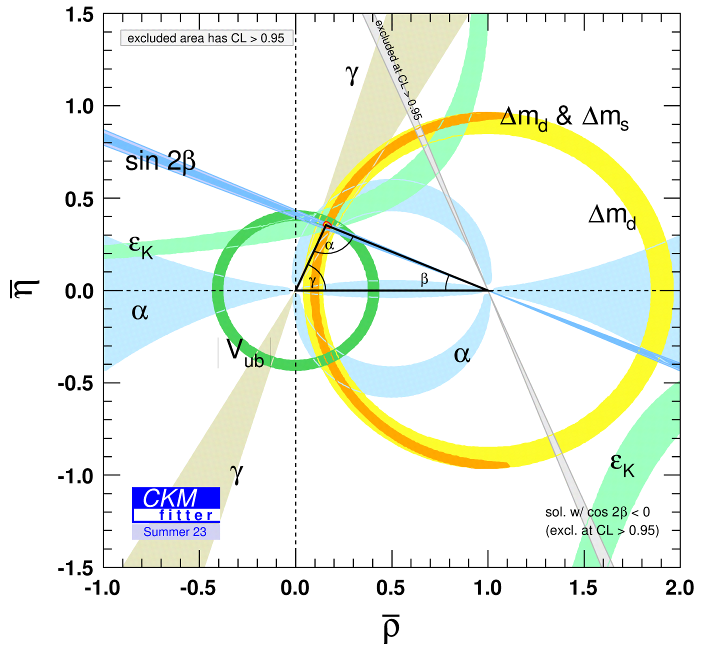
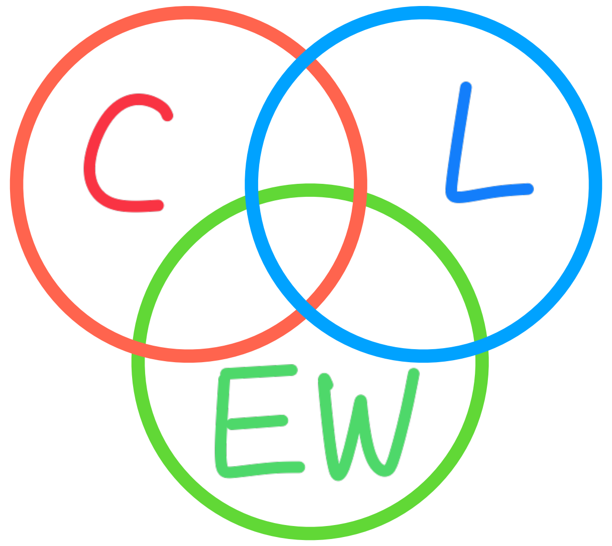
CKM: Fitting SMEFT with a CLEW



Tom Tong



Co-directed by

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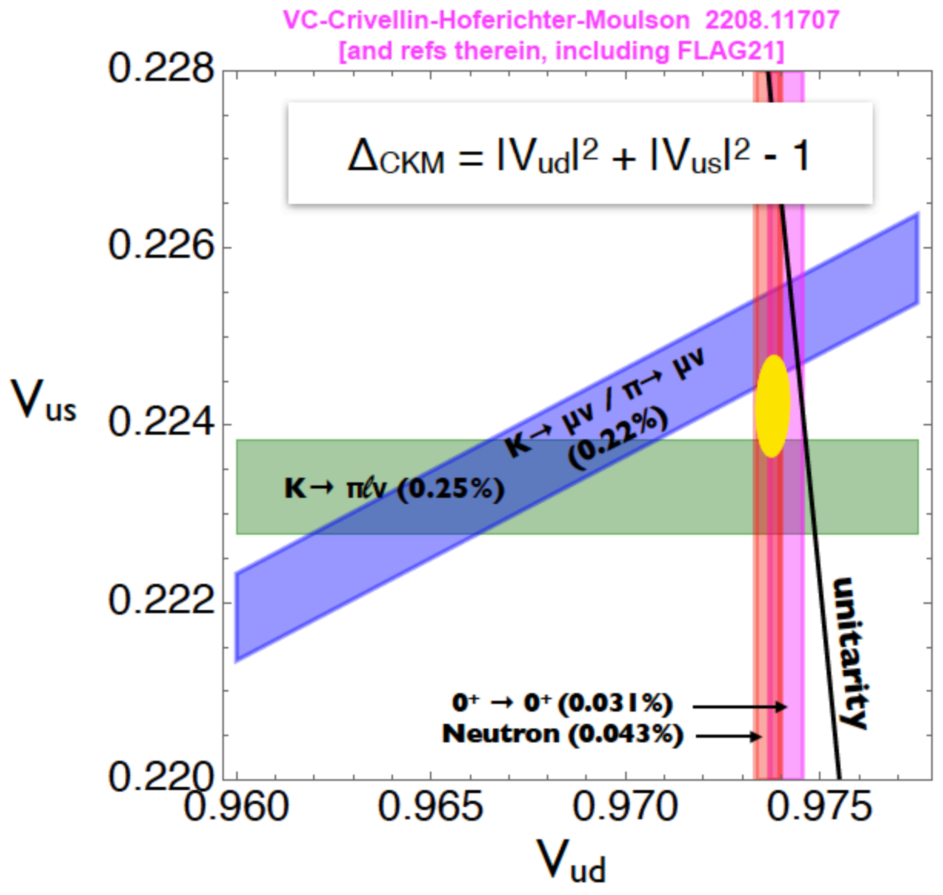
CRC TRR 257

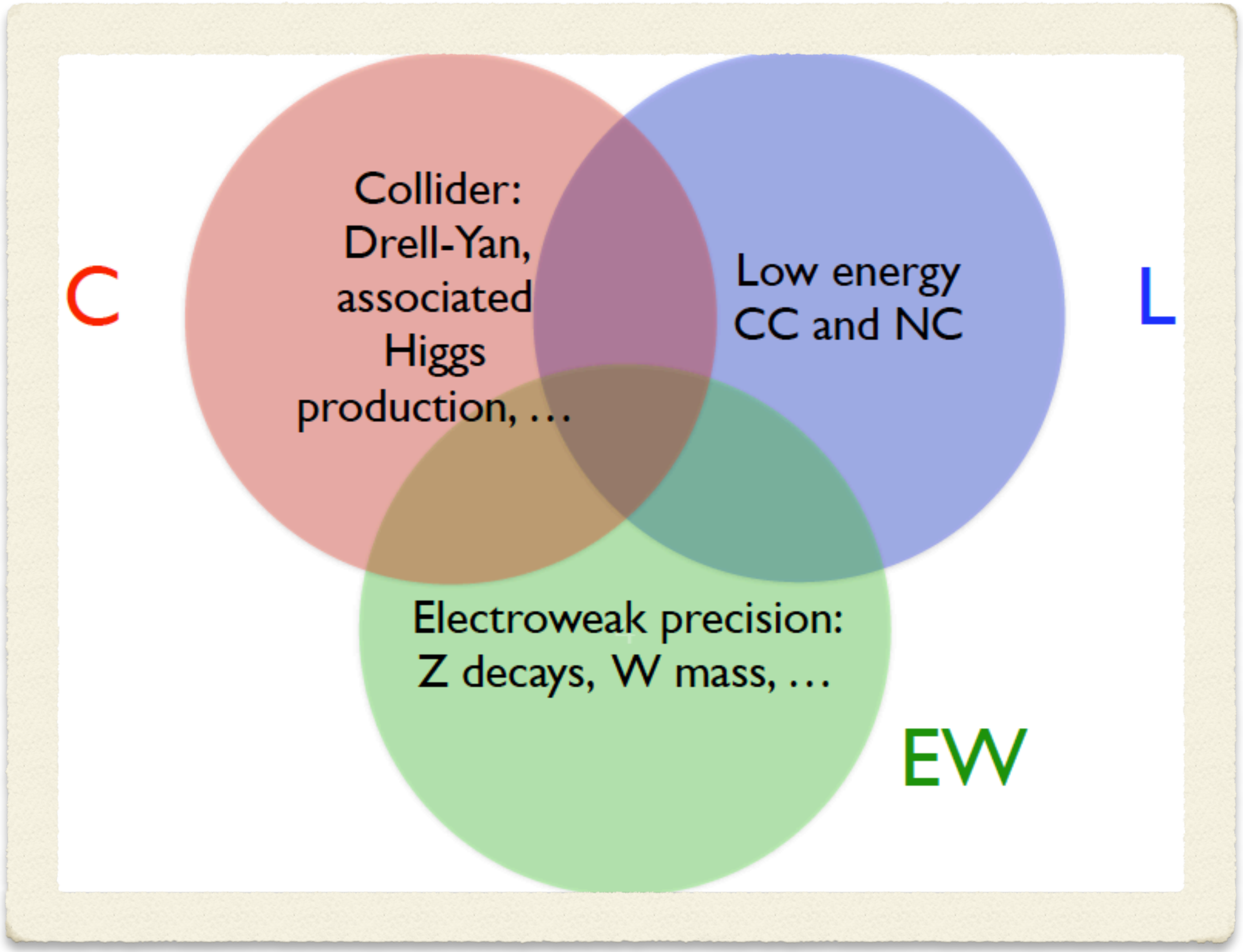
Abstract for the impatient

SMEFT global-fits: two major challenges

Flavor assumptions

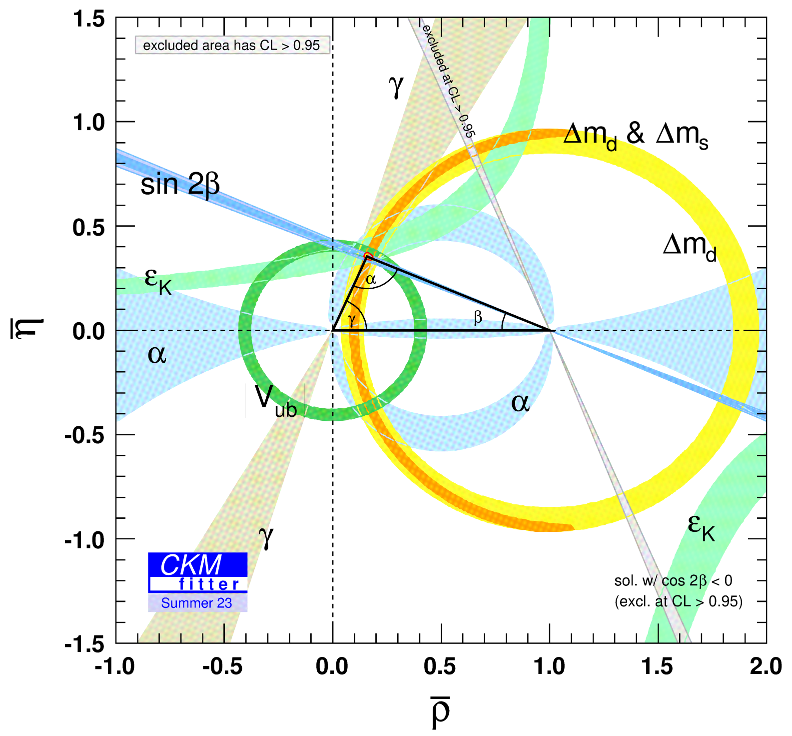


The CLEW framework

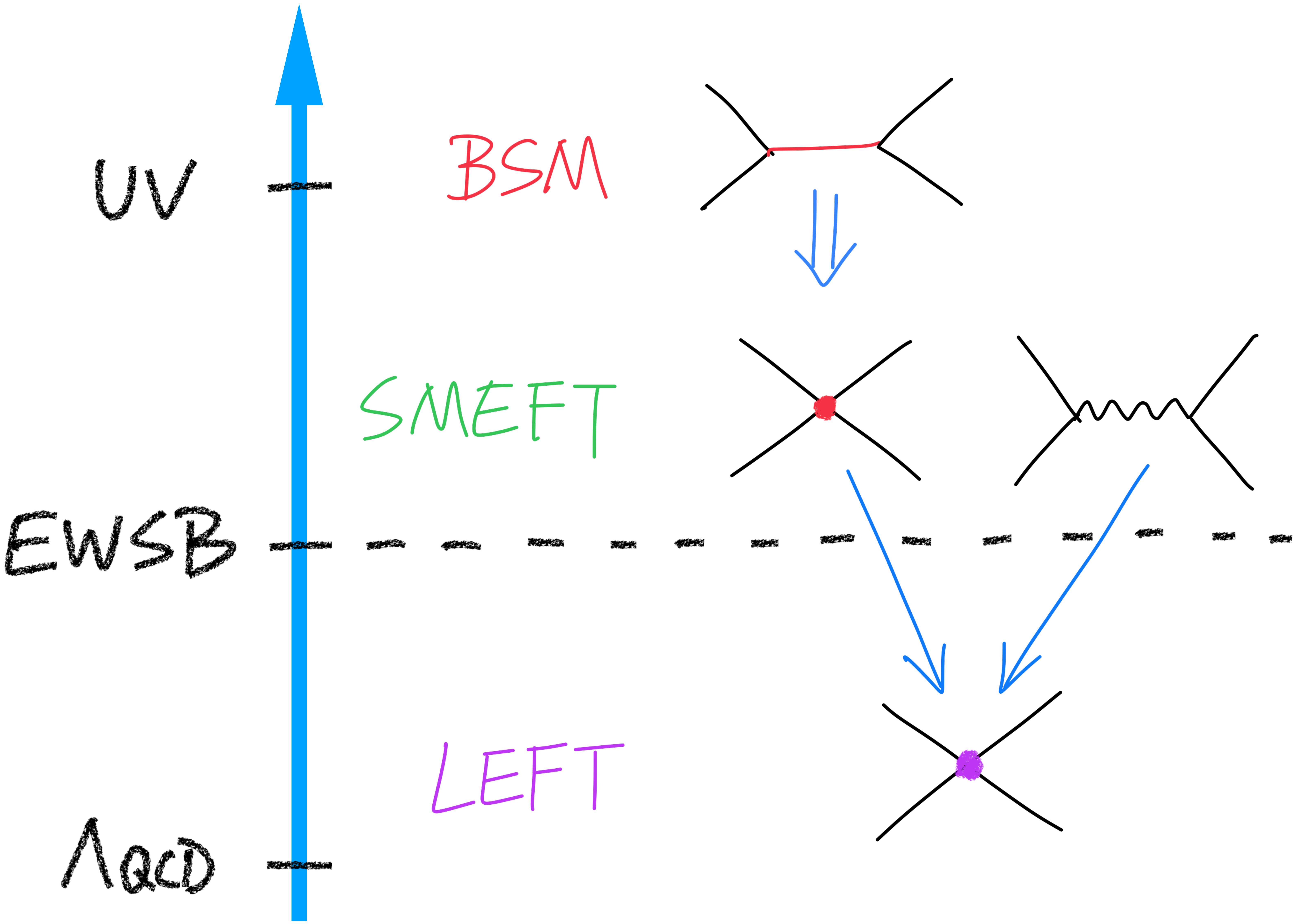


Flavor-assumption-free

Incomplete observables



SMEFT in a nutshell

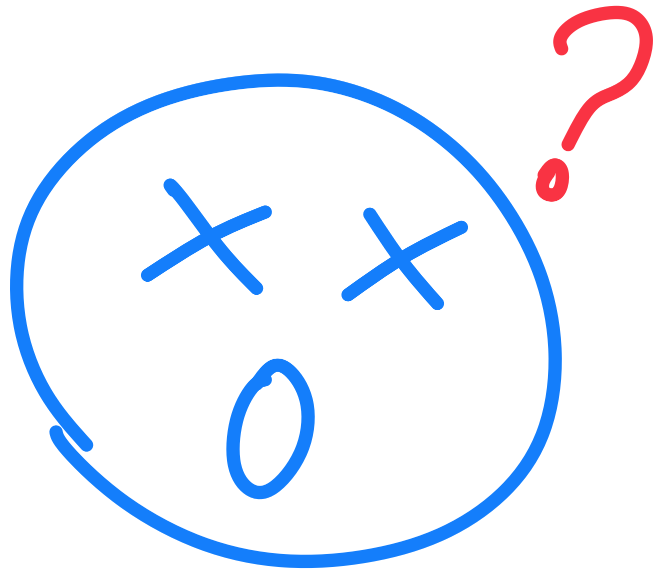


SMEFT at work

$$\mathcal{L}^{\text{dim-6}}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i C_i \mathcal{O}_i^{\text{dim-6}}$$

2499

Too many operators!



Simplify!

Make flavor-symmetry assumptions

$U(3)^5$, MFV, $U(2)^5$, top...

Handpick observables and operators

EWPO + Higgs + top + some flavor...

