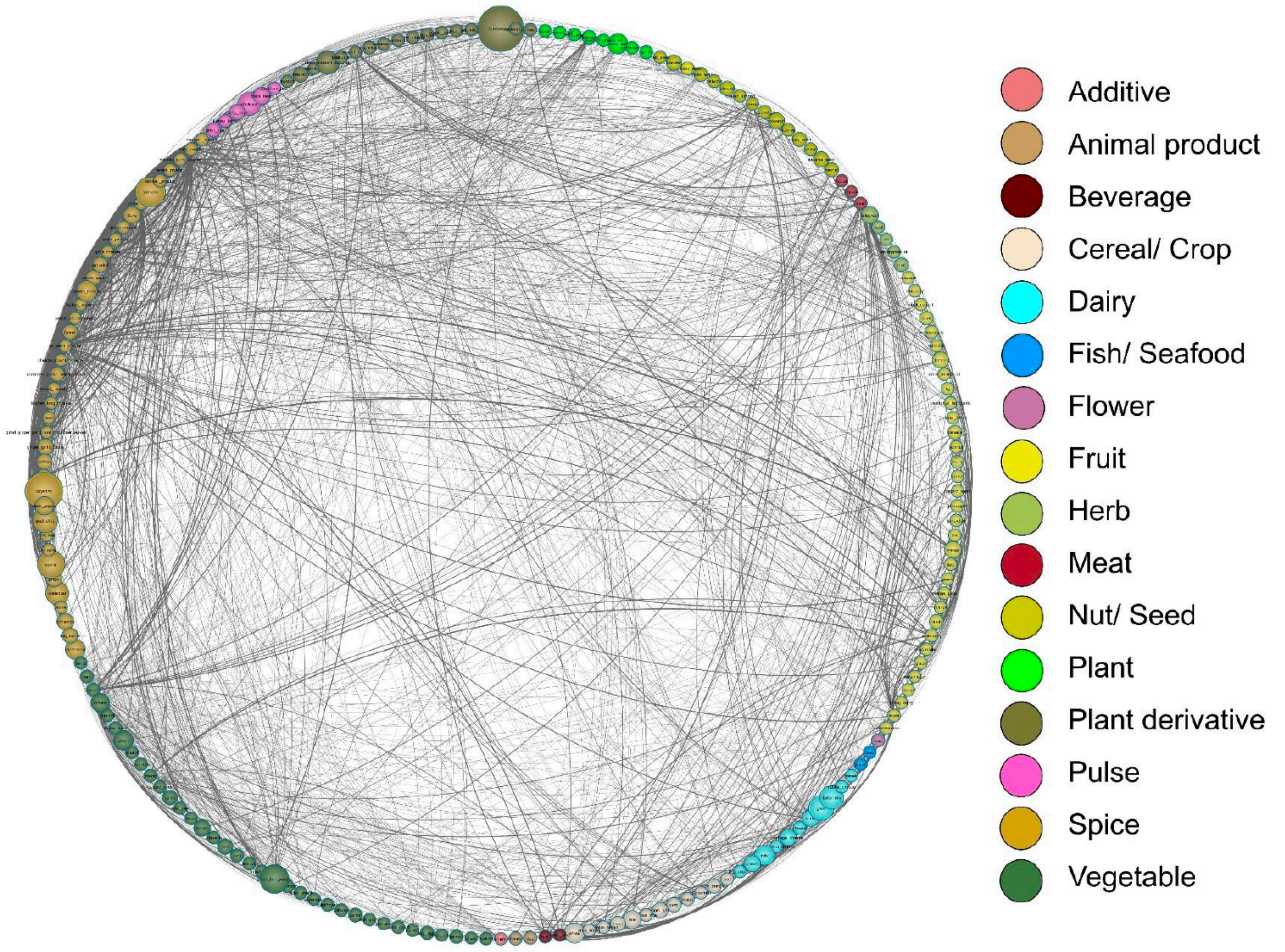
Making friends with flavor

1502.03815



Tom Tong
Center for Particle Physics Siegen, University of Siegen

CPPS Retreat
16 February 2024

Freeze out
Freeze in
and the Flavon

One model working at two scales

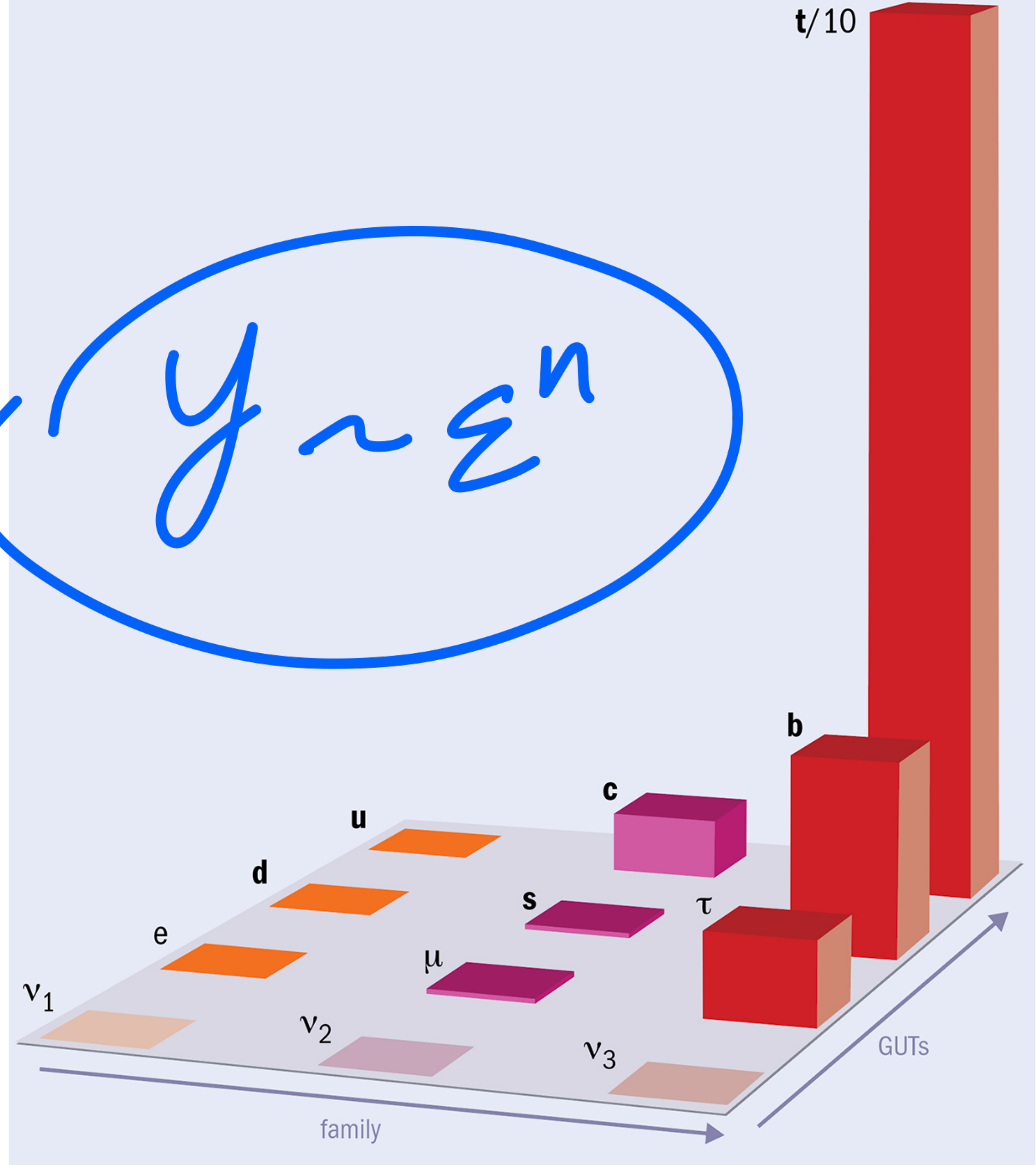
Universität Siegen / TP1 Theoretical Particle Physics
CPPS Center for Particle Physics Siegen

Tom Tong

arXiv: 2307.14972, published in *JCAP*

Co-directed by Rusa Mandal

Hierarchy in the fermion mass

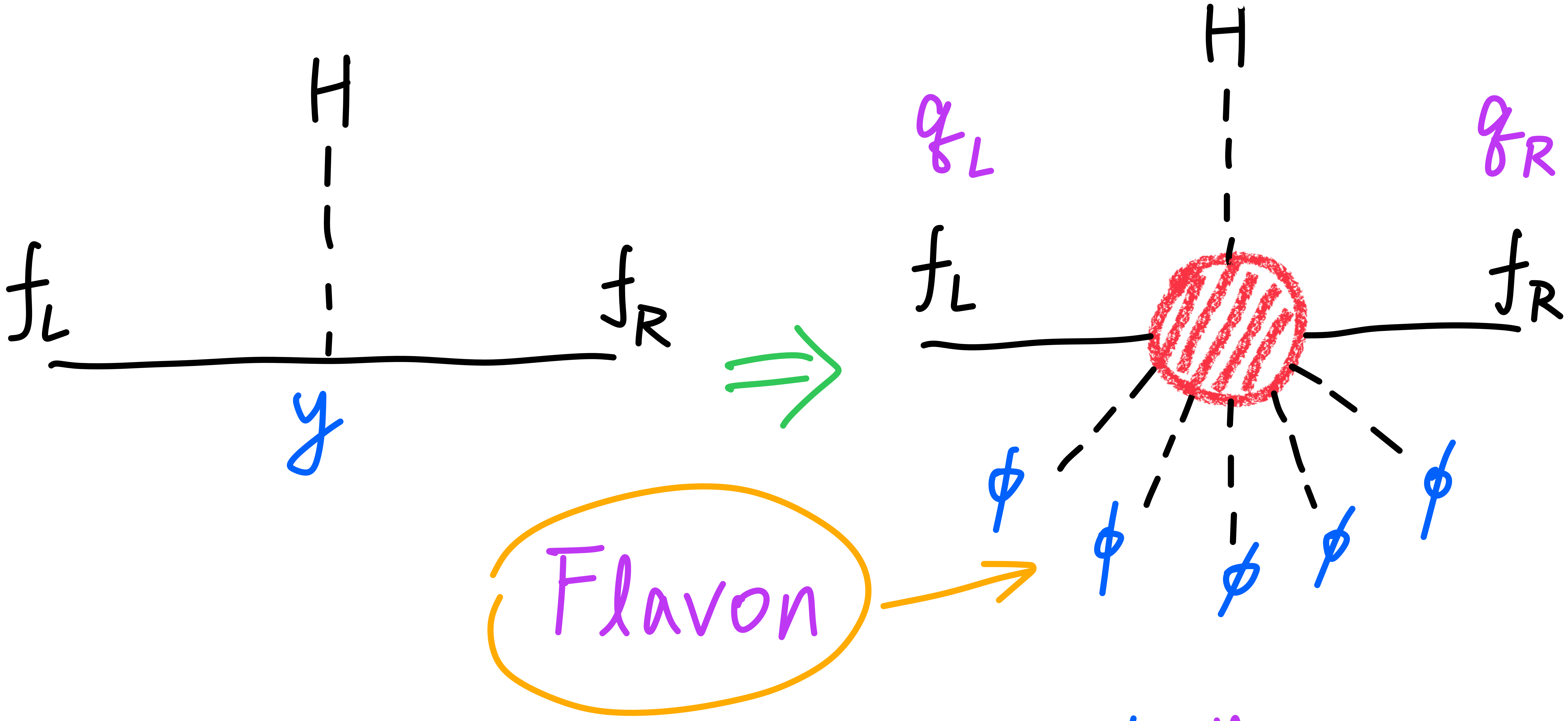


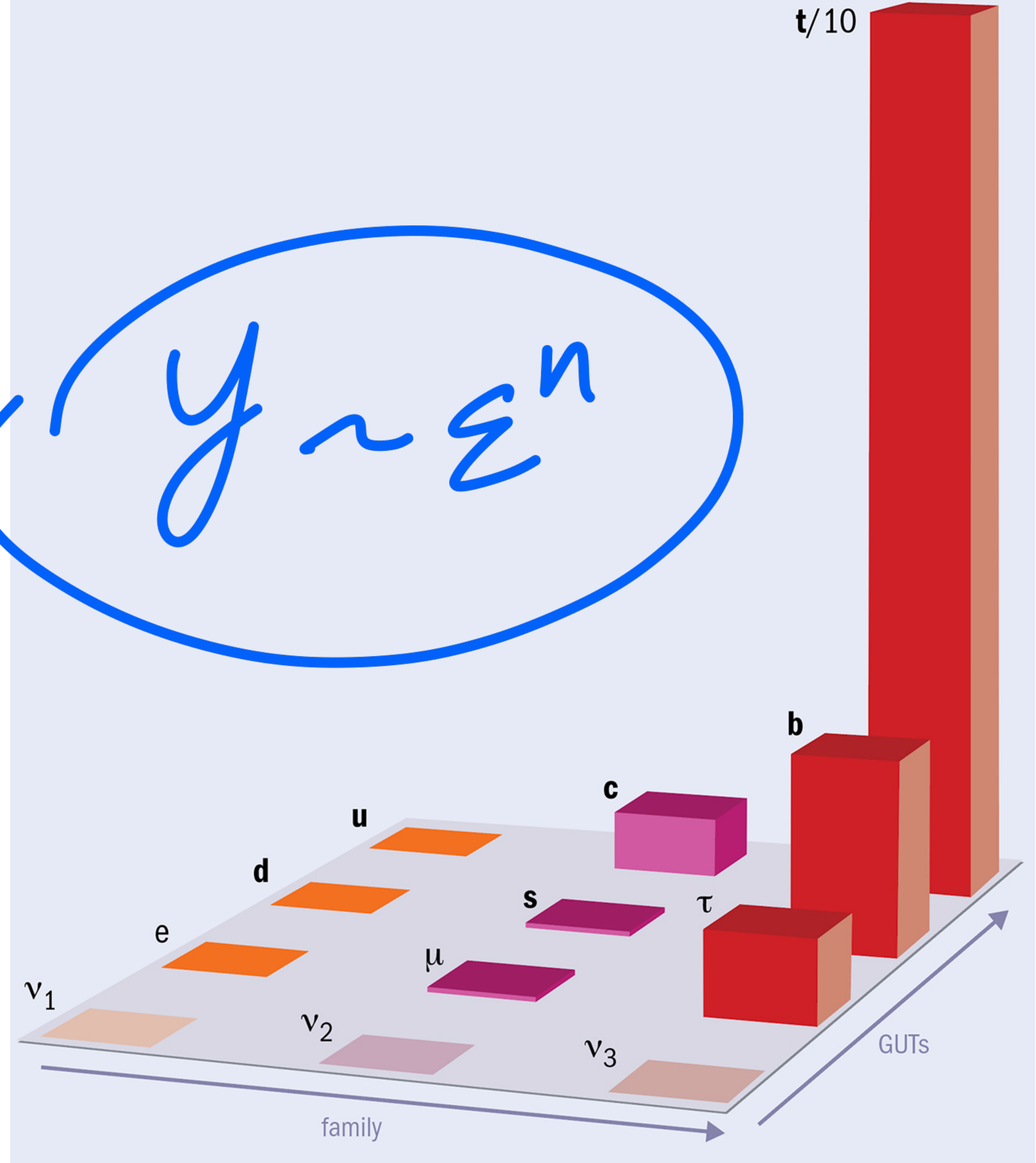
$y \sim \varepsilon^n$

$$\frac{m_e}{m_t} \approx 3\times 10^{-6} \qquad \text{Top Yukawa } y_t \approx 1$$

$$\log_{10}\left(\frac{\text{Mass}\begin{pmatrix} e & \mu & \tau \\ d & s & b \\ u & c & t \end{pmatrix}}{m_t}\right) \approx -\begin{pmatrix} 5.5 & 3.2 & 2 \\ 4.5 & 3.2 & 1.6 \\ 4.8 & 2.1 & 0 \end{pmatrix}$$

