Fitting SMEFT with a CLEW

Towards a true model-independent global analysis

CRC TRR 257
Young Scientists Meeting

Tom Tong

Co-directed by

Vincenzo Cirigliano *Wouter Dekens*
Jordy de Vries *Emanuele Mereghetti*

Abstract for the impatient

"THAT'S THE END OF MY PRESENTATION. ANY QUESTIONS?"

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SMEFT global-fits: two major challenges

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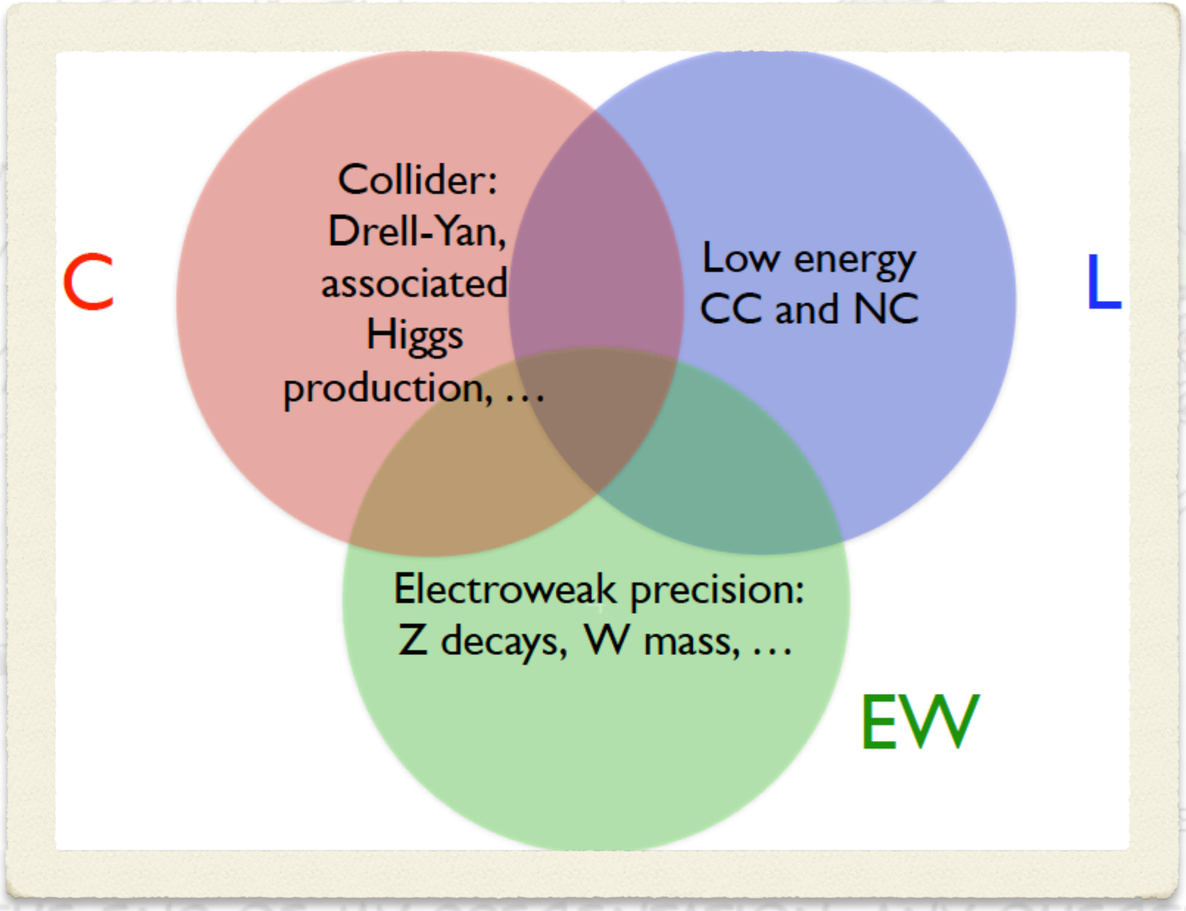
The CLEW framework



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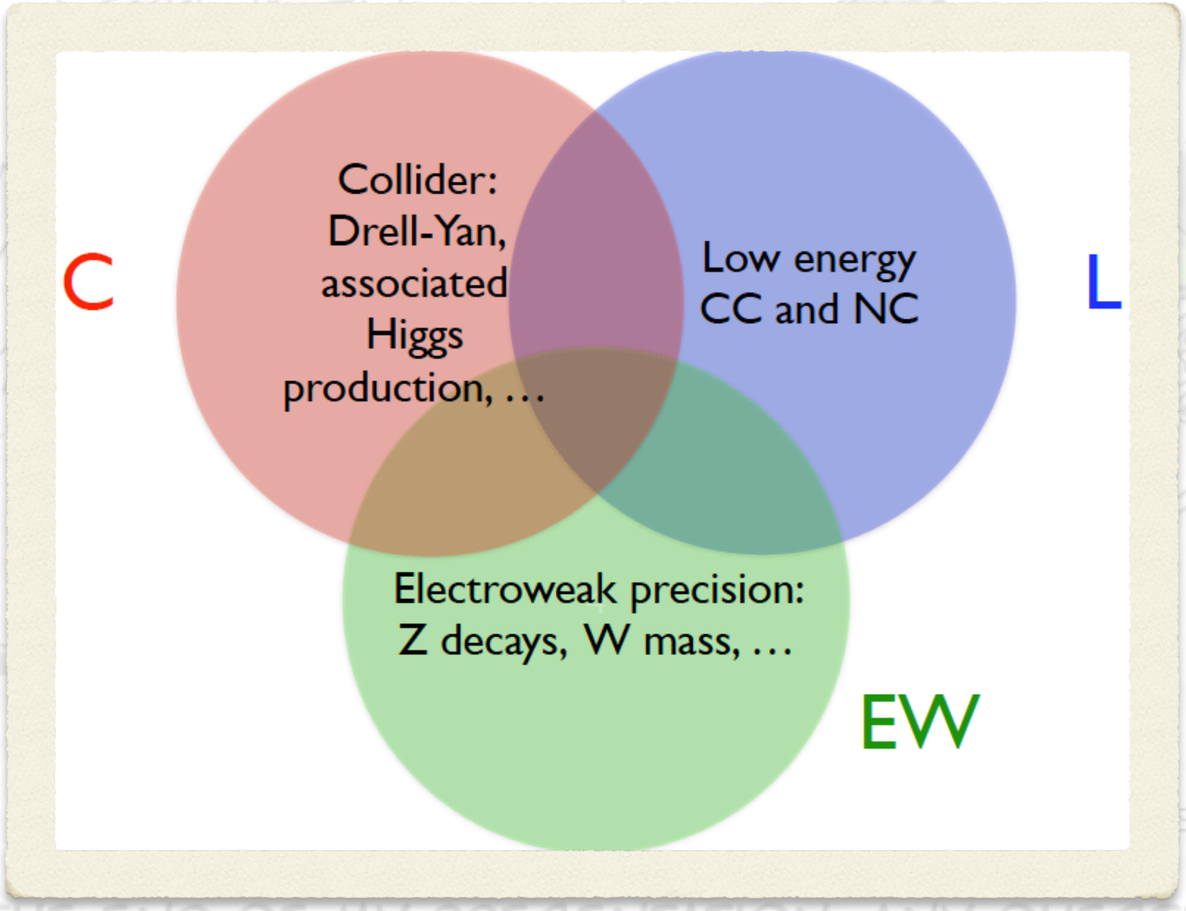

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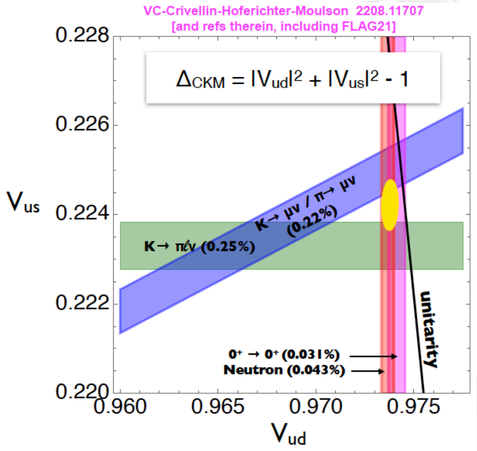

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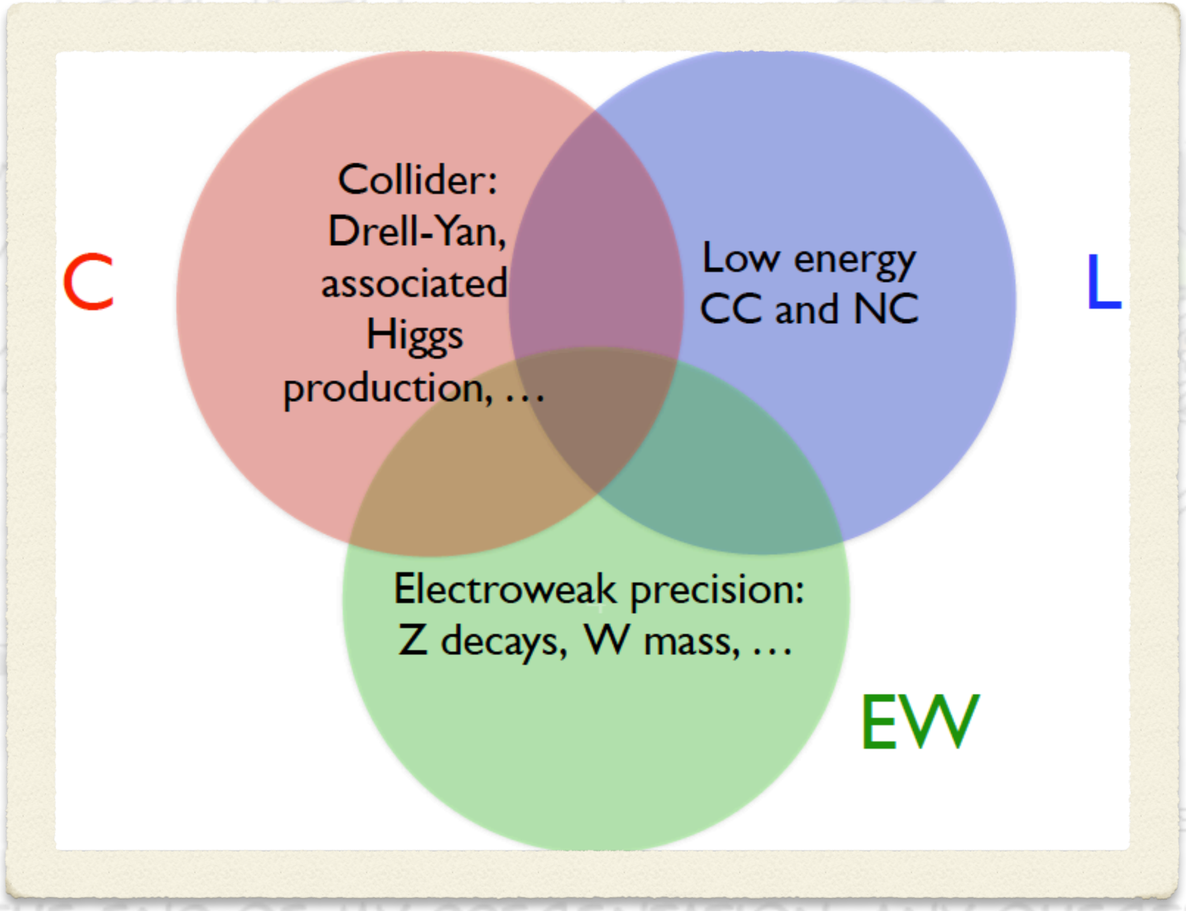

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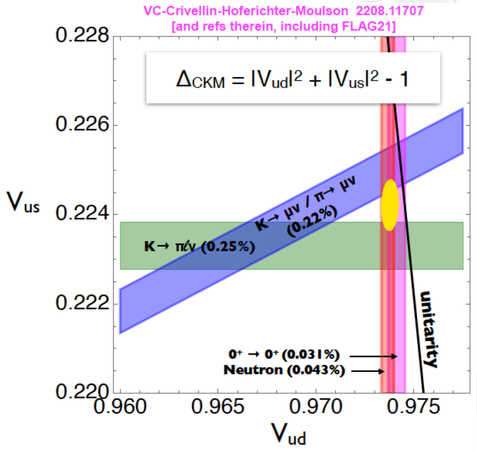

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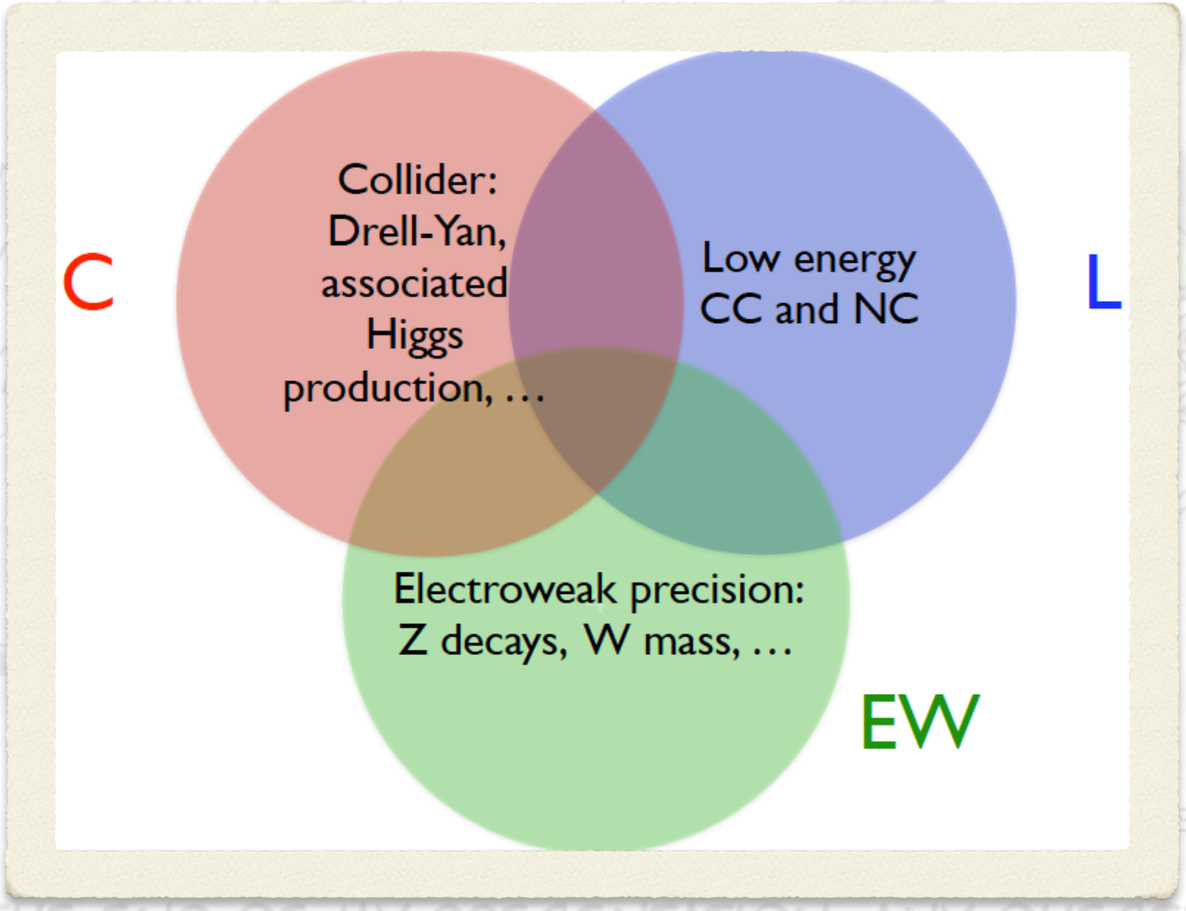

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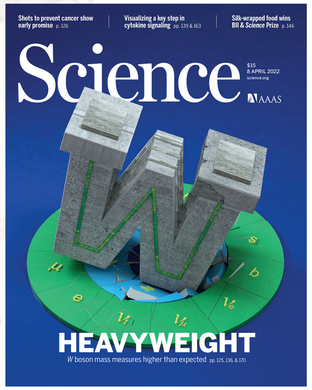
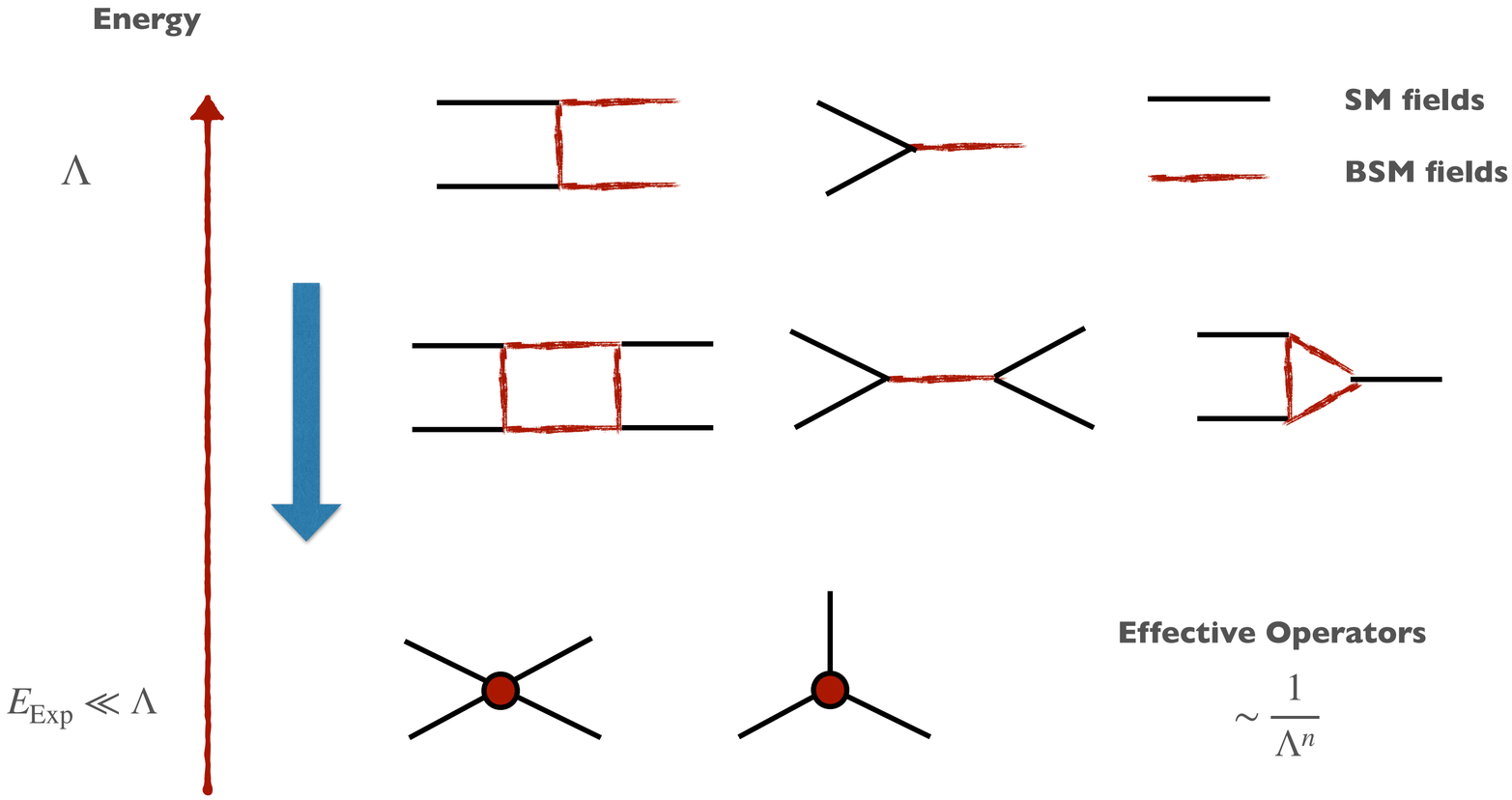


Flavor-symmetry-independent analysis

SMEFT in a nutshell



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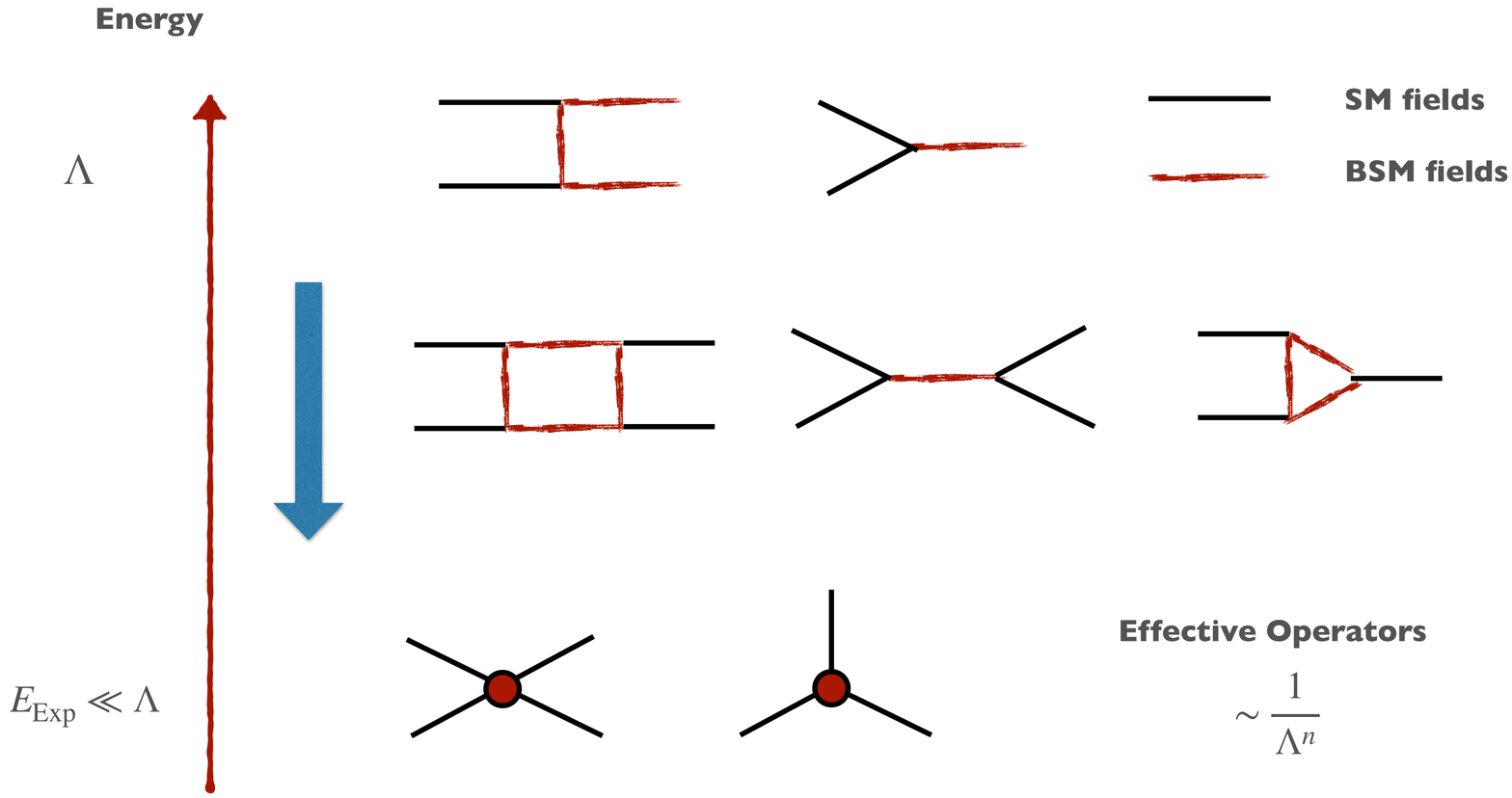
$$\mathcal{L}_{\text{SMEFT}}^{\text{dim-6}} = \mathcal{L}_{\text{SM}} + \sum_i C_i \mathcal{O}_i^{\text{dim-6}}$$



