Marciana 2023 — Lepton Interactions with Nucleons and Nuclei
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Precision beta decays and implications for new physics

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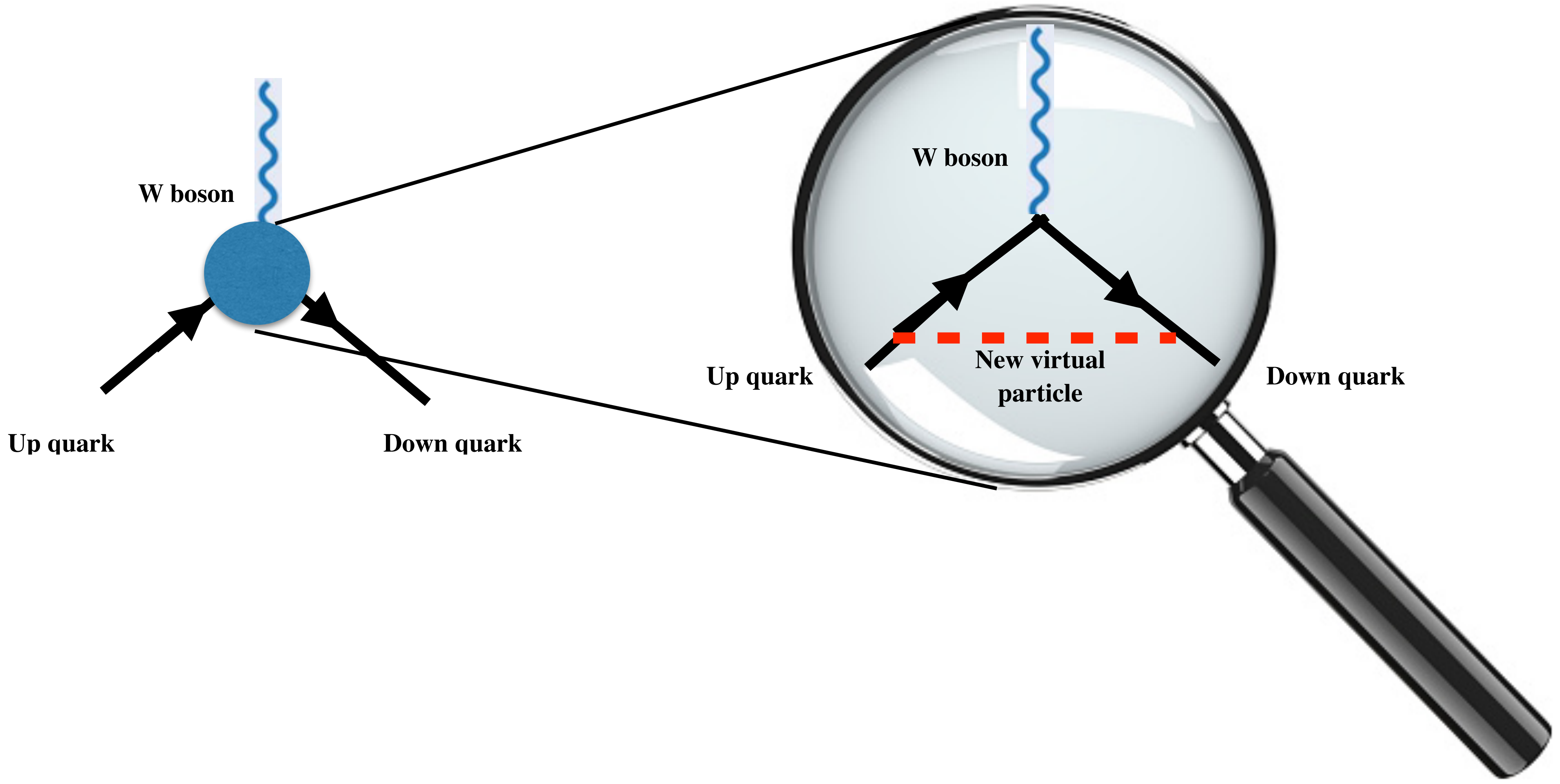
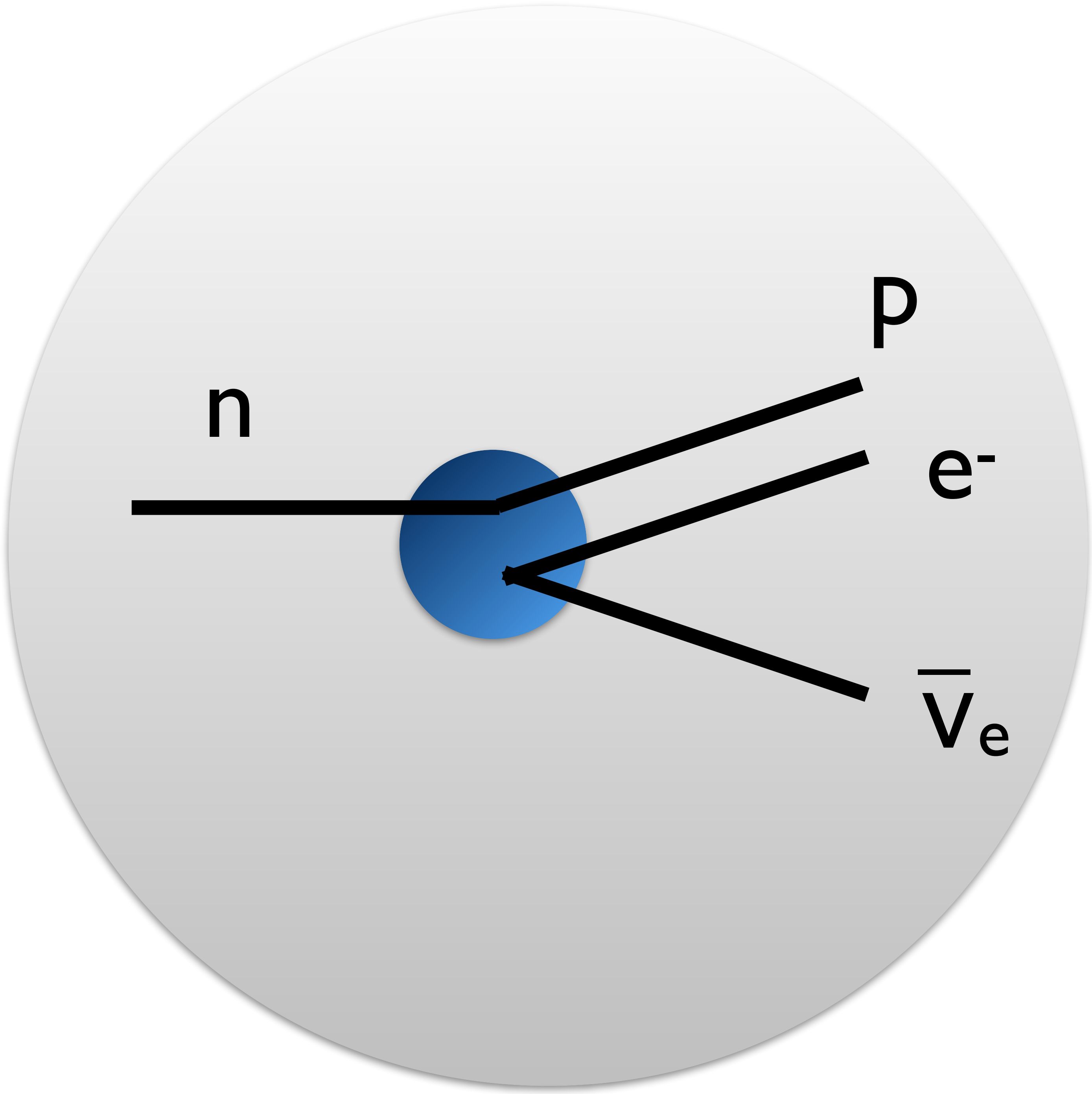
Outline



- Introduction: beta decays in the SM and beyond
- The "Cabibbo angle anomaly"
  - Scrutinize the SM prediction: radiative corrections to neutron decay in EFT
  - Study the implications for new physics: connection to other probes (Z pole, LHC, …)
- Conclusions and outlook

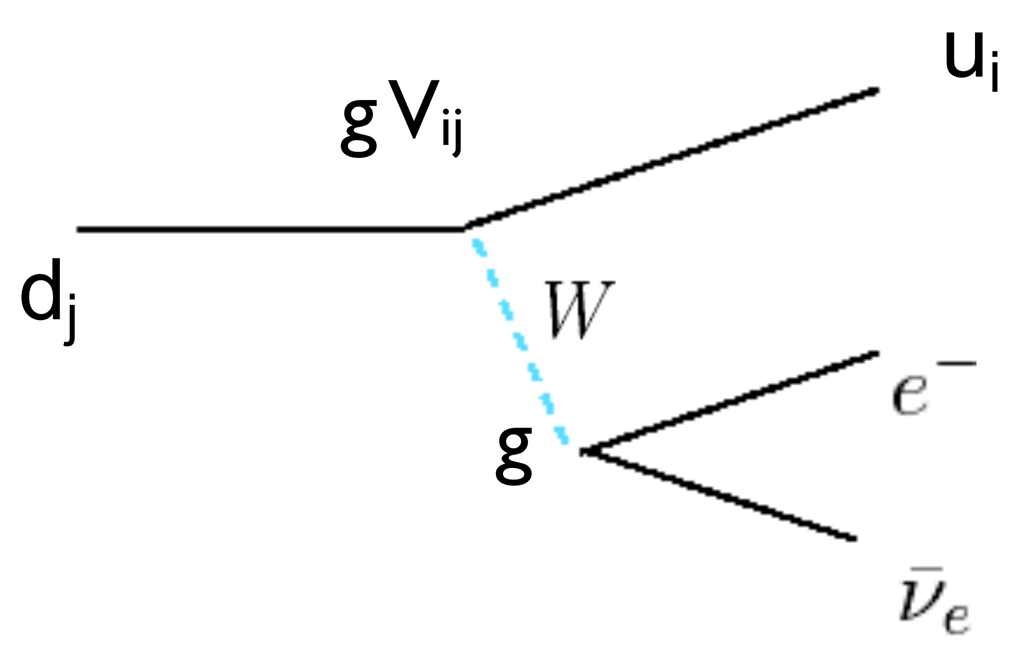
β decays in the SM and beyond

- 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

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

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

Lepton Flavor Universality (LFU)

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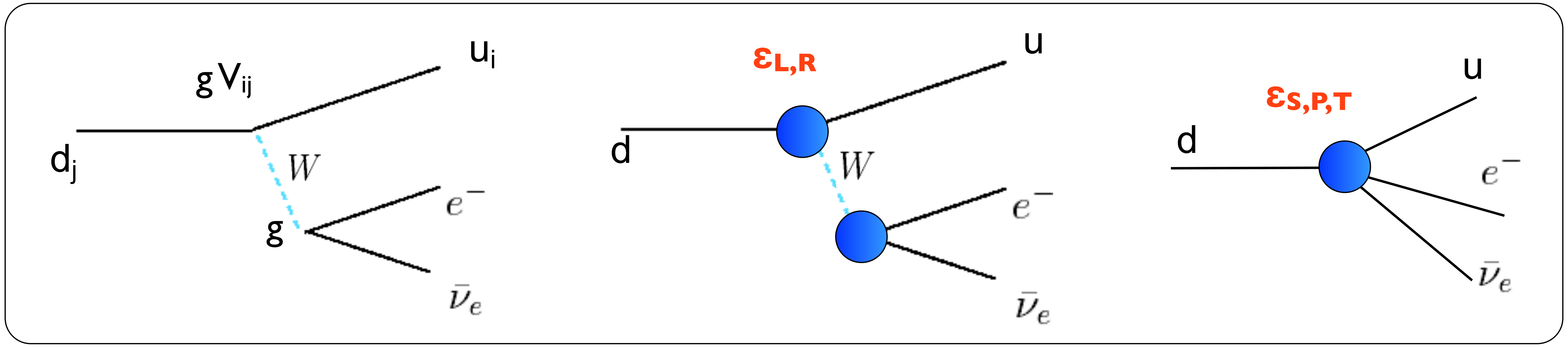
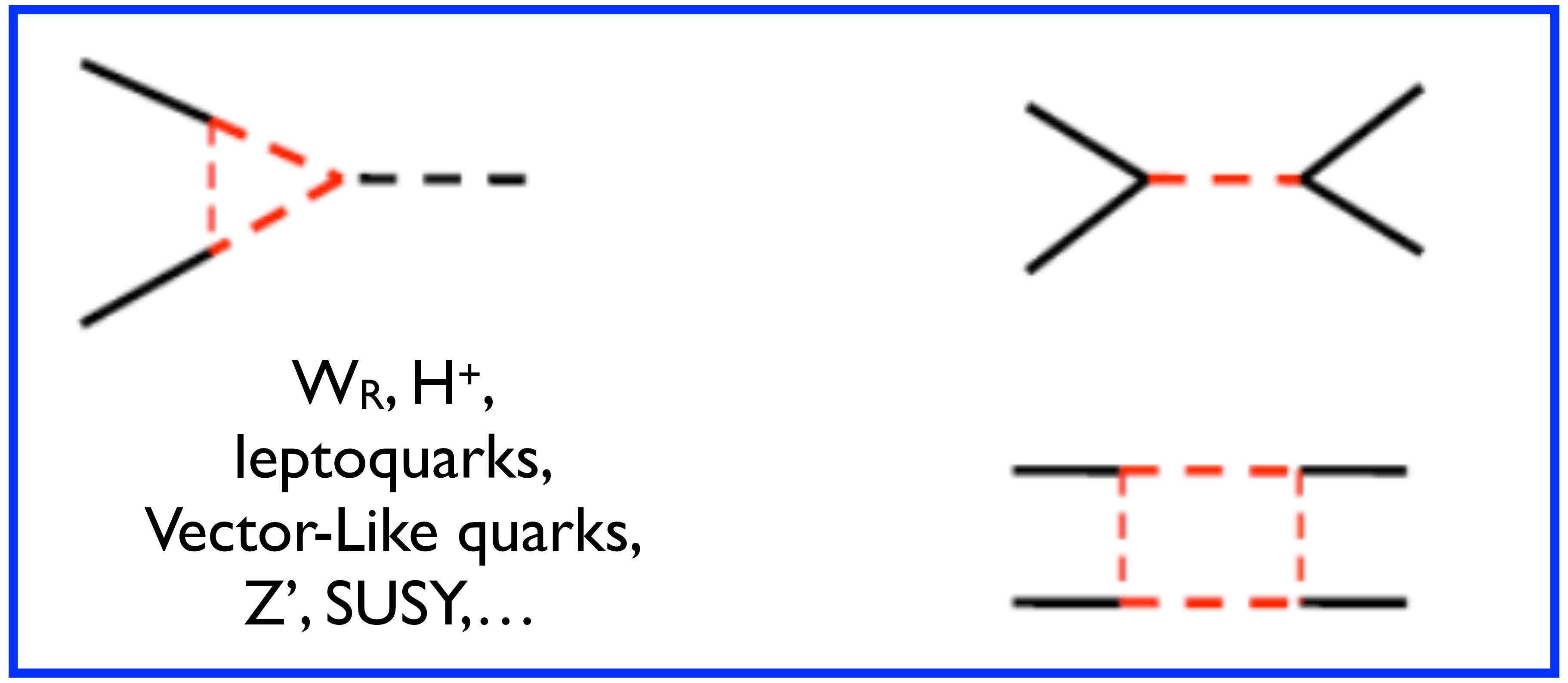


$G_F^{(\beta)} \sim G_F^{(\mu)} V_{ij} \sim 1/v^2 V_{ij}$ $\qquad$ $1/\Lambda^2$ $\qquad$ $1/\Lambda^2$



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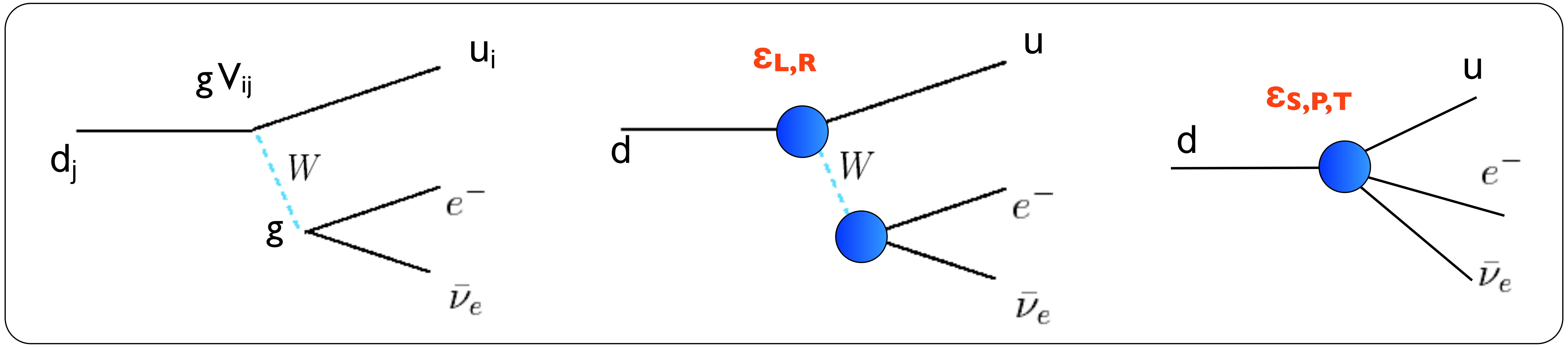


$G_F^{(\beta)} \sim G_F^{(\mu)} V_{ij} \sim 1/v^2 V_{ij}$ $1/\Lambda^2$ $1/\Lambda^2$

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

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

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

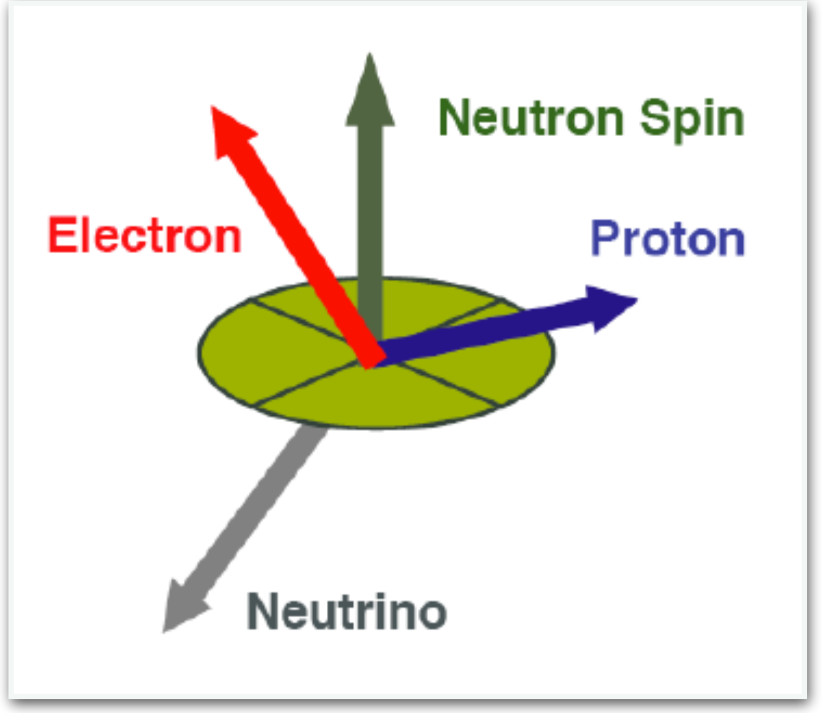
Measure differential decay distributions (mostly sensitive to $\varepsilon_{S,T}$)

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

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

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

See talk by G. King



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 tests

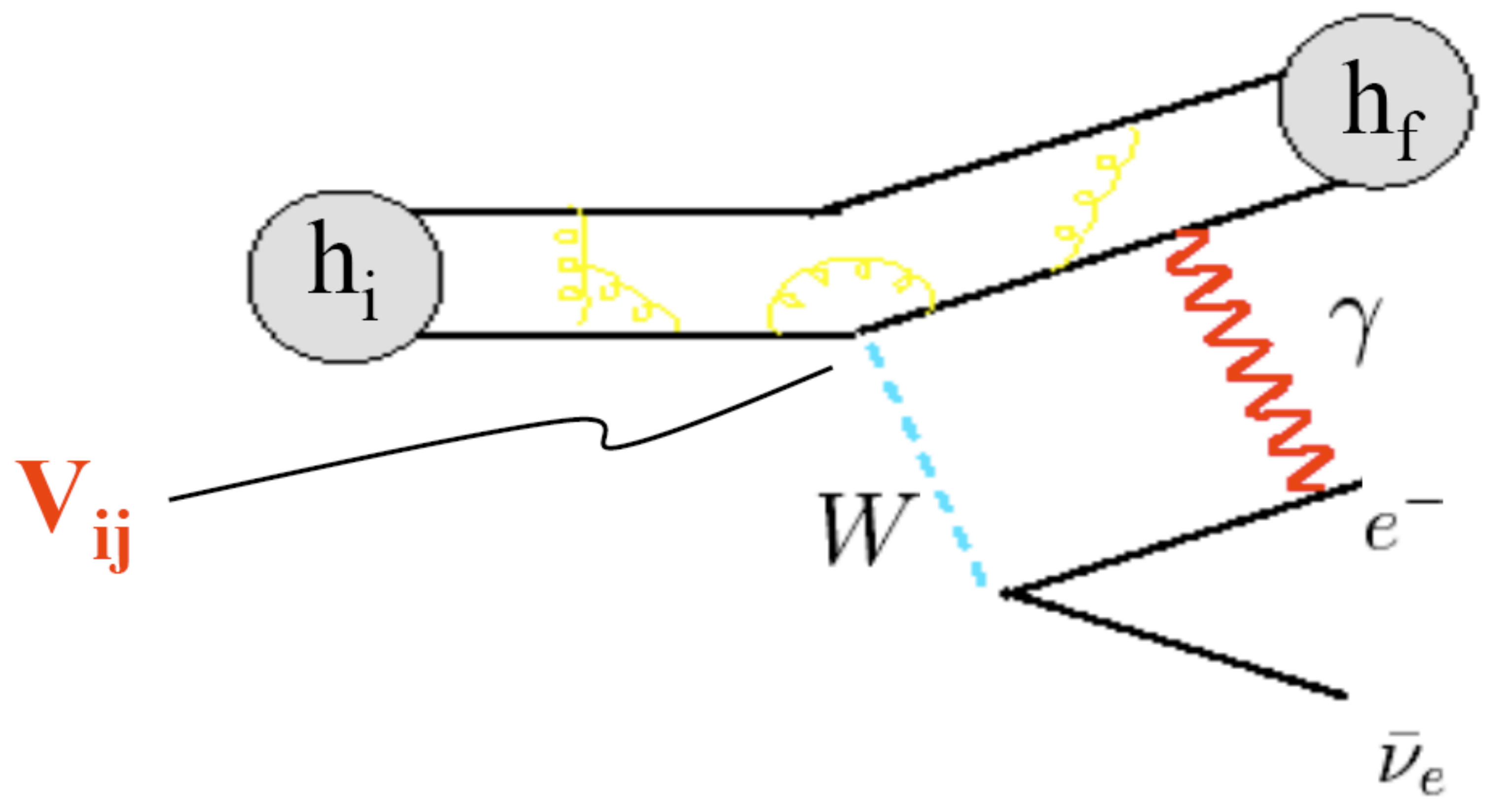
Extract $V_{ud}=\cos\theta_C$ and $V_{us}=\sin\theta_C$ from total decay rates