Casefile: $U(3)^5$ + EWPO

$U(3)_q \times U(3)_u \times U(3)_d \times U(3)_l \times U(3)_e$

Fitting without a CLEW

	EW
$\hat{C}_{Hl}^{(1)}$	0.0026 ± 0.011
$\hat{C}_{Hl}^{(3)}$	-0.019 ± 0.016
$\hat{C}_{He}$	-0.0011 ± 0.0092
$\hat{C}_{Hq}^{(1)}$	-0.033 ± 0.043
$\hat{C}_{Hq}^{(3)}$	-0.056 ± 0.033
$\hat{C}_{Hu}$	-0.02 ± 0.12
$\hat{C}_{Hd}$	-0.54 ± 0.25
C_Δ	-0.11 ± 0.069

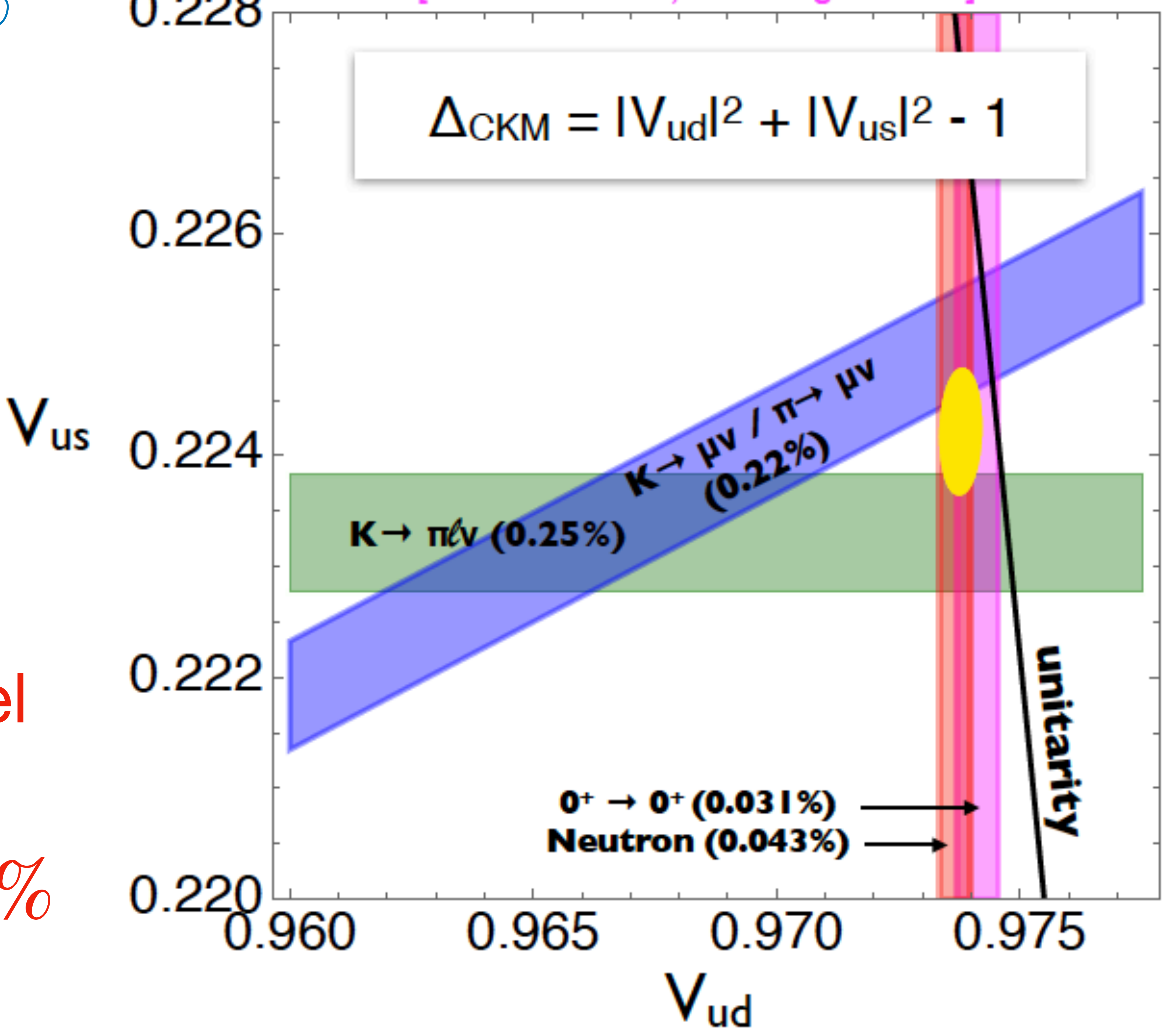
$$\Delta_{CKM}^{exp} \approx -0.15\,\%$$

$\sim 3\sigma$ at permil level

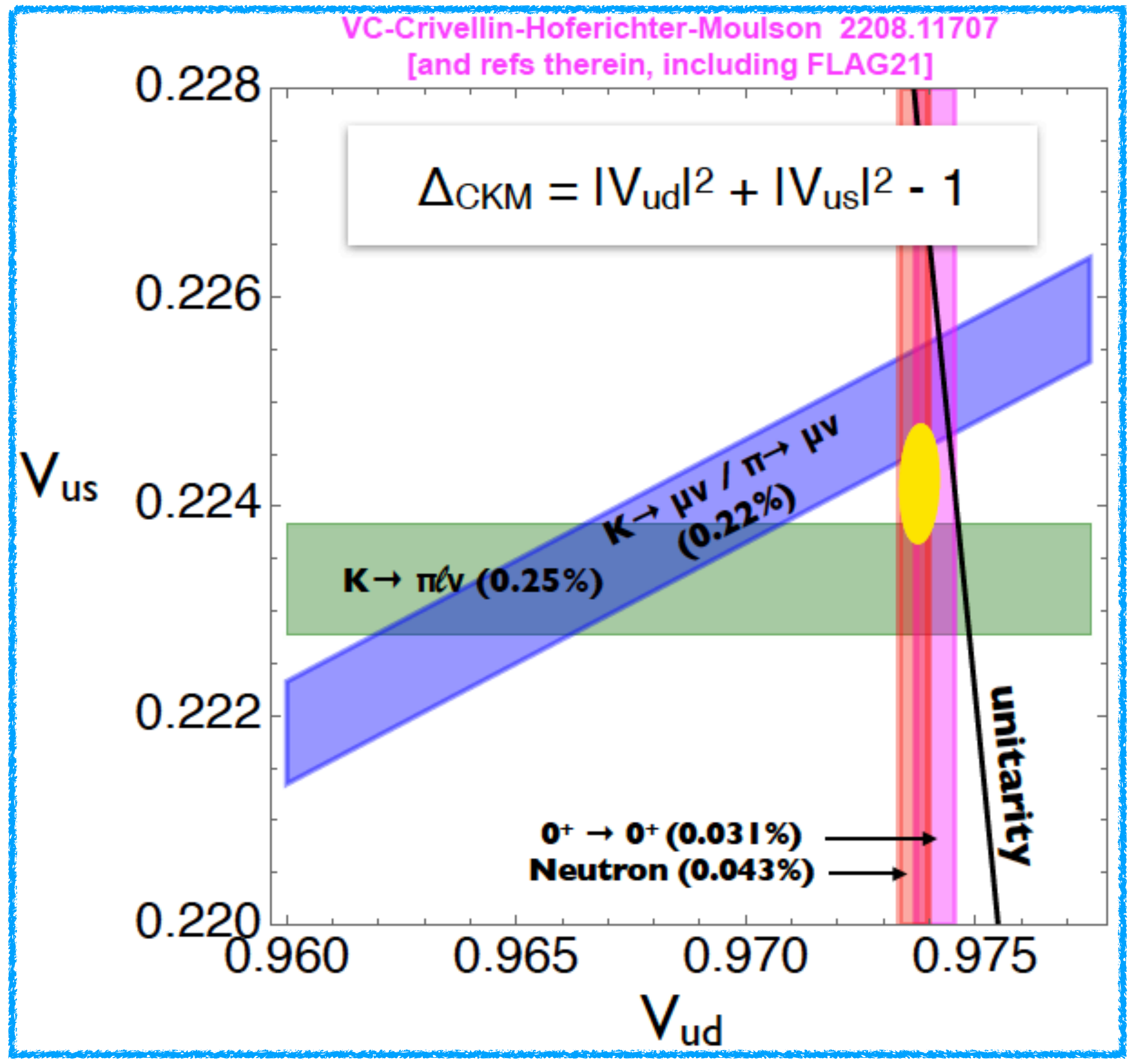
$\sim 2\sigma$ at percent level

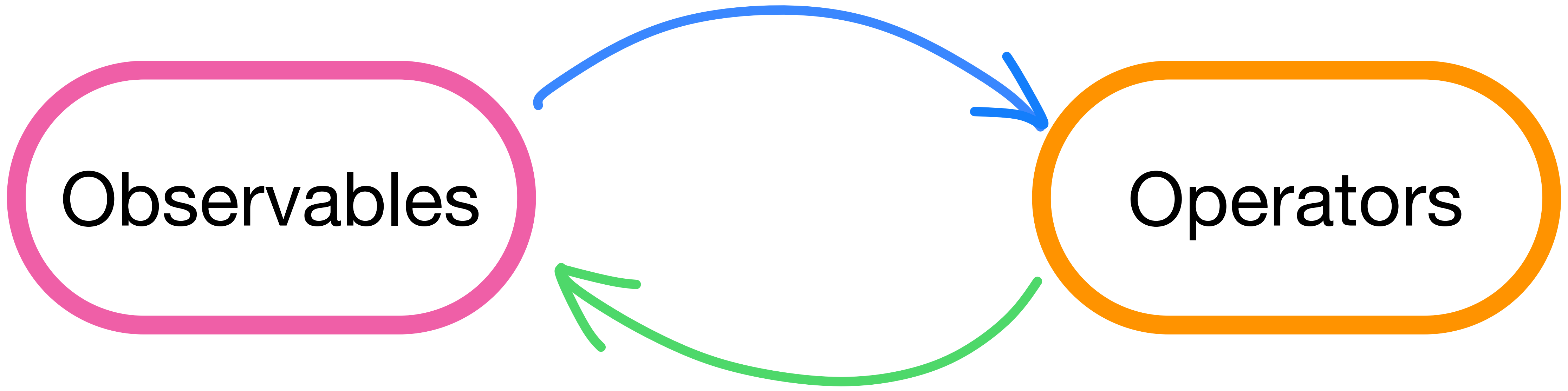
$$2v^2\left[C_{Hq}^{(3)} - C_{Hl}^{(3)} + C_{ll} - C_{lq}^{(3)}\right] = \Delta_{CKM}^{fit} \approx -0.67\,\%$$

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



List all the relevant operators





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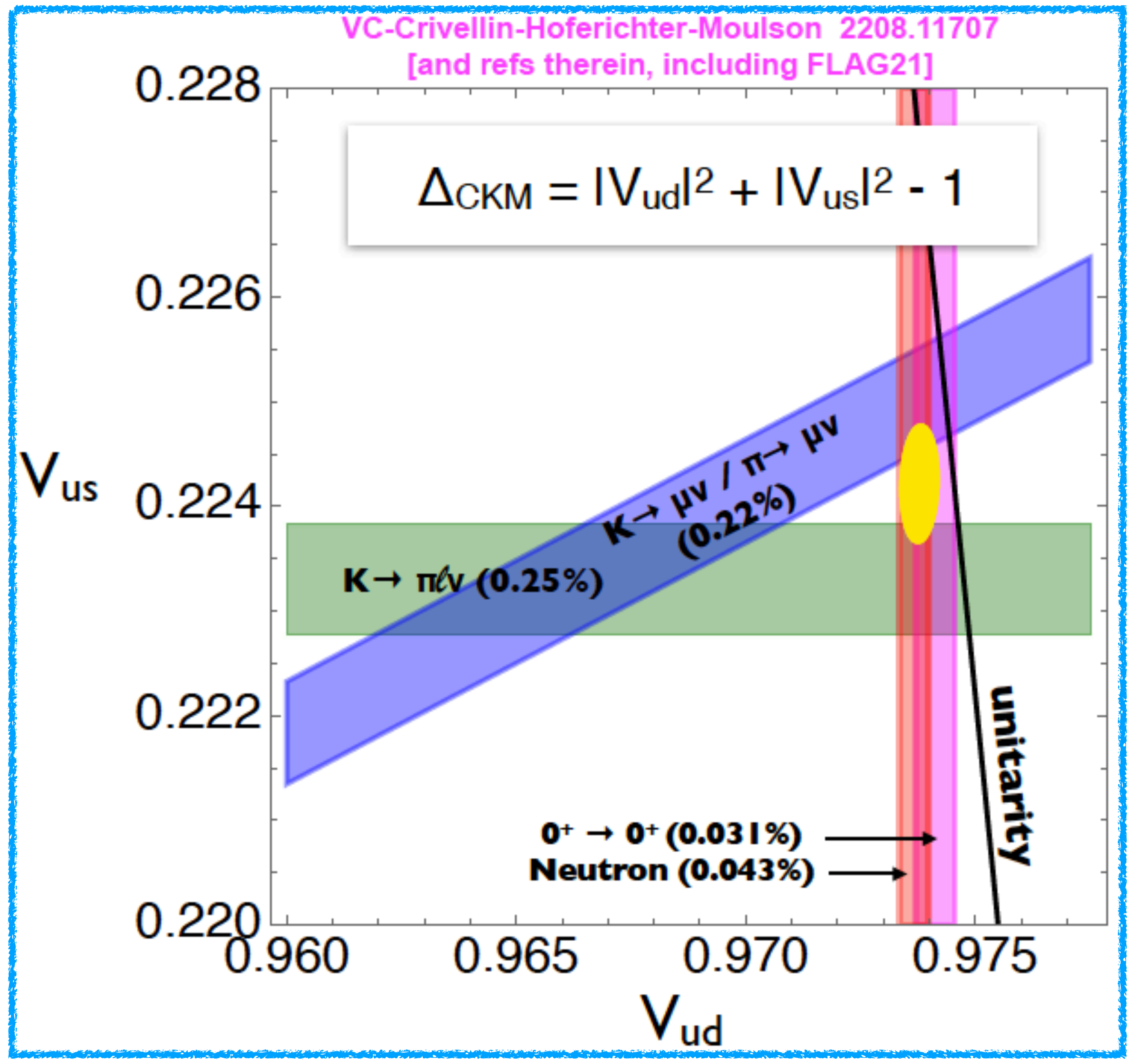
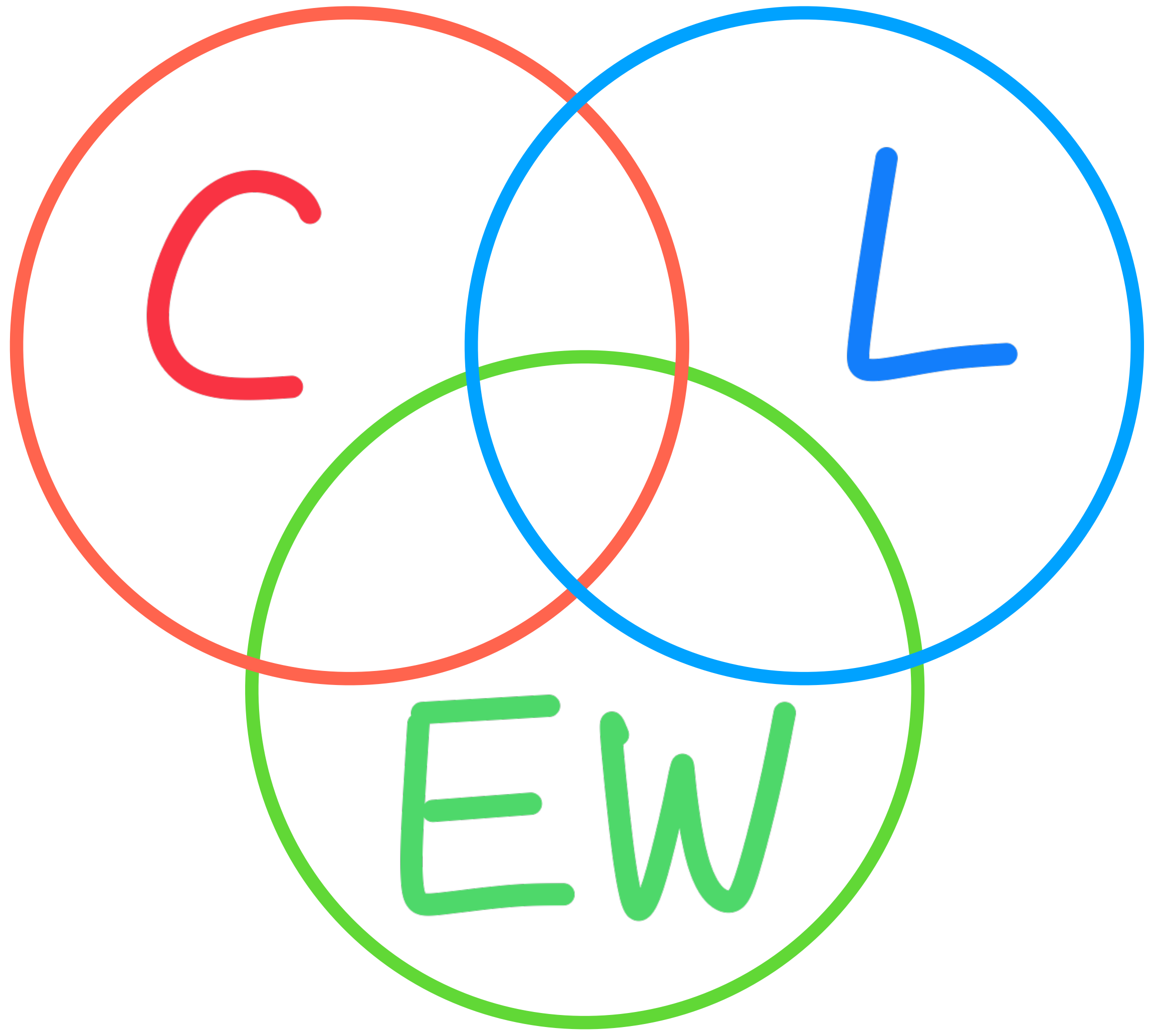
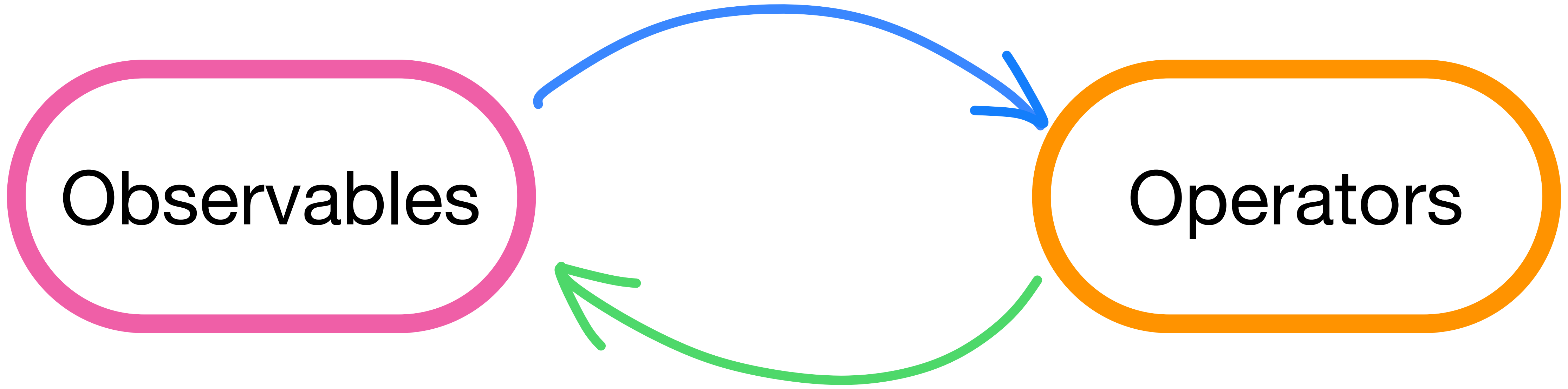
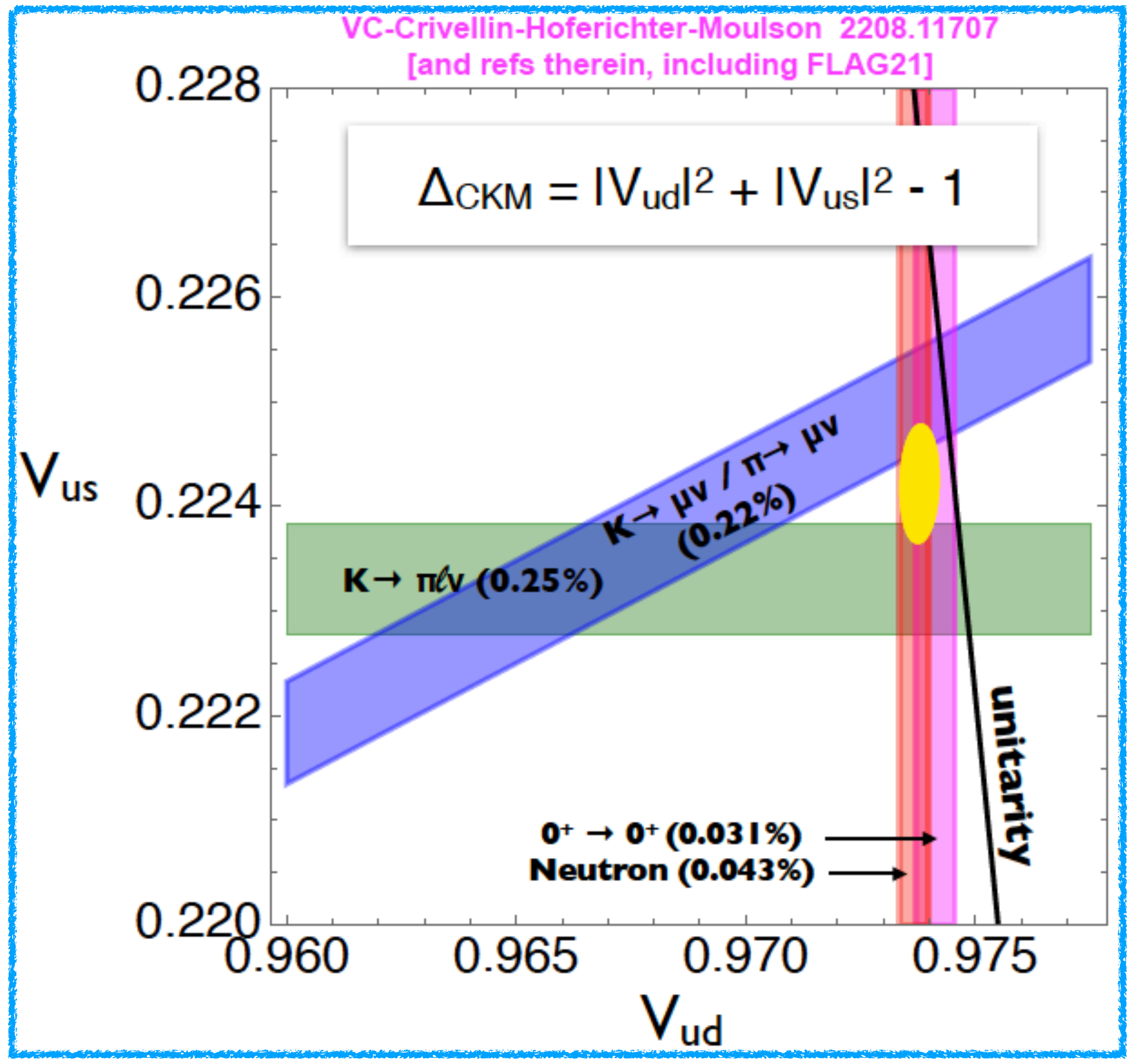
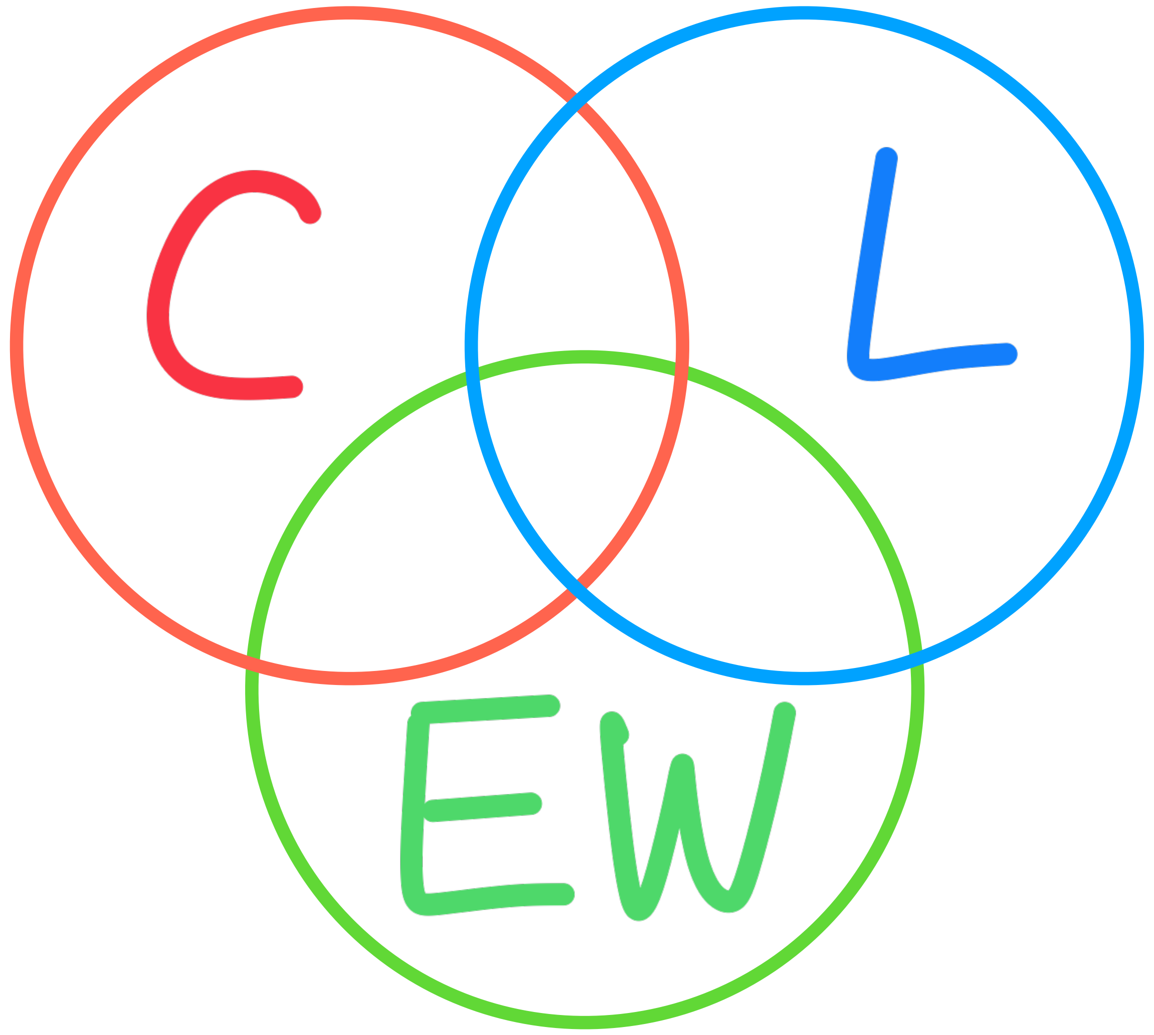


