Fitting SMEFT with a CLEW

Towards a true model-independent global analysis

Dedicated to 2023 DESY. ***Theory Workshop***

UNIVERSITÄT SIEGEN

Center for Particle Physics Siegen

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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Flavor assumptions

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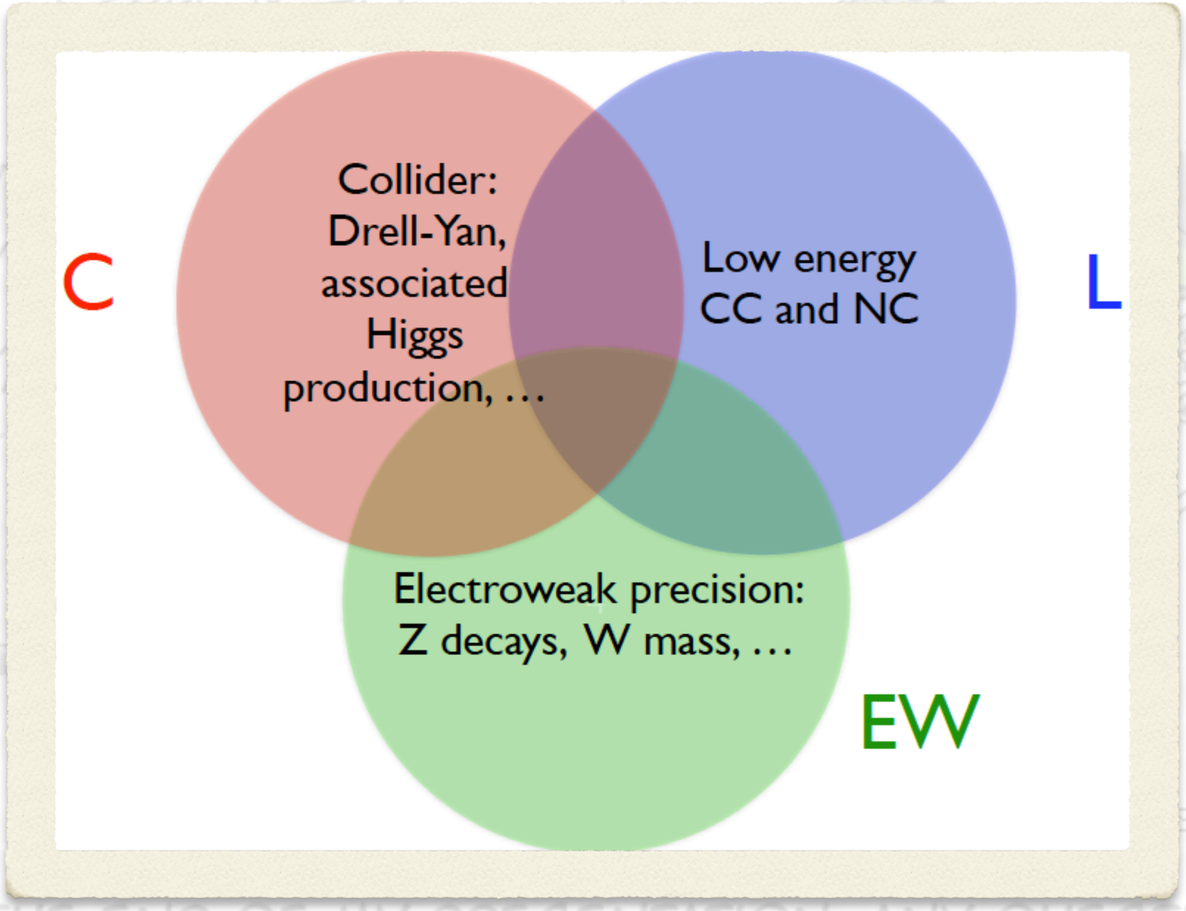