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

CKM element

Hadronic matrix element

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



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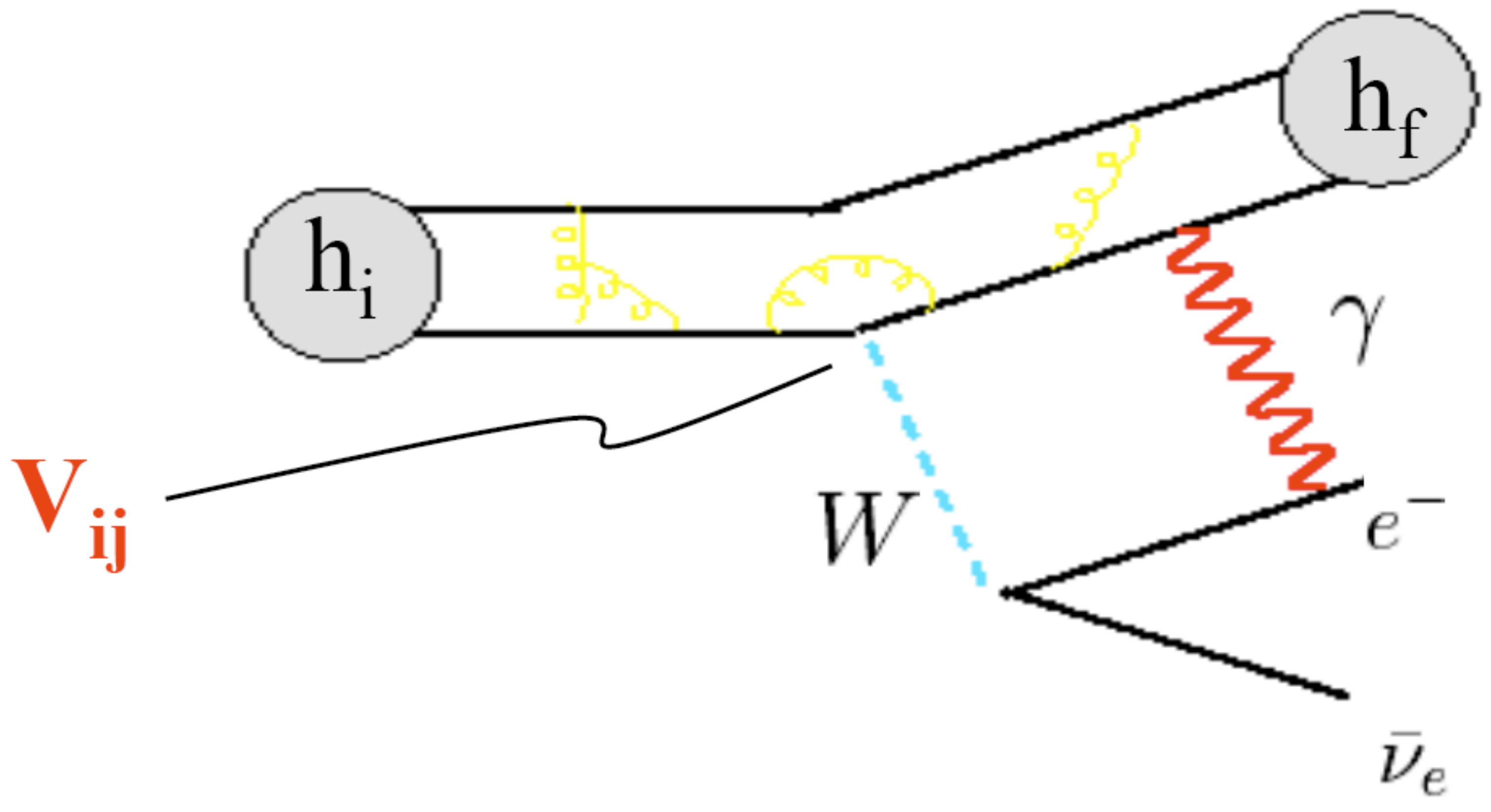
Unitarity test

$$\Delta_{\rm CKM} \equiv |V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 - 1 = 0$$

Paths to V_{ud} and V_{us}

V_{ud}	$0^+ \to 0^+$ $(\pi^\pm \to \pi^0 e\nu)$	$n \to pe\bar{\nu}$ (Mirror transitions)	$\pi \to \mu\nu$	(Hadronic τ decays)
V_{us}	$K \to \pi l \nu$	$(\Lambda \to pe\bar{\nu},\ldots)$	$K \to \mu\nu$	

Quark current mediating the decay → V | V, A | A



Input from *many* experiments and *many* theory papers

Paths to V_{ud} and V_{us}

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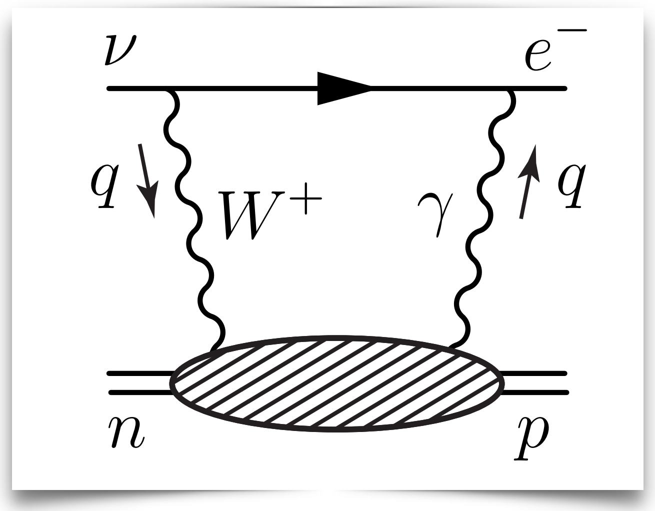
(Hadronic τ decays)

Comment1: Modern approaches to rad. corr. build upon Sirlin current algebra formulation from the '60 & '70s New wave of "inner" radiative corrections (n, nuclei) initiated by dispersive analysis of Seng, Gorchtein, Patel, Ramsey-Musolf 2018, all the way to very recent lattice QCD calculation by Ma et al, 2308.16755



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

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

Hardy-Towner, PRC 2020
Seng et al. 1812.03352
Gorchtein 1812.04229

See talk by Chien Yeah Seng for status of other corrections

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(Hadronic τ decays)

Comment 2: neutron decay is beginning to provide very competitive δV_{ud}

$$V_{ud}^{\text{n, PDG}} = 0.97441(3)_f(13)_{\Delta_R}(82)_\lambda(28)_{\tau_n}[88]_{\text{total}}$$

$$V_{ud}^{\text{n, best}} = 0.97413(3)_f(13)_{\Delta_R}(35)_\lambda(20)_{\tau_n}[43]_{\text{total}}$$ ← Most precise measurements

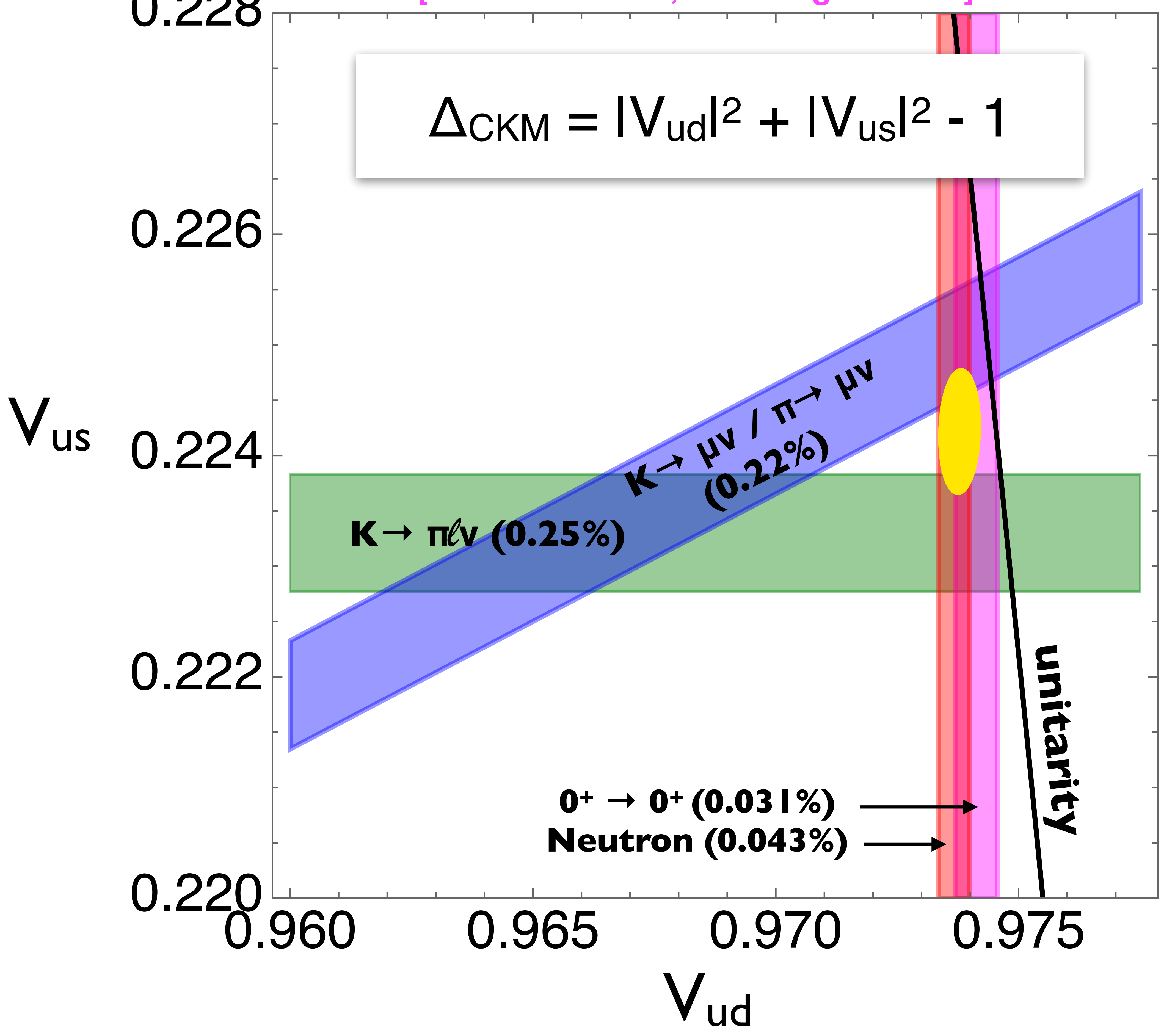
Maerkish et al, 1812.04666 — $\lambda = g_A/g_V$

Gonzalez et al, 2106.10375 — τ_n

The Cabibbo angle "anomaly"

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

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



- The 'anomalies':
  - ~3σ effect in global fit (Δ_{CKM}= −1.48(53) ×10^{-3})
  - V_{ud} and V_{us} from different processes → different Δ_{CKM}
  - ~3σ problem in meson sector (Kl2 vs Kl3)

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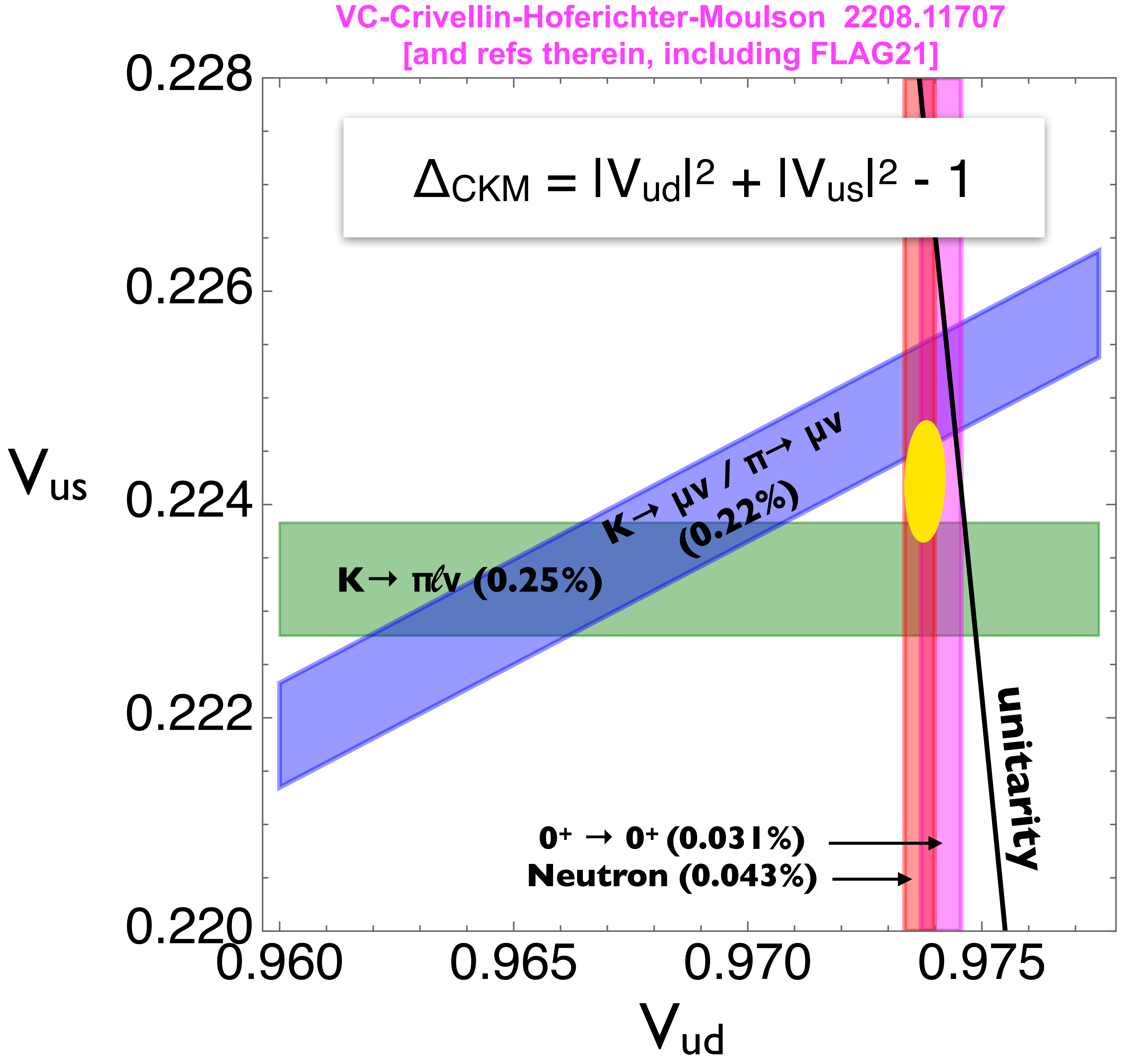

- Expected experimental improvements:
  - neutron decay (will match nominal nuclear uncertainty)
  - pion beta decay (3x to 10x at PIONEER phases II, III)
  - possibly new $K_{\mu 3}/K_{\mu 2}$ BR measurement at NA62 & HIKE
- Further theoretical scrutiny
  - Lattice gauge theory: K→π vector f.f., rad. corr. for Kl3
  - EFT for neutron and nuclei, with goal $\delta\Delta_R \sim 2\times 10^{-4}$
  - …
- Possible BSM explanations: EFT & specific models

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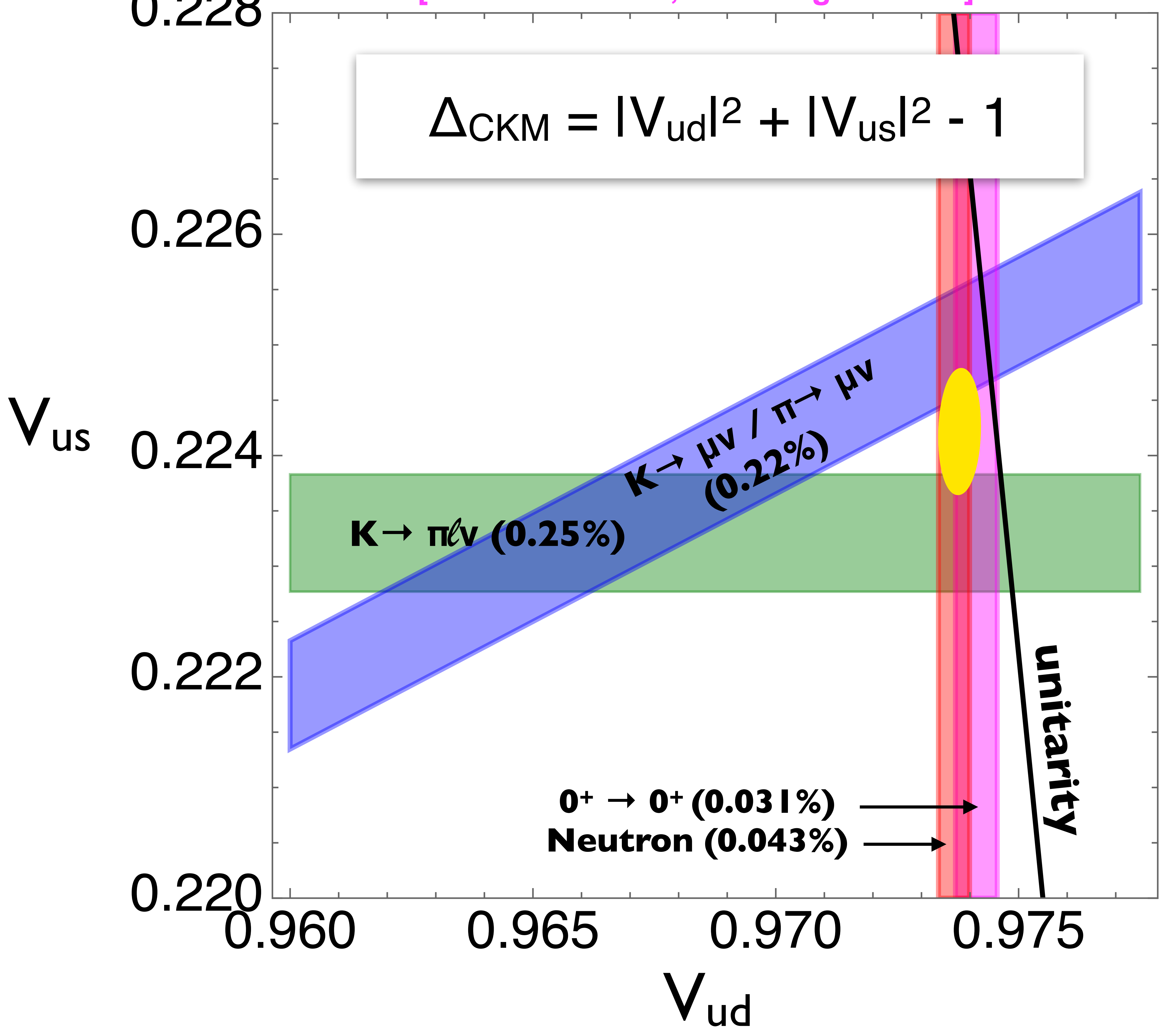

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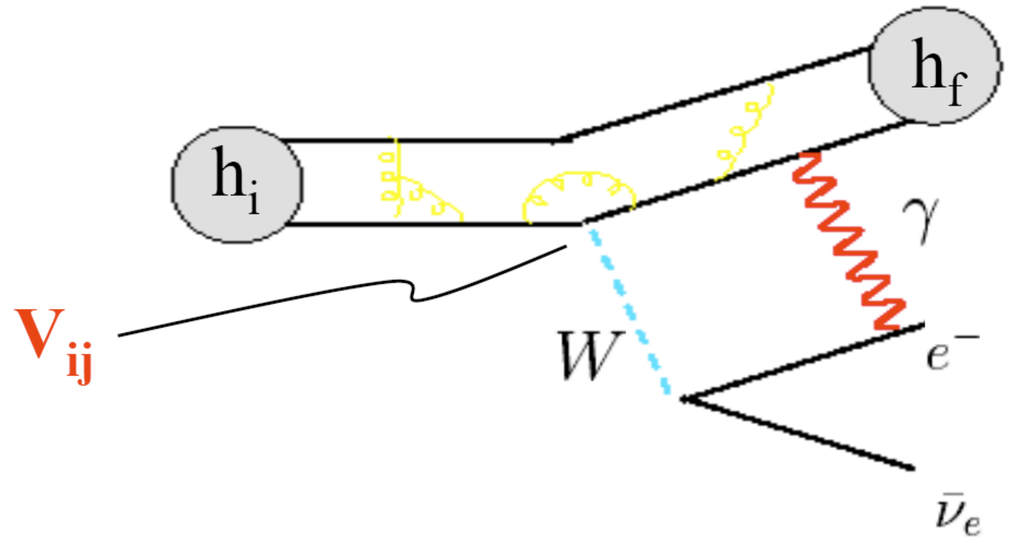
Radiative corrections to neutron beta decay in EFT

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

EFT for neutron decay: why?