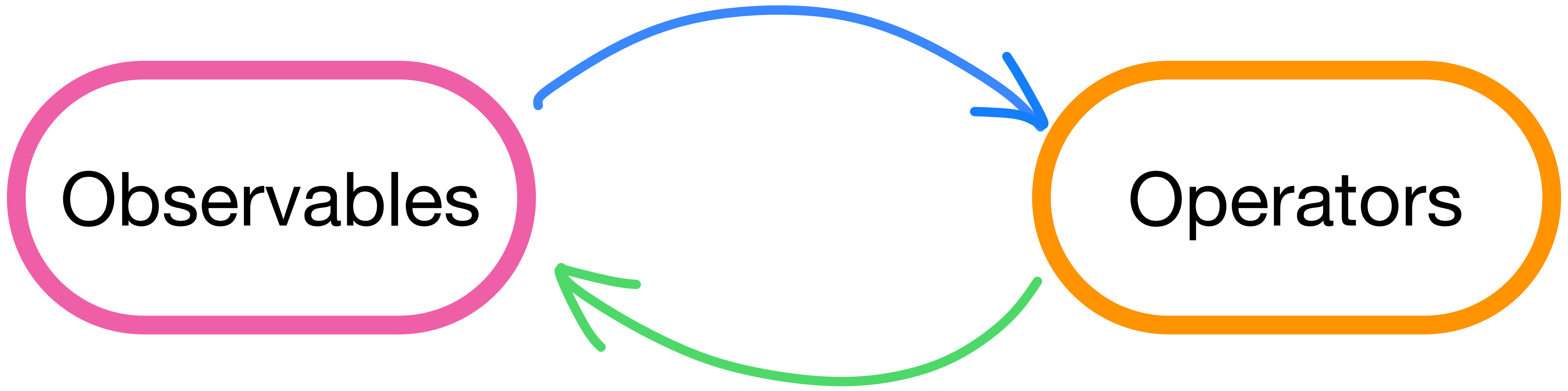




List all the relevant operators



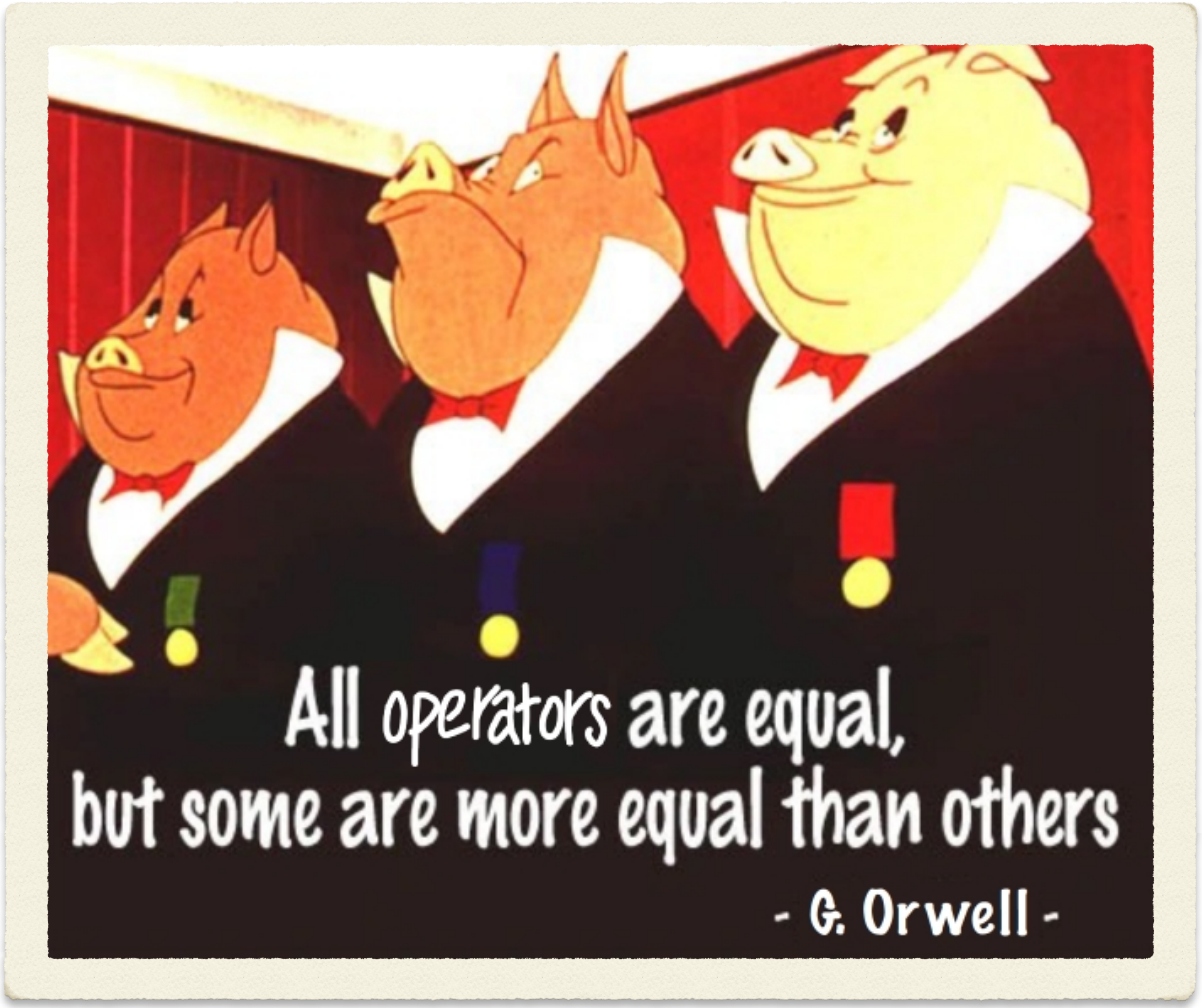




Operators		Low energy CC	EWPO	LHC
$\boldsymbol{H^4D^2}$				
Q_{HD}	$(H^\dagger D^\mu H)^* (H^\dagger D_\mu H)$	parameter shift (m_Z)		
$\boldsymbol{X^2H^2}$				
Q_{HWB}	$H^\dagger \tau^I H\, W^I_{\mu\nu} B^{\mu\nu}$			
		✗	✓	✓
	$\ldots D^I_\mu H)(\bar{l}_p \tau^I \gamma^\mu l_r)$	✓	✓	✓
Q_{He}	$(H^\dagger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

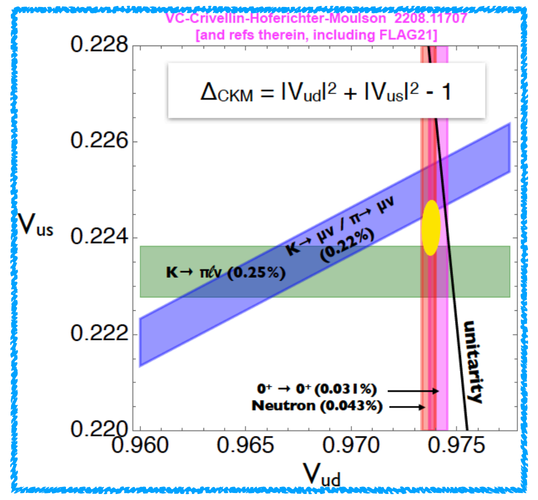
With all flavor indices

All operators are equal, but...



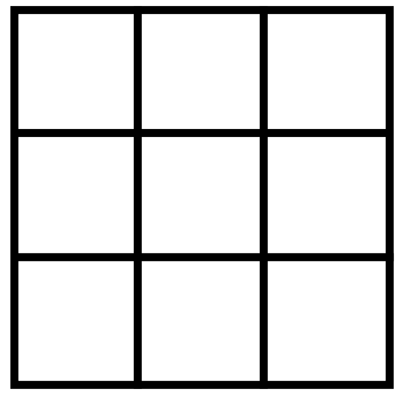
Operators		Low energy CC	EWPO	LHC
$H^4 D^2$				
Q_{HD}	$(H^\dagger D^\mu H)^* (H^\dagger D_\mu H)$	parameter shift (m_Z)		
$X^2 H^2$				
Q_{HWB}	$H^\dagger \tau^I H\, W^I_{\mu\nu} B^{\mu\nu}$			
[illegible]				
[illegible]	[illegible]	✗	✓	✓
[illegible]	$\ldots D^I_\mu H)(\bar{l}_p \tau^I \gamma^\mu l_r)$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

With all flavor indices

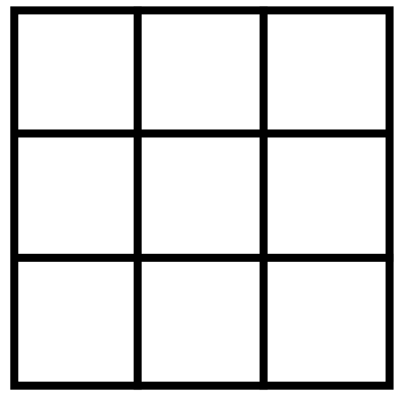


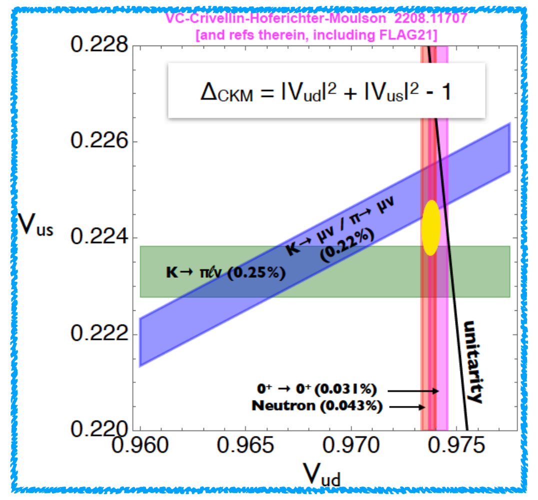
All operators are equal, but...

