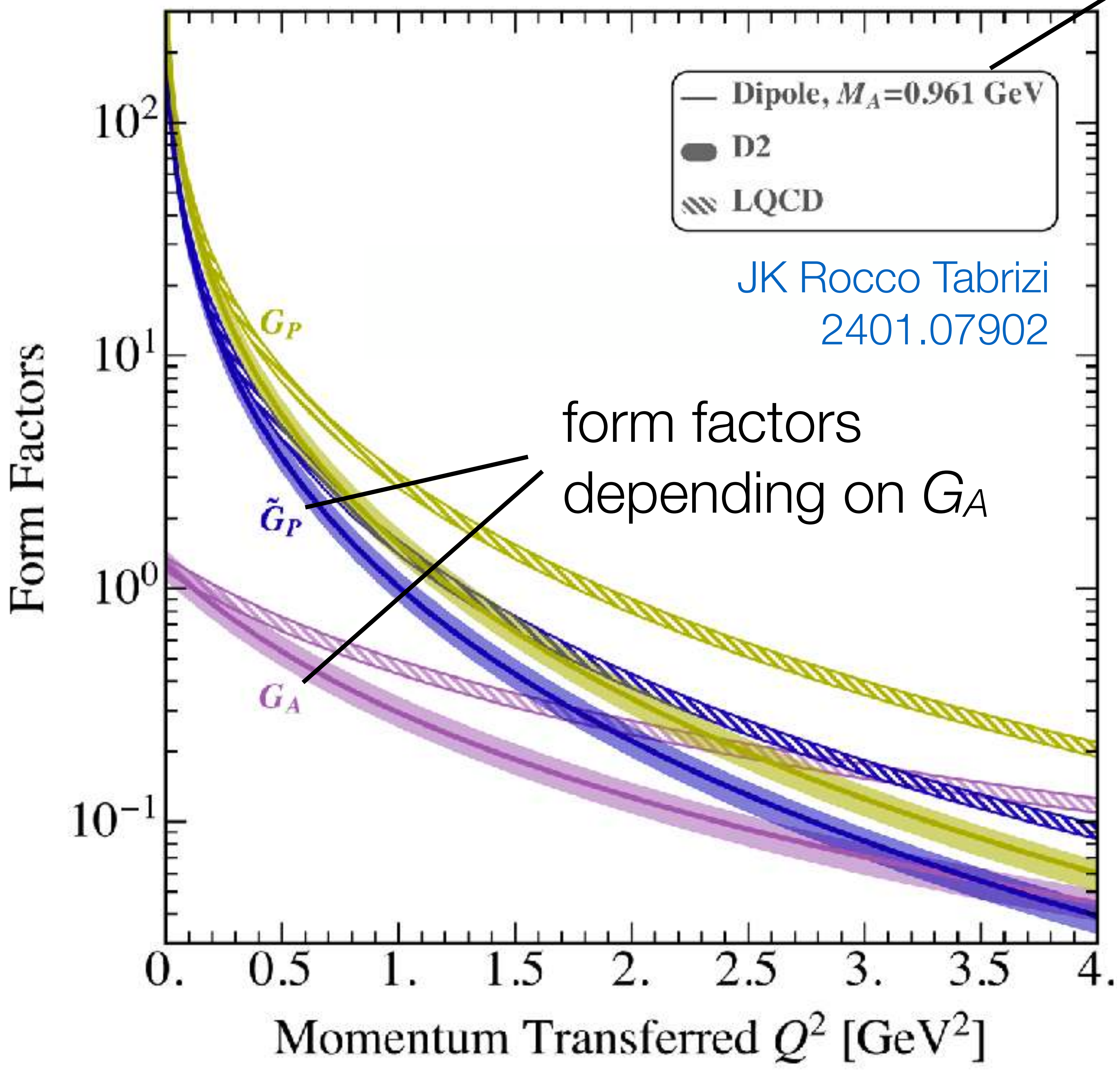
“hic sunt dracones”

