MITP Topical Workshop
"Electroweak Precision Physics from Beta Decays to the Z Pole"
Mainz, October 24-28 2022

Electroweak precision physics: from beta decays to the Z pole

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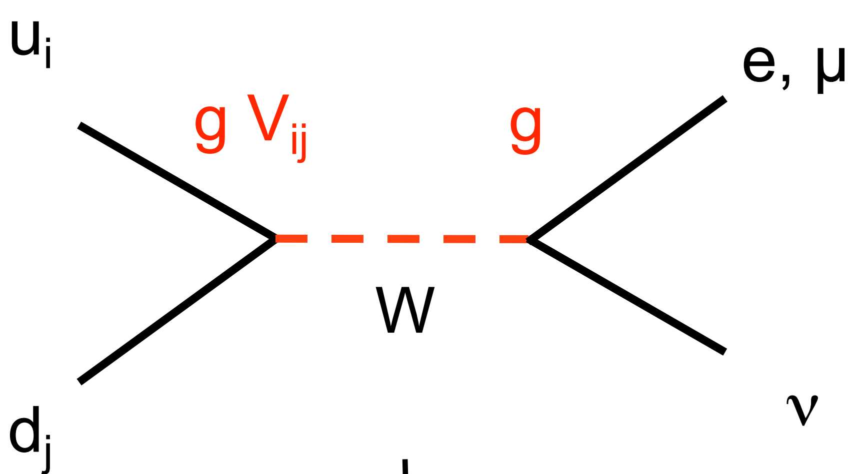
Outline

- Introduction: beta decays in the SM and beyond
- Input on V_{ud}, V_{us}, and the "Cabibbo angle anomaly"
- BSM implications: EFT framework and connection to Z pole & LHC
- Conclusions and outlook

Beta decays in the SM and beyond

- In the SM, mediated by W exchange between L-handed fermions $\Rightarrow$



at low energy $\downarrow$

$[G_F^{(\beta)}]_{ij} \sim g^2 V_{ij}/M_W^2 \sim G_F^{(\mu)}\, V_{ij} \;\sim 1/v^2\, V_{ij}$

- "V-A" imprint in decay distributions
- Universality relations

Lepton universality

$$\boxed{\begin{array}{l} [G_F]_e/[G_F]_\mu = 1 \\ \\ |V_{ud}|^2 + |V_{us}|^2 + |\cancel{V_{ub}}|^2 = 1 \end{array}}$$

Cabibbo universality

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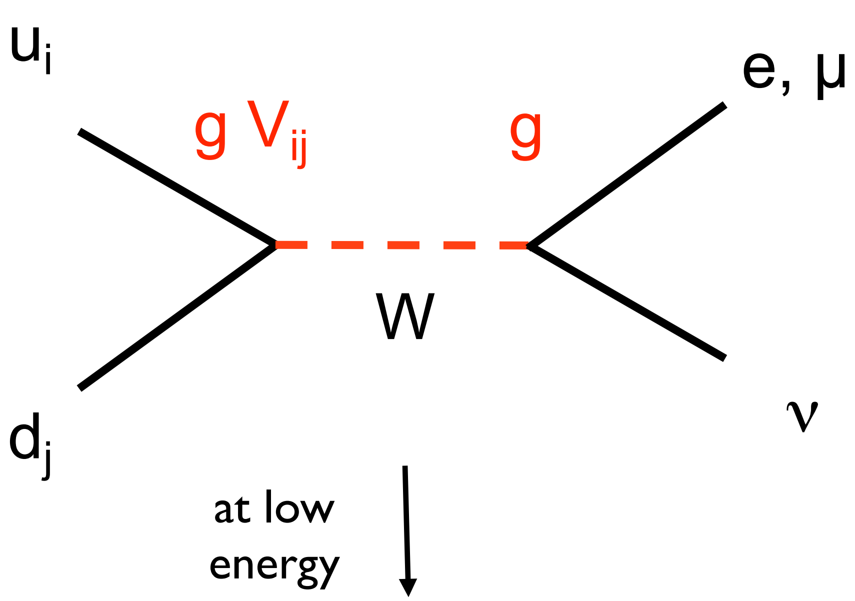

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$$[G_F]_e/[G_F]_\mu = 1$$

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

Cabibbo universality

$$G_F^{(\beta)} \stackrel{\text{def}}{=} \left([G_F^{(\beta)}]_{ud}^2 + [G_F^{(\beta)}]_{us}^2 \right)^{1/2} = G_F^{(\mu)}$$ is a loop-level precision EW test

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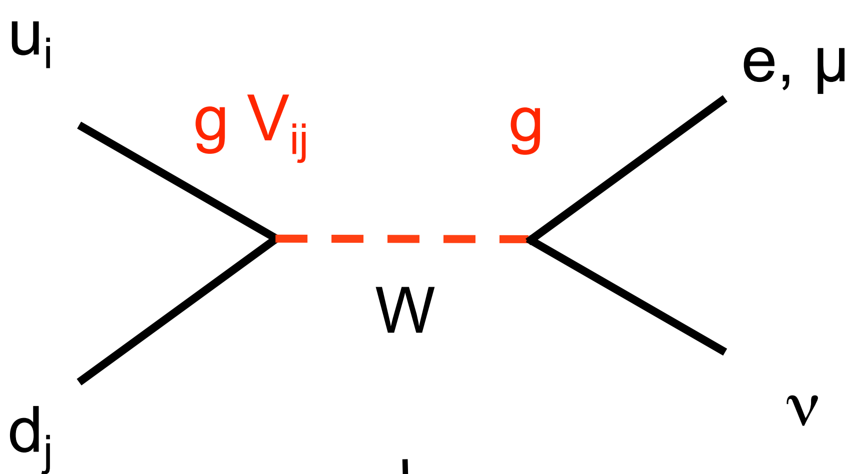

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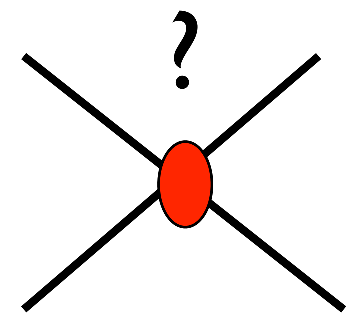


at low energy

$$[G_F^{(\beta)}]_{ij} \sim g^2 V_{ij}/M_W^2 \sim G_F^{(\mu)} V_{ij} \sim 1/v^2\, V_{ij}$$

$$\delta G_F^{(\beta)} \sim 1/\Lambda^2$$

Fractional error on beta decay observables

- BSM effects scale as $(v/\Lambda)^2$, so $\Lambda \sim v/\sqrt{\sigma_{th+exp}}$
- $\sigma_{th+exp} \sim 0.01\%$ $\Rightarrow$ probe effective scale $\Lambda \sim 20$ TeV

V_{ud}, V_{us}, and the Cabibbo Angle Anomaly

Cabibbo universality tests

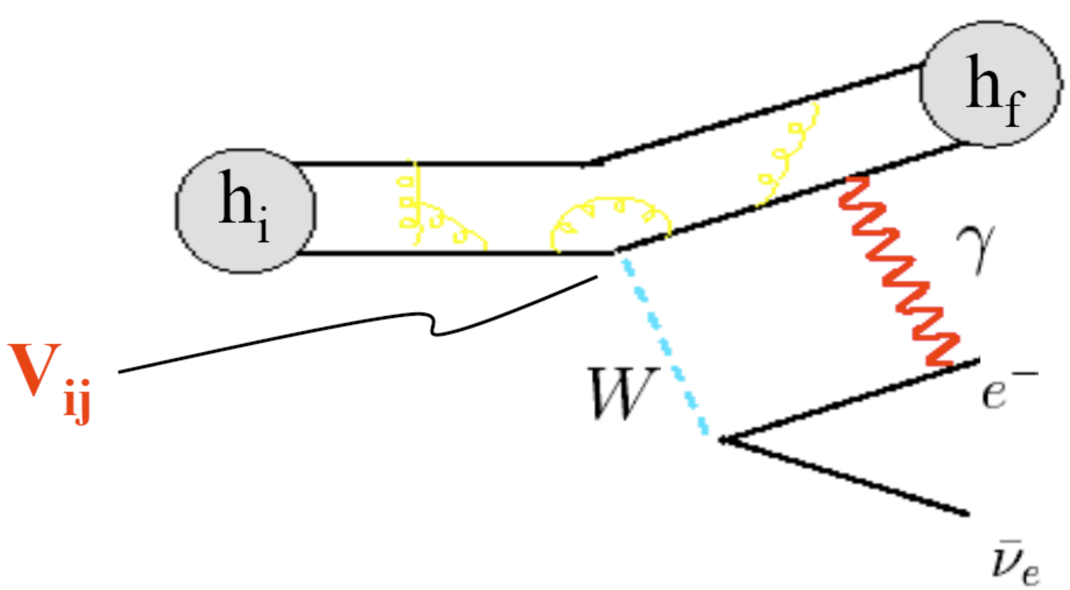
Extract $V_{ud}=\mathrm{Cos}\theta_C$ and $V_{us}=\mathrm{Sin}\theta_C$ from various decays

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

Channel-dependent effective CKM element

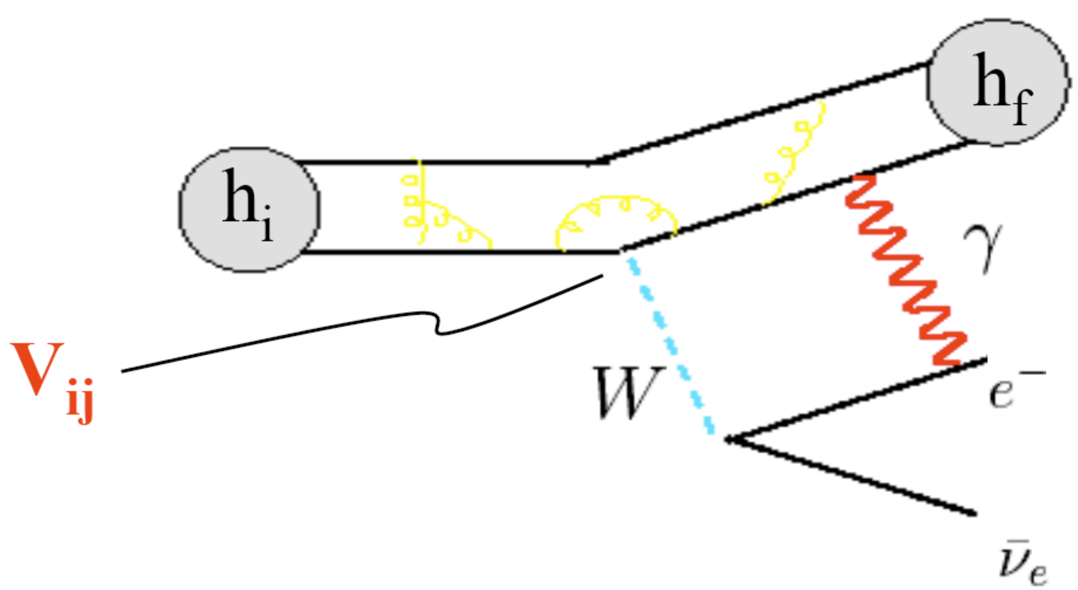
Hadronic matrix element

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



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)	$\pi \to \mu\nu$	$\tau \to h_{NS}\nu$
V_{us}	$K \to \pi l \nu$	$(\Lambda \to pe\bar{\nu},\ldots)$	$K \to \mu\nu$	$\tau \to h_S\nu$



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

All covered in greater detail in other talks at this workshop.

