NOW 2024
Neutrino Oscillation Workshop
Otranto, Sept 2-8 2024

Effective Field Theory for single and double beta decay

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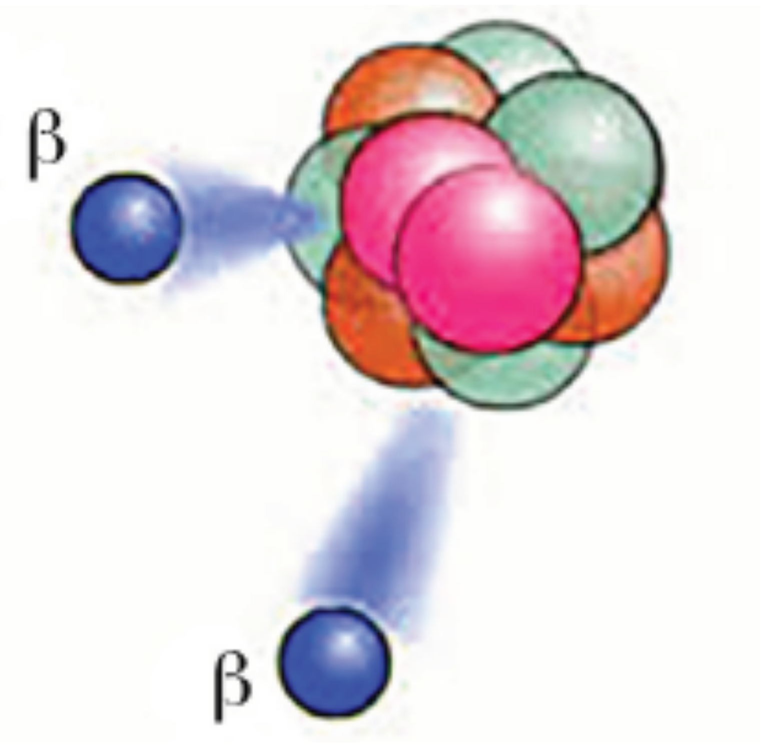
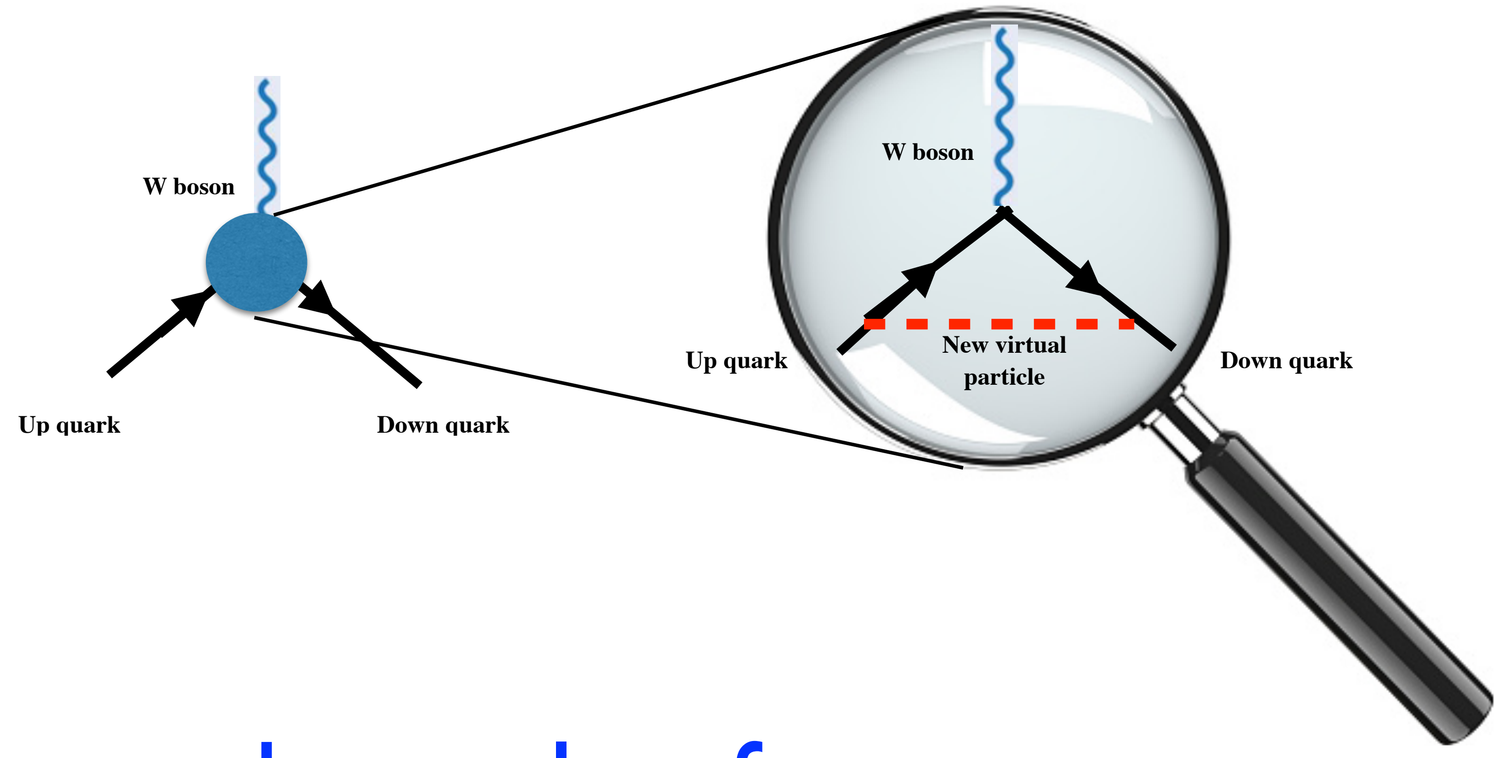
Outline

- Physics motivation and Effective Field Theory (EFT) analysis of:
  - Neutrinoless double beta decay



  - (Single) beta decays of neutron and nuclei



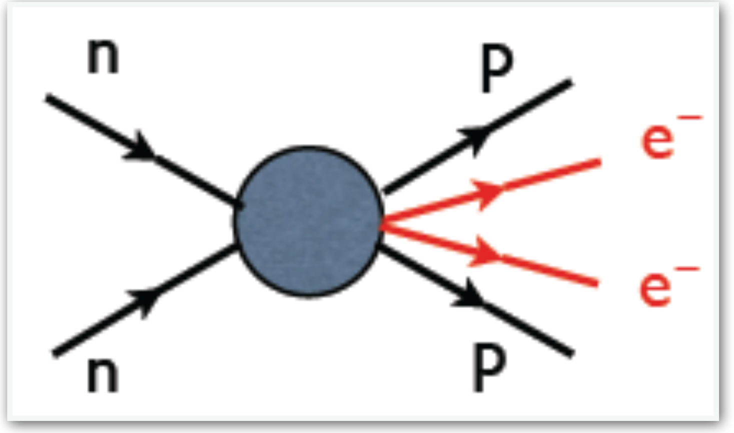
Unifying theme: end-to-end EFT approach, from the scale of new physics down to hadronic / nuclear energies

Lepton Number Violation
&
Neutrinoless double beta decay

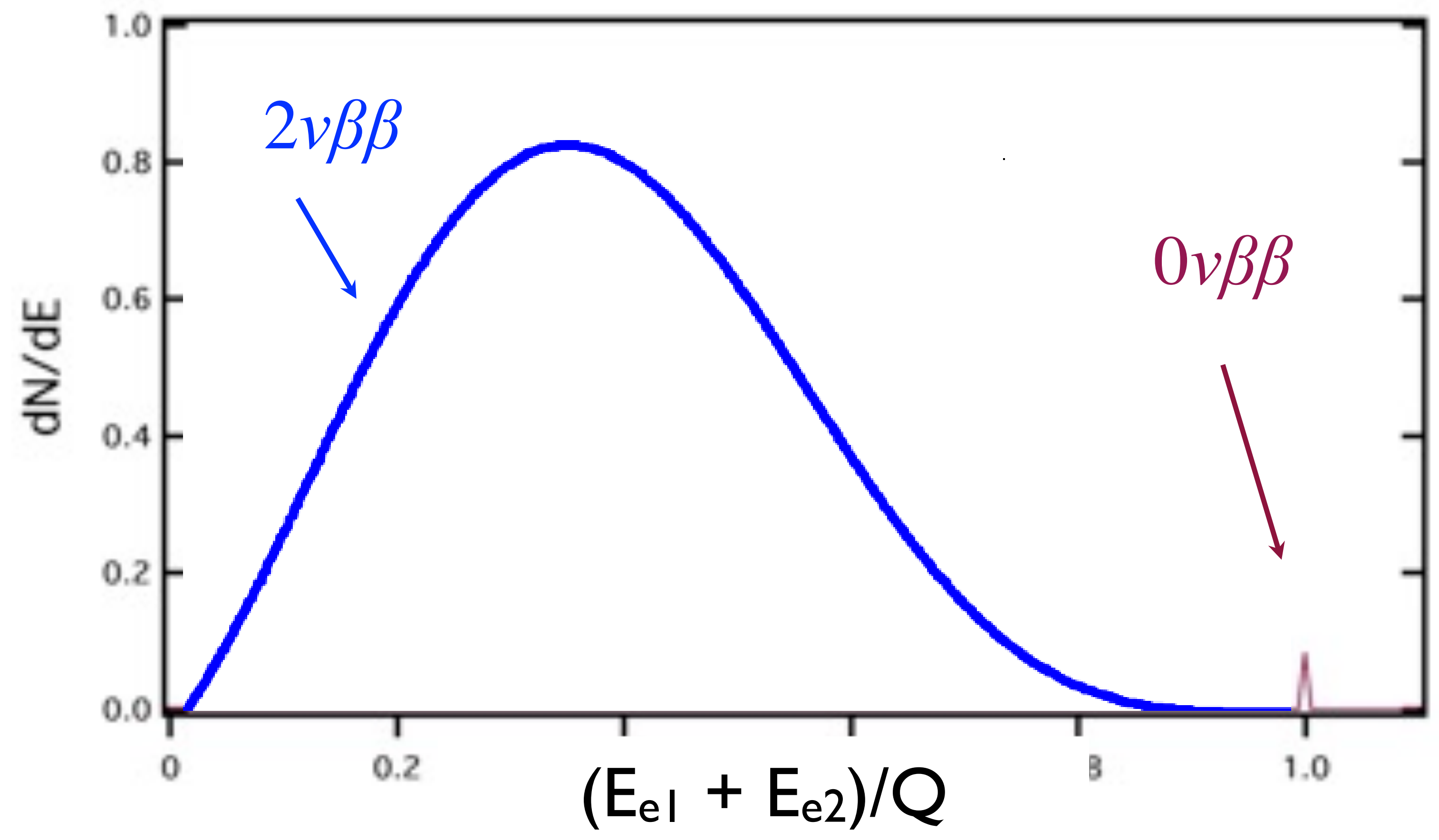
0νββ decay

$$(N,Z) \rightarrow (N-2, Z+2) + e^- + e^-$$

See morning talks by F. Bellini & J. Holt



ΔL=2



Potentially observable only in certain even-even nuclei (^{76}Ge, ^{100}Mo, ^{136}Xe, …) for which single beta decay is energetically forbidden

Observation ⇒ BSM physics, with far reaching implications

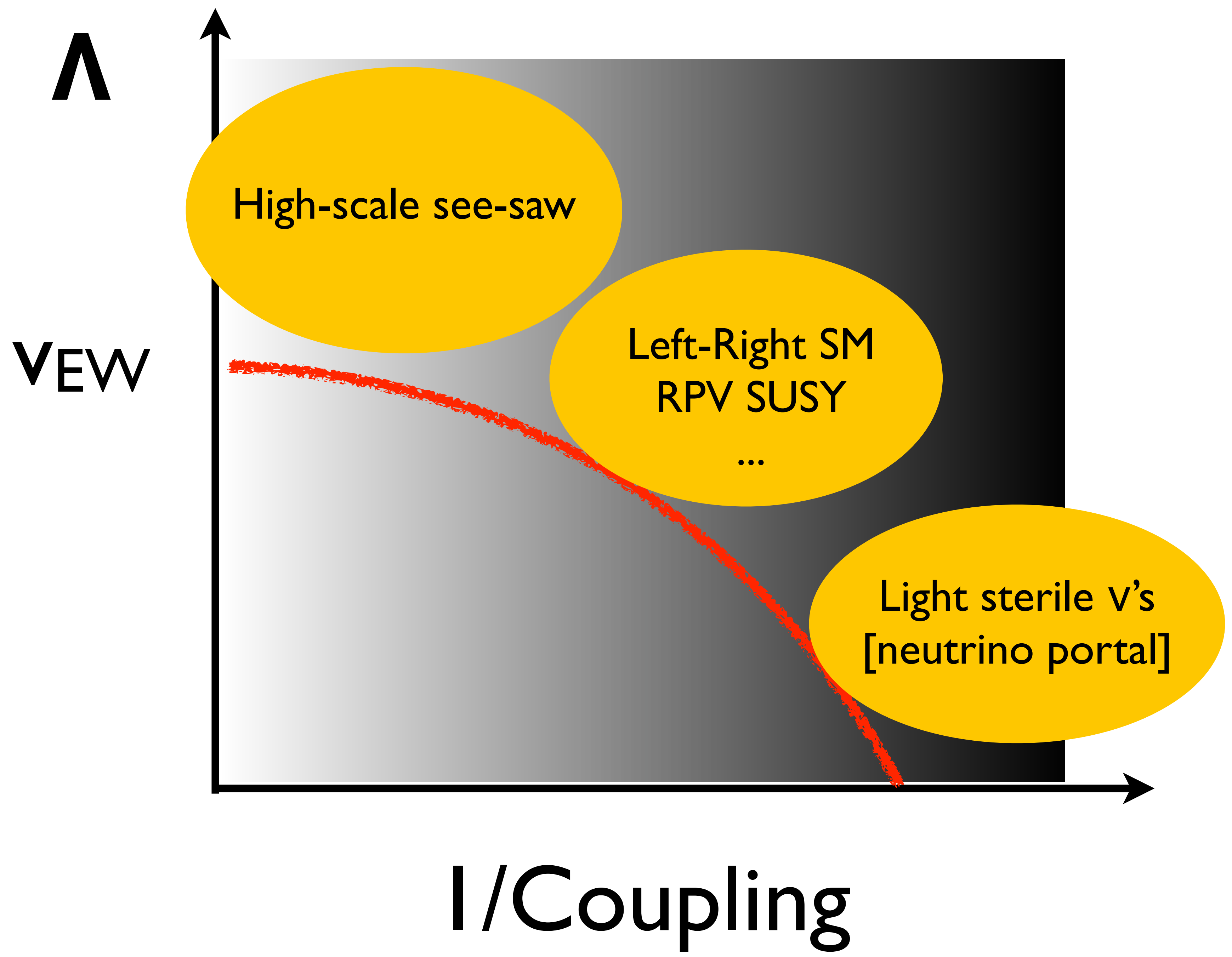
(B-L conserved in the the SM)

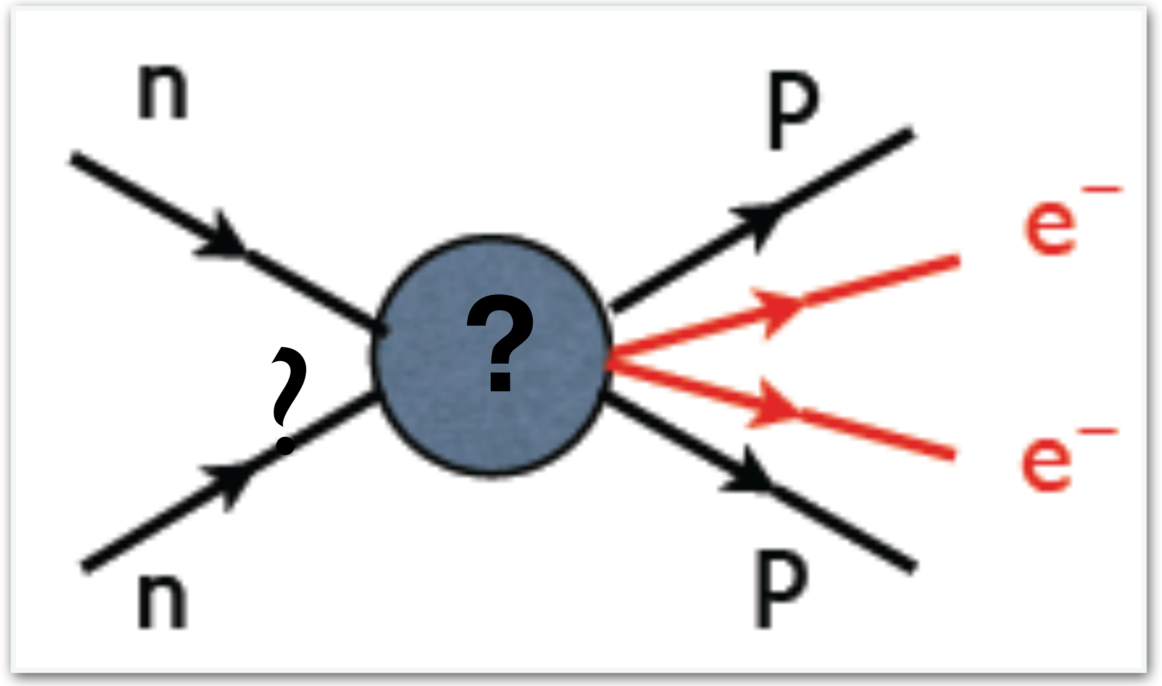
Demonstrate Majorana nature of neutrinos (neutrino=antineutrino)

Establish LNV, key ingredient to generate baryon asymmetry via leptogenesis

0νββ physics reach

- 0νββ searches @ $T_{1/2} > 10^{27\text{-}28}$ yr will have broad sensitivity to mechanisms of Lepton Number Violation (LNV)





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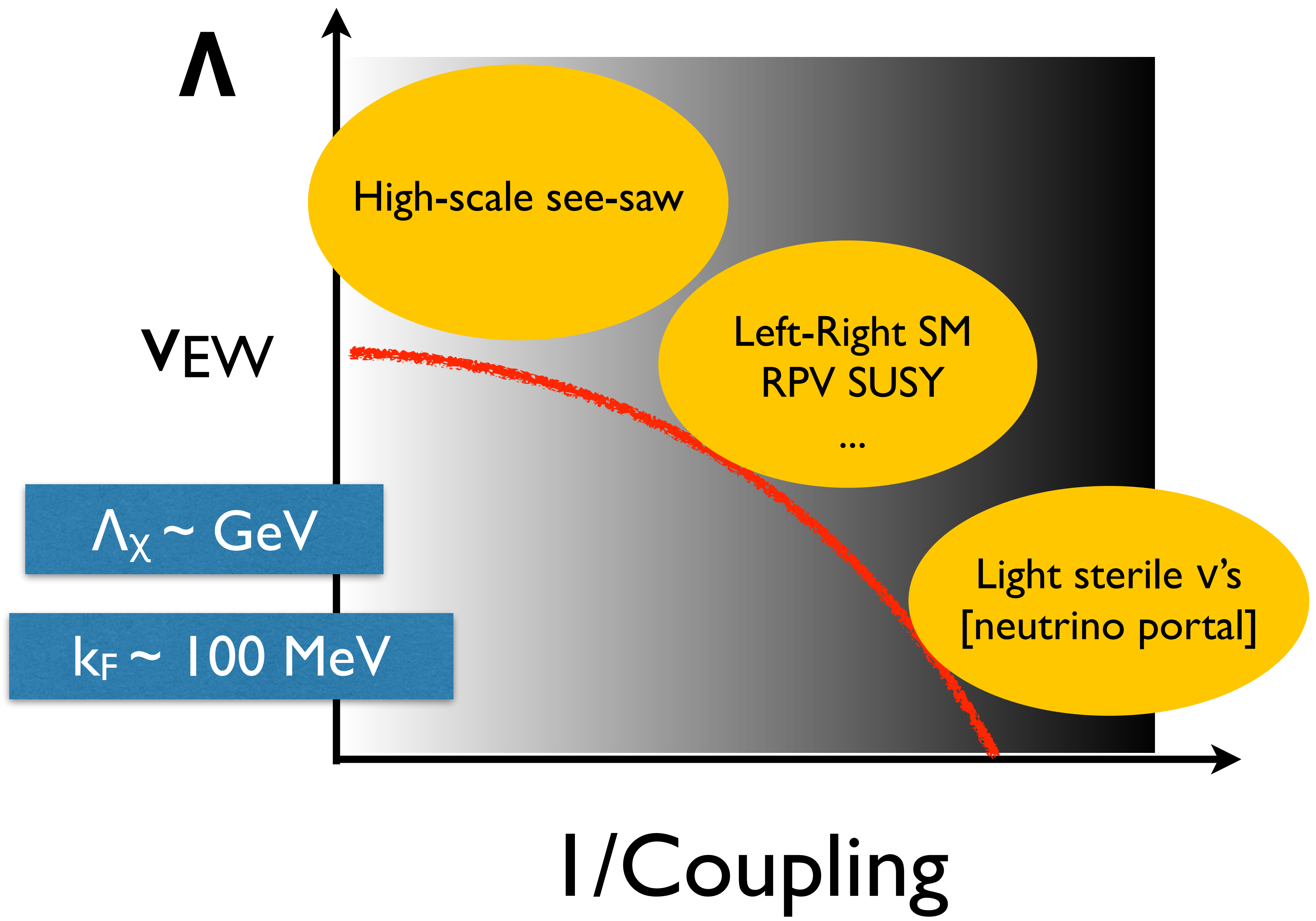
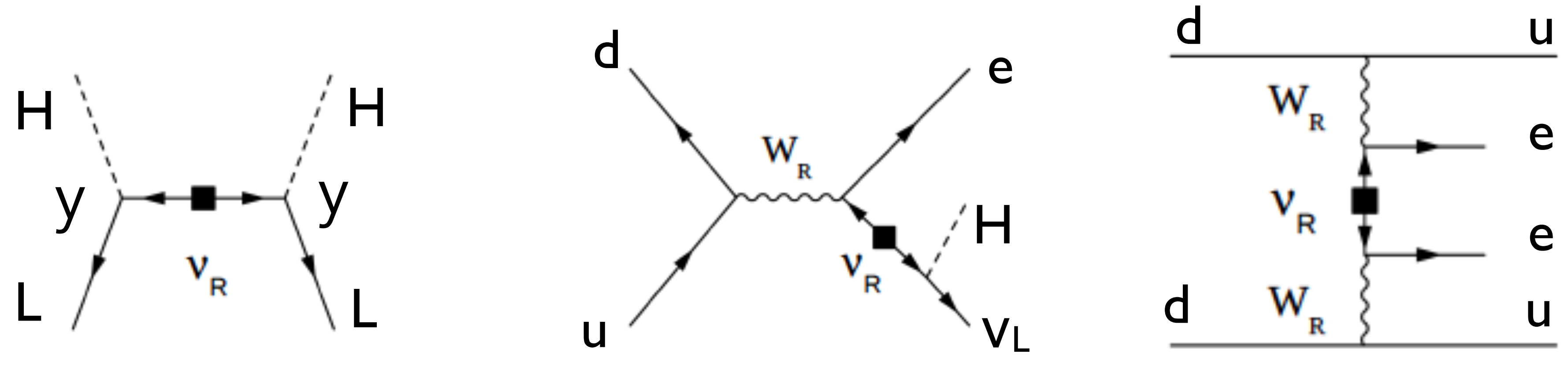