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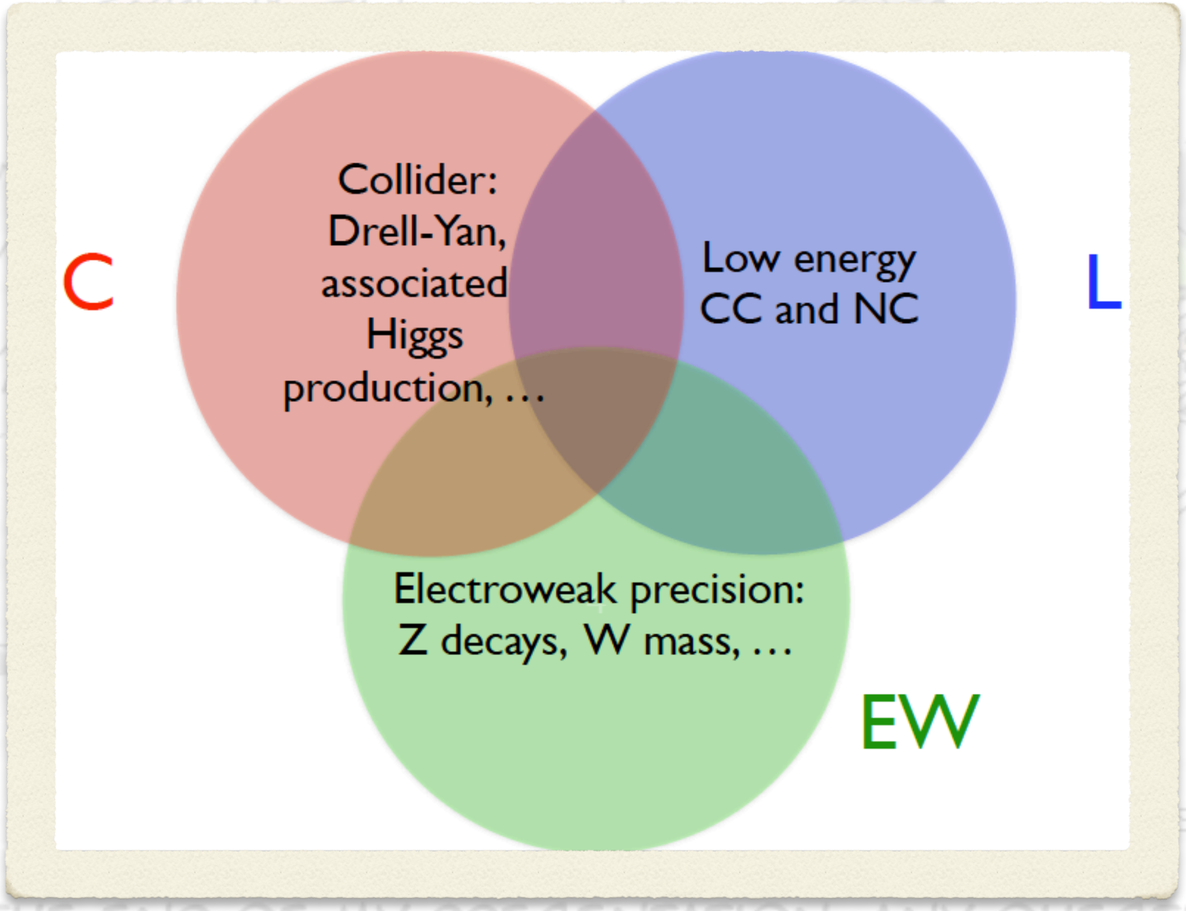

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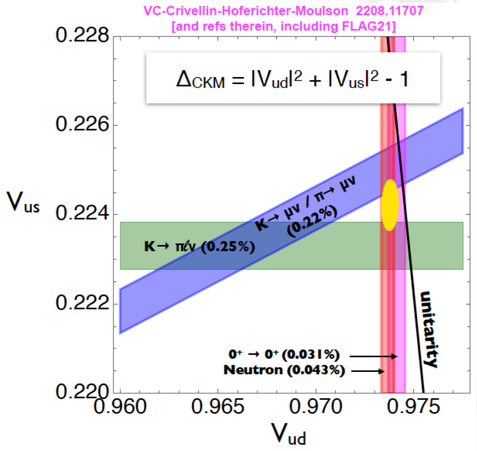

