Standard Model EFT meets Chiral EFT
TRIUMF
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SMEFT meets ChEFT in β decays

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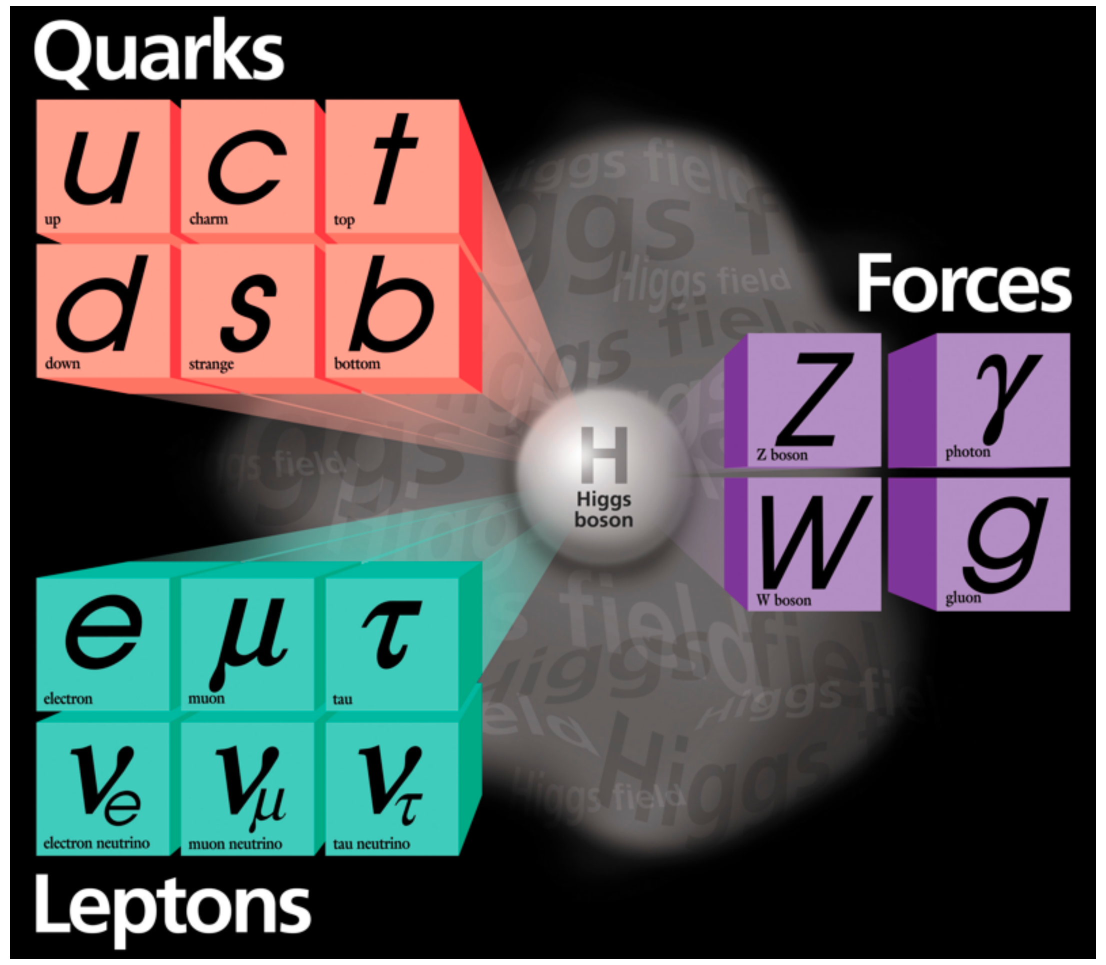
UNIVERSITY of WASHINGTON

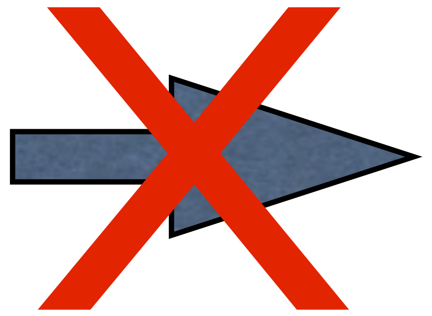
Context: BSM searches at low-energy

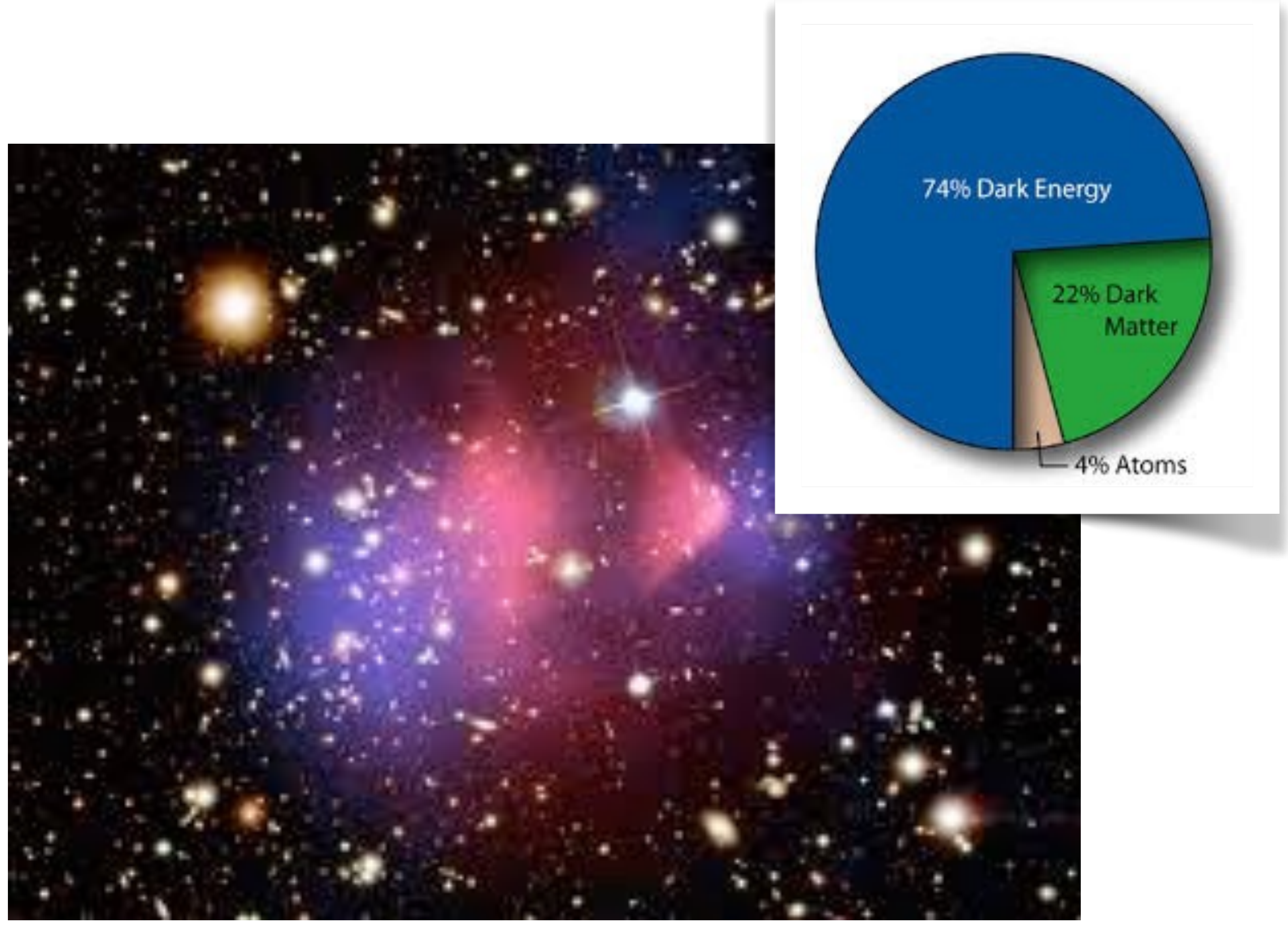
- Low-energy measurements can shed light on shortcomings of the Standard Model

No Neutrino Mass, no Baryon Asymmetry, no Dark Matter, no Dark Energy, …



Credit: Fermilab





Credit: X-ray: NASA/CXC/CfA/M.Markevitch et al.; Optical: NASA/STScI; Magellan/U.Arizona/ D.Clowe et al.; Lensing Map: NASA/STScI; ESO WFI; Magellan/U.Arizona/D.Clowe et al.

Context: BSM searches at low-energy

- Low-energy measurements can shed light on shortcomings of the Standard Model
- Precision / sensitivity frontiers:

Precision tests of SM-allowed processes

- Weak decays
- PV electron scattering
- muon g-2
- …

New force mediators, from dark sectors to multi-TeV

Search for rare / forbidden processes that violate exact or approximate symmetries of the SM

- L and B non conservation
- CP & T violation
- Flavor violation in quarks & leptons
- …

Connection to Sakharov conditions for baryogenesis

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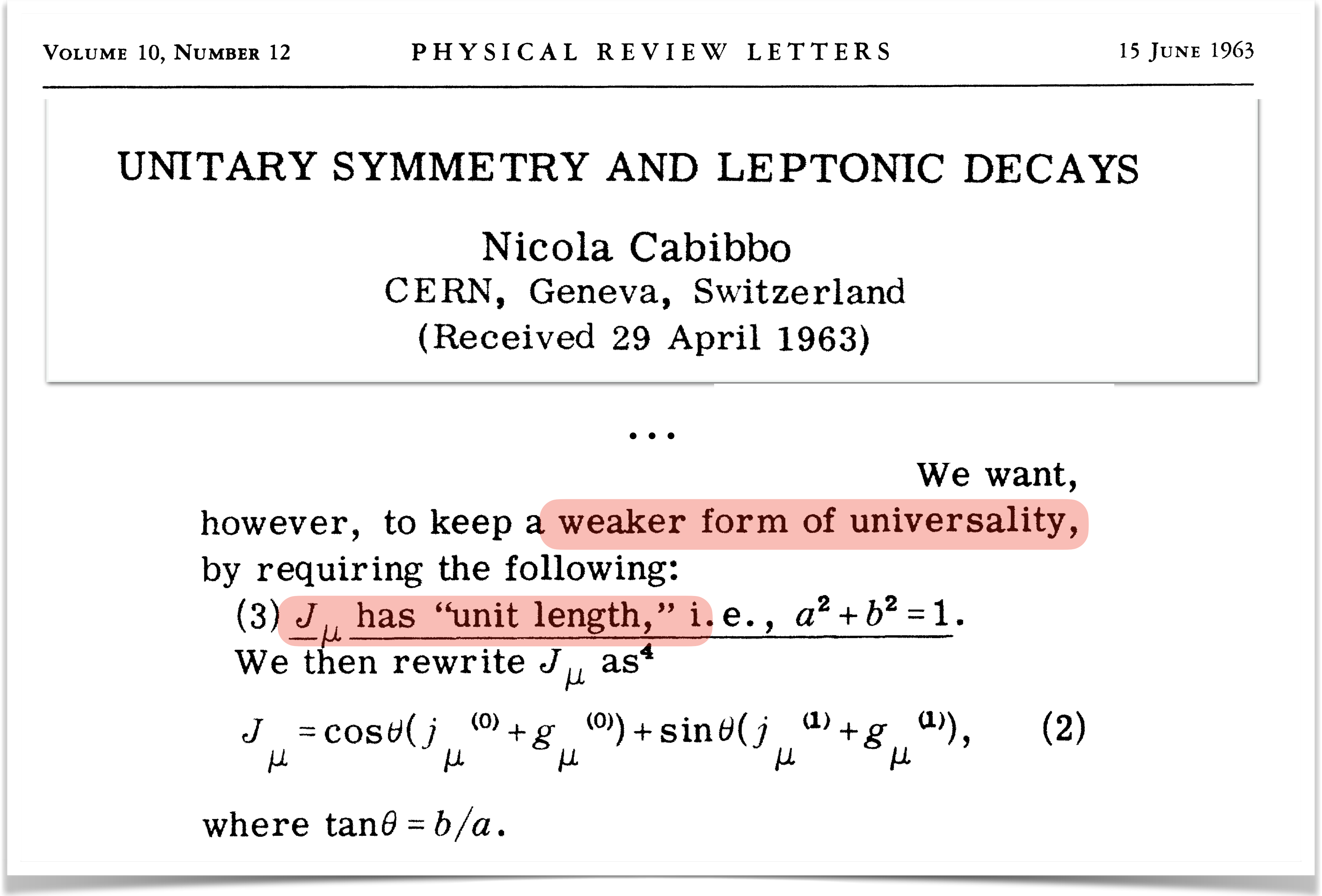
Connection to Sakharov conditions for baryogenesis

Hadronic and nuclear probes — natural meeting ground of SM-EFT and Ch-EFT

Outline

- Precision studies of β decays
    - Cabibbo universality test
    - Radiative corrections to neutron and nuclear β decays in ChEFT
    - Implications for new physics in the SMEFT framework
- Summary and outlook

Cabibbo universality test
(a.k.a. 1st row CKM unitarity test)



VOLUME 10, NUMBER 12 PHYSICAL REVIEW LETTERS 15 JUNE 1963

UNITARY SYMMETRY AND LEPTONIC DECAYS

Nicola Cabibbo
CERN, Geneva, Switzerland
(Received 29 April 1963)

. . .

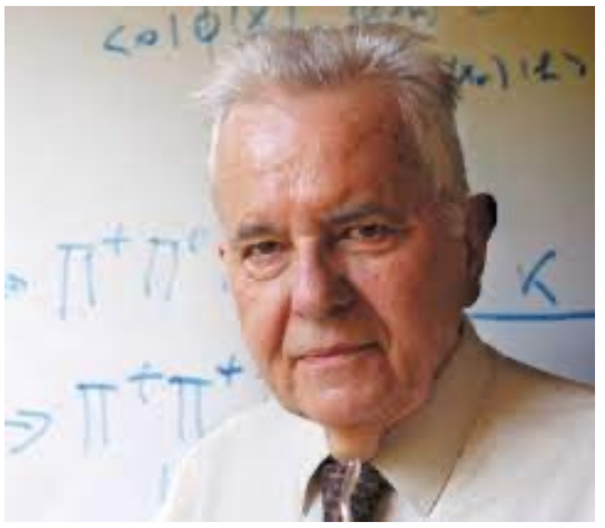
We want, however, to keep a weaker form of universality, by requiring the following:

(3) J_μ has "unit length," i.e., $a^2+b^2=1$.

We then rewrite J_μ as[4]

$$J_\mu = \cos\theta(j_\mu^{(0)}+g_\mu^{(0)}) + \sin\theta(j_\mu^{(1)}+g_\mu^{(1)}), \qquad (2)$$

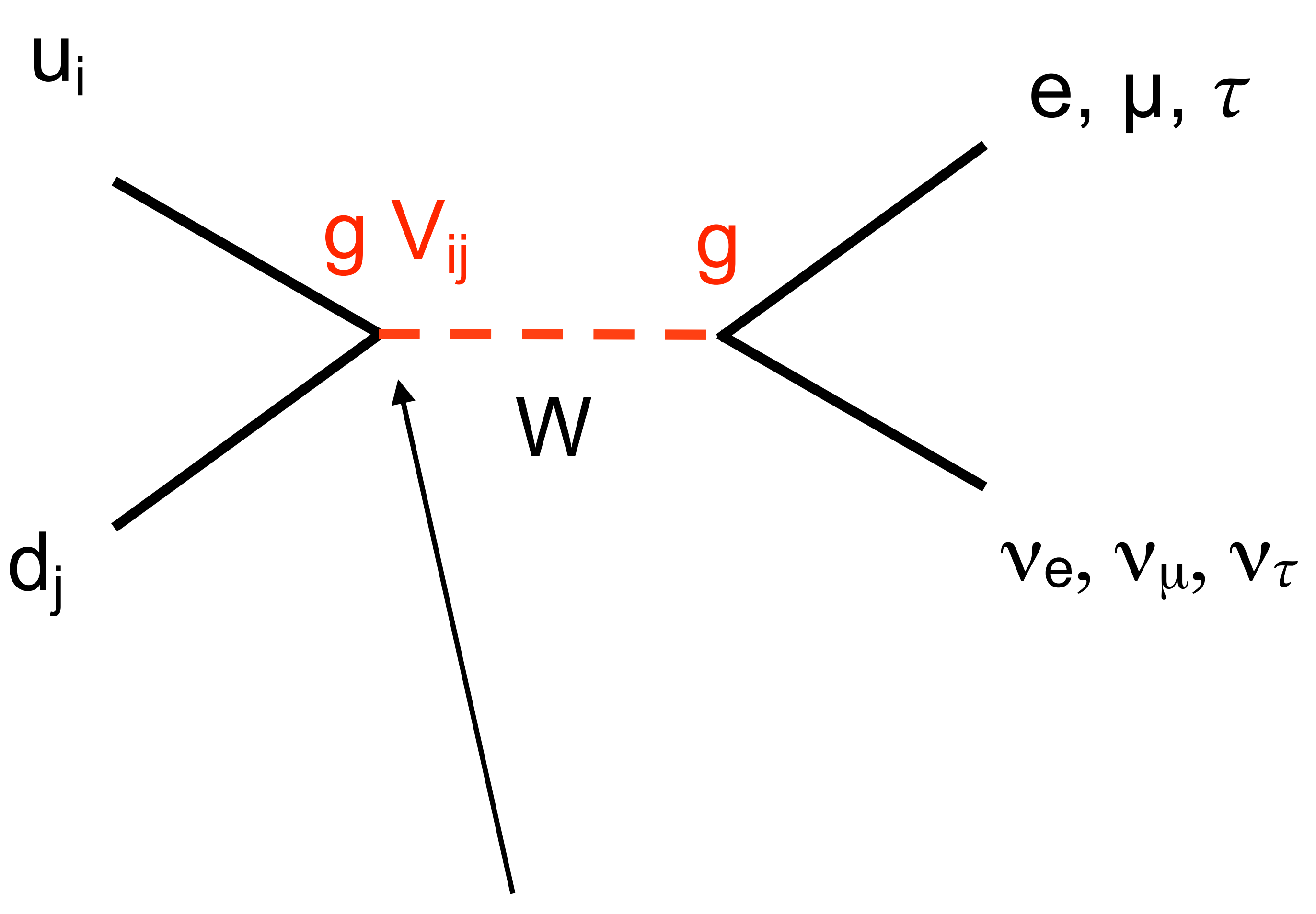
where $\tan\theta = b/a$.



Nicola Cabibbo
(1935-2010)

‘β decays’ in the SM and beyond

- In the SM, W exchange between L-handed fermions ⇒ “V-A” currents & universality relations



$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

Cabibbo-Kobayashi-Maskawa

Cabibbo universality (CKM unitarity)

~0..95 ~0.05 $\sim 1.5 \times 10^{-5}$

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

$\delta V_{ud}/V_{ud} \sim 0.03\%$ $\delta V_{us}/V_{us} \sim 0.2\%$ $\delta V_{ub}/V_{ub} \sim 5\%$

V_{ud} and V_{us} are the most accurately known elements of the CKM matrix ⇒

I[st] row provides the most stringent test of universality & sensitivity to new physics

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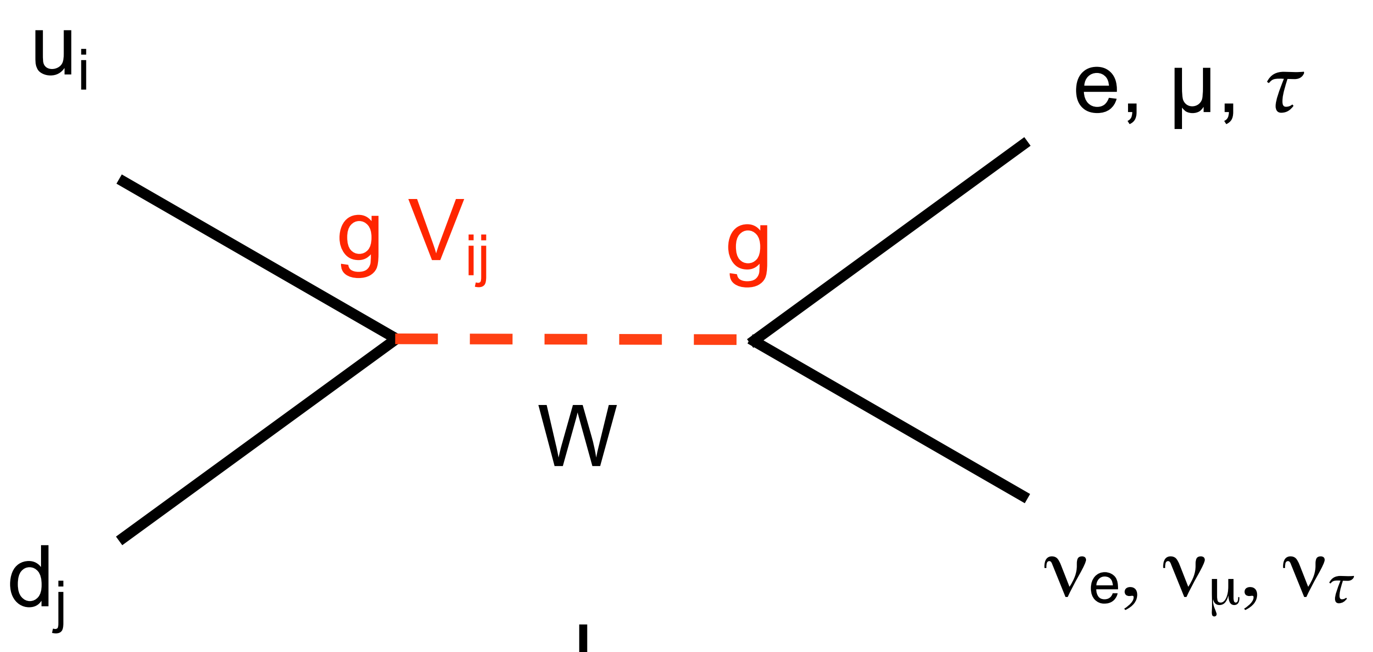

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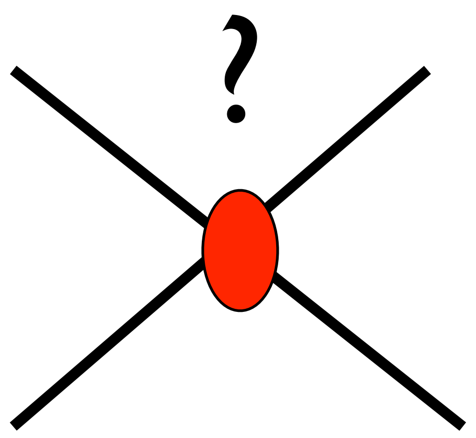


at low energy

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

$1/\Lambda^2$

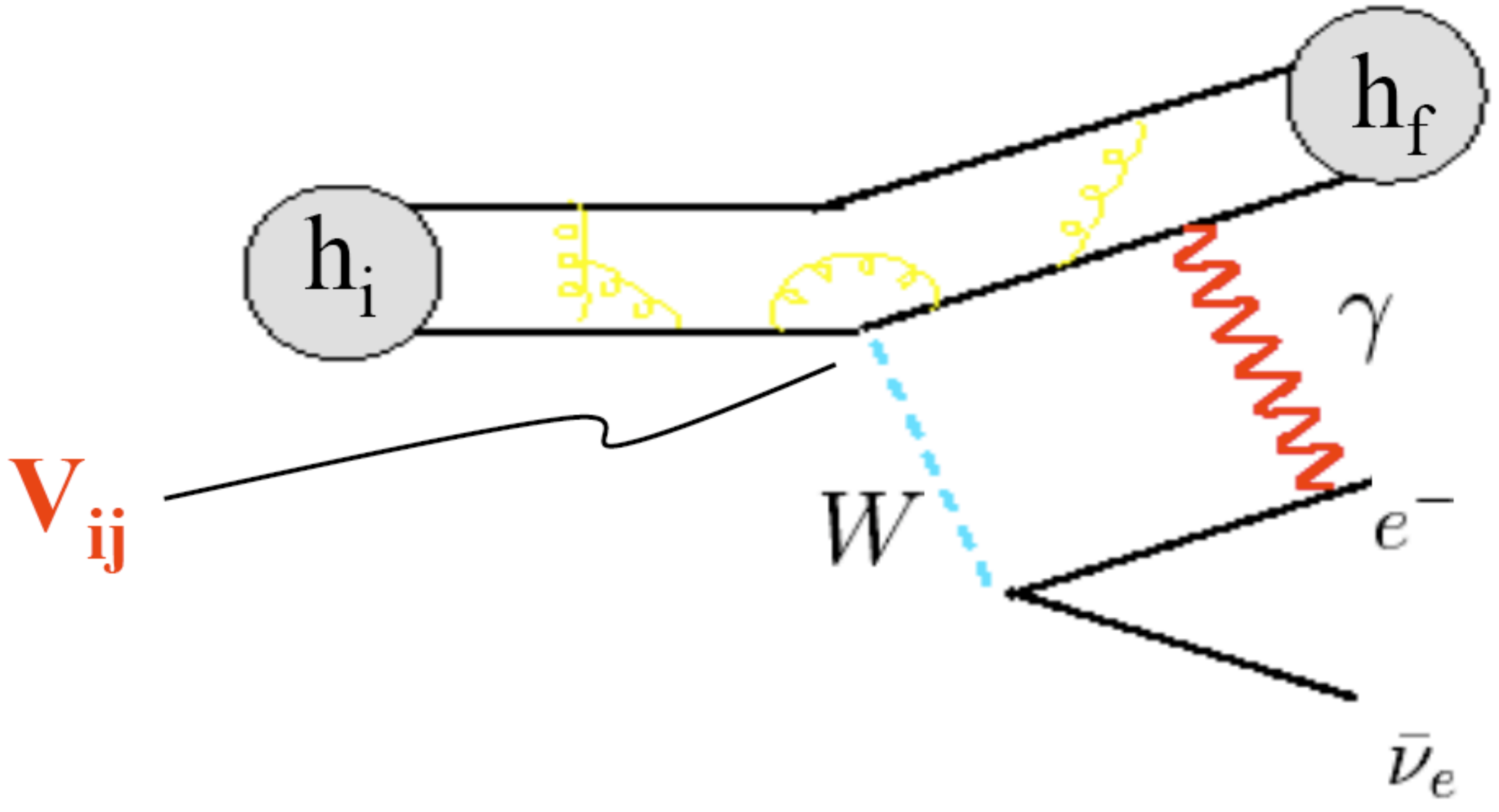
New physics can spoil universality: $|V_{ud}|^2 + |V_{us}|^2 + |\cancel{V_{ub}}|^2 = 1 + O\left(\frac{v^2}{\Lambda^2}\right)$

Current precision ⇒ probe effective scale Λ ~ 10 TeV

Compelling but challenging!

Paths to V_{ud} and V_{us}

	Hadron decays			Lepton decays
V_{ud}	$\pi^{\pm} \to \pi^{0} e \nu$ Nucl. $0^+ \to 0^+$	$n \to p e \nu$ Nucl. mirror decays	$\pi \to \mu\nu$	$\tau \to h_{NS}\nu$
V_{us}	$K \to \pi \, l \, \nu$	$\Lambda \to p e \nu, \ldots$	$K \to \mu\nu$	$\tau \to h_S \nu$
	V	**V, A**	**A**	**V, A**



Cabibbo universality test

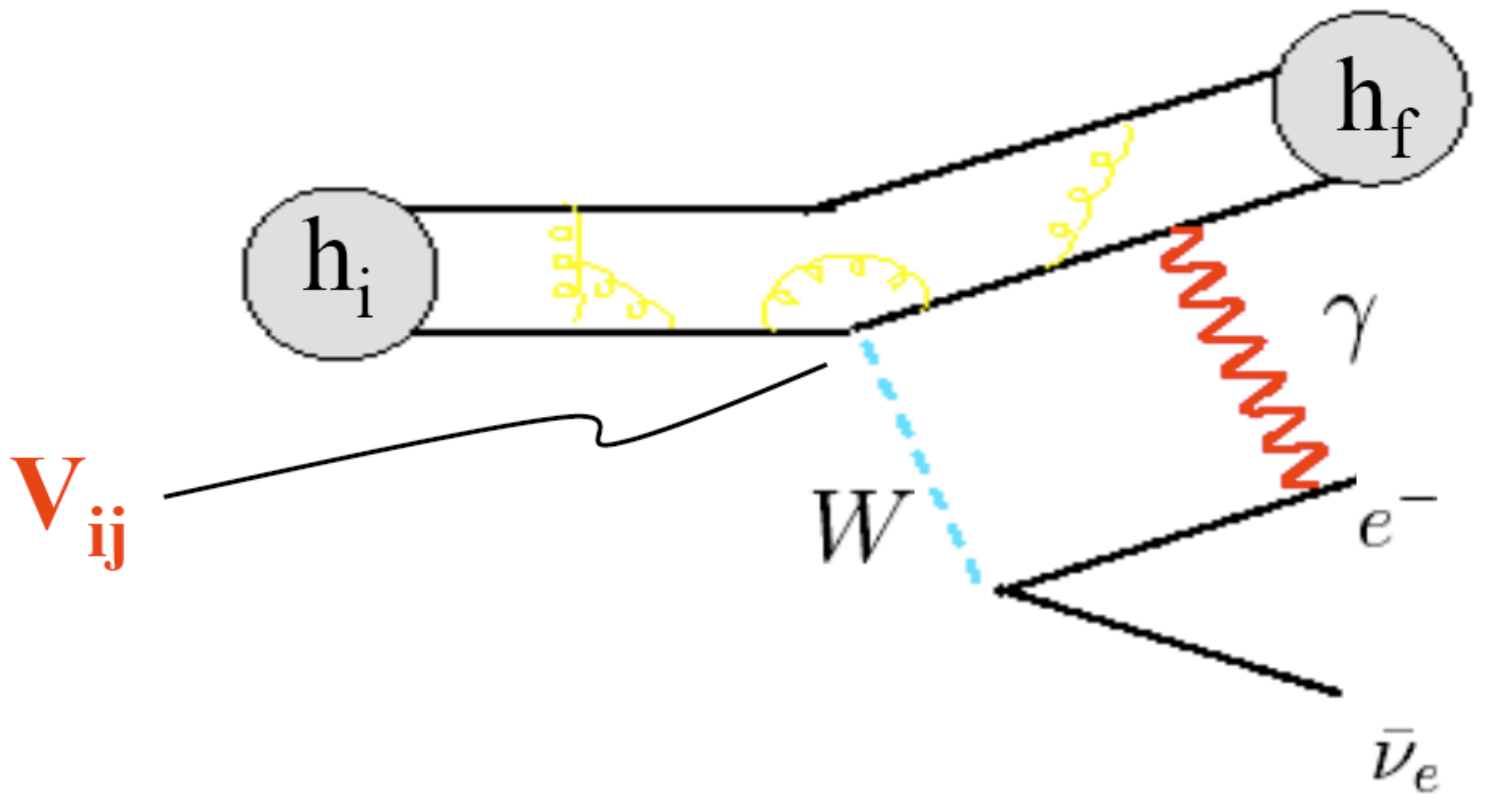
Extract $V_{ud}=\mathrm{Cos}\theta_C$ and $V_{us}=\mathrm{Sin}\theta_C$ from meson, neutron & nuclear decays

$$\Gamma_k = (G_F^{(\mu)})^2 \times |\bar{V}_{ij}|^2 \times |M_{\rm had}|^2 \times (1+\delta_{RC}) \times F_{\rm kin}$$

Channel-dependent effective CKM element

Hadronic matrix element (For the vector current, known in the SU(n_F) symmetry limit)