- Given the widely-separated scales, the impact of 0νββ searches and the relation to other probes of LNV is best analyzed through a tower of EFTs that connect the LNV scale Λ to nuclear scales, with controllable uncertainties

See Snowmass white paper 2203. 21169 and refs therein

‘End-to-end’ EFT framework

E



BSM dynamics

Example:
Left-Right Symmetric Model

Λ
(> TeV)

Full or simplified model is needed to study the cosmological implications of LNV or collider signatures (if Λ~ TeV)

v_{ew} , M_W

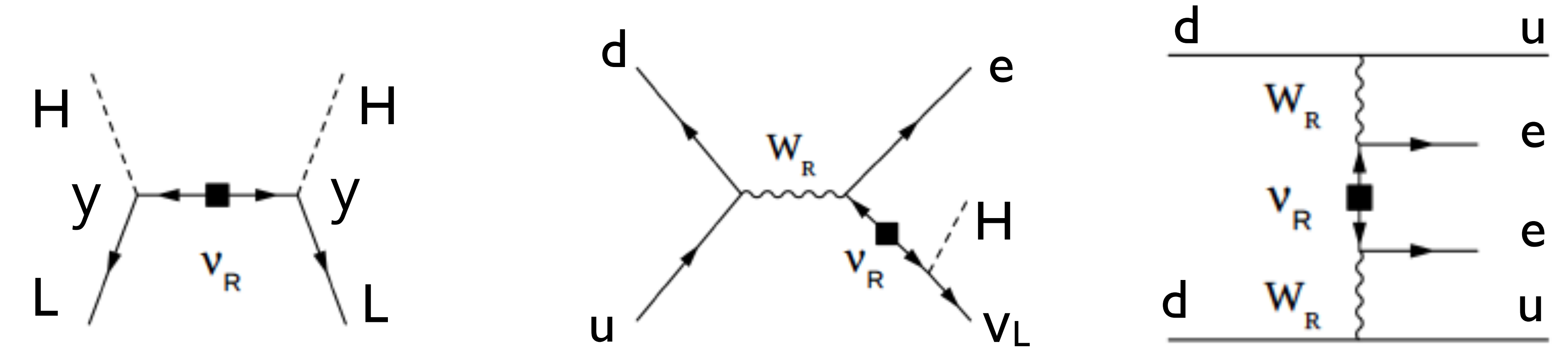
Λ_χ
(~GeV)

For low-energy probes such as 0νββ, it’s much more convenient to match to EFT and do the analysis ‘once and for all’

k_F, m_π

'End-to-end' EFT framework

E



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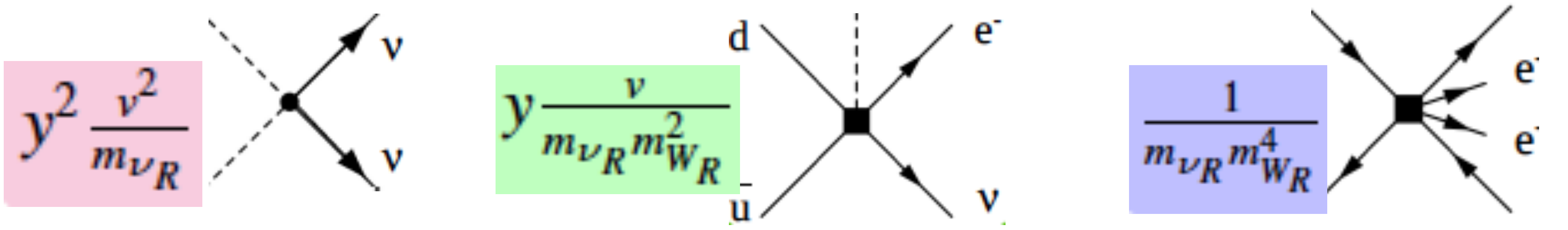


SM-EFT

dim5 — dim7 — dim9

v_{ew} , M_W

Weinberg'79

Babu-Leung '01
...
Lehman 1410.4193

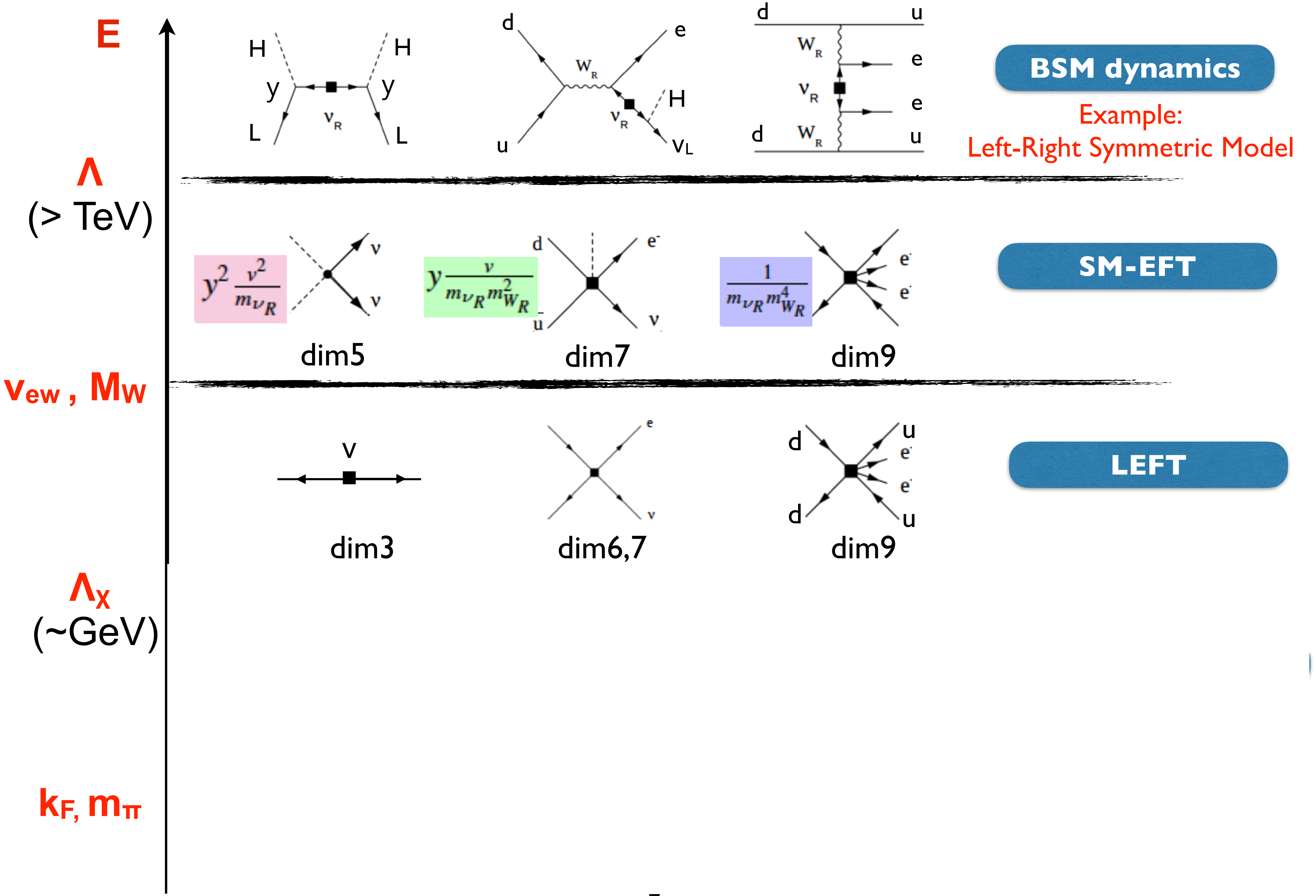
Graesser 1606.04549
Liao and Ma 2007.08125

Λ_χ
(~GeV)

- $\Delta L=2$, $\Delta B=0$ operators appear only at odd dimension — A. Kobach 1604.05726
- Insertions of small dimensionless (Yukawa) coupling can make dim=5,7,9 operators equally important for $\Lambda \sim$ TeV
- ν_R with mass $< \Lambda$ can be included in the framework — Dekens et al. 2002.07182

k_F, m_π

‘End-to-end’ EFT framework



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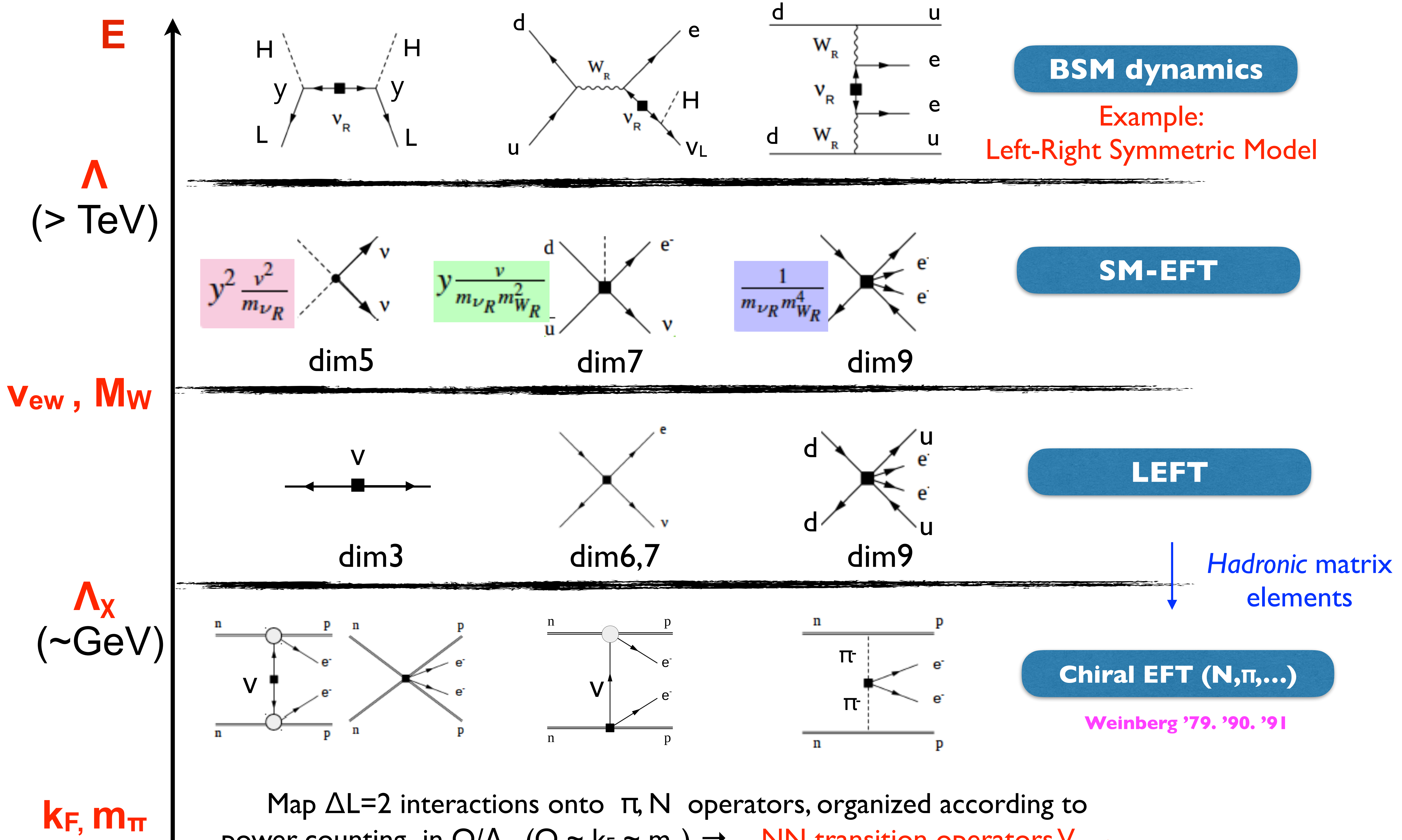
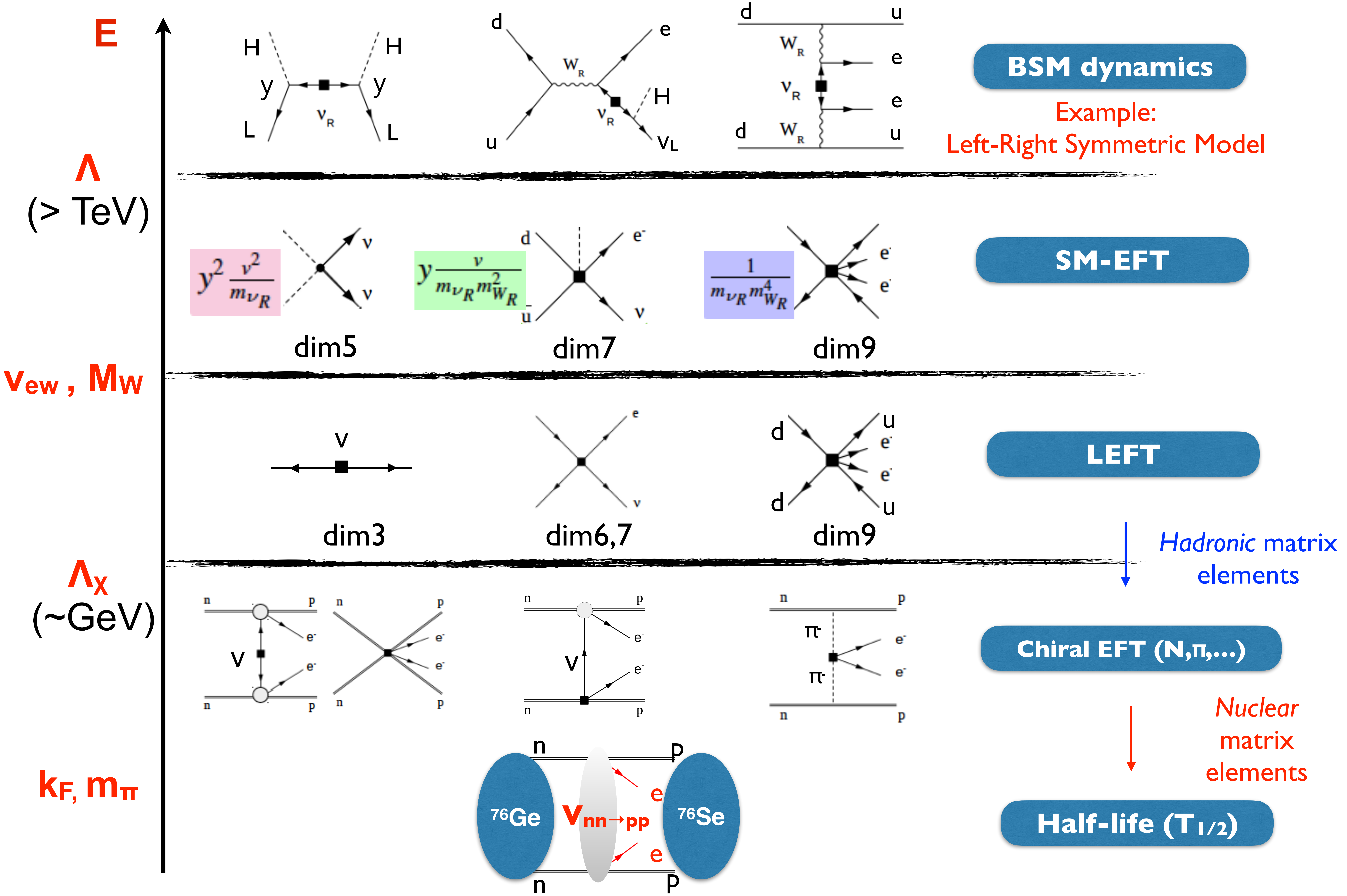


Map ΔL=2 interactions onto π, N operators, organized according to power-counting in Q/Λ_χ ($Q \sim k_F \sim m_\pi$) → NN transition operators $V_{nn\to pp}$

‘End-to-end’ EFT framework



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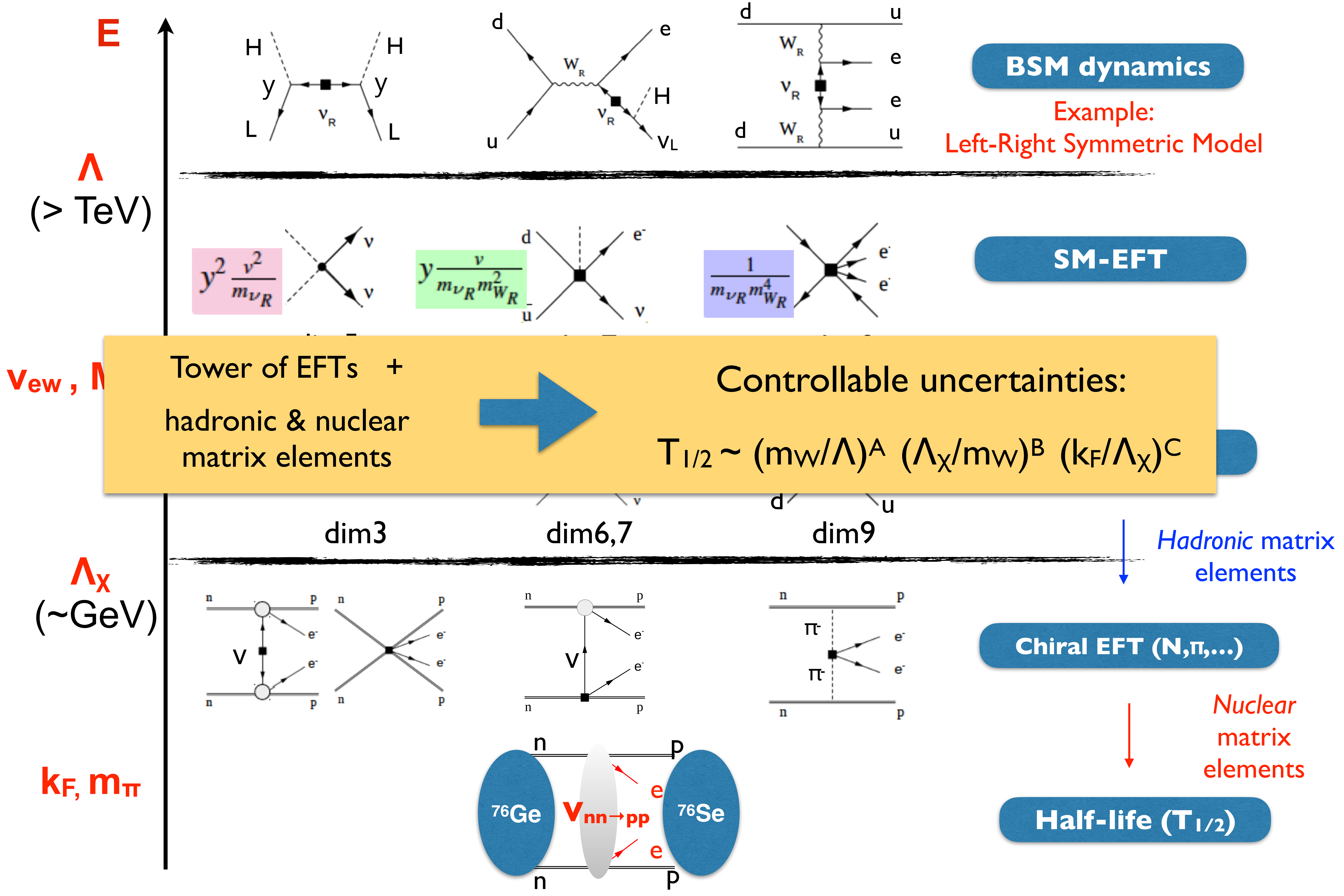
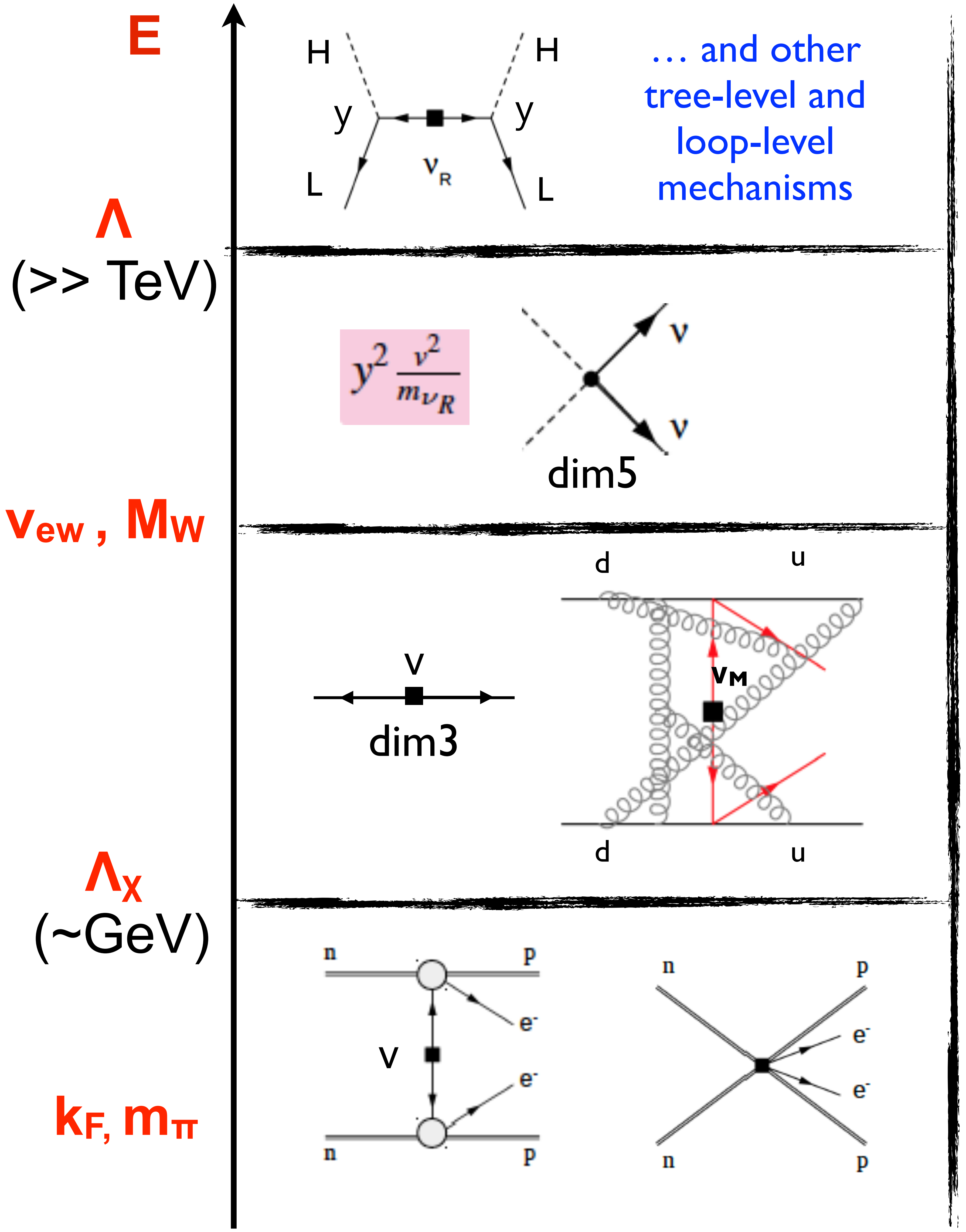


High scale LNV



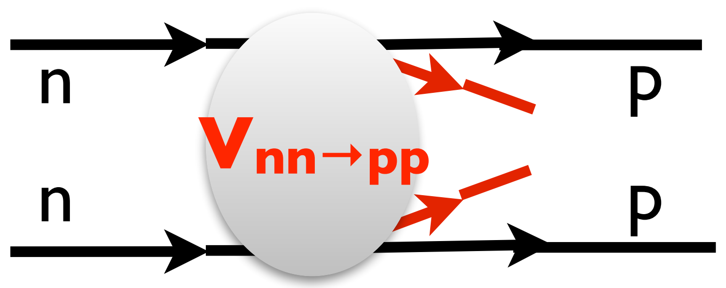
- LNV originates at very high scale (Λ >> v) → dominant low-energy remnant is Weinberg's dim-5 operator:

$$\mathcal{L}_5 = \frac{w_{\alpha\alpha'}}{\Lambda} L_\alpha^T C\epsilon H \, H^T \epsilon L_{\alpha'}$$

- Below the weak scale this is just the neutrino Majorana mass ($m_{\beta\beta} \sim w_{ee}\, v^2/\Lambda$), but let's not forget QCD!