- Widely separated mass scales play a role in neutron decay & EFT approach not fully embraced in the literature



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

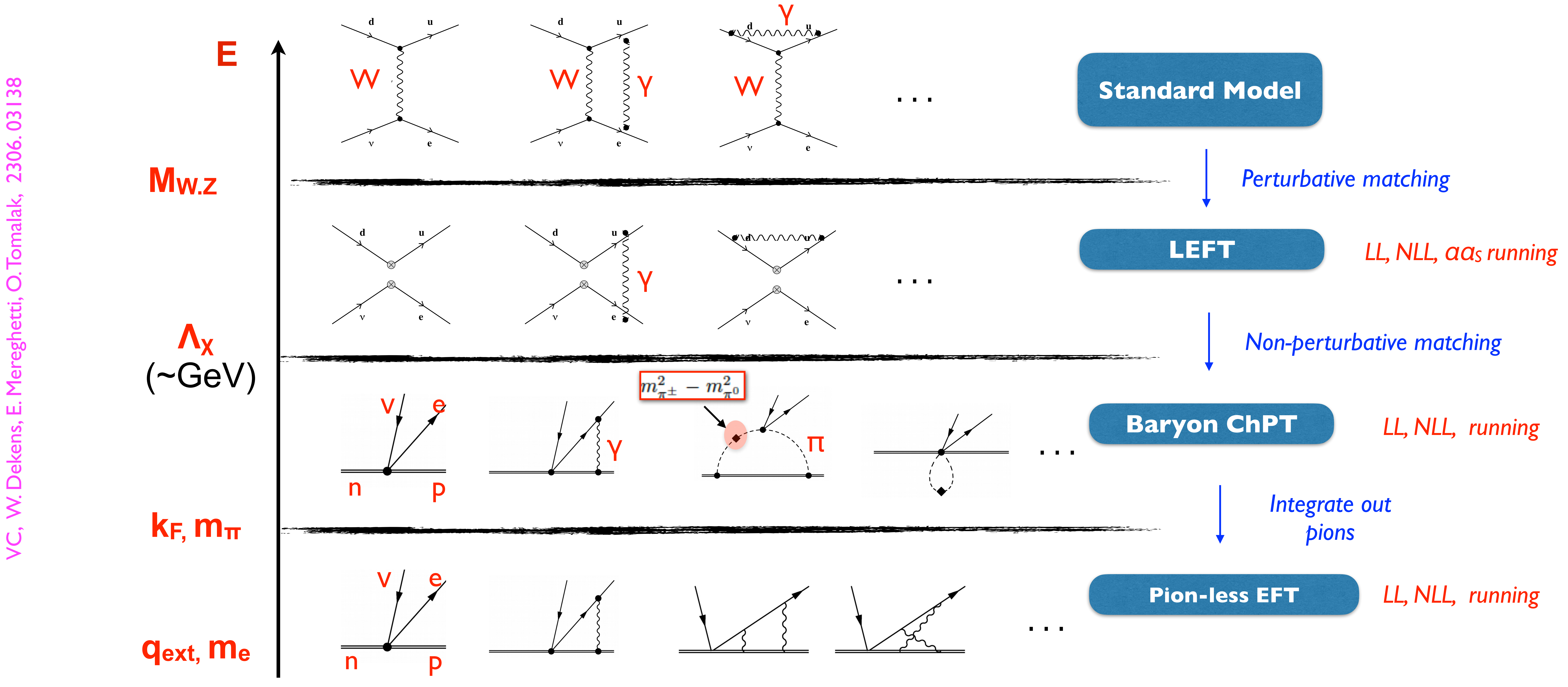
- Small ratios appear as expansion parameters and arguments of logarithms

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

- At the required precision ($\sim 10^{-4}$), need to keep terms of $O(G_F\alpha)$, $O(G_F\alpha\varepsilon_\chi)$, along with leading logarithms (LL~ $(\alpha \ln(\varepsilon))^n$) and next-to-leading logarithms (NLL ~ $\alpha\,(\alpha_S \ln(\varepsilon_W))^n$, $\alpha\,(\alpha \ln(\varepsilon))^n$)

Multi-step strategy

- Matching and running in a tower of EFTs: SM → LEFT → HBChPT → π̸EFT



Corrections to neutron decay

- Convenient starting point for decay rate calculation is an effective theory with nucleons, 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 themselves depend on α, ε_W, ε_χ, ε_π (consistently with the decoupling theorem)

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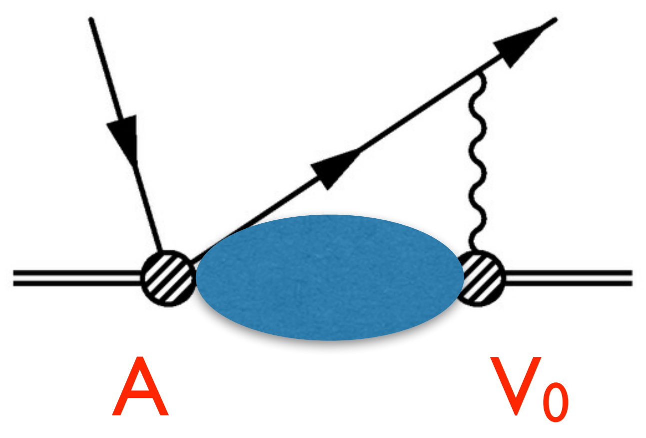
$$g_V(\mu_e) = U(\mu_e, \Lambda_\chi)\left[1 + \overline{\Box}^V_{\rm Had} + \frac{\alpha(\Lambda_\chi)}{\pi}\kappa\right] U(\Lambda_\chi, \mu_W)\, C_\beta(\mu_W)$$

NLL RGE in ChPT and pion-less EFT

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

NLL RGE in LEFT

Wilson Coefficient at $\mu_W \sim m_W$



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g_V and g_A themselves depend on α, ε_W, ε_X, ε_π (consistently with the decoupling theorem)

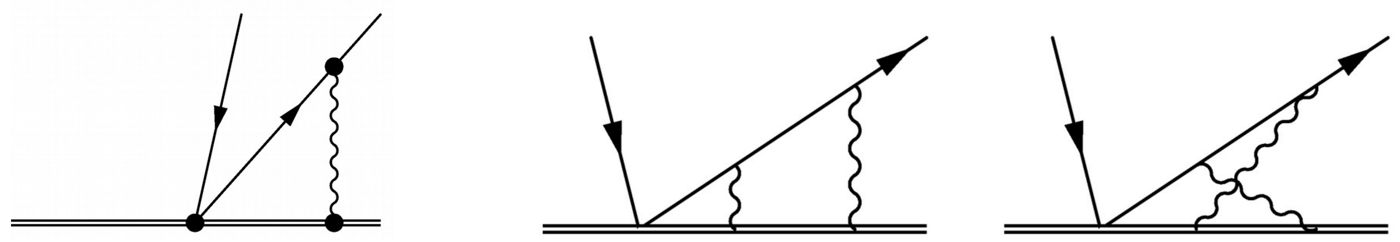
$\lambda = g_A/g_V$

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

Includes electromagnetic shift to g_V and g_A from $E > m_\pi$

Δ_f: Coulomb corrections (photon loops with $\mathcal{L}_{\not\pi}$) & $O(\epsilon_{recoil})$

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



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

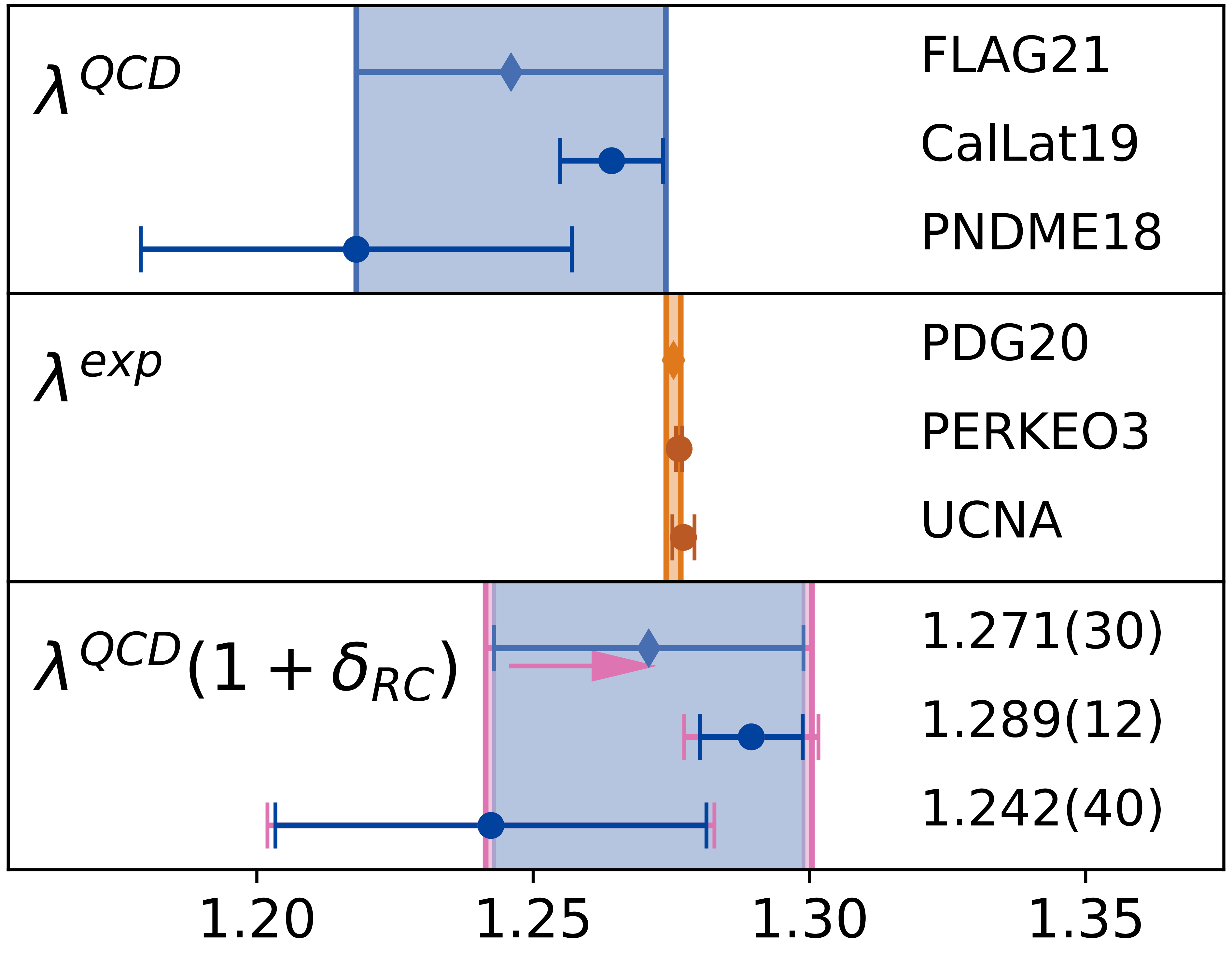
VC, J. de Vries, L. Hayen, E. Mereghetti, A. Walker-Loud 2202.10439

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

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

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

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



Radiative corrections generally improve agreement between data and Lattice QCD

Corrections to total decay rate

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

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

$\lambda = g_A/g_V$

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

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

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$\lambda = g_A/g_V$

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

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

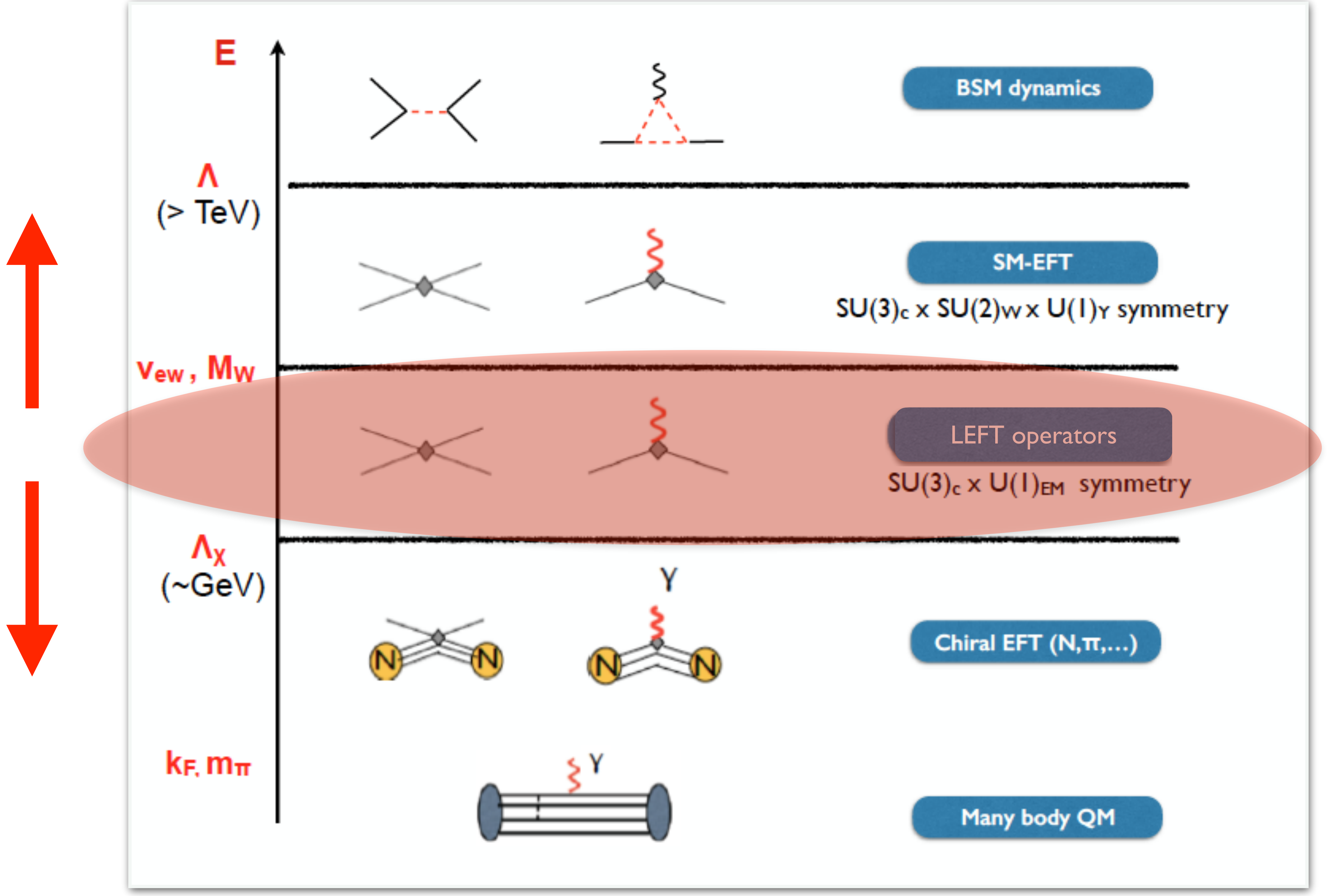
Overall shift of -0.013% in V_{ud} (neutron) compared to previous literature

Implications for new physics

VC, A. Crivellin, M. Hoferichter, M. Moulson, 2208.11707, PLB
VC, W. Dekens, J. deVries, E. Mereghetti, T. Tong 2204.08440, PRD
VC, W. Dekens, J. de Vries, E. Mereghetti, T. Tong, in preparation

Connecting scales & processes — I

To connect UV physics to beta decays, use EFT



- Start with GeV scale effective Lagrangian
  - New physics effects are encoded in ten quark-level couplings
  - Quark-level version of Lee-Yang effective Lagrangian

GeV-scale effective Lagrangian

VC, Gonzalez-Alonso, Jenkins 0908.1754, NPB

VC, Graesser, Gonzalez-Alonso 1210.4553, JHEP

Leptonic interactions

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

Semi-leptonic interactions

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

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

GeV-scale effective Lagrangian

VC, Gonzalez-Alonso, Jenkins 0908.1754, NPB

VC, Graesser, Gonzalez-Alonso 1210.4553, JHEP

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

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

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

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, extracted CKM elements

Elements of the unitary CKM matrix

Known coefficients

BSM effective coupligs

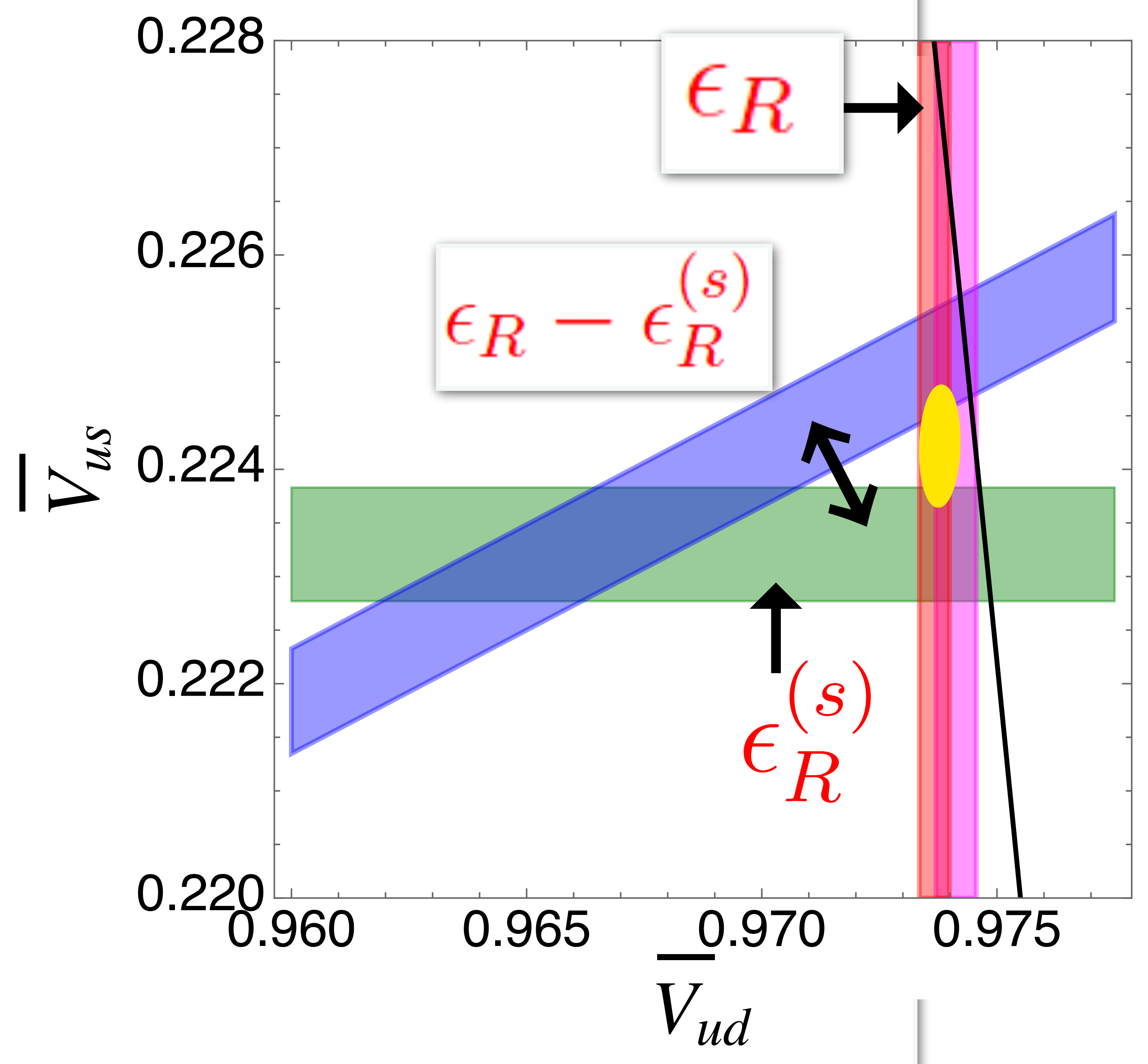
Find set of ε's so that V_{ud} and V_{us} bands meet on the unitarity circle

Right-handed quark couplings

Grossman-Passemar-Schacht
1911.07821 JHEP
Alioli et al 1703.04751, JHEP

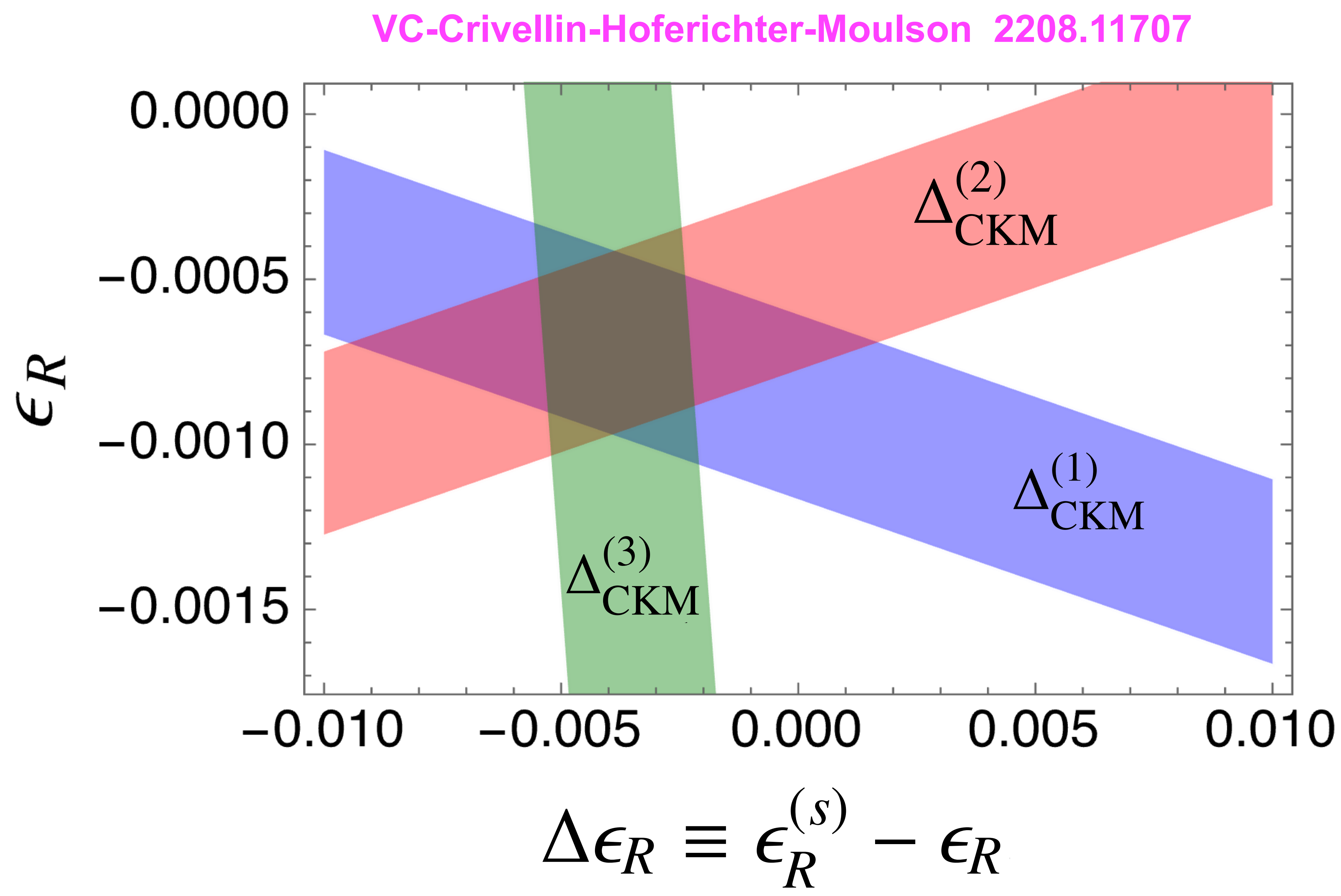
- Right-handed currents (in the ‘ud’ and ‘us' sectors)

$$
\begin{aligned}
|\bar{V}_{ud}|^2_{0^+\to 0^+} &= |V_{ud}|^2\left(1+2\,\epsilon_R\right)\\
|\bar{V}_{ud}|^2_{n\to pe\bar{\nu}} &= |V_{ud}|^2\left(1+2\,\epsilon_R\right)\\
|\bar{V}_{us}|^2_{Ke3} &= |V_{us}|^2\left(1+2\,\epsilon_R^{(s)}\right)\\
|\bar{V}_{ud}|^2_{\pi e3} &= |V_{ud}|^2\left(1+2\,\epsilon_R\right)\\
|\bar{V}_{us}|^2_{K\mu 2} &= |V_{us}|^2\left(1-2\,\epsilon_R^{(s)}\right)\\
|\bar{V}_{ud}|^2_{\pi\mu 2} &= |V_{ud}|^2\left(1-2\,\epsilon_R\right)
\end{aligned}
$$



- CKM elements from vector (axial) channels are shifted by $1+\varepsilon_R$ $(1-\varepsilon_R)$.
  V_{us}/V_{ud} , V_{ud} and V_{us} shift in anti-correlated way, can resolve all tensions!