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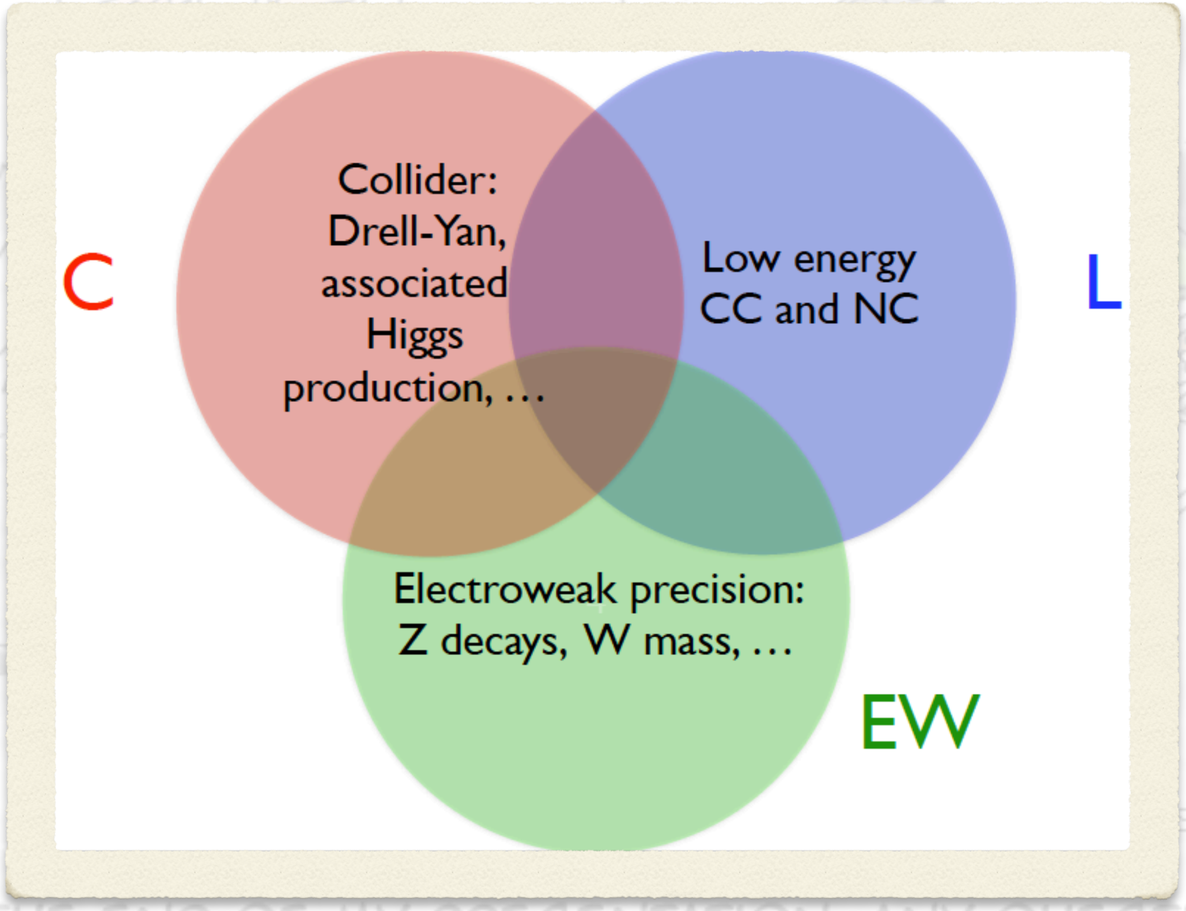

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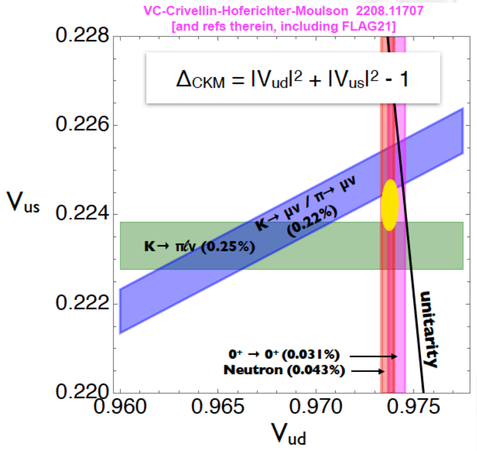