$C_{Hq}^{(1)}$ 3x3



$C_{Hq}^{(3)}$ 3x3

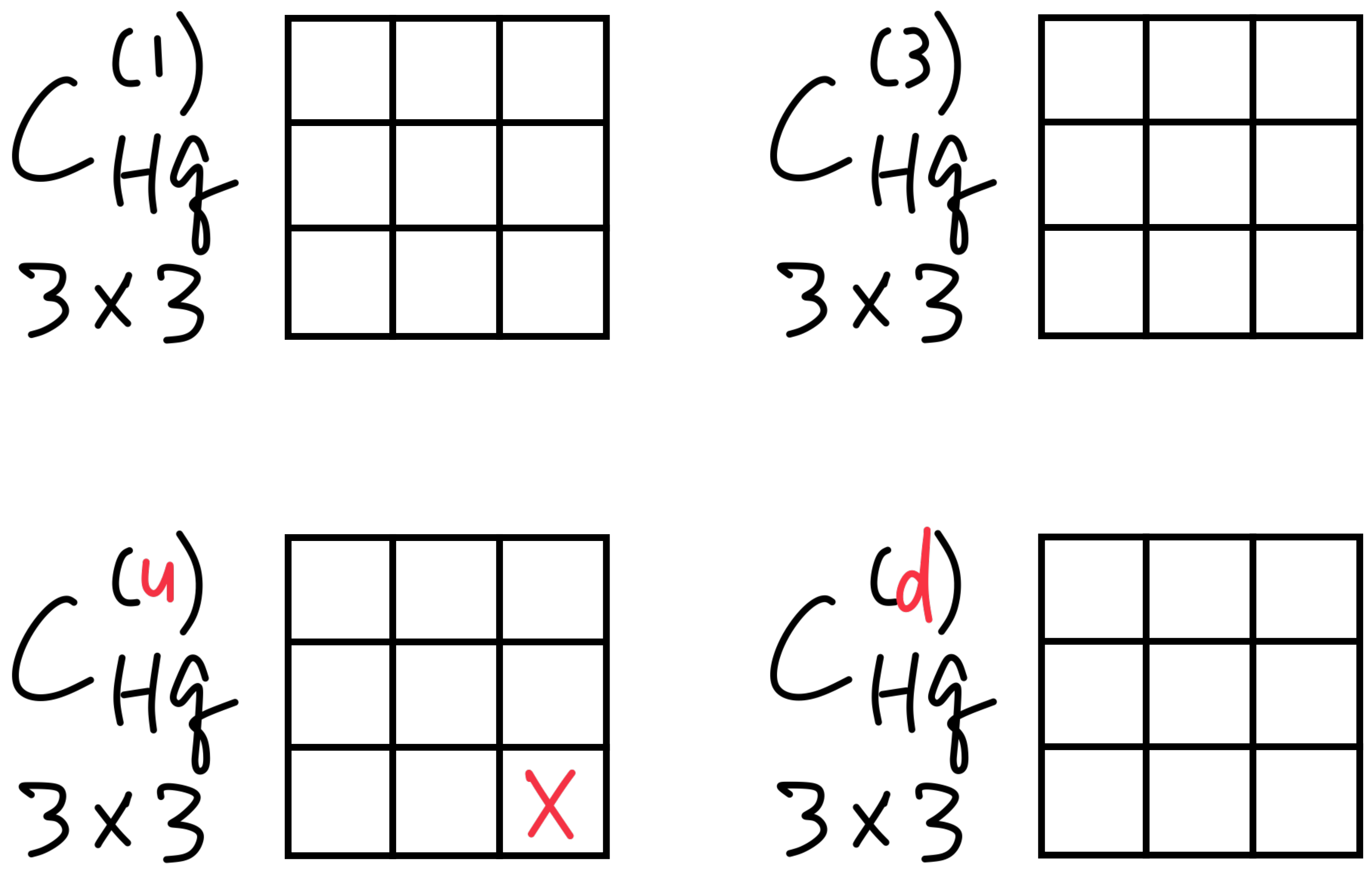


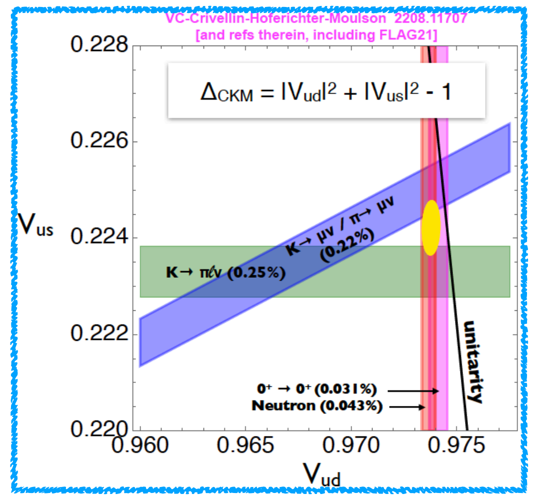


All operators are equal, but...

Basis rotation

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





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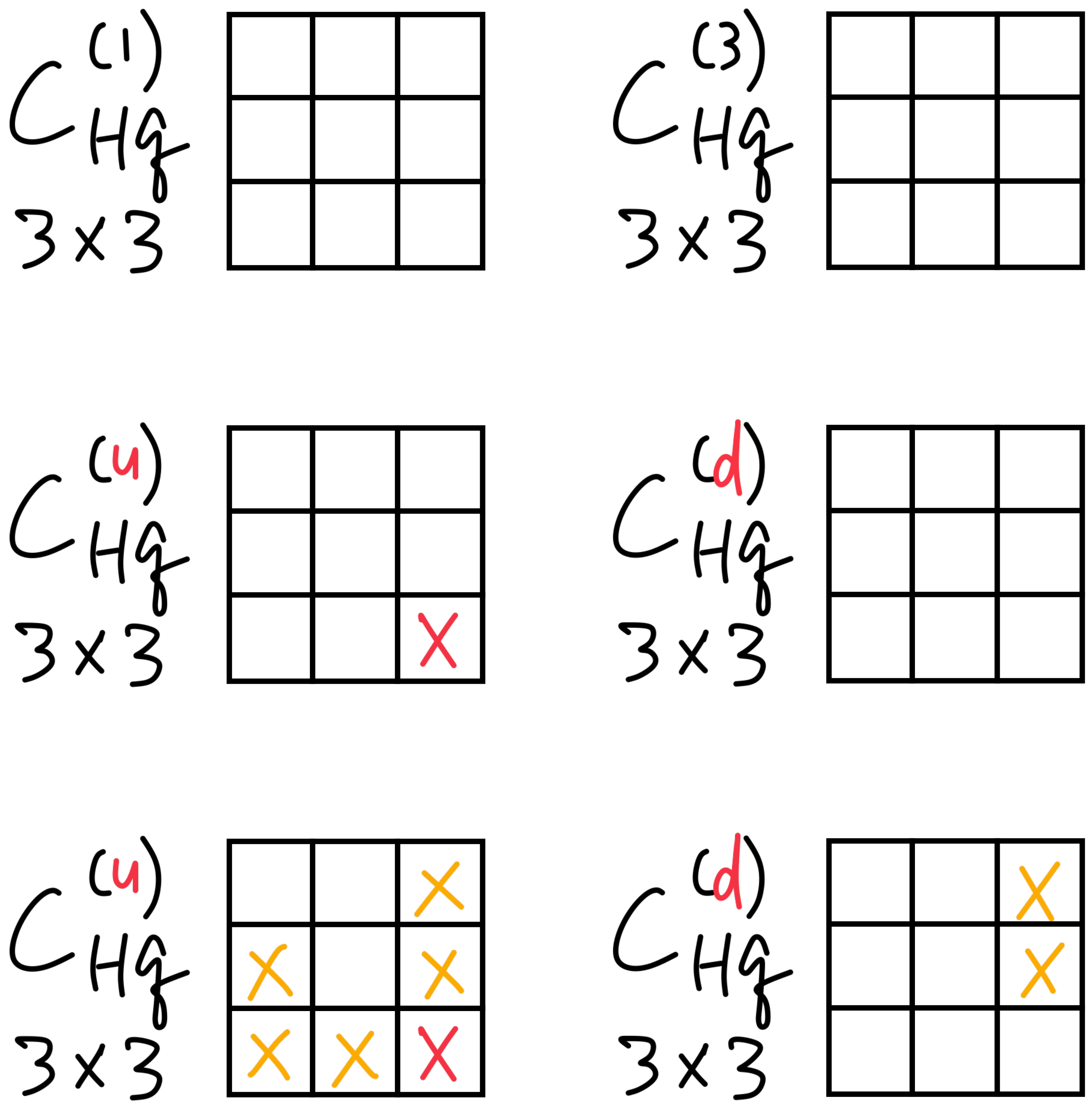
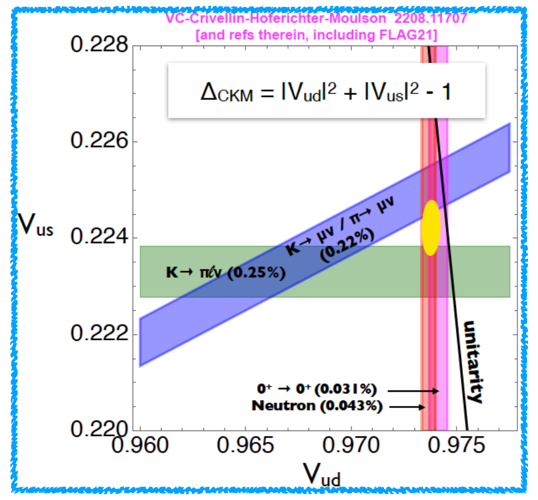
Relative contribution

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





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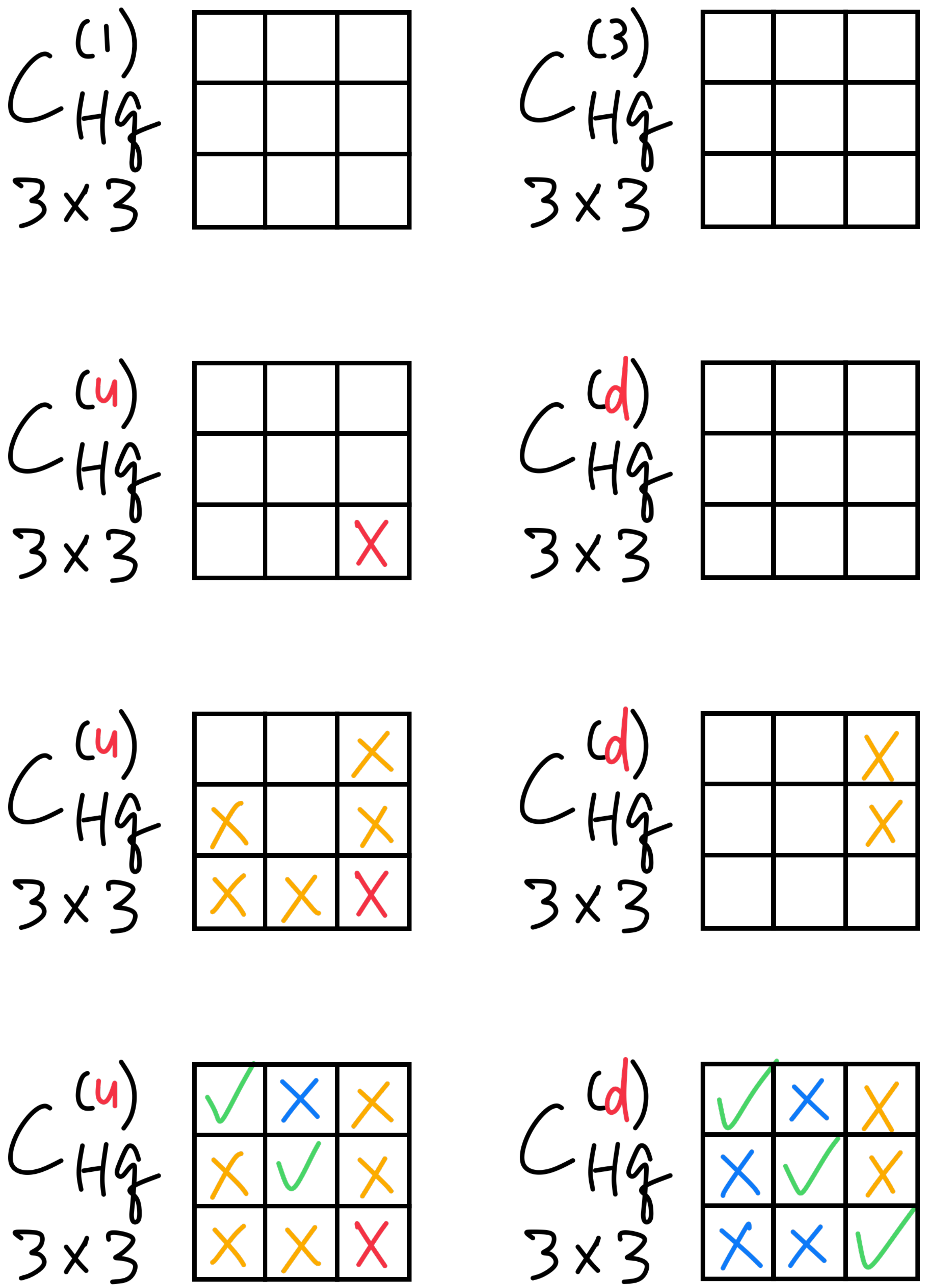
$$C_{Hq}^{(u)} = V\left[C_{Hq}^{(1)} - C_{Hq}^{(3)}\right]V^{\dagger}\,, \qquad C_{Hq}^{(d)} = C_{Hq}^{(1)} + C_{Hq}^{(3)}\,,$$

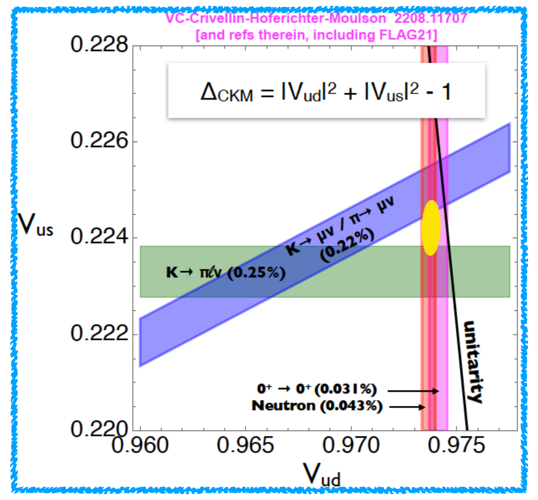
Relative contribution

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

Pheno constraints

FCNC decays of B, D and K mesons





All operators are equal, but...

Basis rotation

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

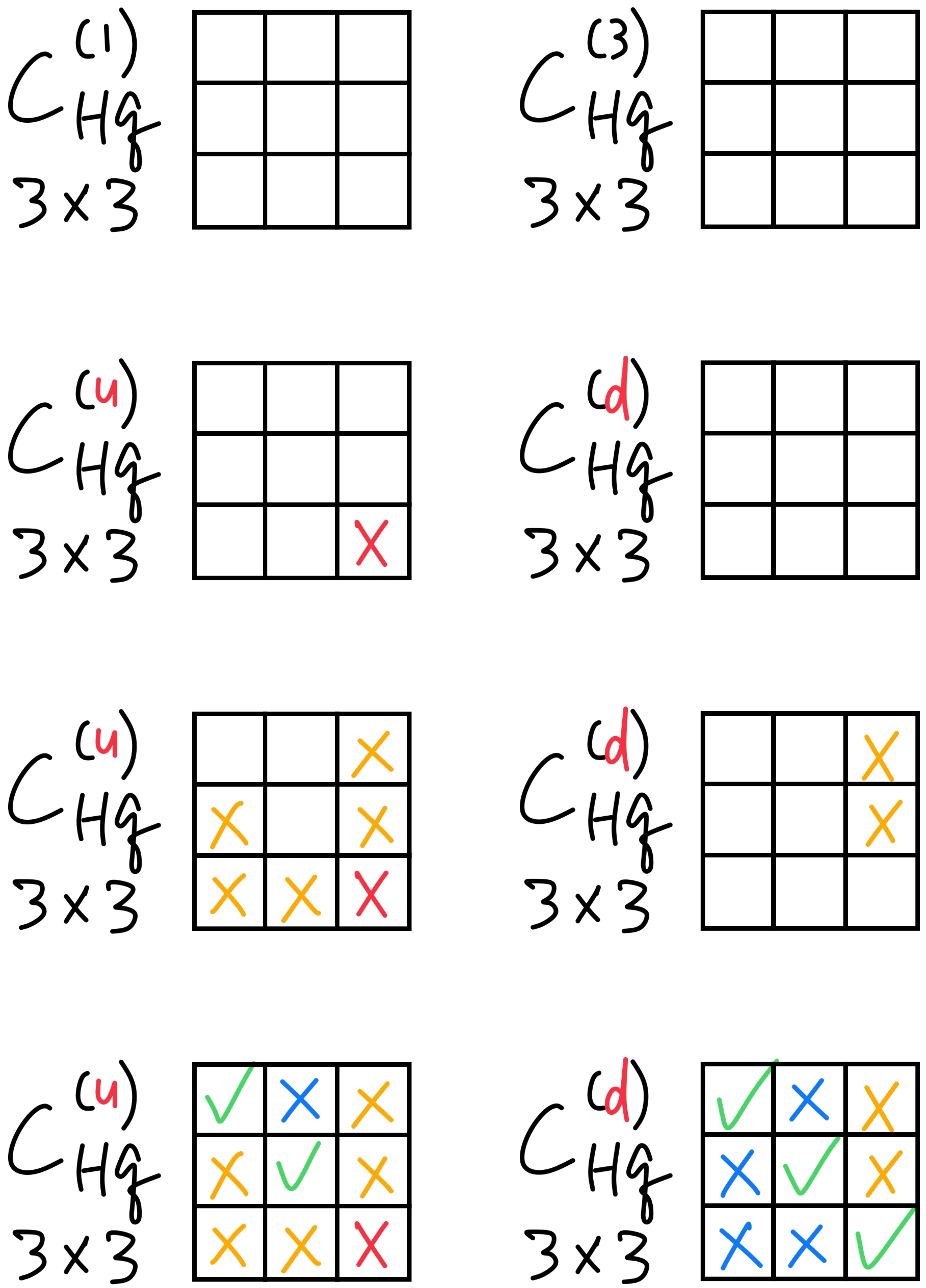
Relative contribution

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

37 in total

Fit!