Radiative corrections: $(\alpha/\pi) \sim 2. \times 10^{-3}$

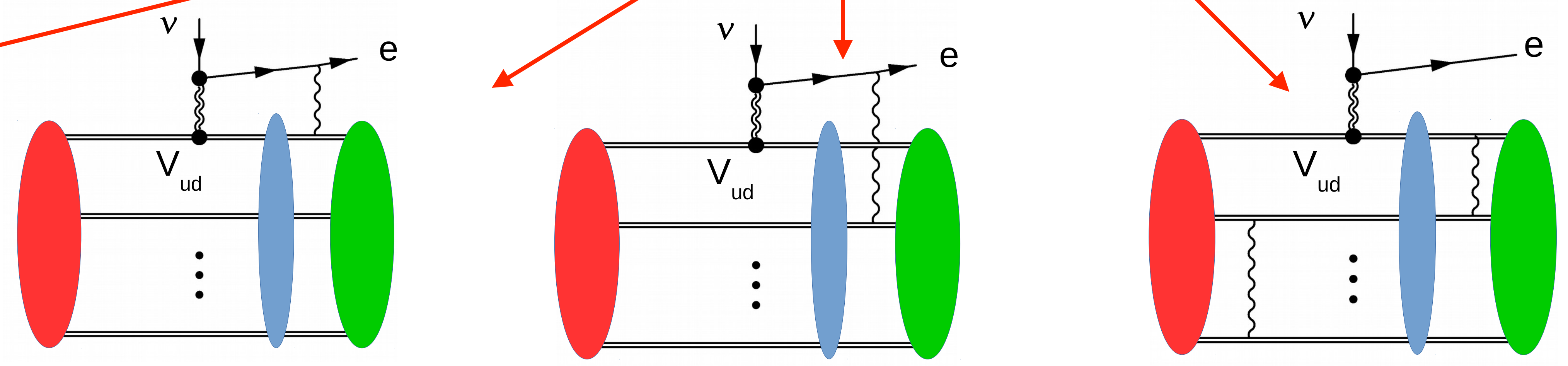


Cabibbo universality test

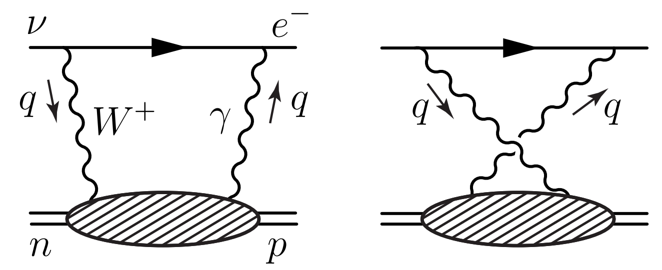
Example: V_{ud} from nuclear $0^+ \rightarrow 0^+$ beta decays

$$|V_{ud}|^2 = \frac{2984.432(3)\ s}{ft\left(1+\delta_R' + \delta_{NS} - \delta_C + \Delta_R^V\right)}$$

Point-like nucleus
'outer corrections'
(depend on Z, $(E_e)^{max}$)

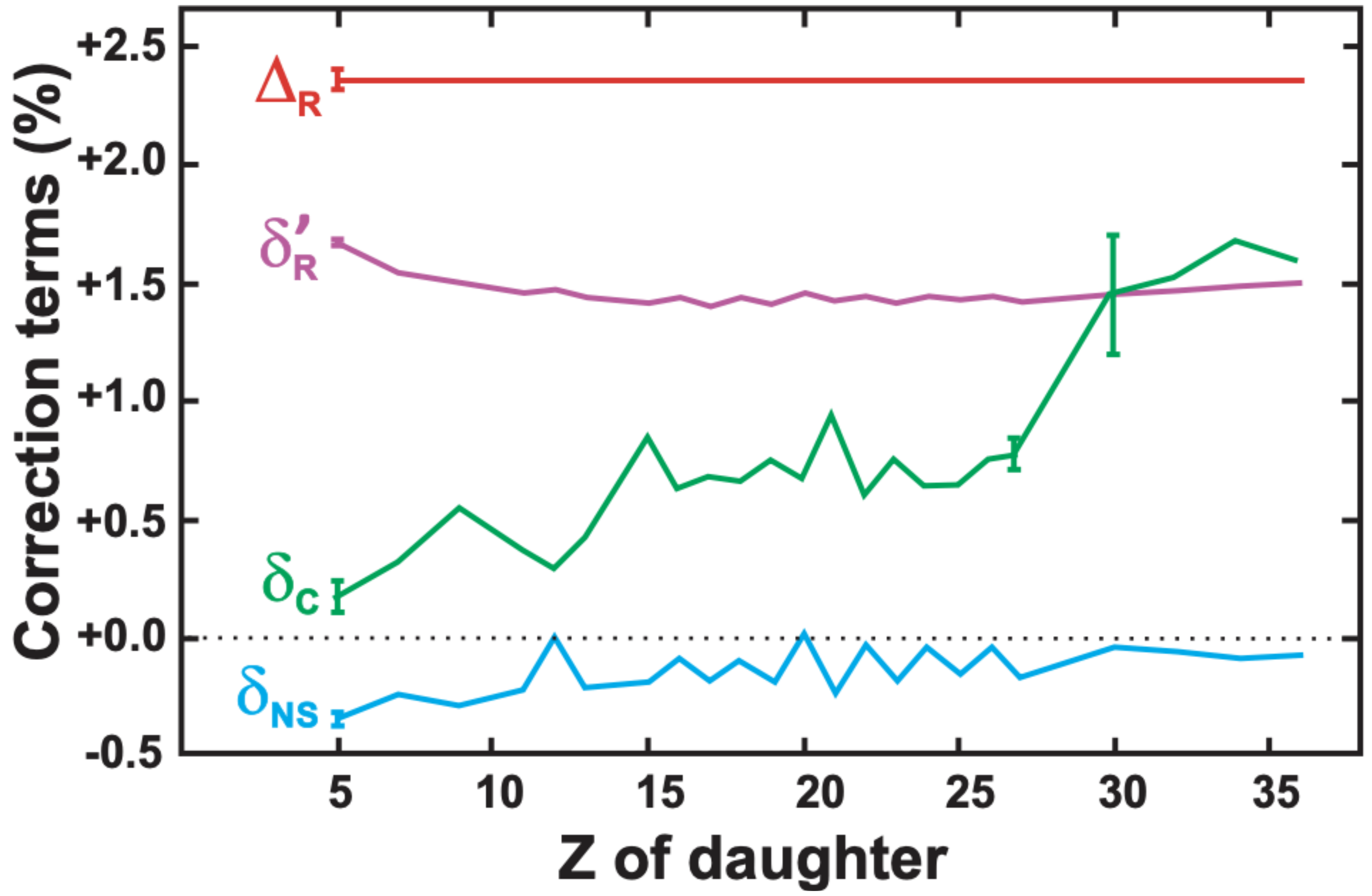


Quark-level corrections &
single nucleon
`γ-W box'



Seng et al. 1807.10197, Czarnecki et al, 1907.06737,
Shiells et al. 2012.01580
Hayen 2010.07262 , Gorchtein-Seng 2106.09185

Hardy-Towner, PRC 2020

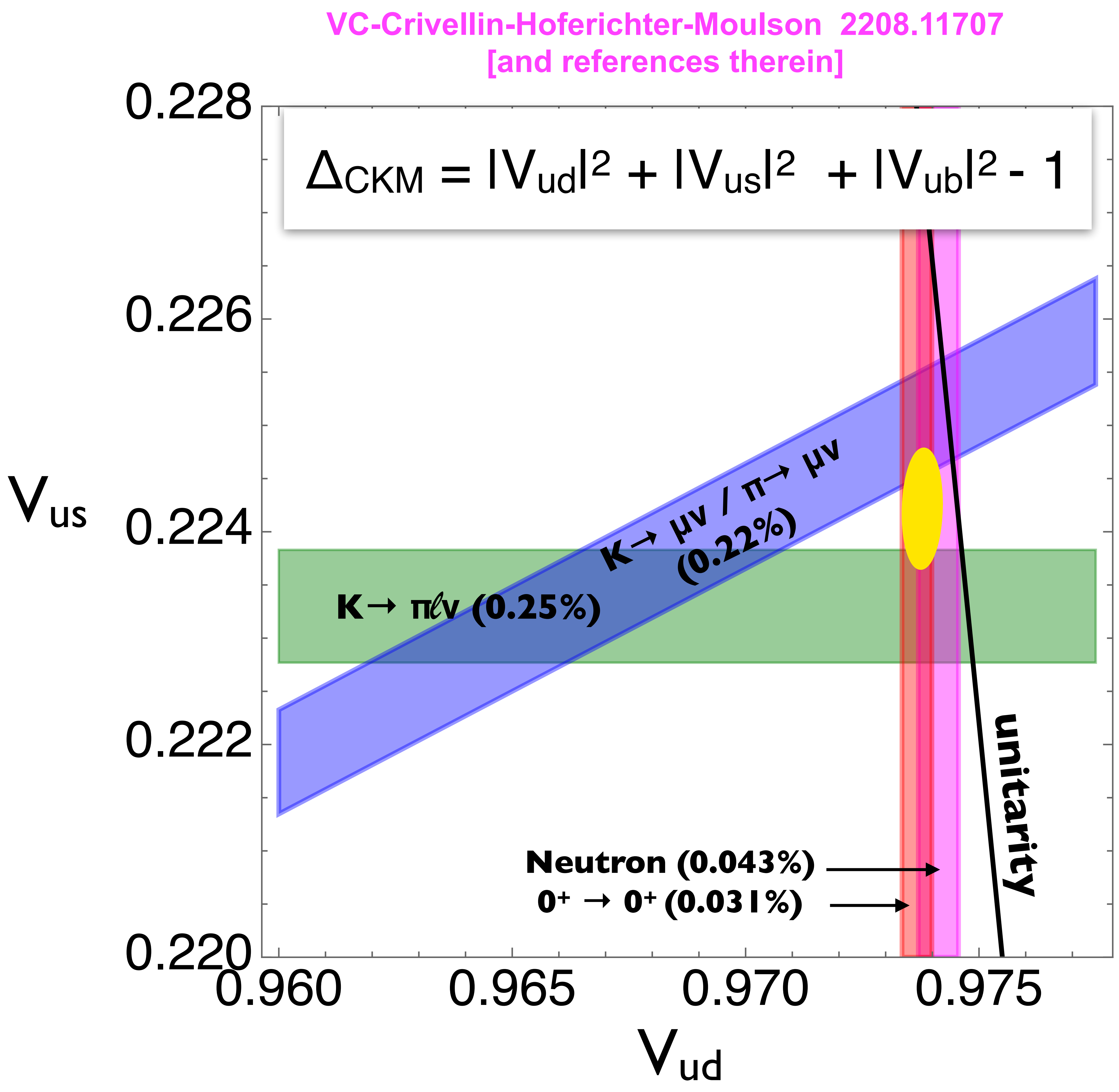


For a review see
Gorchtein, Seng 2311.00044
and references therein

$$V_{ud}^{0^+\to 0^+} = 0.97367(11)_{\rm exp}(13)_{\Delta_R^V}(27)_{\rm NS}[32]_{\rm total}$$

$\delta V_{ud}/V_{ud} \sim 0.03\%$

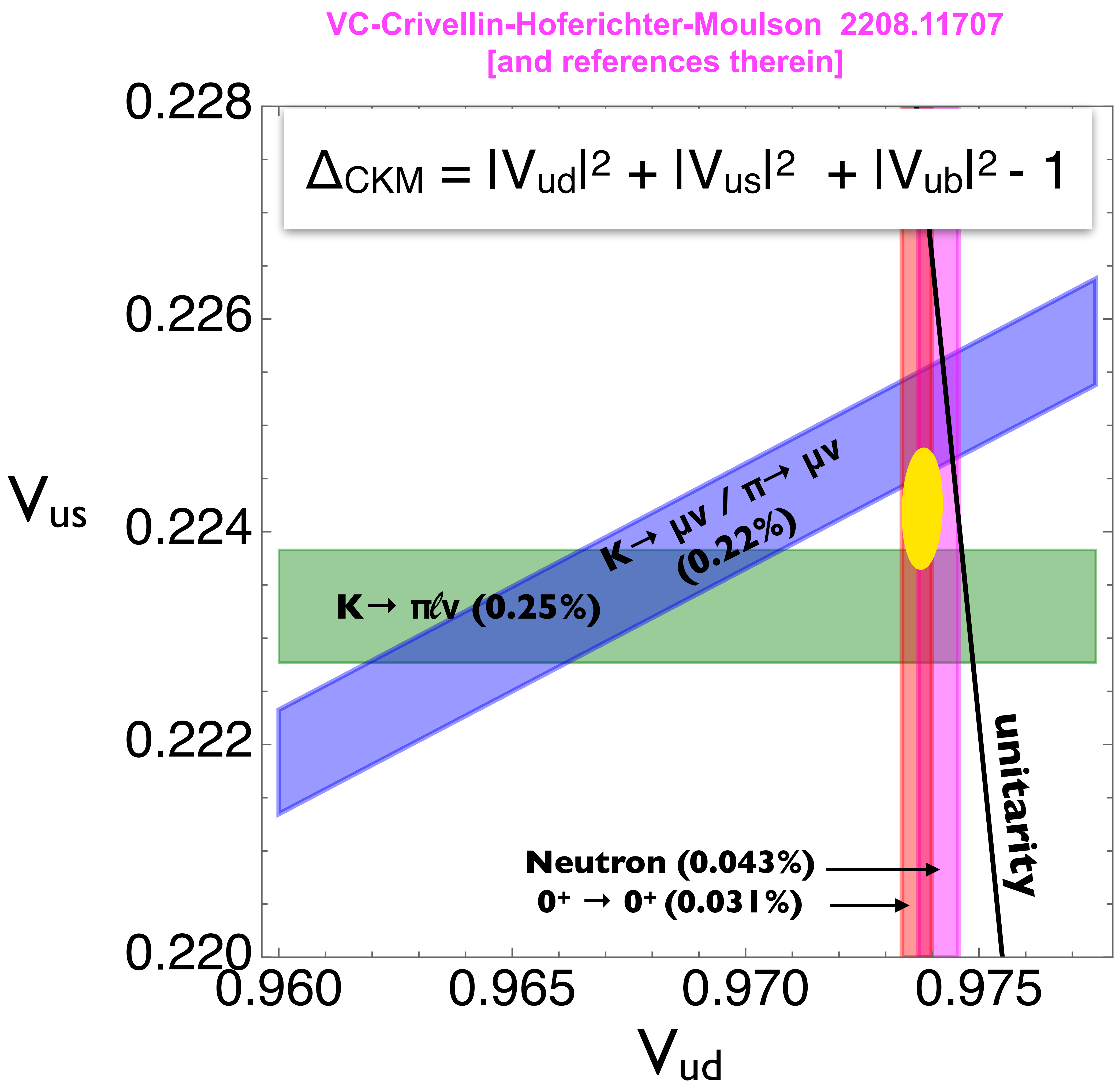
Cabibbo universality test



Cabibbo angle anomaly?

- Bands should intersect in a single region and that region should overlap with the unitarity circle
- ~3σ problem even in meson sector (Kl2 vs Kl3)
- ~3σ effect in global fit ($\Delta_{CKM} = -1.48(53) \times 10^{-3}$)

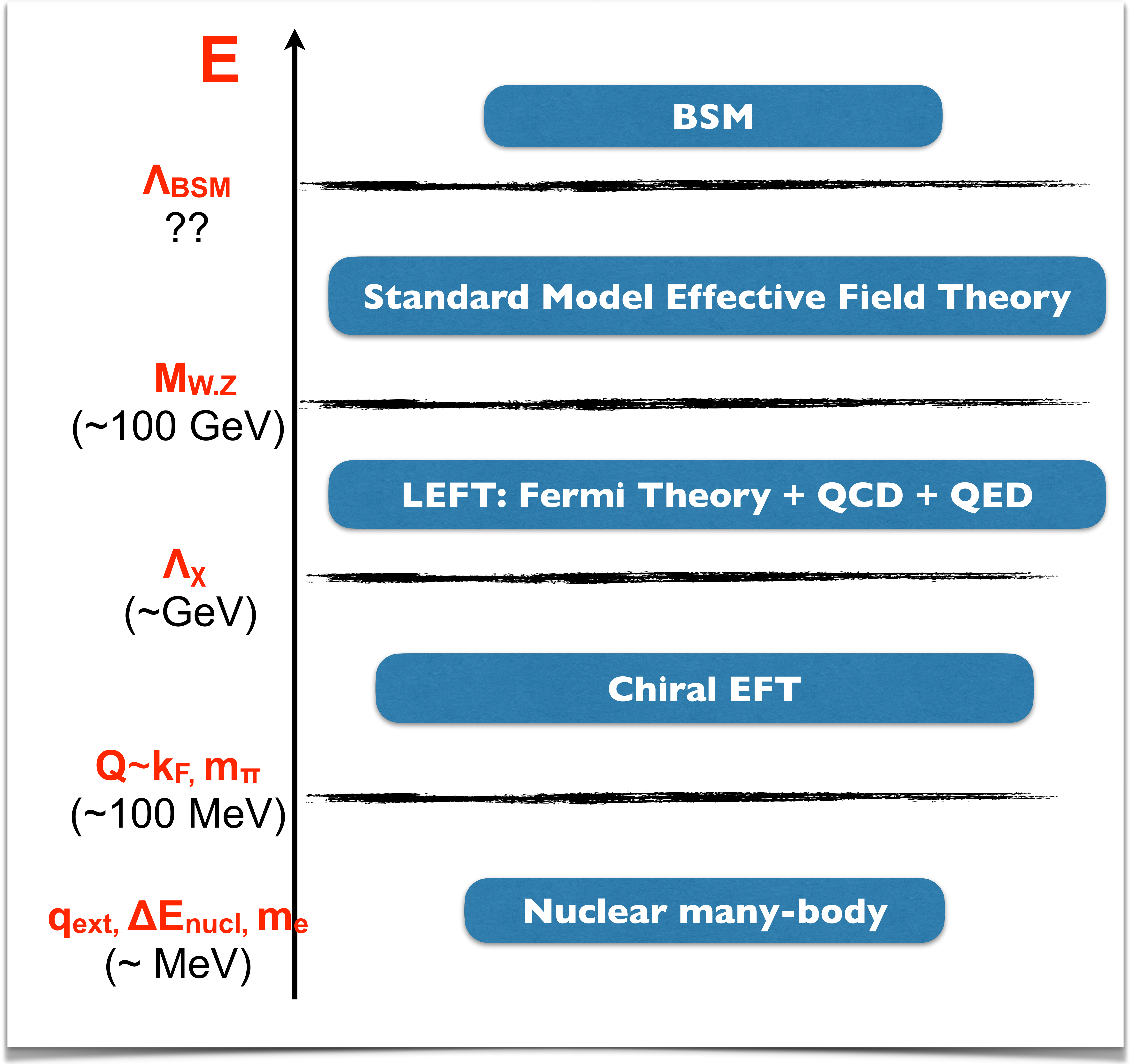
Cabibbo universality test



- Expected experimental improvement:
  - neutron decay (will match nominal nuclear uncertainty)
  - pion beta decay (6x to 10x at PIONEER phases II, III)
  - new $K_{\mu 3}/K_{\mu 2}$ BR measurement at NA62
- Theoretical interpretation framework
  - Though not universally embraced in the literature, need a tower of EFTs from BSM to nuclear scale, with critical non-perturbative input from Lattice QCD, dispersive methods, nuclear many-body calculations

Interpretation framework for β decays

Widely separated scales: $\Lambda_{BSM} \gg M_W \gg \Lambda_\chi \gg Q \sim k_F \sim m_\pi \gg m_e \sim q_{ext}$ ⇒ Tackle through a tower of EFTs



The EFT expands amplitudes in ε's and sums large logarithms ~ $\alpha^{n+m} (\ln(\varepsilon))^n$

$\boxed{\varepsilon_{SMEFT} = (m_W/\Lambda_{BSM})^2}$

$\boxed{\varepsilon_W = (\Lambda_\chi/m_W)^2}$

With key non-perturbative input from Lattice QCD and dispersive methods

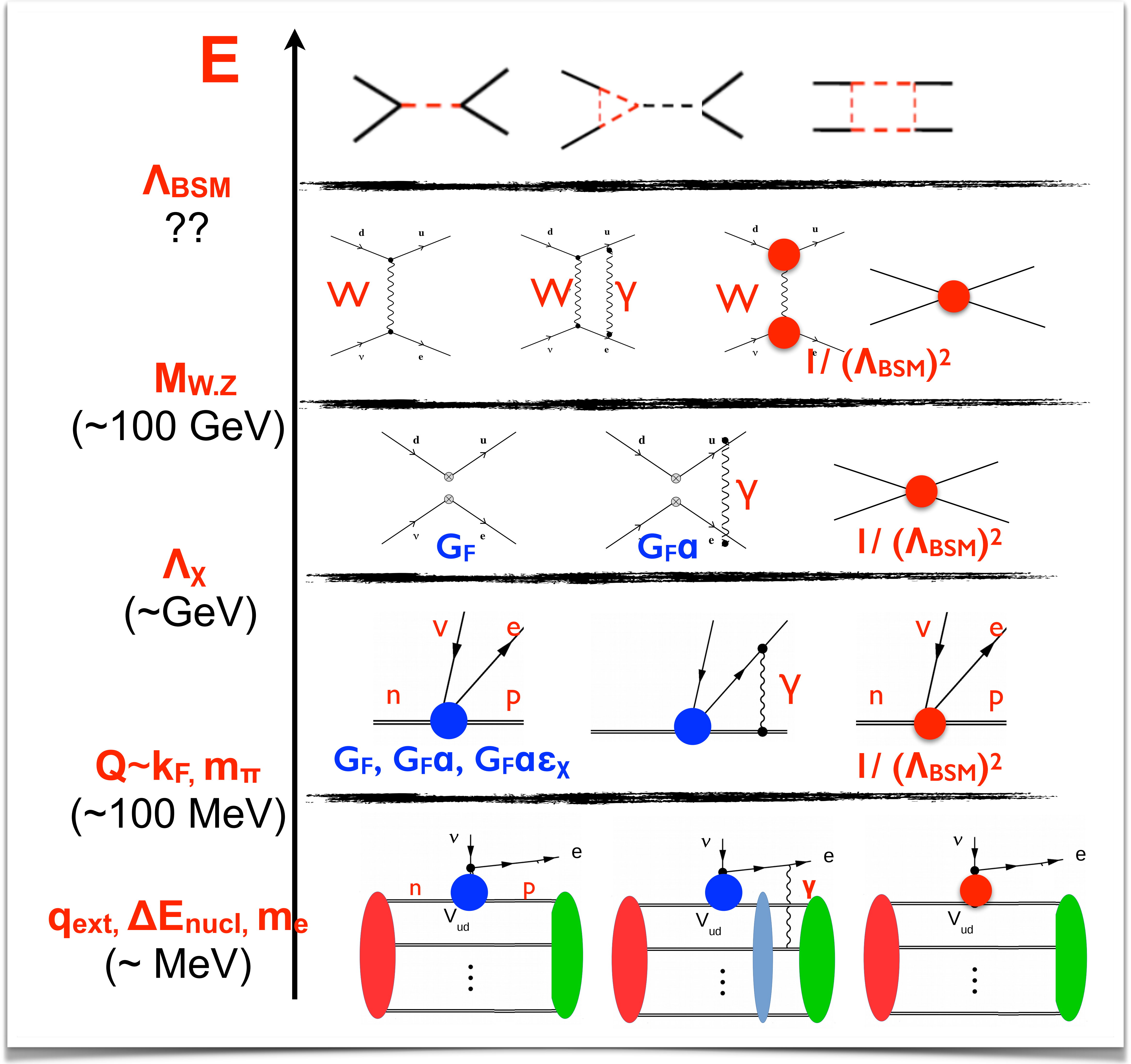
$\boxed{\varepsilon_\chi = Q/\Lambda_\chi}$

$\boxed{\epsilon_{\not\pi} = q_{\rm ext}/m_\pi}$

$\boxed{\epsilon_{\rm recoil} = q_{\rm ext}/\Lambda_\chi}$

Interpretation framework for β decays

Widely separated scales: Λ_{BSM} >> M_W >> Λ_χ >> Q ~ k_F ~ m_π >> m_e ~ q_{ext} ⇒ Tackle through a tower of EFTs



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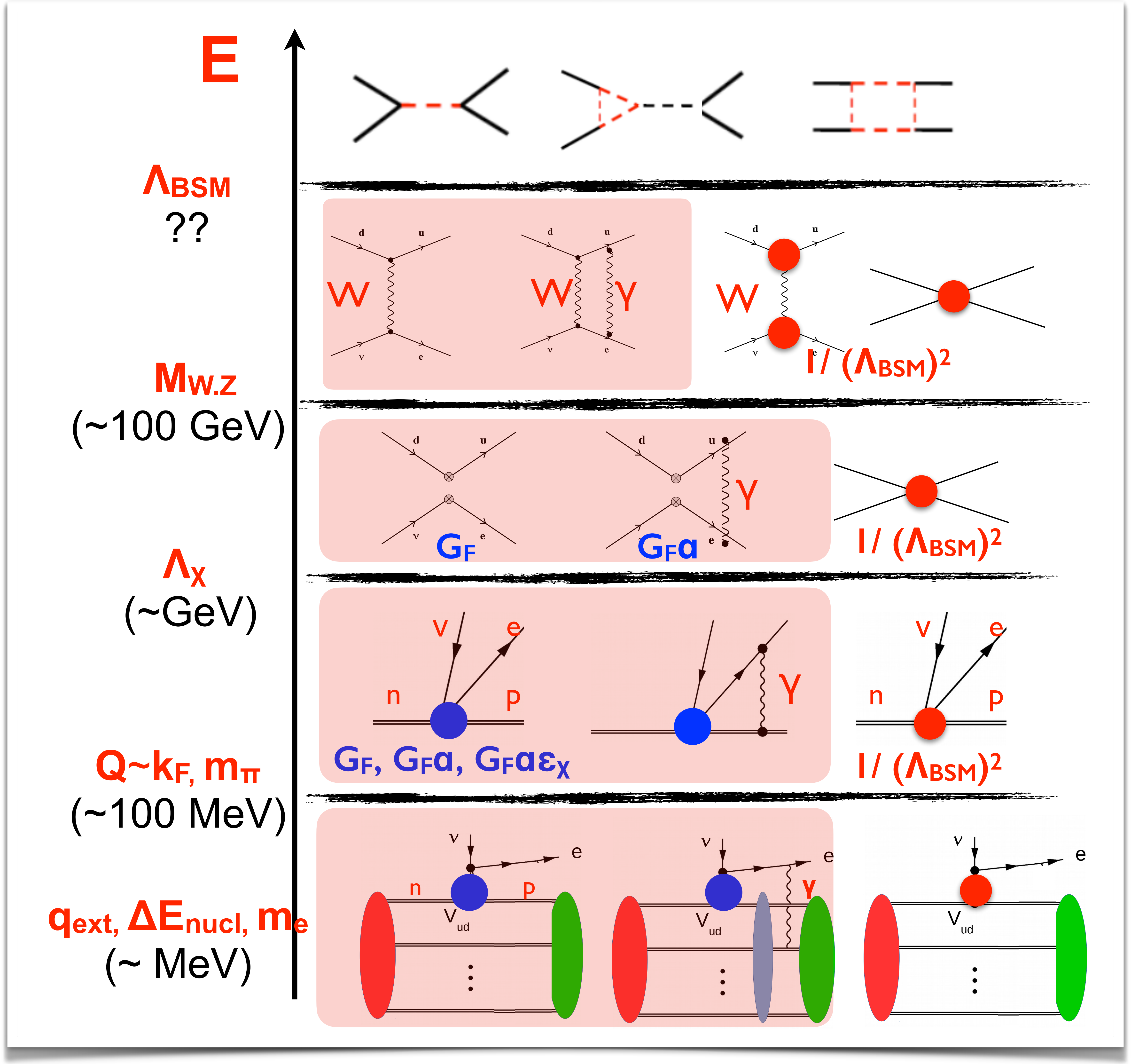

EFT for Standard Model contributions to sub-% level
— radiative corrections

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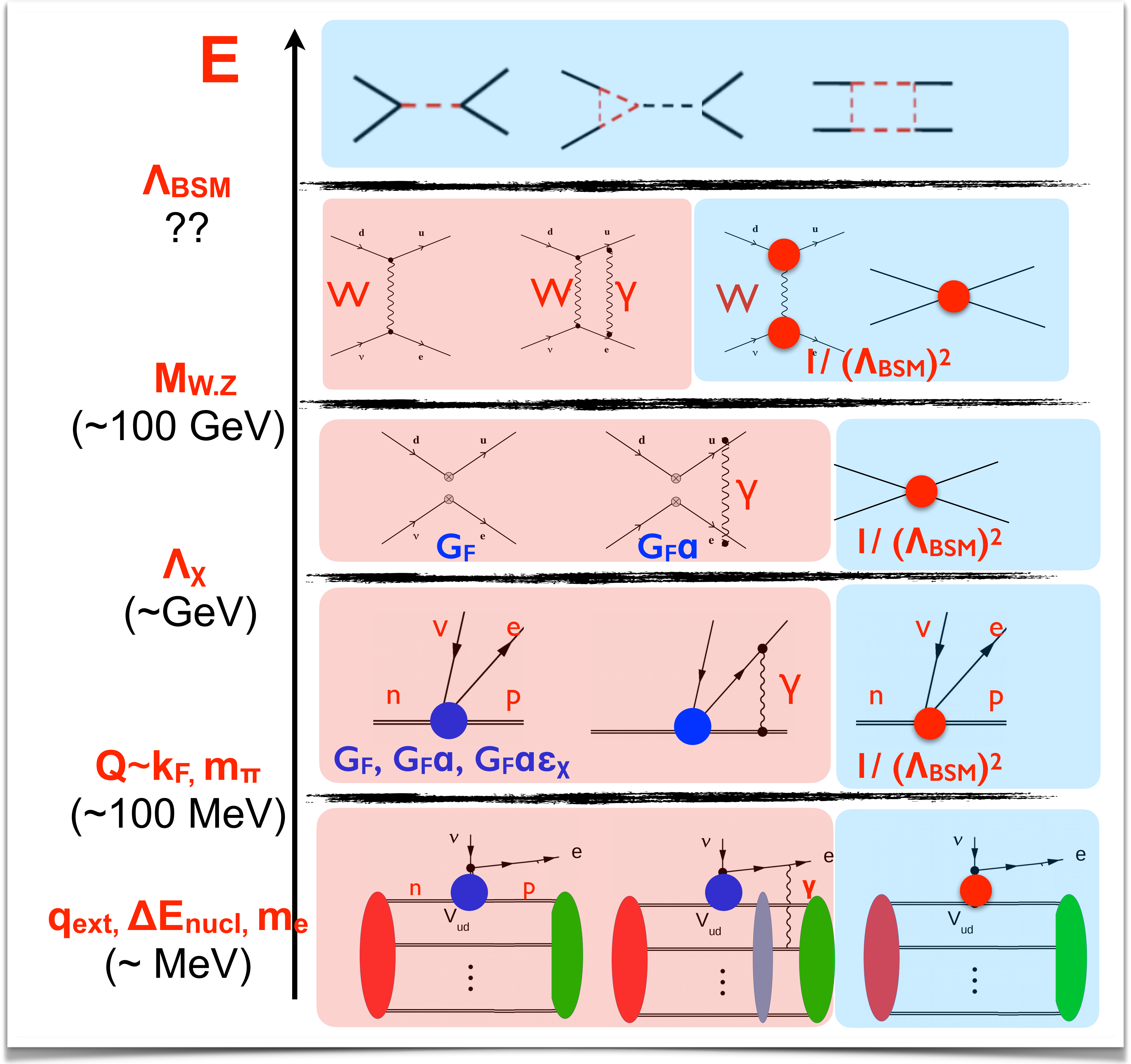
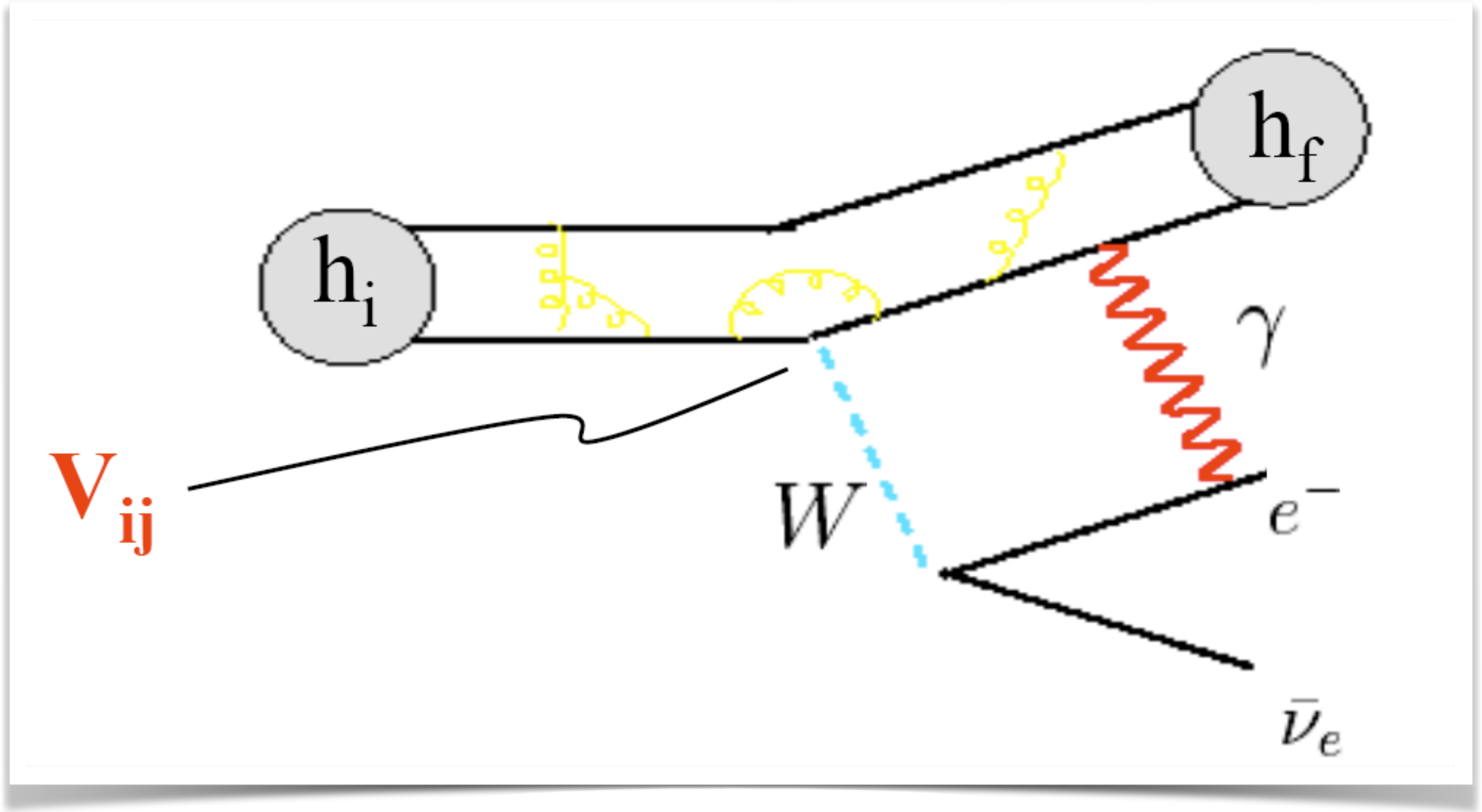