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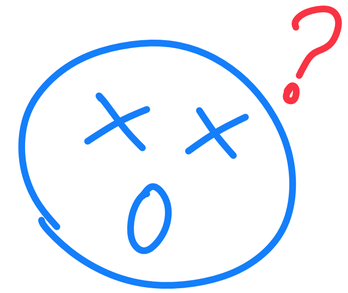

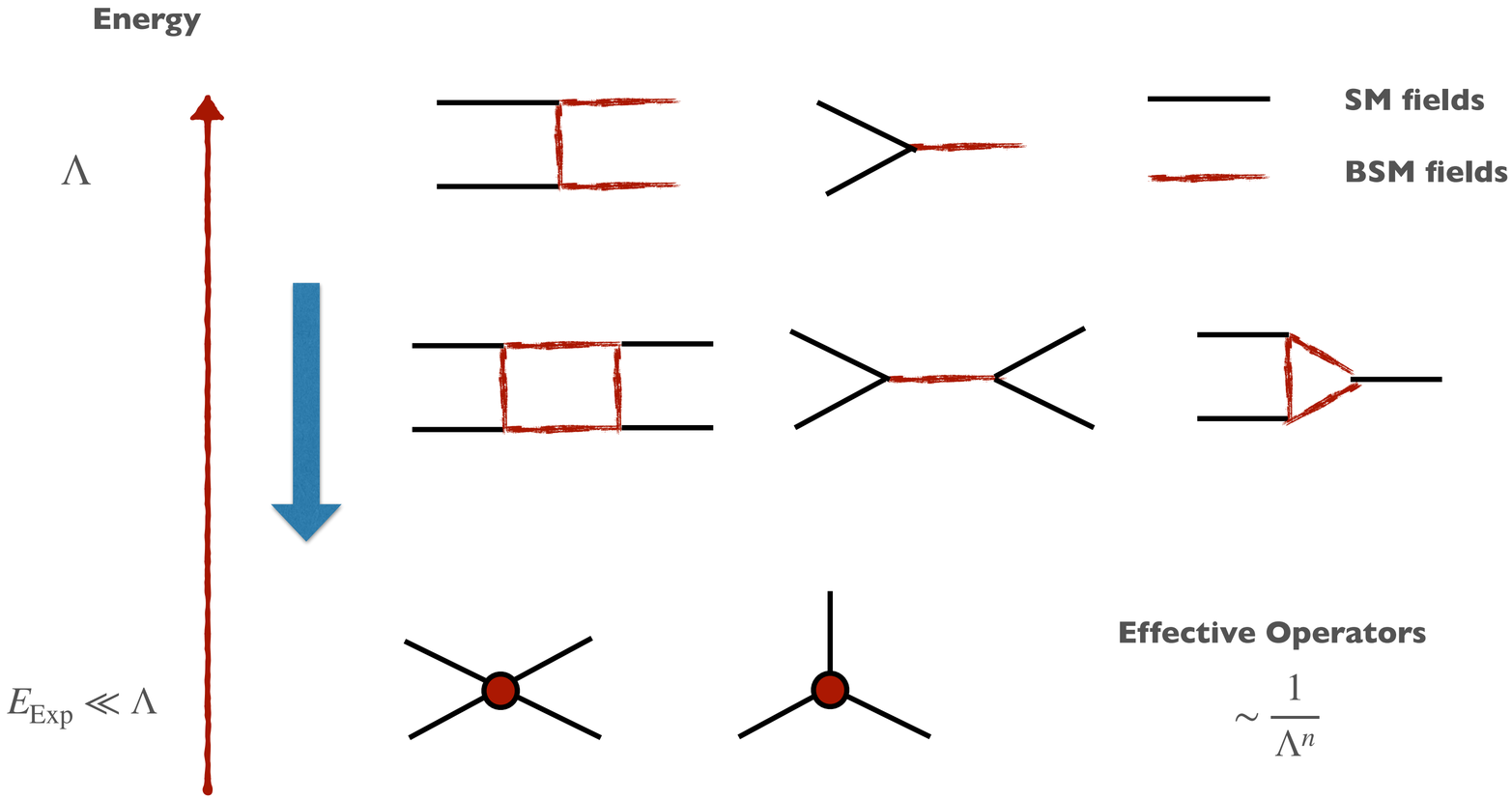

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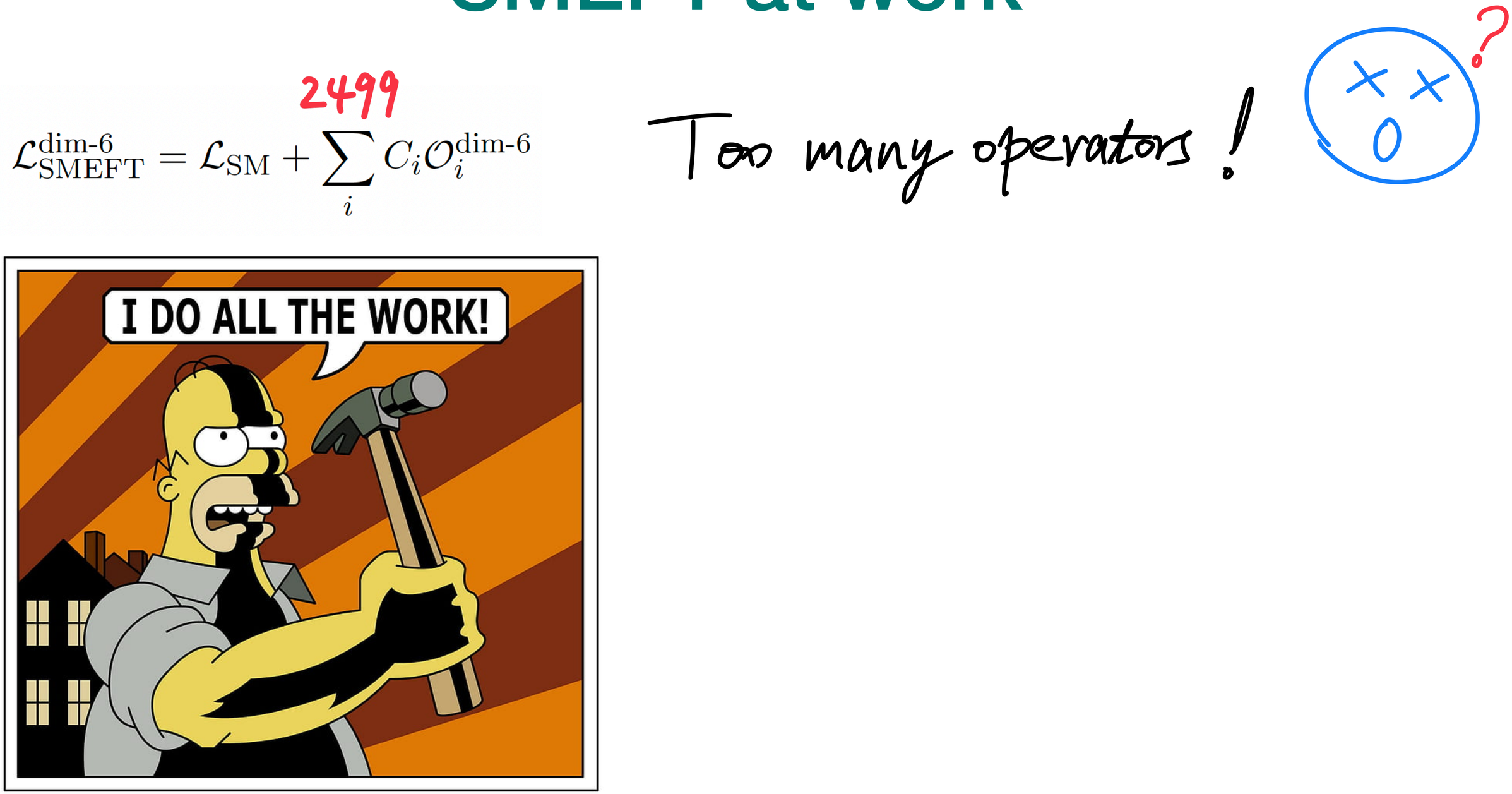

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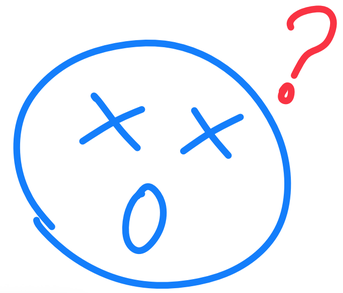

Constrain ALL the operators

with all the observables! Yeah~!

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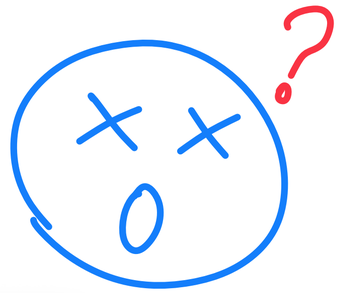

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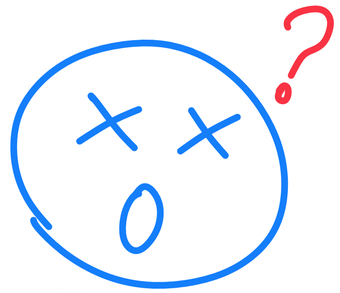

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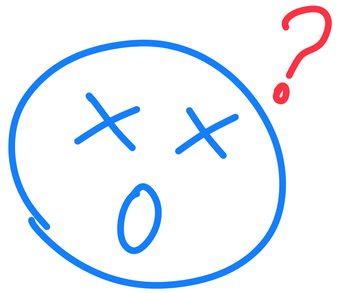

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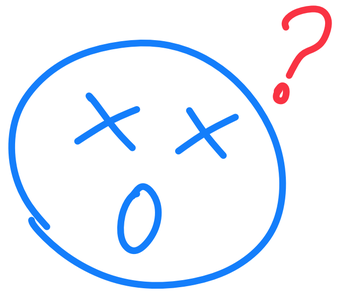

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$U(3)^5$, MFV, $U(2)^5$, top...

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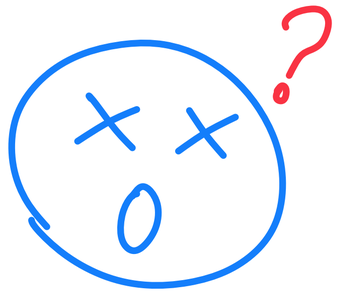

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EWPO + Higgs + top + some flavor...

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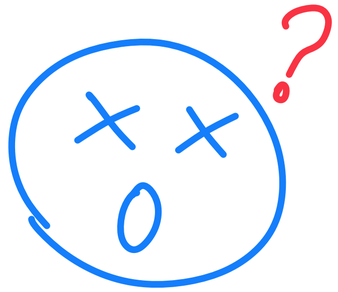

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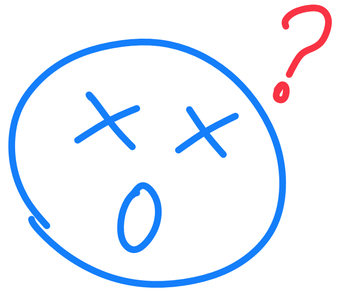

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Casefile: $U(3)^5$ + EWPO

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

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
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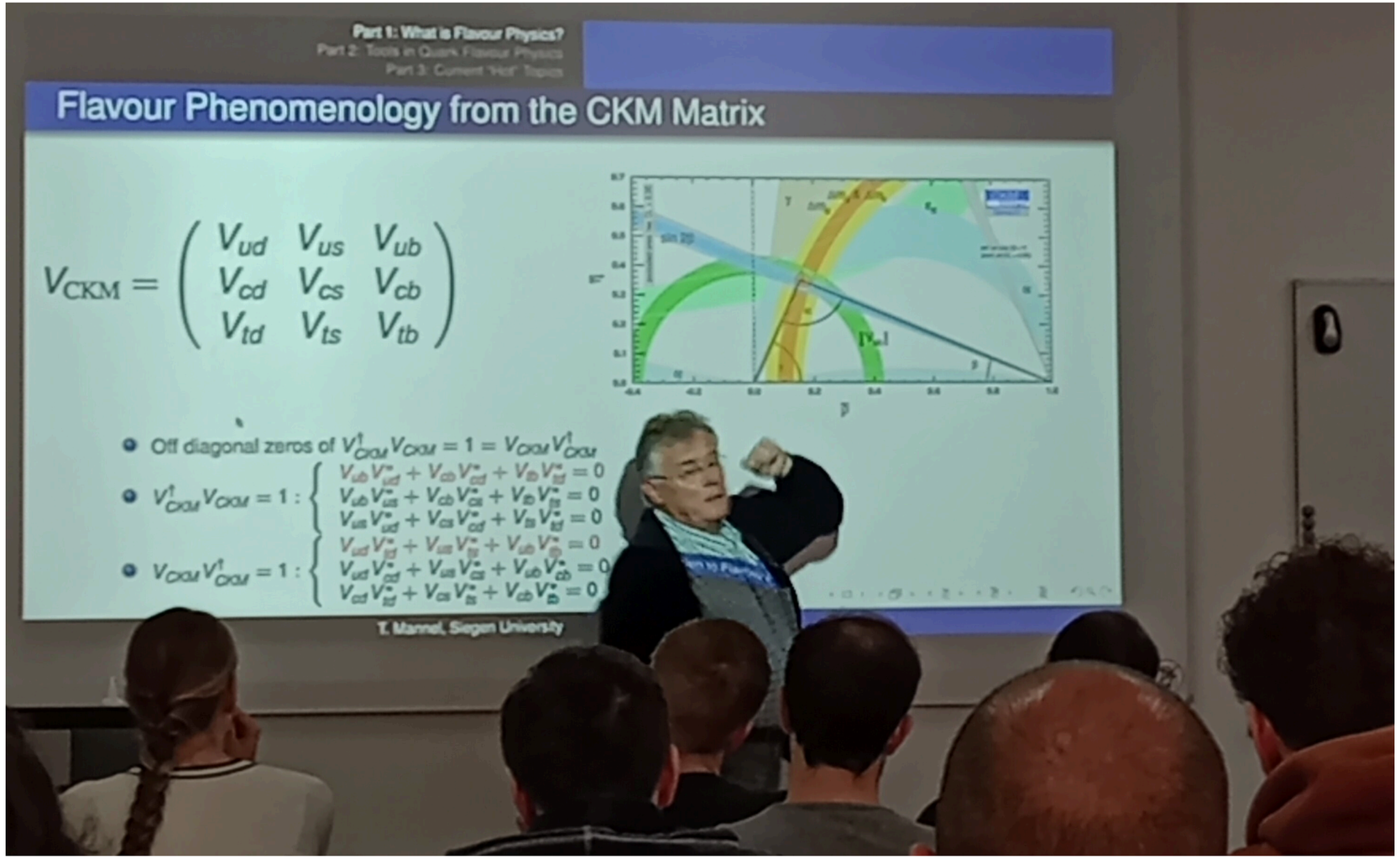

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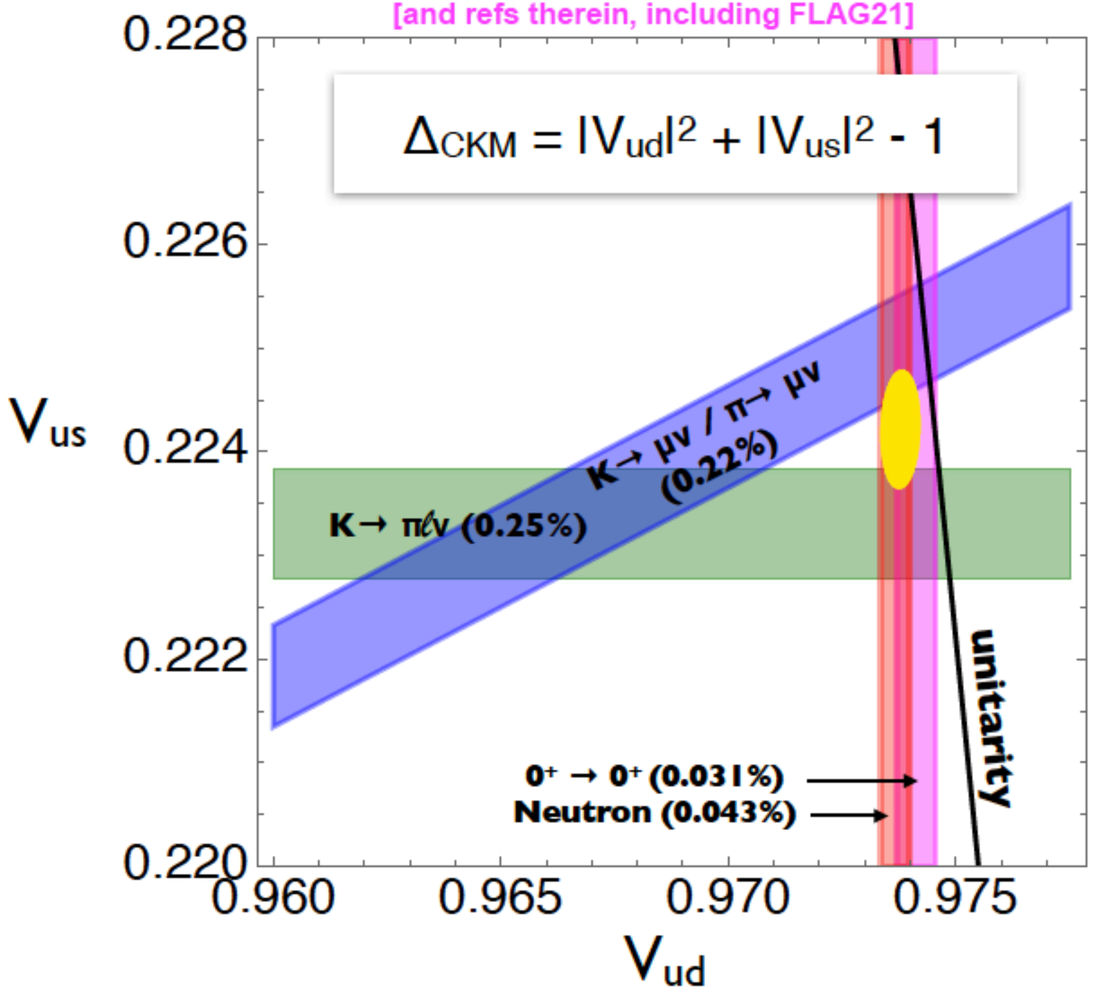
VC-Crivellin-Hoferichter-Moulson 2208.11707
[and refs therein, including FLAG21]



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

$\sim 3\sigma$ at permil level

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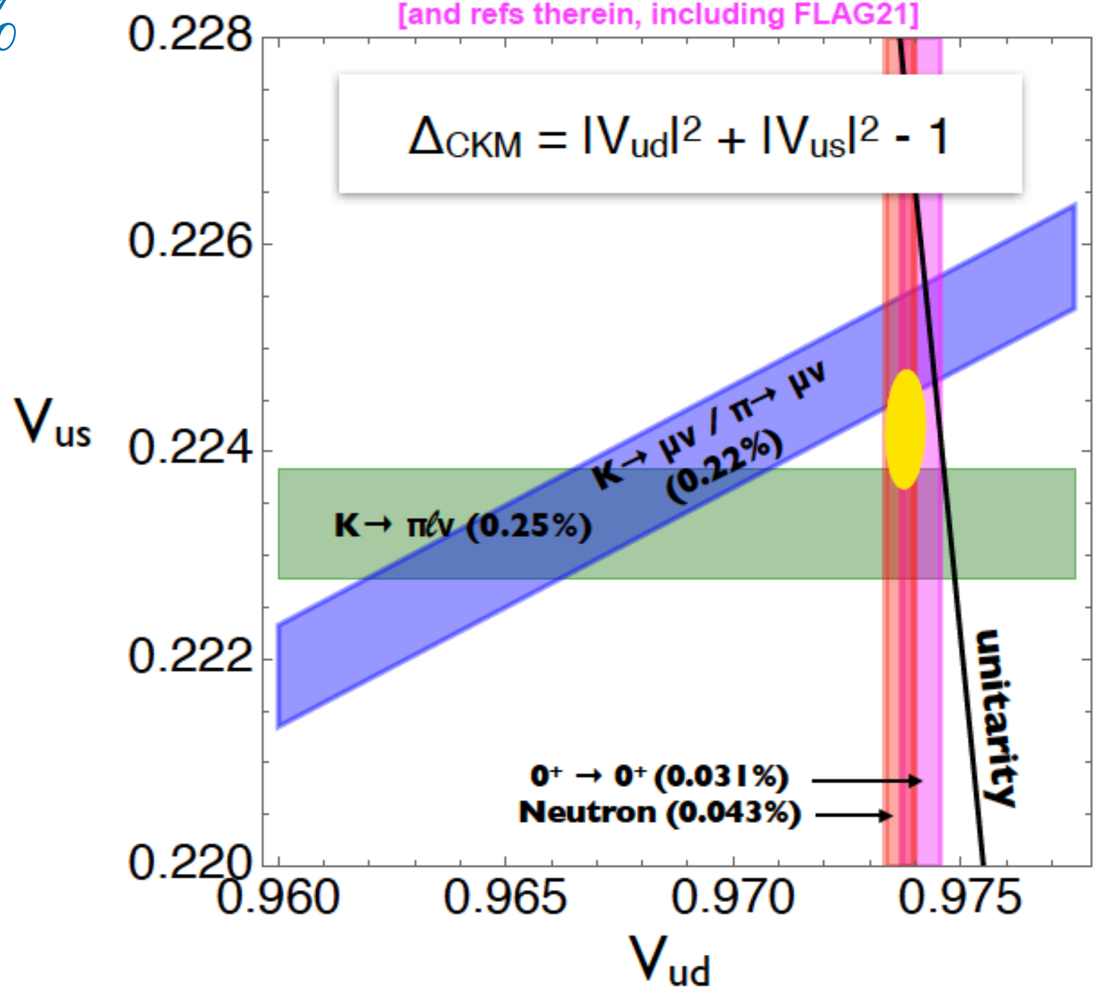