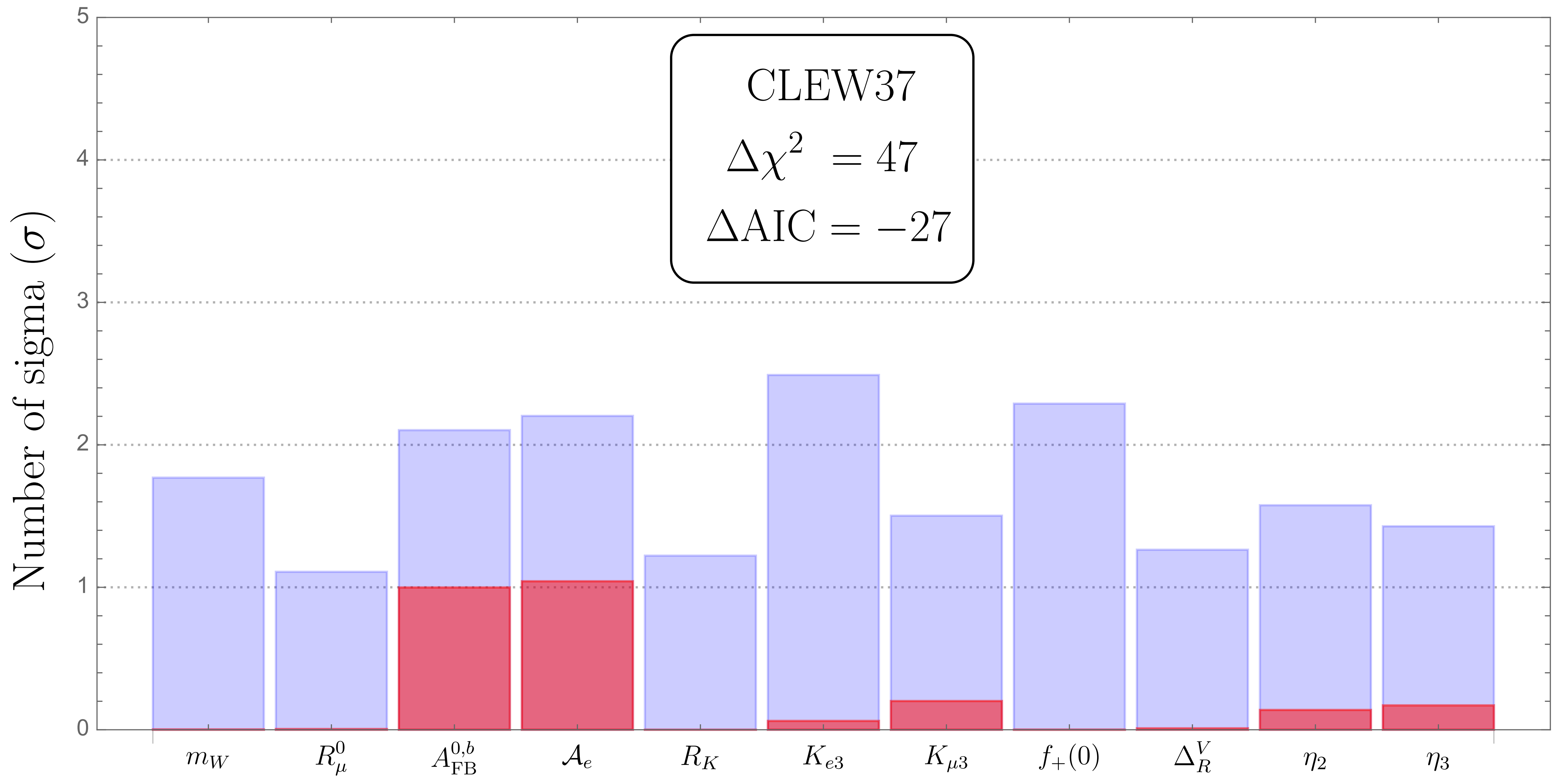
Operators		Low energy CC	EWPO	LHC
H^4D^2				
Q_{HD}	$(H^\dagger D^\mu H)^* (H^\dagger D_\mu H)$	parameter shift (m_Z)		
X^2H^2				
Q_{HWB}	$H^\dagger \tau^I H W^I_{\mu\nu} B^{\mu\nu}$			
		✗	✓	✓
	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{l}_p \tau^I \gamma^\mu l_r)$	✓	✓	✓
Q_{He}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}_p \gamma^\mu e_r)$	✗	✓	✓
$Q^{(1)}_{Hq}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}_p \gamma^\mu q_r)$	✗	✓	✓
$Q^{(3)}_{Hq}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{q}_p \tau^I \gamma^\mu q_r)$	✓	✓	✓
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.				
$Q^{(1)}_{lequ}$	$(\bar{l}^j_p e_r)\epsilon_{jk}(\bar{q}^k_s u_t)$	✓	✗	✓
$Q^{(3)}_{lequ}$	$(\bar{l}^j_p \sigma_{\mu\nu} e_r)\epsilon_{jk}(\bar{q}^k_s \sigma^{\mu\nu} u_t)$	✓	✗	✓

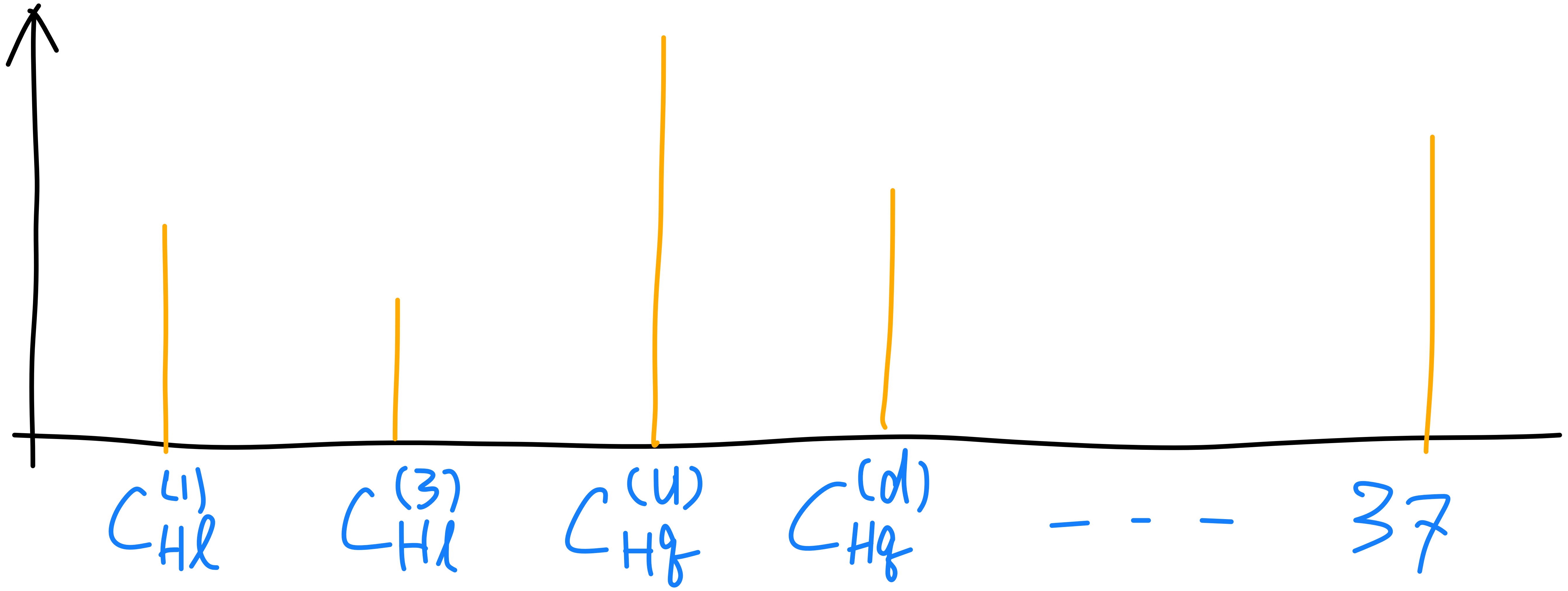
With all flavor indices

Conclusion

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

37 in total





~~Conclusion~~

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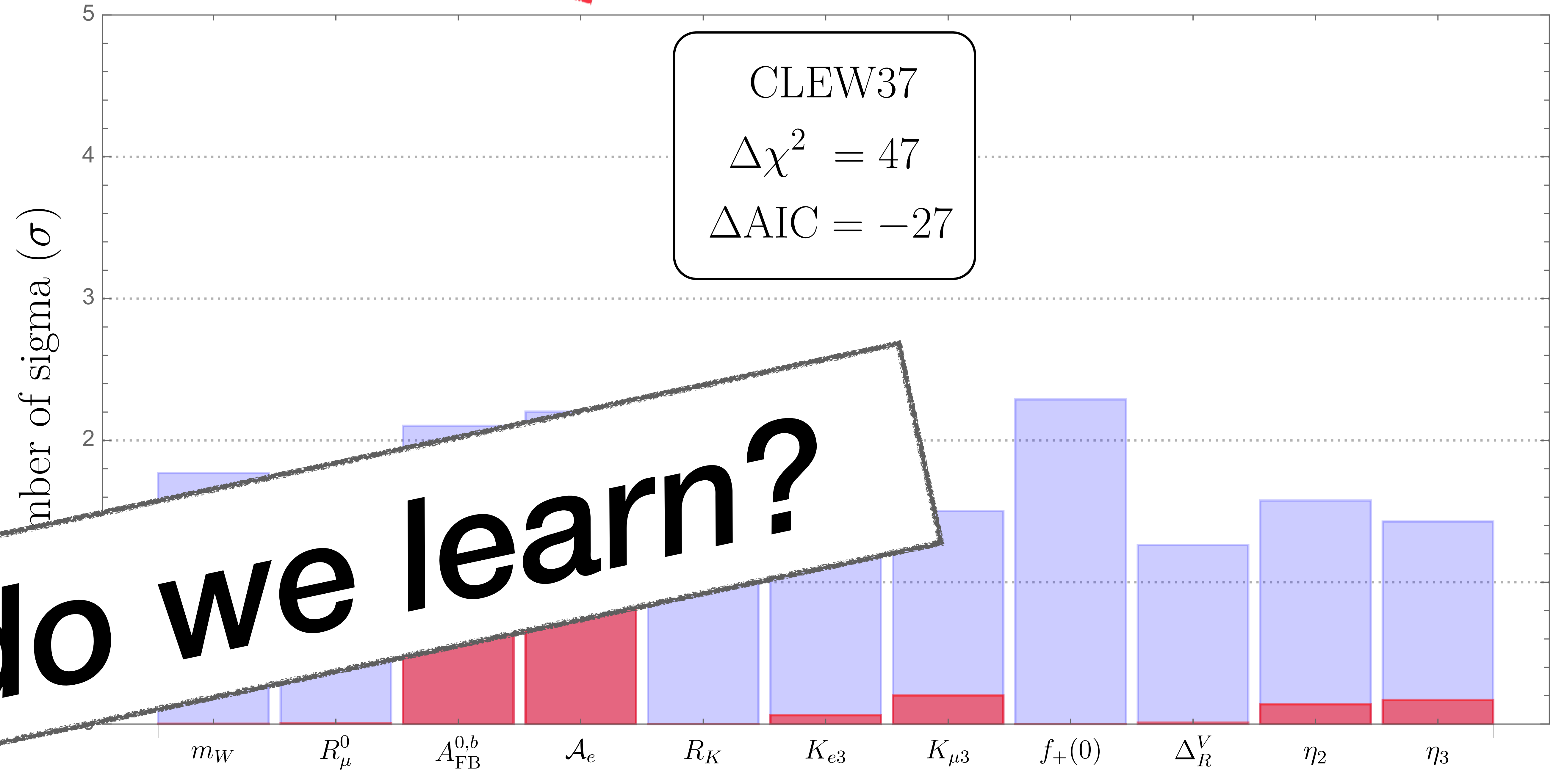
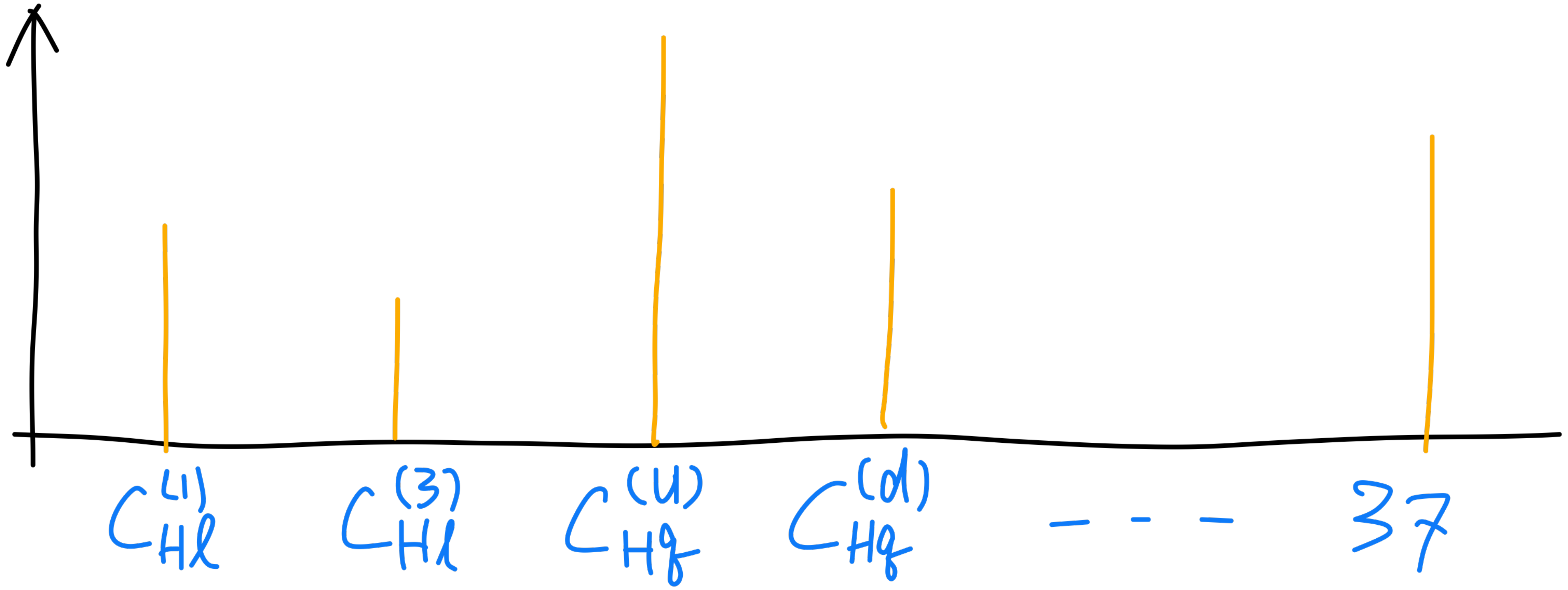
$C^{(d)}_{\substack{lq\\\ell\ell pr}}$, $C_{\substack{ledq\\\ell\ell pr}}$	$\ell \in \{e, \mu\}$
$C^{(u)}_{\substack{lq\\\ell\ell 11}}$, $\bar{C}^{(1,3)}_{\substack{lequ\\\ell\ell 11}}$	$\ell \in \{e, \mu\}$
C_{HD} C_{HWB}	
$C_{\substack{ll\\2112}}$	



What do we learn?



37 in total

Still, some are more equal

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

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

Group them into 10 categories

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

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
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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

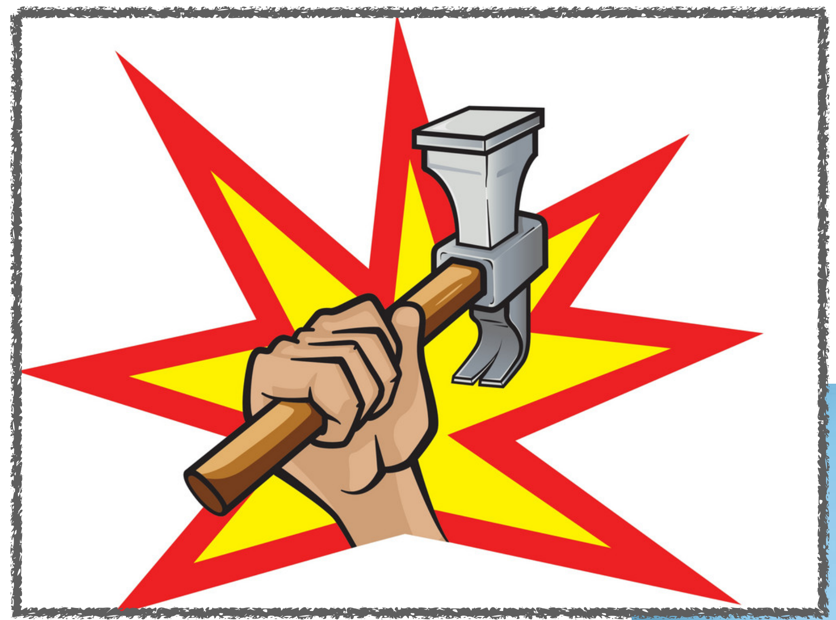
Let's do $2^{37} \approx 10^{11}$ fits!