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm QCD} - \frac{4G_F}{\sqrt{2}} V_{ud}\, \bar{u}_L \gamma^\mu d_L\, \bar{e}_L \gamma_\mu \nu_{eL} - \frac{m_{\beta\beta}}{2} \nu_{eL}^T C \nu_{eL} + {\rm H.c.}$$

- 0νββ mediated by *active* ν_M with potential $V_{nn\to pp}$ with long- and short-range components proportional to $m_{\beta\beta}$

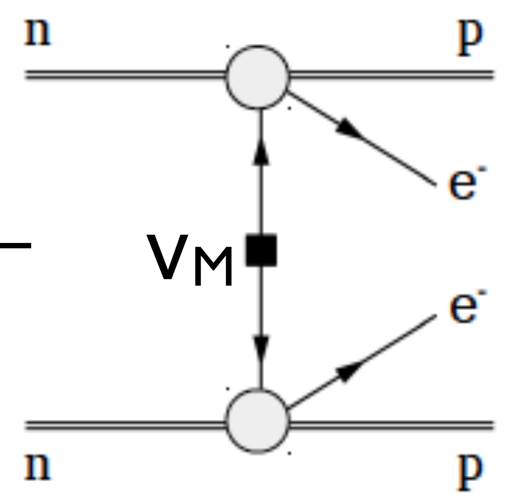


Insights from EFT

VC, W. Dekens, E. Mereghetti, A. Walker-Loud, 1710.01729
VC, W. Dekens, J. de Vries, M. Graesser, E. Mereghetti, S. Pastore, U. van Kolck 1802.10097

- Transition operator to leading order (LO) in Q/Λ_χ ($Q \sim k_F \sim m_\pi$, $\Lambda_\chi \sim$ GeV)

'Usual' ν_M exchange $\sim 1/k_F^2 \sim 1/Q^2$
Coulomb-like potential



$$V_\nu^{(a,b)} = \tau^{+,a}\tau^{+,b}\,\frac{1}{\mathbf{q}^2}\left(J_V^{(a)}(\mathbf{q})J_V^{(b)}(-\mathbf{q}) + J_A^{(a)}(\mathbf{q})J_A^{(b)}(-\mathbf{q})\right)$$

$$J_V \sim 1$$
$$J_A \sim g_A\,\sigma$$

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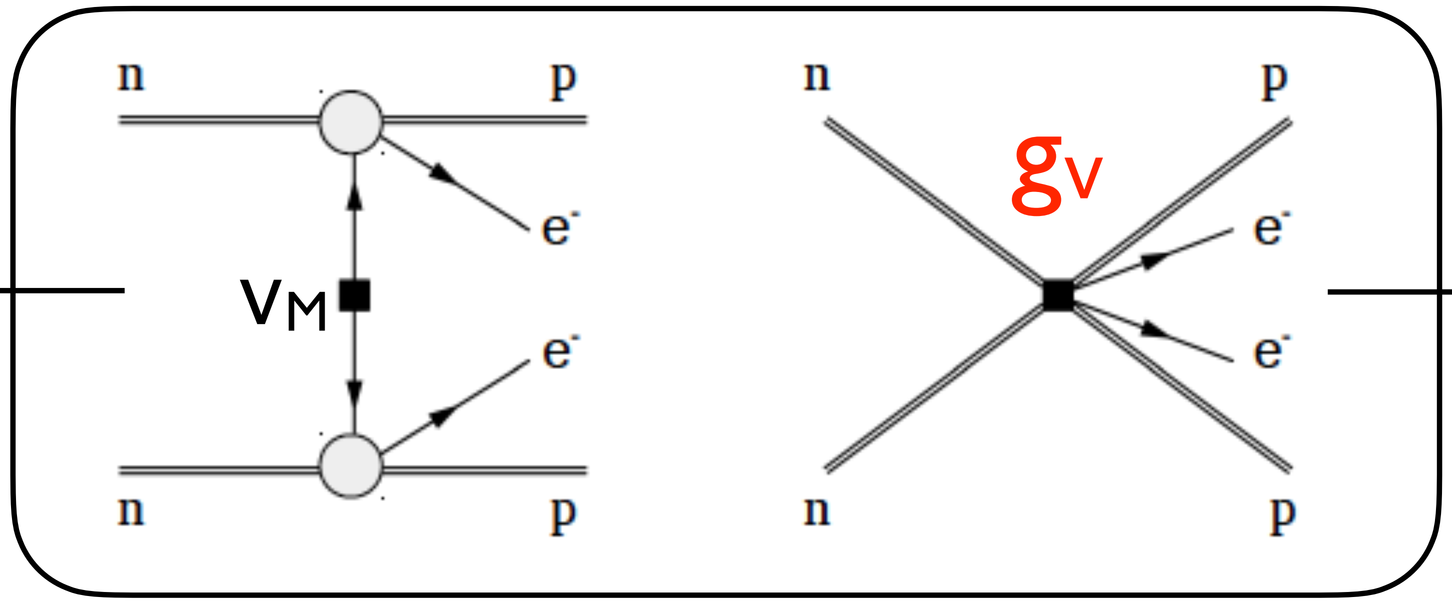
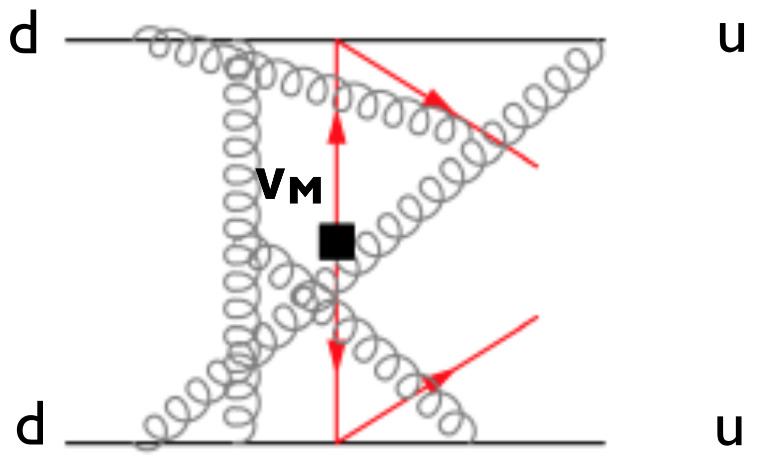


'New': short-range coupling $g_\nu \sim 1/Q^2$



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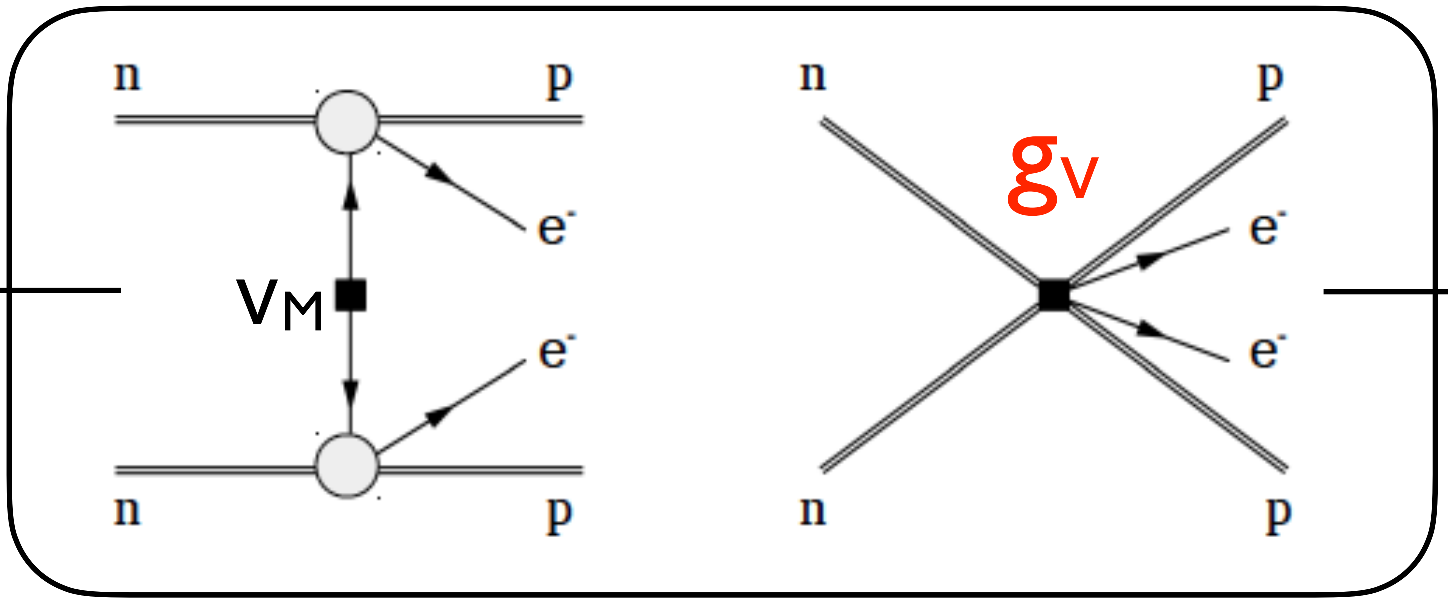
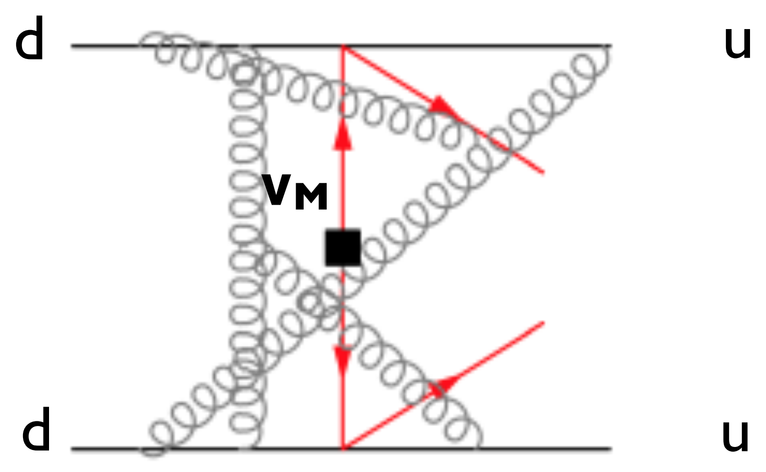
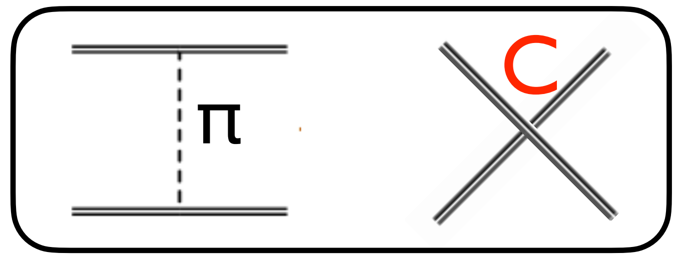


'New': short-range coupling $g_V \sim 1/Q^2$



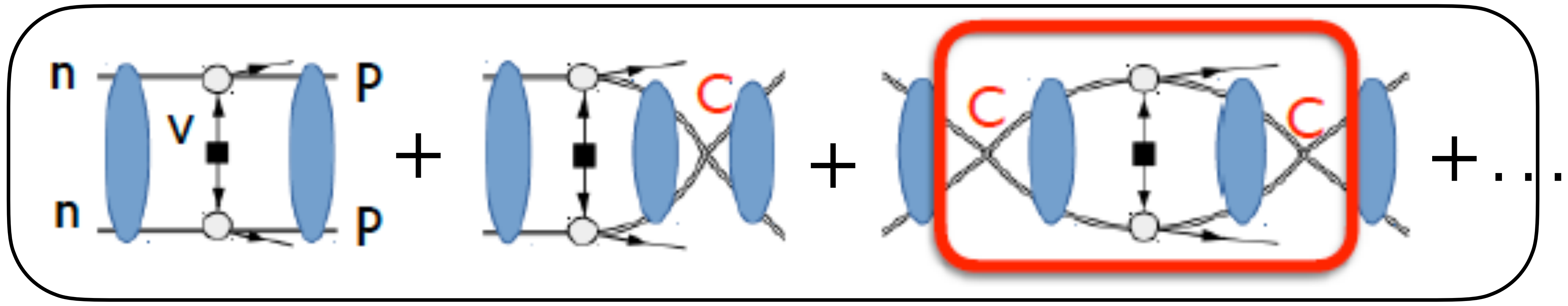
- LO scaling is required by renormalization of $nn \to pp$ amplitude in presence of strong interactions

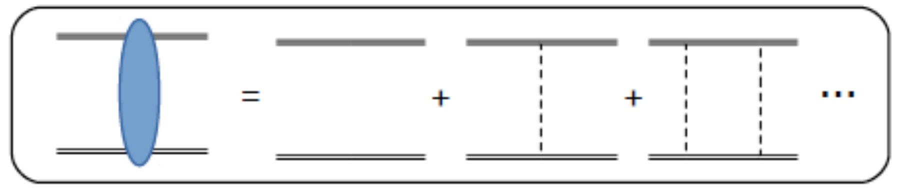
LO strong potential



$C \sim 4\pi/(m_N Q)$

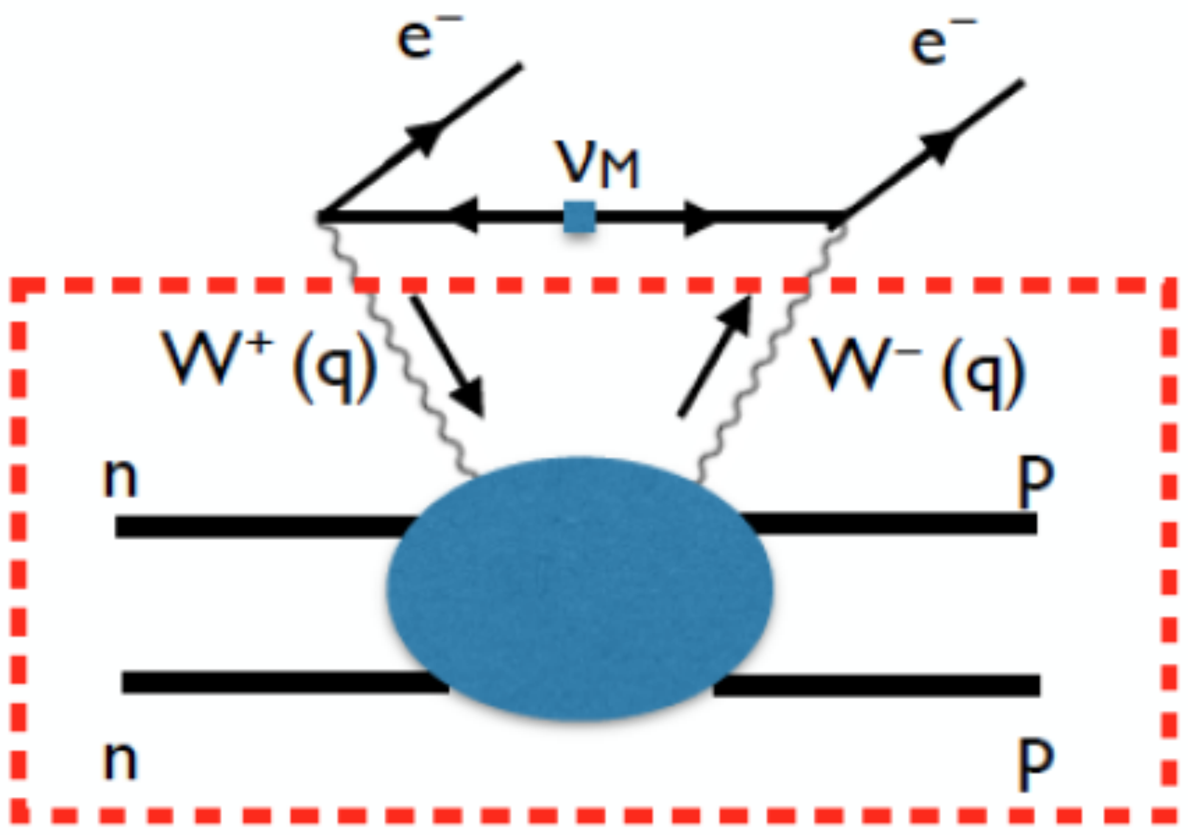
UV divergence $\propto$ $(m_N C/4\pi)^2 \sim 1/Q^2$





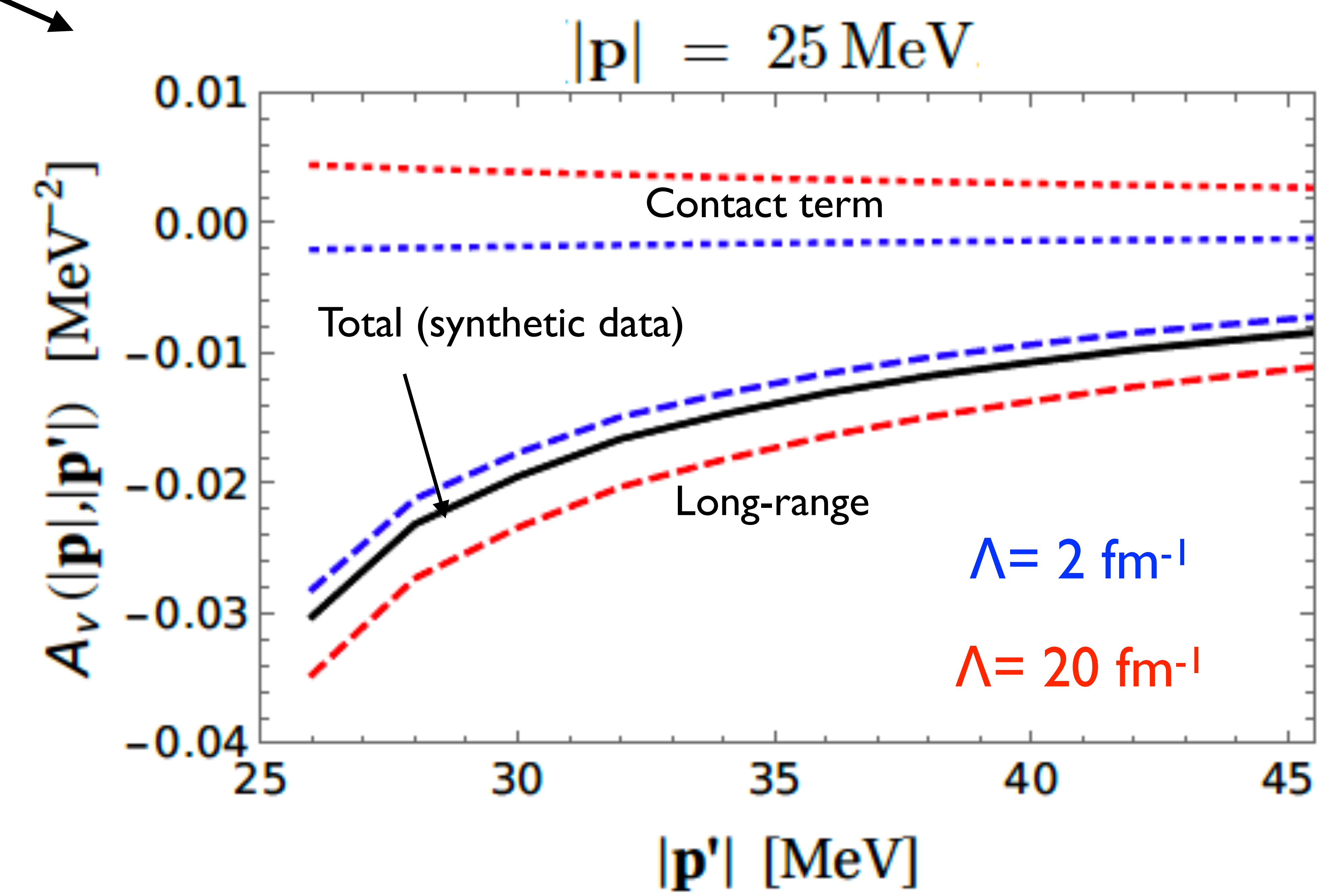
Impact of leading-order contact term

- g_V estimated through dispersive analysis, with ~30% uncertainty (validated with ΔI=2 NN electromagnetic coupling)