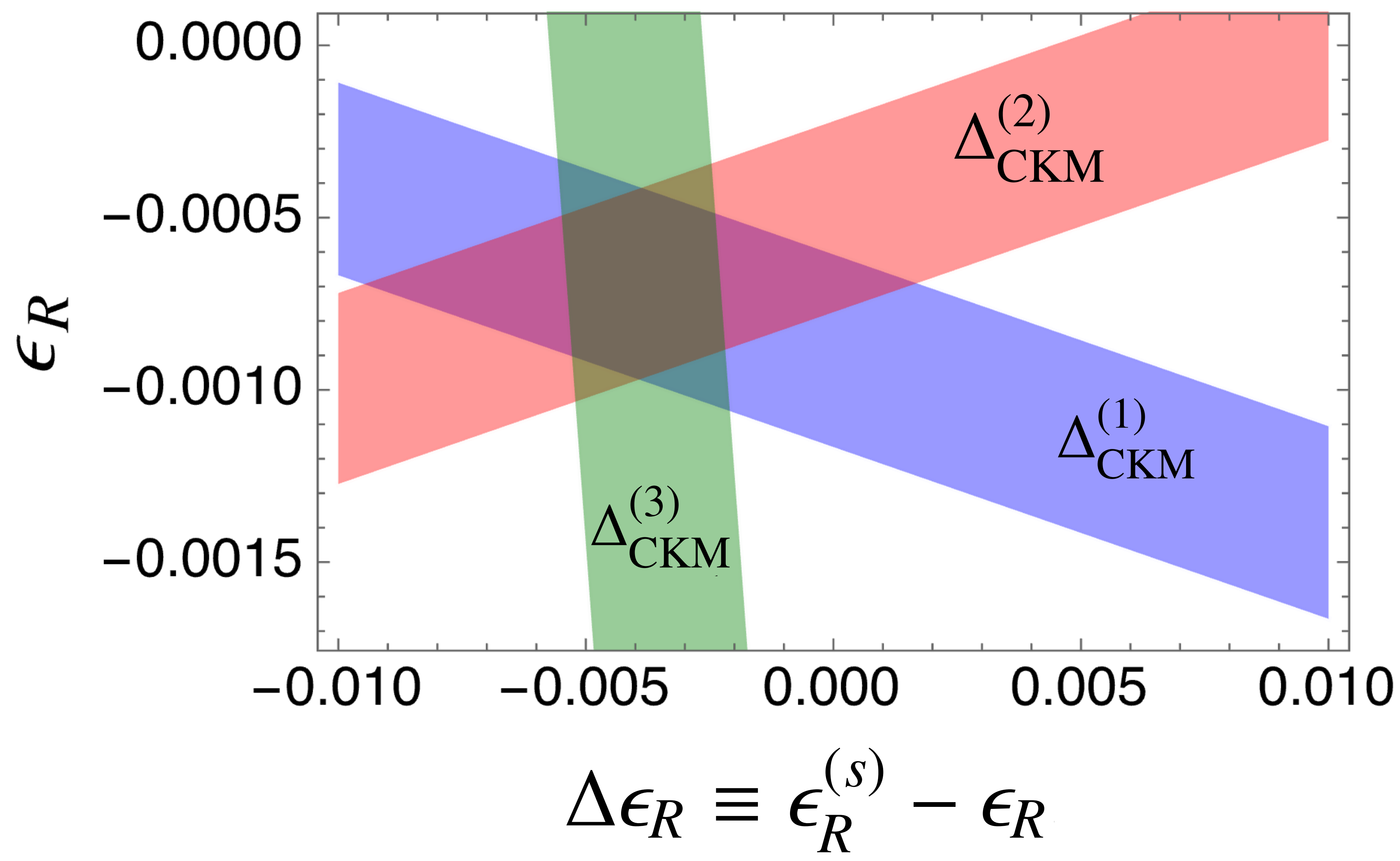
Unveiling R-handed quark currents?



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

Unveiling R-handed quark currents?

VC-Crivellin-Hoferichter-Moulson 2208.11707



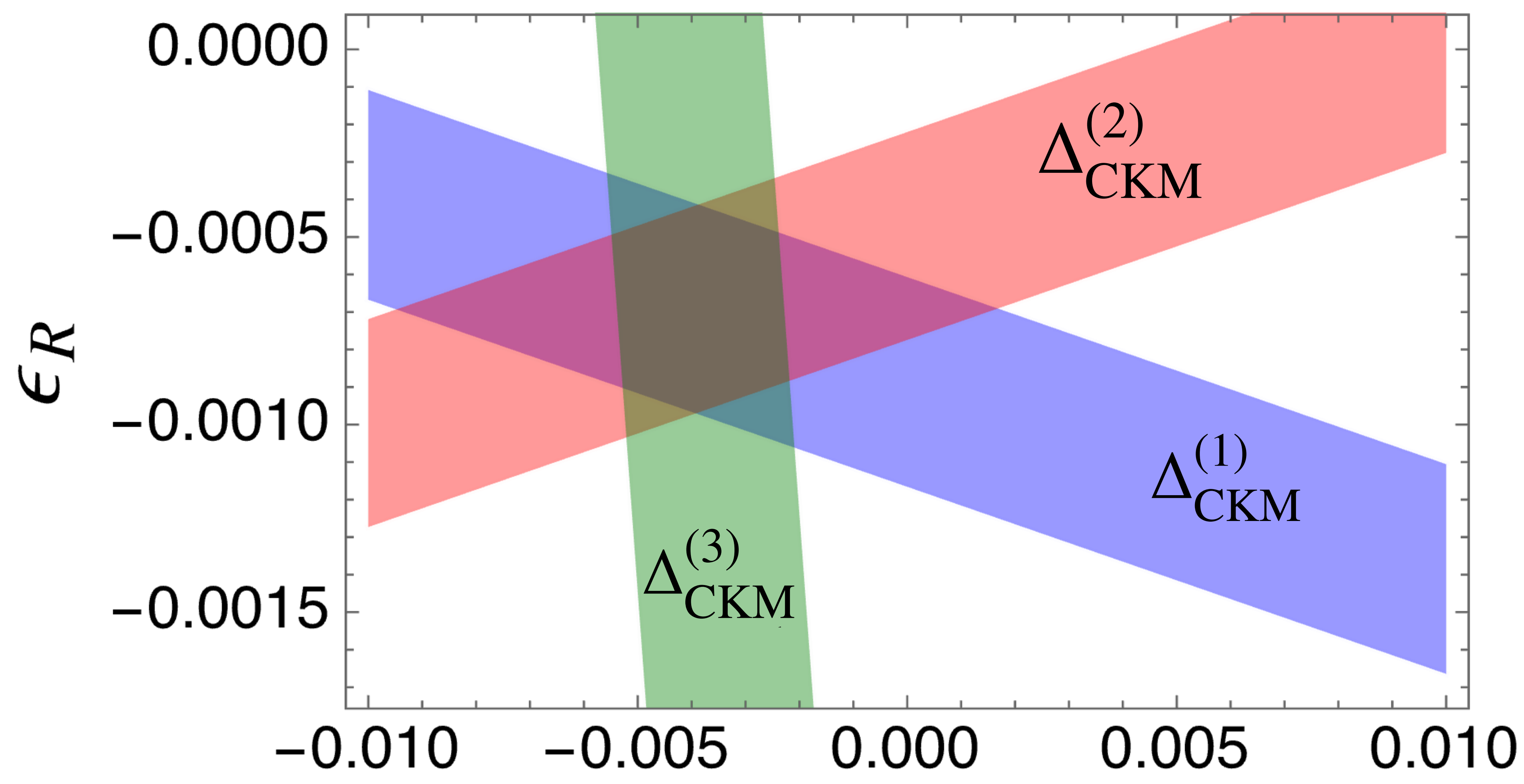
$$\Delta^{(1)}_{\rm CKM} = 2\epsilon_R + 2\Delta\epsilon_R V_{us}^2,$$
$$\Delta^{(2)}_{\rm CKM} = 2\epsilon_R - 2\Delta\epsilon_R V_{us}^2,$$
$$\Delta^{(3)}_{\rm CKM} = 2\epsilon_R + 2\Delta\epsilon_R (2 - V_{us}^2)$$

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

Λ_R ~ 5-10 TeV

Unveiling R-handed quark currents?

VC-Crivellin-Hoferichter-Moulson 2208.11707



$$\Delta\epsilon_R \equiv \epsilon_R^{(s)} - \epsilon_R$$

$$\Delta^{(1)}_{\rm CKM} = 2\epsilon_R + 2\Delta\epsilon_R V_{us}^2,$$
$$\Delta^{(2)}_{\rm CKM} = 2\epsilon_R - 2\Delta\epsilon_R V_{us}^2,$$
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$$\epsilon_R = -0.69(27) \times 10^{-3}$$
$$\Delta\epsilon_R = -3.9(1.6) \times 10^{-3}$$

Λ_R ~ 5-10 TeV

- Preferred ranges are not in conflict with other constraints from β decays

$$\frac{\lambda^{\rm exp}}{\lambda^{\rm QCD}} = 1 + \delta_{\rm RC} - 2\epsilon_R$$

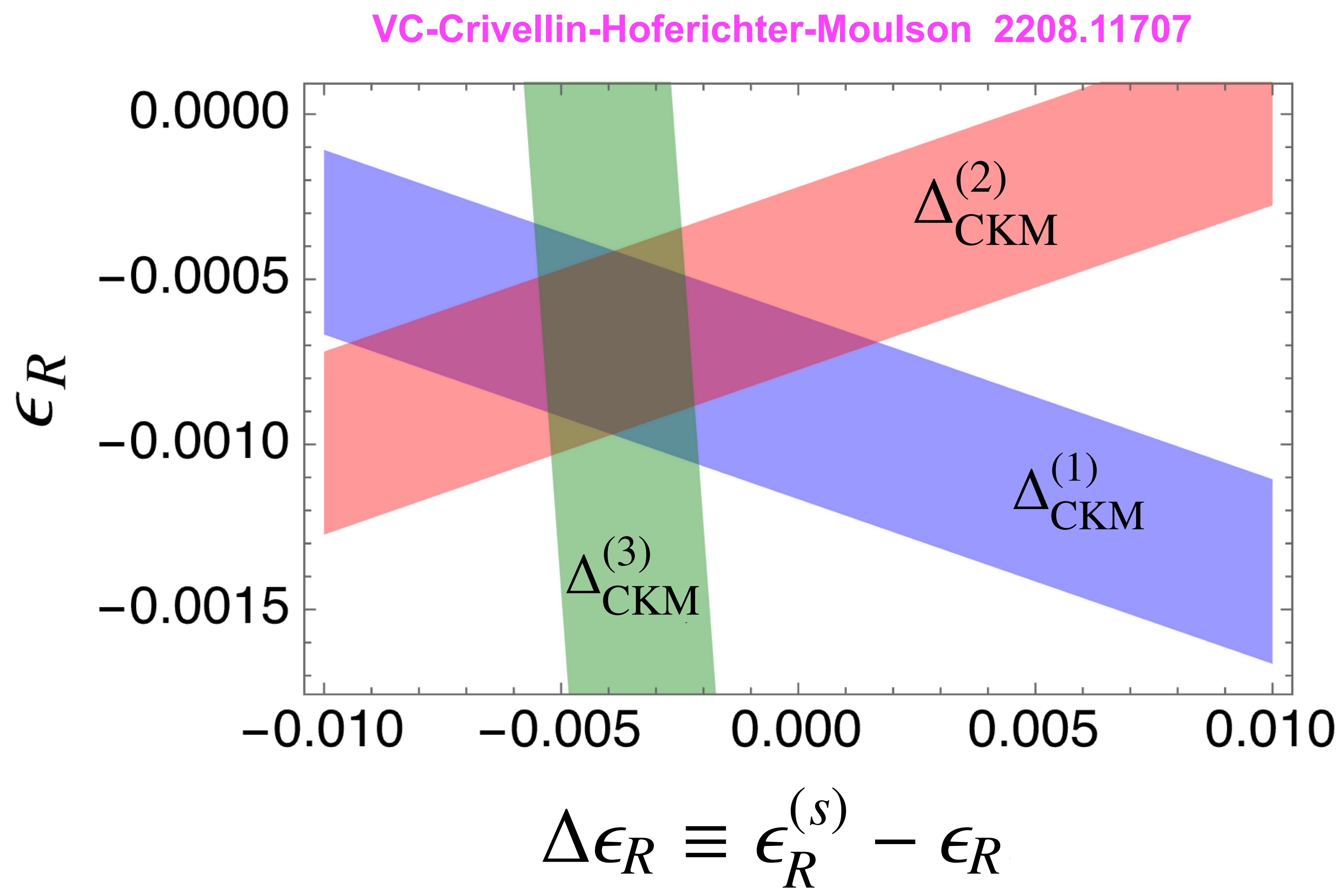
$$\lambda \equiv \frac{g_A}{g_V}$$

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

$$\epsilon_R = -0.2(1.2)\%$$

VC, Hayen, deVries, Mereghetti, Walker-Loud, 2202.10439

Unveiling R-handed quark currents?



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

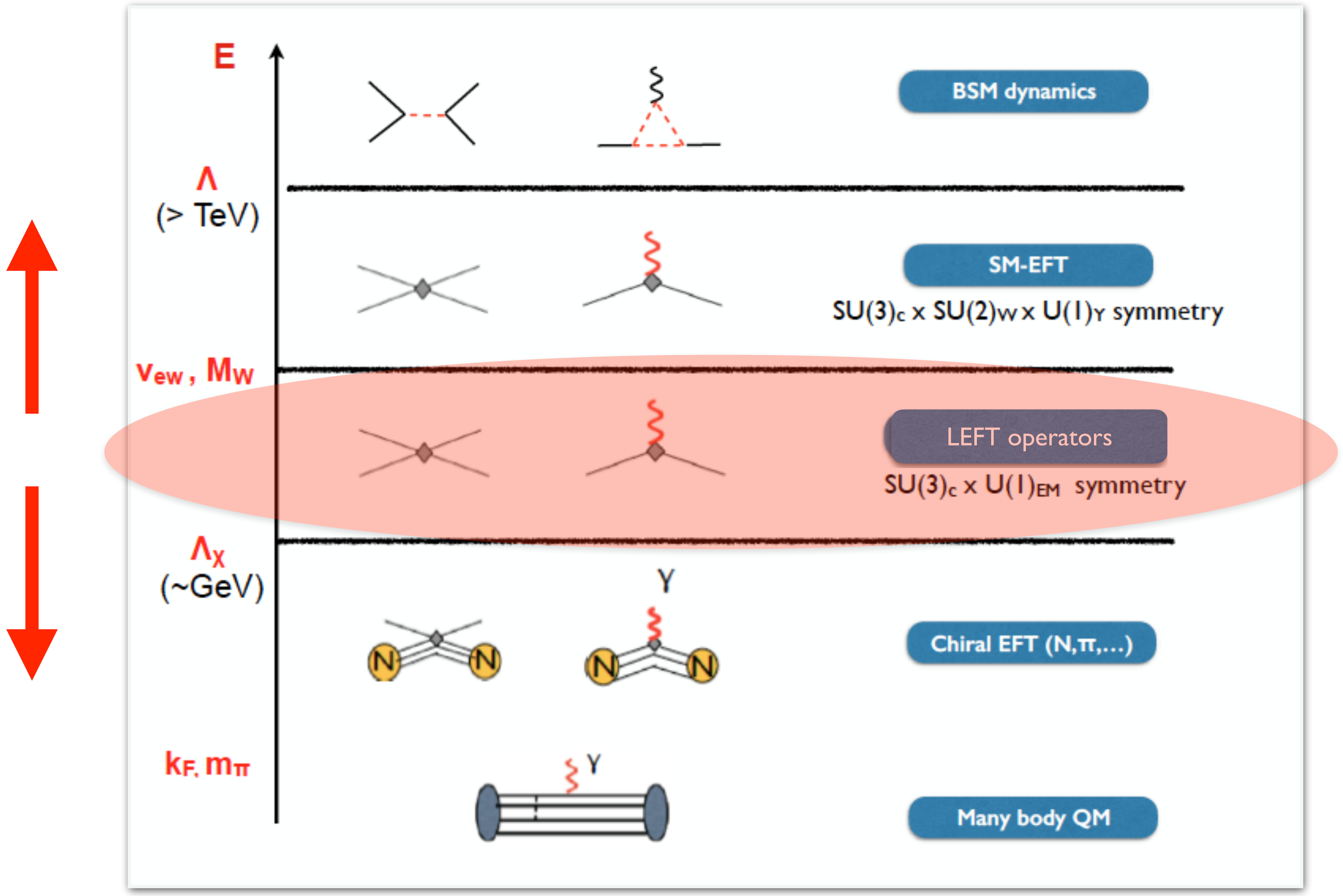
Λ_R ~ 5-10 TeV

- Does the R-handed current explanation survive after taking into account high energy data?

For other BSM explanations, see A. Crivellin 2207.02507 and references therein

Connecting scales & processes — 2

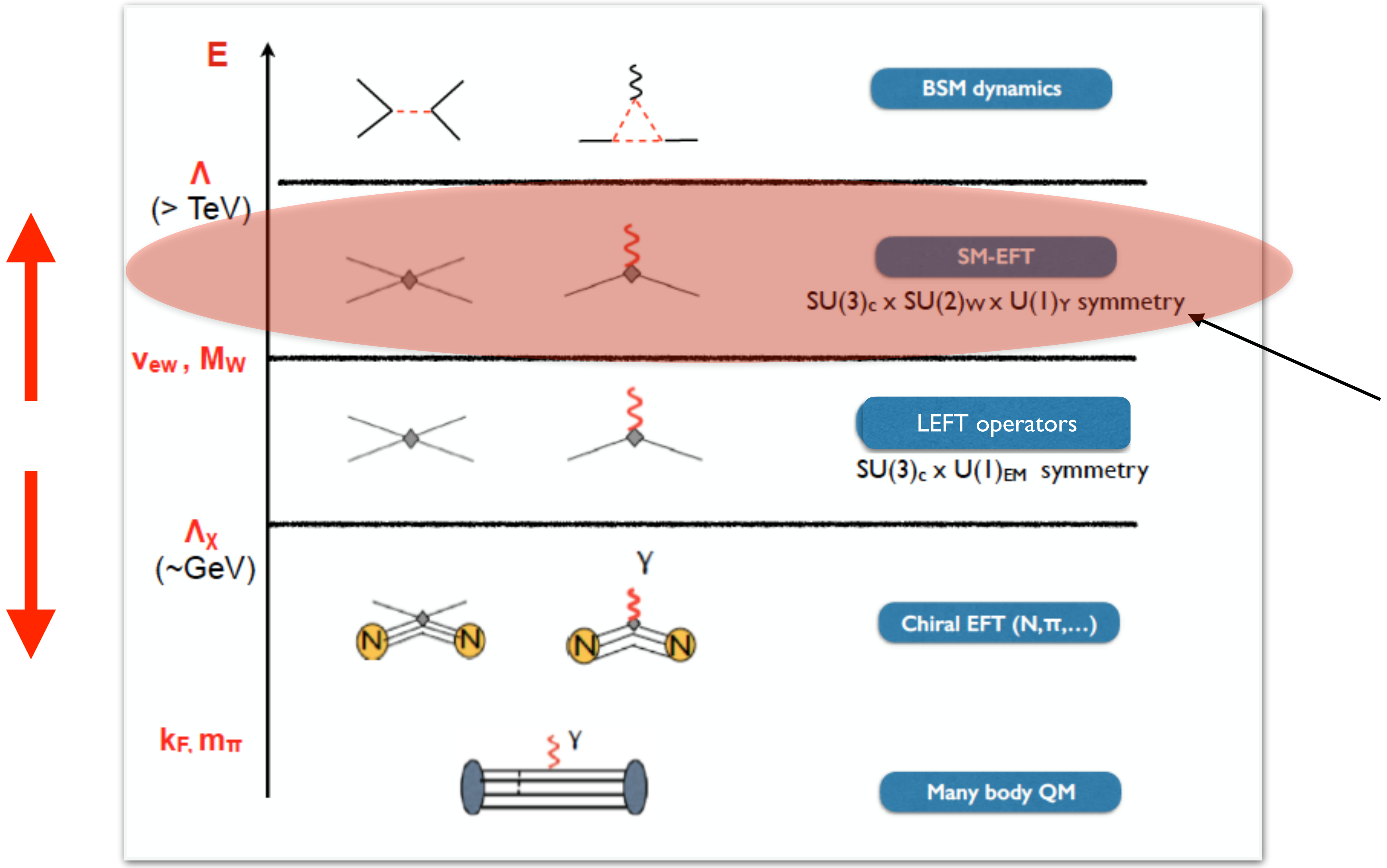
To connect UV physics to beta decays, use EFT