Nucleon Form Factors

three different estimates for the axial form factor



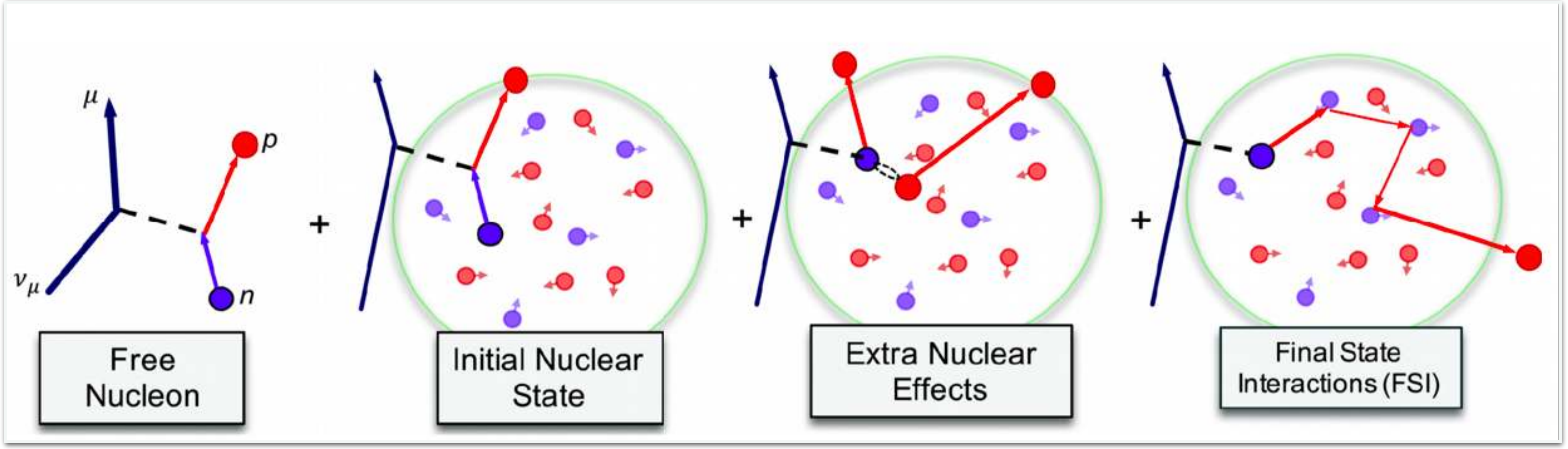
JK Rocco Tabrizi
2401.07902

form factors depending on G_A

Nuclear Effects

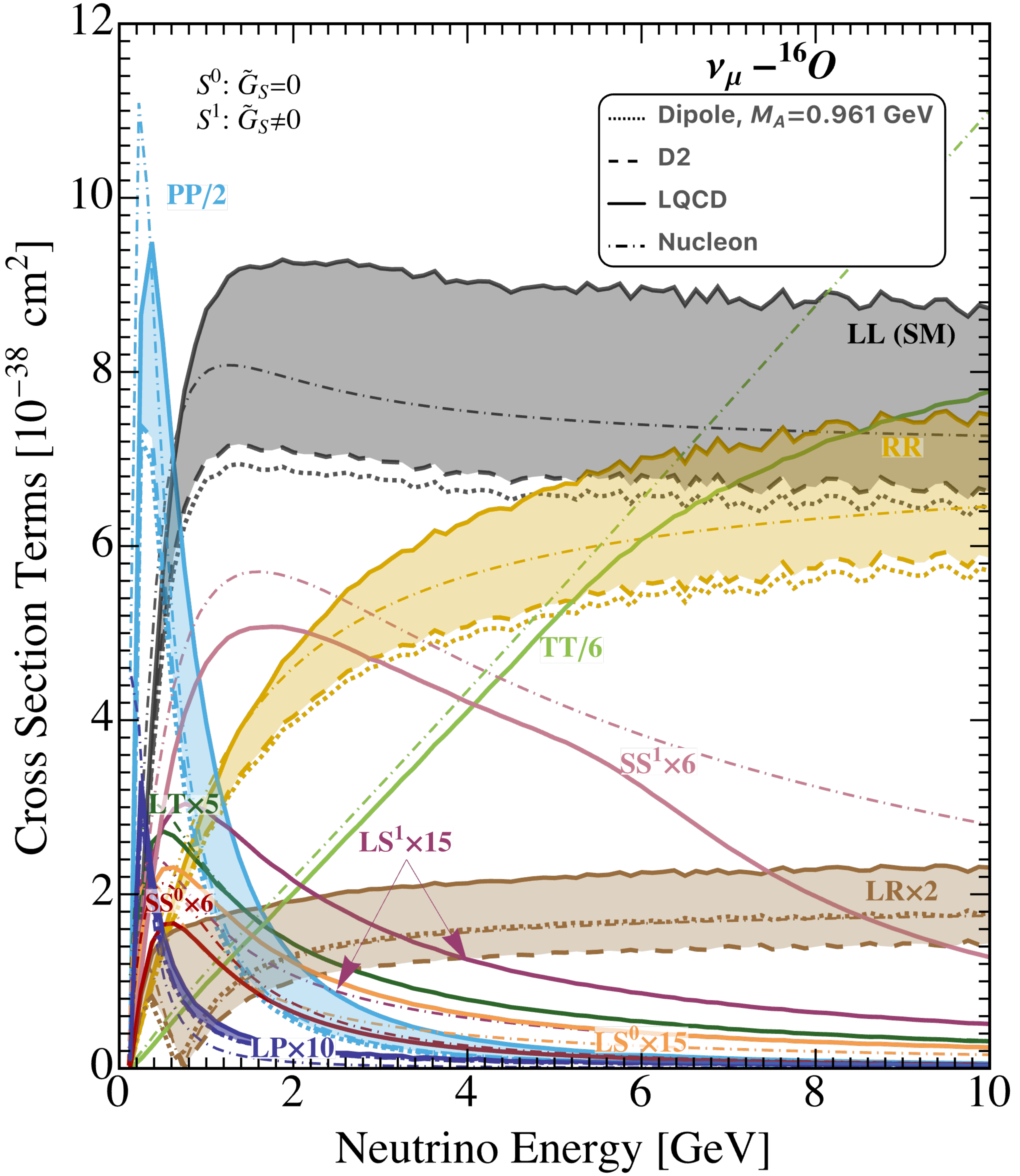
Nuclear Effects

Nuclear Effects

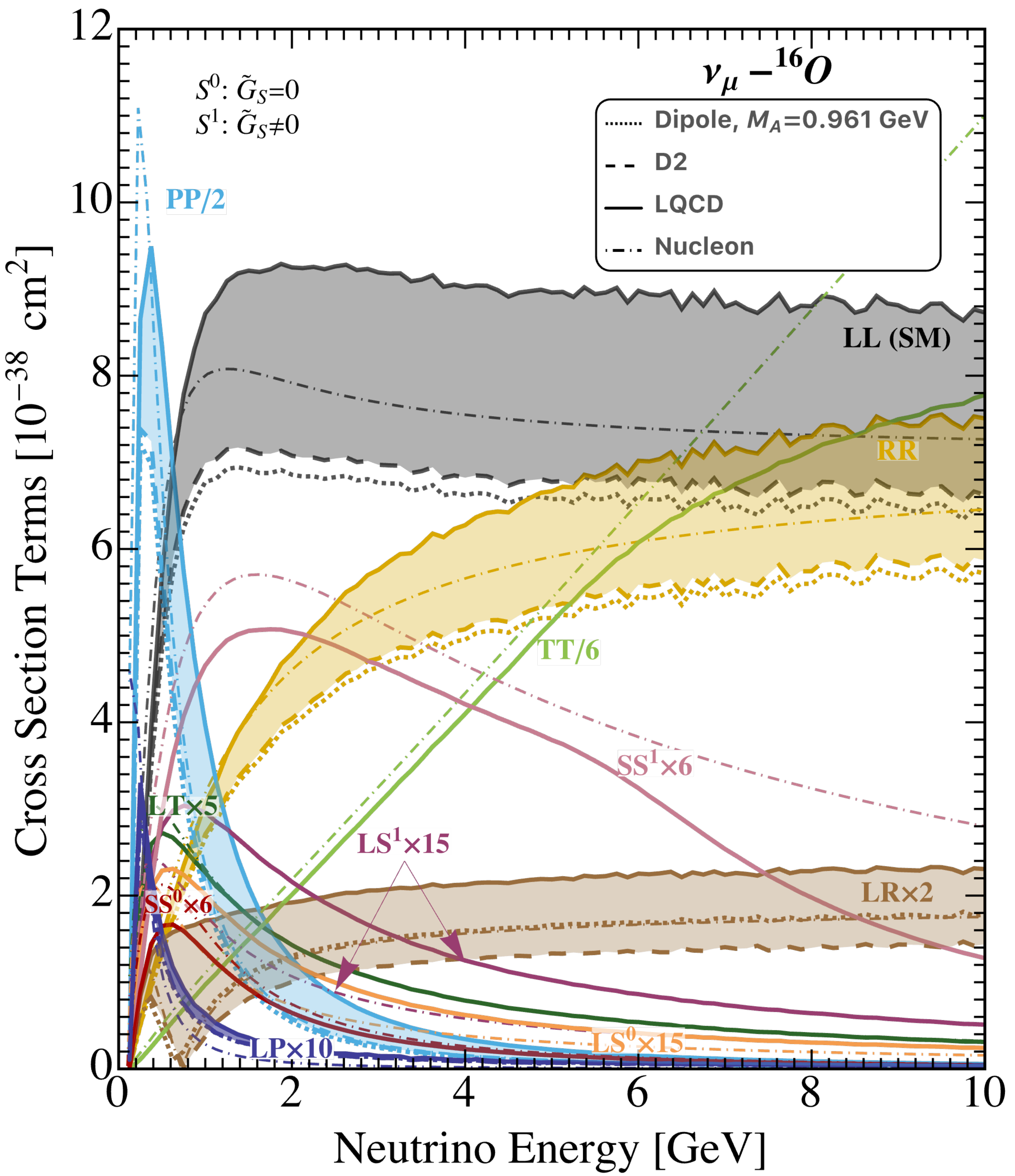


- ☐ initial state of struck nucleon
  (binding energy, Fermi momentum)
  } e.g. spectral functions, shell model, relativistic mean-field theory, Green's function MC, Fermi gas models
- ☐ multi-nucleon effects
  (e.g. two-particle–two-hole (2p2h) processes)
  } dedicated EFT calculations
- ☐ final-state interactions
  (propagation of interaction products out of the nucleus)
  } event generators

New Interactions in QES



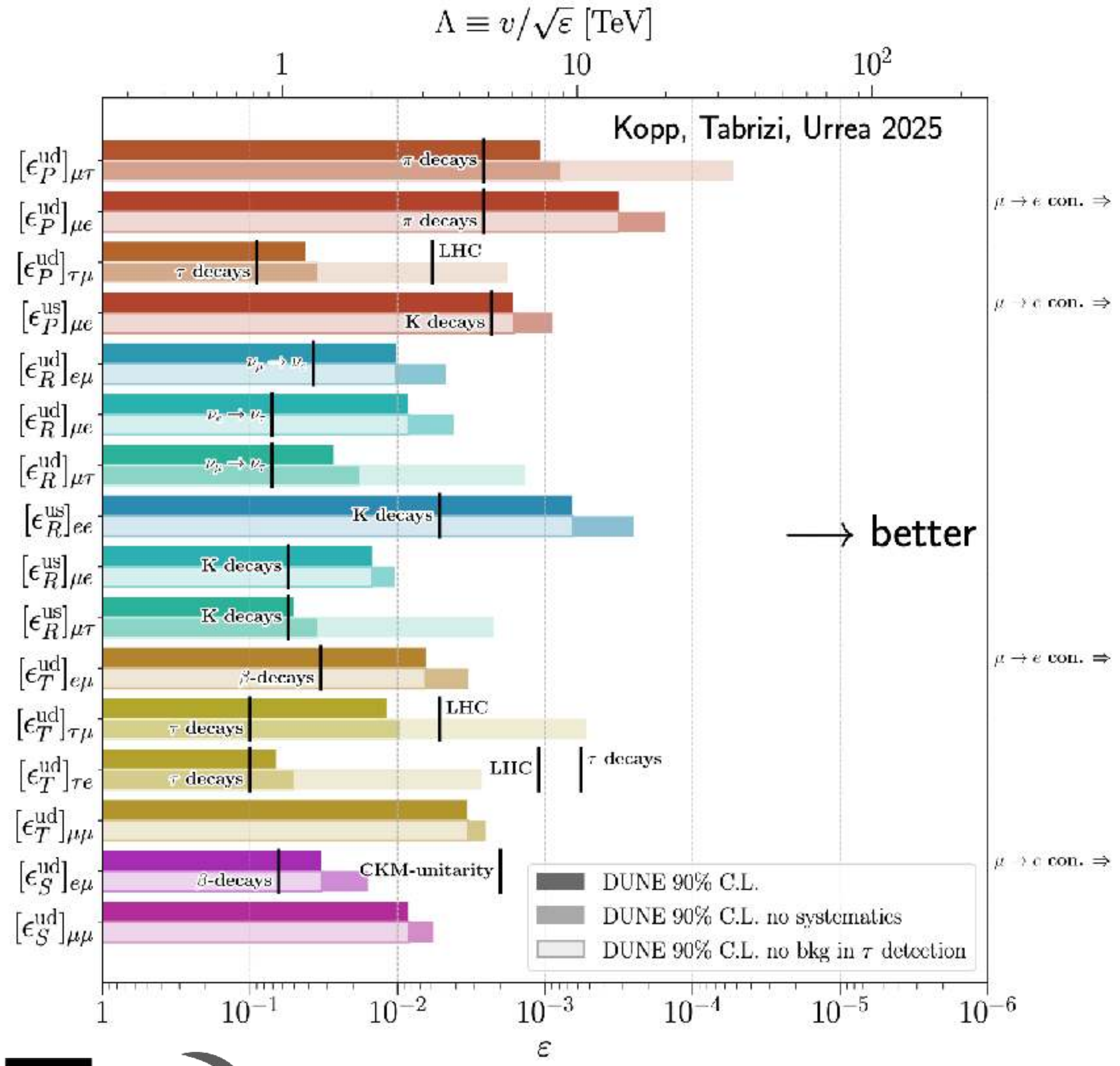
New Interactions in QES

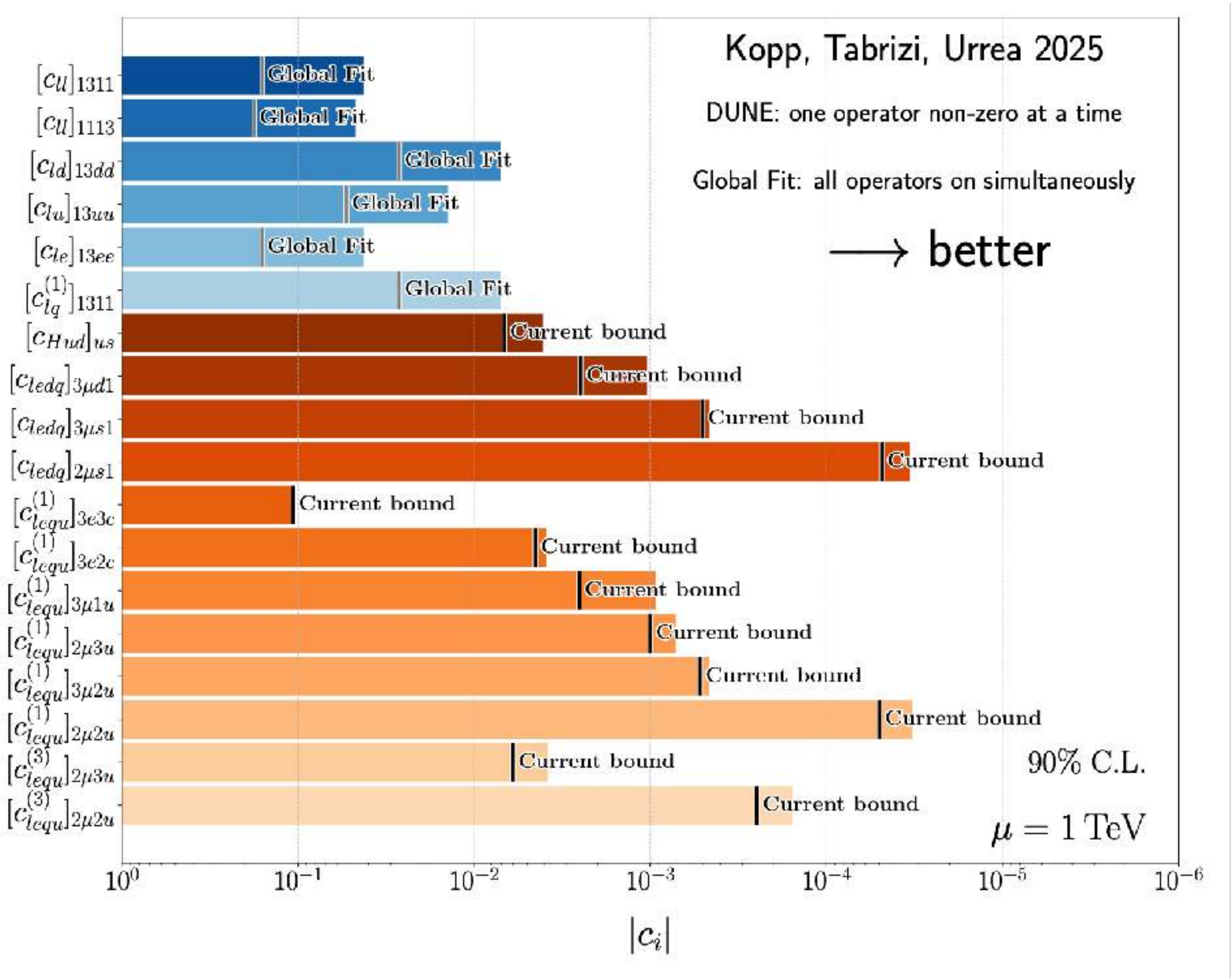


- large uncertainties from axial FF
- some BSM interactions significantly enhanced compared to the SM (e.g. PP: coupling to pions)
- others strongly suppressed

Future Sensitivity Estimates

Future WEFT and SMEFT Constraints



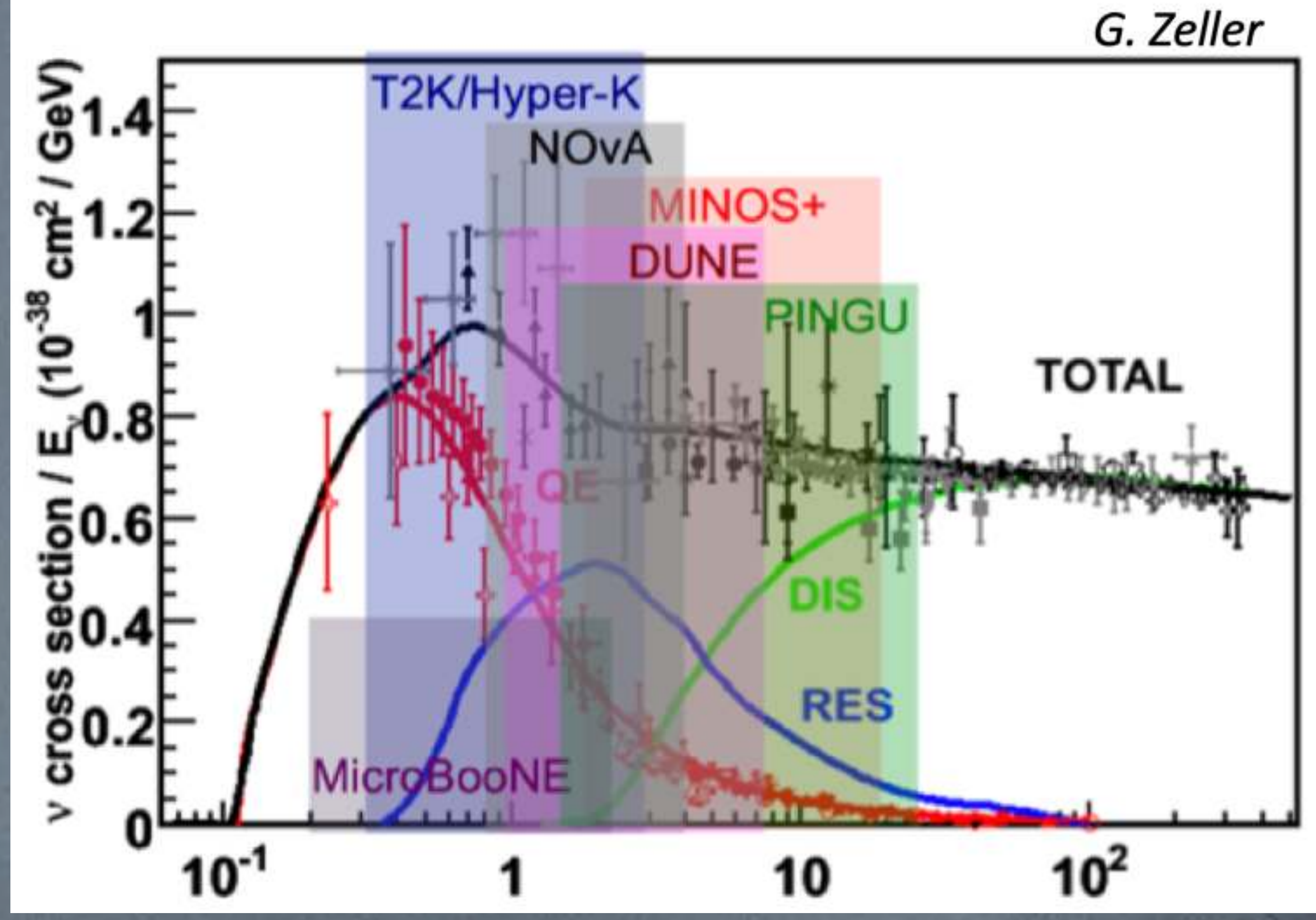


non-neutrino constraints from works by
Cirigliano González-Alonso Falkowski Tabrizi, …