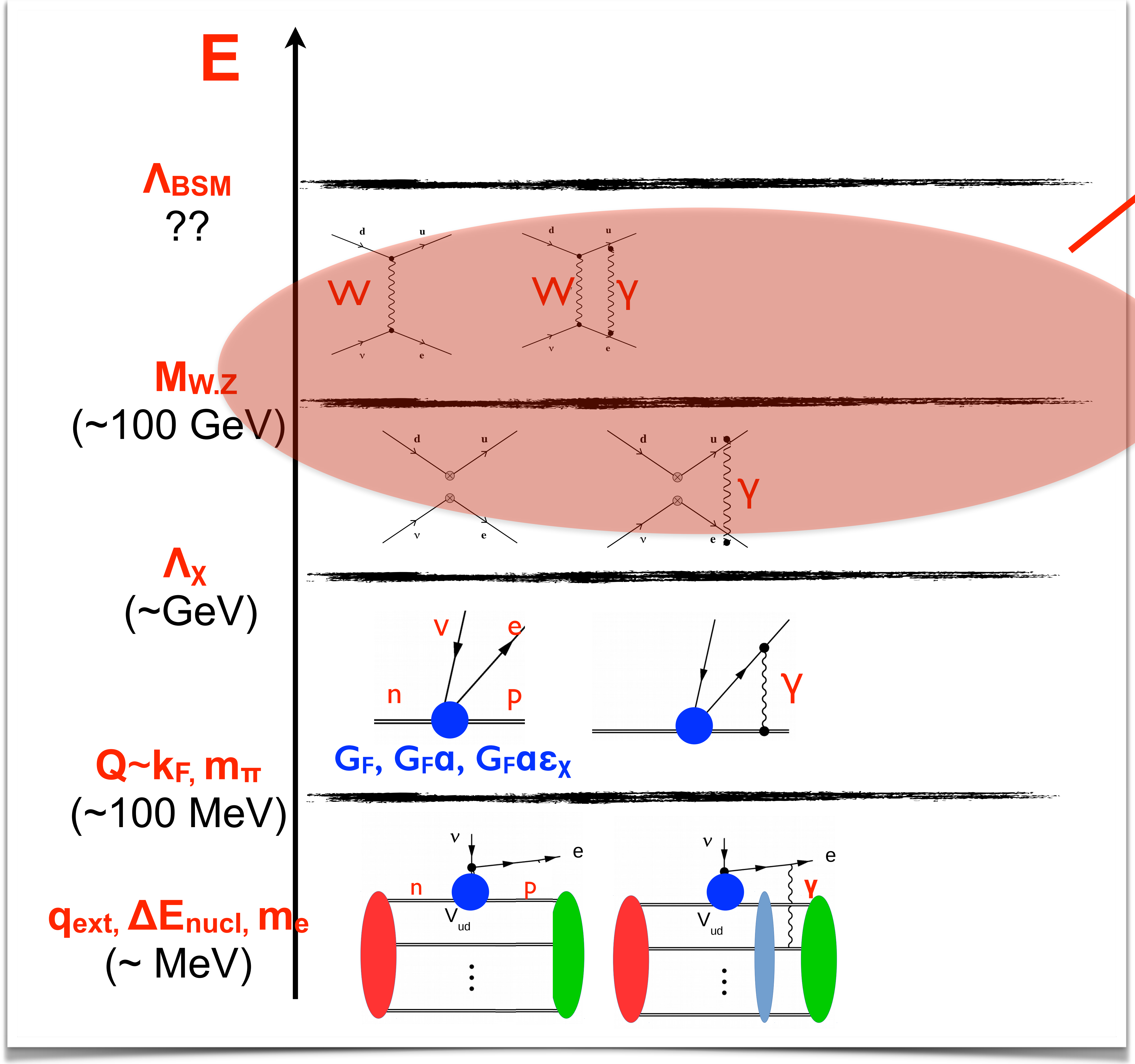
EFT for new physics contributions

EFT for Standard Model contributions to sub-% level
— radiative corrections

‘End-to-end’ EFT approach to radiative corrections in β decays



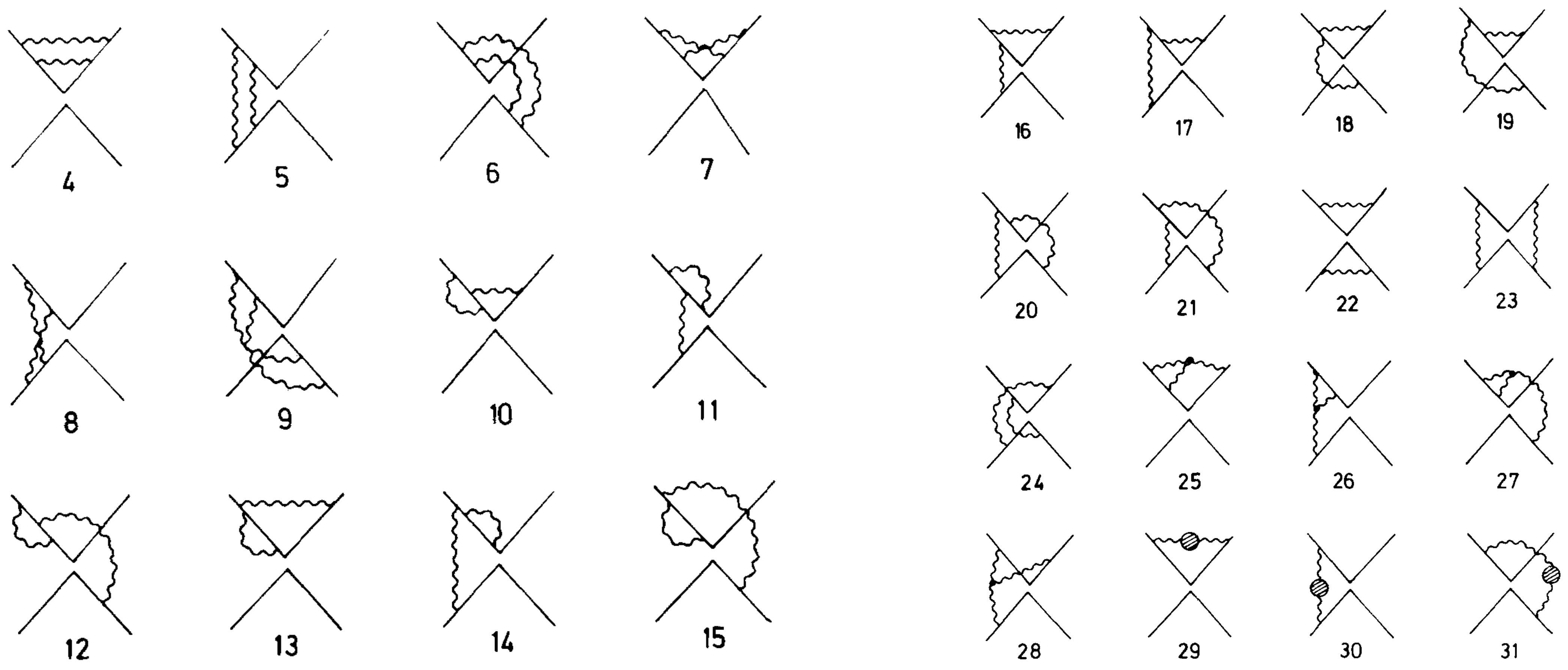
Radiative corrections



$$\mathcal{L}_{\rm Fermi} = -\frac{G_F}{\sqrt{2}} V_{ud}\; C_\beta(\mu)\; \bar{\ell}\gamma_\alpha(1-\gamma_5)\nu_\ell\, \bar{u}\gamma^\alpha(1-\gamma_5)d + \ldots$$

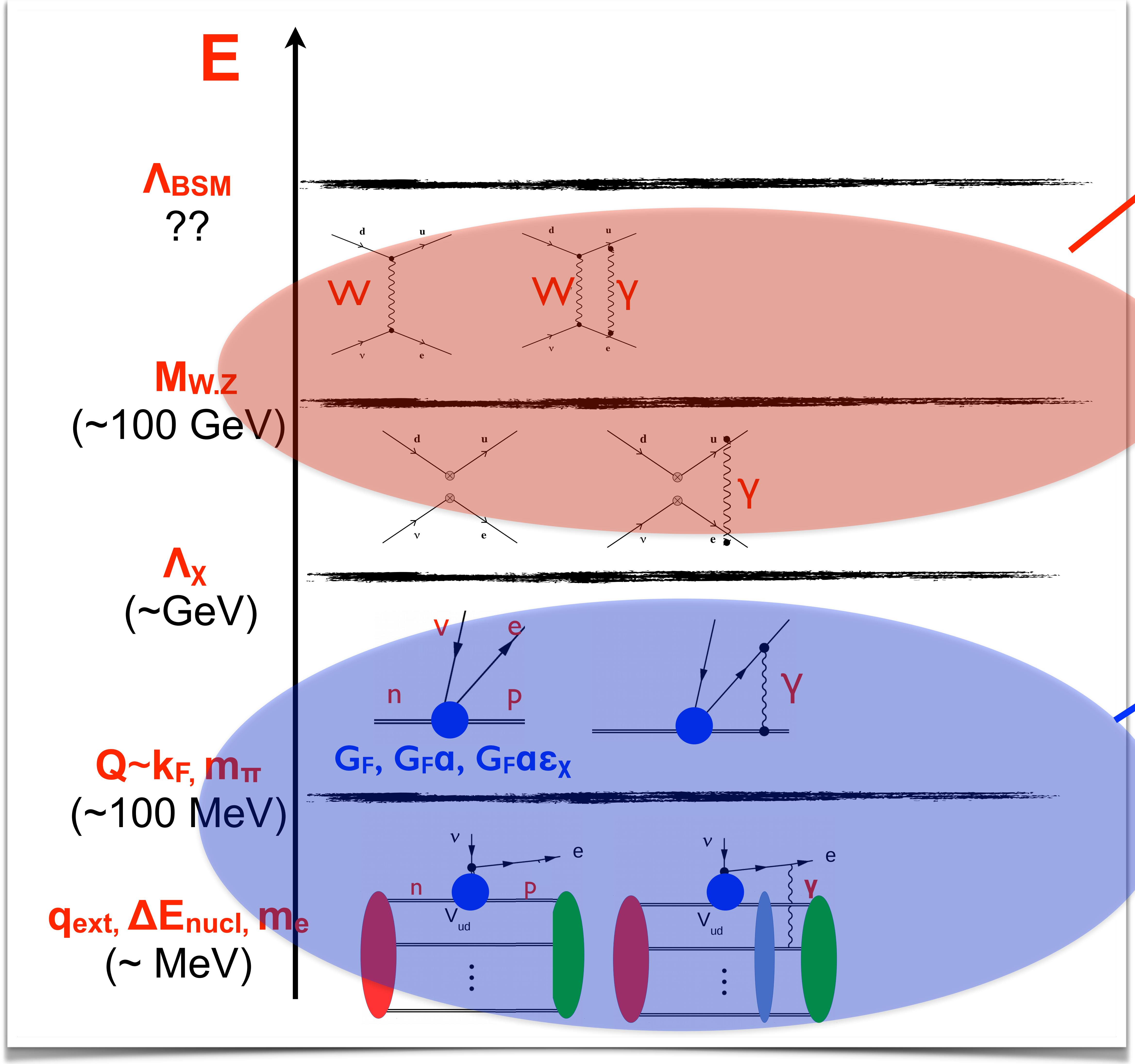
$C_\beta(\mu) \sim 1 + \# \,(\alpha/\pi)\, \ln(M_W/\mu) + \ldots$

Known to LL~ $(\alpha \ln(M_W/\mu))^n$ and NLL ~ $\alpha\, (\alpha_s \ln(M_W/\mu))^n$, $\alpha\, (\alpha \ln(M_W/\mu))^n$



Adapted from Buras-Weisz '90

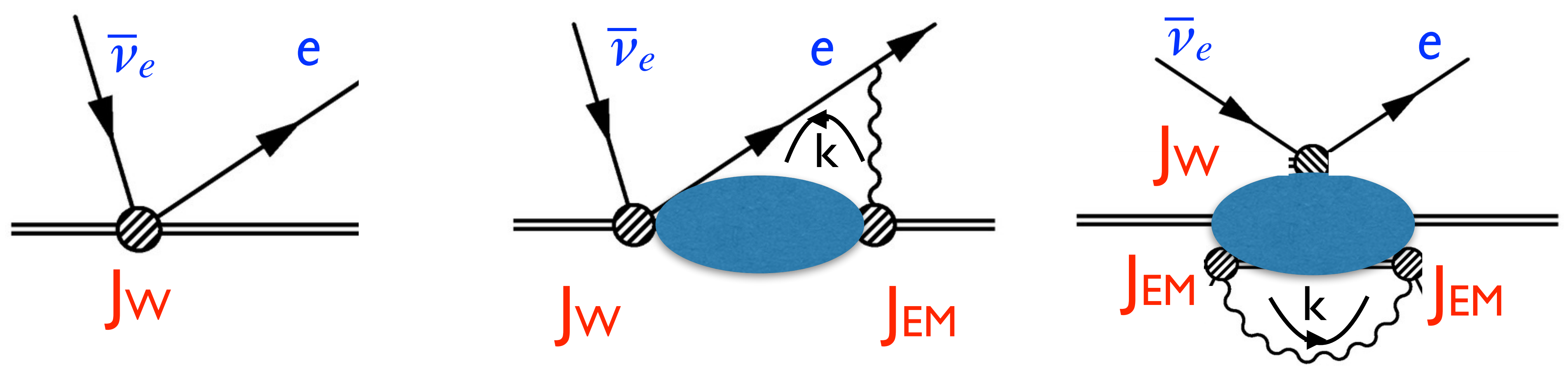
Radiative corrections



$$\mathcal{L}_{\rm Fermi} = -\frac{G_F}{\sqrt{2}} V_{ud}\ {\color{red} C_\beta(\mu)}\ \bar{\ell}\gamma_\alpha(1-\gamma_5)\nu_\ell\, \bar{u}\gamma^\alpha(1-\gamma_5)d + \ldots$$

Matrix elements to O(α)

$$\langle f| \qquad\qquad |i\rangle$$



Contributions from photons of all virtualities — EFT captures them all

Hard: $(k^0, |\mathbf{k}|) > \Lambda_\chi \sim m_N \sim$ GeV
Soft: $(k^0, |\mathbf{k}|) \sim Q \sim k_F \sim m_\pi$
Potential: $(k^0, |\mathbf{k}|) \sim (Q^2/m_N,\ Q)$
Ultrasoft $(k^0, |\mathbf{k}|) \sim Q^2/m_N \ll k_F$

EFT for single nucleon

VC, W. Dekens, E. Mereghetti, O. Tomalak, 2306. 03138, 2410.21404

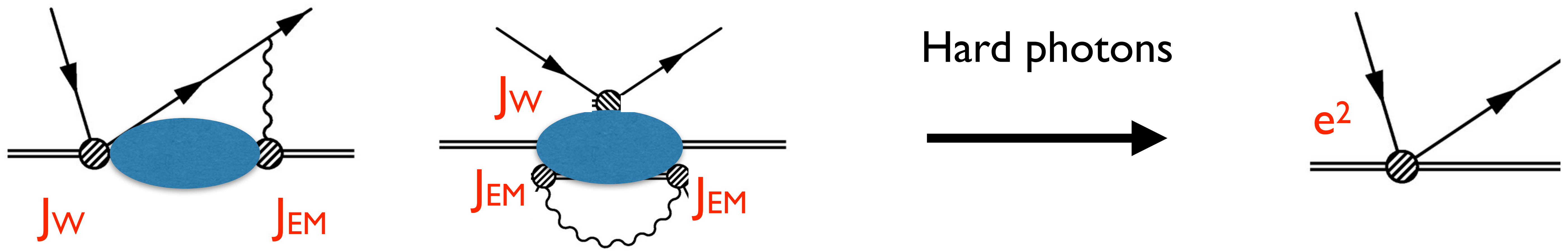
- Baryon ChPT with dynamical leptons and photons

$$\mathcal{L}_{\not\pi} = -\sqrt{2} G_F V_{ud}\ \bar{e}\gamma_\mu P_L \nu_e\ \bar{N}\left(g_V v_\mu - 2 g_A S_\mu\right)\tau^+ N \ + \ \ldots$$

g_V and g_A at $\mu_\chi \sim \Lambda_\chi$ encode effect of hard photons

$$g_V = C_\beta^r \left[1 + \frac{\alpha}{2\pi}\hat{C}_V\right]$$

Combination of chiral LECs of $O(e^2p)$



Operators that involve 2 charge matrices

Ecker-Gassser-Pich-deRafael 1989, Urech 1994, … Knecht et al 1999, …

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- Matching and running: SM → LEFT → ChPT at NLL approximation

$$g_V(\mu_\chi) = \widetilde{U}(\mu_\chi, \Lambda_\chi)\left[1 + \overline{\Box}^V_{\rm Had} + \frac{\alpha(\Lambda_\chi)}{\pi}\kappa\right] U(\Lambda_\chi, \mu_W)\, C_\beta(\mu_W)$$

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NLL RGE in LEFT

Wilson coeff. at $\mu_W \sim m_W$

LL~ $(\alpha \ln(M_W/\Lambda_\chi))^n$

$\mu_{LEFT} \sim \Lambda_\chi$

NLL ~ $\alpha\, (\alpha_s \ln(M_W/\Lambda_\chi))^n$, $\alpha\, (\alpha \ln(M_W/\Lambda_\chi))^n$

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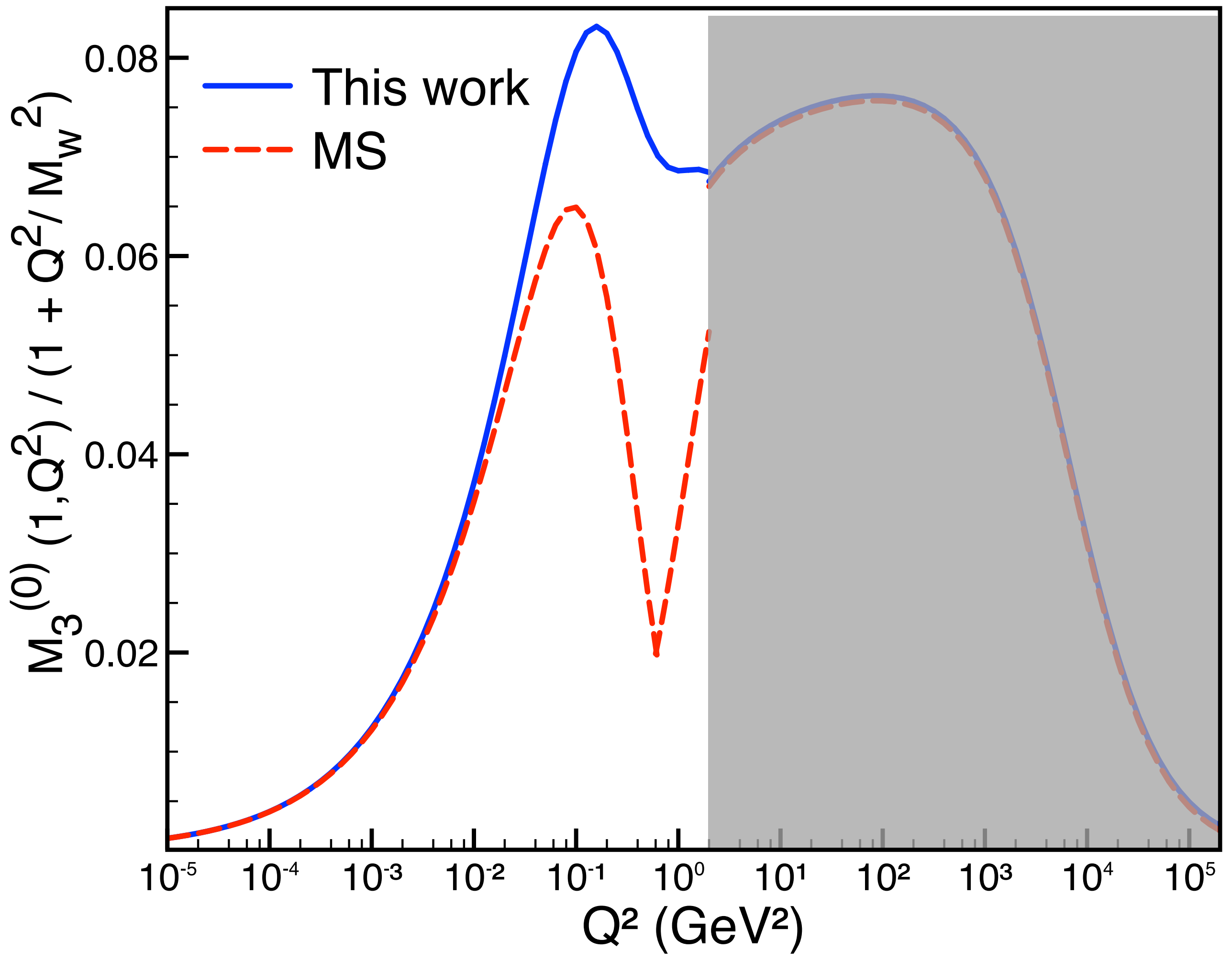
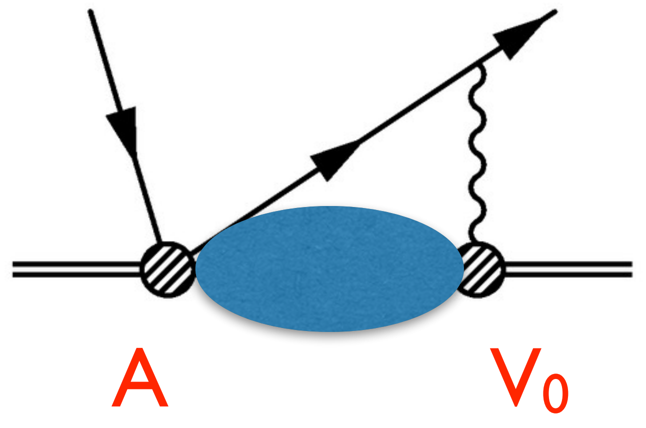


Non-perturbative contribution proportional to the γ-W 'box'
[Seng et al. 1807.10197, 2308.16755]



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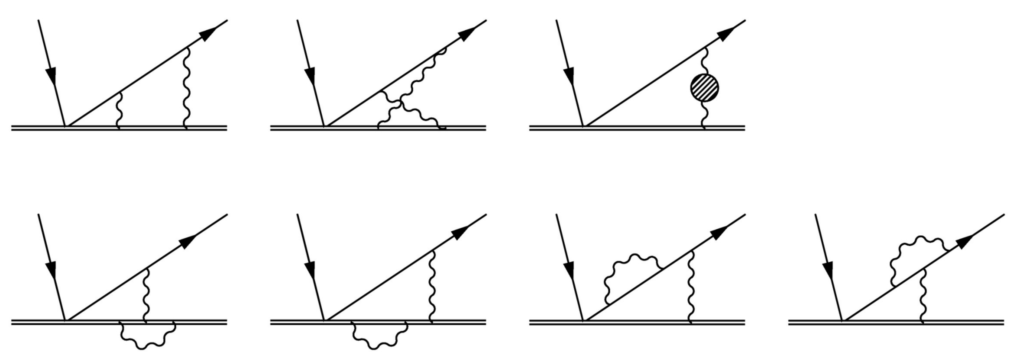
NLL RGE in ChPT
[soft and u-soft photons]

LL~ $(\alpha \ln(\Lambda_\chi/m_e))^n$ $\mu_\chi \sim m_e$

NLL ~ $\alpha\, (\alpha \ln(\Lambda_\chi/m_e))^n$



Adapt from Ji & Ramsey-Musolf '91 and Gimenez '92

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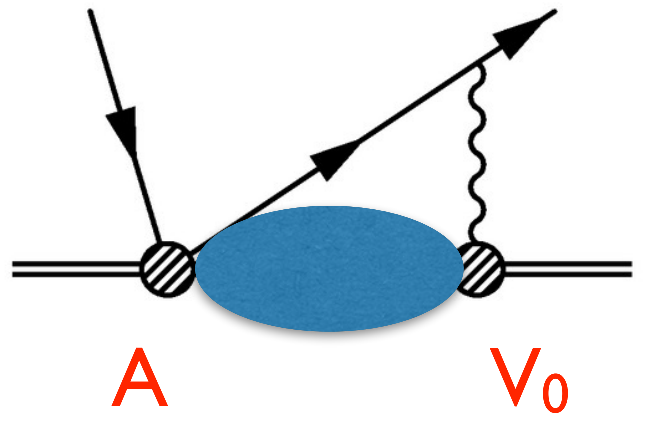

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Dependence on LEFT renormalization scale and scheme(s)** cancels
** Subtraction scheme and treatment of γ_5 & evanescent operators in dim-reg

- Evolve $g_V(\mu_\chi)$ down to $\mu_\chi \sim m_e$ and compute decay rate including virtual (ultra-soft) and real photons

Neutron decay rate

VC, W. Dekens, E. Mereghetti, O. Tomalak, 2306. 03138, 2410.21404

$$\frac{\mathrm{d}\Gamma_n}{\mathrm{d}E_e} = \frac{G_F^2\,|V_{ud}|^2}{(2\pi)^5}\,(1+3\lambda^2)\;p_e E_e (E_0 - E_e)^2\;[g_V(\mu_\chi)]^2\;F_{NR}(\beta)\Big(1+\delta_{\mathrm{RC}}(E_e,\mu_\chi)\Big)\Big(1+\delta_{\mathrm{recoil}}(E_e)\Big)$$

$\lambda = g_A/g_V$ taken from experiment.
It includes the electromagnetic
shift to both g_V and g_A.
Ratio is scale independent.

$(g_V)^2 \sim (1 + O(\alpha))$

Hard and soft
contributions from
matching and running
down to $\mu_\chi \sim m_e$

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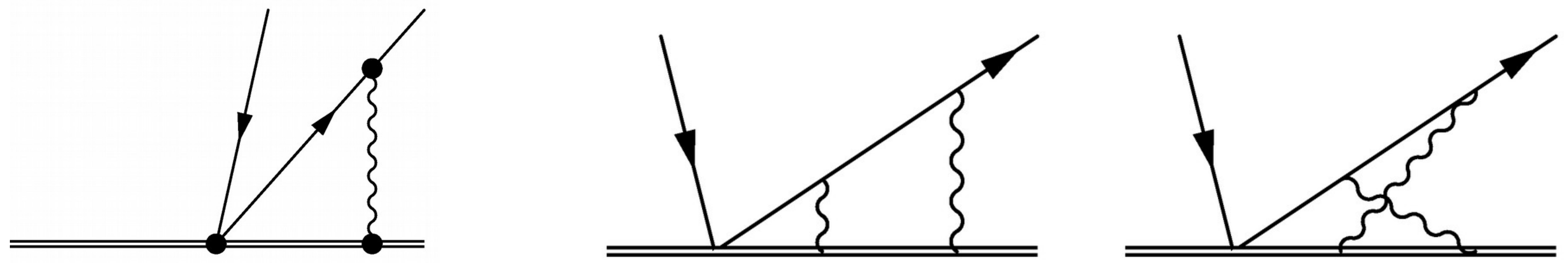
$O(\alpha)$ + $O(\epsilon_{\rm recoil})$ matrix element in the low-energy EFT



Ultra-soft contributions

$(g_V)^2 \sim (1 + O(\alpha))$

Hard and soft contributions from matching and running down to $\mu_\chi \sim m_e$

No large logs but contains enhanced contributions ~ $(\pi\alpha/\beta)$, which we re-sum via the non-relativistic Fermi function *ansatz* (not based on a full 2-loop calculation)

$$F_{NR}(\beta) = \frac{2\pi\alpha}{\beta}\frac{1}{1-e^{-\frac{2\pi\alpha}{\beta}}} \approx 1 + \frac{\pi\alpha}{\beta} + \frac{\pi^2\alpha^2}{3\beta^2} + \dots \xrightarrow[m\to 0]{} 1 + \pi\alpha + \frac{\pi^2\alpha^2}{3} + \dots$$

Enhanced terms are related to IR divergences in the u-soft loops, RG-based re-summation leads to (for $m_e \to 0$)

$$\exp\left[\frac{\pi\alpha}{\beta}\right] \xrightarrow[m\to 0]{} 1 + \pi\alpha + \frac{\pi^2\alpha^2}{2} + \dots$$

Griend-Cao-Hill-Plestid 2501.17916

Neutron decay rate

VC, W. Dekens, E. Mereghetti, O. Tomalak, 2306. 03138, 2410.21404

$$\frac{d\Gamma_n}{dE_e} = \frac{G_F^2\,|V_{ud}|^2}{(2\pi)^5}\,(1+3\lambda^2)\;p_e E_e (E_0 - E_e)^2\;[g_V(\mu_\chi)]^2\;F_{NR}(\beta)\Big(1+\delta_{\rm RC}(E_e,\mu_\chi)\Big)\Big(1+\delta_{\rm recoil}(E_e)\Big)$$

Somewhat arbitrary separation, to align with literature

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

*** Griend-Cao-Hill-Plestid 2501.17916

$$\Delta_f = 3.573(5)_{\alpha\times{\rm recoil}}\,\% \;\rightarrow\; \Delta_f = 3.584(5)_{\alpha\times{\rm recoil}}\,\%$$

(+0.011% shift in the rate)

$$\Delta_R = 4.044(24)_{\rm Had}(8)_{\alpha\alpha_s^2}(7)_{\alpha\epsilon_\chi^2}(5)_{\mu_\chi}[27]_{\rm total}\quad\%$$

Neutron decay rate

VC, W. Dekens, E. Mereghetti, O. Tomalak, 2306. 03138, 2410.21404

$$\frac{d\Gamma_n}{dE_e} = \frac{G_F^2\,|V_{ud}|^2}{(2\pi)^5}\,(1+3\lambda^2)\;p_e E_e (E_0 - E_e)^2\,[g_V(\mu_\chi)]^2\,F_{NR}(\beta)\Big(1+\delta_{\rm RC}(E_e,\mu_\chi)\Big)\Big(1+\delta_{\rm recoil}(E_e)\Big)$$

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

CORRECTION	COMPARISON with LITERATURE*	MAIN SOURCE of DISCREPANCY
$\Delta_f = 3.573(5)\%$	-0.035% $\xrightarrow{***}$ -0.024%	'Fermi function': rel. → non. rel. $\xrightarrow{***}$ factorization
$\Delta_{\rm R} = 4.044(27)\%$	+0.061%	NLL: α^2 Log(m_N/m_e)
$\Delta_{\rm TOT} = 7.761(27)\%.$	+0.026% $\xrightarrow{***}$ +0.037%	Both related to the treatment of $O(\alpha^2)$ 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