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

Connecting scales & processes — 2

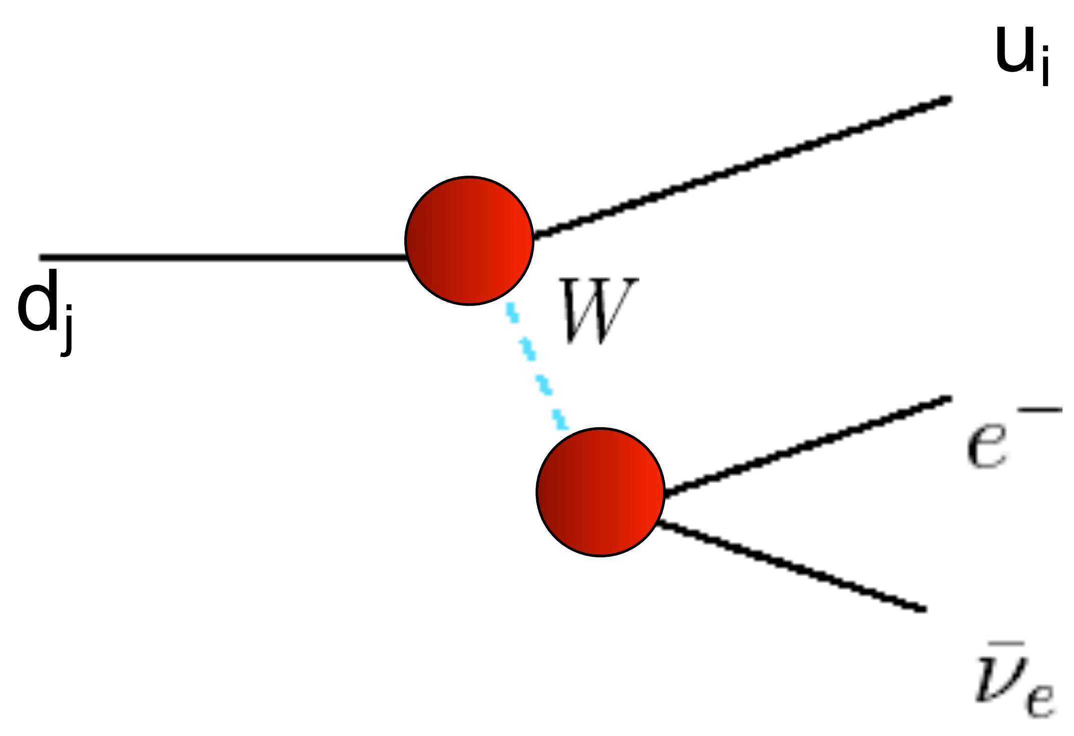
To connect UV physics to beta decays, use EFT



- Need to know high-scale origin of the various ε_α
- Identified by a matching calculation with the SM-EFT at the weak scale

Weak scale effective Lagrangian

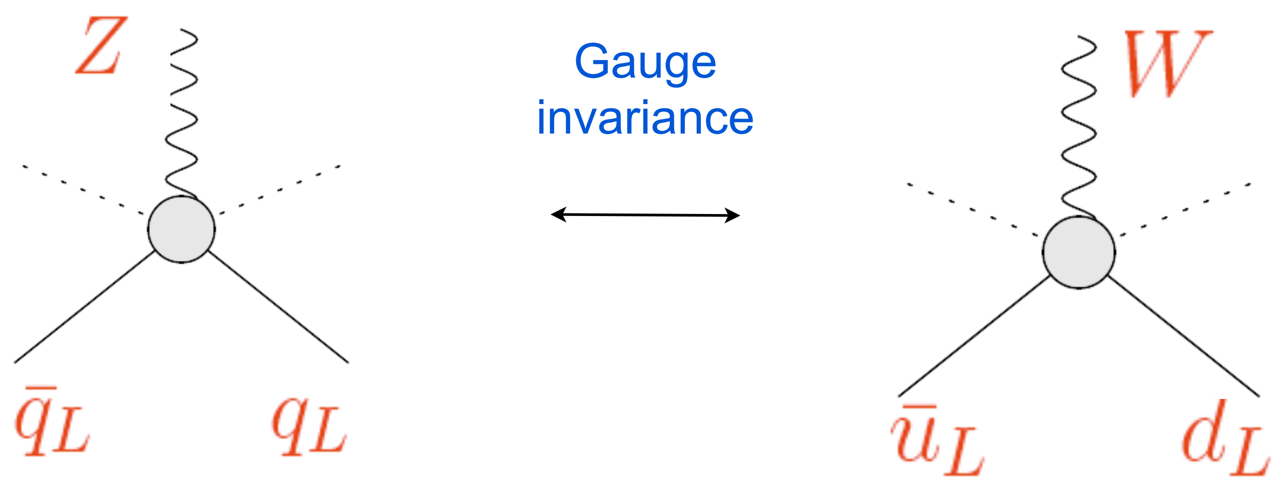
$\varepsilon_{L,R}$ originate from SU(2)xU(1) invariant vertex corrections



Building blocks

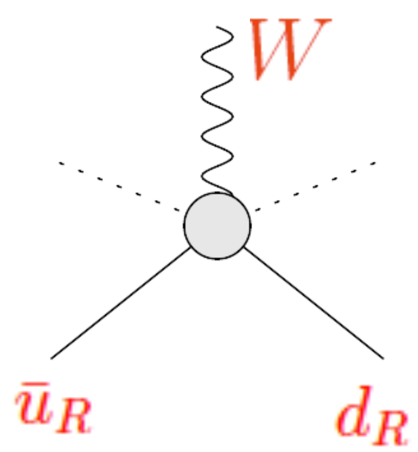
$$l^i = \begin{pmatrix} \nu_L^i \\ e_L^i \end{pmatrix} \quad q^i = \begin{pmatrix} u_L^i \\ d_L^i \end{pmatrix} \quad H = \begin{pmatrix} \varphi^+ \\ \varphi^0 \end{pmatrix}$$

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



ε_L

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



ε_R

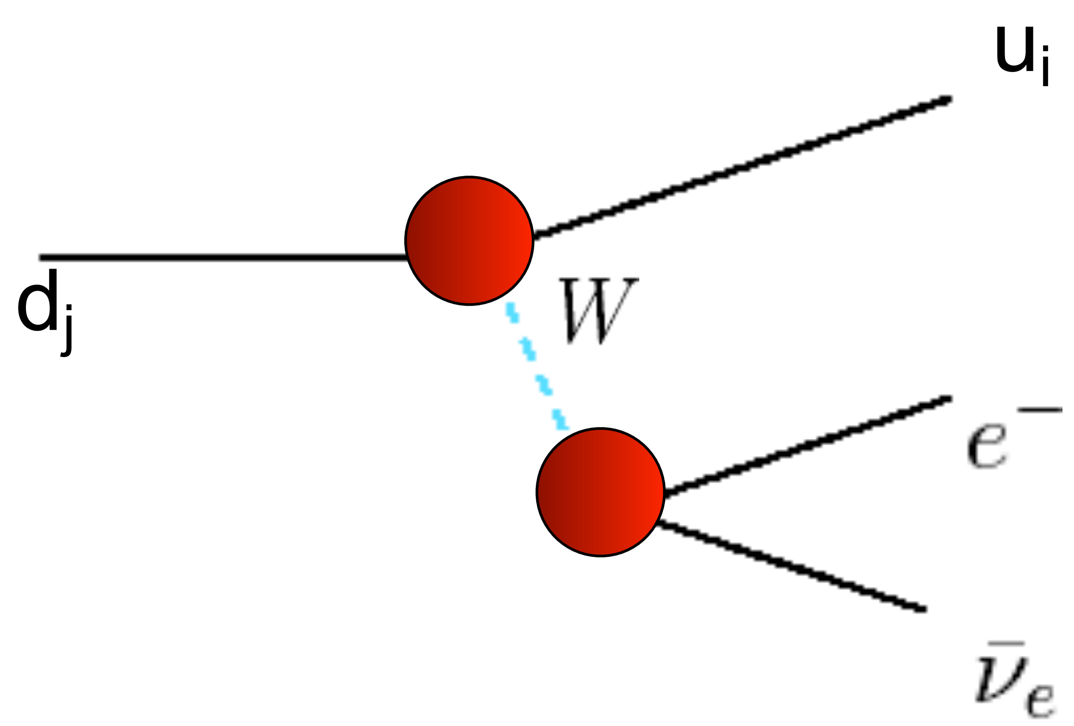
Can be generated by
W_L-W_R mixing in Left-Right symmetric models
or by exchange of vector-like quarks

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

Belfatto-Berezhiani 2103.05549
Belfatto-Trifinopoulos 2302.14097

Weak scale effective Lagrangian

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

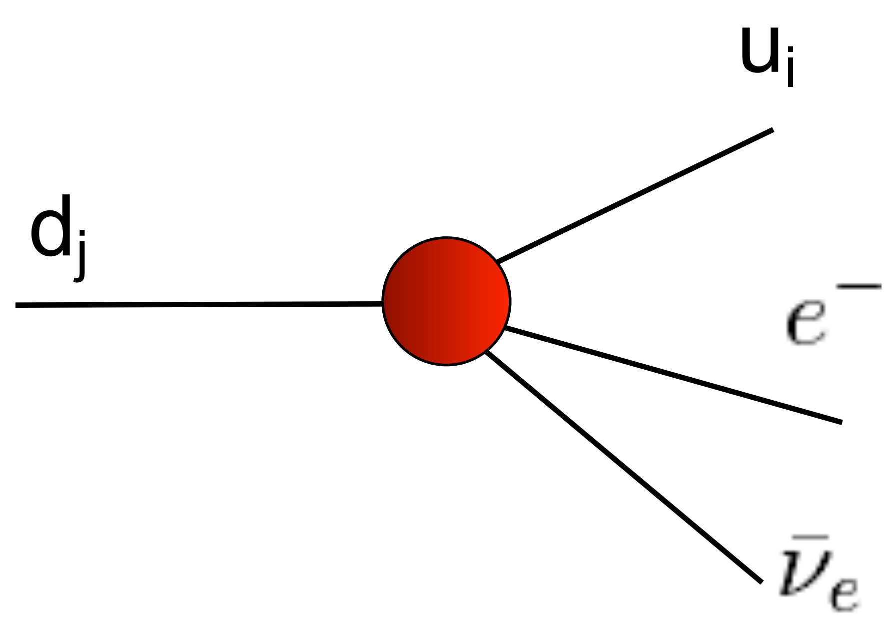


ε_R $$Q_{Hud} = i(\widetilde{H}^\dagger D_\mu H)(\bar{u}_p \gamma^\mu d_r)$$

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

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

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



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

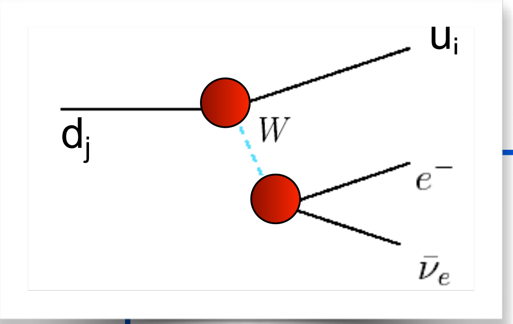
$$O_{lq} = (\bar{l}_a e)\epsilon^{ab}(\bar{q}_b u) + \text{h.c.}$$ $\varepsilon_{S,P}$

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

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

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

High Energy constraints



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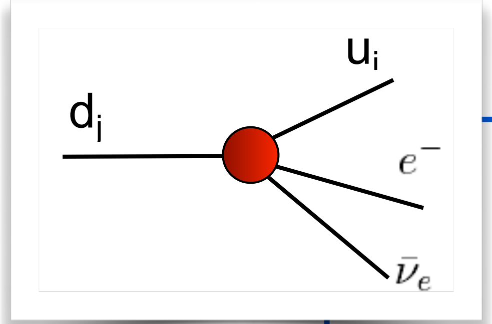

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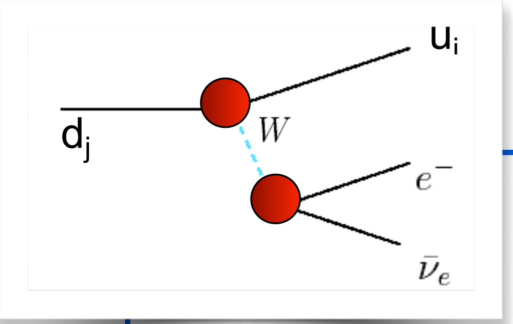
High Energy constraints



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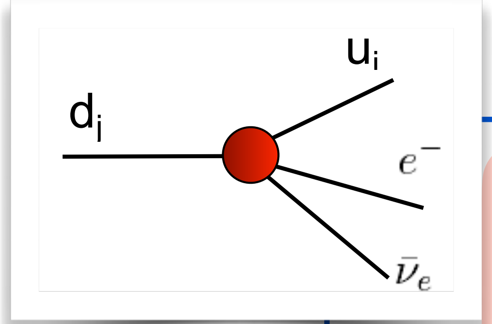

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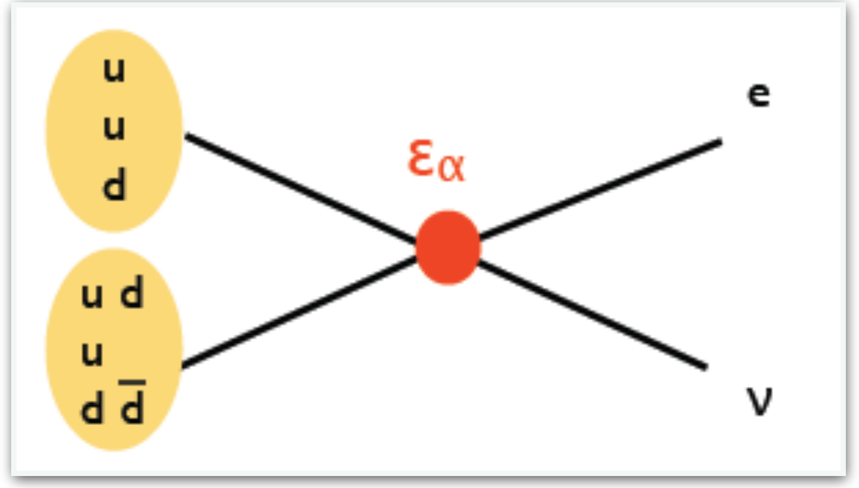
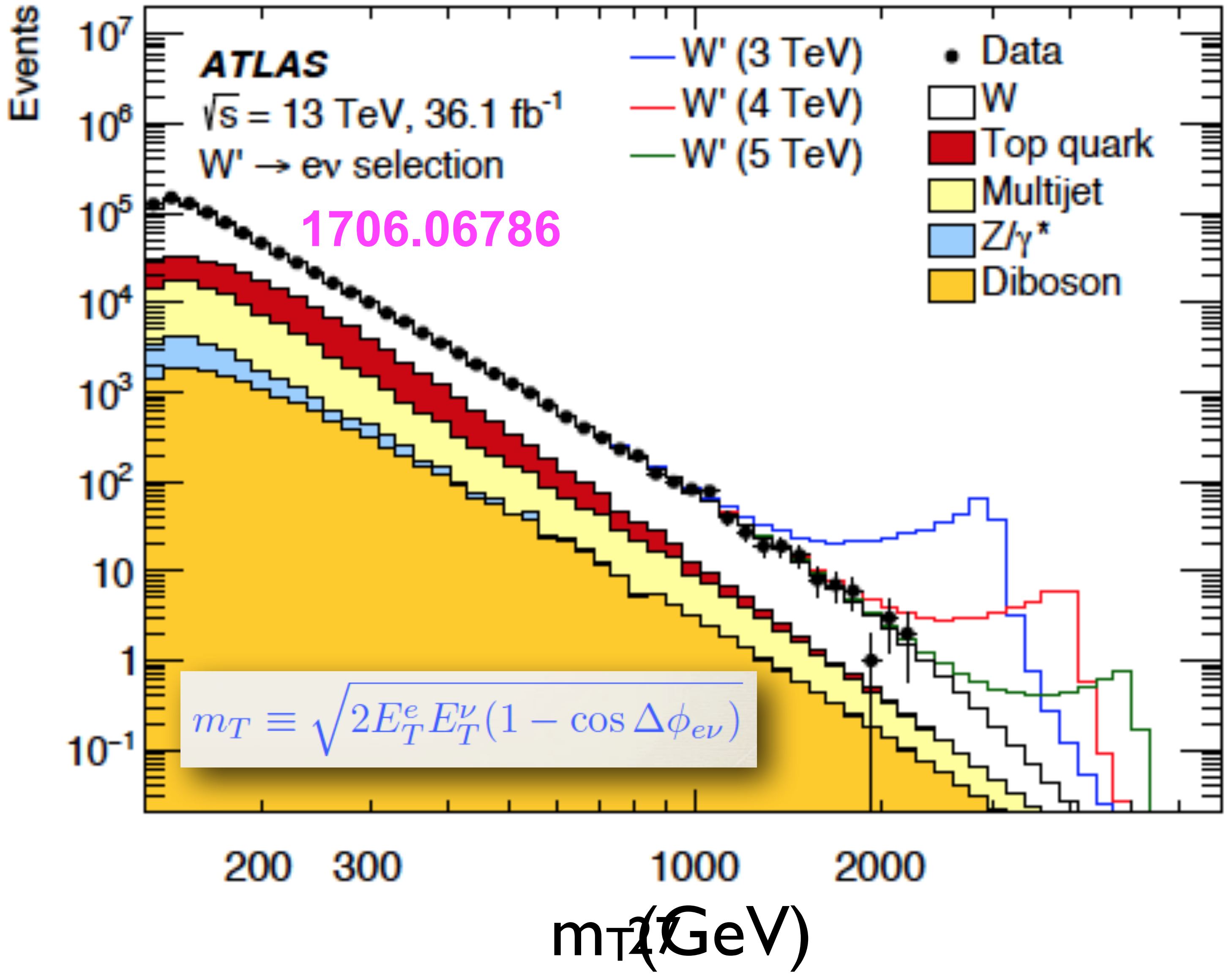
Contribute tp pp → eν+X and pp → e⁺e⁻ +X at the LHC

LHC: pp → eν + X

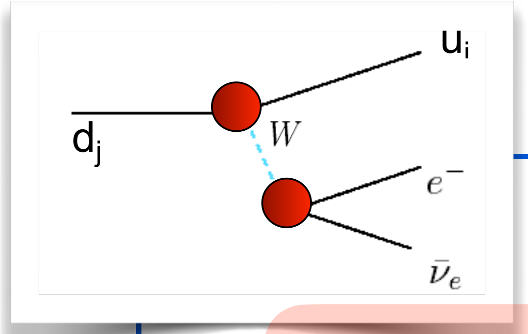




$\varepsilon_\alpha \sim 10^{-3} - 10^{-4}$

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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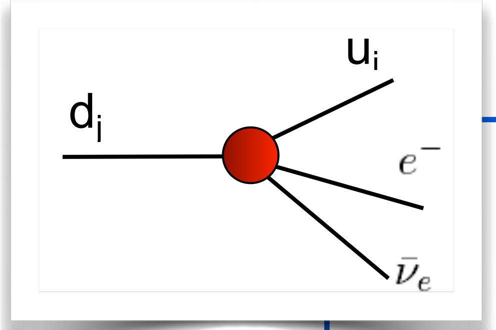

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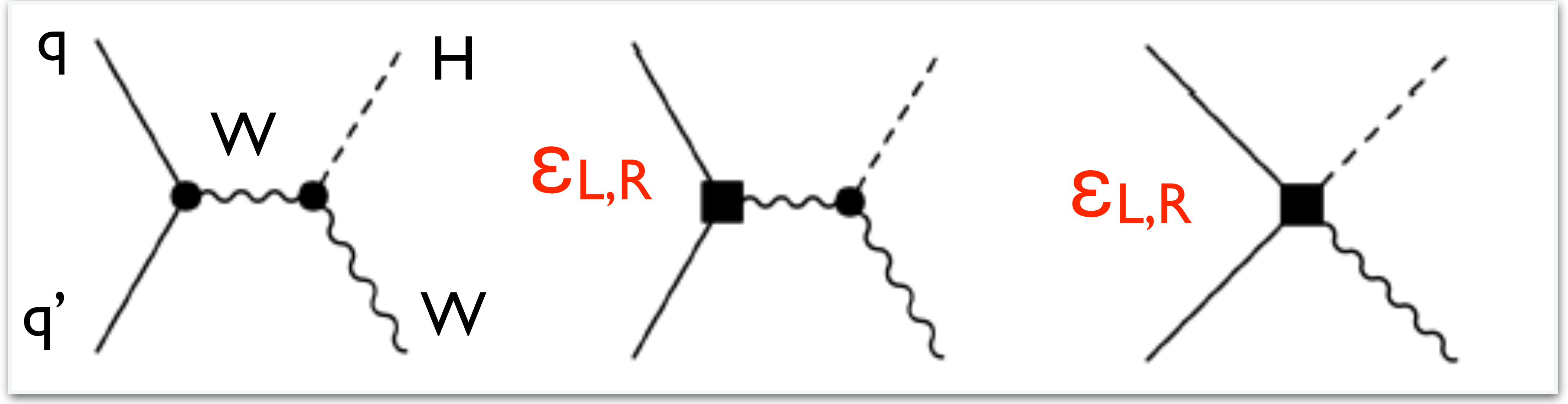
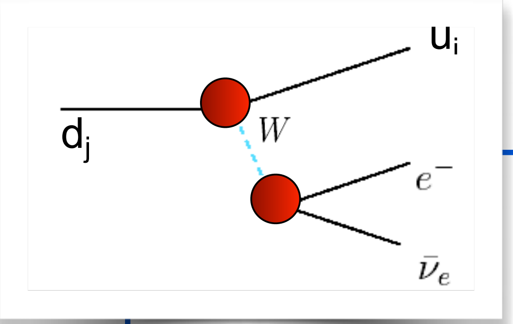
Can be probed at the LHC by associated Higgs + W production



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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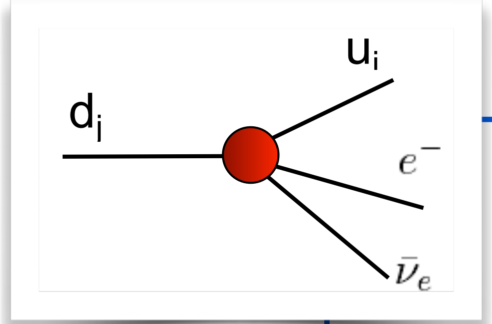