Outlook

≫ 100 GeV	➠	SM Effective Field Theory
~ GeV	➠	Weak Effective Field Theory
MeV–GeV	➠	Chiral EFT
< MeV	➠	pionless EFT

Outlook



≫ 100 GeV	➠	SM Effective Field Theory
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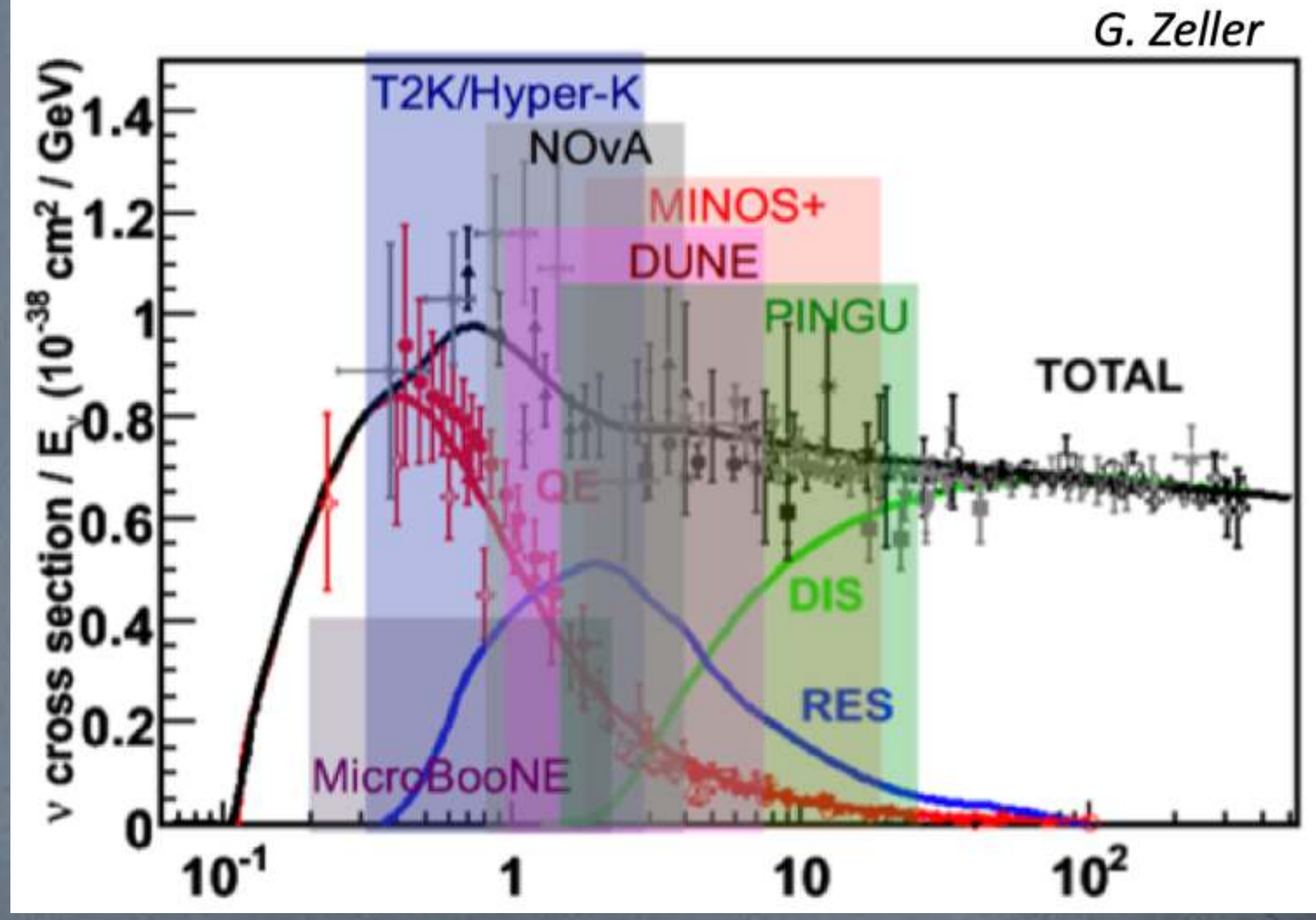
Outlook



≫ 100 GeV	➠	SM Effective Field Theory
~ GeV	➠	Weak Effective Field Theory
~ GeV	➠	Chiral EFT + QCD resonances
MeV–GeV	➠	Chiral EFT
< MeV	➠	pionless EFT

Outlook

- BSM neutrino–nucleus cross sections in the QCD resonance regime
- GLoBES-EFT: fast simulation of neutrino oscillation experiments in SMEFT+WEFT; automated running+matching
- high-dim. parameter space calls for novel fitting techniques:
  - simulation-based inference (using classical + quantum ML)
  - fully differentiable simulations
- Application to real data

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Thank You!

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Bonus Slides

New Interactions in Quasi-Elastic Scattering

- at energies < GeV: neutrino interactions dominated by quasi-elastic scattering (scattering on whole nucleons)
- need to map lepton–quark interactions onto lepton–nucleon interactions

$$\begin{aligned}\mathcal{L}_{\text{WEFT}} \supset -\frac{2V_{ud}}{v^2}\Big\{&[\mathbf{1}+\epsilon_L]_{\alpha\beta}(\bar{q}_u\gamma^\mu P_L q_d)(\bar{\ell}_\alpha\gamma_\mu P_L\nu_\beta) + [\epsilon_R]_{\alpha\beta}(\bar{q}_u\gamma^\mu P_R q_d)(\bar{\ell}_\alpha\gamma_\mu P_L\nu_\beta)\\ &+\frac{1}{2}[\epsilon_S]_{\alpha\beta}(\bar{q}_u q_d)(\bar{\ell}_\alpha P_L\nu_\beta) - \frac{1}{2}[\epsilon_P]_{\alpha\beta}(\bar{q}_u\gamma_5 q_d)(\bar{\ell}_\alpha P_L\nu_\beta)\\ &+\frac{1}{4}[\epsilon_T]_{\alpha\beta}(\bar{q}_u\sigma^{\mu\nu}P_L q_d)(\bar{\ell}_\alpha\sigma_{\mu\nu}P_L\nu_\beta) + \text{h.c.}\Big\}\,.\end{aligned}$$

New Interactions in Quasi-Elastic Scattering (< GeV)

- neutrino scatters on nucleons
- need to map lepton–quark interactions onto lepton–nucleon interactions

$$\frac{d\sigma_{\alpha\beta}}{dQ^2} = \frac{d\hat{\sigma}_{LL,\alpha}}{dQ^2}\delta_{\alpha\beta} + \sum_X \left([\epsilon_X]_{\alpha\beta} \frac{d\hat{\sigma}_{LX,\alpha}}{dQ^2}\delta_{\alpha\beta} + h.c. \right) + \sum_{X,Y,\beta} [\epsilon_X]_{\alpha\beta} [\epsilon_Y]^*_{\alpha\beta} \frac{d\hat{\sigma}_{XY,\alpha}}{dQ^2}$$

New Interactions in Quasi-Elastic Scattering (< GeV)

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SM contribution

$$\frac{d\sigma_{\alpha\beta}}{dQ^2} = \frac{d\hat{\sigma}_{LL,\alpha}}{dQ^2}\delta_{\alpha\beta} + \sum_X \left([\epsilon_X]_{\alpha\beta} \frac{d\hat{\sigma}_{LX,\alpha}}{dQ^2}\delta_{\alpha\beta} + h.c. \right) + \sum_{X,Y,\beta} [\epsilon_X]_{\alpha\beta} [\epsilon_Y]^*_{\alpha\beta} \frac{d\hat{\sigma}_{XY,\alpha}}{dQ^2}$$

New Interactions in Quasi-Elastic Scattering (< GeV)

- neutrino scatters on nucleons
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SM–BSM interference contributions

SM contribution

$$\frac{d\sigma_{\alpha\beta}}{dQ^2} = \frac{d\hat{\sigma}_{LL,\alpha}}{dQ^2}\delta_{\alpha\beta} + \sum_X \left([\epsilon_X]_{\alpha\beta} \frac{d\hat{\sigma}_{LX,\alpha}}{dQ^2}\delta_{\alpha\beta} + h.c. \right) + \sum_{X,Y,\beta} [\epsilon_X]_{\alpha\beta} [\epsilon_Y]^*_{\alpha\beta} \frac{d\hat{\sigma}_{XY,\alpha}}{dQ^2}$$

New Interactions in Quasi-Elastic Scattering (< GeV)

- neutrino scatters on nucleons
- need to map lepton–quark interactions onto lepton–nucleon interactions

SM contribution **SM–BSM interference contributions** **pure BSM contributions**

$$\frac{d\sigma_{\alpha\beta}}{dQ^2} = \frac{d\hat{\sigma}_{LL,\alpha}}{dQ^2}\delta_{\alpha\beta} + \sum_X \left([\epsilon_X]_{\alpha\beta} \frac{d\hat{\sigma}_{LX,\alpha}}{dQ^2}\delta_{\alpha\beta} + h.c. \right) + \sum_{X,Y,\beta} [\epsilon_X]_{\alpha\beta} [\epsilon_Y]^*_{\alpha\beta} \frac{d\hat{\sigma}_{XY,\alpha}}{dQ^2}$$

New Interactions in Quasi-Elastic Scattering

- for each Lorentz structure, decompose into form factors

$$\langle p(p_p)|\bar{q}_u\gamma_\mu q_d|n(p_n)\rangle = \bar{u}_p(p_p)\left[G_V(Q^2)\gamma_\mu + i\frac{\tilde{G}_{T(V)}(Q^2)}{2M_N}\sigma_{\mu\nu}q^\nu - \frac{\tilde{G}_S(Q^2)}{2M_N}q_\mu\right]u_n(p_n)\,,$$

$$\langle p(p_p)|\bar{q}_u\gamma_\mu\gamma_5 q_d|n(p_n)\rangle = \bar{u}_p(p_p)\left[G_A(Q^2)\gamma_\mu\gamma_5 + i\frac{\tilde{G}_{T(A)}(Q^2)}{2M_N}\sigma_{\mu\nu}q^\nu\gamma_5 - \frac{\tilde{G}_P(Q^2)}{2M_N}q_\mu\gamma_5\right]u_n(p_n)\,,$$

$$\langle p(p_p)|\bar{q}_u q_d|n(p_n)\rangle = G_S(Q^2)\,\bar{u}_p(p_p)u_n(p_n)\,,$$

$$\langle p(p_p)|\bar{q}_u\gamma_5 q_d|n(p_n)\rangle = G_P(Q^2)\,\bar{u}_p(p_p)\gamma_5 u_n(p_n)\,,$$

$$\langle p(p_p)|\bar{q}_u\sigma_{\mu\nu}q_d|n(p_n)\rangle = \bar{u}_p(p_p)\Big[G_T(Q^2)\sigma_{\mu\nu} - \frac{i}{M_N}G_T^{(1)}(Q^2)(q_\mu\gamma_\nu - q_\nu\gamma_\mu)$$

$$- \frac{i}{M_N^2}G_T^{(2)}(Q^2)(q_\mu P_\nu - q_\nu P_\mu) - \frac{i}{M_N}G_T^{(3)}(Q^2)(\gamma_\mu\not{q}\gamma_\nu - \gamma_\nu\not{q}\gamma_\mu)\Big]u_n(p_n)\,,$$