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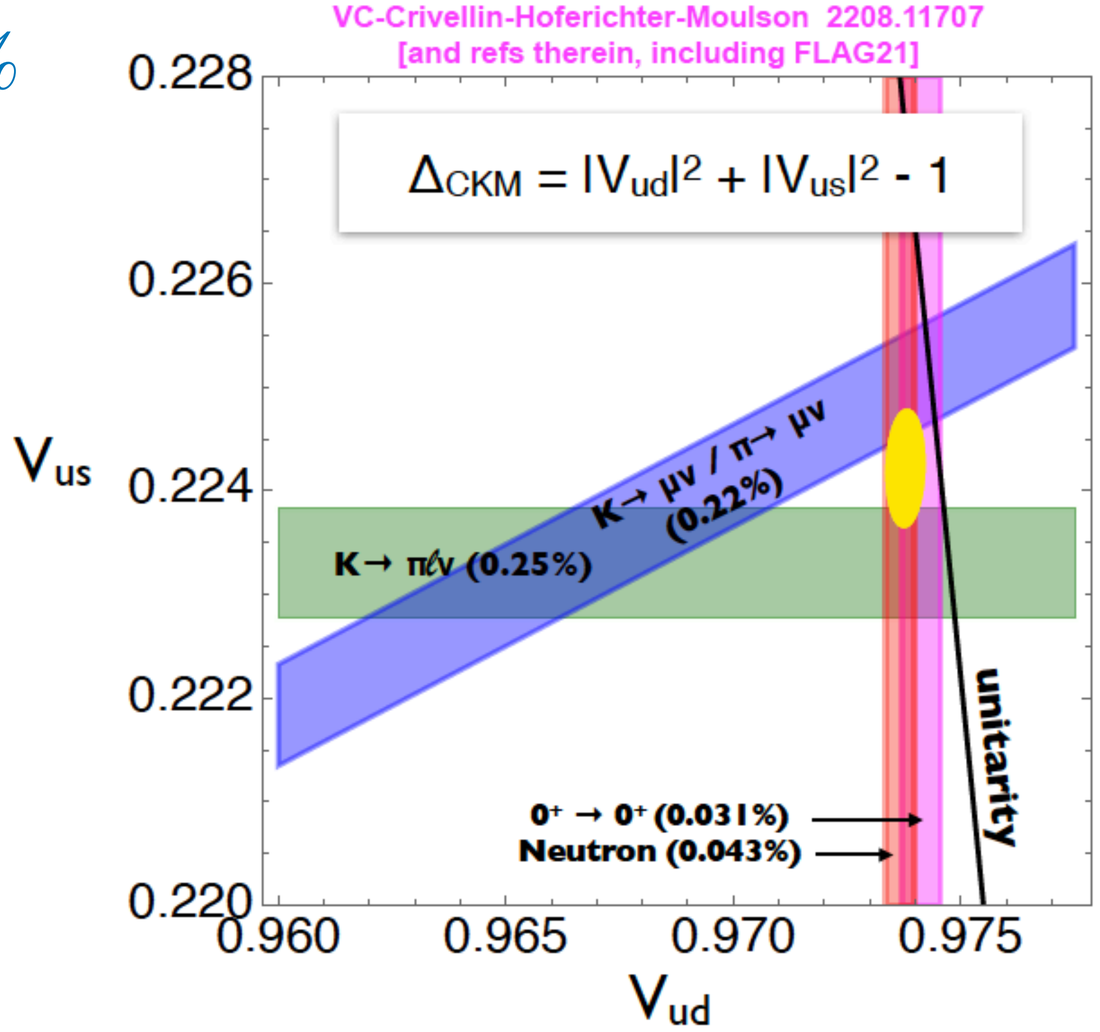

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$$2v^2\left[C_{Hq}^{(3)} - C_{Hl}^{(3)} + C_{ll} - \cancel{C_{lq}^{(3)}}\right] = \Delta_{CKM}^{fit} \approx -0.67\,\%$$

VC-Crivellin-Hoferichter-Moulson 2208.11707
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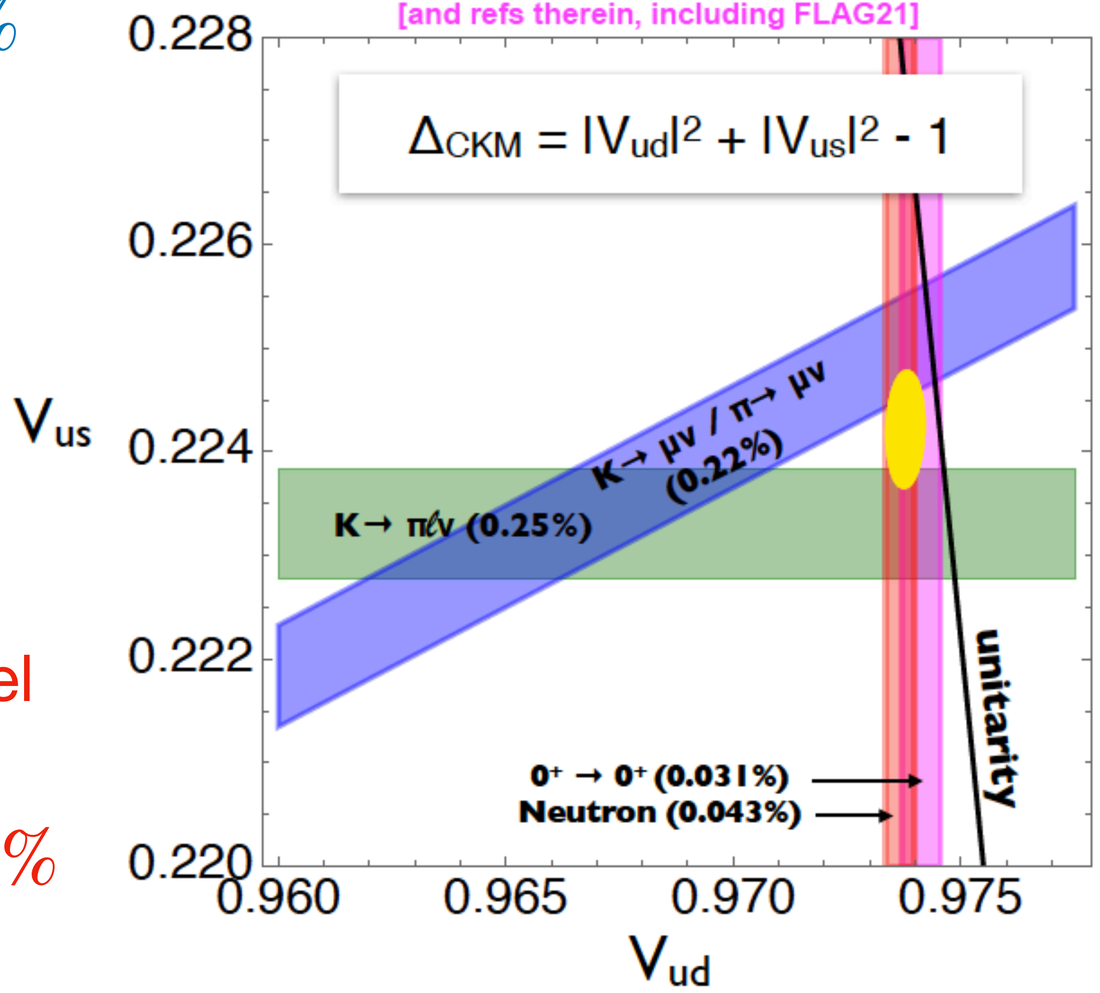

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Our paper 2204.08440

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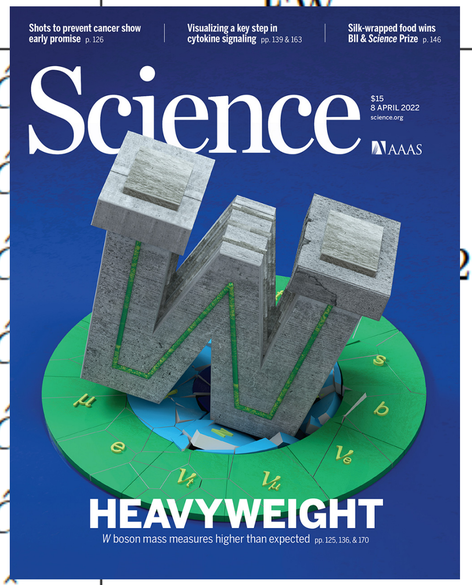

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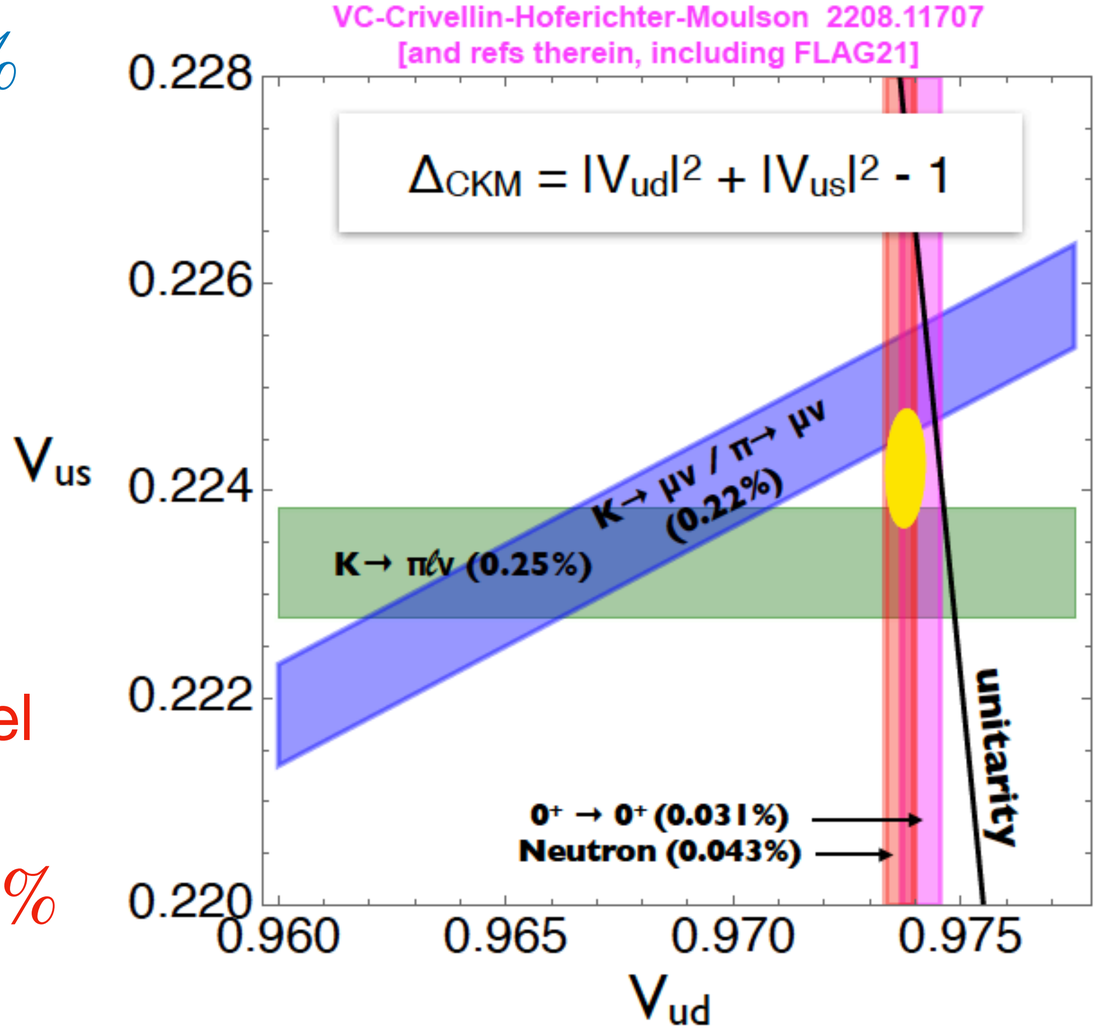
$$2v^2\left[C^{(3)}_{Hq} - C^{(3)}_{Hl} + C_{ll} - C^{(3)}_{lq}\right] = \Delta^{fit}_{CKM} \approx -0.91\,\%$$



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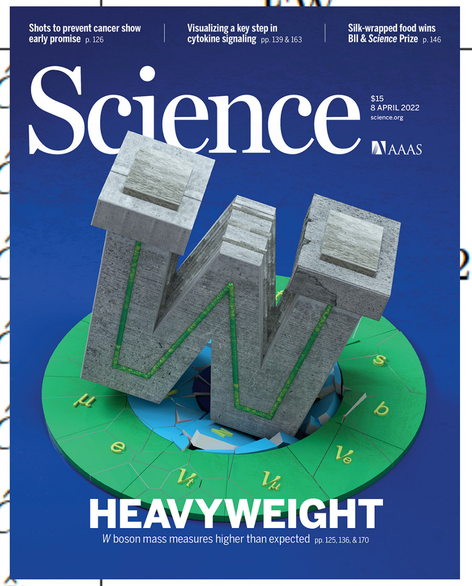

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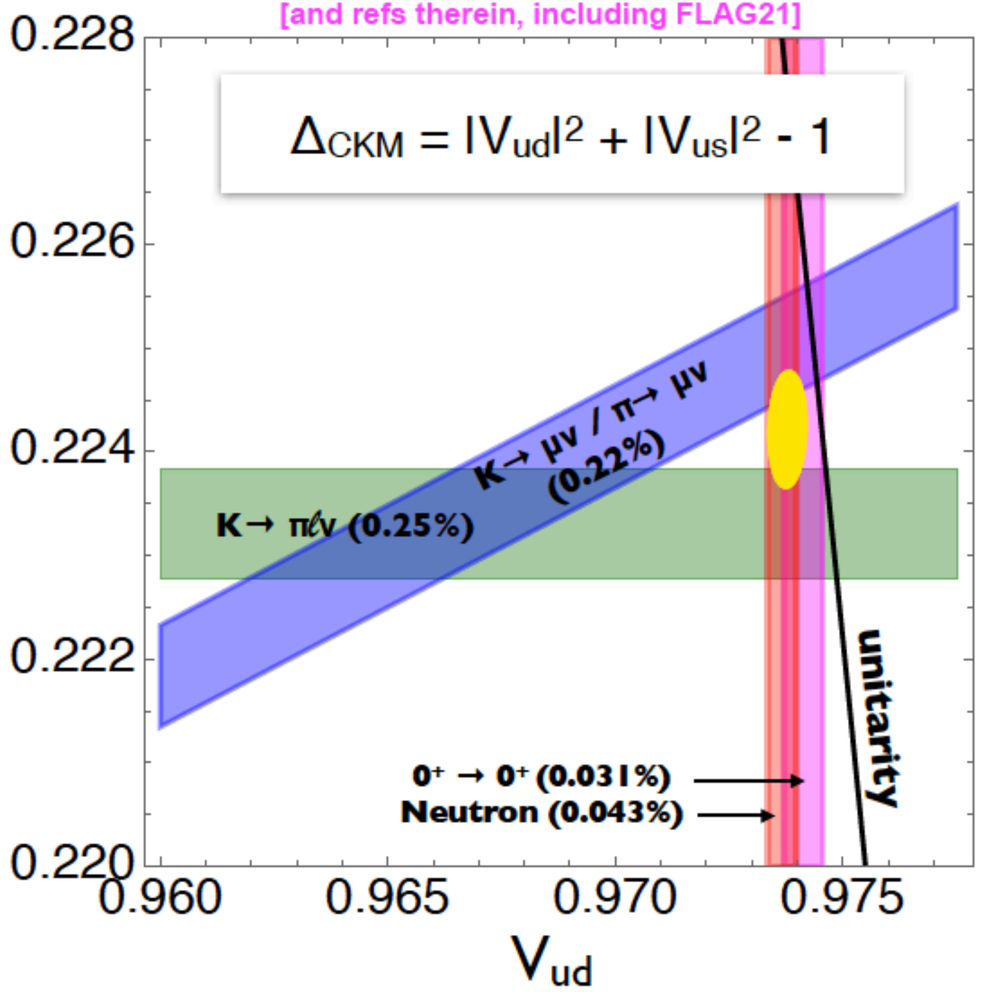

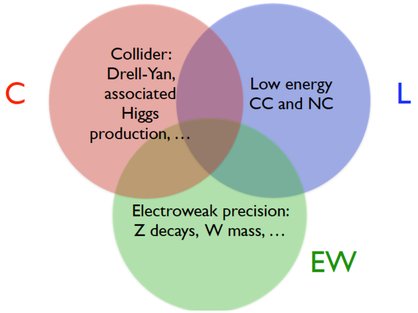

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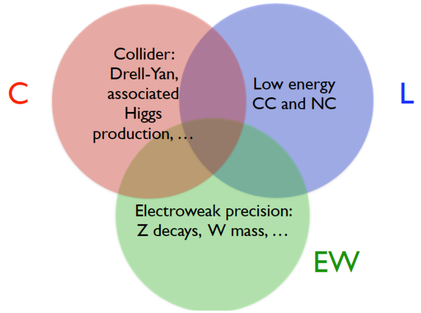

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EW

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$\hat{C}_{Hl}^{(1)}$	-0.0091 ± 0.011
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$\hat{C}_{He}$	-0.024 ± 0.0086
$\hat{C}_{Hq}^{(1)}$	-0.029 ± 0.043
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$\hat{C}_{Hu}$	-0.0046 ± 0.12
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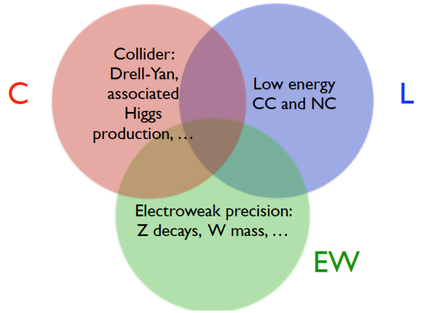

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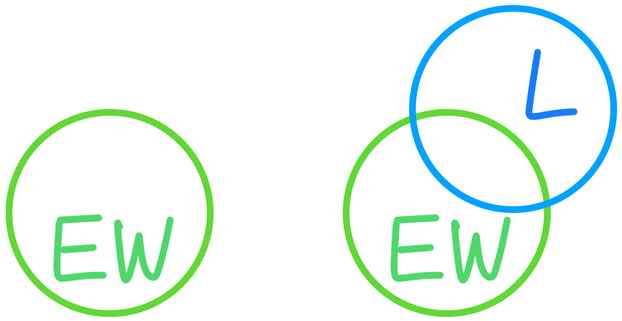

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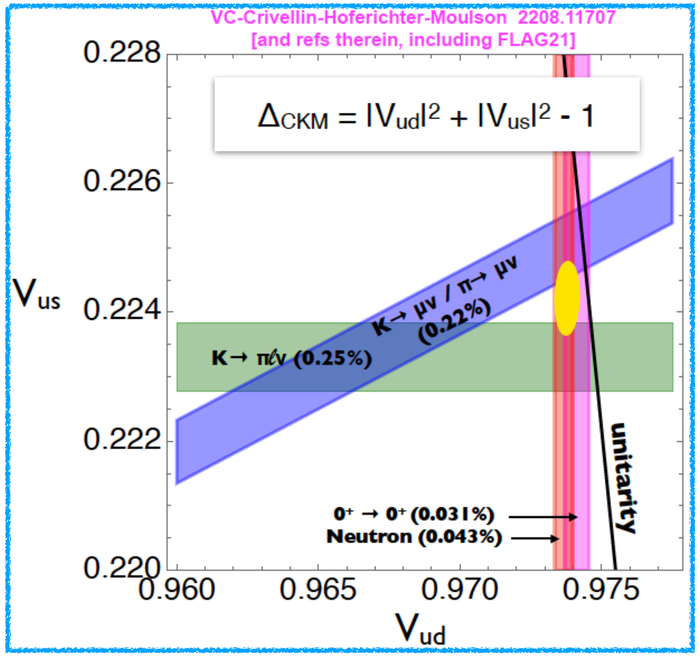
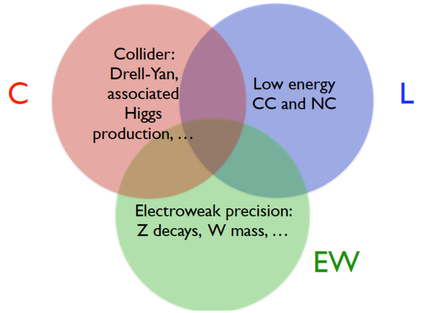
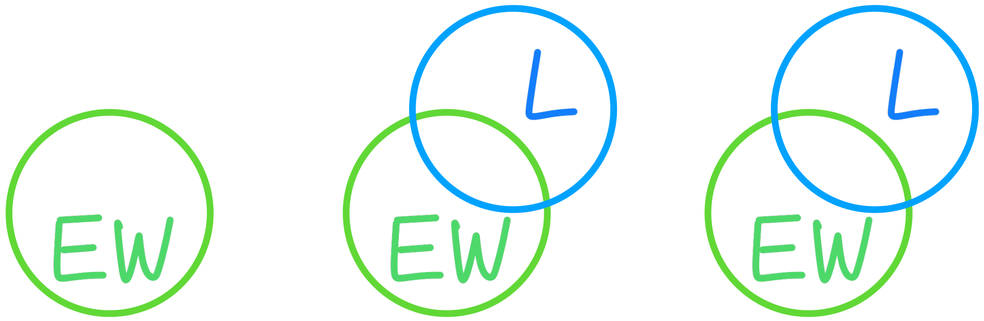
$\hat{C}_{Hu}$	-0.0046 ± 0.12	-0.12 ± 0.098
$\hat{C}_{Hd}$	-0.55 ± 0.25	-0.33 ± 0.22
C_Δ	-0.15 ± 0.068	-0.030 ± 0.0083
$C_{lq}^{(3)}$	–	–

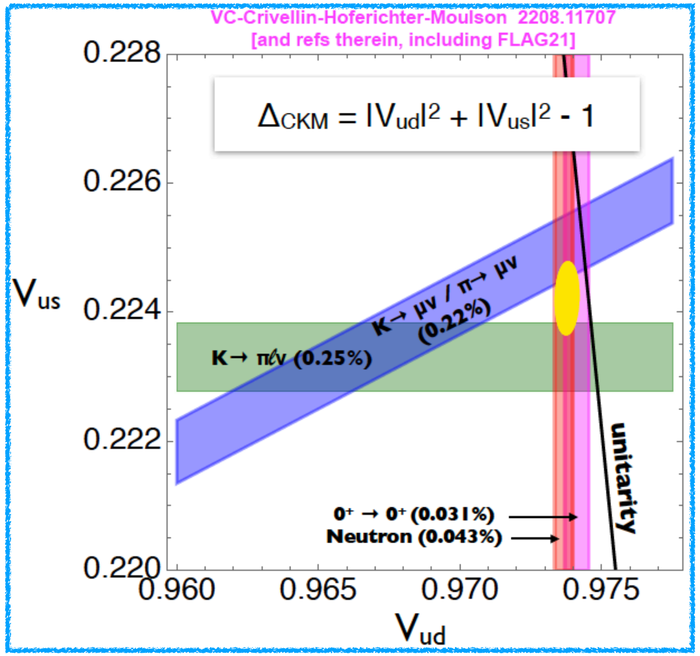


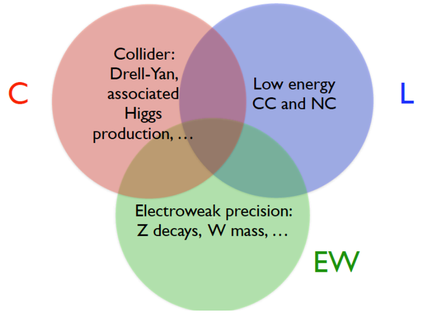


Casefile: $U(3)^5$ + CLEW

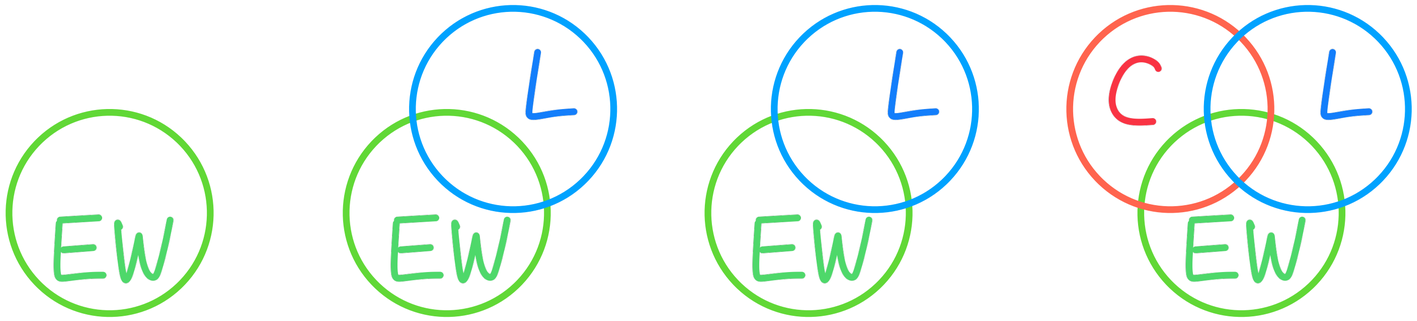


	EW	LEW_1	LEW_2
$\hat{C}_{Hl}^{(1)}$	-0.0091 ± 0.011	-0.016 ± 0.011	-0.0091 ± 0.011
$\hat{C}_{Hl}^{(3)}$	-0.057 ± 0.015	-0.046 ± 0.014	-0.057 ± 0.015
$\hat{C}_{He}$	-0.024 ± 0.0086	-0.027 ± 0.0085	-0.024 ± 0.0086
$\hat{C}_{Hq}^{(1)}$	-0.029 ± 0.043	-0.045 ± 0.042	-0.029 ± 0.043
$\hat{C}_{Hq}^{(3)}$	-0.095 ± 0.032	-0.041 ± 0.014	-0.095 ± 0.032
$\hat{C}_{Hu}$	-0.0046 ± 0.12	-0.12 ± 0.098	-0.0046 ± 0.12
$\hat{C}_{Hd}$	-0.55 ± 0.25	-0.33 ± 0.22	-0.55 ± 0.25
C_Δ	-0.15 ± 0.068	-0.030 ± 0.0083	-0.15 ± 0.068
$C_{lq}^{(3)}$	–	–	-0.063 ± 0.034