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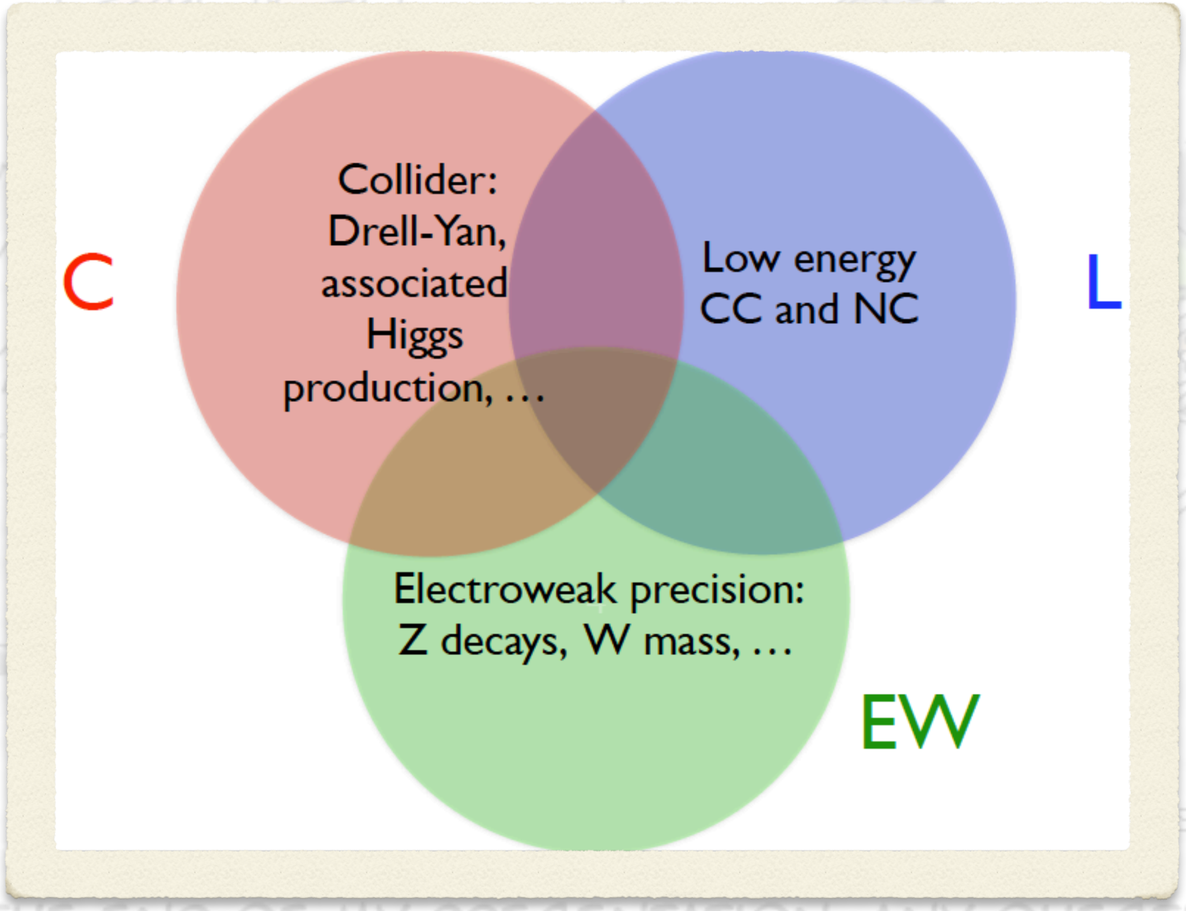

