INT Workshop 26-95W
Testing the Standard Model in Charged-Weak Decays
January 12-16 2026

Beta decays as a probe of new physics

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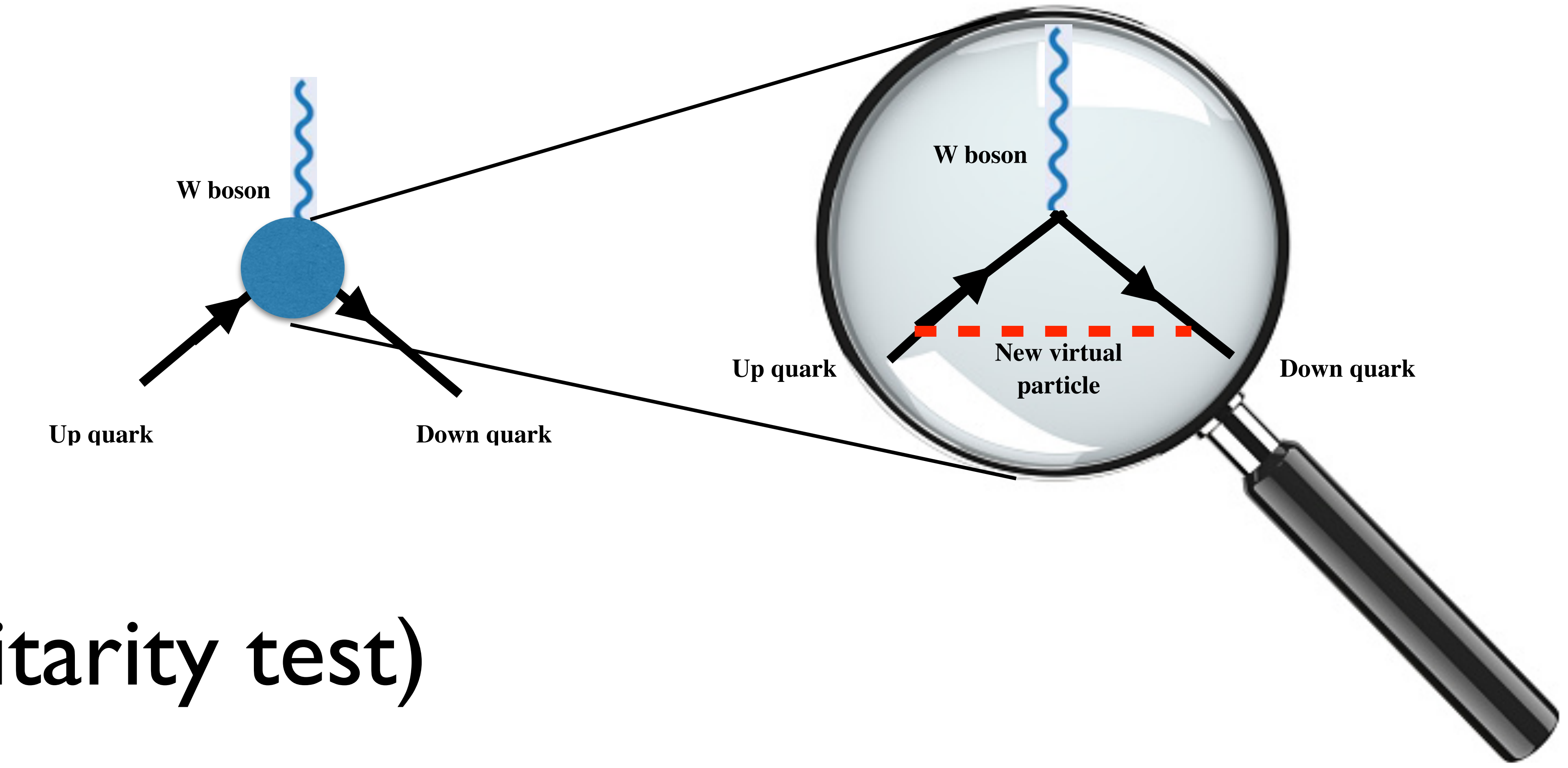
U.S. DEPARTMENT OF ENERGY
Office of Science

UNIVERSITY of WASHINGTON

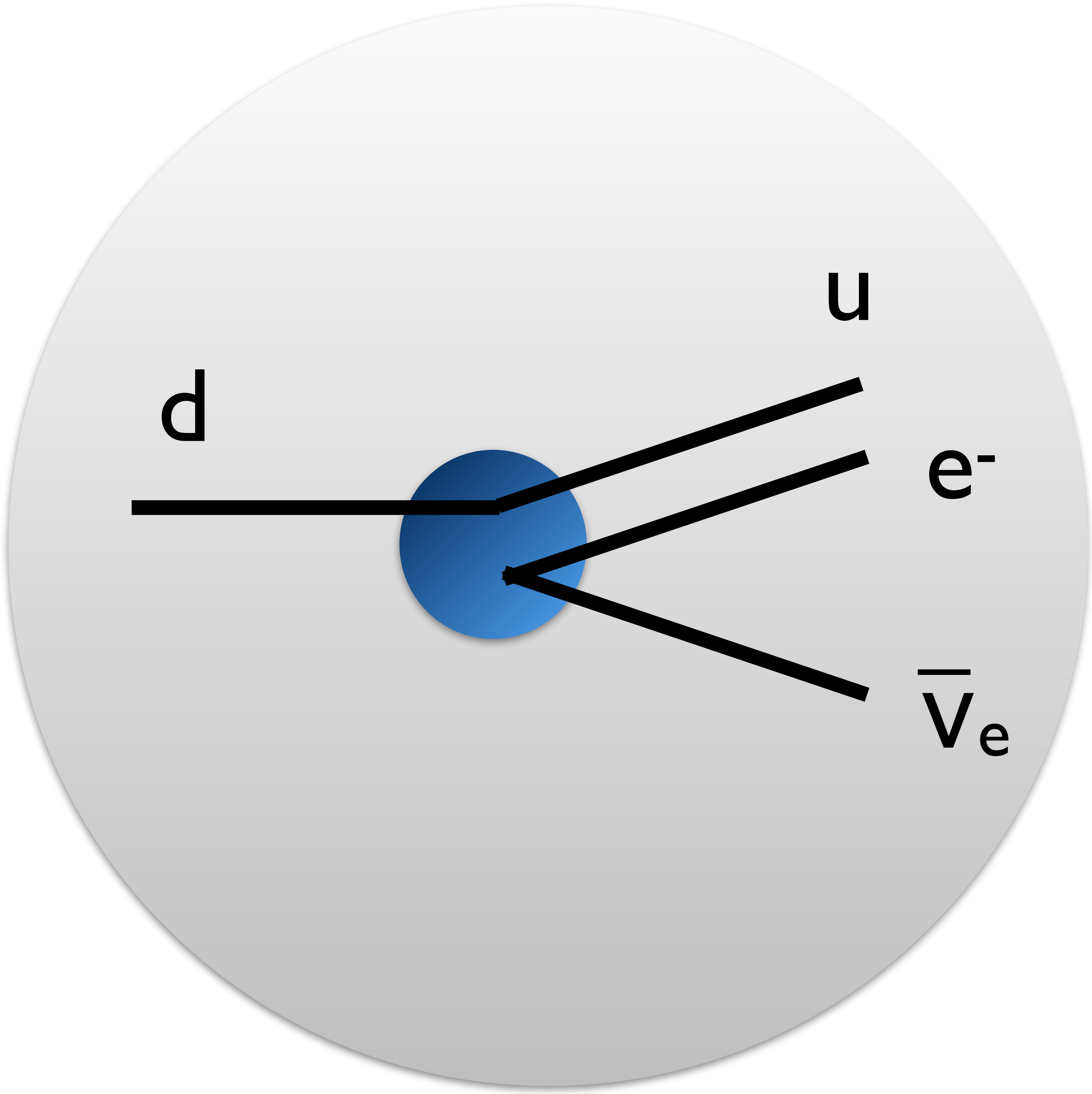
Outline



- Introduction: beta decays in the SM and beyond
- The "Cabibbo universality test" (a.k.a. 1st row CKM unitarity test)
    - Summary of current status
    - Recent progress in SM predictions
    - Implications for new physics & connection to other observables
- Conclusion and outlook

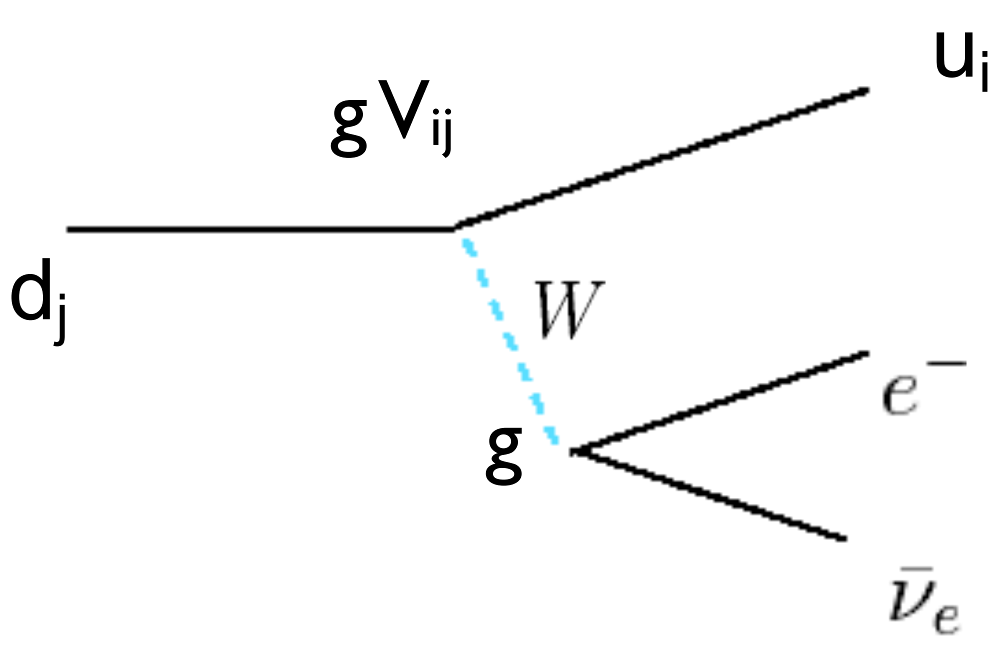
β decays in the SM and beyond

- Beta decays have played a central role in the development of the Standard Model
- Nowadays: precision measurements provide a tool to challenge the SM & probe possible new physics



β decays in the SM and beyond

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



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

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

Cabibbo-Kobayashi-Maskawa

Cabibbo Universality

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

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

Lepton Flavor Universality (LFU)

β decays in the SM and beyond

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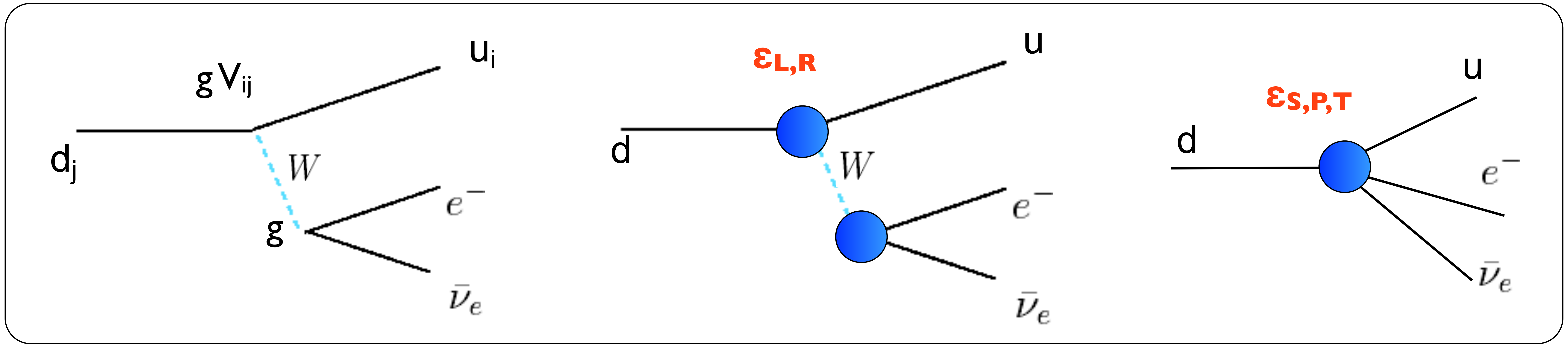
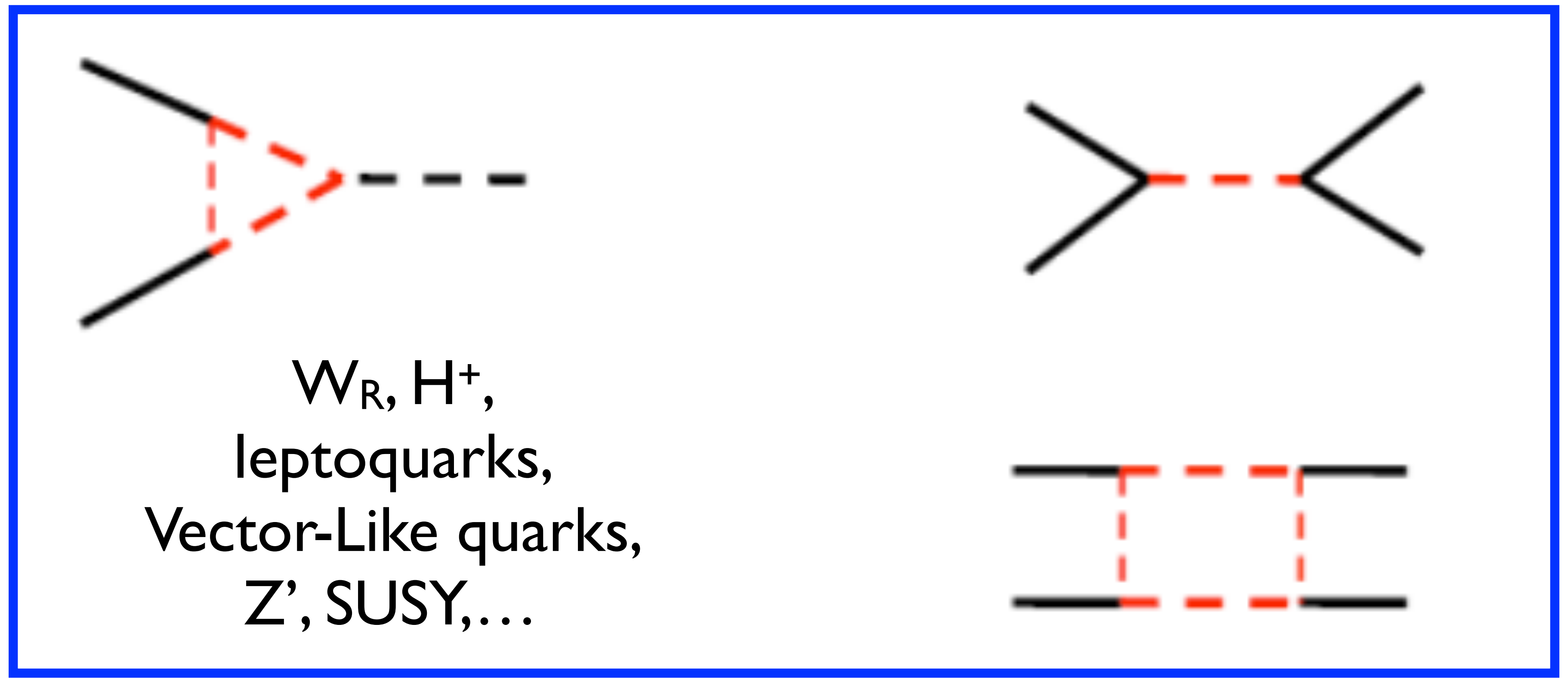


$G_F^{(\beta)} \sim G_F^{(\mu)} V_{ij} \sim 1/v^2 V_{ij}$ $1/\Lambda^2$ $1/\Lambda^2$



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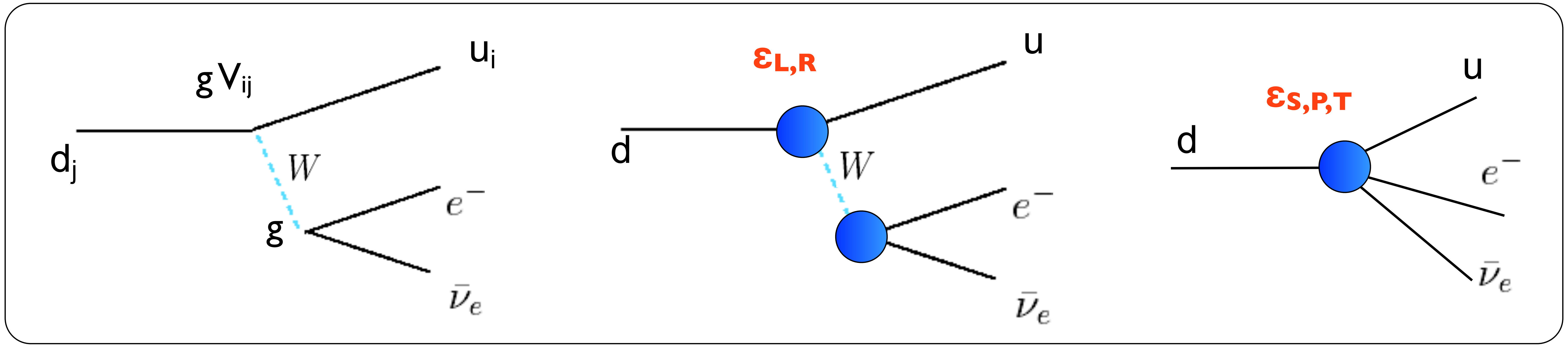


$G_F^{(\beta)} \sim G_F^{(\mu)} V_{ij} \sim 1/v^2 V_{ij}$ $1/\Lambda^2$ $1/\Lambda^2$

E << Λ ↓ $\epsilon_\Gamma \sim \tilde{\epsilon}_\Gamma \sim (v/\Lambda)^2$

$$\mathcal{L}_{\rm SM} - \frac{G_F V_{ud}}{\sqrt{2}} \sum_\Gamma \left[\epsilon_\Gamma \; \bar{\ell}\Gamma\nu_L \cdot \bar{u}\Gamma d \; + \; \tilde{\epsilon}_\Gamma \; \bar{\ell}\Gamma\nu_R \cdot \bar{u}\Gamma d \right]$$

Ten effective couplings $\Gamma = L, R, S, P, T$

- Precision of 0.1-0.01% probes Λ > 10 TeV. Several precision tests are possible….

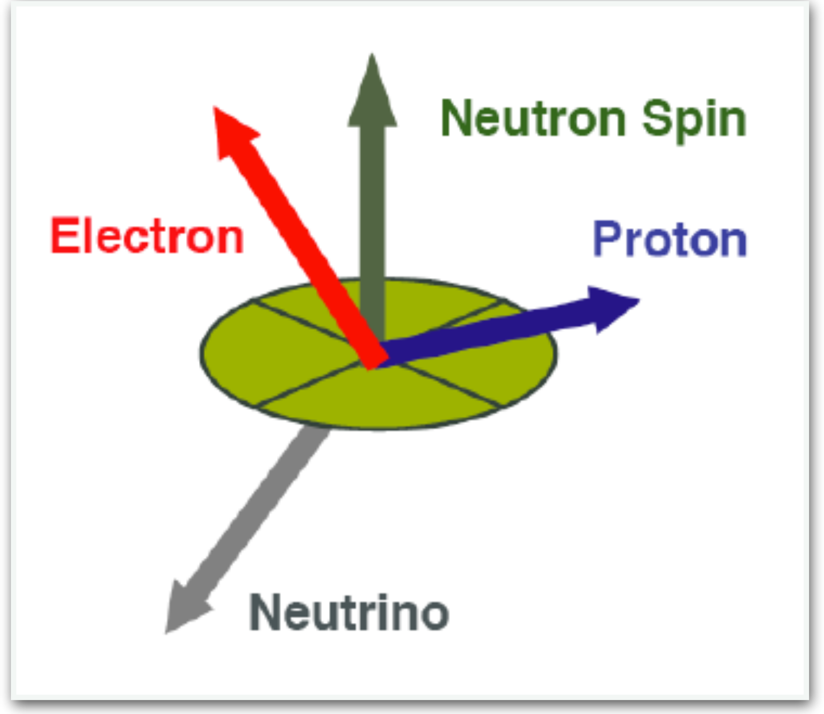
Searches for 'non V-A' currents

Measure differential decay distributions (mostly sensitive to $\varepsilon_{S,T}$)

$$d\Gamma \propto F(E_e) \left\{ 1 + b \frac{m_e}{E_e} + a \frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + \langle \vec{J} \rangle \cdot \left[A \frac{\vec{p}_e}{E_e} + B \frac{\vec{p}_\nu}{E_\nu} + \cdots \right] \right\}$$

Lee-Yang, 1956 **Jackson-Treiman-Wyld 1957**

b ($g_S \varepsilon_S$, $g_T \varepsilon_T$):
distortion of beta spectrum



a(g_A), A(g_A) , B(g_A, $g_\alpha \varepsilon_\alpha$), …
isolated via suitable experimental asymmetries

Bounds on $\varepsilon_{S,T}$ at the 0.1% level, Λ~5-10 TeV

Cabibbo universality test

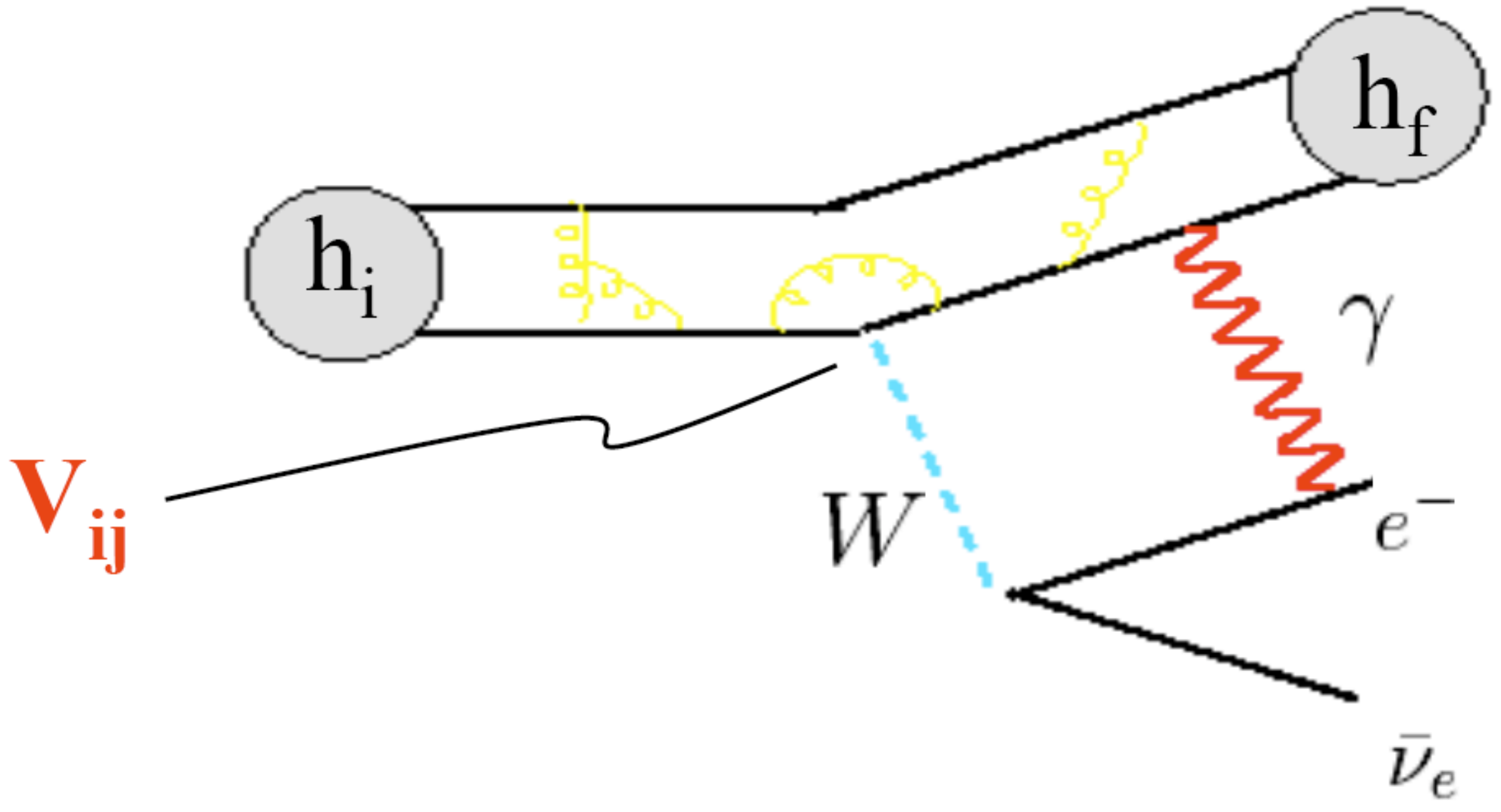
Extract $V_{ud}=\cos\theta_C$ and $V_{us}=\sin\theta_C$ from total decay rates