Here I will present a brief overview

Paths to V_{ud} and V_{us}

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Traditionally "Golden modes" (mediated by the V current):
normalization known in SU(2) [SU(3)] limit,
corrections are 2nd order in SU(2) [SU(3)] breaking

Berhends-Sirlin
Ademollo-Gatto

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- Nuclear $0^+ \to 0^+$ decays:

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

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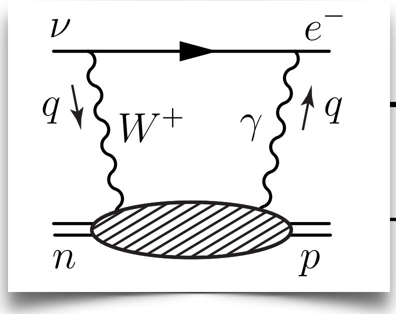

Special thanks to M. Hoferichter

Ref.	Δ_R^V
Marciano, Sirlin 2006	0.02361(38)
Seng, Gorchtein, Patel, Ramsey-Musolf 2018	0.02467(22)
Czarnecki, Marciano, Sirlin 2019	0.02426(32)
Seng, Feng, Gorchtein, Jin 2020	0.02477(24)
Hayen 2020	0.02474(31)
Shiells, Blunden, Melnitchouk 2021	0.02472(18)
VC-Crivellin-Hoferichter-Moulson 2208.11707	0.02467(27)

Combined value (taking into account common input): largest uncertainty from the "Regge region"

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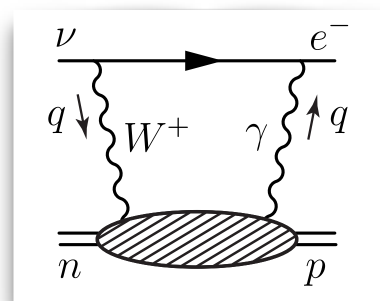
$$|V_{ud}|^2 = \frac{2984.432(3)\ s}{ft\left(1 + \Delta_R^V + \delta'_R + \delta_{NS} - \delta_C\right)}$$

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

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



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- Pion beta decay:
  - Theory in great shape: calculation of radiative corrections with input on γ-W box from lattice QCD
  - Experiment needs order-of-magnitude improvement in precision to be competitive → PIONEER @ PSI

Feng, Gorchtein, Jin, Ma, Seng
2003.09798

PIONEER
2203.01908

Special thanks to M. Hoferichter

$$\boxed{V_{ud}^{\pi,\text{lattice}} = 0.97386(281)_{\text{BR}}(9)_{\tau_\pi}(14)_{\Delta_{\text{RC}}^{\pi\ell}}(28)_{I_{\pi\ell}}[283]_{\text{total}}}$$

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- Kl3 decays:
  - New analysis of radiative corrections based on Sirlin's formalism + lattice. Compatible with older ChPT analysis, but order-of-magnitude smaller uncertainty
  - Lattice calculations of <π|V|K> ($f_+(0)$) keep improving (0.2%)
  - Expt. input has received small updates since 2010

Seng et al, 1910.13209, 2103.00975. 2103.4843. 2107.14708. 2203.05217
Ma et al. 2102.12048
VC, Giannotti, Neufeld 0807.4607

FLAG 21, Aoki et al., 2111.09849

Flavianet WG, 1005.2323
Moulson 1704.04104

$$\boxed{V_{us}^{K_{\ell 3}} = 0.22330(35)_{\rm exp}(39)_{f_+}(8)_{\rm IB}[53]_{\rm total}}$$

Paths to V_{ud} and V_{us}

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Both V and A currents contribute: need experimental input on <A>

- Neutron decay:

$$|V_{ud}|^2 \tau_n \left(1 + 3g_A^2\right)(1 + \Delta_R) = 5099.3(3)s$$

Dispersive γ-W box calculations + other tweaks:
$\Delta_R = 0.03983(27)$

Paths to V_{ud} and V_{us}

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$\Delta_R = 0.03983(27)$

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

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

Most precise measurements imply very competitive δV_{ud}!

Maerkish et al, 1812.04666 Gonzalez et al, 2106.10375

$\lambda = g_A/g_V$

Paths to V_{ud} and V_{us}

V_{ud}	$0^+ \rightarrow 0^+$ $(\pi^\pm \rightarrow \pi^0 e\nu)$	$n \rightarrow pe\bar{\nu}$ (Mirror transitions)	$\pi \rightarrow \mu\nu$	$\tau \rightarrow h_{NS}\nu$
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Both V and A currents contribute: need experimental input on <A>

- Mirror transitions: V_{ud} uncertainty is >3 greater than the one in $0^+ \rightarrow 0^+$

Falkowski et al. 2110.13797

- Hyperon decays: currently lower expt. and theoretical precision

Paths to V_{ud} and V_{us}

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A current transitions: need F_K and F_π

- Lattice QCD calculations of F_K/F_π are at the 0.2% level
- First calculation of radiative and isospin-breaking corrections in Lattice QCD is compatible with ChPT, factor of ~2 more precise
- Expt. input hasn't changed since 2010

FLAG 21, Aoki et al., 2111.09849

Di Carlo et al., 1904.08731

VC-Neufeld, 1102.0563

Flavianet WG, 1005.2323
Moulson 1704.04104

$$\boxed{\left.\frac{V_{us}}{V_{ud}}\right|_{K_{\ell 2}/\pi_{\ell 2}} = 0.23108(23)_{\text{exp}}(42)_{F_K/F_\pi}(16)_{\text{IB}}[51]_{\text{total}},}$$

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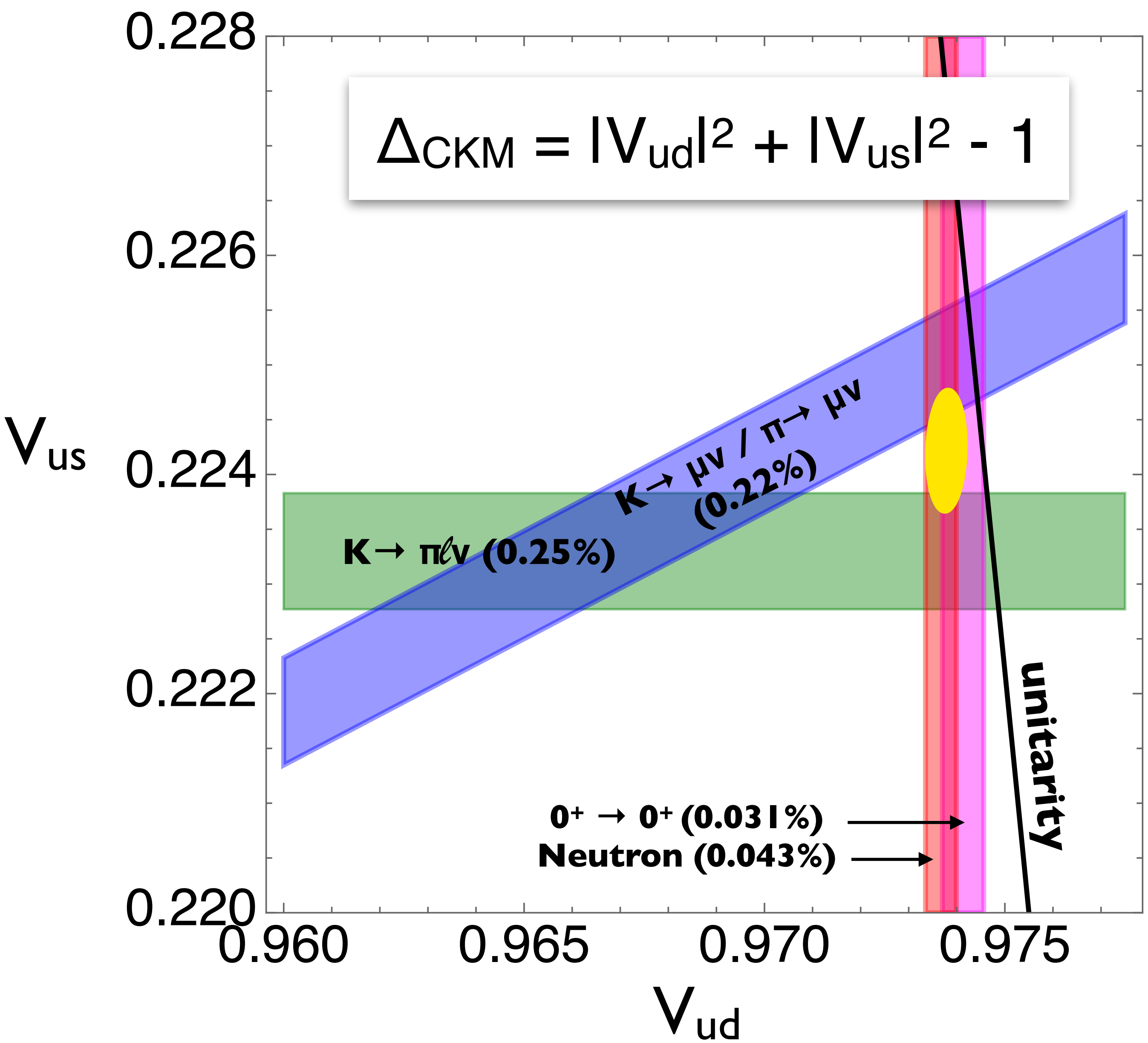
- Information from both inclusive and exclusive modes
- Use OPE to calculate inclusive BRs: very different theory "systematics"
- Currently larger uncertainties on V_{us} compared to K decays → not included in following discussion (see talks on Friday)

Gamiz et al. hep-ph/0212230, hep-ph/0408044,
…
See HFLAG WG (1909.12524) for complete reference list and status

The Cabibbo angle "anomaly"

VC-Crivellin-Hoferichter-Moulson 2208.11707



- Two 'anomalies':
  - ~3σ effect in global fit ($\Delta_{CKM} = -1.48(53) \times 10^{-3}$)
  - ~3σ problem in meson sector (Kl2 vs Kl3)