Global U(1) Froggatt-Nielsen symmetry





$$y \sim \varepsilon^n$$

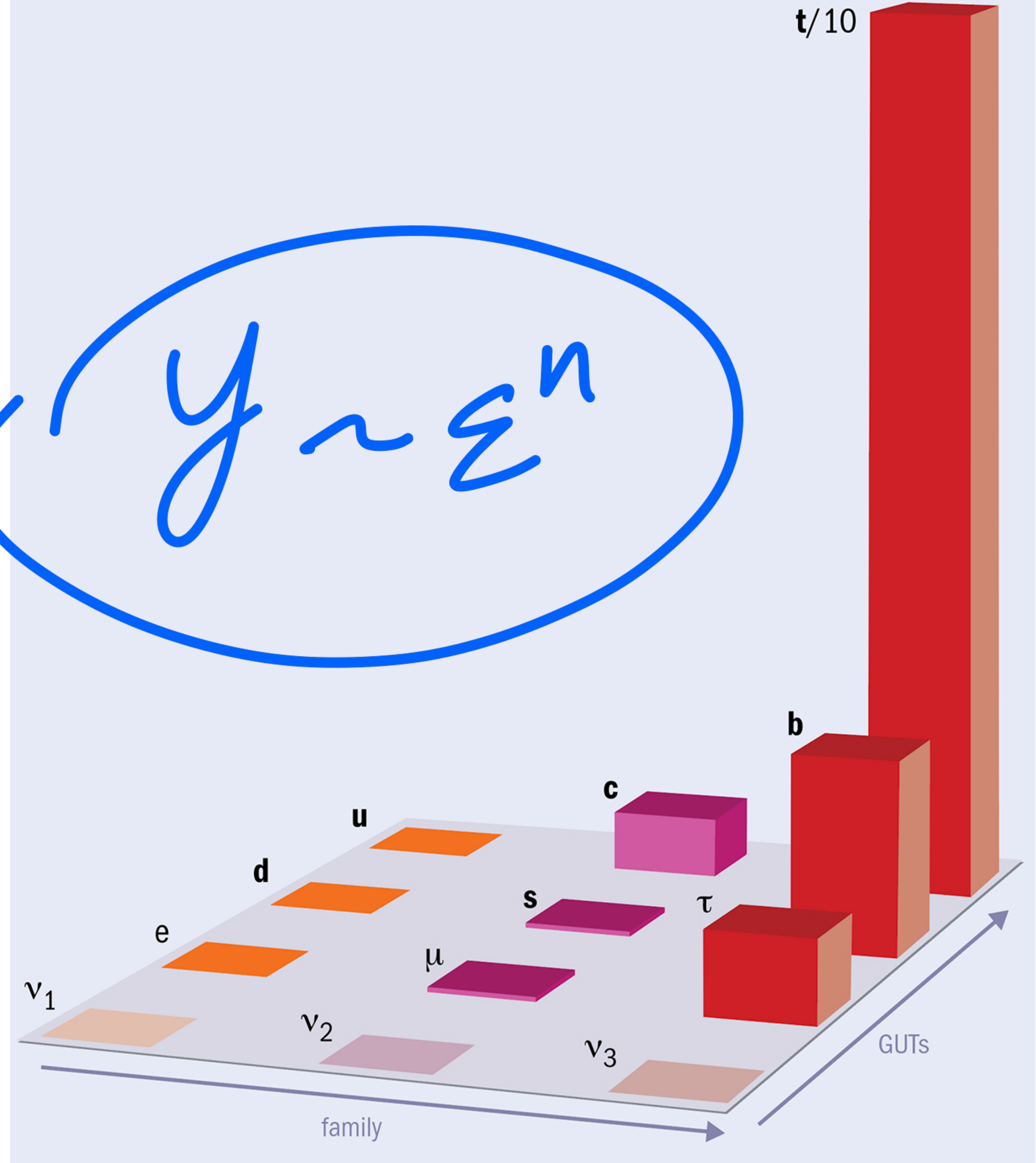
$$y\,\bar{f}_L H f_R \Rightarrow c\left(\frac{\phi}{M}\right)^n \bar{f}_L H f_R$$

$$\begin{cases} c \sim \mathcal{O}(1) \\ \dfrac{\phi \to v_\phi}{M} = \varepsilon \\ q_L - q_R = n \end{cases}$$

Froggatt-Nielsen charges

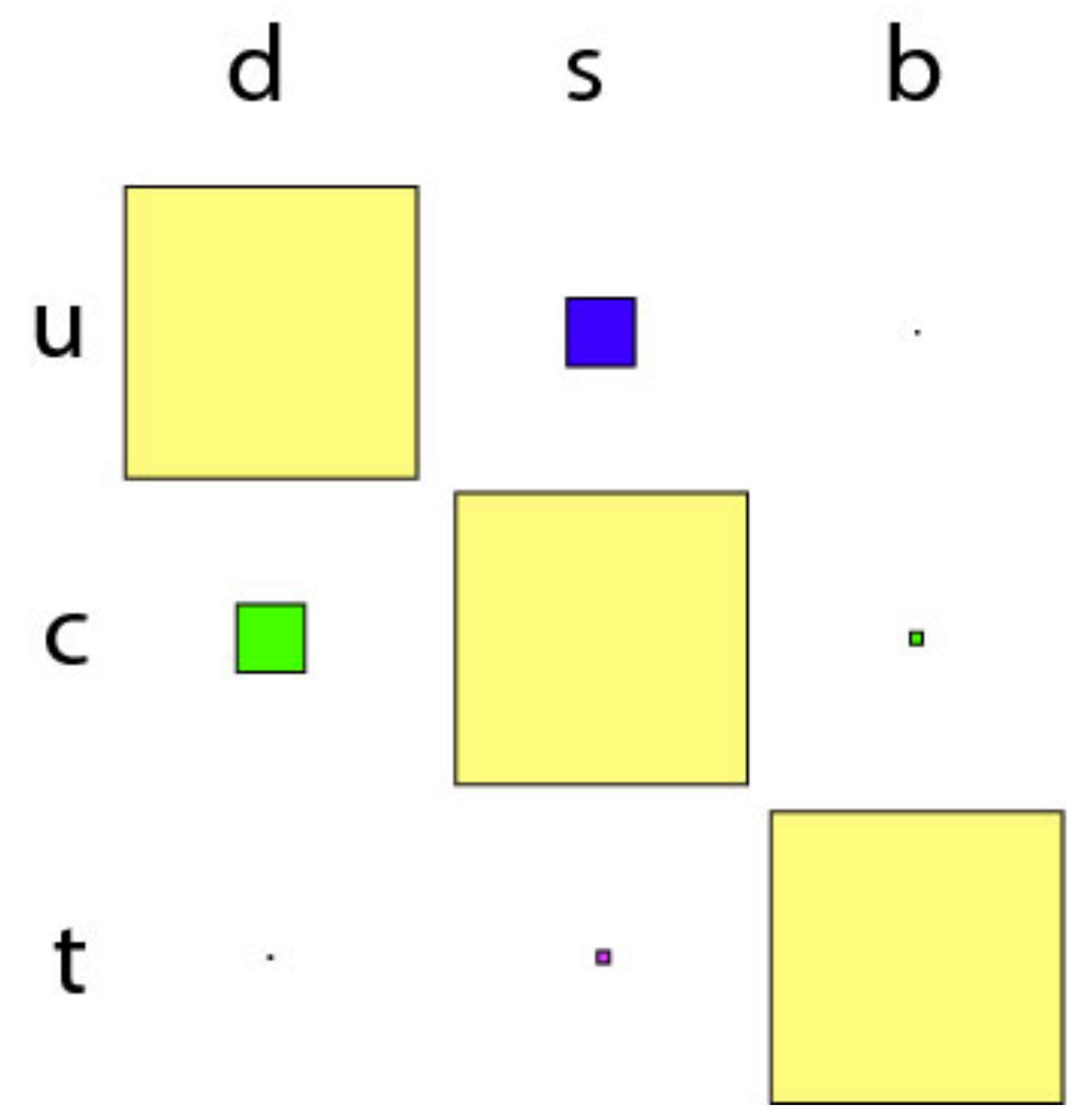
$$\varepsilon = \frac{V_\phi}{M} \approx V_{us} \approx 0.23$$

$$y \sim \varepsilon^n$$



$$n_u^{ij} = \begin{pmatrix} 8 & 4 & 3 \\ 7 & 3 & 2 \\ 5 & 1 & 0 \end{pmatrix}, \quad n_d^{ij} = \begin{pmatrix} 7 & 6 & 6 \\ 6 & 5 & 5 \\ 4 & 3 & 3 \end{pmatrix}, \quad n_e^{ij} = \begin{pmatrix} 9 & 6 & 4 \\ 8 & 5 & 3 \\ 8 & 5 & 3 \end{pmatrix}$$

CKM



$$\begin{pmatrix} q_{Q_1} & q_{Q_2} & q_{Q_3} \\ q_u & q_c & q_t \\ q_d & q_s & q_b \end{pmatrix} = \begin{pmatrix} 3 & 2 & 0 \\ -5 & -1 & 0 \\ -4 & -3 & -3 \end{pmatrix}$$

$$\begin{pmatrix} q_{L_1} & q_{L_2} & q_{L_3} \\ q_e & q_\mu & q_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ -8 & -5 & -3 \end{pmatrix}$$

q_L q_R

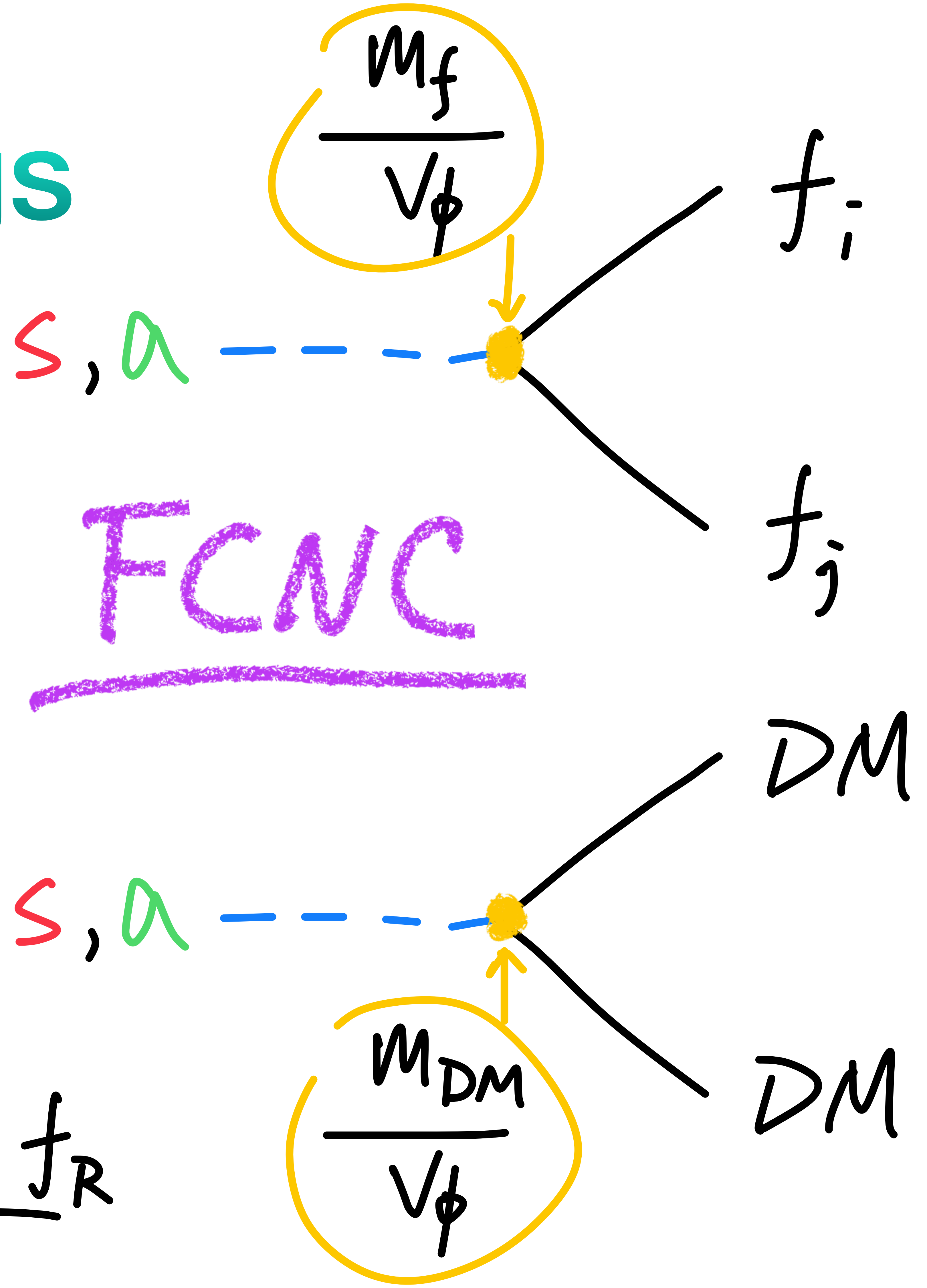
$$\begin{cases} c \sim \mathcal{O}(1) \\ \dfrac{\phi \to V_\phi}{M} = \varepsilon \\ q_L - q_R = n \end{cases}$$