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

Channel-dependent effective CKM element (Contaminated by the BSM ε's)

Hadronic / nuclear matrix element

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



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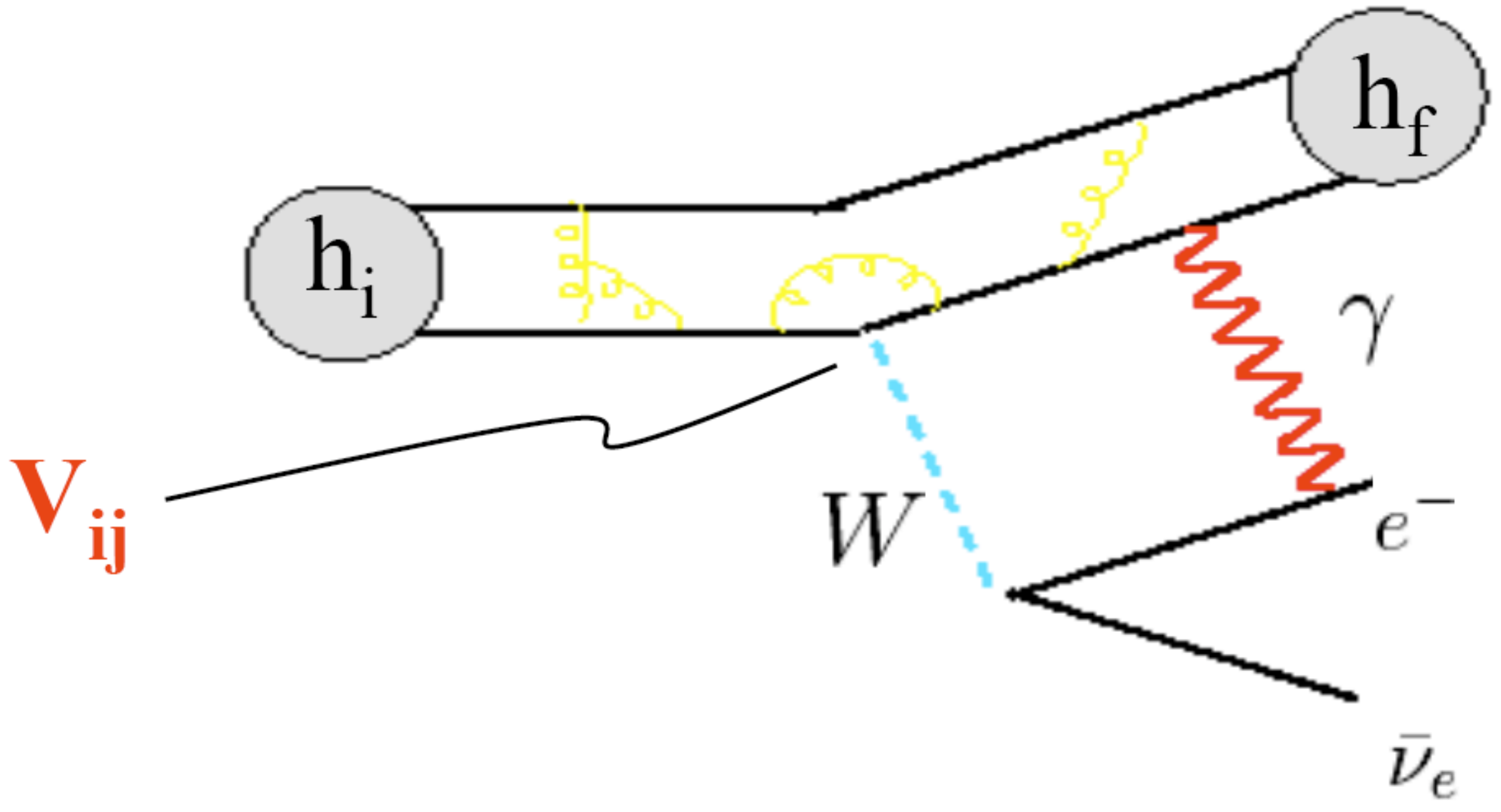
Unitarity test

$$\Delta_{\text{CKM}} \equiv |V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 - 1 = \mathcal{O}\left(\frac{v^2}{\Lambda^2}\right)$$

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**



Matrix elements

	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}	$K \to \pi\, l\, \nu$	$\Lambda \to p e \nu, \ldots$	$K \to \mu\nu$	$\tau \to h_{S}\nu$

Hadronic matrix elements: 'Vector - Axial' quark current

V

V, A

A

V, A

Berhends-Sirlin
Ademollo-Gatto

Traditionally "Golden modes":
$<f|V_\mu|i>$ known in SU(2) [SU(3)] limit
&
corrections are 2nd order in
SU(2) [SU(3)] breaking.
Computed in lattice QCD for $K \to \pi$

Need experimental input on
$<f|A|i> / <f|V|i>$

For neutron and hyperons,
Lattice QCD catching up but
not as precise as experiment

$<0|A_\mu|M>$
(decay constants)
from Lattice QCD
[~0.2%]

Use combination of
data and theory
(pQCD + lattice QCD)

Radiative corrections

	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	$\pi \to \mu \nu$	$\tau \to h_{NS} \nu$
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Electroweak radiative corrections

Mesons and neutron:
well developed perturbative framework, with non-perturbative input from lattice QCD and / or dispersive methods

For leptonic meson decays:
full lattice QCD+QED available

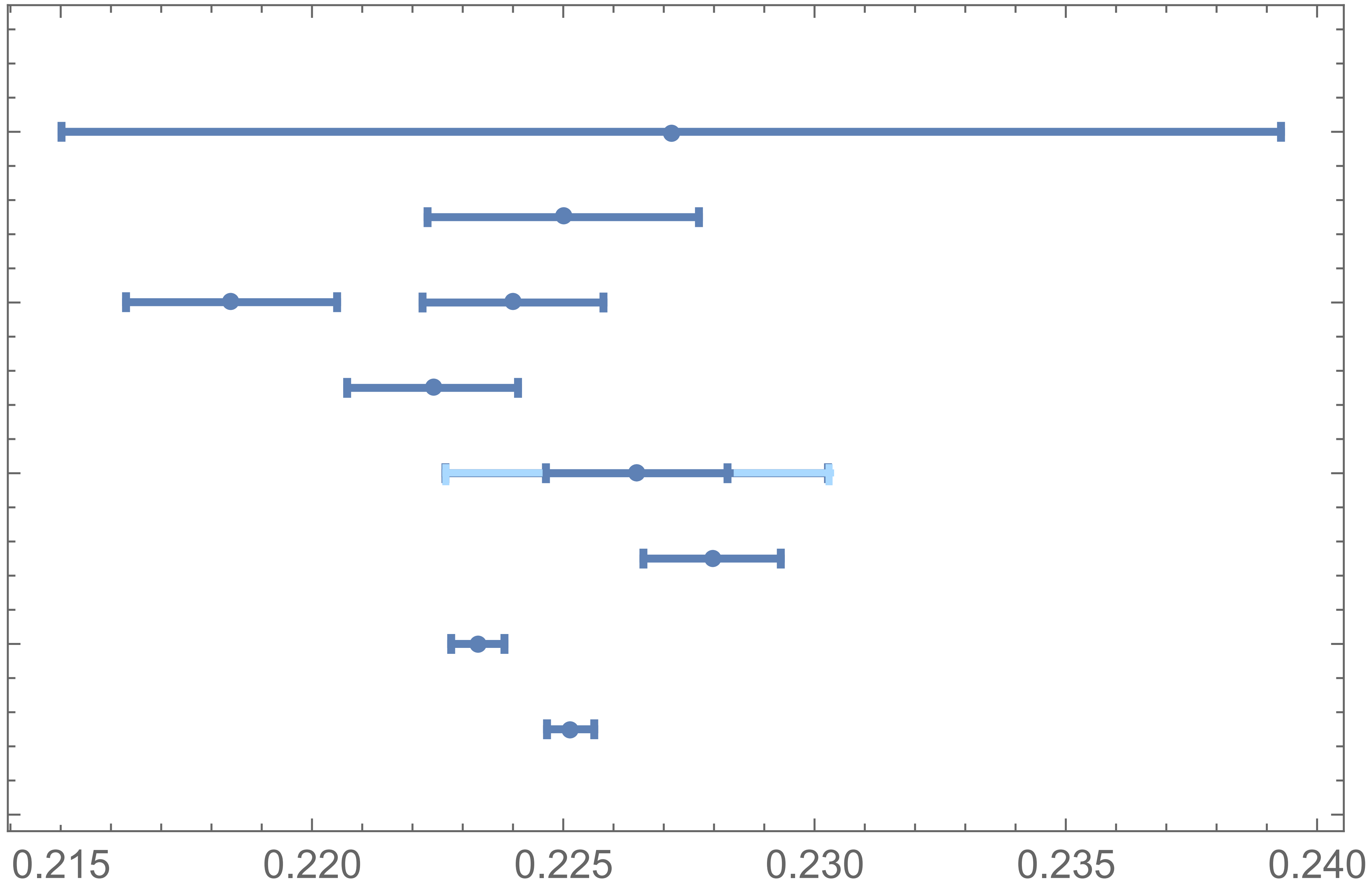
Recent activity to assess nuclear structure uncertainties:

- Dispersive approach
- Chiral EFT

For exclusive channels, difficult to estimate the hadronic structure-dependent effects. Lattice QCD+QED?

The Cabibbo angle — global view

Convert V_{ud} to V_{us} via unitarity

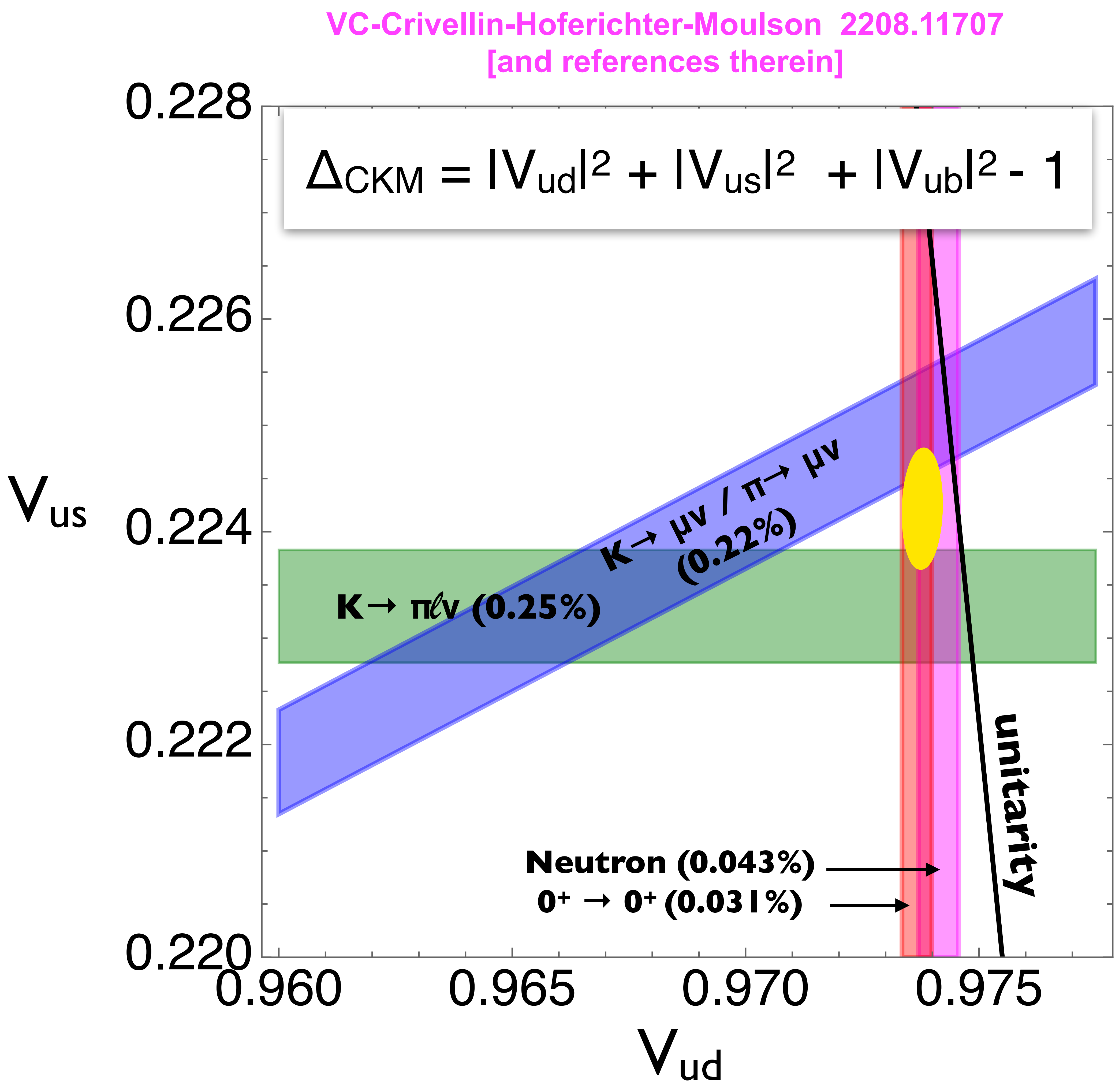


V_{us}

	Fractional uncertainty	Largest uncertainty
$\pi^{\pm} \to \pi^{0} e \nu$	5.3%	EXP
Hyperons	1.2% +?	EXP + TH
τ inclusive	0.8% + ?	EXP + TH
τ exclusive	0.8% + ?	EXP + TH
$n \to p e \nu$	0.8% (1.7%) (PDG)	EXP
$0^{+} \to 0^{+}$	0.6% + ?	TH
$K \to \pi l \nu$	0.24%	EXP + TH
$K \to \mu\nu \;/\; \pi \to \mu\nu$	0.21%	TH

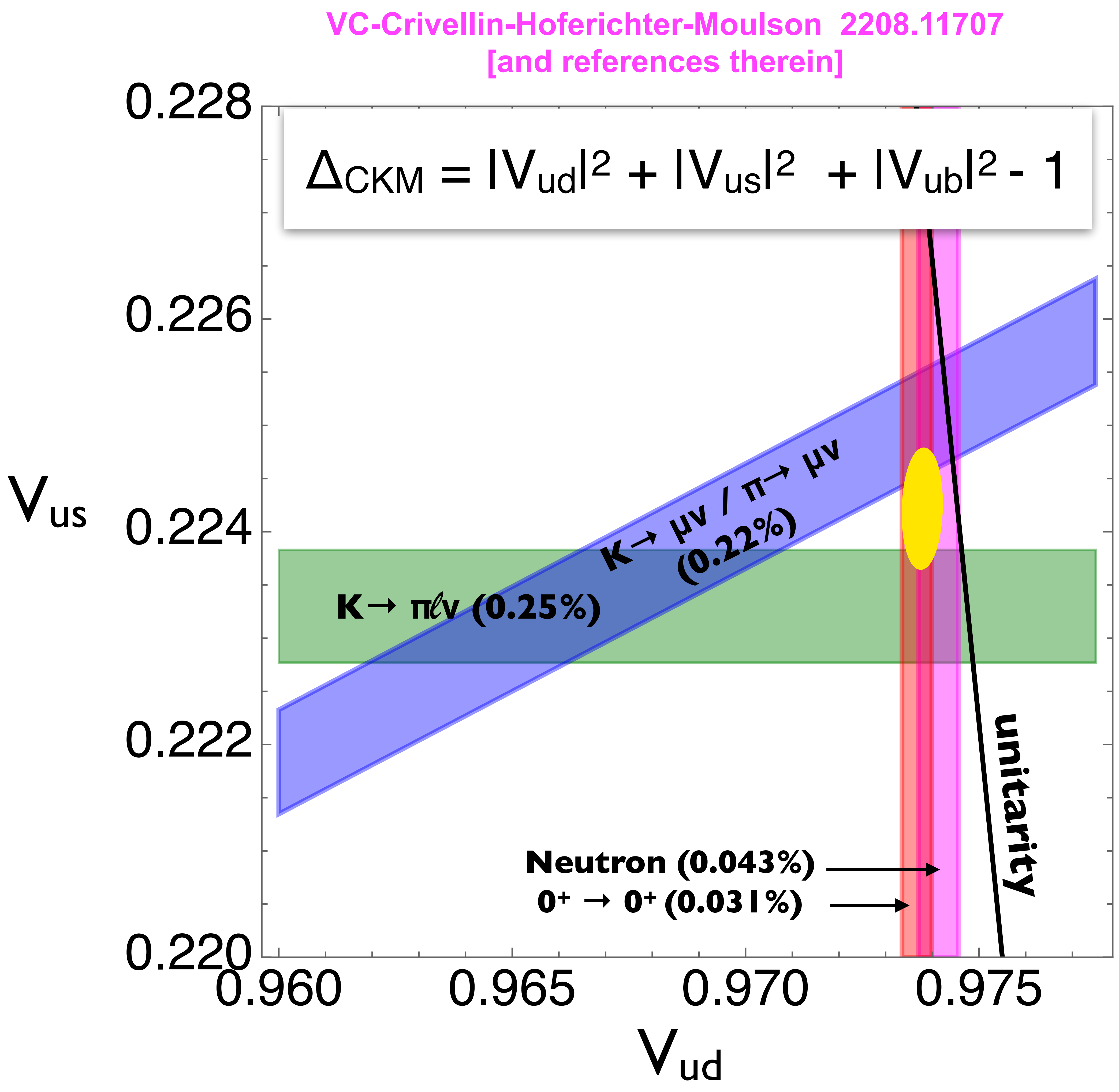
Tension among the most precise determinations

Tensions in the V_{ud}-V_{us} plane



- Bands don't intersect in the same region on the unitarity circle
- ~3σ problem even in meson sector (Kl2 vs Kl3)
- ~3σ effect in global fit ($\Delta_{CKM} = -1.48(53) \times 10^{-3}$)

Tensions in the V_{ud}-V_{us} plane

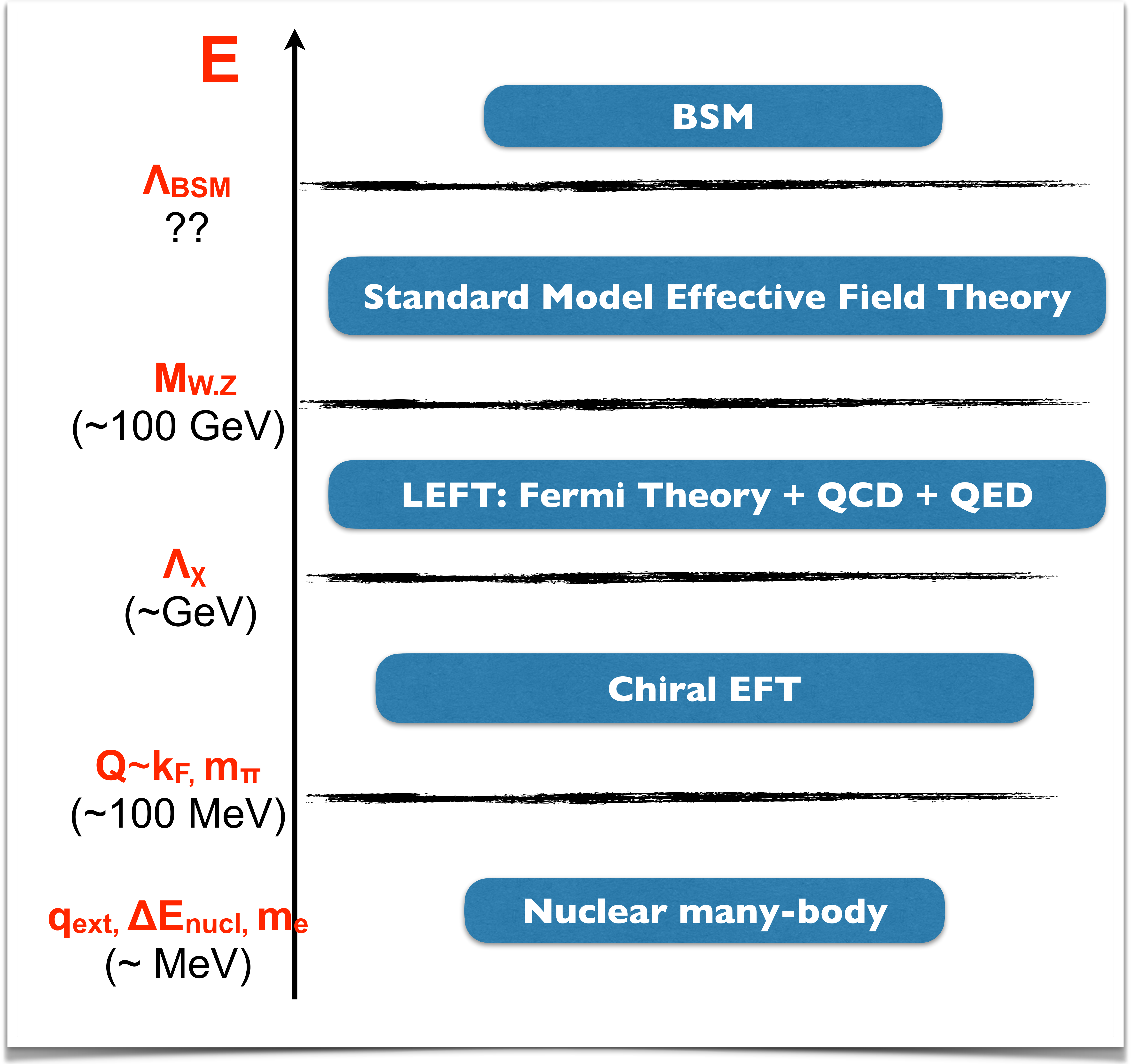


Cabibbo angle anomaly?