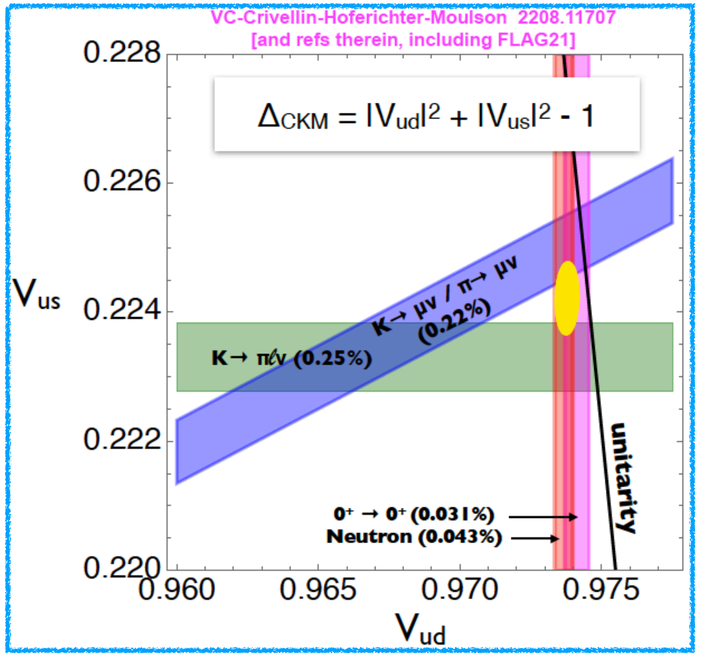




Casefile: $U(3)^5$ + CLEW



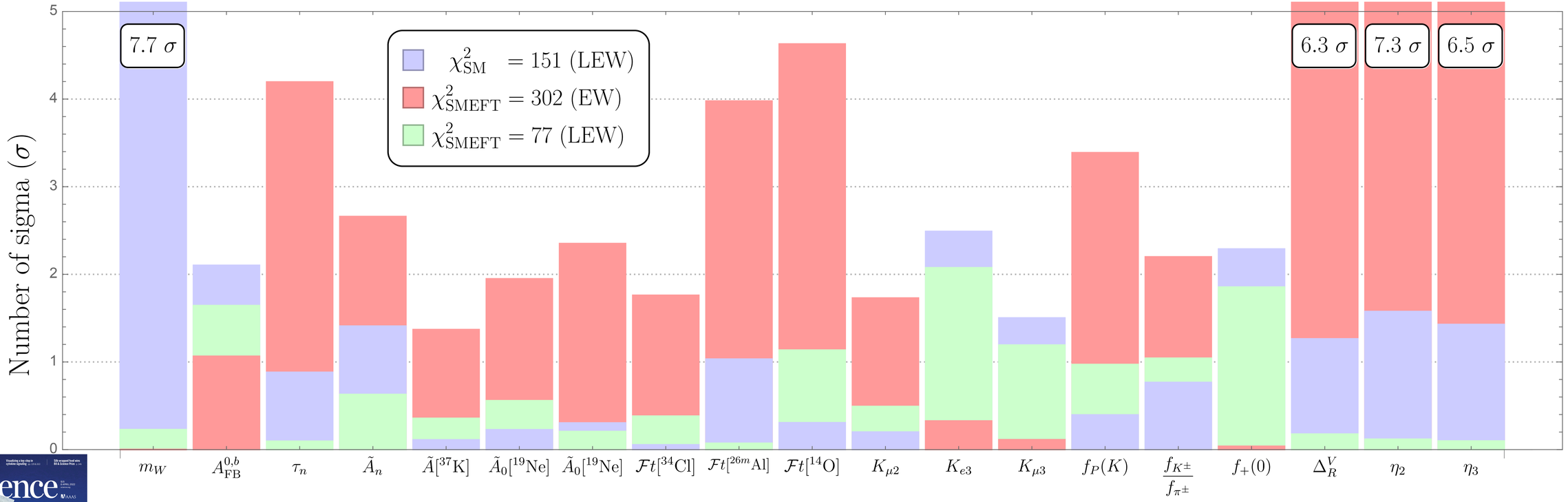
	EW	LEW_1	LEW_2	CLEW
$\hat{C}_{Hl}^{(1)}$	-0.0091 ± 0.011	-0.016 ± 0.011	-0.0091 ± 0.011	-0.016 ± 0.011
$\hat{C}_{Hl}^{(3)}$	-0.057 ± 0.015	-0.046 ± 0.014	-0.057 ± 0.015	-0.046 ± 0.014
$\hat{C}_{He}$	-0.024 ± 0.0086	-0.027 ± 0.0085	-0.024 ± 0.0086	-0.027 ± 0.0085
$\hat{C}_{Hq}^{(1)}$	-0.029 ± 0.043	-0.045 ± 0.042	-0.029 ± 0.043	-0.044 ± 0.042
$\hat{C}_{Hq}^{(3)}$	-0.095 ± 0.032	-0.041 ± 0.014	-0.095 ± 0.032	-0.040 ± 0.014
$\hat{C}_{Hu}$	-0.0046 ± 0.12	-0.12 ± 0.098	-0.0046 ± 0.12	-0.13 ± 0.098
$\hat{C}_{Hd}$	-0.55 ± 0.25	-0.33 ± 0.22	-0.55 ± 0.25	-0.33 ± 0.22
C_Δ	-0.15 ± 0.068	-0.030 ± 0.0083	-0.15 ± 0.068	-0.029 ± 0.0083
$C_{lq}^{(3)}$	–	–	-0.063 ± 0.034	0.00029 ± 0.00058

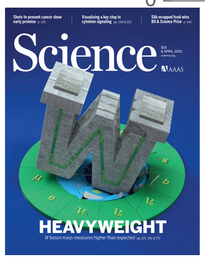


CLEW *versus* No-CLEW

CLEW *versus* No-CLEW

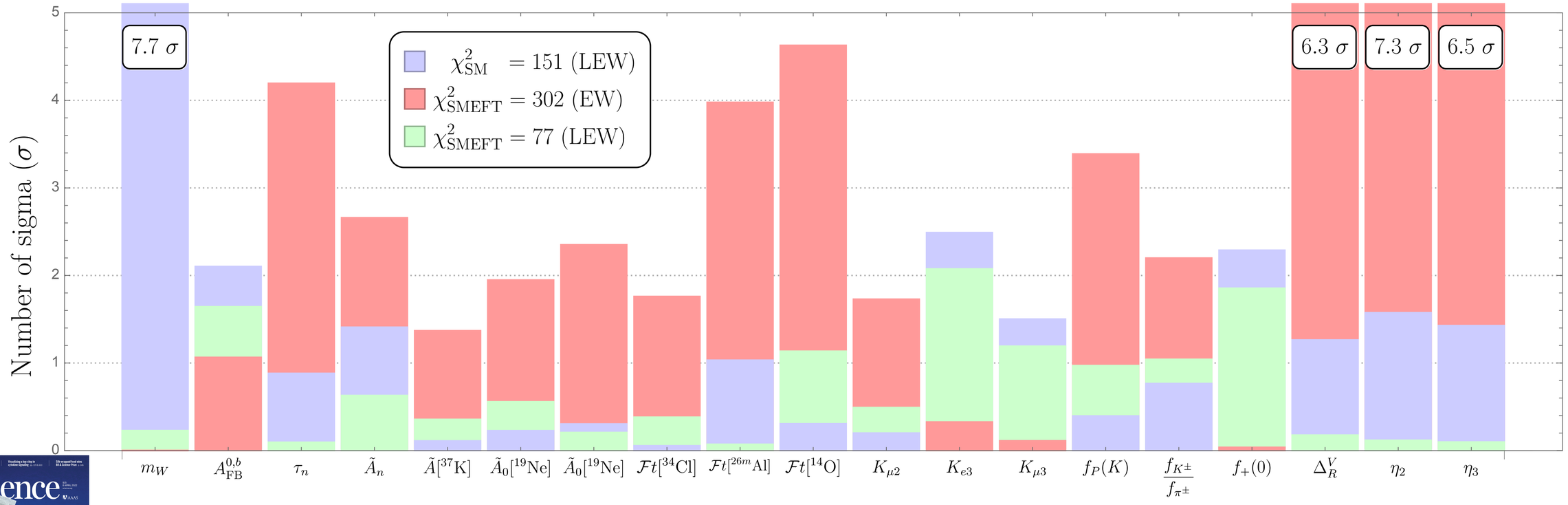
SM

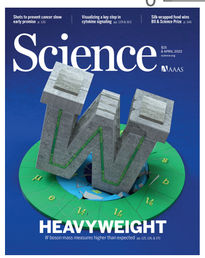




CLEW *versus* No-CLEW

SM

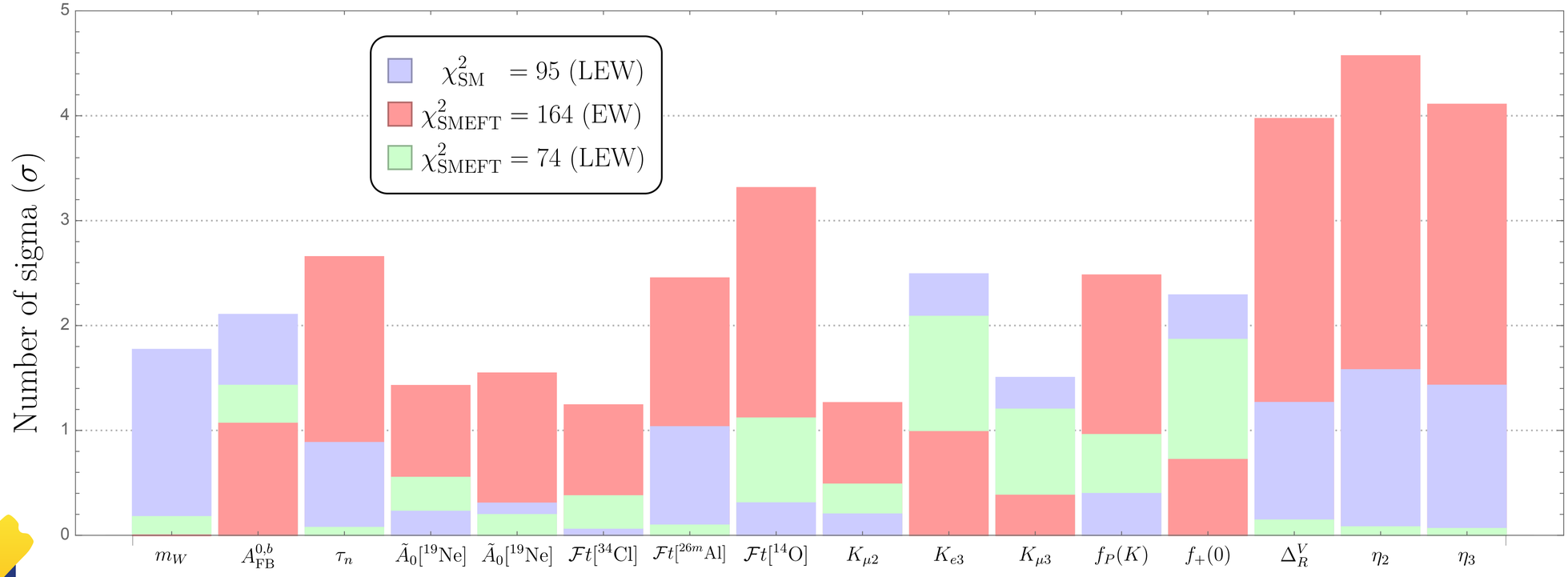




With out a CLEW, SMEFT could be worse than the SM!

CLEW *versus* No-CLEW

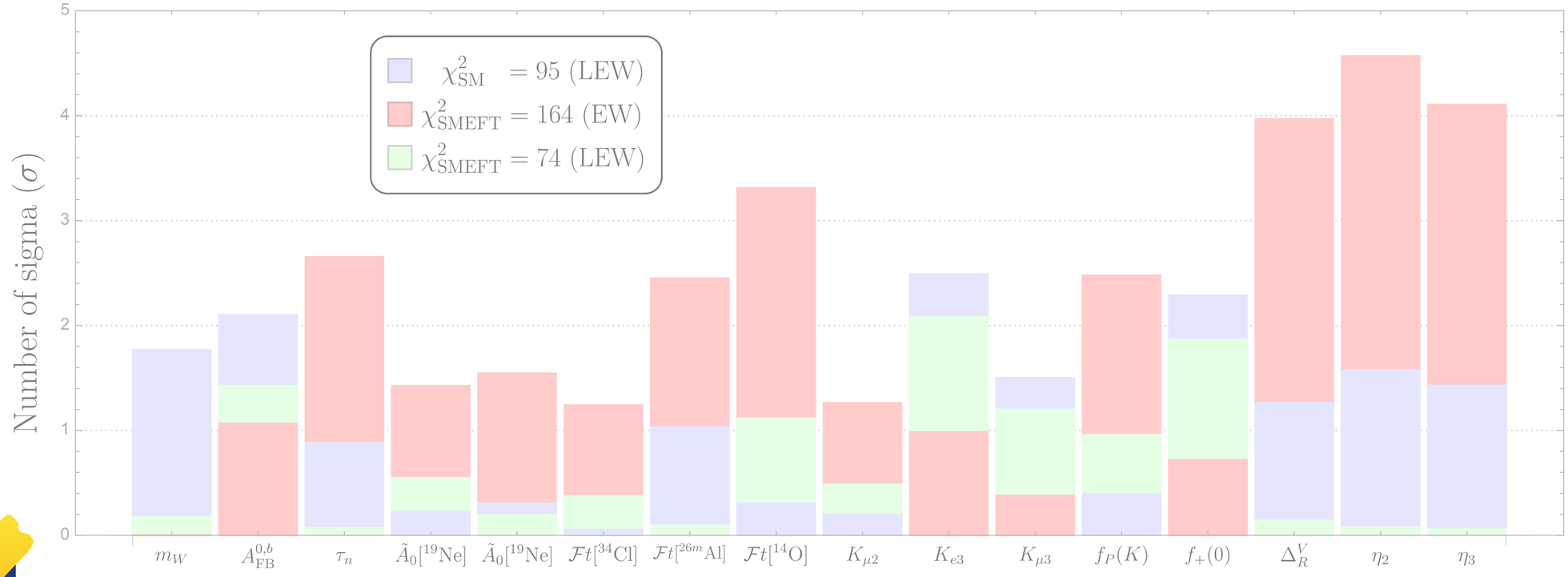
SM



With out a CLEW, SMEFT could be worse than the SM!

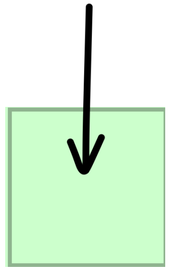
CLEW *versus* No-CLEW

SM

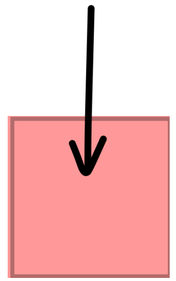


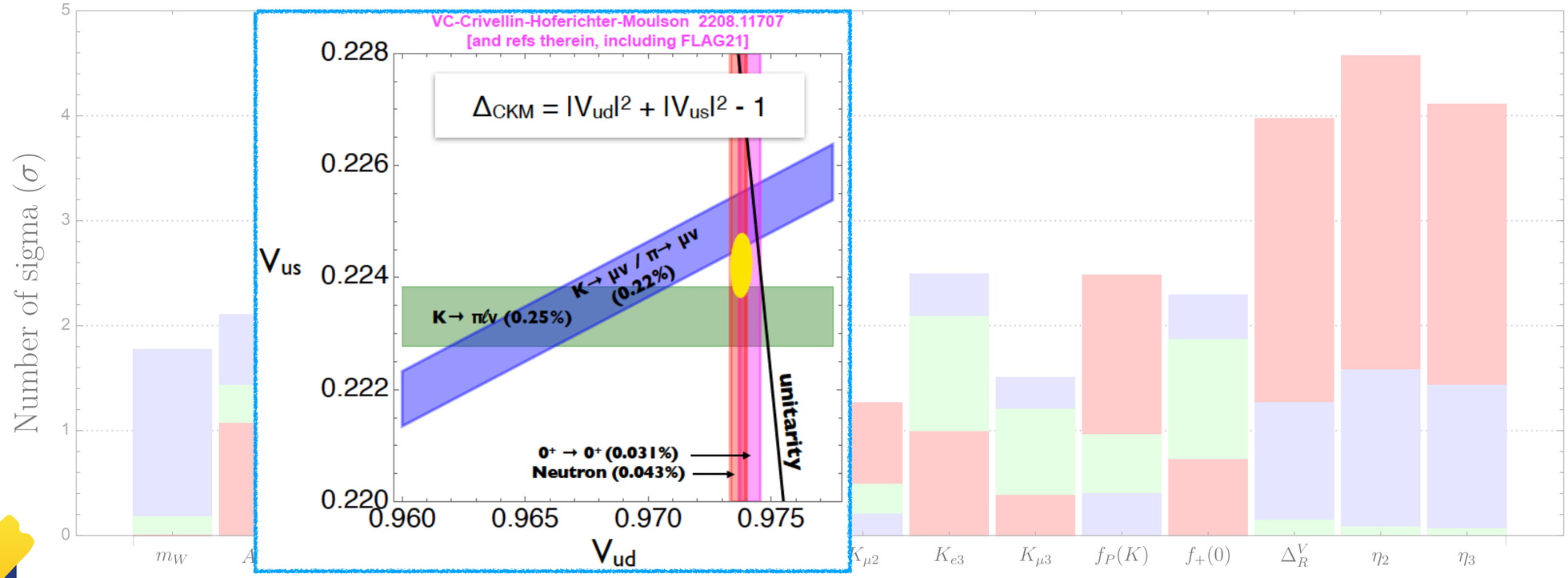
Even with a CLEW, there's another BIG problem to fix!

CLEW *versus* No-CLEW



SM

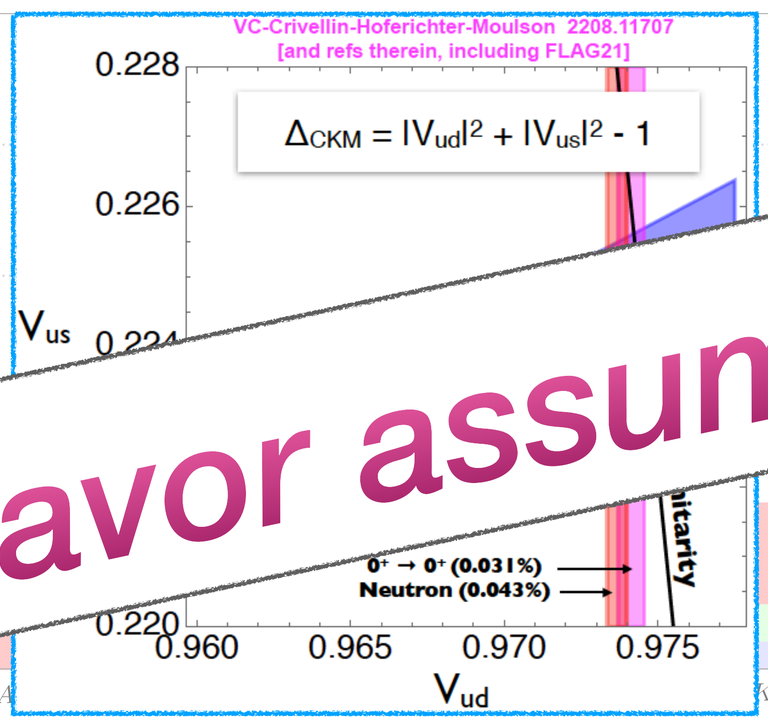




Even with a CLEW, there's another BIG problem to fix!

CLEW *versus* No-CLEW

SM



Flavor assumption: $U(3)^5$

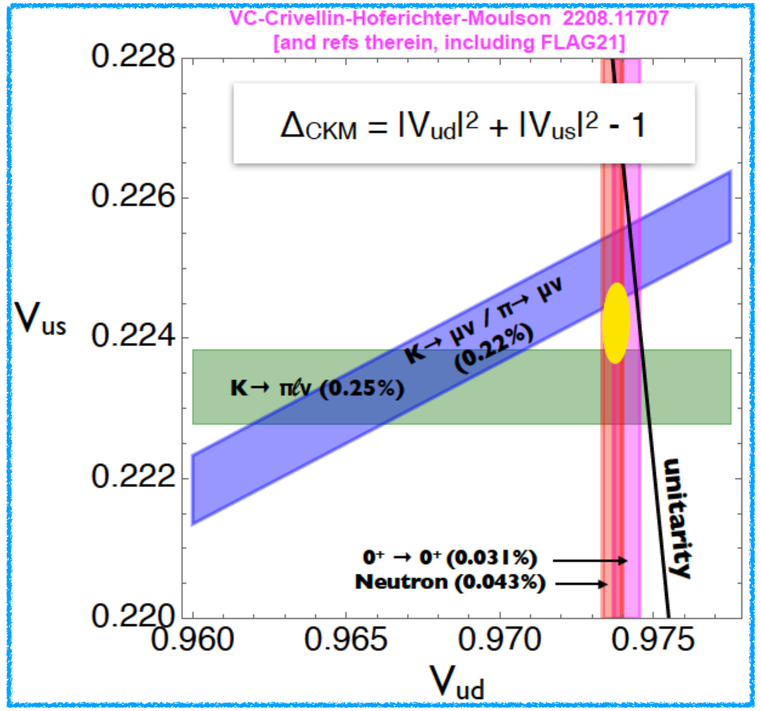
Even with a CLEW, there's another BIG problem to fix!

CLEW *versus* No-CLEW

SM

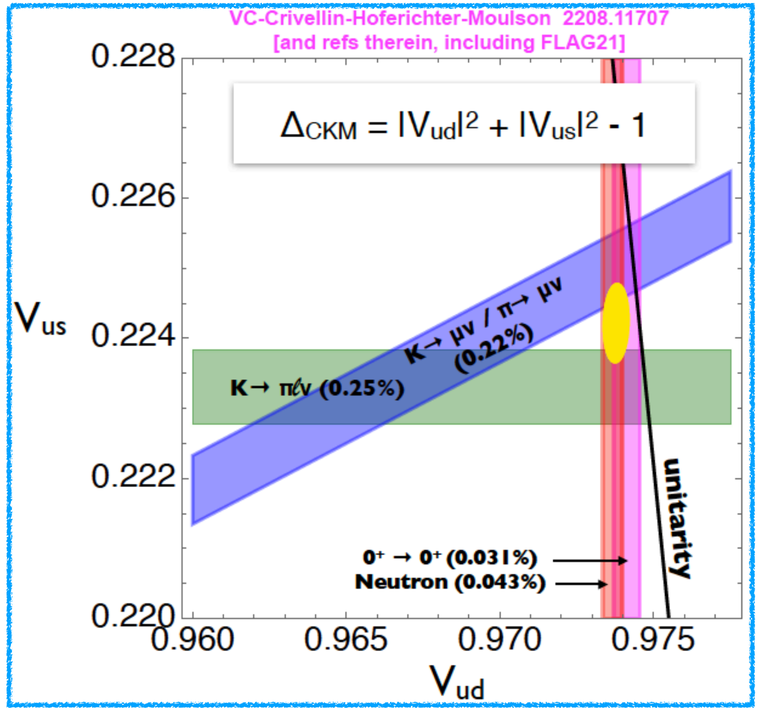
Even with a CLEW, there's another BIG problem to fix!