Impact on V_{ud}

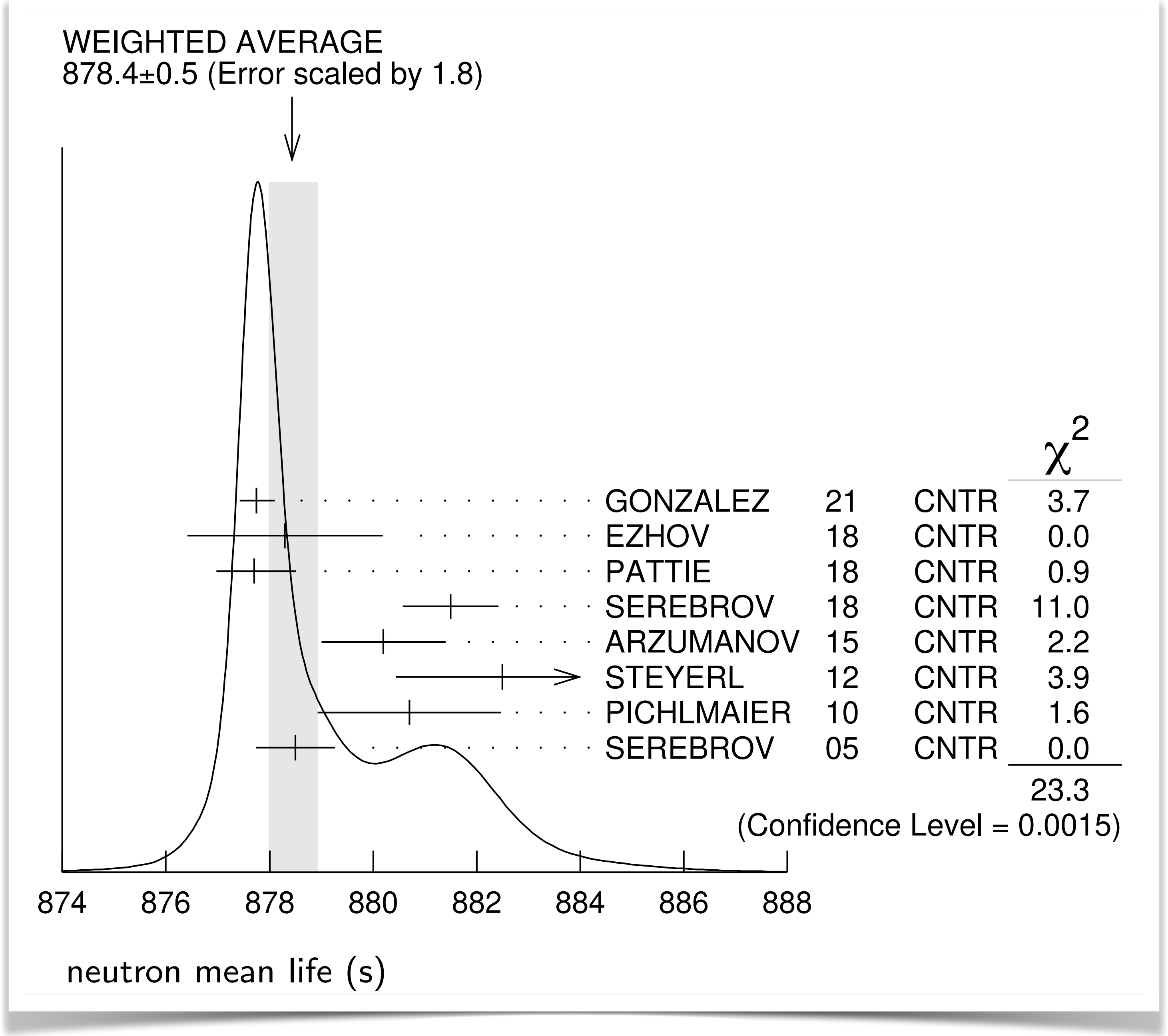
$\lambda = g_A/g_V$

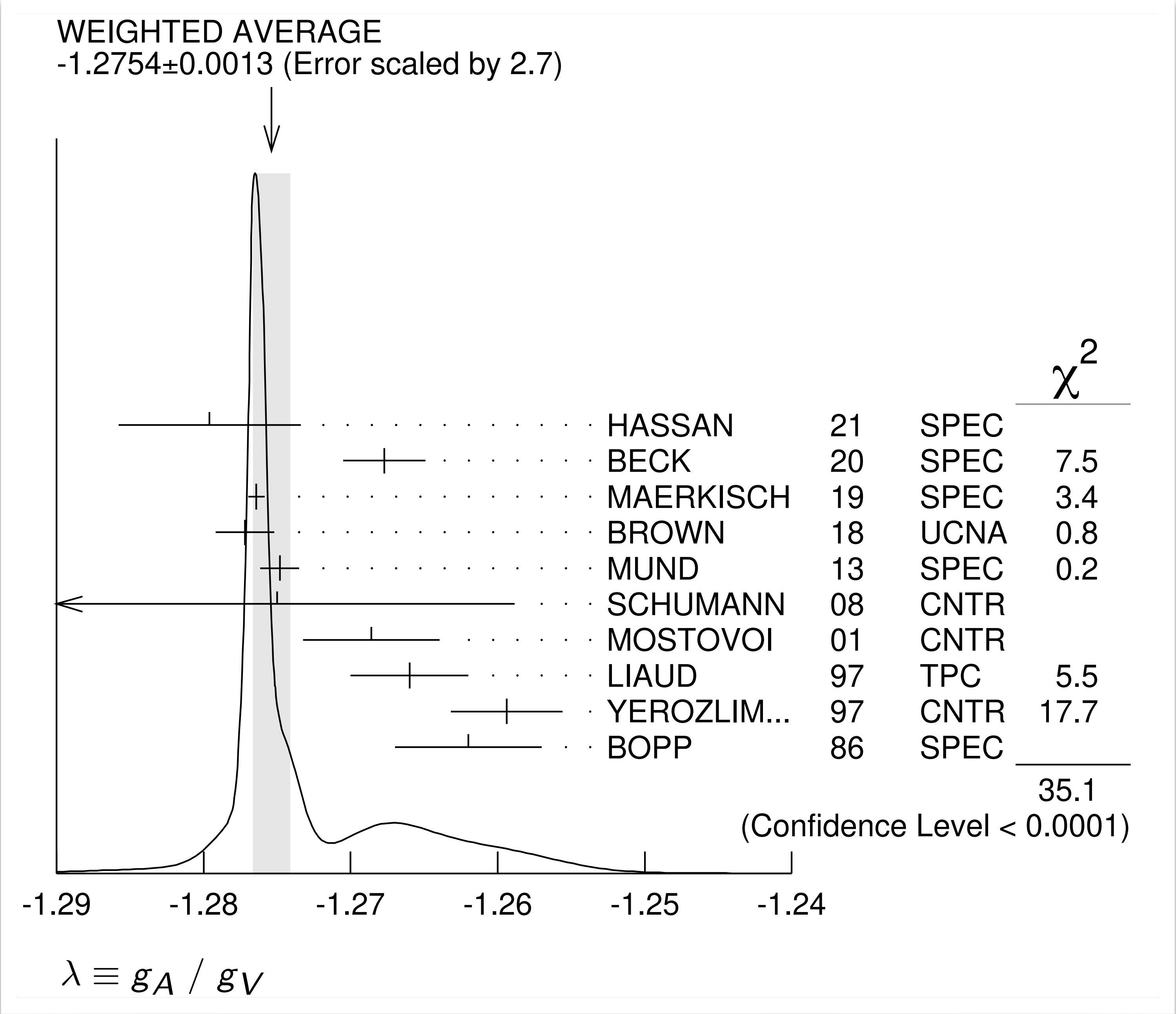
$$\Gamma_n = \frac{G_F^2 |V_{ud}|^2 m_e^5}{2\pi^3} (1 + 3\lambda^2) \cdot f_0 \cdot (1 + \Delta_f) \cdot (1 + \Delta_R),$$

$$\Delta_R = 4.044(27)\%$$
$$\Delta_f = 3.584(5)\ \%$$

VC, W. Dekens, E. Mereghetti, O. Tomalak, 2306. 03138 + Griend-Cao-Hill-Plestid 2501.17916

- Experimental input: PDG averages include large scale factor, particularly for g_A /g_V





Impact on V_{ud}

$\lambda = g_A/g_V$

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

$$\Delta_R = 4.044(27)\%$$
$$\Delta_f = 3.584(5)\,\%$$

VC, W. Dekens, E. Mereghetti, O. Tomalak, 2306. 03138 + Griend-Cao-Hill-Plestid 2501.17916

- Experimental input: PDG averages include large scale factor, particularly for g_A/g_V

Single most precise measurements of lifetime and λ imply very competitive V_{ud}!

Maerkish et al, 1812.04666 Gonzalez et al, 2106.10375

$$V_{ud}^{\mathrm{n,PDG}} = 0.97424(2)_{\Delta_f}(13)_{\Delta_R}(82)_{\lambda}(28)_{\tau_n}[88]_{\mathrm{total}}$$

$$V_{ud}^{\mathrm{n,best}} = 0.97396(2)_{\Delta_f}(13)_{\Delta_R}(35)_{\lambda}(20)_{\tau_n}[42]_{\mathrm{total}}$$

Expect improvements in lifetime and g_A /g. within reach in next 5 years

EFT treatment shifts the results by more than the assigned theoretical uncertainty.

Overall shift of -0.0175% in V_{ud} (neutron) compared to pre-EFT literature — does not help unitarity!

EFT for multi-nucleon systems (I)

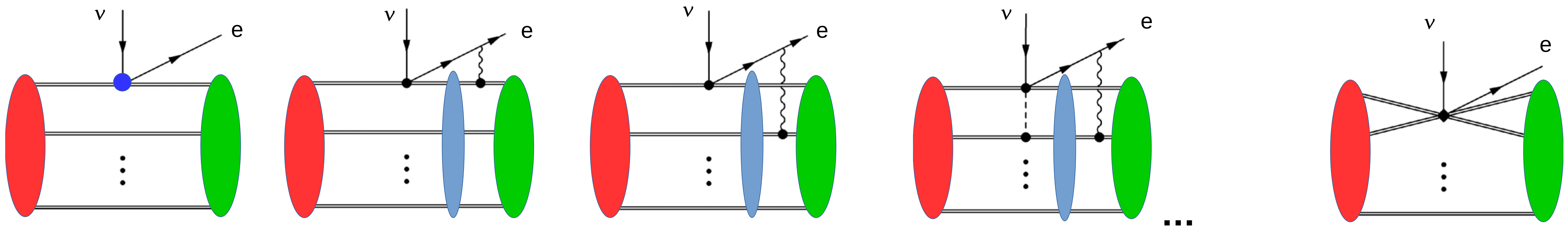
VC, W. Dekens,, J.de Vries, S. Gandolfi, M. Hoferichter, E, Mereghetti, 2405.18469, 2405.18464

- Chiral EFT (NN, NNN, …) with dynamical leptons and photons

- Hard photons leave behind local multi-nucleon electroweak operators (as in the one-nucleon case)

$$\mathcal{L}_W^{2b} = -\sqrt{2}e^2 G_F V_{ud}\, \bar{e}_L \gamma_0 \nu_L \times$$
$$N^\dagger \tau^+ N \left(e^2 g_{V1}^{NN}\, N^\dagger N + e^2 g_{V2}^{NN}\, N^\dagger \tau^3 N \right)$$

- Soft, potential, and ultra-soft photons contribute to multi-nucleon amplitudes



Soft:	$(q^0, \|\mathbf{q}\|) \sim Q \sim k_F \sim m_\pi$
Potential:	$(q^0, \|\mathbf{q}\|) \sim (Q^2/m_N,\ Q)$
Ultrasoft	$(q^0, \|\mathbf{q}\|) \sim Q^2/m_N \ll k_F$

EFT for multi-nucleon systems (2)

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

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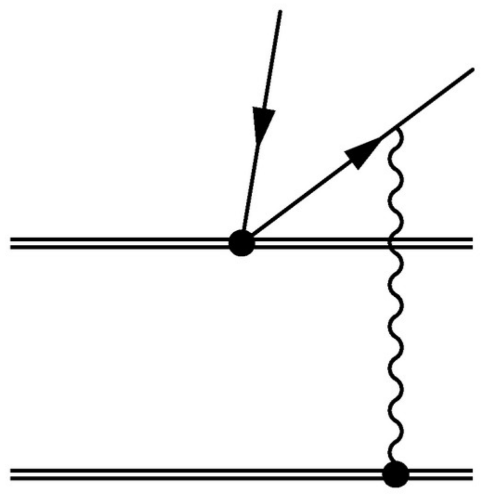
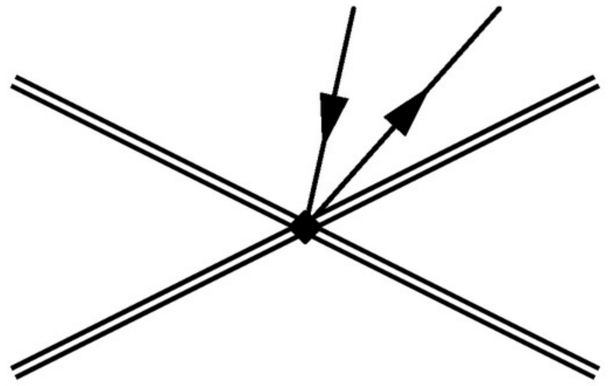
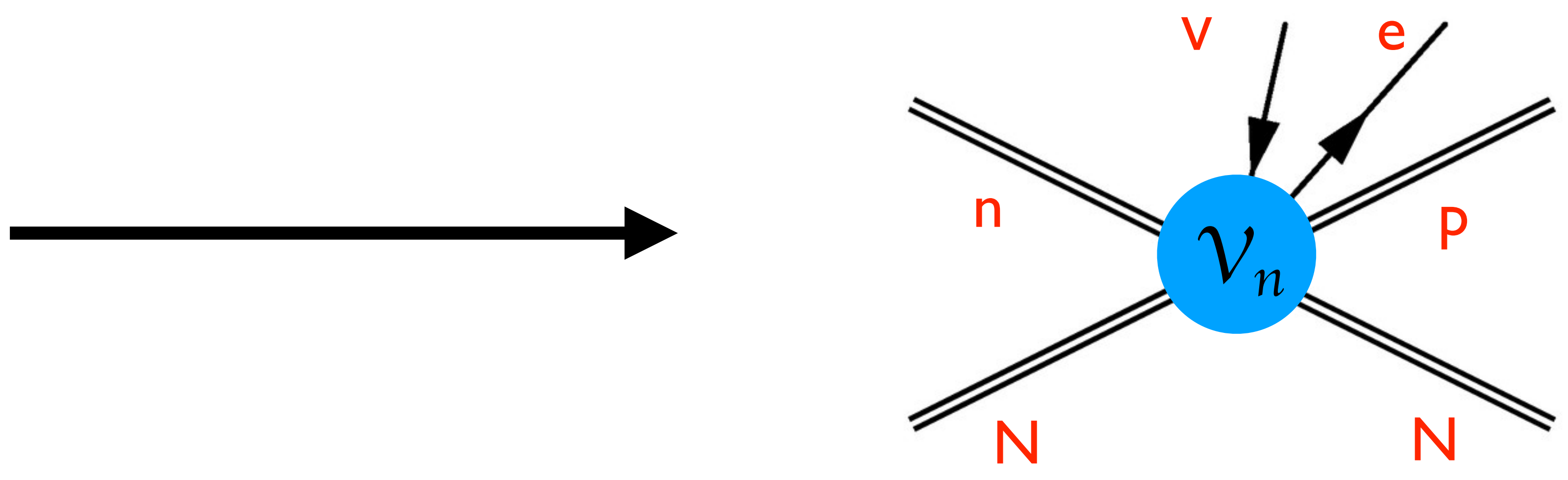
- 'Integrate out' soft & potential photons (and π's) → obtain EW n-body transition operators ('potentials')







$$\mathcal{V}_E \sim \frac{e^2\, E_{e,\nu}}{\mathbf{q}^4} \qquad \mathcal{V}_{\text{mag}} \sim \frac{e^2}{m_N \mathbf{q}^2}$$

$G_F \alpha \epsilon_\pi$ $\quad$ $G_F \alpha \epsilon_\chi$

$$\mathcal{V}_{\text{contact}} \sim e^2\, g^{NN}_{V_1,V_2} \sim e^2 \frac{1}{\Lambda_\chi F_\pi^2}$$

$G_F \alpha \epsilon_\chi$

$$H_{EW} \supset \sqrt{2} G_F V_{ud}\ \bar{e}_L \gamma_0 \nu_L \times \sum_n c_n\, \mathcal{V}_n$$

EFT for multi-nucleon systems (2)

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

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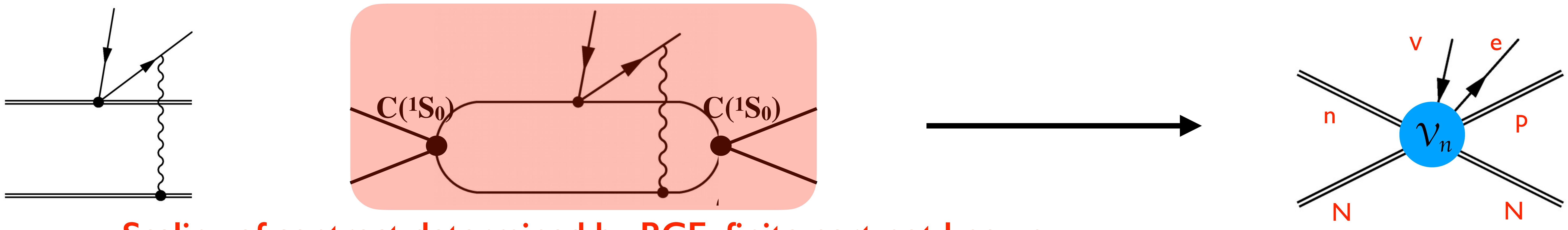

Scaling of contract determined by RGE, finite part not known

$$\mathcal{V}_E \sim \frac{e^2\, E_{e,\nu}}{\mathbf{q}^4} \qquad \mathcal{V}_{\text{mag}} \sim \frac{e^2}{m_N \mathbf{q}^2} \qquad \mathcal{V}_{\text{contact}} \sim e^2\, g^{NN}_{V_1,V_2} \sim e^2 \frac{1}{\Lambda_\chi F_\pi^2}$$

$G_F \alpha \epsilon_\pi$ $\quad$ $G_F \alpha \epsilon_\chi$ $\quad$ $G_F \alpha \epsilon_\chi$

$$H_{EW} \supset \sqrt{2} G_F V_{ud}\ \bar{e}_L \gamma_0 \nu_L \times \sum_n c_n\, \mathcal{V}_n$$

EFT for multi-nucleon systems (3)

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

- Chiral EFT (NN, NNN, …) with dynamical leptons and photons

- Hard photons leave behind local multi-nucleon electroweak operators (as in the one-nucleon case)

$$\mathcal{L}_W^{2\mathrm{b}} = -\sqrt{2}e^2 G_F V_{ud}\ \bar{e}_L \gamma_0 \nu_L \times$$
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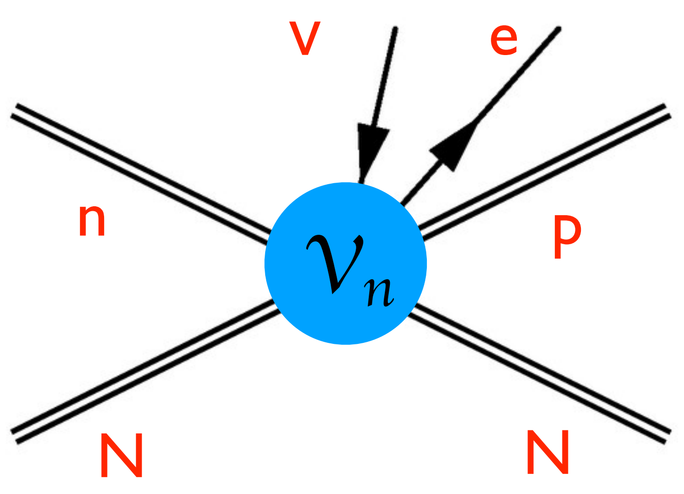
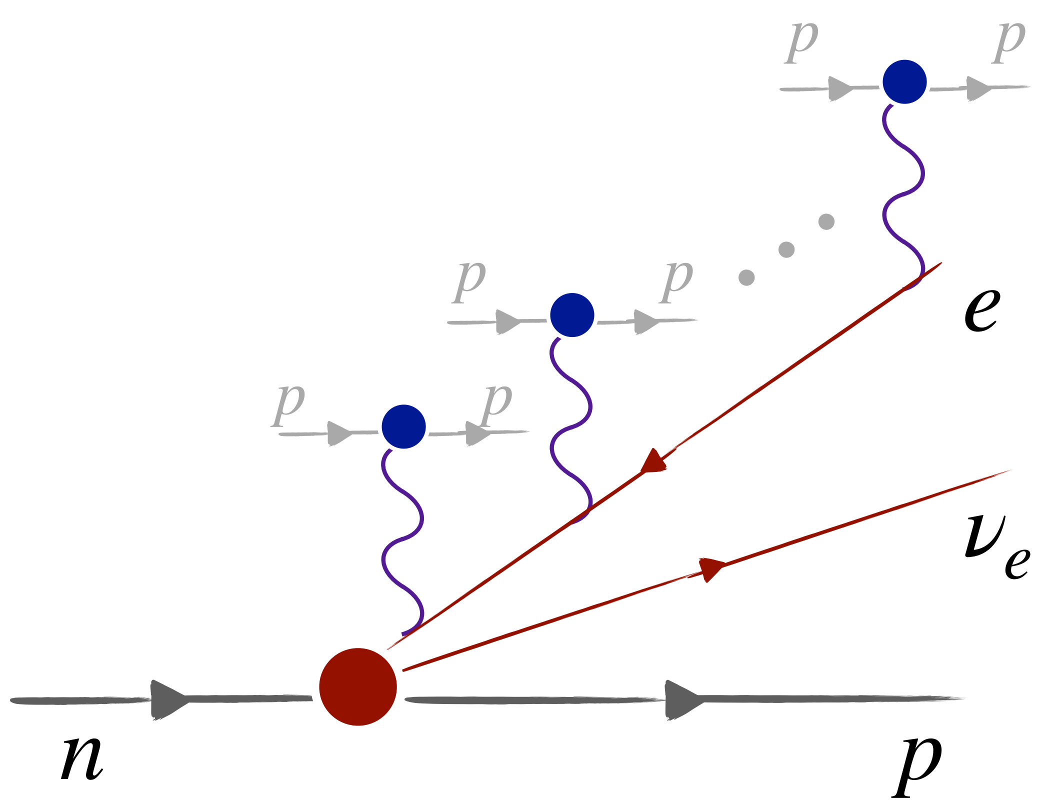
- 'Integrate out' soft & potential photons (and π's) → obtain EW n-body transition operators ('potentials')



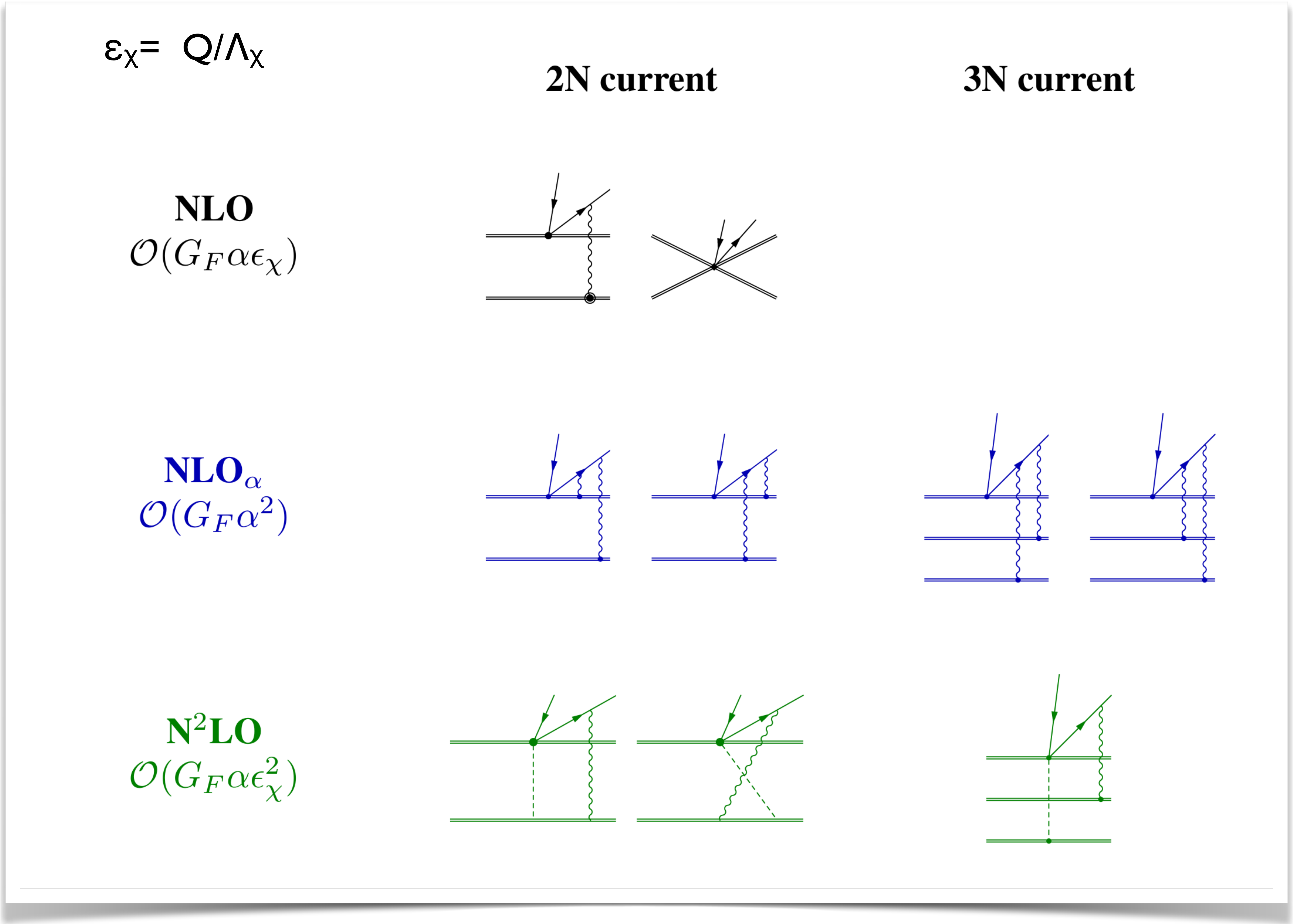
- Ultrasoft photons: Z-dependent running of effective couplings between m_π and m_e & matrix elements at $\mu \sim m_e$

$$H_{EW} \supset \sqrt{2} G_F V_{ud}\ \bar{e}_L \gamma_0 \nu_L \times \sum_n c_n\, \mathcal{V}_n$$



Courtesy of W. Dekens

Summary on ‘EW potentials’



Courtesy of E. Mereghetti

- Identified the leading 2- and 3-body ‘potentials’ that contribute to $\delta_{NS} \sim \Sigma_n\ c_n \langle f \mid \mathcal{V}_n \mid i \rangle$
- NN short-range interactions at $O(G_F \alpha \varepsilon_\chi)$ involve two (unknown) LECs
- Work in progress on N^2LO corrections

Nuclear decay rate

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

- EFT-based decay rate formula reorganizes 'traditional' corrections using EFT principles (e.g. large logs appear only in effective couplings and are re-summed with RGEs)

Ultra-soft

Point-like nucleus, O(α/π)
[Sirlin function]

Hard, soft, potential

Isospin-breaking in wave functions $\langle f|\tau^+|i\rangle$

$$\frac{1}{t}=\frac{G_F^2|V_{ud}|^2 m_e^5}{\pi^3\log 2}\left[C_{\rm eff}^{(g_V)}(\mu)\right]^2\times\left[1+\bar{\delta}'_R(\mu)\right]\left(1+\bar{\delta}_{\rm NS}\right)\left(1-\bar{\delta}_C\right)\bar{f}(\mu),$$

All large logs from RGEs ($\mu > m_e$)

Hard and (ultra) soft

Structure-dependent radiative correction $\langle f|\mathcal{V}_n|i\rangle$

Hard, soft, potential

Ultra-soft

Point-like nucleus, $O((\pi\alpha)^m Z^n)$
[Fermi function**]

Additional corrections: nuclear EW form factor, nuclear recoil, atomic effects.

** See also. K. Borah, R. Hill, R. Plestid, 2309.07343, 2309.15929, 2402.13307

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All large logs from RGEs (μ>m_e)

Hard and (ultra) soft

Structure-dependent radiative correction <f $|\mathcal{V}_n|$i>

Hard, soft, potential

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Additional corrections: nuclear EW form factor, nuclear recoil, atomic effects.

** See also. K. Borah, R. Hill, R. Plestid, 2309.07343, 2309.15929, 2402.13307

- Need for improvement
  - *Two currently unknown LECs contributing to $\delta_{\rm NS}$ to O($G_F\alpha\varepsilon_\chi$)*
  - Two- and three- body potentials to O($G_F\alpha(\varepsilon_\chi)^2$): may be relevant at 0.01%, needed to check EFT convergence
  - Non-logarithmic terms of O($\alpha^2 Z$) in the Fermi function (finite parts of two-loop diagrams)

Impact on V_{ud}: exploratory studies in QMC

- $^{14}O \rightarrow {}^{14}N$: δ_{NS} contributions in rough agreement with corresponding terms in Hardy-Towner 2020

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

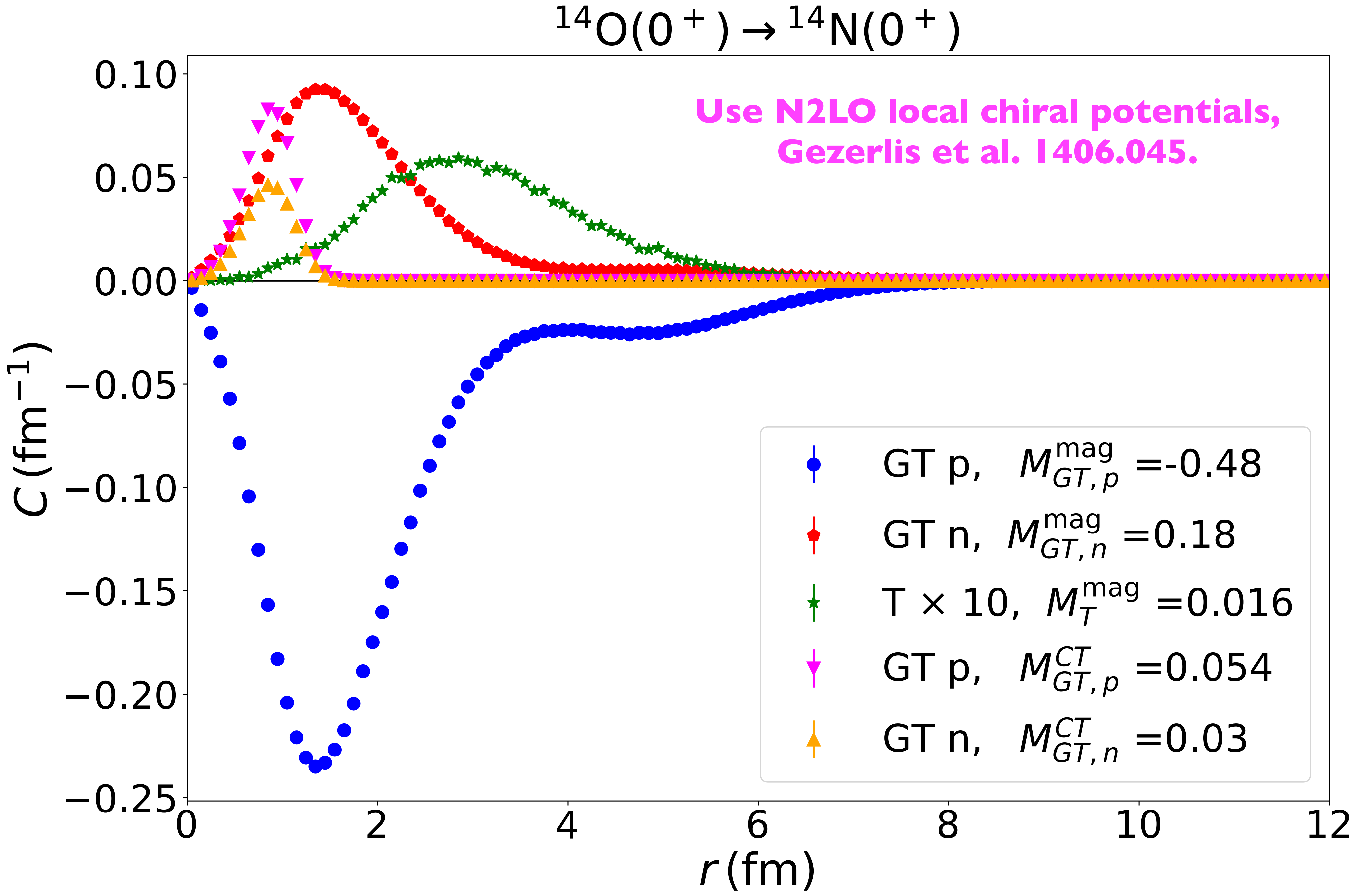
$$V_{ud}\big|_{^{14}O} = 0.97411(10)_{\rm exp}(12)_{g_V}(22)_{\mu}(12)_{\delta_C}(43)_{g_V^{NN}}[55]_{\rm tot}$$

$$V_{ud}^{\rm HT}\big|_{^{14}O} = 0.97405[37]_{\rm tot}$$

(31) from δ_{NS}

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

Largest uncertainty from unknown LECs. Assumes $g_{V1,V2}^{NN} = 1/(4 m_N F_\pi^2)$