- Needed / expected experimental scrutiny:
  - 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 scrutiny:
  - Standard Model predictions with few $\times$ 10^{-4} precision!
  - Study possible BSM explanations that survive the constraints from other precision tests and the LHC

Theory for β decays

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



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

Connection to explicit new physics models

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

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

Non-perturbative input from Lattice QCD and dispersive methods

$\varepsilon_\chi = Q/\Lambda_\chi$

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

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

Theory for β decays

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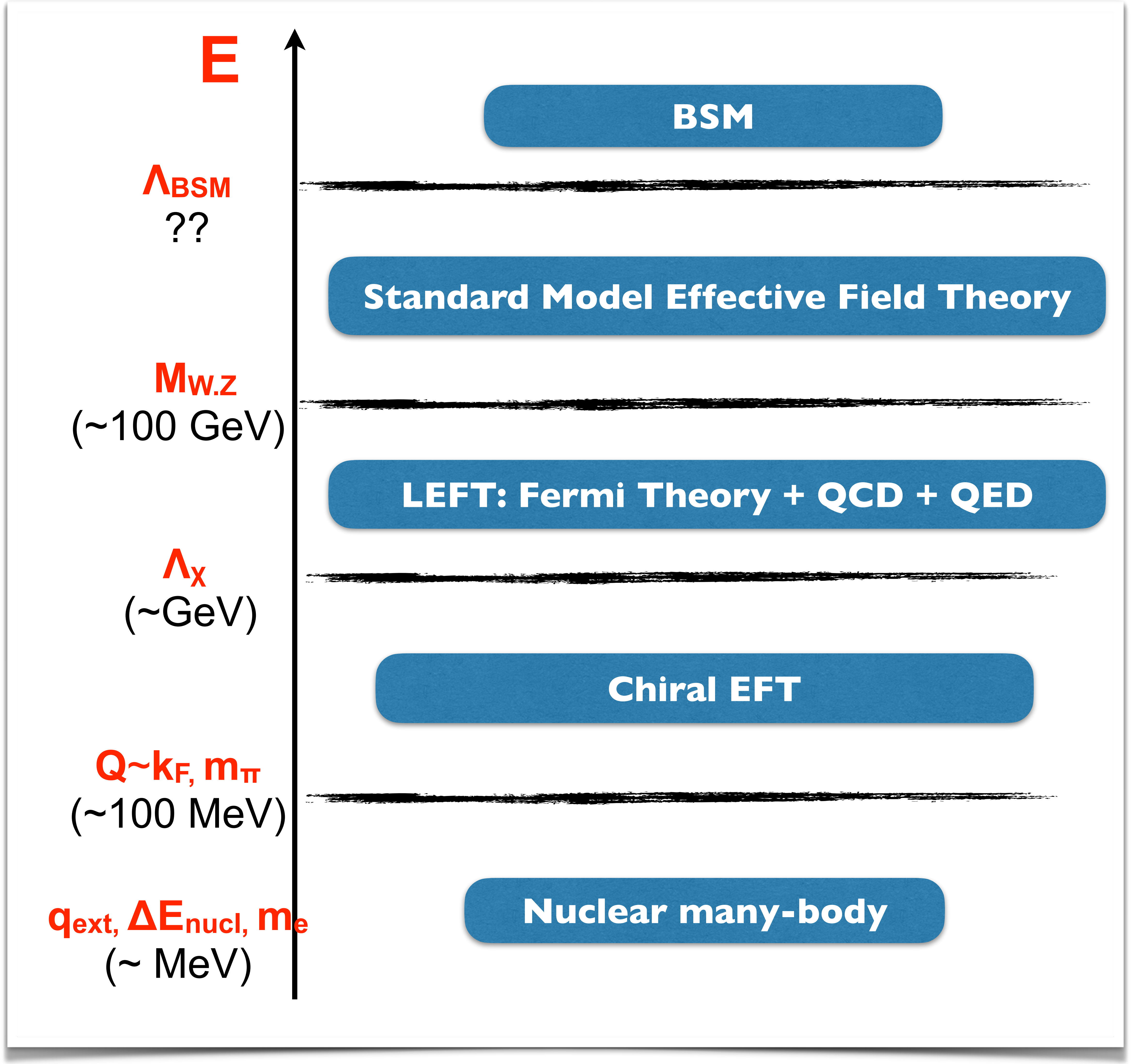

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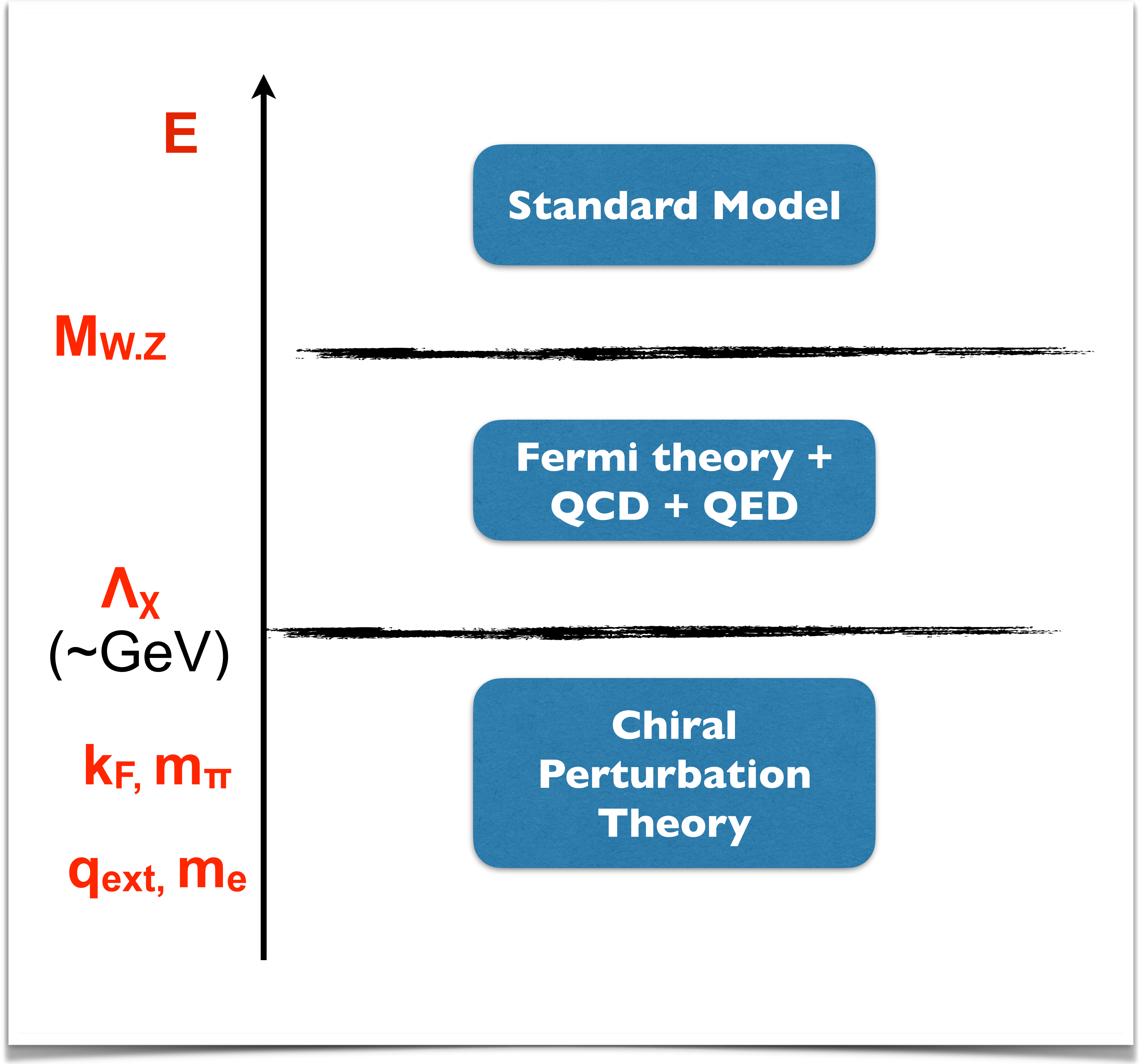
Framework to
(1) organize / improve the Standard Model predictions
(2) study the effects of new physics

Improving the SM predictions

Intense recent theoretical activity on several fronts



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

- Short distance electroweak corrections to NLL ($C_\beta(\mu)$)
- Computation of matrix elements to $O(\alpha)$ and beyond
  - Dispersive methods
  - Lattice QCD
  - EFT for single- and multi-nucleon systems, nuclei
  - First-principles nuclear structure calculations

Improving the SM predictions

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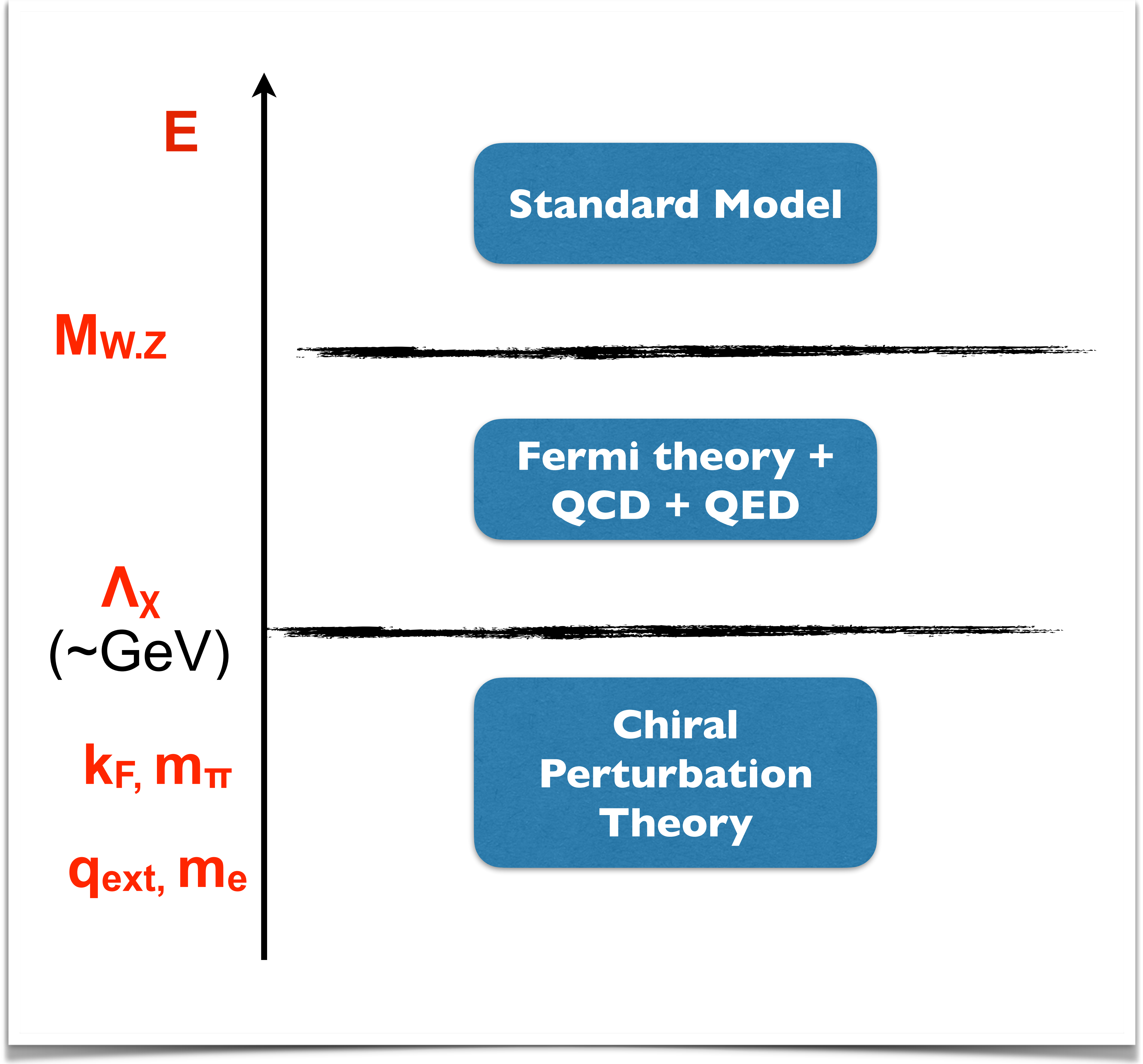

$$\mathcal{L}_{\rm Fermi} = -\frac{G_F}{\sqrt{2}} V_{ud}\, C_\beta(\mu)\ \bar{\ell}\gamma_\alpha(1-\gamma_5)\nu_\ell\, \bar{u}\gamma^\alpha(1-\gamma_5)d + \ldots$$

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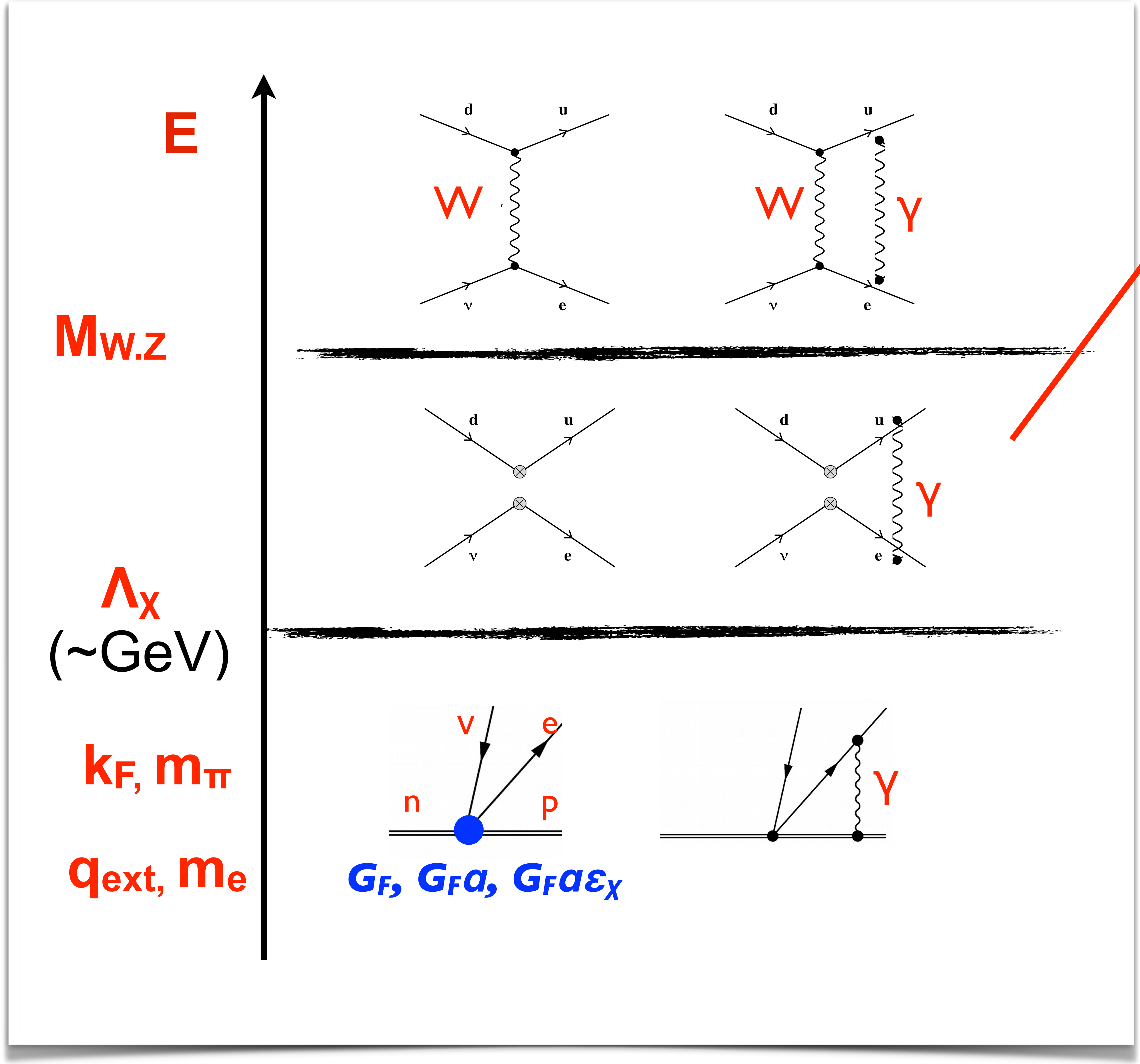
We will hear about most of these during the workshop.
In this talk I discuss progress in neutron decay

EFT machinery at work: neutron decay



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$$C_\beta(\mu) \sim 1 + (\alpha/\pi)\,(k_1 \ln(M_W/\mu) + k_2) + (\alpha/\pi)\,(\alpha_s/\pi)\,(k_3 \ln(M_W/\mu) + k_4) + O((\alpha/\pi)^2)$$

Resummation of large logarithms:

LL ~ $(\alpha \ln(M_W/\mu))^n$ & $\alpha\, (\alpha_s \ln(M_W/\mu))^n$ — Sirlin 1982

NLL ~ $\alpha\, (\alpha \ln(M_W/\mu))^n$ & $\alpha\, \alpha_s\, (\alpha_s \ln(M_W/\mu))^n$

VC, W. Dekens, E. Mereghetti, O. Tomalak, 2306. 03138
Adapted from Buras-Weisz '90

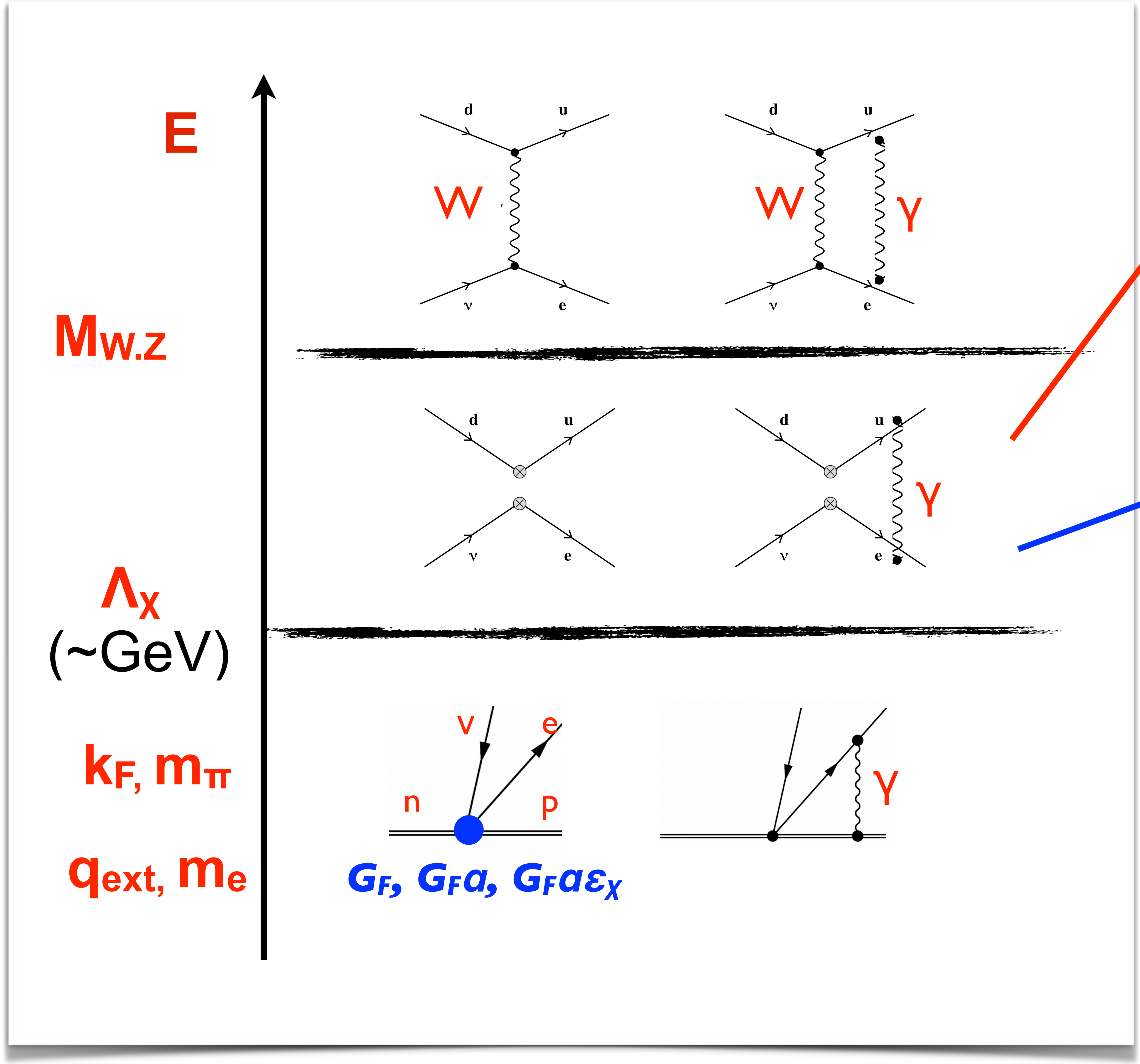
2-loops

M. Gorbahn, F. Moretti, S. Jaeger
2510.27648

3-loops

This improvement applies to all decays

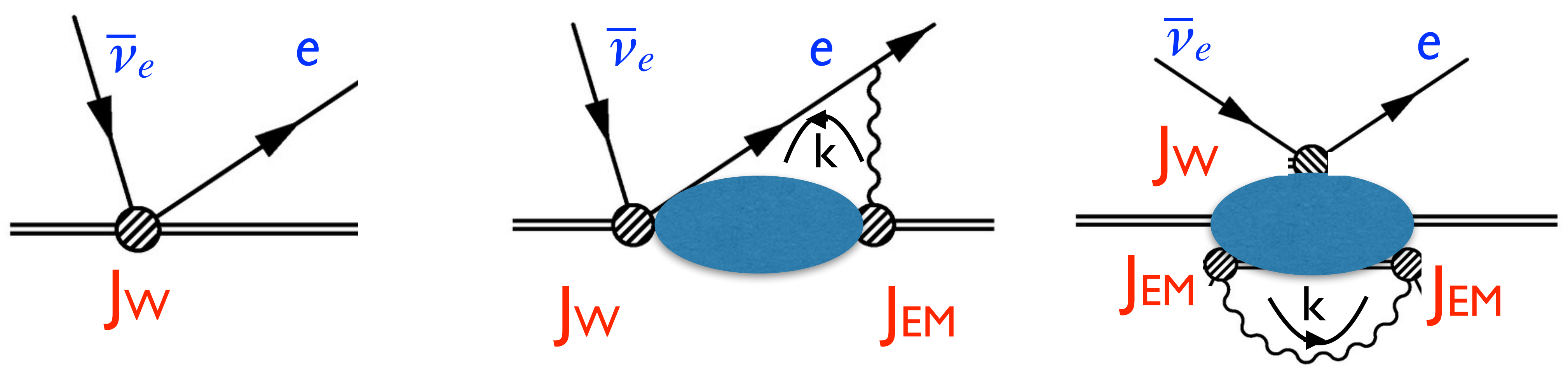
EFT machinery at work: neutron decay



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

Matrix elements to O(α)

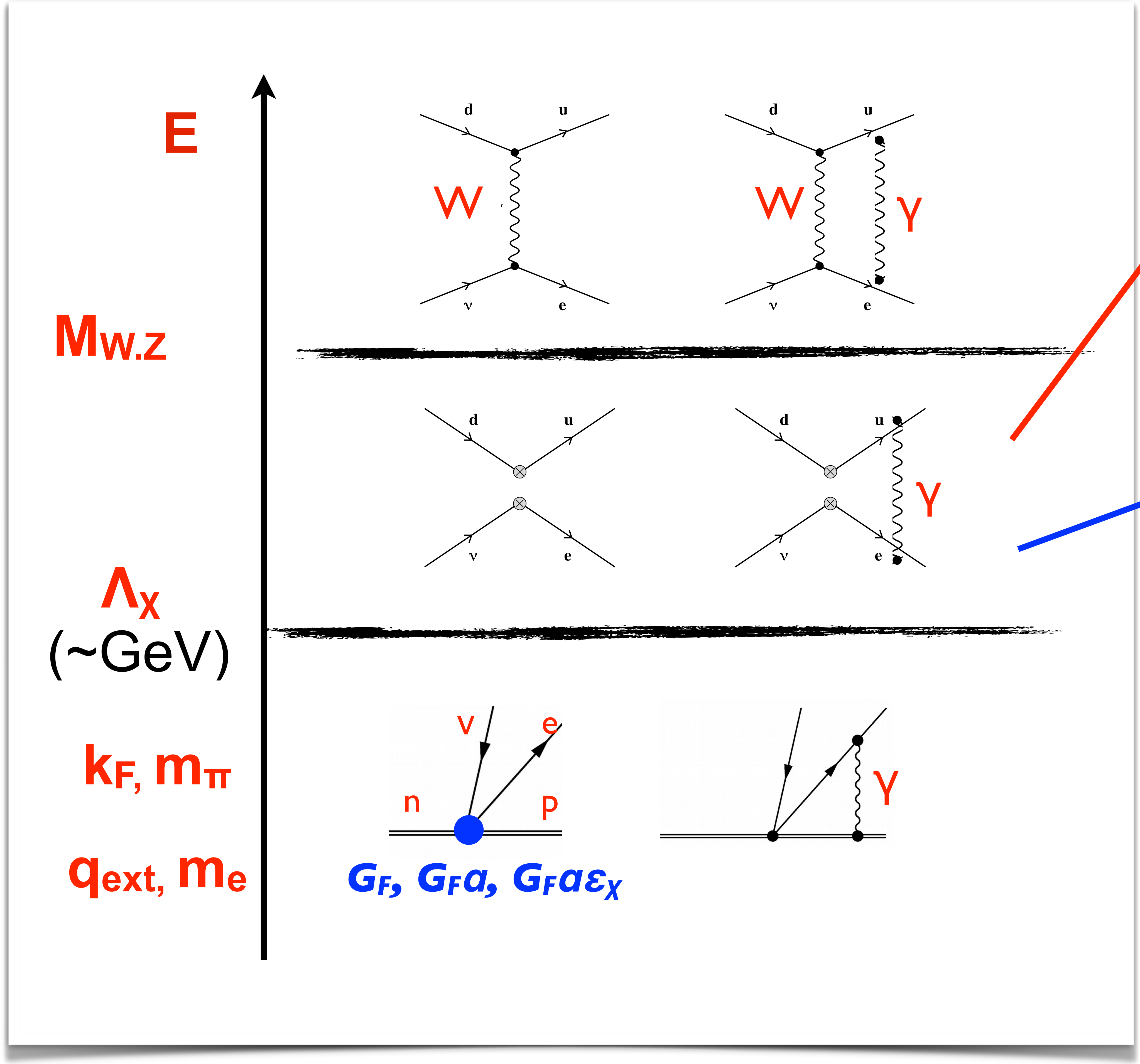
$\langle f|$ $|i\rangle$



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 machinery at work: neutron decay