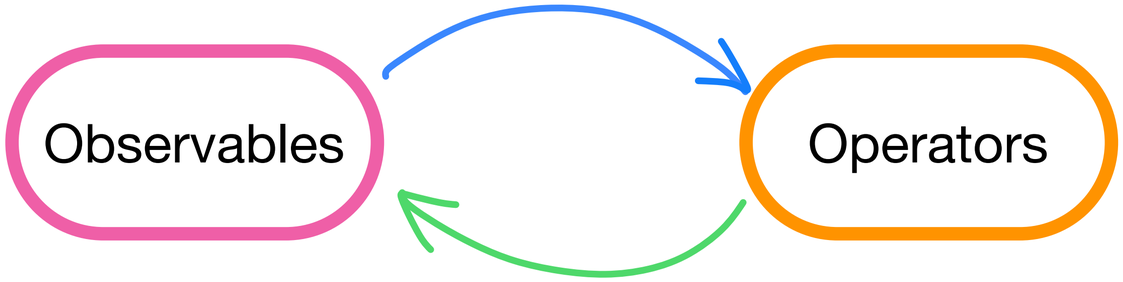
List all the relevant operators



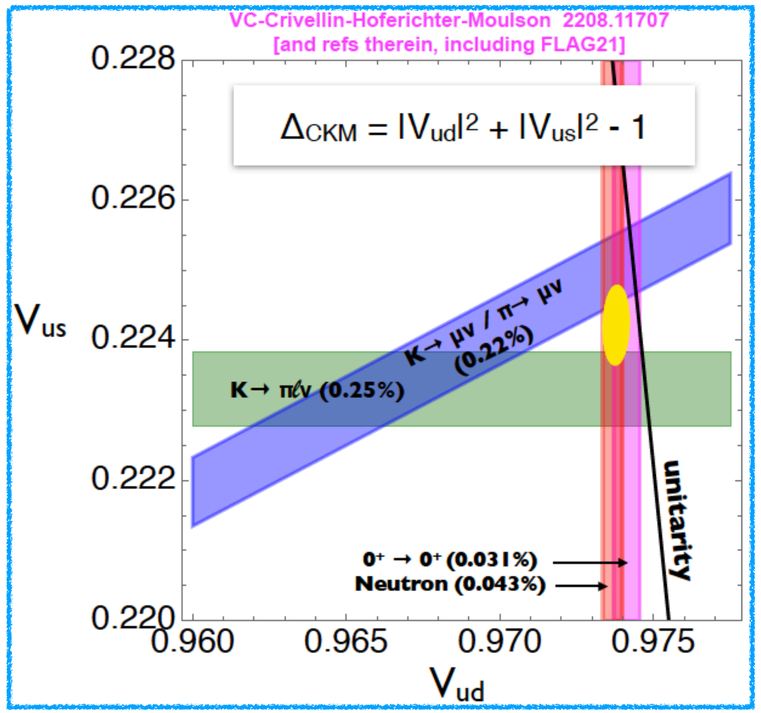
Observables

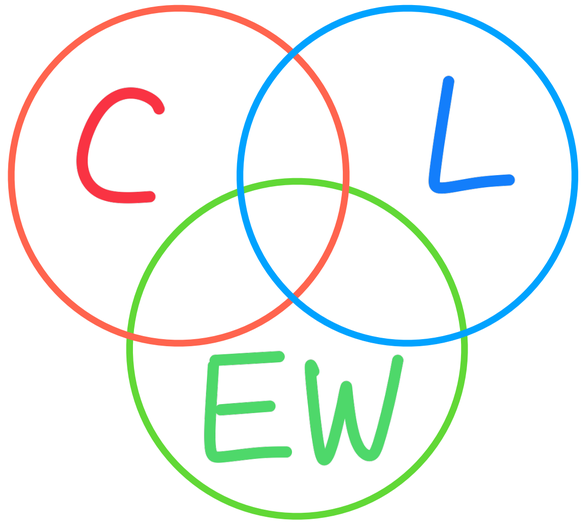
List all the relevant operators

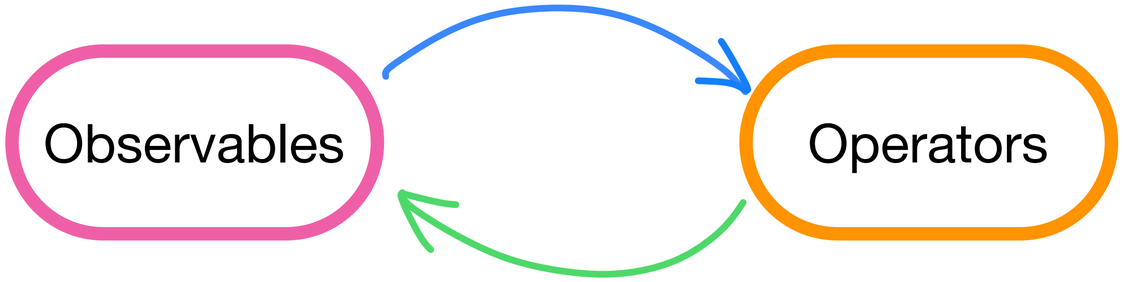




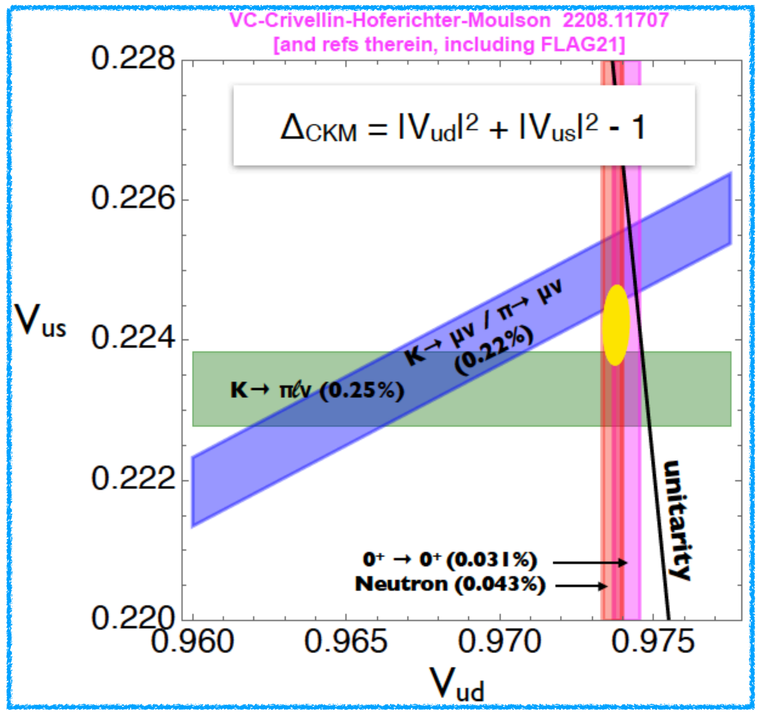
List all the relevant operators

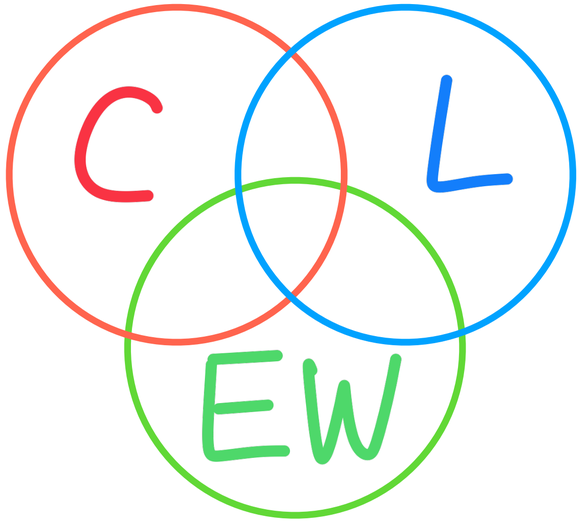


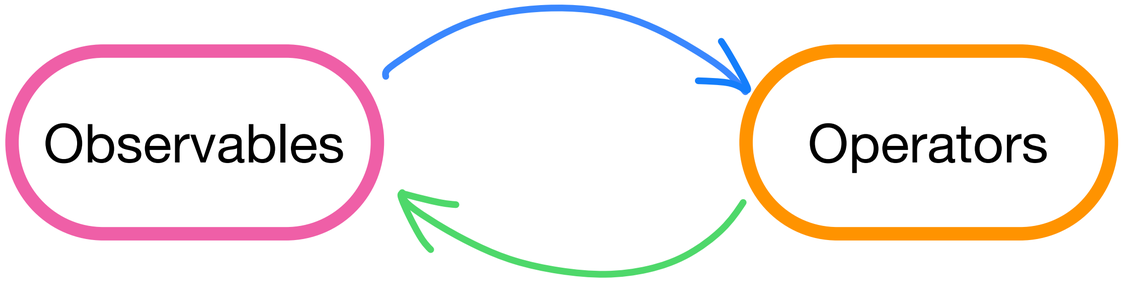




List all the relevant operators



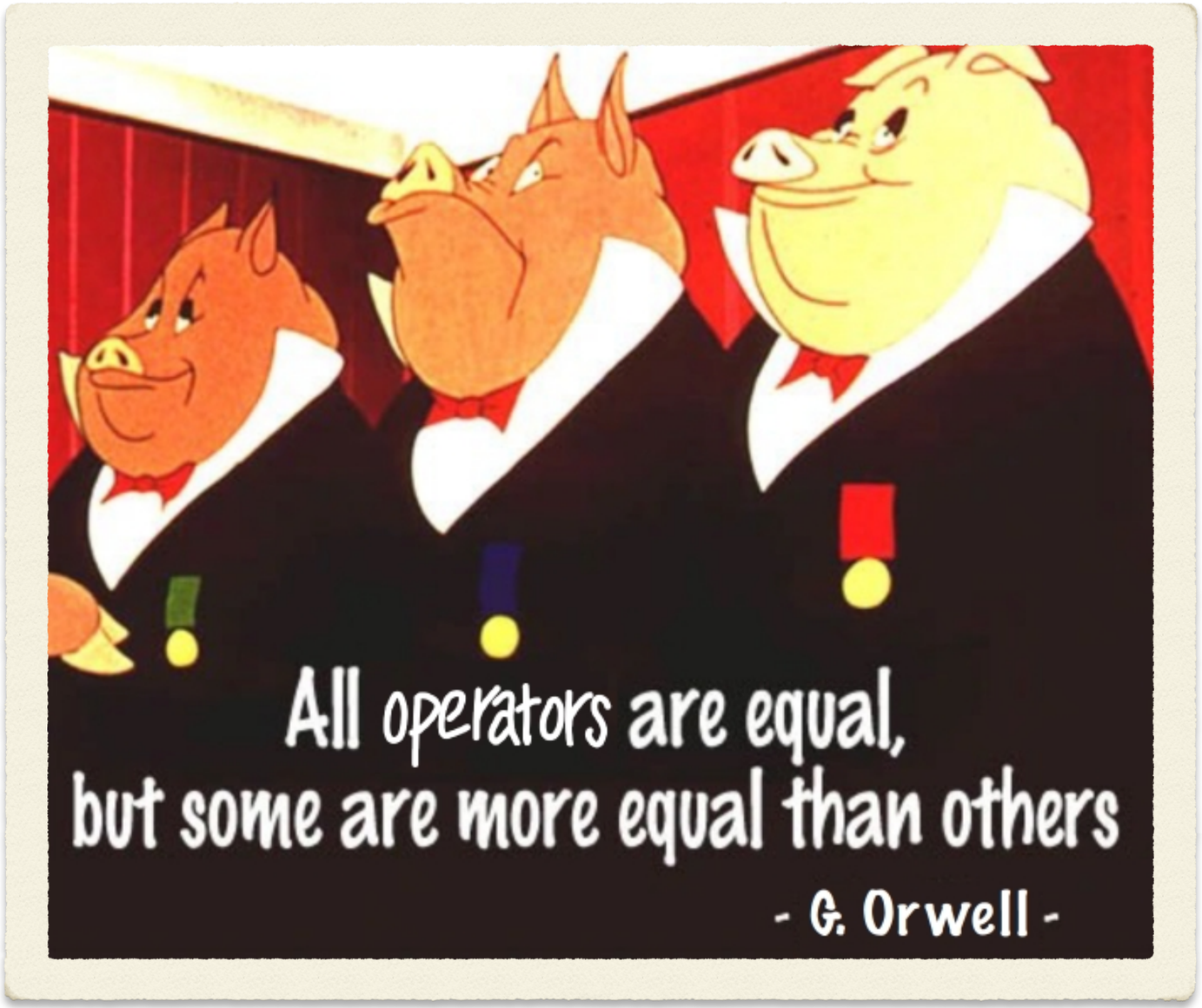




With all flavor indices

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}	$H^\dagger \tau^I H W^I_{\mu\nu} B^{\mu\nu}$			
		✗	✓	✓
	$i D^I_\mu H)(\bar{l}_p \tau^I \gamma^\mu l_r)$	✓	✓	✓
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.				
$Q^{(1)}_{lequ}$	$(\bar{l}^j_p e_r)\epsilon_{jk}(\bar{q}^k_s u_t)$	✓	✗	✓
$Q^{(3)}_{lequ}$	$(\bar{l}^j_p \sigma_{\mu\nu} e_r)\epsilon_{jk}(\bar{q}^k_s \sigma^{\mu\nu} u_t)$	✓	✗	✓

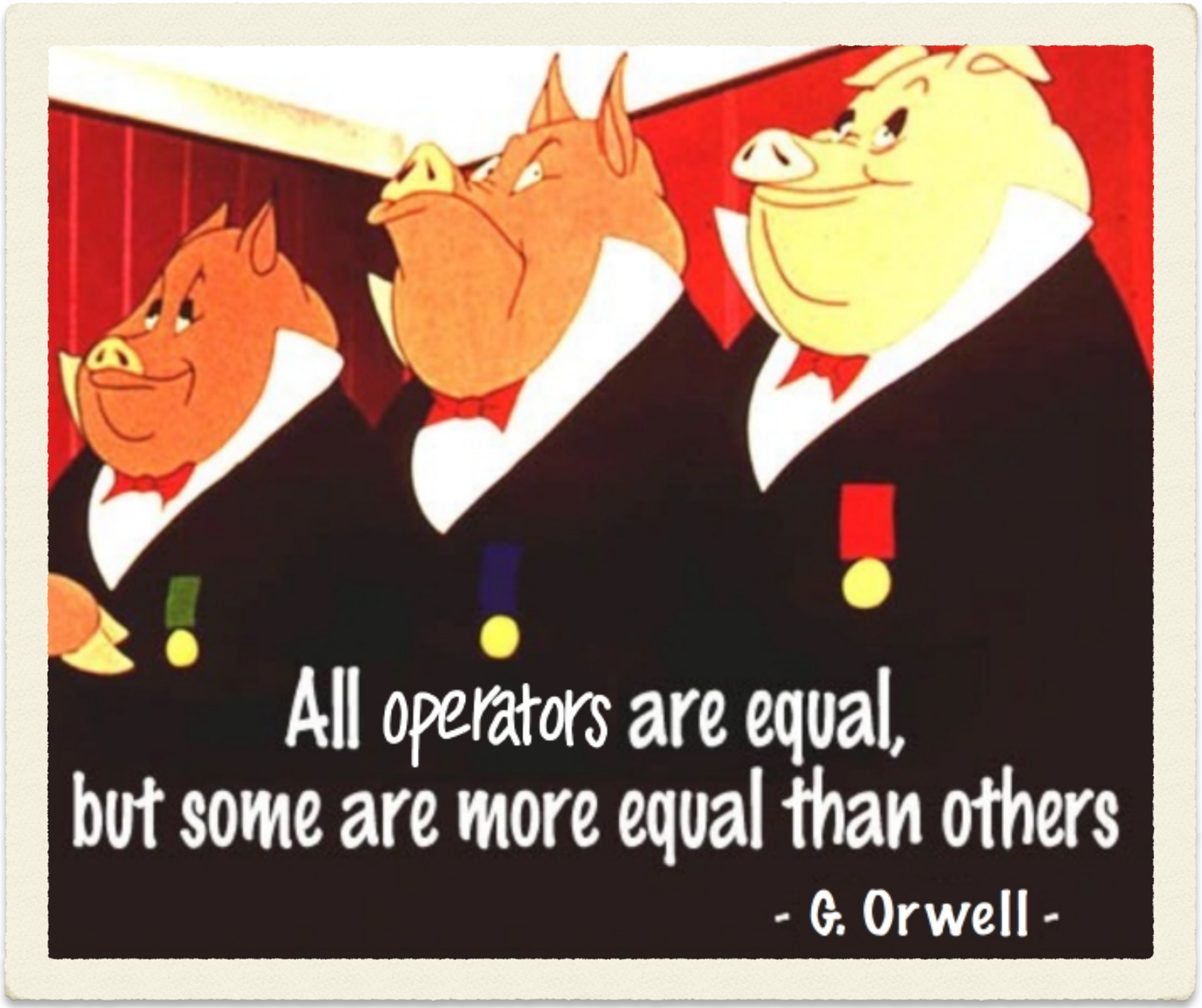
All operators are equal, but...



With all flavor indices

Operators		Low energy CC	EWPO	LHC
H^4D^2				
Q_{HD}	$\left(H^\dagger D^\mu H\right)^* \left(H^\dagger D_\mu H\right)$	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.				
$Q^{(1)}_{lequ}$	$(\bar{l}^j_p e_r)\epsilon_{jk}(\bar{q}^k_s u_t)$	✓	✗	✓
$Q^{(3)}_{lequ}$	$(\bar{l}^j_p \sigma_{\mu\nu} e_r)\epsilon_{jk}(\bar{q}^k_s \sigma^{\mu\nu} u_t)$	✓	✗	✓

All operators are equal, but...



With all flavor indices

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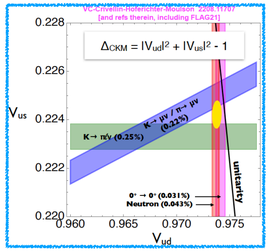
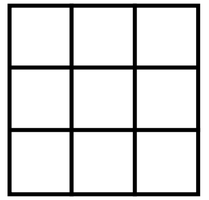
Q_{HD}	$\left(H^\dagger D^\mu H\right)^* \left(H^\dagger D_\mu H\right)$	parameter shift (m_Z)		
X^2H^2				
Q_{HWB}	$H^\dagger \tau^I H W^I_{\mu\nu} B^{\mu\nu}$			
		✗	✓	✓
	$i D^I_\mu H)(\bar{l}_p \tau^I \gamma^\mu l_r)$	✓	✓	✓
Q_{He}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{e}_p \gamma^\mu e_r)$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

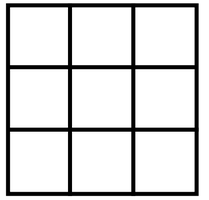


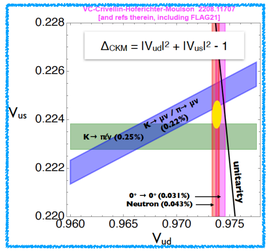
All operators are equal, but...

$C_{Hq}^{(1)}$ 3×3



$C_{Hq}^{(3)}$ 3×3



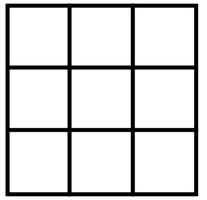


All operators are equal, but...

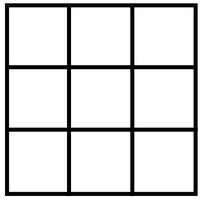
Basis rotation

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

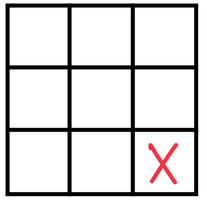
$C_{Hq}^{(1)}$ 3×3



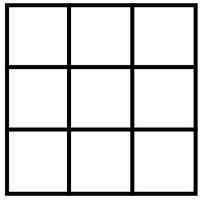
$C_{Hq}^{(3)}$ 3×3

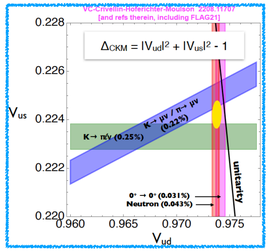


$C_{Hq}^{(u)}$ 3×3



$C_{Hq}^{(d)}$ 3×3





All operators are equal, but...

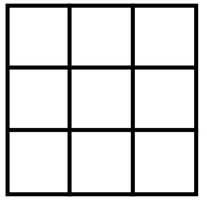
Basis rotation

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

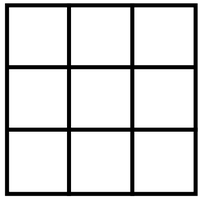
Relative contribution

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

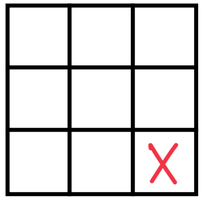
$C_{Hq}^{(1)}$ 3×3



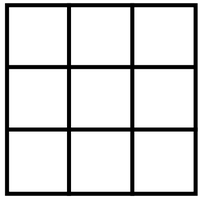
$C_{Hq}^{(3)}$ 3×3



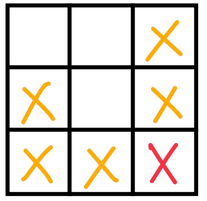
$C_{Hq}^{(u)}$ 3×3



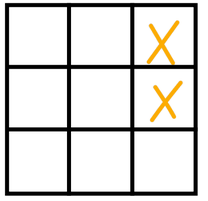
$C_{Hq}^{(d)}$ 3×3

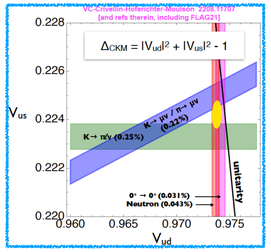


$C_{Hq}^{(u)}$ 3×3



$C_{Hq}^{(d)}$ 3×3





All operators are equal, but...

