New opportunities for beyond-the-Standard Model searches at the EIC
Center for Frontiers in Nuclear Science, Stony Brook
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The Standard Model Effective Field Theory and low-energy experiments

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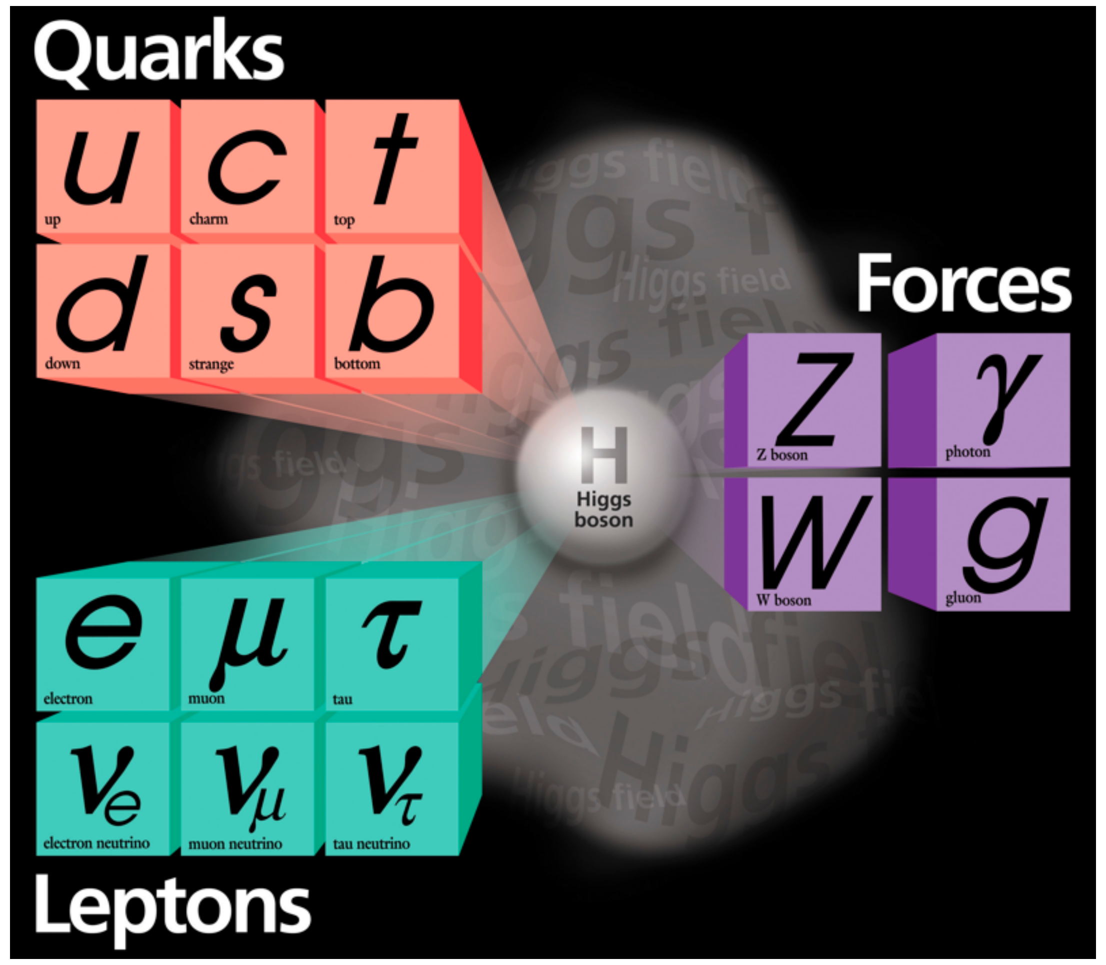
Outline

- BSM searches at low-energy: landscape and theoretical tools
- Worked example: SMEFT analysis of charged current weak interactions and the "Cabibbo angle anomaly"
- Conclusions and outlook

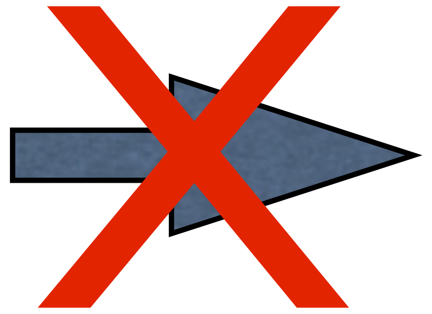
Searching for new physics at low-energy

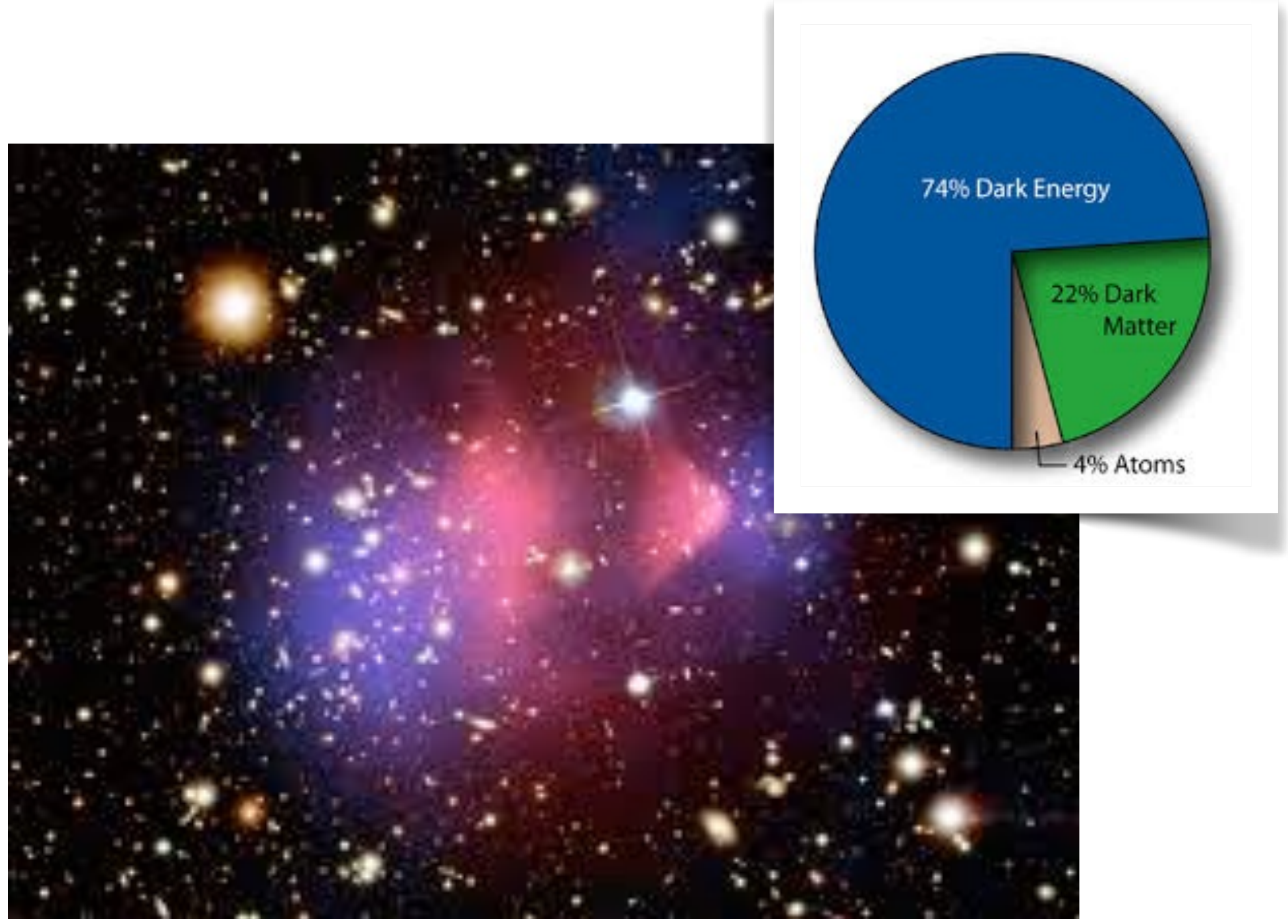
- Low-energy measurements can shed light on shortcomings of the Standard Model

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



Credit: Fermilab





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

Searching for new physics at low-energy

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

- Precision / sensitivity frontiers:

Precision tests of SM-allowed processes

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

New force mediators, from dark sectors to multi-TeV

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

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

Connection to Sakharov conditions for baryogenesis

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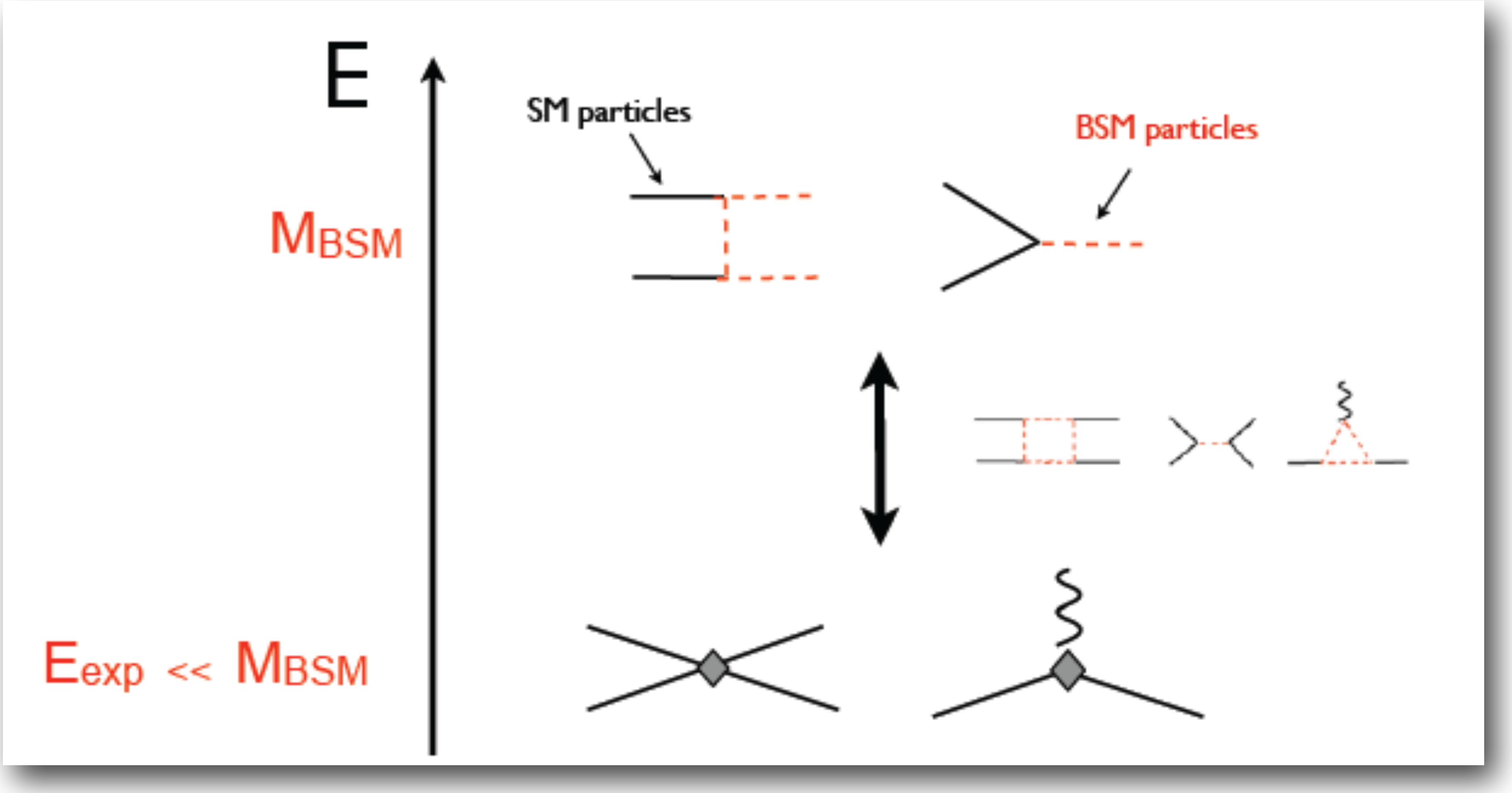
Connection to Sakharov conditions for baryogenesis

Implications of high-scale BSM physics at low-energy are efficiently analyzed with EFT methods (scale separation!)

General framework

- Describe new physics originating at $\Lambda \gg v_{ew}$ through local operators of increasing mass dimension



$[\Lambda \leftrightarrow M_{BSM}]$ $\quad C_i\ [g_{\rm BSM},\ M_a/M_b]$

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{SM} + \frac{C^{(5)}}{\Lambda} O^{(5)} + \sum_i \frac{C_i^{(6)}}{\Lambda^2} O_i^{(6)} + \ldots$$

Weinberg 1979,
Wilczek-Zee 1979,
Buchmuller-Wyler 1986,
....

Grzadkowski-Iskrzynksi- Misiak-Rosiek 2010,
Alonso, Jenkins, Manohar, Trott 2013
…

- "Standard Model EFT" (SMEFT):
  - ★ Build operators out of SM fields
  - ★ Impose Lorentz + SM gauge symmetry
  - ★ Organize operators according to mass dimension: power counting in E/Λ, M_W/Λ.
    At a given order the EFT is renormalizable and predictive

General framework

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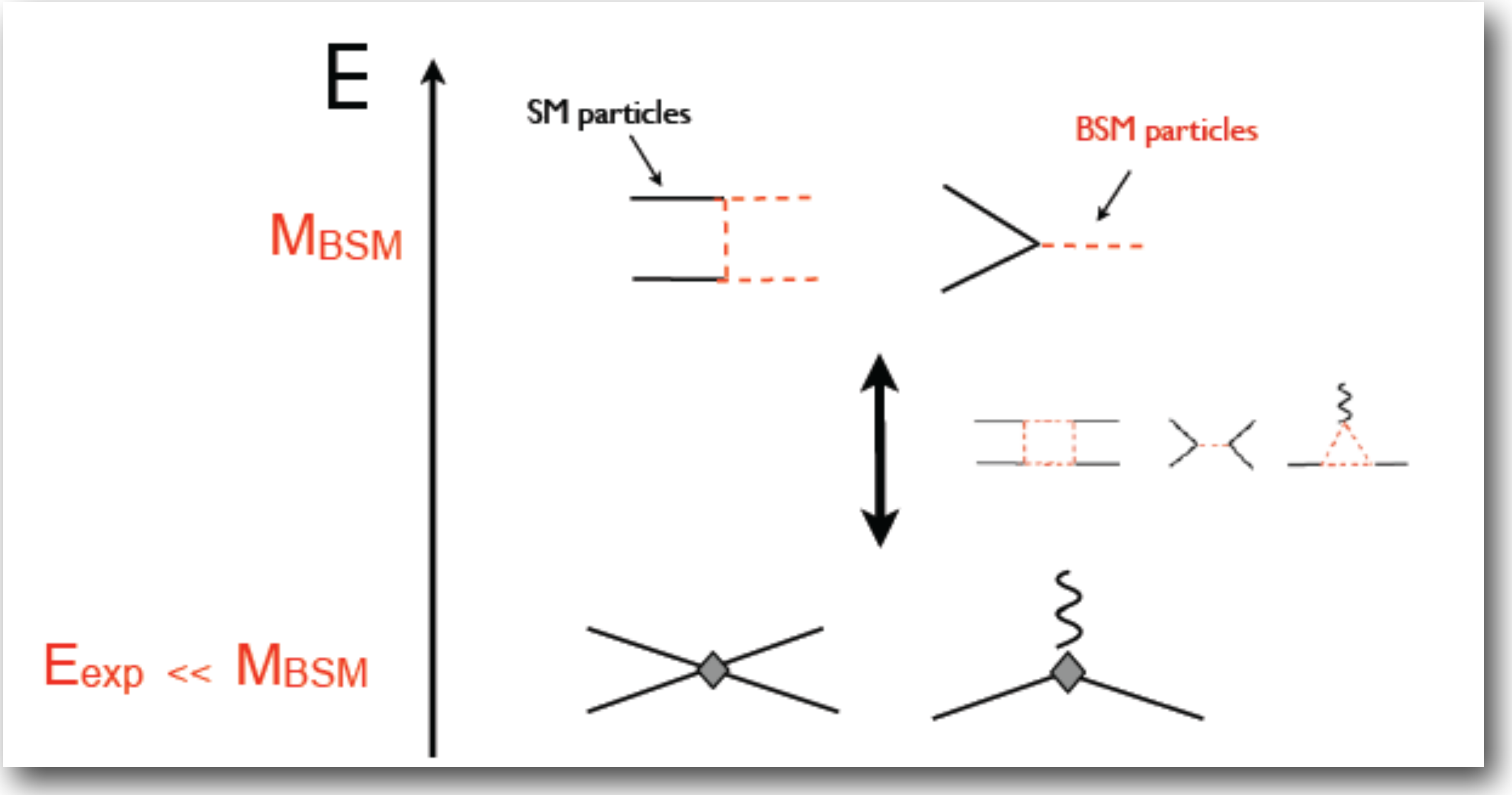


[$\Lambda \leftrightarrow M_{BSM}$] $C_i \; [g_{\rm BSM}, \; M_a/M_b]$

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{SM} + \frac{C^{(5)}}{\Lambda} O^{(5)} + \sum_i \frac{C_i^{(6)}}{\Lambda^2} O_i^{(6)} + \ldots$$

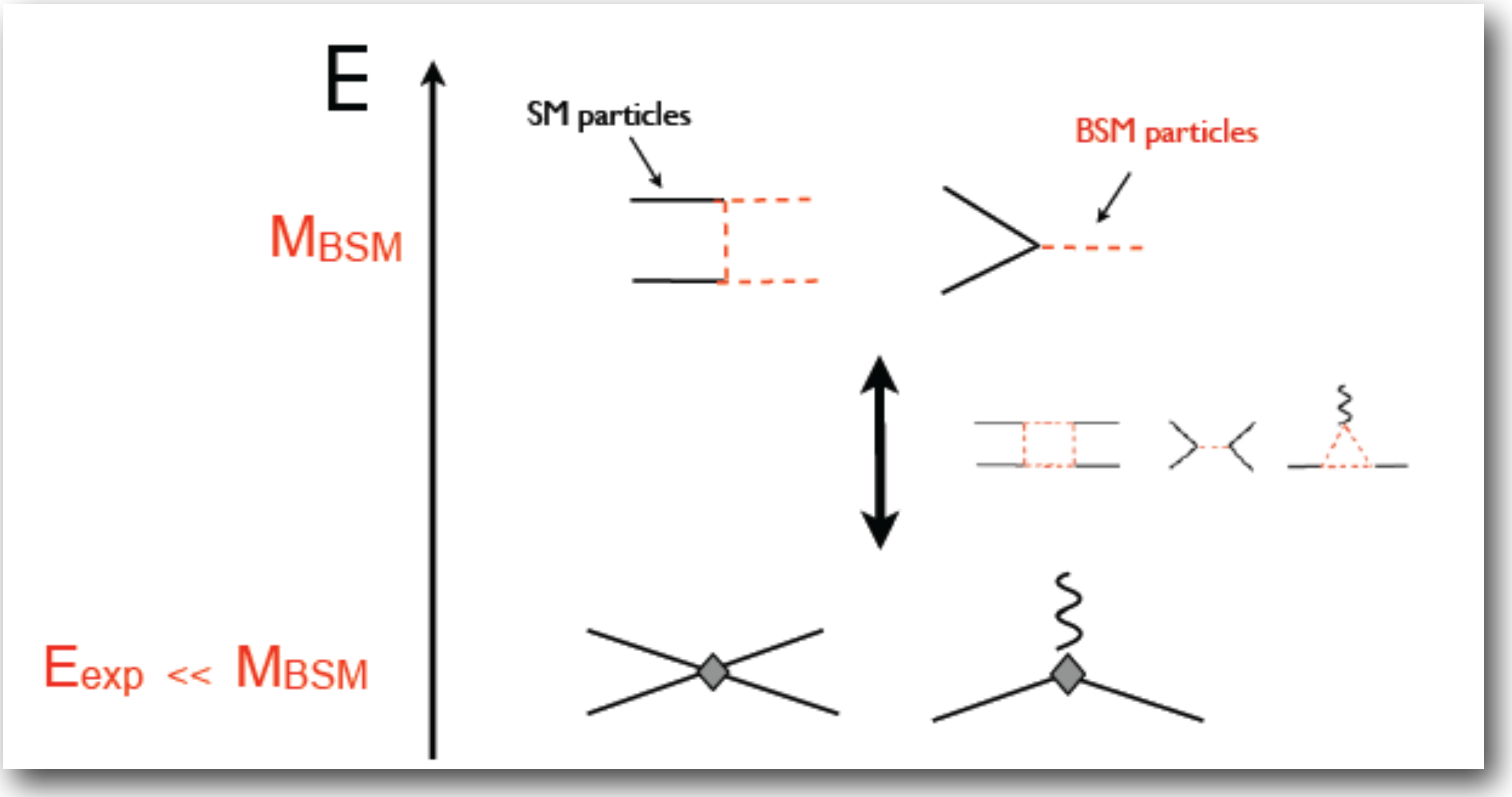
$\Delta L=2$ $\Delta B=1$, CPV, FCNC, …

- Symmetries in SMEFT:

  - B, L, $L_{e,\mu,\tau}$ not enforced: per Weinberg's definition, they are "accidental" in the SM, i.e. consequence of keeping operators of dimension ≤ 4 built out of SM fields & SM gauge group

General framework

- Describe new physics originating at Λ >> v_{ew} through local operators of increasing mass dimension



[Λ ↔ M_{BSM}] $C_i \; [g_{\rm BSM}, \; M_a/M_b]$

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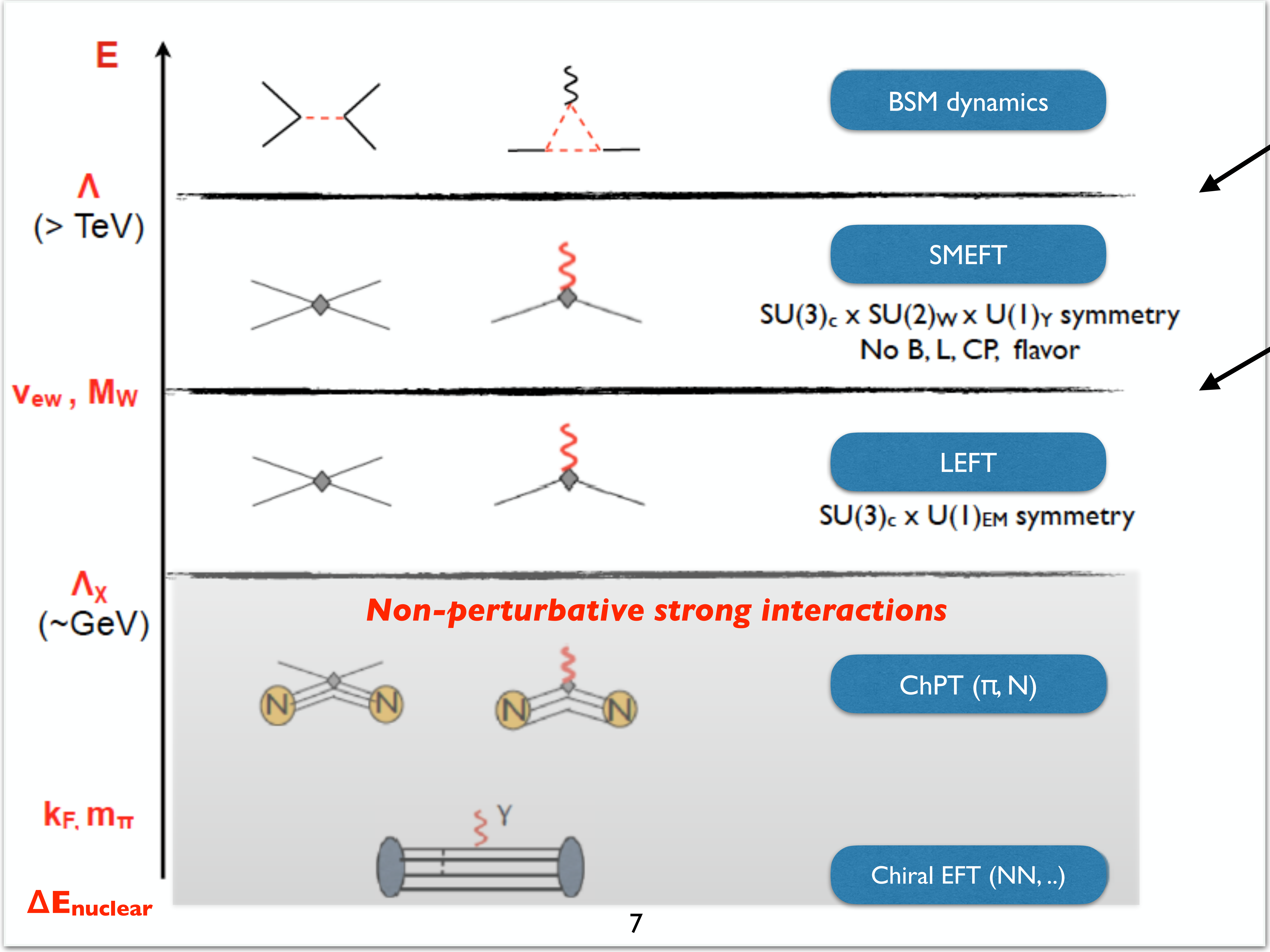
ΔL=2   ΔB=1, CPV, FCNC, …

- Beyond SMEFT: other EFTs differ in the assumptions about particle content and/or symmetry realization
  - νSMEFT: SMEFT + ν_R
  - HEFT: Higgs h is an SU(2) singlet. More general Higgs potential
  - …

Connecting scales

To connect new physics to low-energy, use a tower of EFTs in which SMEFT is the SM-BSM link

- Use appropriate degrees of freedom in each range of energies
- Write down all interactions consistent with the given symmetries
- At each threshold, need appropriate perturbative or non-perturbative matching conditions: $A_{hi} = A_{low}$
- Expand amplitudes to a given order in m_{low}/m_{hi}



Matching BSM theory to SMEFT

Perturbative matching within SM

Hadronic matrix elements

Nuclear matrix elements

Two classes of SMEFT operators (↔ probes)

Operators that violate approximate or exact symmetries of the SM: mediate rare or forbidden processes (proton decay, $0\nu\beta\beta$, EDMs, $\mu\to e$, quark flavor violation, …)

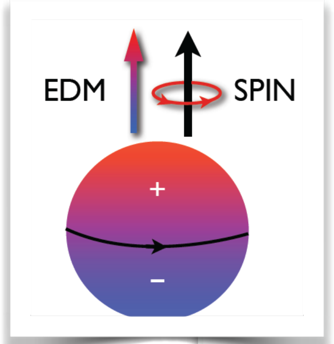
Operators that give corrections to SM “allowed” processes: probe them with precision measurements (muon g-2, weak decays, electron scattering ...)

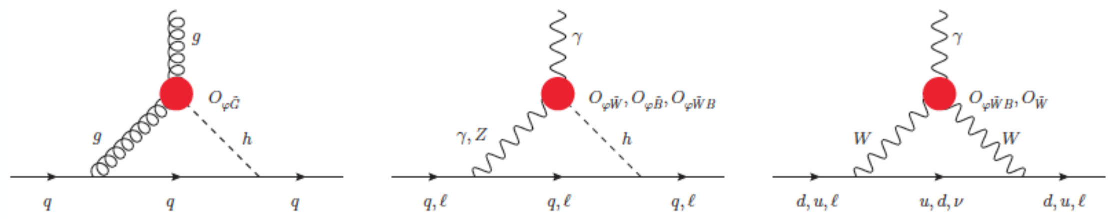
Two classes of SMEFT operators (↔ probes)

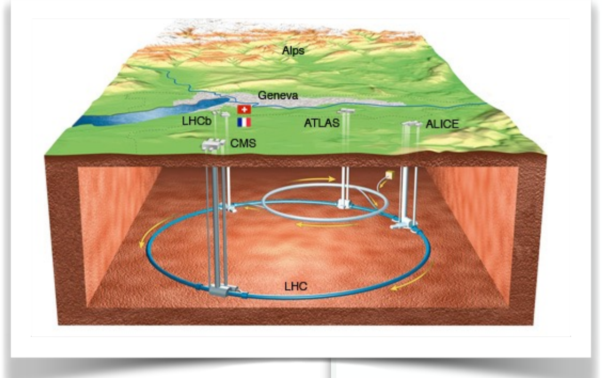
Operators that violate approximate or exact symmetries of the SM: mediate rare or forbidden processes (proton decay, $0\nu\beta\beta$, EDMs, $\mu \to e$, quark flavor violation, …)

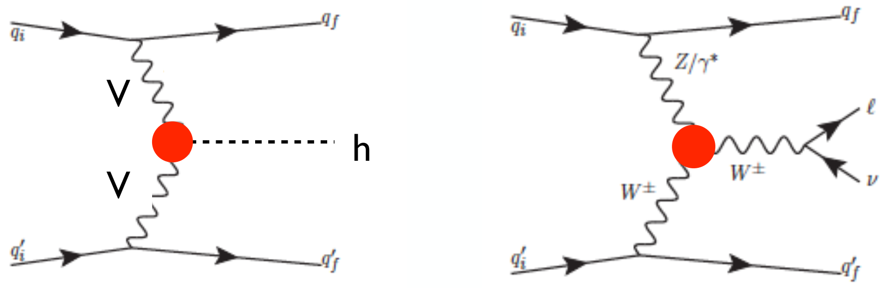
Discussed in following talks, with an eye to the connection between low-E and collider probes (including EIC)

CP violation





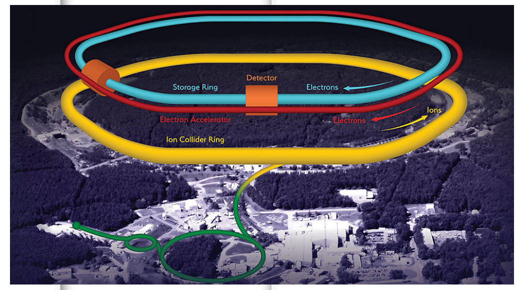


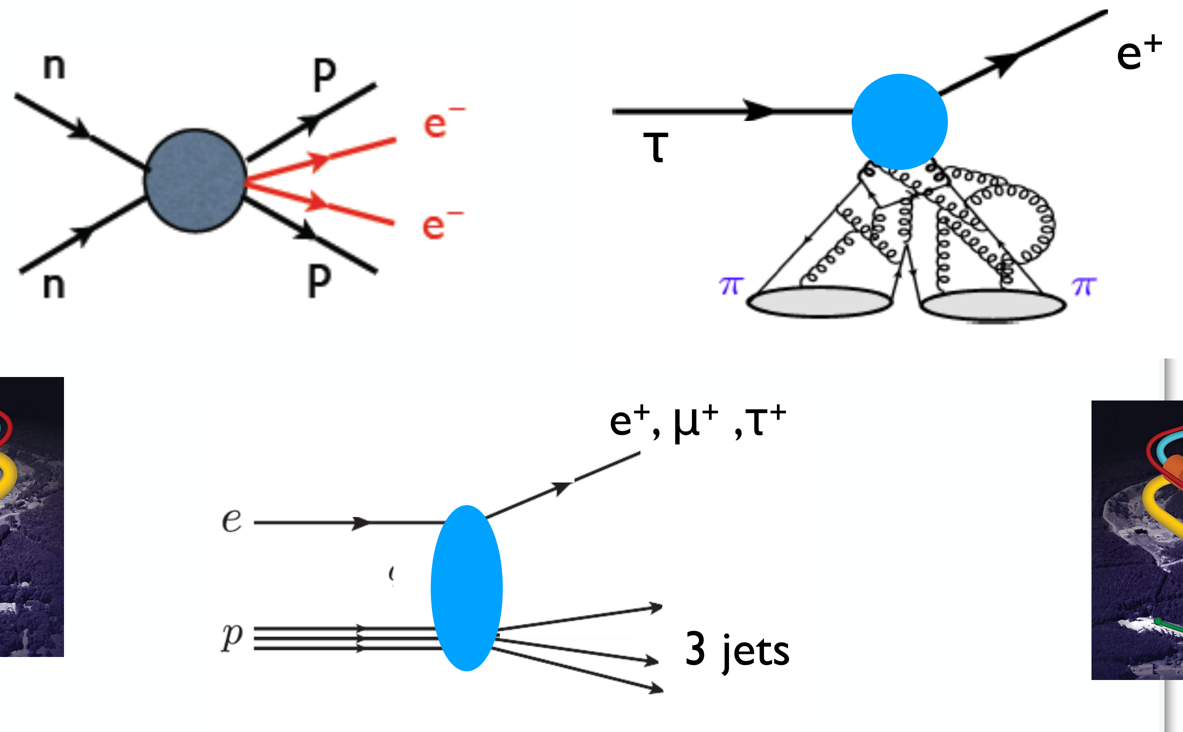


Emanuele Mereghetti

ΔL=2 processes

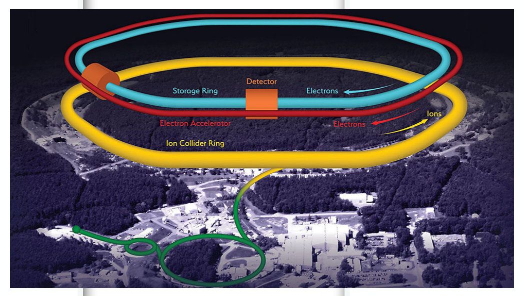
SMEFT & νSMEFT

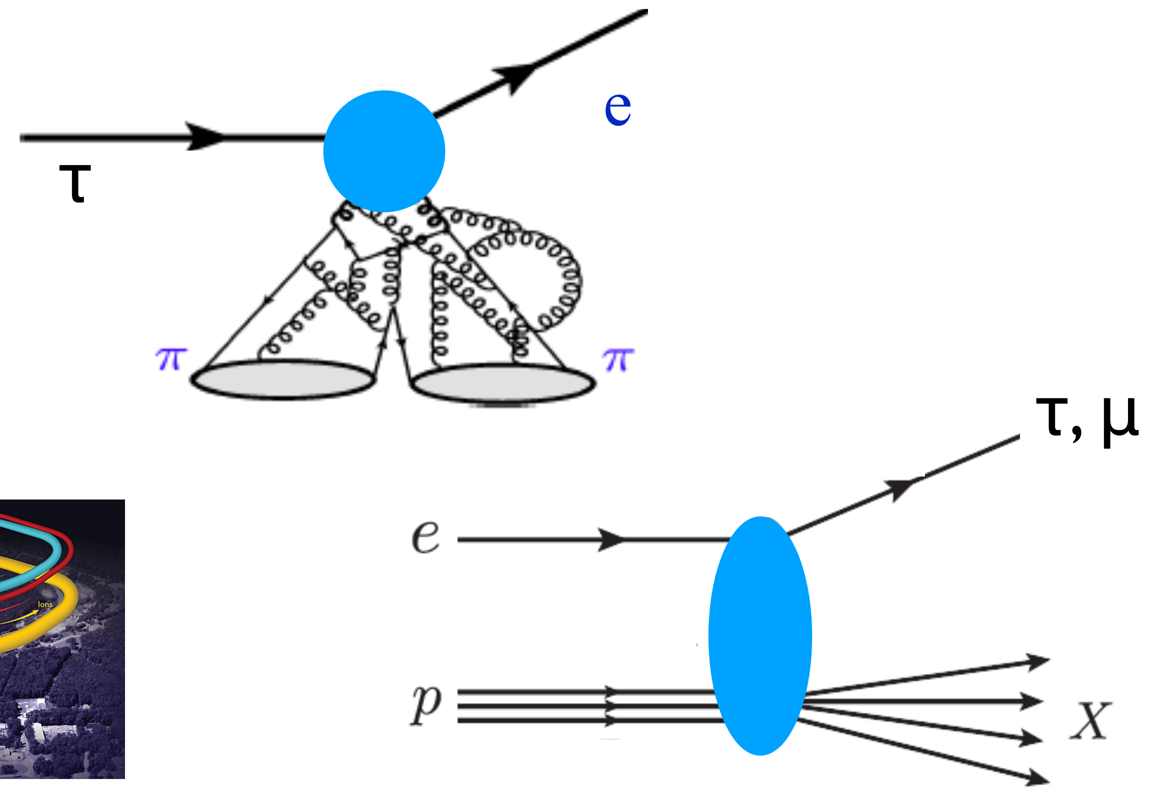




Sebastian Urrutia-Quiroga

LFV processes





Kaori Fuyuto

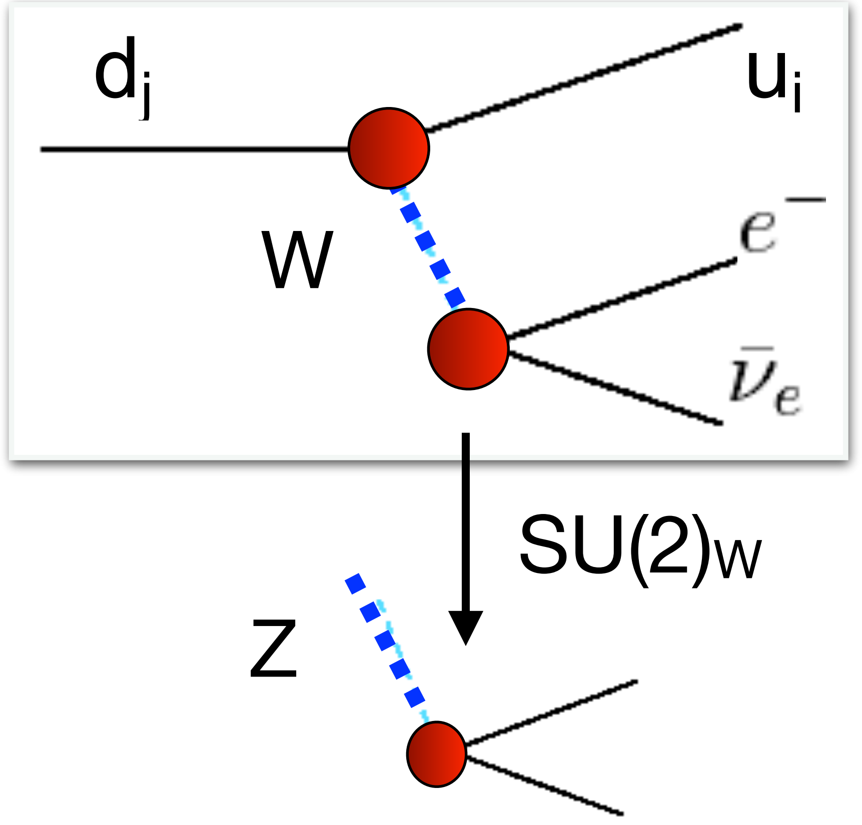
Two classes of SMEFT operators (↔ probes)

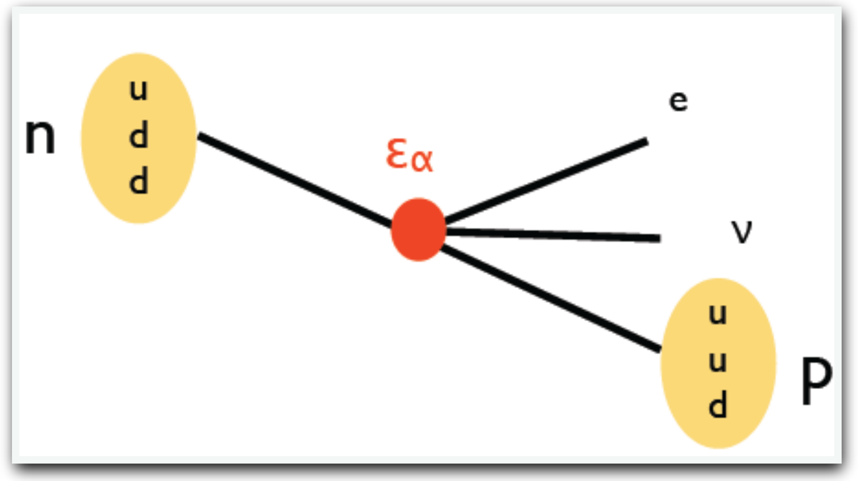
Operators that violate approximate or exact symmetries of the SM: mediate rare or forbidden processes (proton decay, $0\nu\beta\beta$, EDMs, $\mu\to e$, quark flavor violation, …)

Operators that give corrections to SM "allowed" processes: probe them with precision measurements (muon g-2, weak decays, electron scattering ...)