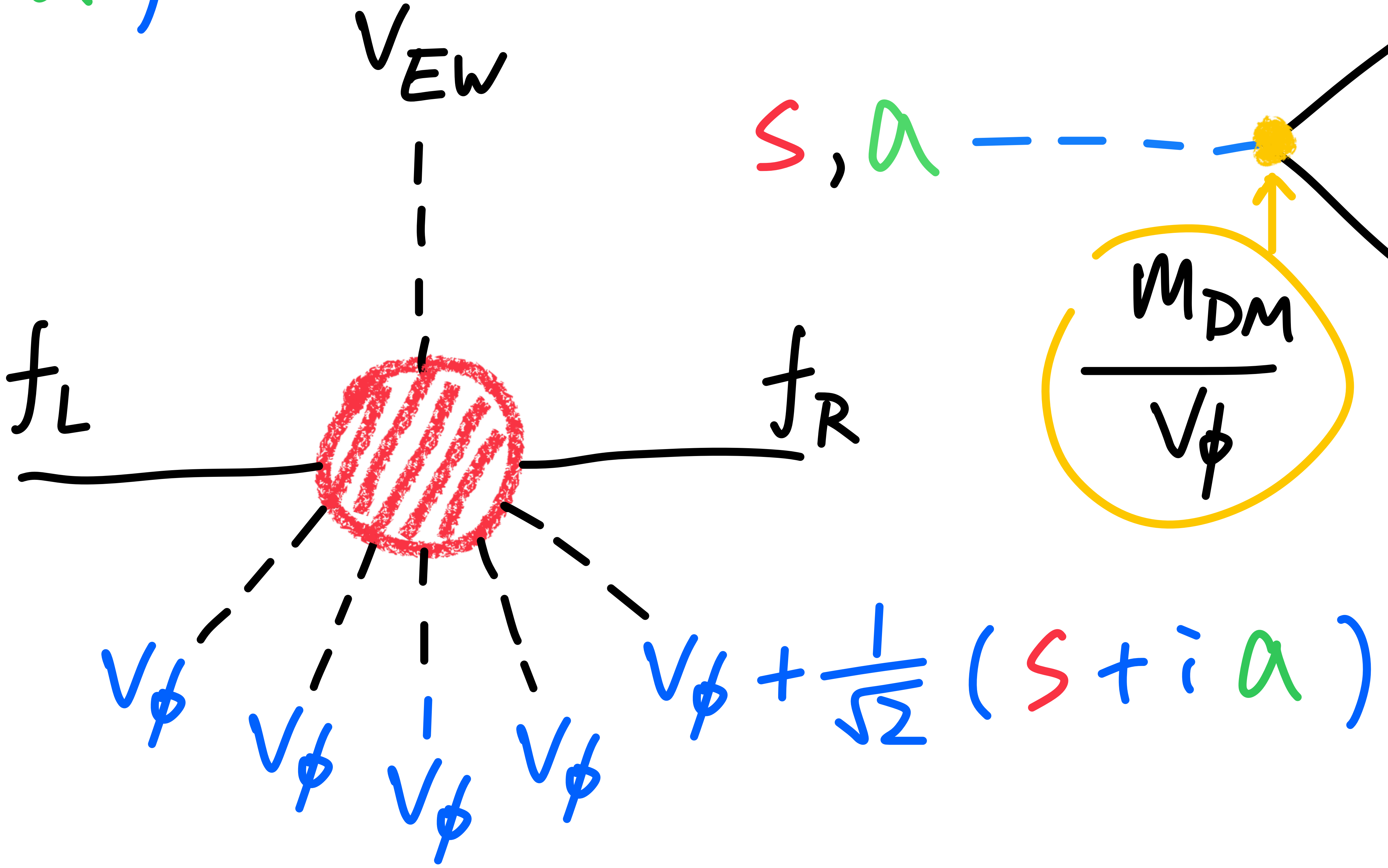
Flavon couplings

$$H \to v_{EW} + \frac{1}{\sqrt{2}}(h + i G_0)$$

$$\phi \to v_\phi + \frac{1}{\sqrt{2}}(s + i a)$$

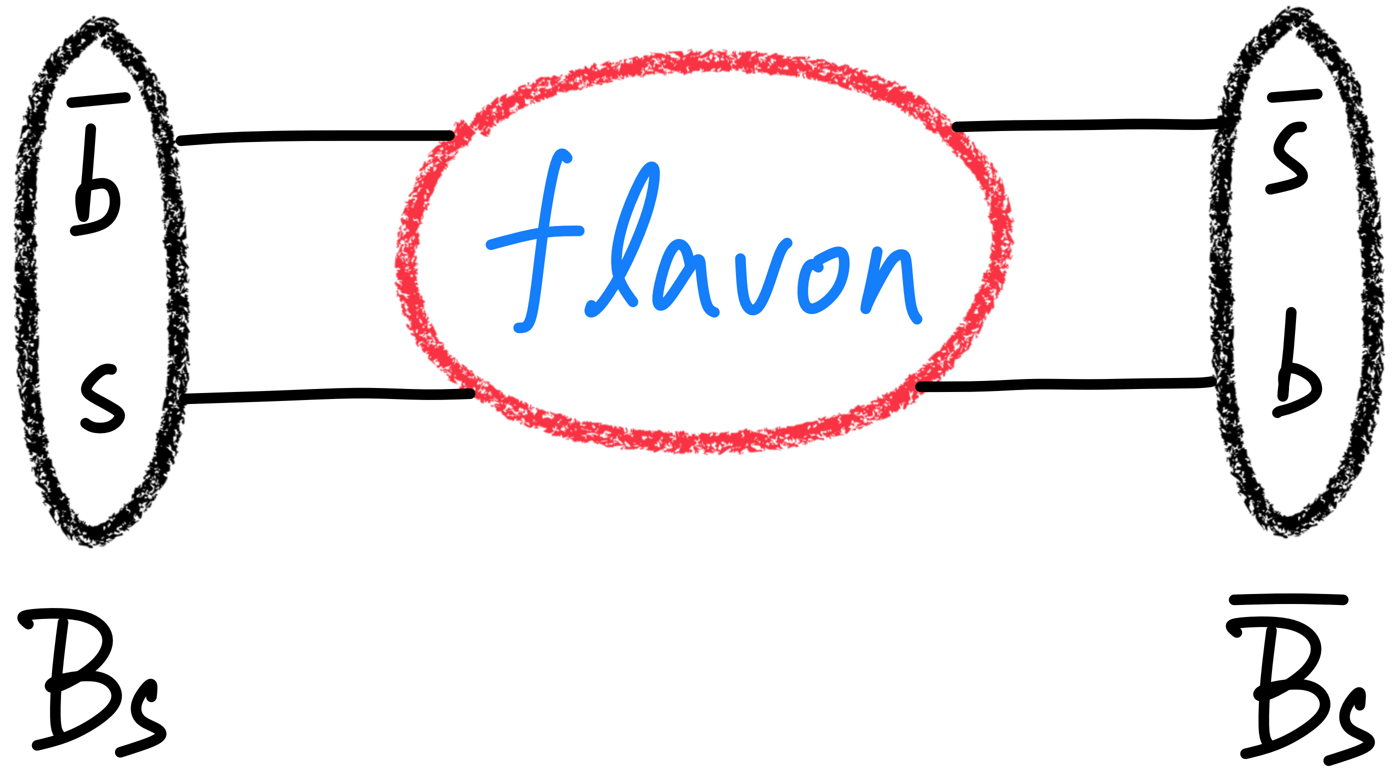
$$\begin{cases} m_s \sim v_\phi \\ 10\,\text{GeV} \leq m_a \ll m_s \end{cases}$$





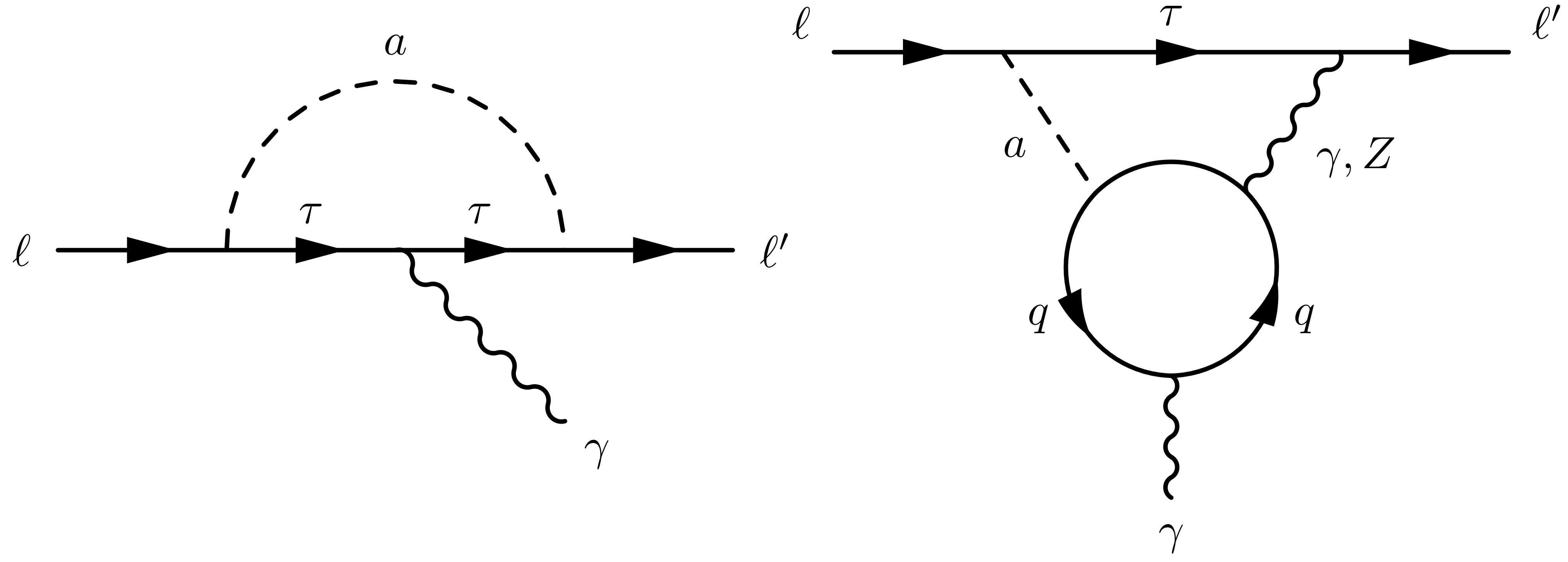
Experimental constraints

B-meson mixing



$$\left(\frac{m_a}{100\,\text{GeV}}\right)\times\left(\frac{v_\phi}{\text{TeV}}\right) > 1.8$$

$\mu \to e\gamma$ (MEG)

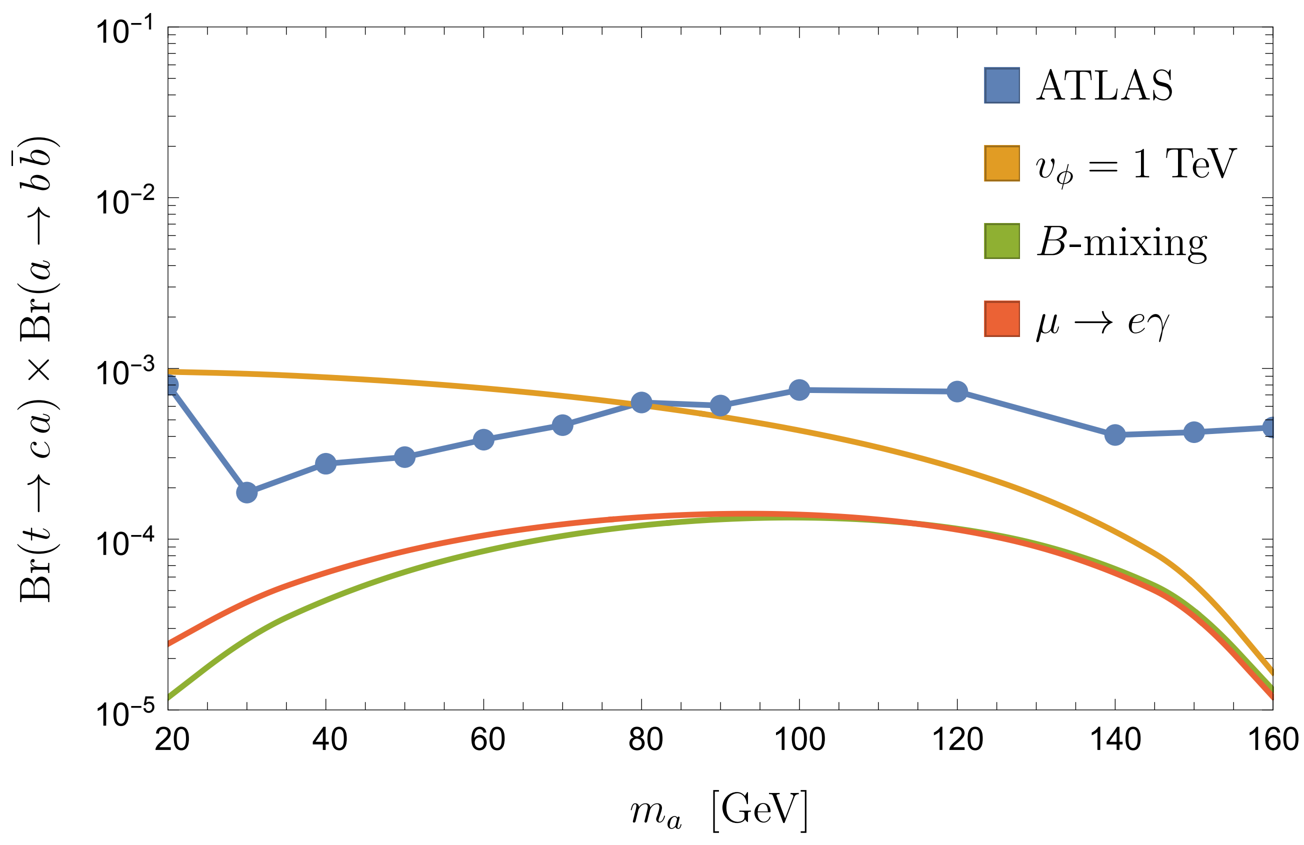


$$\left(\frac{m_a}{100\,\text{GeV}}\right)\times\left(\frac{v_\phi}{\text{TeV}}\right) > 1.9$$