Basis rotation

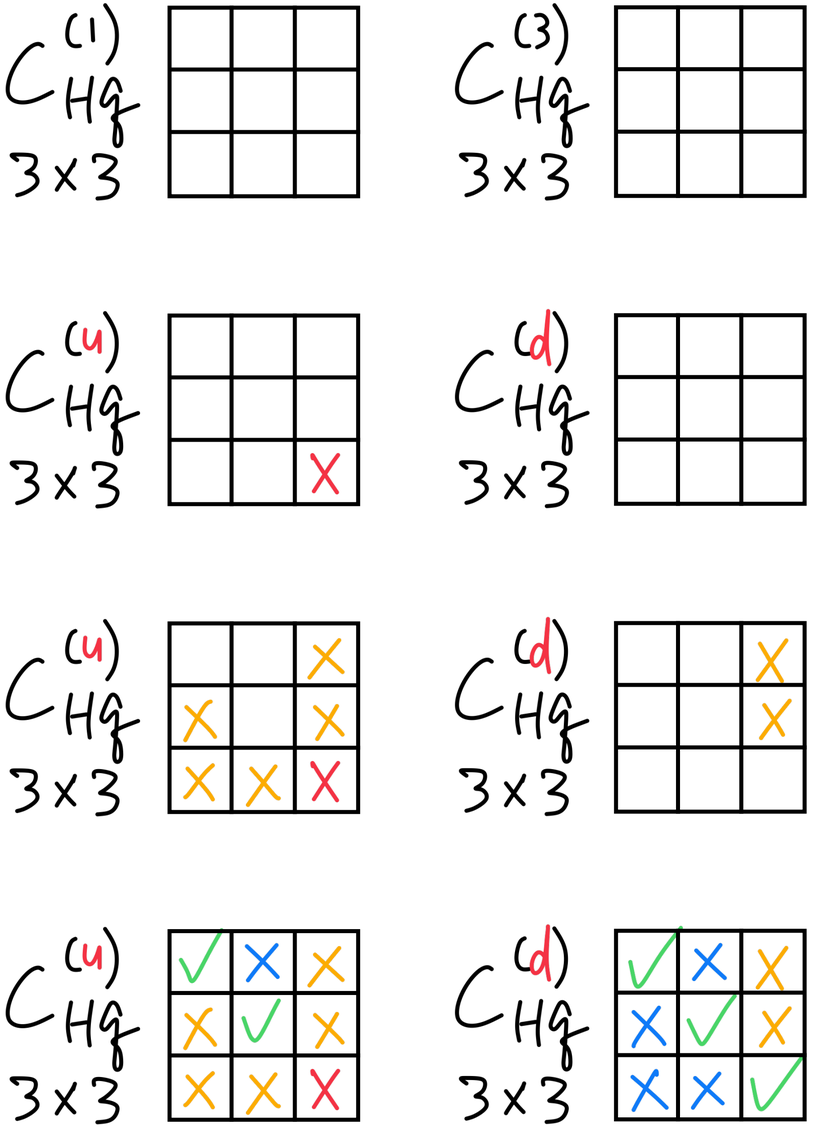
$$C_{Hq}^{(u)} = V\left[C_{Hq}^{(1)} - C_{Hq}^{(3)}\right]V^\dagger, \qquad C_{Hq}^{(d)} = C_{Hq}^{(1)} + C_{Hq}^{(3)},$$

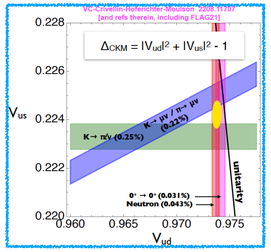
Relative contribution

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

Pheno constraints

FCNC decays of B, D and K mesons





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

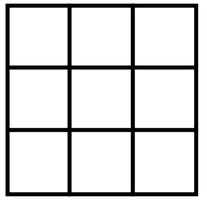
Suppressed by $|V_{us}|^2$ or (V_{ts}/V_{us})

Pheno constraints

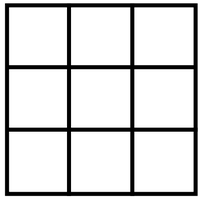
FCNC decays of B, D and K mesons

"More-equal" operators

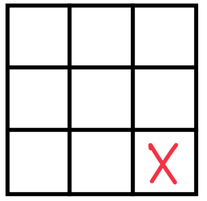
$C_{Hq}^{(1)}$ 3×3



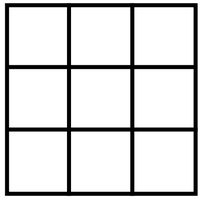
$C_{Hq}^{(3)}$ 3×3



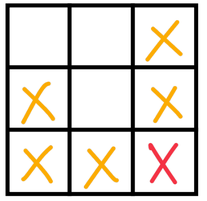
$C_{Hq}^{(u)}$ 3×3



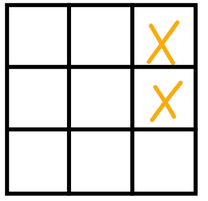
$C_{Hq}^{(d)}$ 3×3



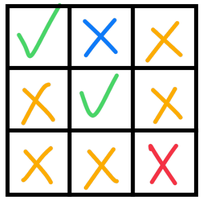
$C_{Hq}^{(u)}$ 3×3



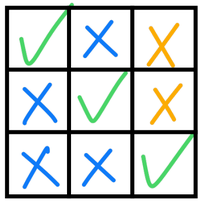
$C_{Hq}^{(d)}$ 3×3



$C_{Hq}^{(u)}$ 3×3



$C_{Hq}^{(d)}$ 3×3



37 operators are "more equal"

Operators		Low energy CC	EWPO	LHC
H^4D^2				
Q_{HD}	$\left(H^\dagger D^\mu H\right)^* \left(H^\dagger D_\mu H\right)$	parameter shift (m_Z)		
X^2H^2				
Q_{HWB}	$H^\dagger \tau^I H W^I_{\mu\nu} B^{\mu\nu}$			
		✗	✓	✓
	$i D^I_\mu H)(\bar{l}_p \tau^I \gamma^\mu l_r)$	✓	✓	✓
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

37 operators are "more equal"

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

37 in total

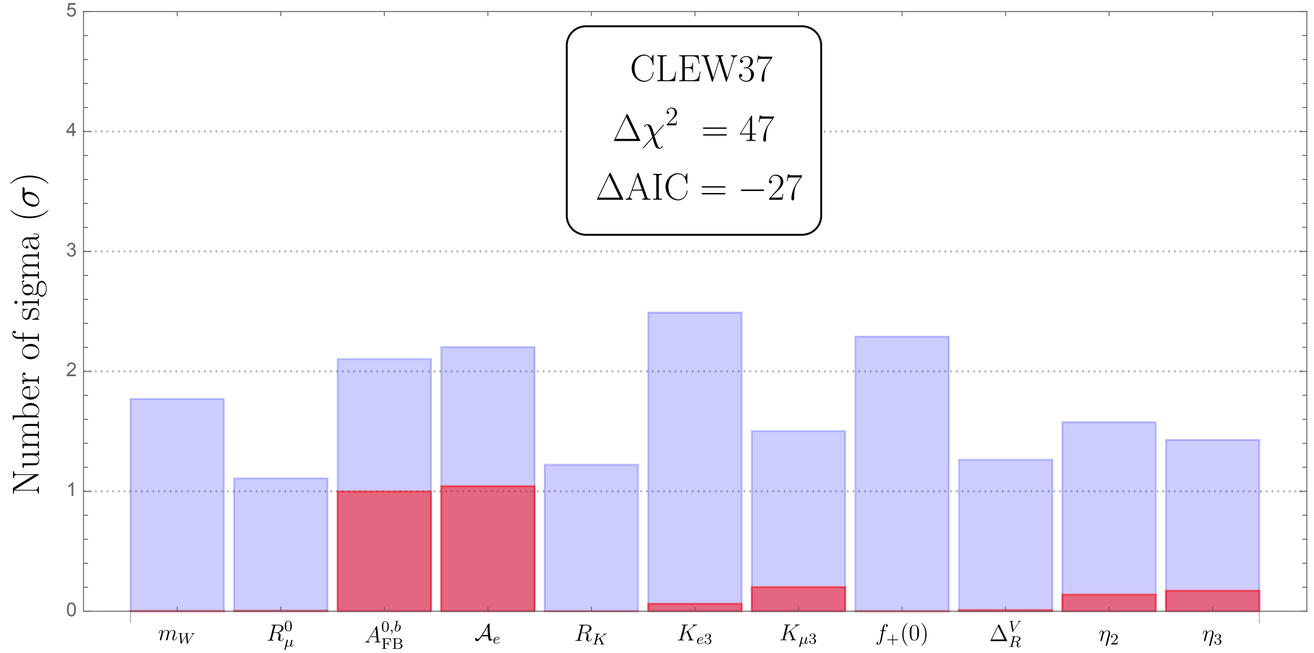
With all flavor indices

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}	$H^\dagger \tau^I H W^I_{\mu\nu} B^{\mu\nu}$			
		✗	✓	✓
	$i D^I_\mu H)(\bar{l}_p \tau^I \gamma^\mu l_r)$	✓	✓	✓
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.				
$Q^{(1)}_{lequ}$	$(\bar{l}^j_p e_r)\epsilon_{jk}(\bar{q}^k_s u_t)$	✓	✗	✓
$Q^{(3)}_{lequ}$	$(\bar{l}^j_p \sigma_{\mu\nu} e_r)\epsilon_{jk}(\bar{q}^k_s \sigma^{\mu\nu} u_t)$	✓	✗	✓

Let's fit these 37 operators

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

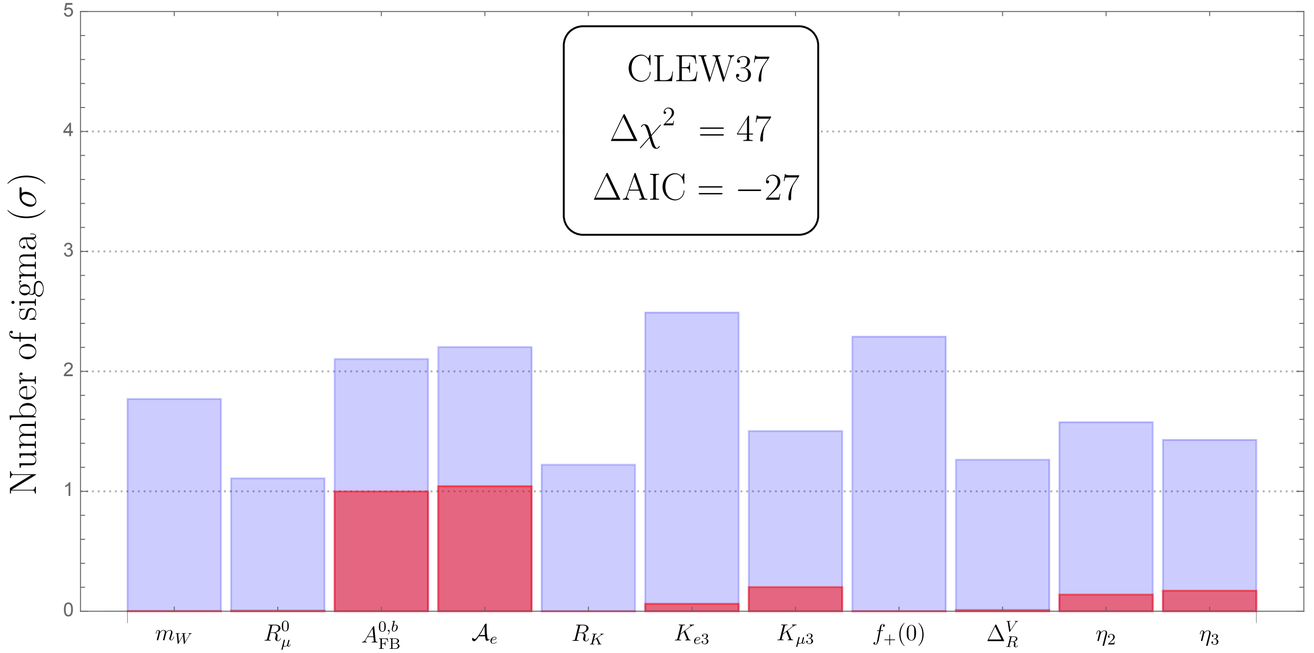
37 in total

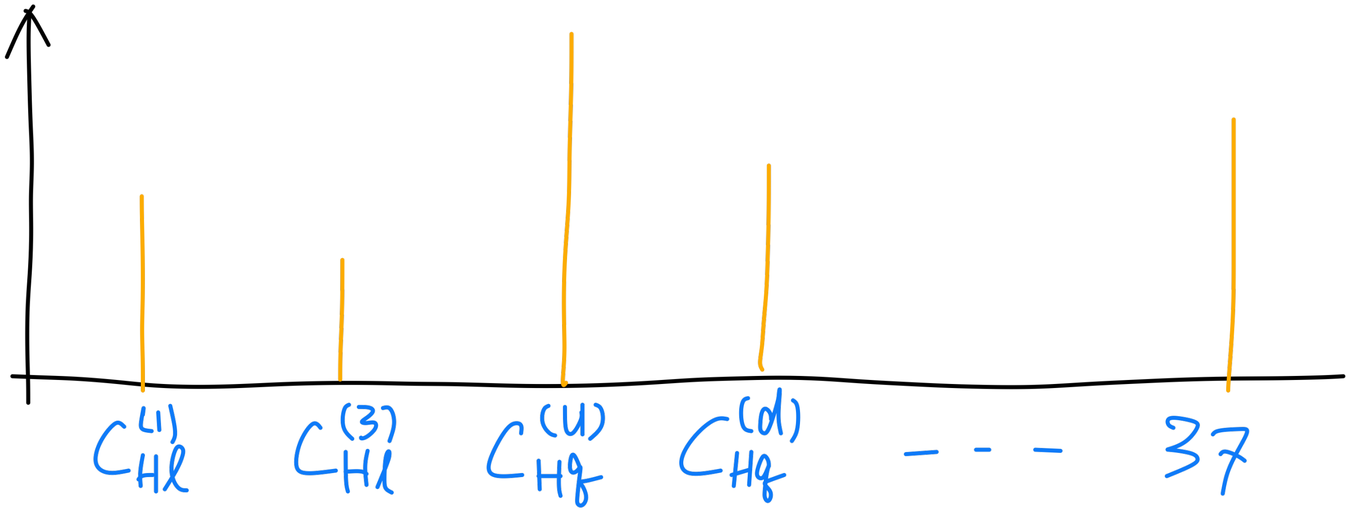


Conclusion

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

37 in total

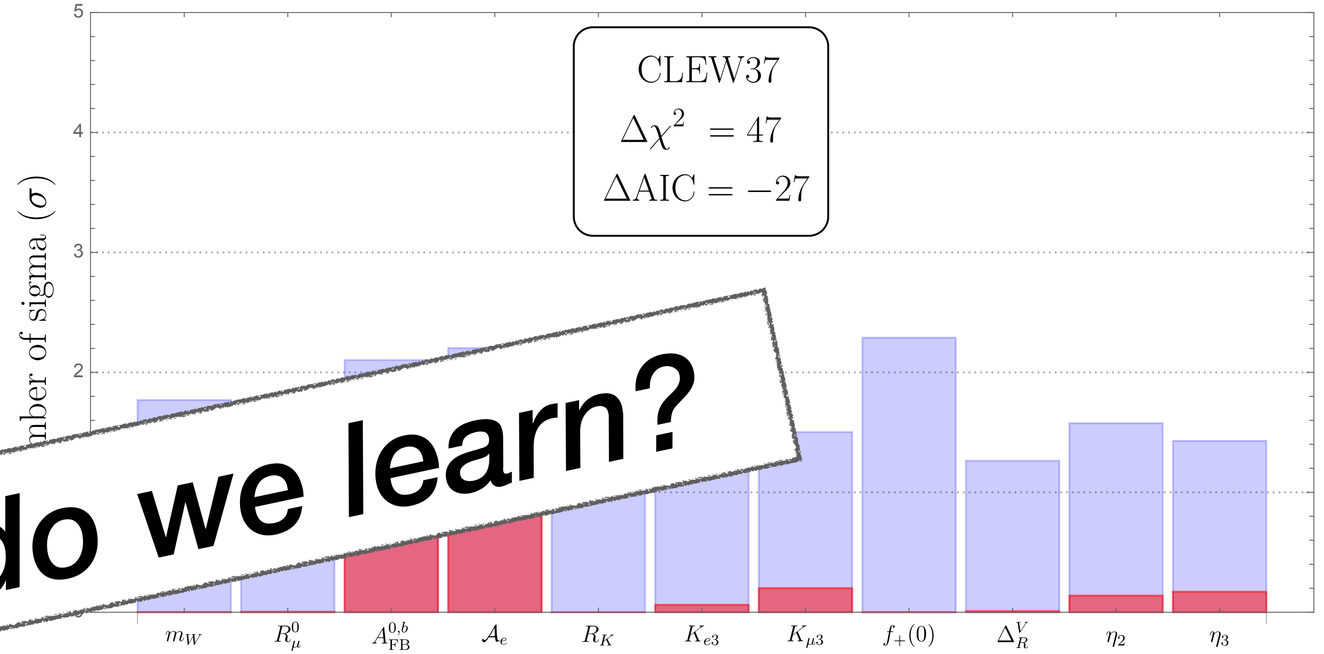




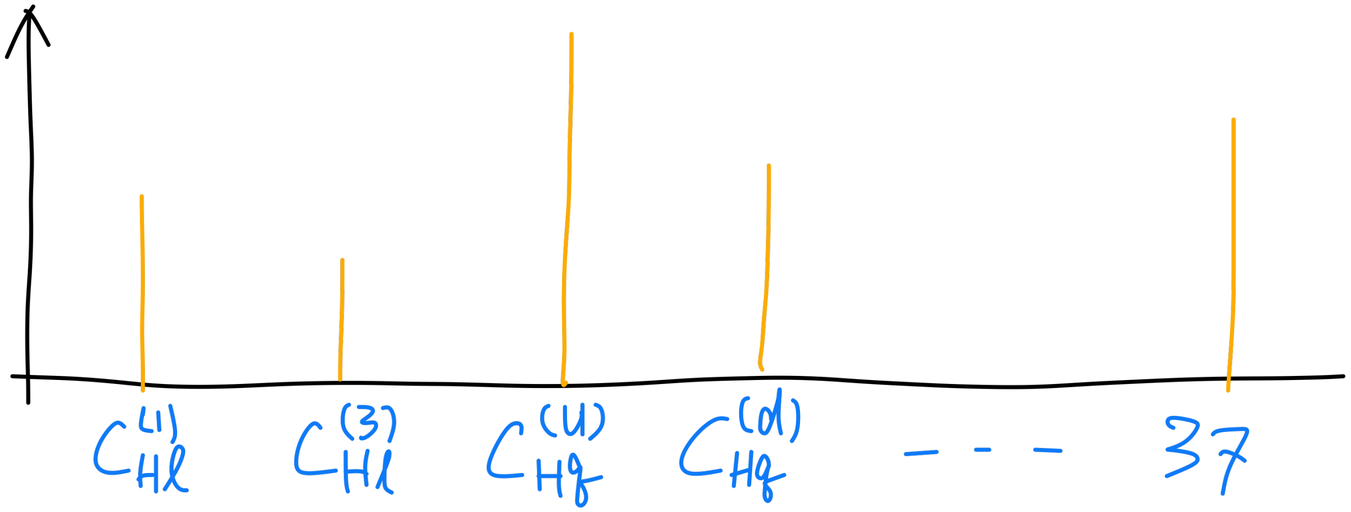
Conclusion

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

37 in total



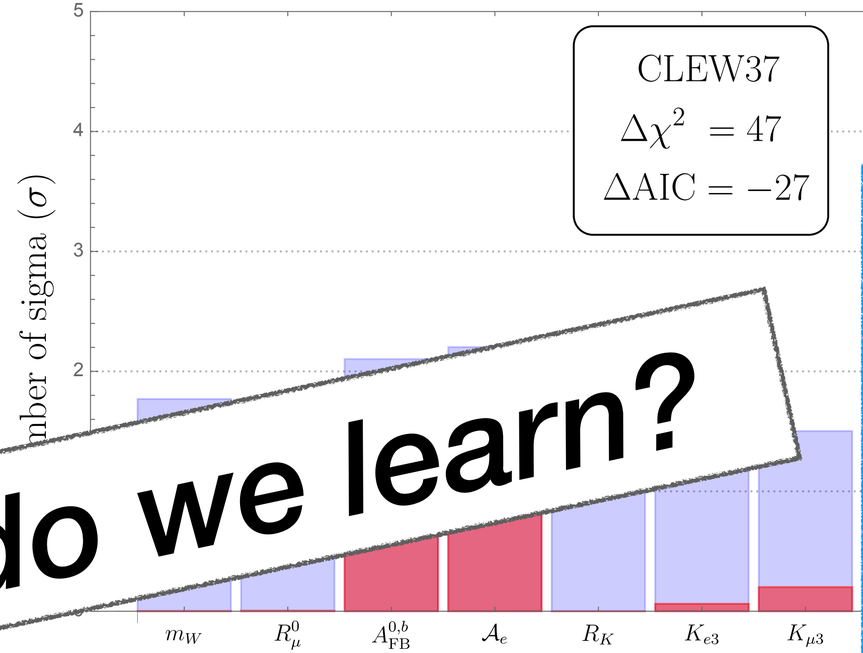
What do we learn?