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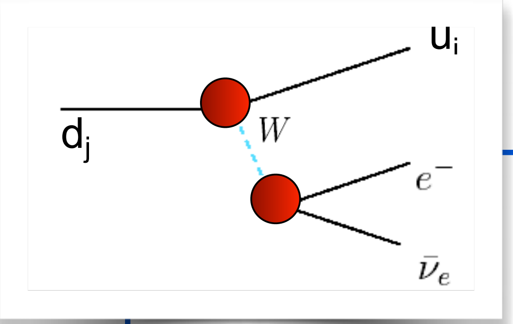
Contribute to Z-pole and other precision electroweak (EW) observables, including** M_W

High Energy constraints



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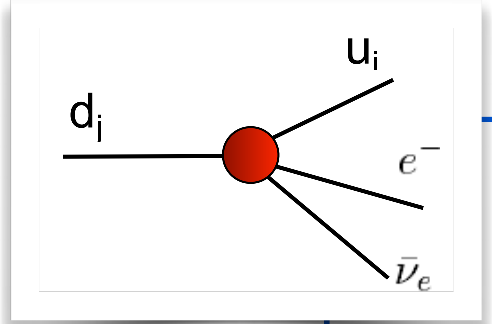

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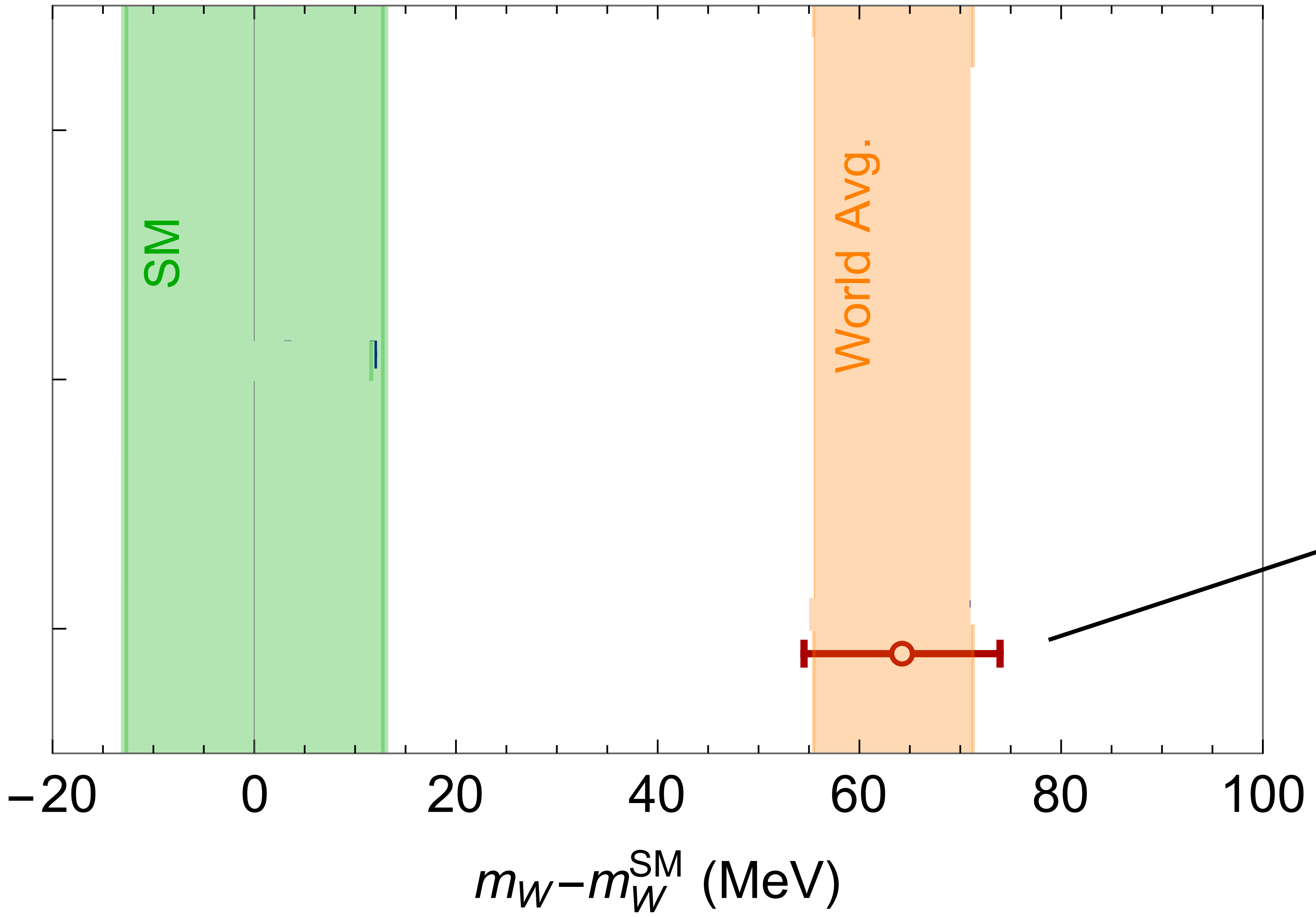
Contribute to Z-pole and other precision electroweak (EW) observables, including M_W**



In fact, explanations of M_W anomaly in SMEFT (beyond oblique corrections) are in tension with Δ_{CKM}

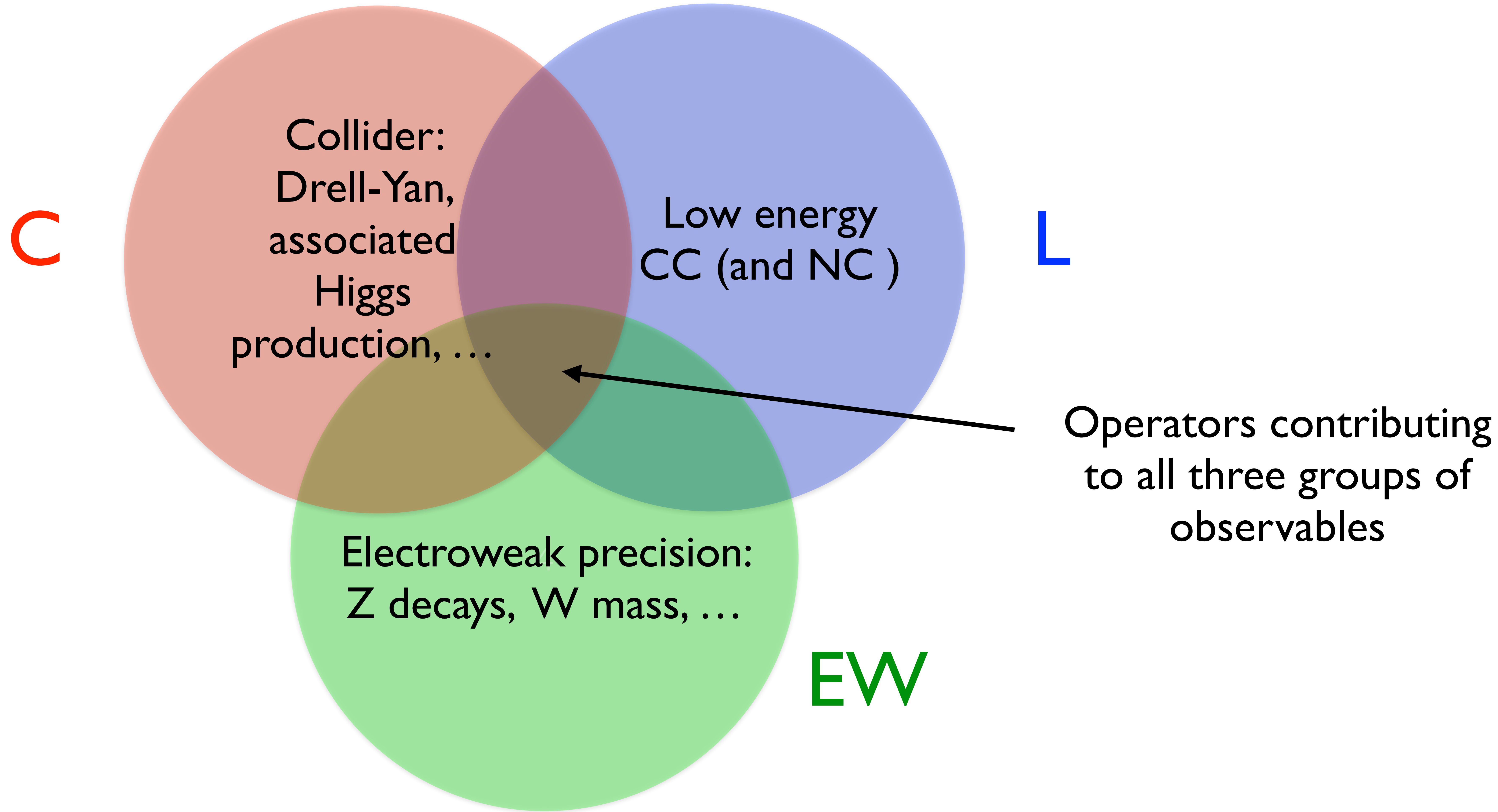
Global fit to EWPO $\Rightarrow$ $\Delta_{\rm CKM}^{\rm EWfit} = -(0.012 \pm 0.005)$,

deBlas et al 2204.04204,
Bagnaschi et al 2204.05260, …

VC, Dekens, deVries, Mereghetti, Tong 2204.08440

The CLEW framework

- So we see that a consistent analysis of beta decays in the SM-EFT requires using data from



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

Lessons from CLEWed analysis

- CLEW analysis with no assumption about flavor symmetry requires 37 effective couplings

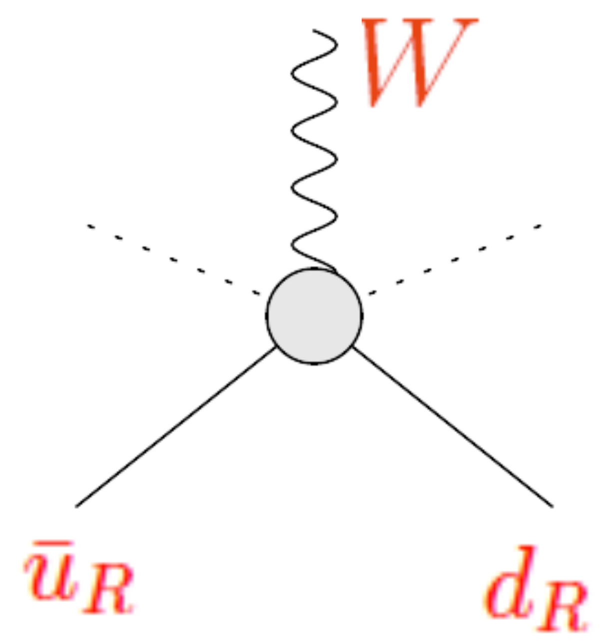
- Do they all matter? No.

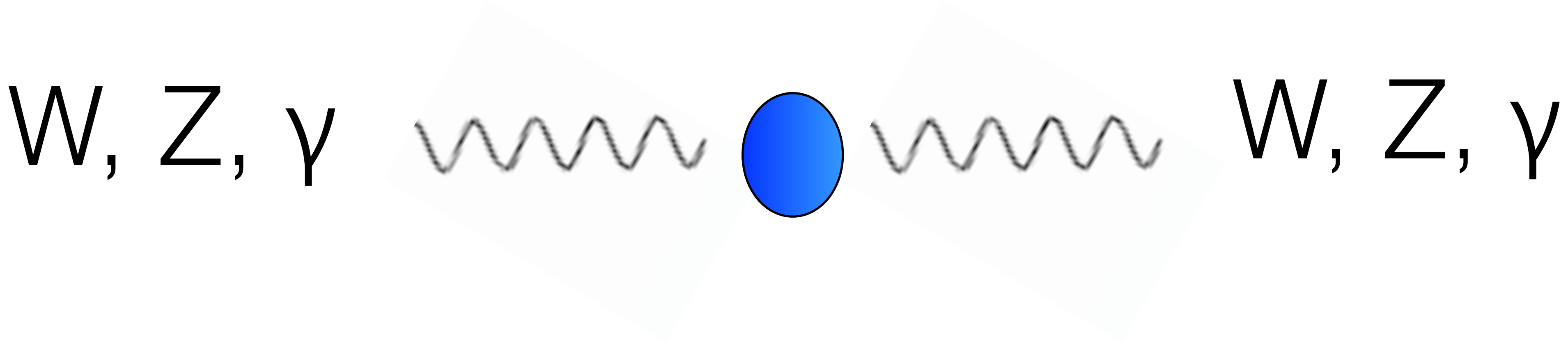
    - The best fit (with the lowest AIC = 2k - ln(L)) is given by just including the two RH CC vertex corrections

    - Next best fit is obtained by adding LH vertex corrections which slightly improve the EWPO

    - When including the CDF value of m_W, best fit also include oblique parameters (S,T) besides the RH CC vertex correction

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





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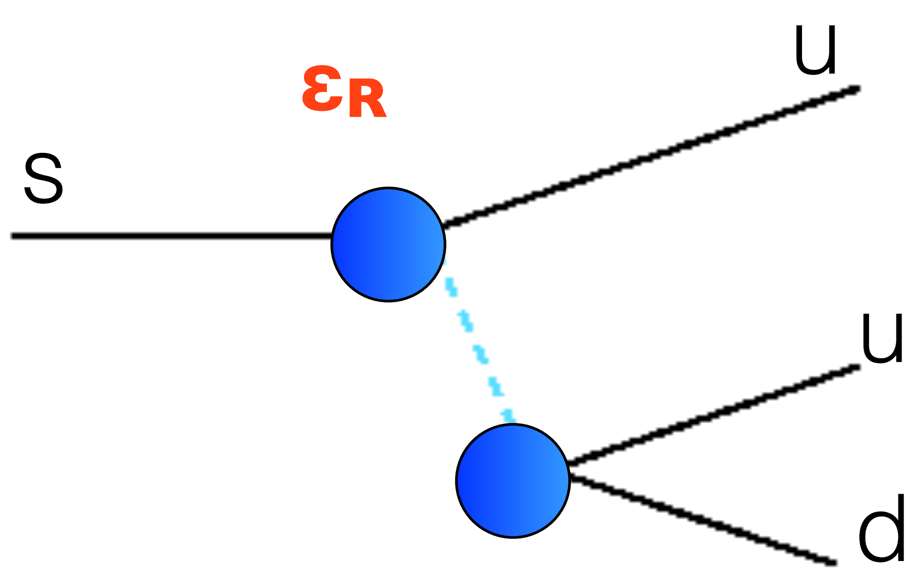
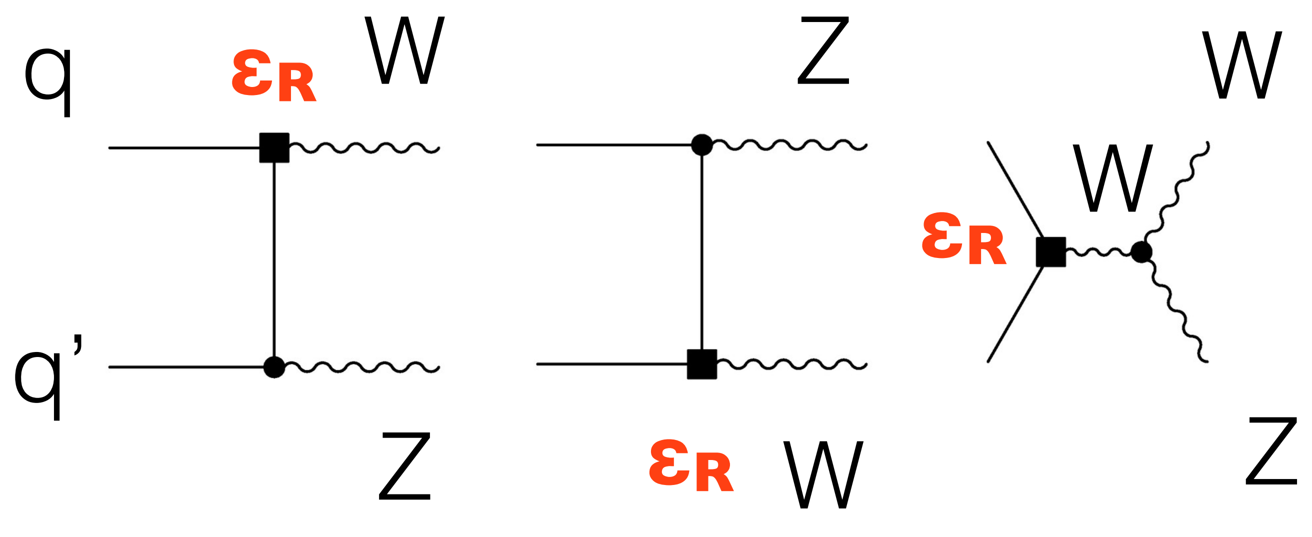
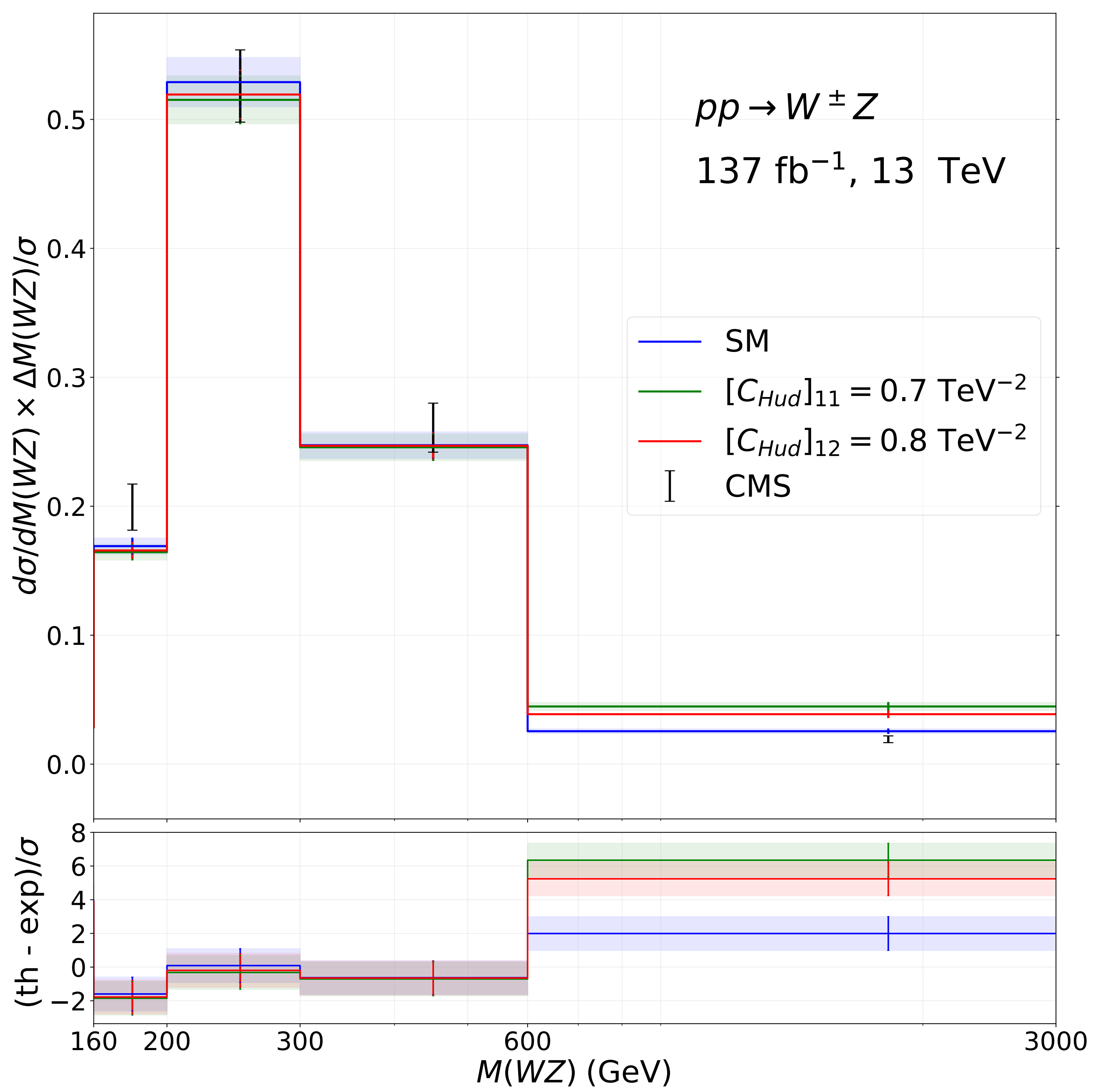
VC, W. Dekens, J. De Vries, E. Mereghetti, T. Tong, in preparation