- Provided ‘synthetic data’ for the nn→pp amplitude to be used to fit g_V with regulators used in nuclear calculations

[1] VC, Dekens, deVries, Hoferichter, Mereghetti, 2012.11602, 2102.03371



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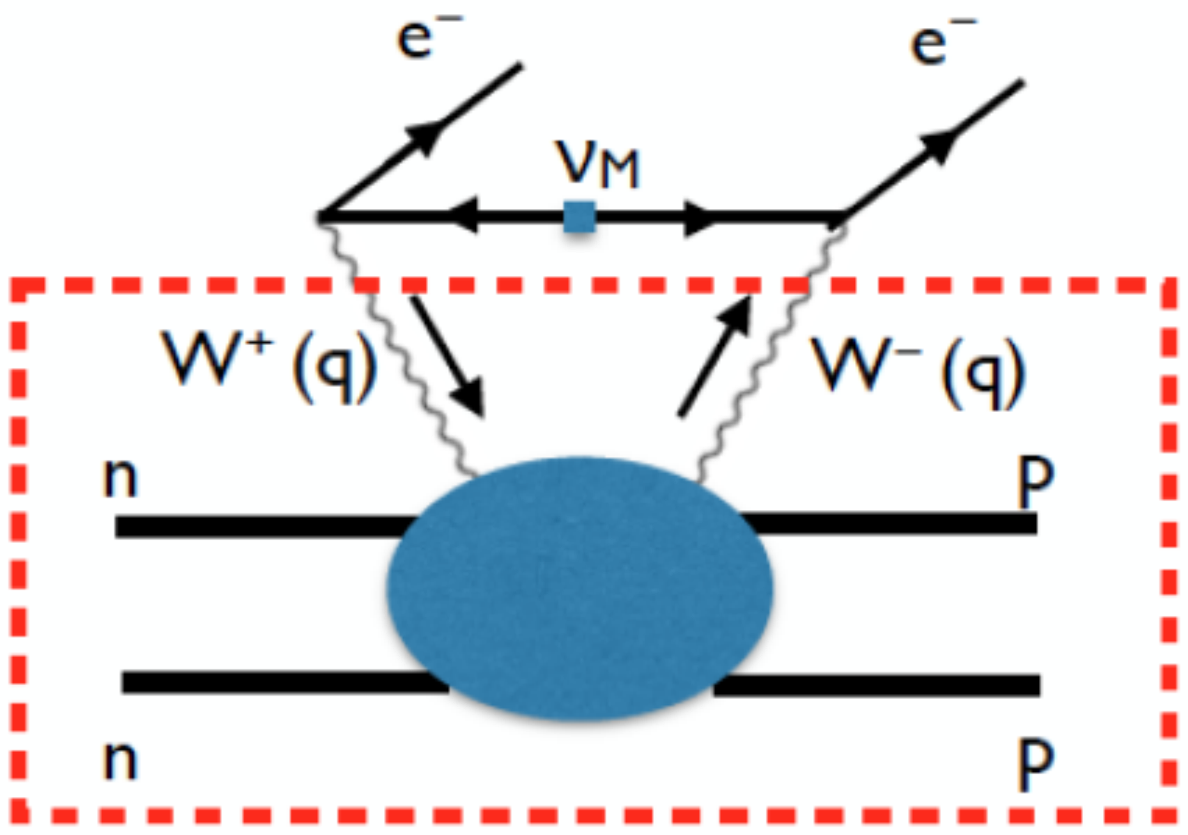

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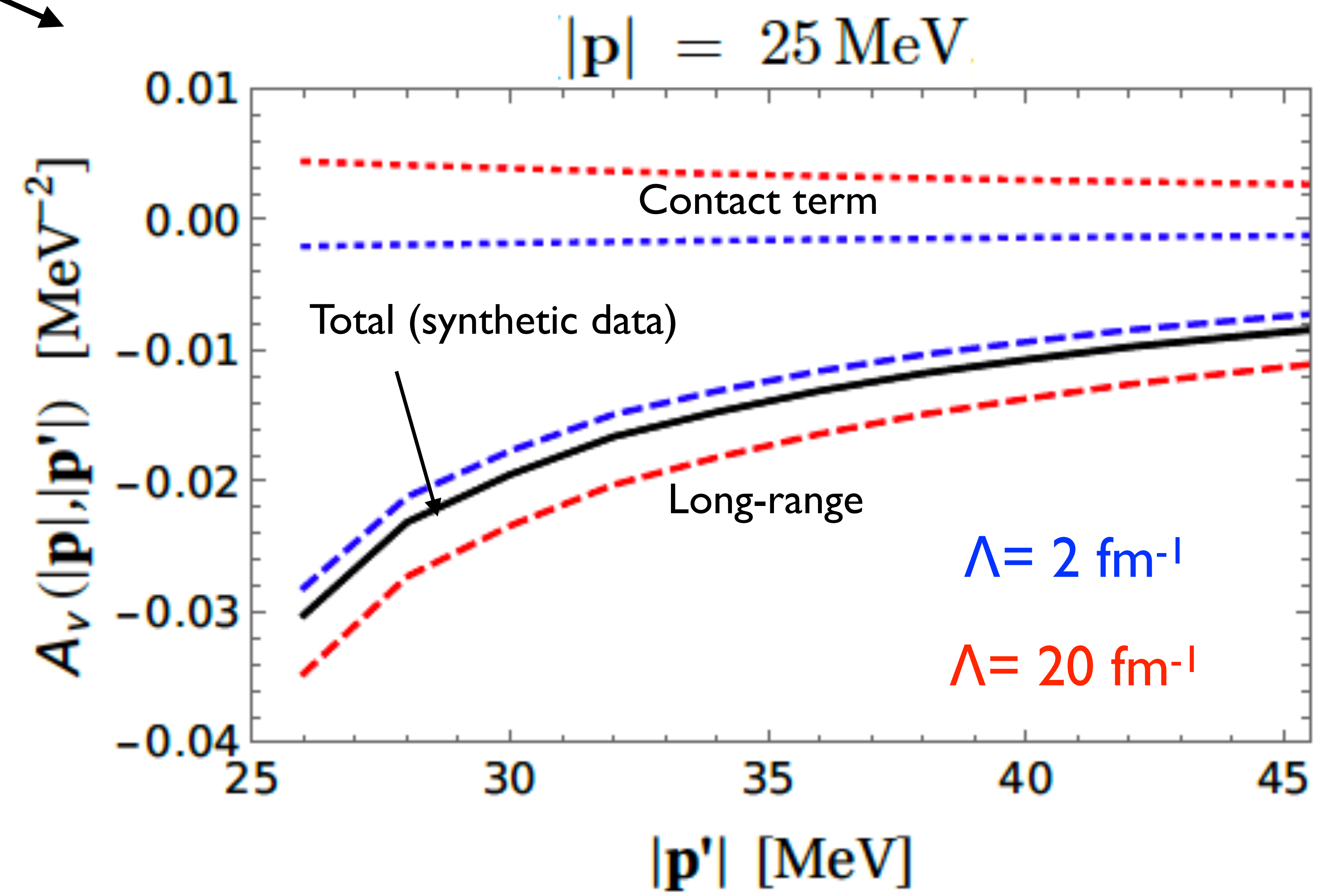

- Contact term fitted to synthetic data [2] and used in ab-initio calculations in ^{48}Ca [2], ^{130}Te [3], ^{136}Xe, [3], ^{76}Ge [4]: enhances matrix elements by ~40% [Ge] and >50% [Te, Xe]

[2] Wirth, Yao, Hergert, 2105.05415 [3] Belley et al, 2307.15156 [4] Belley et al, 2308.15634

See talk by Jason Holt for details and implications on $m_{\beta\beta}$

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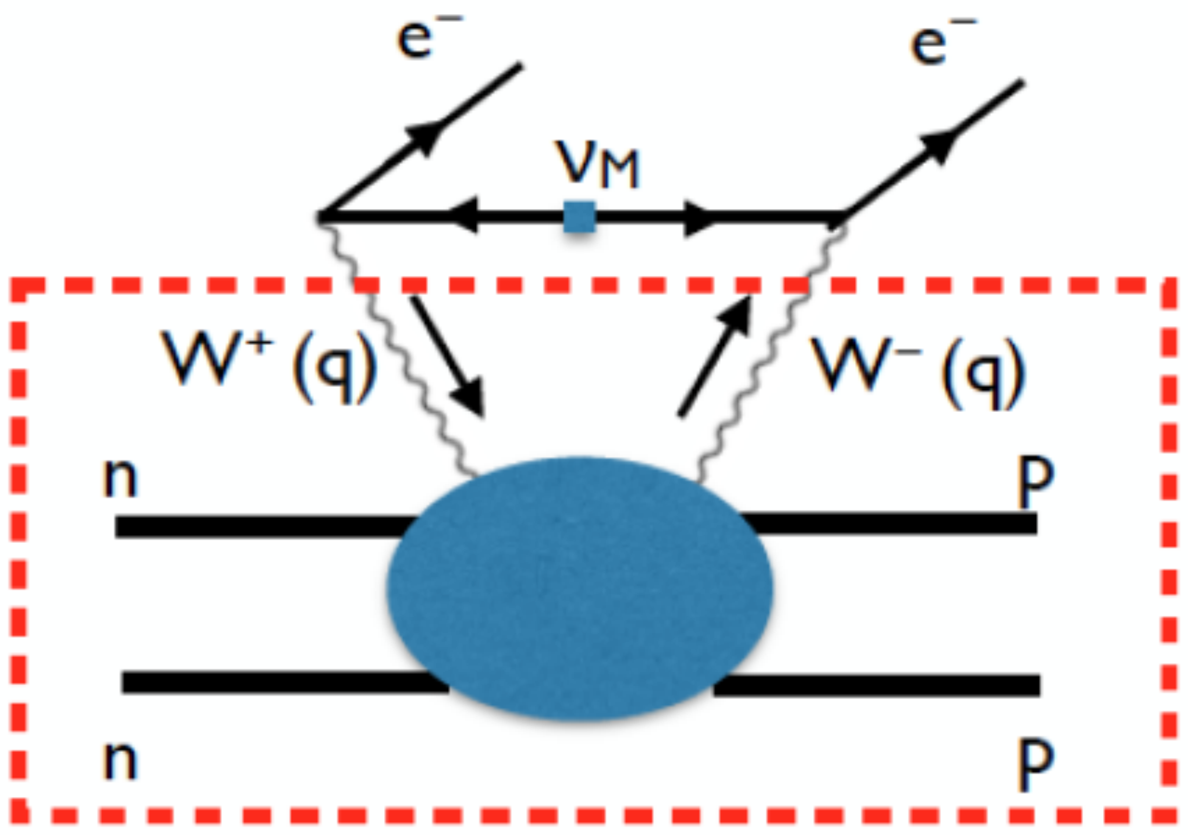

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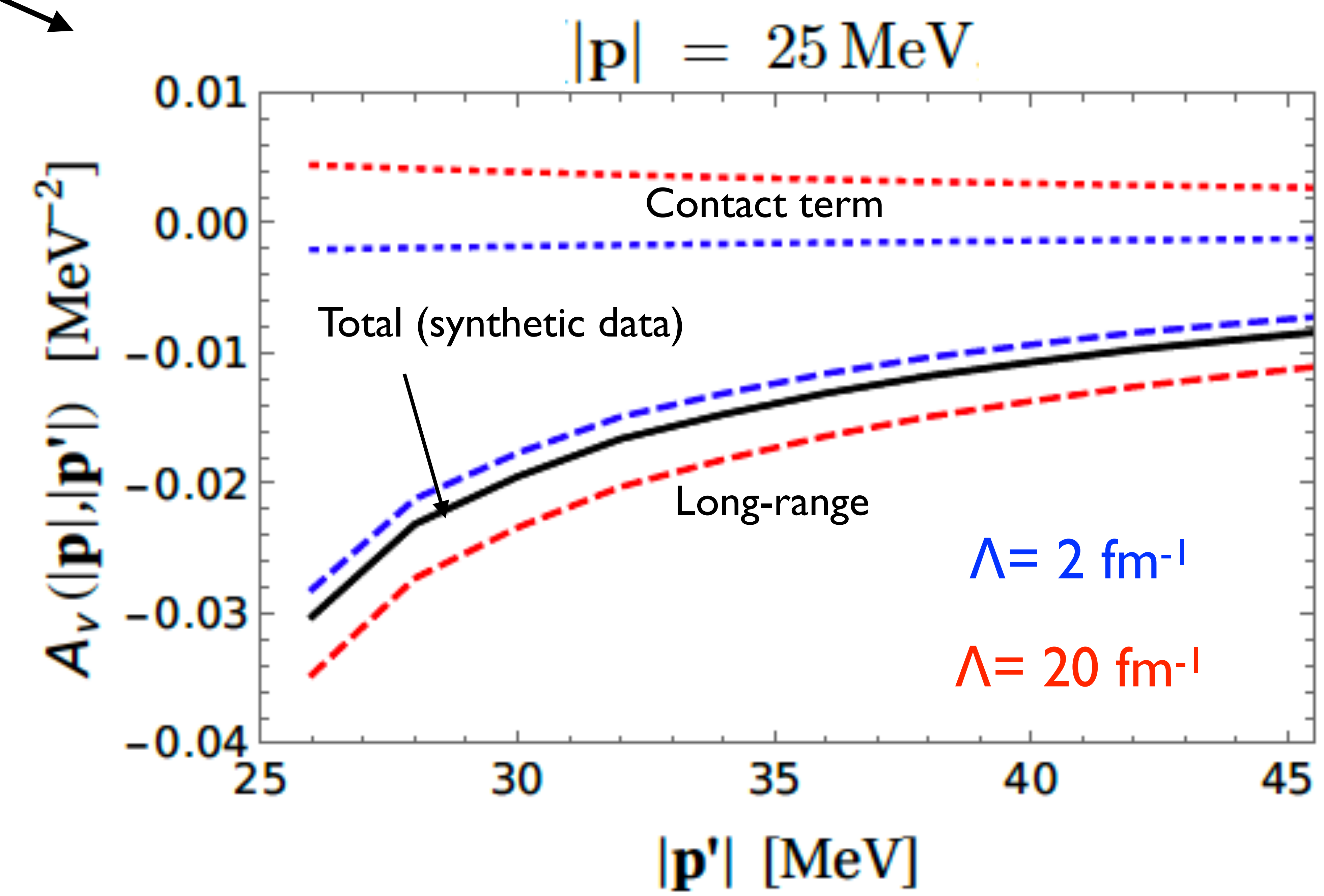
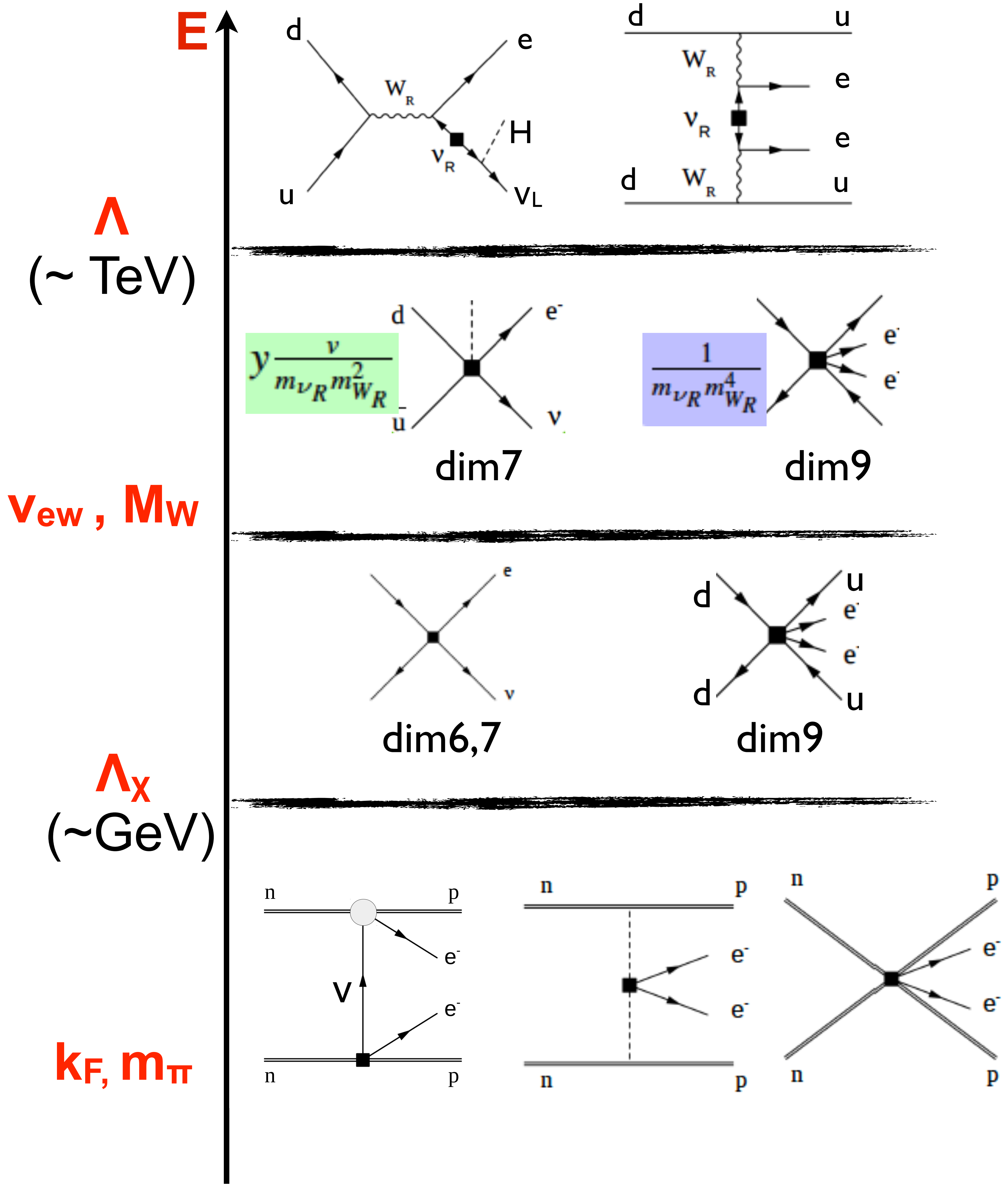
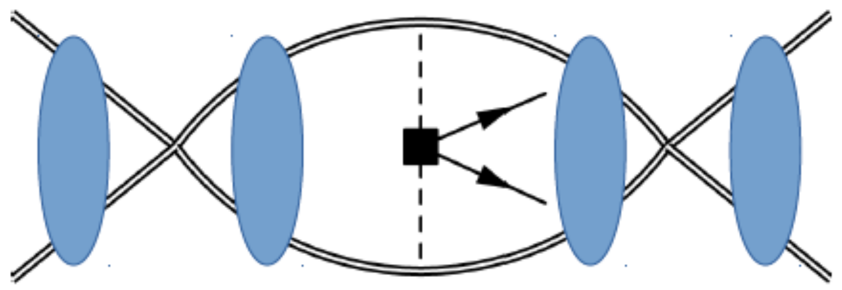


Overall uncertainties still sizable but improvable!
Progress requires theoretical activity at the interface of EFT, lattice QCD, and nuclear structure

~TeV-scale LNV



- Higher dim operators arise in well motivated models. Can compete with Dim=5 operator if Λ~ O(1-10 TeV)
- 31 operators up to dimension 9
- New mechanisms at the hadronic scale: need appropriate chiral EFT treatment



Renromalization requires a contact terms at the same order as pion-range

VC, W. Dekens, J. de Vries, M. Graesser, E. Mereghetti [1806.02780]

- Not including pion- and short-range effects leads to factor ~ $(Q/\Lambda_\chi)^2$ ~1/100 reduction in sensitivity to new physics!