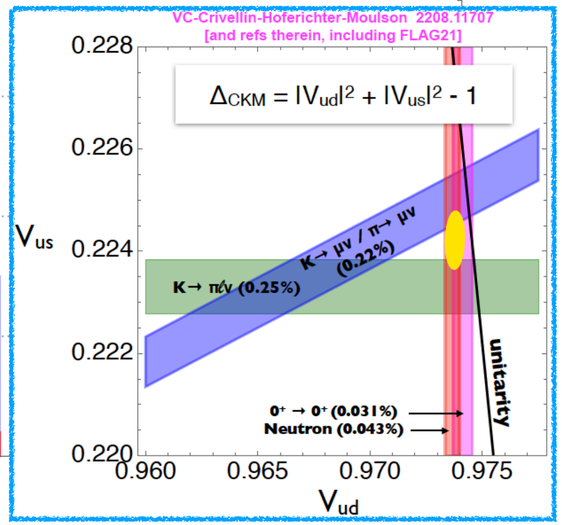


Conclusion

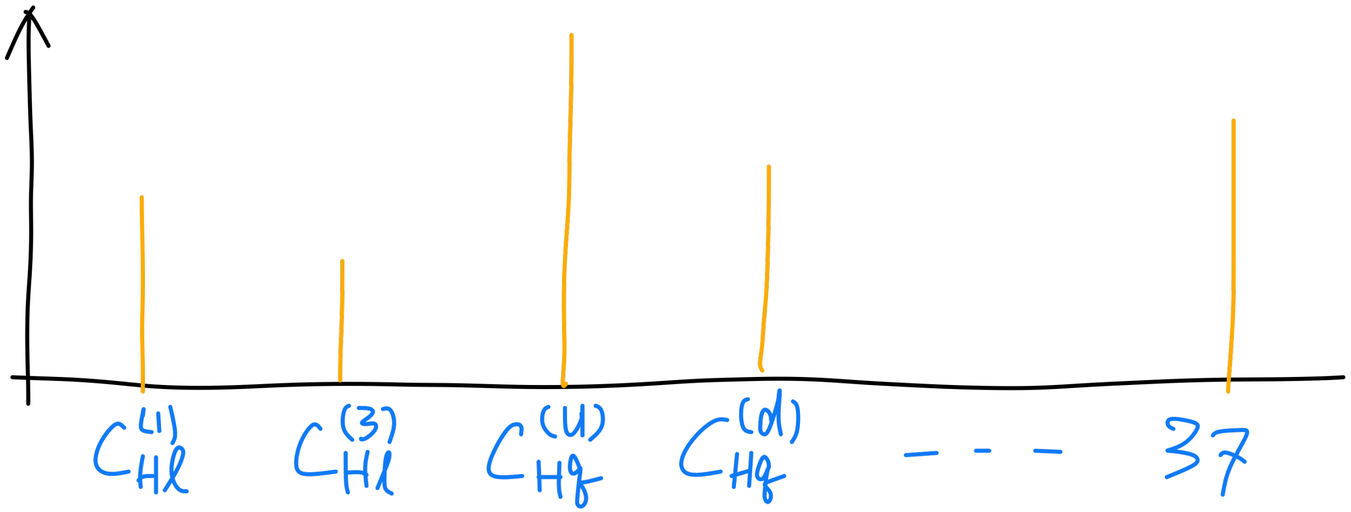
Global analysis	Indices
$C^{(1,3)}_{Hl\,pr}$, $C_{He\,pr}$	$pr \in \{ee, \mu\mu, \tau\tau\}$
$C^{(d)}_{Hq\,pr}$, $C_{Hd\,pr}$	$pr \in \{11, 22, 33\}$
$C^{(u)}_{Hq\,pr}$, $C_{Hu\,pr}$	$pr \in \{11, 22\}$
$C_{Hud\,pr}$	$pr \in \{11, 12\}$
$C^{(d)}_{lq\,\ell\ell pr}$, $C_{ledq\,\ell\ell pr}$	$\ell \in \{e,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

37 in total





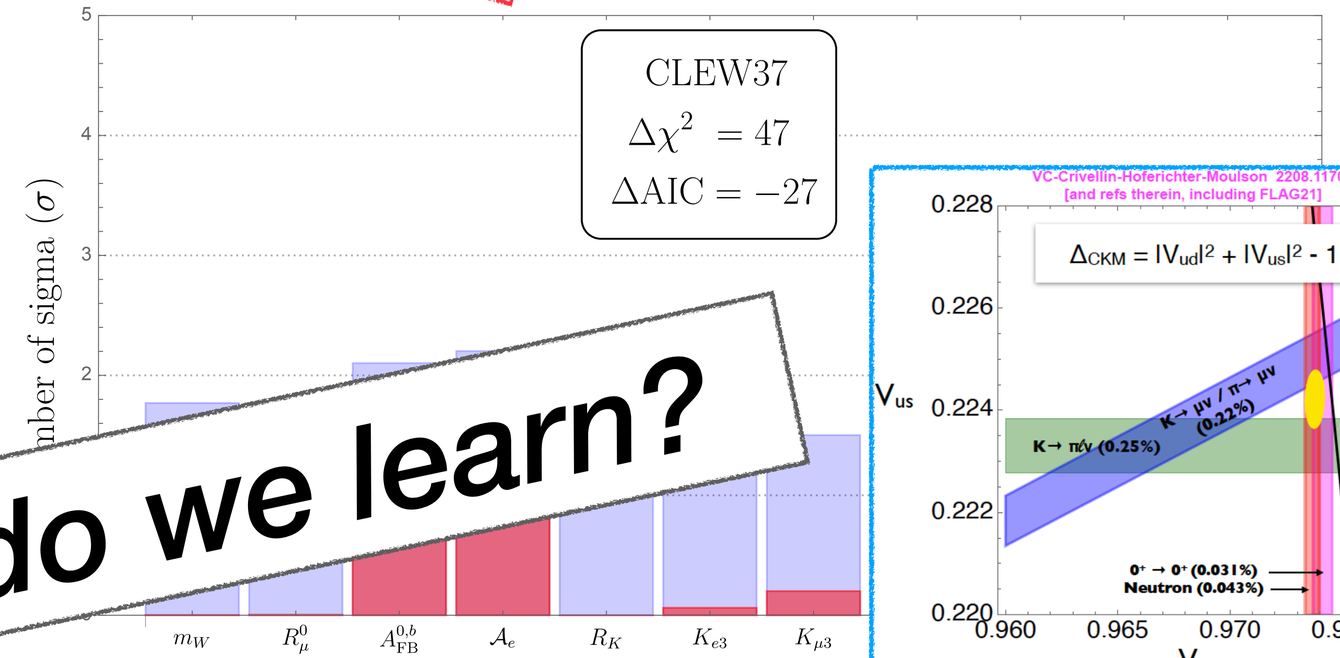
What do we learn?



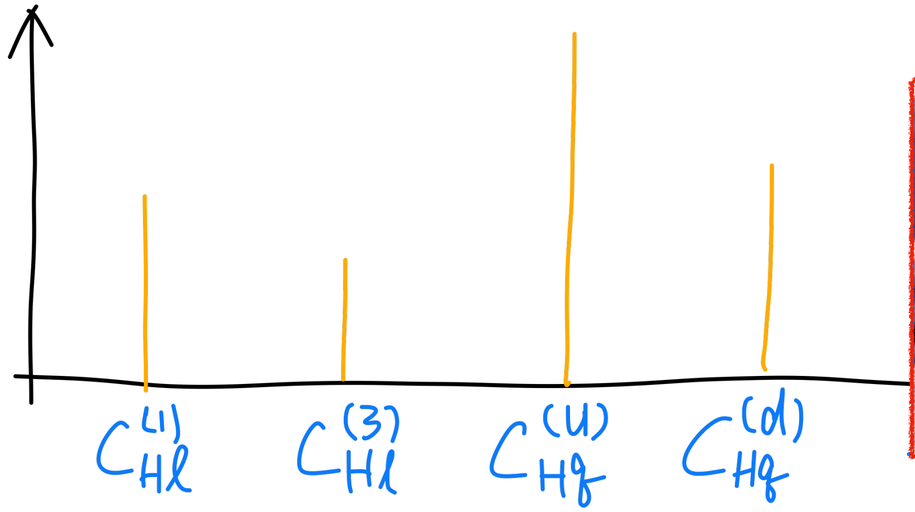
~~Conclusion~~

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

37 in total



What do we learn?



All the 37 are equal, but...

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}	
$C_{\substack{ll \\ 2112}}$		

Still, some are more equal

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

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

Still, some are more equal

Global analysis	Indices
$C^{(1,3)}_{Hl\,pr}$, $C_{He\,pr}$	$pr \in \{ee, \mu\mu, \tau\tau\}$
$C^{(d)}_{Hq\,pr}$, $C_{Hd\,pr}$	$pr \in \{11, 22, 33\}$
$C^{(u)}_{Hq\,pr}$, $C_{Hu\,pr}$	$pr \in \{11, 22\}$
$C_{Hud\,pr}$	$pr \in \{11, 12\}$
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~~Let's do $2^{37} \approx 10^{11}$ fits!~~

Group them into 10 categories

Global analysis	Indices
$C^{(1,3)}_{Hl\,pr}$, $C_{He\,pr}$	$pr \in \{ee, \mu\mu, \tau\tau\}$
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Let's do ~~$2^{37} \approx 10^{11}$~~ fits!

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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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

AIC and one thousand fits

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X.	$C_{lequ}^{(3)}$	Tensor 4-fermion	2

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

AIC and one thousand fits

Akaike Information Criterion

$$\textbf{AIC} = \chi^2 + 2 \times (\textbf{number of Ops.})$$

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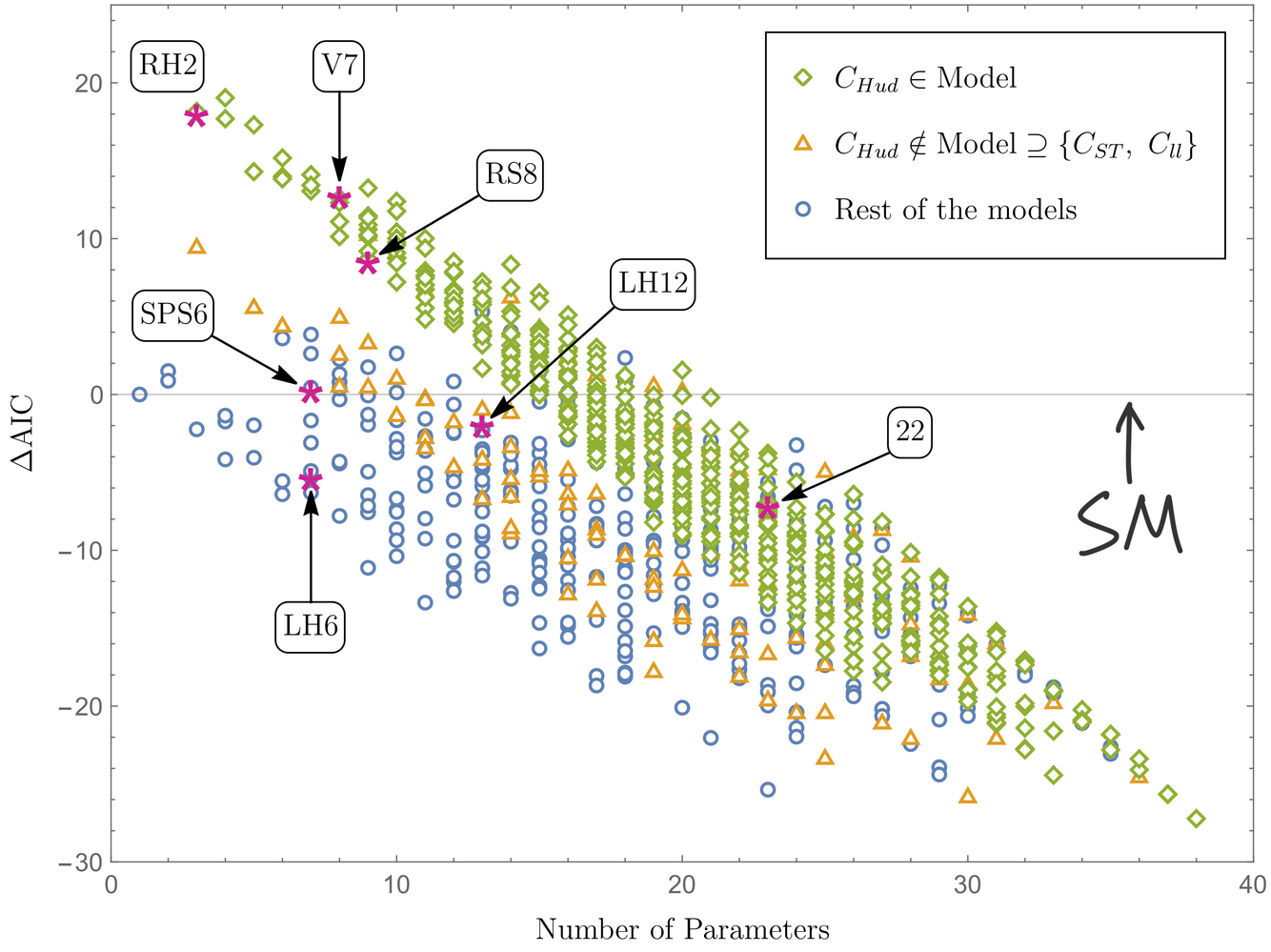
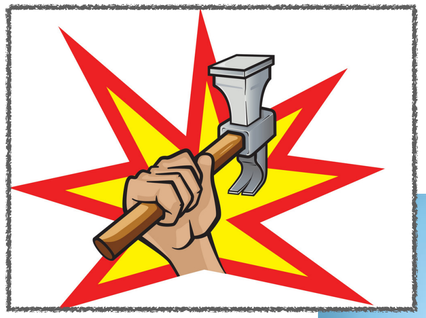


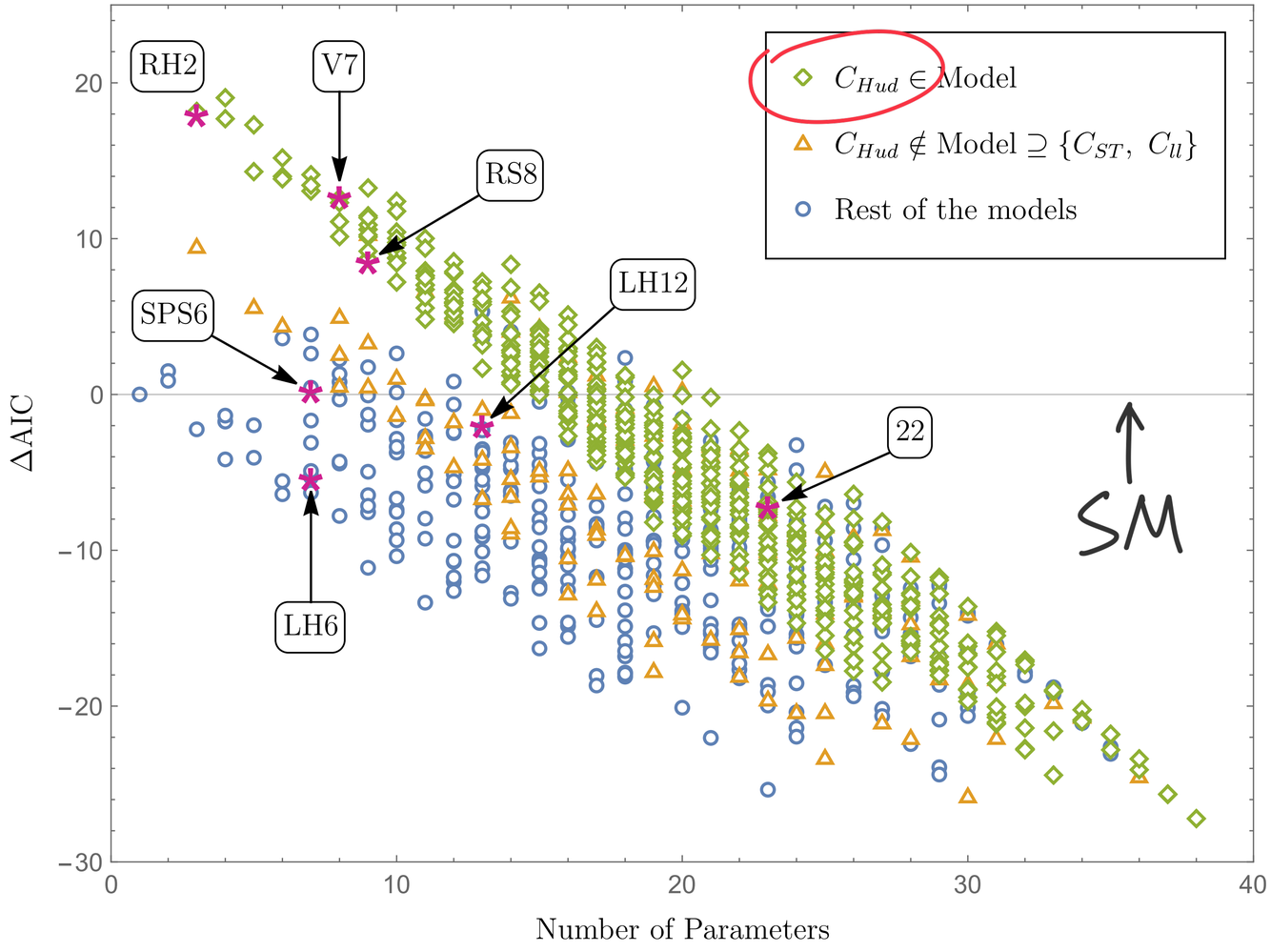
Higher the ΔAIC, better the model

AIC and one thousand fits

Akaike Information Criterion

$$\textbf{AIC} = \chi^2 + 2 \times (\textbf{number of Ops.})$$





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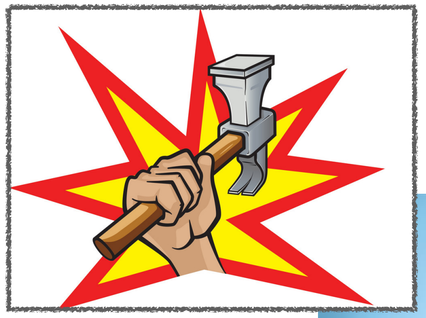
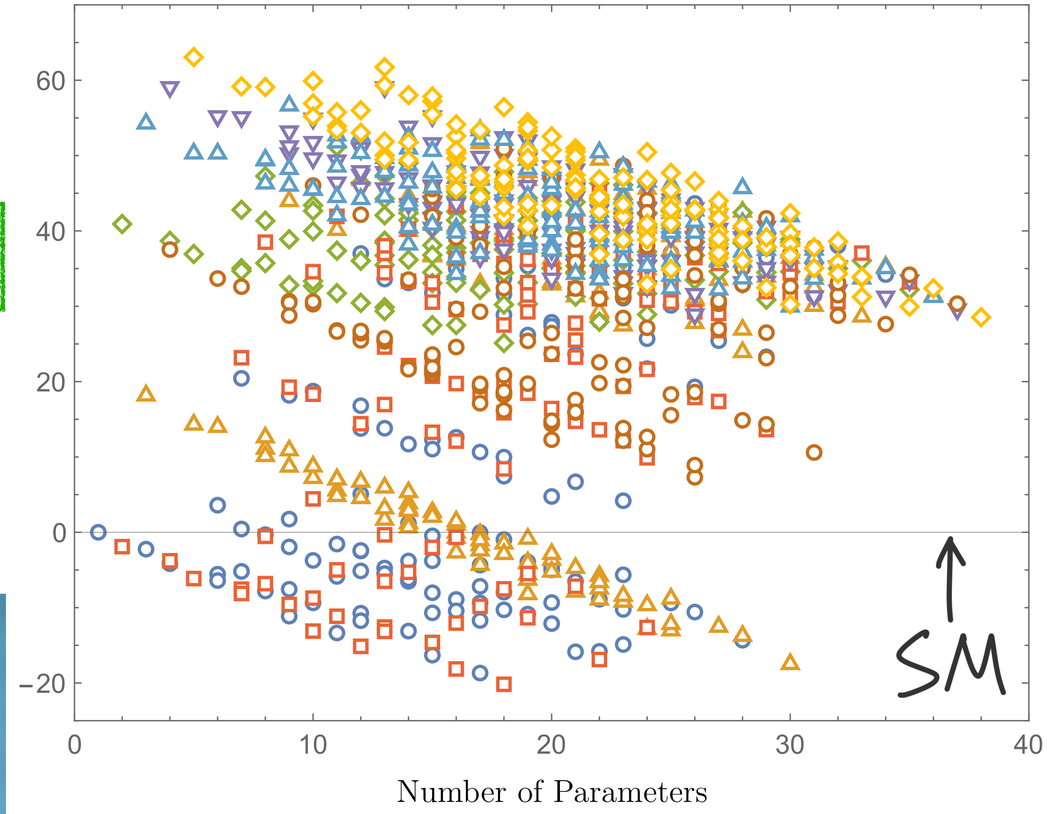




$\text{Model} \cap \{C_{Hud},\ C_{ST},\ C_{ll}\}$

$= \{C_{Hud},\ C_{ST},\ C_{ll}\}$

$\{C_{ST},\ C_{ll}\}$

$\{C_{Hud},\ C_{ll}\}$

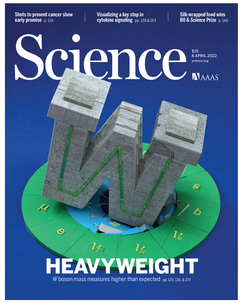
$\{C_{Hud},\ C_{ST}\}$

C_{ll}

C_{ST}

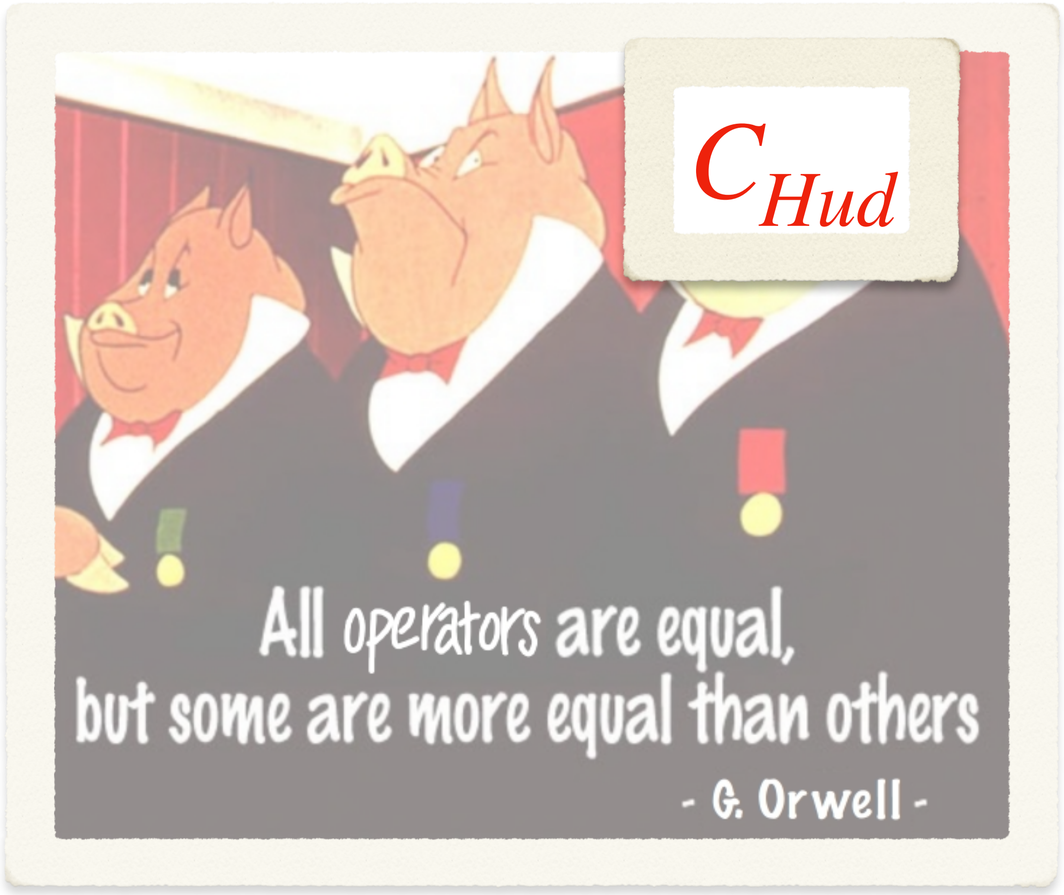
C_{Hud}

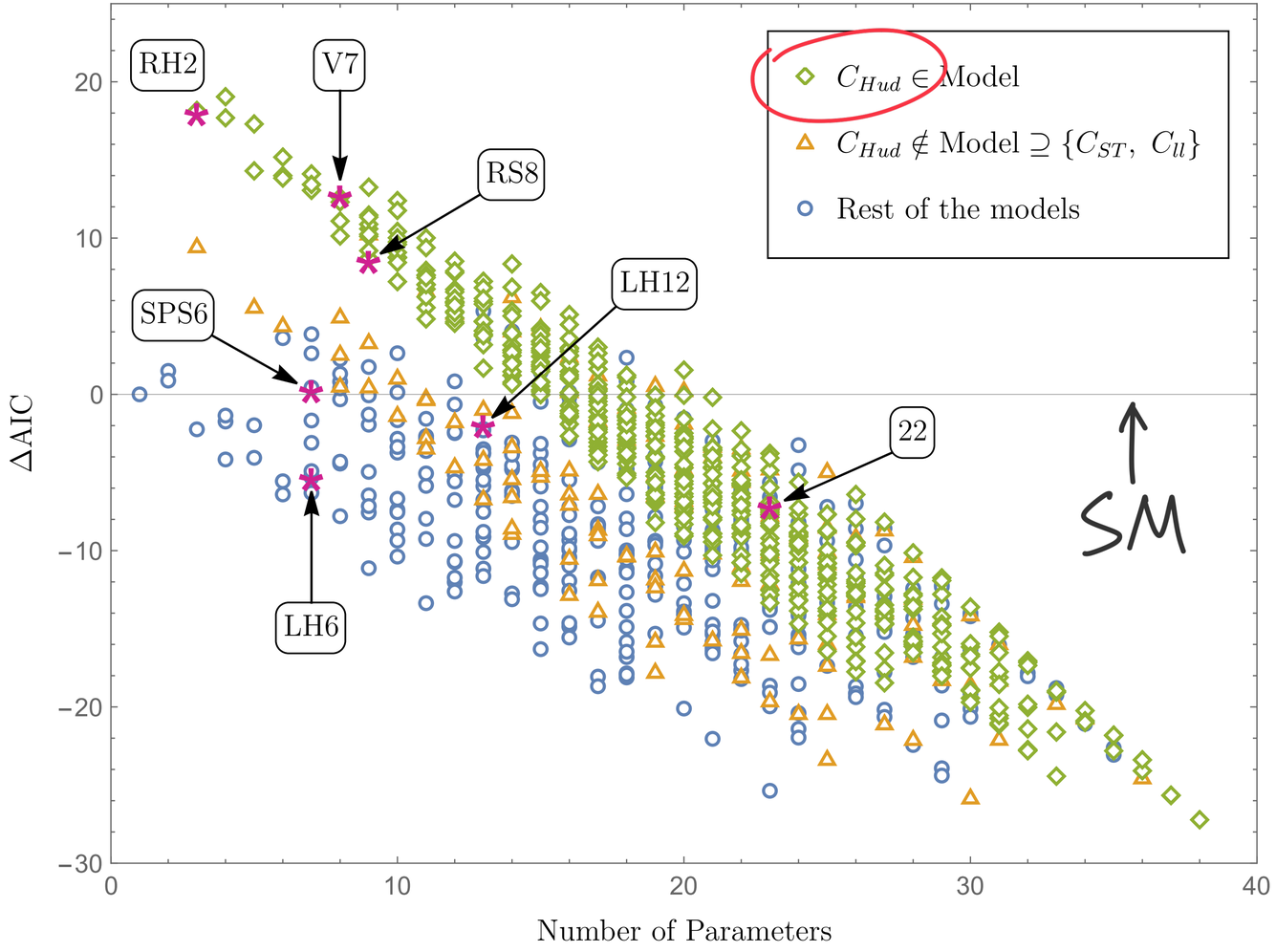
$\emptyset$



Higher the ΔAIC, better the model

Who is C_{Hud} ?