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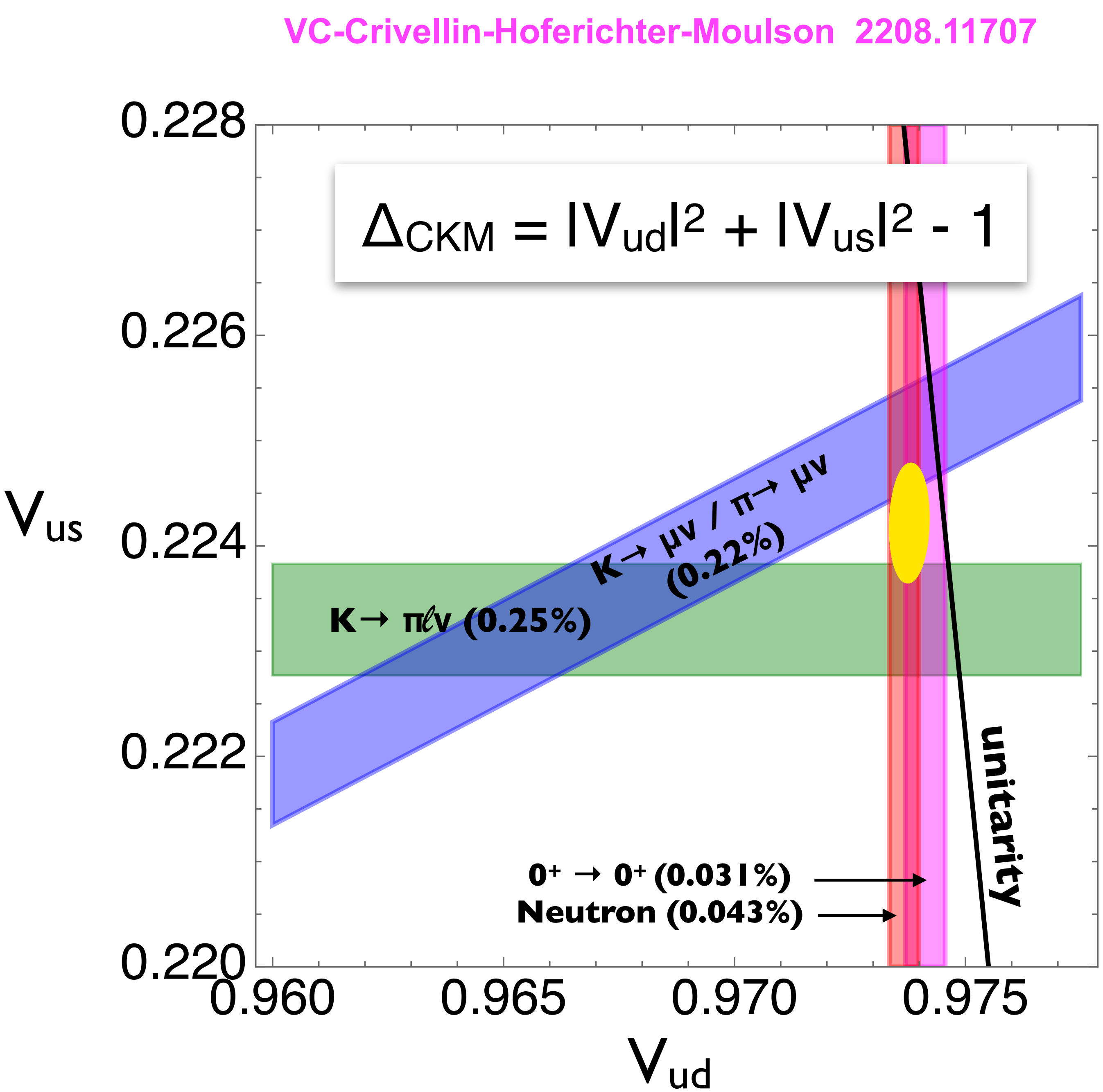

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  - ~3σ effect in global fit ($\Delta_{CKM} = -1.48(53) \times 10^{-3}$)
  - ~3σ problem in meson sector (Kl2 vs Kl3)

- Three versions of Δ_{CKM}:

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

Desirable next experimental steps

- Neutron decay: aim for $\delta\tau_n \sim 0.1$s and $\delta g_A/g_A \sim 0.01\%$ ($\delta a/a$, $\delta A/A \sim 0.05\%$) to match current error on Δ_R and get $\delta V_{ud} \sim 1.5\ 10^{-4}$
- Pion beta decay: 3x to 10x at PIONEER phases II, III [10+ years]

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- Pion beta decay: 3x to 10x at PIONEER phases II, III [10+ years]
- New $K_{\mu3}/K_{\mu2}$ BR measurement at NA62 will shed light on Kl3 vs Kl2 tension
  - Kl2 database dominated by KLOE (2007)
  - Global fit to kaon data not so great (p-value ~1%)

Special thanks to M. Hoferichter

	current fit	$K_{\mu3}/K_{\mu2}$ BR at 0.5% central	$K_{\mu3}/K_{\mu2}$ BR at 0.5% $+2\sigma$	$K_{\mu3}/K_{\mu2}$ BR at 0.5% -2σ	$K_{\mu3}/K_{\mu2}$ BR at 0.2% central	$K_{\mu3}/K_{\mu2}$ BR at 0.2% $+2\sigma$	$K_{\mu3}/K_{\mu2}$ BR at 0.2% -2σ
$\frac{V_{us}}{V_{ud}}\Big\vert_{K_{\ell2}/\pi_{\ell2}}$	0.23108(51)	0.23108(50)	0.23085(51)	0.23133(51)	0.23108(49)	0.23071(51)	0.23147(52)
$V_{us}^{K_{\ell3}}$	0.22330(53)	0.22337(51)	0.22360(52)	0.22309(54)	0.22342(49)	0.22386(52)	0.22287(52)
$10^2\Delta^{(3)}_{\rm CKM}$	$-1.64(63)$	$-1.57(60)$	$-1.18(62)$	$-2.02(63)$	$-1.53(59)$	$-0.83(62)$	$-2.33(62)$
	-2.6σ	-2.6σ	-1.9σ	-3.2σ	-2.6σ	-1.4σ	-3.8σ

Tension 'resolved'

VC-Crivellin-Hoferichter-Moulson 2208.11707

Tension 'confirmed' or strengthened, pointing towards BSM

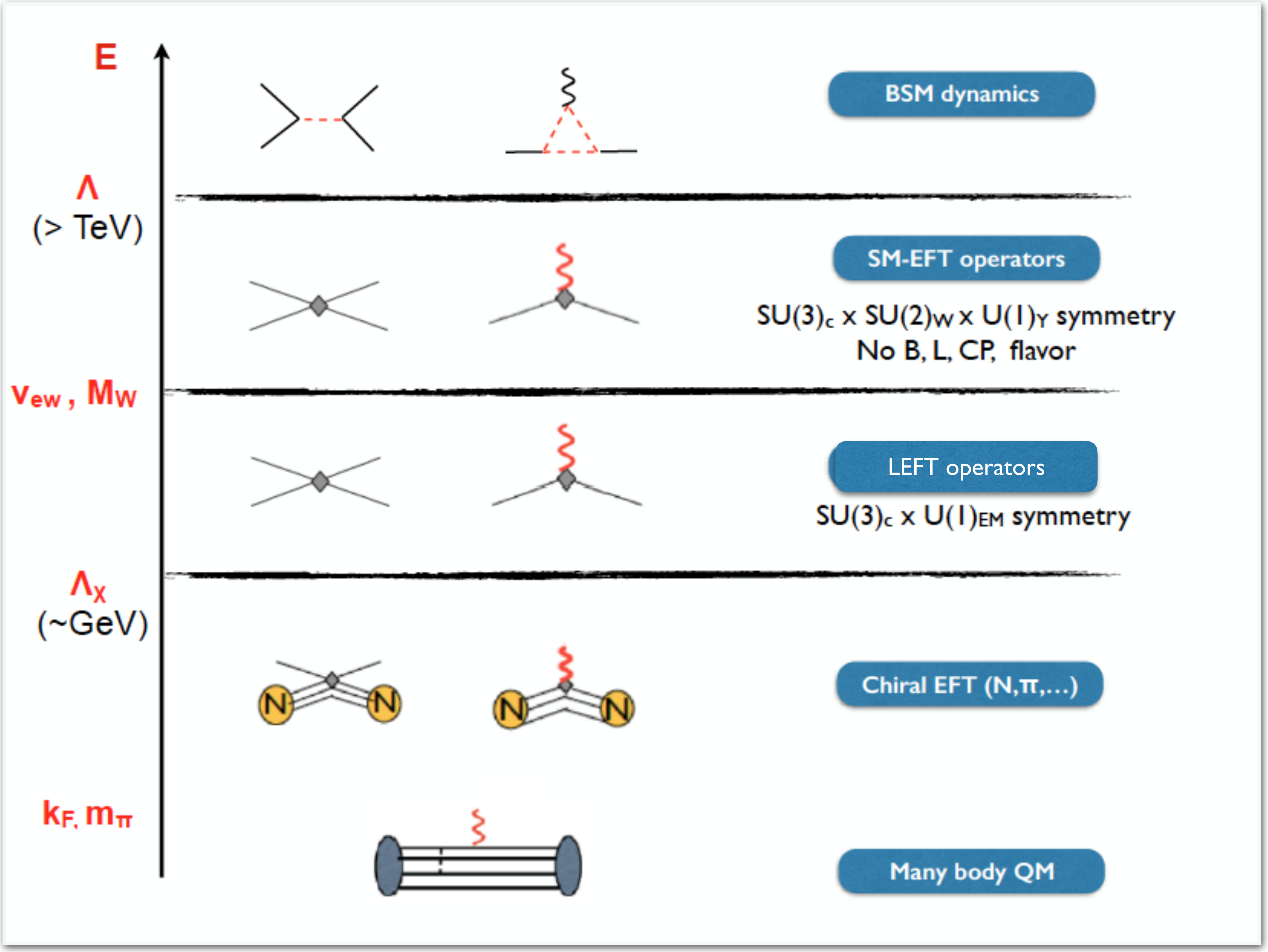
Desirable next theoretical steps

- Refined systematics in $f_+(0)$ and F_K/F_π lattice QCD calculations
- Radiative corrections in lattice QCD
  - $K \to \mu\nu / \pi \to \mu\nu$: more than one lattice collaboration
  - $K \to \pi l \nu$ and $\pi^+ \to \pi^0 e^+ \nu$:
    - More than one lattice collaboration
    - Beyond γ-W box
  - Neutron decay: γ-W box and beyond
  - All decays: think hard about 'isospin' scheme dependence
- Nuclear decays: EFT framework + ab-initio calculations for δ_{NS}, δ_C

BSM implications (1)

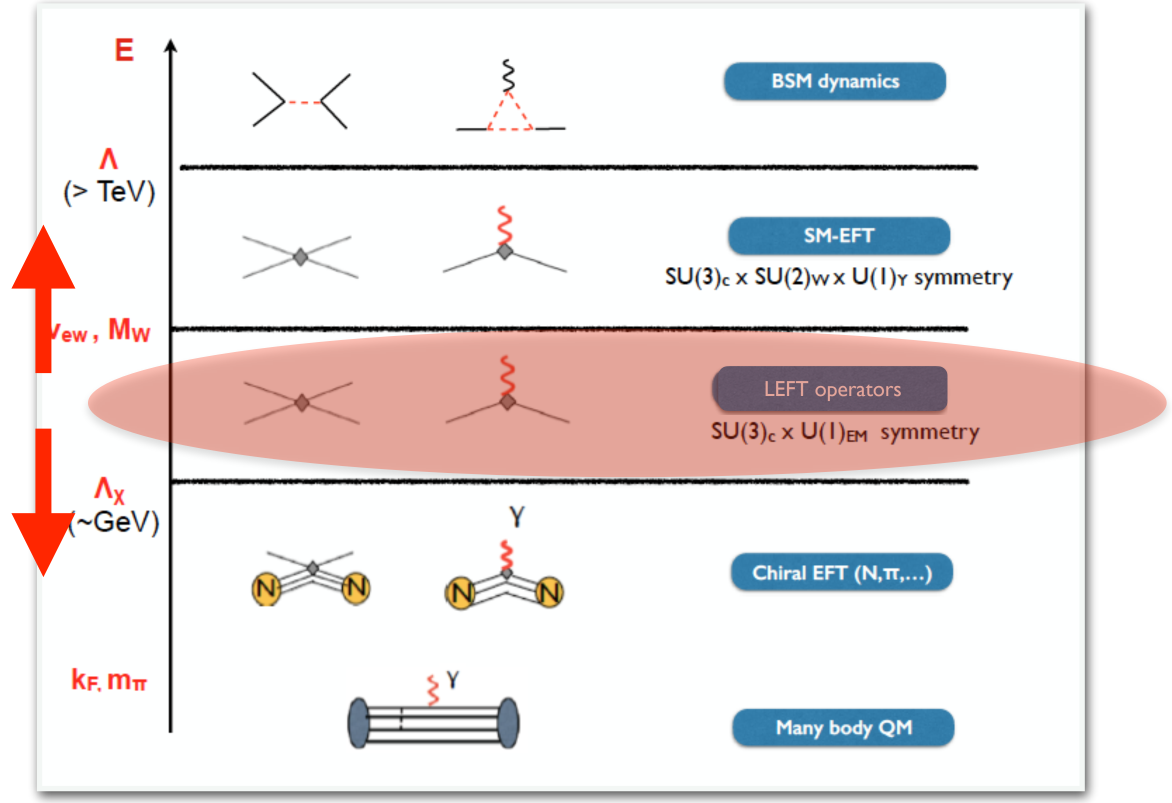
Connecting scales — EFT

To connect UV physics to beta decays, use EFT



Effective Lagrangian at E~GeV

- New physics effects are encoded in ten quark-level couplings



- Quark-level version of Lee-Yang effective Lagrangian

Low-energy effective Lagrangian

VC, Gonzalez-Alonso, Jenkins 0908.1754, NPB

VC, Graesser, Gonzalez-Alonso 1210.4553, JHEP

Leptonic interactions

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

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Semi-leptonic interactions

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

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

Low-energy 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

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

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

Semi-leptonic interactions

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

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

For global analysis of beta decays in this framework see:

Falkowski, Gonzalez-Alonso, Naviliat-Cuncic, 2010.13797

Corrections to V_{ud} and V_{us}

$$
\begin{aligned}
|\bar{V}_{ud}|_i^2 &= |V_{ud}|^2 \left(1 + \sum_\alpha C_{i\alpha} \epsilon_\alpha\right) \\
|\bar{V}_{us}|_j^2 &= |V_{us}|^2 \left(1 + \sum_\alpha C_{j\alpha} \epsilon_\alpha\right)
\end{aligned}
$$

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

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

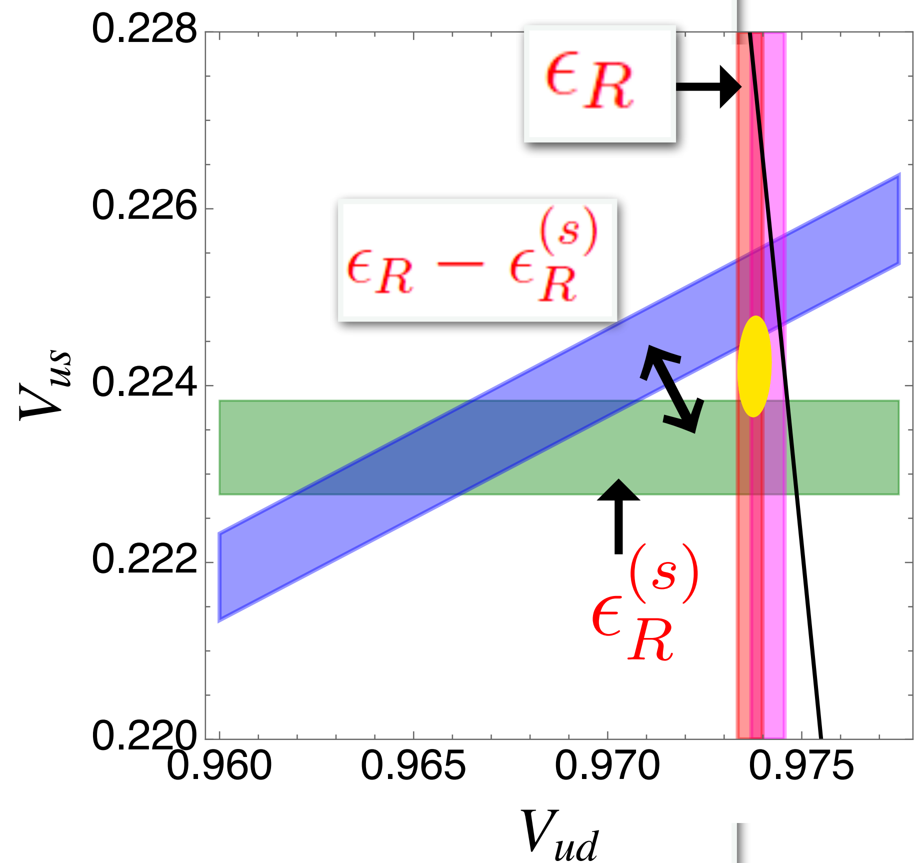
$\varepsilon_T^{(s)}$: suppressed by m_{lept}/m_K

Right-handed quark couplings

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

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

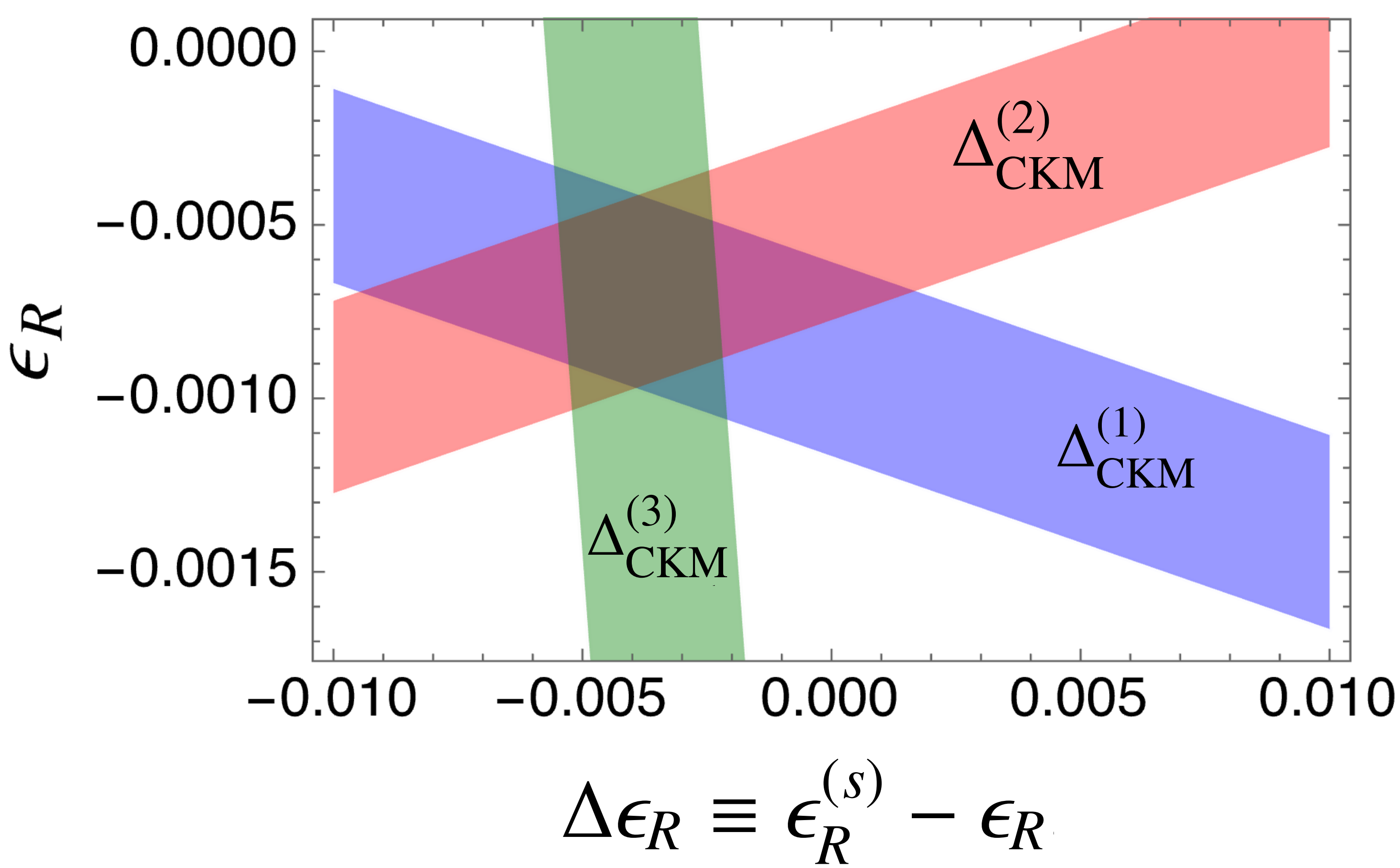
$$
\begin{aligned}
|\bar{V}_{ud}|^2_{0^+\to 0^+} &= |V_{ud}|^2\left(1+2\,\epsilon_R\right)\\
|\bar{V}_{ud}|^2_{n\to pe\bar{\nu}} &= |V_{ud}|^2\left(1+2\,\epsilon_R\right)\\
|\bar{V}_{us}|^2_{Ke3} &= |V_{us}|^2\left(1+2\,\epsilon_R^{(s)}\right)\\
|\bar{V}_{ud}|^2_{\pi e3} &= |V_{ud}|^2\left(1+2\,\epsilon_R\right)\\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



- 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 correlated way, can resolve all tensions!

Unveiling R-handed quark currents?