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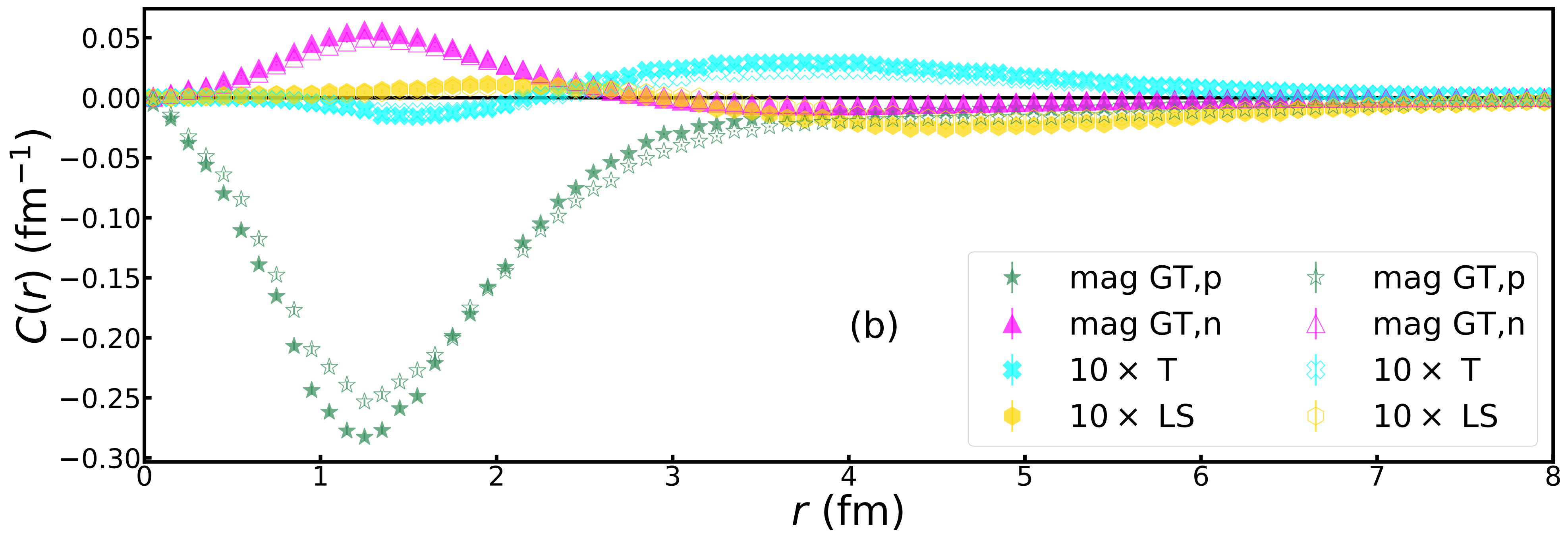
(31) from δ_{NS}

- $^{10}C \rightarrow {}^{10}B$:

$$V_{ud}\big|_{^{10}C} = 0.97355(66)_{\rm exp}(12)_{g_V}(17)_{\mu}(9)_{\delta_C}(38)_{g_V^{\rm NN}}$$

0.02% spread from use of different chiral Hamiltonians

King-Carlson-Flores-Gandolfi-Mereghetti-Pastore-Piarulli-Wiringa, arXiv:2509.07310



Empty and filled symbols correspond to two different chiral interactions

Impact on V_{ud}: exploratory studies in QMC

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

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

- $^{10}C \rightarrow {}^{10}B$: Reasonable agreement with HT & dispersive + NCSM

$$V_{ud}\big|_{^{10}C} = 0.97355(66)_{\rm exp}(12)_{g_V}(17)_{\mu}(9)_{\delta_C}(38)_{g_V^{\rm NN}}$$

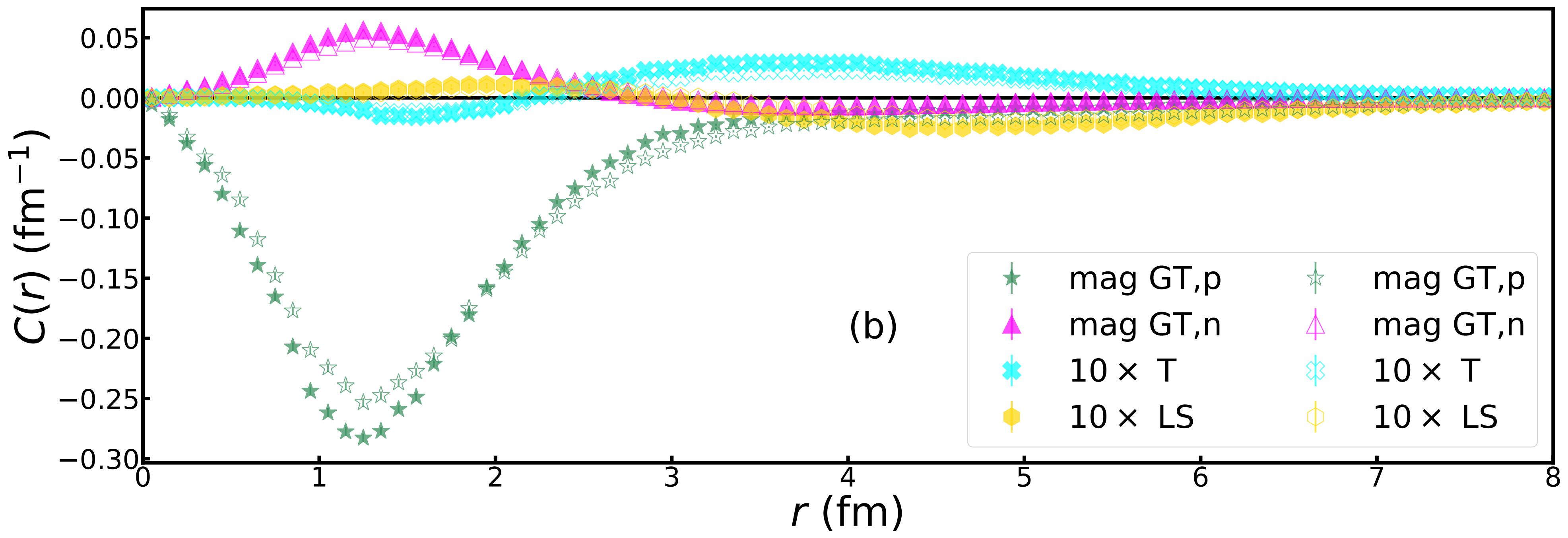
$$V_{ud}\big|^{\rm HT}_{^{10}C} = 0.97318(66)_{\rm exp}(9)_{\Delta_R^V}(24)_{\delta_{\rm NS}}(9)_{\delta_C}$$

$$V_{ud}\big|^{\rm NCSM}_{^{10}C} = 0.97317(66)_{\rm exp}(9)_{\Delta_R^V}(16)_{\delta_{\rm NS}}(9)_{\delta_C}$$

0.02% spread from use of different chiral Hamiltonians

Gennari, Drissi, Gorchtein, Navratil,, Seng, Phys. Rev. Lett. 134, 012501 (2025)

King-Carlson-Flores-Gandolfi-Mereghetti-Pastore-Piarulli-Wiringa, arXiv:2509.07310

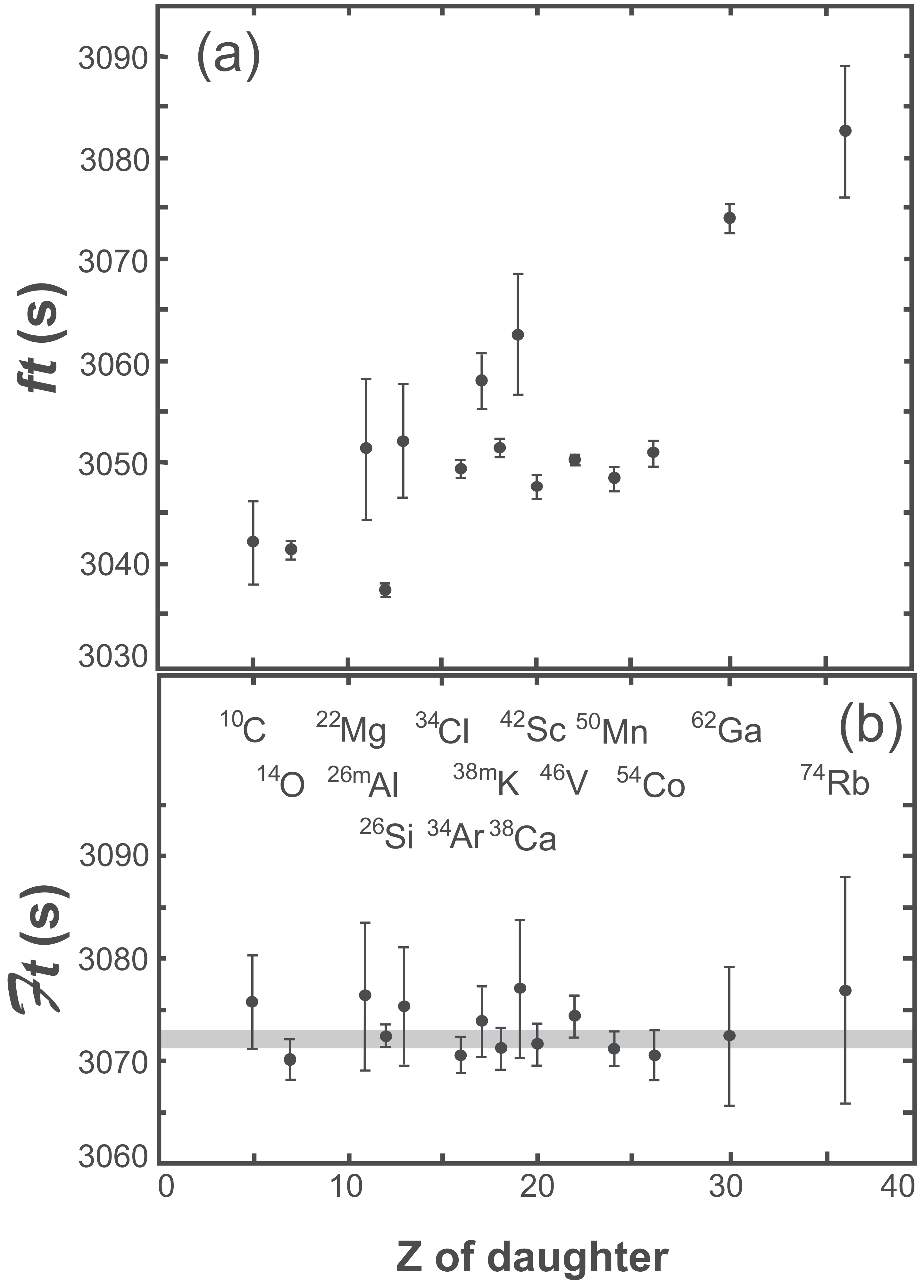


Empty and filled symbols correspond to two different chiral interactions

Path forward in the EFT approach

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

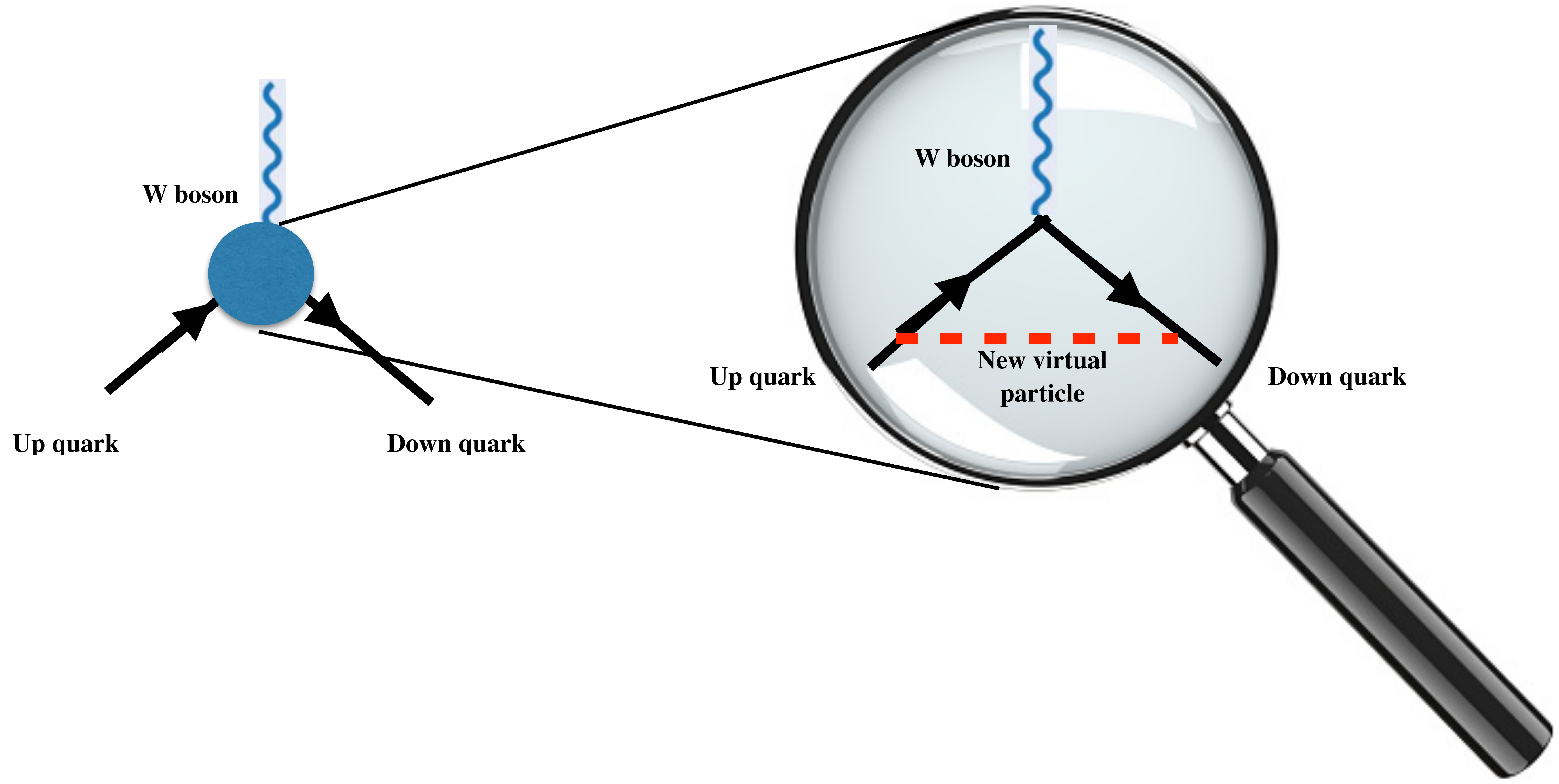
Hardy-Towner, PRC 2020



- EFT has identified new method to compute structure-dependent corrections and (temporarily) increased the uncertainty. But in the long run it will allow for robust uncertainty quantification

- LECs can be obtained by
  - Fitting data (along with V_{ud} and possibly BSM effective couplings) once NME calculations for several isotopes become available
  - Theory: dispersive analysis, Lattice QCD

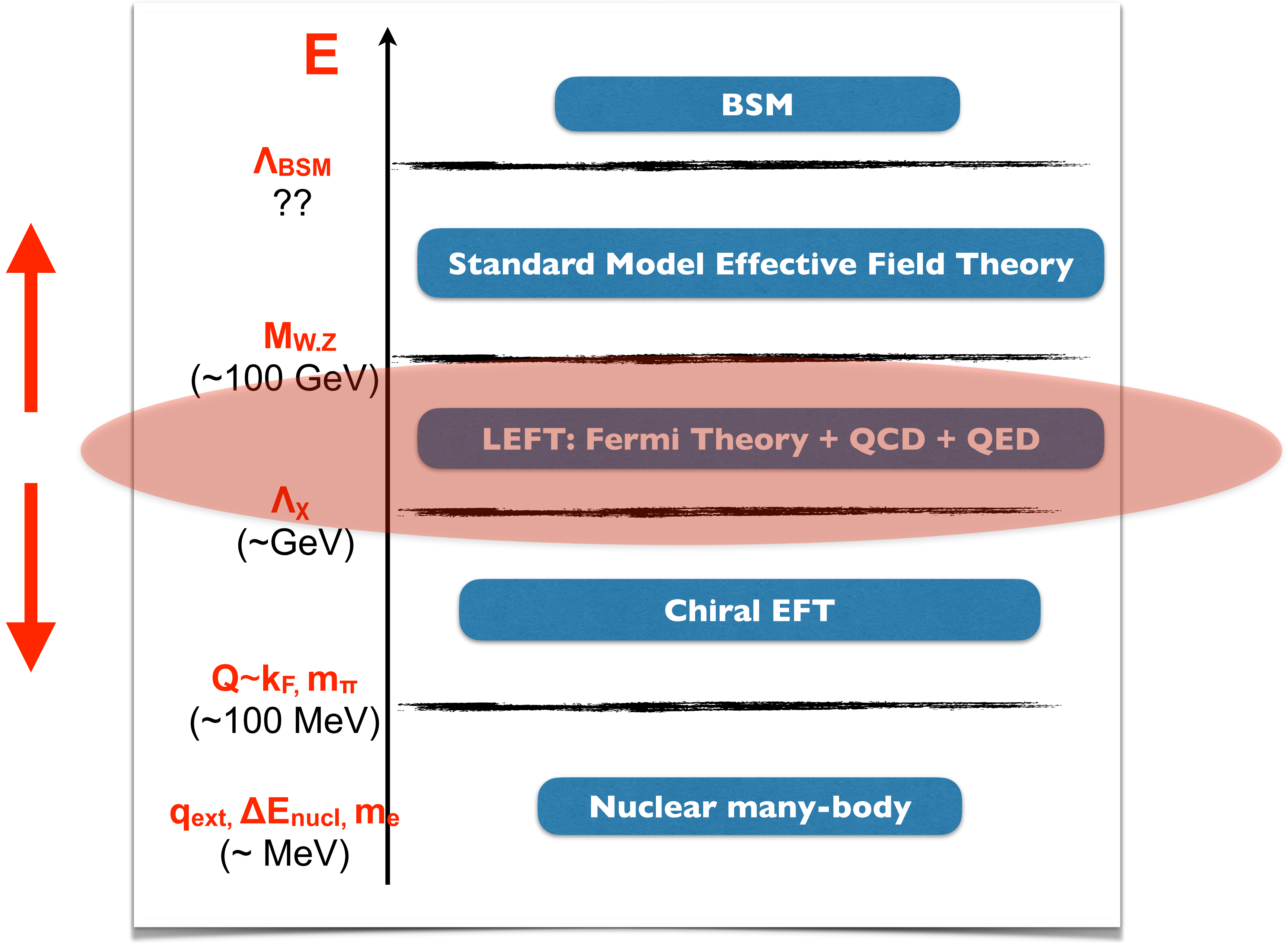
Implications for new physics



What can precision β decays teach us about new physics?
(Whether or not the Cabibbo anomaly survives scrutiny)

Connecting scales & processes (I)

To connect UV physics to beta decays, use EFT



- Start with GeV scale effective Lagrangian
  - Leading (dim-6) new physics effects are encoded in 5 quark-level operators (up to flavor indices)
  - Quark-level version of Lee-Yang (1956) effective Lagrangian

GeV-scale effective Lagrangian (LEFT)

Leptonic interactions

$$\mathcal{L}_{CC}^{(\mu)} = -\frac{G_F^{(0)}}{\sqrt{2}}\left(1+\epsilon_L^{(\mu)}\right)\bar{e}\gamma^\rho(1-\gamma_5)\nu_e \cdot \bar{\nu}_\mu\gamma_\rho(1-\gamma_5)\mu \; + \; \ldots$$

$$\frac{G_F^{(\mu)} V_{ud}}{\sqrt{2}}\left(1-\epsilon_L^{(\mu)}\right)$$

Semi-leptonic interactions

$$\begin{aligned}
\mathcal{L}_{\rm CC} \;=\; -\frac{G_F^{(0)} V_{uD}}{\sqrt{2}} \times \Big[& \left(1+\epsilon_L^{\ell D}\right) \bar{e}\gamma_\mu(1-\gamma_5)\nu_\ell \cdot \bar{u}\gamma^\mu(1-\gamma_5)d \\
& + \epsilon_R^D \; \bar{\ell}\gamma_\mu(1-\gamma_5)\nu_\ell \cdot \bar{u}\gamma^\mu(1+\gamma_5)d \\
& + \epsilon_S^{\ell D} \; \bar{\ell}(1-\gamma_5)\nu_\ell \cdot \bar{u}d \\
& - \epsilon_P^{\ell D} \; \bar{\ell}(1-\gamma_5)\nu_\ell \cdot \bar{u}\gamma_5 d \\
& + \epsilon_T^{\ell D} \; \bar{\ell}\sigma_{\mu\nu}(1-\gamma_5)\nu_\ell \cdot \bar{u}\sigma^{\mu\nu}(1-\gamma_5)d \Big] + \text{h.c.}
\end{aligned}$$

$D = d, s$

$\ell = e, \mu$

$\epsilon_i \sim (v/\Lambda)^2$

VC, Gonzalez-Alonso, Jenkins 0908.1754

VC, Graesser, Gonzalez-Alonso 1210.4553

Gonzalez-Alonso, Camalich 1605.07114, 1706.00410

...

Corrections to V_{ud} and V_{us}

$$|\bar{V}_{ud}|_i^2 = |V_{ud}|^2 \left(1 + \sum_\alpha C_{i\alpha}\epsilon_\alpha\right)$$

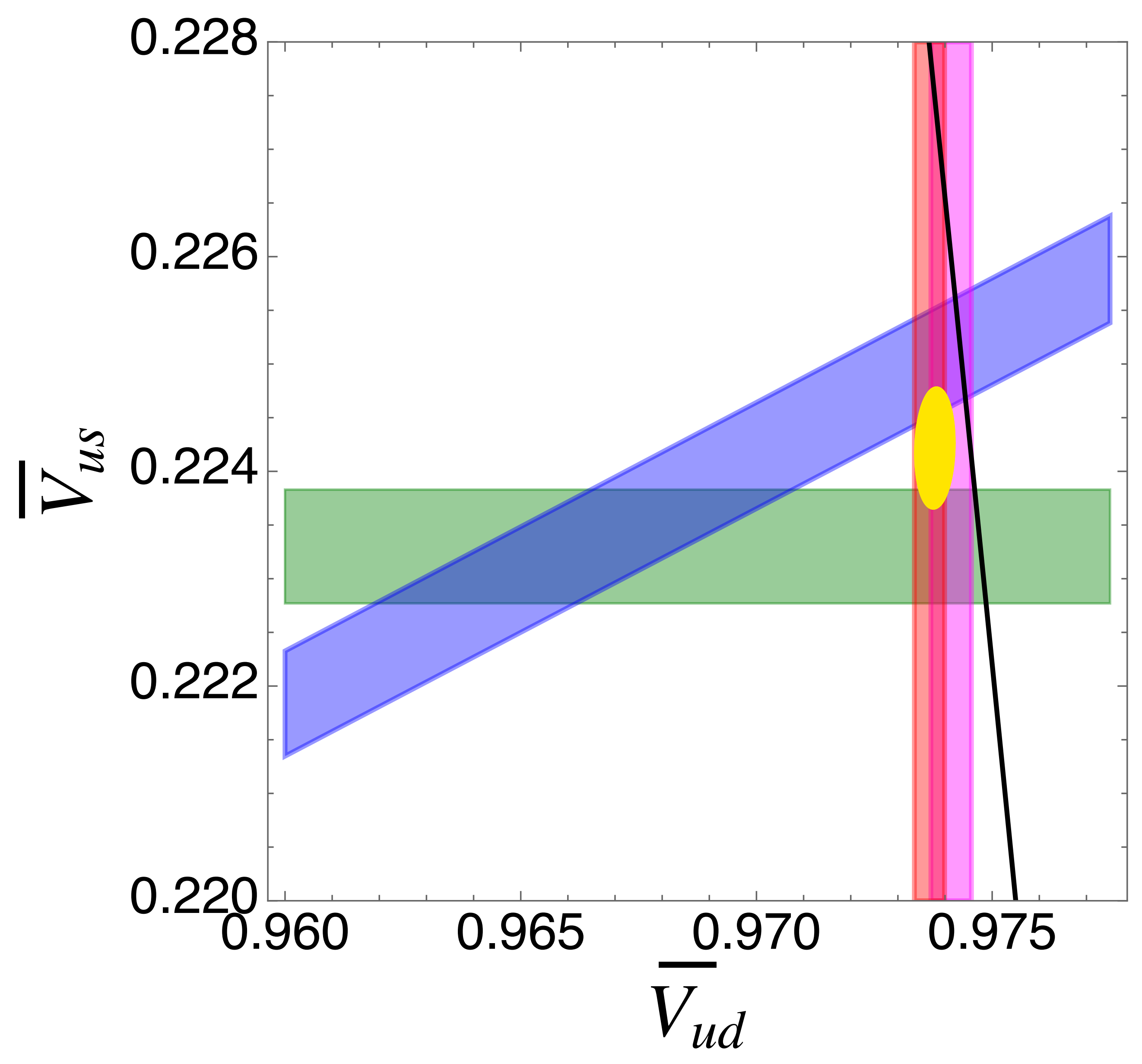
$$|\bar{V}_{us}|_j^2 = |V_{us}|^2 \left(1 + \sum_\alpha C_{j\alpha}\epsilon_\alpha\right)$$

Channel-dependent CKM elements extracted in the 'SM-like analysis'

Elements of the unitary CKM matrix

Calculable coefficients

BSM effective coupligs



Find set of ε's so that V_{ud} and V_{us} bands meet on the unitarity circle

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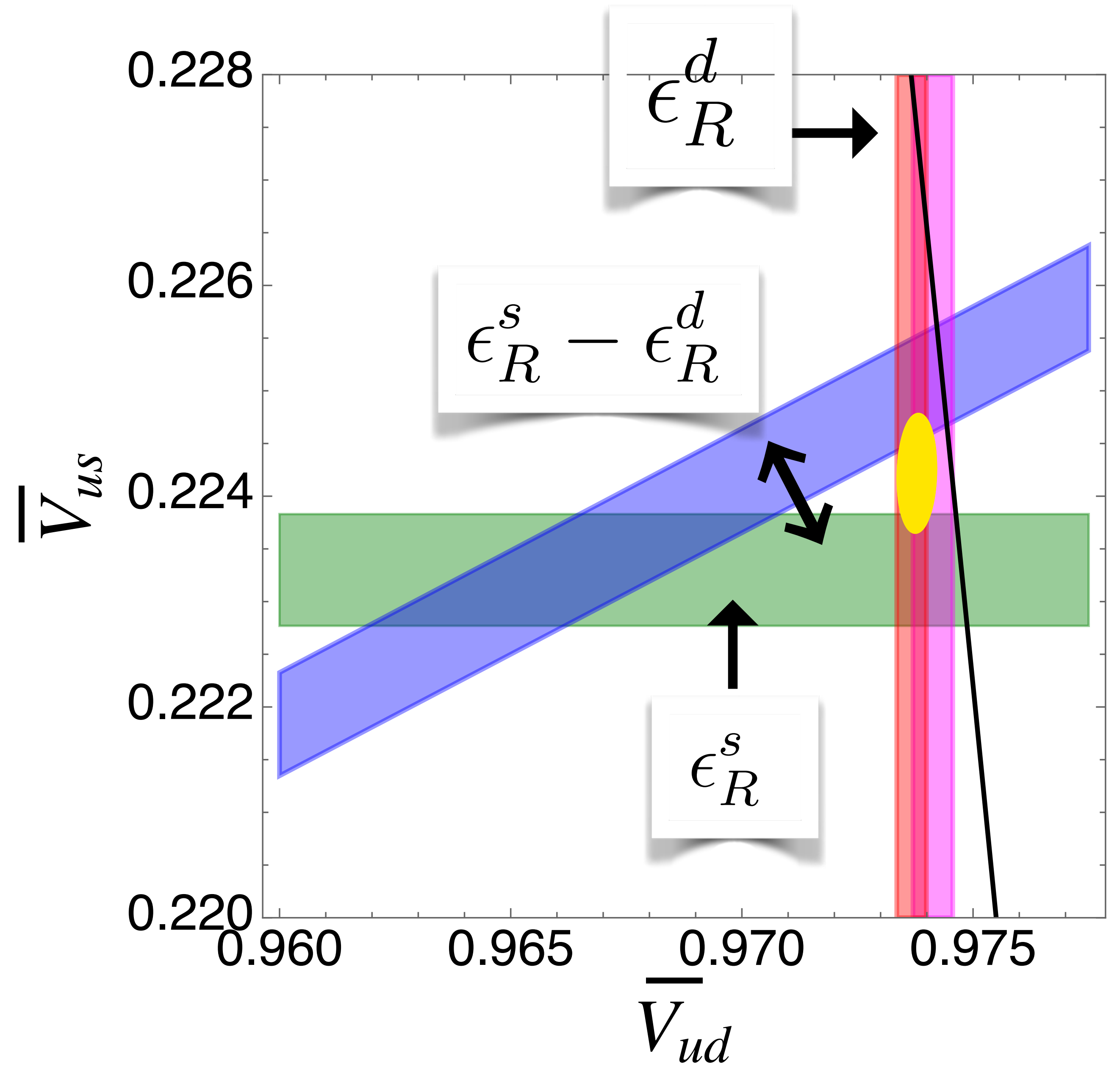


Find set of ε's so that V_{ud} and V_{us} bands meet on the unitarity circle

Grossman-Passemar-Schacht 1911.07821

Belfatto-Berezhiani 2103.05549.

VC, Diaz-Calderon, Falkowski, Gonzalez-Alonso, Rodriguez-Sanchez 2112.02087

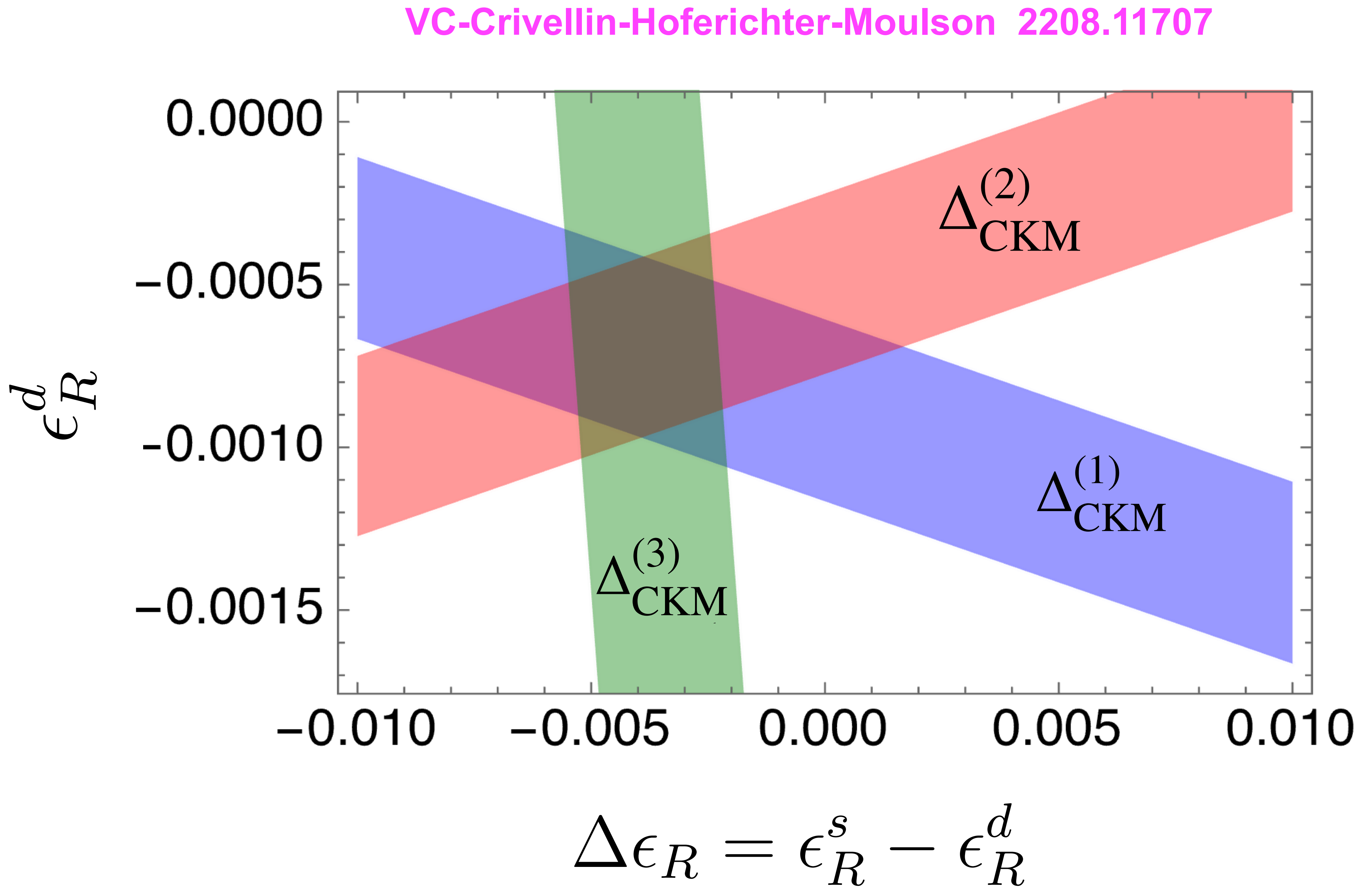
VC-Crivellin-Hoferichter-Moulson 2208.11707

...