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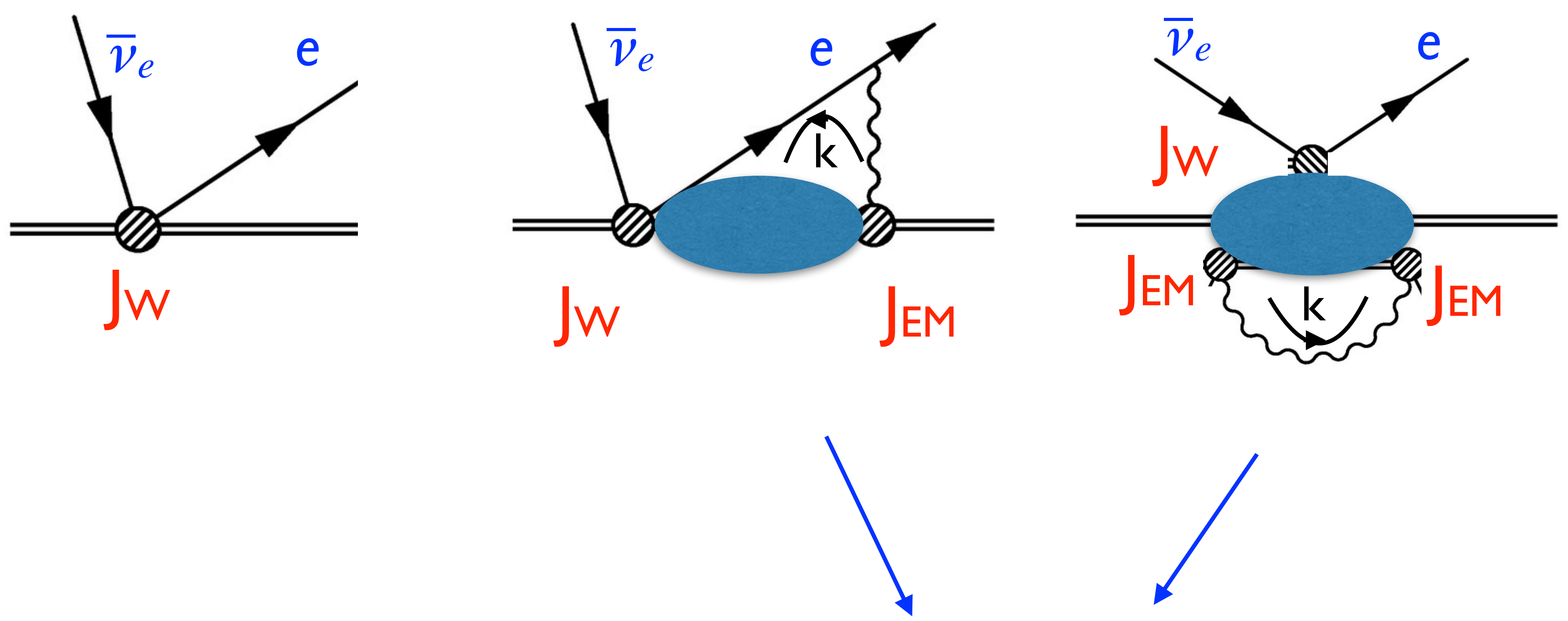
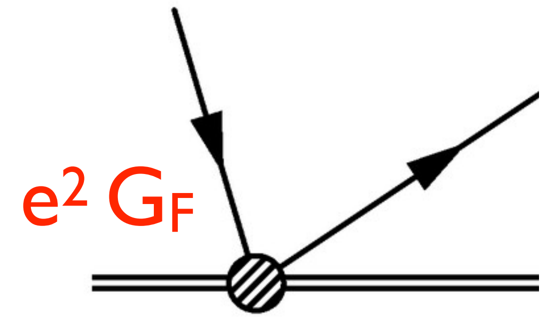
Matrix elements to O(α)

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



Hard photons
[(k^0, |**k**|) >~ Λ_χ ~ m_N ~ GeV]
leave behind local
interactions at low energy



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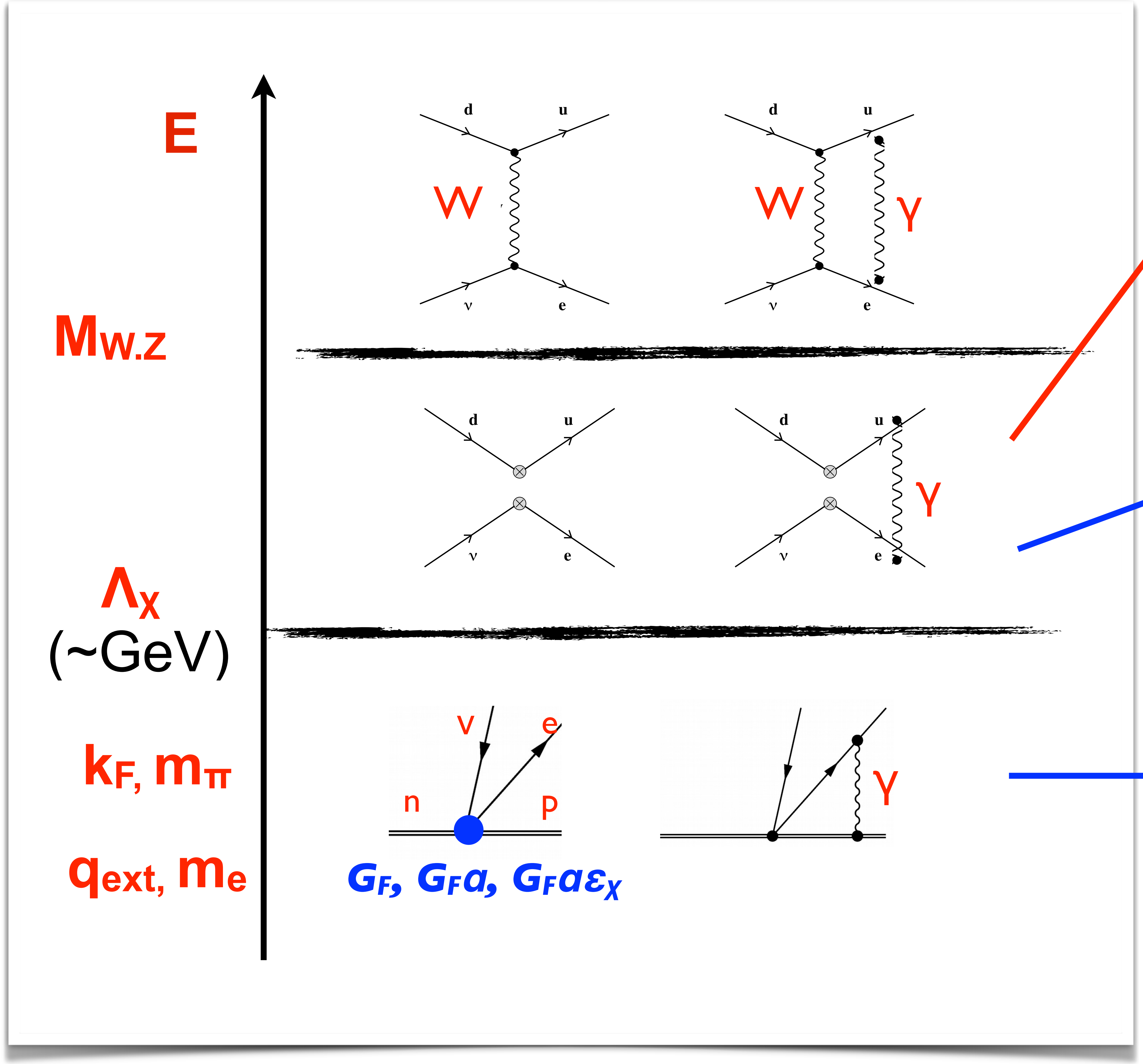

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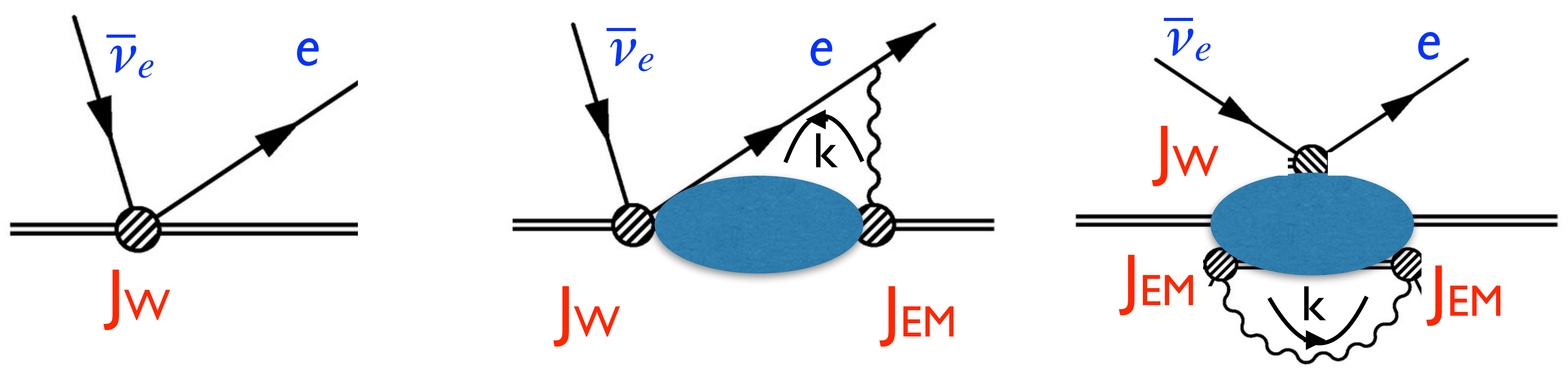
Matrix elements to O(α)

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



Baryon ChPT with dynamical leptons and photons (soft / ultrasoft)

$$\mathcal{L}_{\pi\!\!\!/} = -\sqrt{2} G_F V_{ud}\ \bar{e}\gamma_\mu P_L \nu_e\ \bar{N}\left(g_V v_\mu - 2 g_A S_\mu\right)\tau^+ N\ + \ \ldots$$

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

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

Combination of chiral LECs of O(e²p)

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

Evolving from high- to low-scale

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

- The effective vector coupling

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

NLL RGE in LEFT @ μ_{LEFT} : $\mu_W \to \Lambda_\chi$

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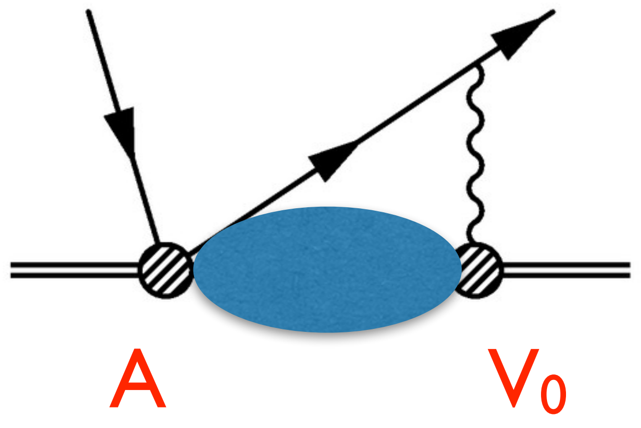
NLL RGE in LEFT @ $\mu_{\rm LEFT}$: $\mu_W \to \Lambda_\chi$

Non-perturbative contribution proportional to the γ-W 'box', suitably matched to cancel 'scheme choices' in NLL RGE evolutions



$$\overline{\Box}^V_{\rm had}(\mu_0) = \frac{e^2}{i}\int \frac{d^4q}{(2\pi)^4}\frac{\nu^2+Q^2}{Q^4}\left[\frac{T_3(\nu,Q^2)}{2m_N\nu} - \frac{2}{3}\frac{1}{Q^2+\mu_0^2}\left(1-\frac{\alpha_s(\mu_0^2)}{\pi}\right)\right].$$

Seng et al. 1807.10197, Ma et al. 2308.16755
Czarnecki-Marciano-Sirlin, 1907.06737
Hayen 2010.07262
Shiells-Blunden-Melnitchouk 2012.01580

Evolving from high- to low-scale

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

- The effective vector coupling

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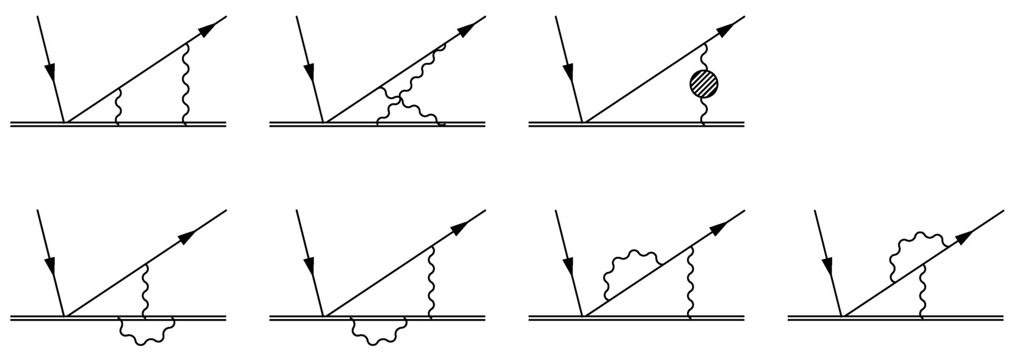
NLL RGE in LEFT @ $\mu_{\rm LEFT}$: $\mu_W \to \Lambda_\chi$

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

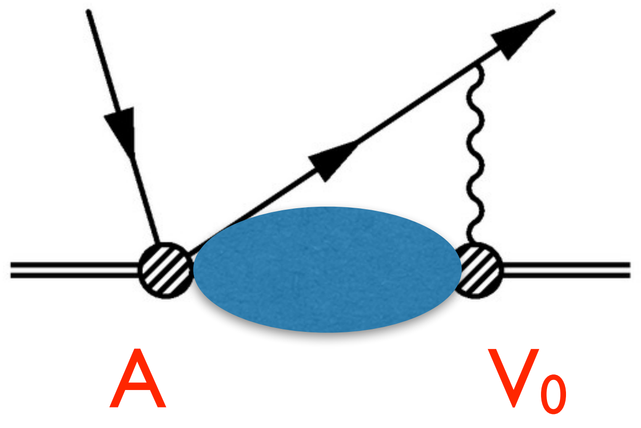
LL~ $(\alpha \ln(\Lambda_\chi/m_e))^n$ $\mu_\chi \sim m_e$

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



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

Non-perturbative contribution proportional to the γ-W 'box', suitably matched to cancel 'scheme choices' in NLL RGE evolutions



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

- The effective vector coupling

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

- Need input on hadronic box up to $Q^2 = 2$ GeV^2

Combination** of dispersive results
(Used in following numerics)

$\longrightarrow$ $$\overline{\Box}^V_{\rm Had}(Q^2 \leq 2{\rm GeV}^2) = 1.56(12)\cdot 10^{-3}$$

VC-Crivellin-Hoferichter-Moulson 2208.11707 **
Seng et al. 1807.10197,
Czarnecki-Marciano-Sirlin, 1907.06737
Hayen 2010.07262
Shiells-Blunden-Melnitchouk 2012.01580

Lattice QCD

$\longrightarrow$ $$\overline{\Box}^V_{\rm Had}(Q^2 \leq 2{\rm GeV}^2) = 1.49(7)\cdot 10^{-3}$$

Ma et al. 2308.16755

More on this: Tuesday afternoon discussion

Evolving from high- to low-scale

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

- The effective vector coupling

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

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Lattice QCD $\longrightarrow$ $\overline{\Box}^V_{\rm Had}(Q^2 \leq 2{\rm GeV}^2) = 1.49(7) \cdot 10^{-3}$

Ma et al. 2308.16755

- With $g_V(\mu_\chi)$ at $\mu_\chi \sim m_e$ → compute matrix element and decay rate including virtual (ultra-soft) and real photons

Corrections to neutron decay rate

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

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

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

Δ_R: proportional to $(g_V(m_e))^2 \times (1 + O(\alpha)$ virtual and real effects from $\mathcal{L}_{\not\pi}$)

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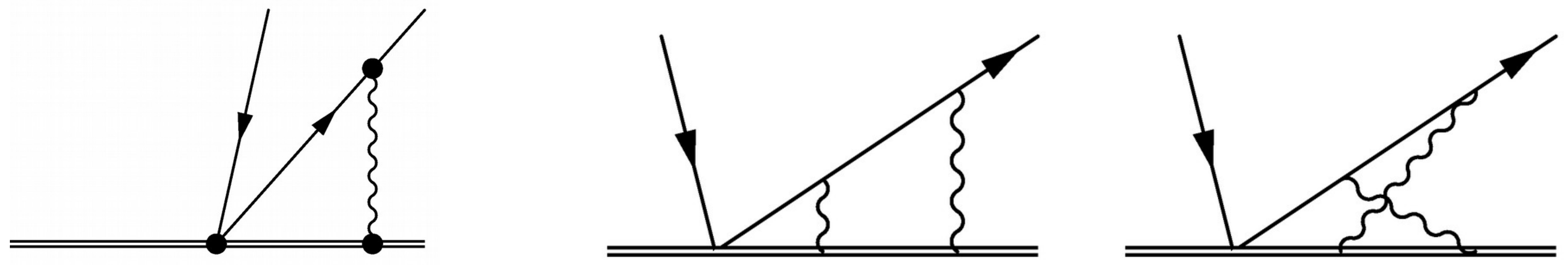
$O(\alpha^n)$ + $O(\epsilon_{recoil})$ |matrix element|^2 in the low-energy EFT



Ultra-soft photons

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

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

RG-based re-summation (for $m_e \to 0$) leads to +0.011% in Δ_f compared to our *ansatz*

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

Vander Griend-Cao-Hill-Plestid 2501.17916

Corrections to neutron decay rate

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

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

$$\Delta_f = 3.584(5)\,\%$$

Includes result from Vander Griend-Cao-Hill-Plestid 2501.17916

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

Corrections to neutron decay rate

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

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↓

4.030

Recent NLL(s) analysis
(3-loop anomalous dimension
and 2-loop finite parts) translates
into shift of -1.4 10^{-4} in Δ_R

M. Gorbahn, F. Moretti, S. Jaeger
2510.27648

Corrections to neutron decay rate

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

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CORRECTION	COMPARISON with LITERATURE*	MAIN SOURCE of DISCREPANCY
$\Delta_f = 3.584(5)\,\%$	-0.024%	'Fermi function'
$\Delta_R = 4.030(27)\%$	+0.061% - 0.014%	NLL: $\alpha^2 \, \mathrm{Log}(m_N/m_e)$
$\Delta_{TOT} = 7.758(27)\%$	+0.037% - 0.014%	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}

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

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

Maerkish et al, 1812.04666 Gonzalez et al, 2106.10375

$$V_{ud}^{\mathrm{n,PDG}} = 0.97417(2)_{\Delta_f}(13)_{\Delta_R}(82)_{\lambda}(28)_{\tau_n}[88]_{\mathrm{total}}$$

$$V_{ud}^{\mathrm{n,best}} = 0.97389(2)_{\Delta_f}(13)_{\Delta_R}(35)_{\lambda}(20)_{\tau_n}[42]_{\mathrm{total}}$$

EFT treatment revealed shifts (of different signs) in V_{ud} at the level of (1-3) x 10^{-4}

Larger than hadronic uncertainty and relevant for CKM tests

Looking forward to improvements in lifetime and $\lambda = g_A / g_V$

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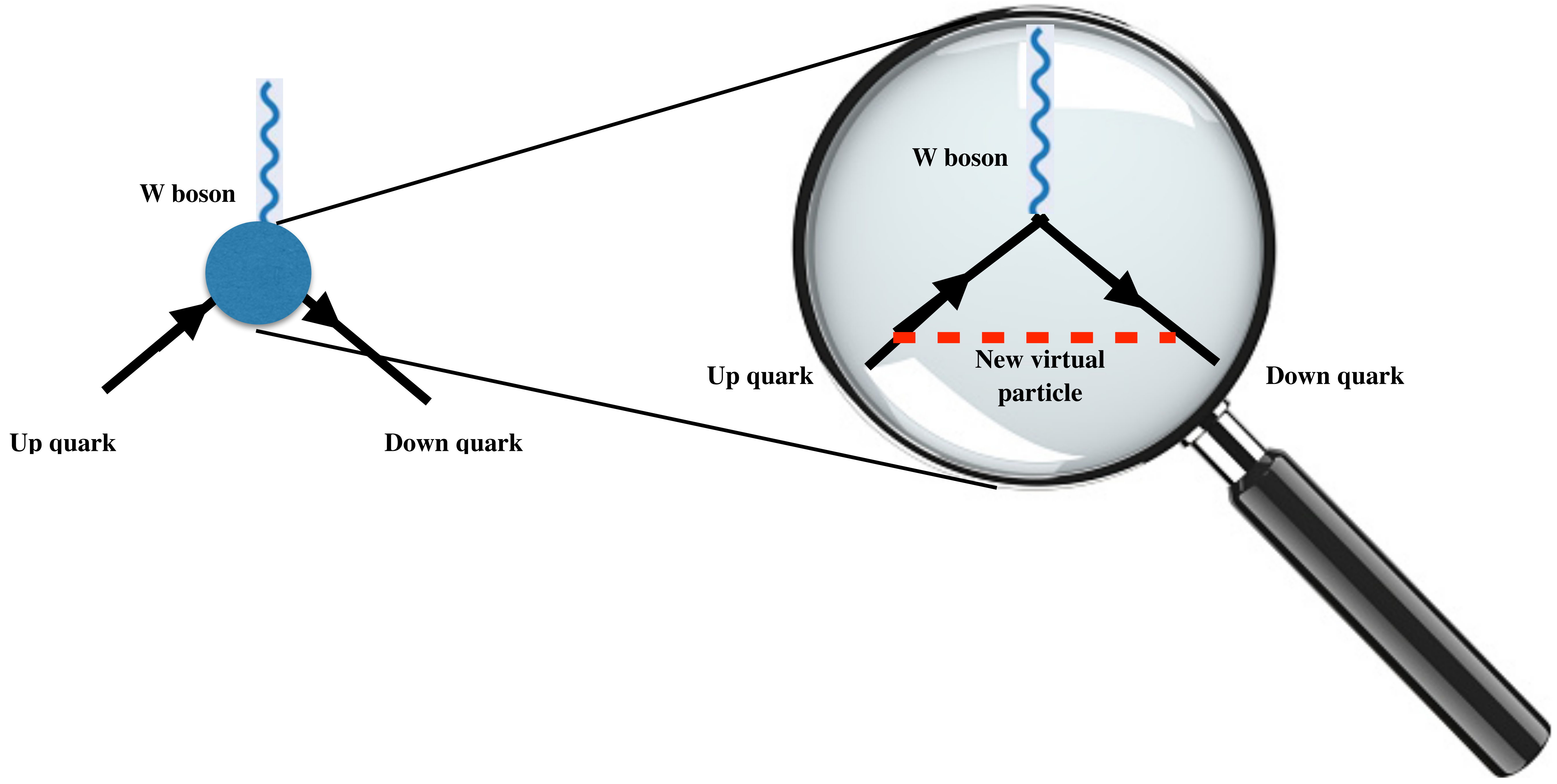
Larger than hadronic uncertainty and relevant for CKM tests