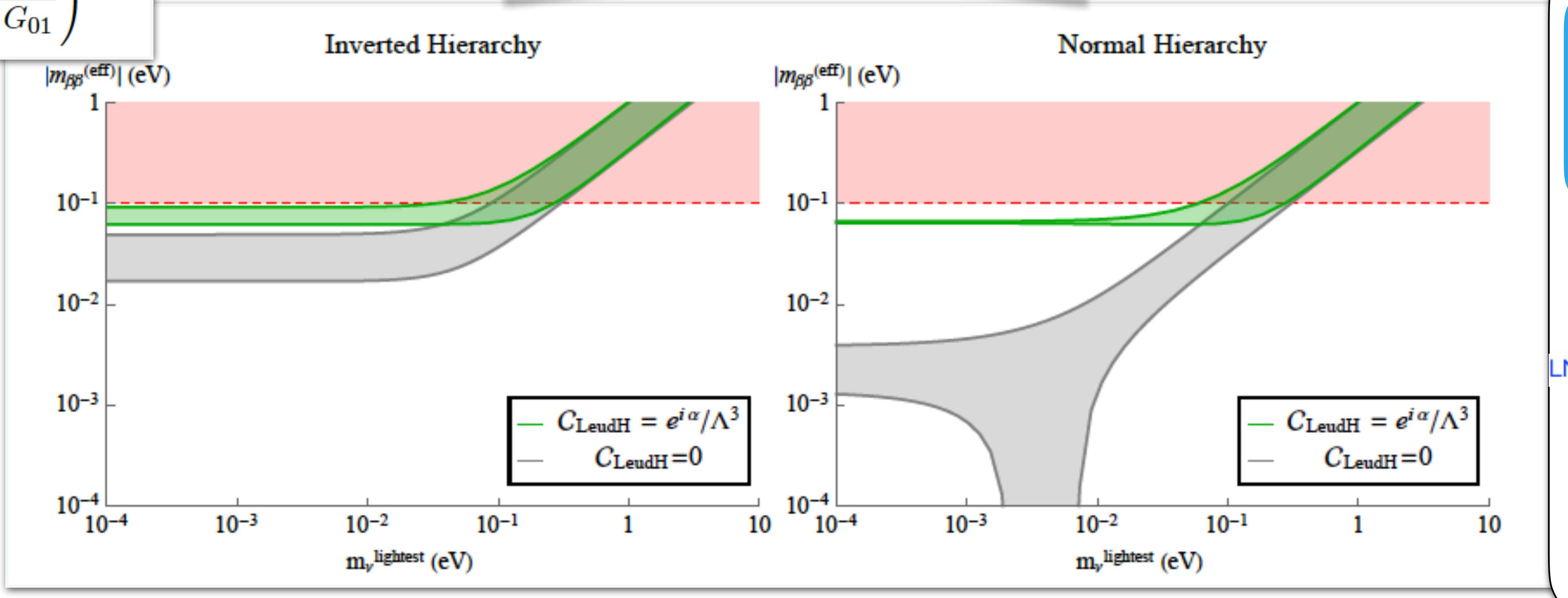
Phenomenological interest

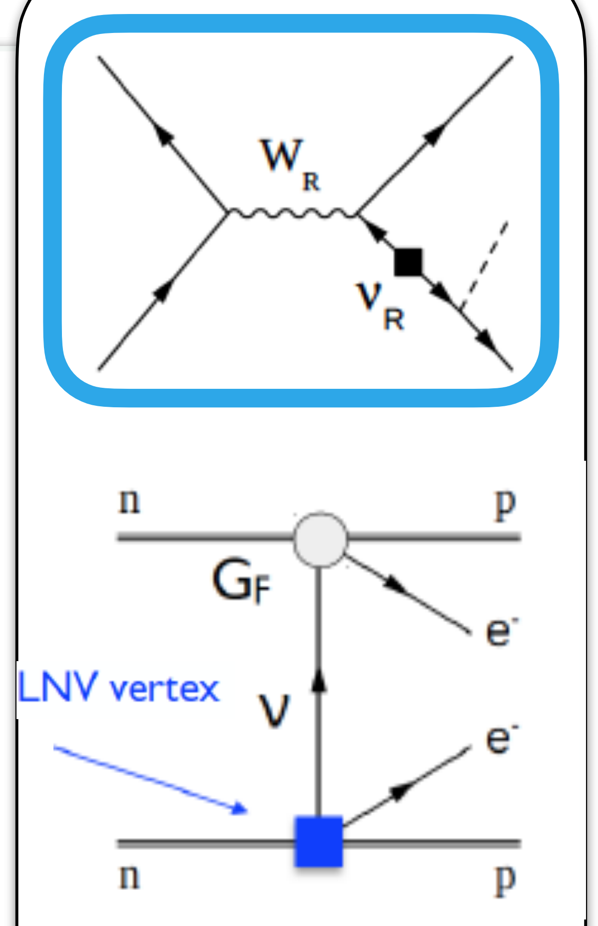
- TeV-scale LNV induces contributions to $0\nu\beta\beta$ *not directly related to the exchange of light neutrinos,* within reach of planned experiments

New contributions can add incoherently *or interfere with* $m_{\beta\beta}$, significantly affecting the interpretation of experimental results

$$C_{LeudH}\,\epsilon_{ij}\,(\bar{d}\gamma^{\mu}u)\,(L_m^T C\gamma_{\mu}e)\,H_j$$

$$m_{\beta\beta}^{(\mathrm{eff})} = \frac{m_e}{g_A^2 M_\nu}\left(\frac{T_{1/2}^{0\nu}}{G_{01}}\right)^{-1/2}$$





$\Lambda = 40$ TeV

VC, W. Dekens, J. de Vries, M. Graesser, E. Mereghetti, 1708.09390

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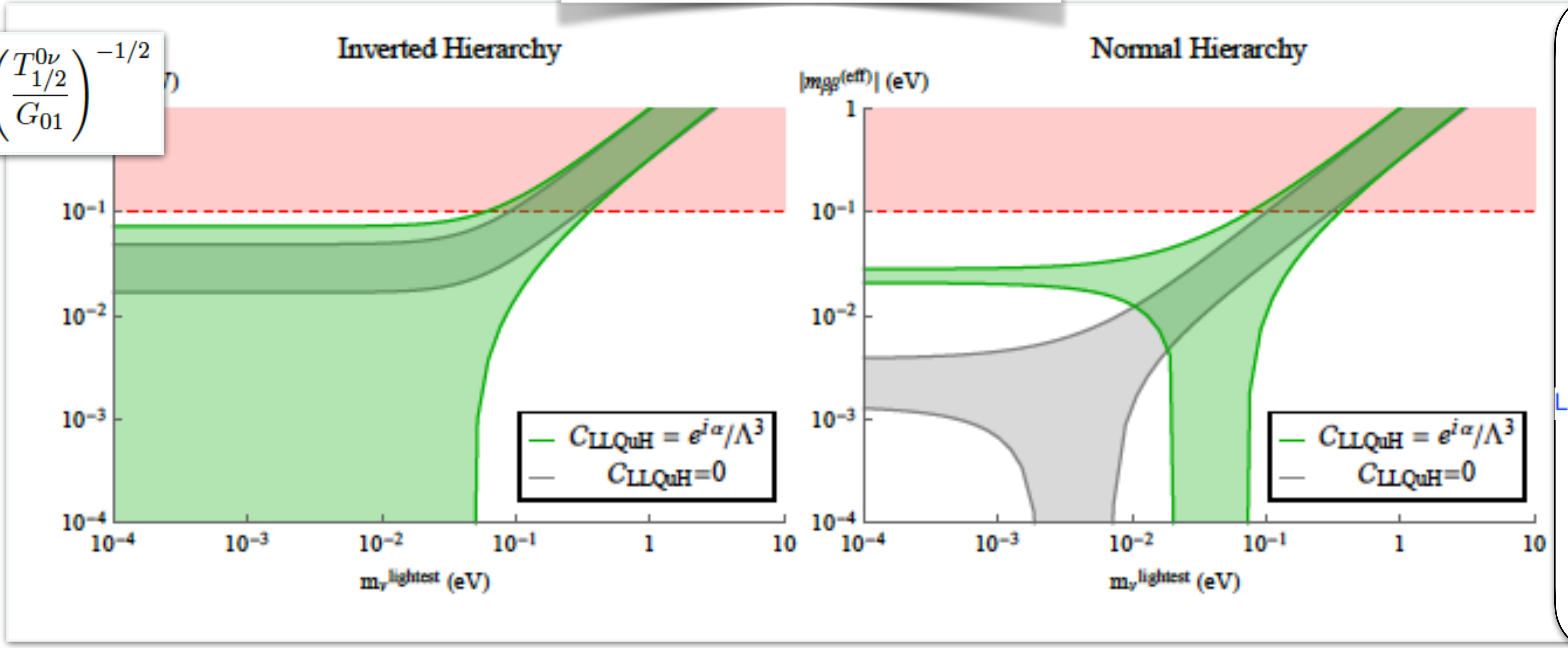
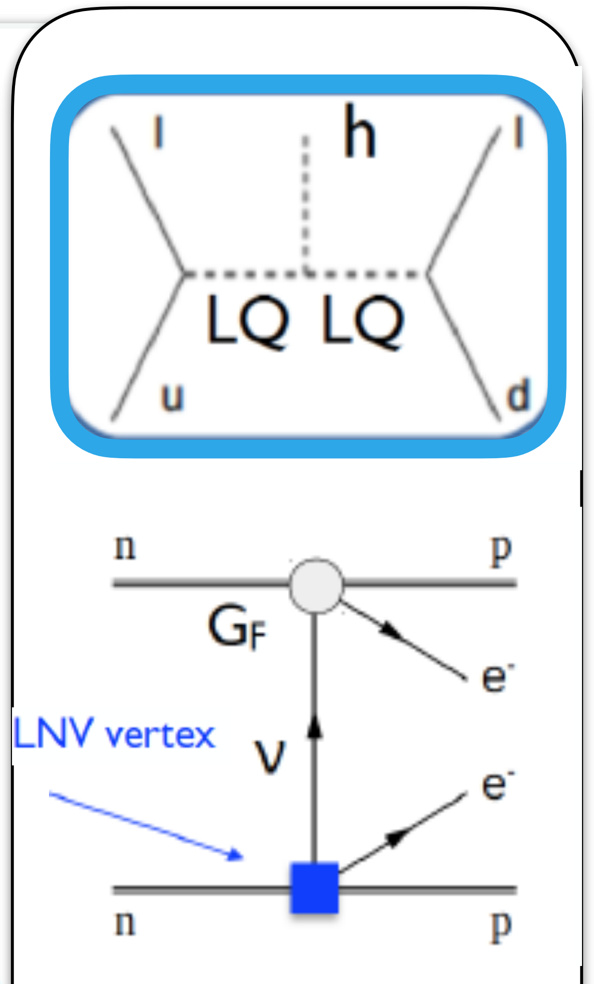
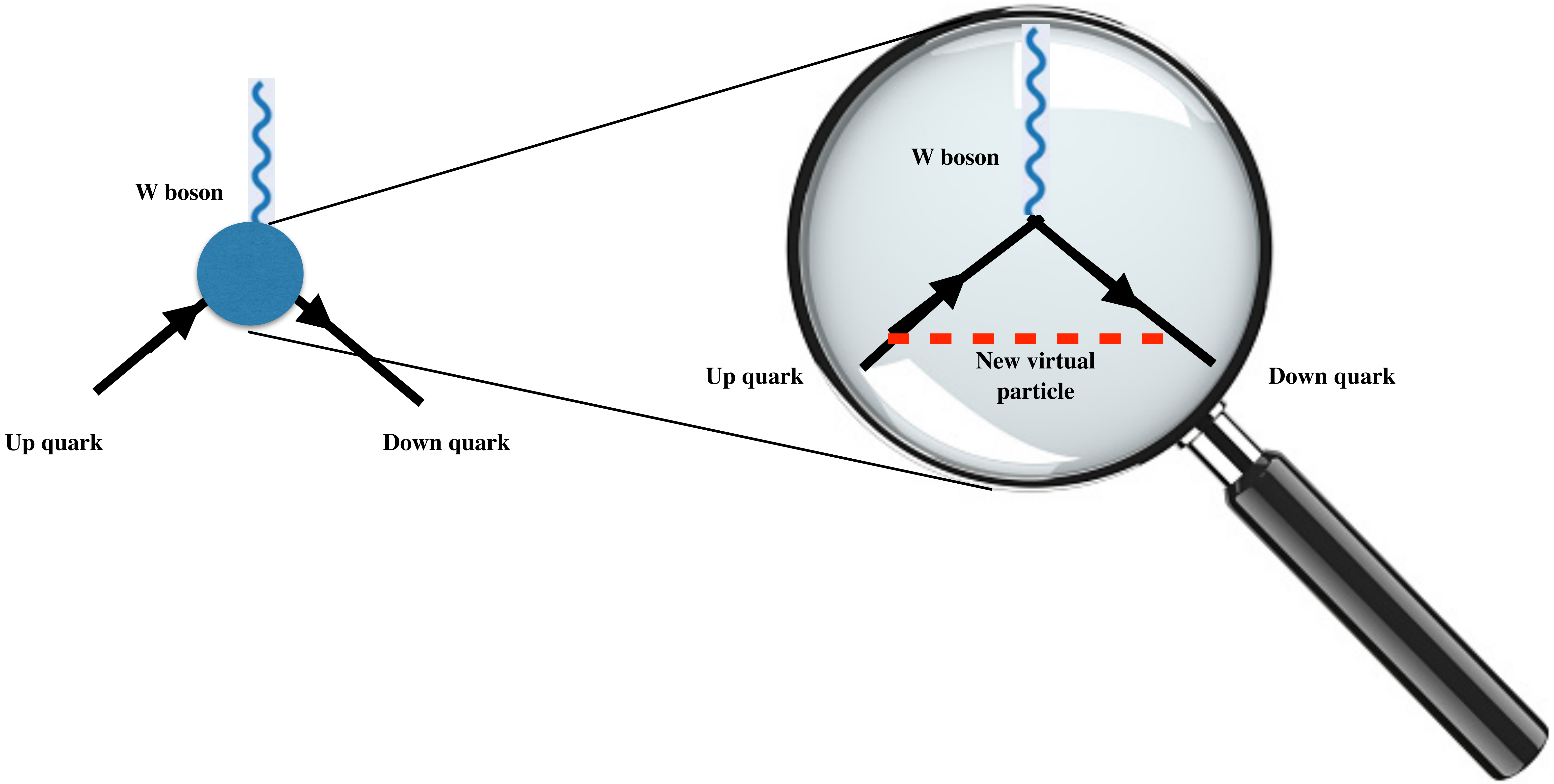




$\Lambda = 600$ TeV

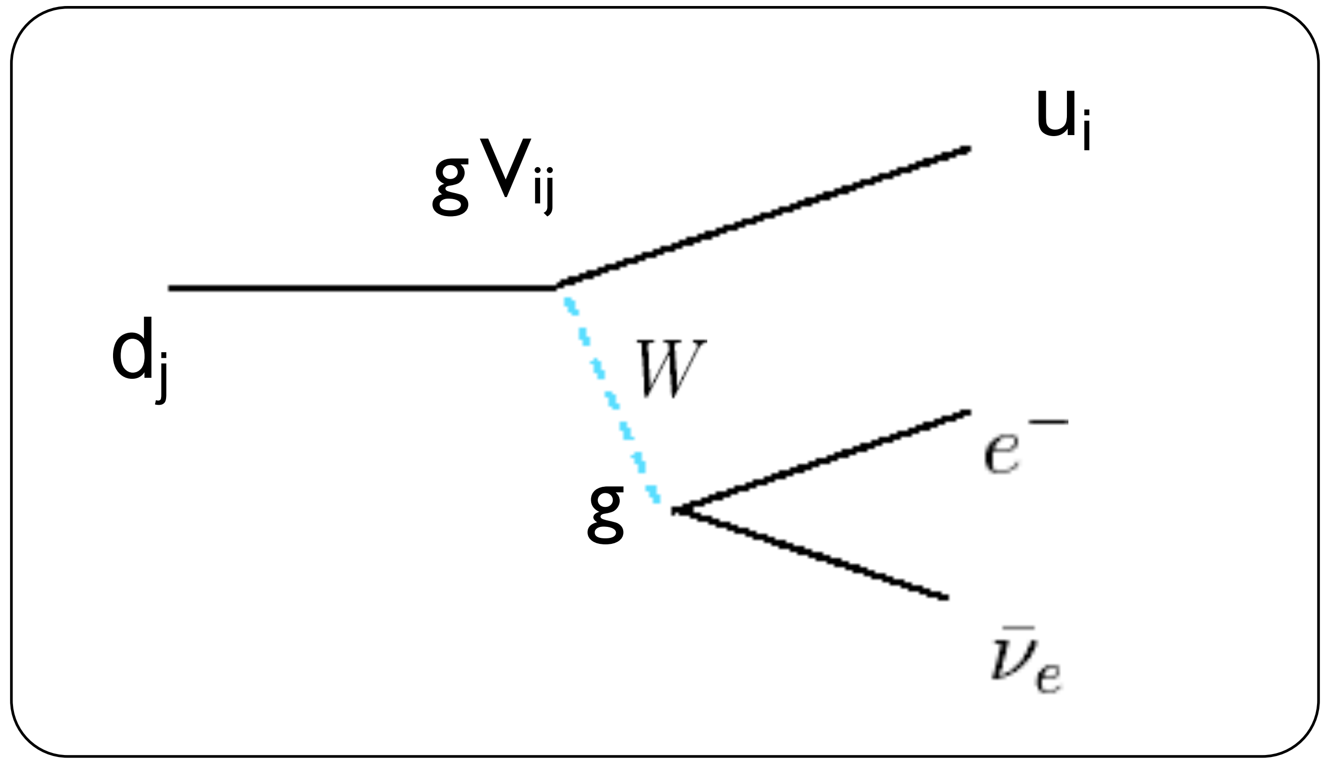
VC, W. Dekens, J. de Vries, M. Graesser, E. Mereghetti, 1708.09390

Precision beta decays



β decays in the SM and beyond

- In the SM, mediated by W exchange ⇒ only "V-A"; Cabibbo universality; lepton universality



$G_F^{(\beta)} \sim G_F^{(\mu)} V_{ij} \sim 1/v^2 \, V_{ij}$

Cabibbo Universality

$$|V_{ud}|^2 + |V_{us}|^2 + \cancel{|V_{ub}|^2} = 1$$

$$[G_F]_e / [G_F]_\mu = 1$$

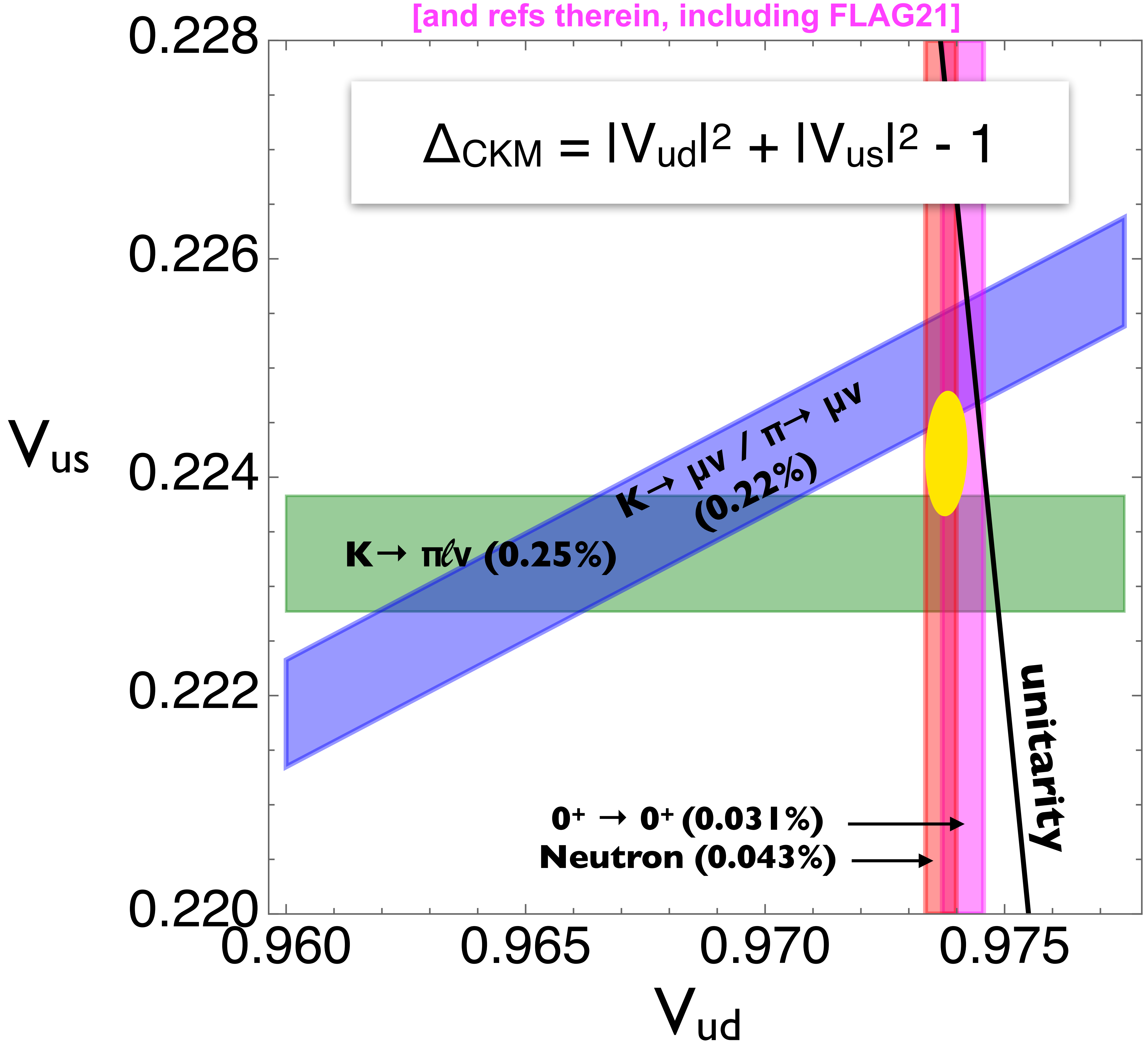
Lepton Flavor Universality (LFU)