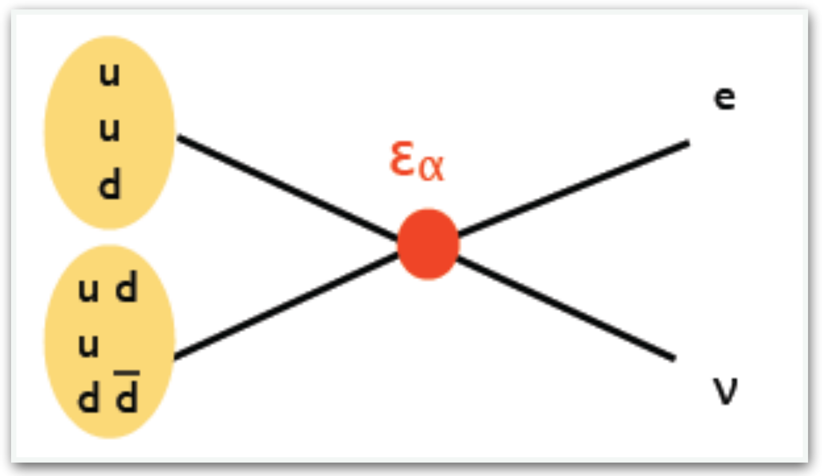
In the rest of this talk

Precision tests with weak charged currents
(from β decays to precision EW tests and LHC)

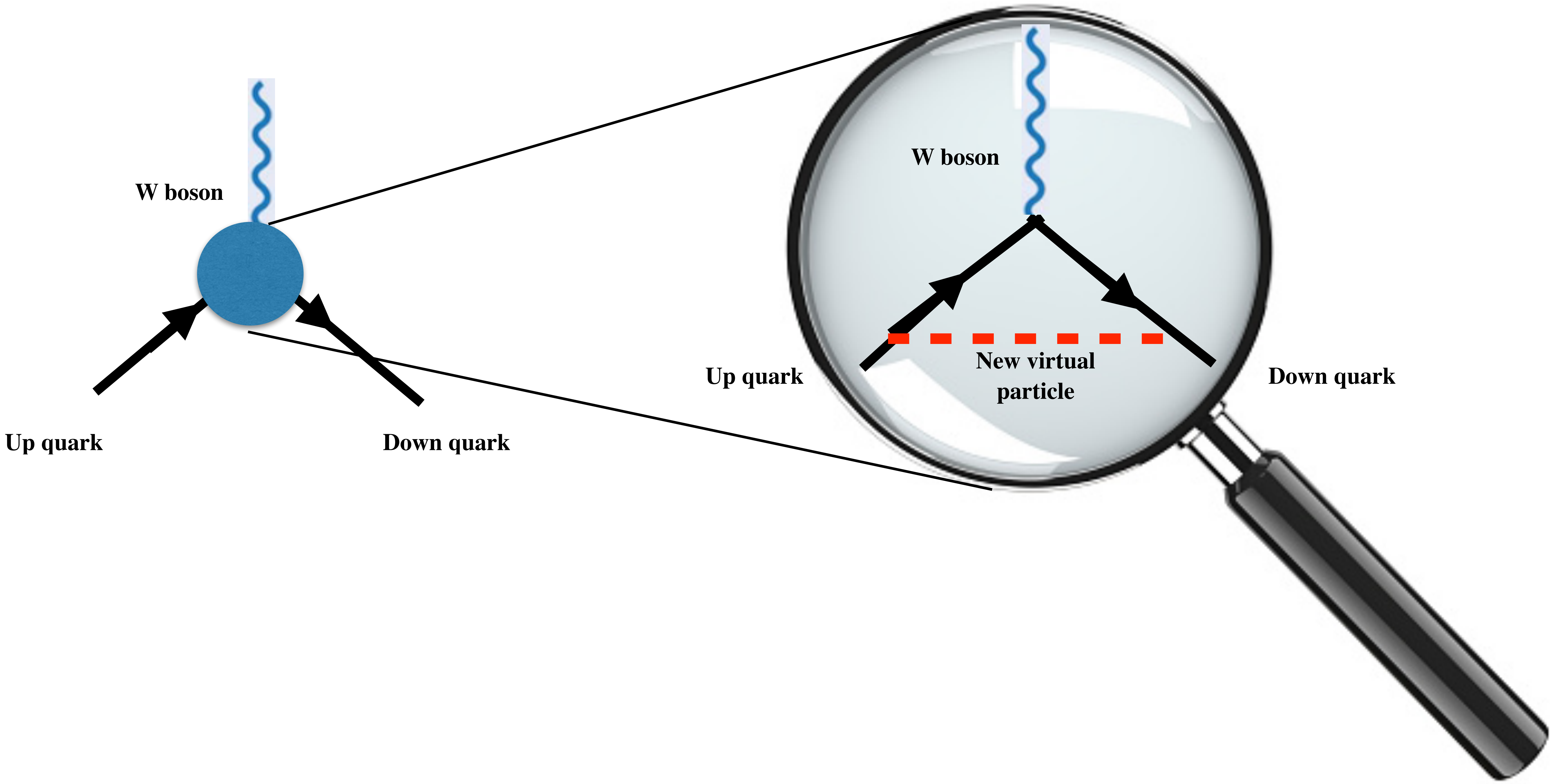




LHC: $pp \to e\nu + X$

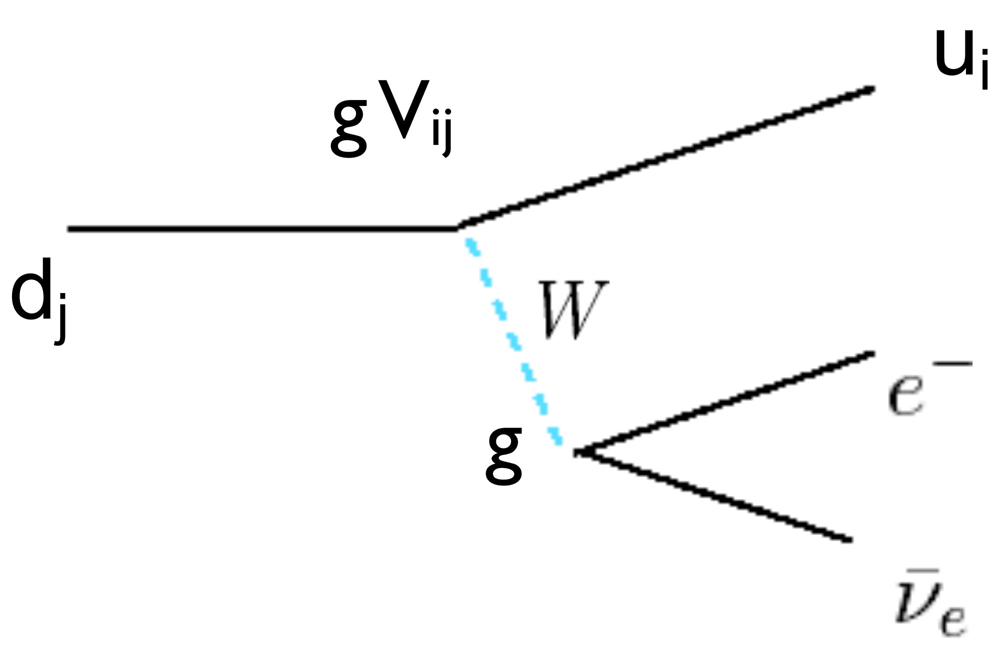


Precision tests with weak charged currents



Charged current at low energy: ‘β decays’

- In the SM, W exchange ⇒ only “V-A” + Cabibbo and 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)

Charged current at low energy: ‘β decays’

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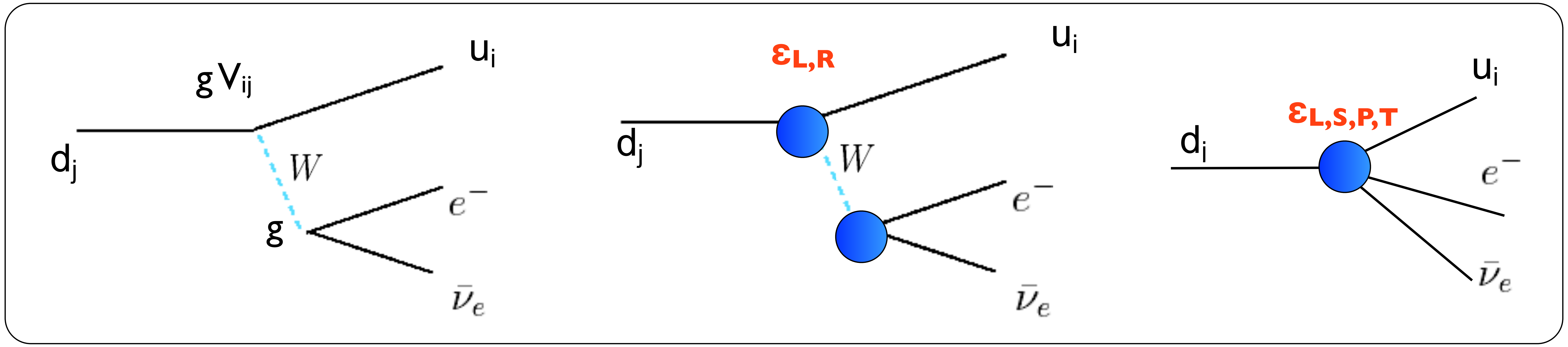


$\varepsilon_\Gamma \sim (v/\Lambda)^2$

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

- New physics can spoil universality. With current precision of 0.1-0.01% we can probe Λ > 10 TeV

~0..95 ~0.05 ~1.5 ×10^{-5}

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

$\delta V_{ud}/V_{ud} \sim 0.02\%$ $\delta V_{us}/V_{us} \sim 0.2\%$ $\delta V_{ub}/V_{ub} \sim 5\%$

$R_{e/\mu} = \Gamma(\pi \to e\nu)/\Gamma(\pi \to \mu\nu)$

$$R_{e/\mu}(\mathrm{SM}) = 1.23524(015) \times 10^{-4}$$ 0.01%

$$R_{e/\mu}(\mathrm{Exp}) = 1.23270(230) \times 10^{-4}$$ 0.18%

Cabibbo universality tests

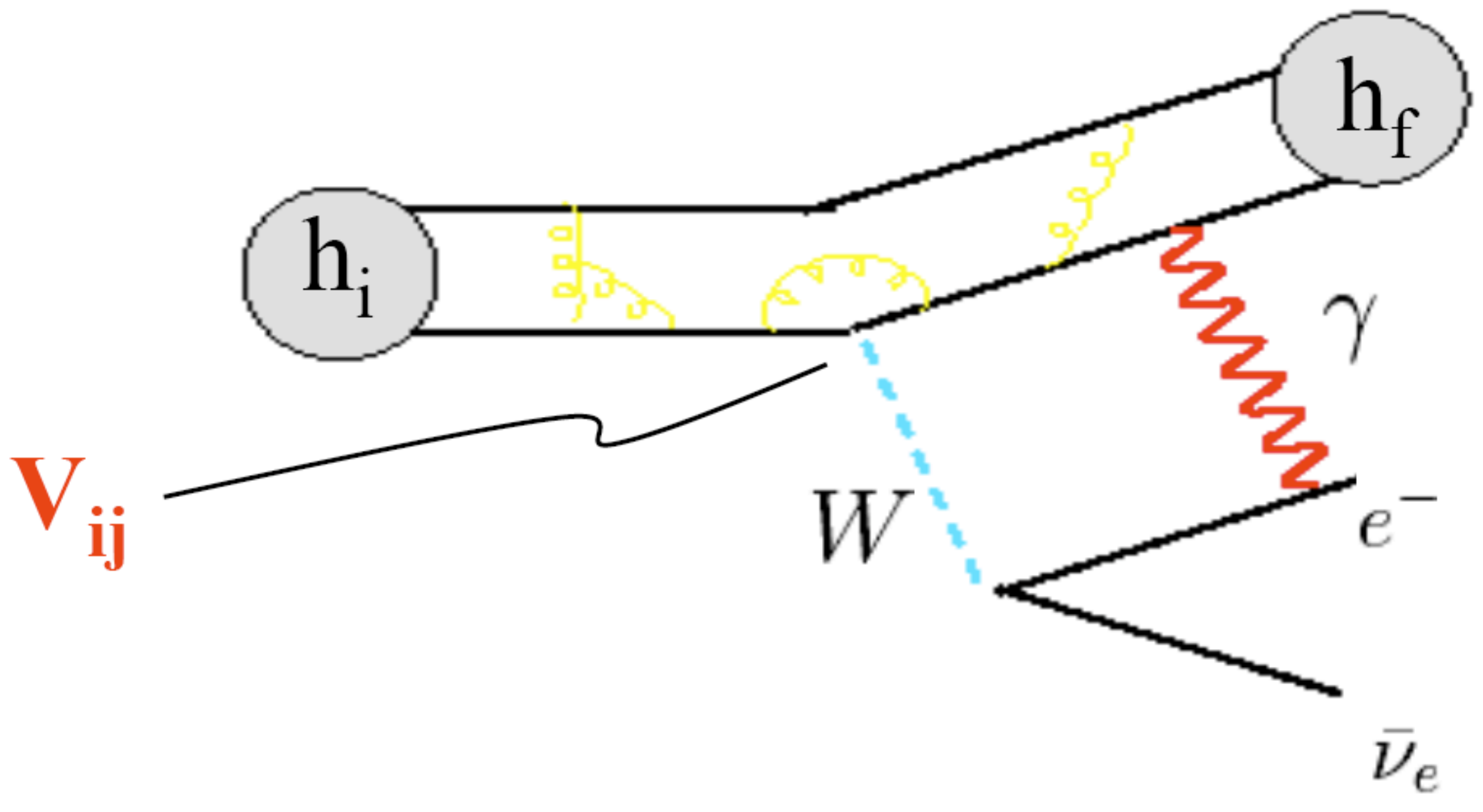
Extract $V_{ud} = \cos\theta_C$ and $V_{us} = \sin\theta_C$ from meson, neutron & nuclear decays

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

Channel-dependent effective CKM element

Hadronic matrix element

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



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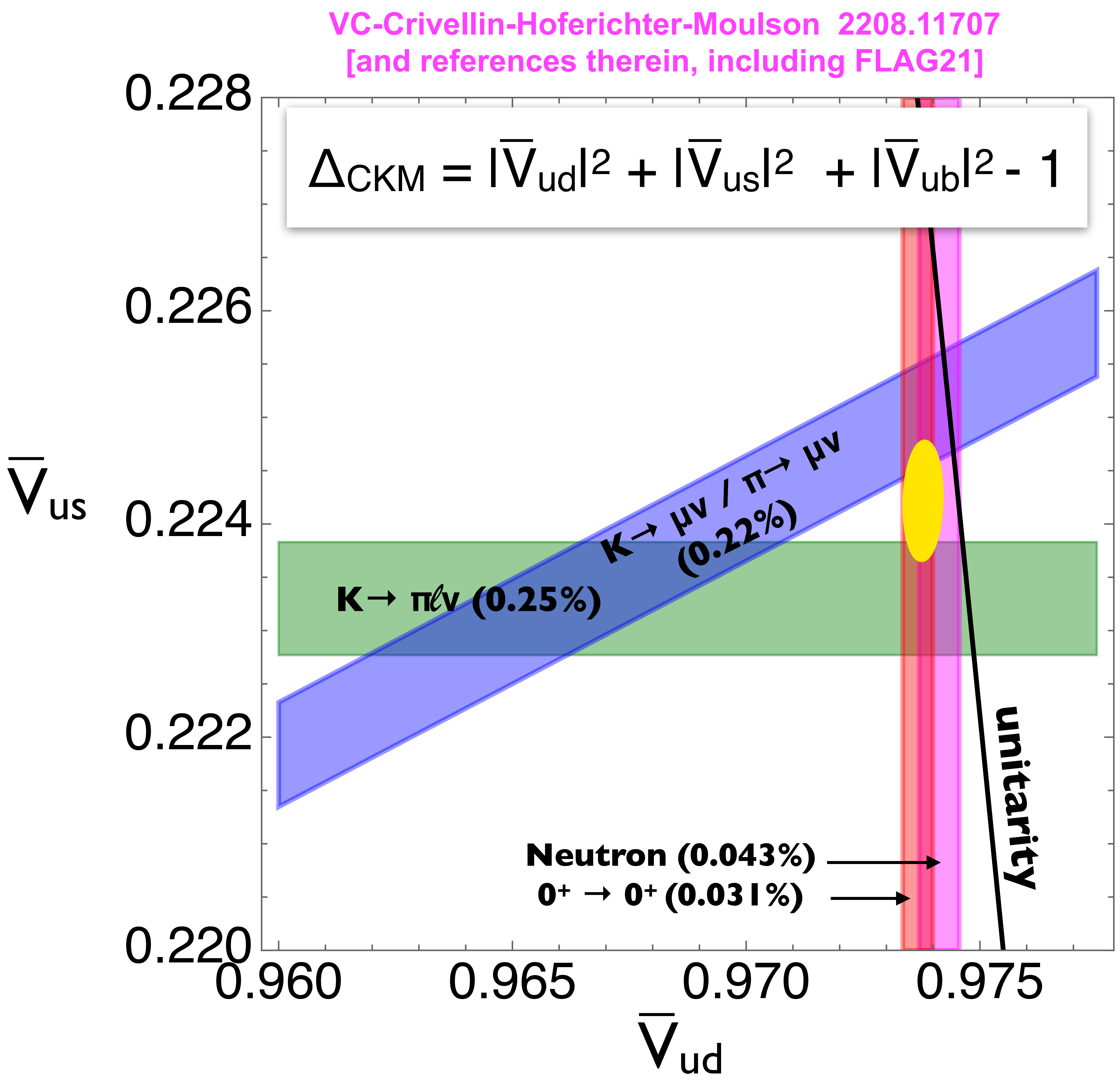
$$|\bar{V}_{ij}|^2 = |V_{ij}|^2 \times \left(1 + \sum_\alpha c_k^\alpha \, \epsilon_\alpha\right)$$

Calculable coefficients

BSM effective couplings

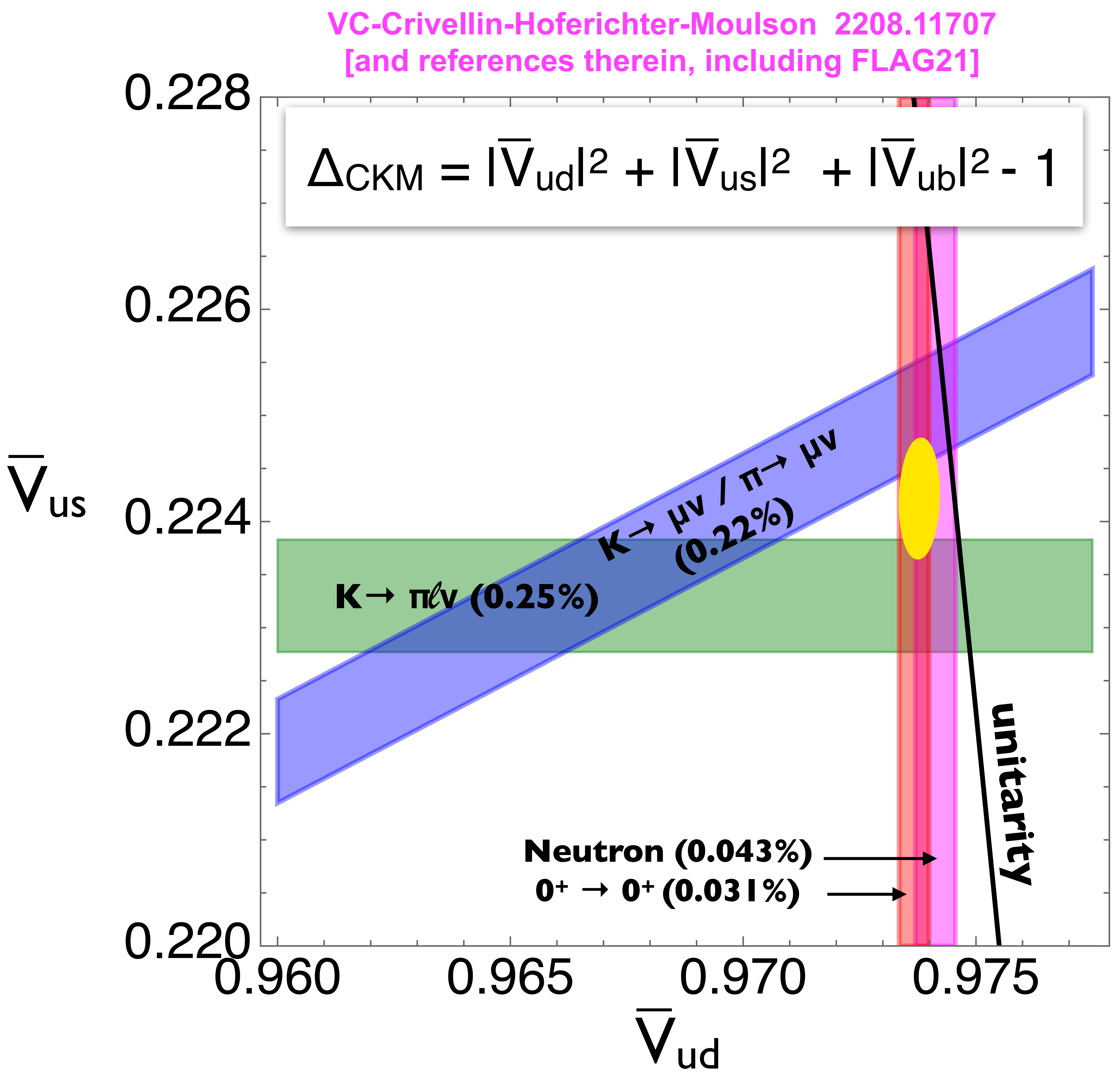
$$|\bar{V}_{ud}|^2 + |\bar{V}_{us}|^2 + |\bar{V}_{ub}|^2 = 1 + \Delta_{\rm CKM}(\epsilon_i)$$

The Cabibbo Angle Anomaly



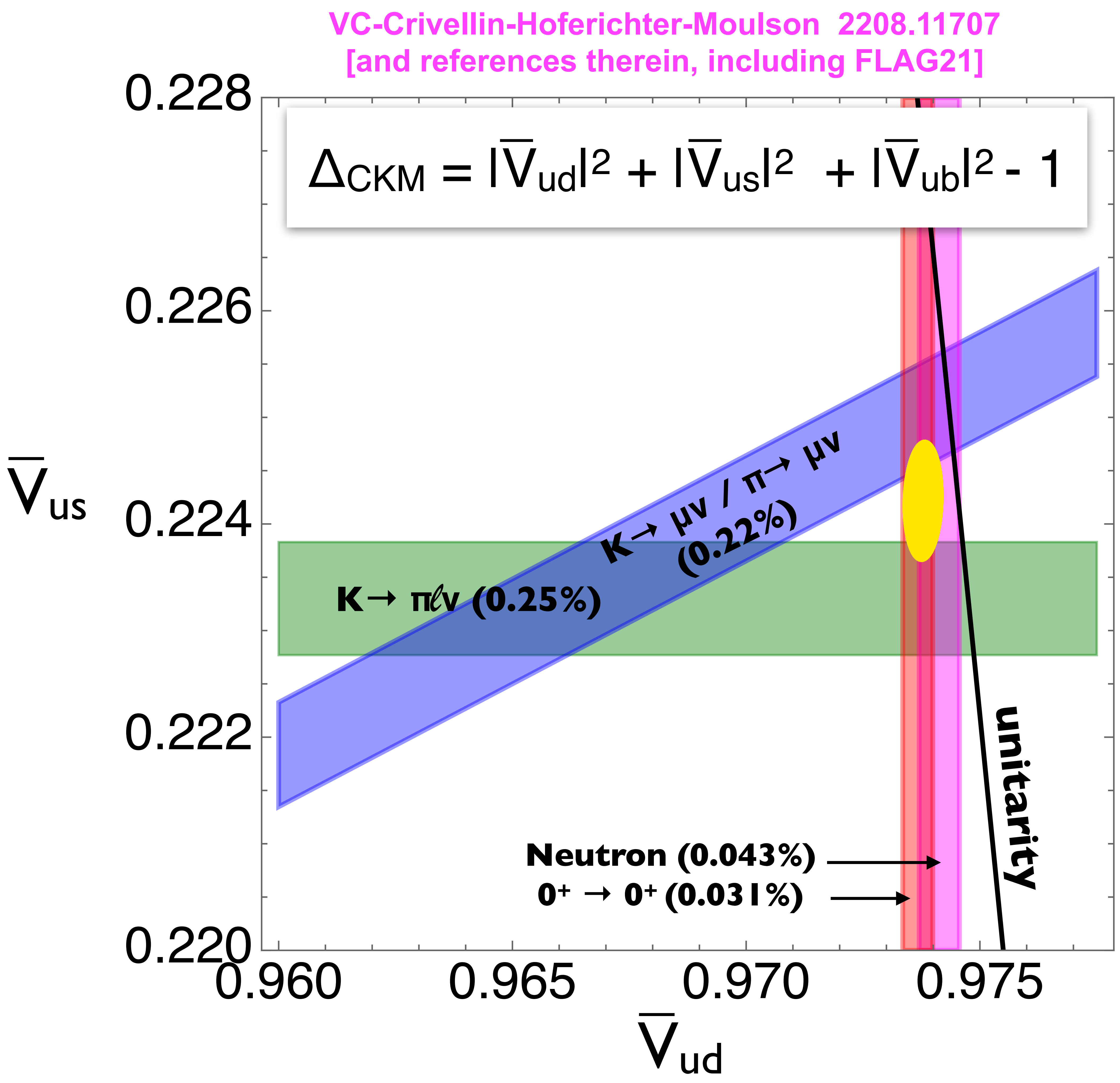
- Bands should intersect in a single region and that region should overlap with the unitarity circle
- ~3σ problem even in meson sector (Kl2 vs Kl3)
- ~3σ effect in global fit ($\Delta_{CKM} = -1.48(53) \times 10^{-3}$)

The Cabibbo Angle Anomaly



- Expected experimental improvement:
  - neutron decay (will match nominal nuclear uncertainty)
  - pion beta decay (6x to 10x at PIONEER phases II, III)
  - new $K_{\mu3}/K_{\mu2}$ BR measurement at NA62
- Expected theoretical scrutiny
  - Lattice: K→π vector f.f. and rad. corr. for Kl3
  - EFT for neutron and nuclei, with goal $\delta\Delta_{RC} \sim 2\times 10^{-4}$
  - Ab-initio nuclear structure calculations
  - ….
- Possible BSM explanations

The Cabibbo Angle Anomaly



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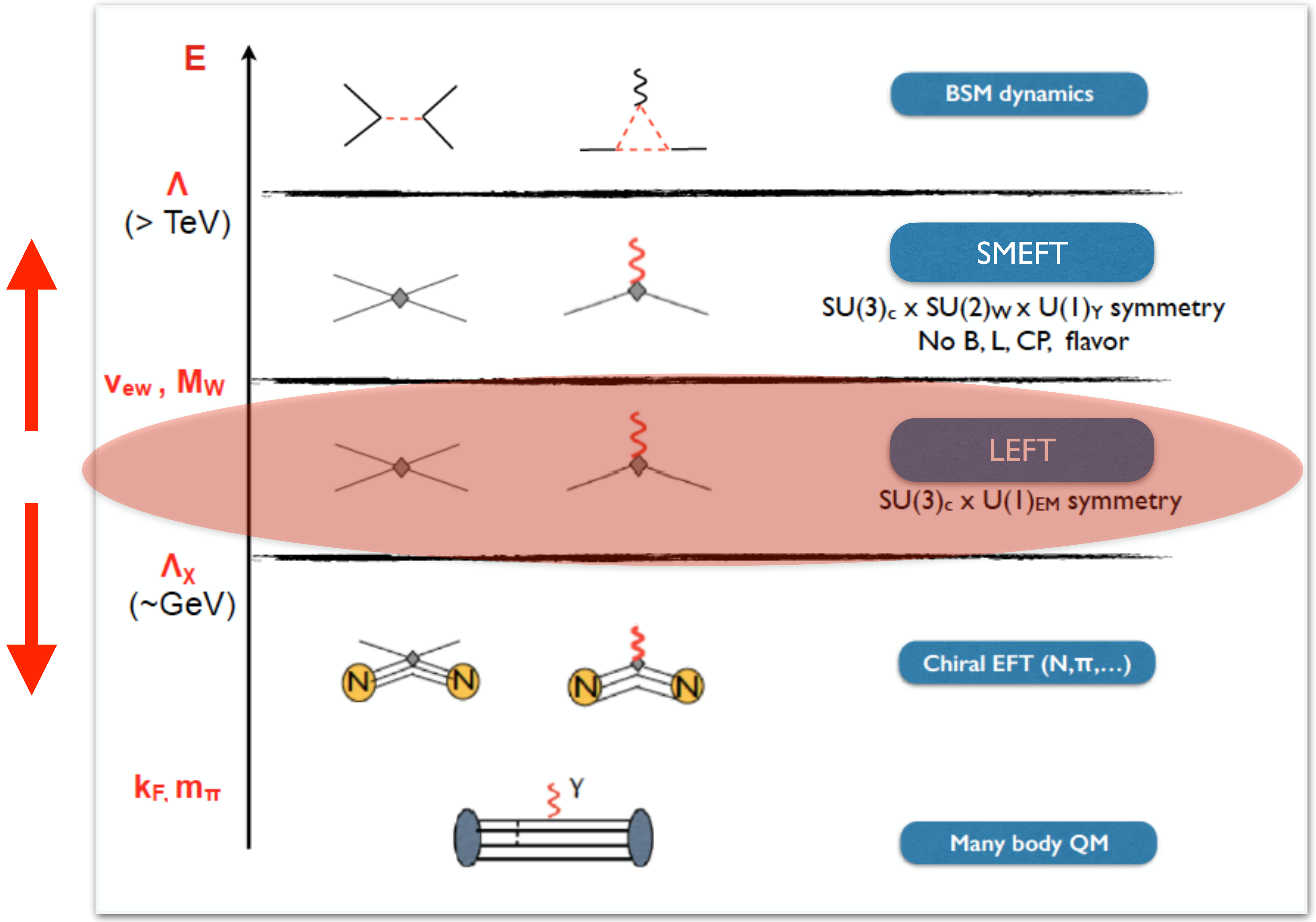
Will discuss in the SMEFT framework

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 effective Lagrangian

GeV-scale effective Lagrangian (LEFT)

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

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

$D = d, s$

$\ell = e, \mu$

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

GeV-scale effective Lagrangian (LEFT)