New Interactions in Quasi-Elastic Scattering

- fo … cture, decompose into form factors

vector FF
well measured in
electron–nucleon scattering

$$\langle p(p_p)|\bar{q}_u \gamma_\mu q_d|n(p_n)\rangle = \bar{u}_p(p_p)\left[G_V(Q^2)\gamma_\mu + i\frac{\tilde{G}_{T(V)}(Q^2)}{2M_N}\sigma_{\mu\nu}q^\nu - \frac{\tilde{G}_S(Q^2)}{2M_N}q_\mu\right]u_n(p_n)\,,$$

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$$\langle p(p_p)|\bar{q}_u q_d|n(p_n)\rangle = G_S(Q^2)\,\bar{u}_p(p_p)u_n(p_n)\,,$$

$$\langle p(p_p)|\bar{q}_u \gamma_5 q_d|n(p_n)\rangle = G_P(Q^2)\,\bar{u}_p(p_p)\gamma_5 u_n(p_n)\,,$$

$$\langle p(p_p)|\bar{q}_u \sigma_{\mu\nu} q_d|n(p_n)\rangle = \bar{u}_p(p_p)\Big[G_T(Q^2)\sigma_{\mu\nu} - \frac{i}{M_N}G_T^{(1)}(Q^2)(q_\mu\gamma_\nu - q_\nu\gamma_\mu)$$
$$- \frac{i}{M_N^2}G_T^{(2)}(Q^2)(q_\mu P_\nu - q_\nu P_\mu) - \frac{i}{M_N}G_T^{(3)}(Q^2)(\gamma_\mu \not{q}\gamma_\nu - \gamma_\nu \not{q}\gamma_\mu)\Big]u_n(p_n)\,,$$

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$$G_A(Q^2) = \frac{g_A}{\left(1 + \frac{Q^2}{m_A^2}\right)^2}$$

axial coupling constant (from neutron decay)

axial mass

  - overconstrained (experiments don't agree on the value of m_A)
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$$G_A(Q^2) = \sum_{k=0}^{\infty} a_k \left[z(Q^2)\right]^k \qquad z(Q^2; t_0, t_{\text{cut}}) = \frac{\sqrt{t_{\text{cut}} + Q^2} - \sqrt{t_{\text{cut}} - t_0}}{\sqrt{t_{\text{cut}} + Q^2} + \sqrt{t_{\text{cut}} - t_0}} \qquad t_{\text{cut}} \leq (3M_\pi)^2$$

functional form motivated by analyticity arguments

coefficients determined by fit to data or lattice

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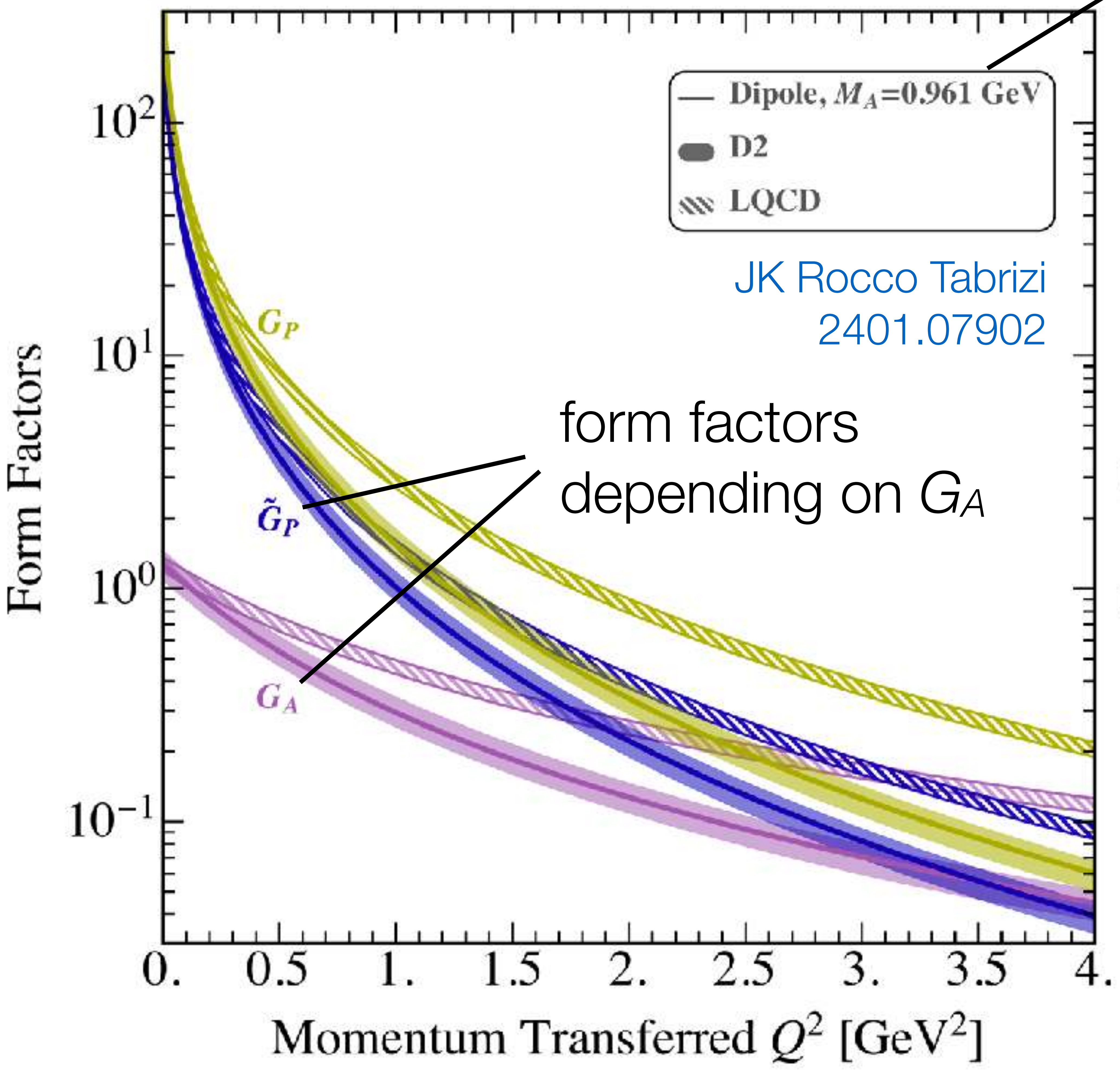
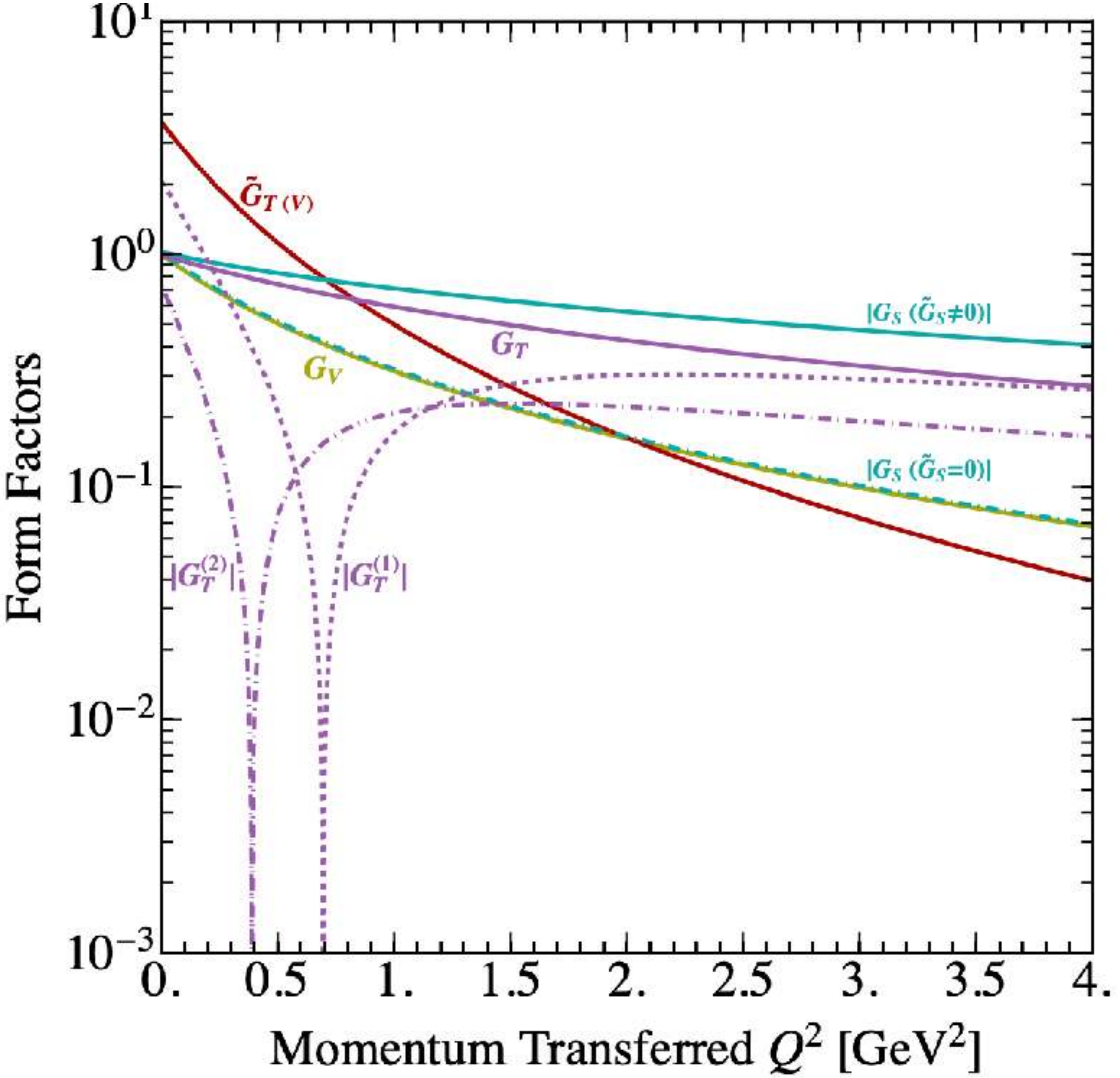
three different estimates
for the axial form factor





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- Ward identities
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induced pseudoscalar FF
- assume pion-pole dominance (PPD)

$$G_P(Q^2) = G_P(0) m_\pi^2/(Q^2 + m_\pi^2)$$

- leads to

$$\tilde{G}_P(Q^2) = -\frac{4M_N^2}{Q^2 + m_\pi^2} G_A(Q^2)$$

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JG|U PRISMA++

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complicated parameterisation
with coefficient from lattice QCD

Nuclear Effects

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- describe nucleons as free, non-interacting particles in a potential well
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Spectral functions

- factorization (struck nucleon) ⊗ (remnant nucleus)

$$|\Psi_f^A\rangle = |p'\rangle \otimes |\Psi_n^{A-1}, p_{A-1}\rangle$$

- spectral function describes momentum distribution of struck nucleon

$$P_h(\vec{p}_N, E^*) = \sum_n \left| \langle \Psi_0^A [|p_N\rangle \otimes |\Psi_n^{A-1}\rangle] \right|^2 \times \delta(E^* + E_0^A - E_n^{A-1} + m_N)$$