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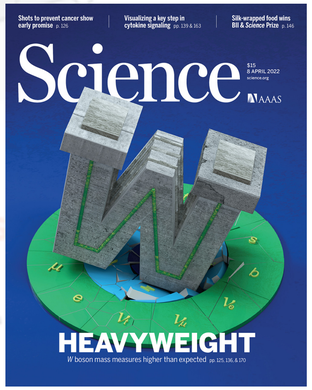
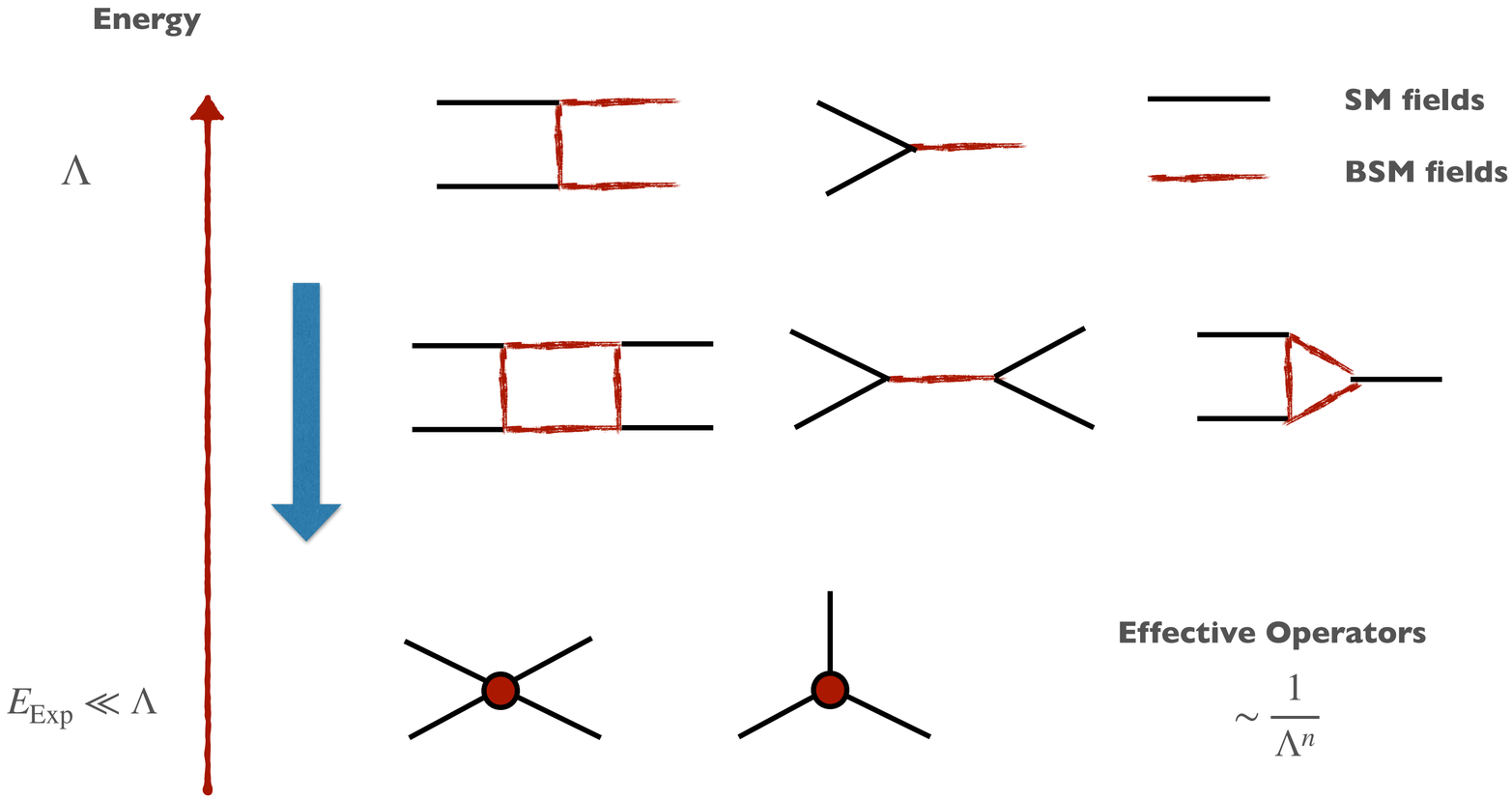