VC, Gonzalez-Alonso, Jenkins 0908.1754, NPB

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

Semi-leptonic interactions

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

$D = d, s$

$\ell = e, \mu$

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

Corrections to V_{ud} and V_{us}

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

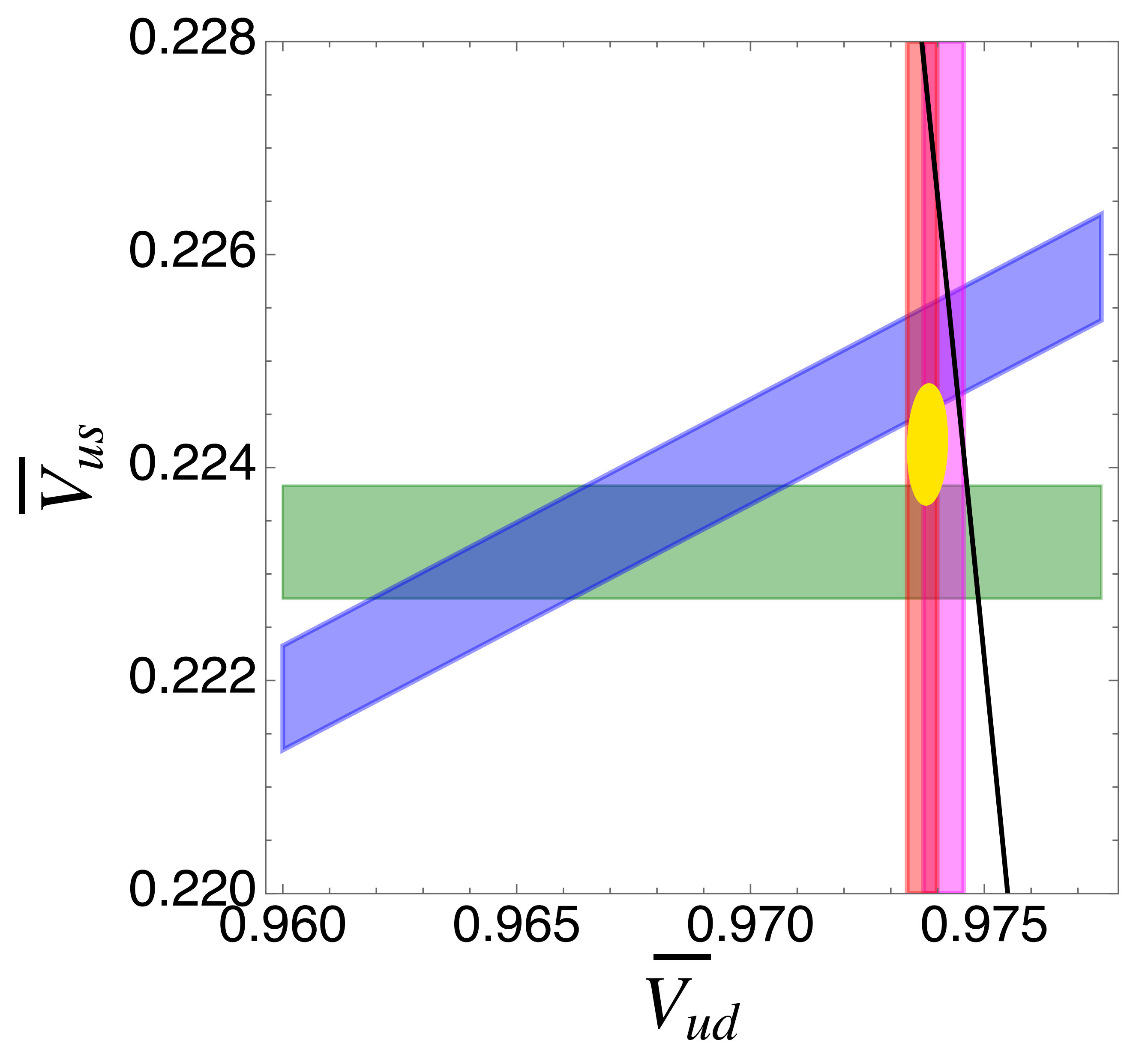
$$|\bar{V}_{us}|_j^2 = |V_{us}|^2 \left(1 + \sum_\alpha C_{j\alpha}\epsilon_\alpha\right)$$

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

Elements of the unitary CKM matrix

Known coefficients

BSM effective coupligs



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

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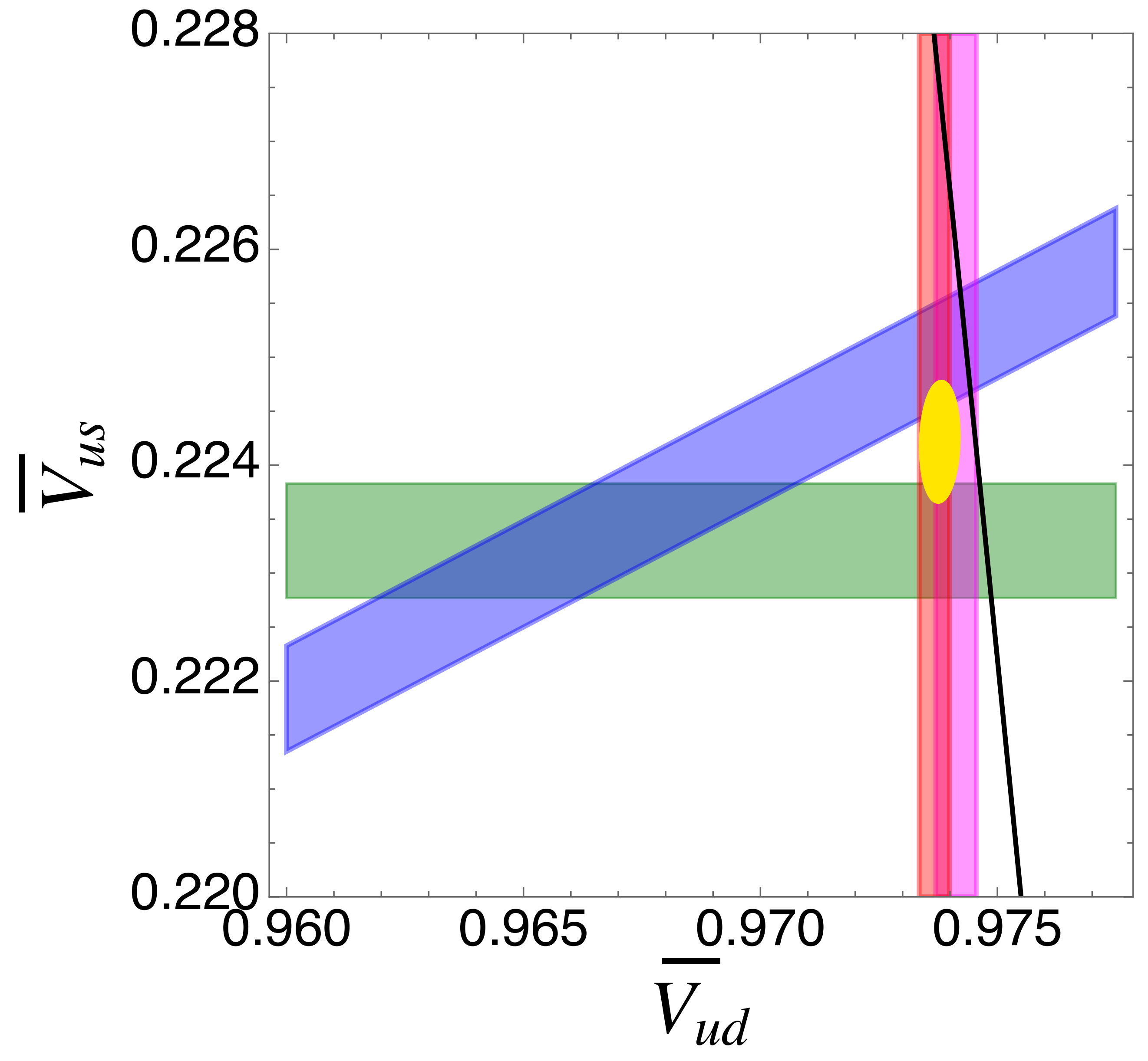


Find set of ε's so that V_{ud} and V_{us} bands meet on the unitarity circle

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

Right-handed quark couplings

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

Alioli et al 1703.04751
Grossman-Passemar-Schacht 1911.07821
VC-Crivellin-Hoferichter-Moulson 2208.11707
VC, W. Dekens, J. De Vries, E. Mereghetti, T. Tong, 2311.00021

$$|\bar{V}_{ud}|^2_{0^+\to 0^+} = |V_{ud}|^2 \left(1 + 2\,\epsilon_R^d\right)$$

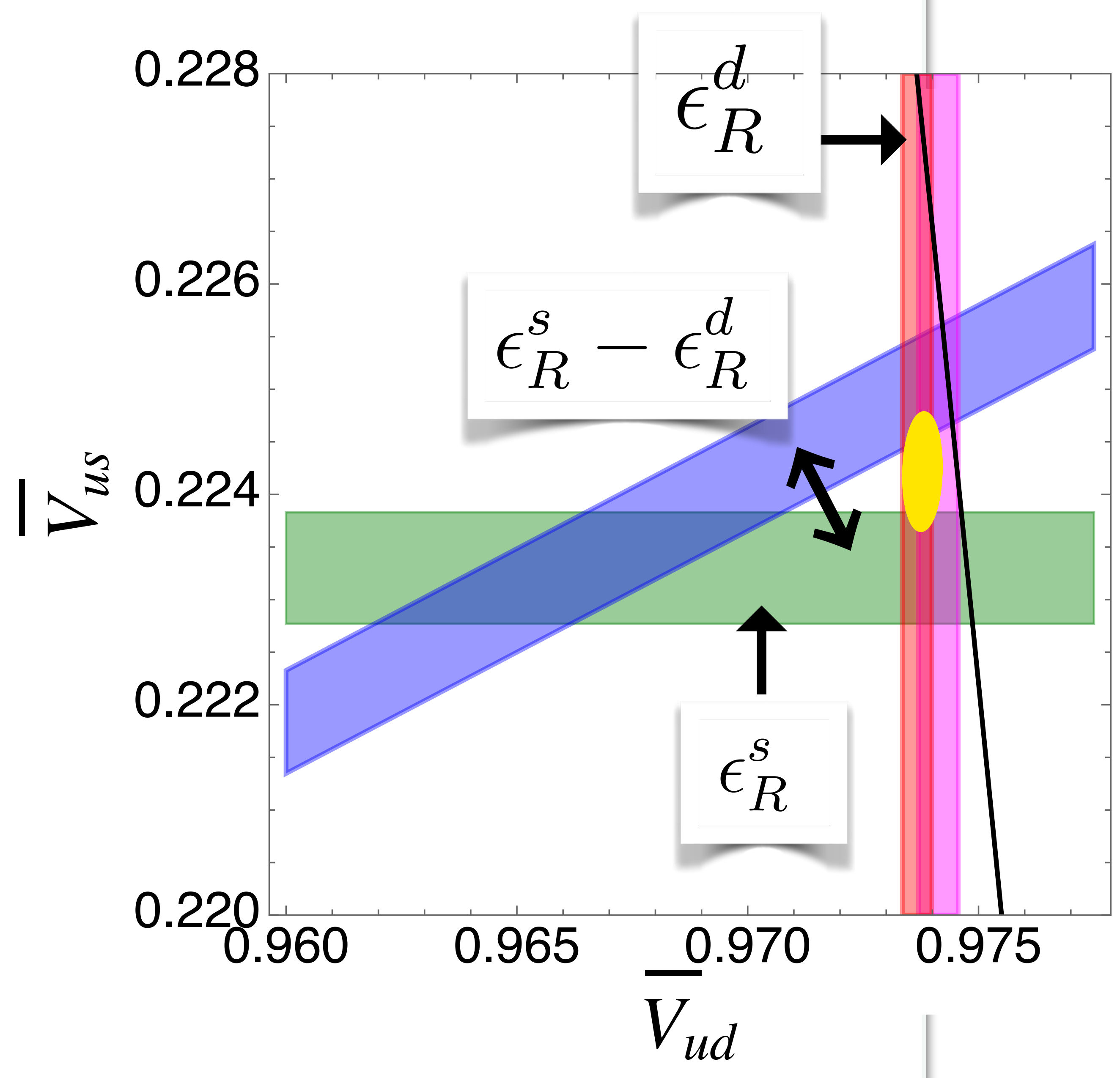
$$|\bar{V}_{ud}|^2_{n\to pe\bar{\nu}} = |V_{ud}|^2 \left(1 + 2\,\epsilon_R^d\right)$$

$$|\bar{V}_{us}|^2_{Ke3} = |V_{us}|^2 \left(1 + 2\,\epsilon_R^s\right)$$

$$|\bar{V}_{ud}|^2_{\pi e3} = |V_{ud}|^2 \left(1 + 2\,\epsilon_R^d\right)$$

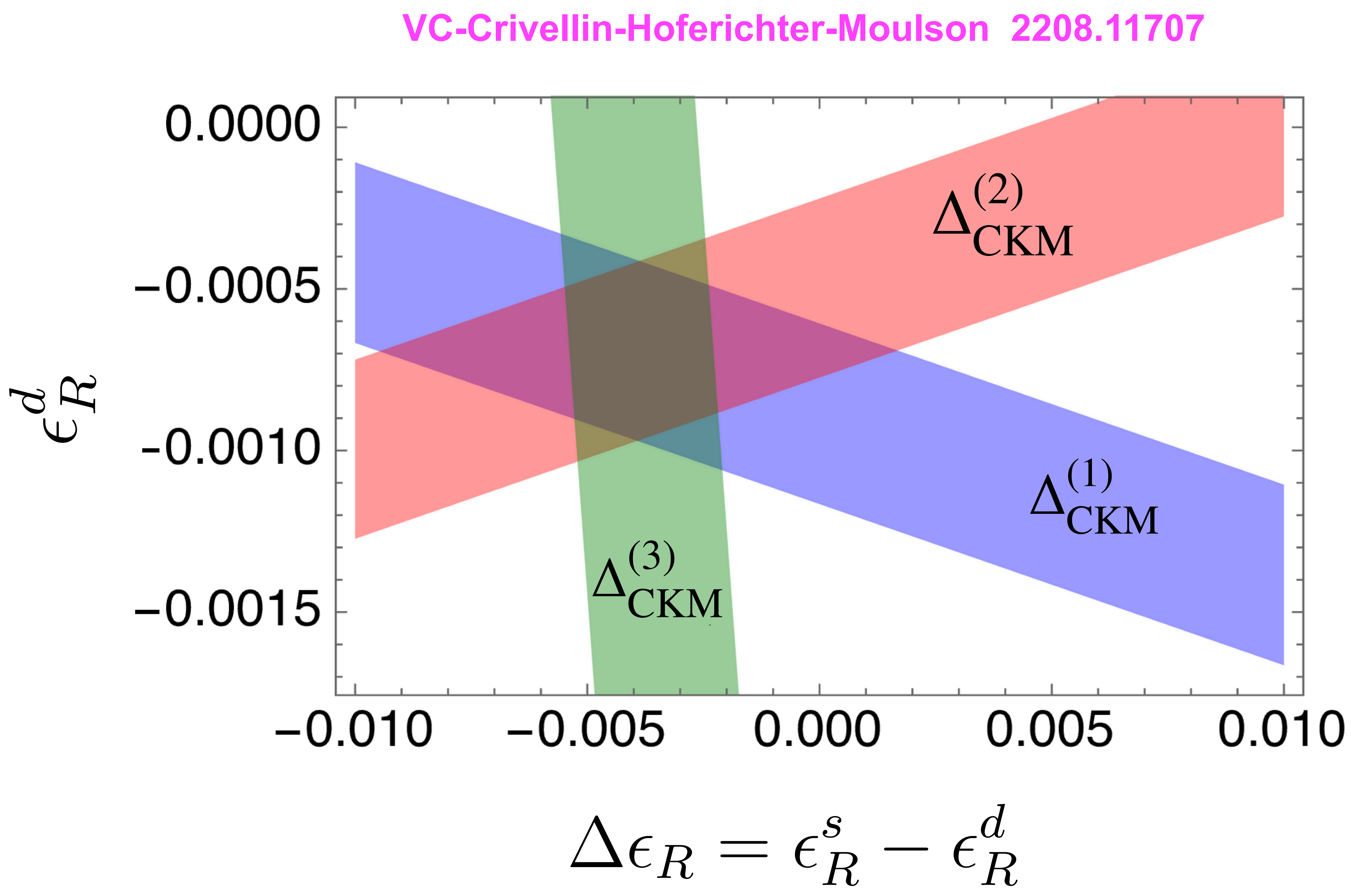
$$|\bar{V}_{us}|^2_{K\mu 2} = |V_{us}|^2 \left(1 - 2\,\epsilon_R^s\right)$$

$$|\bar{V}_{ud}|^2_{\pi\mu 2} = |V_{ud}|^2 \left(1 - 2\,\epsilon_R^d\right)$$



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

Unveiling R-handed quark currents?



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

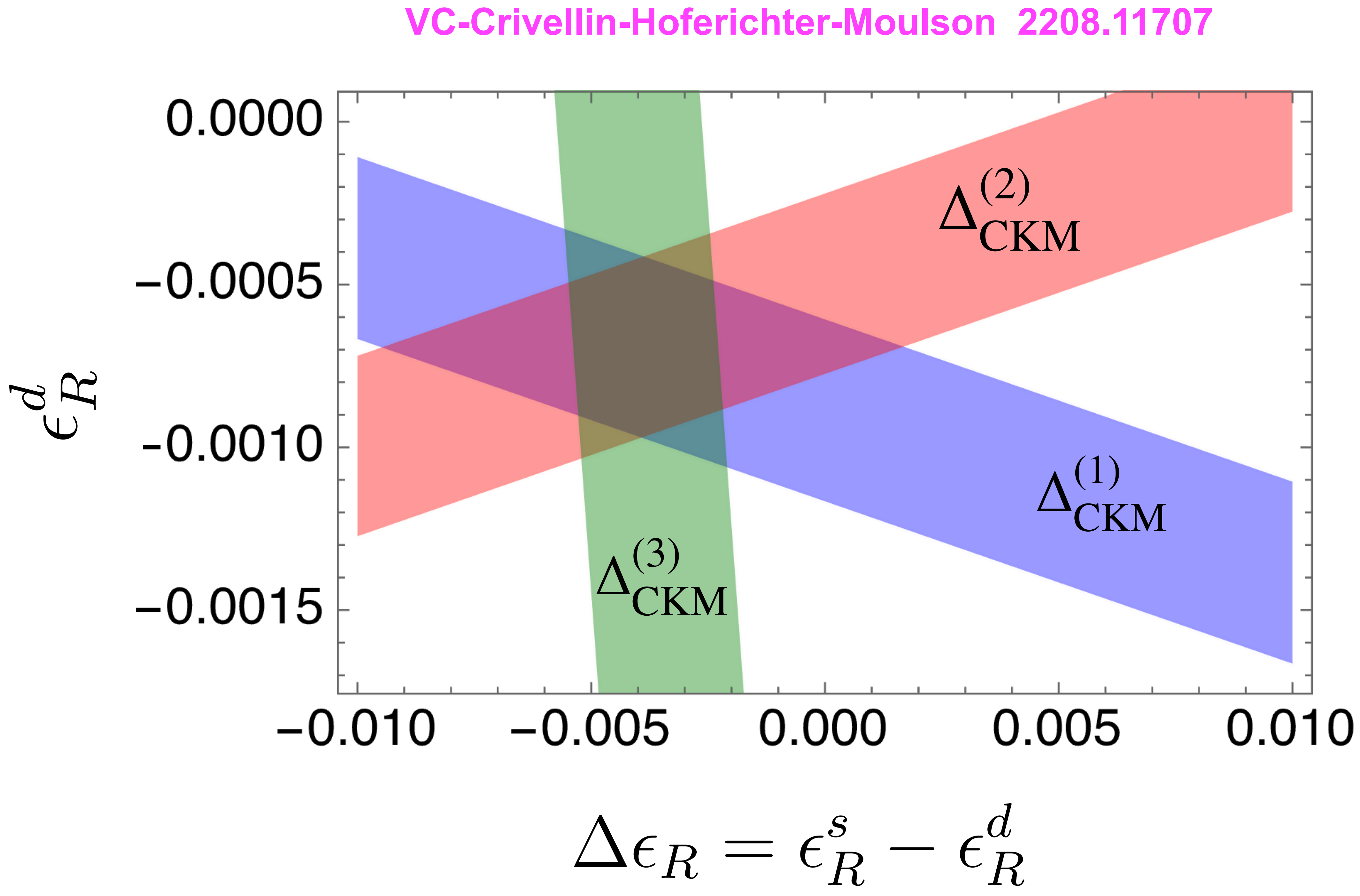
↓

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

Λ_R ~5-10 TeV

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

Unveiling R-handed quark currents?



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

↓

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

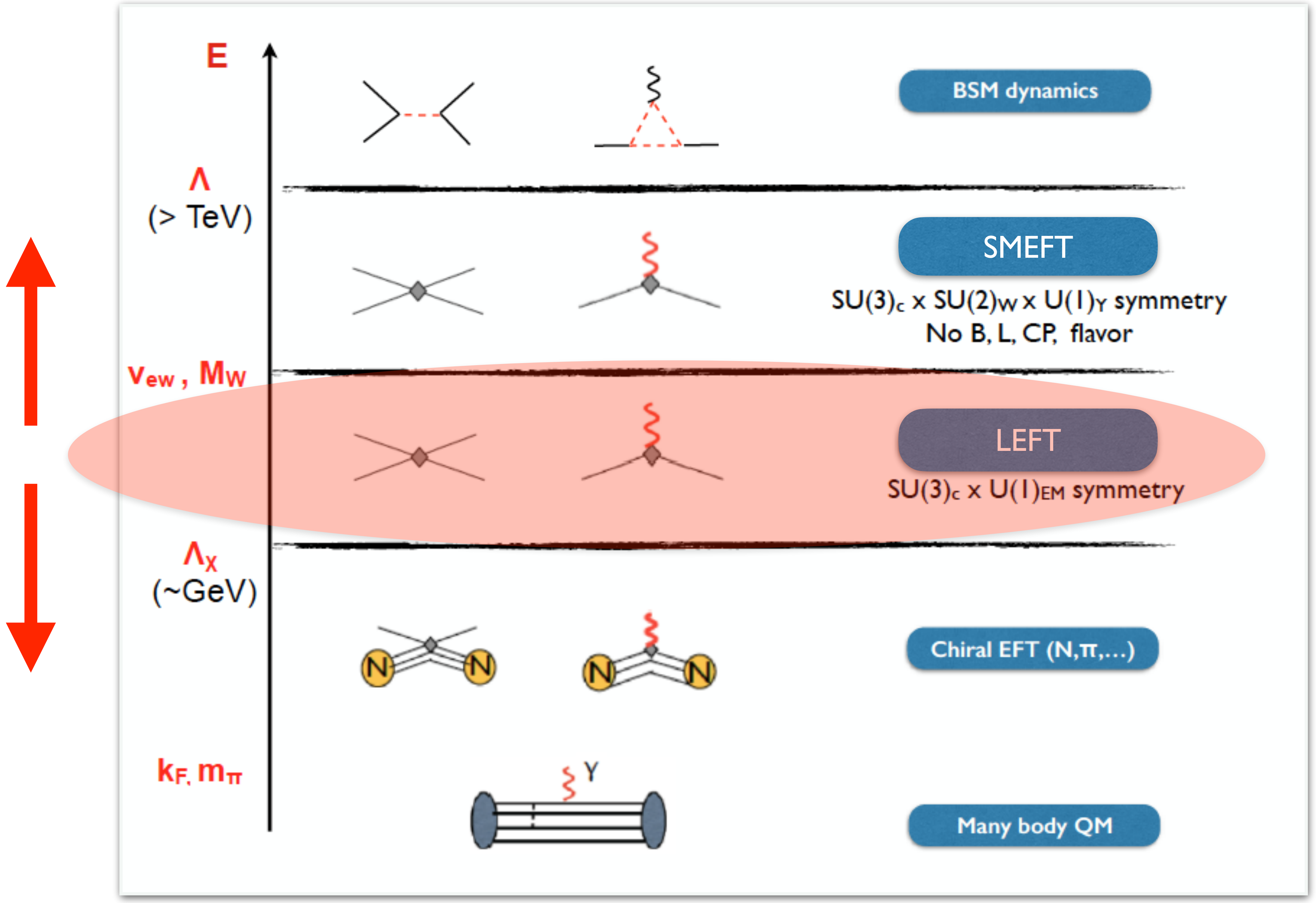
$$
\Delta\epsilon_R = -3.9(1.6) \times 10^{-3}
$$

Λ_R ~5-10 TeV

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

Connecting scales & processes (2)

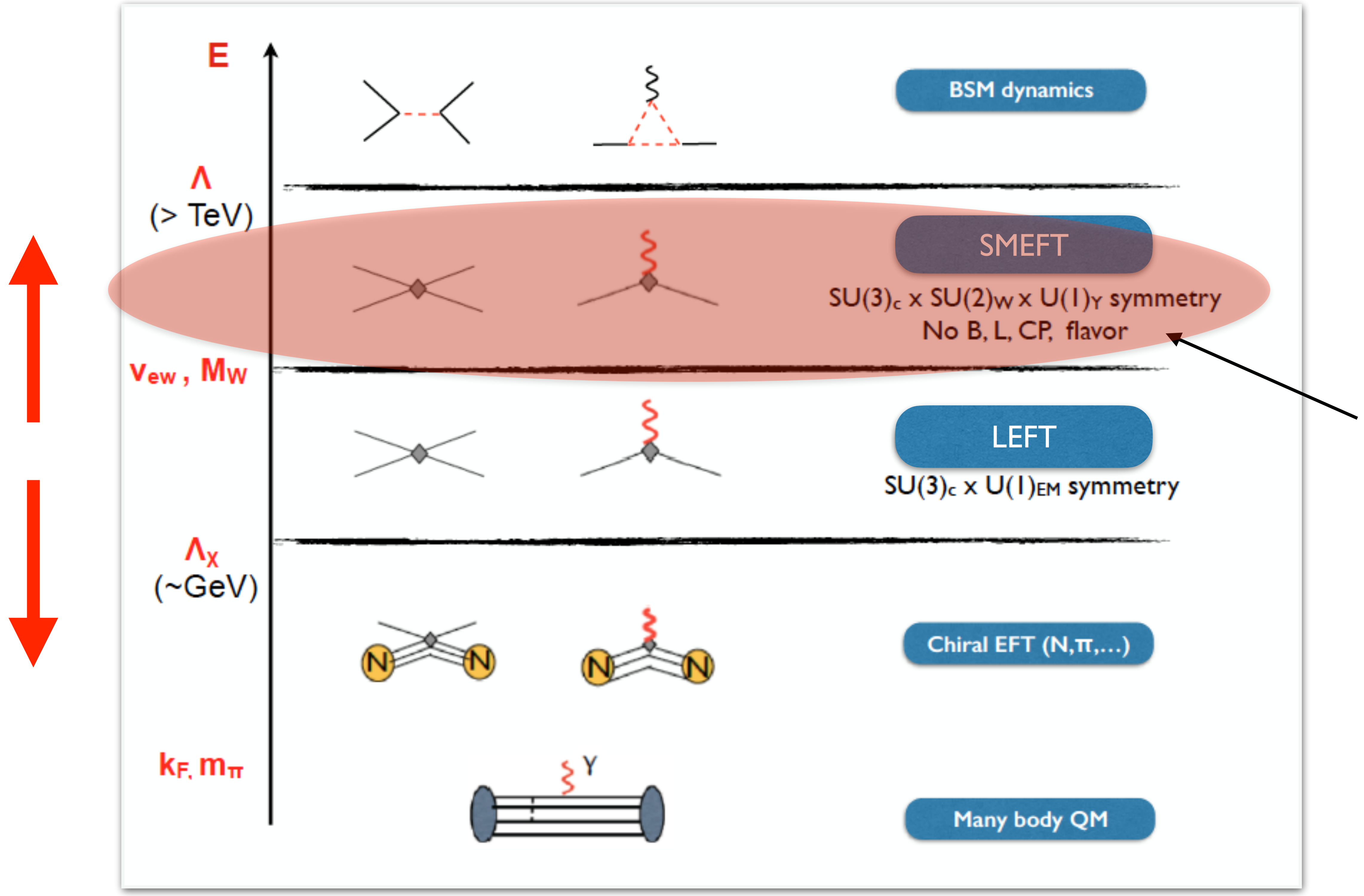
To connect UV physics to beta decays, use EFT



- 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
- Tree-level LEFT-SMEFT (dim-6) matching at scale μ_W ~ 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

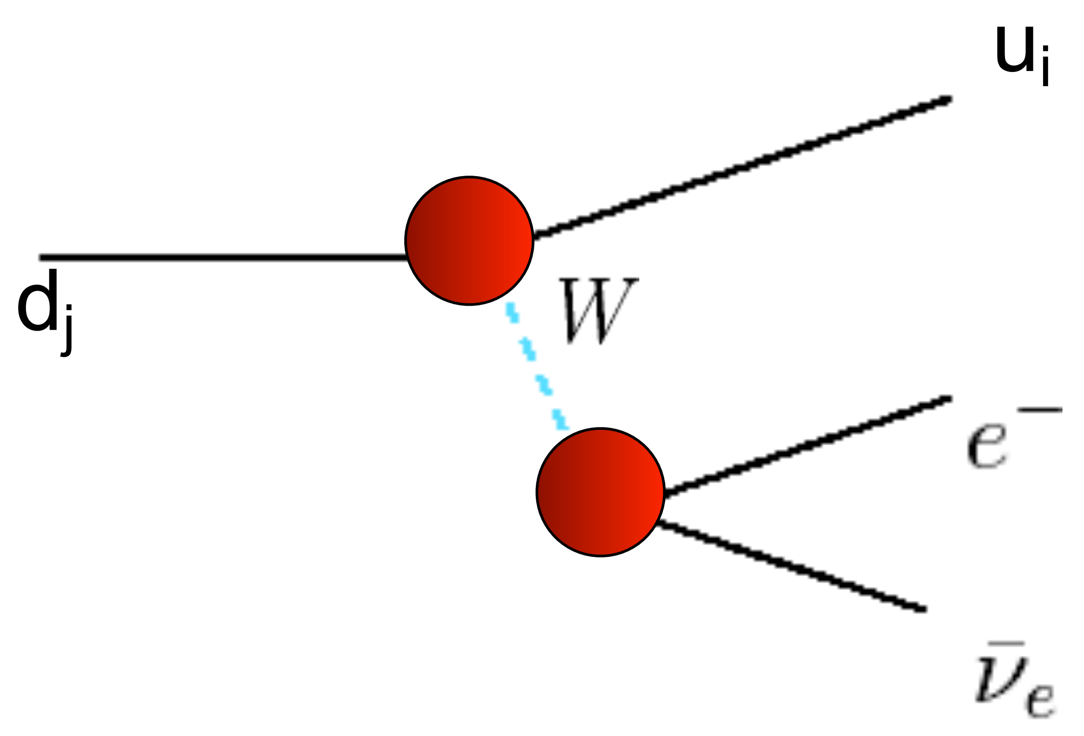
M. Dawid, VC, W. Dekens 2402.06723

- One loop SMEFT-LEFT matching also known

W. Dekens, P, Stoffer 1908.05295

Weak scale effective Lagrangian (SMEFT)

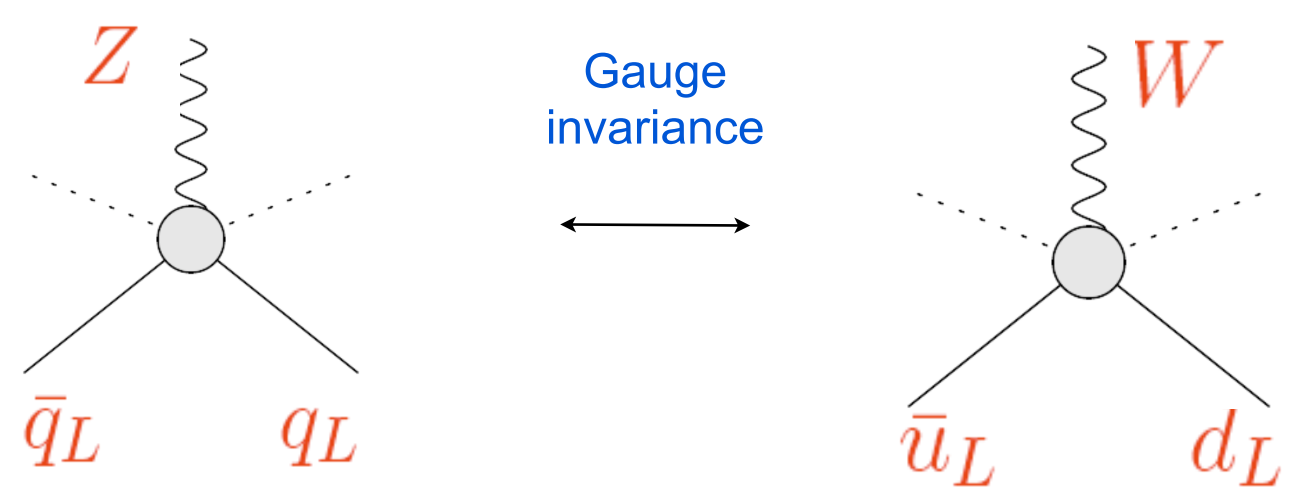
$\varepsilon_{L,R}$ originate from SU(2)xU(1) invariant vertex corrections



Building blocks

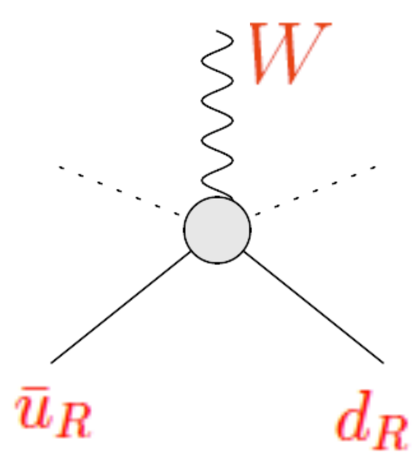
$$l^i = \begin{pmatrix} \nu_L^i \\ e_L^i \end{pmatrix} \quad q^i = \begin{pmatrix} u_L^i \\ d_L^i \end{pmatrix} \quad H = \begin{pmatrix} \varphi^+ \\ \varphi^0 \end{pmatrix}$$

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



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

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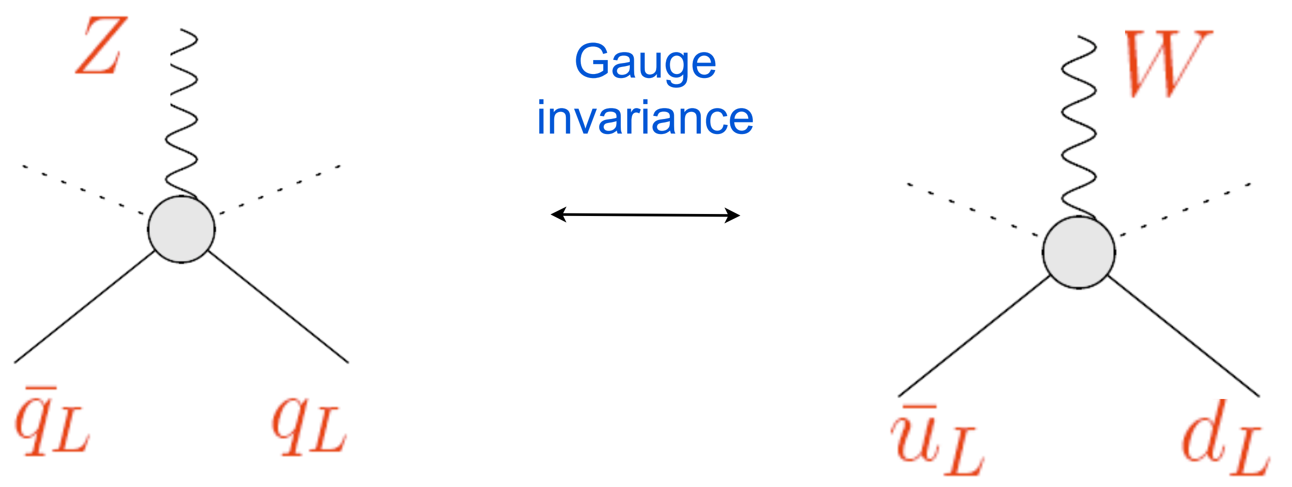
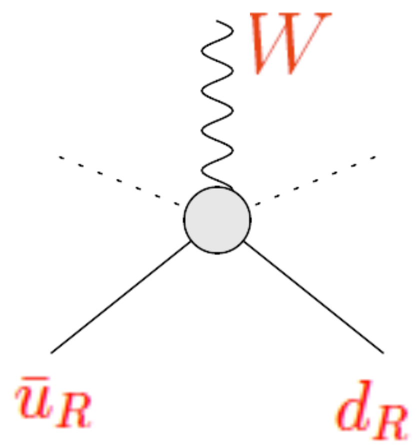