Simplest 'solution': right-handed (V+A) quark currents.

Shift $V_{ud,us}$ from vector (axial) channels by $1+\epsilon_R$ $(1-\epsilon_R)$, can resolve all tensions

Unveiling R-handed quark currents?



$$
\begin{aligned}
\Delta^{(1)}_{CKM} &= |V_{ud}^{\beta}|^2 + |V_{us}^{K_{\ell 3}}|^2 - 1 \\
&= -1.76(56) \times 10^{-3} \\
\Delta^{(2)}_{CKM} &= |V_{ud}^{\beta}|^2 + |V_{us}^{K_{\ell 2}/\pi_{\ell 2},\beta}|^2 - 1 \\
&= -0.98(58) \times 10^{-3} \\
\Delta^{(3)}_{CKM} &= |V_{ud}^{K_{\ell 2}/\pi_{\ell 2},K_{\ell 3}}|^2 + |V_{us}^{K_{\ell 3}}|^2 - 1 \\
&= -1.64(63) \times 10^{-2}
\end{aligned}
$$

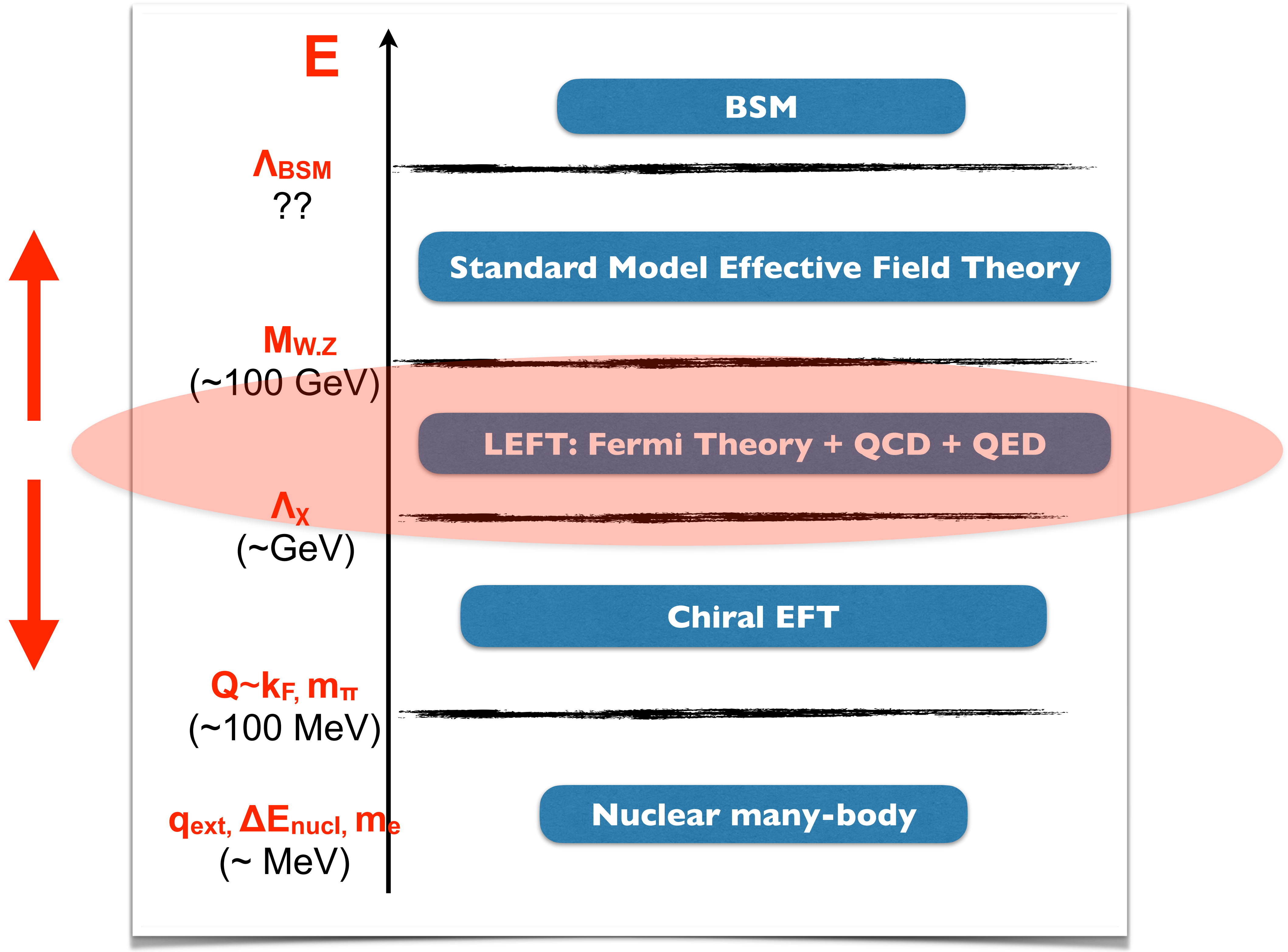
$$
\boxed{\begin{aligned}
\epsilon_R^d &= -0.69(27) \times 10^{-3} \\
\Delta\epsilon_R &= -3.9(1.6) \times 10^{-3}
\end{aligned}}
$$

Λ_R ~5-10 TeV

- Preferred ranges are not (yet) in conflict with constraints from other low-E probes
- Does the R-handed current explanation survive after taking into account high energy probes?

Connecting scales & processes (2)

To connect UV physics to beta decays, use EFT



- Need to know high-scale origin of the various ε_α

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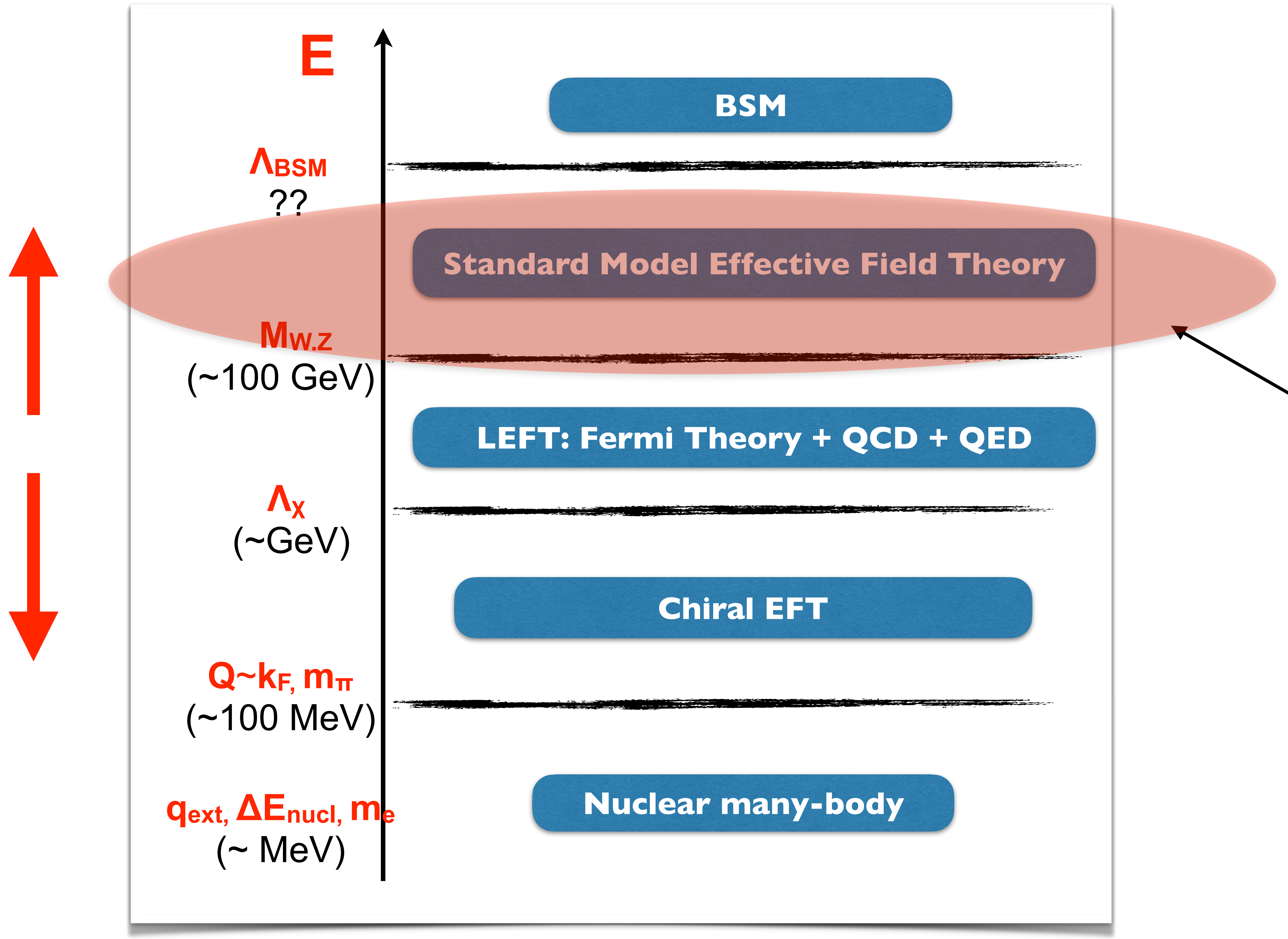
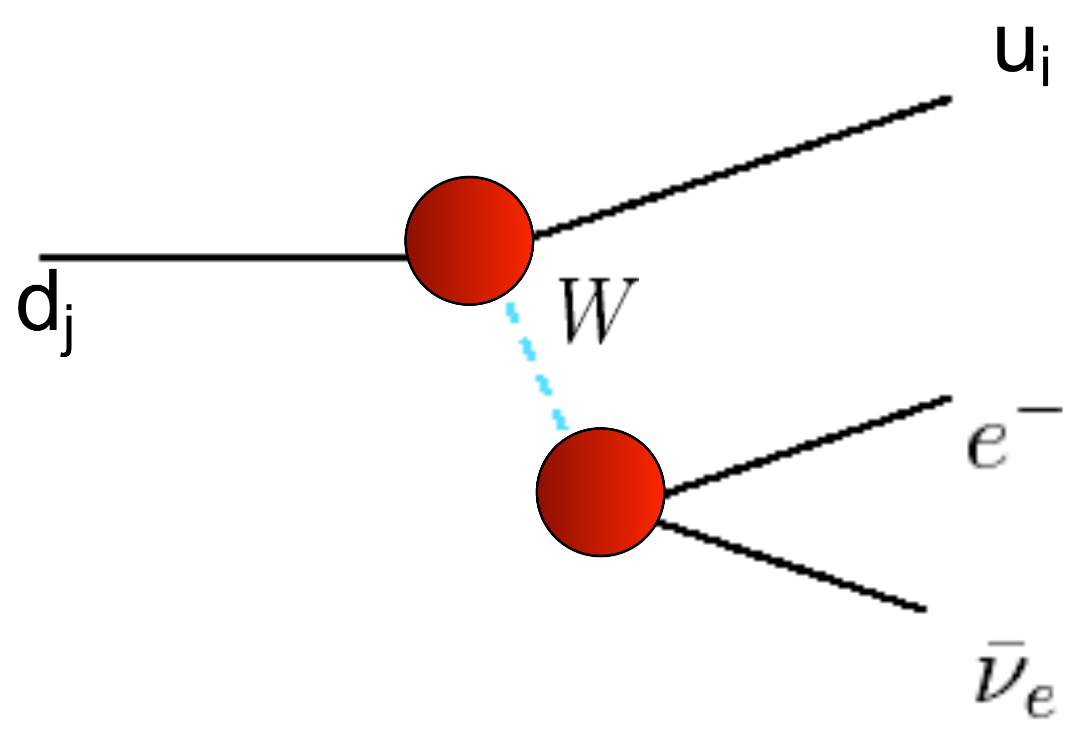


- Need to know high-scale origin of the various ε_α
- At the weak scale match LEFT & SMEFT

SMEFT origin of the low-energy operators

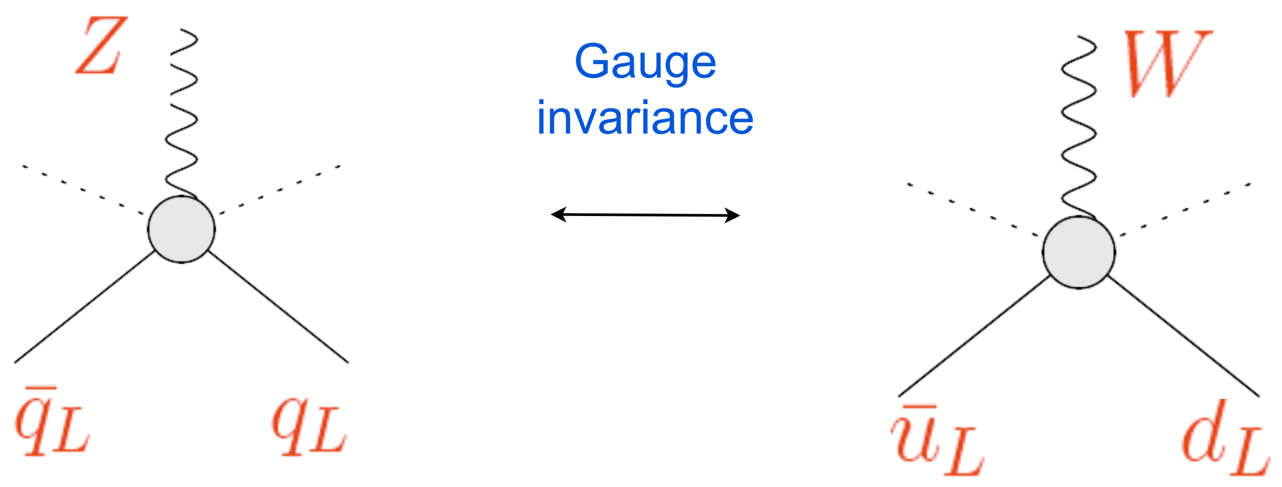
$\varepsilon_{L,R}$ originate from SU(2)xU(1) invariant vertex corrections



Building blocks

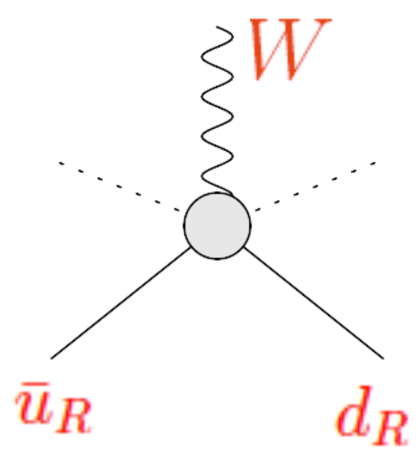
$$l^i = \begin{pmatrix} \nu_L^i \\ e_L^i \end{pmatrix} \quad q^i = \begin{pmatrix} u_L^i \\ d_L^i \end{pmatrix} \quad H = \begin{pmatrix} \varphi^+ \\ \varphi^0 \end{pmatrix}$$

$$Q_{Hq}^{(3)} = (H^\dagger i \overleftrightarrow{D}_\mu^I H)(\bar{q}_p \tau^I \gamma^\mu q_r)$$



ε_L

$$Q_{Hud} = i(\widetilde{H}^\dagger D_\mu H)(\bar{u}_p \gamma^\mu d_r)$$



ε_R

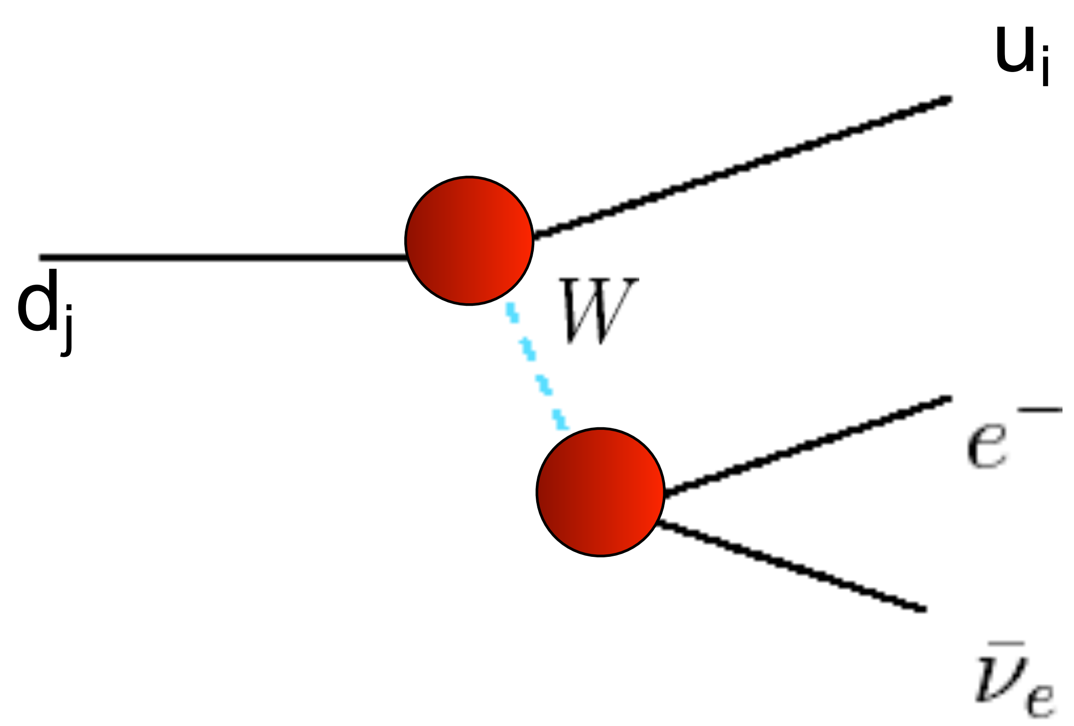
Can be generated by
W_L-W_R mixing in Left-Right symmetric models
or by exchange of vector-like quarks

Dekens, Andreoli, de Vries, Mereghetti, Oosterhof, 2107.10852

Belfatto-Berezhiani 2103.05549
Belfatto-Trifinopoulos 2302.14097

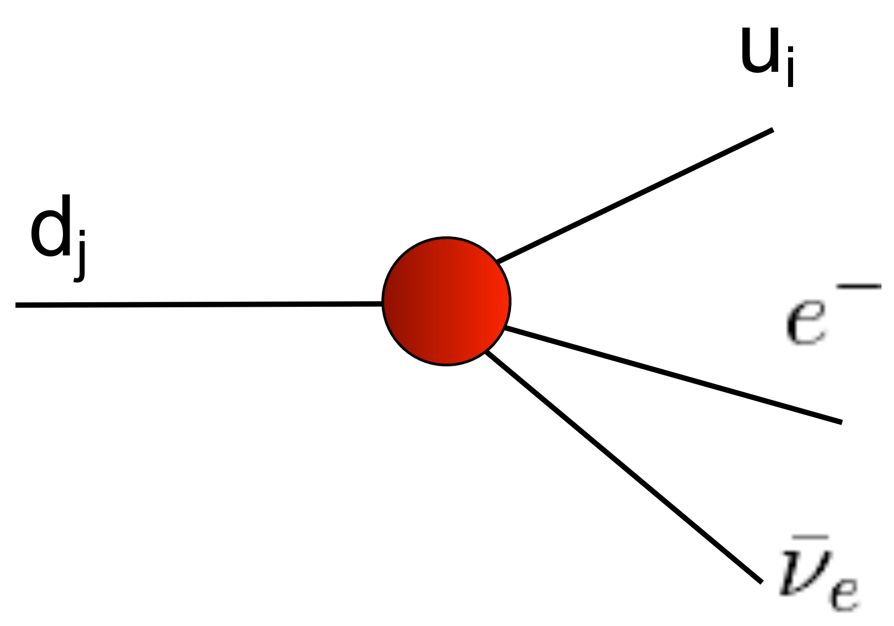
SMEFT origin of the low-energy operators

$\varepsilon_{L,R}$ originate from SU(2)xU(1) invariant vertex corrections



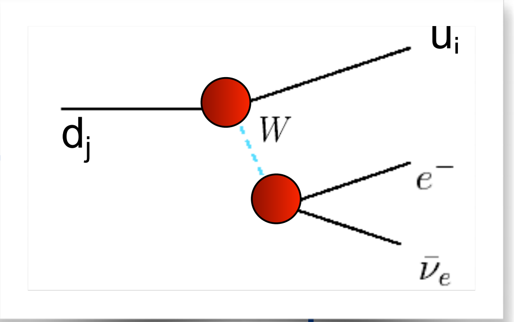
ε_R	$Q_{Hud} = i(\widetilde{H}^\dagger D_\mu H)(\bar{u}_p\gamma^\mu d_r)$	
ε_L	$Q_{Hq}^{(3)} = (H^\dagger i\overleftrightarrow{D}_\mu^I H)(\bar{q}_p\tau^I\gamma^\mu q_r)$	
ε_L	$Q_{Hl}^{(3)} = (H^\dagger i\overleftrightarrow{D}_\mu^I H)(\bar{l}_p\tau^I\gamma^\mu l_r)$	

$\varepsilon_{S,P,T}$ and additional contributions to ε_L arise from SU(2)xU(1) invariant 4-fermion operators



$Q_{ledq} = (\bar{\ell}e)(\bar{d}q) + \text{h.c.}$	$\varepsilon_{S,P}$	
$Q_{lequ}^{(1)} = (\bar{l}_a e)\epsilon^{ab}(\bar{q}_b u) + \text{h.c.}$	$\varepsilon_{S,P}$	
$Q_{lequ}^{(3)} = (\bar{l}_a\sigma^{\mu\nu}e)\epsilon^{ab}(\bar{q}_b\sigma_{\mu\nu}u) + \text{h.c.}$	ε_T	
$Q_{lq}^{(3)} = \bar{l}\gamma_\mu\sigma^a l\ \bar{q}\gamma^\mu\sigma^a q$	ε_L	
$Q_{ll} = \bar{l}\gamma_\mu l\ \bar{l}\gamma^\mu l$	ε_L	

High Energy constraints



ε_R $$Q_{Hud} = i(\widetilde{H}^\dagger D_\mu H)(\bar{u}_p \gamma^\mu d_r)$$

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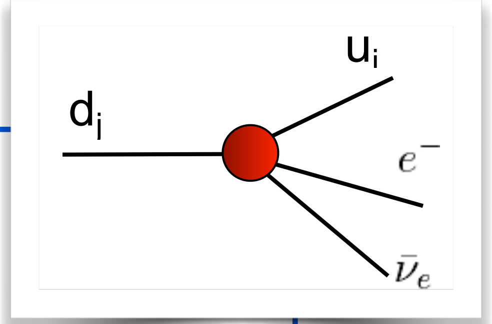

$\varepsilon_{S,P}$ $$Q_{ledq} = (\bar{\ell}e)(\bar{d}q) + \text{h.c.}$$

$\varepsilon_{S,P}$ $$Q_{lequ}^{(1)} = (\bar{l}_a e)\epsilon^{ab}(\bar{q}_b u) + \text{h.c.}$$

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ε_L $$Q_{lq}^{(3)} = \bar{l}\gamma_\mu \sigma^a l \; \bar{q}\gamma^\mu \sigma^a q$$

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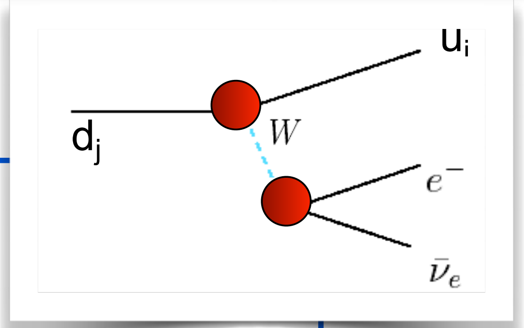
High Energy constraints



ε_R $$Q_{Hud} = i(\widetilde{H}^\dagger D_\mu H)(\bar{u}_p \gamma^\mu d_r)$$

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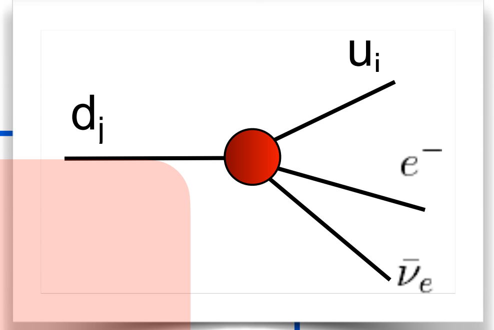

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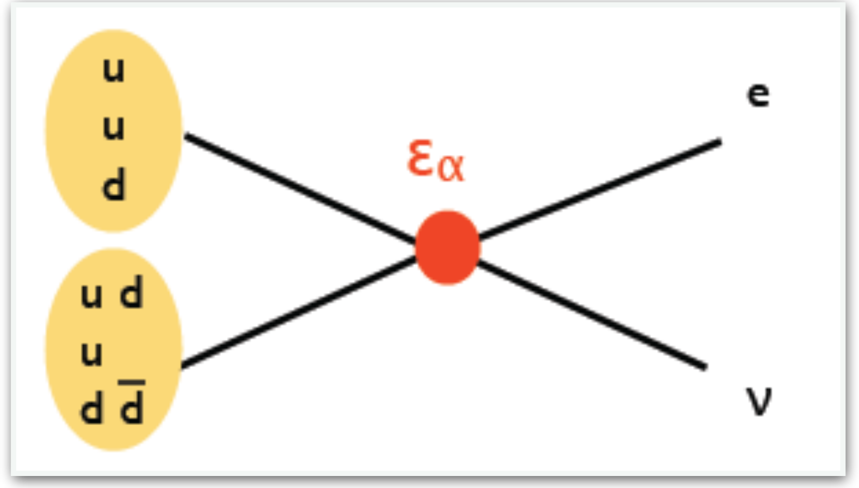
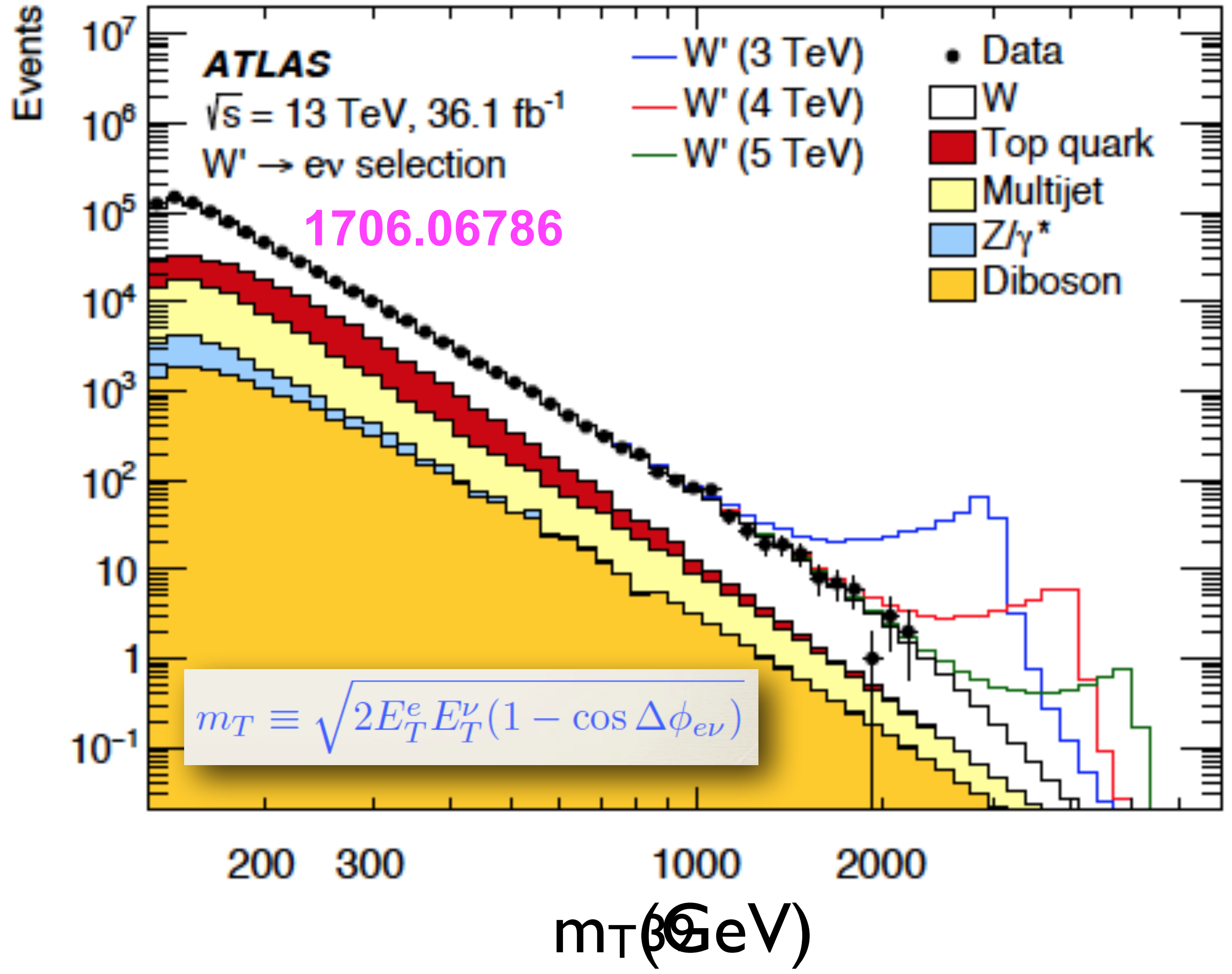
Contribute tp pp → eν+X and pp → e⁺e⁻ +X at the LHC

LHC: pp → eν + X

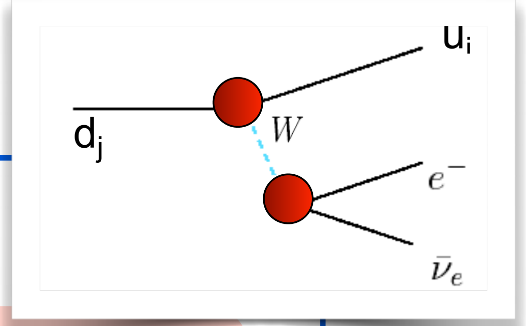




$\boxed{\varepsilon_\alpha \sim 10^{-3} - 10^{-4}}$

VC, Graesser, Gonzalez-Alonso 1210.4553
Alioli-Dekens-Girard-Mereghetti 1804.07407
Gupta et al. 1806.09006
Boughezal-Mereghetti-Petriello 2106.05337
...