Looking forward to improvements in lifetime and $\lambda = g_A / g_V$

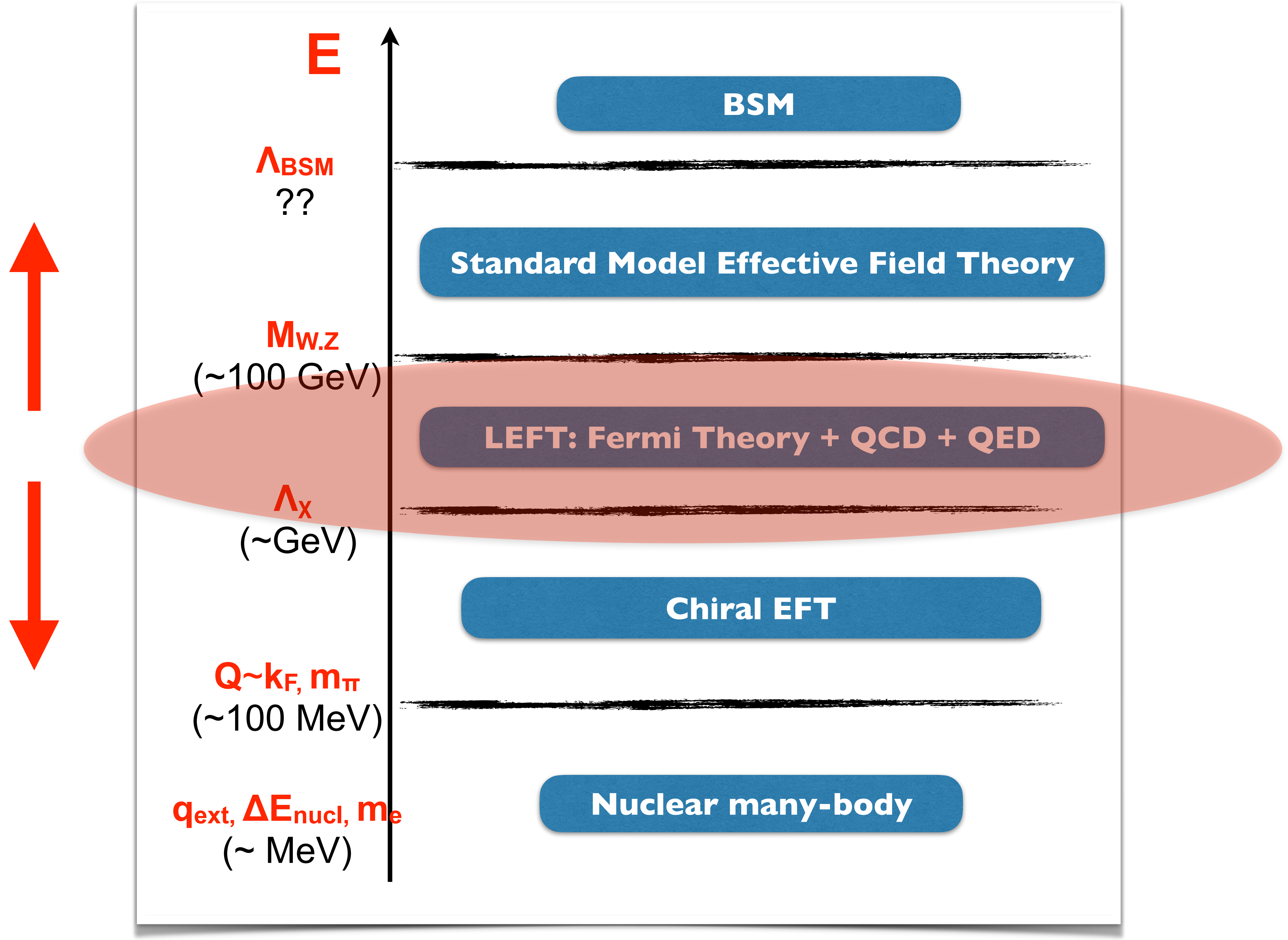
Take all numbers with a grain of salt: updates obtained from linear shifts to the results in 2306.03138

Implications for new physics



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

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

$D = d, s$

$\ell = e, \mu$

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

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}

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

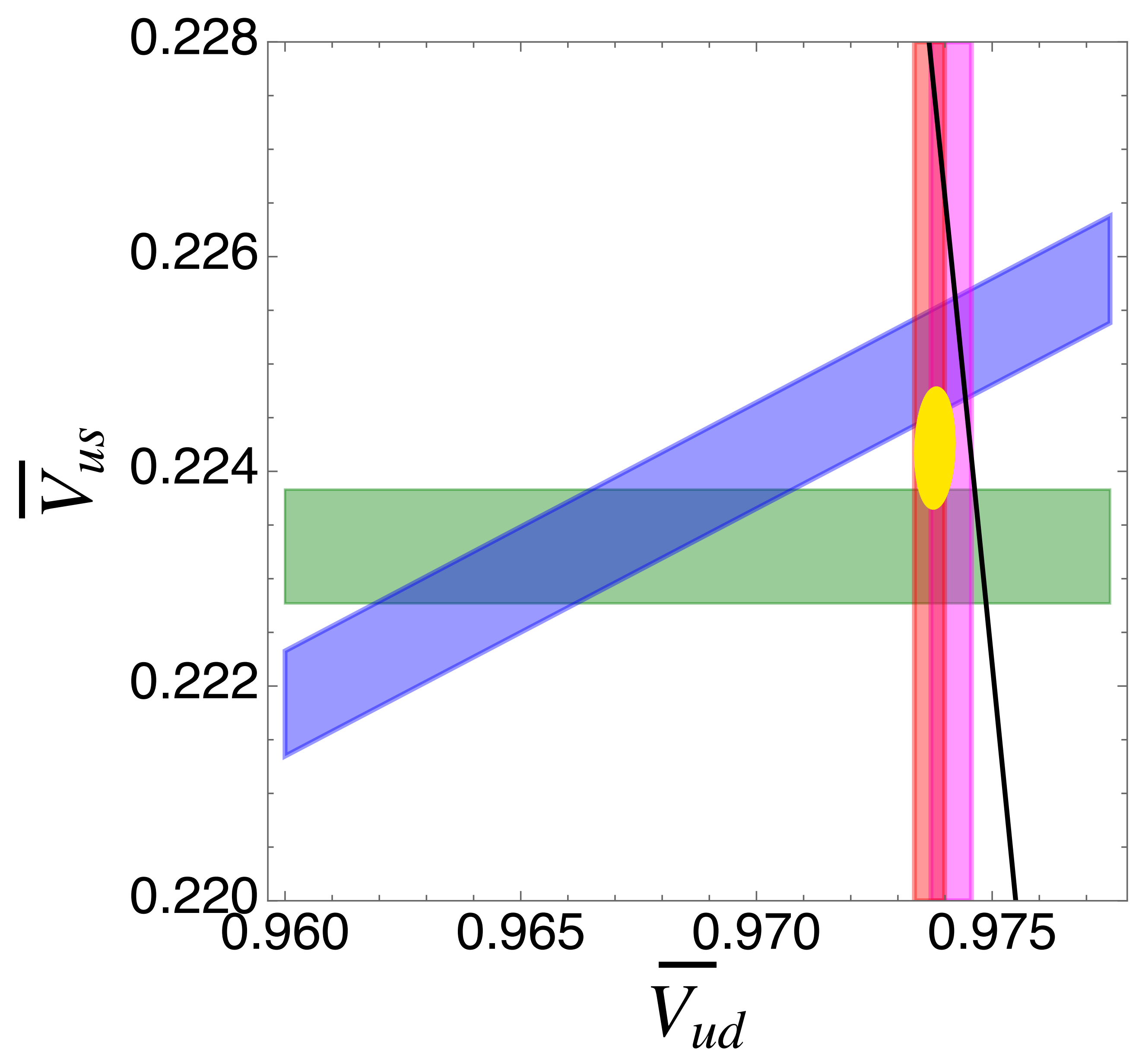
$$|\bar{V}_{us}|_j^2 = |V_{us}|^2 \left(1 + \sum_\alpha C_{j\alpha} \epsilon_\alpha\right)$$

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

Corrections to V_{ud} and V_{us}

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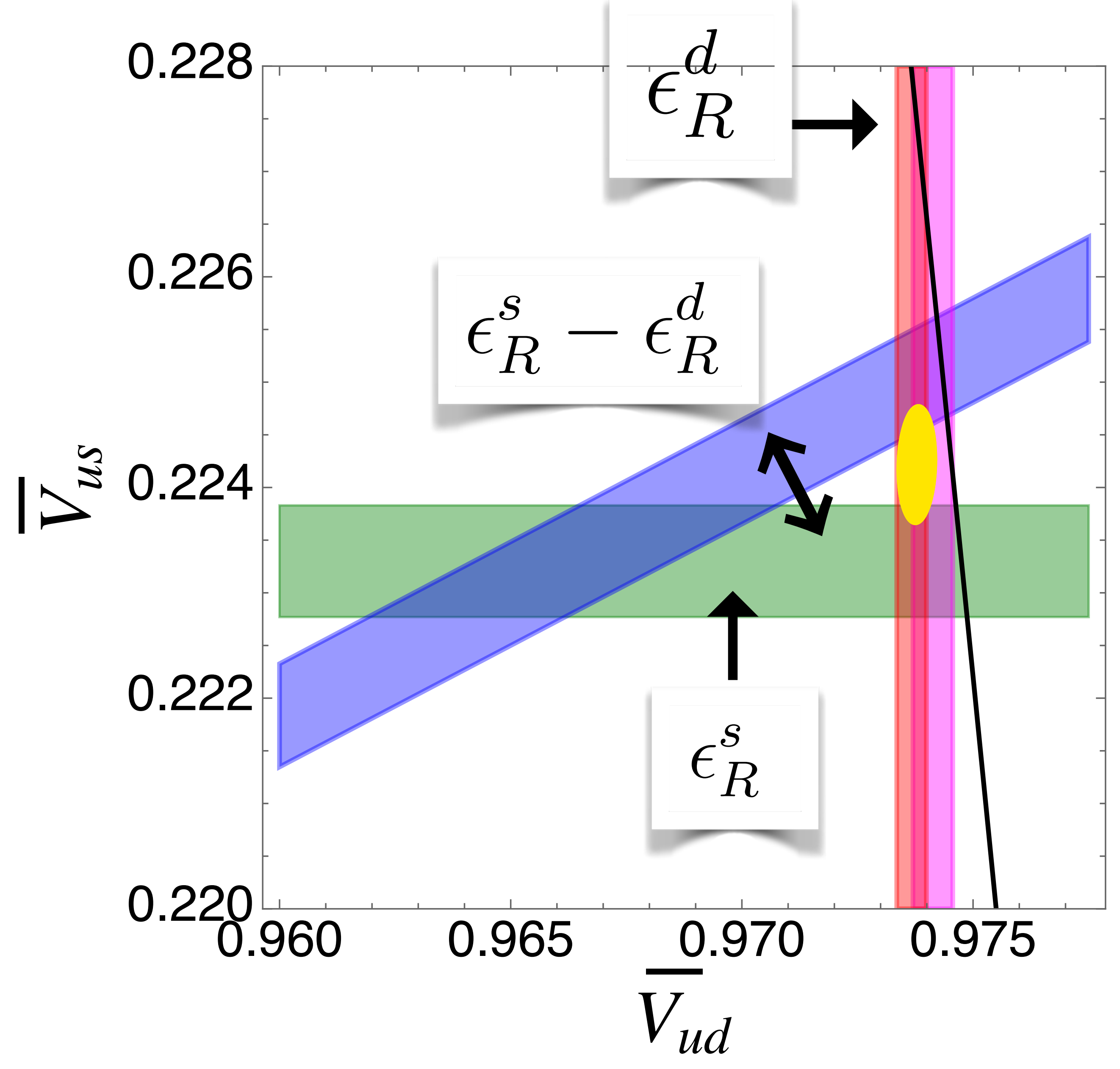


Find set of ε's so that V_{ud} and V_{us} bands meet on the unitarity circle

Grossman-Passemar-Schacht 1911.07821

Belfatto-Berezhiani 2103.05549.

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

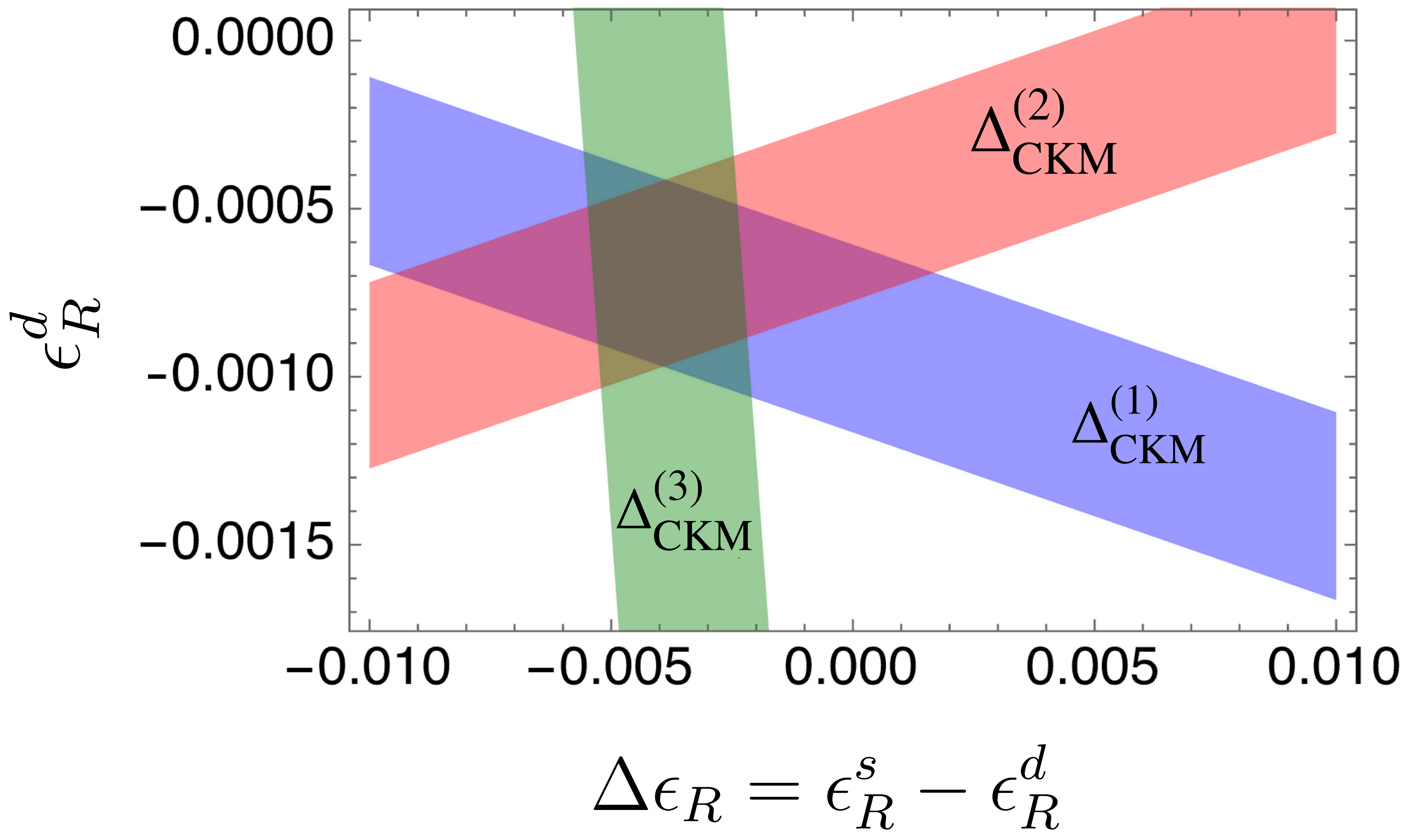
VC-Crivellin-Hoferichter-Moulson 2208.11707

...

Simplest 'solution': right-handed (V+A) quark currents.
Shift $V_{ud,us}$ from vector (axial) channels by $1+\varepsilon_R$ $(1-\varepsilon_R)$, can resolve all tensions

Unveiling R-handed quark currents?

VC-Crivellin-Hoferichter-Moulson 2208.11707



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

↓

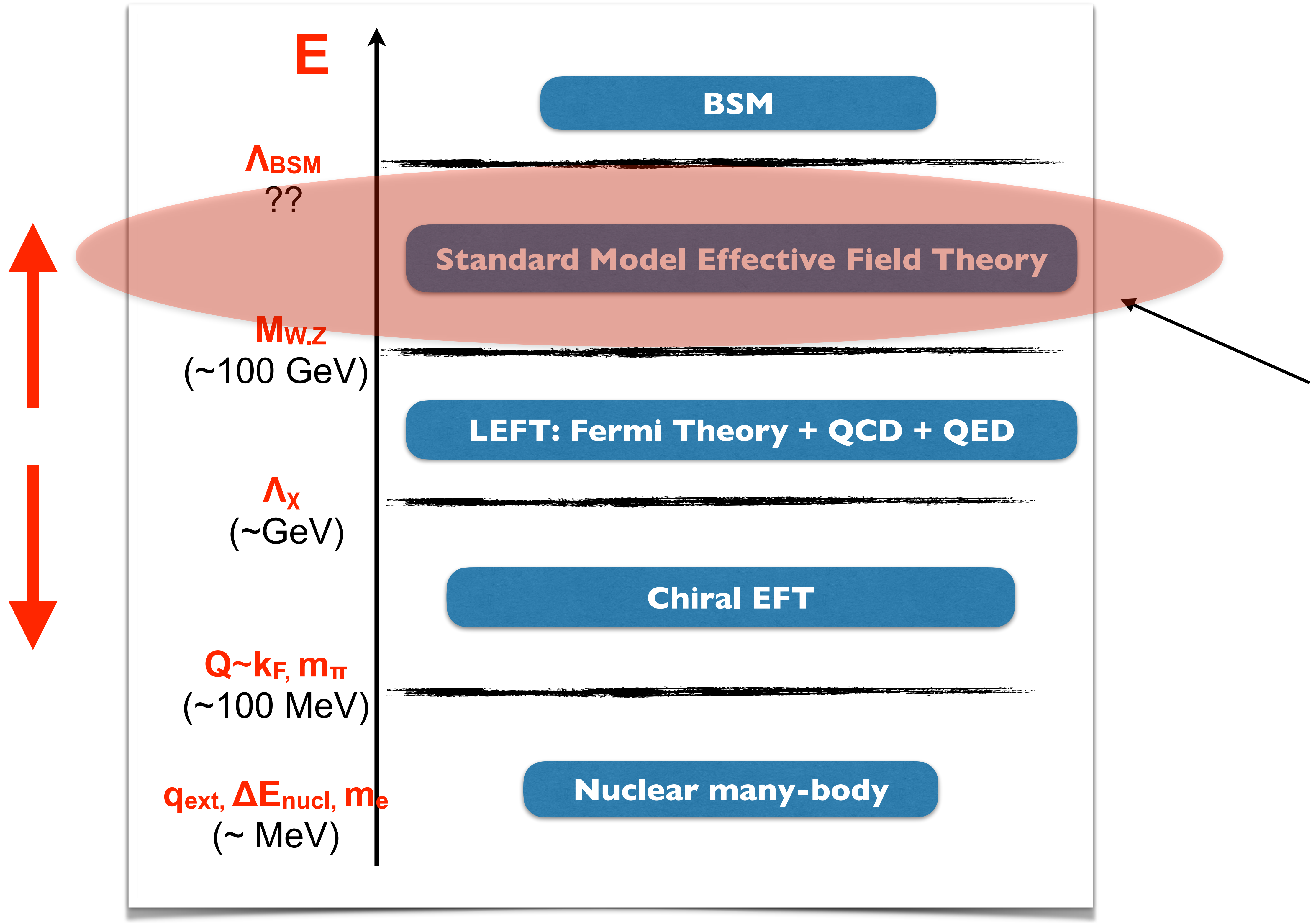
$$\epsilon_R^d = -0.69(27) \times 10^{-3}$$
$$\Delta\epsilon_R = -3.9(1.6) \times 10^{-3}$$

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



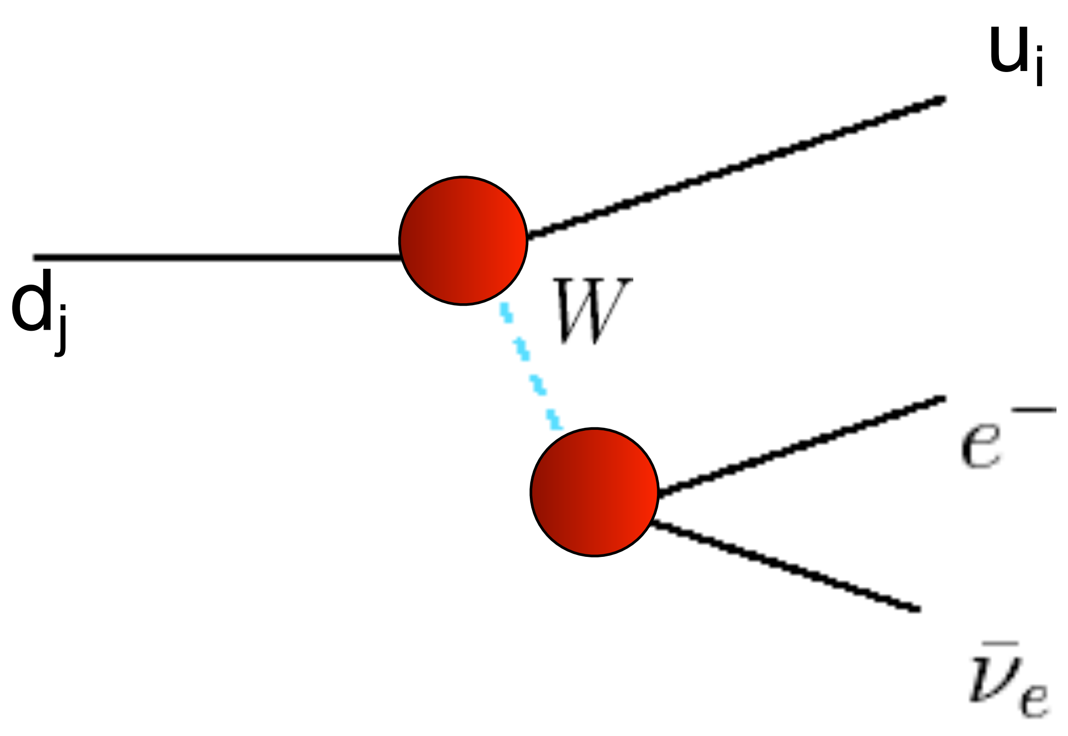
- Need to know high-scale origin of the various ε_α
- Tree-level LEFT-SMEFT (dim-6) matching at scale $\mu_W \sim 246$ GeV
- Leading-log SMEFT (dim-6) running between Λ and μ_W is known R. Alonso, E. Jenkins, A. Manohar, M. Trott, 1308.2627, 1310.4838, 1312. 2014