ε_L

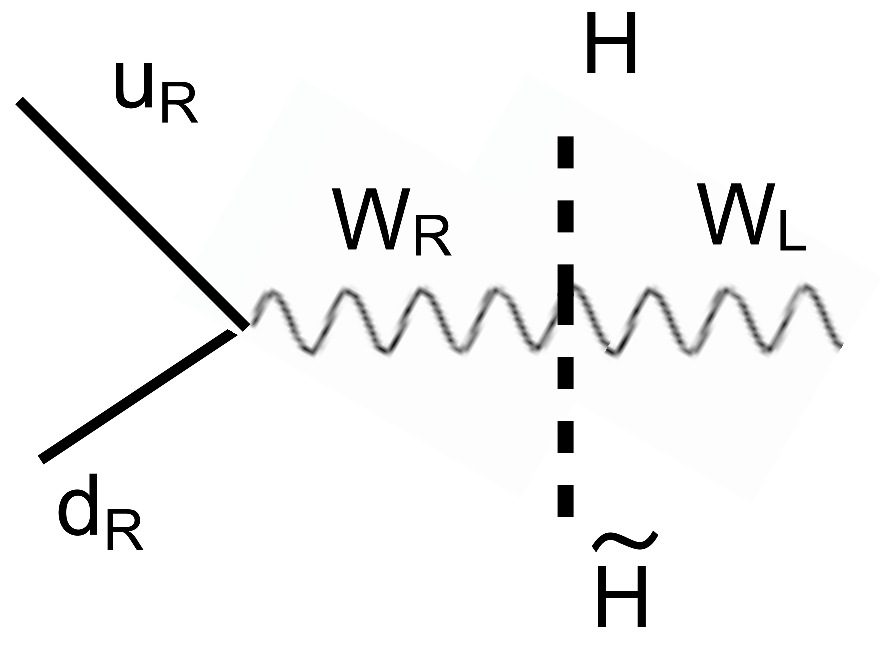
$$Q_{Hud} = i(\widetilde{H}^\dagger D_\mu H)(\bar{u}_p \gamma^\mu d_r)$$



ε_R

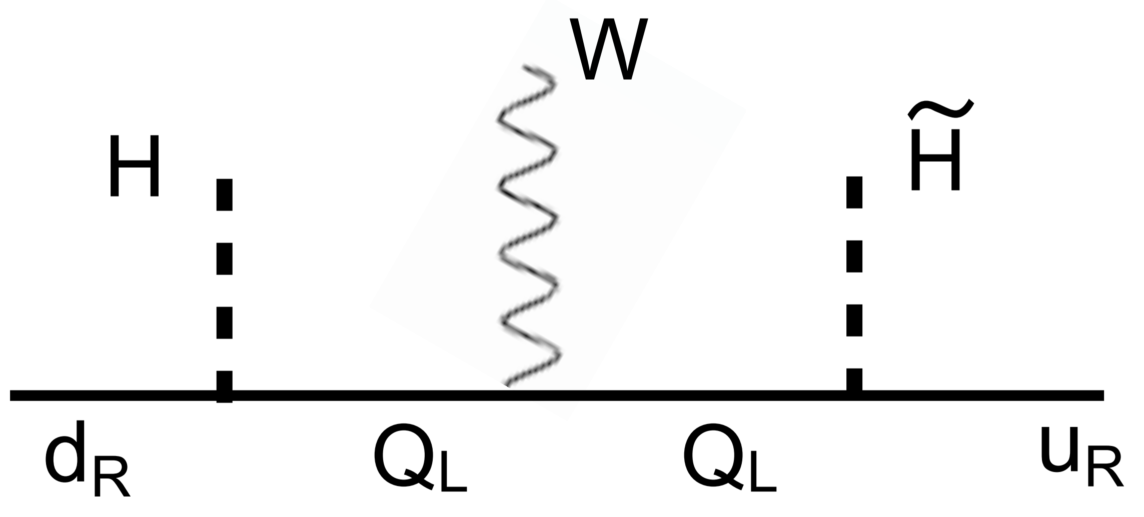
W_L-W_R mixing in LRSM

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



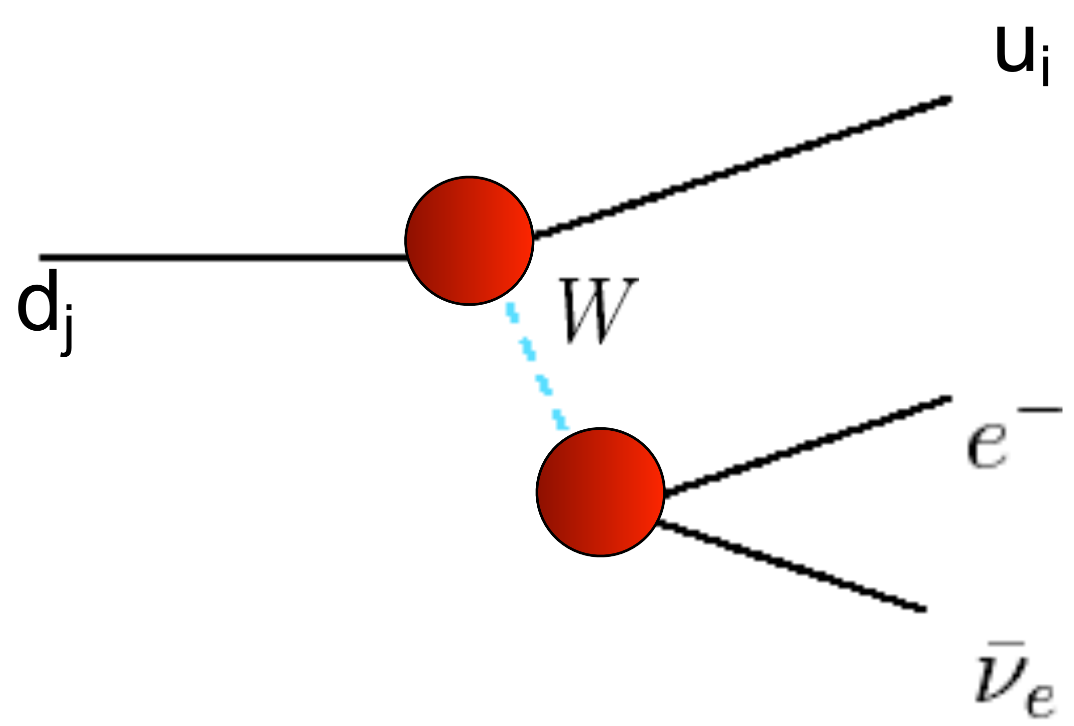
Vector-like quarks

Belfatto-Berezhiani 2103.05549. …
Belfatto-Trifinopoulos 2302.14097



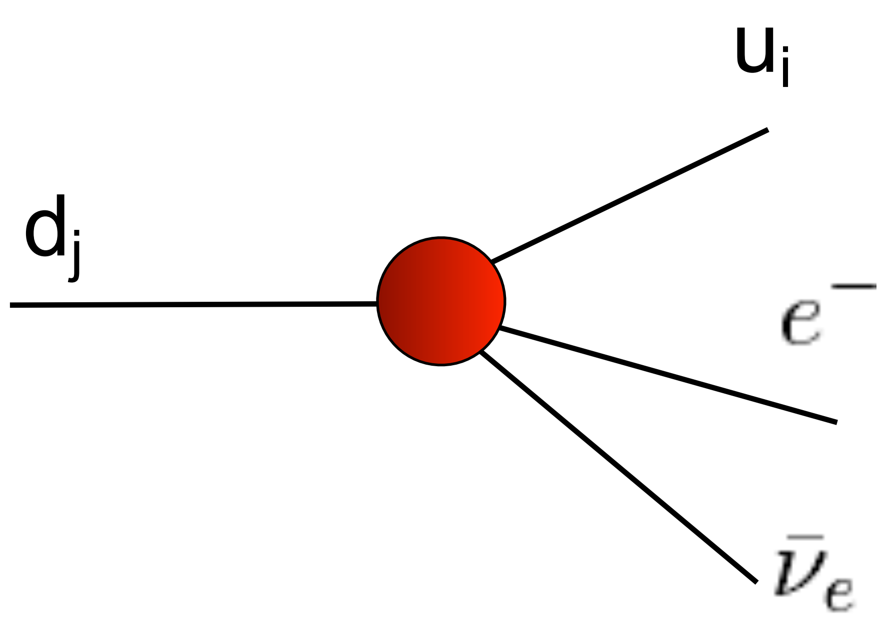
Weak scale effective Lagrangian (SMEFT)

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



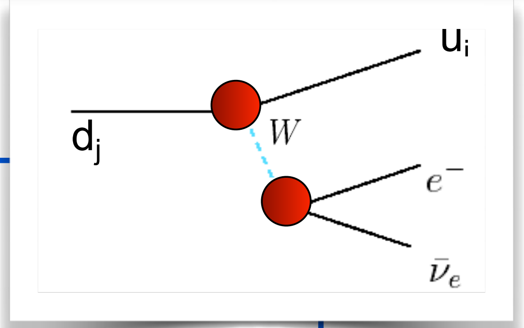
$$
\begin{aligned}
Q_{Hud} &= i(\widetilde{H}^\dagger D_\mu H)(\bar{u}_p \gamma^\mu d_r) && \varepsilon_R \\
Q_{Hq}^{(3)} &= (H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar{q}_p \tau^I \gamma^\mu q_r) && \varepsilon_L \\
Q_{Hl}^{(3)} &= (H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar{l}_p \tau^I \gamma^\mu l_r) && \varepsilon_L
\end{aligned}
$$

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



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

High Energy constraints



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

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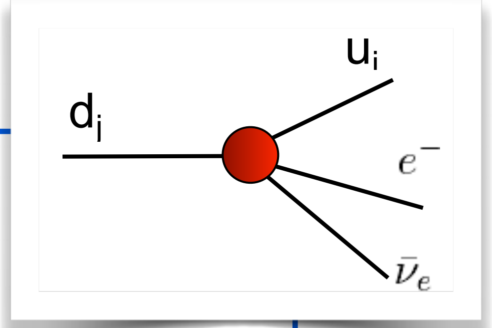

$\varepsilon_{S,P}$ $$Q_{ledq} = (\bar{\ell} e)(\bar{d} q) + \text{h.c.}$$

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

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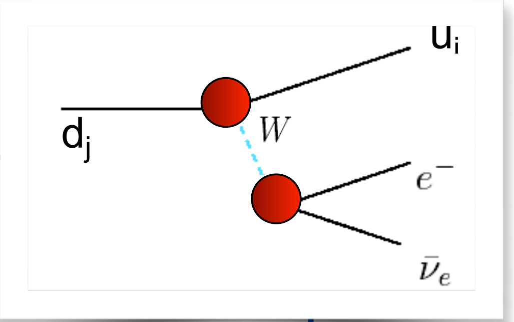
High Energy constraints



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

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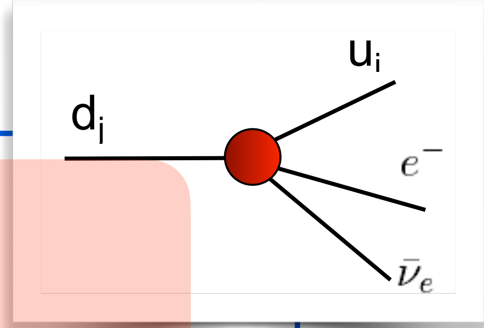

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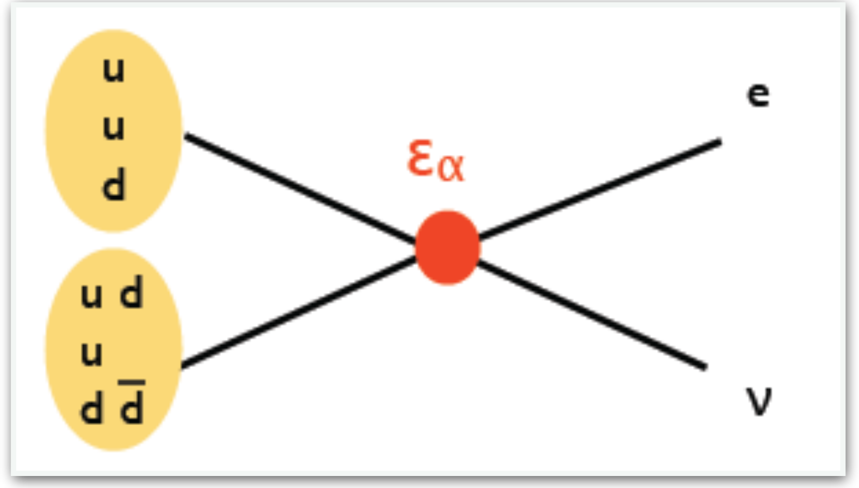
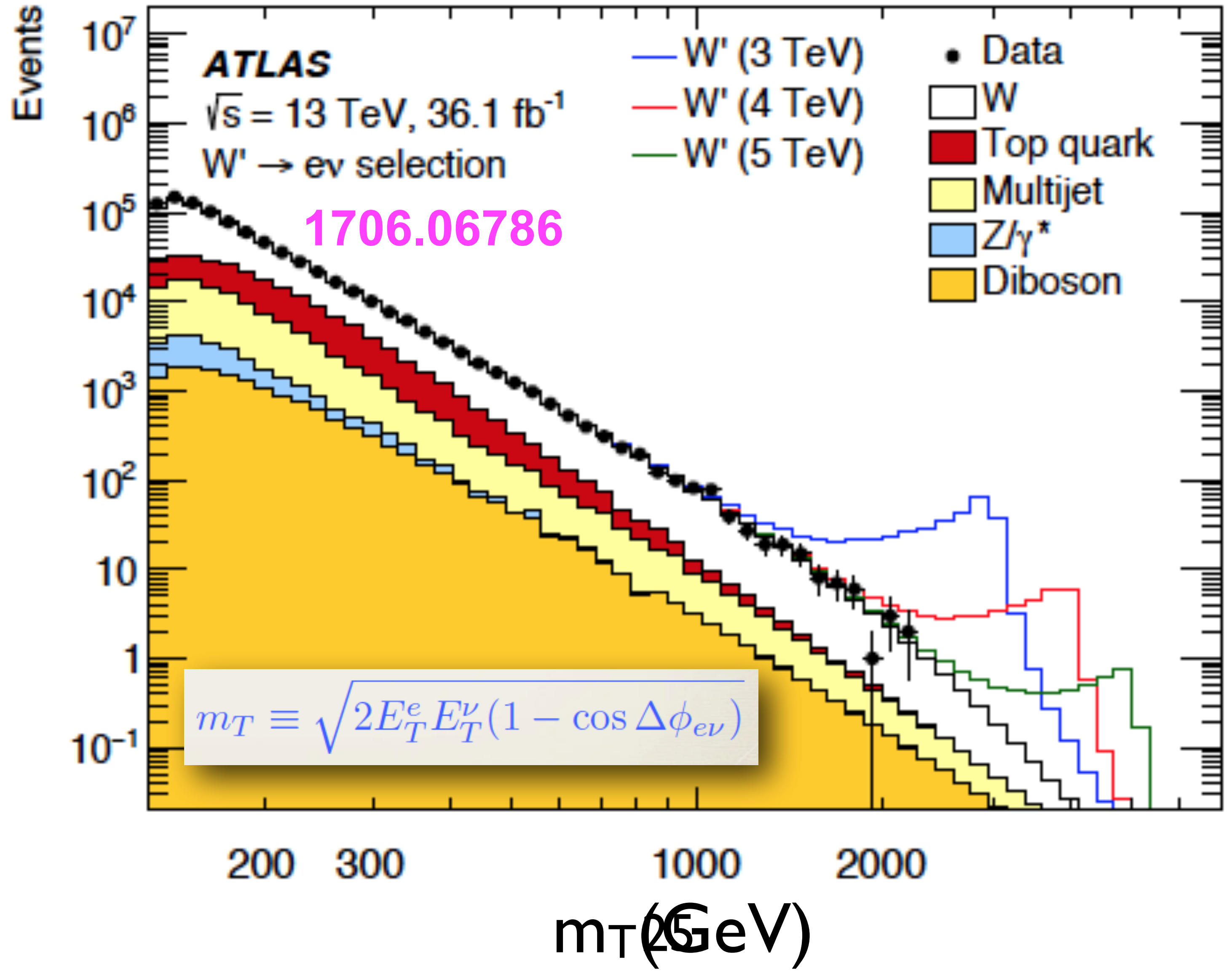
Contribute tp pp → eν+X and pp → e⁺e⁻ +X at the LHC

LHC: pp → eν + X

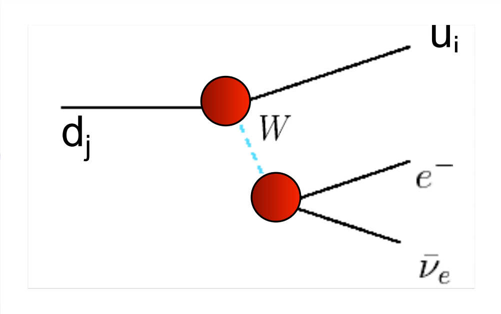




$\varepsilon_\alpha \sim 10^{-3}$ - 10^{-4}

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

High Energy constraints



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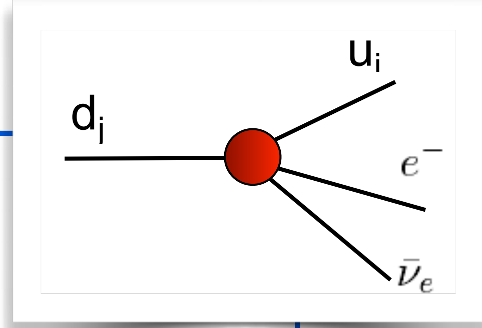

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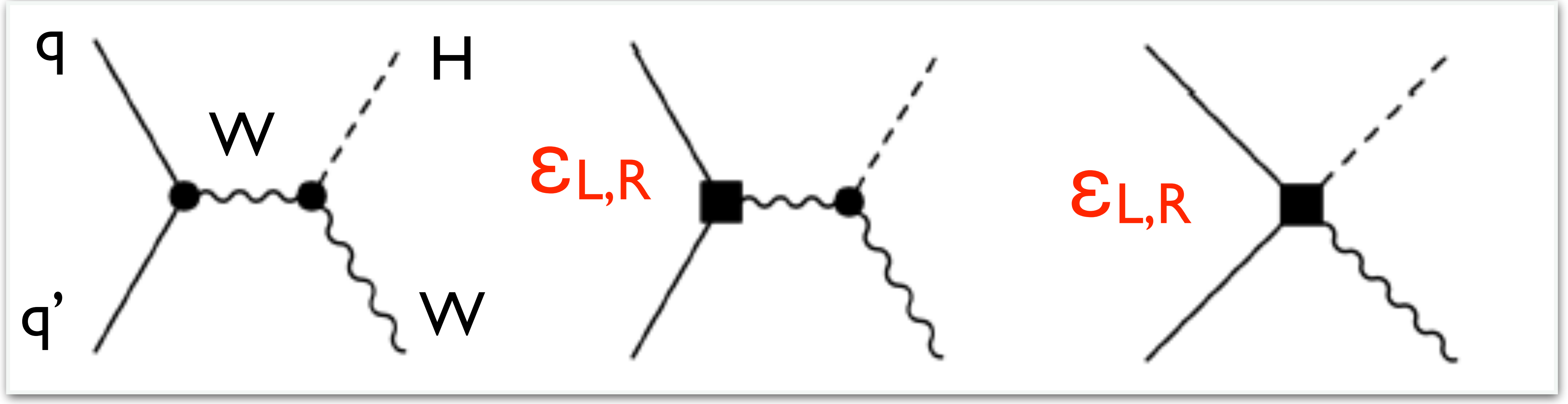
ε_L $$Q_{ll} = \bar{l}\gamma_\mu l \; \bar{l}\gamma^\mu l$$

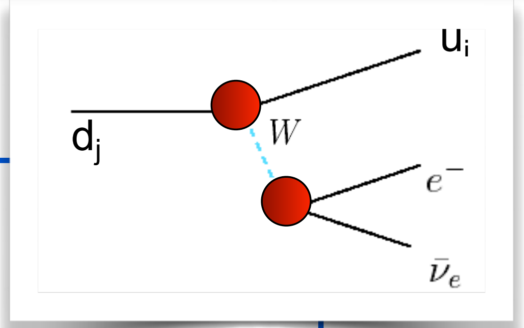
Can be probed at the LHC by associated Higgs + W production



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

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

High Energy constraints



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

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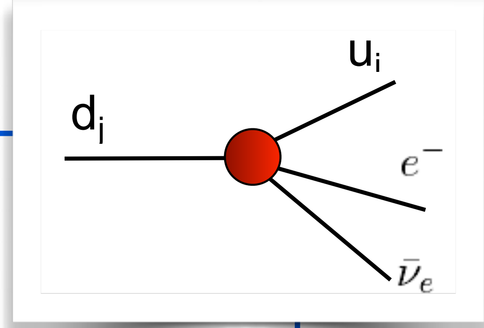

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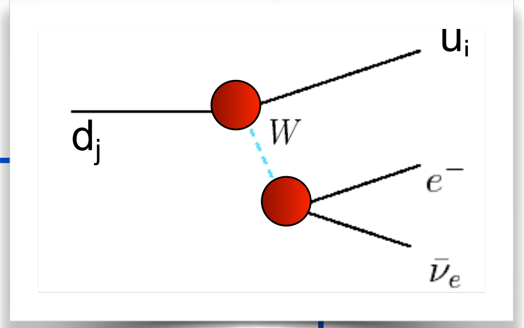
Contribute to Z-pole and other precision electroweak (EW) observables, including** M_W

High Energy constraints



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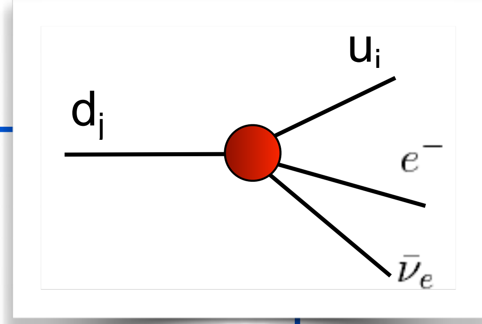

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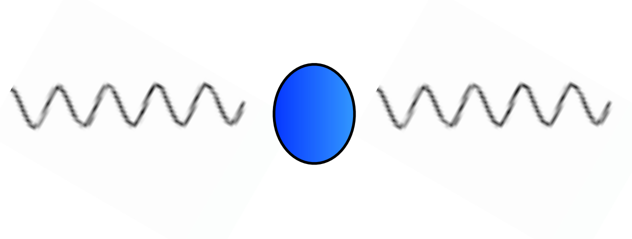
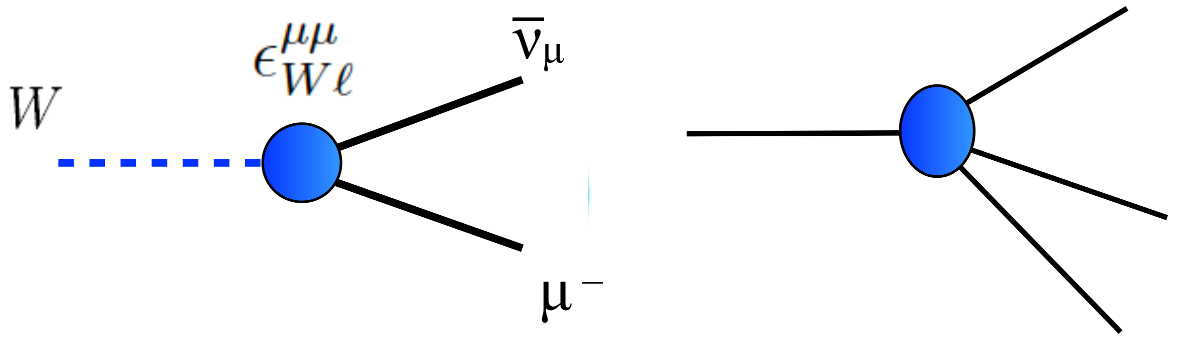
Contribute to Z-pole and other precision electroweak (EW) observables, including** M_W

Example:

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



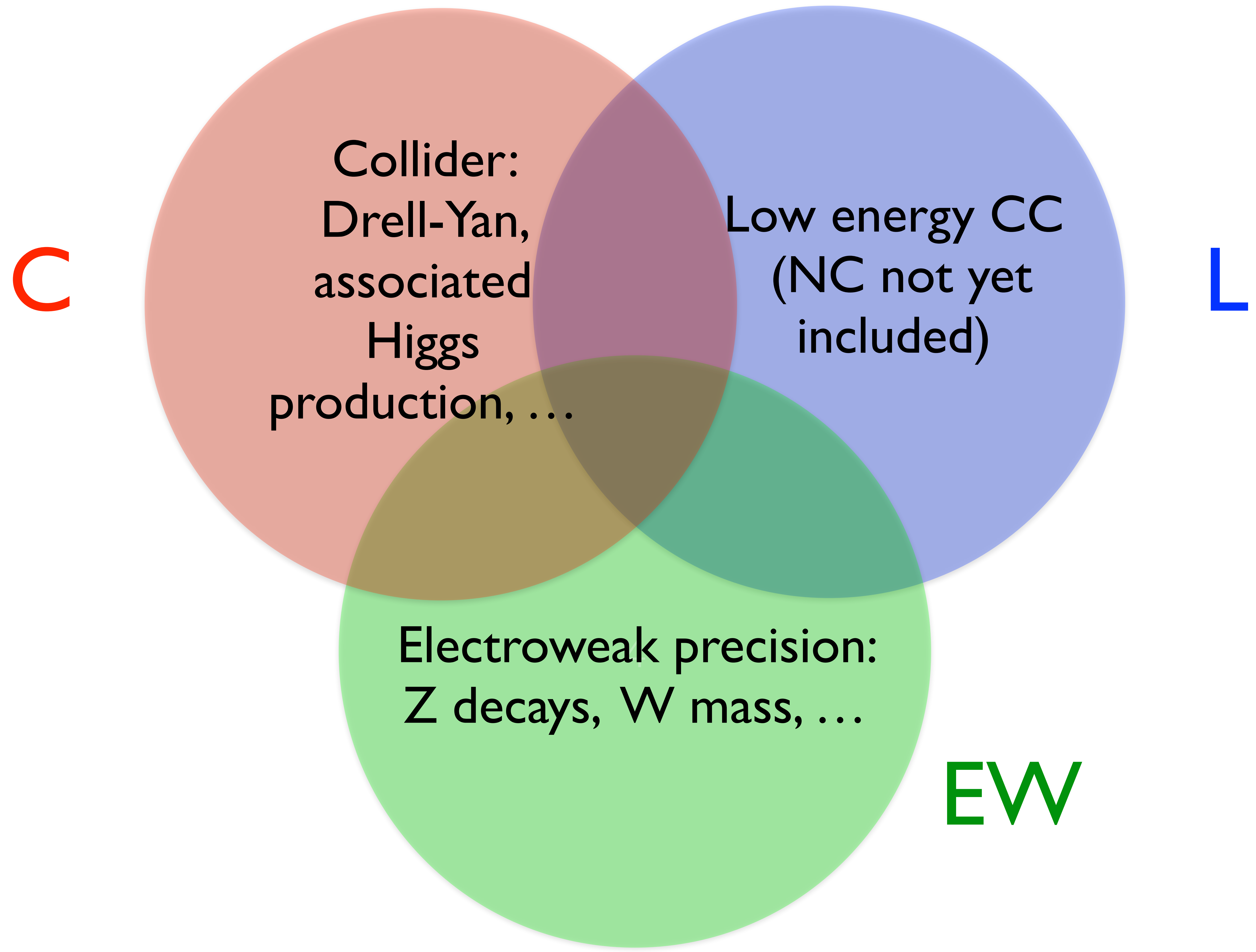
‘Oblique corrections’



Shift to G_F

The CLEW framework

- A consistent analysis of β-decays in SMEFT requires data from, Collider, Low energy, and ElectroWeak tests



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

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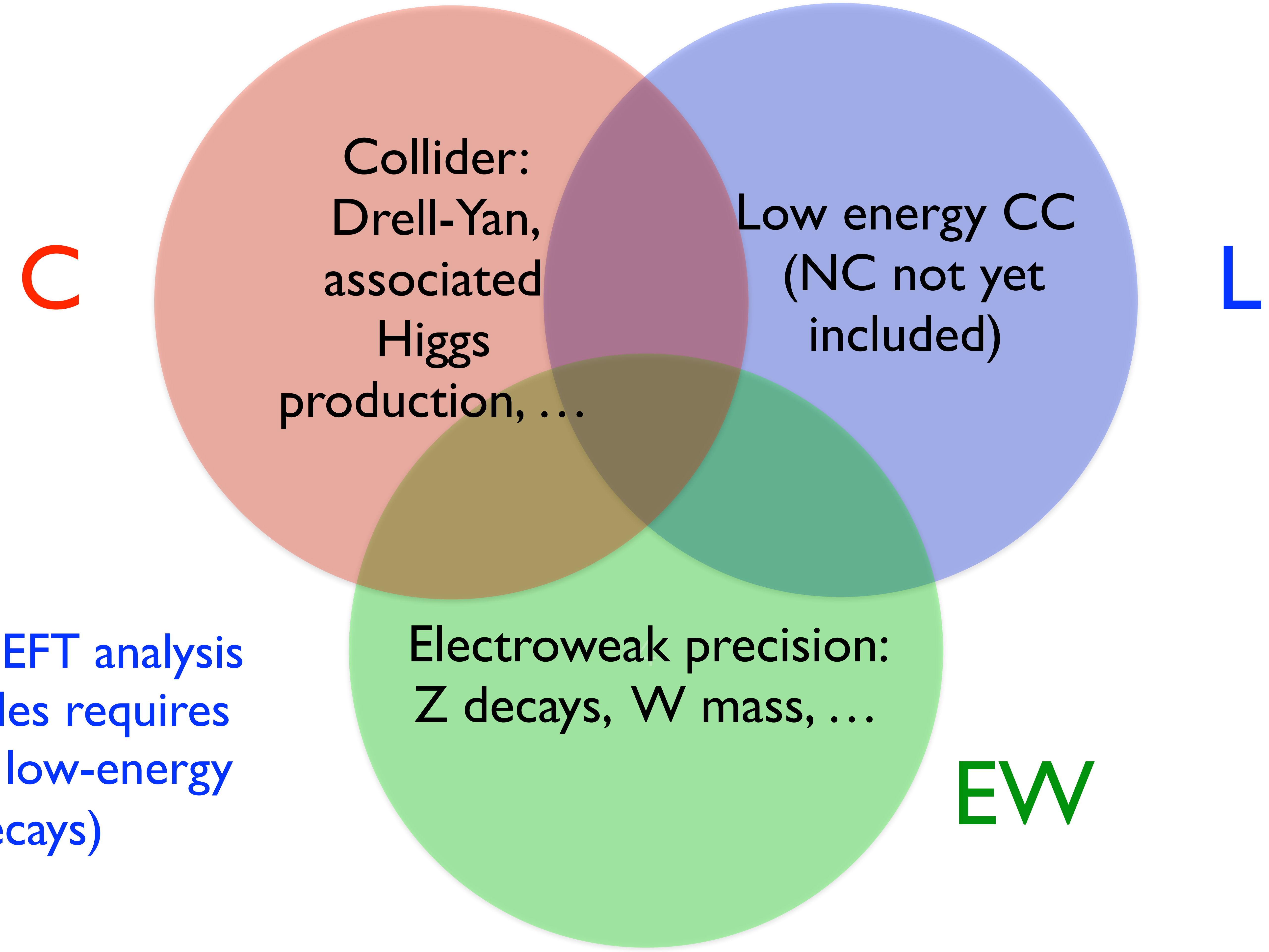

Corollary: a consistent SMEFT analysis of precision EW observables requires including constraints from low-energy CC processes (β-decays)

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

The CLEW framework

- A consistent analysis of β-decays in SMEFT requires data from, Collider, Low energy, and ElectroWeak tests

- Minimal set of operators involved **

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

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 $(\sin\theta_W)$		
$\boldsymbol{\psi^2 H^2 D}$				
$Q^{(1)}_{Hl}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{l}_p \gamma^\mu l_r)$	✗	✓	✓
$Q^{(3)}_{Hl}$	$(H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar{l}_p \tau^I \gamma^\mu l_r)$	✓	✓	✓
Q_{He}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{e}_p \gamma^\mu e_r)$	✗	✓	✓
$Q^{(1)}_{Hq}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{q}_p \gamma^\mu q_r)$	✗	✓	✓
$Q^{(3)}_{Hq}$	$(H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar{q}_p \tau^I \gamma^\mu q_r)$	✓	✓	✓
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)		
$Q^{(1)}_{lq}$	$(\bar{l}_p \gamma^\mu l_r)(\bar{q}_s \gamma_\mu q_t)$	✗	✓	✓
$Q^{(3)}_{lq}$	$(\bar{l}_p \gamma^\mu \tau^I l_r)(\bar{q}_s \gamma_\mu \tau^I q_t)$	✓	✓	✓
$\boldsymbol{(\bar{L}R)(\bar{R}L)}$ + h.c.				
Q_{ledq}	$(\bar{l}^j_p e_r)(\bar{d}_s q_{tj})$	✓	✗	✓
$\boldsymbol{(\bar{L}R)(\bar{L}R)}$ + h.c.				
$Q^{(1)}_{lequ}$	$(\bar{l}^j_p e_r)\epsilon_{jk}(\bar{q}^k_s u_t)$	✓	✗	✓
$Q^{(3)}_{lequ}$	$(\bar{l}^j_p \sigma_{\mu\nu} e_r)\epsilon_{jk}(\bar{q}^k_s \sigma^{\mu\nu} u_t)$	✓	✗	✓

The CLEW framework

- A consistent analysis of β-decays in SMEFT requires data from, Collider, Low energy, and ElectroWeak tests
- Minimal set of operators involved **

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ψ^2H^2D				
$Q^{(1)}_{Hl}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{l}_p \gamma^\mu l_r)$	✗	✓	✓
$Q^{(3)}_{Hl}$	$(H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar{l}_p \tau^I \gamma^\mu l_r)$	✓	✓	✓
Q_{He}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{e}_p \gamma^\mu e_r)$	✗	✓	✓
$Q^{(1)}_{Hq}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{q}_p \gamma^\mu q_r)$	✗	✓	✓
$Q^{(3)}_{Hq}$	$(H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar{q}_p \tau^I \gamma^\mu q_r)$	✓	✓	✓
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
$(\bar{L}L)(\bar{L}L)$				
Q_{ll}	$(\bar{l}_p \gamma^\mu l_r)(\bar{l}_s \gamma_\mu l_t)$	parameter shift (G_F)		
$Q^{(1)}_{lq}$	$(\bar{l}_p \gamma^\mu l_r)(\bar{q}_s \gamma_\mu q_t)$	✗	✓	✓
$Q^{(3)}_{lq}$	$(\bar{l}_p \gamma^\mu \tau^I l_r)(\bar{q}_s \gamma_\mu \tau^I q_t)$	✓	✓	✓
$(\bar{L}R)(\bar{R}L)$ + h.c.				
Q_{ledq}	$(\bar{l}^j_p e_r)(\bar{d}_s q_{tj})$	✓	✗	✓
$(\bar{L}R)(\bar{L}R)$ + h.c.				
$Q^{(1)}_{lequ}$	$(\bar{l}^j_p e_r)\epsilon_{jk}(\bar{q}^k_s u_t)$	✓	✗	✓
$Q^{(3)}_{lequ}$	$(\bar{l}^j_p \sigma_{\mu\nu} e_r)\epsilon_{jk}(\bar{q}^k_s \sigma^{\mu\nu} u_t)$	✓	✗	✓

** 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. Do not expect big impact on the operators kept in our current analysis.