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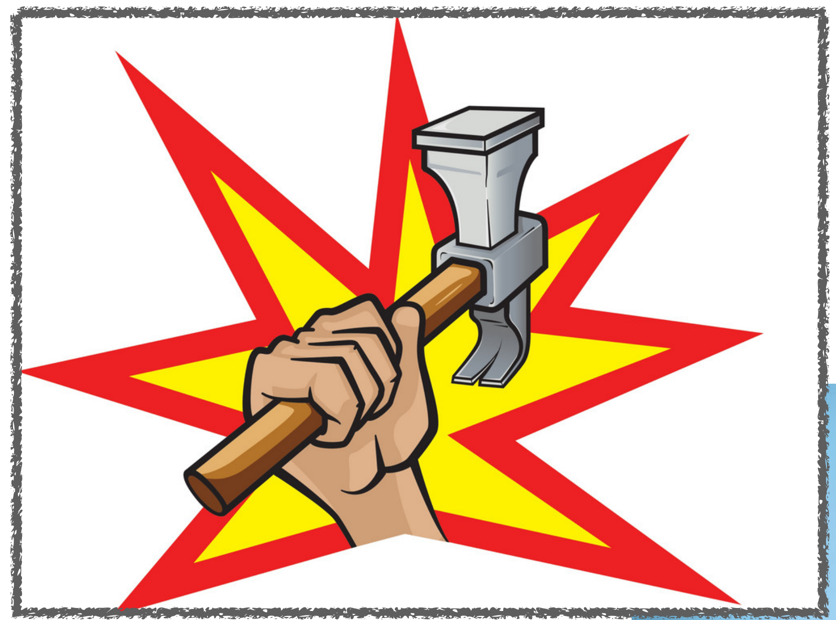
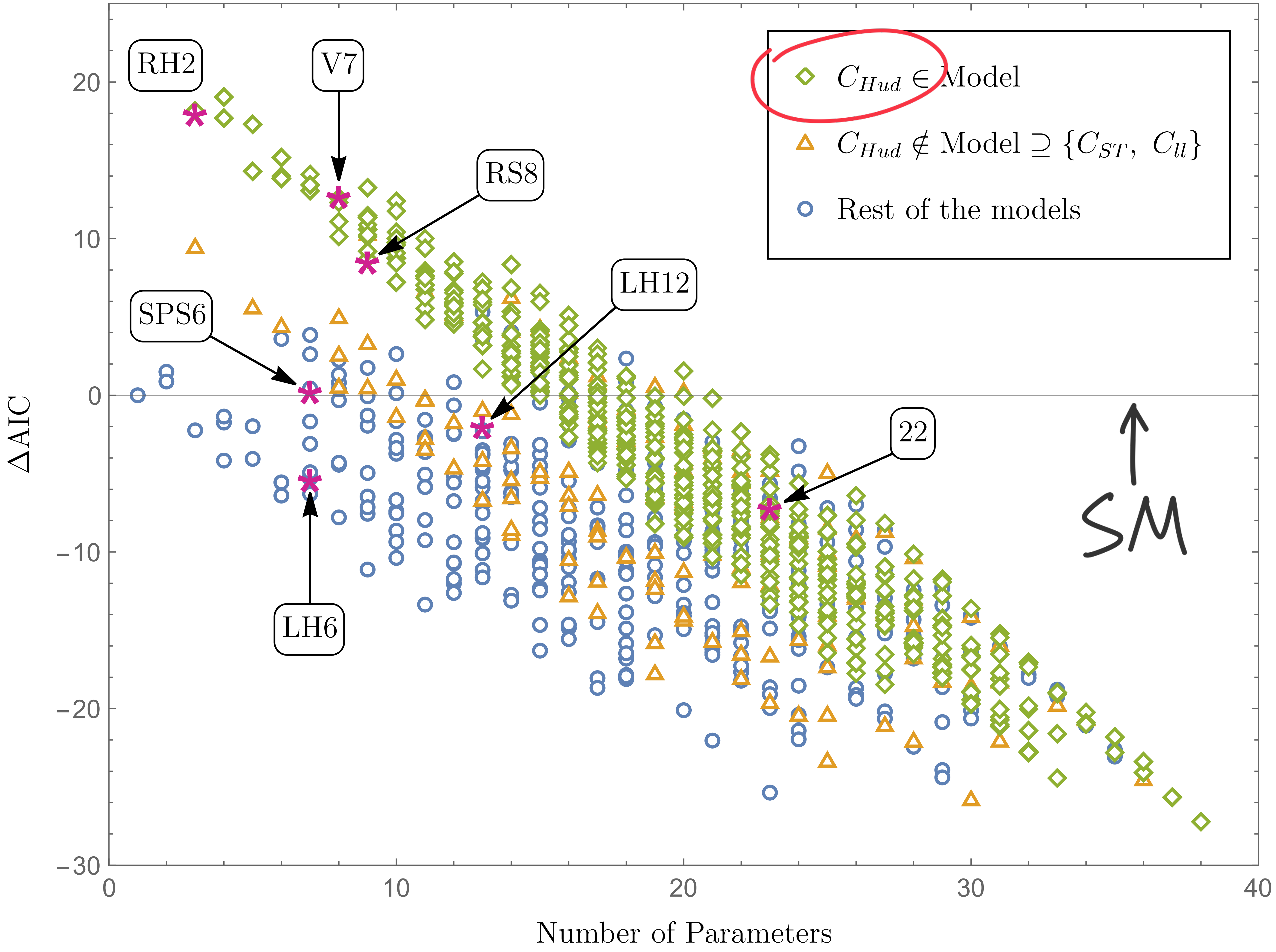
Let's do $2^{10} = 1024$ **fits!**

AIC and one thousand fits

Akaike Information Criterion

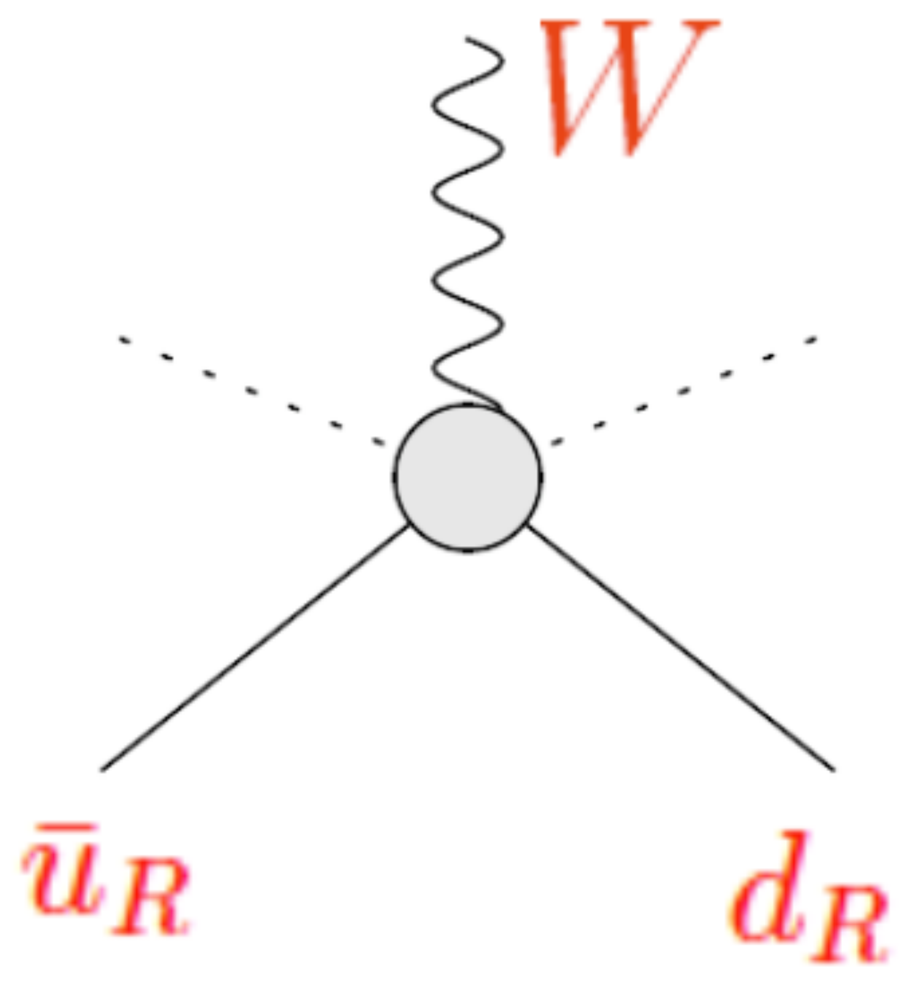
AIC $= \chi^2 + 2 \times$ (**number of Ops.**)





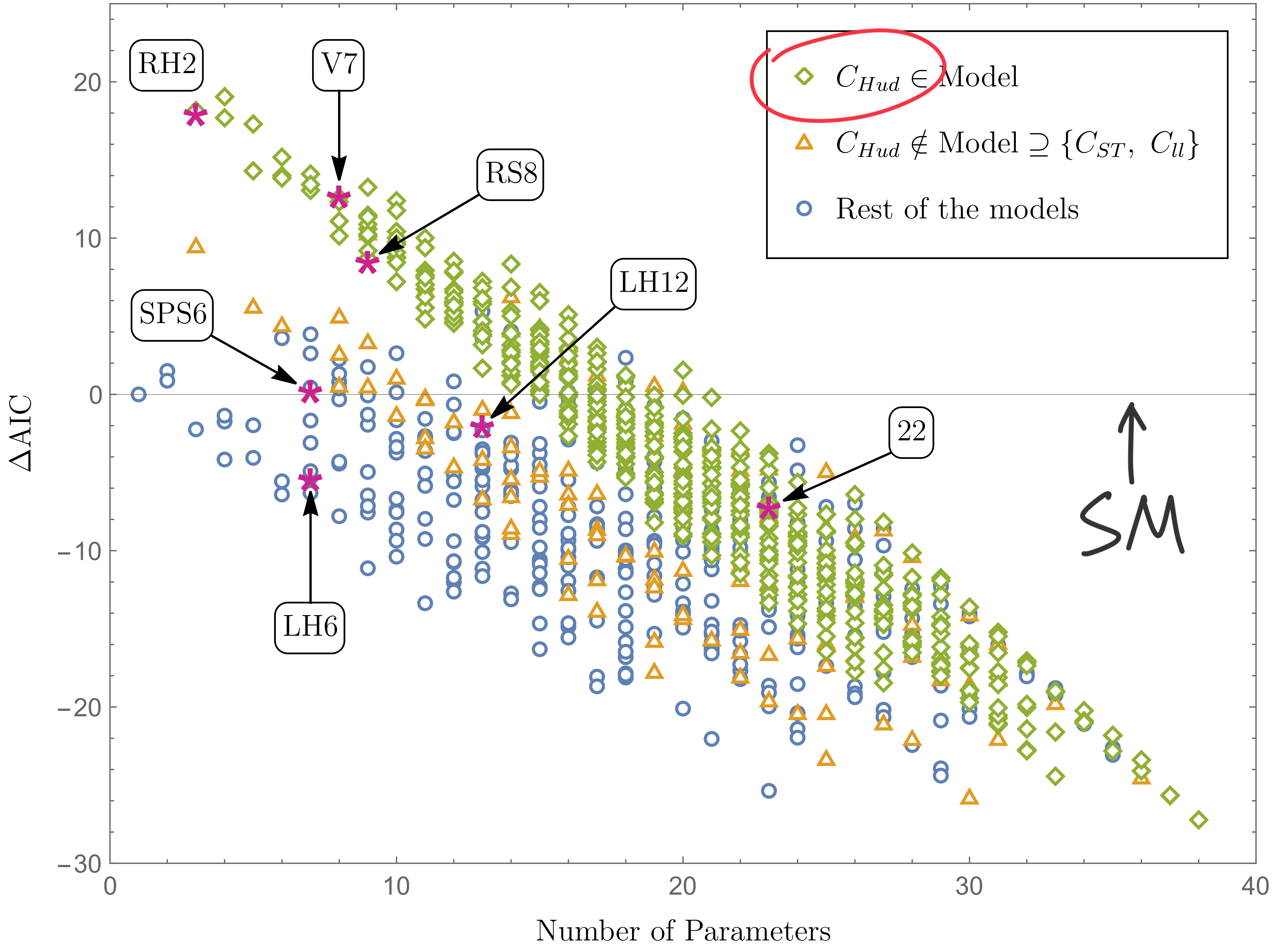
Higher the ΔAIC, better the model

Who is C_{Hud}?



C_{Hud}

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



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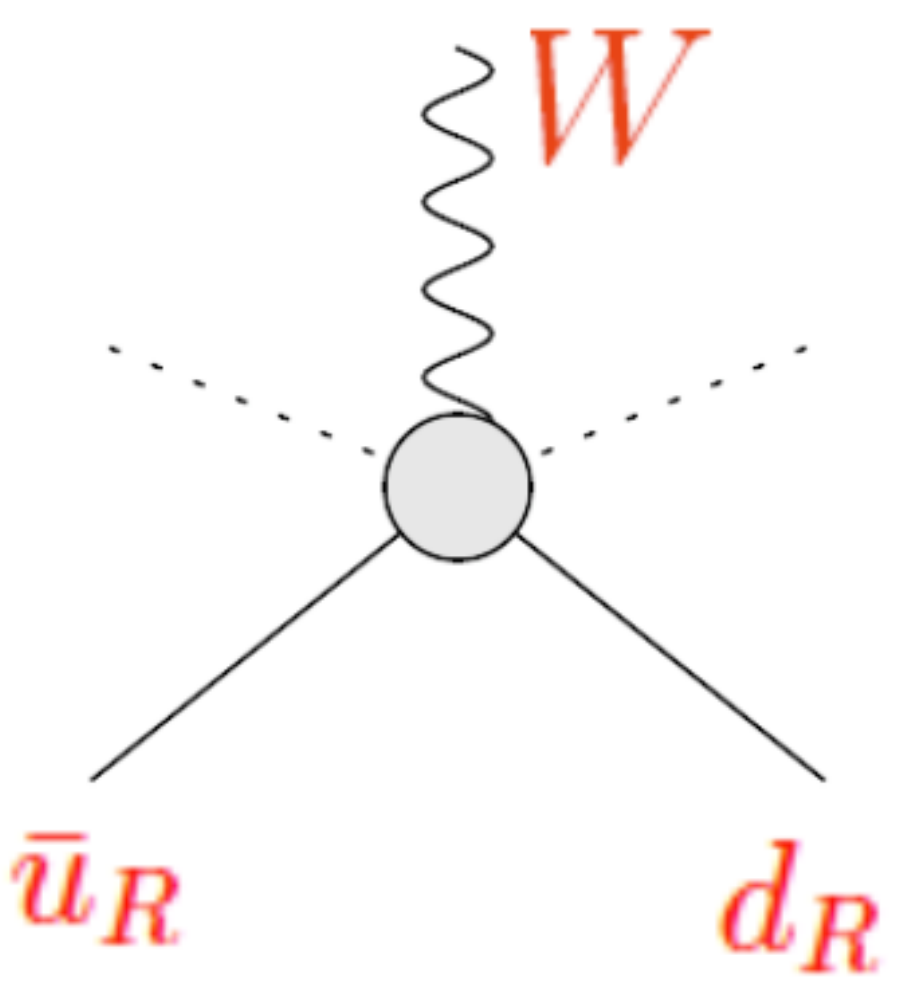
Who is C_{Hud} ?



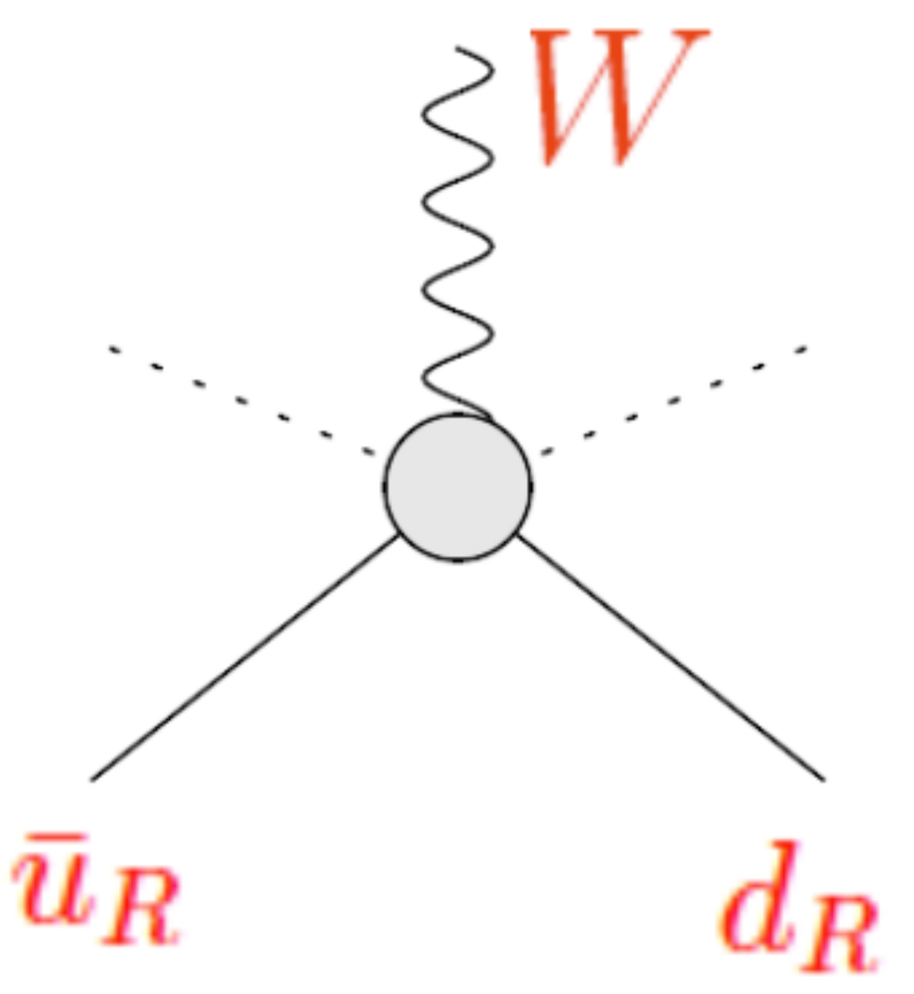
C_{Hud} $\sim Y_u Y_d^\dagger$ in MFV

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

LEFT

$$\mathcal{L}_\beta = -\frac{G_F}{\sqrt{2}} V_{uD} \Big[\; \bar{\ell}\gamma_\mu(1-\gamma_5)\nu_\ell \Big(\big(1+\epsilon_L^{\ell D} - \epsilon_L^\mu\big) \; \bar{u}\gamma^\mu(1-\gamma_5)D + \epsilon_R^{\ell D}\, \bar{u}\gamma^\mu(1+\gamma_5)D \Big)$$
$$+ \bar{\ell}(1-\gamma_5)\nu_\ell \; \big(\epsilon_S^{\ell D}\, \bar{u}D + \epsilon_P^{\ell D}\, \bar{u}\gamma_5 D\big) + \epsilon_T^{\ell D} \;\; \bar{\ell}\sigma_{\mu\nu}(1-\gamma_5)\nu_\ell\, \bar{u}\sigma^{\mu\nu}(1-\gamma_5)D \Big] + \text{h.c.}\,,$$

Who is C_{Hud}?