*For $m_a \lesssim 100$ GeV

Top decay ATLAS

$$\text{Br}(t \to c\,a) \times \text{Br}(a \to b\bar{b})$$

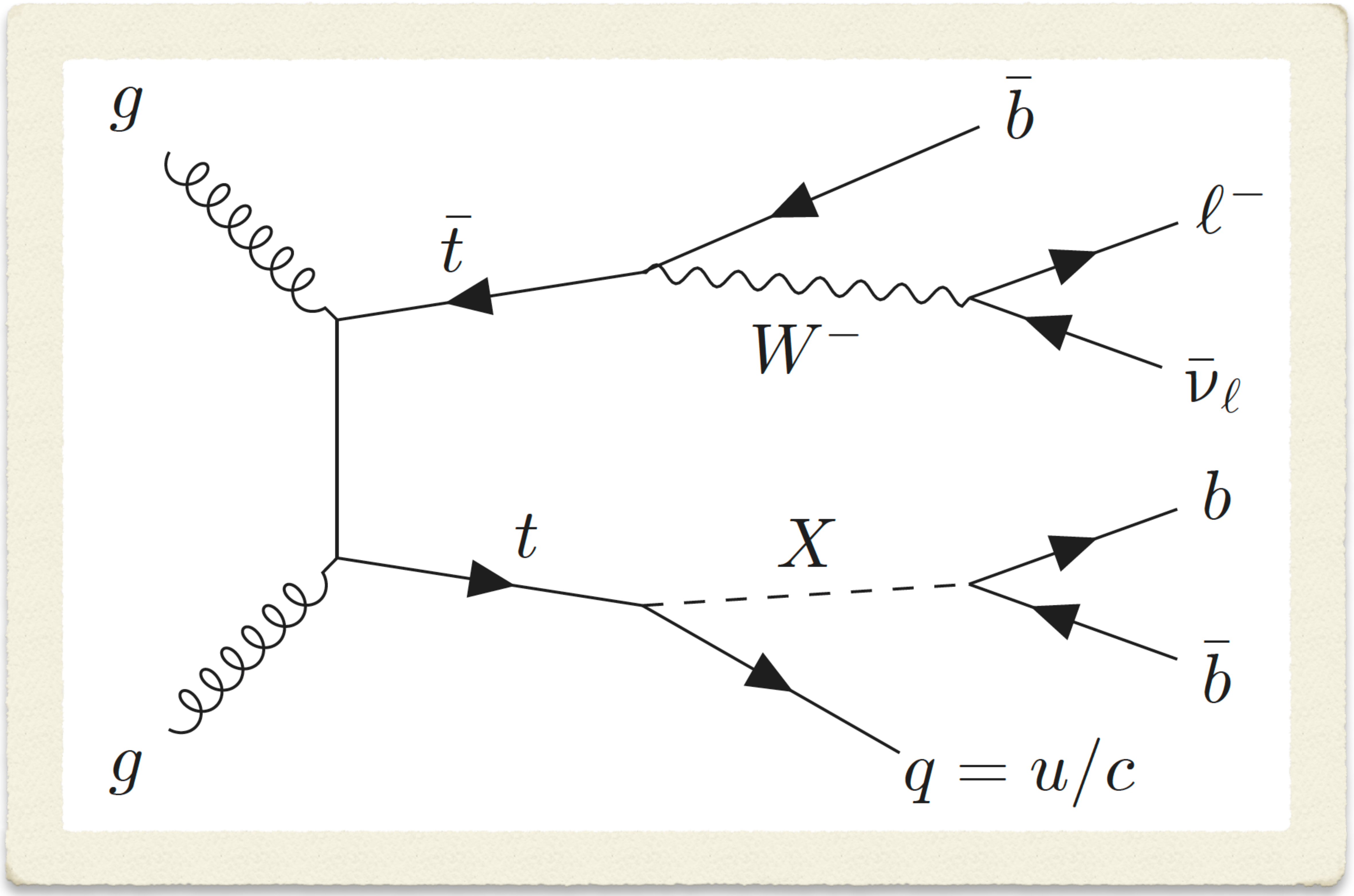


High Energy Physics – Experiment

[Submitted on 10 Jan 2023 (v1), last revised 8 Sep 2023 (this version, v2)]

Search for a new scalar resonance in flavour-changing neutral-current top-quark decays $t \to qX$ ($q = u, c$), with $X \to b\bar{b}$, in proton-proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

ATLAS Collaboration



One-loop analysis of β decays in SMEFT

Maria Dawid, Vincenzo Cirigliano, Wouter Dekens

Institute for Nuclear Theory,
University of Washington, Seattle WA 98195-1550, USA

One at a time

While Eq. (3.7) provides the general contributions, we explore below the simplified scenario in which only one coefficient is nonzero at the high energy scale Λ. This leads to conservative constraints on the C_x operators, as long as there are no significant cancelations between different SMEFT operators. The most stringent constraints (corresponding $\delta C_x \leqslant 5 \times 10^{-2}$) are graphically illustrated in Fig. 2 and reported in Table 1, along with a comparison to limits obtained from other observables.

$C_x(\Lambda = 5\,\text{TeV})$	Constraint from β decays	Strongest constraints from other processes	Process
$C^{(3)}_{\substack{qq\\1133}}$	0.004 ± 0.0013	$-0.0073 \pm 0.006^*$	Top production [47]
		± 0.0009	Δm_K [48]
$C^{(3)}_{\substack{lq\\2233}}$	-0.008 ± 0.0025	-0.00024 ± 0.00021	B decays [49]
$C_{\substack{ll\\1122}}$	-0.018 ± 0.005	-0.0018 ± 0.0029	Muon pair production [50]
$C^{(1)}_{\substack{qq\\1331}}$	-0.031 ± 0.009	$-0.035 \pm 0.027^*$	Top production [47]
		± 0.0009	Δm_K [48]
$C^{(3)}_{\substack{qq\\1331}}$	-0.03 ± 0.009	$-0.042 \pm 0.024^*$	Top production [47]
		± 0.0009	Δm_K [48]

Fitting SMEFT with a CLEW

Towards a true model-independent global analysis

Universität Siegen / TP1 Theoretical Particle Physics
CPPS Center for Particle Physics Siegen