Bussolotti-Boughezial-Simsek 2306.05564, Boughezial et al. 2303.08257, 2204.07557
Crivellin et al., 2107.13569

What about flavor?

- Most analyses impose flavor symmetry to reduce number of couplings (e.g. only 9 Wilson Coefficients in the CLEW analysis if assume $U(3)^5$). However:
  - Lead to model-dependence (e.g. excludes classes of operators / models such as LRSM)
  - Results depend strongly on flavor assumptions L. Bellafronte, S. Dawson, P. P. Giardino 2304.00029

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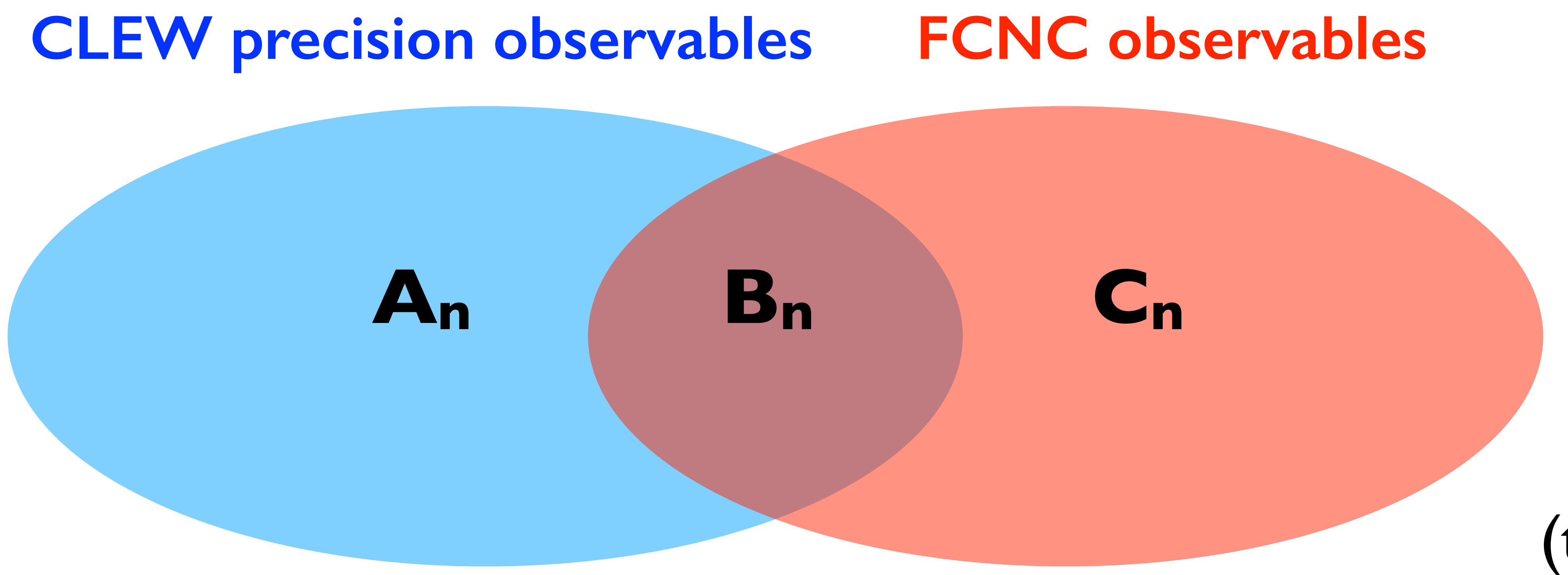
L. Bellafronte, S. Dawson, P. P. Giardino 2304.00029

- 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 appear in CLEW observables suppressed by powers of λ_C~0.2
⇒ Set B_n=0. Expect minimal impact on A_n
(testable with more computing and people-power)

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

↑ ~ factorized likelihood

What about flavor?

CLEW analysis with no assumption about flavor symmetry requires 37 couplings

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

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

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

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

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

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

A CLEWed global analysis

Large fits (e.g. with 37 Wilson Coefficients) not particularly enlightening

Not all operators matter for the fit!

A CLEWed global analysis

Large fits (e.g. with 37 Wilson Coefficients) not particularly enlightening

Not all operators matter for the fit!

Extreme example: CLEW37 fit with CDF input for m_W

- Best fit W.C.'s are all consistent with zero at the 2-σ level
- Analyze eigenvectors of the covariance matrix, their corresponding best fit values, and their (uncorrelated) variance ⇒ A handful of eigenvectors are non-zero at > 3-σ significance

$$
\begin{aligned}
0.51\,C_{ST} + 0.33\,C^{(3)}_{\substack{Hl\\22}} + 0.45\,C_{\substack{ledq\\2222}} - 0.40\,\bar{C}^{(1)}_{\substack{lequ\\2211}} - 0.34\,C_{\substack{ll\\2112}} &= -0.0016 \times (3.7 \pm 1)\,\mathrm{TeV}^{-2} \\
0.41\,C_{ST} - 0.47\,C^{(3)}_{\substack{Hl\\22}} + 0.42\,C_{\substack{ll\\2112}} &= -0.0030 \times (6.5 \pm 1)\,\mathrm{TeV}^{-2} \\
-0.83\,C_{\substack{He\\11}} - 0.34\,C^{(1)}_{\substack{Hl\\11}} - 0.31\,C^{(3)}_{\substack{Hl\\11}} &= 0.0093 \times (3 \pm 1)\,\mathrm{TeV}^{-2}\,.
\end{aligned}
$$

A CLEWed global analysis

Large fits (e.g. with 37 Wilson Coefficients) not particularly enlightening

Not all operators matter for the fit!

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

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

# of estimated parameters

Minimization of AIC:

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

A CLEWed global analysis

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

Operators grouped in 10 categories

Scanned this model space

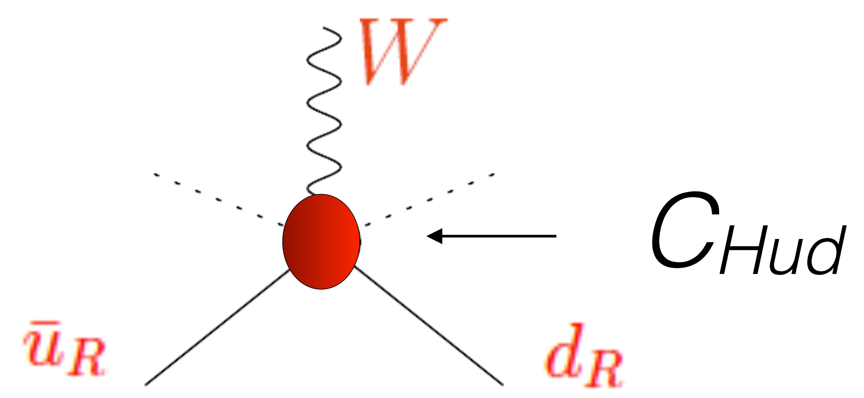
2^{10} = 1024 'models'

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

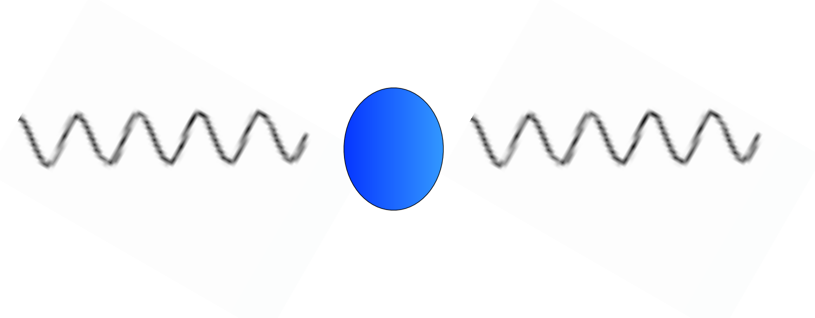
A CLEWed global analysis

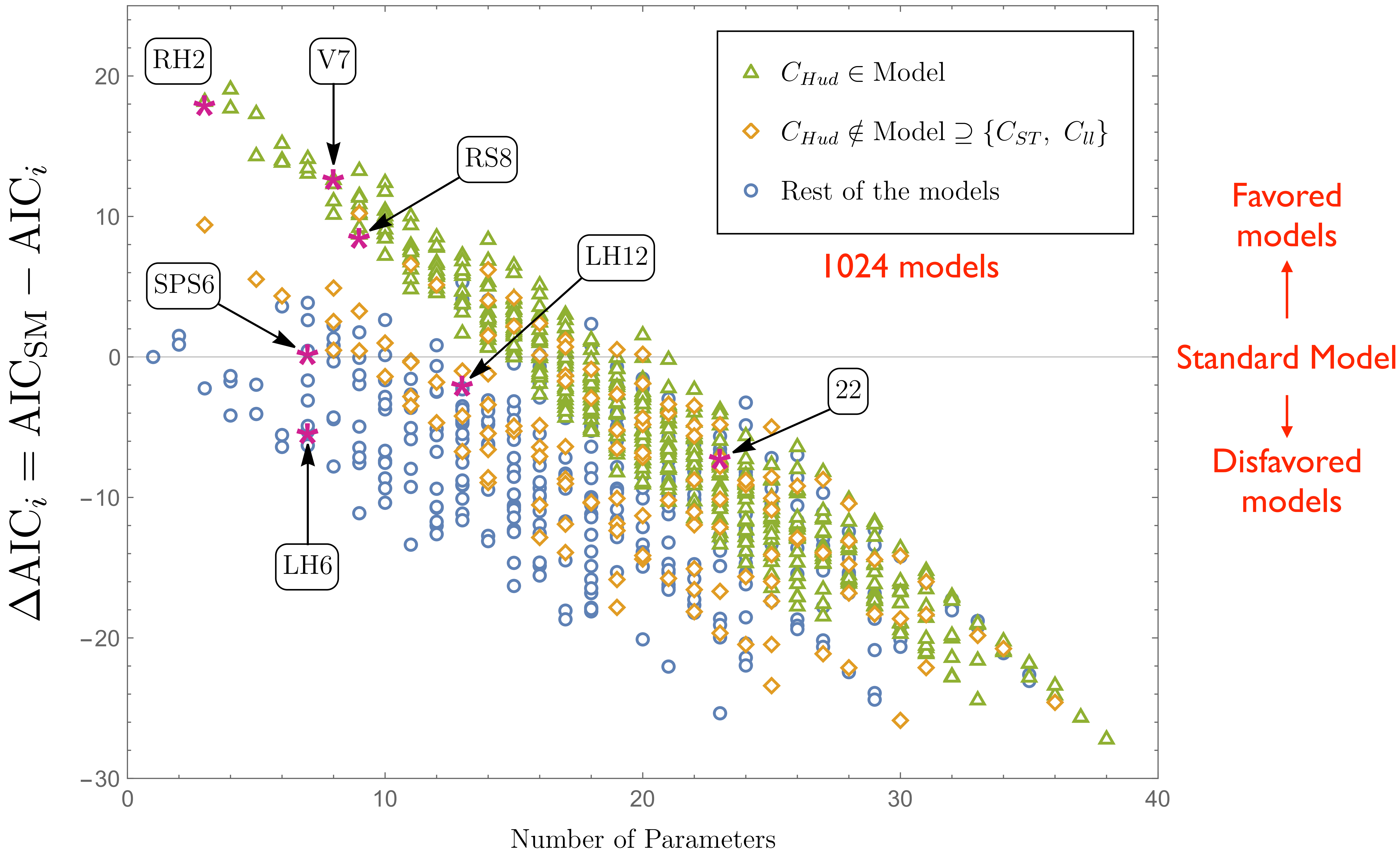
VC, W. Dekens, J. De Vries, E. Mereghetti, T. Tong, JHEP 03 (24) 33, arXiv: 2311.00021

- 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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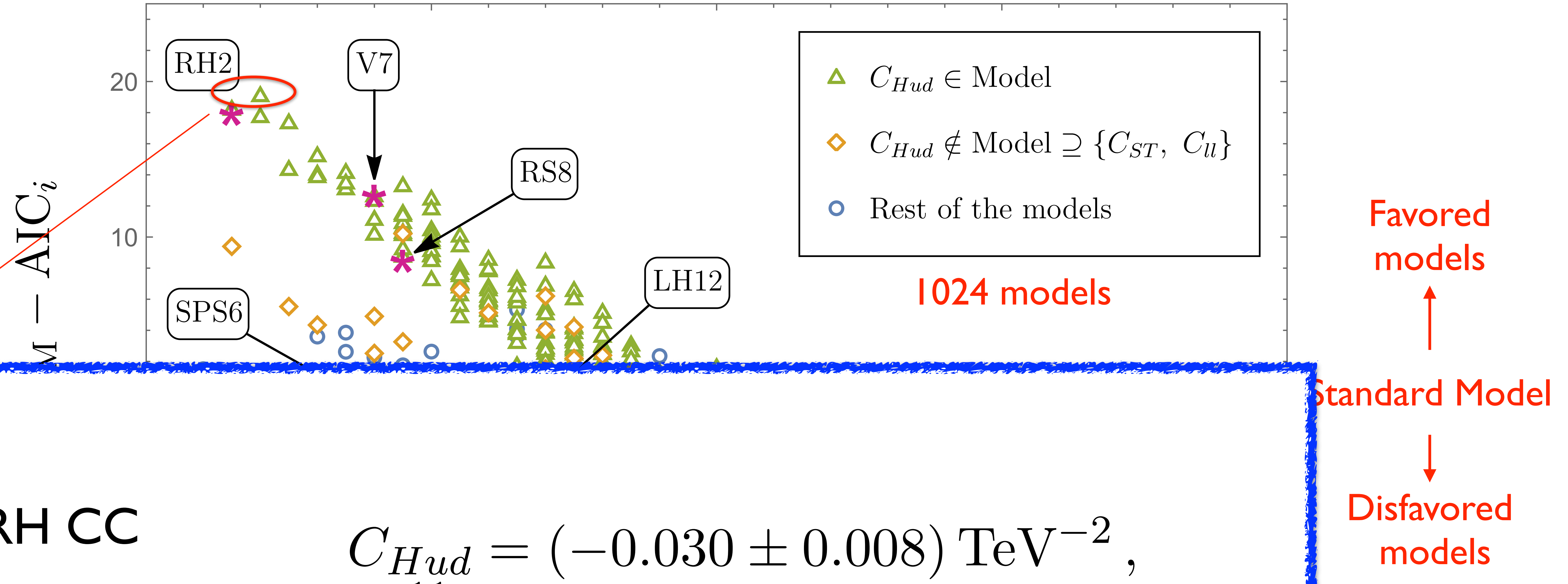
- Model
also fa



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)

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

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

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

A CLEWed global analysis

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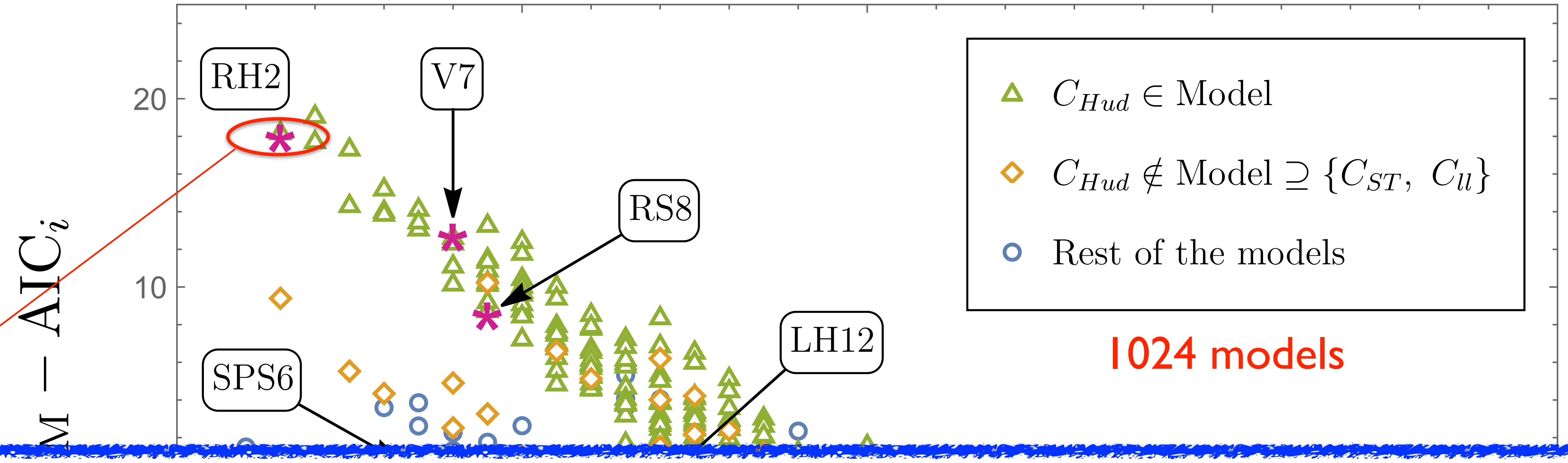
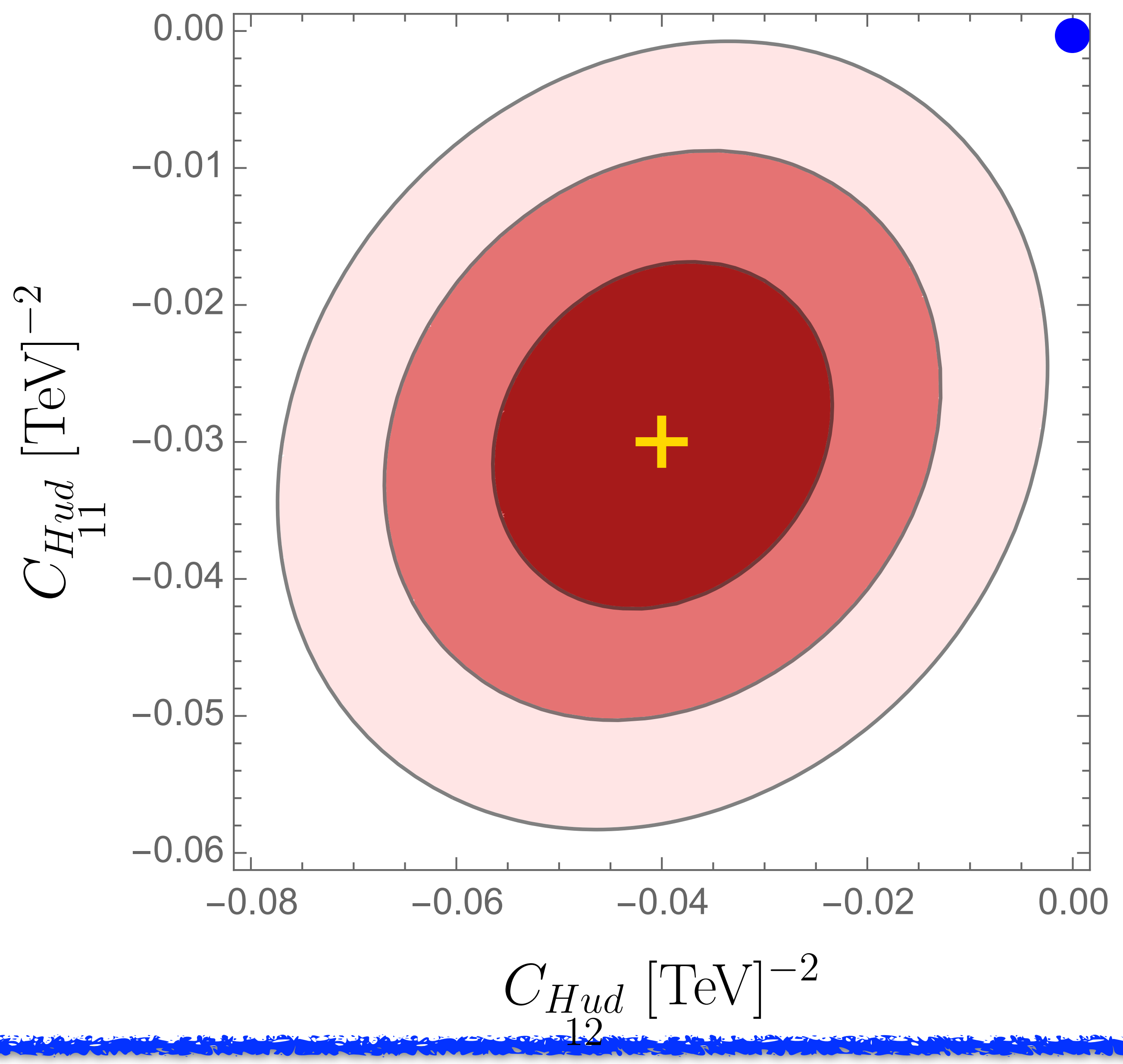
  also fa



Favored models
↑
Standard Model
↓
Disfavored models

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



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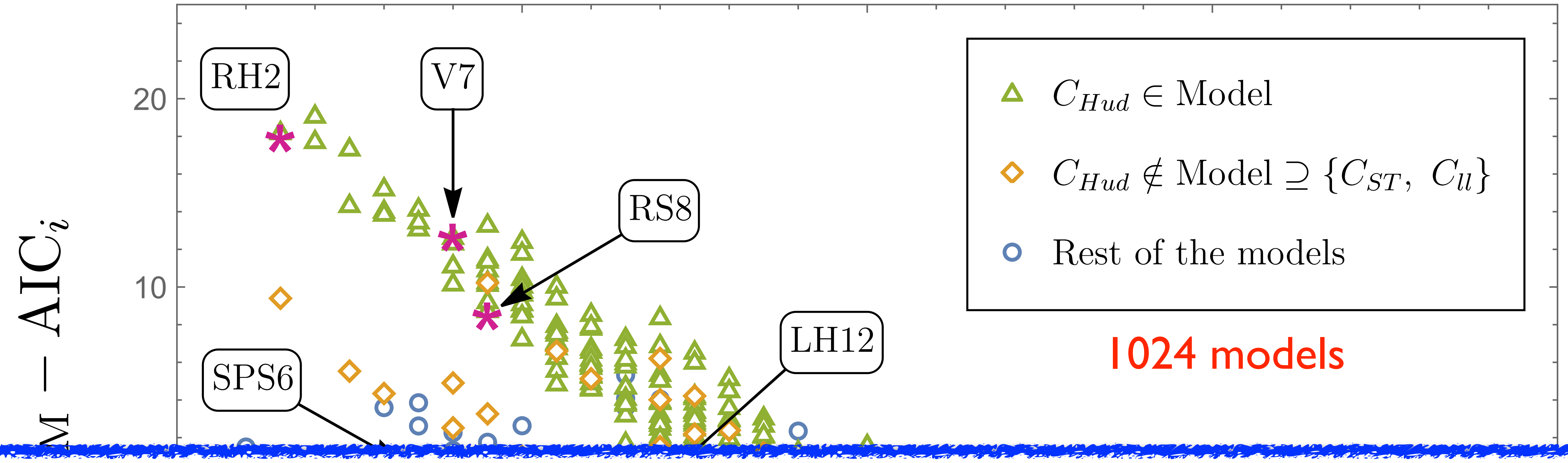


Favored models
Standard Model
Disfavored models

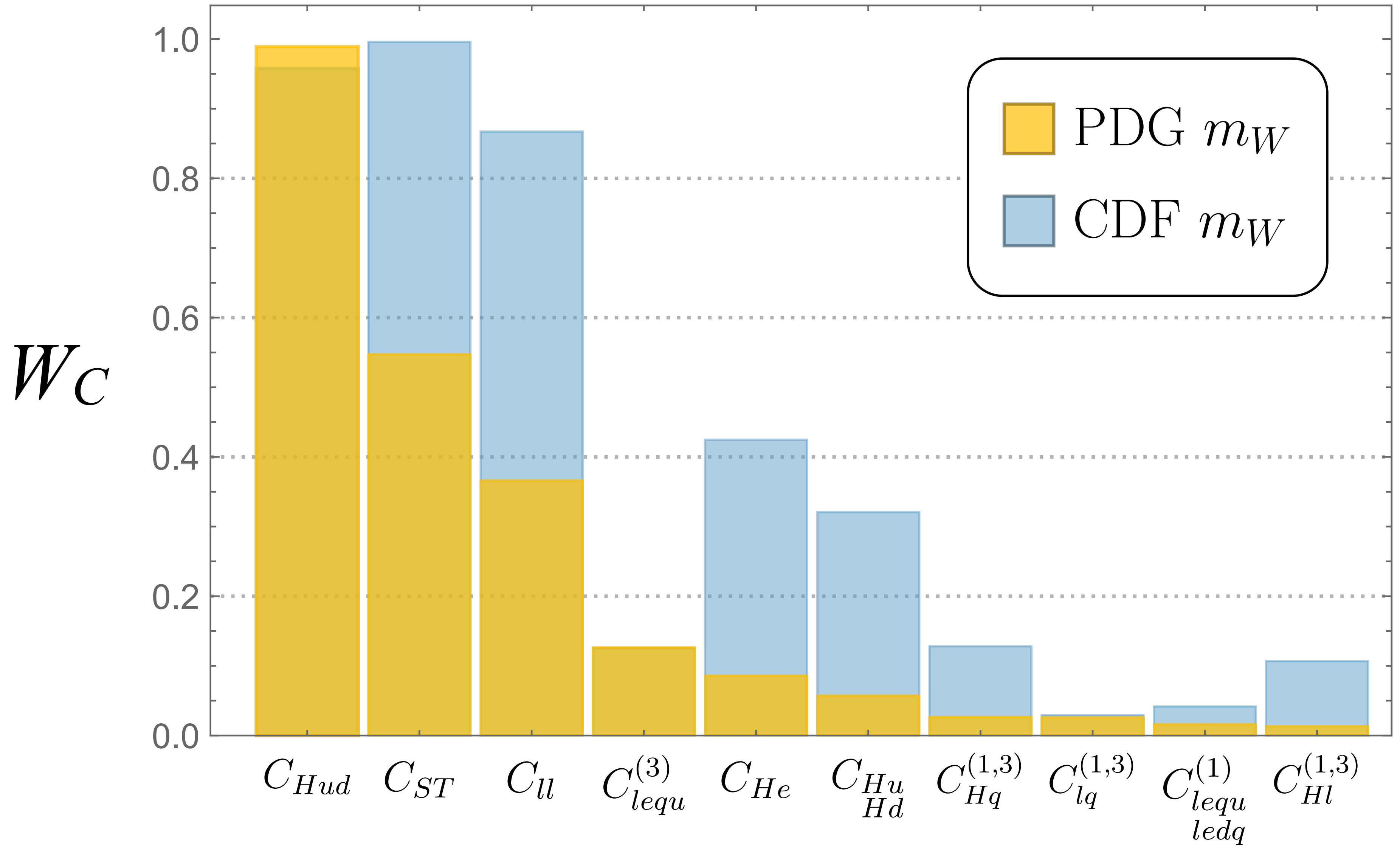
- Most important operators: R-handed CC, oblique corrections, 4-lepton
- R-handed neutral currents (C_{He}, C_{Hd}) appear in 'next best models': mitigate some Z-pole tensions

Weight for model 'I'

$$w_i = \frac{e^{\frac{1}{2}\Delta \mathrm{AIC}_i}}{\sum_j e^{\frac{1}{2}\Delta \mathrm{AIC}_j}}$$

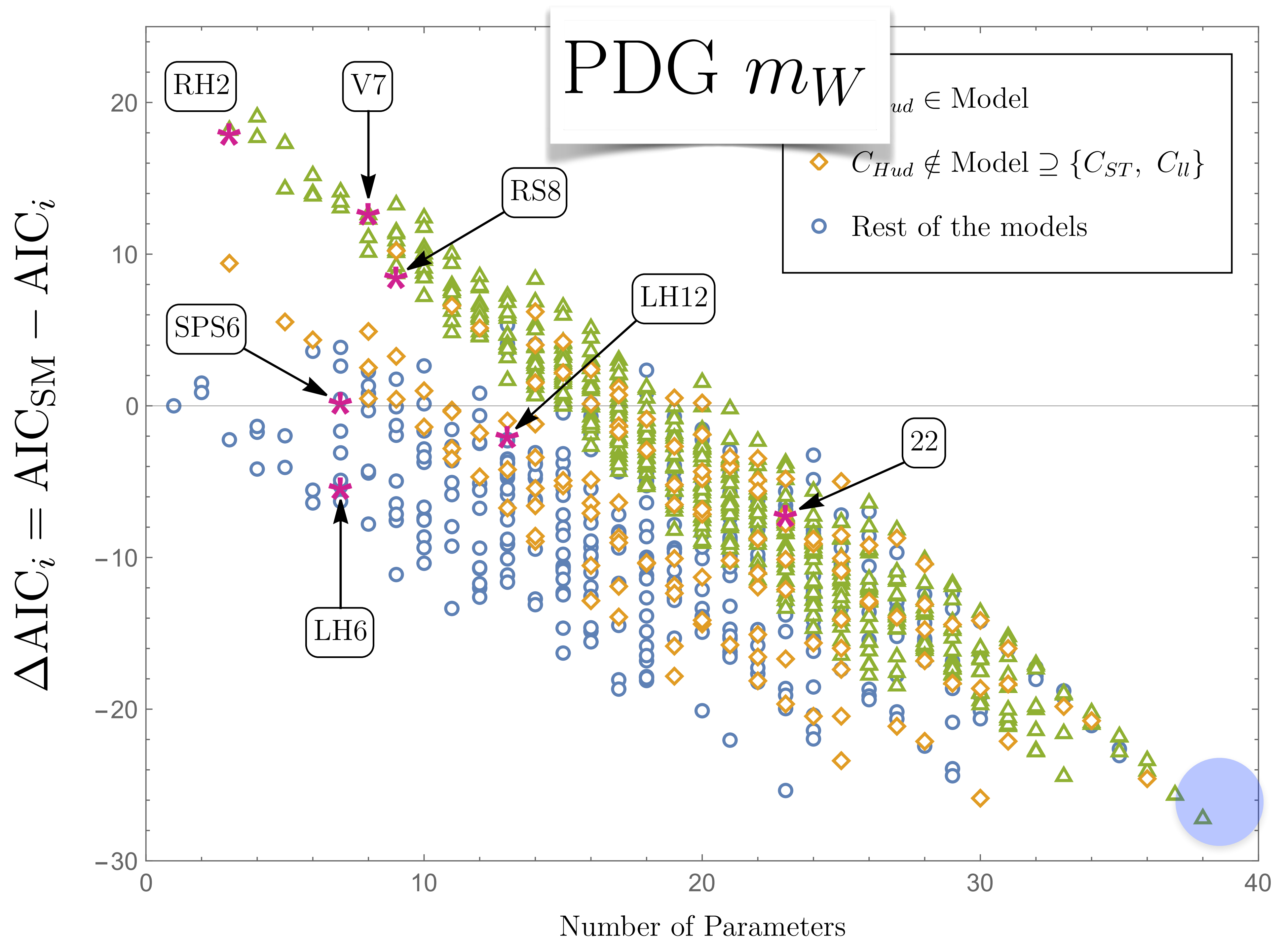
Sum of the weights of models in which θ is turned on