VC-Crivellin-Hoferichter-Moulson 2208.11707

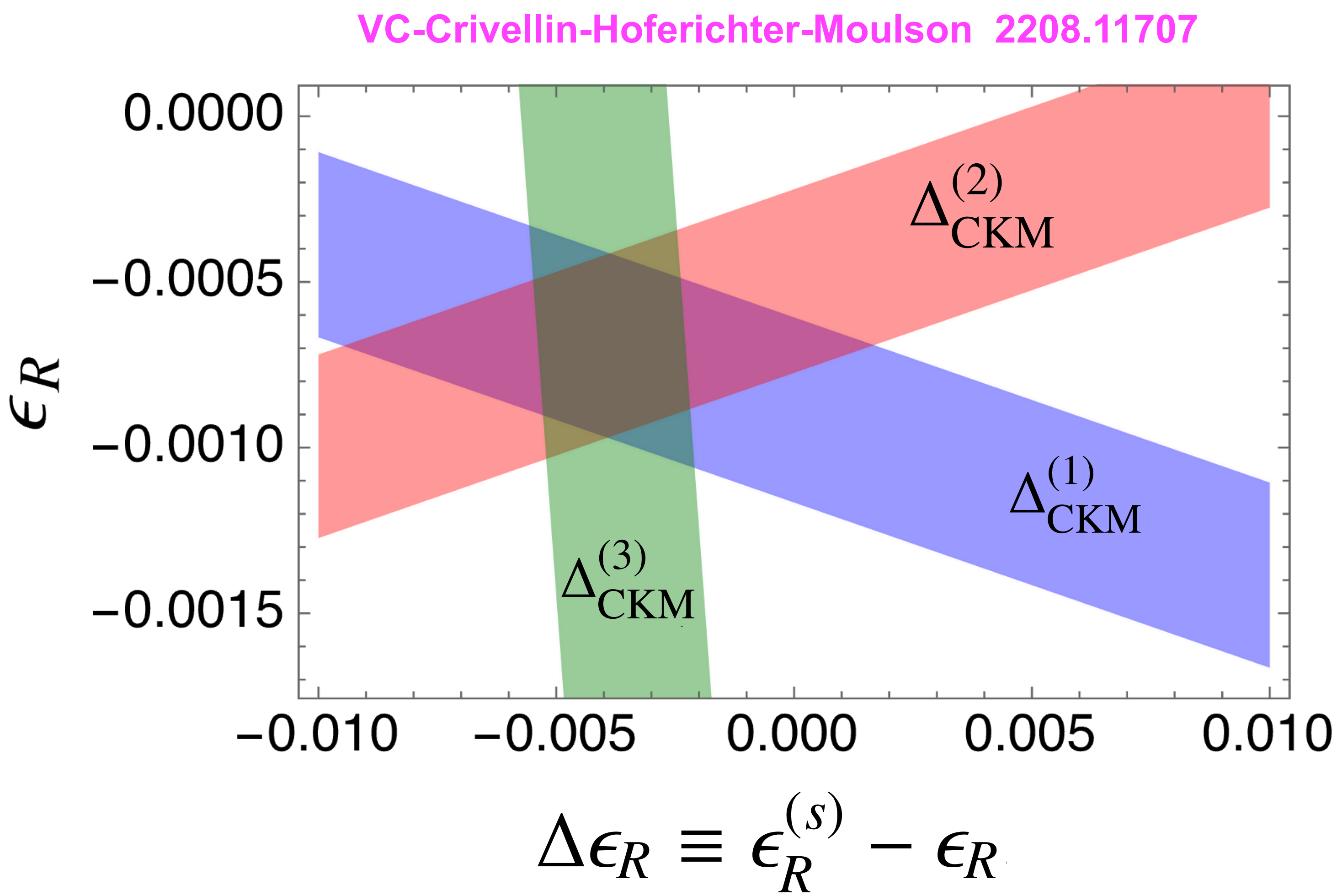


$$\Delta^{(1)}_{\rm CKM} = 2\epsilon_R + 2\Delta\epsilon_R V_{us}^2,$$
$$\Delta^{(2)}_{\rm CKM} = 2\epsilon_R - 2\Delta\epsilon_R V_{us}^2,$$
$$\Delta^{(3)}_{\rm CKM} = 2\epsilon_R + 2\Delta\epsilon_R (2 - V_{us}^2)$$

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

Λ_R ~ 5-10 TeV   2.5σ effect

Unveiling R-handed quark currents?



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Λ_R ~ 5-10 TeV   2.5σ effect

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

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

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

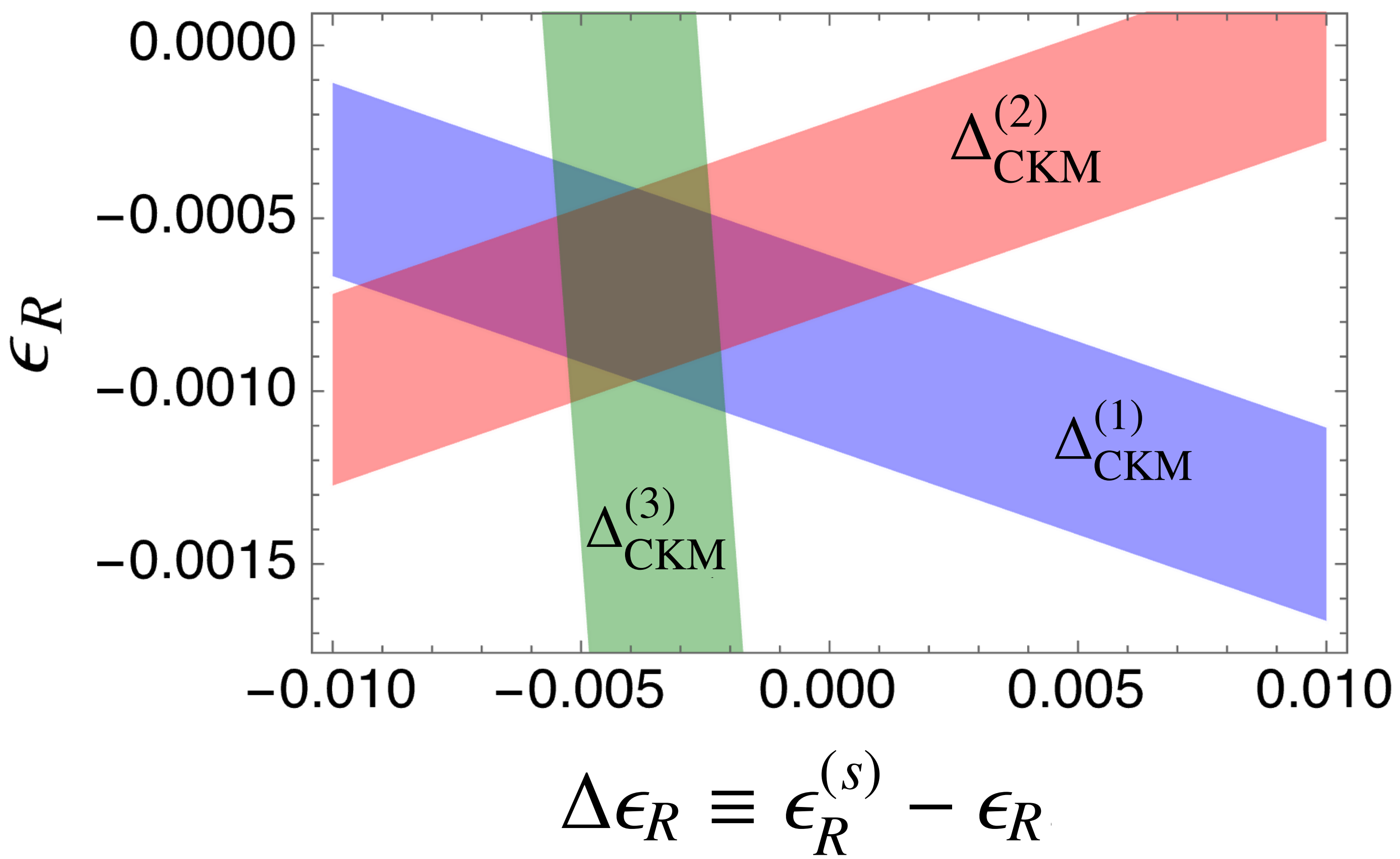
$$\lambda \equiv \frac{g_A}{g_V}$$

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

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

Unveiling R-handed quark currents?

VC-Crivellin-Hoferichter-Moulson 2208.11707



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Λ_R ~ 5-10 TeV   2.5σ effect

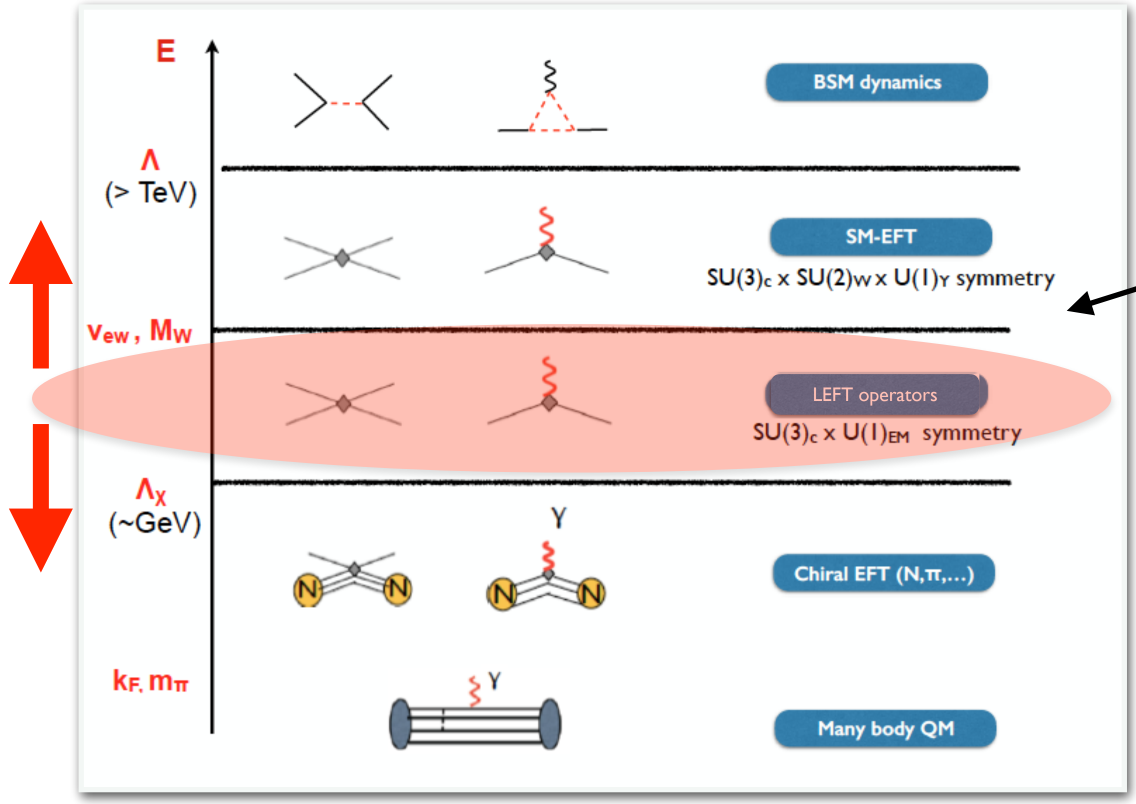
- … nor with high energy data, at least at the EFT level (see later)

For other BSM explanations, see A. Crivellin 2207.02507 and references therein [and talks at this workshop]

BSM implications (II): connection to high energy

Connection with High Energy probes

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



At the weak scale
Match SM-EFT and
SM-EFT'

- Model-independent statements possible in <u>"heavy BSM" scenarios</u>:
  M_{BSM} > TeV → new physics looks point-like at LHC scales

VC, Gonzalez-Alonso, Jenkins 0908.1754

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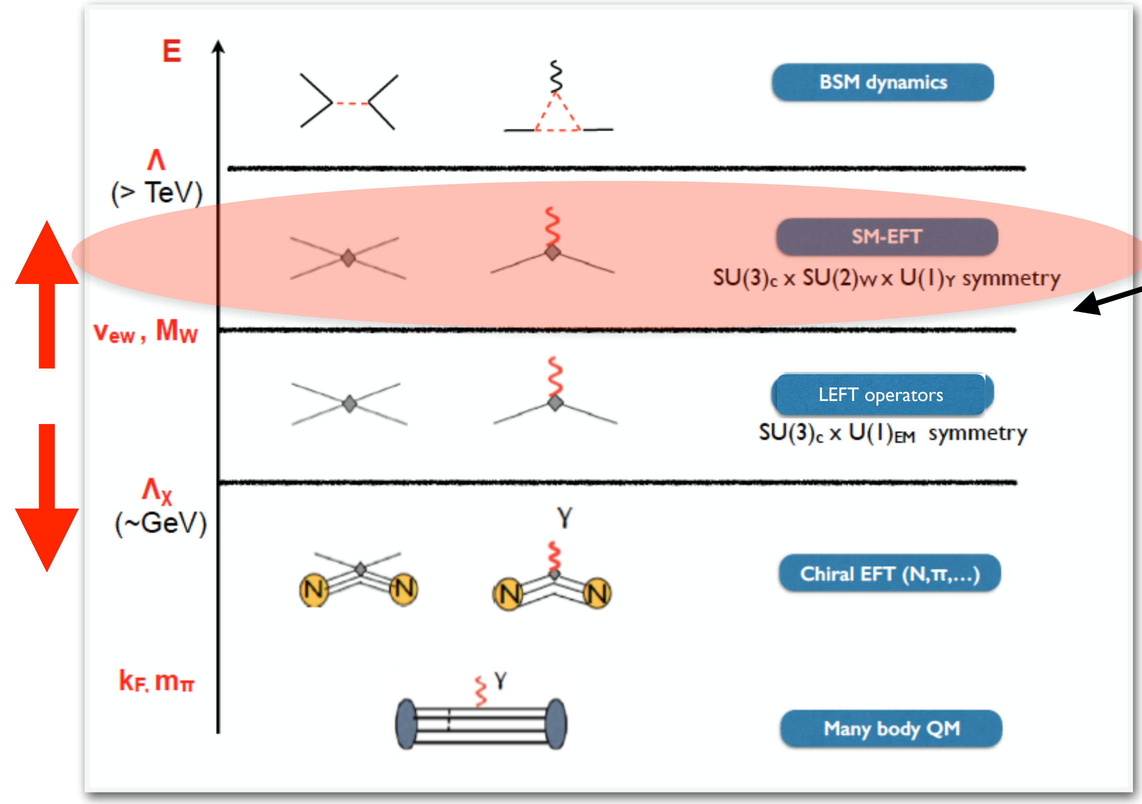
- Need to know high-scale origin of the various ε_α