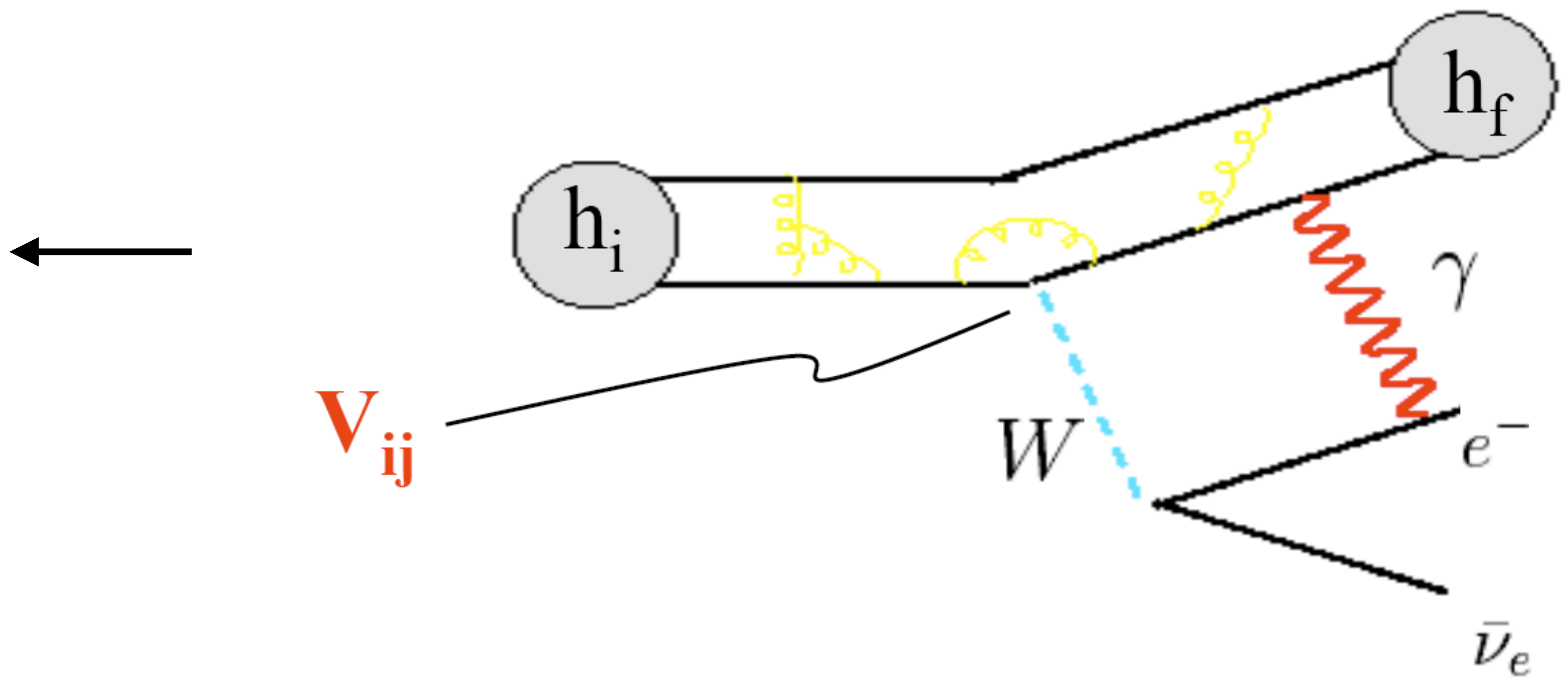
- New physics can spoil universality relations. Precision of 0.1-0.01% probes Λ > 10 TeV
- Focus on Cabibbo universality test (1st row CKM unitarity)

The Cabibbo angle "anomaly"

$$\Gamma = G_F^2 \times |V_{ij}|^2 \times |M_{\rm had}|^2 \times (1+\Delta_R) \times F_{\rm kin}$$

VC-Crivellin-Hoferichter-Moulson 2208.11707
[and refs therein, including FLAG21]





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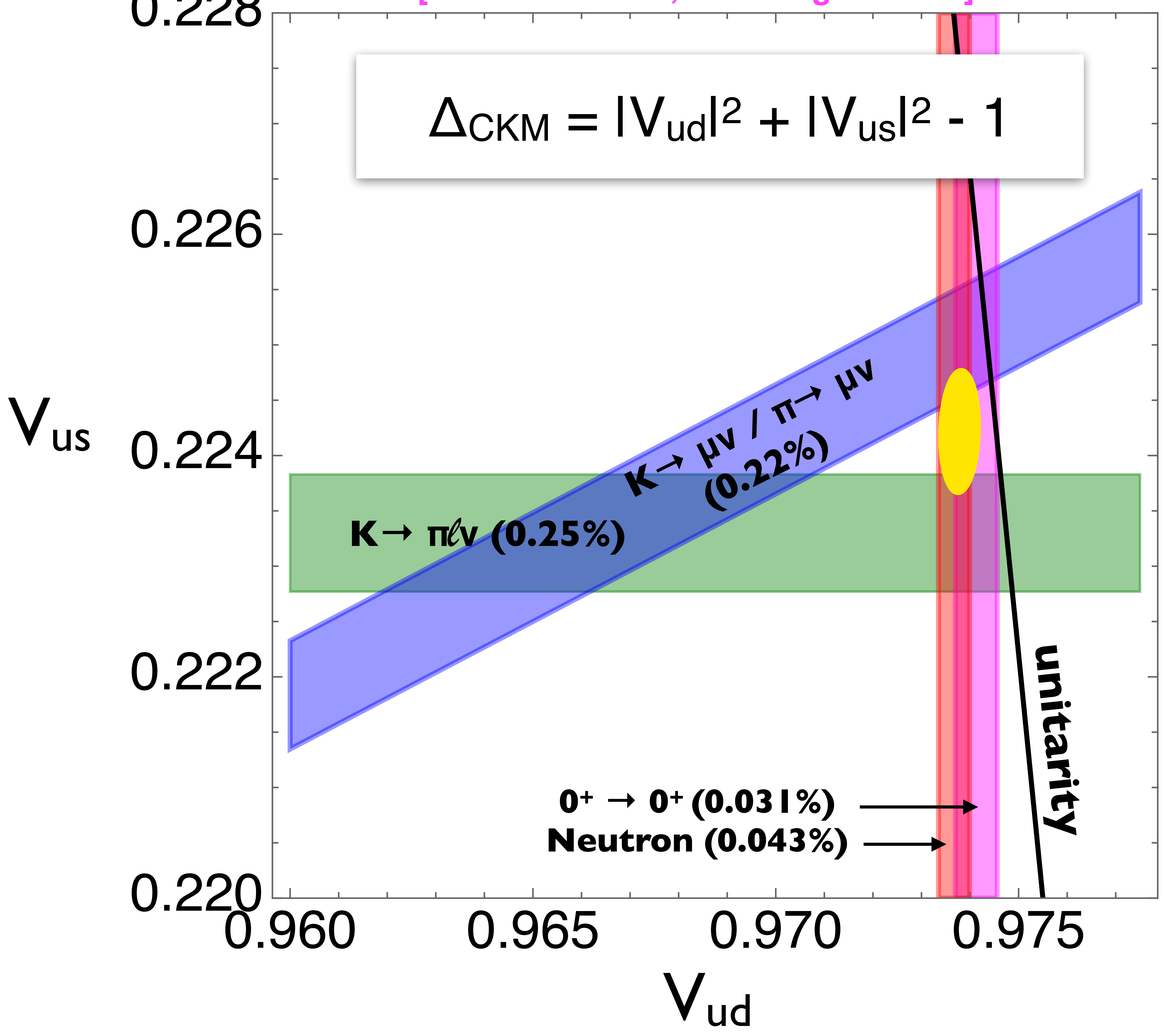

- The 'anomalies':
  - ~3σ effect in global fit (Δ_{CKM}= −1.48(53) ×10^{-3})
  - ~3σ problem in meson sector (Kl2 vs Kl3)

- Can be explained by BSM physics (R-handed quark currents), but need to scrutinize the SM input!

Grossman-Passemar-Schacht 1911.07821
VC-Crivellin-Hoferichter-Moulson 2208.11707
Belfatto-Berezhiani 1906.02714, 2103.05549; Belfatto-Trifinopoulos 2302.14097
VC, W. Dekens, J. De Vries, E. Mereghetti, T. Tong, 2311.00021

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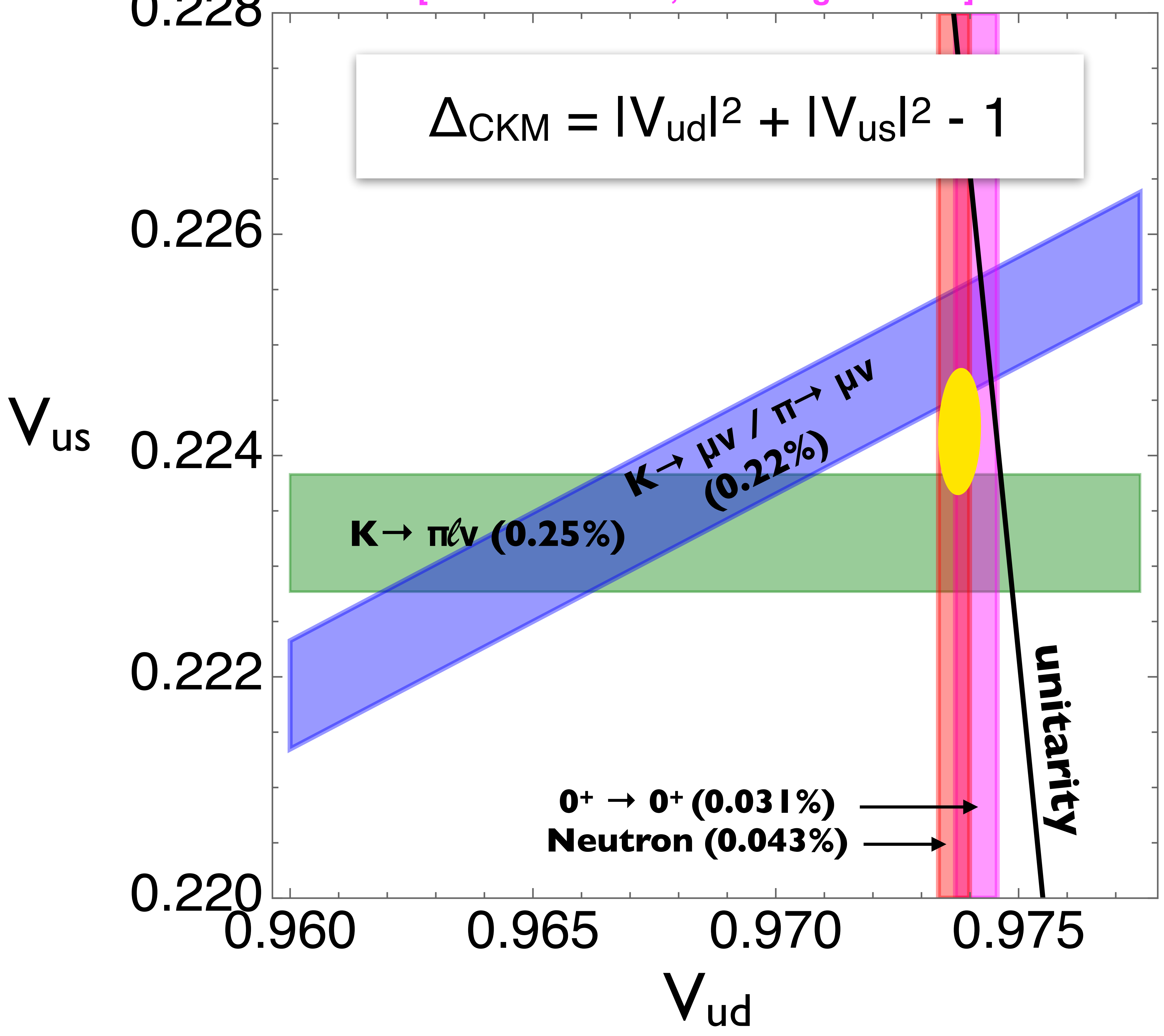

- Expected experimental improvements:
  - neutron decay
  - pion beta decay (PIONEER @PSI)
  - new $K_{\mu3}/K_{\mu2}$ BR measurement at NA62
- Further theoretical scrutiny
  - Lattice QCD: K→π vector f.f. , rad. corr. for Kl3
  - EFT for radiative corrections neutron and nuclei, with precision goal ~ 2-3 × 10^{-4}
  - …

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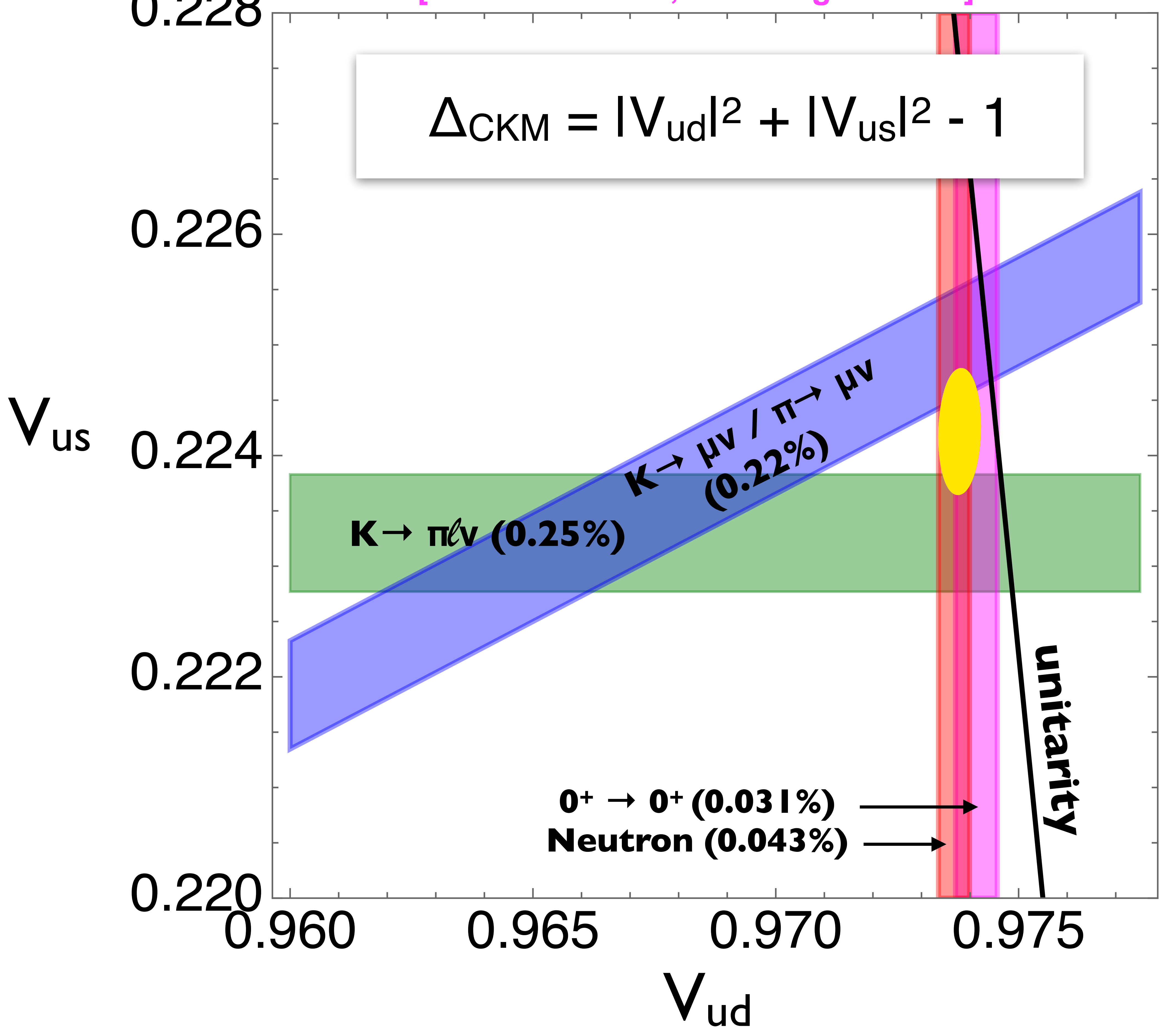
VC-Crivellin-Hoferichter-Moulson 2208.11707
[and refs therein, including FLAG21]



- Expected experimental improvements:
  - neutron decay
  - pion beta decay (PIONEER @PSI)
  - new $K_{\mu 3}/K_{\mu 2}$ BR measurement at NA62
- Further theoretical scrutiny
  - Lattice QCD: K→π vector f.f. , rad. corr. for Kl3
  - EFT for radiative corrections neutron and nuclei, with precision goal ~ 2-3 × 10^{-4}
  - …

Multi-step strategy

- Matching and running in a tower of EFTs: SM → LEFT → ChPT → π̸EFT, χEFT

One nucleon

Multi nucleons

VC, J. de Vries, L. Hayen, E. Mereghetti, A. Walker-Loud 2202.10439, PRL
VC, W. Dekens, E. Mereghetti, O. Tomalak, 2306. 03138, PRD

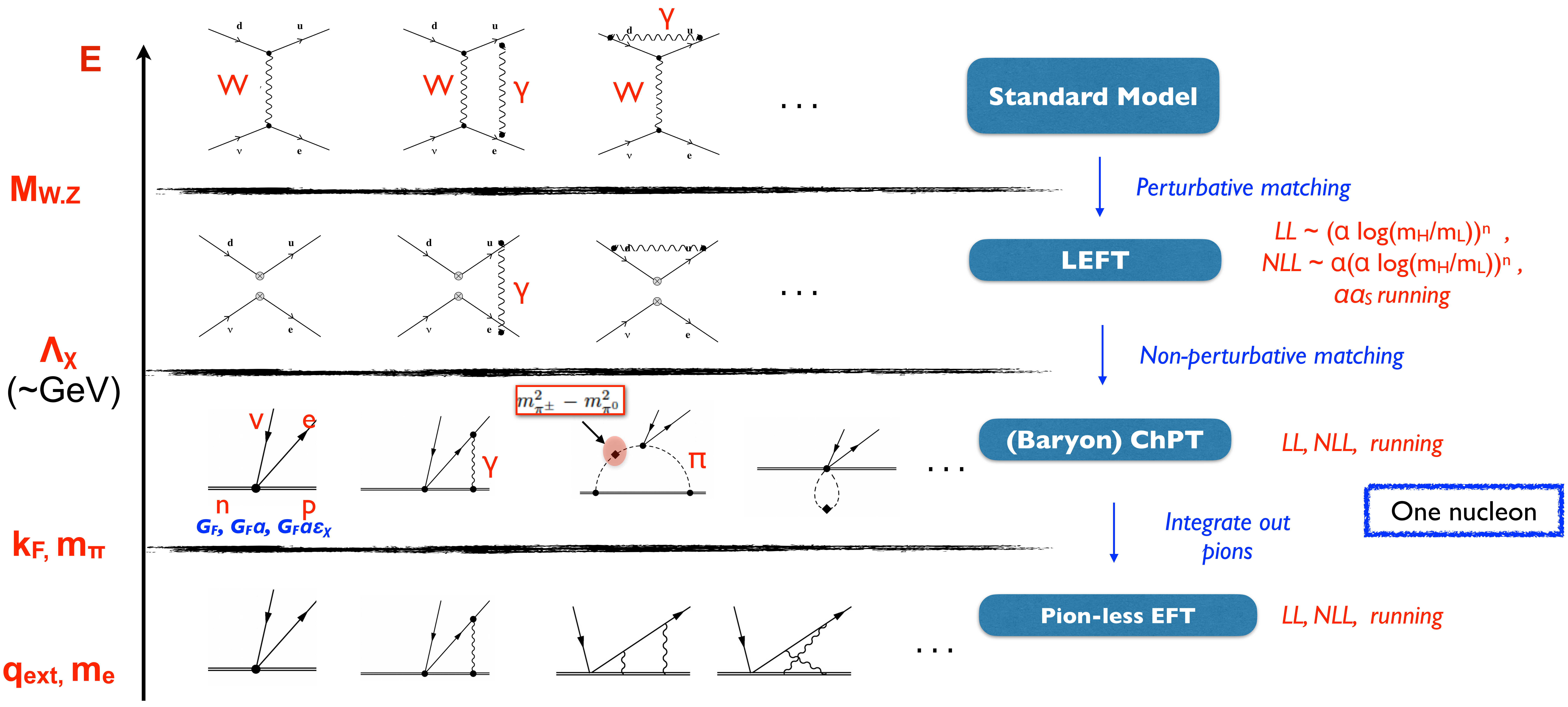
VC, W. Dekens,, J.de Vries, S. Gandolfi, M. Hoferichter, E, Mereghetti, 2405.18469 & 2405.18464

Point-like nucleus

K. Borah, R. Hill, R. Plestid, 2309.07343, 2309.15929, 2402.13307

Multi-step strategy

- Matching and running in a tower of EFTs: SM → LEFT → ChPT → π̸EFT, χEFT



New effects in neutron decay

- Larger radiative correction to decay rate shifts V_{ud} by -0.013% [effect due to large NLL ~ $\alpha^2 \, \mathrm{Log}(m_N/m_e)$]

VC, W. Dekens, E. Mereghetti, O. Tomalak, 2306. 03138

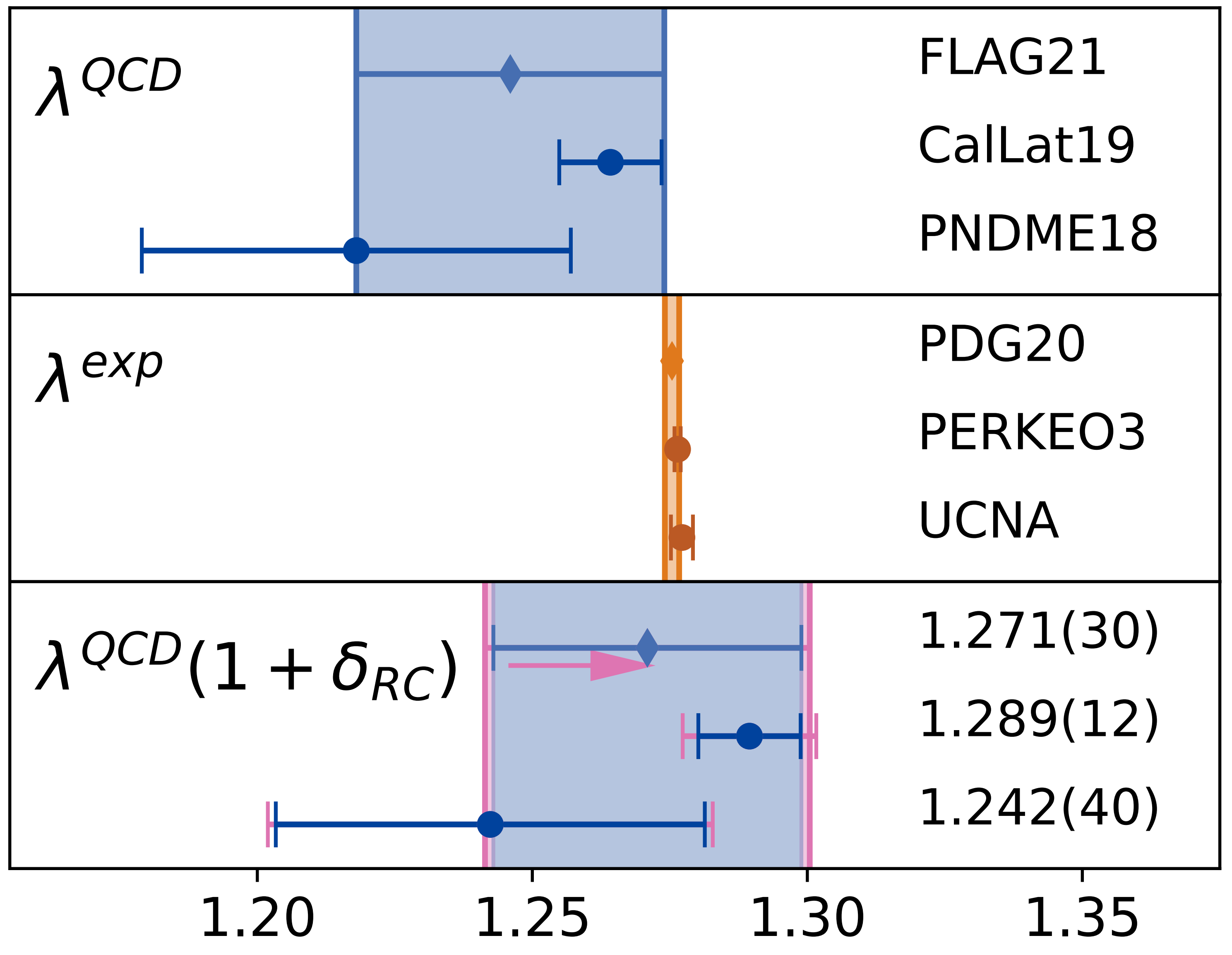
- (g_A/g_V) gets %-level corrections proportional to the pion EM mass splitting, 100x larger than previous estimate