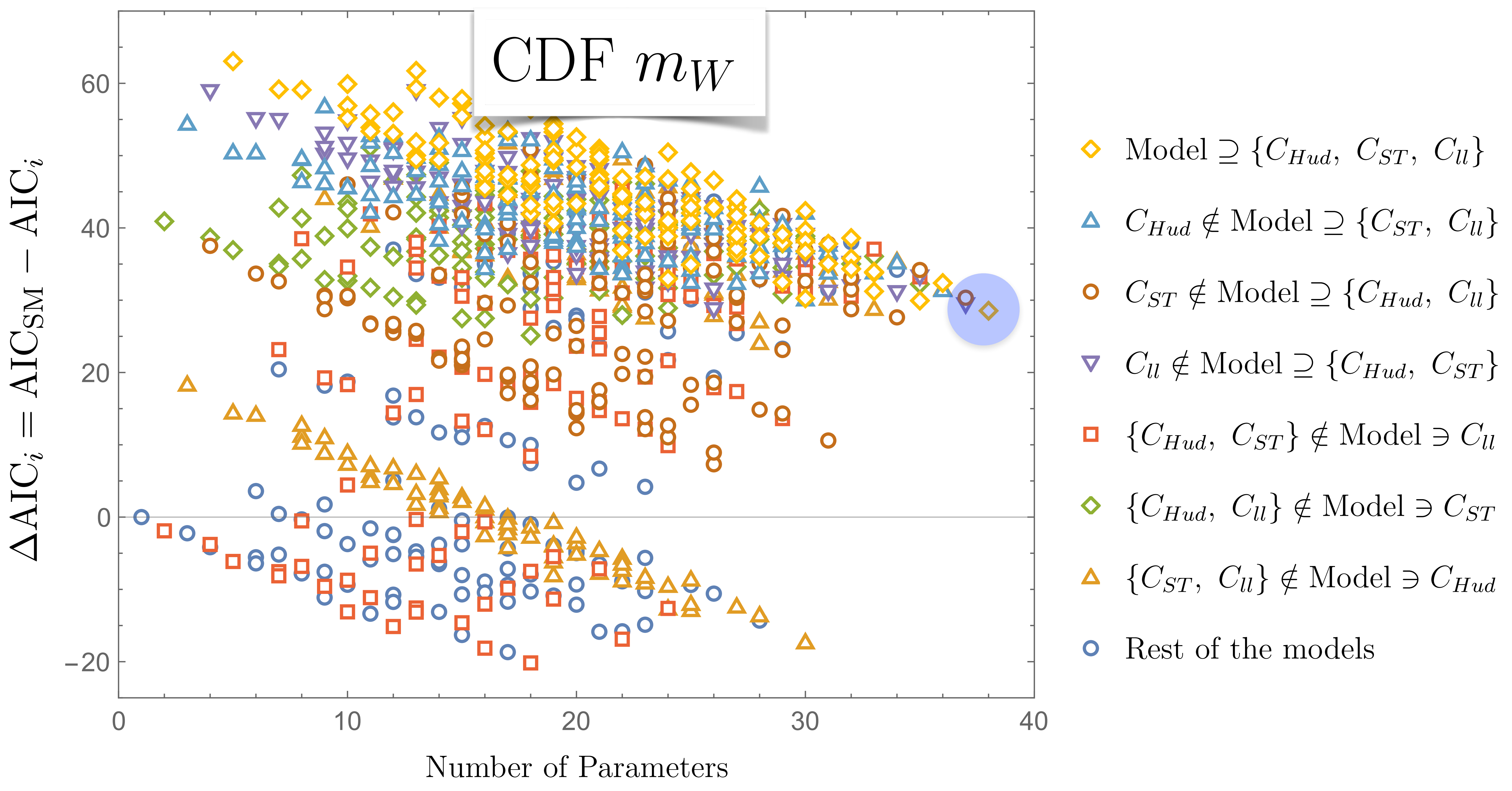
$$W_\theta = \sum_i w_i I_\theta(i)$$



A CLEWed global analysis

- Qualitatively similar** conclusions if one includes the CDF m_W measurement





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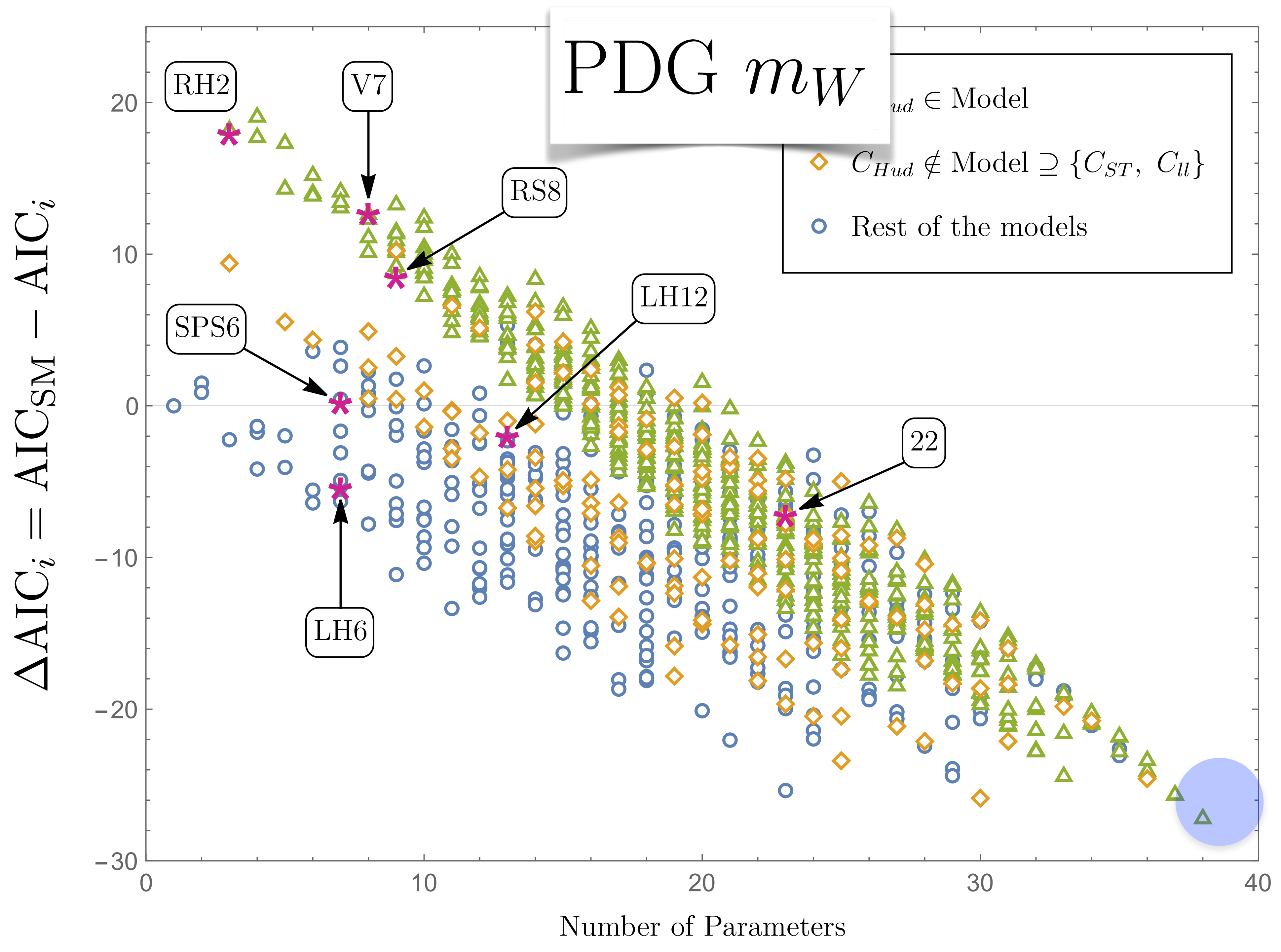
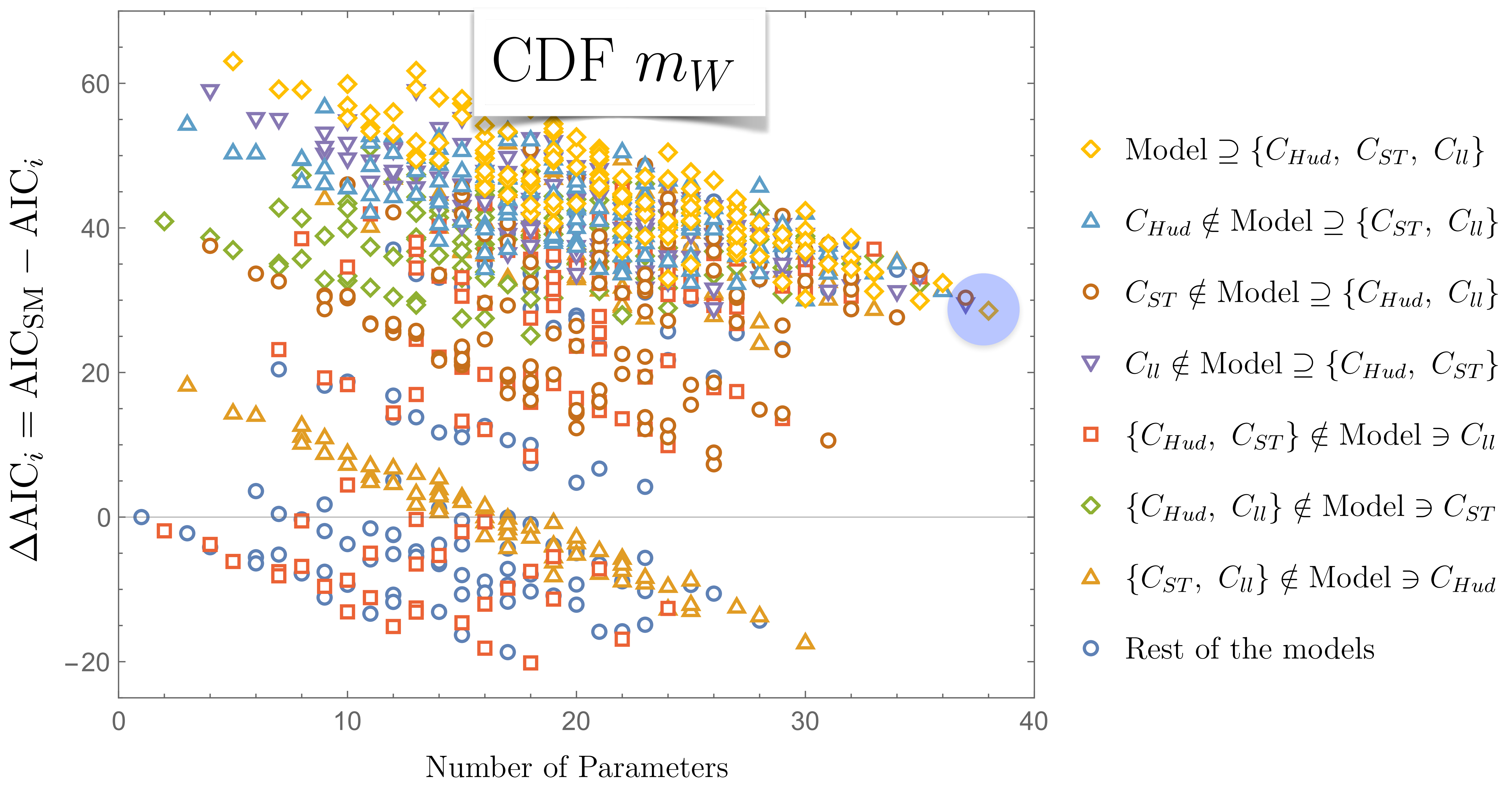


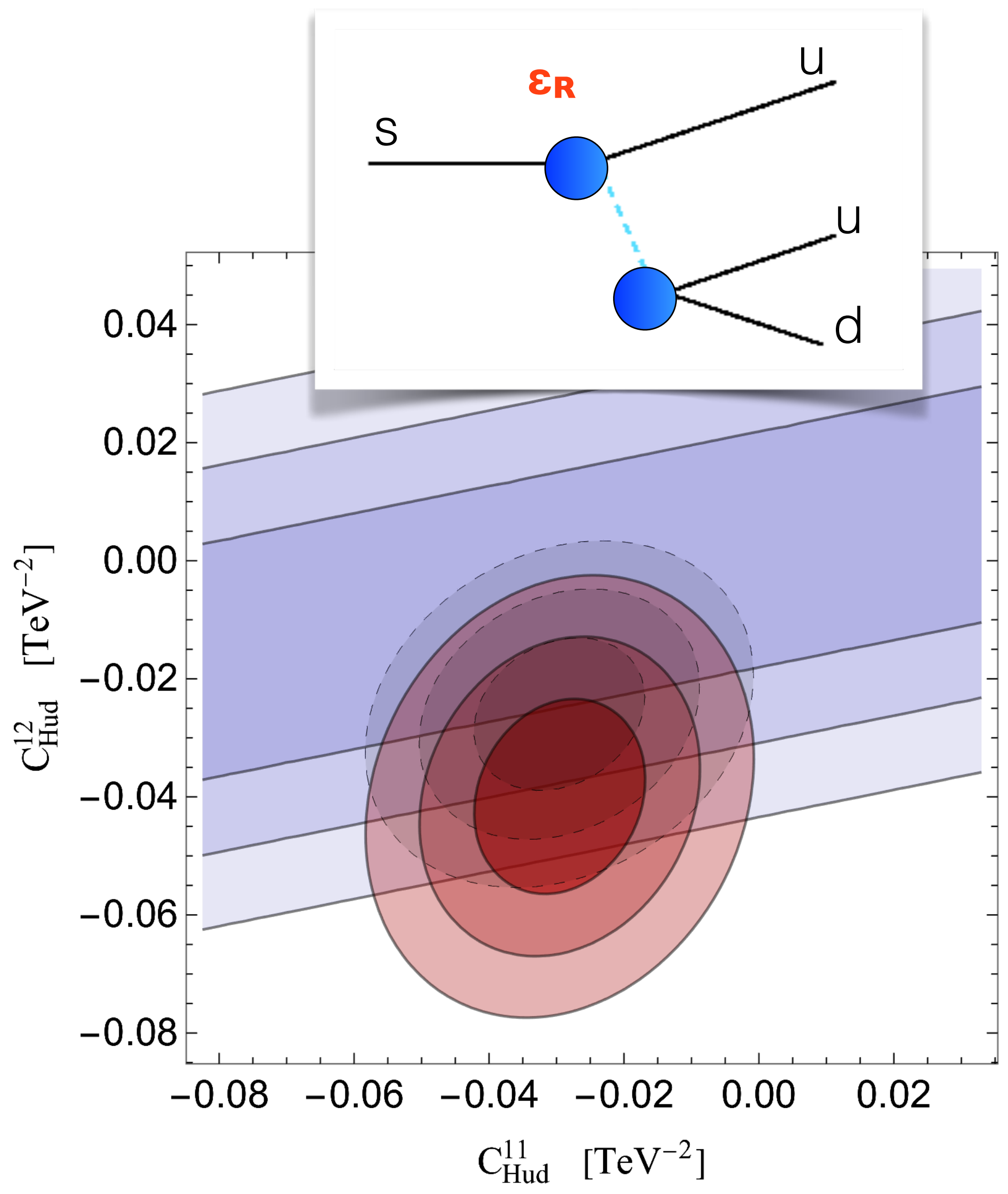


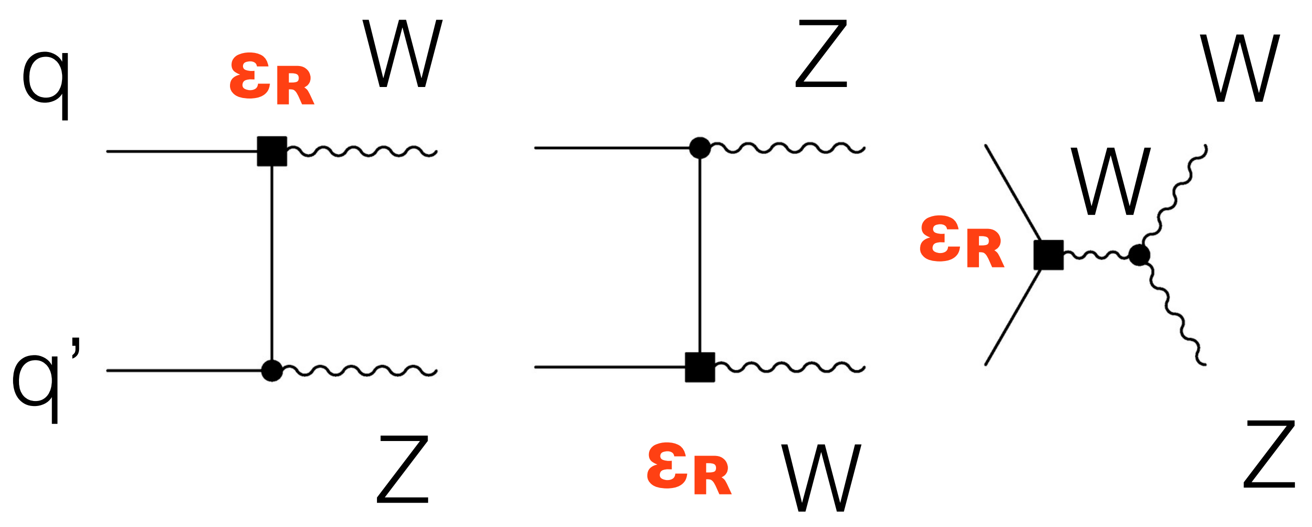
CKM "anomaly" not ruled out by other data!
Unitarity test provides relevant input to unravel possible new physics.

Falsifying R-handed current hypothesis

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

- Currently less-sensitive probes of R-handed couplings
  - g_A/g_V: neutron decay vs Lattice QCD (need ~ order of magnitude theoretical improvement)
  - $K \to (\pi\pi)_{I=2}$ decay amplitude: experiment vs Lattice QCD (difficult to improve)
  - WH & WZ production at the High Luminosity LHC will reach sensitivity need to test the R-handed current solution to the Cabibbo angle anomaly



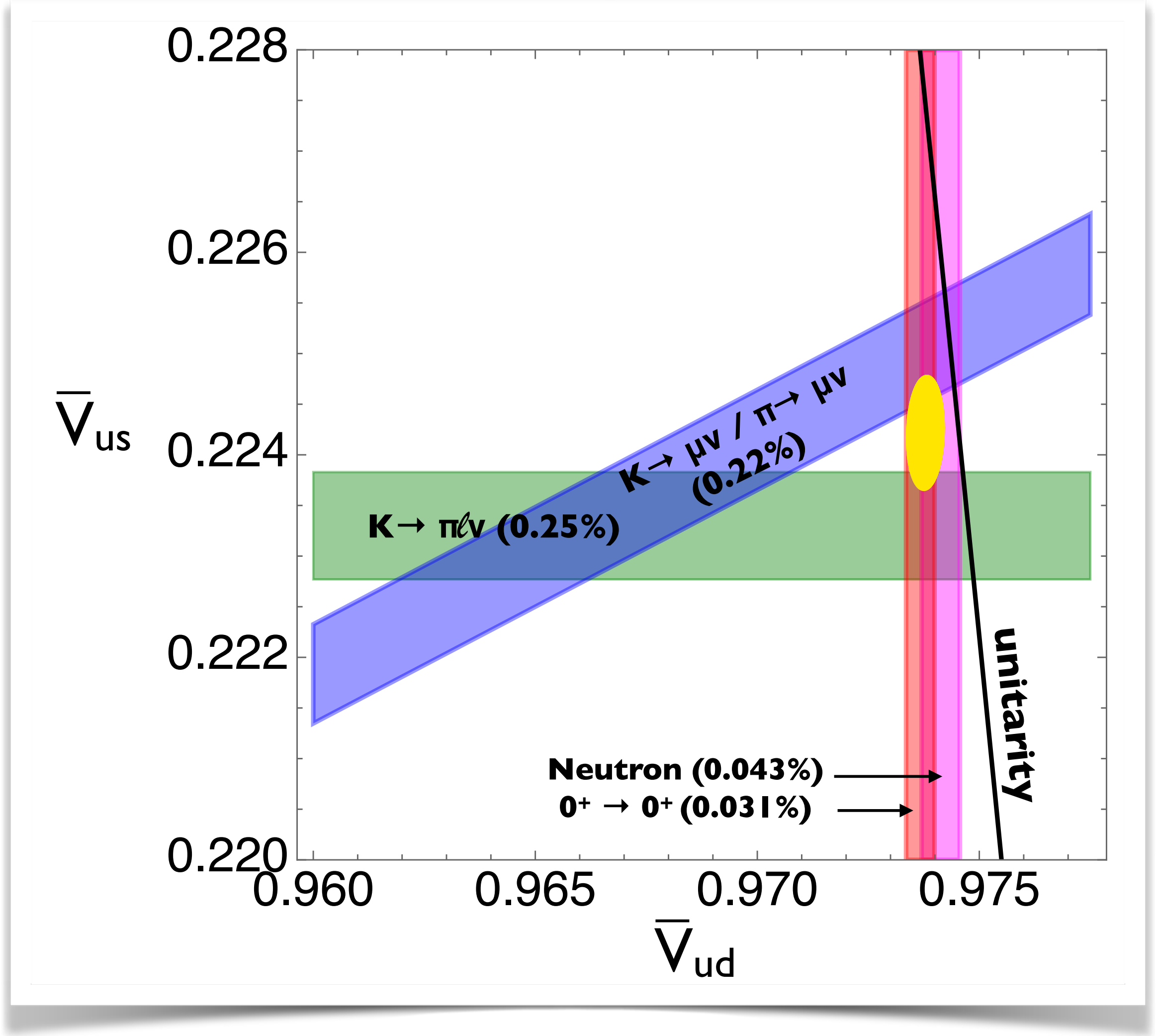


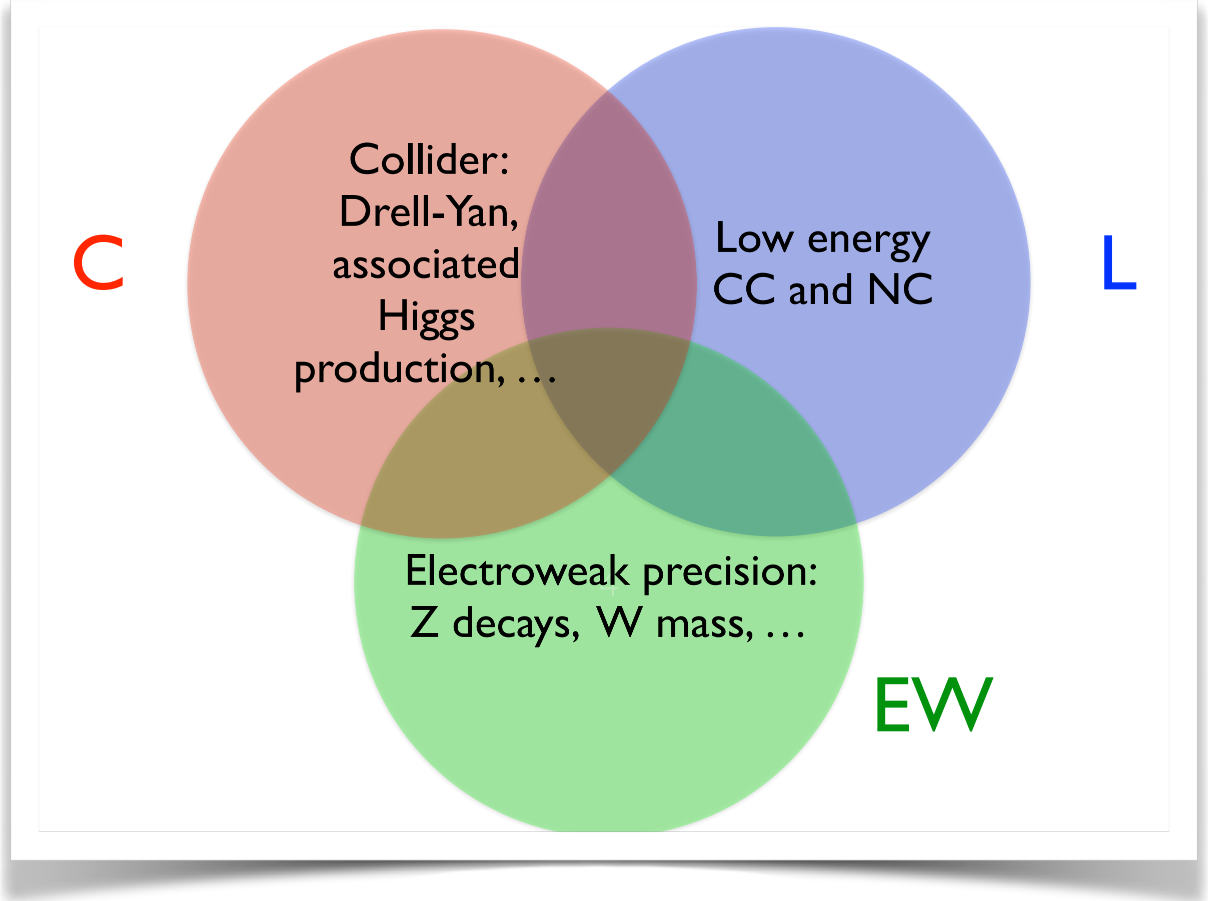
Summary and outlook

- 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

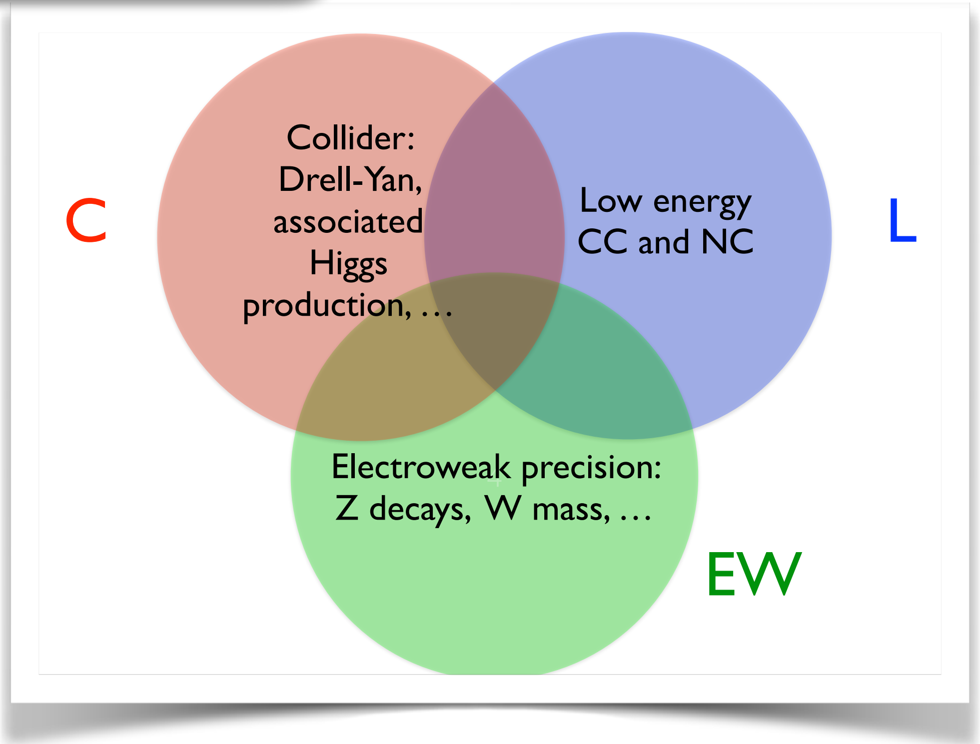
- Simplest BSM explanations of Cabibbo anomaly given by "right-handed vertex corrections" in the SMEFT language

- CLEW framework is necessary for consistent analysis and RH CC 'explanation' of the Cabibbo anomaly survives CLEWed analysis





Summary and outlook



- The traditional set of EWPO considered in the literature should be extended (both in the $U(3)^5$ and general flavor case) to include at least low-energy CC processes & Drell-Yan: they constrain subset of couplings at similar precision!

- Flavor symmetry assumptions reintroduce model-dependence in the SMEFT approach. Flavor symmetries can make the analysis 'blind' to simple BSM scenarios (e.g. $U(3)^5$ and RH currents). We argued that likelihood can be approximately factorized.

- A SMEFT-based 'model selection' analysis (with AIC or other metric) can be quite insightful and ultimately should help unraveling the underlying new physics if anomalies arise / survive

- Towards a complete (tree-level) SMEFT analysis of precision observables that do not involve FCNC and CPV:
    - Observables that currently have weaker sensitivity: K decays; HW, ZW production at the LHC
    - NC processes: PVES, APV, DIS (→ EIC)

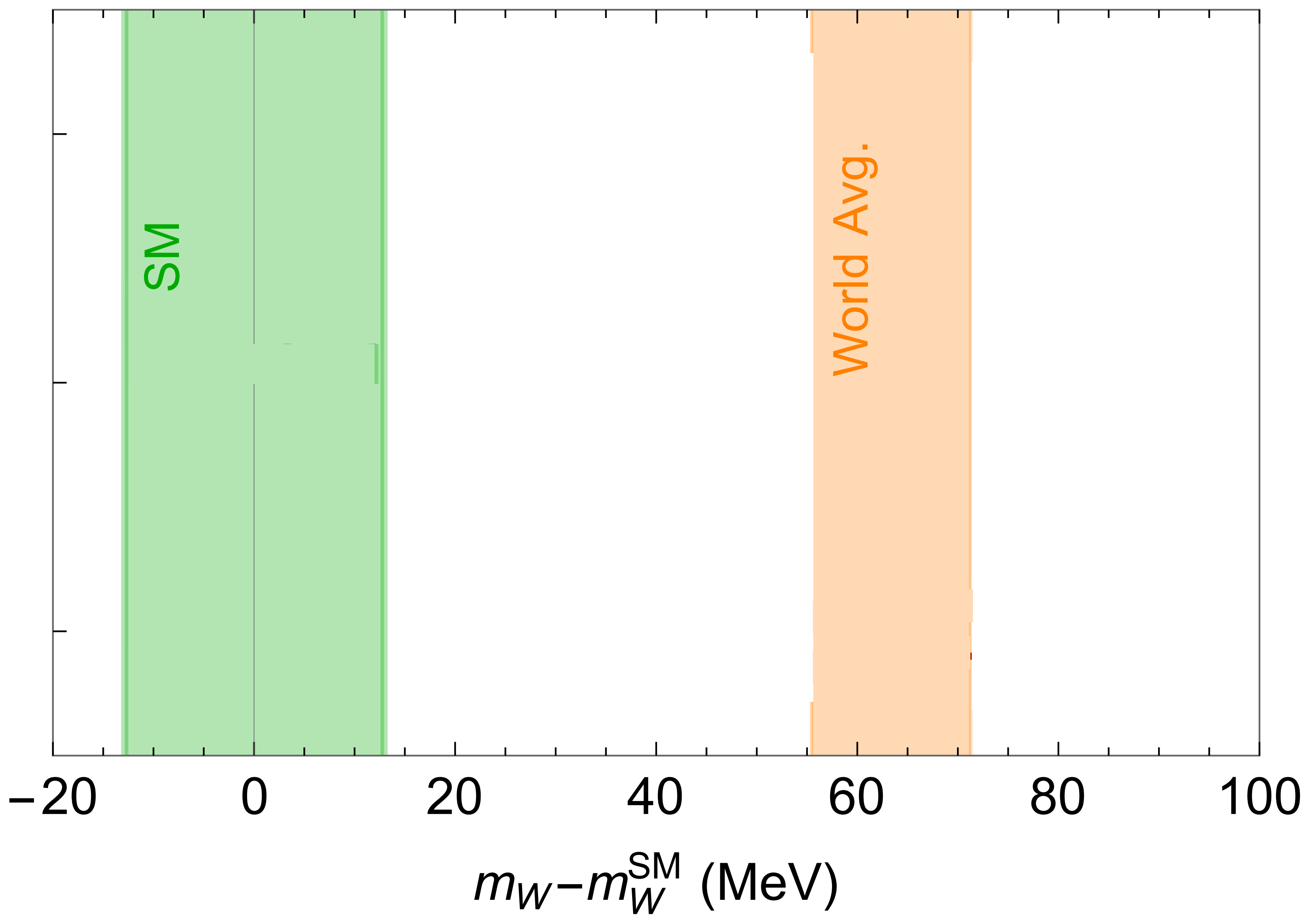
Backup

Δ_{CKM} and EW precision fits (1)

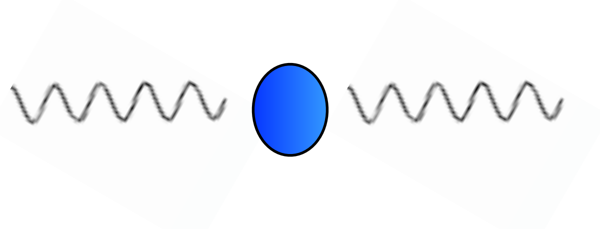
VC, Dekens, deVries, Mereghetti, Tong 2204.08440, 2311.00021

- Cabibbo universality test quantitatively and qualitatively affects global fits to precision EW observables
- Example: explanations of m_W 'anomaly' in SMEFT + $U(3)^5$

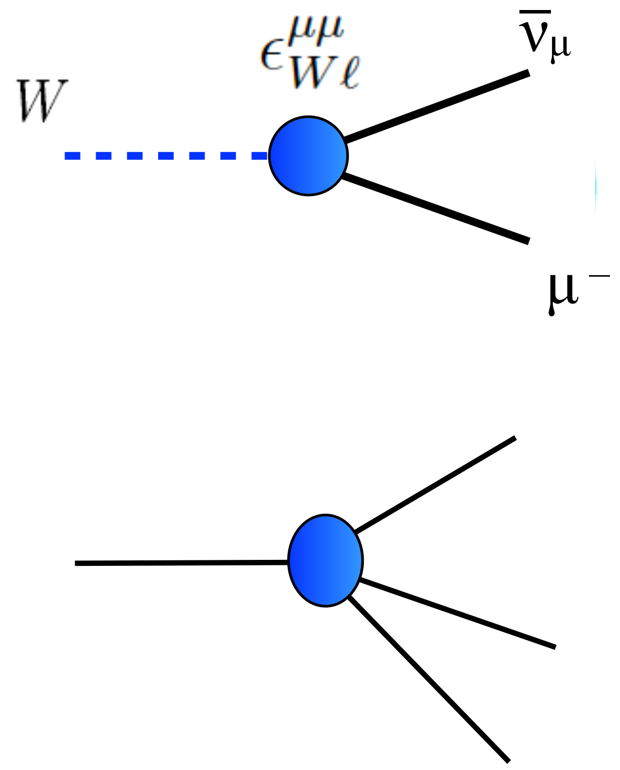
$$\frac{\delta m_W^2}{m_W^2} = v^2 \, \frac{s_w c_w}{s_w^2 - c_w^2} \left[2\, C_{HWB} + \frac{c_w}{2 s_w}\, C_{HD} + \frac{s_w}{c_w} \left(2\, C_{Hl}^{(3)} - \hat{C}_{ll} \right) \right]$$



'Oblique corrections'