- used like a PDF
- determined e.g. in electron–nucleon scattering

Incorporation of Nuclear Effects via Spectral Functions

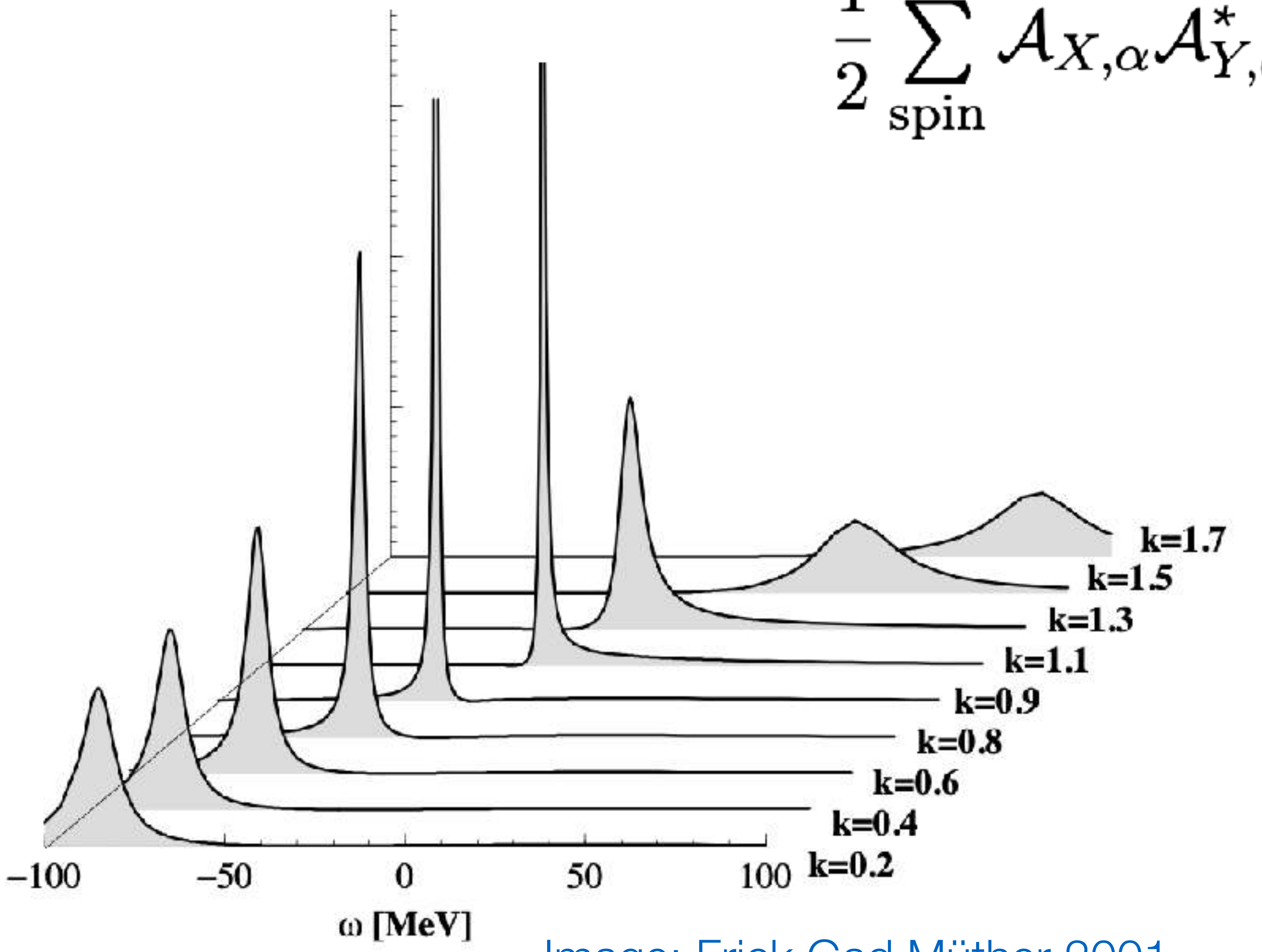

Image: Frick Gad Müther 2001

$$\frac{1}{2}\sum_{\text{spin}} \mathcal{A}_{X,\alpha}\mathcal{A}^*_{Y,\alpha} = \frac{1}{2}\int \frac{d^3p_N}{(2\pi)^3} P_h(\mathbf{p}_N, E^*) \frac{m_N}{e(\mathbf{p}_N)} \frac{m_N}{e(\mathbf{q}+\mathbf{p}_N)} \times \sum_{\text{spin}}\sum_N A_{X,\alpha} A^*_{Y,\alpha}\,\delta\big(\tilde{\omega} + e(\mathbf{p}_N) - e(\mathbf{q}+\mathbf{p}_N)\big),$$

FASER Sensitivity to EFT

- theoretically straightforward: ν scattering described in terms of PDFs
- though flux uncertainties remain a problem
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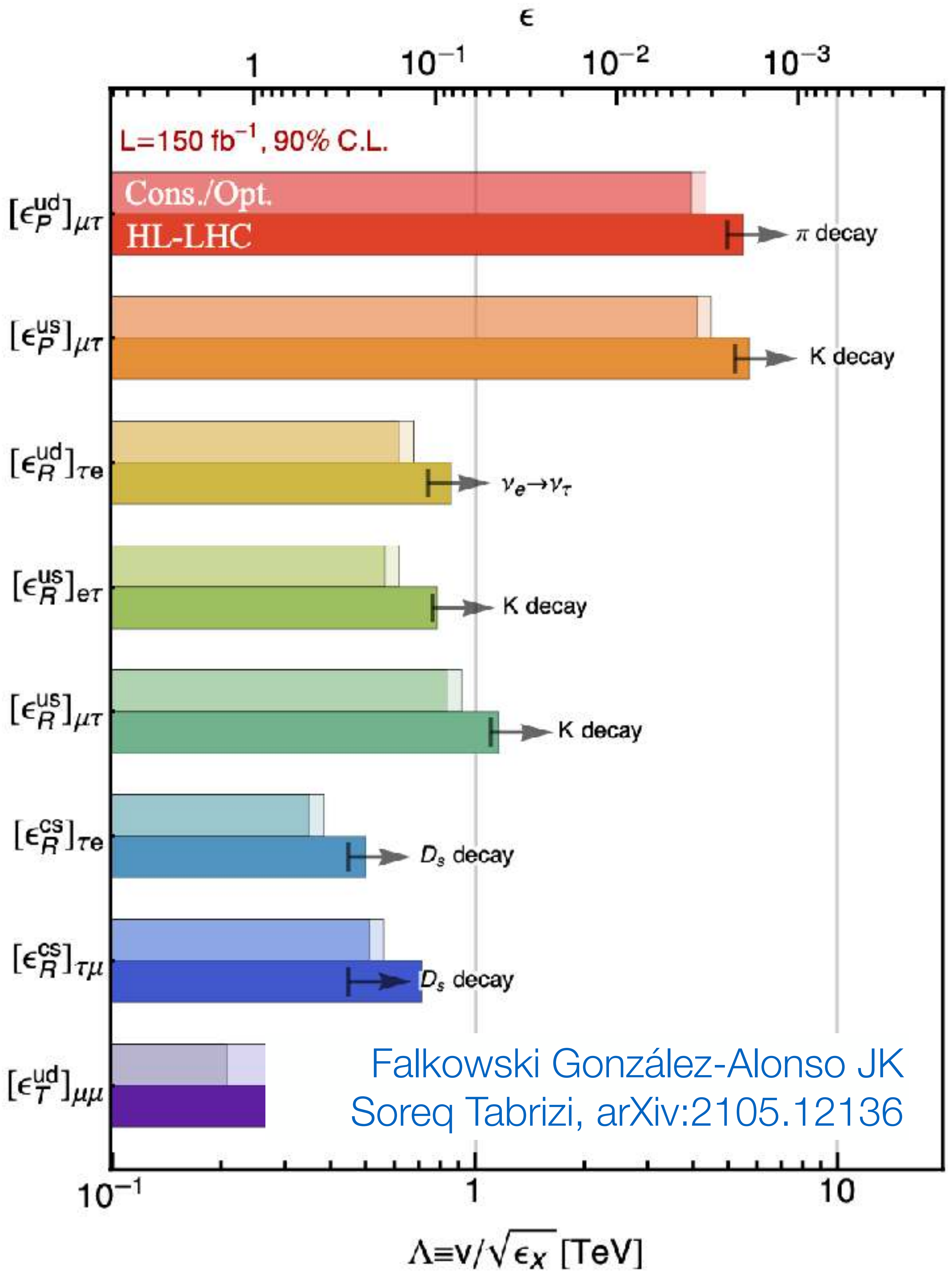

Falkowski González-Alonso JK Soreq Tabrizi, arXiv:2105.12136

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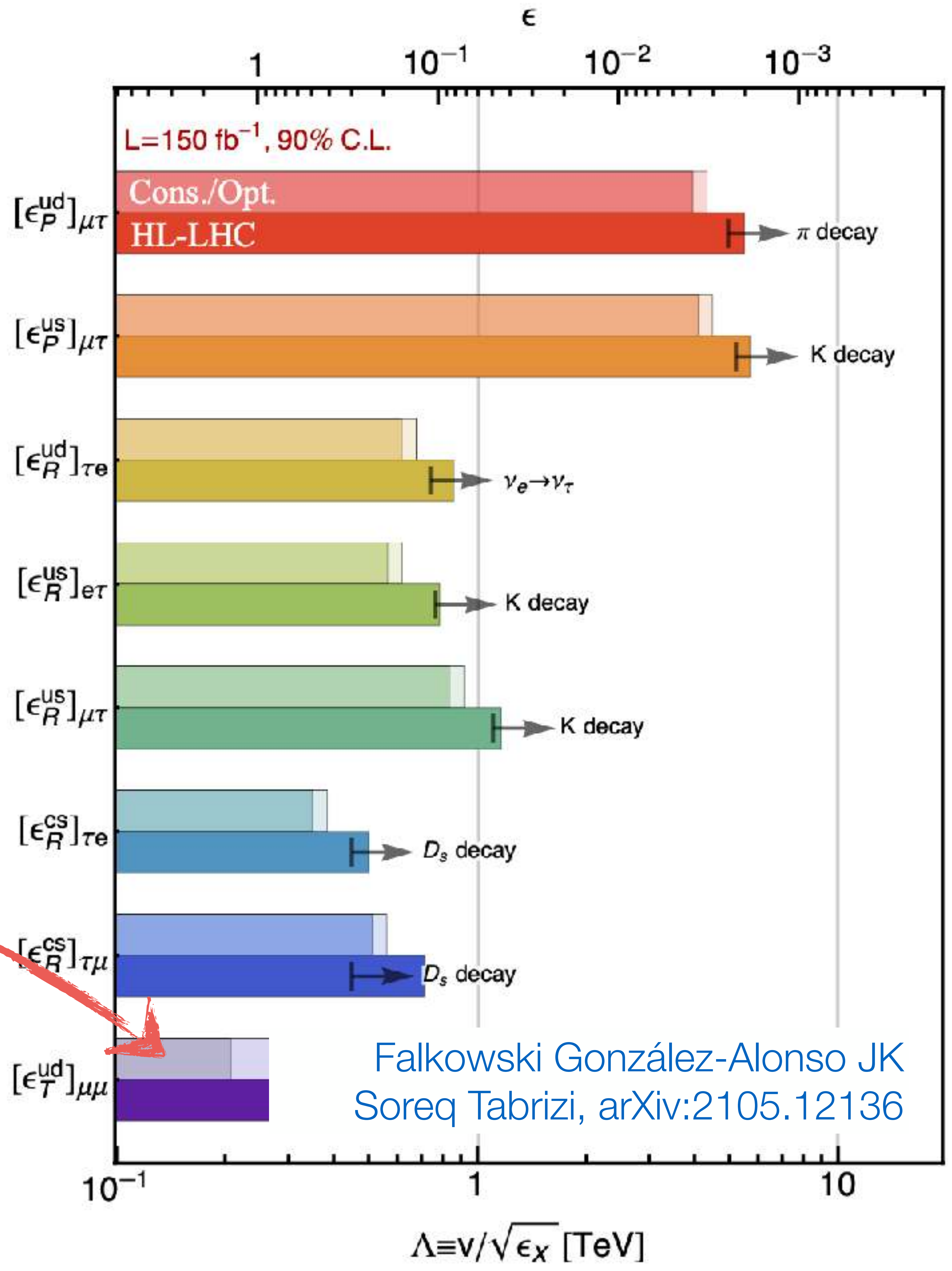
conservative scenario
flux uncertainties 30% / 40% / 50%
for ν_e / ν_μ / ν_τ