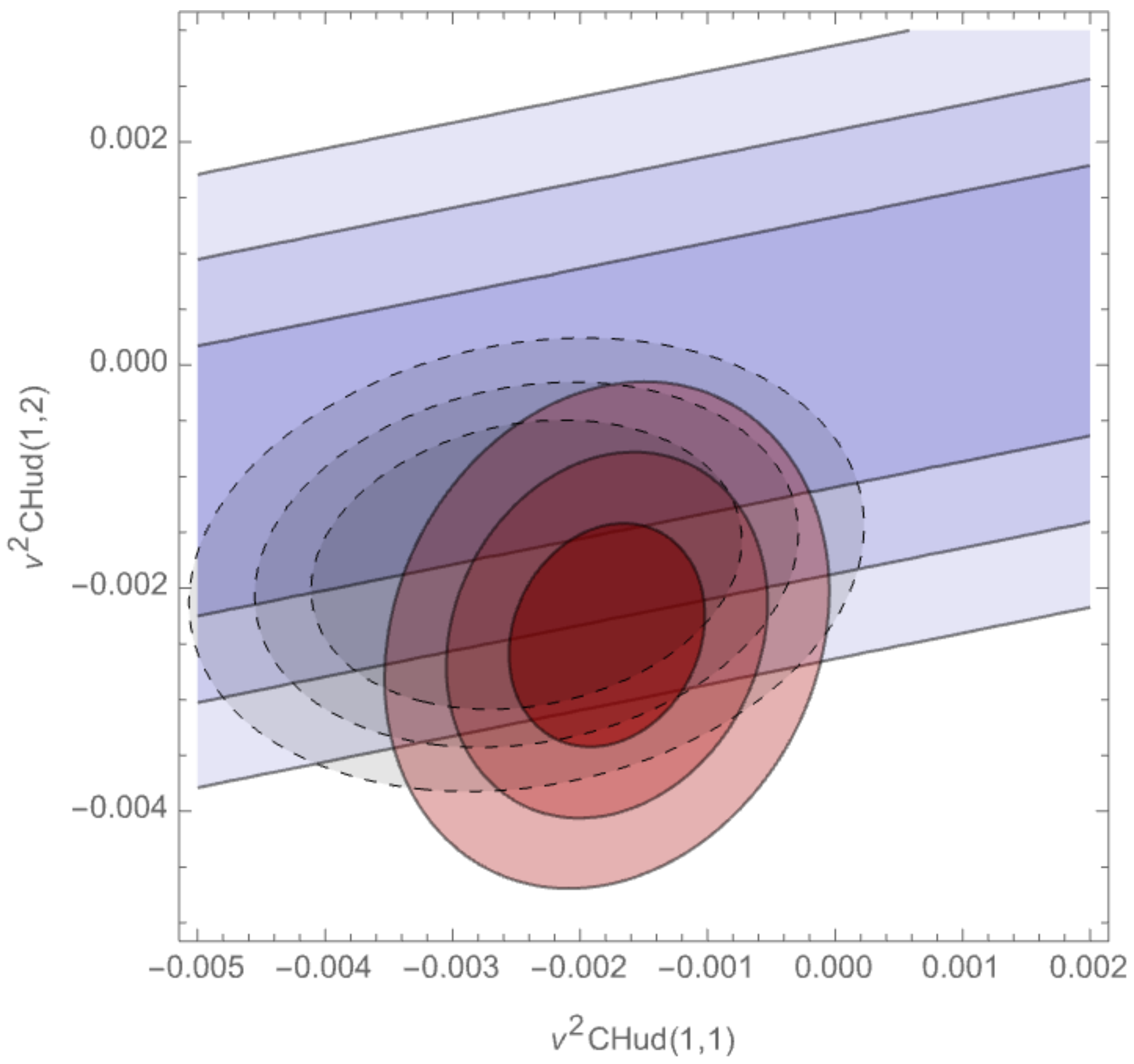
Falsifying R-handed current hypothesis

- Two options (besides comparing g_A from experiment and Lattice QCD)
  - $K \to (\pi\pi)_{I=2}$ decay amplitude: experiment vs Lattice QCD
  - WH & WZ production at the High Luminosity LHC





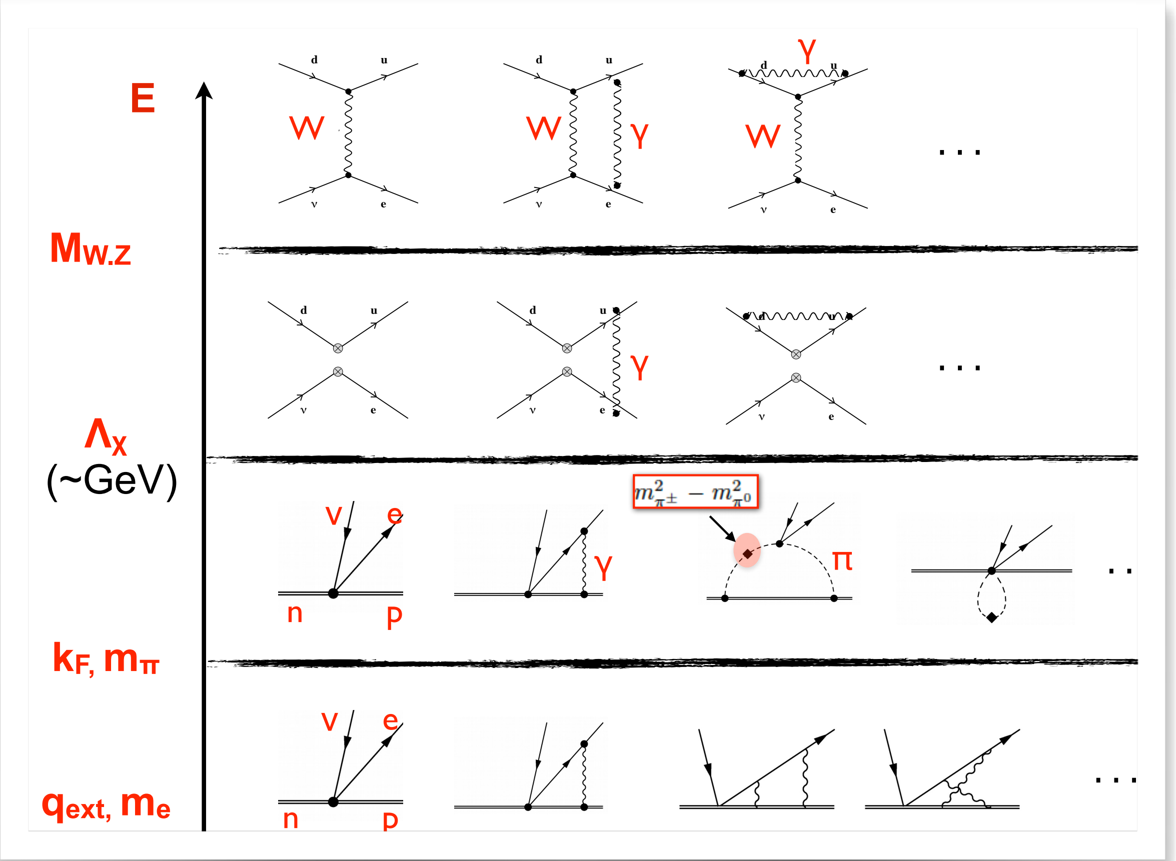




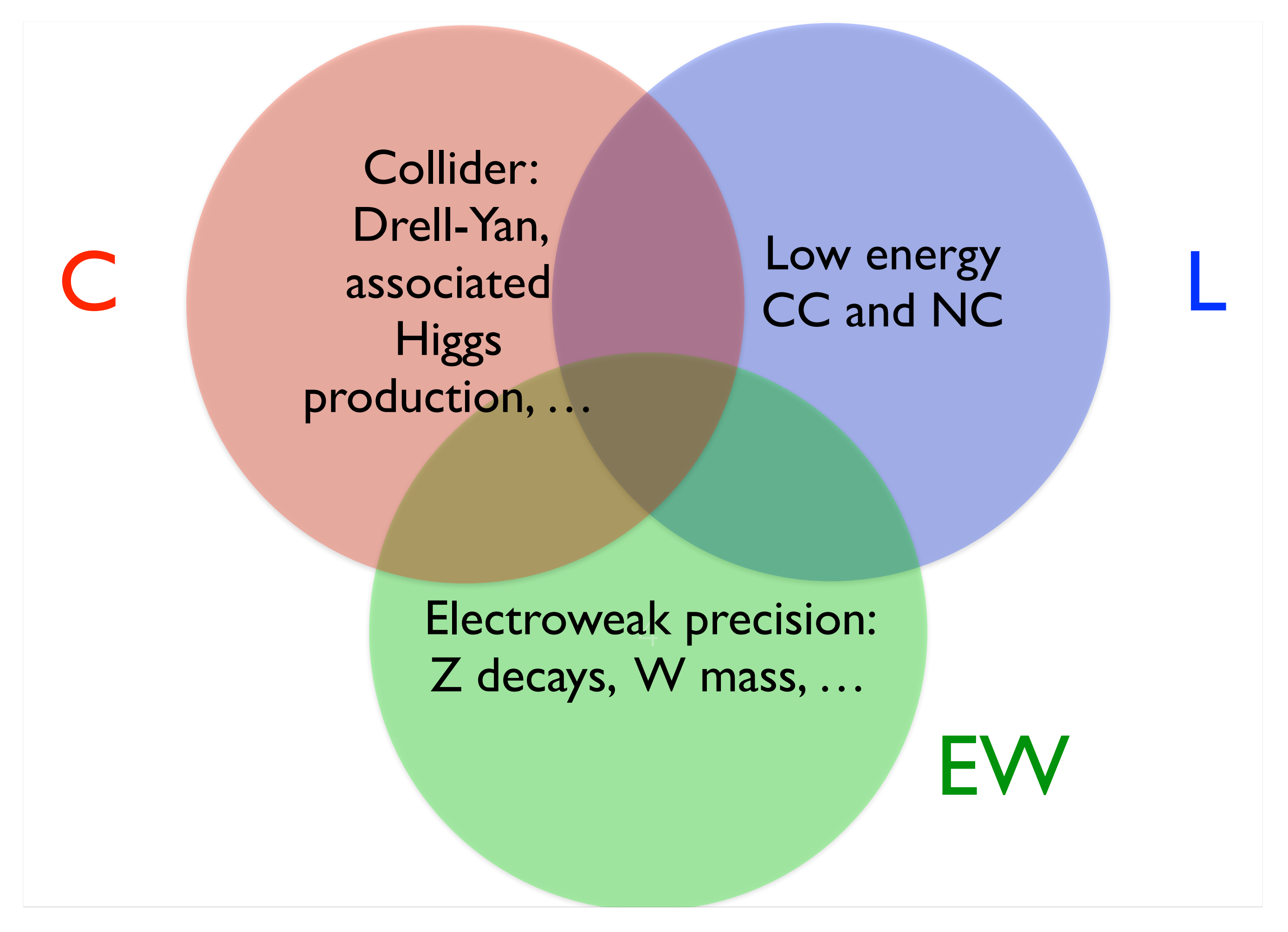
VC, W. Dekens, J. De Vries, E. Mereghetti, T. Tong, in preparation

Conclusions & Outlook

- The Cabibbo angle anomaly is one of few low-energy "cracks" in the SM, probing new physics up to $\Lambda \sim 20$ TeV — big deal if confirmed, requires both experimental and theoretical scrutiny



- A new analysis of neutron beta decay through a tower of EFTs allowed us to reach NLL accuracy and revealed %-level corrections to g_A/g_V.
Future work: development of EFT for few nucleon systems & interface with ab-initio nuclear calculations

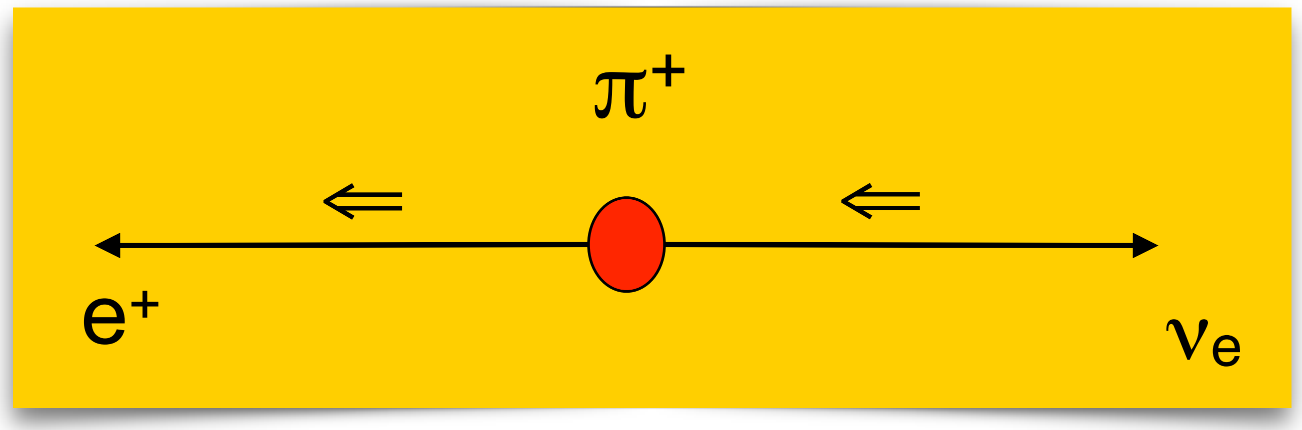


- Most natural BSM explanations of Cabibbo anomaly are "right-handed vertex corrections" in the EFT language
- CLEW framework is necessary for consistent analysis. RH CC 'explanation' of the Cabibbo anomaly survives CLEWed analysis

Backup

Pion decay and Lepton Flavor Universality

- $R_{e/\mu} = \Gamma(\pi \to e\nu)/\Gamma(\pi \to \mu\nu)$ helicity suppressed the SM (V-A), zero if $m_e \to 0$

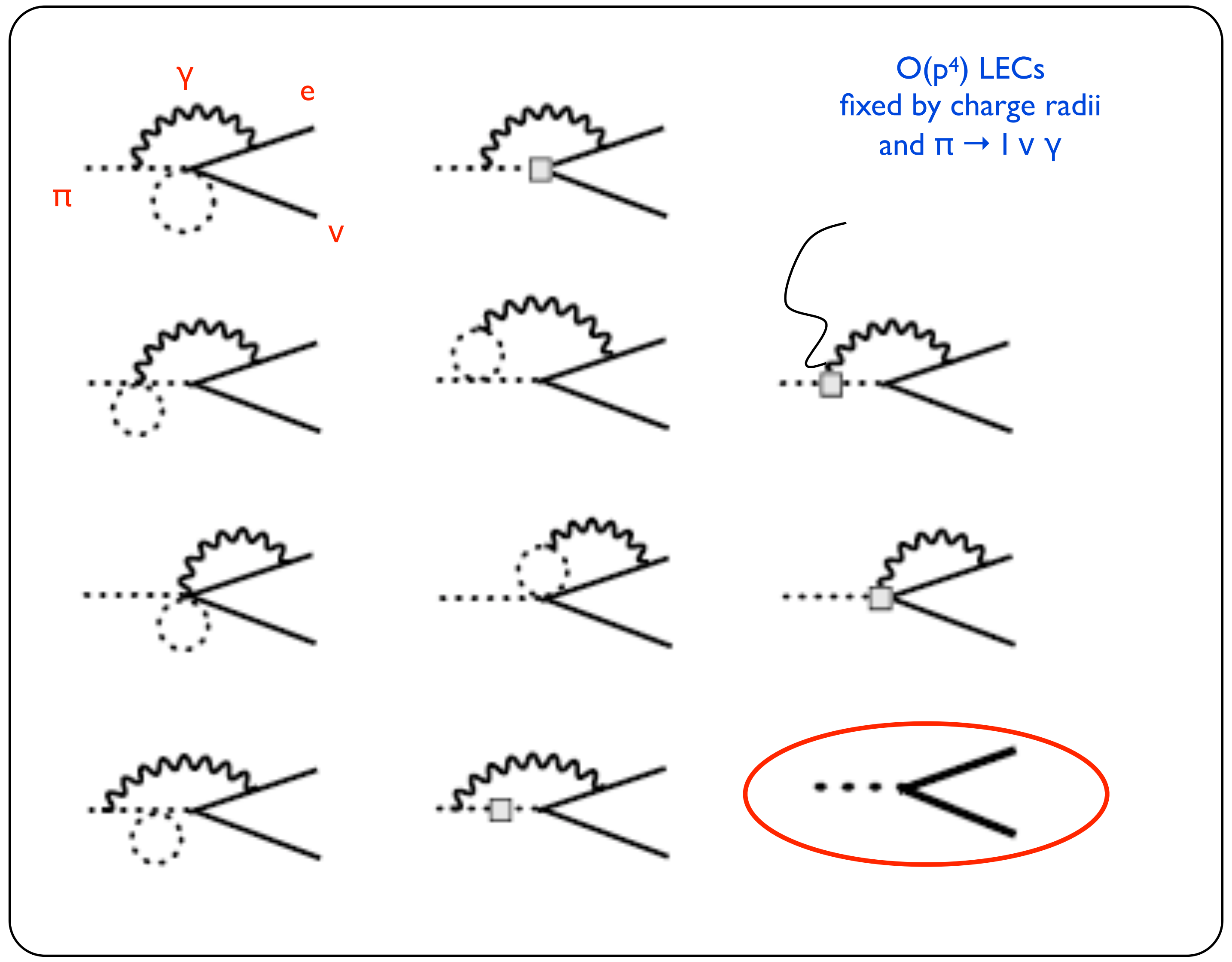


- $\sigma_{exp} \sim 15\sigma_{th} \Rightarrow$ pristine LFU test possible

VC-Rosell 0707.3439

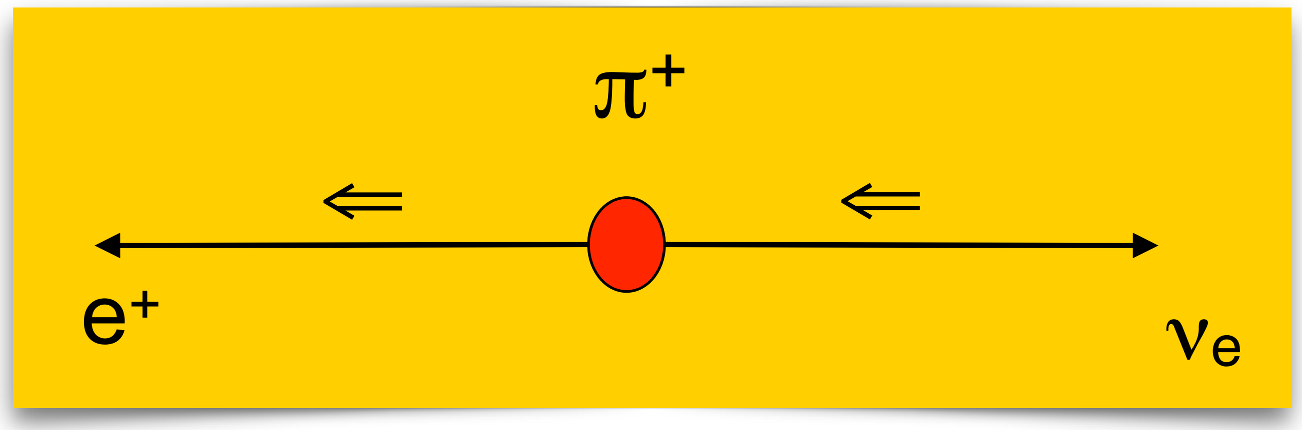
$$R_{e/\mu}(\mathrm{SM}) = 1.23524(015) \times 10^{-4}$$
$$R_{e/\mu}(\mathrm{Exp}) = 1.23270(230) \times 10^{-4}$$

PIENU Coll.



Pion decay and Lepton Flavor Universality

- $R_{e/\mu} = \Gamma(\pi \to e\nu)/\Gamma(\pi \to \mu\nu)$ helicity suppressed the SM (V-A), zero if $m_e \to 0$



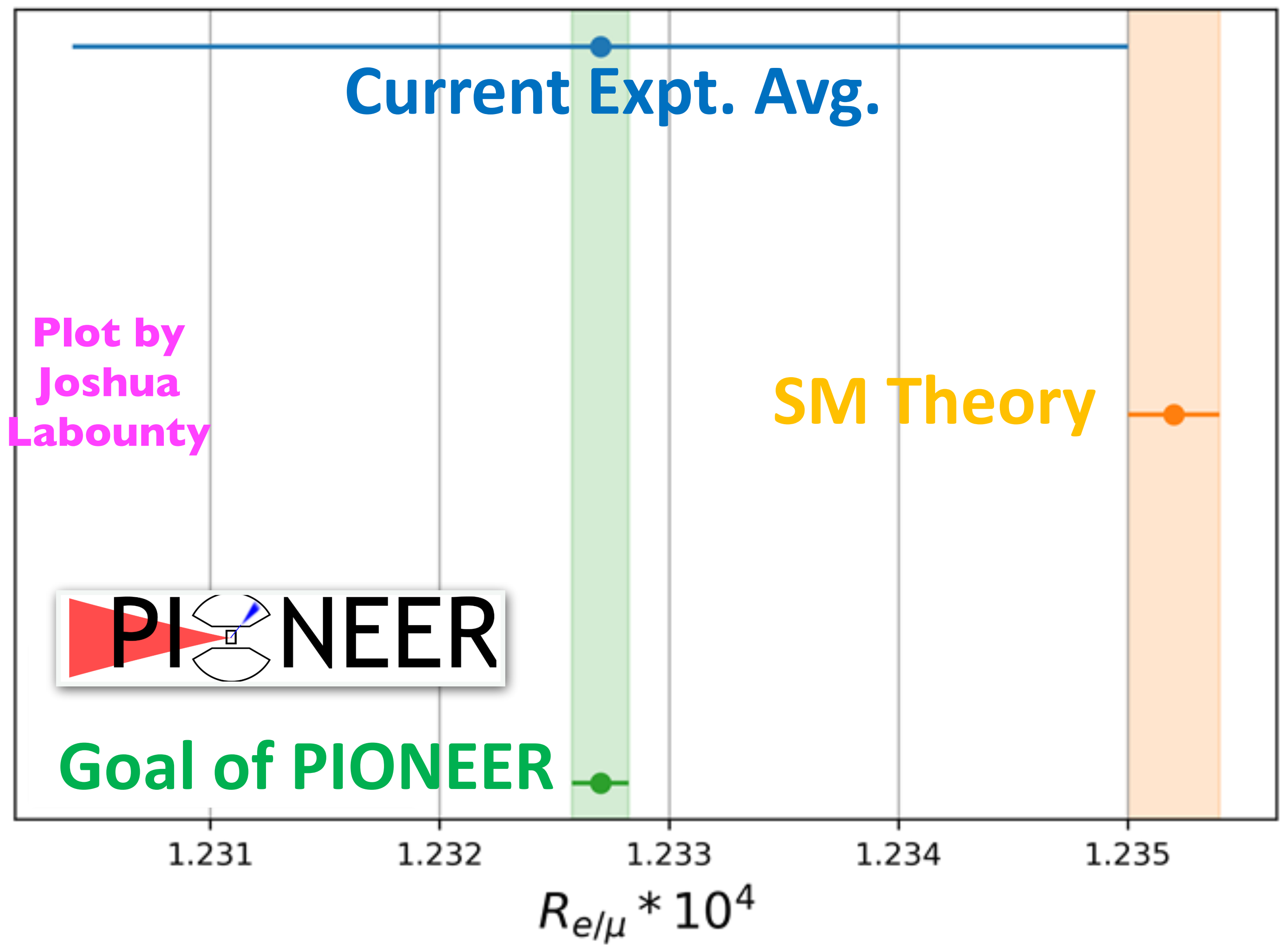
VC-Rosell 0707.3439

$$R_{e/\mu}(\mathrm{SM}) = 1.23524(015) \times 10^{-4}$$
$$R_{e/\mu}(\mathrm{Exp}) = 1.23270(230) \times 10^{-4}$$

PIENU Coll.

- $\sigma_{exp} \sim 15\sigma_{th} \Rightarrow$ pristine LFU test possible

- PIONEER @ PSI will match theoretical uncertainty. Order of magnitude gap — room for surprises! Will probe scales $\Lambda_A \sim 30$ TeV or $\Lambda_P \sim 1000$ TeV (helicity!)