C_{Hud} ~ $Y_u Y_d^\dagger$ in MFV

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

LEFT

- Left-Right Symmetric Models

  2107.10852

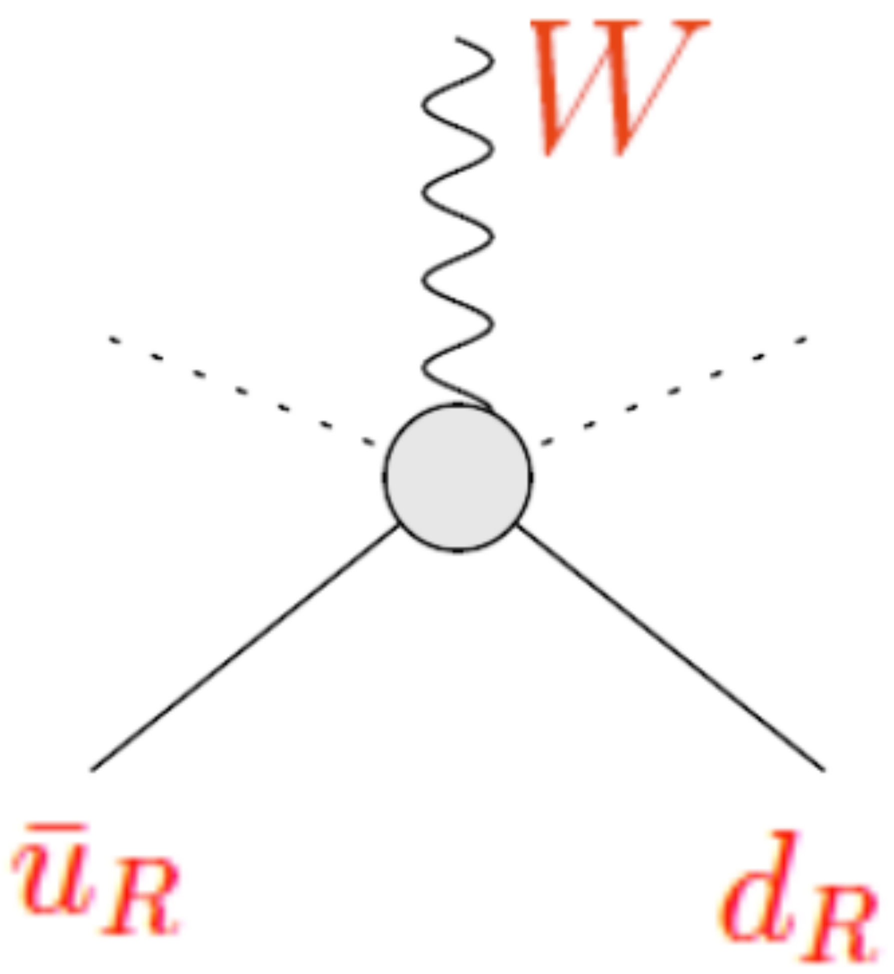
- Vector-Like Quarks ~ $\mathcal{O}$(TeV)

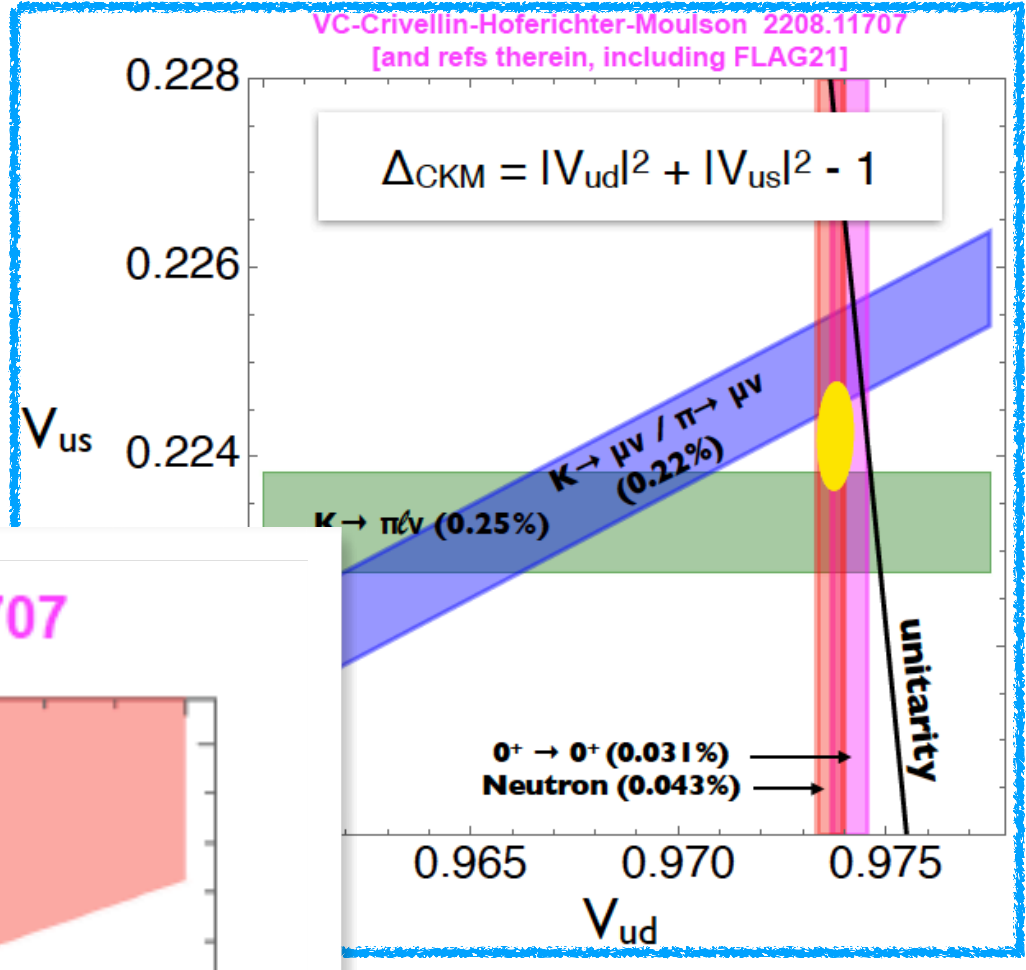
  2212.06862, 2302.14097

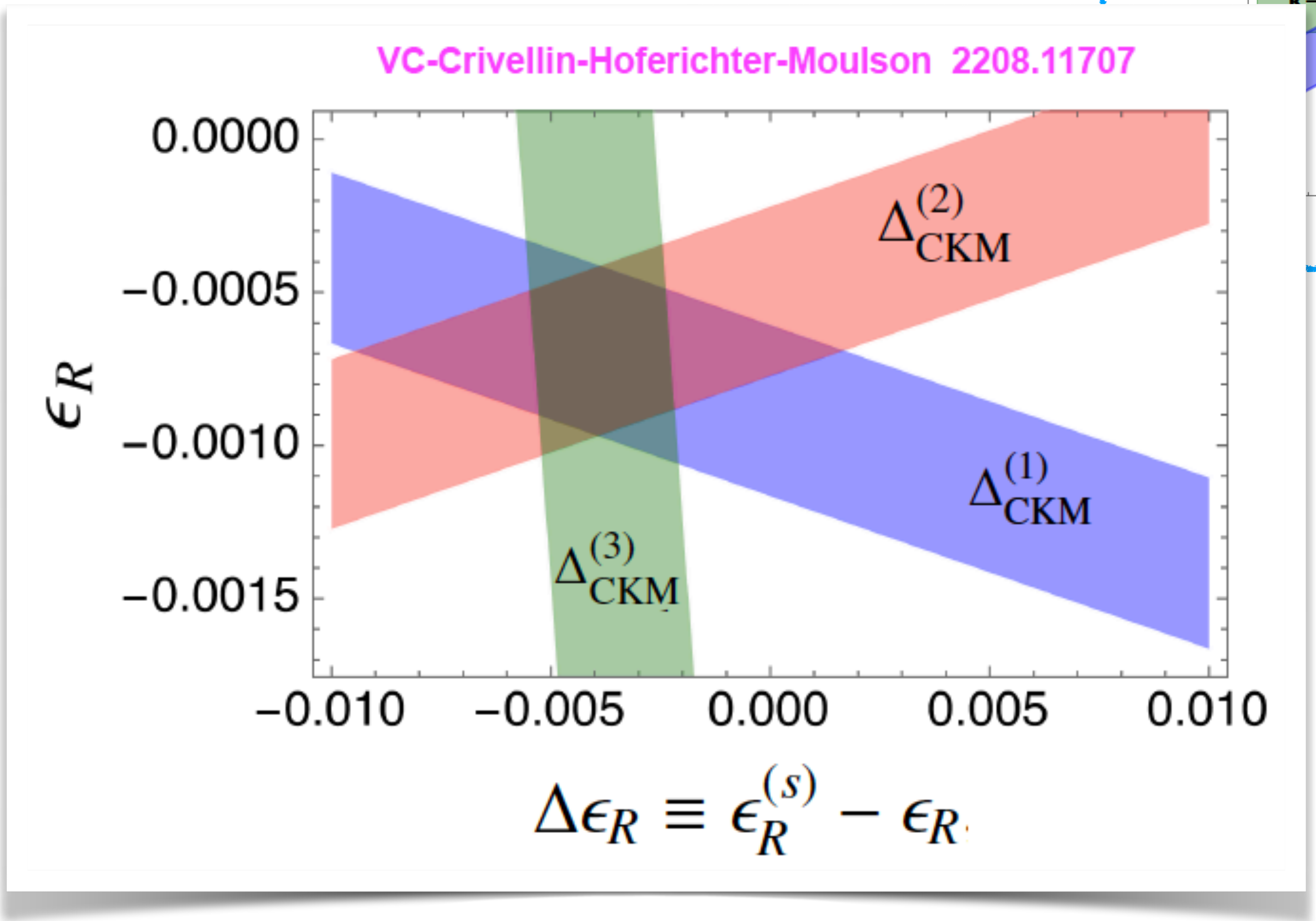
$$+\epsilon_L^{\ell D} - \epsilon_L^{\mu}\Big)\ \bar{u}\gamma^\mu(1-\gamma_5)D + \epsilon_R^{\ell D}\,\bar{u}\gamma^\mu(1+\gamma_5)D\Big)$$

$$\gamma_5 D\Big) + \epsilon_T^{\ell D}\ \bar{\ell}\sigma_{\mu\nu}(1-\gamma_5)\nu_\ell\,\bar{u}\sigma^{\mu\nu}(1-\gamma_5)D\Big] + \text{h.c.},$$

C_{Hud} solves Cabibbo







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

- Left-Right Symmetric Models

  2107.10852

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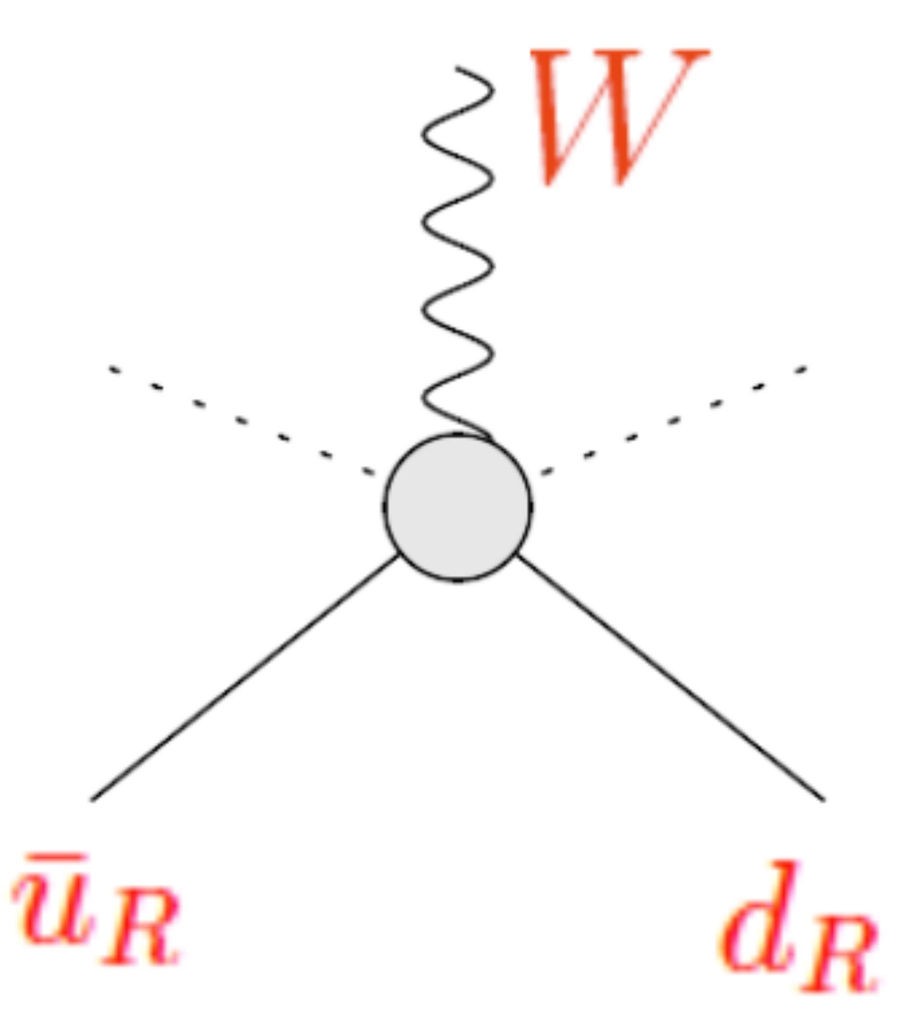
  2212.06862, 2302.14097

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

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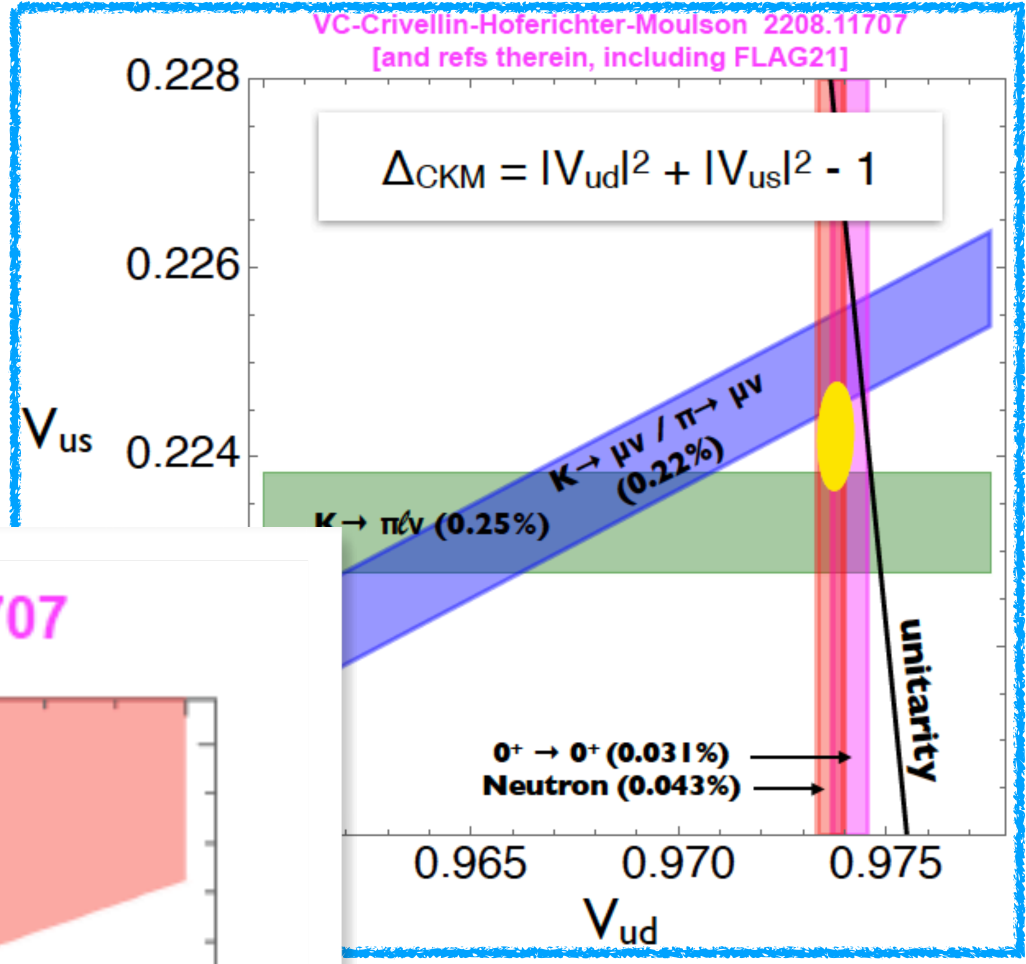