Shift to G_F



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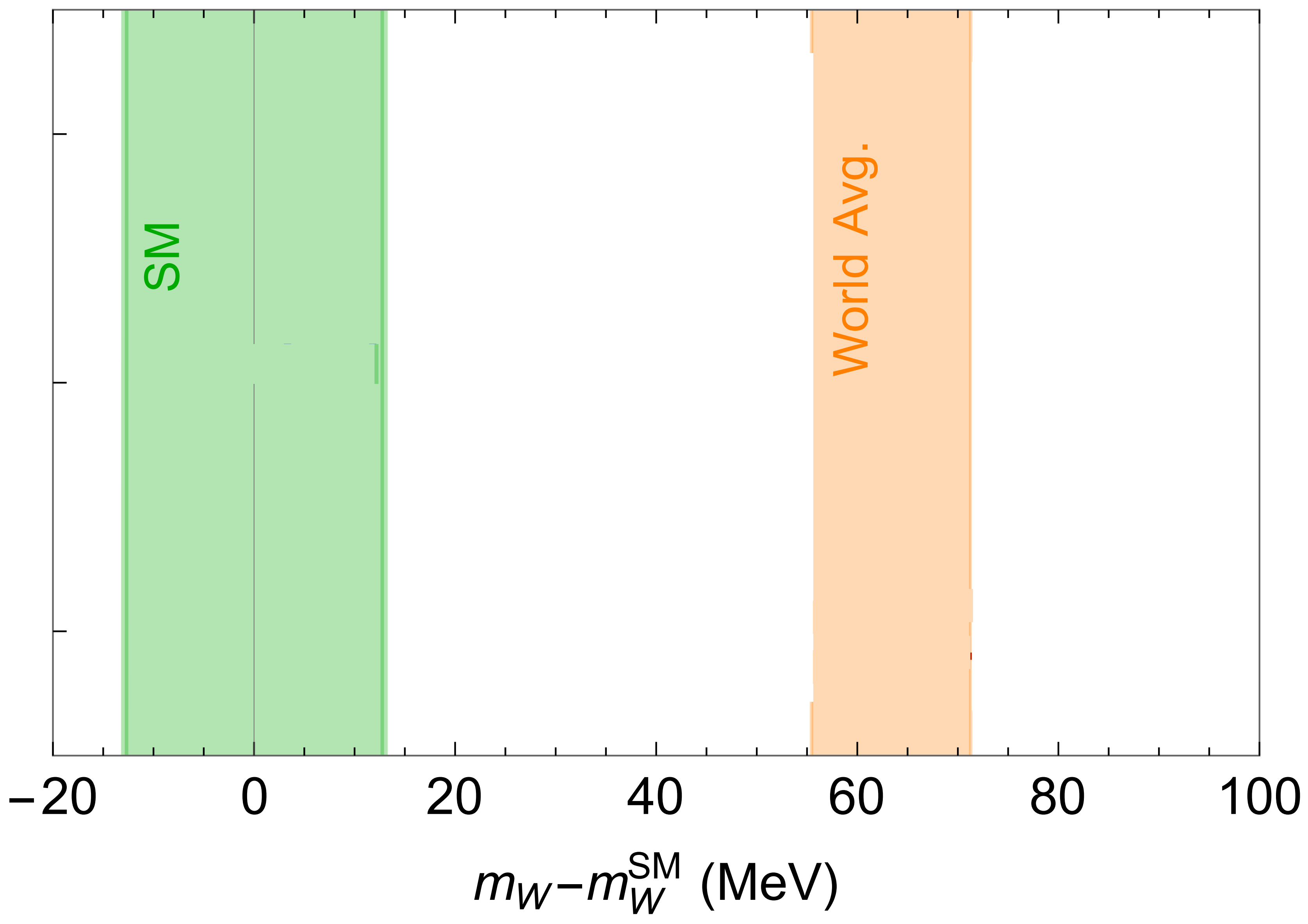
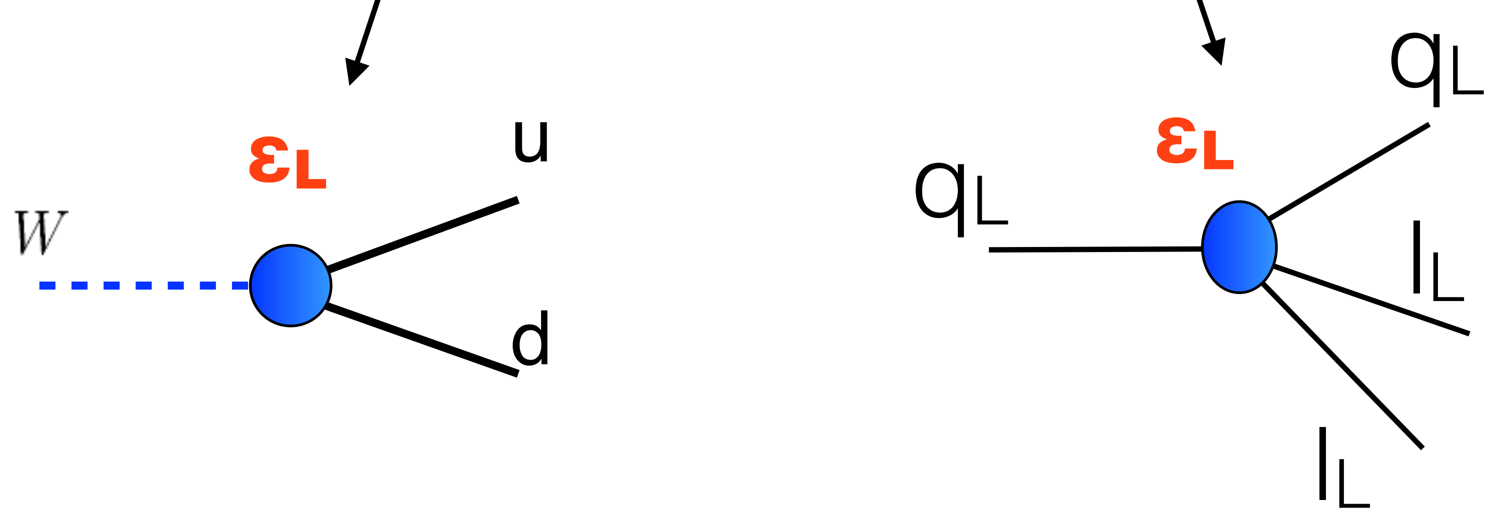


$$\Delta_{\rm CKM} = v^2 \left[C_\Delta - 2\, C_{lq}^{(3)} \right]$$

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



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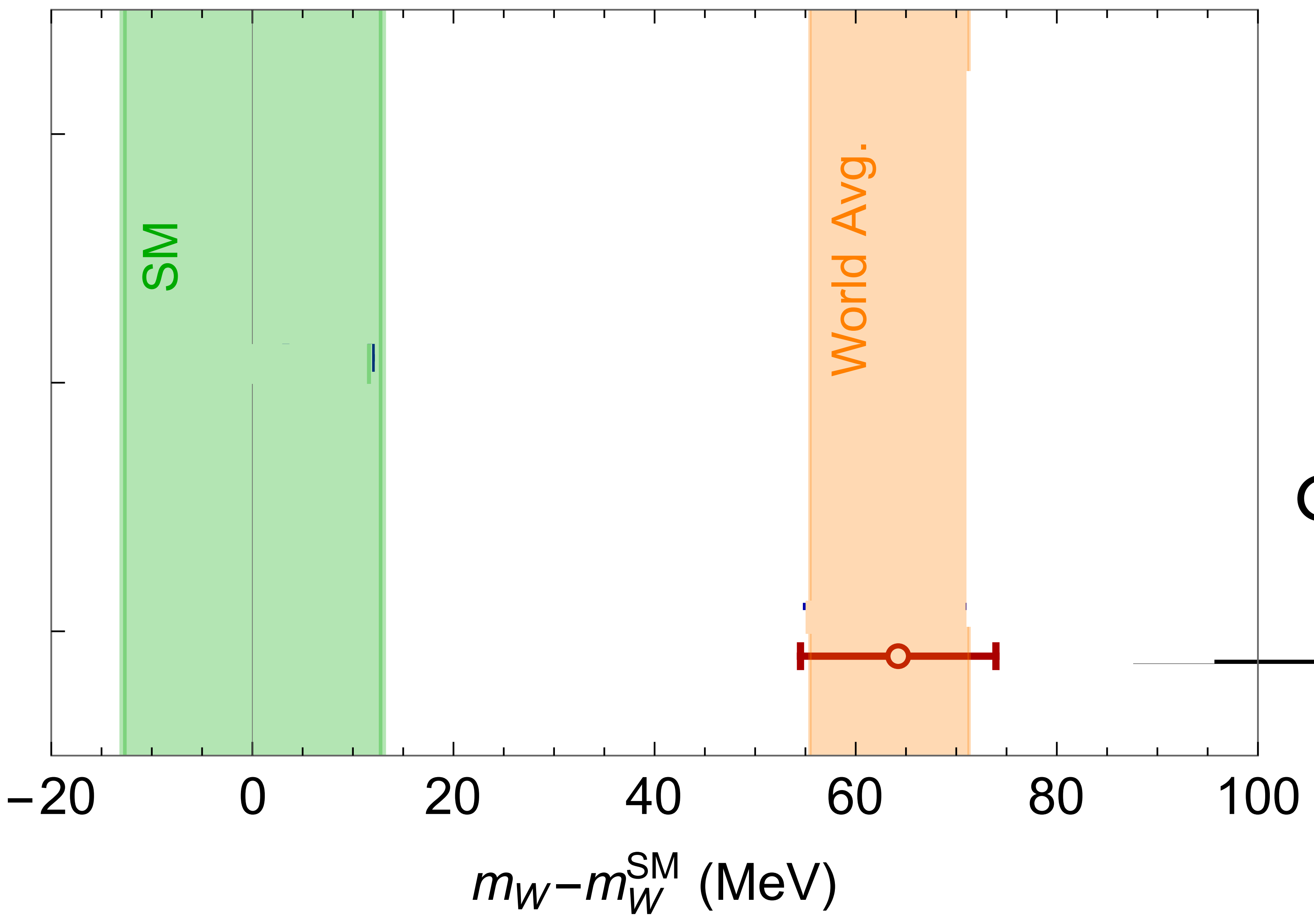

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deBlas et al 2204.04204, Bagnaschi et al 2204.05260, …

Global fit to EWPO without Δ_{CKM} ⇒ too large a C_Δ

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

Δ_{CKM} and EW precision fits (2)

VC, Dekens, deVries, Mereghetti, Tong 2204.08440, 2311.00021

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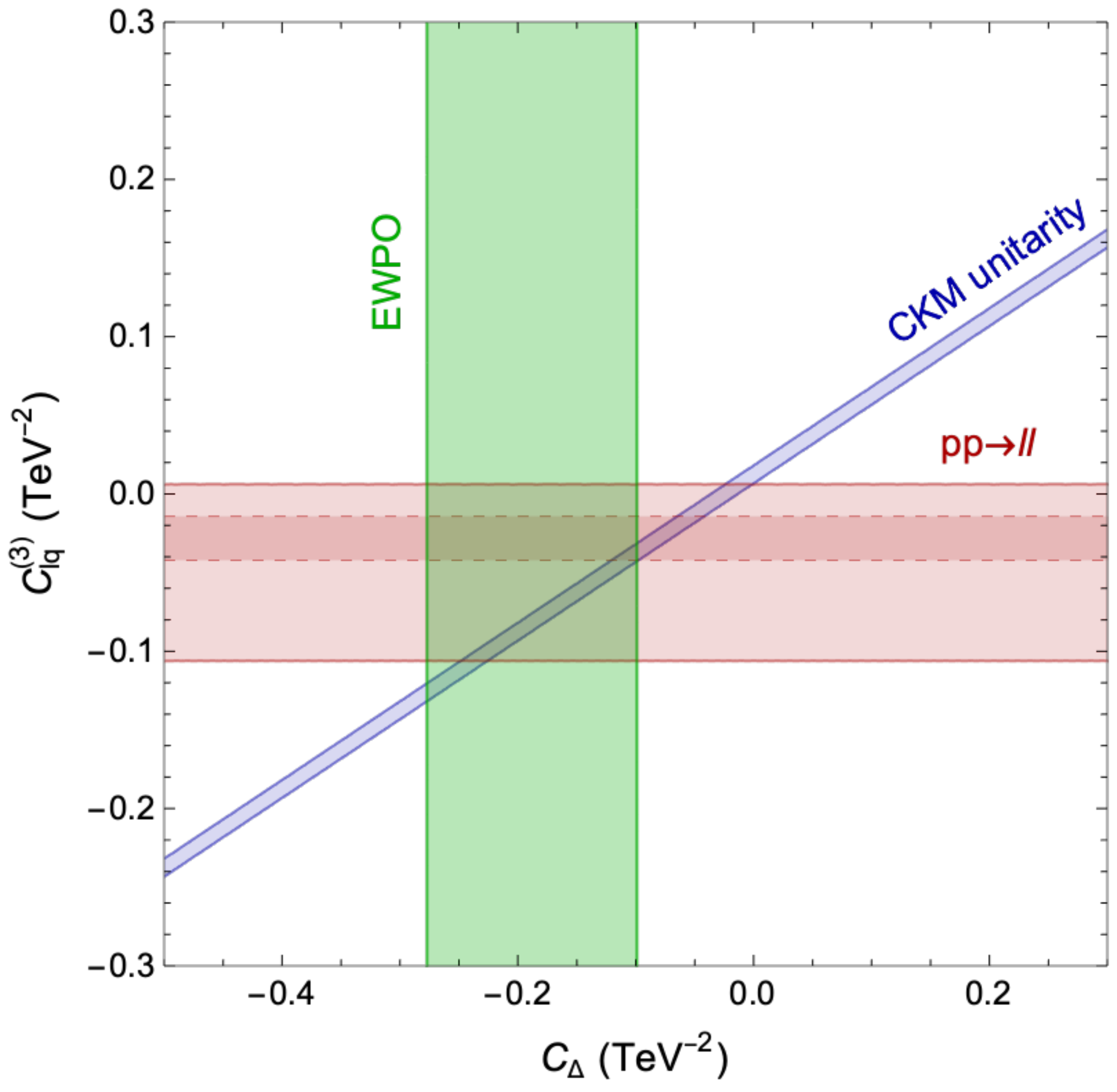

$$\Delta_{\rm CKM} = v^2 \left[C_\Delta - 2\, C_{lq}^{(3)} \right]$$

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

- Include Δ_{CKM} & decouple from m_W by turning on $C_{lq}^{(3)}$: but constraints from Drell-Yan at the LHC can't be ignored!

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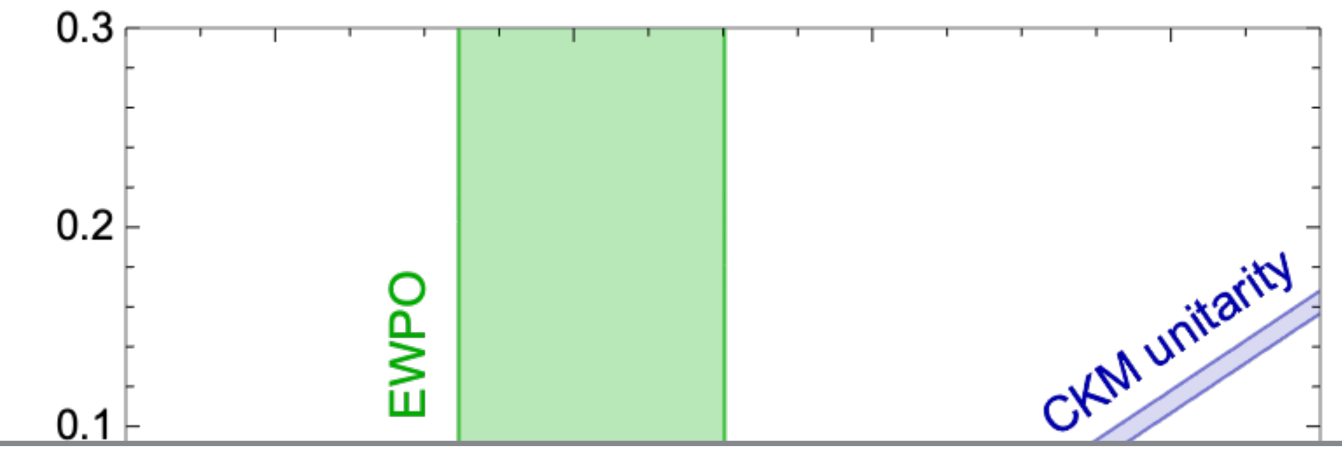


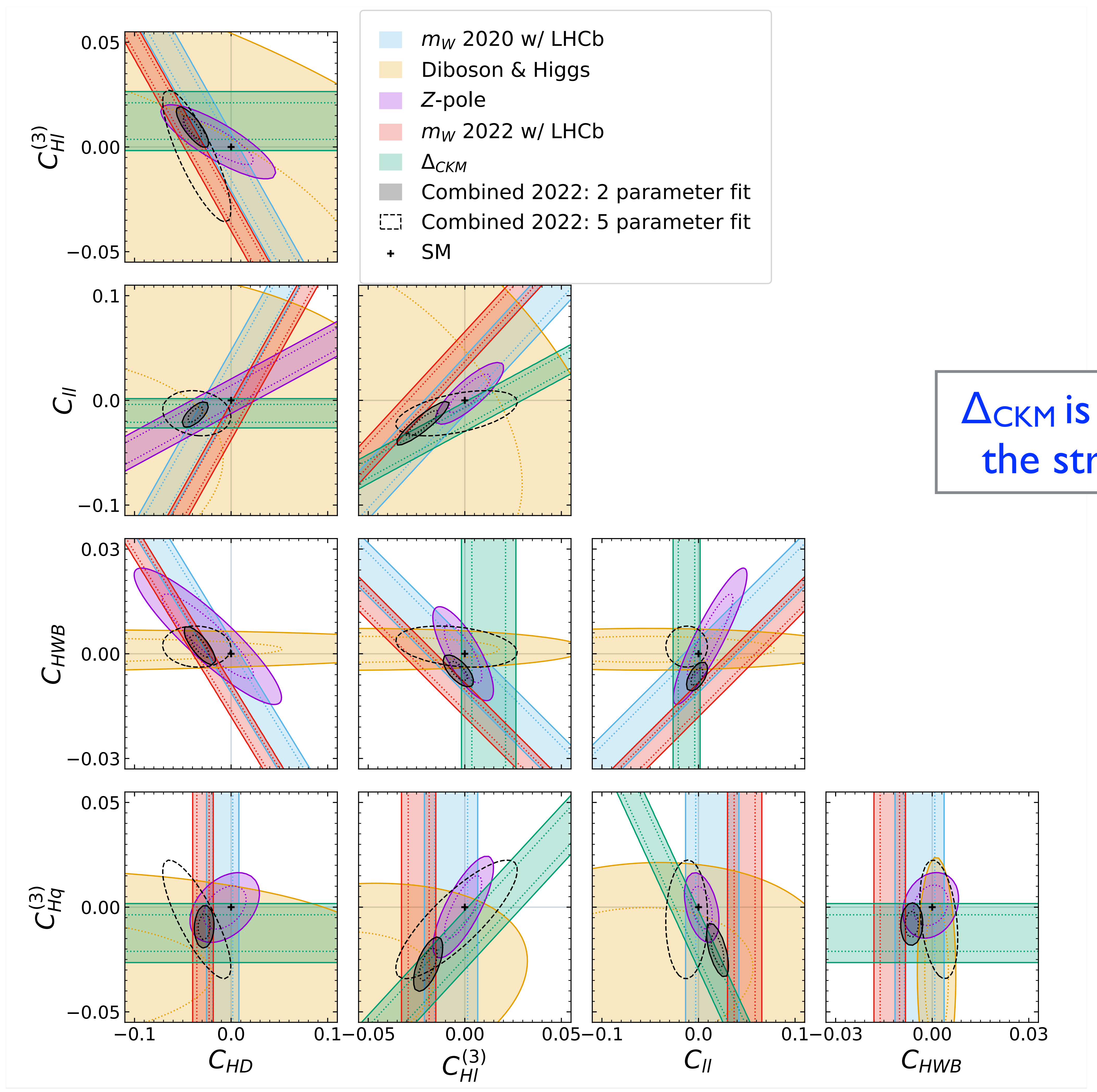
$$\Delta_{\rm CKM} = v^2 \left[C_\Delta - 2\, C_{lq}^{(3)} \right]$$

Quantitative point: best fit values for effective couplings with or without Δ_{CKM} change

Qualitative point: global analyses of 'electroweak precision observables' should be extended to include low-energy (such as Δ_{CKM}) and collider (such as Drell-Yan) observables

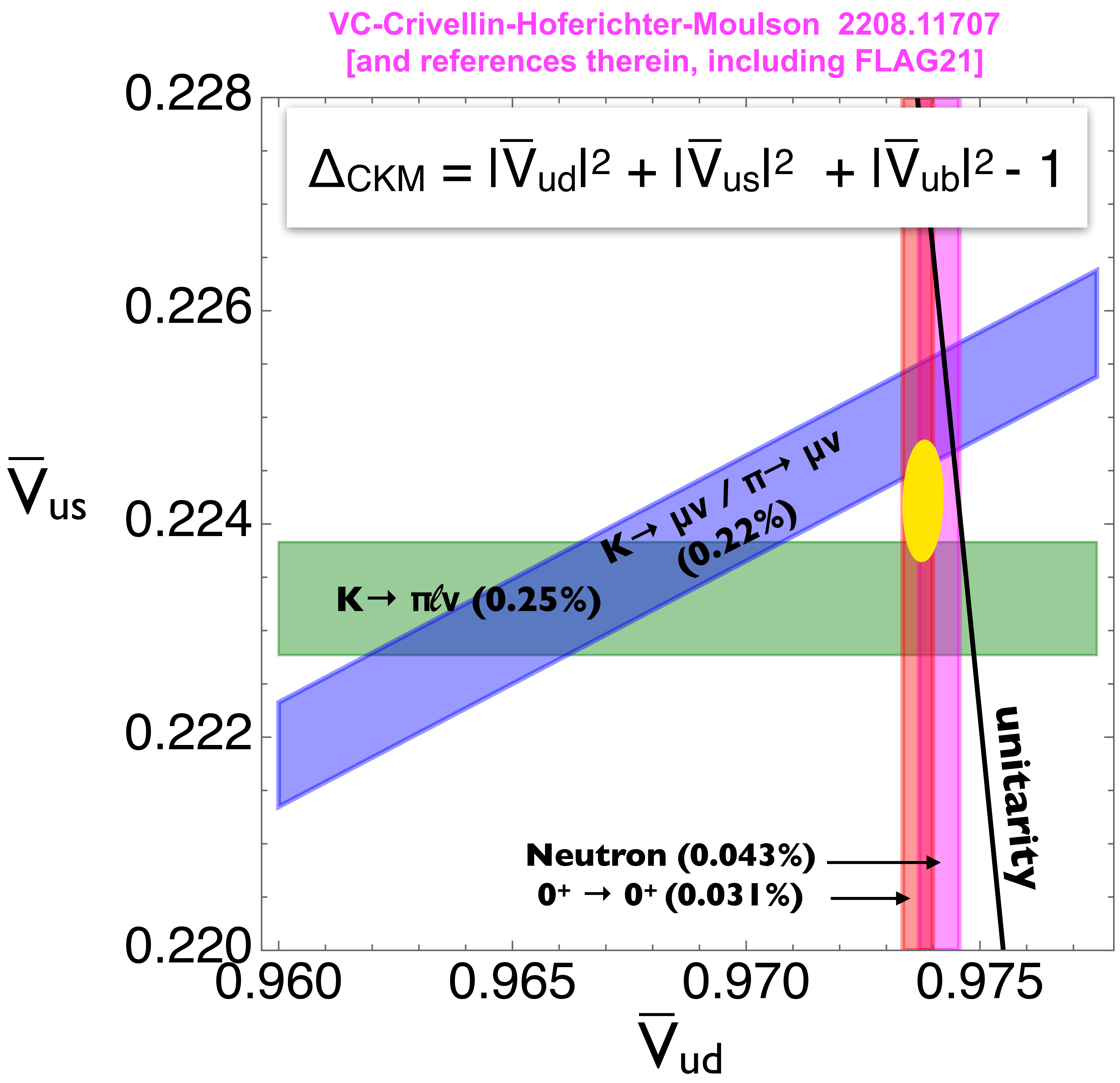
Δ_{CKM} and EW precision fits (3)

Bagnaschi et al 2204.05260



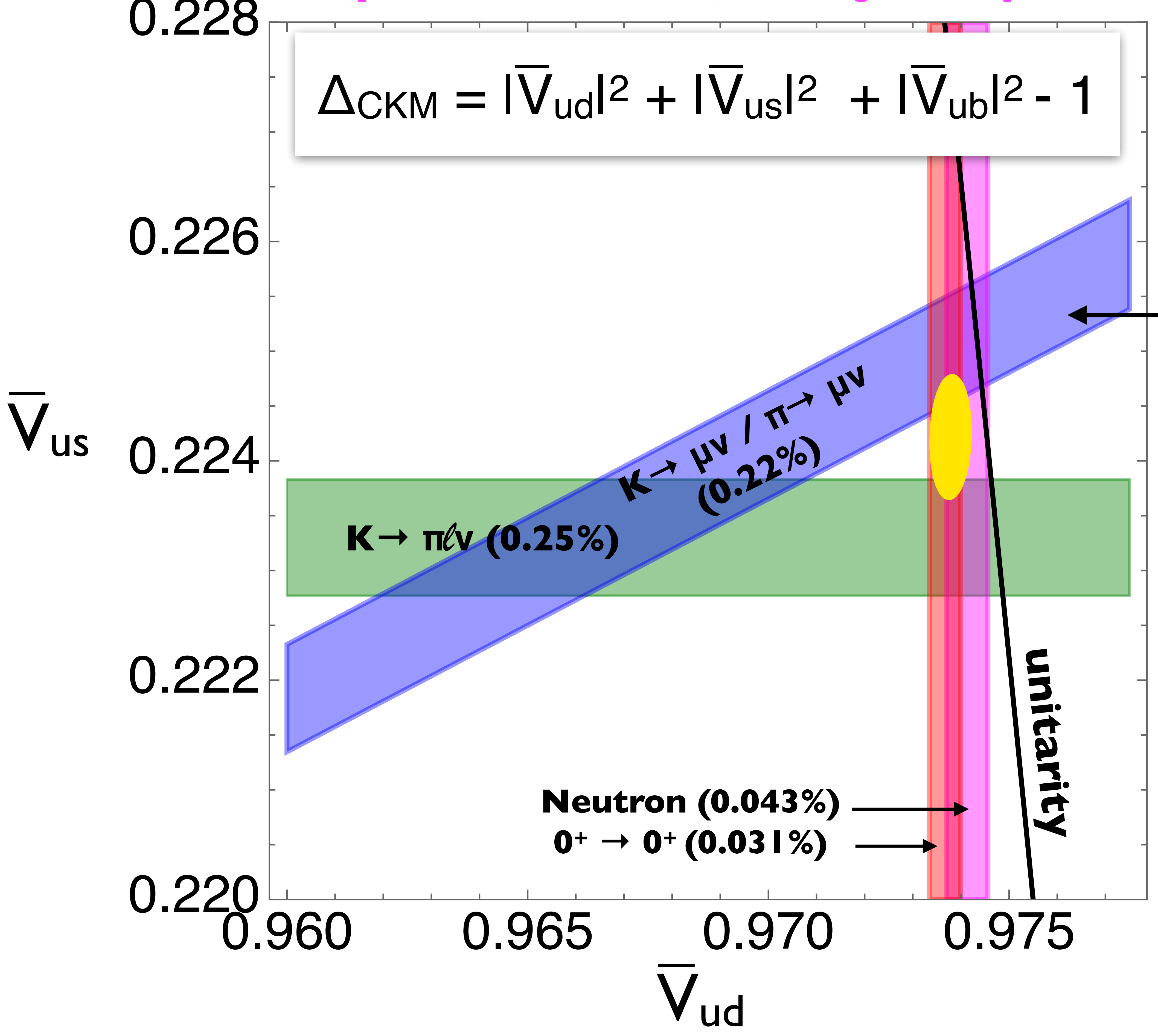
Δ_{CKM} is at the same level of the strongest constraints

Status of Cabibbo universality test



Status of Cabibbo universality test

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



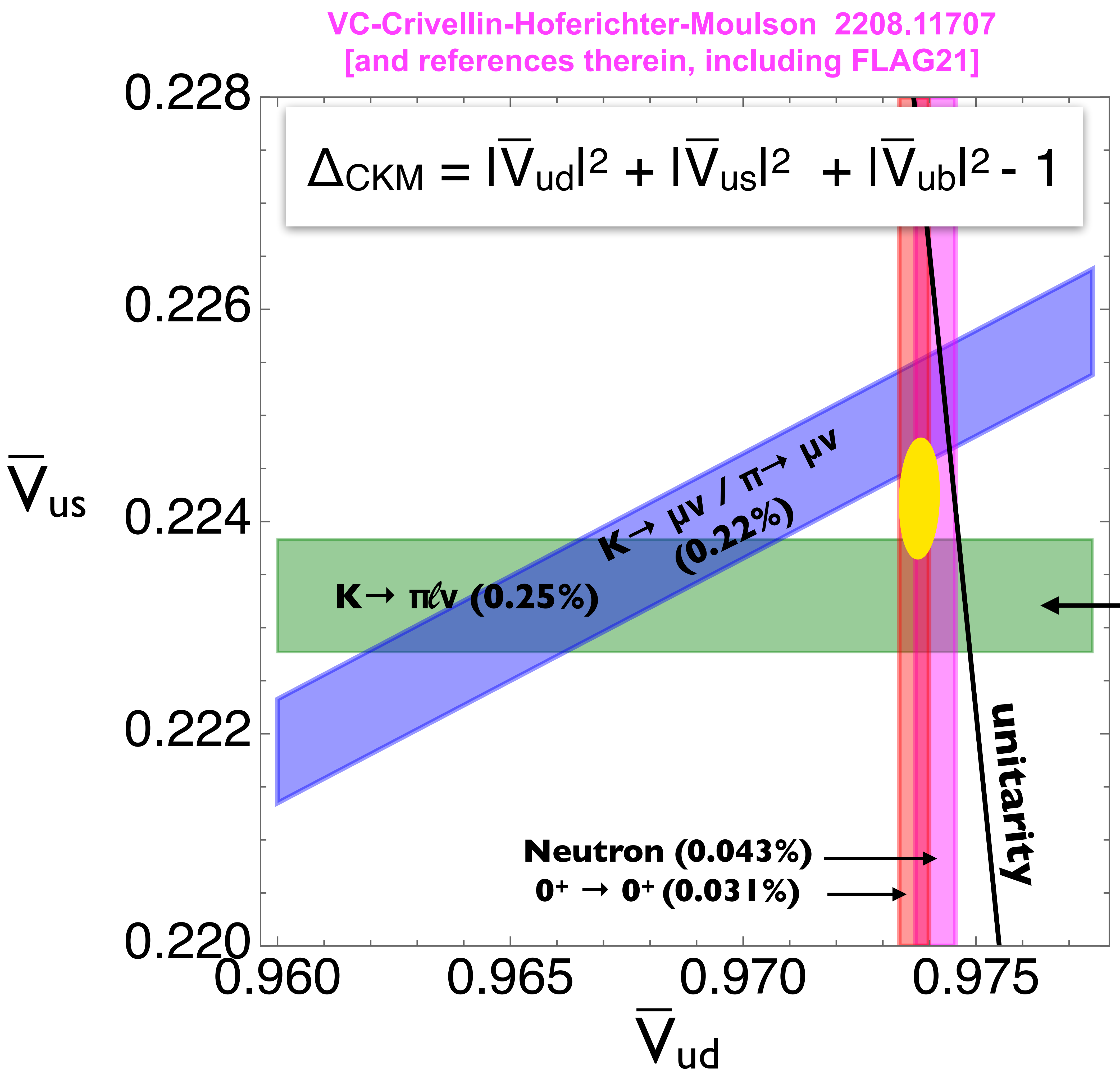
Ratio of decay constants s from Lattice QCD

QED + strong isospin-breaking: Lattice QCD and ChPT

ChPT: VC-Neufeld, 1102.0563
LQCD:
FLAG: 2111.09849
Di Carlo et al., 1904.08731
Boyle et al., 2211.12865

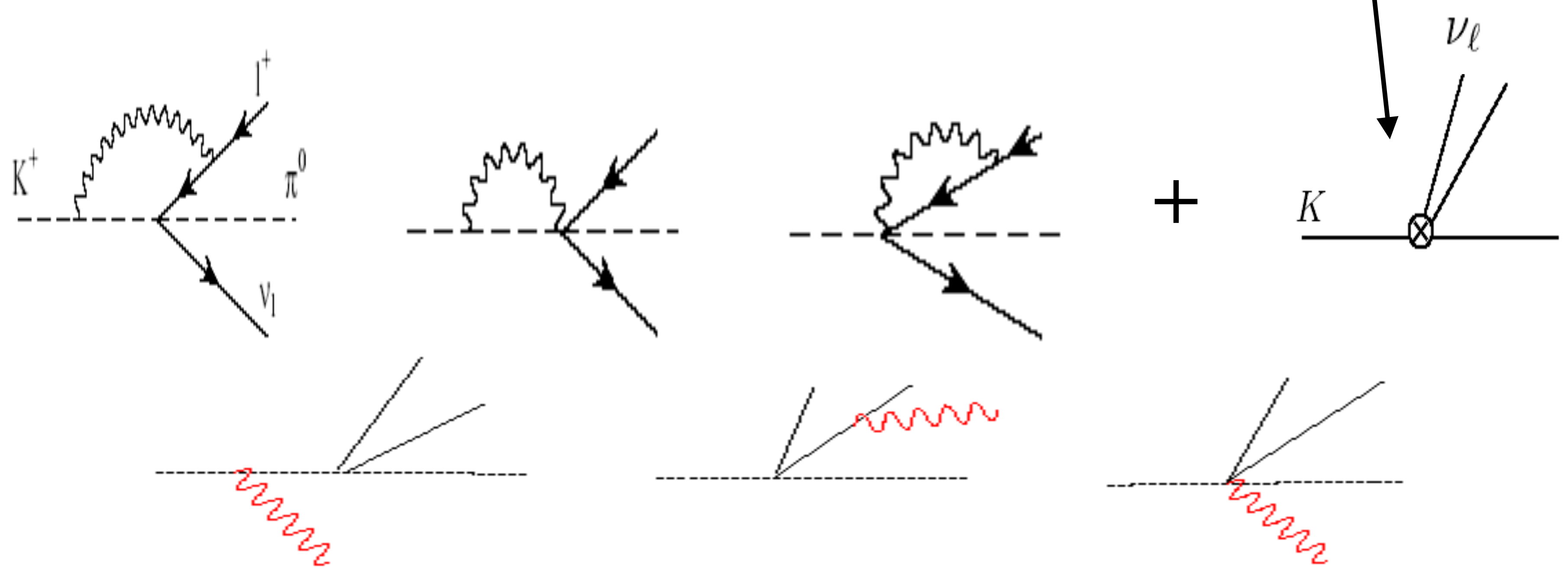
No contact (LEC): contribution cancels in the ratio!