High Energy constraints



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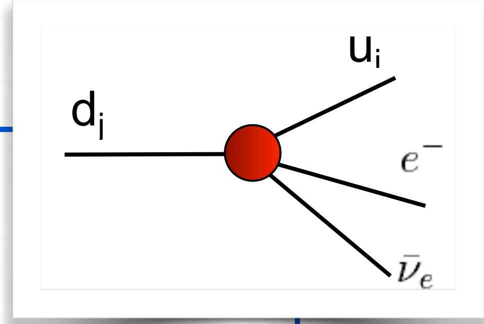

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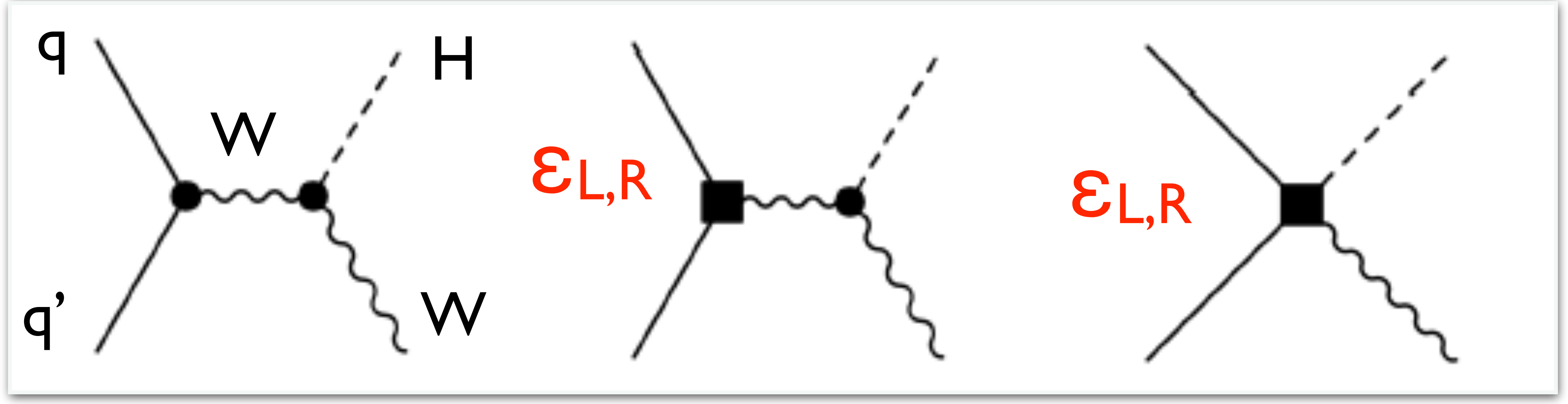
ε_L $$Q_{ll} = \bar{l}\gamma_\mu l \; \bar{l}\gamma^\mu l$$

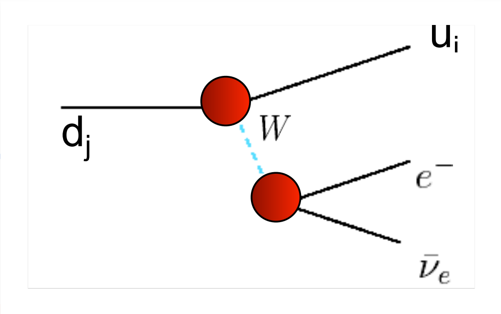
Can be probed at the LHC by associated Higgs + W production

S. Alioli, VC, W. Dekens, J. de Vries, E. Mereghetti 1703.04751



Current LHC results allow for to $\varepsilon_{L,R} \sim 5\%$

High Energy constraints



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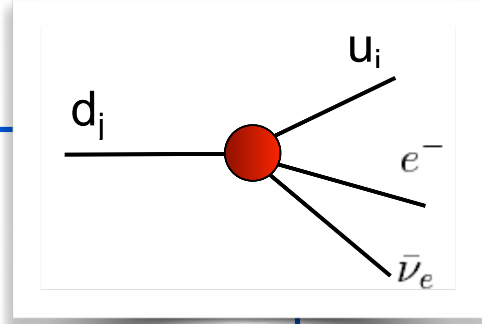

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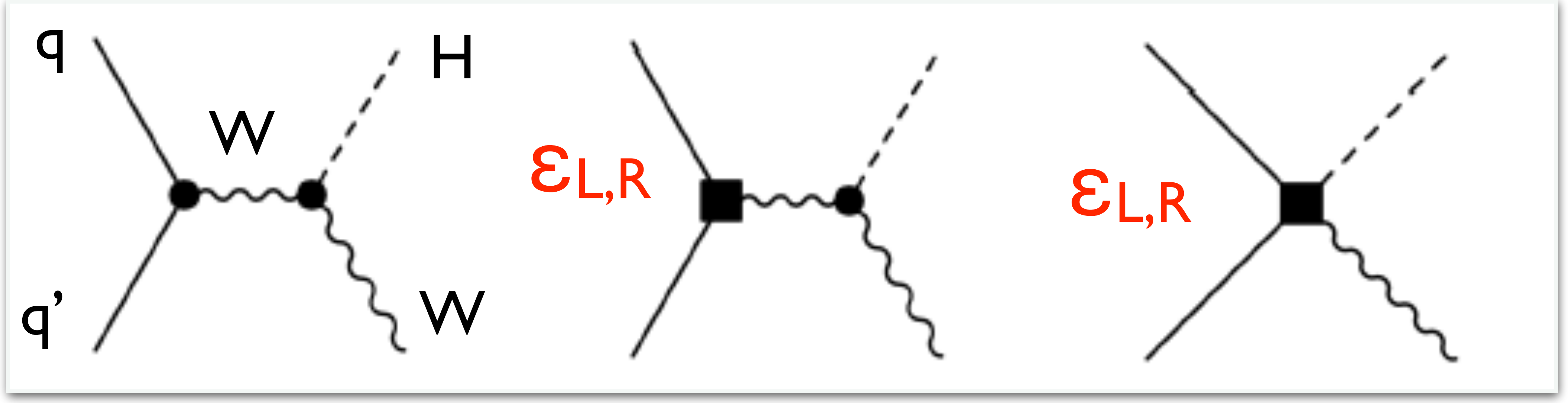


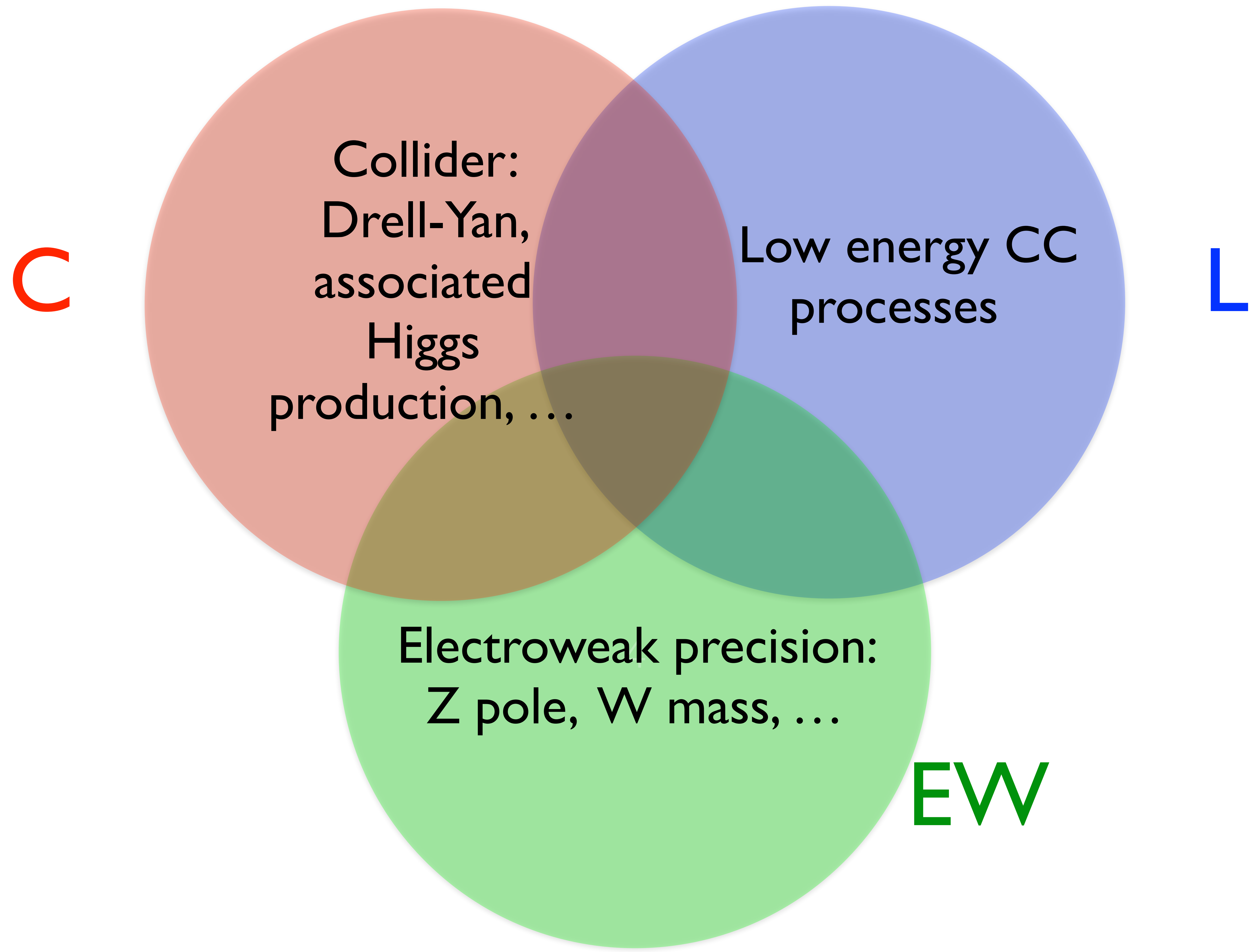
Current LHC results allow for to $\varepsilon_{L,R}$ ~ 5%

Contribute to Z-pole and other precision electroweak (EW) observables, including M_W

The CLEW framework

VC, W. Dekens, J. De Vries, E. Mereghetti, T. Tong, 2311.00021

- An informed global analysis of β-decays in SMEFT requires data from Collider, Low energy, and ElectroWeak tests



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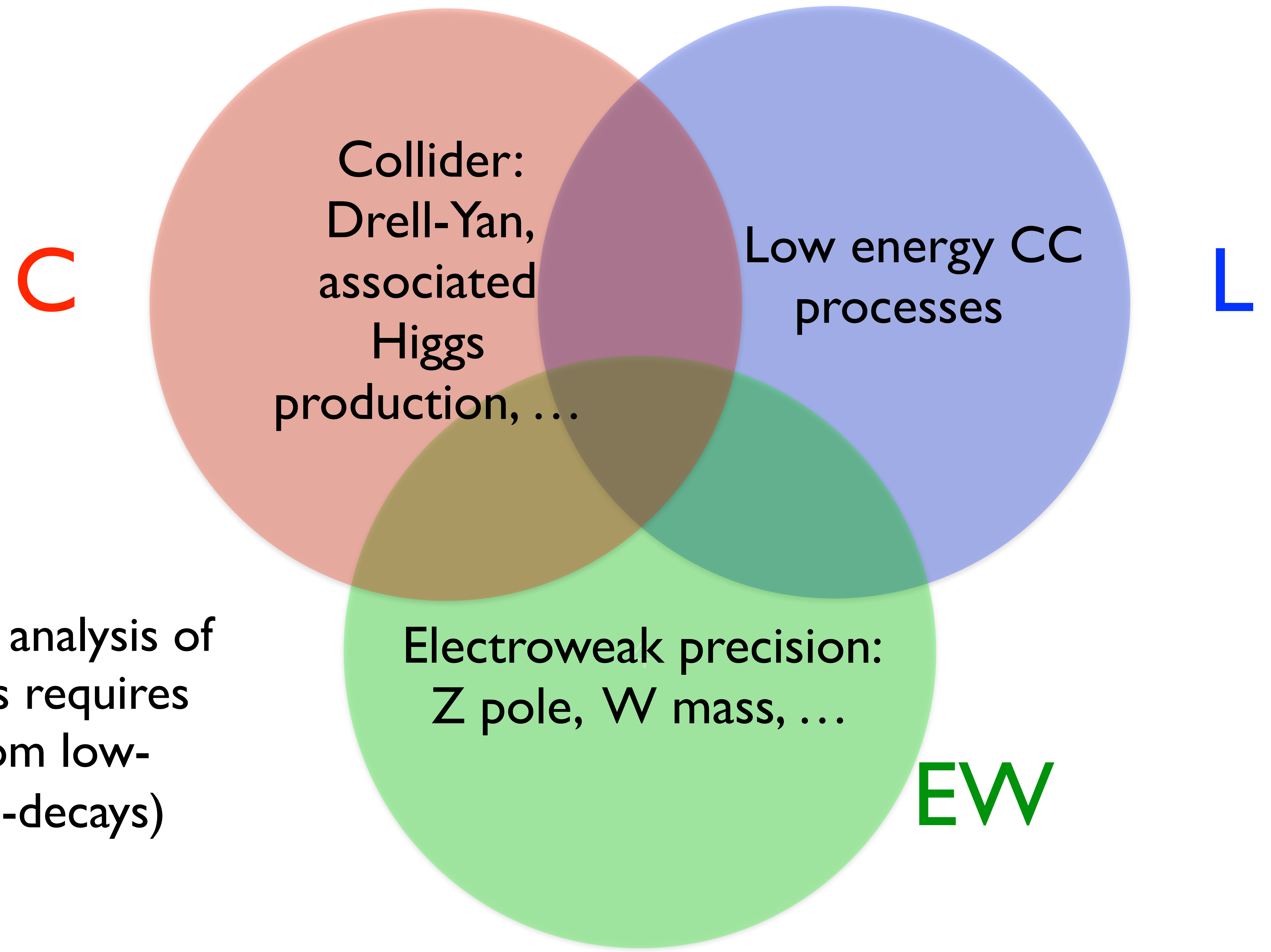

Corollary: a global SMEFT analysis of precision EW observables requires including constraints from low-energy CC processes (β-decays)

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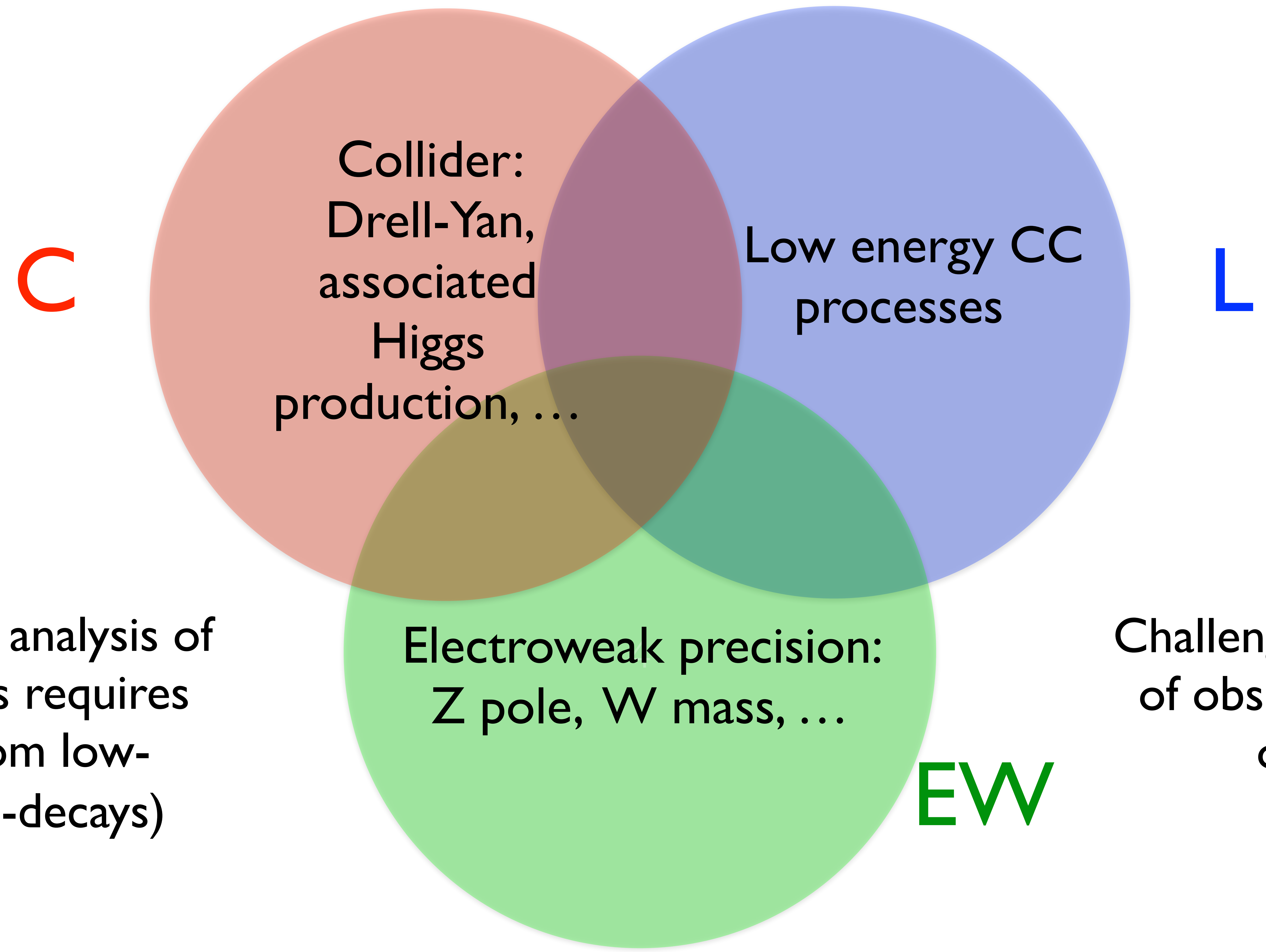


Corollary: a global SMEFT analysis of precision EW observables requires including constraints from low-energy CC processes (β-decays)

Challenge: identify a manageable set of observables and corresponding operators that 'closes' (at least at tree level)

The CLEW framework

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \sum_i C_i Q_i$$

Operators		L	EW	C
$\boldsymbol{H^4 D^2}$				
Q_{HD}	$\left(H^\dagger D^\mu H\right)^* \left(H^\dagger D_\mu H\right)$	parameter shift (m_Z)		
$\boldsymbol{X^2 H^2}$				
Q_{HWB}	$H^\dagger \tau^I H\, W^I_{\mu\nu} B^{\mu\nu}$	parameter shift $(\sin\theta_W)$		
$\boldsymbol{\psi^2 H^2 D}$				
$Q_{Hl}^{(1)}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{l}_p \gamma^\mu l_r)$	✗	✓	✓
$Q_{Hl}^{(3)}$	$(H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar{l}_p \tau^I \gamma^\mu l_r)$	✓	✓	✓
Q_{He}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{e}_p \gamma^\mu e_r)$	✗	✓	✓
$Q_{Hq}^{(1)}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{q}_p \gamma^\mu q_r)$	✗	✓	✓
$Q_{Hq}^{(3)}$	$(H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar{q}_p \tau^I \gamma^\mu q_r)$	✓	✓	✓
Q_{Hu}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{u}_p \gamma^\mu u_r)$	✗	✓	✓
Q_{Hd}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{d}_p \gamma^\mu d_r)$	✗	✓	✓
Q_{Hud} + h.c.	$i(\widetilde{H}^\dagger D_\mu H)(\bar{u}_p \gamma^\mu d_r)$	✓	✗	✓

Operators		L	EW	C
$\boldsymbol{(\bar{L}L)(\bar{L}L)}$				
Q_{ll}	$(\bar{l}_p \gamma^\mu l_r)(\bar{l}_s \gamma_\mu l_t)$	parameter shift (G_F)		
$Q_{lq}^{(1)}$	$(\bar{l}_p \gamma^\mu l_r)(\bar{q}_s \gamma_\mu q_t)$	✗	✓	✓
$Q_{lq}^{(3)}$	$(\bar{l}_p \gamma^\mu \tau^I l_r)(\bar{q}_s \gamma_\mu \tau^I q_t)$	✓	✓	✓
$\boldsymbol{(\bar{L}R)(\bar{R}L)}$ + h.c.				
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_{tj})$	✓	✗	✓
$\boldsymbol{(\bar{L}R)(\bar{L}R)}$ + h.c.				
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\epsilon_{jk}(\bar{q}_s^k u_t)$	✓	✗	✓
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j \sigma_{\mu\nu} e_r)\epsilon_{jk}(\bar{q}_s^k \sigma^{\mu\nu} u_t)$	✓	✗	✓

** We are not including ‘ld, lu, ed, eu, qe’ 4-fermion operators that affect Drell-Yan (included in our analysis), NC processes at low-E & DIS (*not* included in our analysis). Inclusion of such operators would lead to a ~ closed set of observables ⊗ operators.

What about flavor?

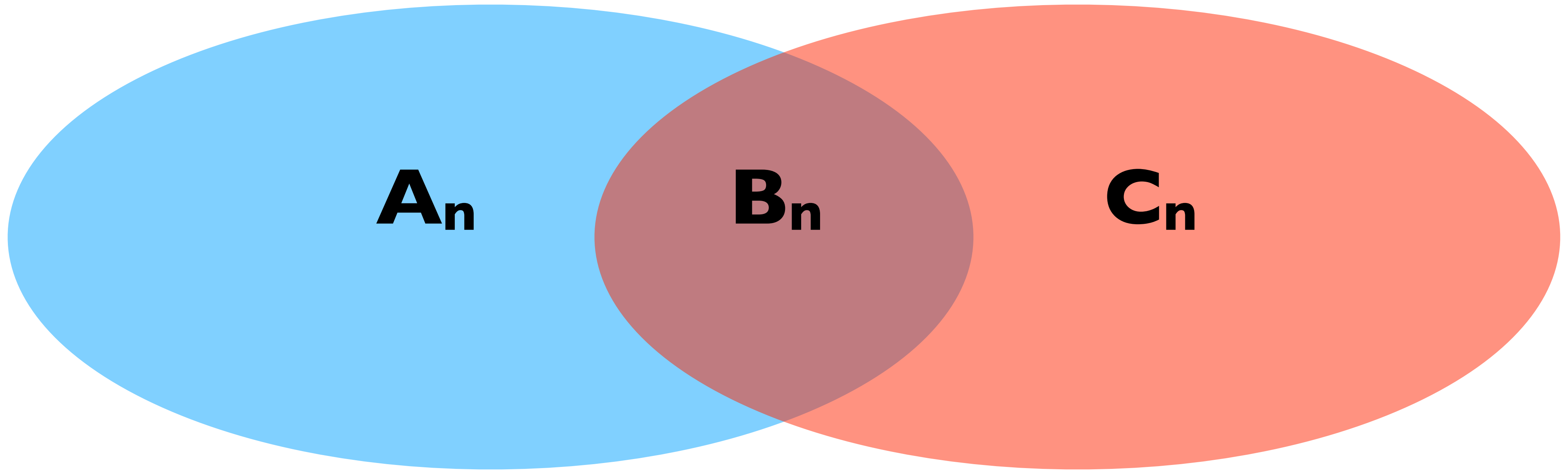
- Most SMEFT analyses impose flavor symmetry to reduce number of couplings. However
    - This re-introduces model-dependence (e.g. excludes classes of operators / models such as LRSM)
    - Results can depend strongly on flavor assumptions

L. Bellafronte, S. Dawson, P. P. Giardino 2304.00029

- We perform a flavor-assumption-independent analysis: exploit approximate decoupling of CLEW and FCNC

CLEW precision observables FCNC observables

Wilson Coefficients:
A_n, B_n, C_n



B_n strongly constrained by FCNC.
Often B_n appears in CLEW observables suppressed by powers of $V_{us} = \lambda_C \sim 0.2$

$$\boxed{\mathcal{L}_{tot} = \mathcal{L}_{CLEW}(A_n, B_n) \times \mathcal{L}_{FCNC}\,(B_n\; C_n) \times \ldots \rightarrow \mathcal{L}_{tot} = \mathcal{L}_{CLEW}(A_n, B_n{=}0) \times \mathcal{L}_{FCNC}\,(B_n\; C_n) \times \ldots}$$

~ factorized likelihood.
Expect minimal impact on A_n

A CLEWed global analysis

The CLEW analysis with no flavor symmetry assumptions requires 37 couplings

Large fits are not particularly enlightening:

Not all operators matter!

To gain qualitative and quantitative insight on most relevant operators (model selection), use the Akaike Information Criterion

$$\boxed{\mathrm{AIC} = (\chi^2)_{\mathrm{min}} + 2\,k}$$

# of estimated parameters

Minimization of AIC:

balance between goodness of fit (rewarded) and proliferation of parameters (penalized)

A CLEWed global analysis

- Scanned model space by ‘turning on’ certain classes of effective couplings

Category	Operators	Description	# of Ops.
I.	C_{ST}	Oblique corrections	1
II.	C_{Hud}	RH charged currents	2
III.	$C_{Hl}^{(1)}$ $C_{Hl}^{(3)}$	LH lepton vertices	6
IV.	C_{He}	RH lepton vertices	3
V.	$C_{Hq}^{(u)}$ $C_{Hq}^{(d)}$	LH quark vertices	5
VI.	C_{Hu} C_{Hd}	RH quark vertices	5
VII.	C_{ll}	Lepton 4-fermion	1
VIII.	$C_{lq}^{(u)}$ $C_{lq}^{(d)}$	Semileptonic 4-fermion	6
IX.	C_{ledq} $C_{lequ}^{(1)}$	Scalar 4-fermion	6
X.	$C_{lequ}^{(3)}$	Tensor 4-fermion	2

Operators grouped in 10 categories

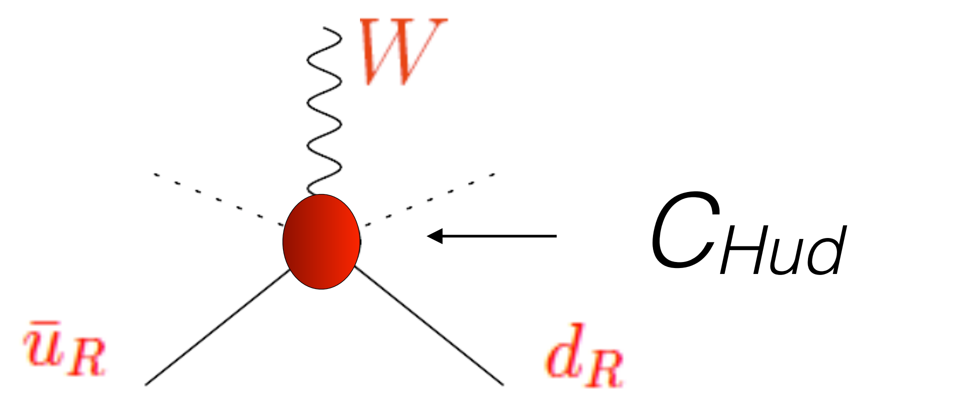
Scanned this model space

$2^{10} = 1024$ ‘models’

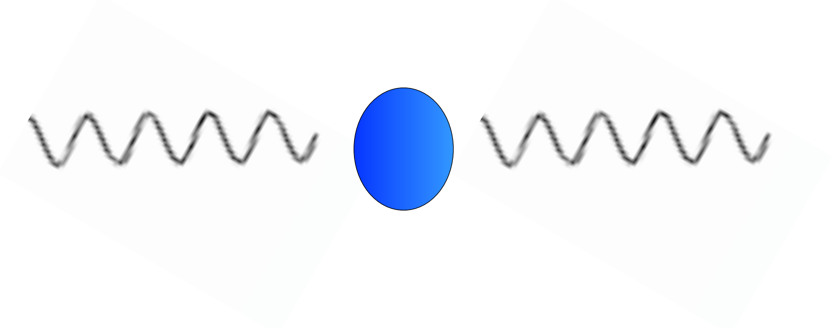
A CLEWed global analysis

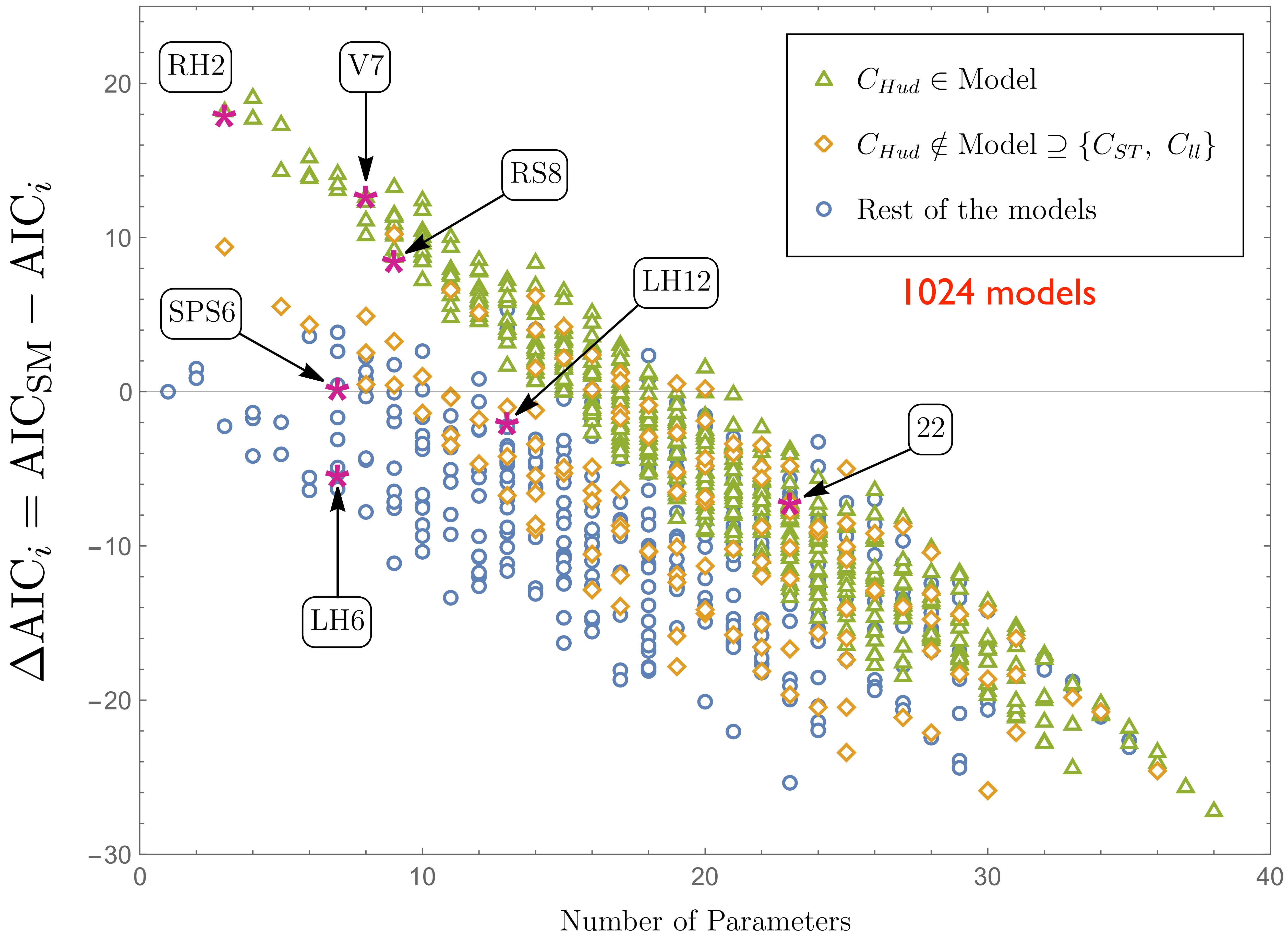
VC, W. Dekens, J. De Vries, E. Mereghetti, T. Tong, JHEP 03 (24) 33, arXiv: 2311.00021

- Scanned model space by 'turning on' certain classes of effective couplings
- Akaike Information Criterion favors models with Right-Handed Charged Currents of quarks



- Models with oblique corrections (C_{ST}) also fare better than SM





Favored models

Standard Model

Disfavored models

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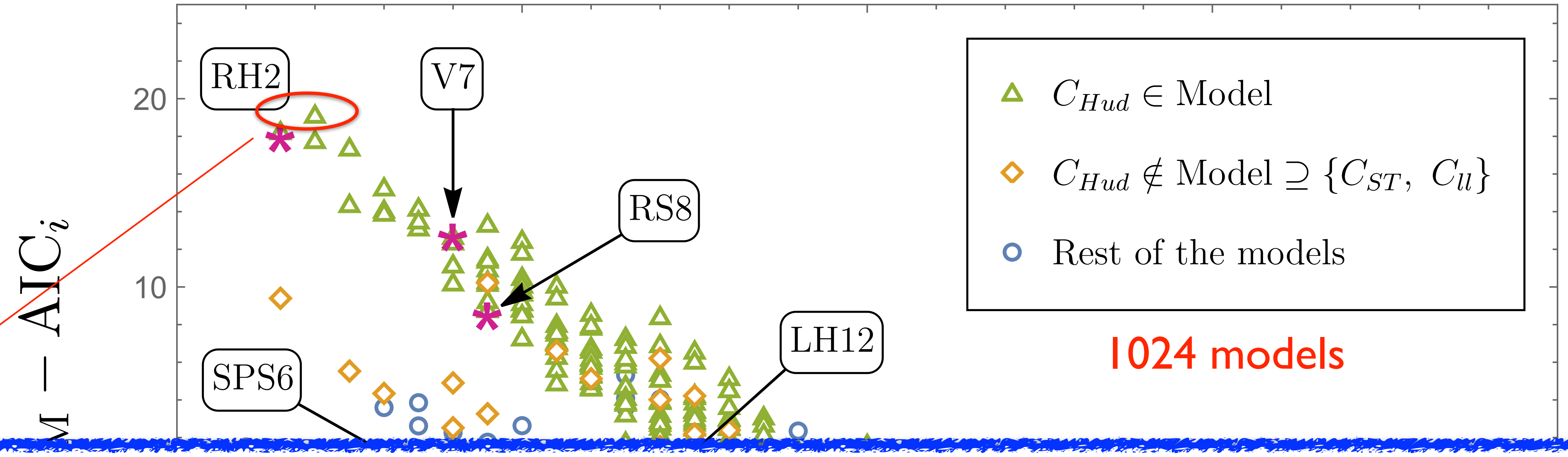

Favored models

Standard Model

Disfavored models

The winner (ΔAIC=19): two RH CC vertex corrections and a combination of oblique parameters

(UV completions? Vector-like quarks generate RH CC at tree level and oblique at 1-loop)

$$C_{Hud_{11}} = (-0.030 \pm 0.008)\ \mathrm{TeV}^{-2}\,,$$

$$C_{Hud_{12}} = (-0.040 \pm 0.011)\ \mathrm{TeV}^{-2}\,,$$

$$C_{ST} = (-0.0038 \pm 0.0022)\ \mathrm{TeV}^{-2}\,.$$

A CLEWed global analysis

VC, W. Dekens, J. De Vries, E. Mereghetti, T. Tong, JHEP 03 (24) 33, arXiv: 2311.00021