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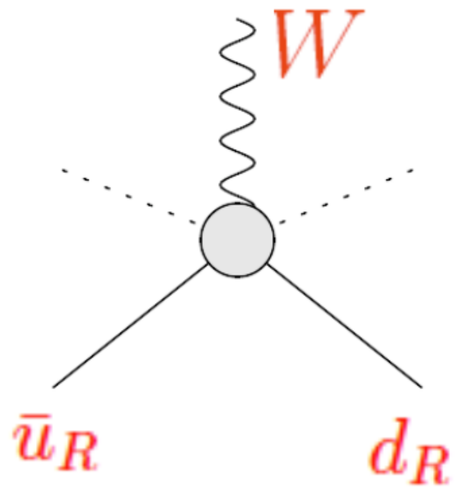
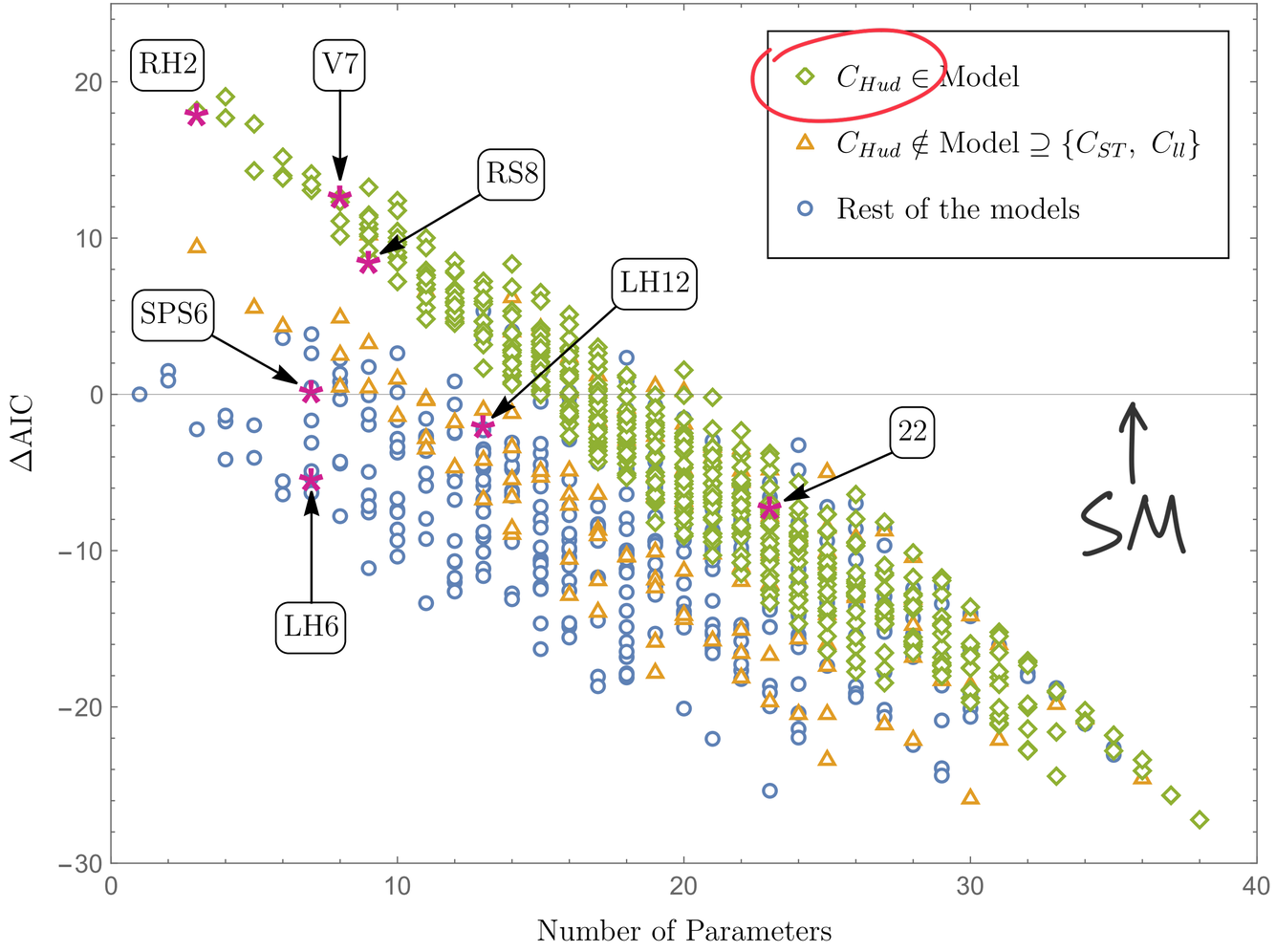
Who is C_{Hud} ?



C_{Hud}

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



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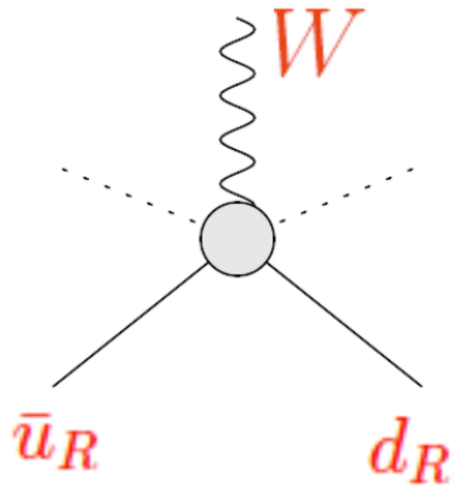
Who is C_{Hud} ?



C_{Hud}

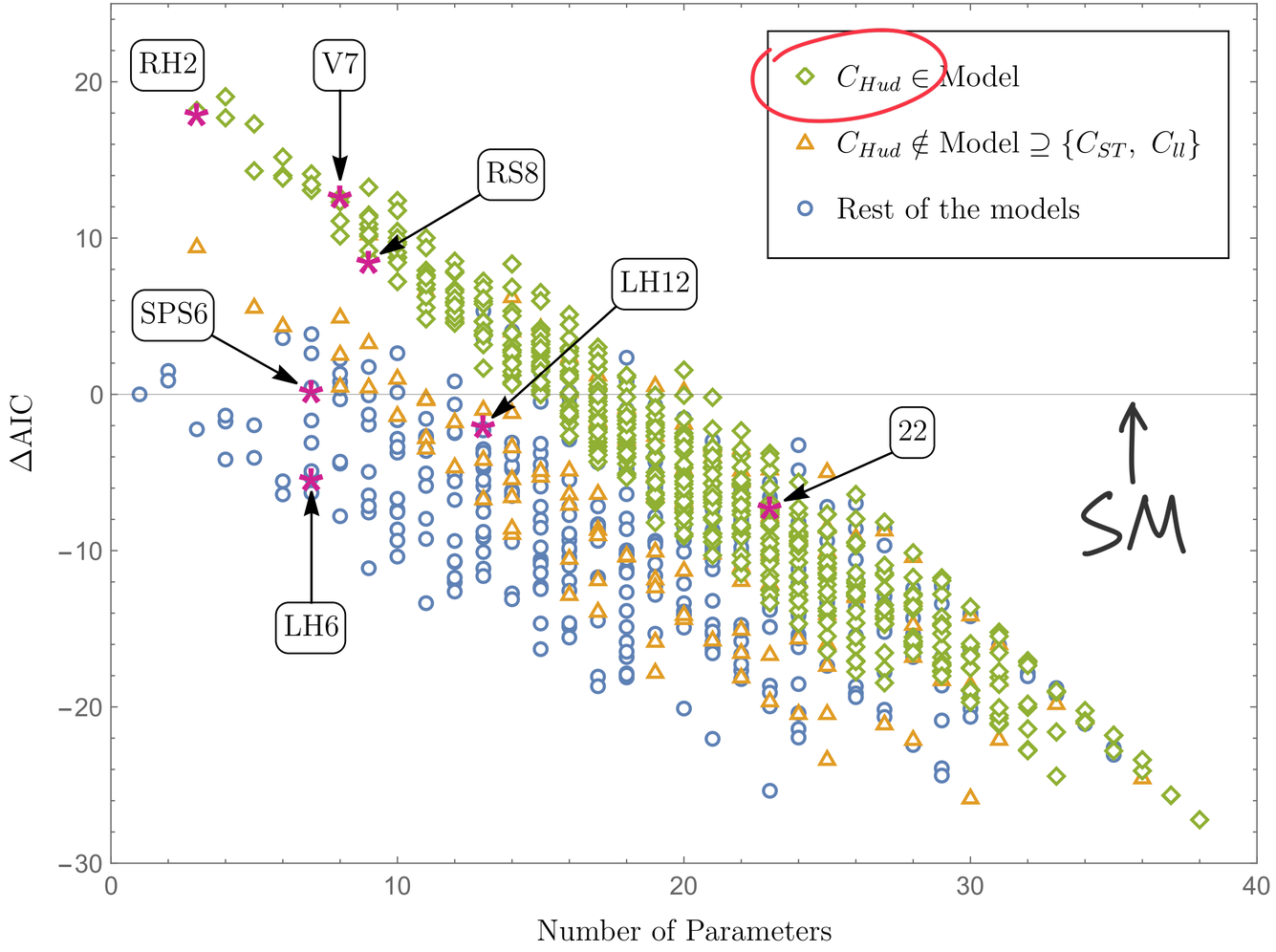
$$Q_{Hud} = i(\widetilde{H}^\dagger D_\mu H)(\bar{u}_p \gamma^\mu d_r)$$

- Left-Right Symmetric Models

  2107.10852

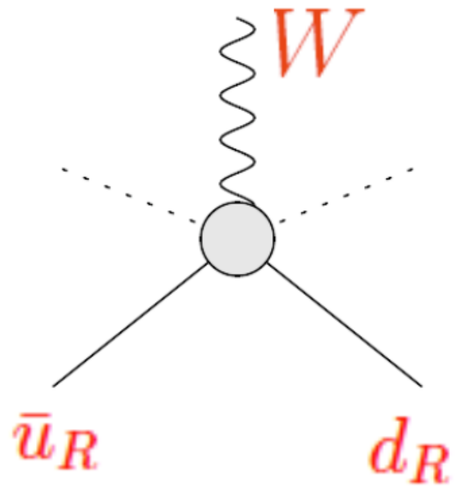
- Vector-Like Quarks ~ $\mathcal{O}$(TeV)

  2212.06862, 2302.14097



Higher the ΔAIC, better the model

C_{Hud} solves Cabibbo



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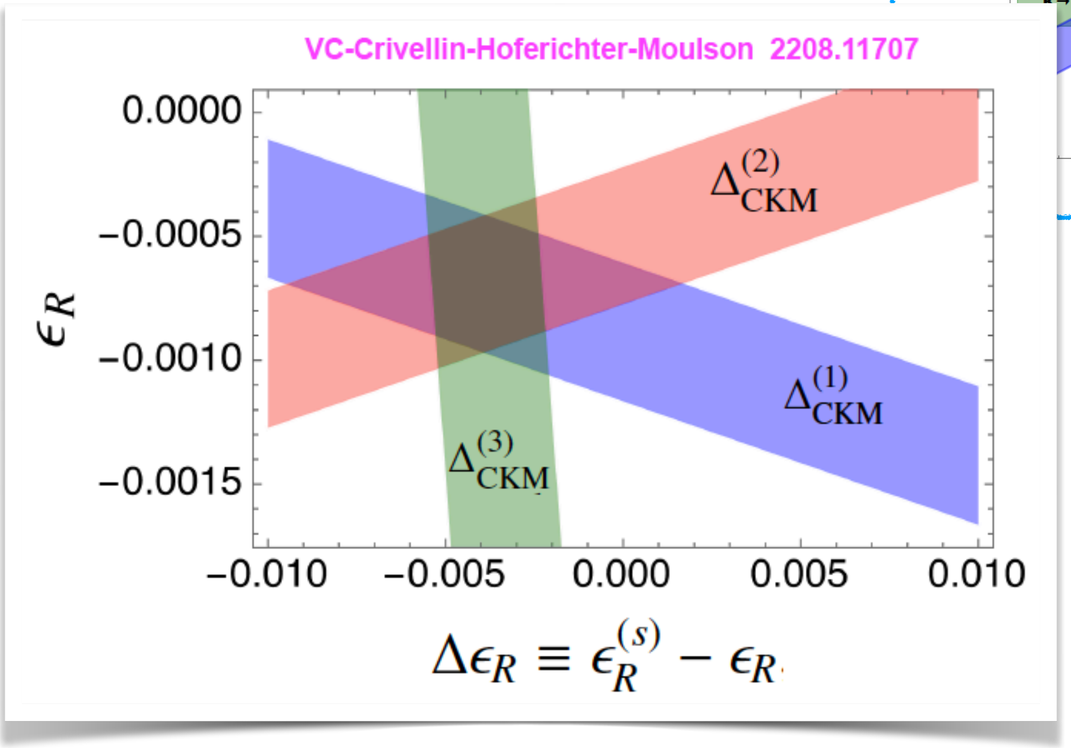
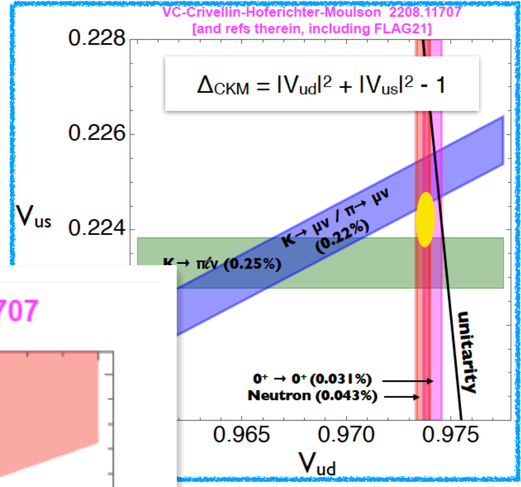
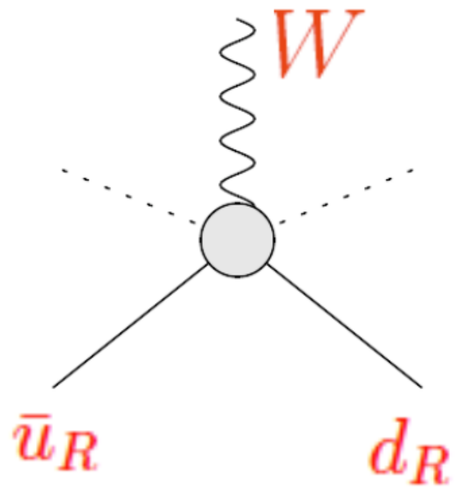




Falsifying C_{Hud}



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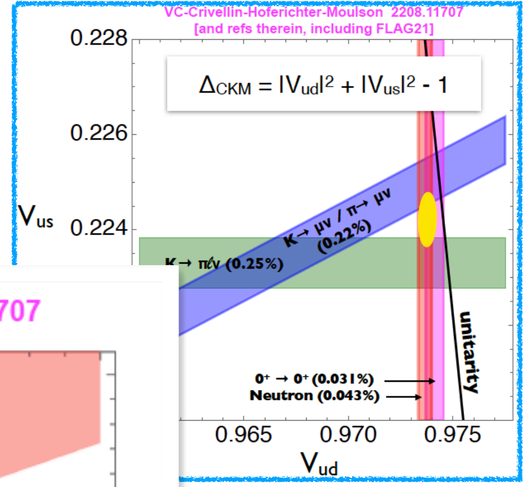
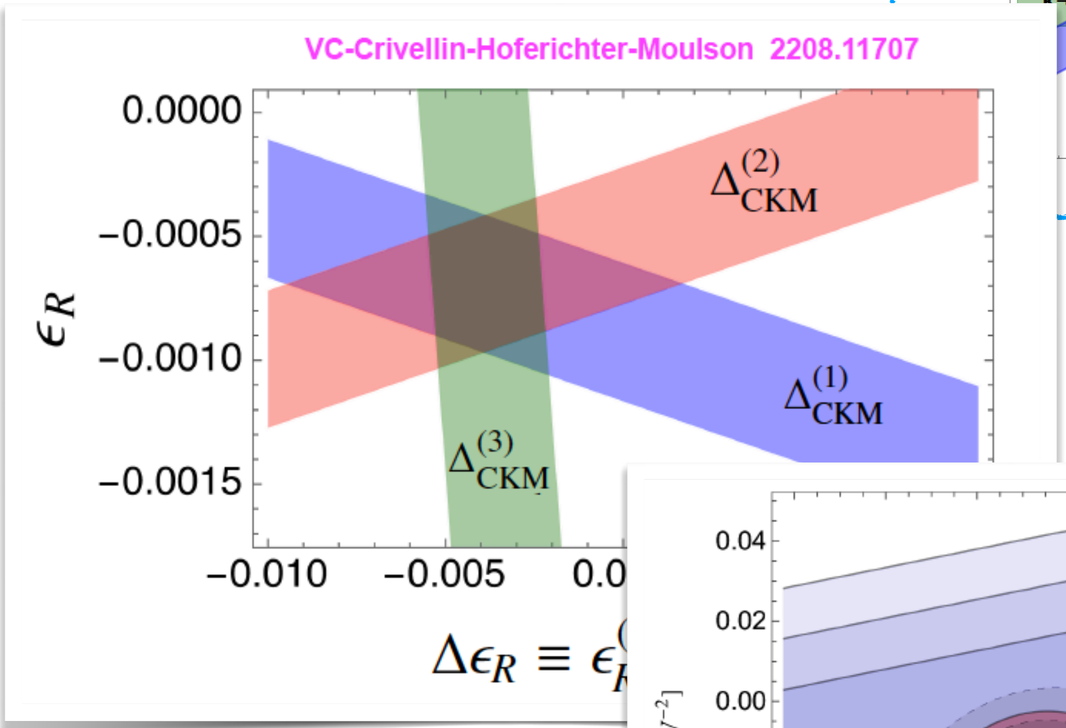
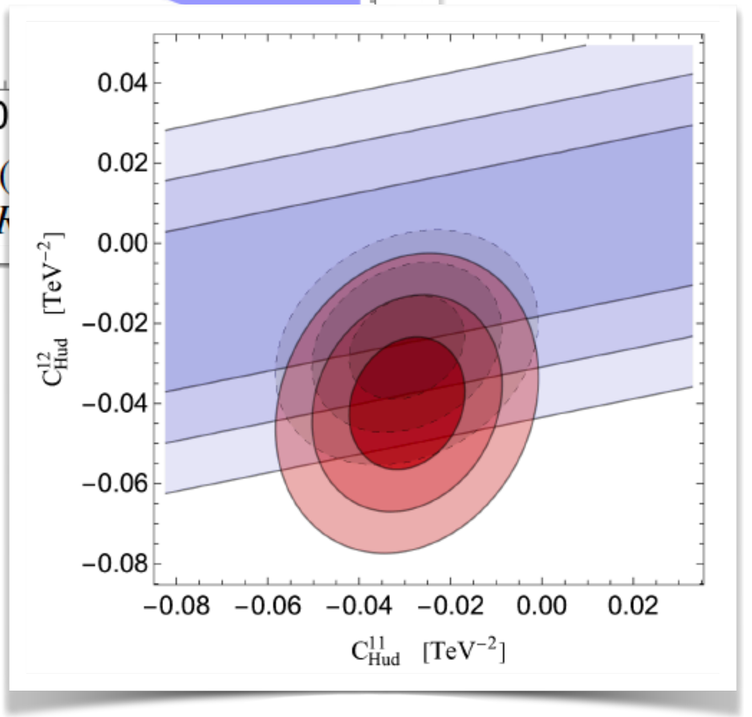
$K \to \pi\pi$







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
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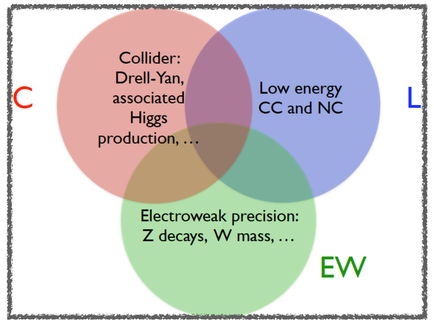
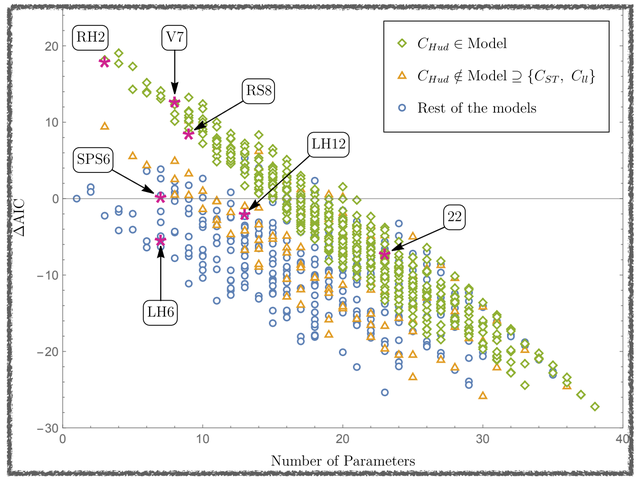
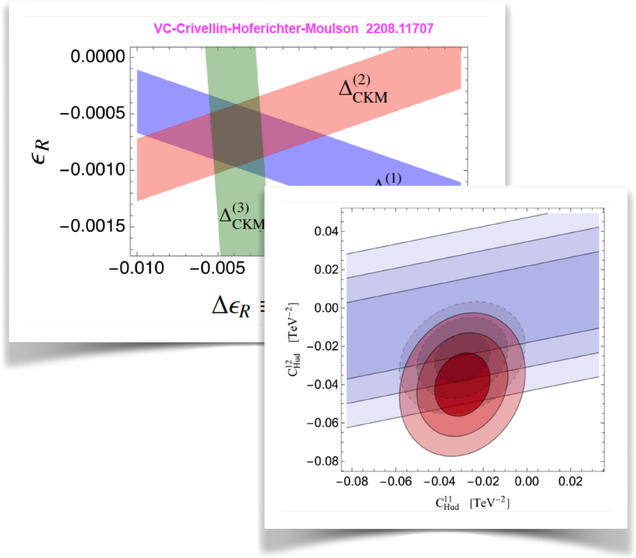
C_{Hud}







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**

'klü

1 : a ball of thread, yarn, or cord