VC, J. de Vries, L. Hayen, E. Mereghetti, A. Walker-Loud 2202.10439

$$\frac{\lambda^{\rm exp}}{\lambda^{\rm QCD}} = 1 + \delta_{\rm RC}$$

$$\delta_{RC} \simeq (2.0 \pm 0.6)\%$$

Large uncertainty due to unknown LEC that could be determined by future lattice calculations

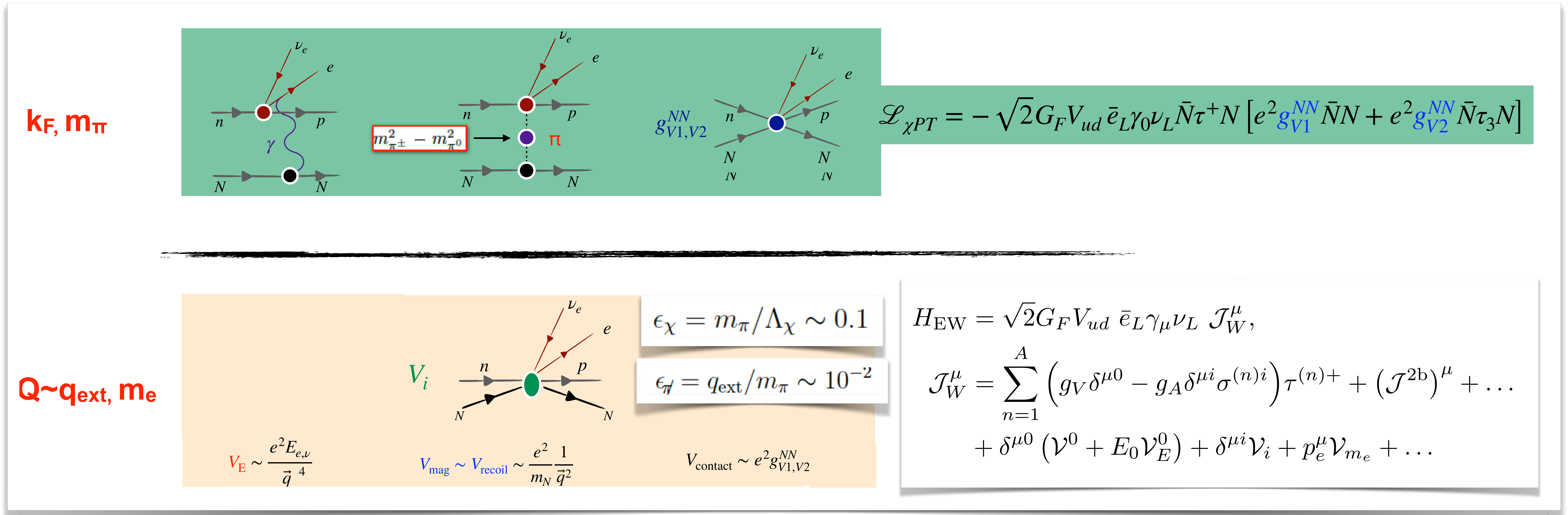


Radiative corrections generally improve agreement between data and Lattice QCD

New effects in nuclear decays

VC, W. Dekens,, J.de Vries, S. Gandolfi, M. Hoferichter, E, Mereghetti, 2405.18469, 2405.18464

- Hard photons induce NN → NNeν contact interactions ⇒ `Weak potentials' of O($G_F \alpha \varepsilon_\chi$) involve two currently unknown LECs ⇒ δV_{ud} (nuclear structure) ~ 0.00031_{models} → 0.00052_{EFT}
- LECs can be obtained by fitting data, once NME calculations for several isotopes become available



EFT has identified new correction and (temporarily) increased the uncertainty….
But in the long run it’s the only viable approach to quantify the uncertainties.

Conclusions

- EFT is a great tool to connect electroweak and higher scales to nuclear energies, with quantifiable uncertainties
- Illustrated with two examples

EFT is crucial to assess impact of ton-scale $0\nu\beta\beta$ searches

- Relates $0\nu\beta\beta$ to underlying LNV dynamics (and collider & cosmology)
- Organizes contributions to hadronic and nuclear matrix elements → control uncertainties

EFT methods can shed light on the 'Cabibbo angle anomaly' one of few low-energy "cracks" in the SM

- Seamlessly include next-to-leading logarithmic perturbative effects
- Uncovered new short-range nuclear structure-dependent effects needed to reach the ~3×10^{-4} precision in V_{ud}
- This framework may become of interest for neutrino-nucleus scattering at low energy

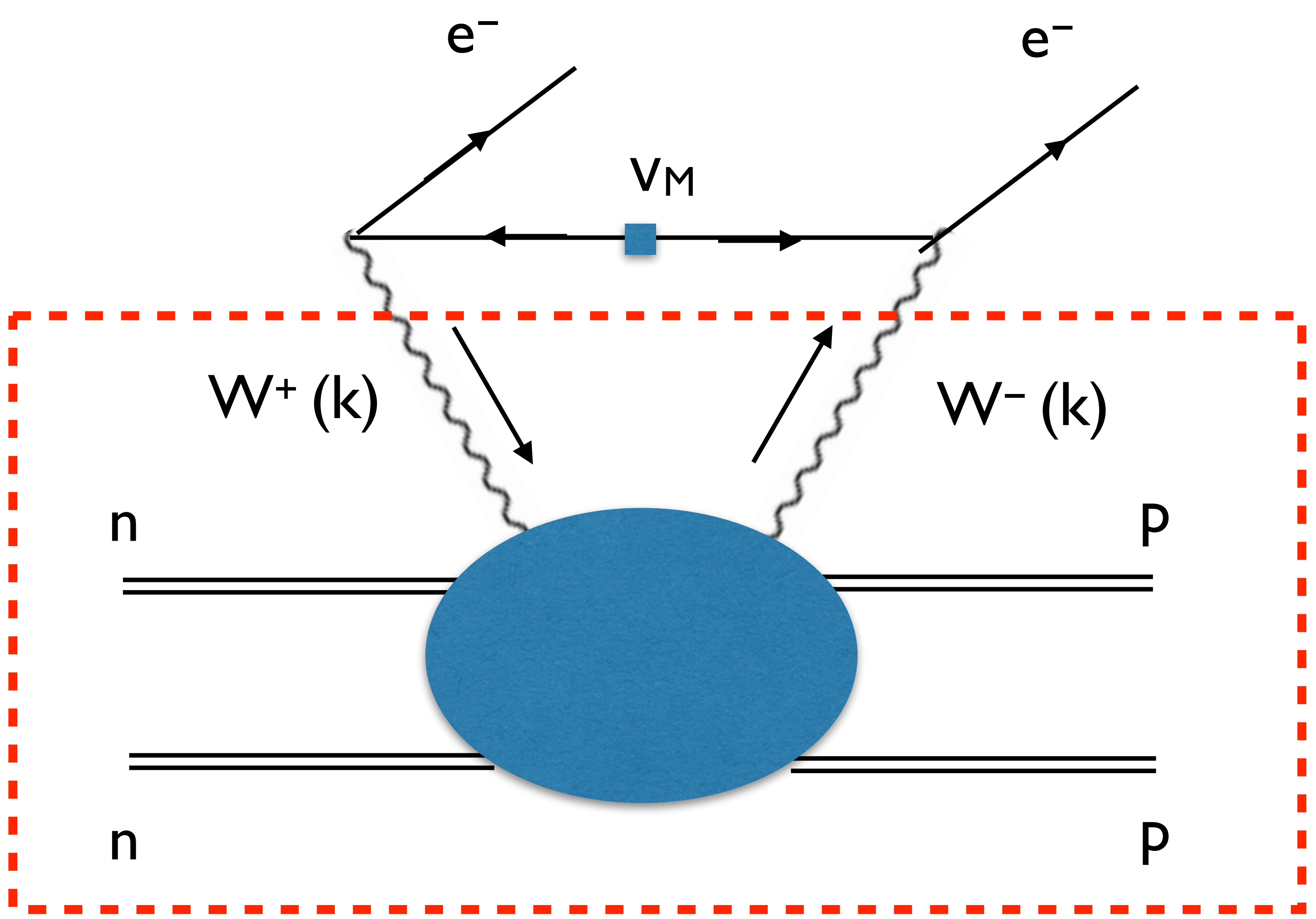
Backup: double beta decay

Estimating the contact term (1)

VC, Dekens, deVries, Hoferichter, Mereghetti, 2012.11602, 2102.03371

- Useful representation of the amplitude

$$\mathcal{A}_\nu \propto \int \frac{d^4k}{(2\pi)^4} \frac{g_{\alpha\beta}}{k^2 + i\epsilon} \int d^4x \, e^{ik\cdot x} \langle pp | T\{ j_{\mathrm{w}}^{\alpha}(x) j_{\mathrm{w}}^{\beta}(0)\} | nn \rangle$$



Forward "Compton" amplitude

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VC, Dekens, deVries, Hoferichter, Mereghetti, 2012.11602, 2102.03371

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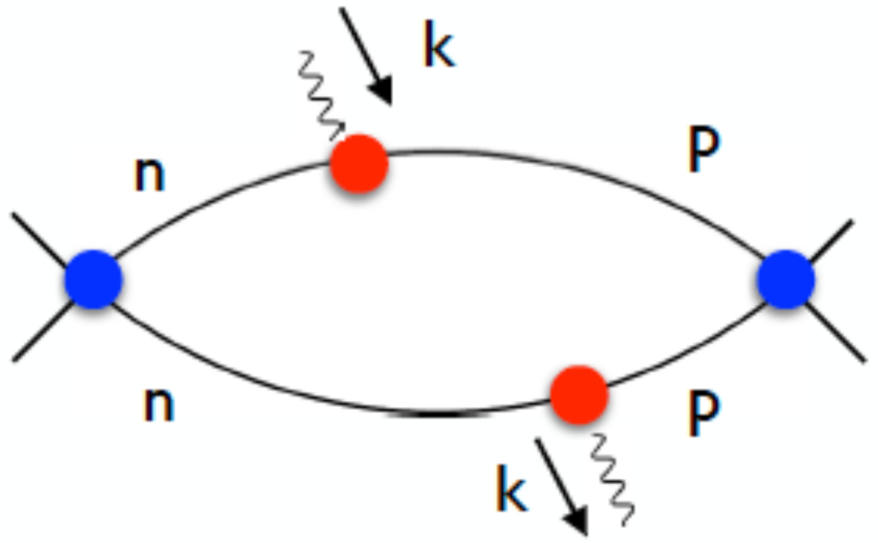
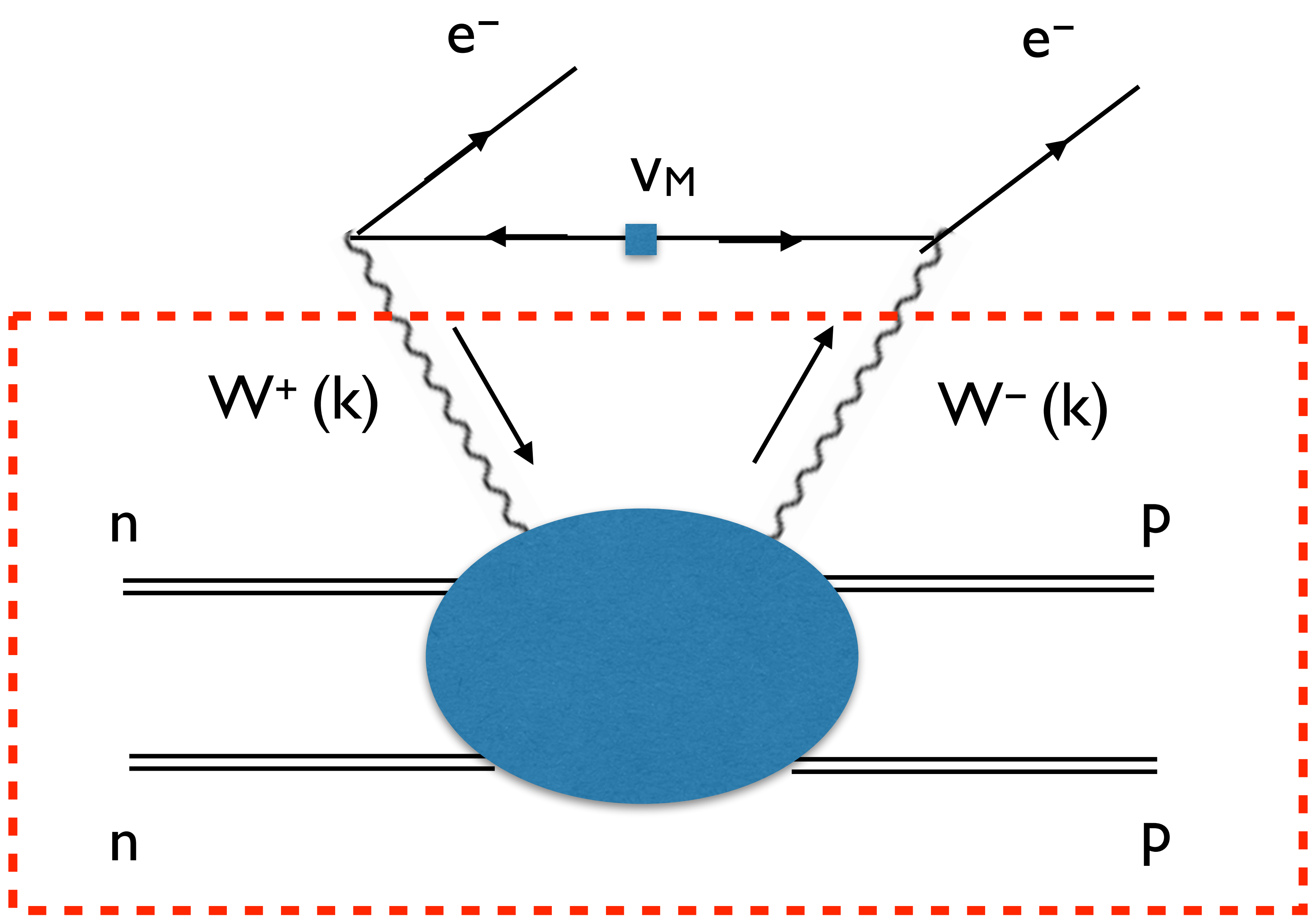
Low k: chiral EFT to NLO

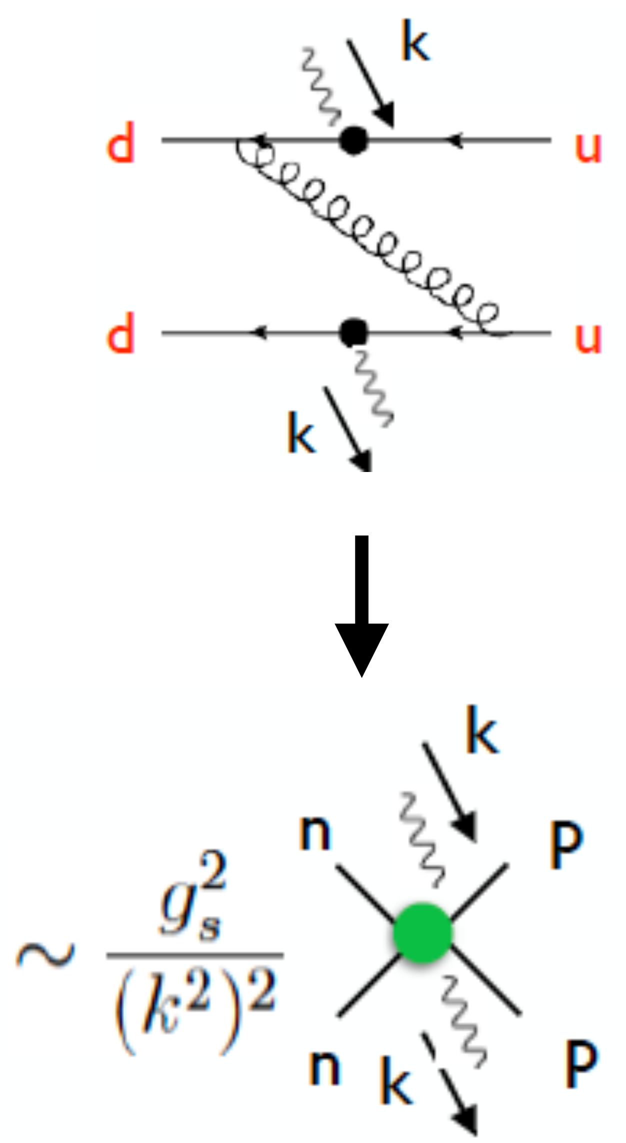


Intermediate k: resonance contributions
in and ,
πNN intermediate state, …



Forward "Compton" amplitude

High k: QCD OPE

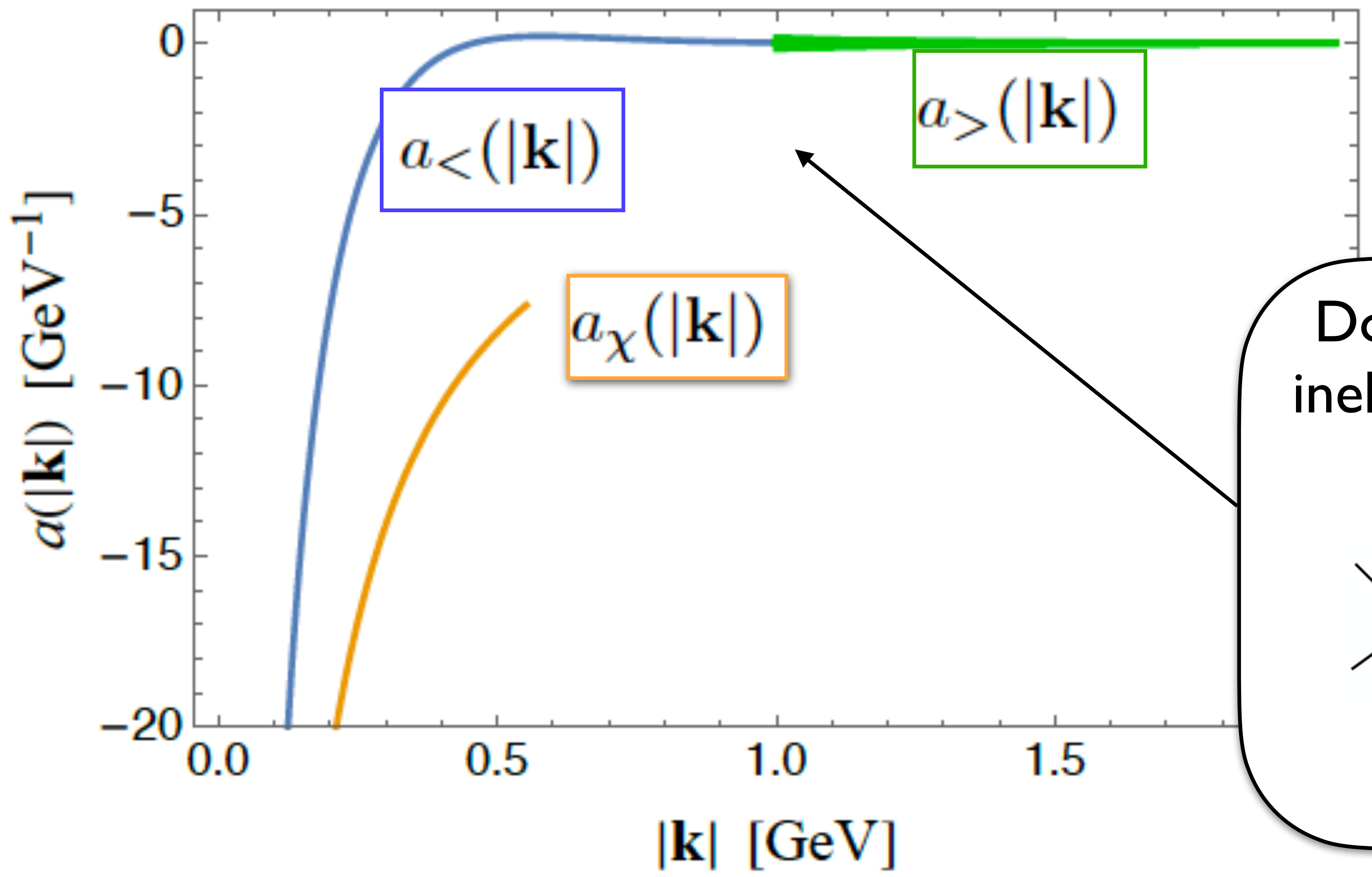


Estimating the contact term (2)