Flavor-symmetry-independent analysis

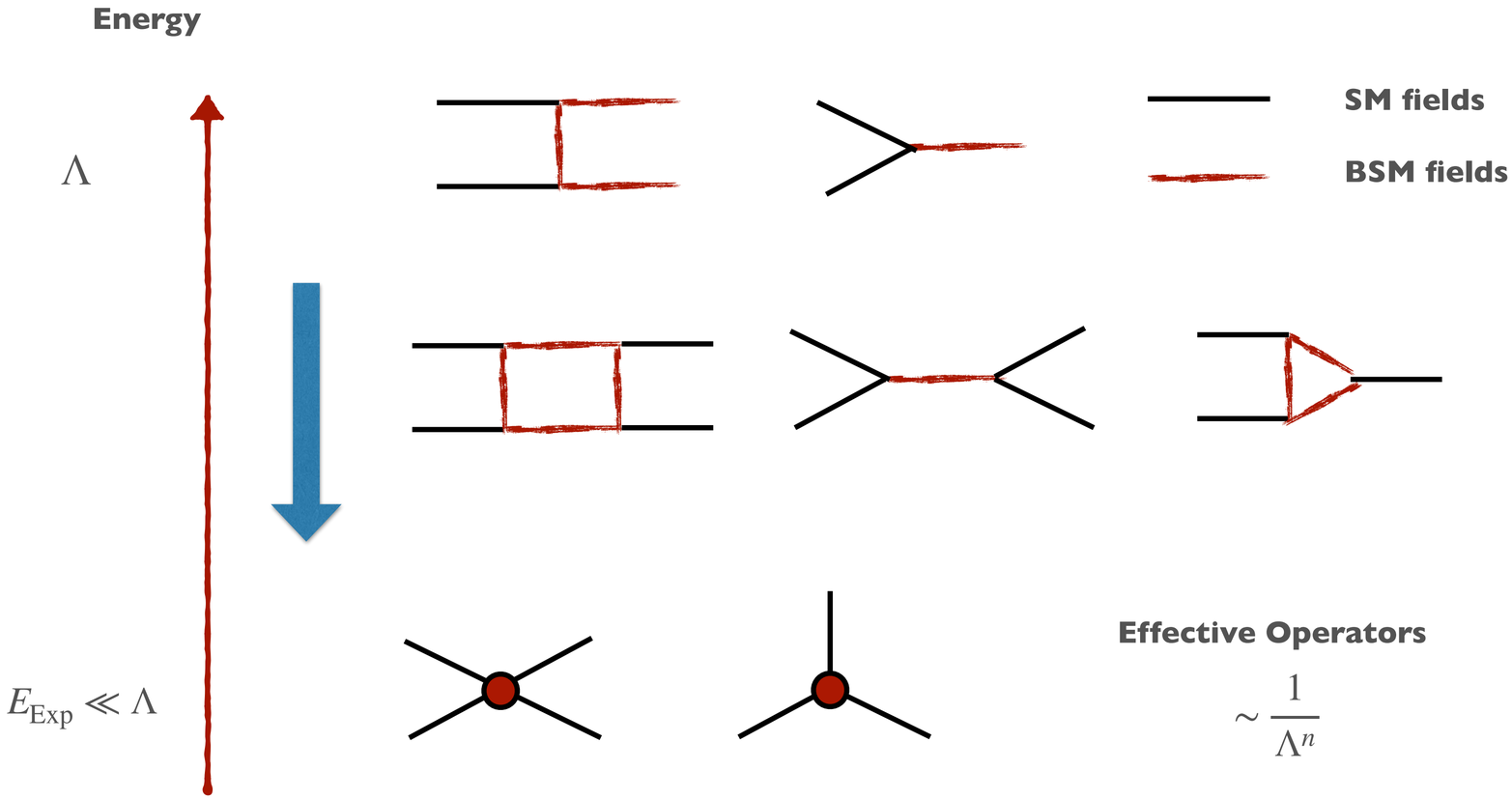
SMEFT in a nutshell



SMEFT in a nutshell

2499

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



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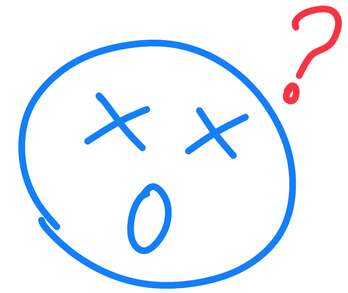