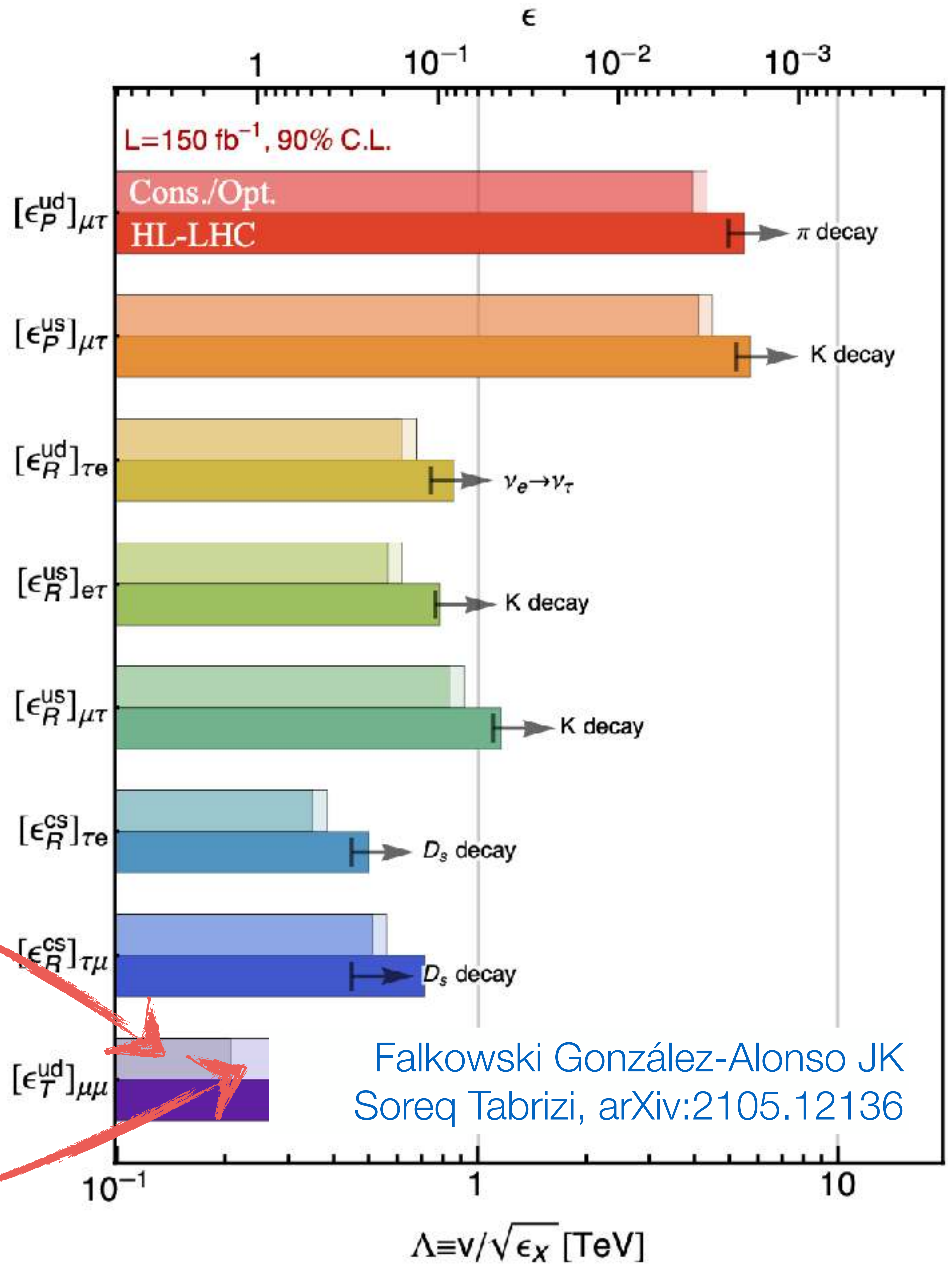
Falkowski González-Alonso JK Soreq Tabrizi, arXiv:2105.12136

FASER Sensitivity to EFT

- theoretically straightforward: ν scattering described in terms of PDFs
- though flux uncertainties remain a problem
- competitive with rare meson decays in some channels

conservative scenario
flux uncertainties 30% / 40% / 50%
for ν_e / ν_μ / ν_τ

optimistic scenario
flux uncertainties 5% / 10% / 15%
for ν_e / ν_μ / ν_τ



Falkowski González-Alonso JK Soreq Tabrizi, arXiv:2105.12136

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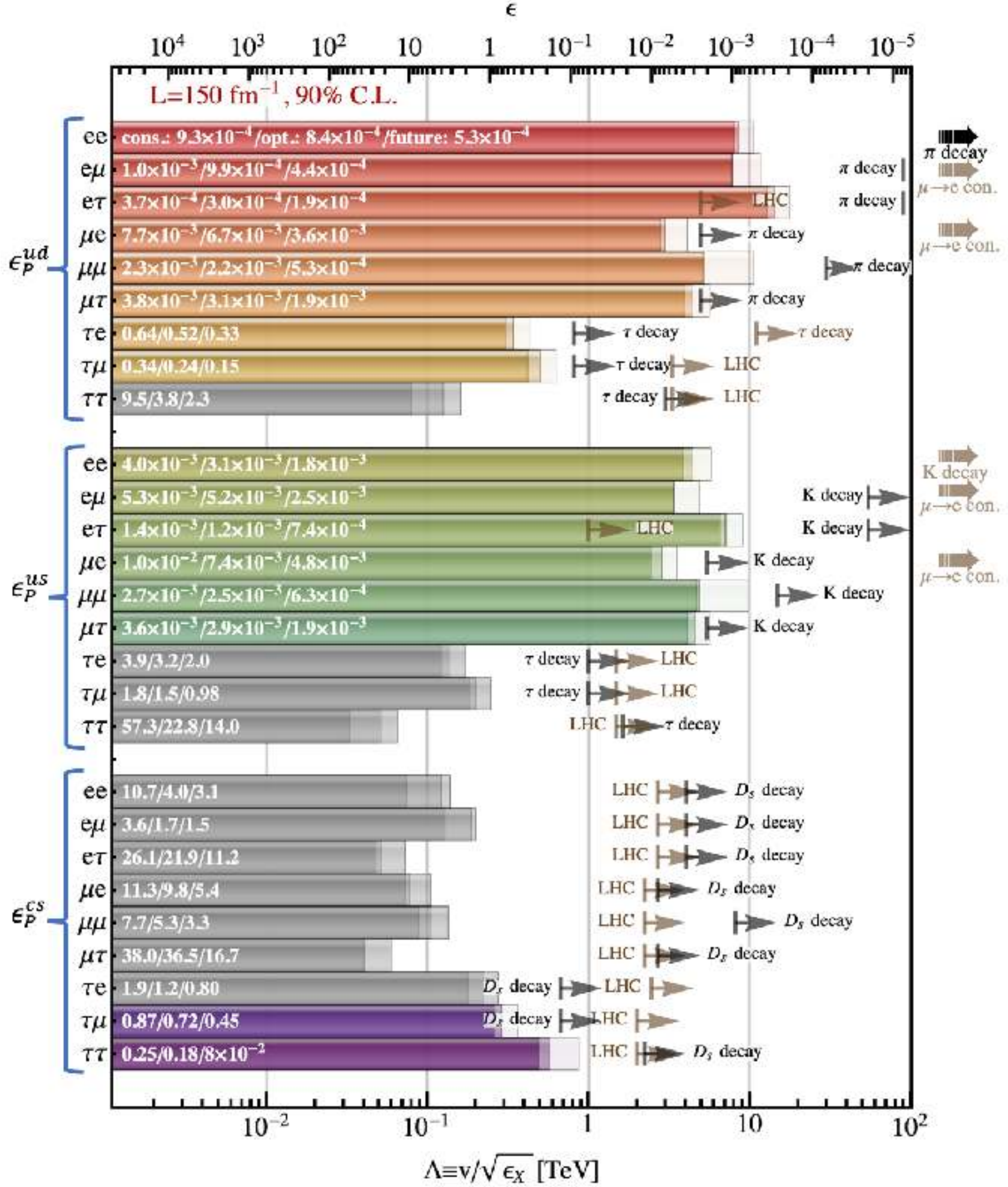
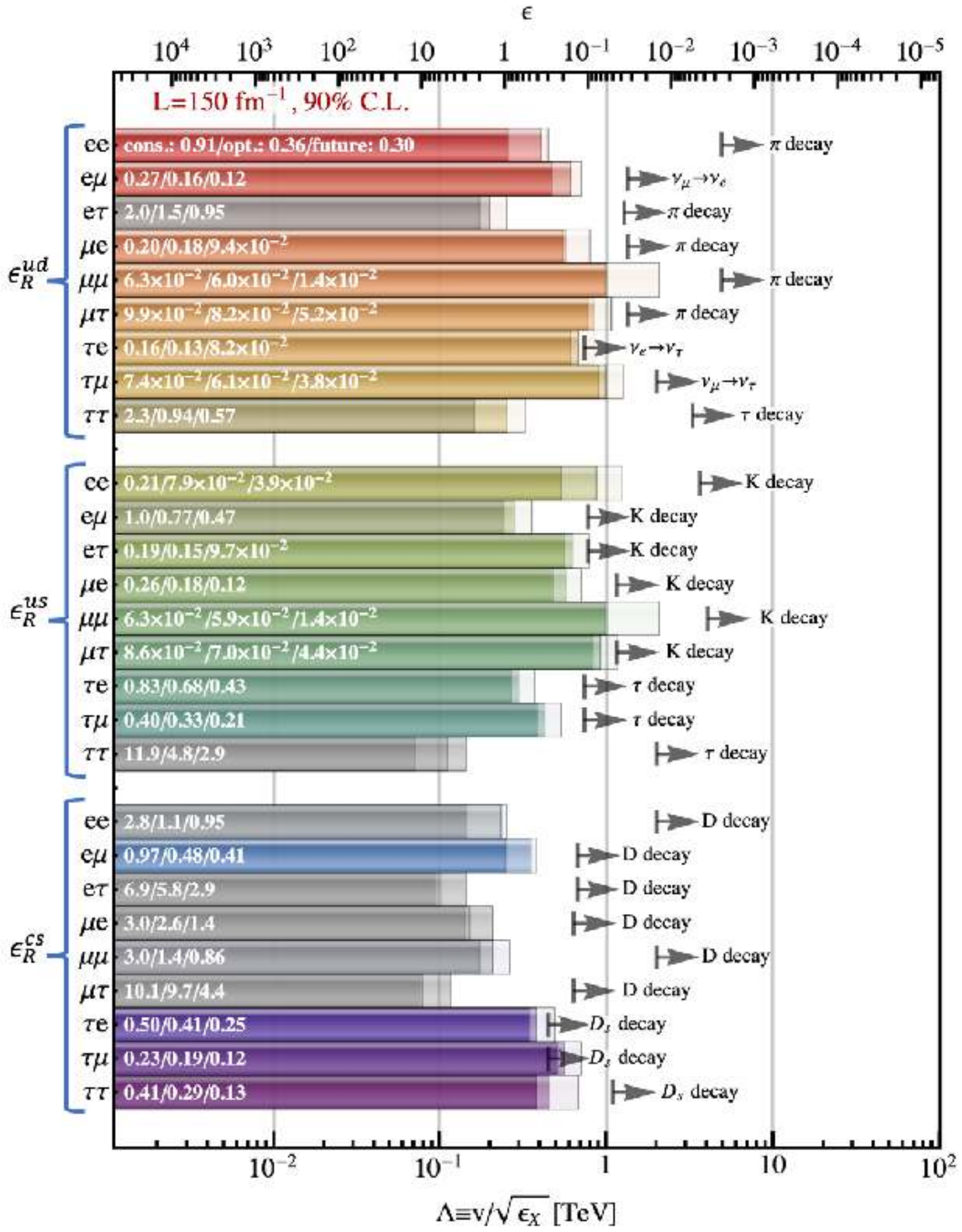
FASER Sensitivity