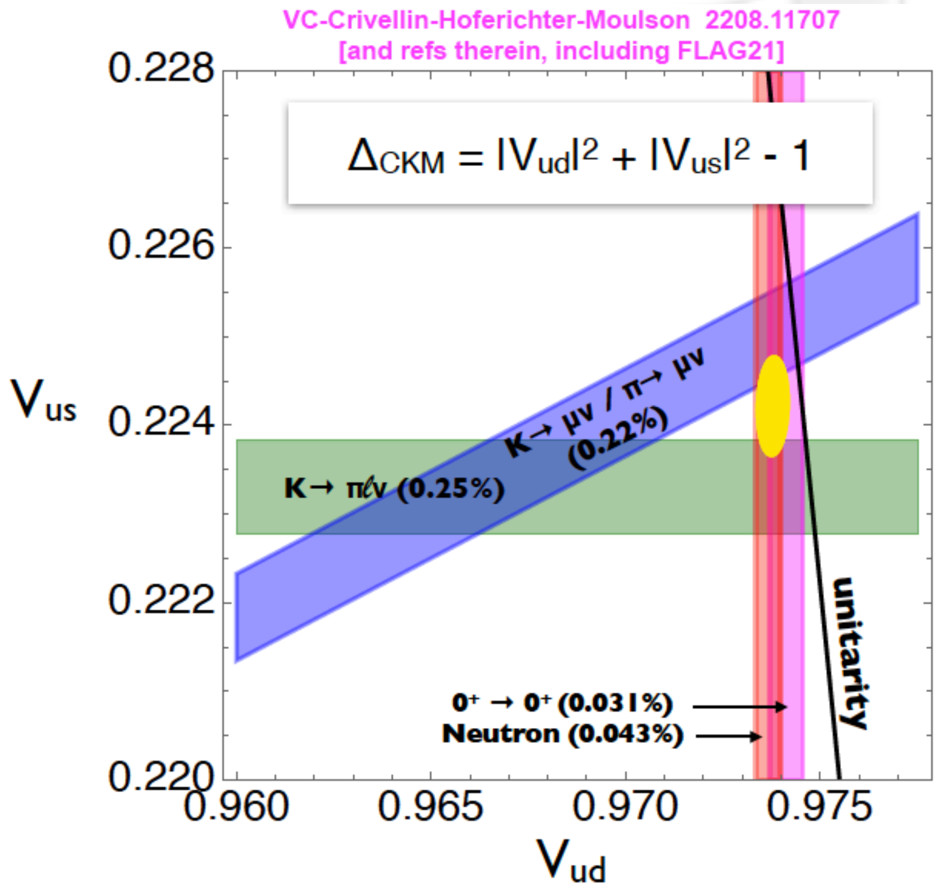
Tom Tong

arXiv: 2311.00021, published in *JHEP*

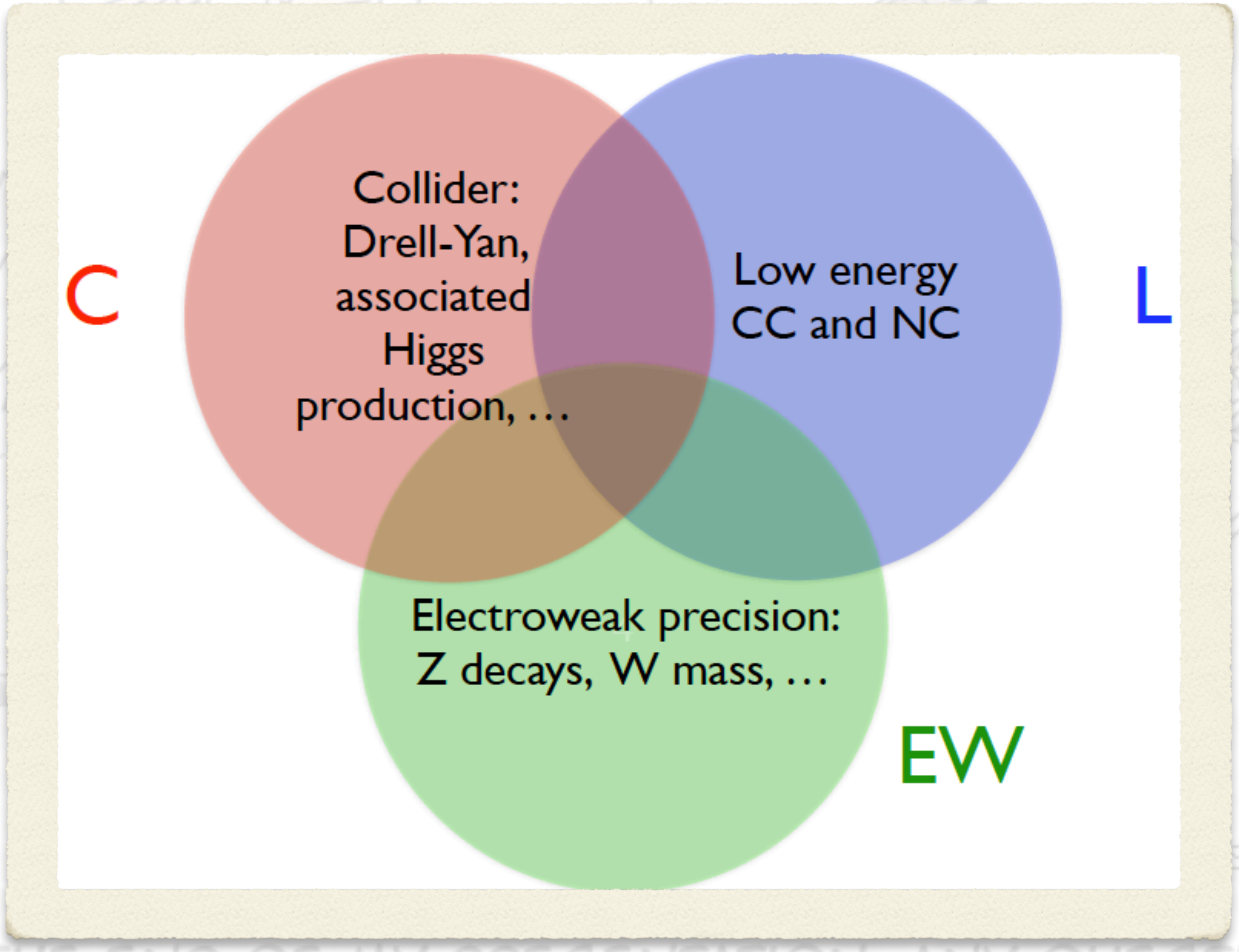
Abstract for the impatient

SMEFT global-fits: two major challenges

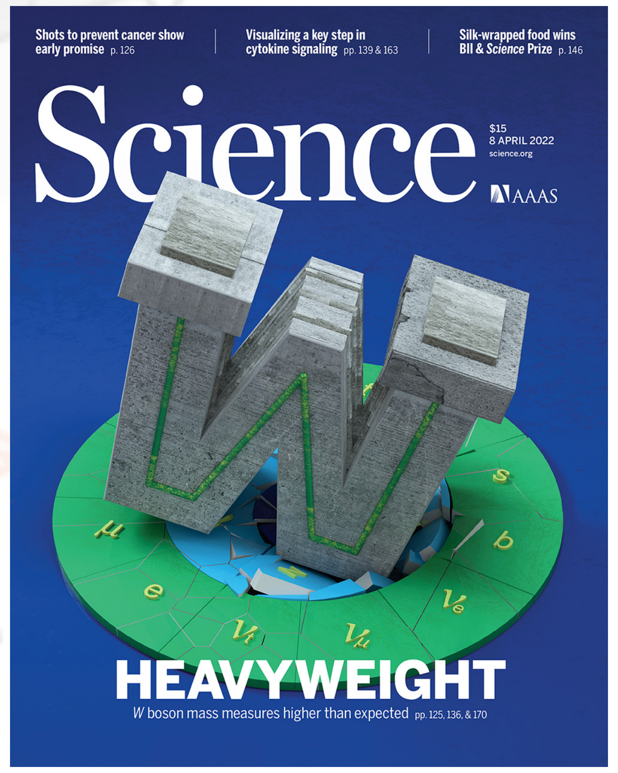
Flavor assumptions



The CLEW framework

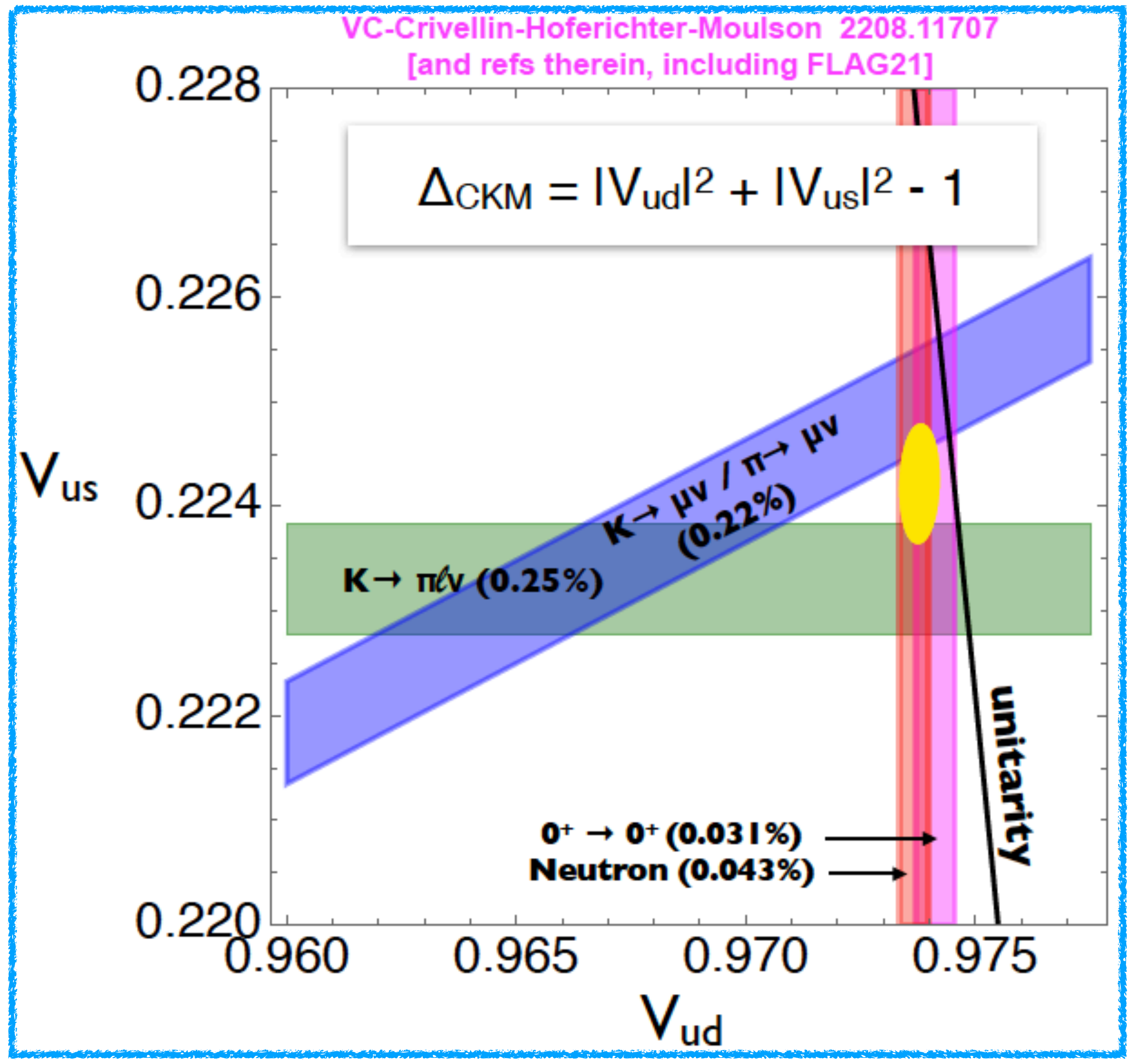


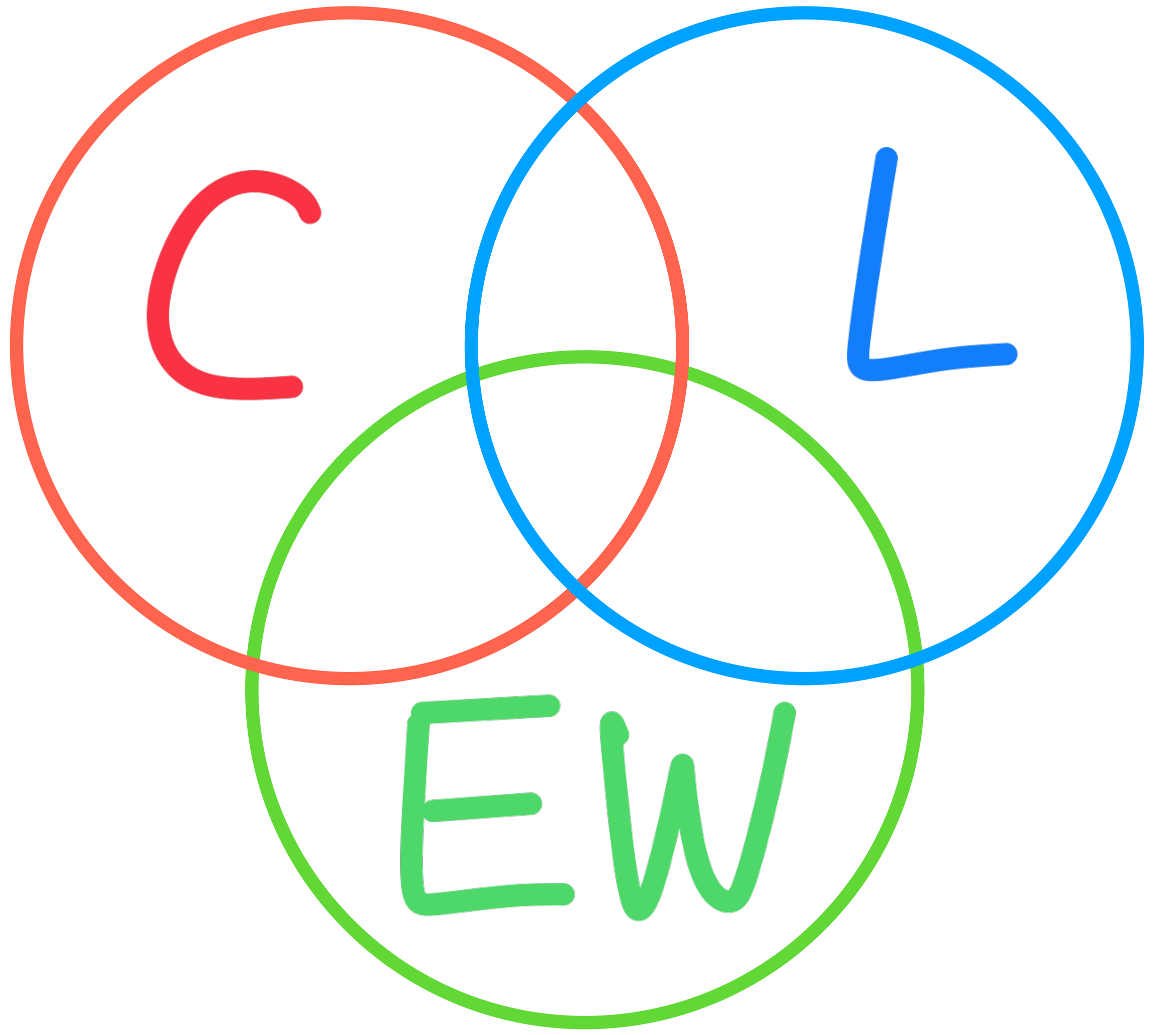
Incomplete observables

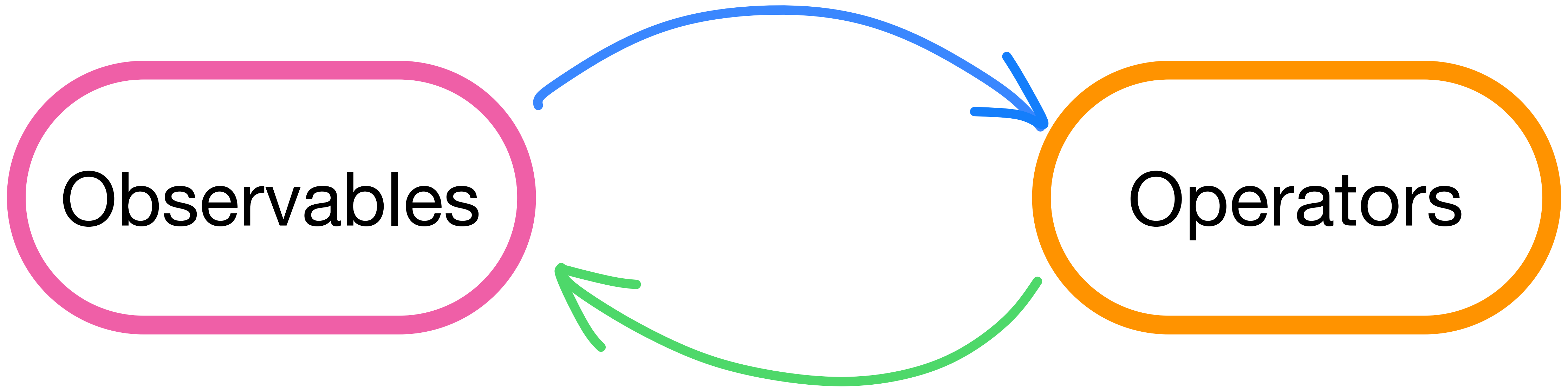


Flavor-symmetry-independent analysis

List all the relevant operators



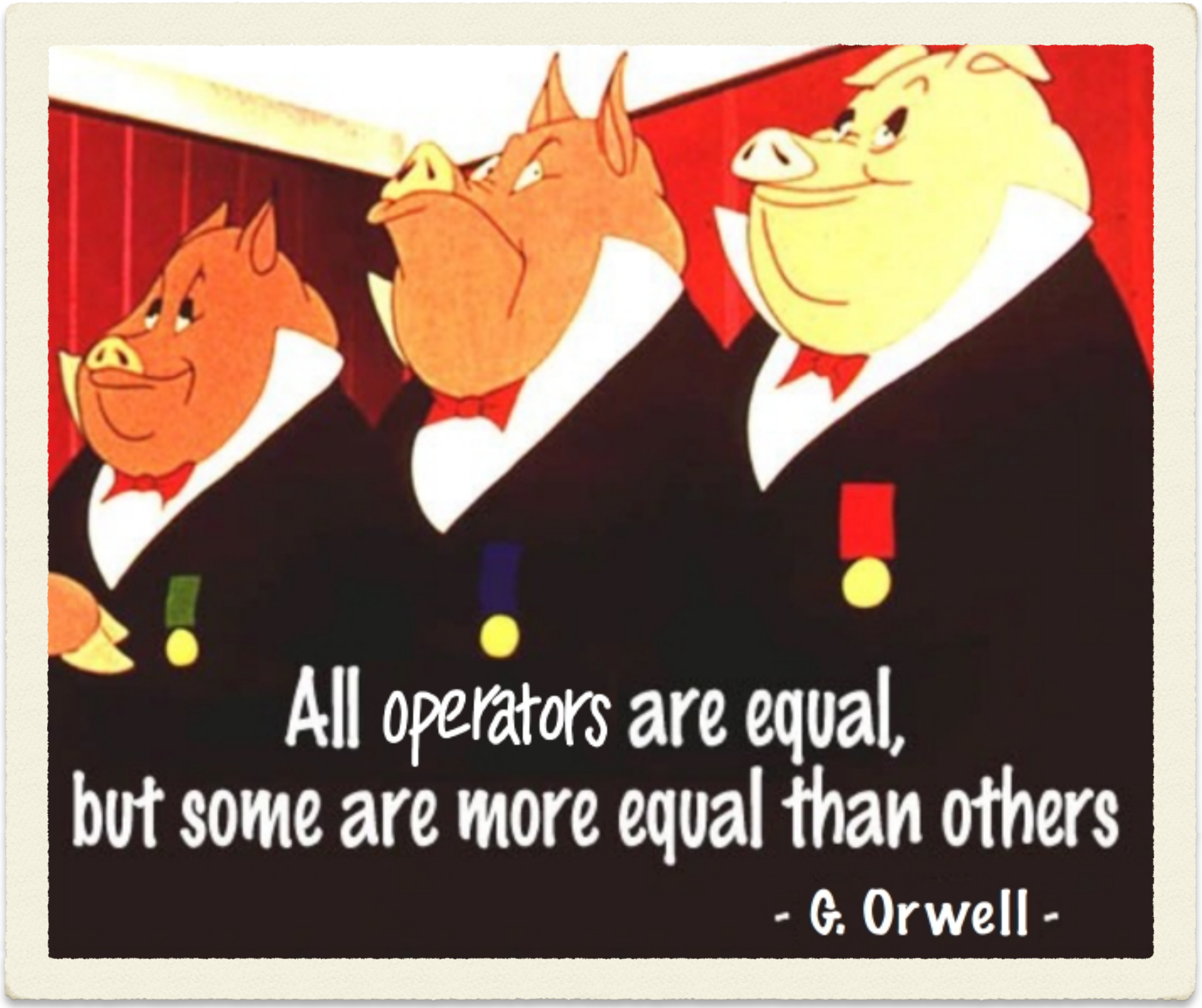




Operators		Low energy CC	EWPO	LHC
H^4D^2				
Q_{HD}	$(H^\dagger D^\mu H)^* (H^\dagger D_\mu H)$	parameter shift (m_Z)		
X^2H^2				
Q_{HWB}	$H^\dagger \tau^I H\, W^I_{\mu\nu} B^{\mu\nu}$			
[illegible]				
[illegible]	[illegible]	✗	✓	✓
[illegible]	$(H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar{l}_p \tau^I \gamma^\mu l_r)$	✓	✓	✓
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.	$i(\widetilde{H}^\dagger D_\mu H)(\bar{u}_p \gamma^\mu d_r)$	✓	✗	✓
$(\bar{L}L)(\bar{L}L)$				
Q_{ll}	$(\bar{l}_p \gamma^\mu l_r)(\bar{l}_s \gamma_\mu l_t)$	parameter shift ($G_F^{(\mu)}$)		
$Q^{(1)}_{lq}$	$(\bar{l}_p \gamma^\mu l_r)(\bar{q}_s \gamma_\mu q_t)$	✗	✗	✓
$Q^{(3)}_{lq}$	$(\bar{l}_p \gamma^\mu \tau^I l_r)(\bar{q}_s \gamma_\mu \tau^I q_t)$	✓	✗	✓
$(\bar{L}R)(\bar{R}L)$ + h.c.				
Q_{ledq}	$(\bar{l}^j_p e_r)(\bar{d}_s q_{tj})$	✓	✗	✓
$(\bar{L}R)(\bar{L}R)$ + h.c.				
$Q^{(1)}_{lequ}$	$(\bar{l}^j_p e_r)\epsilon_{jk}(\bar{q}^k_s u_t)$	✓	✗	✓
$Q^{(3)}_{lequ}$	$(\bar{l}^j_p \sigma_{\mu\nu} e_r)\epsilon_{jk}(\bar{q}^k_s \sigma^{\mu\nu} u_t)$	✓	✗	✓

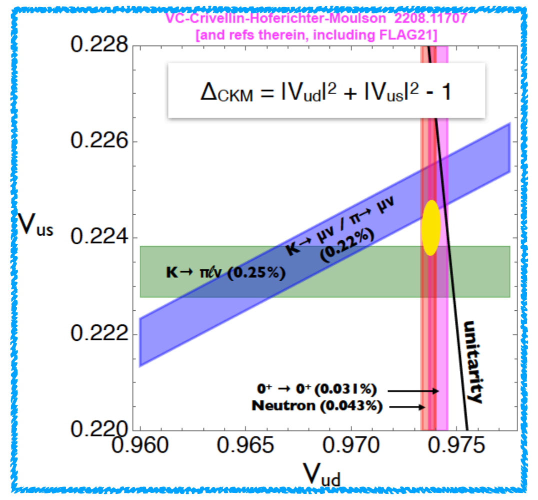
With all flavor indices

All operators are equal, but...