  M. Dawid, VC, W. Dekens 2402.06723
- One loop SMEFT-LEFT matching also known

  W. Dekens, P, Stoffer 1908.05295

SMEFT origin of the low-energy operators

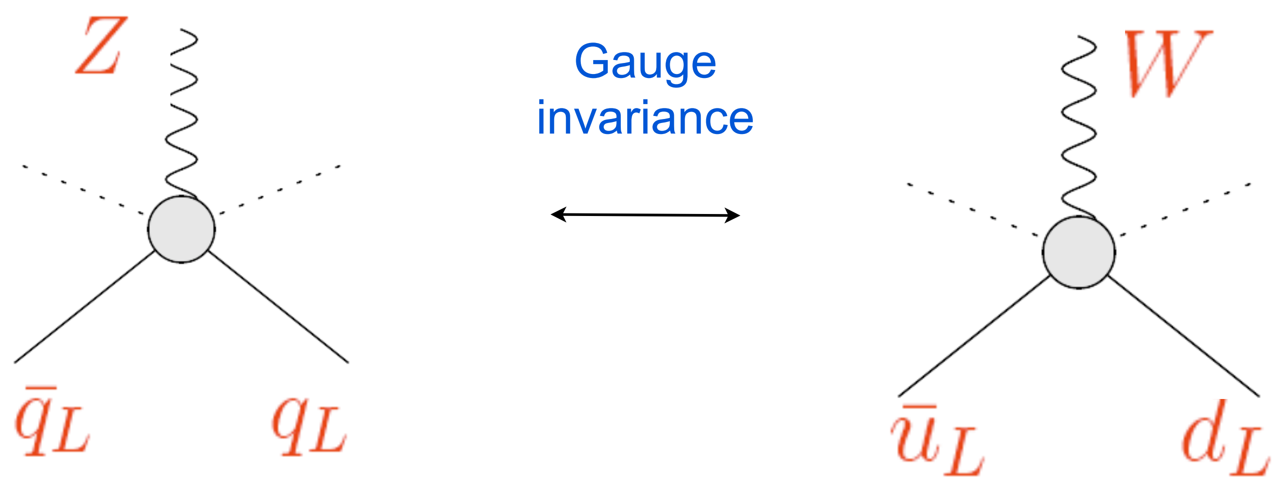
$\varepsilon_{L,R}$ originate from SU(2)xU(1) invariant vertex corrections



Building blocks

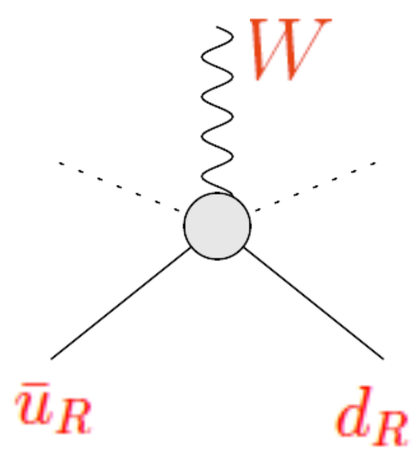
$$l^i = \begin{pmatrix} \nu_L^i \\ e_L^i \end{pmatrix} \quad q^i = \begin{pmatrix} u_L^i \\ d_L^i \end{pmatrix} \quad H = \begin{pmatrix} \varphi^+ \\ \varphi^0 \end{pmatrix}$$

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



ε_L

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



ε_R

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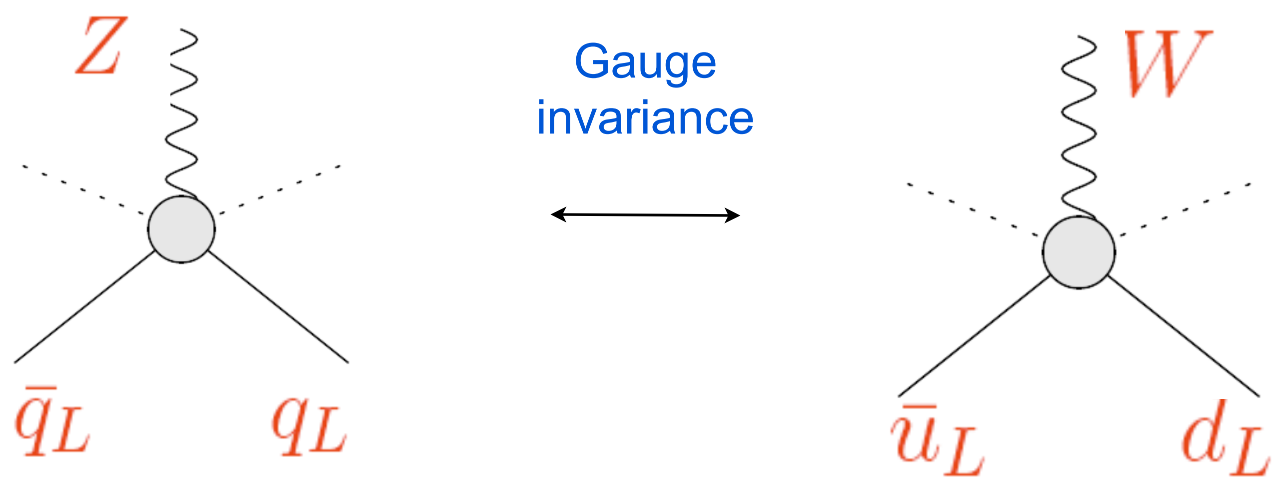
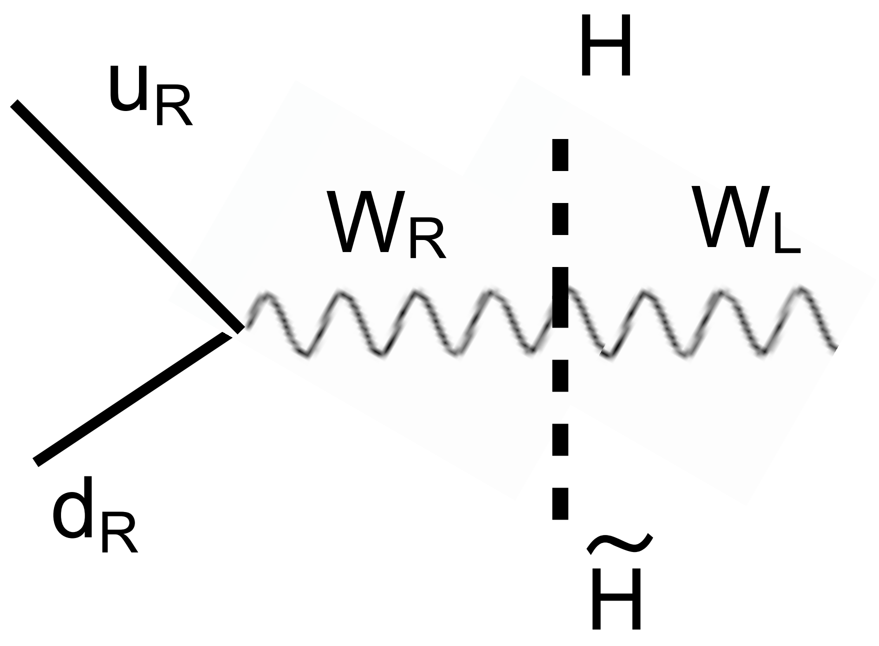


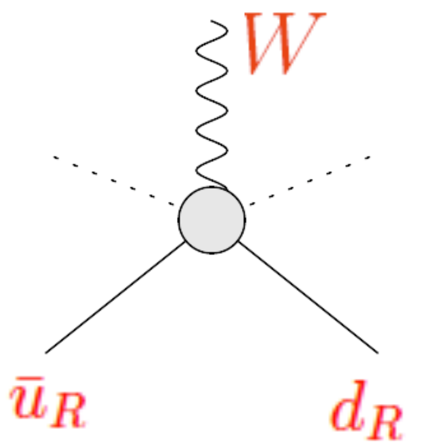
ε_L

WL-WR mixing in LRSM

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



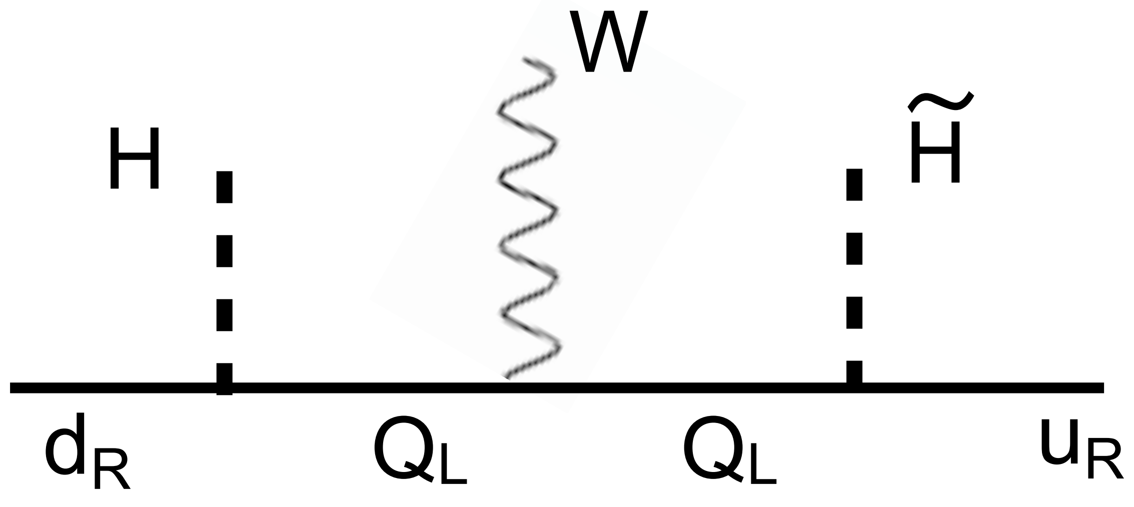
$$Q_{Hud} = i(\widetilde{H}^\dagger D_\mu H)(\bar{u}_p \gamma^\mu d_r)$$



ε_R

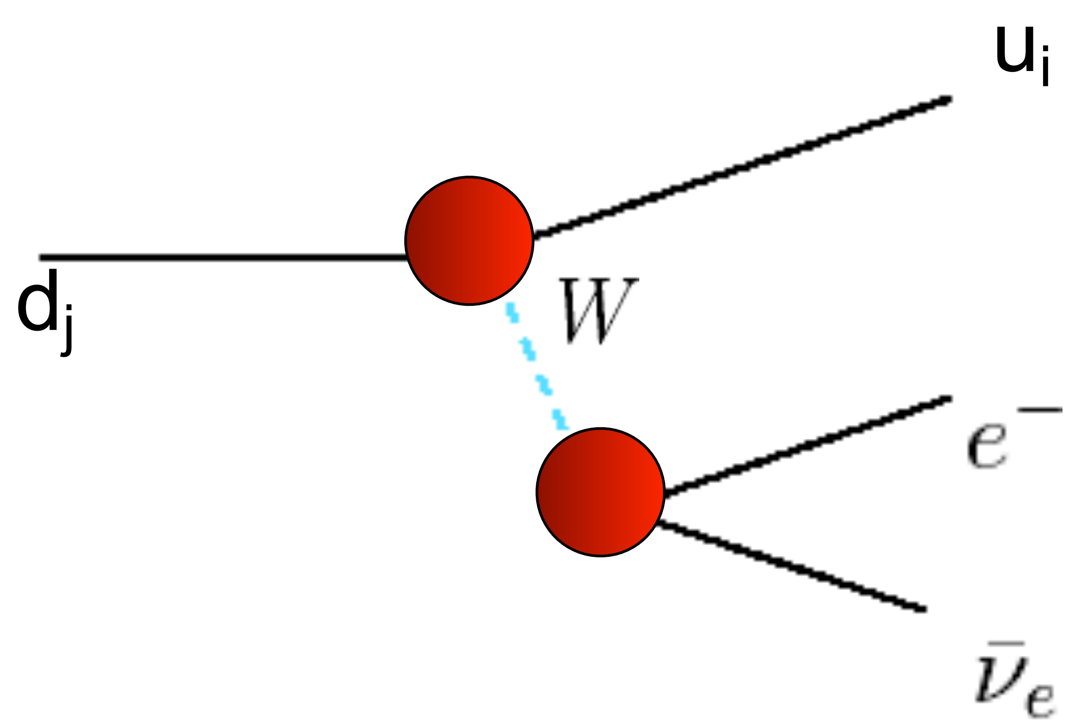
Vector-like quarks

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

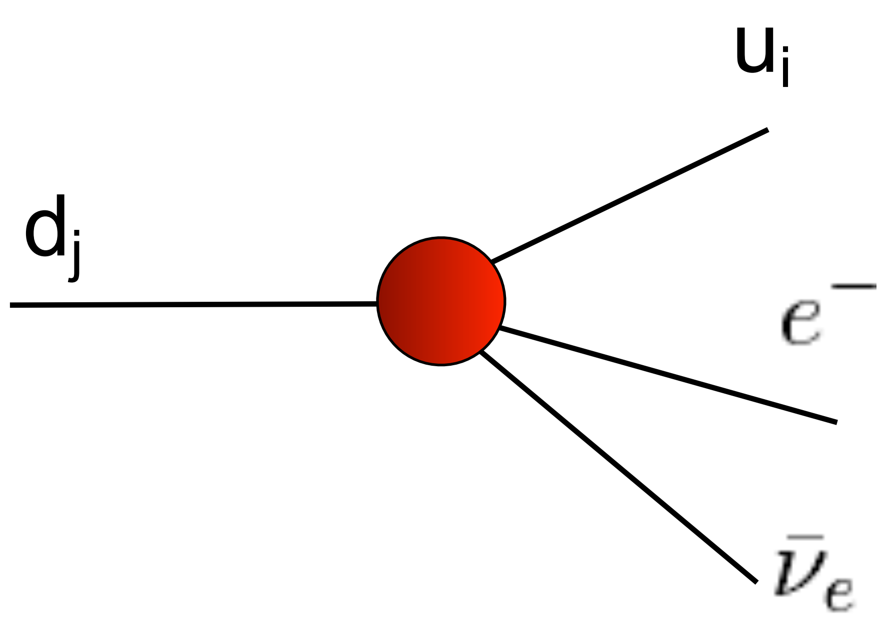


ε_R $\quad Q_{Hud} = i(\widetilde{H}^\dagger D_\mu H)(\bar{u}_p \gamma^\mu d_r)$

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

ε_L $\quad Q^{(3)}_{Hl} = (H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar{l}_p \tau^I \gamma^\mu l_r)$

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



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

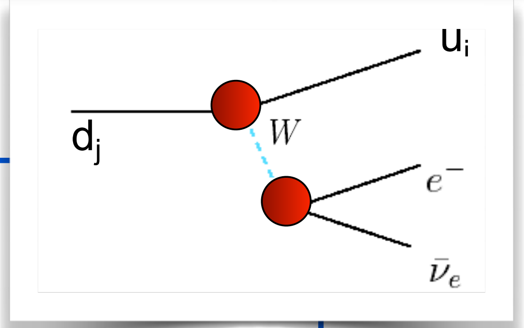
$Q^{(1)}_{lequ} = (\bar{l}_a e)\epsilon^{ab}(\bar{q}_b u) + \text{h.c.}$ $\quad \varepsilon_{S,P}$

$Q^{(3)}_{lequ} = (\bar{l}_a \sigma^{\mu\nu} e)\epsilon^{ab}(\bar{q}_b \sigma_{\mu\nu} u) + \text{h.c.}$ $\quad \varepsilon_T$

$Q^{(3)}_{lq} = \bar{l}\gamma_\mu \sigma^a l \; \bar{q}\gamma^\mu \sigma^a q$ $\quad \varepsilon_L$

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

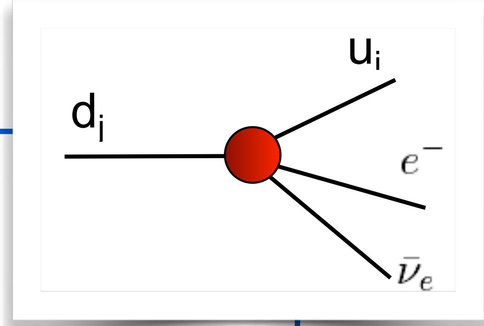
High Energy constraints



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: $$Q_{Hl}^{(3)} = (H^\dagger i \overleftrightarrow{D}_\mu^I H)(\bar{l}_p \tau^I \gamma^\mu l_r)$$



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

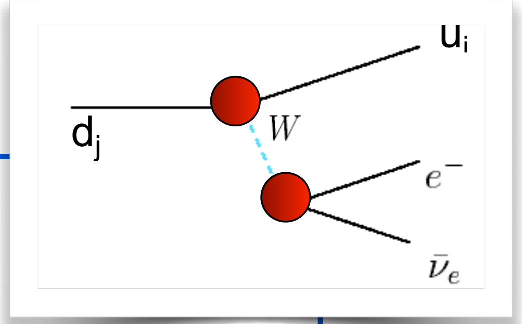
$\varepsilon_{S,P}$: $$Q_{lequ}^{(1)} = (\bar{l}_a e)\epsilon^{ab}(\bar{q}_b u) + \text{h.c.}$$

ε_T: $$Q_{lequ}^{(3)} = (\bar{l}_a \sigma^{\mu\nu} e)\epsilon^{ab}(\bar{q}_b \sigma_{\mu\nu} u) + \text{h.c.}$$

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

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

High Energy constraints



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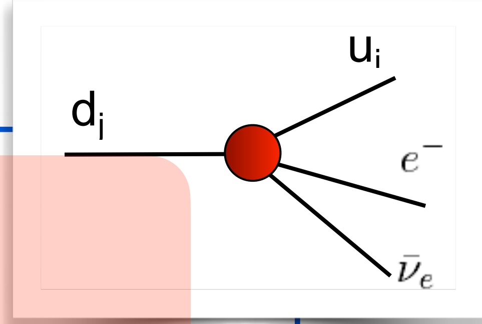

$\varepsilon_{S,P}$: $Q_{ledq} = (\bar{\ell} e)(\bar{d} q) + \text{h.c.}$

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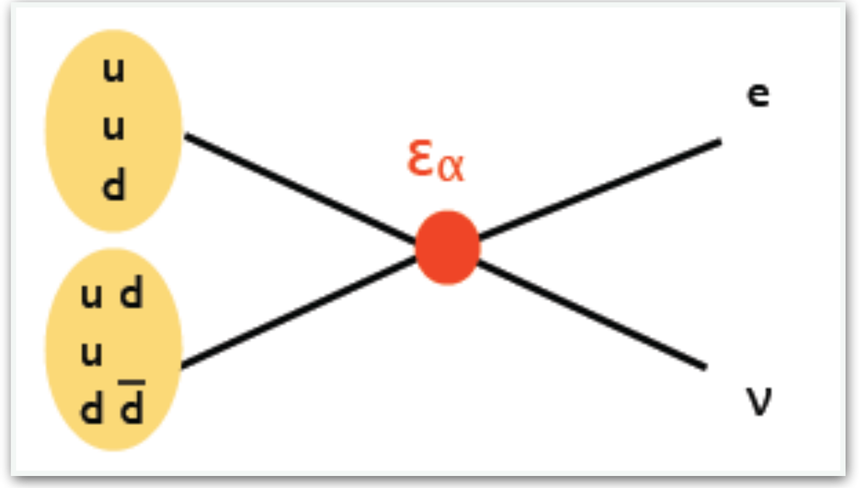
ε_T: $Q_{lequ}^{(3)} = (\bar{l}_a \sigma^{\mu\nu} e)\epsilon^{ab}(\bar{q}_b \sigma_{\mu\nu} u) + \text{h.c.}$

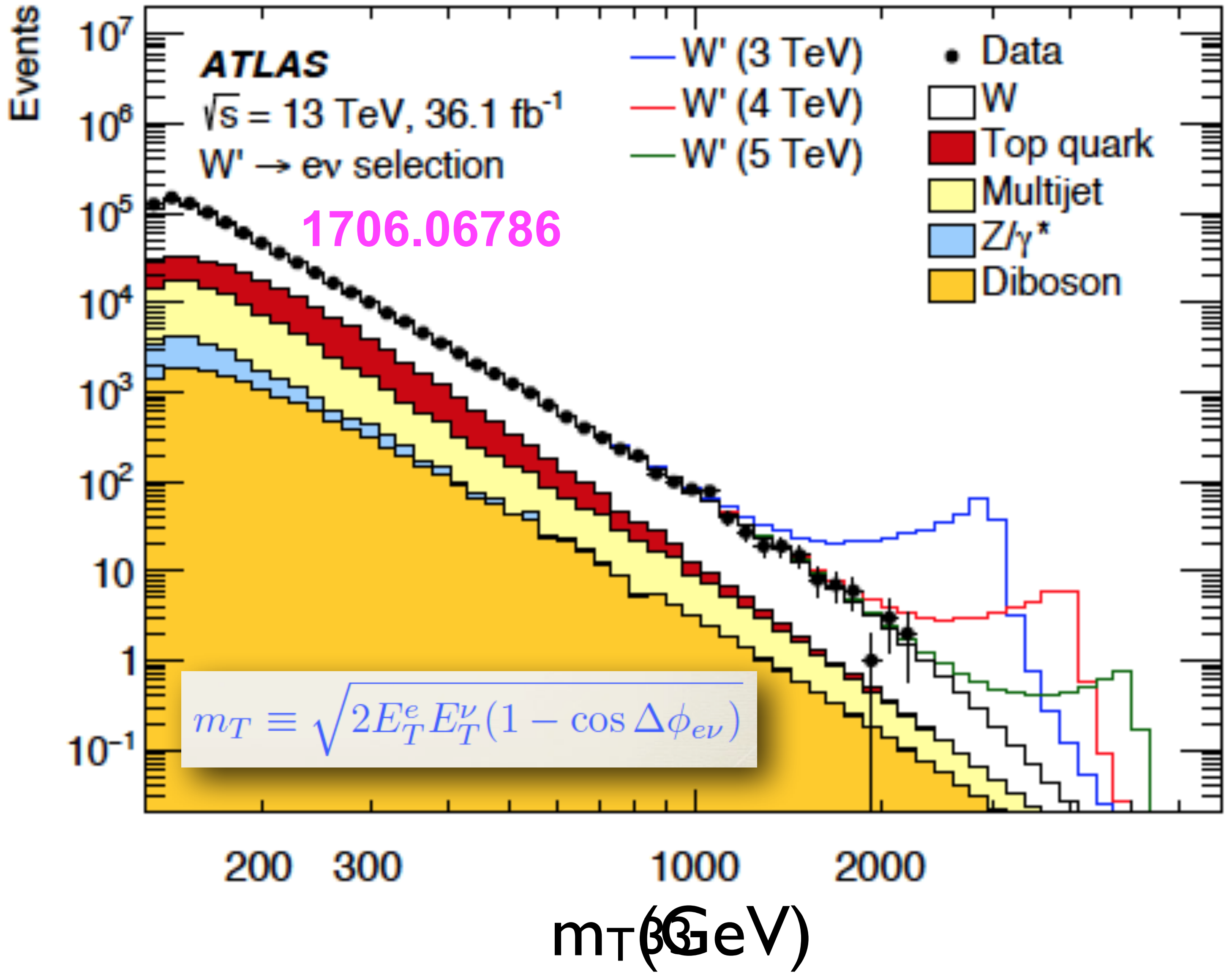
ε_L: $Q_{lq}^{(3)} = \bar{l}\gamma_\mu \sigma^a l \; \bar{q}\gamma^\mu \sigma^a q$