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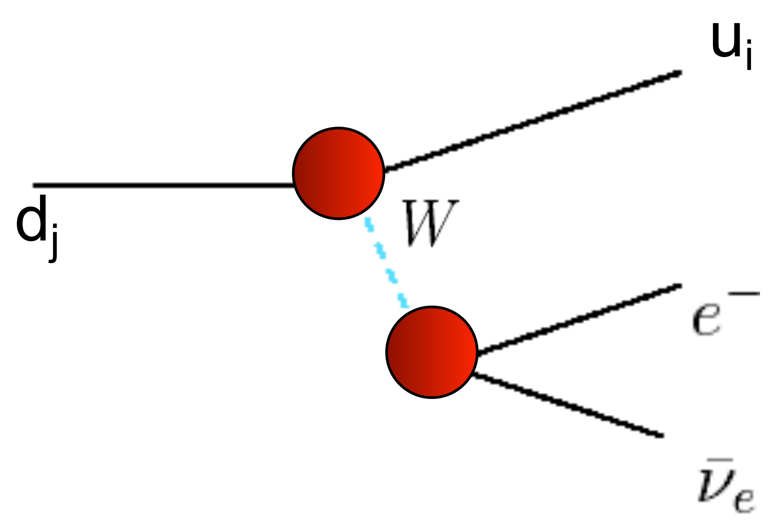
VC, Gonzalez-Alonso, Jenkins 0908.1754

Connection with High Energy probes

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

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



VC, Gonzalez-Alonso, Jenkins 0908.1754

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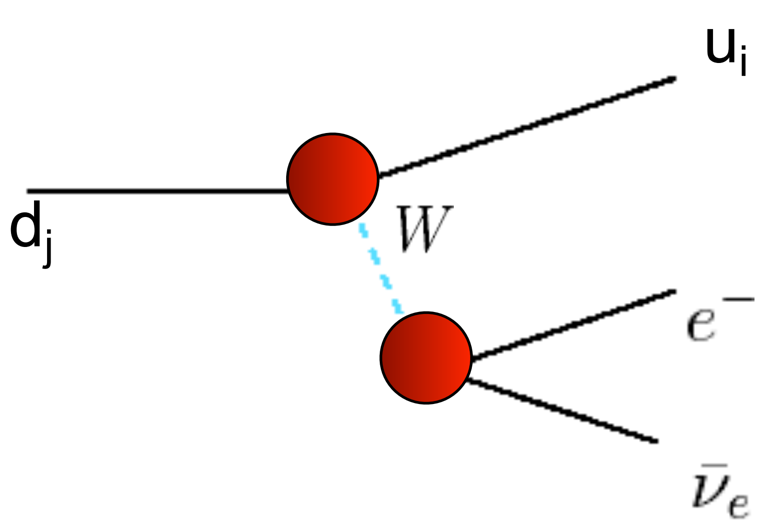
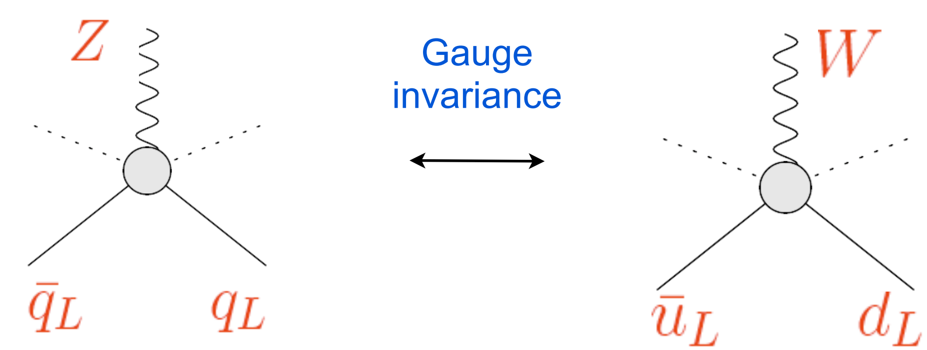


Building blocks

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

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



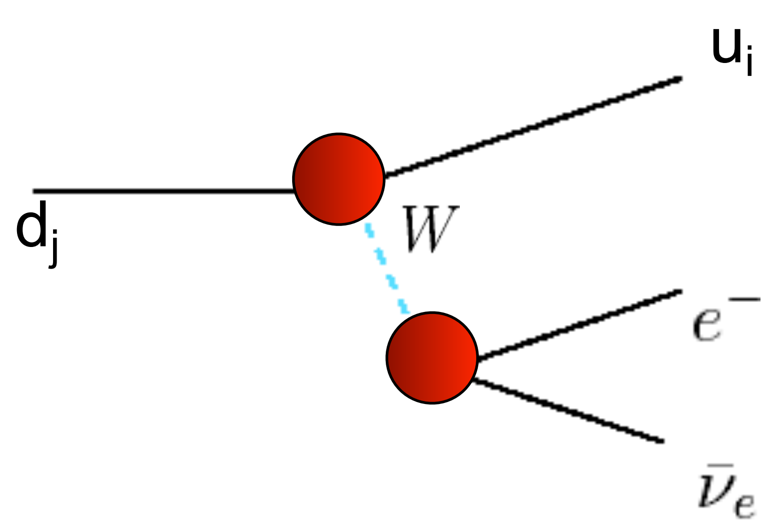
(and similar operator for leptonic vertex corrections)

VC, Gonzalez-Alonso, Jenkins 0908.1754

Connection with High Energy probes

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

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



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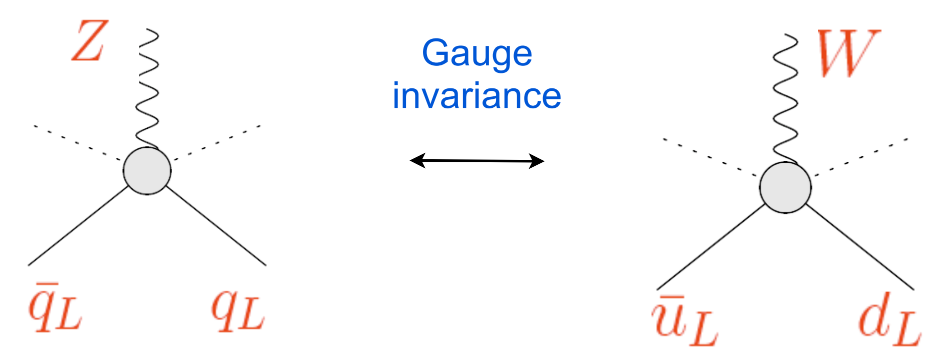
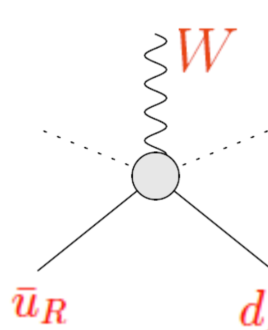


$$Q_{Hud} = i(\widetilde{H}^\dagger D_\mu H)(\bar{u}_p \gamma^\mu d_r)$$



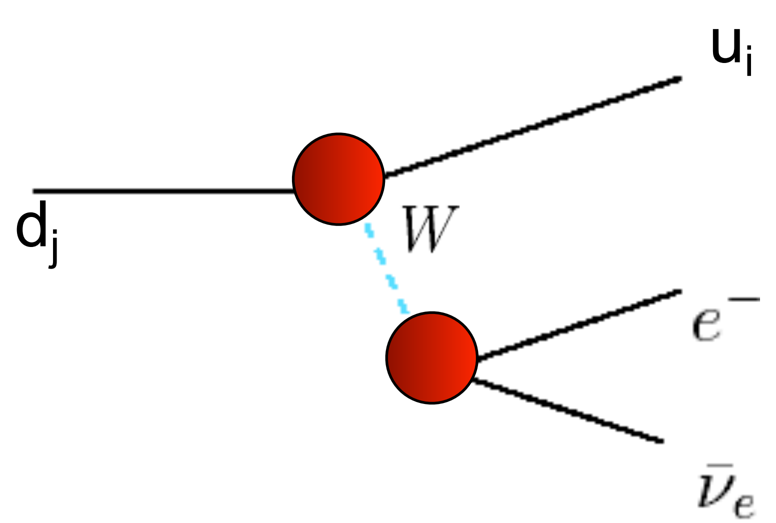
E.g. from W_L-W_R mixing in Left-Right symmetric models or VL quarks

VC, Gonzalez-Alonso, Jenkins 0908.1754

Connection with High Energy probes

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

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



$$
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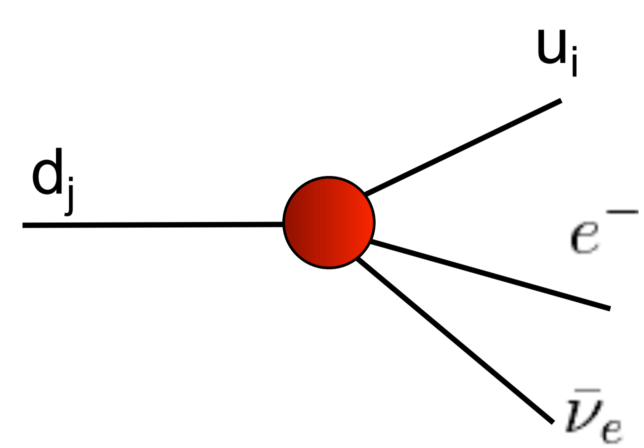
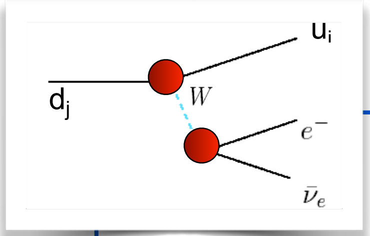
\end{aligned}
$$