Operators		Low energy CC	EWPO	LHC
H^4D^2				
Q_{HD}	$(H^\dagger D^\mu H)^* (H^\dagger D_\mu H)$	parameter shift (m_Z)		
X^2H^2				
Q_{HWB}	$H^\dagger \tau^I H W^I_{\mu\nu} B^{\mu\nu}$	[illegible]	[illegible]	[illegible]
[illegible]				
[illegible]	[illegible]	✗	✓	✓
[illegible]	$(H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar{l}_p \tau^I \gamma^\mu l_r)$	✓	✓	✓
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.	$i(\tilde{H}^\dagger D_\mu H)(\bar{u}_p \gamma^\mu d_r)$	✓	✗	✓
$(\bar{L}L)(\bar{L}L)$				
Q_{ll}	$(\bar{l}_p \gamma^\mu l_r)(\bar{l}_s \gamma_\mu l_t)$	parameter shift ($G_F^{(\mu)}$)		
$Q^{(1)}_{lq}$	$(\bar{l}_p \gamma^\mu l_r)(\bar{q}_s \gamma_\mu q_t)$	✗	✗	✓
$Q^{(3)}_{lq}$	$(\bar{l}_p \gamma^\mu \tau^I l_r)(\bar{q}_s \gamma_\mu \tau^I q_t)$	✓	✗	✓
$(\bar{L}R)(\bar{R}L)$ + h.c.				
Q_{ledq}	$(\bar{l}^j_p e_r)(\bar{d}_s q_{tj})$	✓	✗	✓
$(\bar{L}R)(\bar{L}R)$ + h.c.				
$Q^{(1)}_{lequ}$	$(\bar{l}^j_p e_r)\epsilon_{jk}(\bar{q}^k_s u_t)$	✓	✗	✓
$Q^{(3)}_{lequ}$	$(\bar{l}^j_p \sigma_{\mu\nu} e_r)\epsilon_{jk}(\bar{q}^k_s \sigma^{\mu\nu} u_t)$	✓	✗	✓

With all flavor indices



All operators are equal, but...

Basis rotation

$$C_{Hq}^{(u)} = V\left[C_{Hq}^{(1)} - C_{Hq}^{(3)}\right]V^\dagger\,, \qquad C_{Hq}^{(d)} = C_{Hq}^{(1)} + C_{Hq}^{(3)}\,,$$

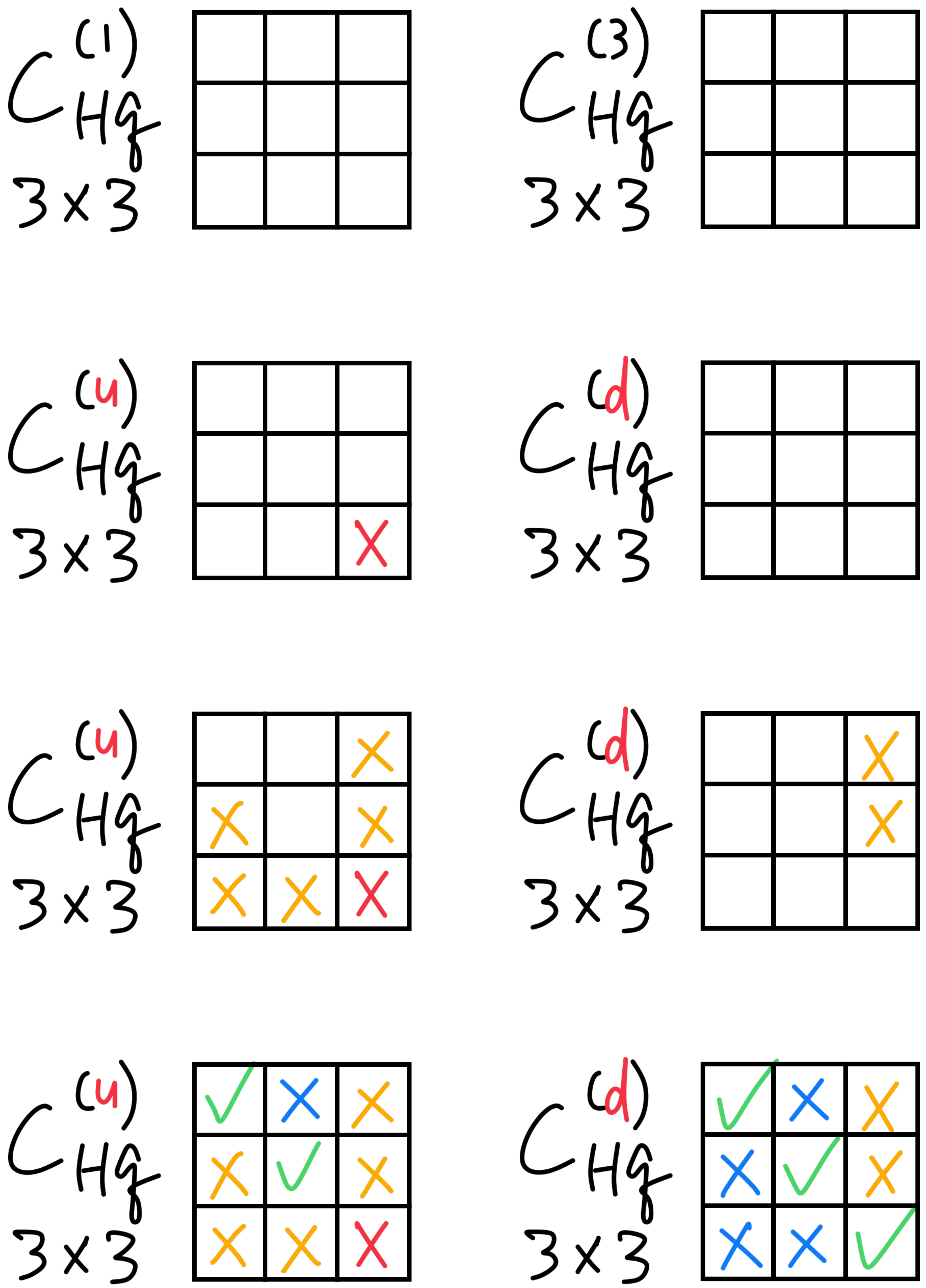
Relative contribution

Suppressed by $|V_{us}|^2$ or (V_{ts}/V_{us})

Pheno constraints

FCNC decays of B, D and K mesons

"More-equal" operators



37 operators are "more equal"

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

37 in total

Operators		Low energy CC	EWPO	LHC
$\boldsymbol{H^4D^2}$				
Q_{HD}	$(H^\dagger D^\mu H)^* (H^\dagger D_\mu H)$	parameter shift (m_Z)		
$\boldsymbol{X^2H^2}$				
Q_{HWB}	$H^\dagger \tau^I H\, W^I_{\mu\nu} B^{\mu\nu}$			
[illegible]				
[illegible]	[illegible]	✗	✓	✓
[illegible]	$(H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar{l}_p \tau^I \gamma^\mu l_r)$	✓	✓	✓
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.	$i(\tilde{H}^\dagger D_\mu H)(\bar{u}_p \gamma^\mu d_r)$	✓	✗	✓
$\boldsymbol{(\bar{L}L)(\bar{L}L)}$				
Q_{ll}	$(\bar{l}_p \gamma^\mu l_r)(\bar{l}_s \gamma_\mu l_t)$	parameter shift $(G_F^{(\mu)})$		
$Q^{(1)}_{lq}$	$(\bar{l}_p \gamma^\mu l_r)(\bar{q}_s \gamma_\mu q_t)$	✗	✗	✓
$Q^{(3)}_{lq}$	$(\bar{l}_p \gamma^\mu \tau^I l_r)(\bar{q}_s \gamma_\mu \tau^I q_t)$	✓	✗	✓
$\boldsymbol{(\bar{L}R)(\bar{R}L)}$ + h.c.				
Q_{ledq}	$(\bar{l}^j_p e_r)(\bar{d}_s q_{tj})$	✓	✗	✓
$\boldsymbol{(\bar{L}R)(\bar{L}R)}$ + h.c.				
$Q^{(1)}_{lequ}$	$(\bar{l}^j_p e_r)\epsilon_{jk}(\bar{q}^k_s u_t)$	✓	✗	✓
$Q^{(3)}_{lequ}$	$(\bar{l}^j_p \sigma_{\mu\nu} e_r)\epsilon_{jk}(\bar{q}^k_s \sigma^{\mu\nu} u_t)$	✓	✗	✓

With all flavor indices

Group them into 10 categories

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

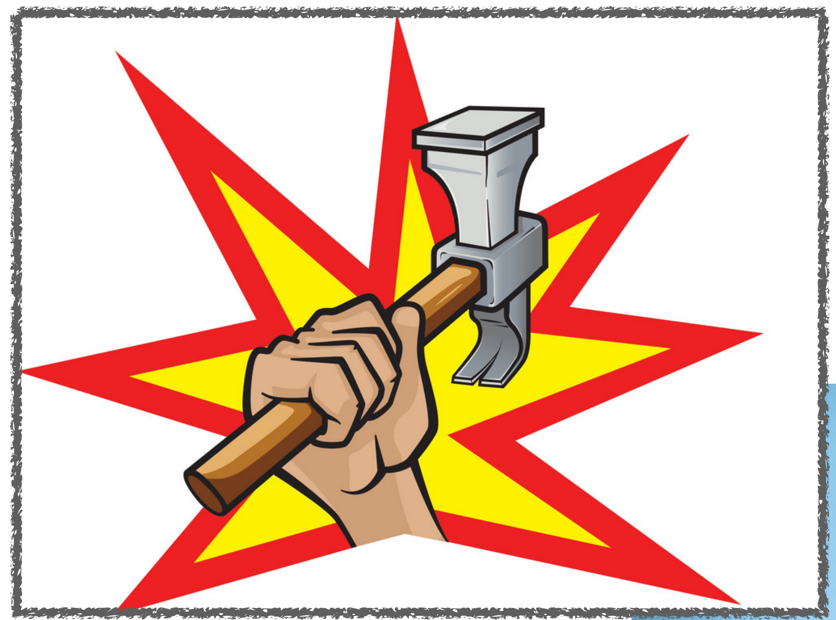
Category	Operators	Description	# of Ops.
I.	C_{ST}	Oblique corrections	1
II.	C_{Hud}	RH charged currents	2
III.	$C^{(1)}_{Hl}$ $C^{(3)}_{Hl}$	LH lepton vertices	6
IV.	C_{He}	RH lepton vertices	3
V.	$C^{(u)}_{Hq}$ $C^{(d)}_{Hq}$	LH quark vertices	5
VI.	C_{Hu} C_{Hd}	RH quark vertices	5
VII.	C_{ll}	Lepton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

Let's do $2^{37} \approx 10^{11}$ fits!

AIC and one thousand fits

Akaike Information Criterion

AIC $= \chi^2 + 2 \times ($**number of Ops.**$)$



Category	Operators	Description	# of Ops.
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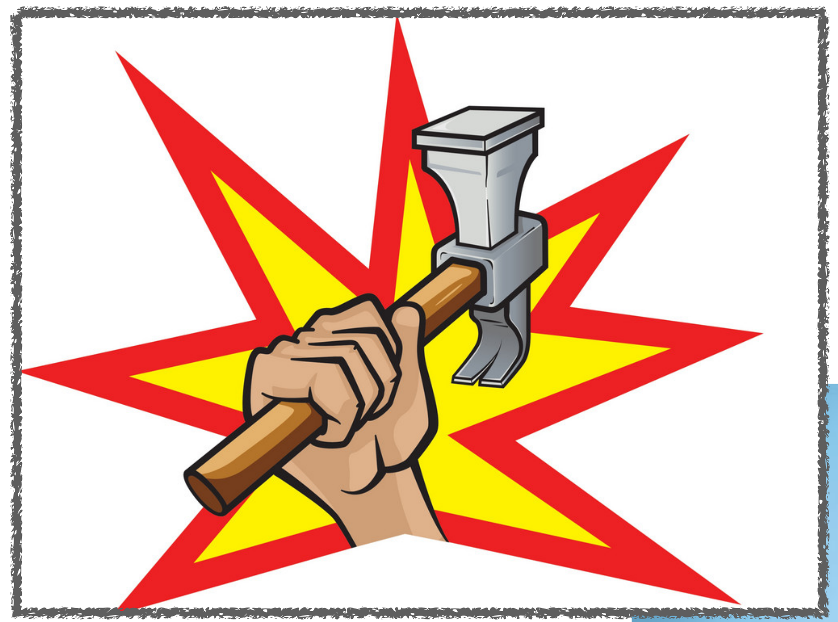
IX.	C_{ledq} $C^{(1)}_{lequ}$	Scalar 4-fermion	6
X.	$C^{(3)}_{lequ}$	Tensor 4-fermion	2