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

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

LHC: pp → eν + X

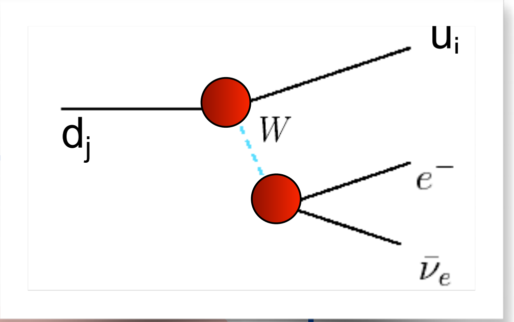




$\varepsilon_\alpha \sim 10^{-3} - 10^{-4}$

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

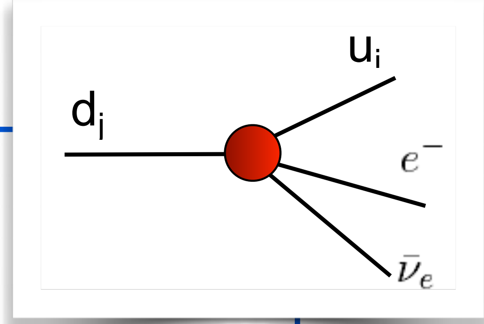
High Energy constraints



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

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

ε_L $$Q_{Hl}^{(3)} = (H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar{l}_p \tau^I \gamma^\mu l_r)$$



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

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

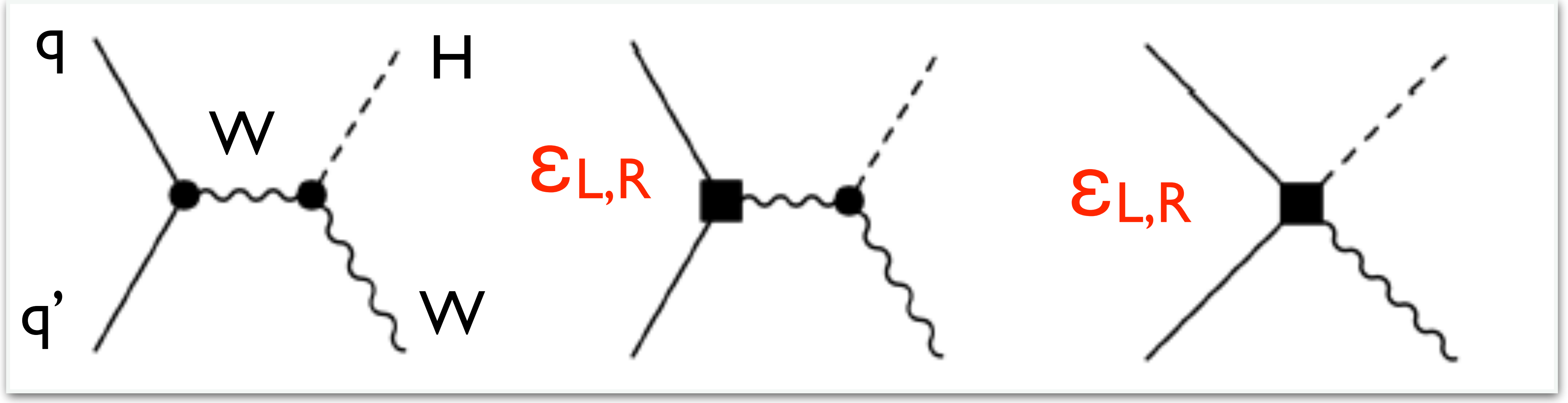
ε_T $$Q_{lequ}^{(3)} = (\bar{l}_a \sigma^{\mu\nu} e)\epsilon^{ab}(\bar{q}_b \sigma_{\mu\nu} u) + \text{h.c.}$$

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

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

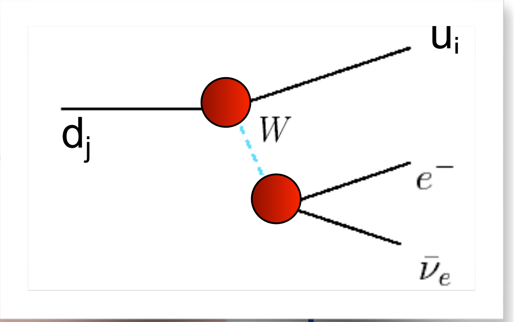
Can be probed at the LHC by associated Higgs + W production

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



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

High Energy constraints



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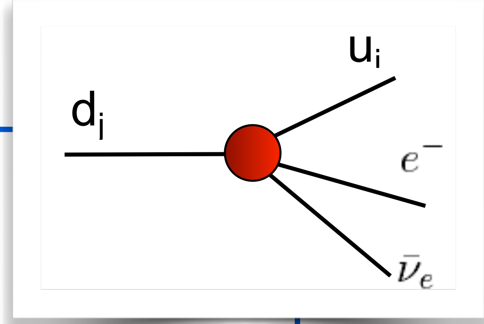

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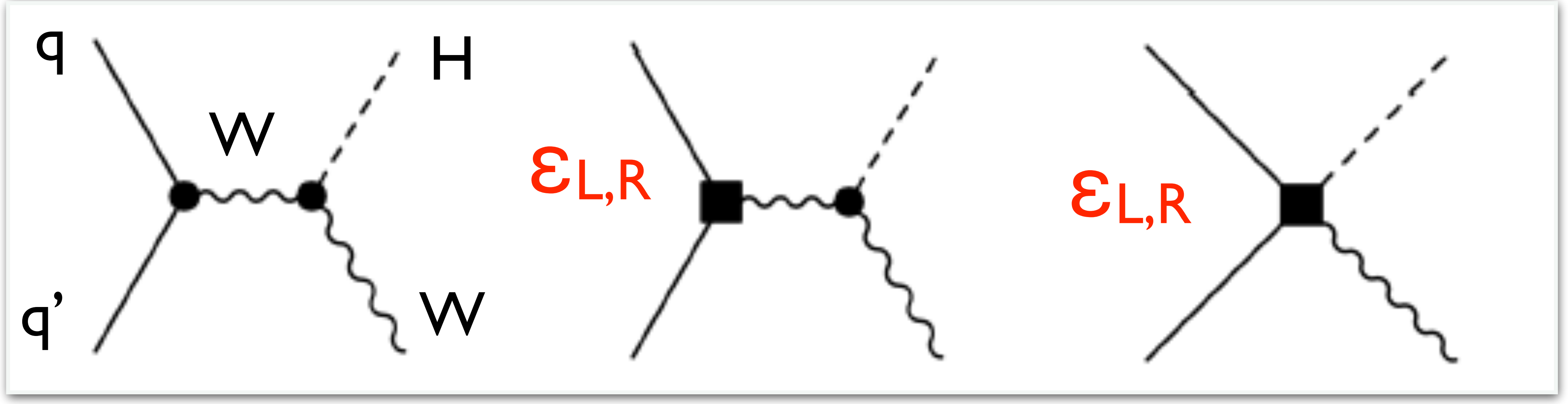


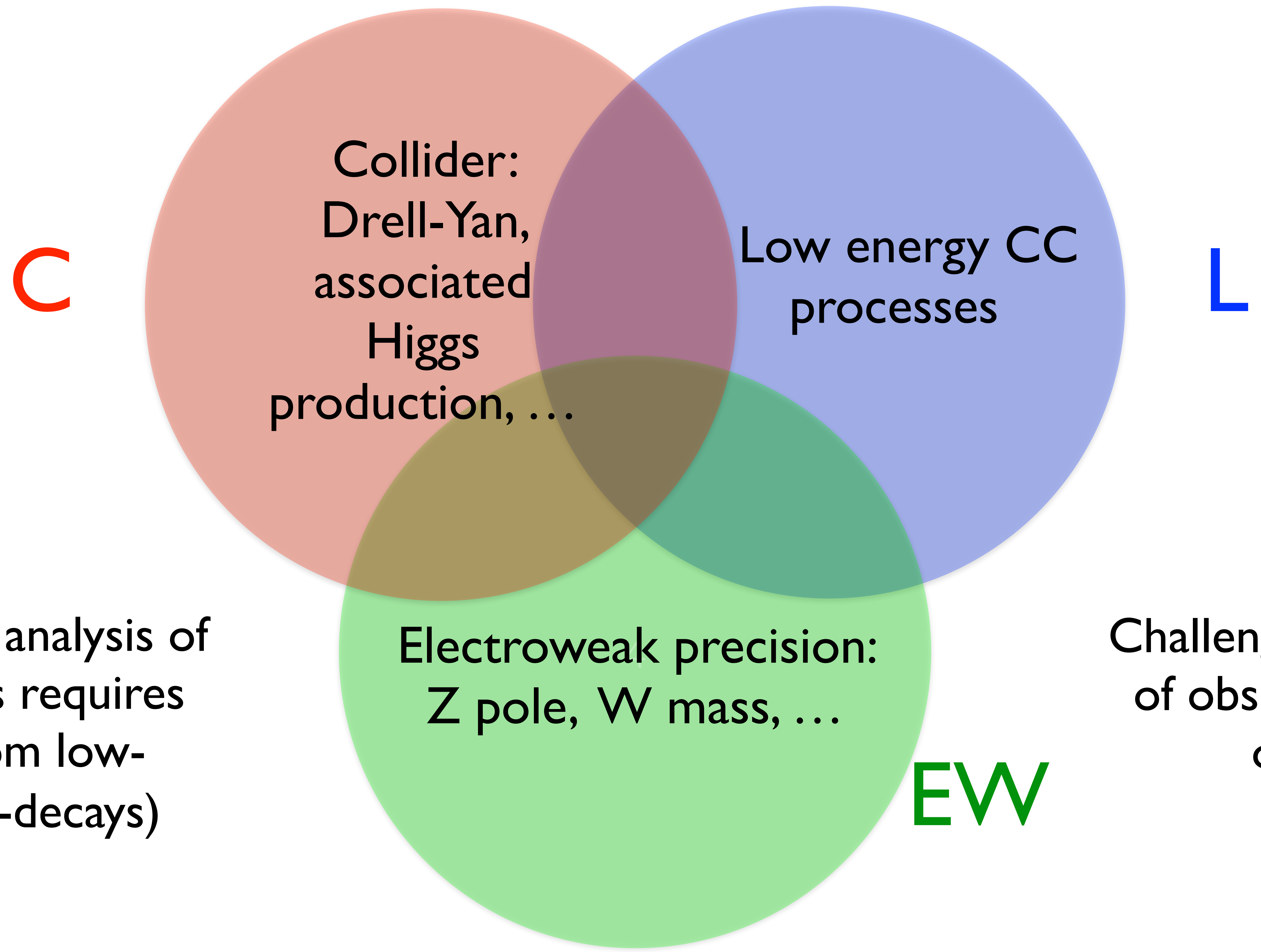
Current LHC results allow for to $\varepsilon_{L,R} \sim 5\%$

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



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)

A CLEWed global analysis

The CLEW analysis with no flavor symmetry assumptions requires 37 couplings
But not all operators matter

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

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

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

Operators grouped in 10 categories

Scanned this model space

2^{10} = 1024 ‘models’

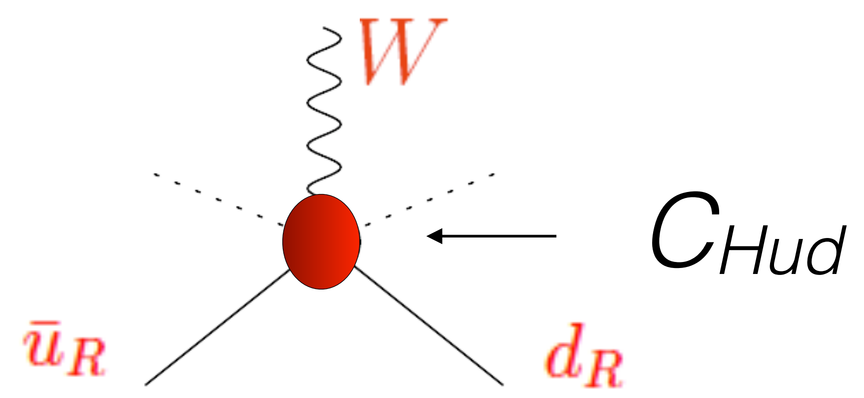
Category	Operators	Description	# of Ops.
I.	C_{ST}	Oblique corrections	1
II.	C_{Hud}	RH charged currents	2
III.	$C_{Hl}^{(1)}$ $C_{Hl}^{(3)}$	LH lepton vertices	6
IV.	C_{He}	RH lepton vertices	3
V.	$C_{Hq}^{(u)}$ $C_{Hq}^{(d)}$	LH quark vertices	5
VI.	C_{Hu} C_{Hd}	RH quark vertices	5
VII.	C_{ll}	Lepton 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

A CLEWed global analysis

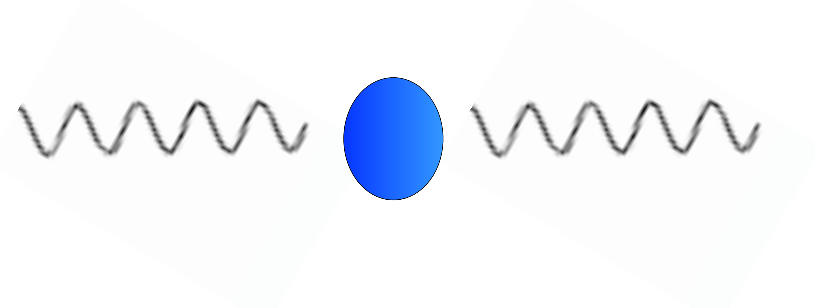
VC, W. Dekens, J. De Vries, E. Mereghetti, T. Tong, JHEP 03 (24) 33, arXiv: 2311.00021

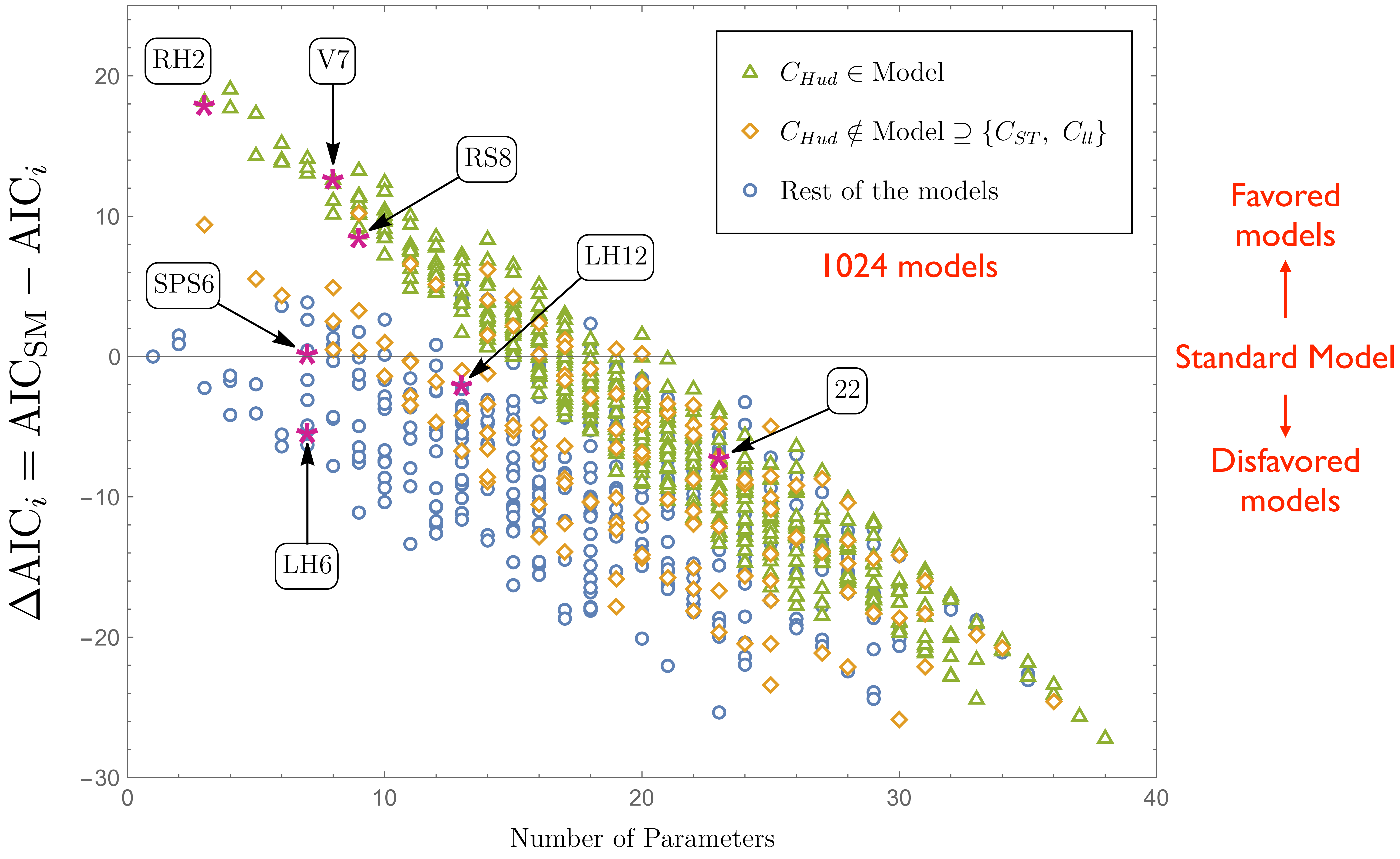
- Scanned model space by ‘turning on’ certain classes of effective couplings

- Akaike Information Criterion favors models with Right-Handed Charged Currents of quarks



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





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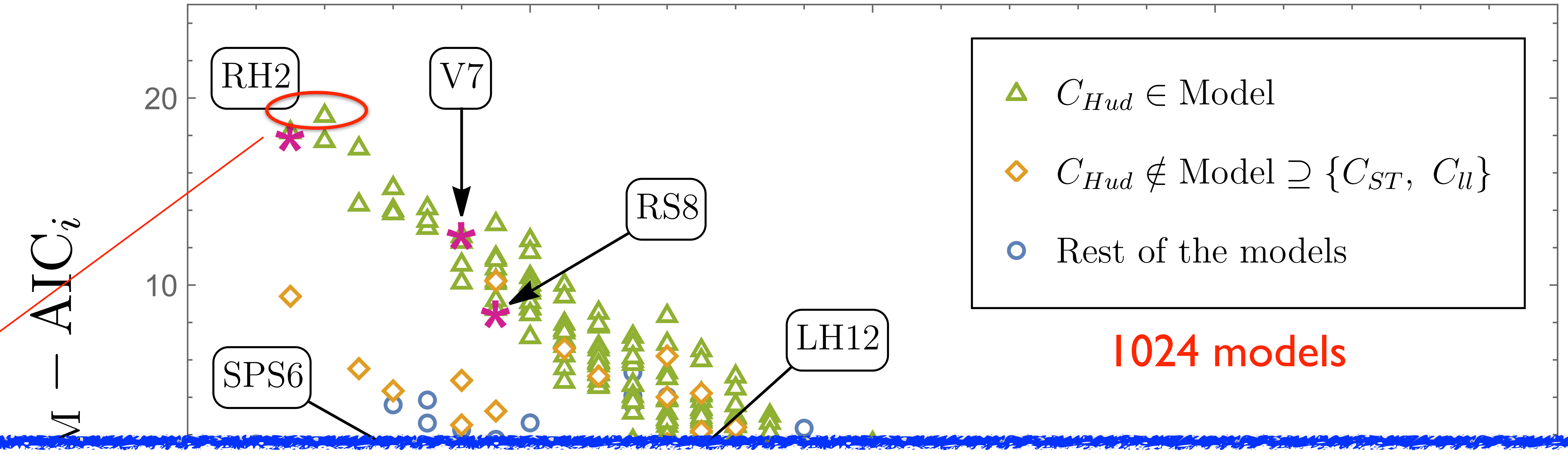


Favored models

Standard Model

Disfavored models

- Model… also fa…

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)

See talk by Benedetta Belfatto

$$C_{\substack{Hud\\11}} = (-0.030 \pm 0.008)\ \text{TeV}^{-2}\,,$$

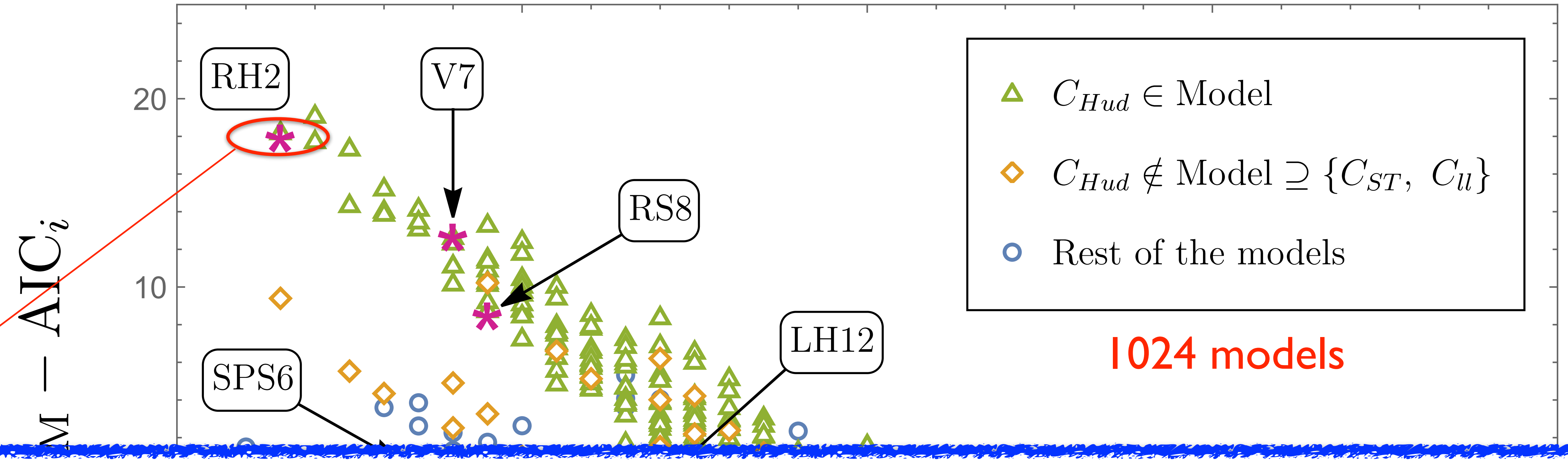
$$C_{\substack{Hud\\12}} = (-0.040 \pm 0.011)\ \text{TeV}^{-2}\,,$$