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



$$
\begin{aligned}
O_{qde} &= (\bar{\ell} e)(\bar{d} q) + \text{h.c.} \\
O_{lq} &= (\bar{l}_a e)\epsilon^{ab}(\bar{q}_b u) + \text{h.c.} \\
O_{lq}^t &= (\bar{l}_a \sigma^{\mu\nu} e)\epsilon^{ab}(\bar{q}_b \sigma_{\mu\nu} u) + \text{h.c.} \\
O_{lq}^{(3)} &= \bar{l}\gamma_\mu \sigma^a l \; \bar{q}\gamma^\mu \sigma^a q \\
O_{ll} &= \bar{l}\gamma_\mu l \; \bar{l}\gamma^\mu l
\end{aligned}
$$

High Energy constraints



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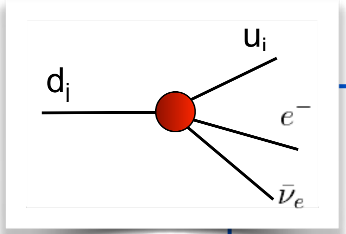

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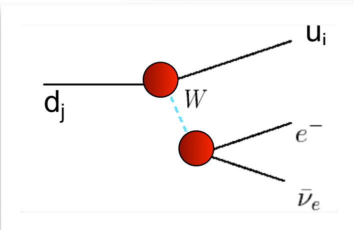
High Energy constraints



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

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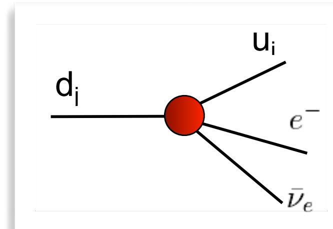

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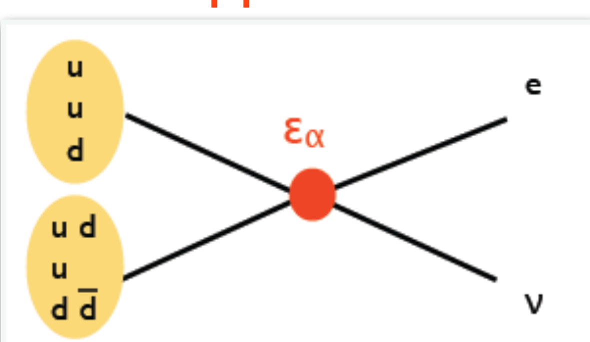
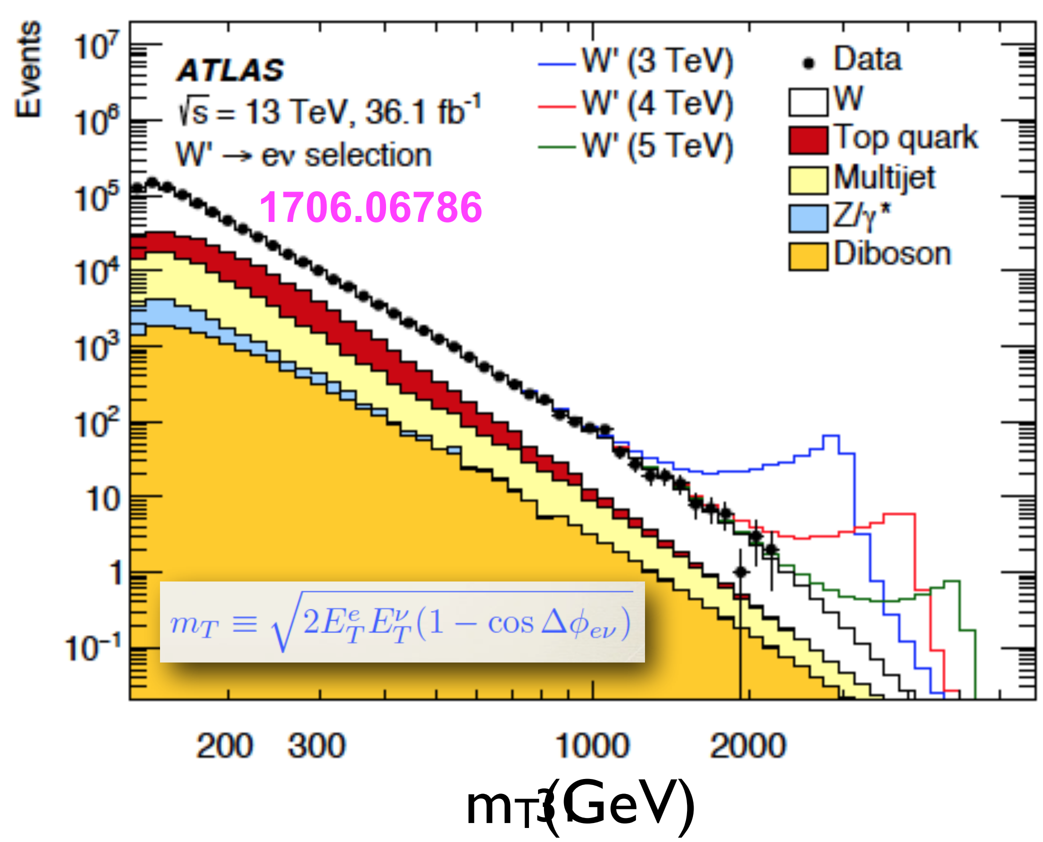
$$O_{ll} = \bar{l}\gamma_\mu l \; \bar{l}\gamma^\mu l$$

Constrained by pp → eν+X and pp → e⁺e⁻ +X at the LHC

LHC: pp → eν + X



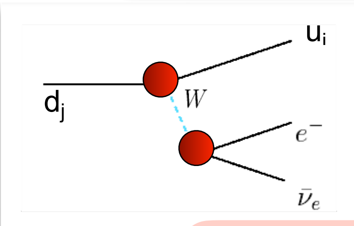


$\boxed{\varepsilon_\alpha \sim 10^{-3} - 10^{-4}}$

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

Updates underway

High Energy constraints



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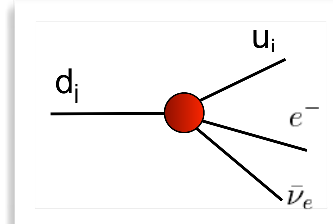

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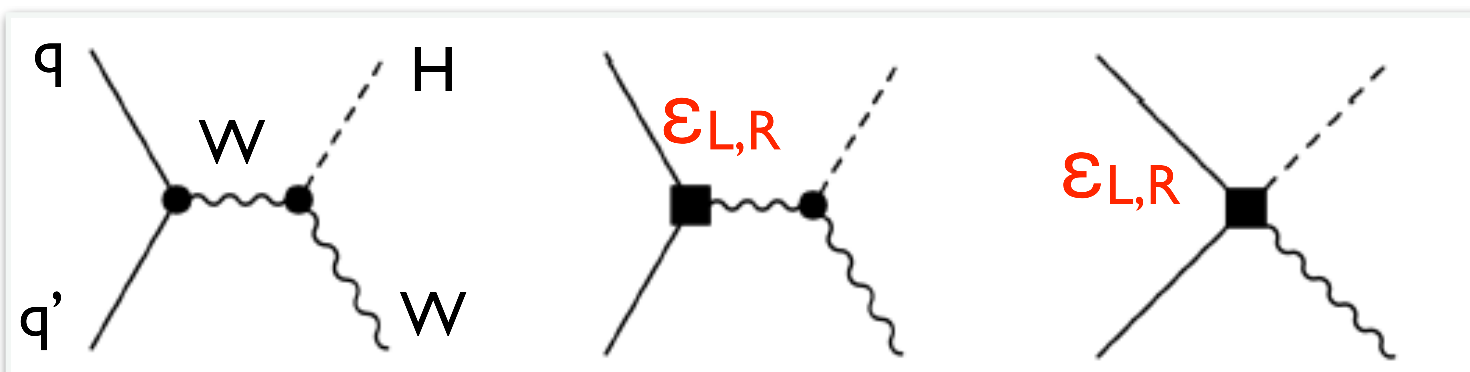
\end{aligned}
$$

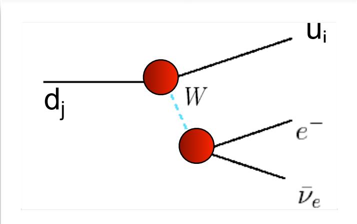
Can be probed at the LHC by associated Higgs + W production (5-10%)



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

LHC run 2 projection ($\mu_{WH} = 1.0 \pm 0.1$) would lead to $\varepsilon_{L,R} \sim$ 3-4%

High Energy constraints



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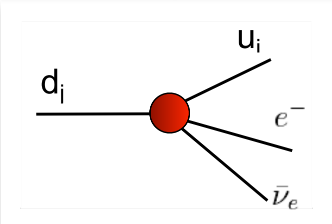

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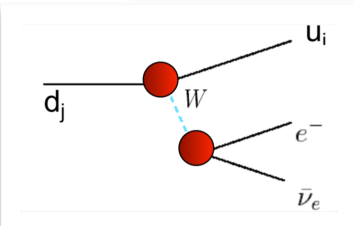
Constrained by Z-pole (and σ_{had}). Included** in 'precision EW' fits

…
VC, Gonzalez-Alonso, Jenkins 0908.1754
…
Crivellin et al. 2008.01113
Crivellin et al. 2102.02825
…
de Blas et al. 2204.04204,
Bagnaschi et al. 2204.05260,
Balkin et al. 2204.05992
…

High Energy constraints



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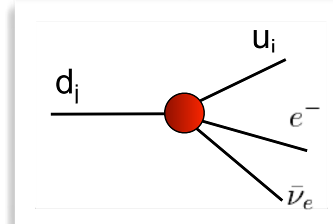

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\end{aligned}
$$

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

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

Constrained by Z-pole (and σ_{had}). Included** in 'precision EW' fits

- These operators control Δ_{CKM} in the MFV limit ($U(3)^5$ flavor symmetry)

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

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

...
VC, Gonzalez-Alonso, Jenkins 0908.1754
...
Crivellin et al. 2008.01113
Crivellin et al. 2102.02825
...
de Blas et al. 2204.04204,
Bagnaschi et al. 2204.05260,
Balkin et al. 2204.05992
...