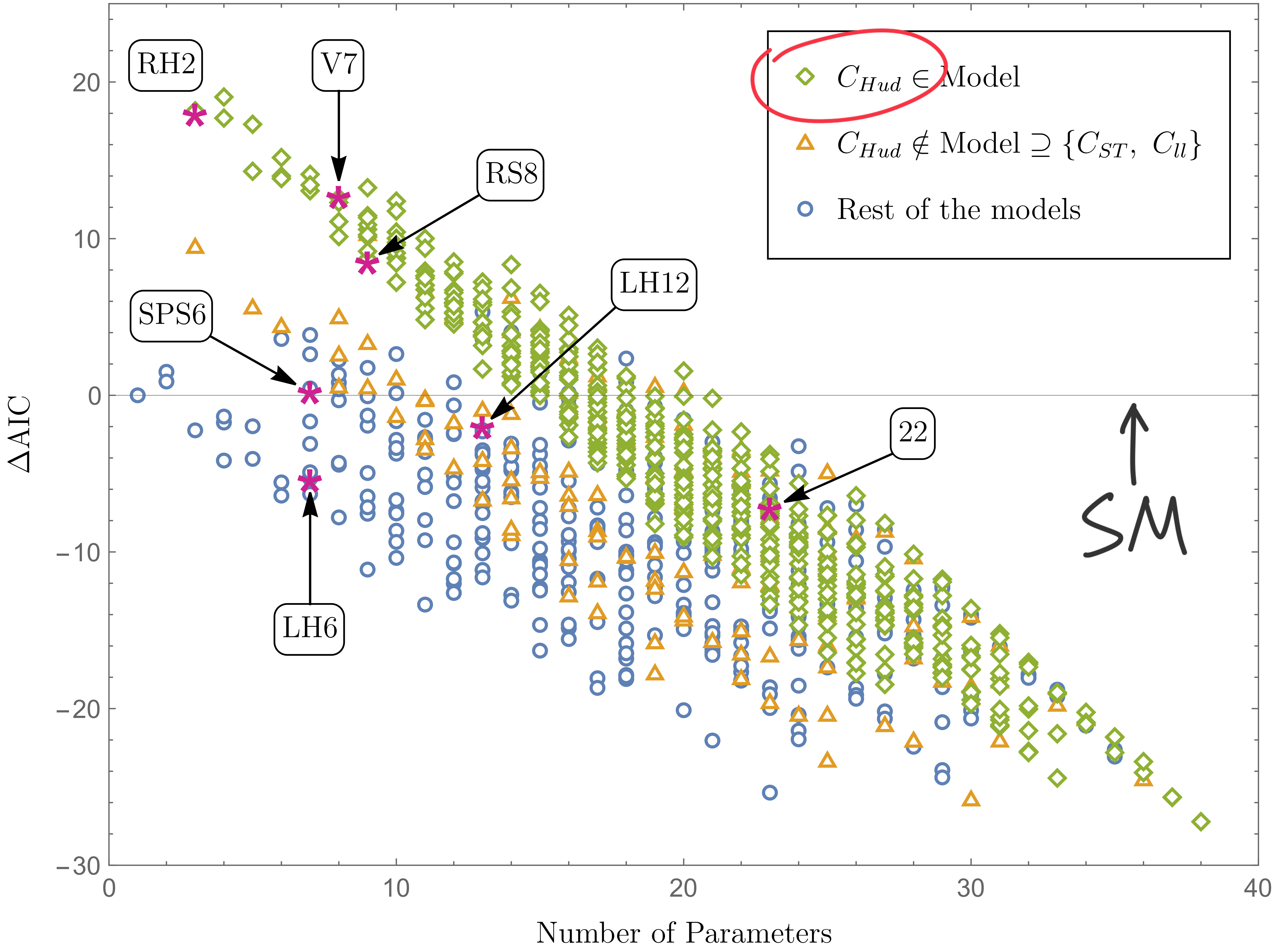
Let's do $2^{10} = 1024$ **fits!**

AIC and one thousand fits

Akaike Information Criterion

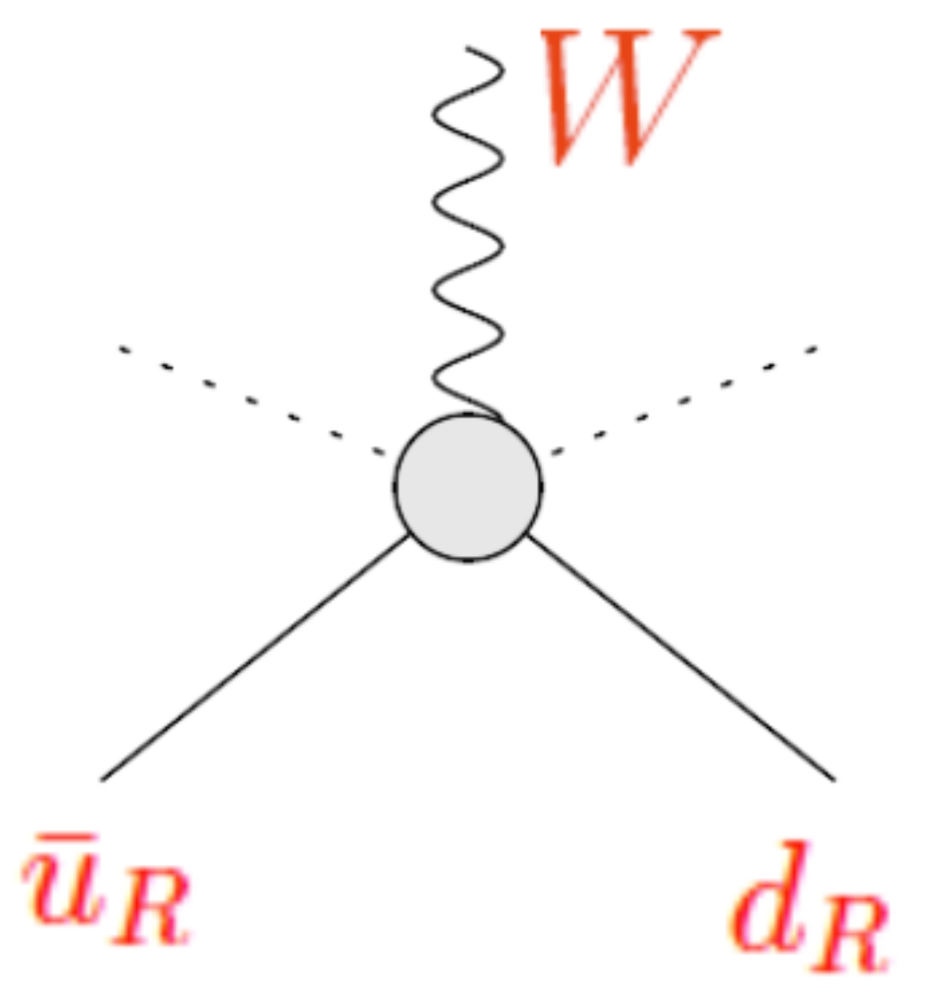
AIC $= \chi^2 + 2 \times$ (**number of Ops.**)





Higher the ΔAIC, better the model

Who is C_{Hud}?



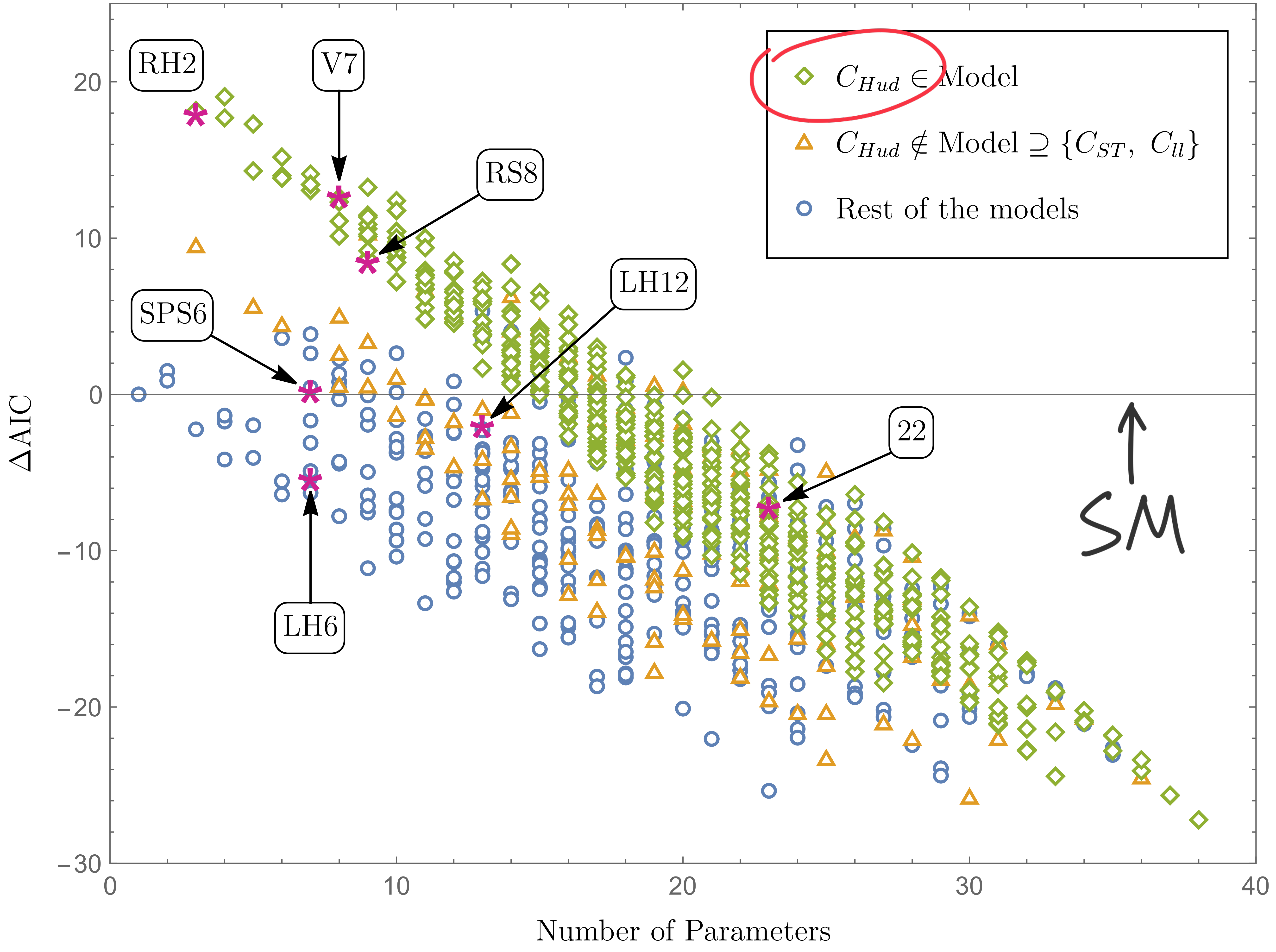
$$Q_{Hud} = i(\widetilde{H}^\dagger D_\mu H)(\bar{u}_p \gamma^\mu d_r)$$

- Left-Right Symmetric Models

  2107.10852

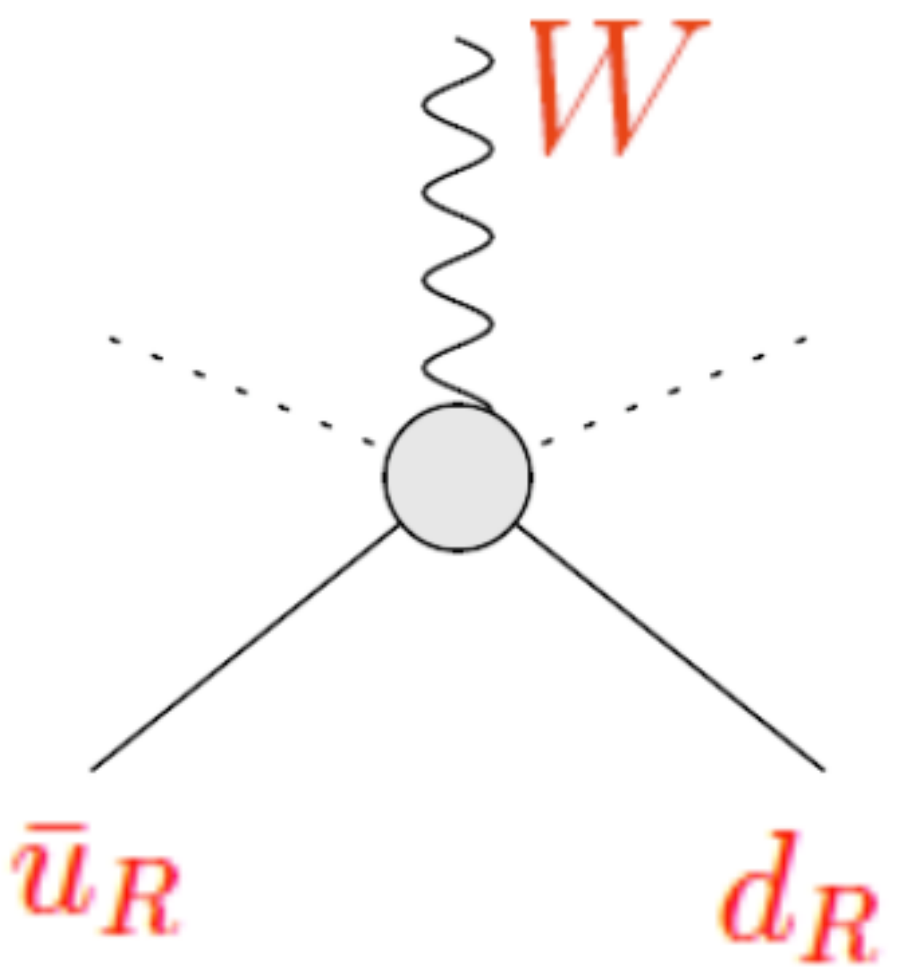
- Vector-Like Quarks ~ $\mathcal{O}$(TeV)