Corrections to V_{ud} and V_{us}

- General case

$$
\begin{aligned}
|\bar{V}_{ud}|^2_{0^+\to 0^+} &= |V_{ud}|^2 \left(1 + 2\,(\epsilon_L^{ee} + \epsilon_R - \epsilon_L^{(\mu)}) + c^S_{0^+}(Z)\ \epsilon_S^{ee}\right) \\
|\bar{V}_{ud}|^2_{n\to pe\bar{\nu}} &= |V_{ud}|^2 \left(1\ +\ 2\,(\epsilon_L^{ee} + \epsilon_R - \epsilon_L^{(\mu)}) + c^S_n \epsilon_S^{ee} + c^T_n \epsilon_T^{ee}\right) \\
|\bar{V}_{us}|^2_{Ke3} &= |V_{us}|^2 \left(1 + 2\,(\epsilon_L^{ee(s)} + \epsilon_R^{(s)} - \epsilon_L^{(\mu)})\right) \\
|\bar{V}_{ud}|^2_{\pi e3} &= |V_{ud}|^2 \left(1 + 2\,(\epsilon_L^{ee} + \epsilon_R - \epsilon_L^{(\mu)})\right) \\
|\bar{V}_{us}|^2_{K\mu 2} &= |V_{us}|^2 \left(1 + 2\,(\epsilon_L^{\mu\mu(s)} - \epsilon_R^{(s)} - \epsilon_L^{(\mu)}) - 2\frac{B_0}{m_\ell}\,\epsilon_P^{\mu\mu(s)}\right) \\
|\bar{V}_{ud}|^2_{\pi\mu 2} &= |V_{ud}|^2 \left(1 + 2\,(\epsilon_L^{\mu\mu} - \epsilon_R - \epsilon_L^{(\mu)}) - 2\frac{B_0}{m_\ell}\,\epsilon_P^{\mu\mu}\right)
\end{aligned}
$$

$\varepsilon_S^{(s)}$: shifts the slope of the scalar form factor, at levels well below EXP and TH uncertainties

$\varepsilon_T^{(s)}$: suppressed by m_{lept}/m_K

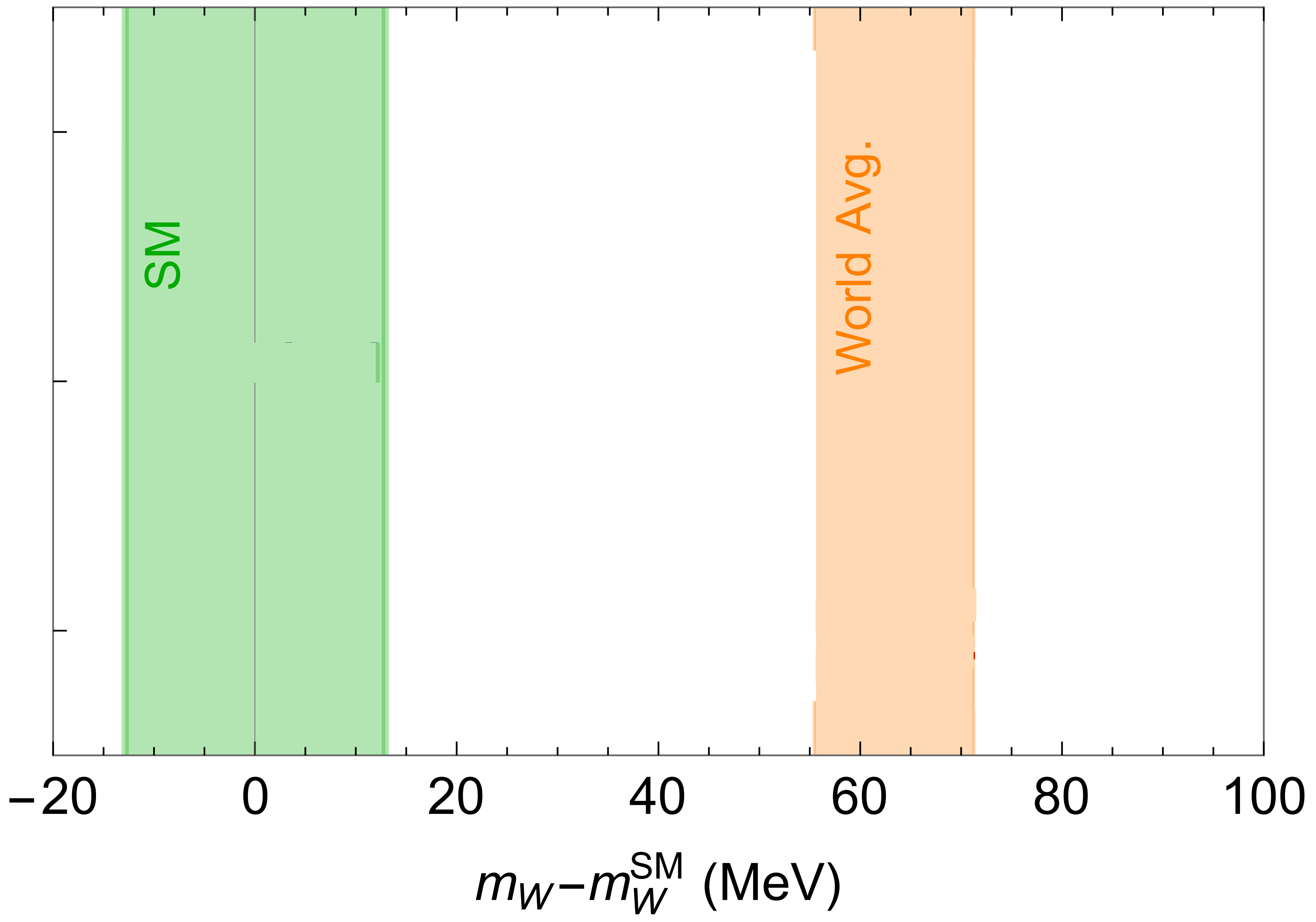
Connection to EW precision tests

VC, Dekens, deVries, Mereghetti, Tong 2204.08440

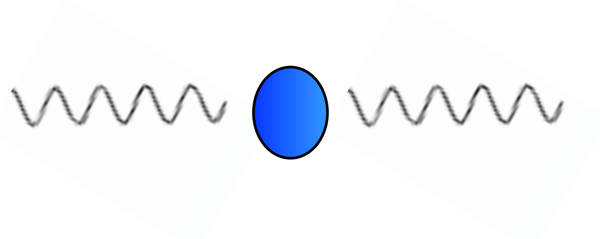
- Explanations of M_W anomaly in SMEFT + Minimal Flavor Violation (beyond oblique corrections) are in tension with Δ_{CKM}

deBlas et al 2204.04204, Bagnaschi et al 2204.05260, …

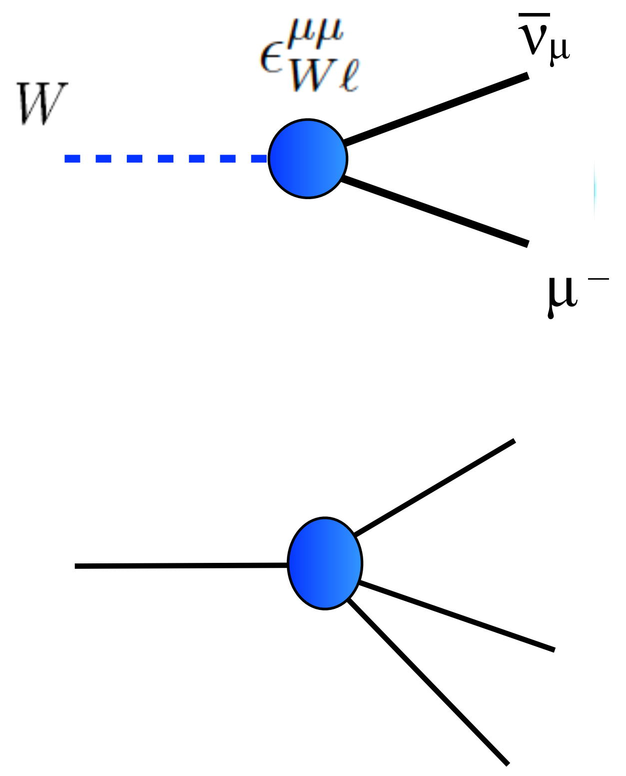
$$\frac{\delta m_W^2}{m_W^2} = v^2 \, \frac{s_w c_w}{s_w^2 - c_w^2} \left[2\, C_{HWB} + \frac{c_w}{2 s_w} C_{HD} + \frac{s_w}{c_w} \left(2\, C_{Hl}^{(3)} - C_{ll} \right) \right]$$



‘Oblique corrections’



Shift to G_F



Connection to EW precision tests

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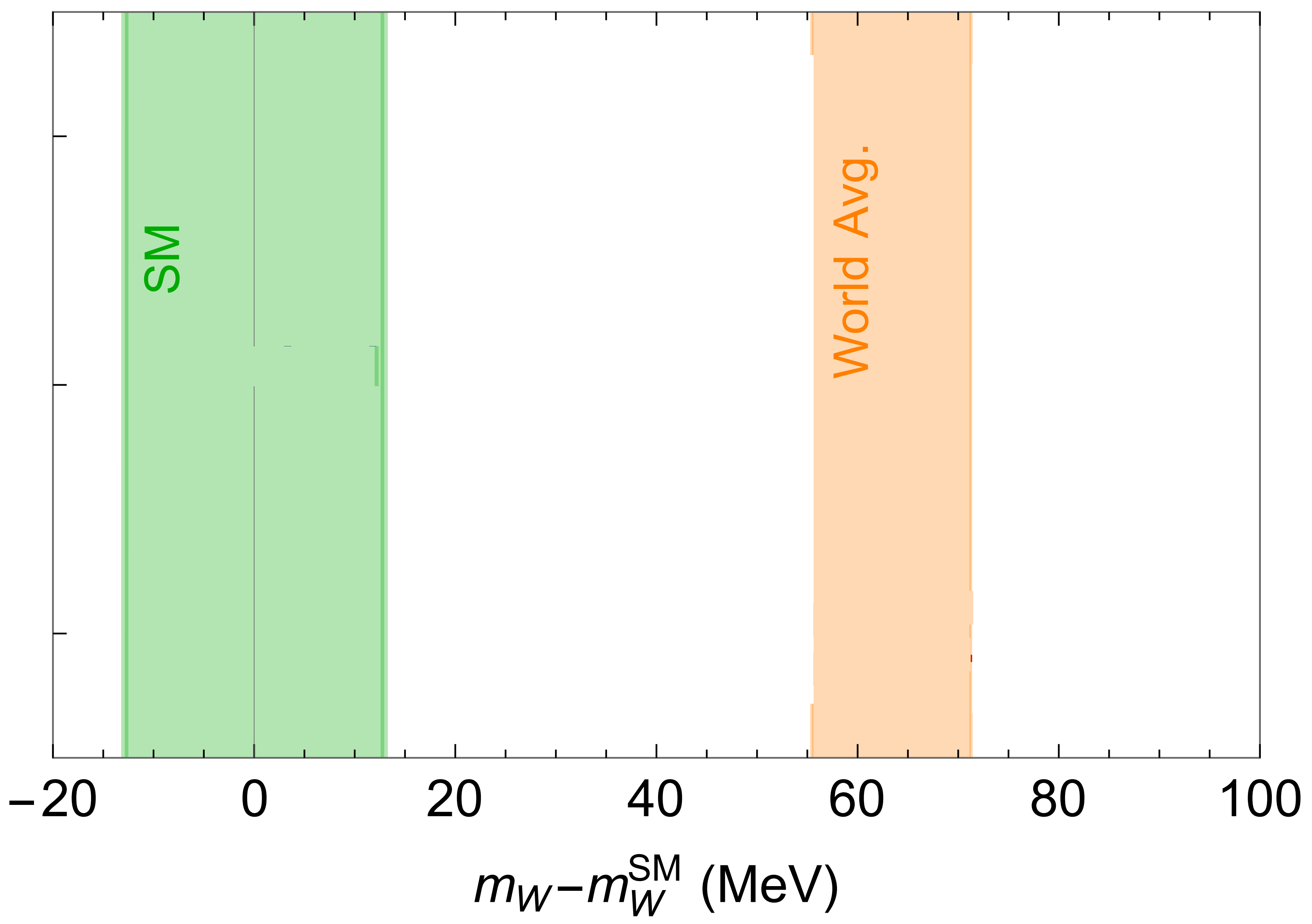
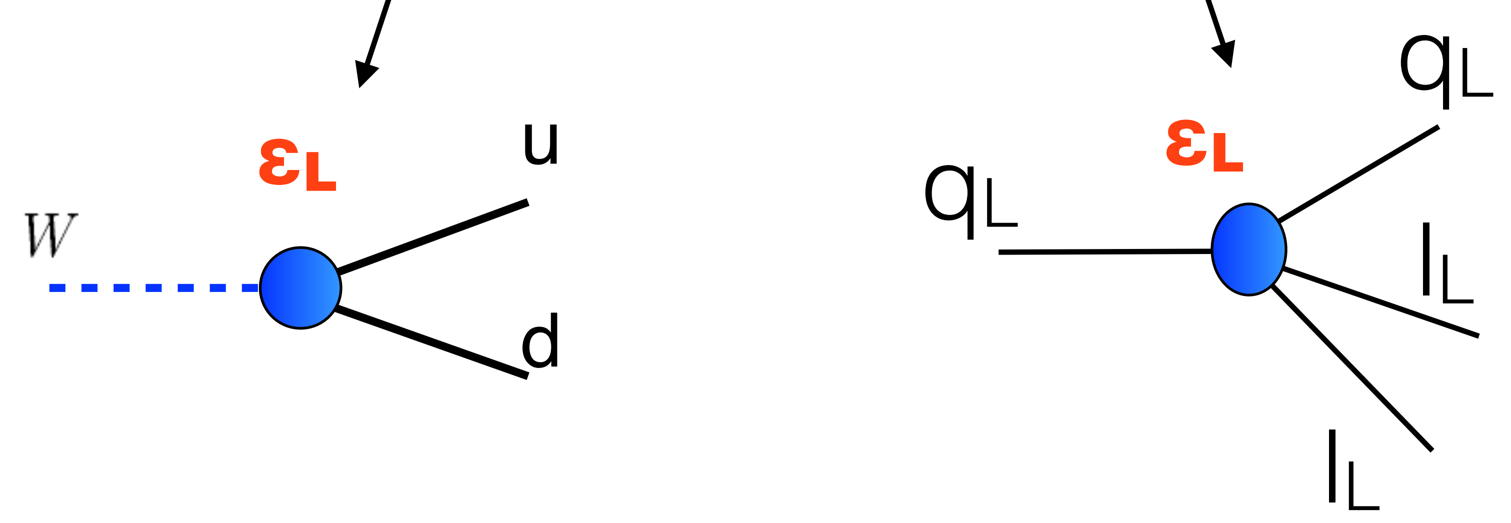


$$\Delta_{\rm CKM} = v^2 \left[C_\Delta - 2\, C_{lq}^{(3)} \right]$$

$$C_\Delta = 2 \left[C_{Hq}^{(3)} - C_{Hl}^{(3)} + \hat{C}_{ll} \right]$$

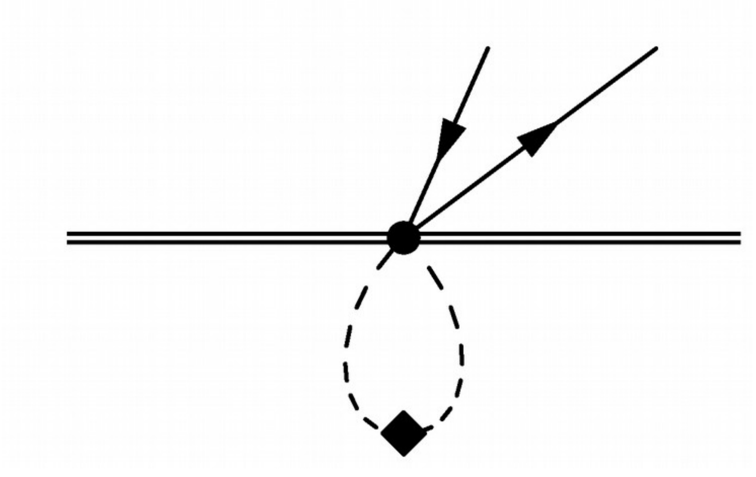


$\lambda = g_A/g_V$ to $O(\alpha)$ and $O(\alpha\epsilon_\chi)$

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, much larger than previous estimate

Hayen 2010.07262,
Gorchtein-Seng 2106.0918



. . .

$$\frac{\lambda^{\rm exp}}{\lambda^{\rm QCD}} = 1 + \frac{\alpha}{2\pi}\left(\Delta^{(0)}_{\rm em} + \Delta^{(1)}_{\rm em} + \ldots\right) \qquad \Delta^{(n)}_{\rm em} \sim O(\epsilon^n_\chi)$$

$$m^2_{\pi^\pm} - m^2_{\pi^0} = 2e^2 F^2_\pi Z_\pi \qquad Z_\pi \simeq 0.8$$

Combination of unknown ChPT LECs

$$\Delta^{(0)}_{\rm em} = Z_\pi \left[\frac{1+3g_A^{(0)\,2}}{2}\left(\log\frac{\mu^2}{m_\pi^2} - 1\right) - g_A^{(0)2}\right] + \hat{C}(\mu)$$

$$\Delta^{(1)}_{\rm em} = Z_\pi\, 4\pi m_\pi \left[c_4 - c_3 + \frac{3}{8m_N} + \frac{9}{16 m_N} g_A^{(0)2}\right]$$

$c_{3,4}$ are LECs from $\mathcal{L}^{p^2}_{\pi N}$
They can be determined by analysis of pion-nucleon scattering

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

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

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$$\frac{\lambda^{\rm exp}}{\lambda^{\rm QCD}} = 1 + \frac{\alpha}{2\pi}\left(\Delta_{\rm em}^{(0)} + \Delta_{\rm em}^{(1)} + \dots\right)$$

$$\Delta_{\rm em}^{(n)} \sim O(\epsilon_\chi^n)$$

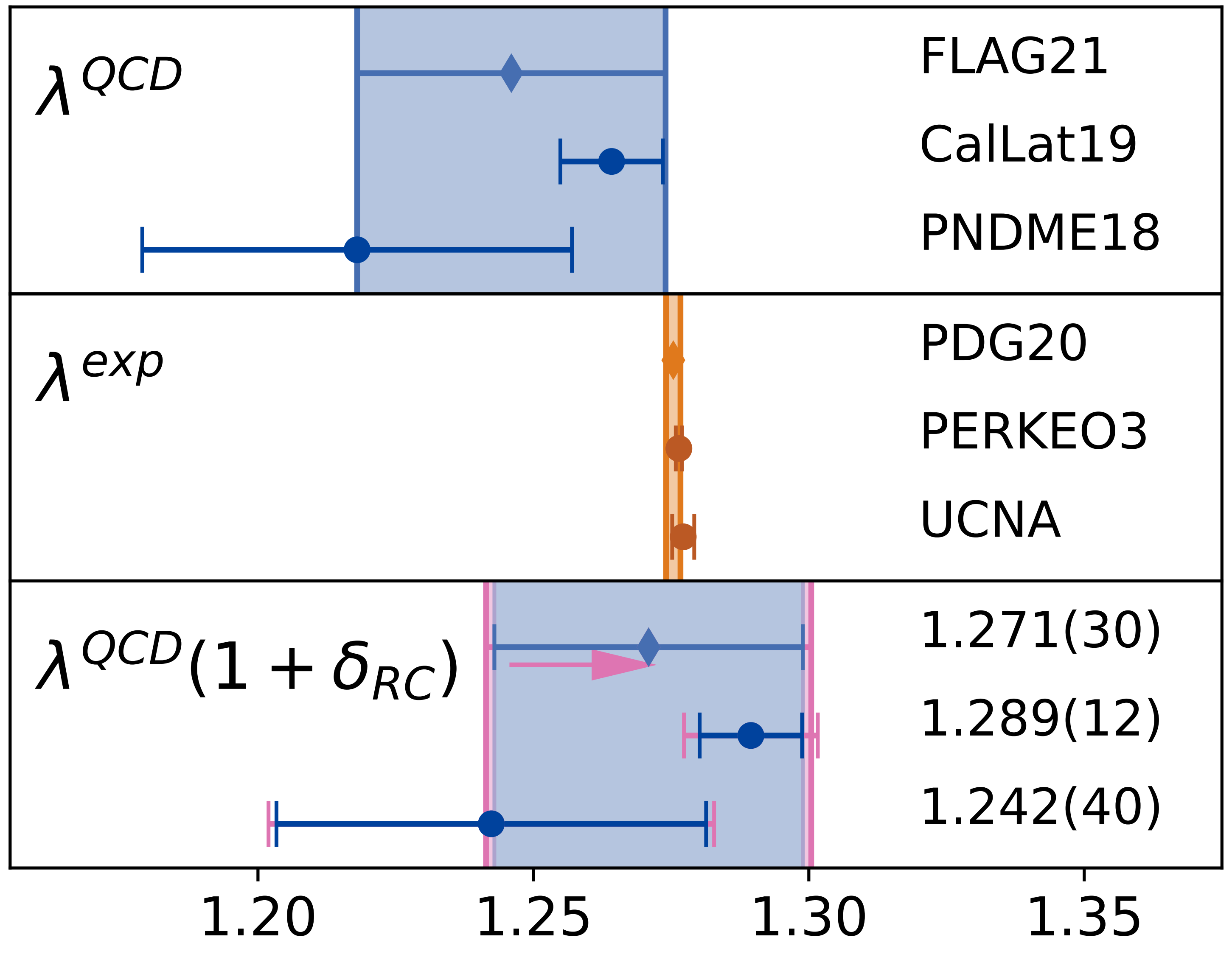
$$\frac{\alpha}{2\pi}\Delta_{\rm em}^{(0)} \in \{0.25, 0.65\}\cdot 10^{-2} \quad \longleftarrow \quad \mu \in \{m_N/2, m_N\}$$

$$\frac{\alpha}{2\pi}\Delta_{\rm em}^{(1)} = \{1.15, 1,70, 1.85\}\cdot 10^{-2} \quad \longleftarrow$$

$c_{3,4}$ are LECs at NLO, N2LO, N3LO

Siemens et al., 1610.08978

$$\frac{\alpha}{2\pi}\Delta_{\rm em}^{(0+1)} \in \{1.4, 2.5\}\cdot 10^{-2}$$



Radiative corrections generally improve agreement between data and Lattice QCD

- Large NLO correction understood in terms of large LECs $c_{3,4} \sim 5$ GeV^{-1} dominated by Δ-exchange
- Convergence cannot be fully assessed due to unknown LEC