- Δ_{CKM} should be included in global EW fits to SMEFT couplings

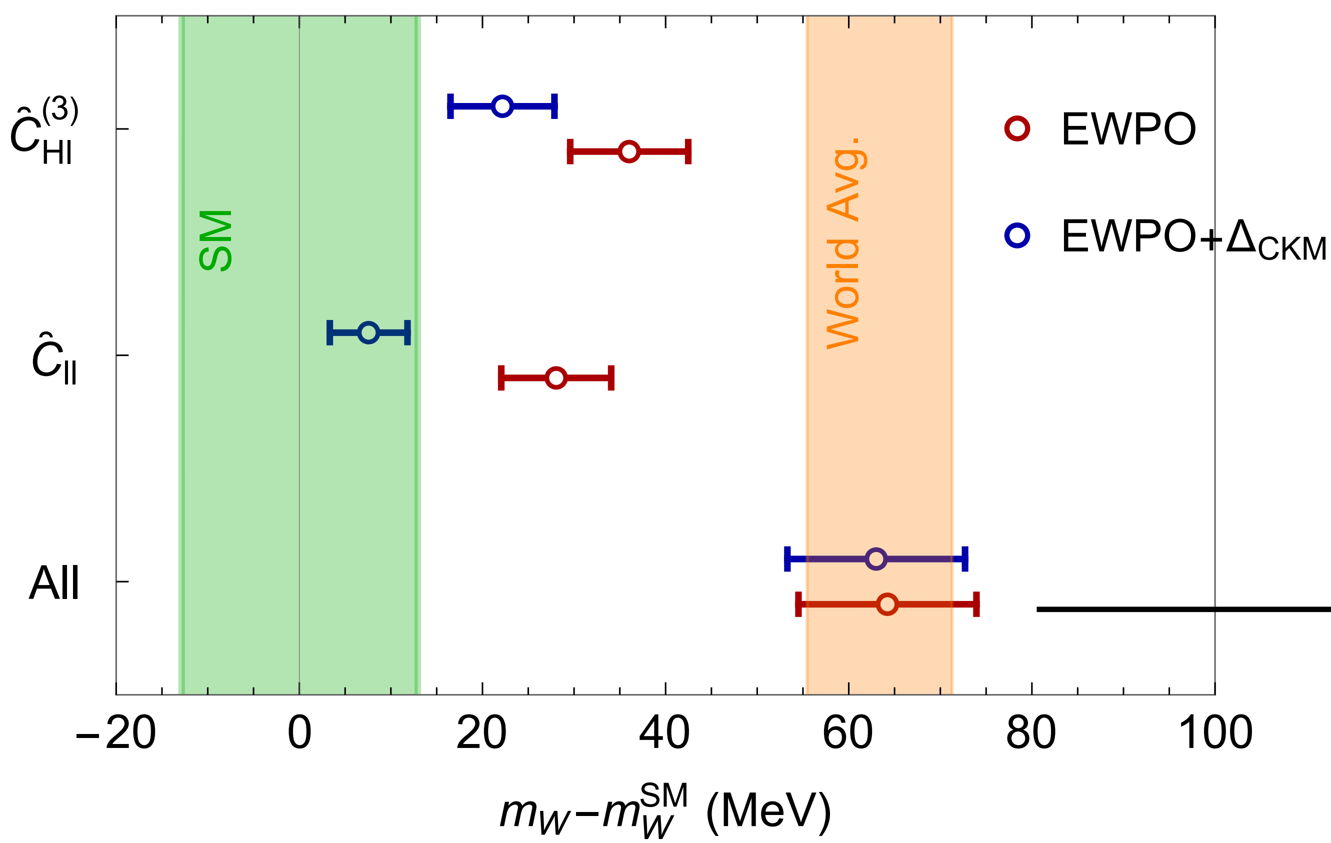
Examples of impact of Δ_{CKM} (I)

VC, Dekens, deVries, Mereghetti, Tong 2204.08440

- Explanations of M_W anomaly in SMEFT (beyond oblique corrections) are in tension with Δ_{CKM} in MFV limit

deBlas et al 2204.04204,
Bagnaschi et al 2204.05260, …

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



MFV

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

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

$$\Delta_{\rm CKM}^{\rm EWfit} = -(0.012 \pm 0.005)\,,$$

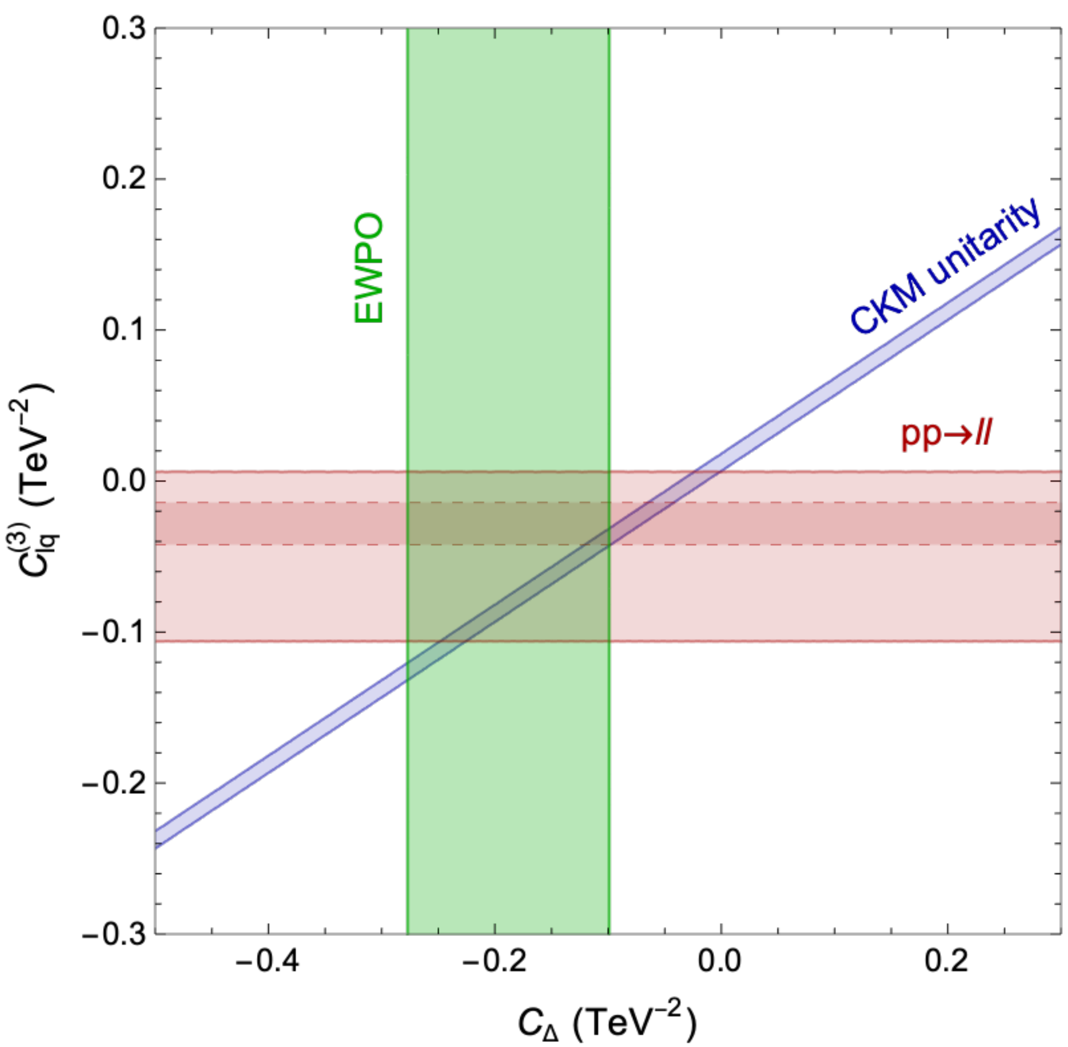
Examples of impact of $\Delta_{\rm CKM}$ (1)

VC, Dekens, deVries, Mereghetti, Tong 2204.08440

- Explanations of M_W anomaly in SMEFT (beyond oblique corrections) are in tension with $\Delta_{\rm CKM}$ in MFV limit

deBlas et al 2204.04204,
Bagnaschi et al 2204.05260, …

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



MFV

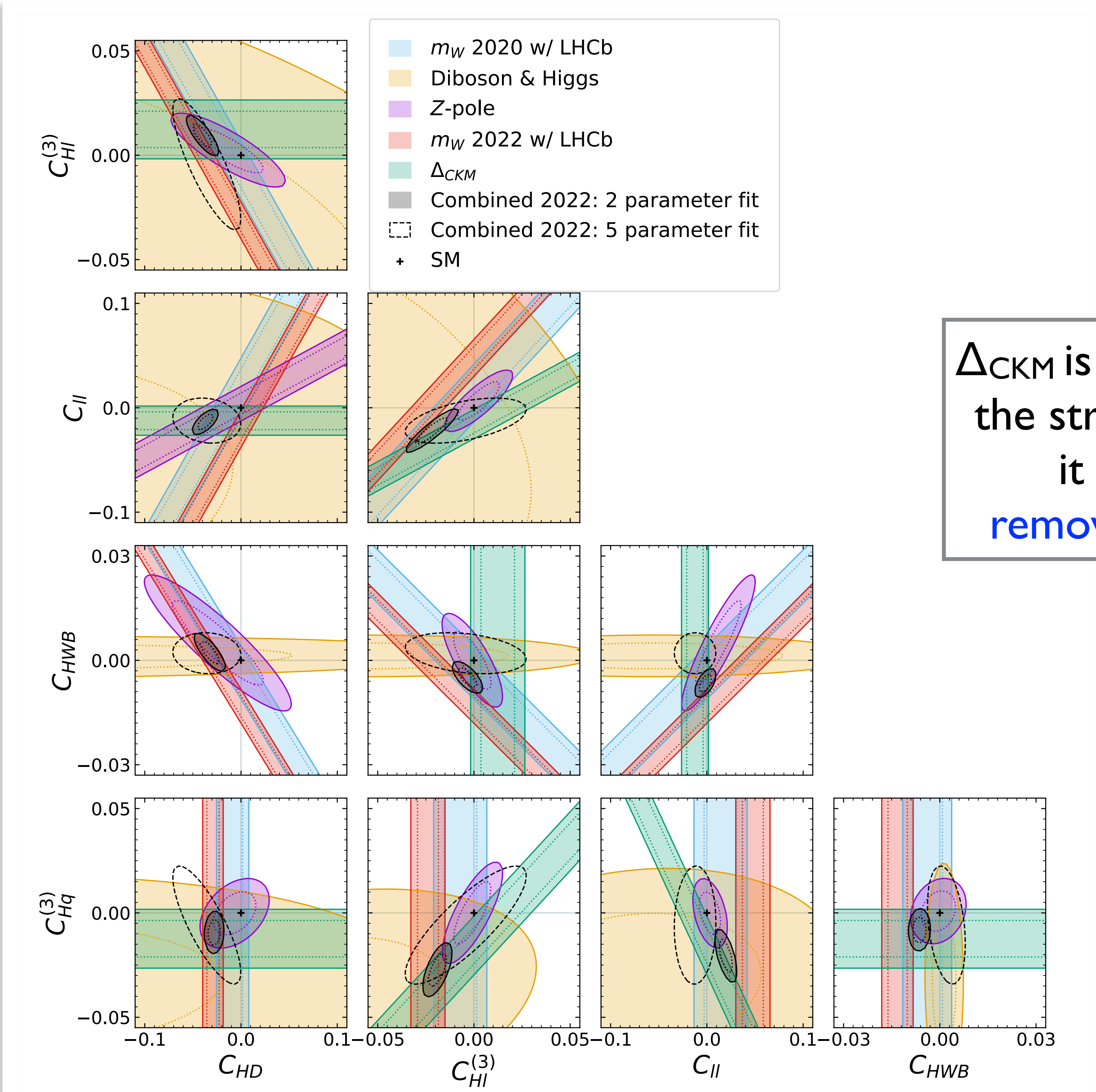
$$\Delta_{\rm CKM} = v^2\left[C_\Delta - 2\,C_{lq}^{(3)}\right]$$

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

- Decouple by turning on $C_{lq}^{(3)}$: but constraints from Drell-Yan at the LHC are catching up and will test this scenario

Examples of impact of Δ_{CKM} (2)

Bagnaschi et al 2204.05260



Δ_{CKM} is at the same level of the strongest constraints: it contributes to removing flat directions

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!

- Therefore, it deserves both experimental and theoretical scrutiny / improvement
  - Experiment: neutron, K, π
  - Theory [my point of view]: (i) radiative correction with lattice QCD for neutron, K, π; (ii) EFT+ and ab-initio methods for nuclei

- Most likely BSM explanations are "vertex corrections" in the EFT language

- Even now, precision on Δ_{CKM} warrants its inclusion in precision EW fits