  2212.06862, 2302.14097



Higher the ΔAIC, better the model

Falsifying C_{Hud}



C_{Hud}

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

- Left-Right Symmetric Models

  2107.10852

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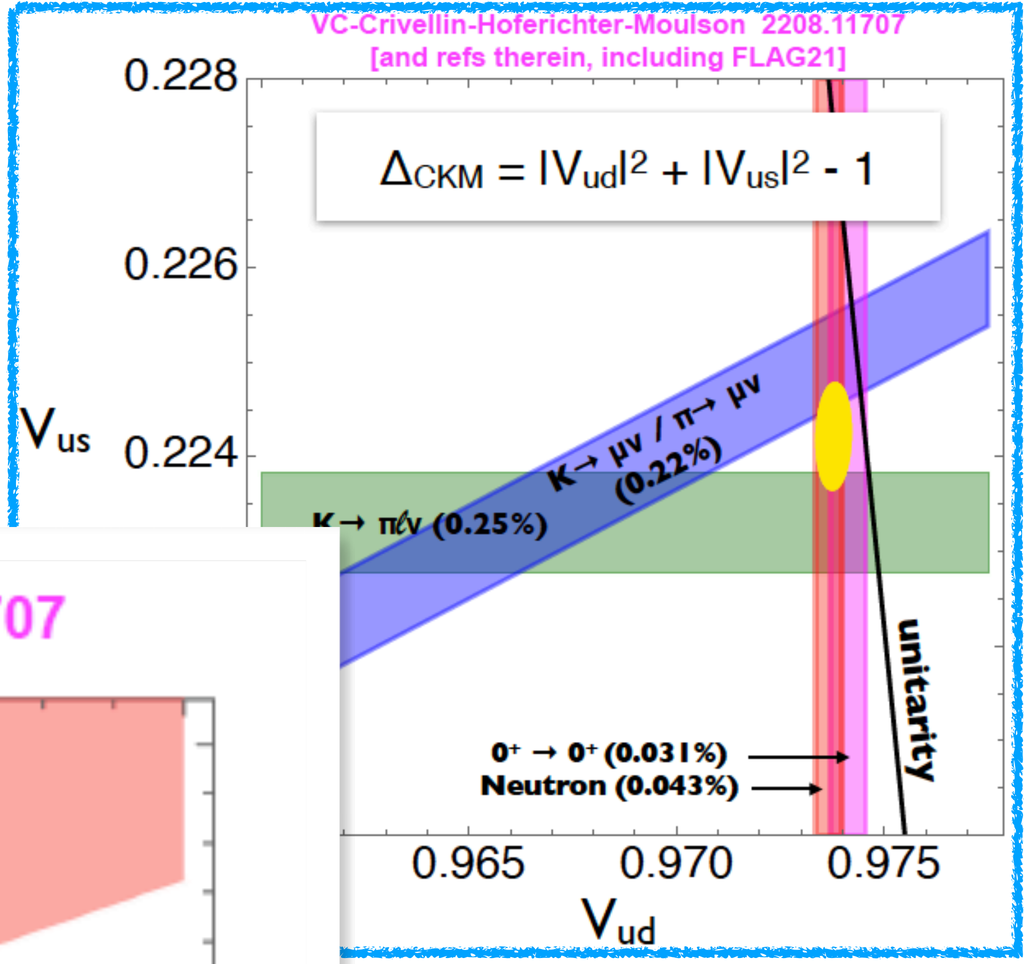
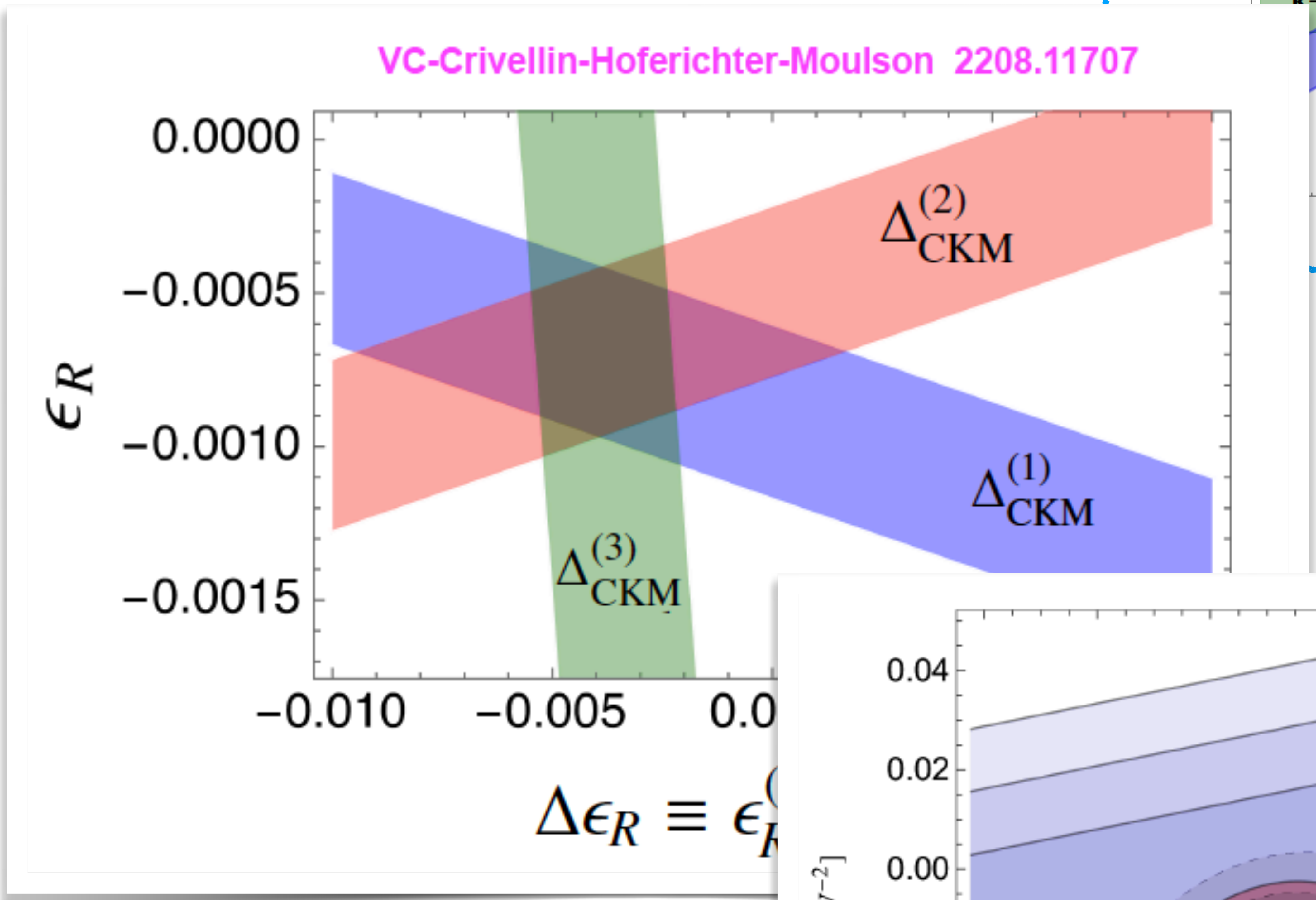
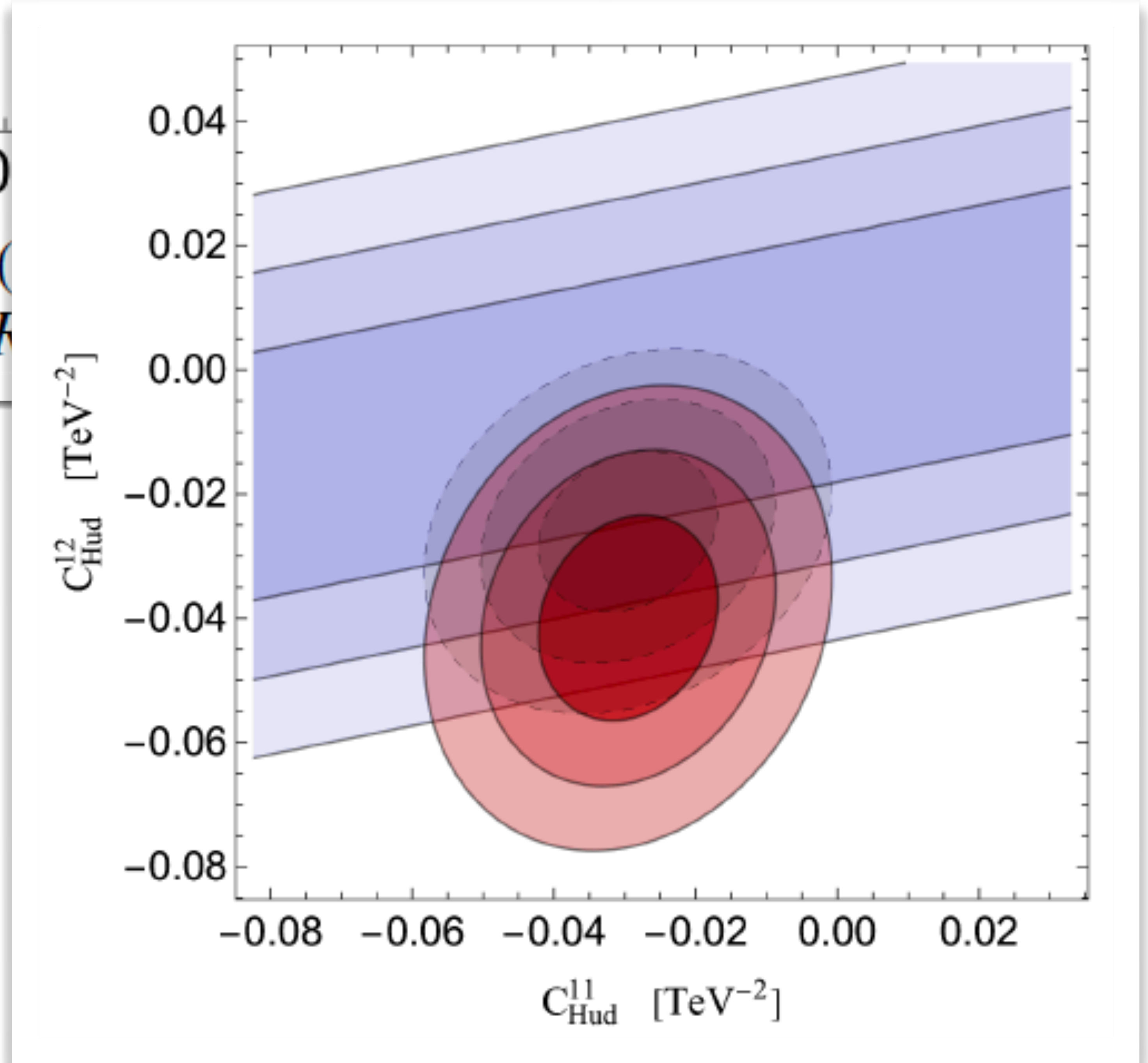
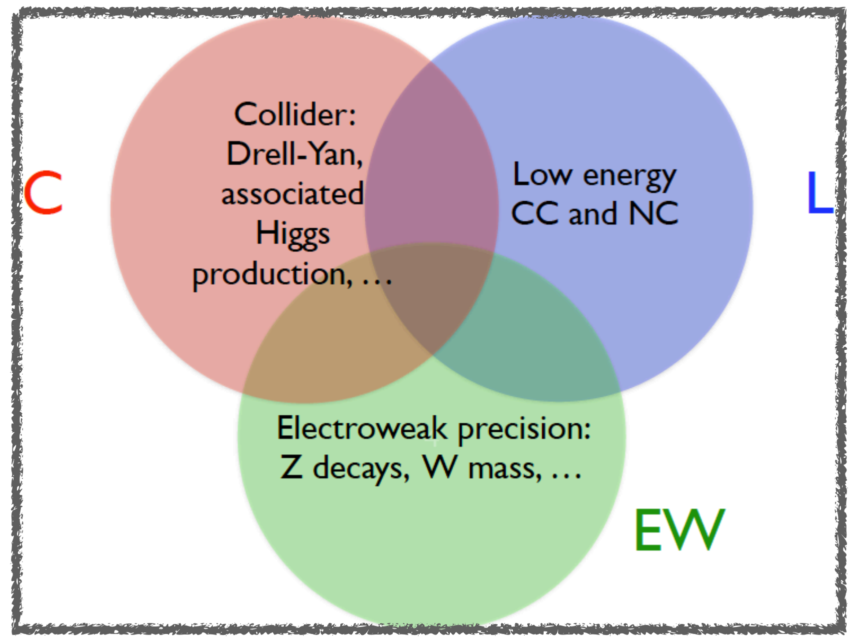




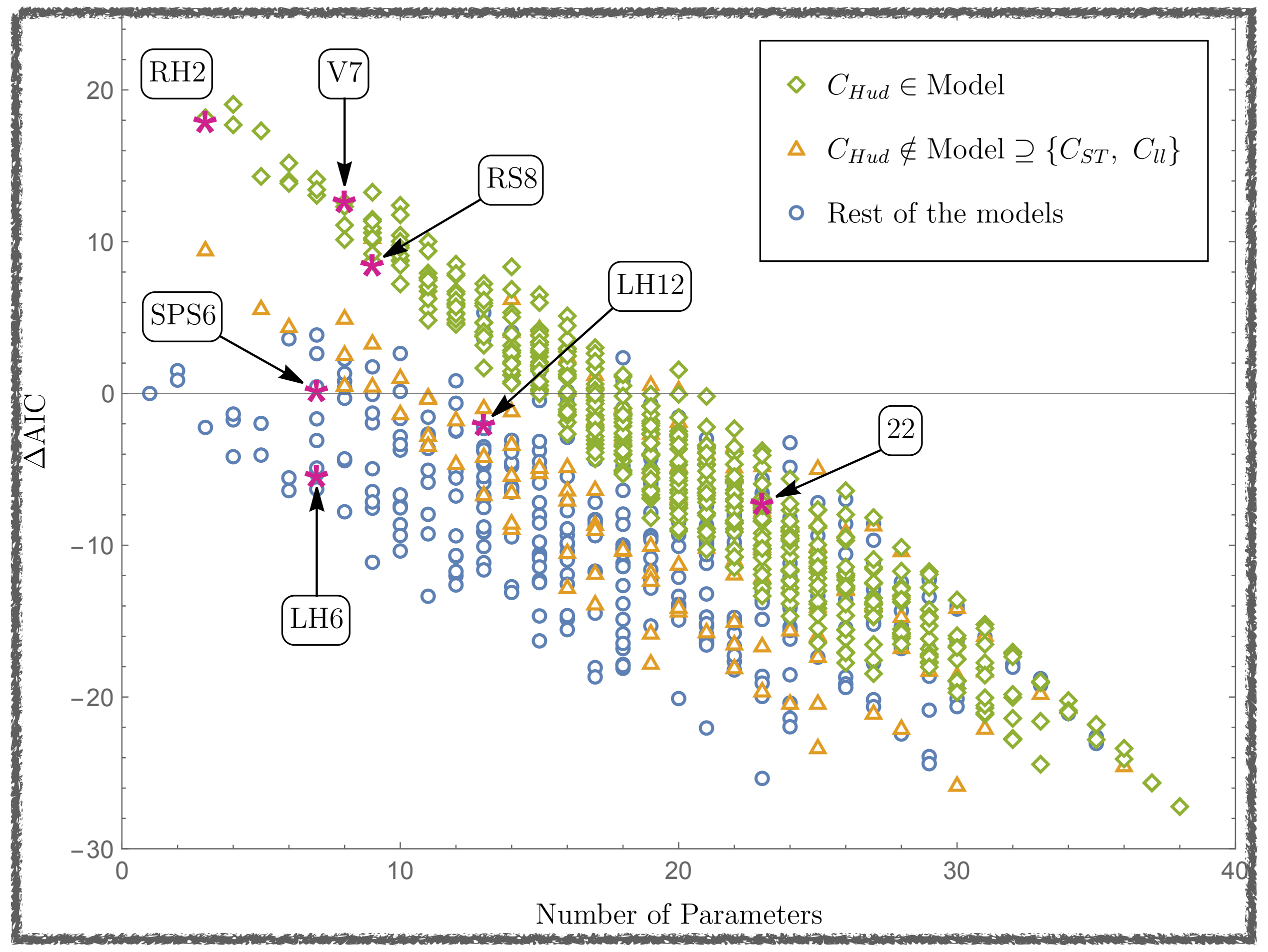


$K \to \pi\pi$

Summary: the CLEW framework



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.	$C_{lq}^{(u)}$ $C_{lq}^{(d)}$	Semilepton 4-fermion	6
IX.	C_{ledq} $C_{lequ}^{(1)}$	Scalar 4-fermion	6
X.	$C_{lequ}^{(3)}$	Tensor 4-fermion	2



C_{Hud}