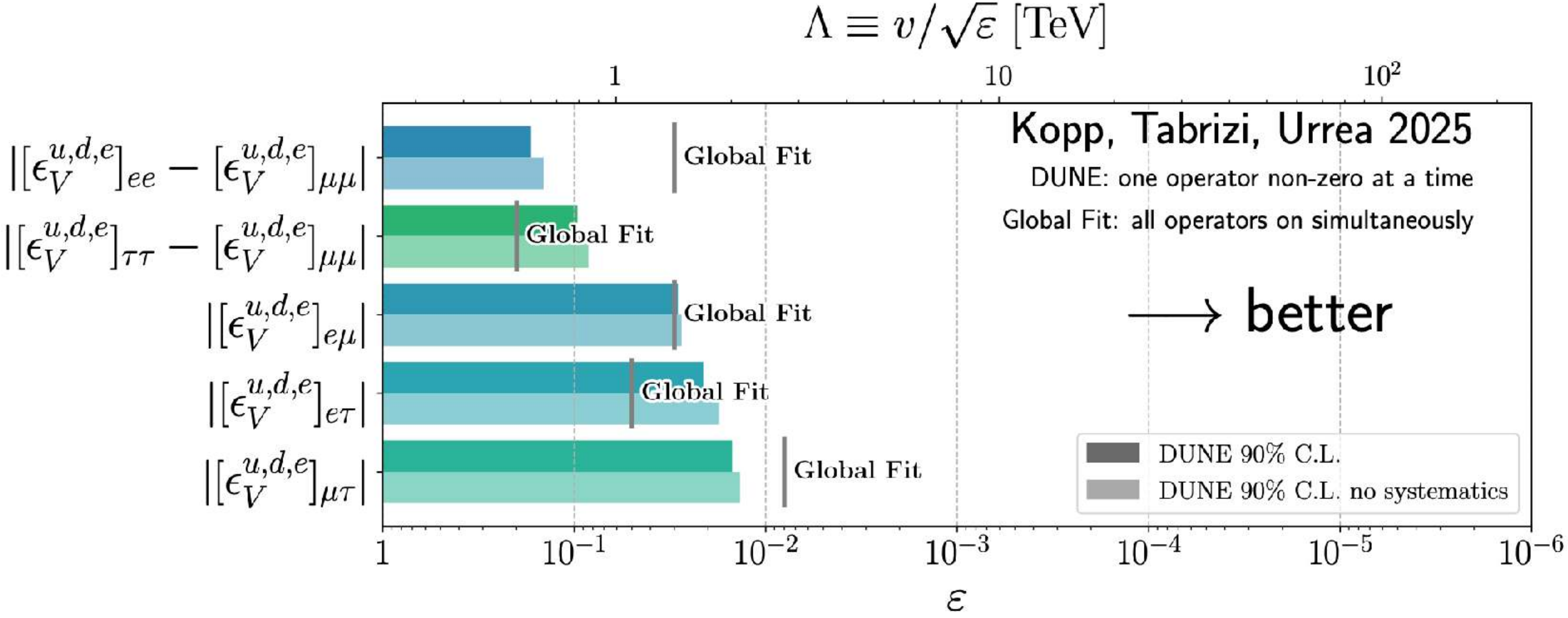
Falkowski González-Alonso JK Soreq Tabrizi, arXiv:2105.12136





Anomalous Neutral Currents – Future Limits

- DUNE will be probing new physics at the TeV scale



Anomalous Neutral Currents – Future Limits

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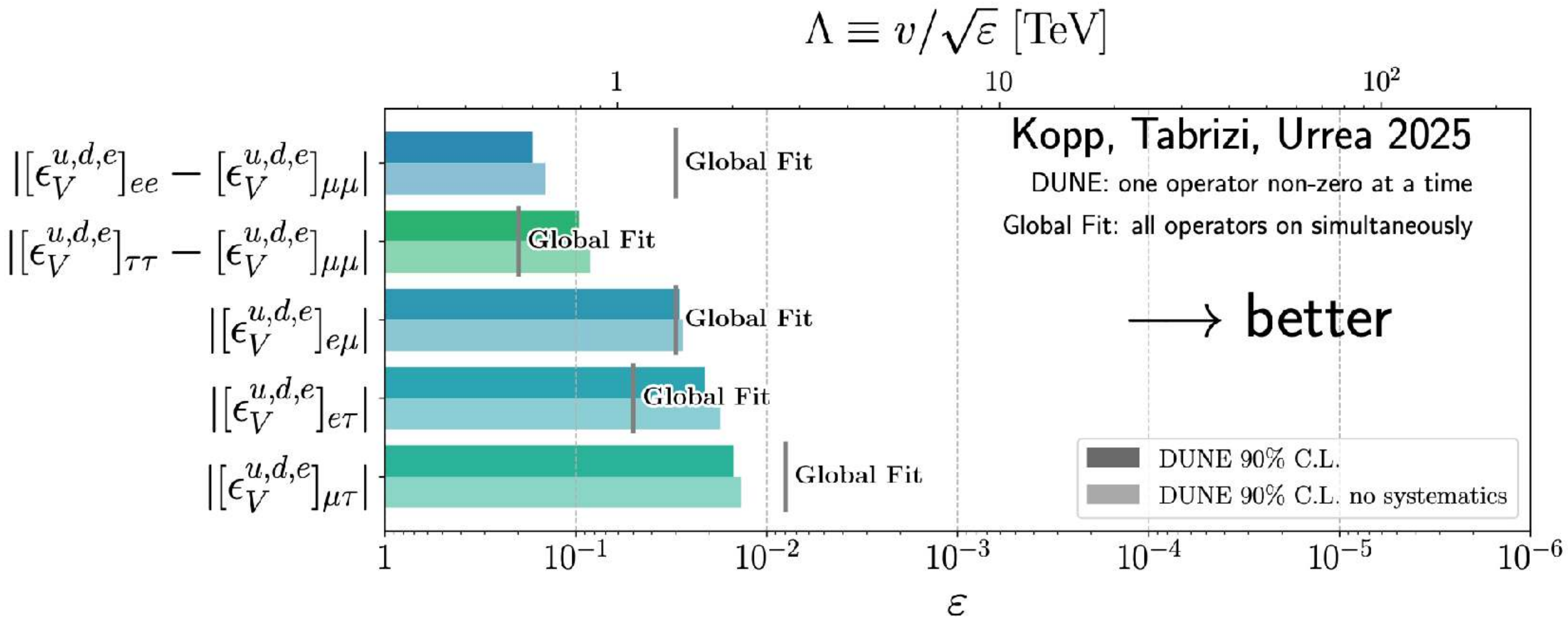
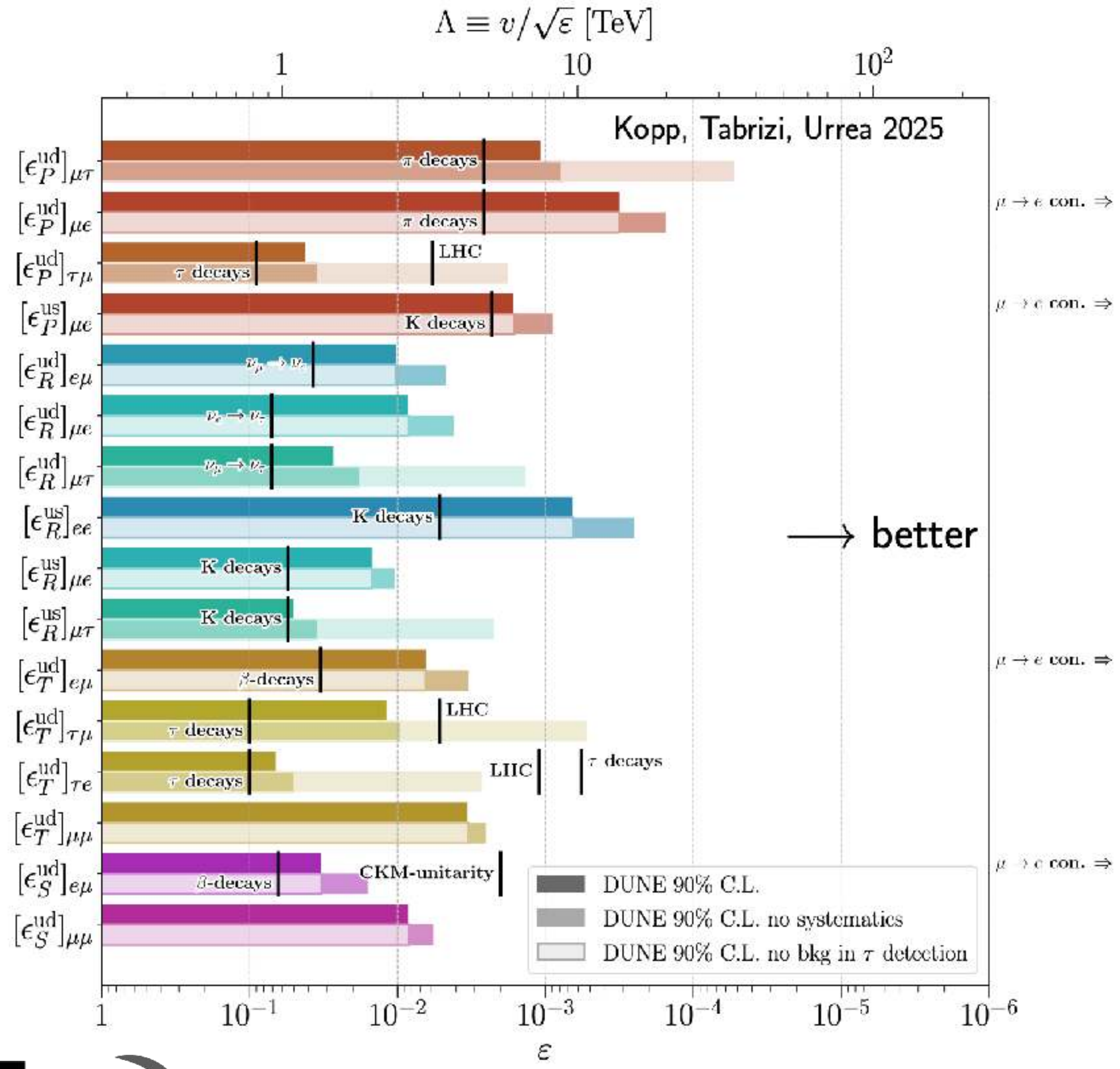
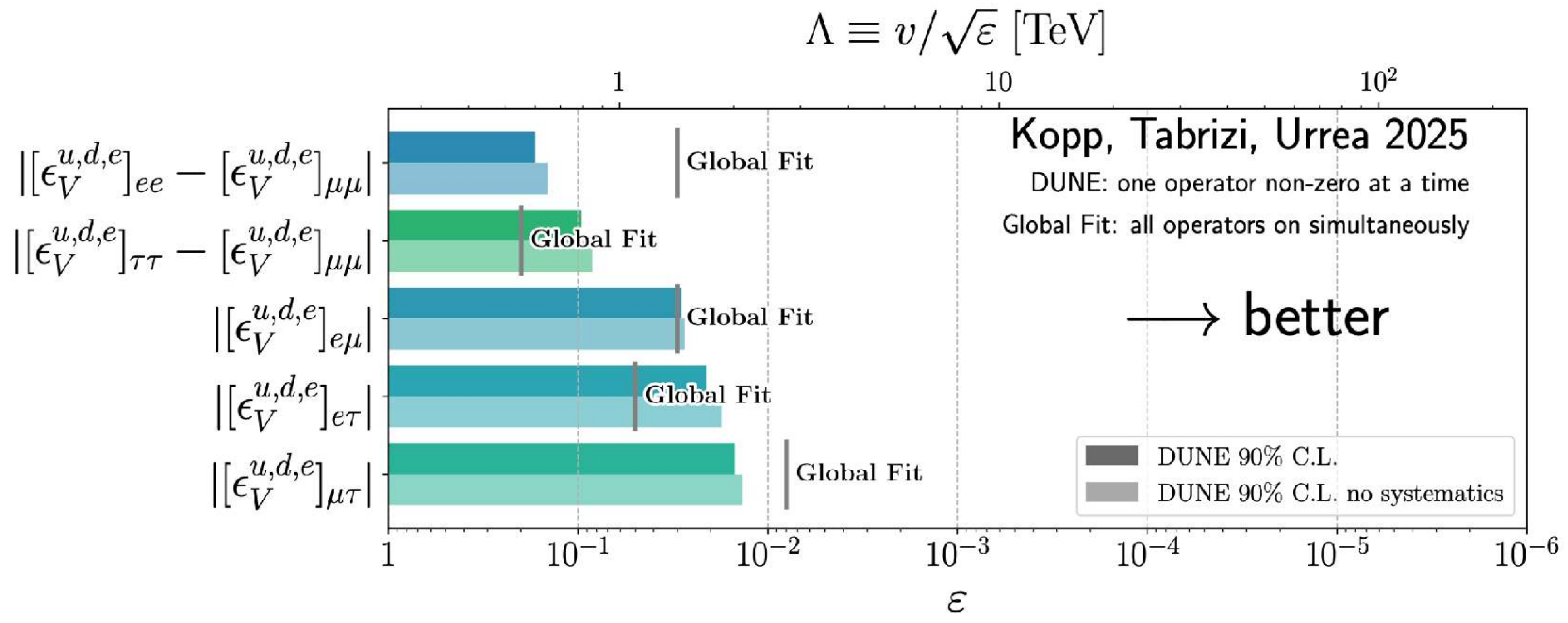