Status of Cabibbo universality test



<π |V|K> form factor from Lattice QCD FLAG: 2111.09849

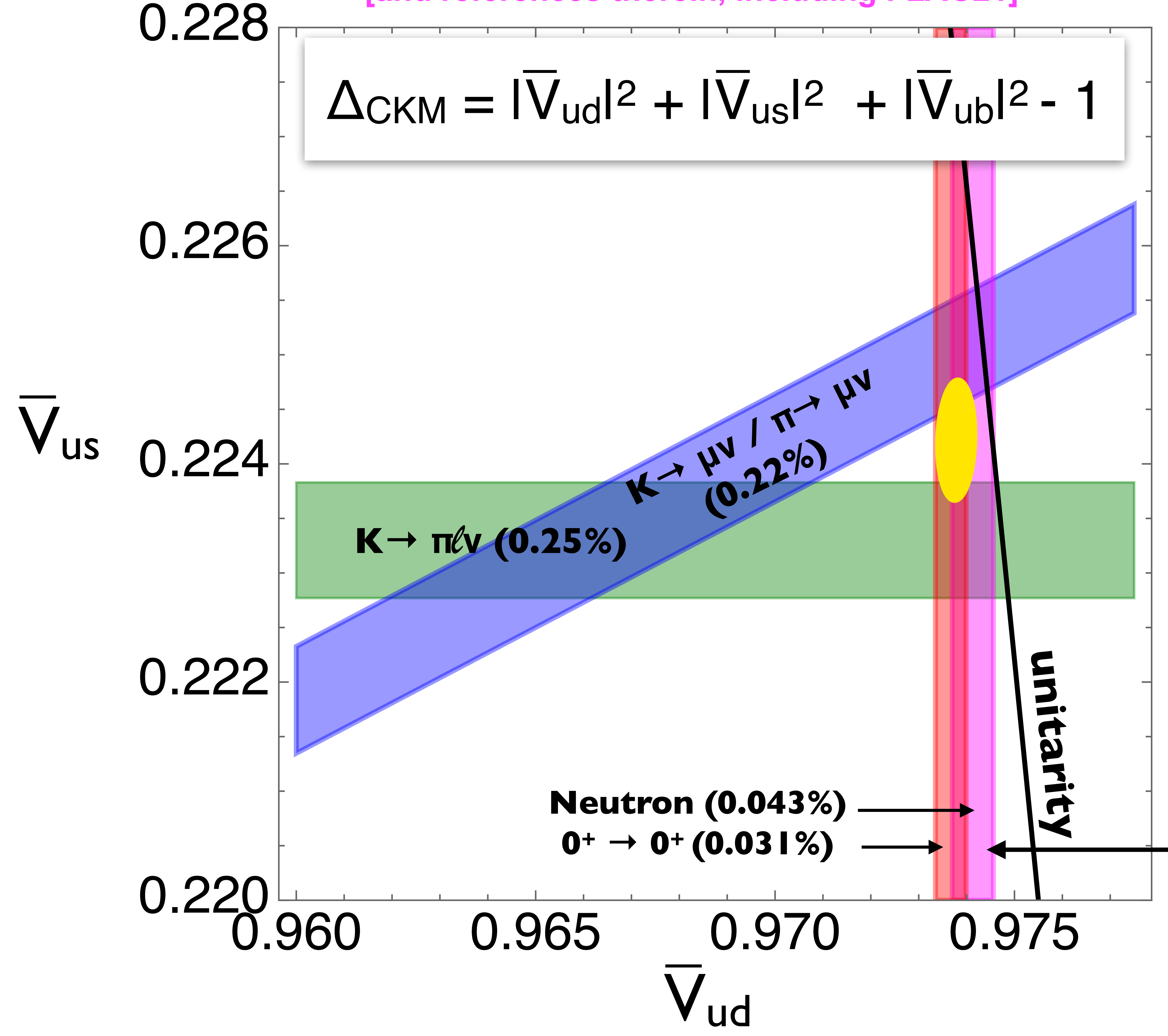
QED + strong isospin-breaking: ChPT + LECs estimated with dispersive methods and LQCD



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

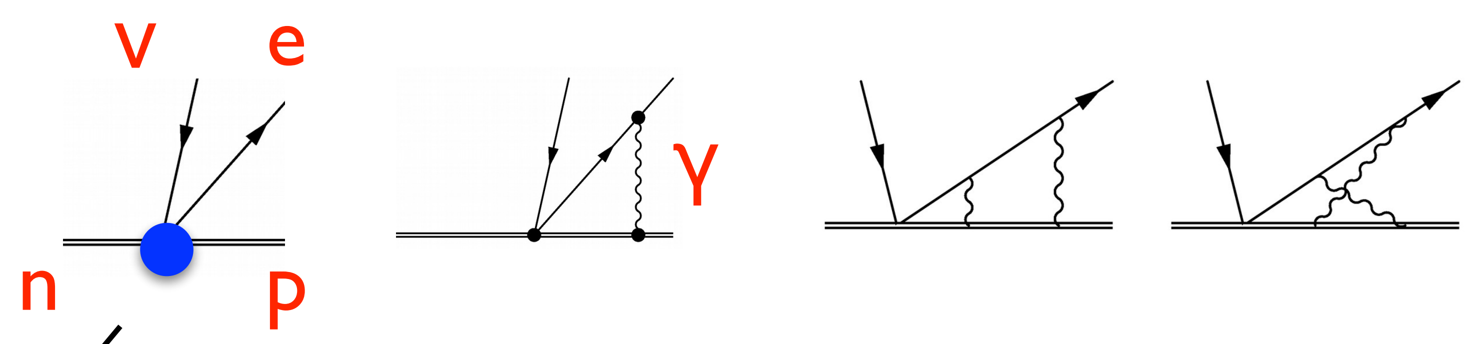
Status of Cabibbo universality test

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



τ_n and <p|A|n> form experiment (use most precise results)

<p|V|n> with QED: ChPT + LECs estimated with dispersive methods and LQCD

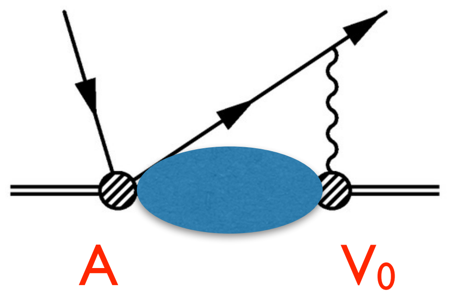


$$g_V(\mu_e) = U(\mu_e, \Lambda_\chi) \left[1 + \overline{\Box}^V_{\rm Had} + \frac{\alpha(\Lambda_\chi)}{\pi}\,\kappa\right] U(\Lambda_\chi, \mu_W)\; C_\beta(\mu_W)$$

NLL RGE in ChPT and pion-less EFT

Non-perturbative contribution

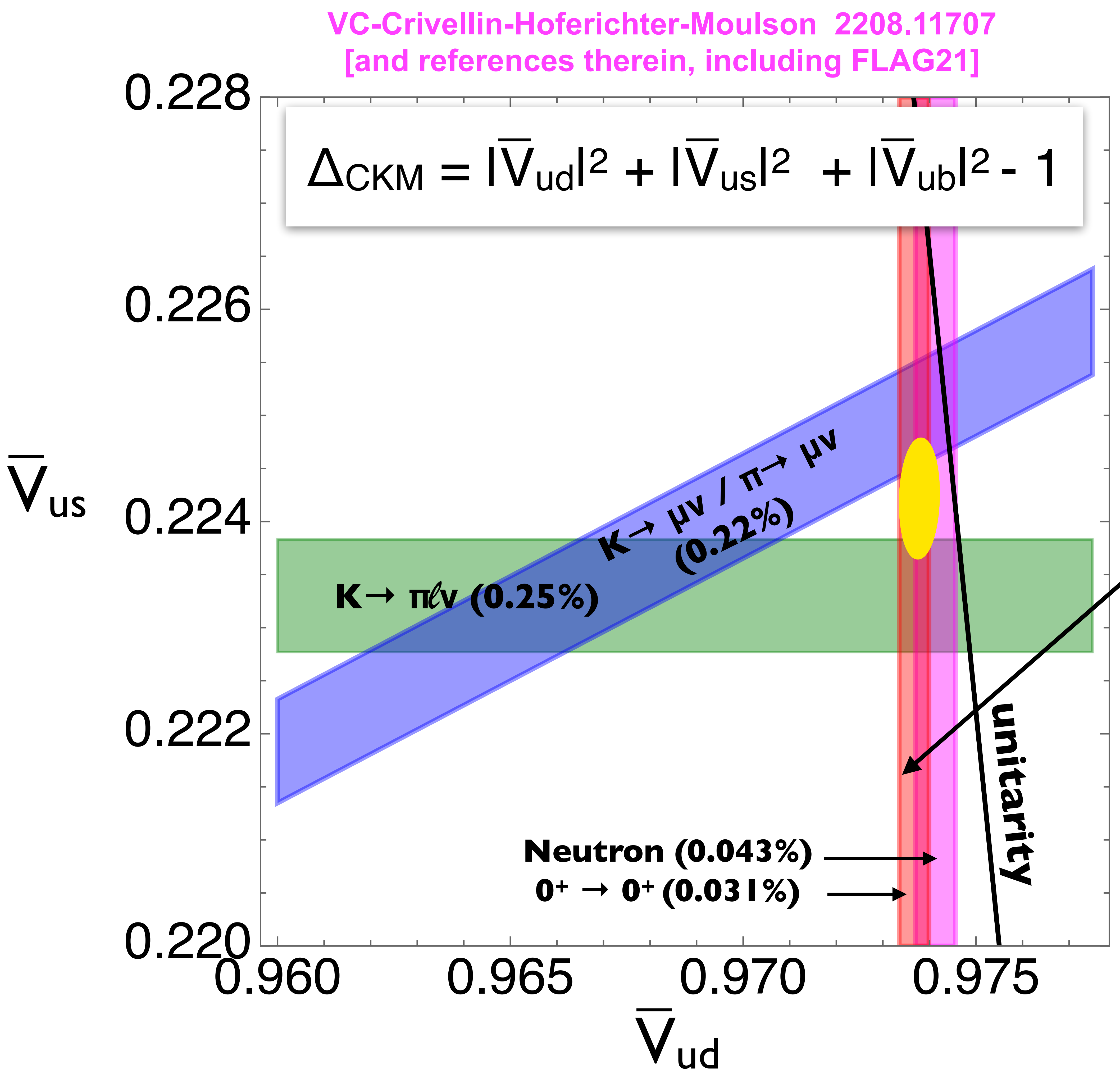
NLL RGE in LEFT



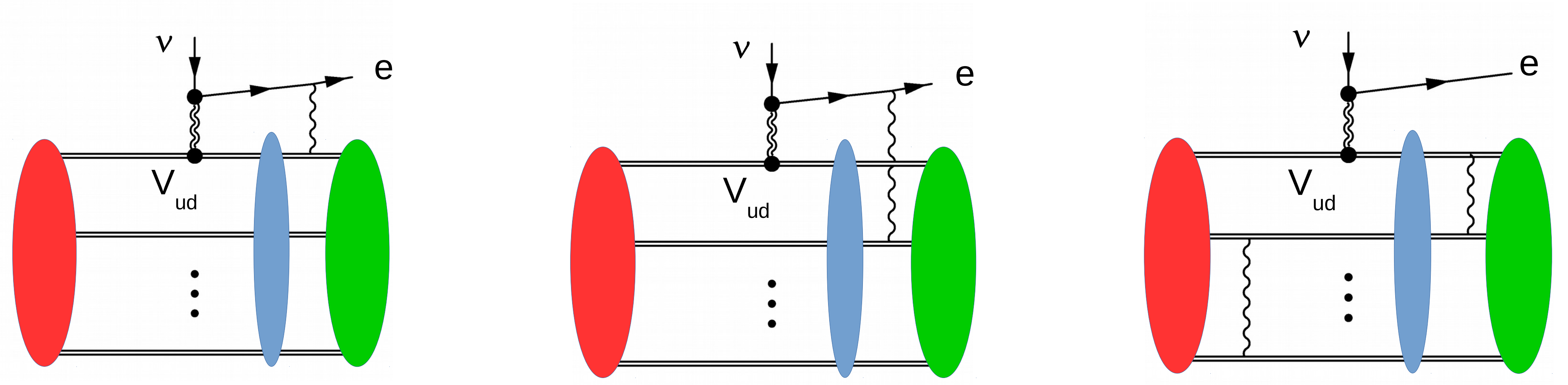
Wilson Coefficient at $\mu_W \sim m_W$

Matching and running: VC-Dekens-Mereghetti-Tomalak 2306.03138
Input from dispersive theory and LQCD
[Seng et al. 1807.10197, 2308.16755]

Status of Cabibbo universality test



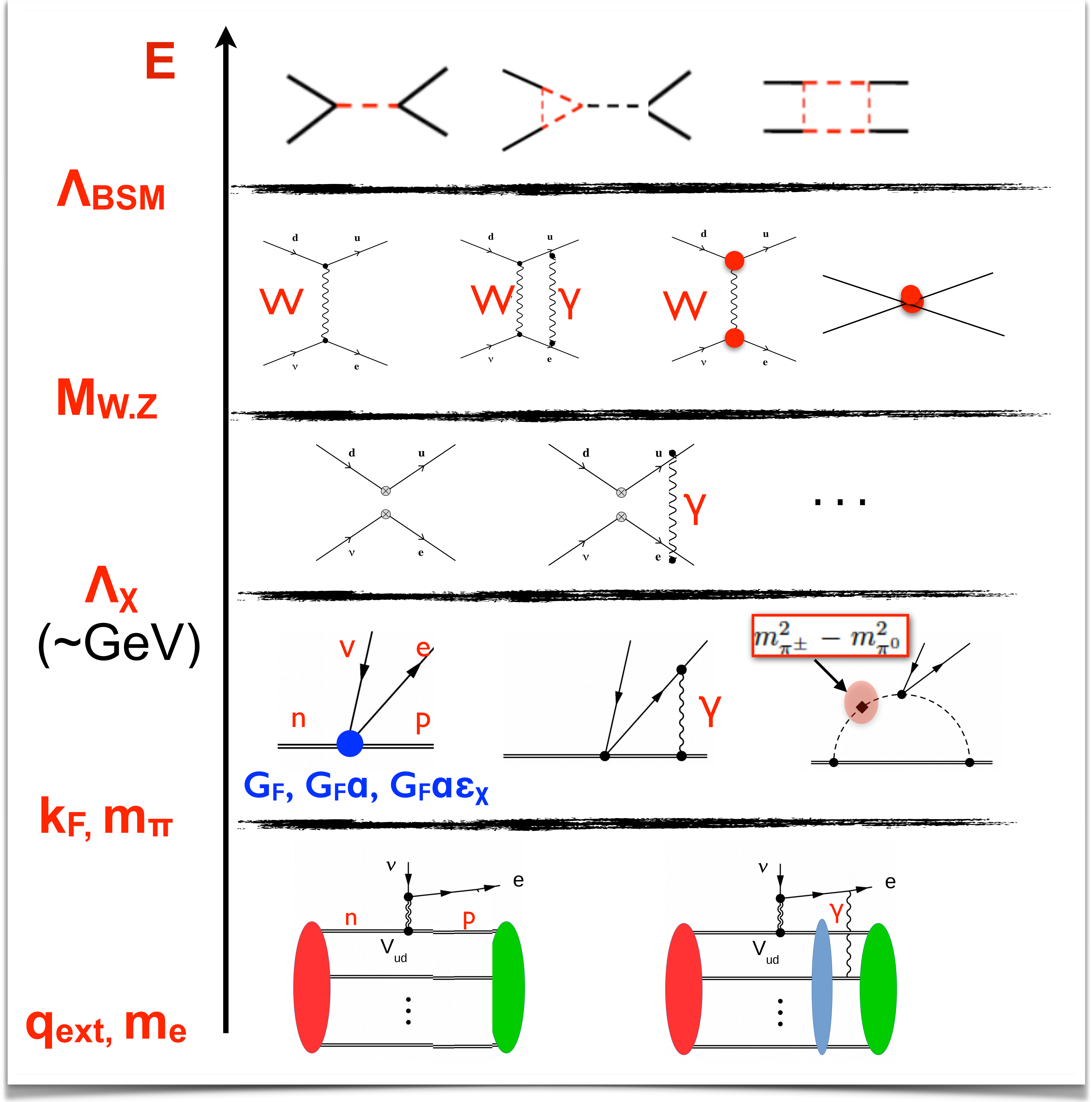
Long history. Current bottleneck from nuclear-structure dependent radiative corrections



Towner-Hardy 2020 PRC
Gorchtein, Seng 2311.00044 and references therein

EFT for semileptonic CC processes

Widely separated scales: Λ_{BSM}, M_W, Λ_χ, m_π, m_e ~ q_{ext} ⇒ Tackle the problem through a tower of EFTs



One nucleon

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

Multi nucleons

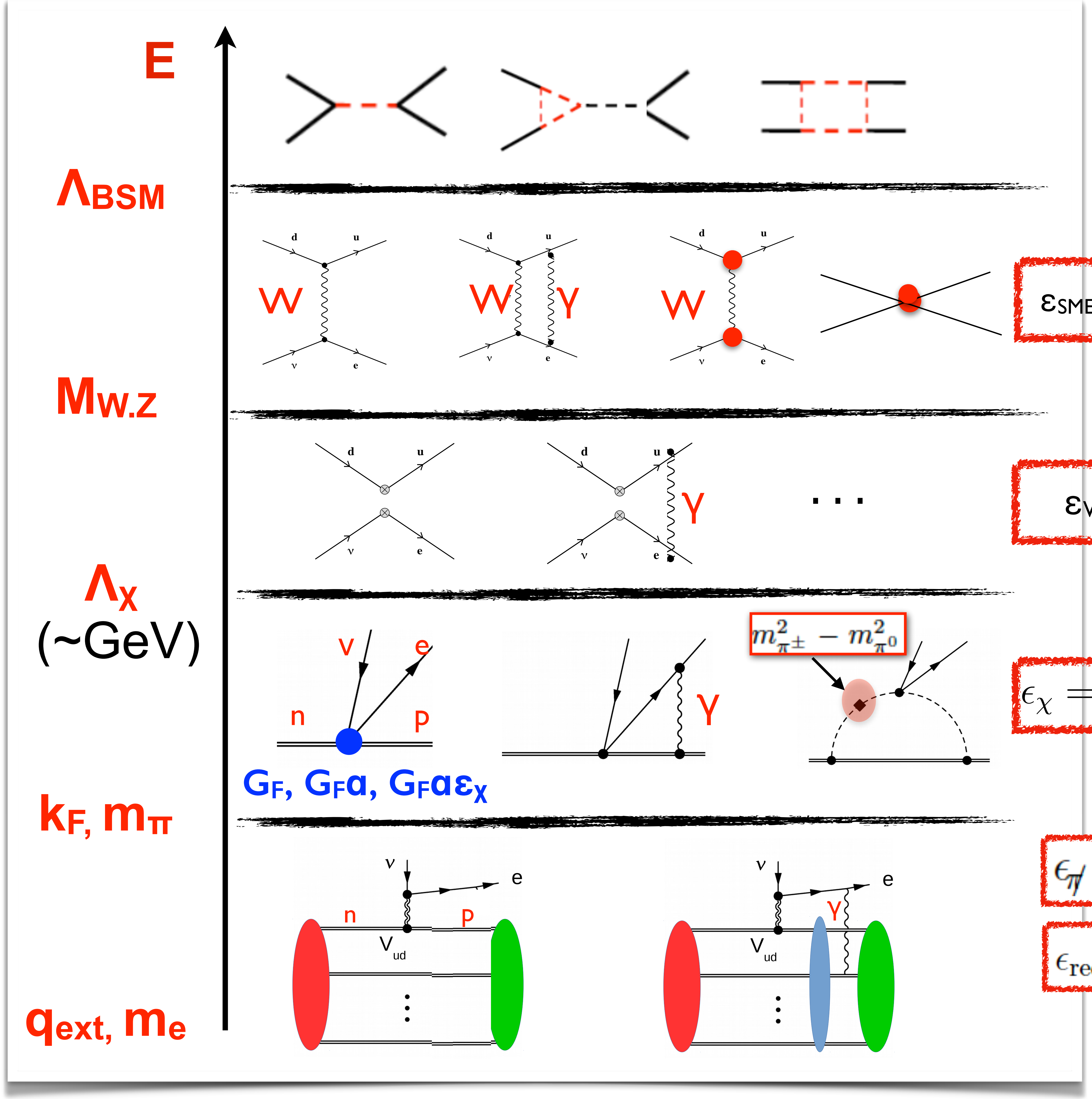
VC, W. Dekens,, J.de Vries, S. Gandolfi, M. Hoferichter, E, Mereghetti, 2405.18469 & 2405.18464

Point-like nucleus

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

EFT for semileptonic CC processes

Widely separated scales: Λ_{BSM}, M_W, Λ_χ, m_π, $m_e \sim q_{ext}$ ⇒ Tackle the problem through a tower of EFTs



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

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

$\epsilon_\chi = \{k_F, m_{\pi,K}\}/\Lambda_\chi$

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

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

BSM

↓ *Perturbative matching*

Standard Model Effective Field Theory

↓ *Perturbative matching*

LEFT: Fermi Theory + QCD + QED

↓ *Non-perturbative matching: Lattice QCD, dispersion relations, data, …*

Chiral Perturbation Theory

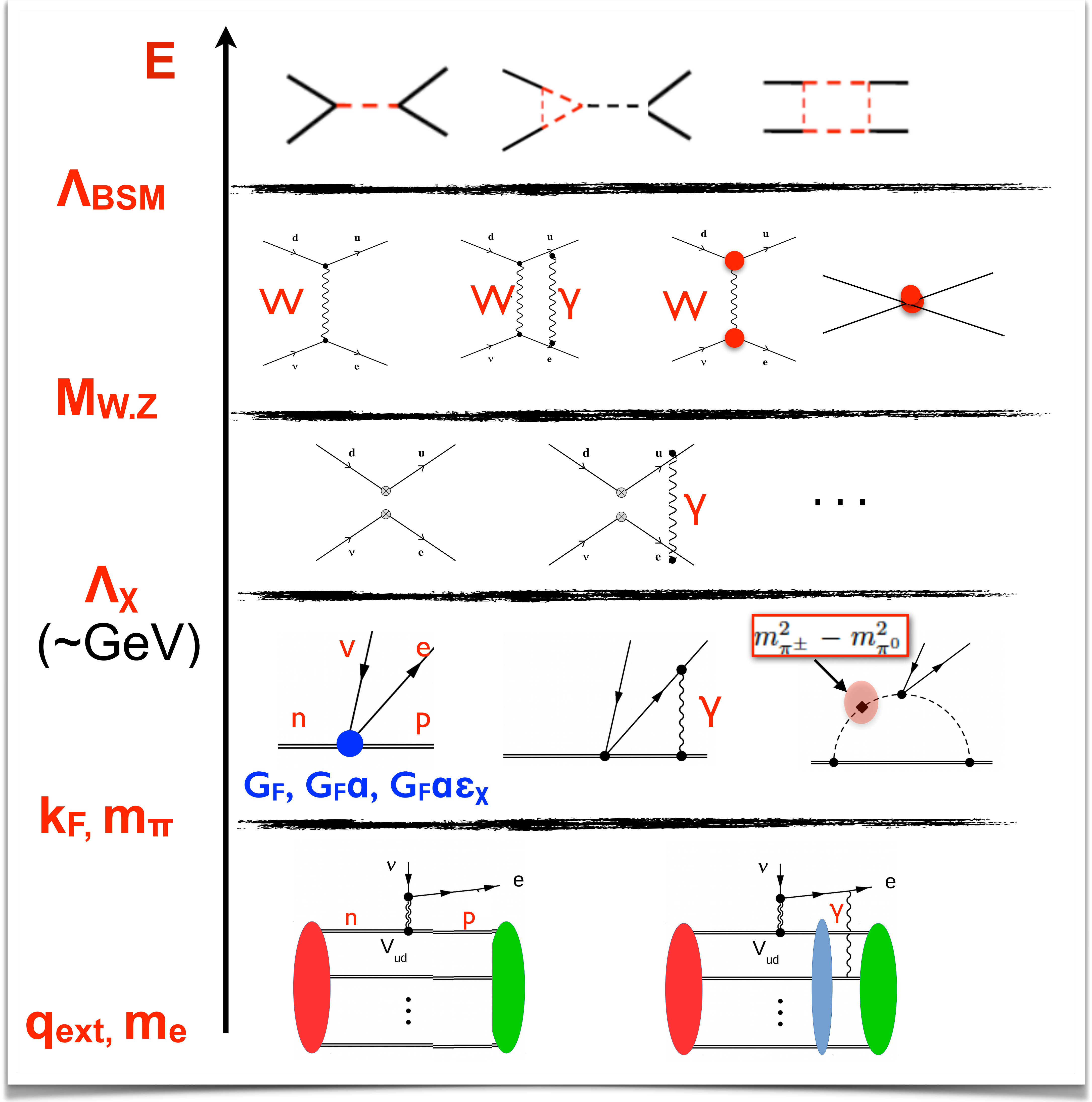
↓ *Integrate out pions*

Chiral & pion-less EFT

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

EFT for semileptonic CC processes

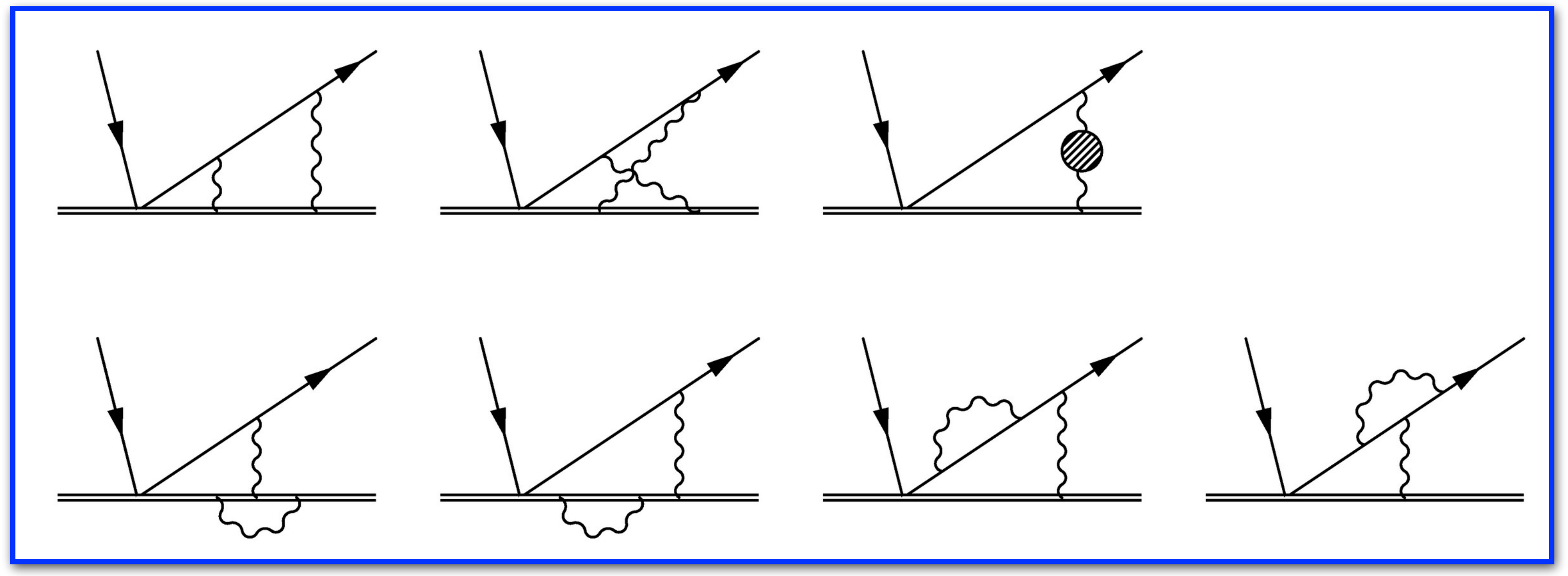
Widely separated scales: Λ_{BSM}, M_W, Λ_χ, m_π, $m_e \sim q_{ext}$ ⇒ Tackle the problem through a tower of EFTs



Single nucleon

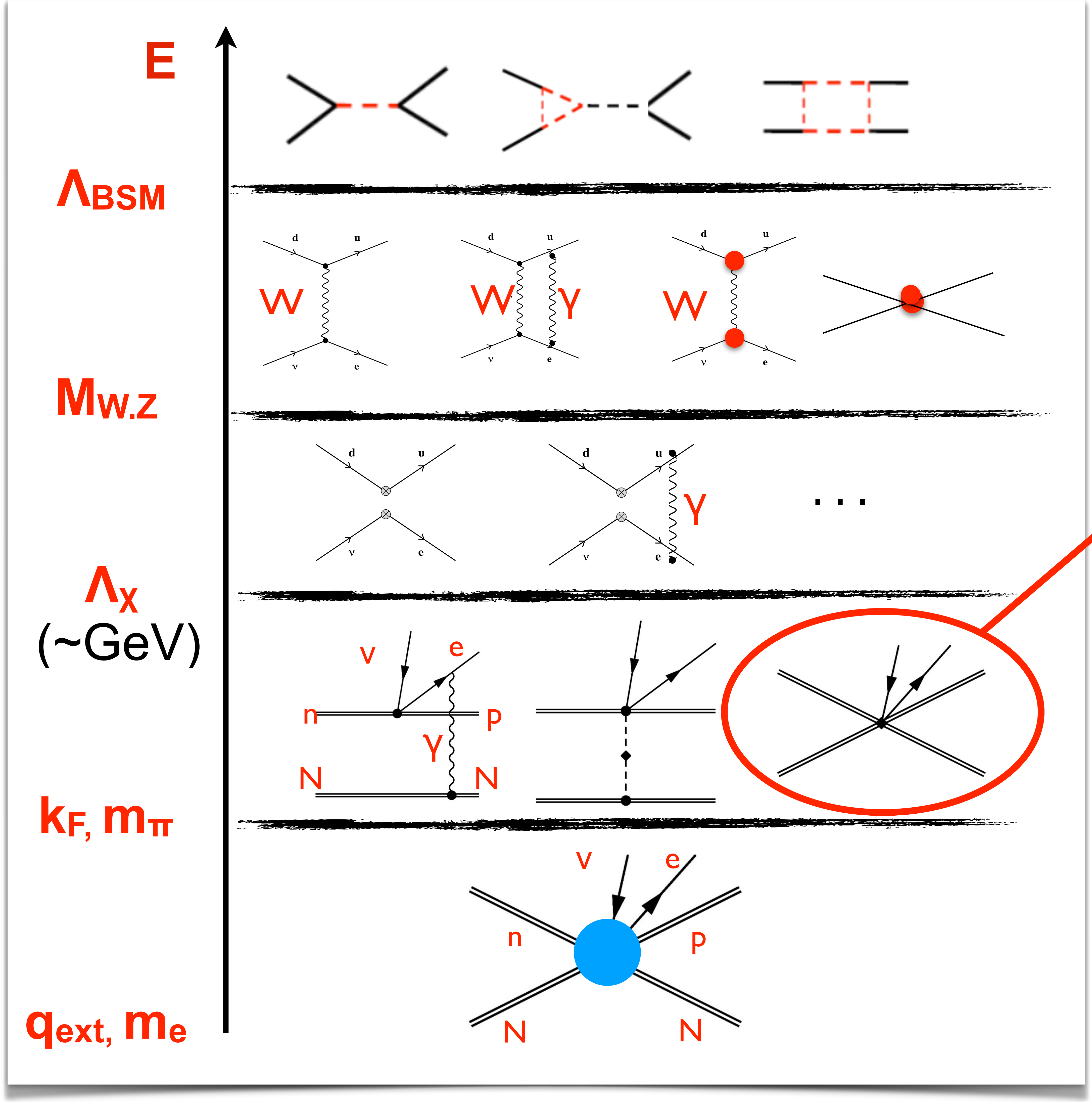
Larger radiative correction to neutron decay rate shifts V_{ud} by -0.013%

[effect due to difference in treatment of the NLL ~ $\alpha^2 \mathrm{Log}(m_N/m_e)$ terms]



EFT for semileptonic CC processes

Widely separated scales: Λ_{BSM}, M_W, Λ_χ, m_π, $m_e \sim q_{ext}$ ⇒ Tackle the problem through a tower of EFTs



Multi nucleon

Hard photons induce NN → NNeν contacts ⇒

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

Renormalization ⇒ $g_{V1,V2}^{NN} \sim \dfrac{1}{F_\pi^2 \Lambda_\chi}$

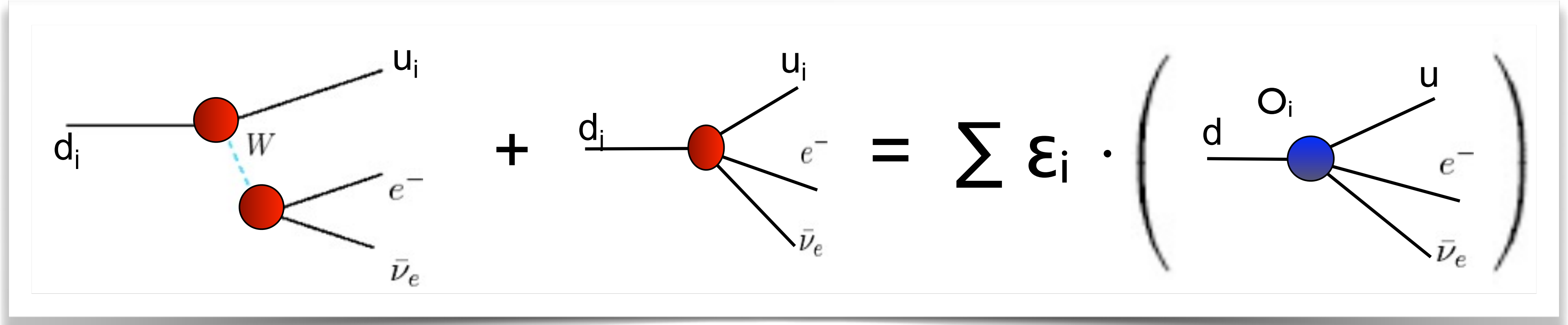
δ_{NS} in EFT: weak two body potentials of $O(G_F \alpha \varepsilon_\chi)$

(Recall $m_\pi/\Lambda_\chi \sim 0.1$)

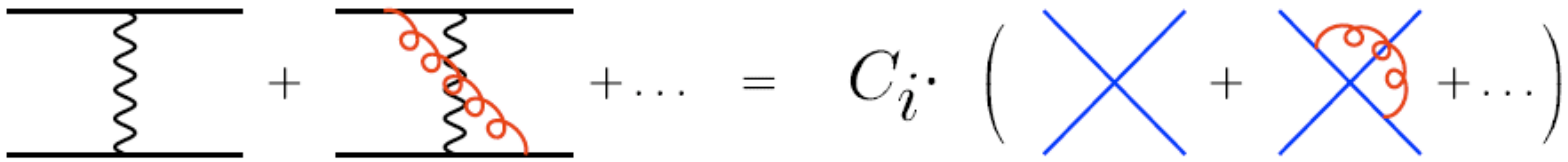
Two currently unknown LECs!

SMEFT → LEFT matching

- Wilson coefficients determined from the matching condition $A_{SMEFT} = A_{LEFT}$
- Tree-level matching for BSM operators determines $\varepsilon_{L,R,S,P,T}$



- Loop-level matching for SM operators (QED / QCD loops needed for precision)



"Full" theory (higher scale EFT) "Effective theory" (lower scale EFT)

$$\mathcal{L}_{CC} \to -\frac{G_F V_{ud}}{\sqrt{2}} \, C_\beta(\mu) \; \bar{e}_a \gamma_\alpha (1-\gamma_5)\nu_b \cdot \bar{u}\gamma^\alpha (1-\gamma_5) d + \ldots$$

$$C_\beta(\mu) = 1 + \frac{\alpha}{\pi} \log \frac{M_Z}{\mu} + \ldots$$ ⟵ Large log @ $\mu \ll M_Z$

Corrections to V_{ud} and V_{us}

- General case

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

$\varepsilon_S^{(s)}$: 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

Electroweak precision observables

Obs.	Expt. Value		SM Prediction		Obs.	Expt. Value		SM Prediction	
Γ_Z (GeV)	2.4955(23)	[53, 113]	2.49414(56)	[60]	m_W (GeV)	80.4335(94)	[39]	80.3545(42)	[60]
σ^0_{had} (nb)	41.480(33)	[53, 113]	41.4929(53)	[60]	Γ_W (GeV)	2.085(42)	[3]	2.08782(52)	[60]
R^0_e	20.804(50)	[53, 113]	20.7464(63)	[60]	R_{Wc}	0.49(4)	[3]	0.50	
R^0_μ	20.784(34)	[53, 113]			R_σ	0.998(41)	[114]	1	
R^0_τ	20.764(45)	[53, 113]			$\text{Br}(W \to e\nu)$	0.1071(16)	[3]	0.108386(24)	[60]
$A^{0,e}_{\text{FB}}$	0.0145(25)	[53, 113]	0.016191(70)	[60]	$\text{Br}(W \to \mu\nu)$	0.1063(15)	[3]	0.108386(24)	[60]
$A^{0,\mu}_{\text{FB}}$	0.0169(13)	[53, 113]			$\text{Br}(W \to \tau\nu)$	0.1138(21)	[3]	0.108386(24)	[60]
$A^{0,\tau}_{\text{FB}}$	0.0188(17)	[53, 113]			$\frac{\Gamma(W\to\mu\nu)}{\Gamma(W\to e\nu)}$	0.982(24)	[3]	1	
R^0_b	0.21629(66)	[53]	0.215880(19)	[60]	$\frac{\Gamma(W\to\mu\nu)}{\Gamma(W\to e\nu)}$	1.020(19)	[3]		
R^0_c	0.1721(30)	[53]	0.172198(20)	[60]	$\frac{\Gamma(W\to\mu\nu)}{\Gamma(W\to e\nu)}$	1.003(10)	[3]		
$A^{0,b}_{\text{FB}}$	0.0996(16)	[53]	0.10300(23)	[60]	$\frac{\Gamma(W\to\tau\nu)}{\Gamma(W\to e\nu)}$	0.961(61)	[3]		
$A^{0,c}_{\text{FB}}$	0.0707(35)	[53]	0.07358(18)	[60]	$\frac{\Gamma(W\to\tau\nu)}{\Gamma(W\to\mu\nu)}$	0.992(13)	[3]		
$\mathcal{A}_c$	0.67(3)	[53]	0.66775(14)	[60]	$A_4(0-0.8)$	0.0195(15)	[115]	0.0144(7)	[116]
$\mathcal{A}_b$	0.923(20)	[53]	0.934727(25)	[60]	$A_4(0.8-1.6)$	0.0448(16)	[115]	0.0471(17)	[116]
$\mathcal{A}_e$	0.1516(21)	[53]	0.14692(32)	[60]	$A_4(1.6-2.5)$	0.0923(26)	[115]	0.0928(21)	[116]
$\mathcal{A}_\mu$	0.142(15)	[53]			$A_4(2.5-3.6)$	0.1445(46)	[115]	0.1464(21)	[116]
$\mathcal{A}_\tau$	0.136(15)	[53]			$g_V^{(u)}$	0.201(112)	[117]	0.192	[118]
$\mathcal{A}_e^{\tau\,\text{pol}}$	0.1498(49)	[53]			$g_V^{(d)}$	-0.351(251)	[117]	-0.347	[118]
$\mathcal{A}_\tau^{\tau\,\text{pol}}$	0.1439(43)	[53]			$g_A^{(u)}$	0.50(11)	[117]	0.501	[118]
$\mathcal{A}_s$	0.895(91)	[119]	0.935637(26)	[60]	$g_A^{(d)}$	-0.497(165)	[117]	-0.502	[118]
R_{uc}	0.166(9)	[3]	0.172220(20)	[60]					

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