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

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
- Model
also fa

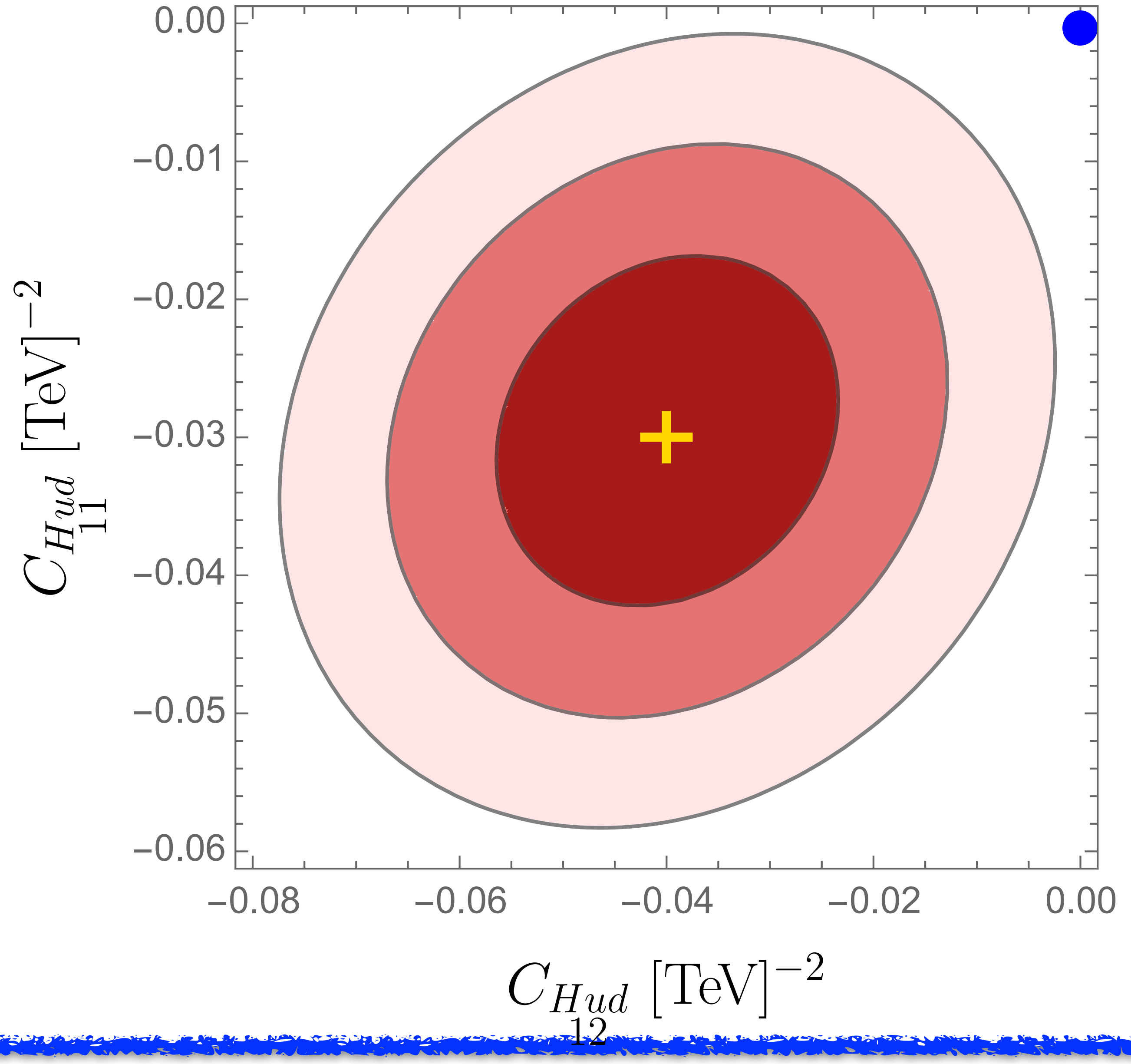


Favored models

Standard Model

Disfavored models

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



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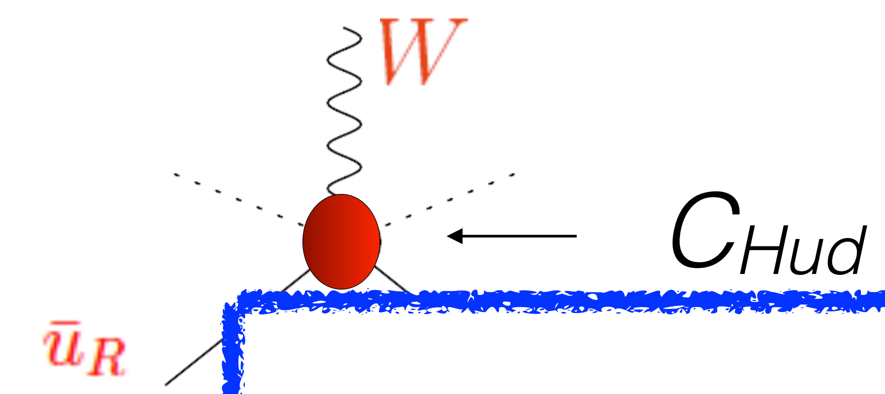
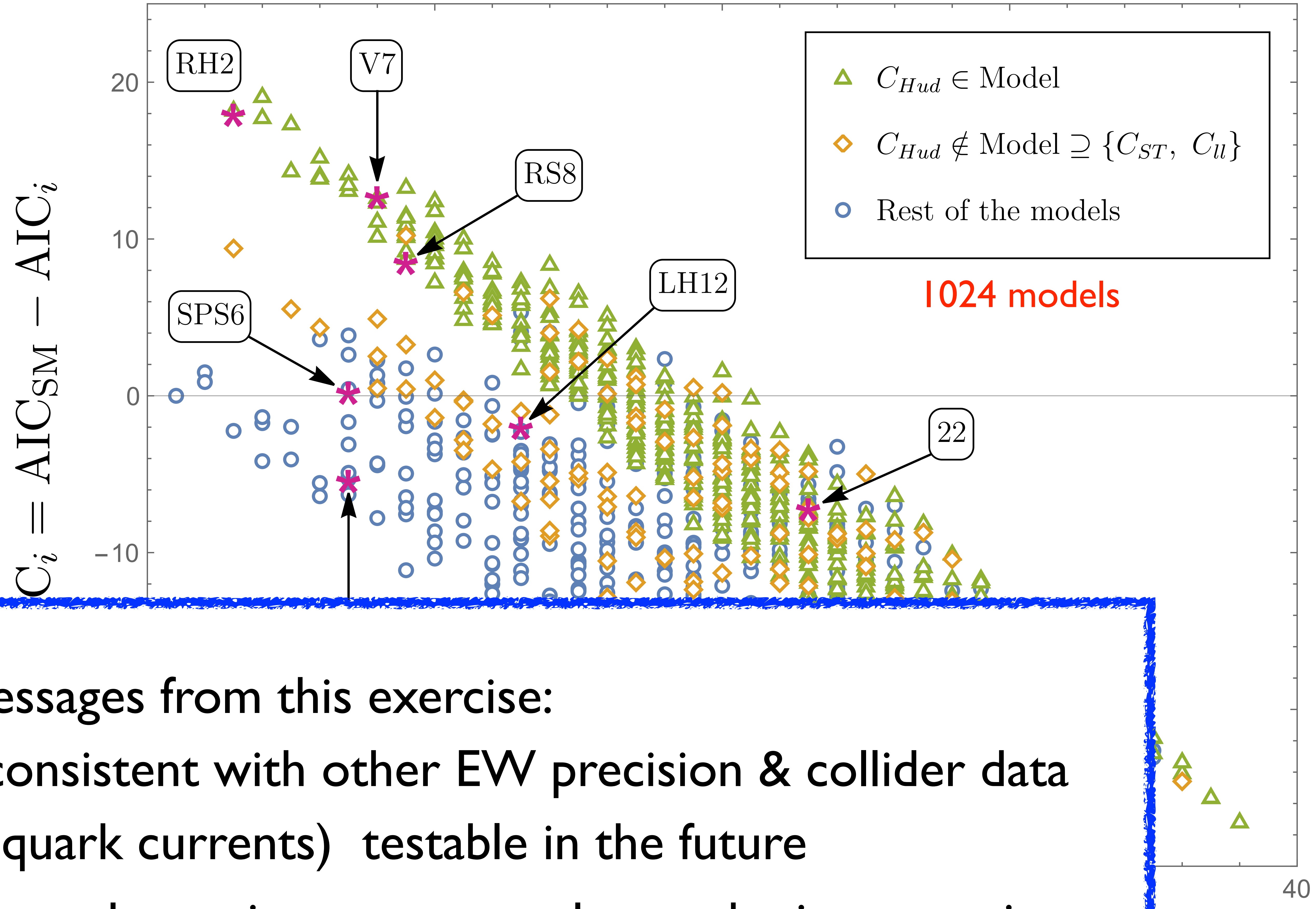




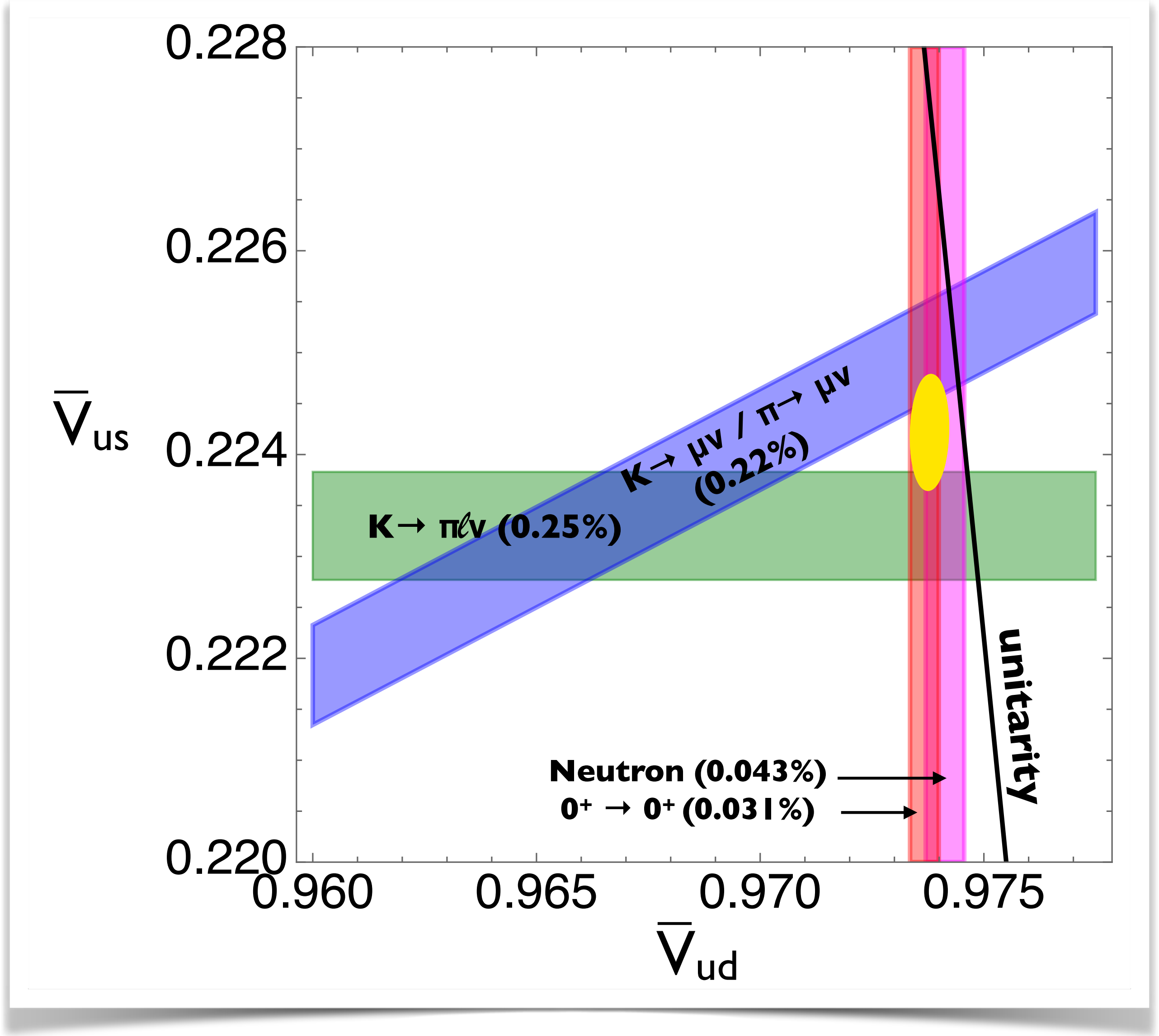
- Models with o... also fare bette...

Messages from this exercise:

- "Cabibbo anomaly" still consistent with other EW precision & collider data
- "Preferred solution" (RH quark currents) testable in the future
- CKM unitarity test provides relevant input to unravel new physics scenarios

Conclusions and outlook

- Precision studies of β decays are a great tool to test the Standard Model and explore what may lie beyond

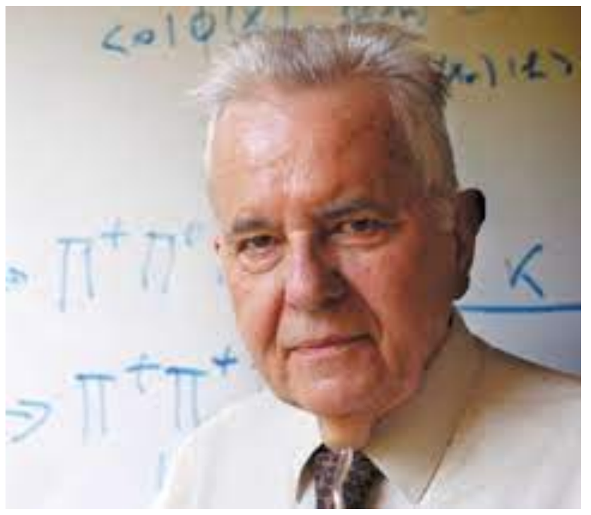


- Current tensions in Cabibbo universality test could point to new physics at Λ ~ few TeV

- Further scrutiny is needed & there is lots of activity in the community
  - Experiment: nuclei, neutron, K, π, τ
  - Theory: lattice QCD+QED for neutron, K, π, τ; EFT+ dispersive + first-principles methods for nuclei; …

Backup

Cabibbo universality test



Nicola Cabibbo
(1935-2010)

~0..95 ~0.05 ~1.5 ×10[-5]

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

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

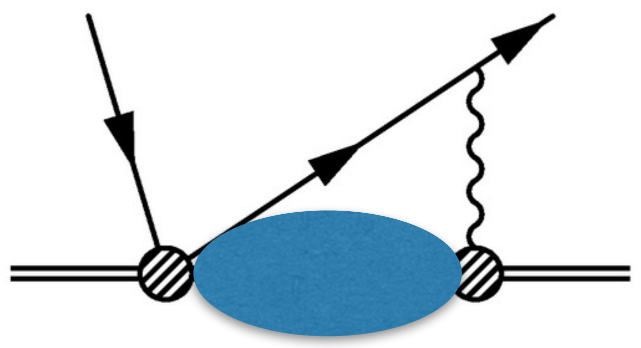
V_{ud} and V_{us} are the most accurately known elements of the CKM matrix ⇒

1st row provides the most stringent test of universality & sensitivity to new physics

Vector coupling g_V

$$g_V(\mu_\chi) = \overline{C}^r_\beta(\mu)\left[1 + \overline{\Box}^V_{\text{Had}}(\mu_0) - \frac{\alpha(\mu_\chi)}{2\pi}\left(\frac{5}{8} + \frac{3}{4}\ln\frac{\mu_\chi^2}{\mu_0^2} + \left(1 - \frac{\alpha_s}{4\pi}\right)\ln\frac{\mu_0^2}{\mu^2}\right)\right]$$

$\overline{\Box}^V_{\text{Had}}(\mu_0)$ is the usual 'box' up to $Q^2 \sim (\mu_0)^2$



$$\overline{\Box}^V_{\text{Had}}(\mu_0) = -e^2 \int \frac{i d^4 q}{(2\pi)^4} \frac{\nu^2 + Q^2}{Q^4}\left[\frac{T_3(\nu, Q^2)}{2m_N \nu} - \frac{2}{3}\frac{1}{Q^2 + \mu_0^2}\left(1 - \frac{\alpha_s(\mu_0^2)}{\pi}\right)\right]$$

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

$$\nu = v \cdot q$$

$$T^{\mu\nu}_{VA,0} = i\varepsilon^{\mu\nu\sigma\rho} q_\rho v_\sigma \frac{T_3}{4m_N \nu} + \cdots$$

$$T^{\mu\nu}_{VV(A),0}(q, v) = \frac{\tau^a_{ij}\delta^{\sigma'\sigma}}{12}\frac{i}{6}\int d^d x\, e^{iq\cdot x}\langle N(k, \sigma', j)|T\left[\bar{q}\gamma^\mu q(x)\,\bar{q}\gamma^\nu(\gamma_5)\tau^a q(0)\right]|N(k, \sigma, i)\rangle$$

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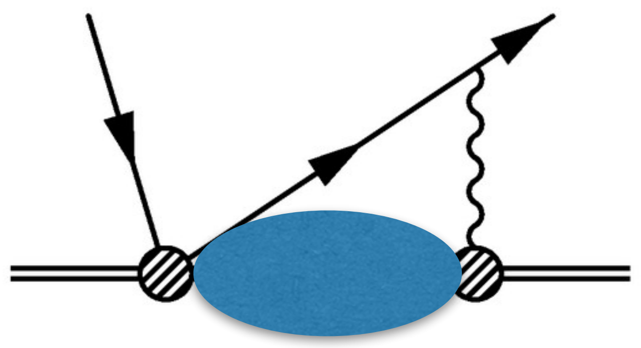

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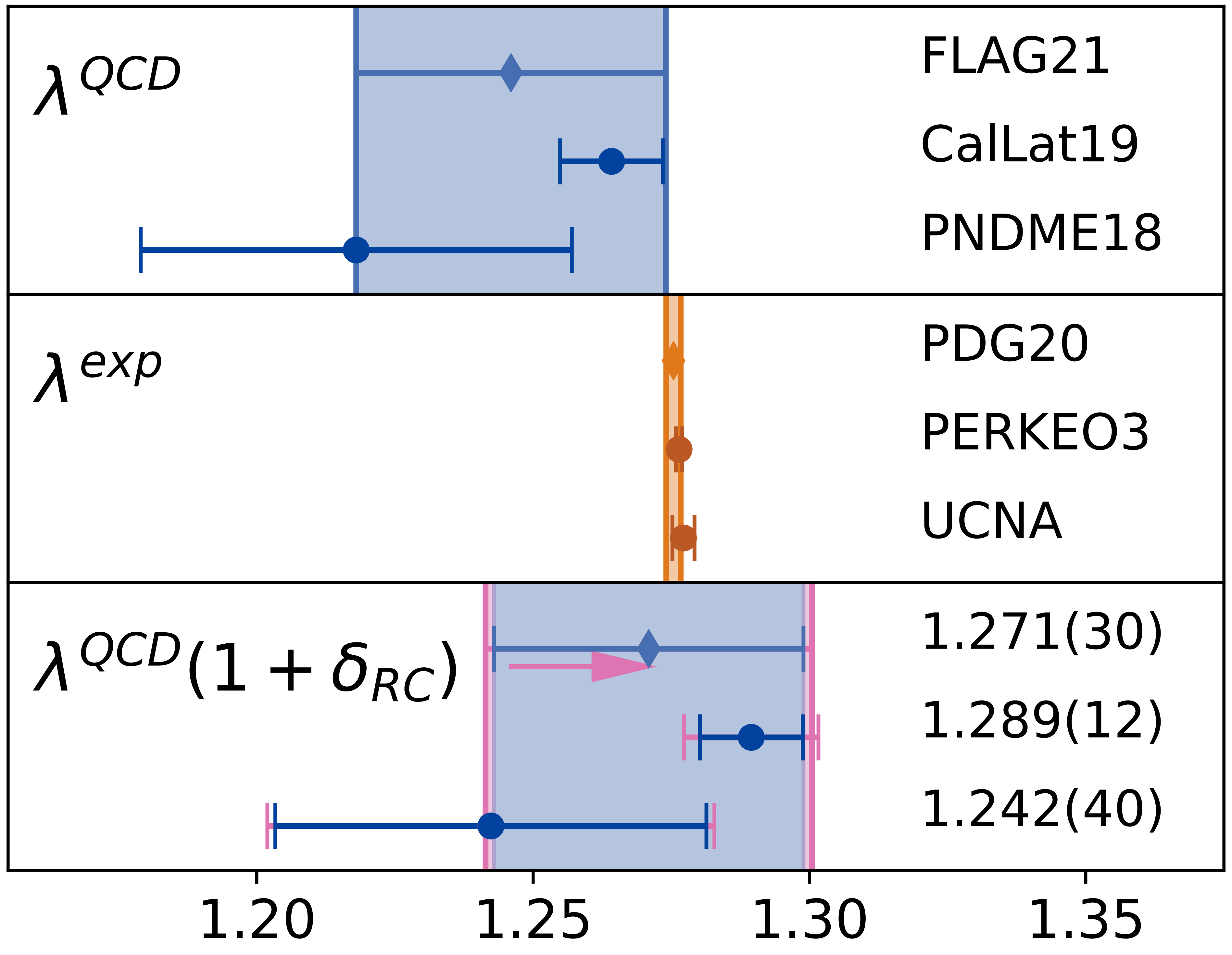
$$Q^2 = -q^2$$
$$\nu = v\cdot q$$

- Use non-perturbative input on T_3 from dispersive analysis or LQCD   Seng et al. 1807.10197, 2308.16755
- No dependence on scheme, μ and μ_0 (up to higher perturbative orders)
- For $\mu_\chi \sim \mu \sim \mu_0 \sim 1$ GeV all large logs are in the NLO Wilson coefficient $\overline{C}^r_\beta(\mu)$
- Dependence on μ_χ canceled by loops in pion-less EFT

g_A/g_V to $O(\alpha)$ and $O(\alpha\epsilon_\chi)$

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

- (g_A/g_V) gets %-level corrections proportional to the pion EM mass splitting (100x larger than previous estimates)
- Radiative corrections generally improve agreement between data (neutron decay) and lattice QCD calculations



$$\lambda \equiv \frac{g_A}{g_V}$$

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

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

Scale variation + knownLECs

Unknown LECs

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

CY Seng 2403.08976

VC, W. Dekens, E. Mereghetti, O. Tomalak, arXiv: 2410.21404

The CLEW framework

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

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}	$(\bar{l}^j_p e_r)(\bar{d}_s q_{tj})$	✓	✗	✓
$\boldsymbol{(\bar{L}R)(\bar{L}R)}$ + h.c.				
$Q_{lequ}^{(1)}$	$(\bar{l}^j_p e_r)\epsilon_{jk}(\bar{q}^k_s u_t)$	✓	✗	✓
$Q_{lequ}^{(3)}$	$(\bar{l}^j_p\sigma_{\mu\nu} e_r)\epsilon_{jk}(\bar{q}^k_s\sigma^{\mu\nu} u_t)$	✓	✗	✓

** 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.

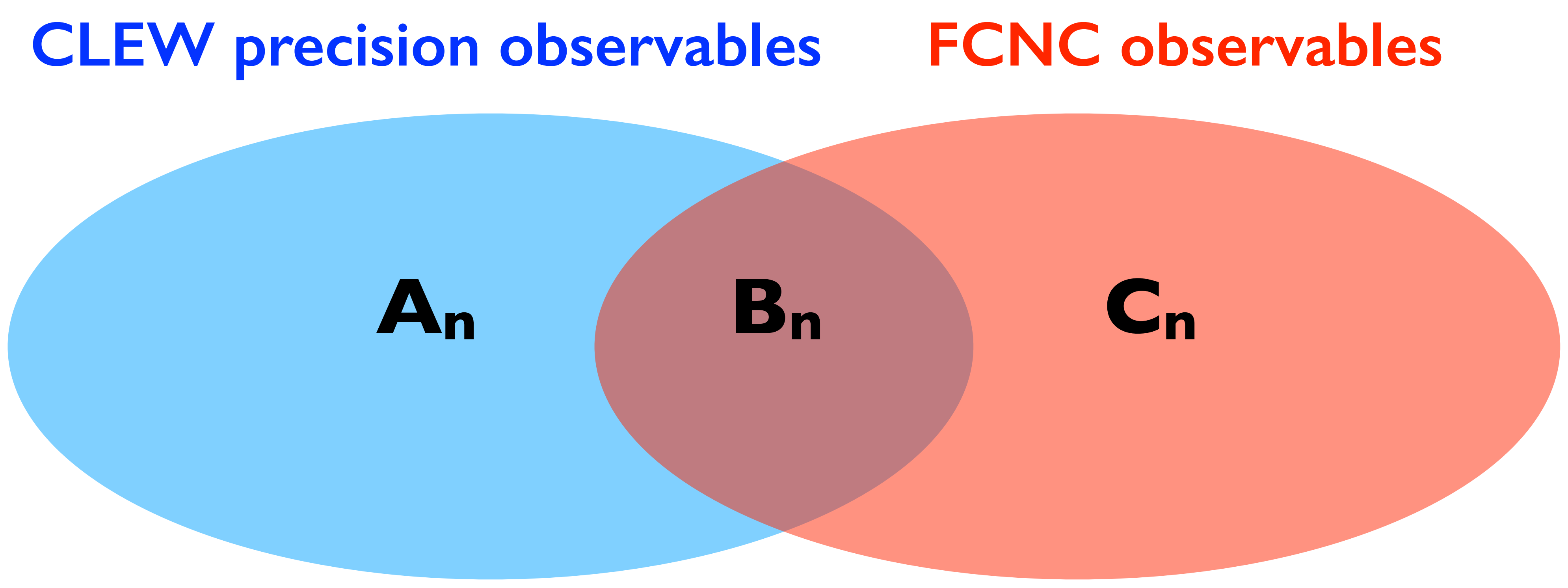
What about flavor?

- 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

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 $V_{us} = \lambda_C \sim 0.2$

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

~ factorized likelihood.
Expect minimal impact on A_n

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