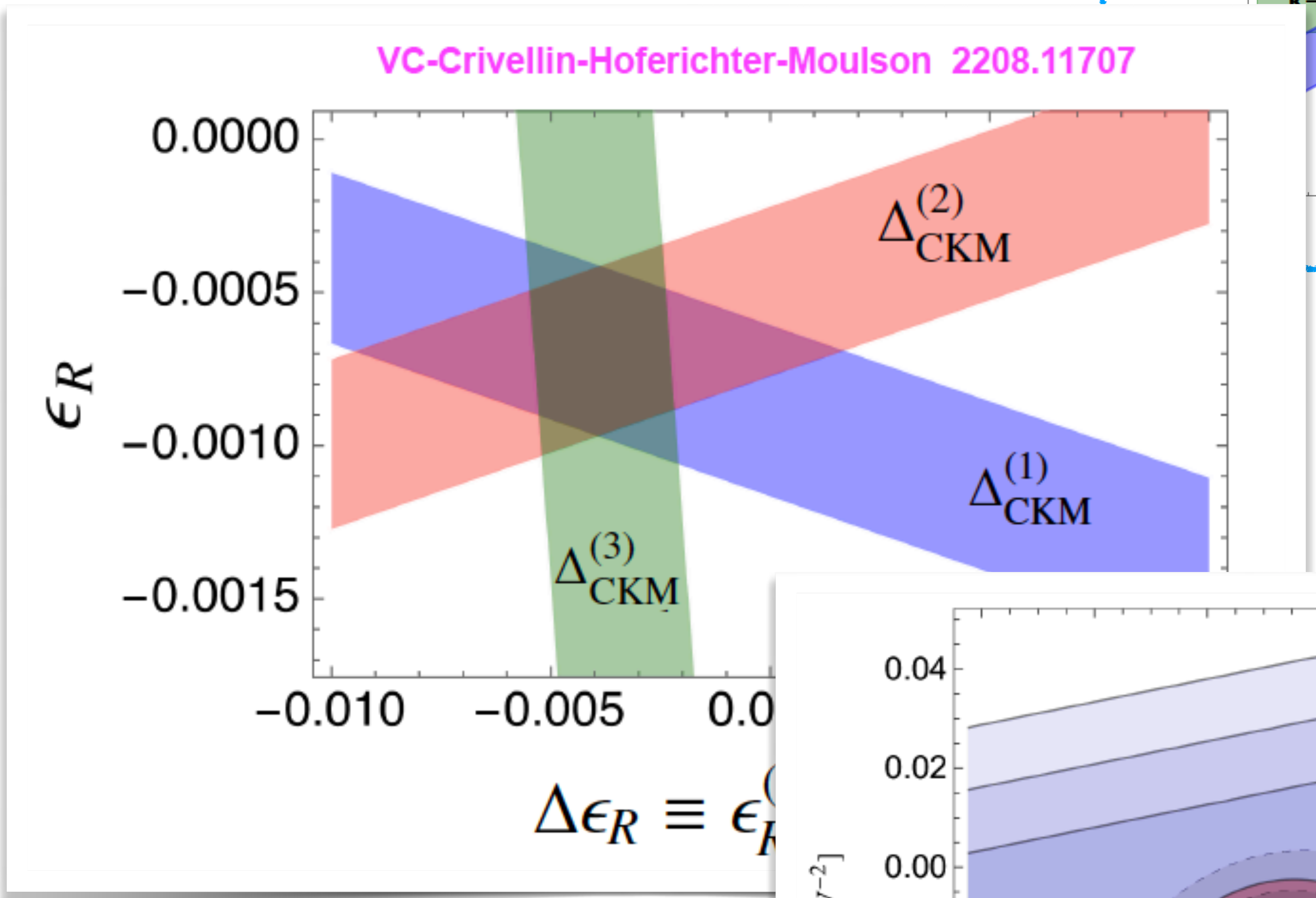

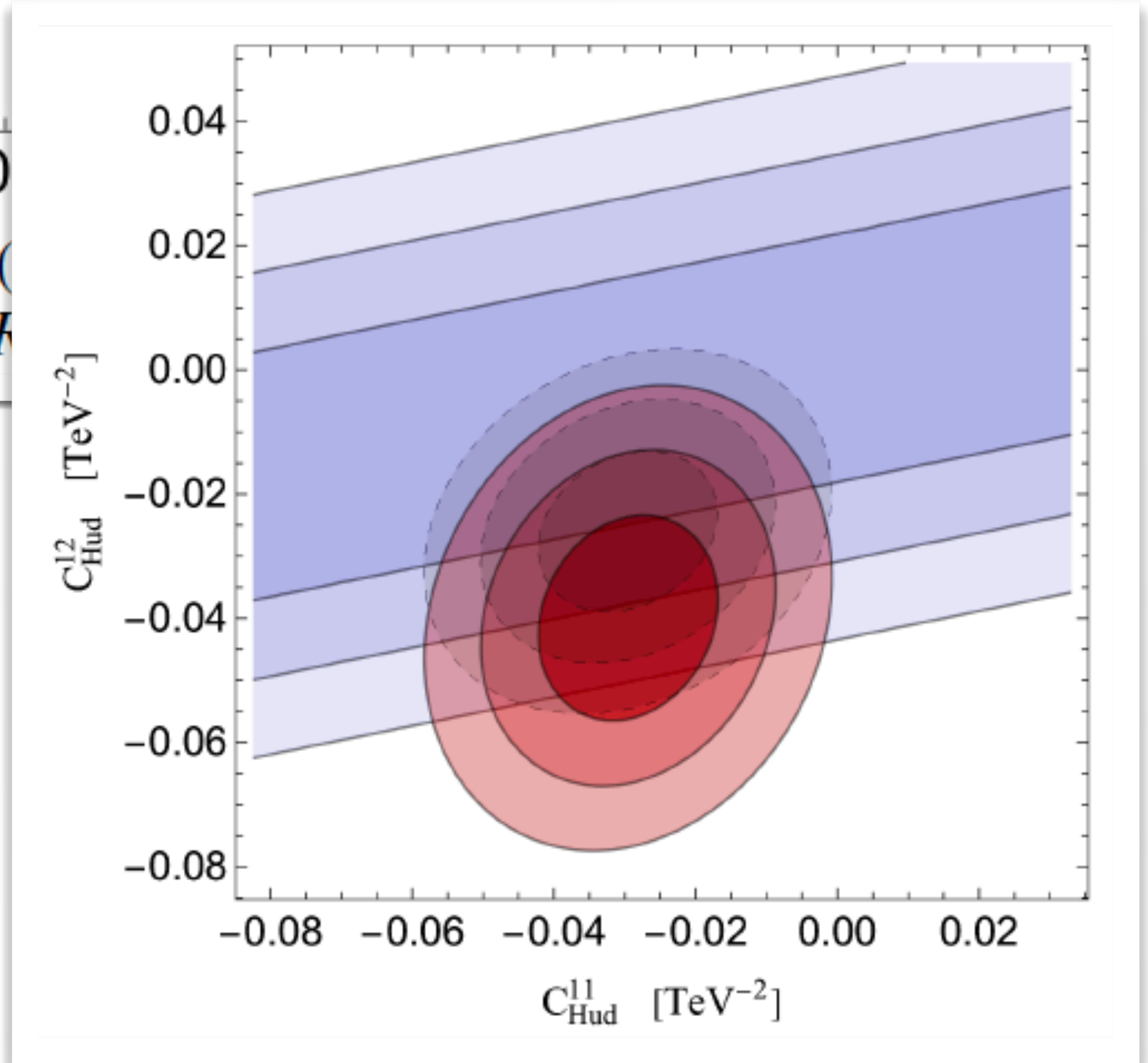

$K \to \pi\pi$

A_2 from RBC/UKQCD

Summary: the CLEW framework

Category	Operators	Description	# of Ops.
I.	C_{ST}	Oblique corrections	1
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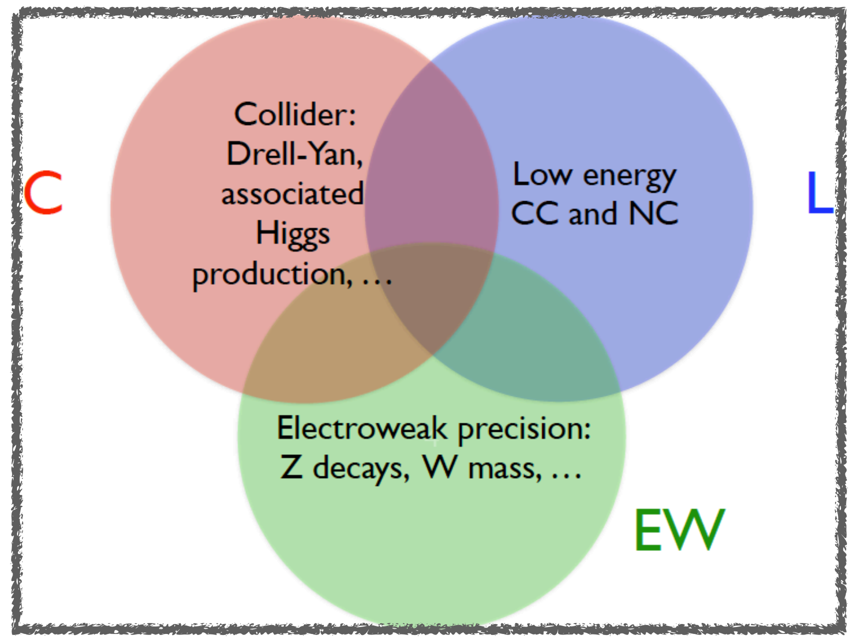
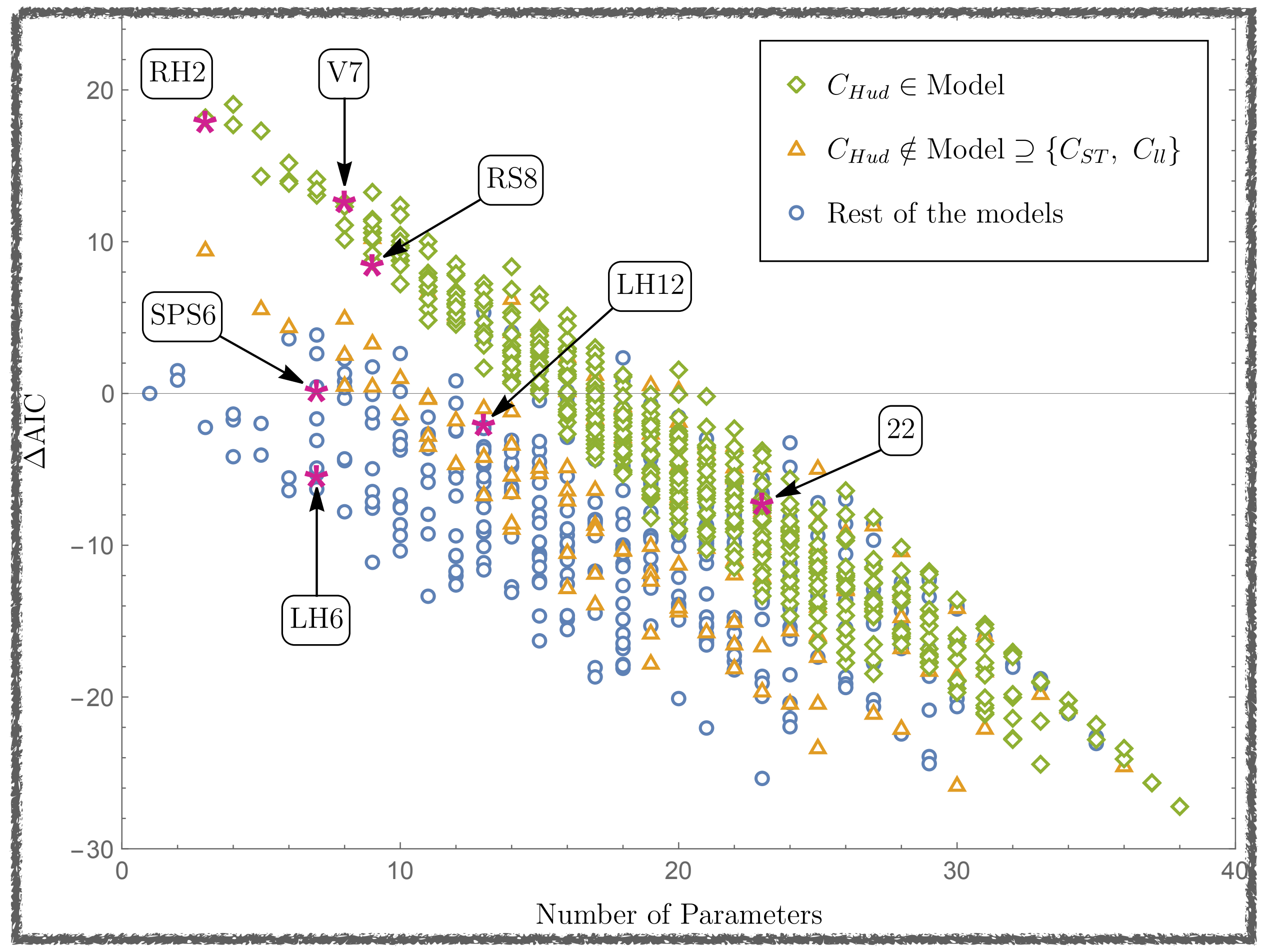
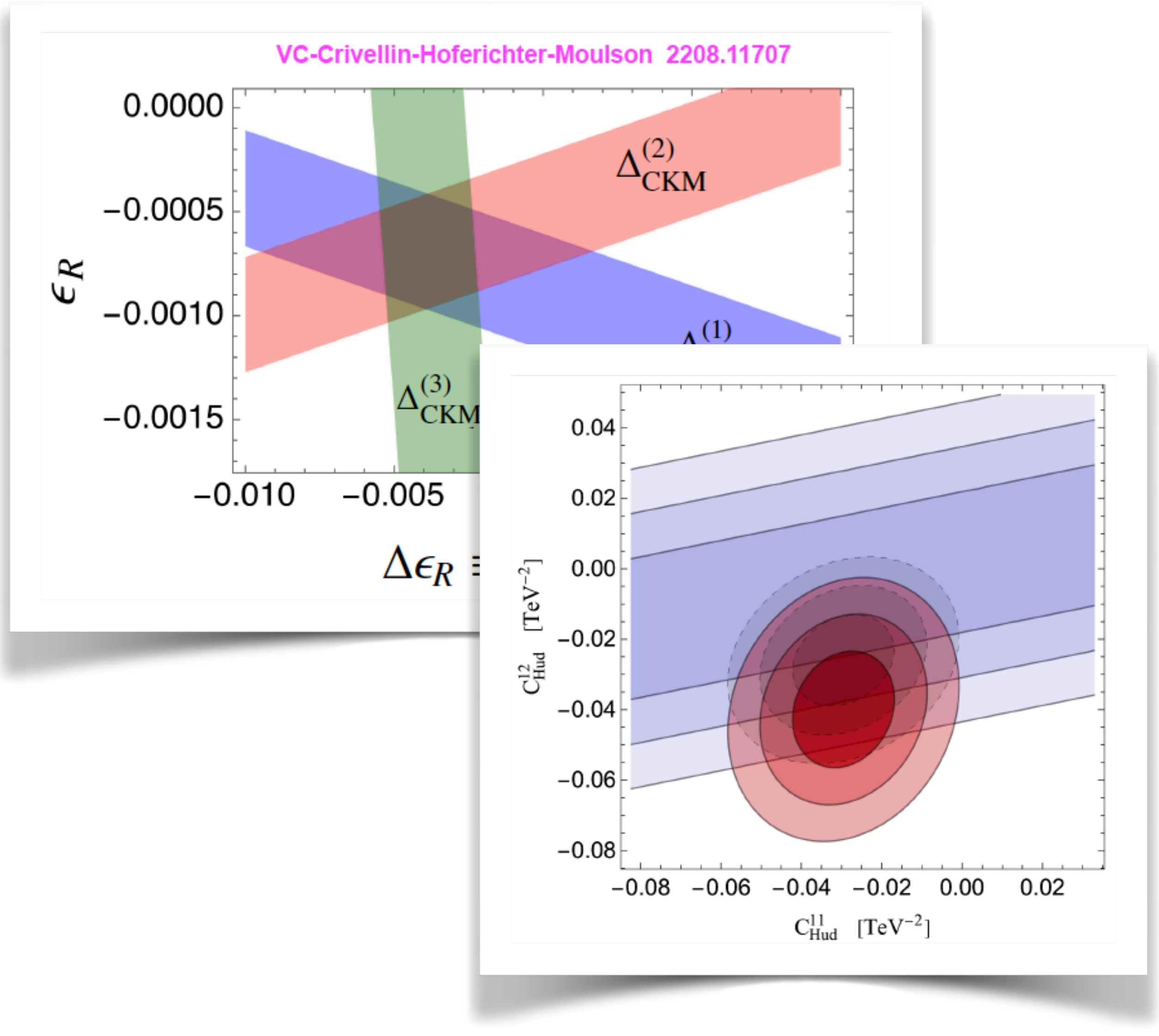
C_{Hud}







Finale

Did you know?

The "ball of thread" meaning of *clew* (from Middle English *clewe* and ultimately from Old English *cliewen*) has been with us since before the 12th century. In Greek mythology, Ariadne gave a ball of thread to Theseus so that he could use it to find his way out of her father's labyrinth. This, and similar tales, gave rise to the use of *clew* for anything that could guide a person through a difficult place. This use led, in turn, to the meaning "a piece of evidence that leads one toward the solution of a problem." Today, the variant spelling *clue*, which appeared in the 17th century, is the more common spelling for the "evidence" sense, but you'll find *clew* in some famous works of literature.

Merriam-Webster | Dictionary | Thesaurus | clew

Dictionary

Definition

noun

verb

clew 1 of 2 **noun**

ˈklü

1 : a ball of thread, yarn, or cord