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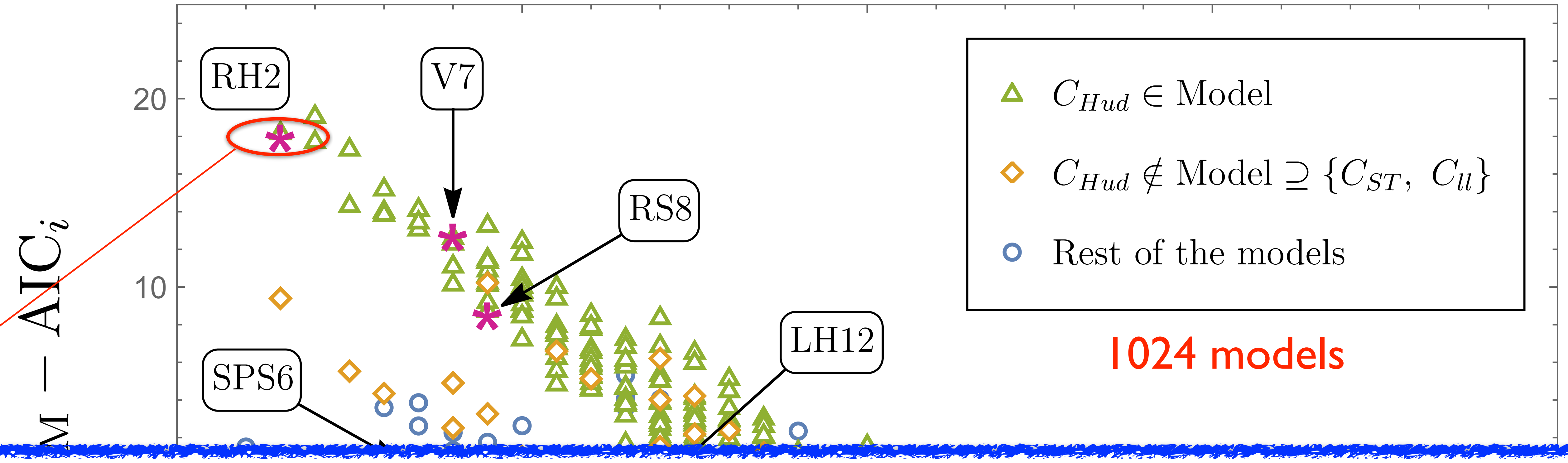
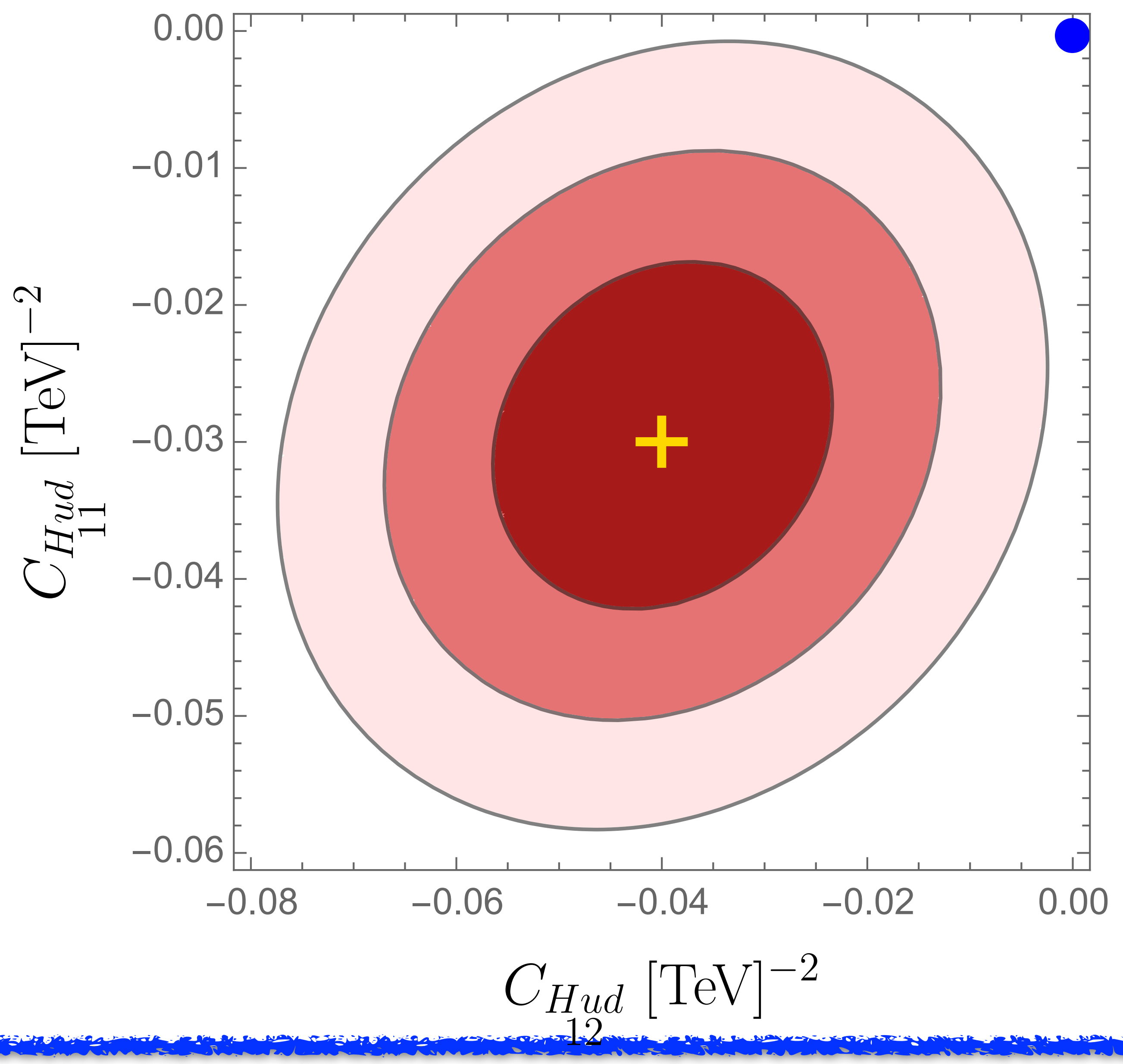


Favored models

Standard Model

Disfavored models

The runner-up (ΔAIC=18):
just two RH CC vertex corrections!



A CLEWed global analysis

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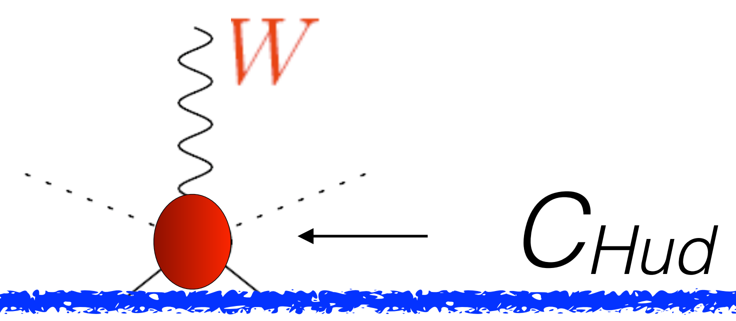

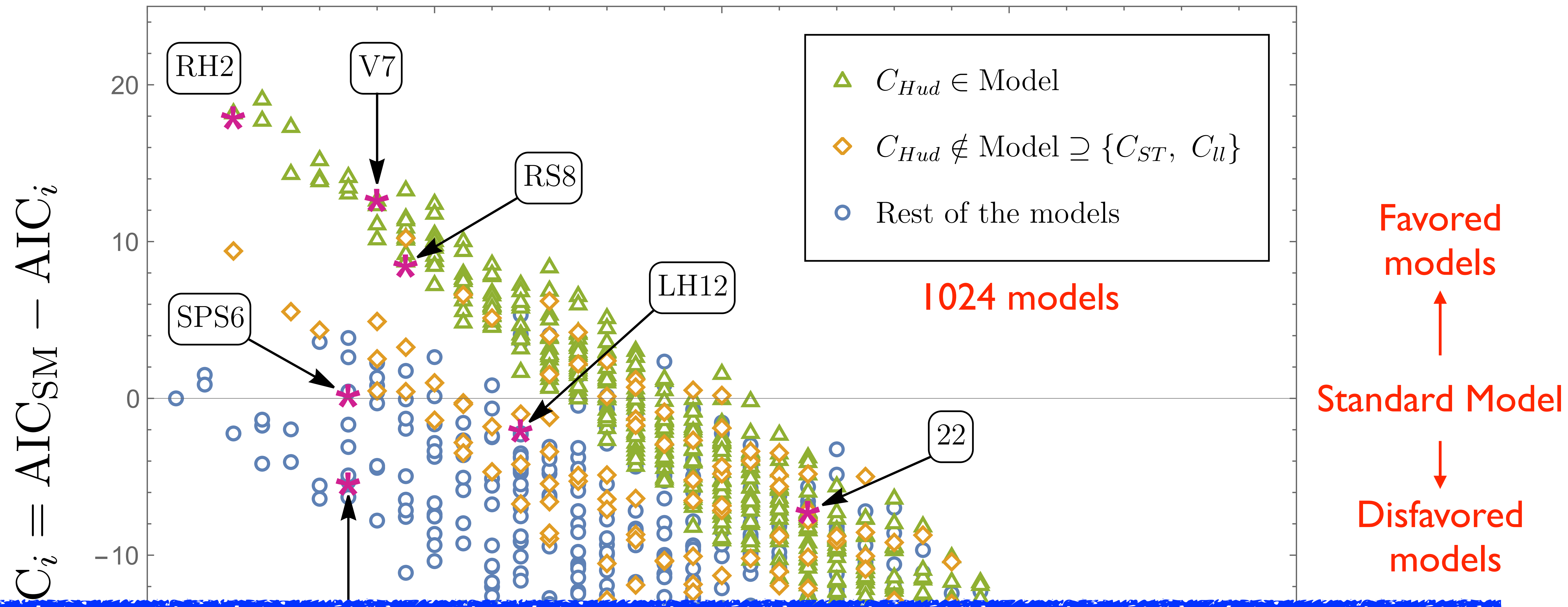

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Messages:

- Cabibbo "anomaly" and its explanation in terms of RH quark currents are consistent with other precision data
- Unitarity test provides / will provide relevant input to unravel new physics scenarios

Falsifying R-handed current hypothesis

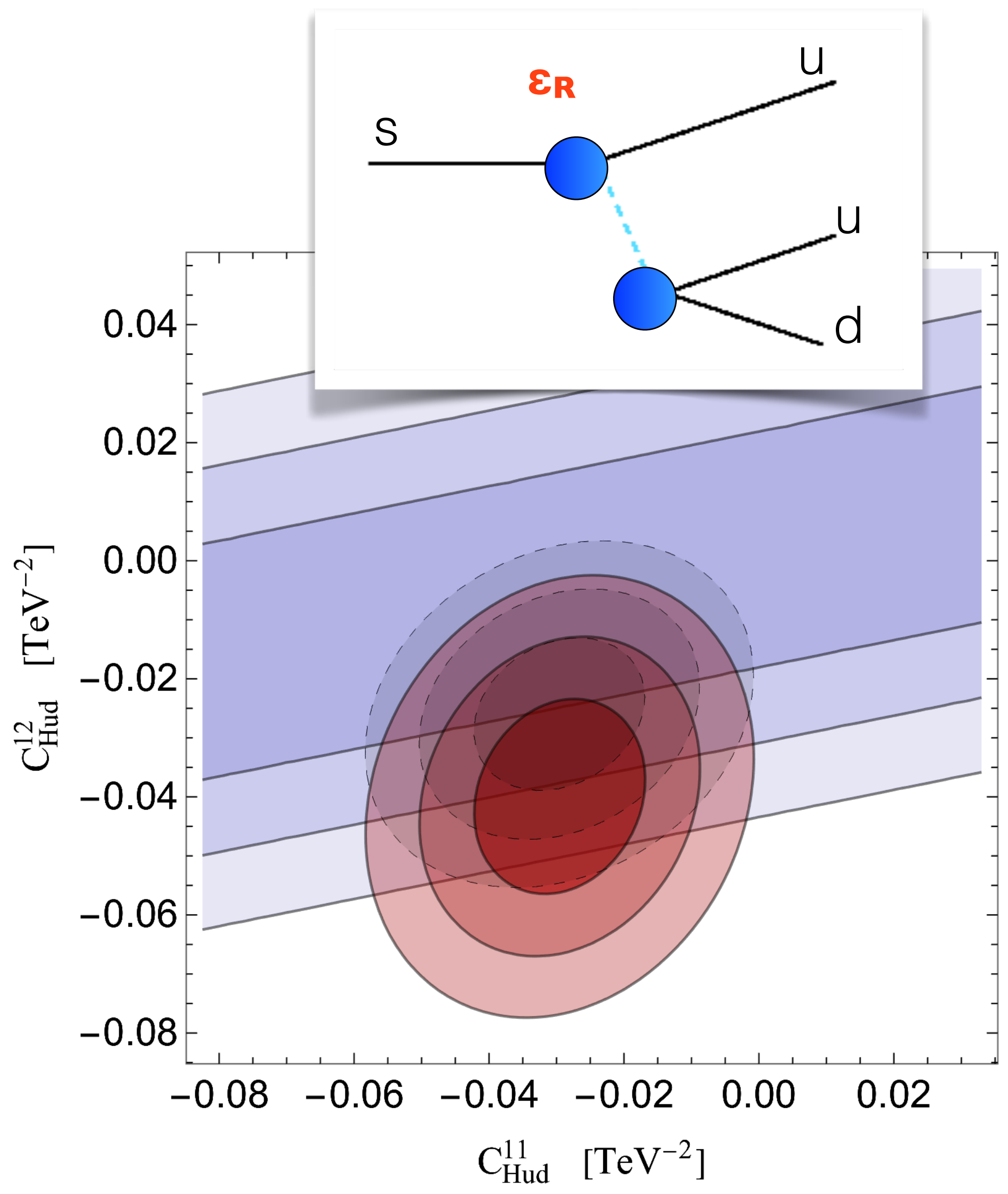
VC, W. Dekens, J. De Vries, E. Mereghetti, T. Tong, 2311.00021

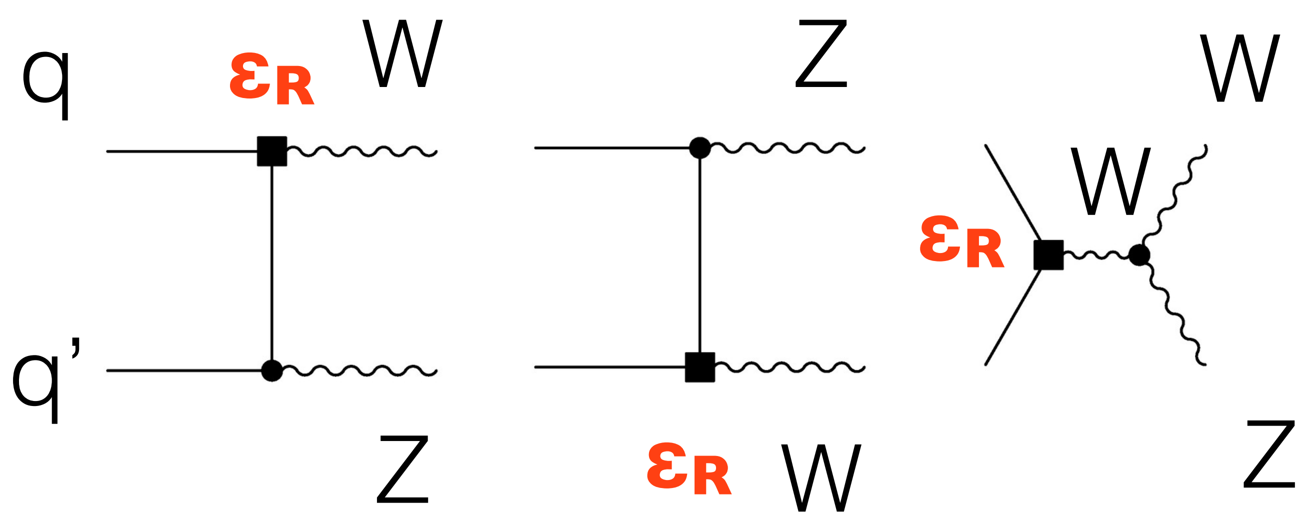
- Currently less-sensitive probes of R-handed couplings

  - g_A/g_V: neutron decay vs Lattice QCD (need ~ order of magnitude theoretical improvement)

  - $K \to (\pi\pi)_{I=2}$ decay amplitude: experiment vs Lattice QCD (difficult to improve)

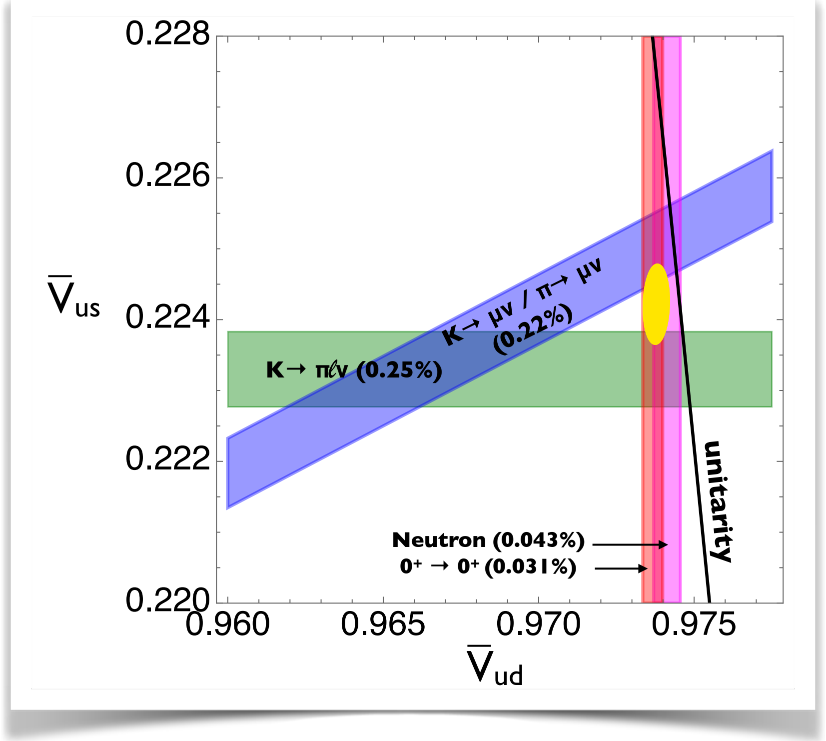
  - WH & WZ production at the High Luminosity LHC will reach sensitivity need to test the R-handed current solution to the Cabibbo angle anomaly



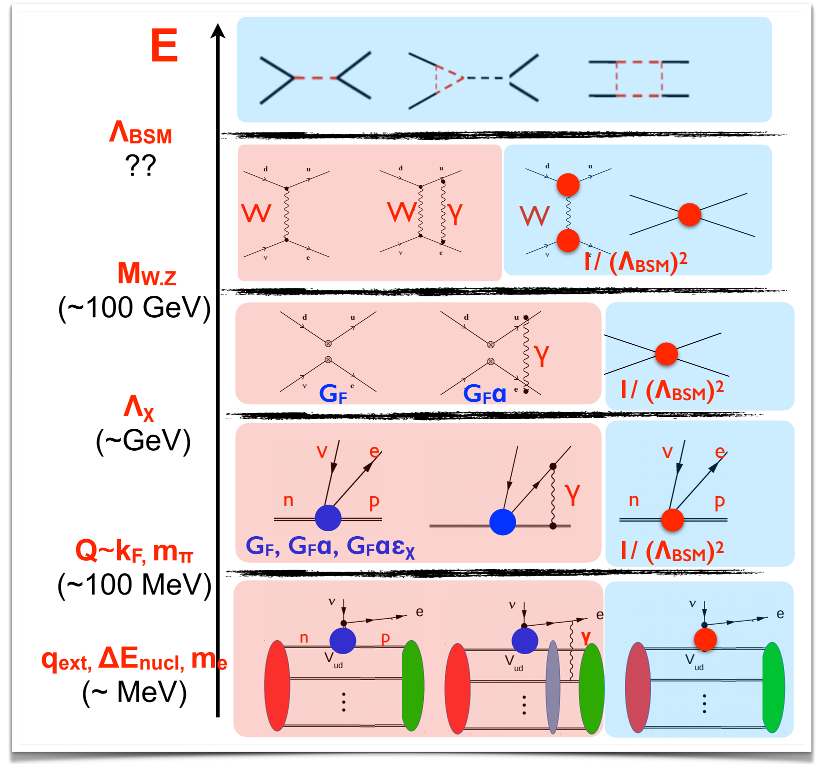


Summary and outlook

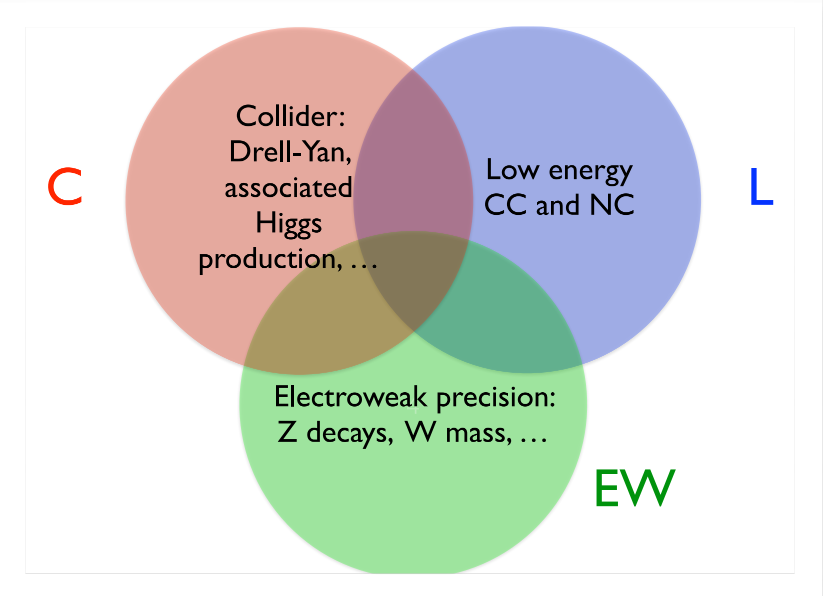
- ChEFT and SMEFT work together to sharpen the Cabibbo universality test, one of few low-energy "cracks" in the SM, probing effective scales up to $\Lambda \sim 20$ TeV.



- Chiral EFT:
  - Framework for computing radiative correction and achieve robust uncertainty
  - Uncovered new effects in neutron and nuclear decays, relevant at the 0.02% precision



- SMEFT
  - CLEW framework is necessary for consistent analysis of precision β decays
  - RH CC 'explanation' survives the flavor-assumption-independent CLEWed analysis
  - A SMEFT-based 'model selection' analysis (with AIC or other metric) can be insightful in dealing with current / future anomalies



Backup

LEFT → ChPT matching (I)

....
Knecht et al, hep-ph/9909284
Descotes-Genon & Moussallam hep-ph/0505077

- Trick: introduce electromagnetic ($q_{L,R}$) and weak (q_W) spurions in LEFT

$$\mathcal{L}_{\rm LEFT} = \bar{q}_L \not{l} q_L + \bar{q}_R \not{r} q_R - e\left(\bar{q}_L \mathbf{q}_L \not{A} q_L + \bar{q}_R \mathbf{q}_R \not{A} q_R\right) + \left(\bar{e}_L \gamma_\rho \nu_{eL}\, \bar{q}_L \mathbf{q}_W \gamma^\rho q_L + \text{h.c.}\right) + \ldots + \mathcal{L}_{\rm LEFT}^{\rm CT}$$

Classical sources $\bar{l}_\mu \;\; \bar{r}_\mu$ $\qquad \mathbf{q}_L = \mathbf{q}_R = \text{diag}(Q_u, Q_d),$ $\qquad \mathbf{q}_W = -2\sqrt{2}\,\mathrm{G_F} V_{ud} C^r_\beta\, \tau^+$

- Invariance under local G = $SU(2)_L \times SU(2)_R \times U(1)_V$

  if spurions transform as

$$q_L \to L(x) e^{i\alpha_V(x)} q_L, \quad q_R \to R(x) e^{i\alpha_V(x)} q_R$$
$$\mathbf{q}_R \to R \mathbf{q}_R R^\dagger \qquad \mathbf{q}_{L,W} \to L \mathbf{q}_{L,W} L^\dagger$$

- Matching: will require that the LEFT and ChPT generating functionals lead to same Green functions

$$e^{iW_{\rm LEFT}[\mathbf{q}_L, \mathbf{q}_R, \mathbf{q}_W, \ldots]} = \int [d\Phi]_{\rm LEFT}\; e^{i\int dx \mathcal{L}_{\rm LEFT}[\mathbf{q}_L, \mathbf{q}_R, \mathbf{q}_W, \ldots]}$$

LEFT → ChPT matching (2)

- Include electroweak spurions in ChPT, by constructing operators invariant under G

O(p)

$$\mathcal{L}^{p}_{\pi N} = \bar{N}_v iv \cdot (\partial + \Gamma) N_v + g_A^{(0)} \bar{N}_v S \cdot u N_v$$

$$u = \exp(i\boldsymbol{\pi} \cdot \boldsymbol{\tau}/(2F_\pi))$$

$$\Gamma_\mu = \frac{1}{2}\left[u(\partial_\mu - il_\mu)u^\dagger + u^\dagger(\partial_\mu - ir_\mu)u\right] \qquad u_\mu = i\left[u^\dagger(\partial_\mu - ir_\mu)u - u(\partial_\mu - il_\mu)u^\dagger\right]$$

$$l_\mu = \bar{l}_\mu - e\mathbf{q}_L A_\mu + \mathbf{q}_W\, \bar{e}_L \gamma_\mu \nu_{eL} + \mathbf{q}_W^\dagger \bar{\nu}_{eL} \gamma_\mu e_L,$$
$$r_\mu = \bar{r}_\mu - e\mathbf{q}_R A_\mu.$$

O(e²p)

$$\mathcal{L}^{e^2p}_{\pi N\ell} = e^2 \sum_{i=1}^{6} \bar{e}_L \gamma_\rho \nu_{eL} \bar{N}_v \left(V_i v^\rho - 2A_i g_A^{(0)} S^\rho\right) \mathrm{O}_i N_v + \mathrm{h.c.}$$

$$\mathrm{O}_1 = [\mathcal{Q}_L, \mathcal{Q}_L^W], \qquad \mathrm{O}_2 = [\mathcal{Q}_R, \mathcal{Q}_L^W],$$
$$\mathrm{O}_3 = \{\mathcal{Q}_L, \mathcal{Q}_L^W\}, \qquad \mathrm{O}_4 = \{\mathcal{Q}_R, \mathcal{Q}_L^W\},$$
$$\mathrm{O}_5 = \langle \mathcal{Q}_L \mathcal{Q}_L^W \rangle, \qquad \mathrm{O}_6 = \langle \mathcal{Q}_R \mathcal{Q}_L^W \rangle.$$

$$\mathcal{Q}_L = u\mathbf{q}_L u^\dagger$$
$$\mathcal{Q}_R = u^\dagger \mathbf{q}_R u,$$
$$\mathcal{Q}_L^W = u\mathbf{q}_W u^\dagger$$

Operators included in CLEW analysis

CLEW analysis with no assumption about flavor symmetry requires 37 couplings

Global analysis	Indices (mass eigenstates)
$\underset{pr}{C^{(1,3)}_{Hl}}\,,\quad \underset{pr}{C_{He}}$	$pr \in \{ee,\ \mu\mu,\ \tau\tau\}$
$\underset{pr}{C^{(d)}_{Hq}}\,,\quad \underset{pr}{C_{Hd}}$	$pr \in \{11, 22, 33\}$
$\underset{pr}{C^{(u)}_{Hq}}\,,\quad \underset{pr}{C_{Hu}}$	$pr \in \{11, 22\}$
$\underset{pr}{C_{Hud}}$	$pr \in \{11, 12\}$
$\underset{\ell\ell pr}{C^{(d)}_{lq}}\,,\quad \underset{\ell\ell pr}{C_{ledq}}$	$\ell \in \{e, \mu\}\,,\quad pr \in \{11, 22\}$
$\underset{\ell\ell 11}{C^{(u)}_{lq}}\,,\quad \underset{\ell\ell 11}{\bar{C}^{(1,3)}_{lequ}}$	$\ell \in \{e, \mu\}$
C_{ST}	
$\underset{2112}{C_{ll}}$	

$$\begin{pmatrix} C_{ST} \\ C_{TS} \end{pmatrix} \equiv \frac{1}{\sqrt{c_w^2 + 16 s_w^2}} \begin{pmatrix} 4s_w & c_w \\ -c_w & 4s_w \end{pmatrix} \begin{pmatrix} C_{HWB} \\ C_{HD} \end{pmatrix}$$

$$C^{(d)}_{Hq} = C^{(1)}_{Hq} + C^{(3)}_{Hq}$$

$$C^{(u)}_{Hq} = V \left[C^{(1)}_{Hq} - C^{(3)}_{Hq} \right] V^\dagger$$

$$C^{(d)}_{lq} = C^{(1)}_{lq} + C^{(3)}_{lq}$$

$$C^{(u)}_{lq} = V \left[C^{(1)}_{lq} - C^{(3)}_{lq} \right] V^\dagger$$

Electroweak precision observables

Obs.	Expt. Value		SM Prediction	
Γ_Z (GeV)	2.4955(23)	[53, 113]	2.49414(56)	[60]
σ^0_{had} (nb)	41.480(33)	[53, 113]	41.4929(53)	[60]
R^0_e	20.804(50)	[53, 113]	20.7464(63)	[60]
R^0_μ	20.784(34)	[53, 113]		
R^0_τ	20.764(45)	[53, 113]		
$A^{0,e}_{\text{FB}}$	0.0145(25)	[53, 113]	0.016191(70)	[60]
$A^{0,\mu}_{\text{FB}}$	0.0169(13)	[53, 113]		
$A^{0,\tau}_{\text{FB}}$	0.0188(17)	[53, 113]		
R^0_b	0.21629(66)	[53]	0.215880(19)	[60]
R^0_c	0.1721(30)	[53]	0.172198(20)	[60]
$A^{0,b}_{\text{FB}}$	0.0996(16)	[53]	0.10300(23)	[60]
$A^{0,c}_{\text{FB}}$	0.0707(35)	[53]	0.07358(18)	[60]
$\mathcal{A}_c$	0.67(3)	[53]	0.66775(14)	[60]
$\mathcal{A}_b$	0.923(20)	[53]	0.934727(25)	[60]
$\mathcal{A}_e$	0.1516(21)	[53]	0.14692(32)	[60]
$\mathcal{A}_\mu$	0.142(15)	[53]		
$\mathcal{A}_\tau$	0.136(15)	[53]		
$\mathcal{A}_e^{\tau\,\text{pol}}$	0.1498(49)	[53]		
$\mathcal{A}_\tau^{\tau\,\text{pol}}$	0.1439(43)	[53]		
$\mathcal{A}_s$	0.895(91)	[119]	0.935637(26)	[60]
R_{uc}	0.166(9)	[3]	0.172220(20)	[60]

Obs.	Expt. Value		SM Prediction	
m_W (GeV)	80.4335(94)	[39]	80.3545(42)	[60]
Γ_W (GeV)	2.085(42)	[3]	2.08782(52)	[60]
R_{Wc}	0.49(4)	[3]	0.50	
R_σ	0.998(41)	[114]	1	
$\text{Br}(W \to e\nu)$	0.1071(16)	[3]	0.108386(24)	[60]
$\text{Br}(W \to \mu\nu)$	0.1063(15)	[3]	0.108386(24)	[60]
$\text{Br}(W \to \tau\nu)$	0.1138(21)	[3]	0.108386(24)	[60]
$\frac{\Gamma(W\to\mu\nu)}{\Gamma(W\to e\nu)}$	0.982(24)	[3]	1	
$\frac{\Gamma(W\to\mu\nu)}{\Gamma(W\to e\nu)}$	1.020(19)	[3]		
$\frac{\Gamma(W\to\mu\nu)}{\Gamma(W\to e\nu)}$	1.003(10)	[3]		
$\frac{\Gamma(W\to\tau\nu)}{\Gamma(W\to e\nu)}$	0.961(61)	[3]		
$\frac{\Gamma(W\to\tau\nu)}{\Gamma(W\to\mu\nu)}$	0.992(13)	[3]		
$A_4(0-0.8)$	0.0195(15)	[115]	0.0144(7)	[116]
$A_4(0.8-1.6)$	0.0448(16)	[115]	0.0471(17)	[116]
$A_4(1.6-2.5)$	0.0923(26)	[115]	0.0928(21)	[116]
$A_4(2.5-3.6)$	0.1445(46)	[115]	0.1464(21)	[116]
$g_V^{(u)}$	0.201(112)	[117]	0.192	[118]
$g_V^{(d)}$	-0.351(251)	[117]	-0.347	[118]
$g_A^{(u)}$	0.50(11)	[117]	0.501	[118]
$g_A^{(d)}$	-0.497(165)	[117]	-0.502	[118]

VC, W. Dekens, J. De Vries, E. Mereghetti, T. Tong, 2311.00021
And references therein