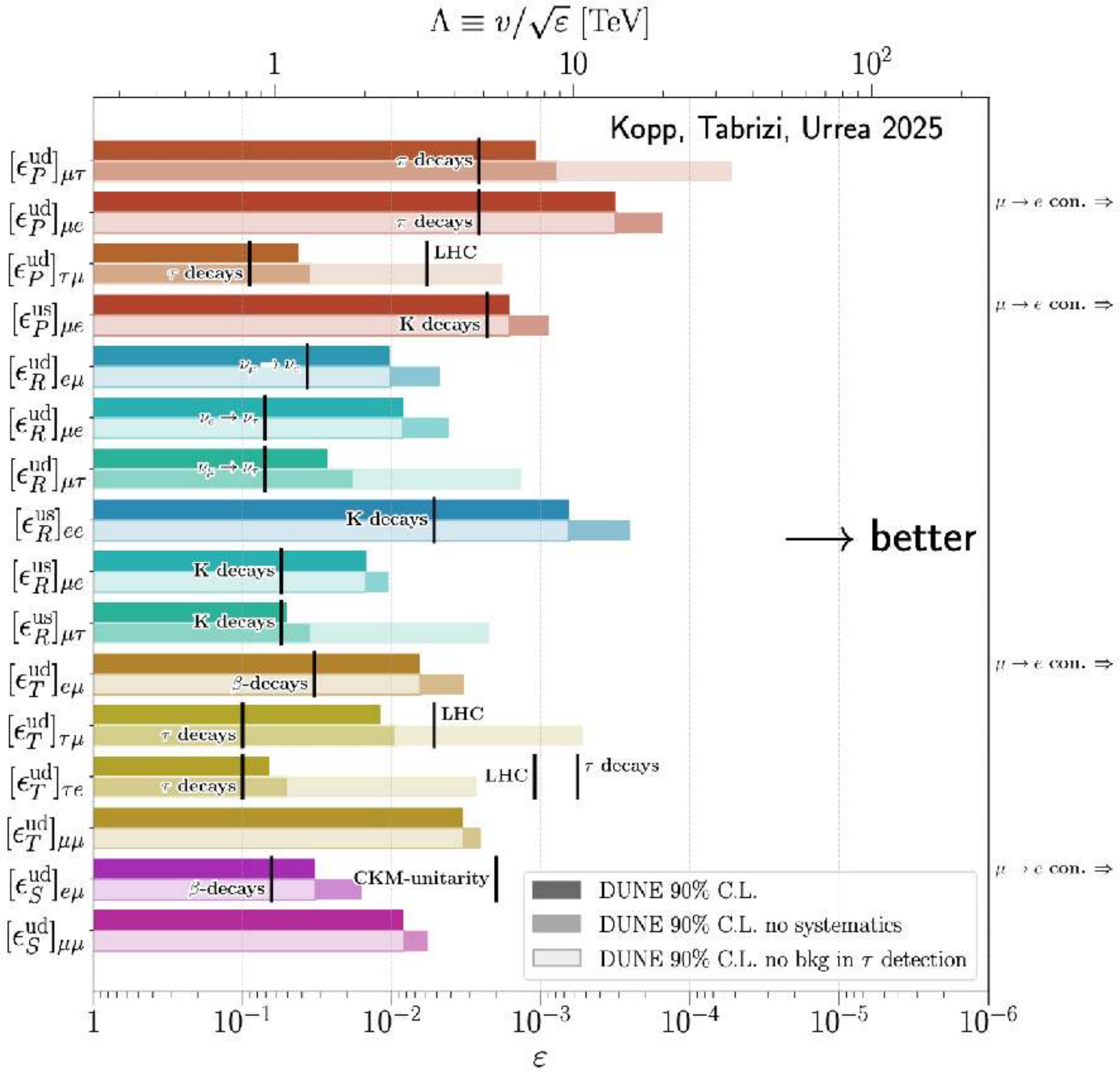
- Caveats
  - WEFT must be embedded in UV-complete theory like SMEFT
  - WEFT constraints ("NSI formalism") neglect relations between operators in SMEFT
  - for comparison with other experiments: WEFT–SMEFT matching, RGE running

WEFT Constraints from DUNE



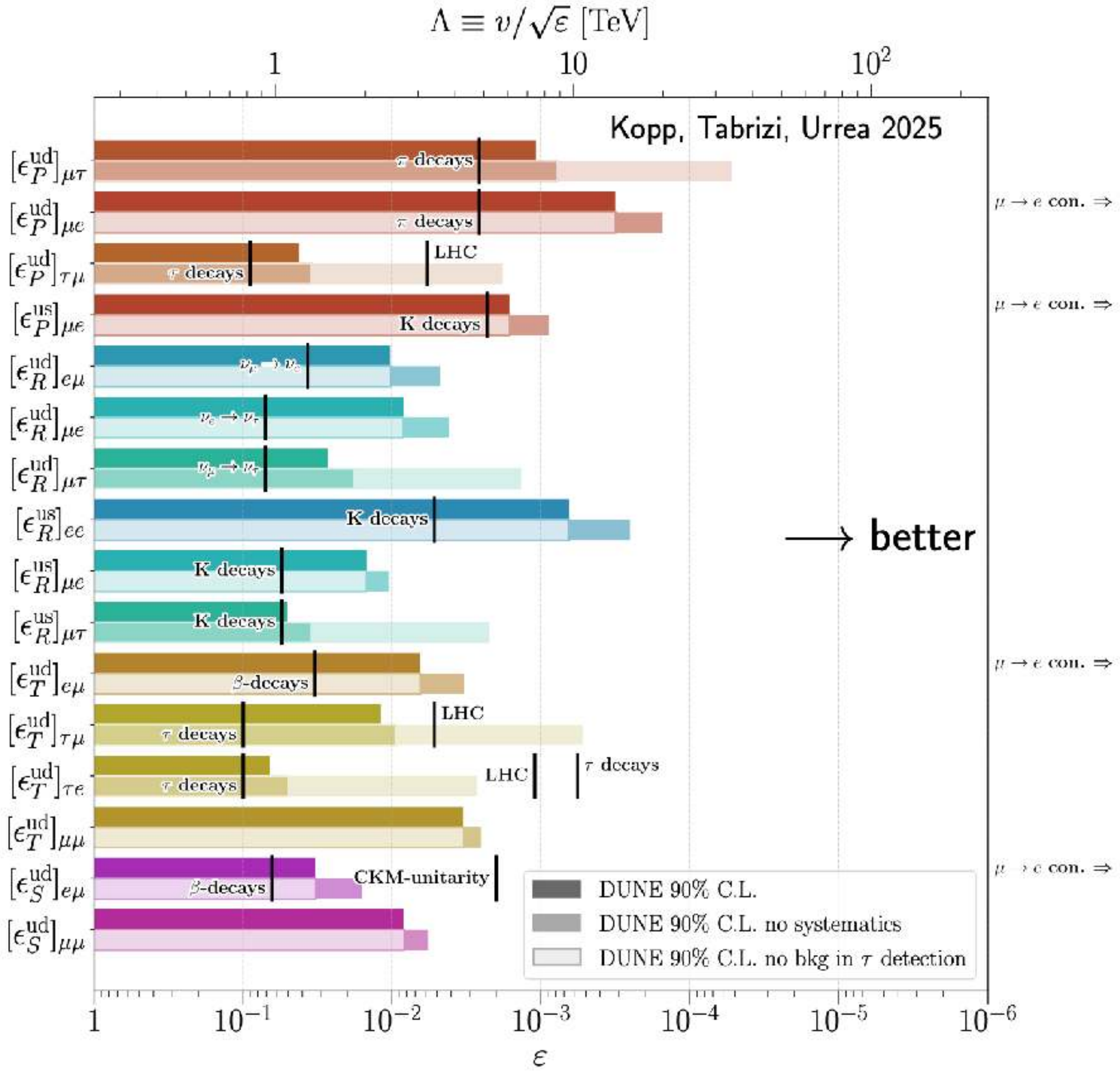


SMEFT Constraints from DUNE



SMEFT Constraints from DUNE

- GLoBES-EFT
  - fast simulation of neutrino oscillation experiments including new physics
  - implements QES cross sections including new physics
  - either WEFT or SMEFT parameterisation
  - automatic SMEFT–WEFT matching
  - automatic renormalisation group running



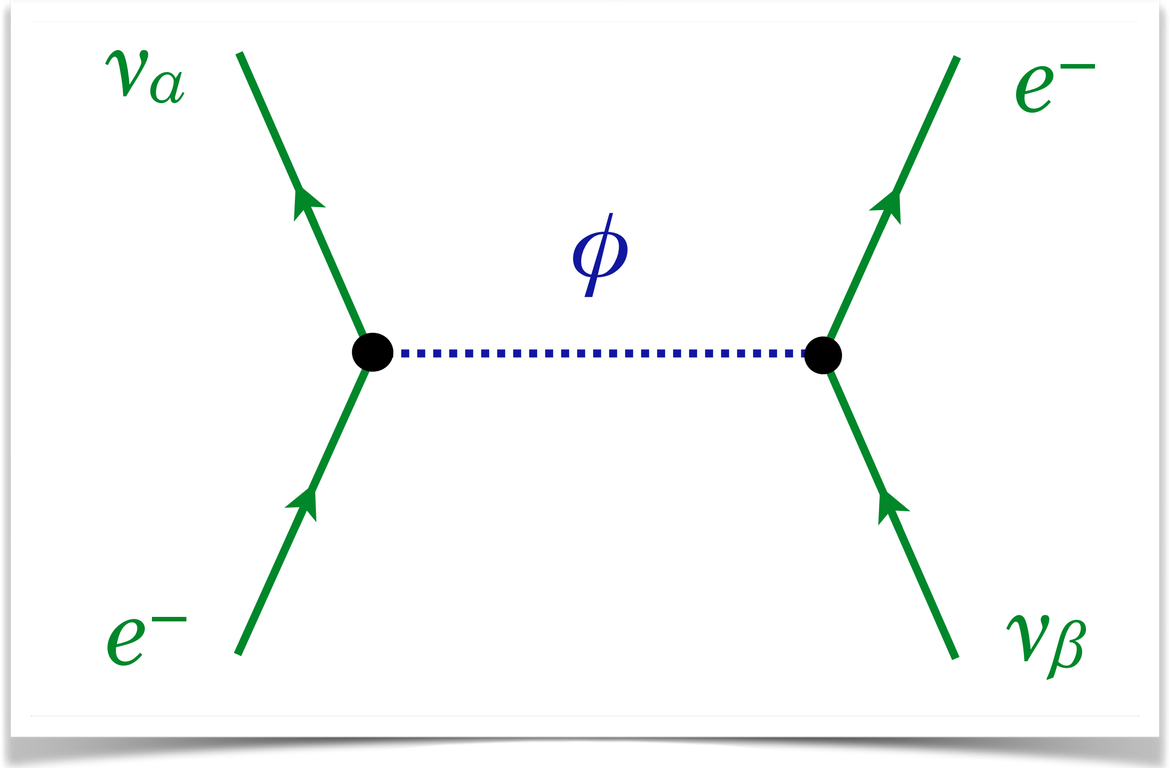
PRiSMA++

Are New $\mathcal{O}(0.01\,G_F)$ Couplings Realistic?

- standard lore: because of $SU(2)_L$ invariance, new neutrino interactions are accompanied by similar couplings of charged leptons ➠ strong constraints
- but not always: consider charged $SU(2)_L$ singlet ϕ^+

$$\mathcal{L} \supset \frac{\xi^{\alpha\beta}}{2} \bar{L}_a^{c,\alpha} \epsilon_{ab} L_b^{\beta} \phi^+$$

$$\mathcal{L}_{\text{EFT}} \supset \frac{\xi^{\alpha\beta}\xi^{\gamma\delta*}}{4m_\phi^2} \left[\bar{L}_a^{c,\alpha} \epsilon_{ab} L_b^{\beta}\right] \left[\bar{L}_a^{c,\delta} \epsilon_{ab} L_b^{\gamma}\right]$$



- coupling can arise naturally from TeV-scale new physics

Crivellin Kirk Manzari Panizzi arXiv:2012.09845