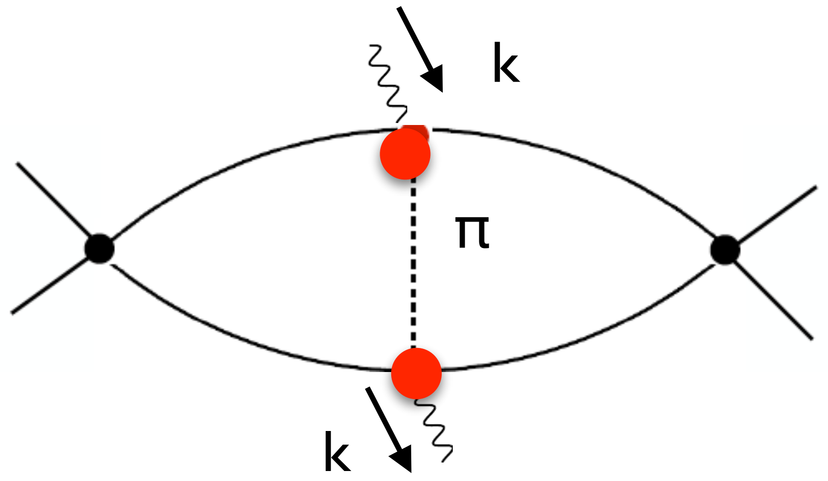
VC, Dekens, deVries, Hoferichter, Mereghetti, 2012.11602, 2102.03371

- Determine $C_{1,2}$ with ~ 30% uncertainty (dominated by intermediate k)

$$\mathcal{A}_\nu \propto \int_0^\Lambda d|\mathbf{k}|\; a_<(|\mathbf{k}|) + \int_\Lambda^\infty d|\mathbf{k}|\; a_>(|\mathbf{k}|)$$



Dominant uncertainty from inelastic channels (NNπ, …):



Estimating the contact term (2)

VC, Dekens, deVries, Hoferichter, Mereghetti, 2012.11602, 2102.03371

- Determine $C_{1,2}$ with ~ 30% uncertainty (dominated by intermediate k)

- Validation: $C_1+C_2 \Rightarrow (a_{nn}+a_{pp})/2 - a_{np}$ = 15.5(4.5) fm versus 10.4(2) fm (exp)

- Provided 'synthetic data' for the nn→pp amplitude at threshold

- First calculation of $^{48}Ca \rightarrow {}^{48}Ti$ with contact fitted to synthetic data ⇒ contact term enhances nuclear matrix element by (43±7)%

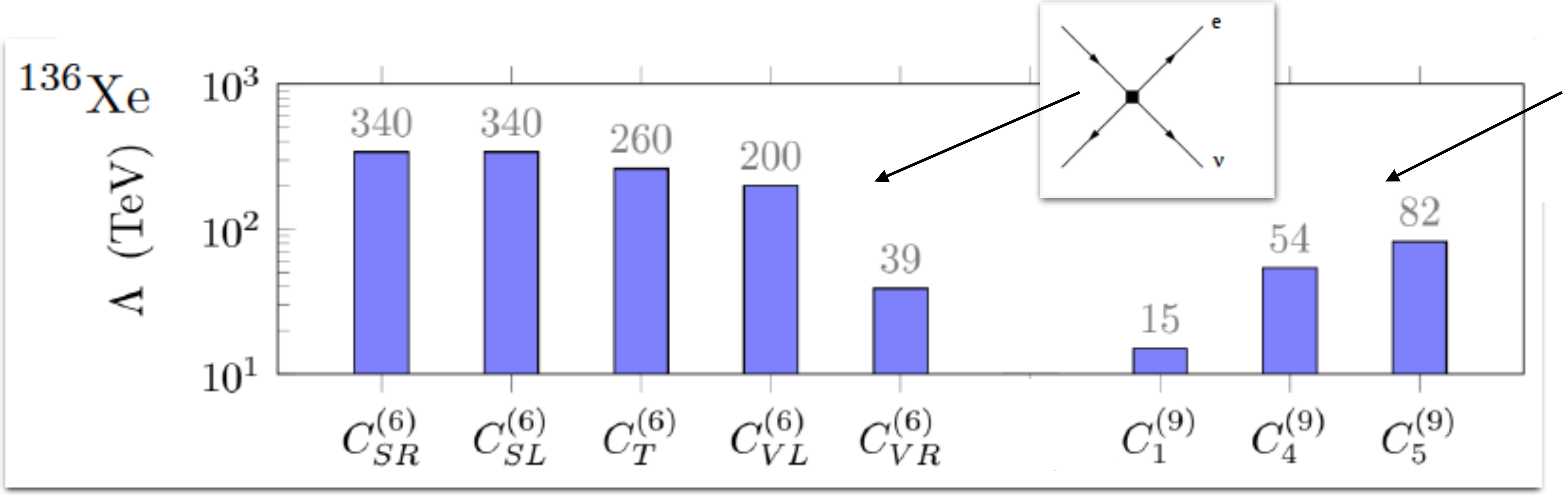
Wirth, Yao, Hergert, 2105.05415

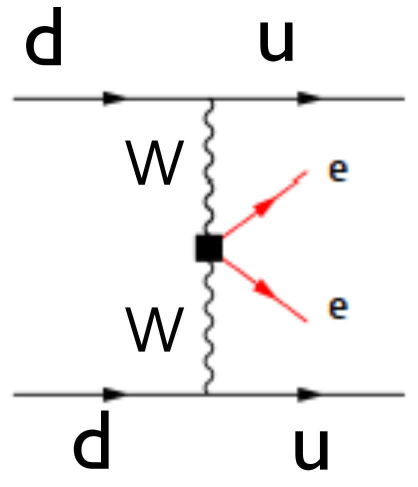
What scales are we probing?

VC, W. Dekens, J. de Vries, M. Graesser, E. Mereghetti, 1806.02780

Dim 7 in SM-EFT

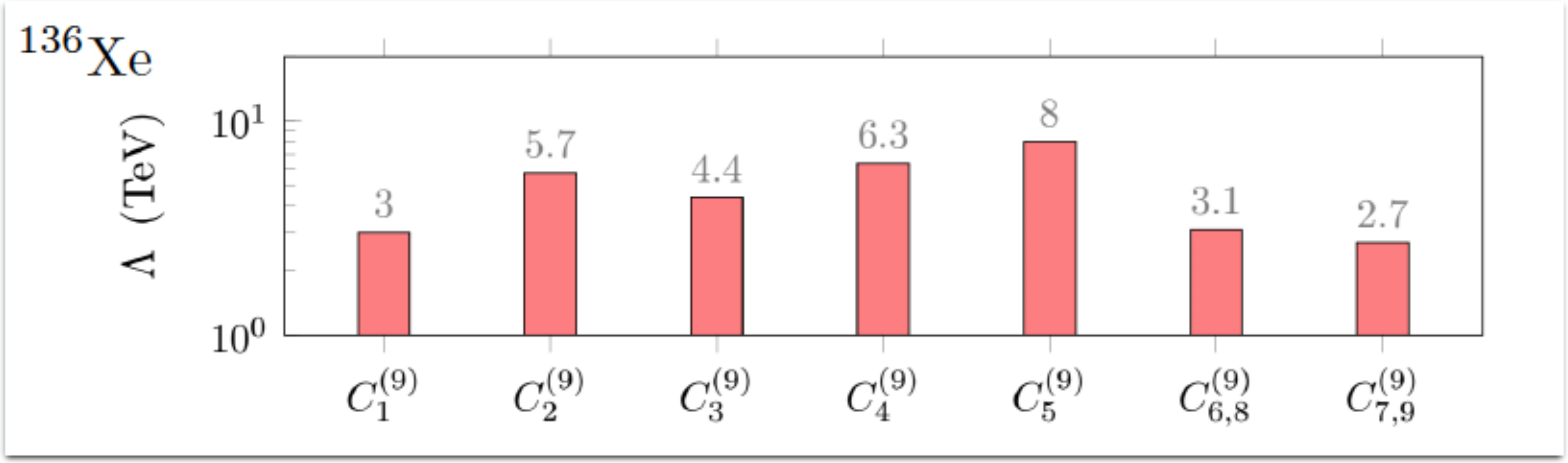
$(v/\Lambda)^3$

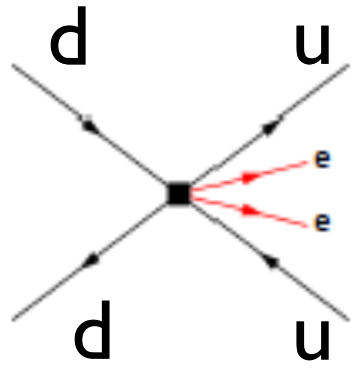




Dim 9 in SM-EFT

$(v/\Lambda)^5$





Bounds reflect dependence on Λ_χ/Λ and Q/Λ_χ

Phenomenological interest

- TeV-scale LNV induces contributions to $0\nu\beta\beta$ *not directly related to the exchange of light neutrinos,* within reach of planned experiments

New contributions can add incoherently *or interfere with* $m_{\beta\beta}$, significantly affecting the interpretation of experimental results

- TeV-scale LNV may lead to correlated or precursor signal at LHC: $pp \to ee\, jj$ (important to unravel the mechanism)

Keung-Senjanovic '83

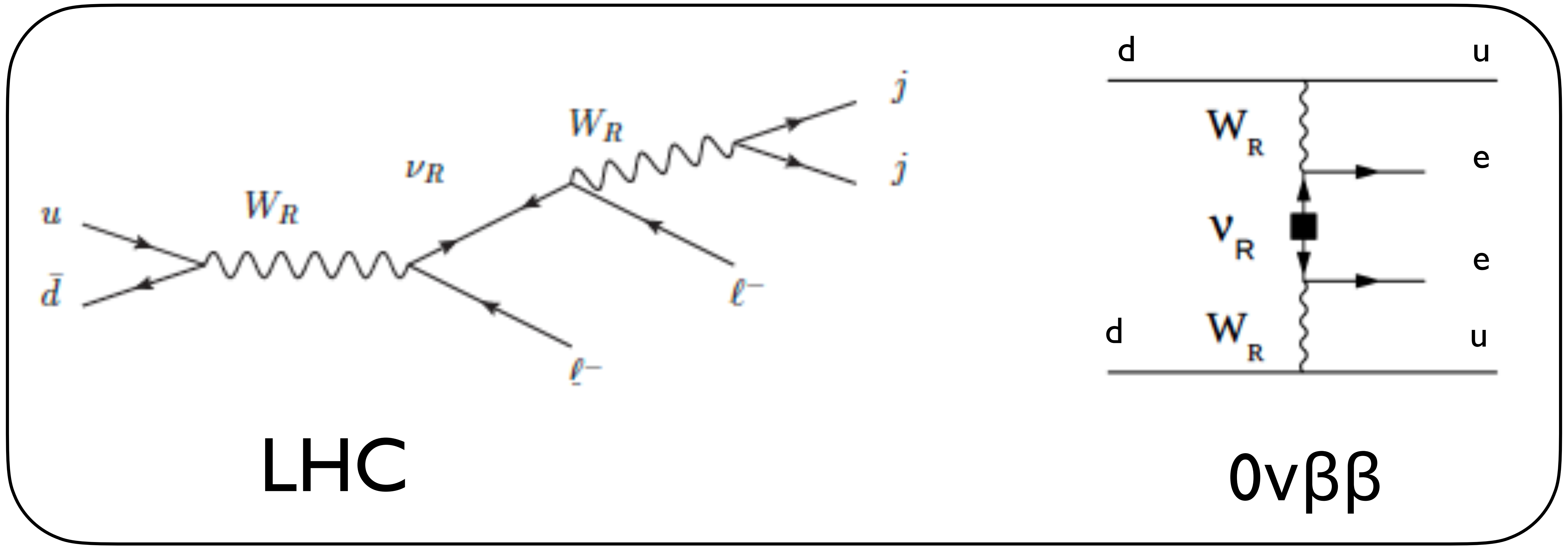
Maiezza-Nemevesek-Nesti- Senjanovic 1005.5160

Helo-Kovalenko-Hirsch-Pas 1303.0899, 1307.4849

Cai, Han, Li, Ruiz 1711.02180

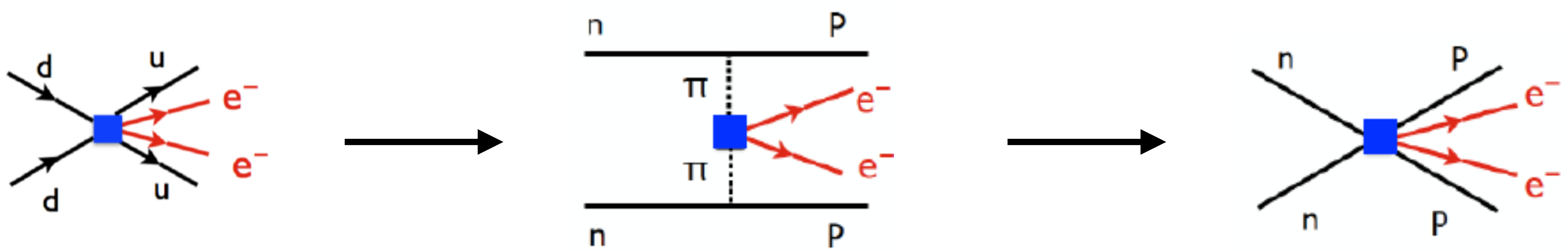
Peng, Ramsey-Musolf, Winslow, 1508.0444
...

Classic LRSM example



Hadronic theory developments

- Leading order hadronic realization of dim-9 operators:



In Weinberg's counting, pion-exchange contribution dominates

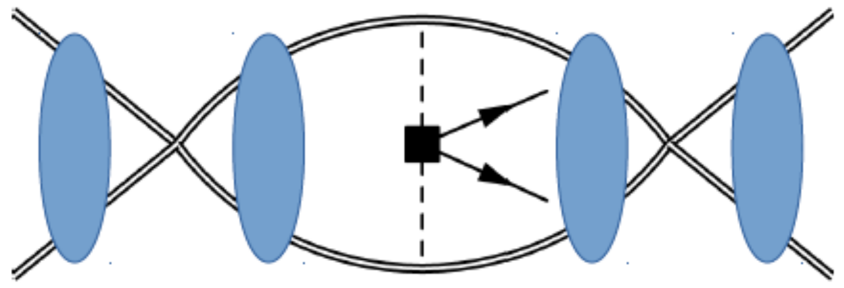
Prezeau, Ramsey-Musolf, Vogel hep-ph/0303205

Vergados 1982,
Faessler, Kovalenko, Simkovic, Schweiger 1996

ππ matrix element known from Lattice QCD at <10%

Nicholson et al (CalLat), 1805.02634

Renromalization requires a contact at the same order!



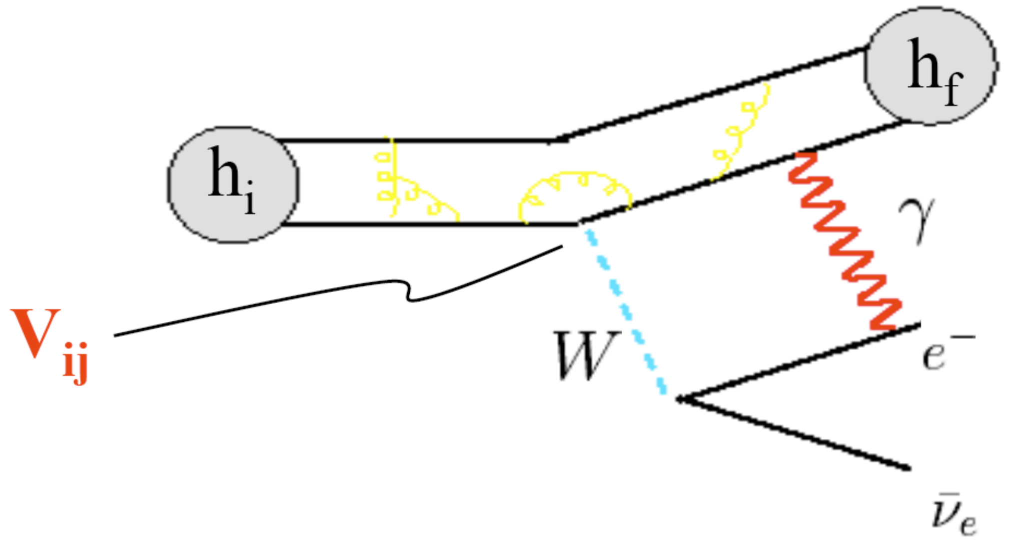
VC, W. Dekens, J. de Vries, M. Graesser, E. Mereghetti [1806.02780]

- Several unknown LO NN contact couplings! Opportunity for LQCD

Backup: beta decay

EFT for radiative corrections: why?

- Widely separated mass scales play a role in neutron and nuclear beta decays



	$M_{W,Z}$	Weak scale
$\gg$	$\Lambda_\chi \sim m_N \sim 4\pi F_\pi \sim 1\ \mathrm{GeV}$	χSB & nucleon mass scale
$\gg$	$m_\pi \sim 140\ \mathrm{MeV}$	Pion mass / hadronic structure
$\gg$	$q_{\rm ext} \sim m_n - m_p \sim m_e \sim 1\ \mathrm{MeV}$	Q value, nuclear excitations

- Small ratios appear as expansion parameters and arguments of logarithms

$$\epsilon_W = \Lambda_\chi / M_W \sim 10^{-2} \qquad \epsilon_\chi = m_\pi/\Lambda_\chi \sim 0.1 \qquad \epsilon_{\rm recoil} = q_{\rm ext}/\Lambda_\chi \sim 10^{-3} \sim \alpha/\pi \qquad \epsilon_{\not\pi} = q_{\rm ext}/m_\pi \sim 10^{-2}$$

- At the required precision ($\sim 10^{-4}$), need to keep terms of $O(G_F\alpha)$, $O(G_F\alpha\epsilon_\chi)$, $O(G_F\epsilon_{\rm recoil})$, along with leading logarithms (LL~ $(\alpha \ln(\epsilon))^n$) and next-to-leading logarithms (NLL ~ $\alpha\,(\alpha_s \ln(\epsilon_W))^n$, $\alpha\,(\alpha \ln(\epsilon))^n$)

Neutron decay (I): decay rate and V_{ud}

VC, W. Dekens, E. Mereghetti, O. Tomalak, 2306. 03138

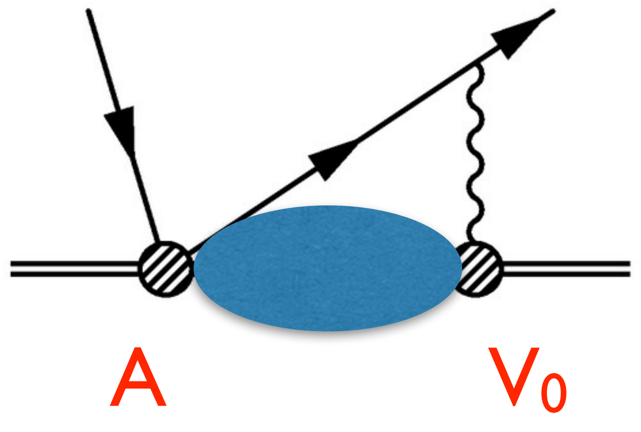
$$\Gamma_n = \frac{G_F^2 |V_{ud}|^2 m_e^5}{2\pi^3} (1+3\lambda^2) \cdot f_0 \cdot (1+\Delta_f) \cdot (1+\Delta_R),$$

$\lambda = g_A/g_V$

$$\Delta_f = 3.573(5)\%$$

$$\Delta_R = 4.044(24)_{\mathrm{Had}}(8)_{\alpha\alpha_s^2}(7)_{\alpha\epsilon_\chi^2}(5)_{\mu_\chi}[27]_{\mathrm{total}} \times 10^{-2}$$

Non-perturbative contribution proportional to the γ-W 'box' [Seng et al. 1807.10197]



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$\lambda = g_A/g_V$

CORRECTION	COMPARISON with LITERATURE**	MAIN SOURCE of DISCREPANCY
$\Delta_f = 3.573(5)\%$	-0.035%	NR vs relativistic Fermi function
$\Delta_R = 4.044(27)\%$	+0.061%	$\alpha^2 \operatorname{Log}(m_N/m_e)$
$\Delta_{TOT} = 7.761(27)\%.$	+0.026%	Both related to the treatment of NLL corrections in the hadronic EFT

** As compiled in VC, A. Crivellin, M. Hoferichter, M. Moulson, 2208.11707. Non-perturbative input in Δ_R is the same

Overall shift of -0.013% in V_{ud} (neutron) compared to previous literature

$0^+ \rightarrow 0^+$ nuclear decay rate

- EFT-based decay rate formula reorganizes 'traditional' corrections in terms of 'matching and running' (e.g. $C_{eff}^{(g_V)}$)

Courtesy of Wouter Dekens

$$\frac{d\Gamma}{dE_e d\Omega_e d\Omega_\nu} = \frac{2(G_F V_{ud})^2}{(2\pi)^5} W(E_e, \mathbf{p}_e\, \mathbf{p}_\nu)\, \tilde{C}(E_e)\, \bar{F}(\beta,\mu)\, \left[1 + \tilde{\delta}'_R(E_e,\mu)\right] (1 - \bar{\delta}_C) \left[1 + \tilde{\delta}_{\rm NS}(E_e,\mu)\right] \left[C_{\rm eff}^{(g_V)}(\mu)\right]^2$$

Shape/atomic/recoil corrections

Fermi function π^2, Z enhanced

Outer correction $\mathcal{O}(\alpha/\pi)$

Isospin correction

Nuclear structure dependence

RG/matching effects $\mu \gtrsim m_e$

- $\tilde{C}(E_e)$, $\tilde{\delta}_C$, $\tilde{\delta}_{NS}$ require nuclear structure input: good prospects of using 'ab initio' methods

- Significant new effect is in $\tilde{\delta}_{NS}$: short range potentials associated with currently unknown LECs

EFT for nuclear decays: impact on V_{ud}

- Exploratory study in $^{14}O \to {}^{14}N$ decay (Quantum Monte Carlo calculation of relevant matrix element)

$$V_{ud} = 0.97364(12)_{g_V}(10)_{\rm exp}(22)_{\bar{f}}(13)_{\delta_{NS}^{\rm non-LEC}}(44)_{\delta_{NS}^{\rm LEC}}(12)_{\delta_c}[55]_{\rm total}$$

Residual scale dependence due to missing terms of $O(\alpha^2 Z)$ in the Fermi function

Largest uncertainty. Assumes $g^{NN}_{V1,V2} = 1/(4 m_N F_\pi^2)$

LECs can be obtained by fitting data, once NME calculations for several isotopes become available. Dispersive methods and lattice QCD can also be useful

- To be compared with Towner-Hardy 2020 result (from $^{14}O \to {}^{14}N$ decay alone):

$$V_{ud} = 0.97405(37)_{\rm total}$$

(31) from δ_{NS}