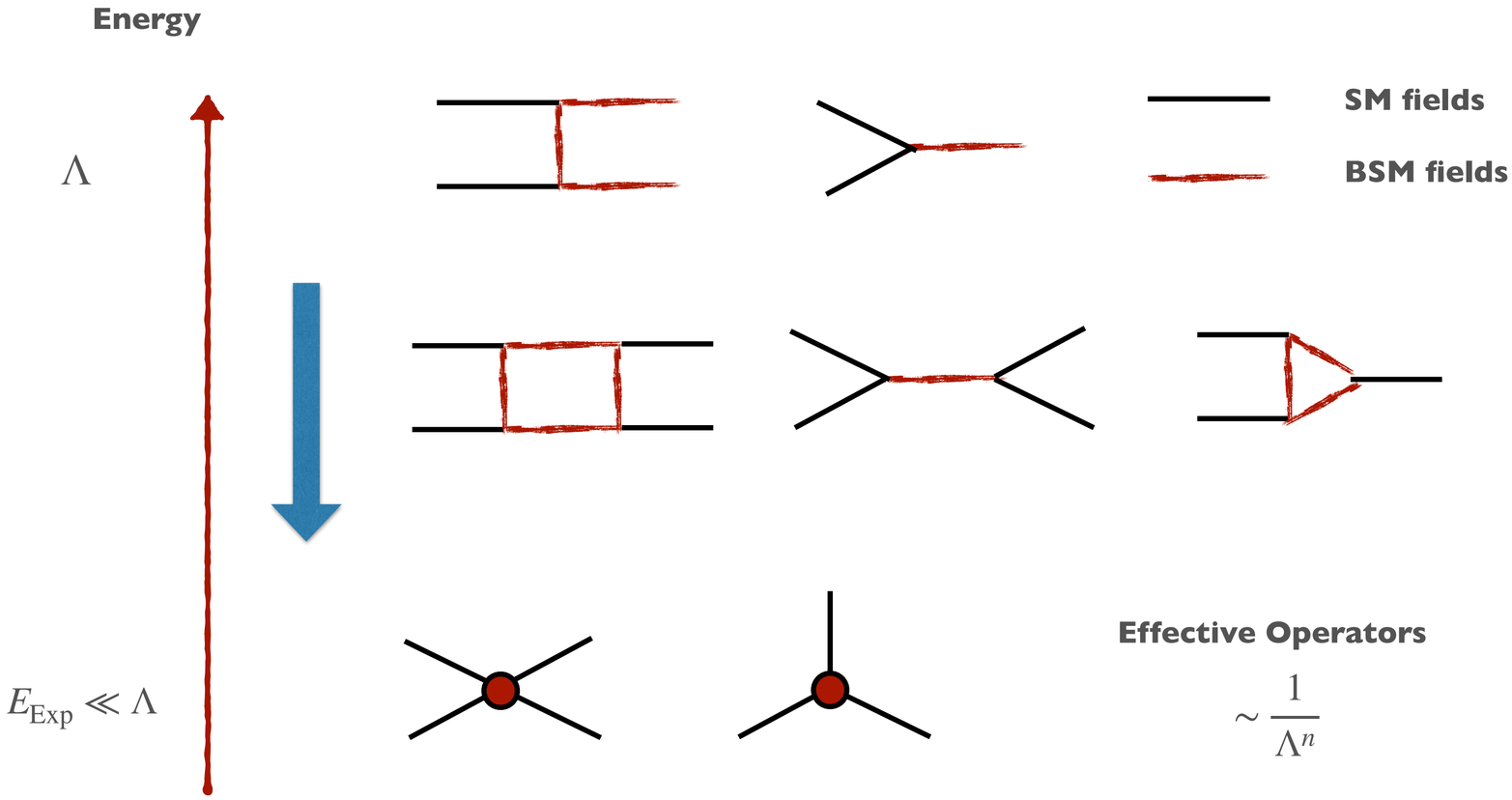

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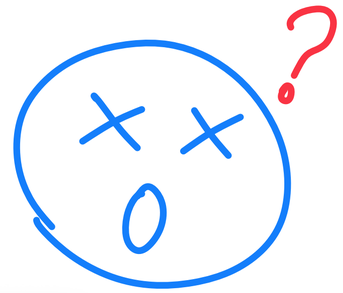

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with all the observables! Yeah~!

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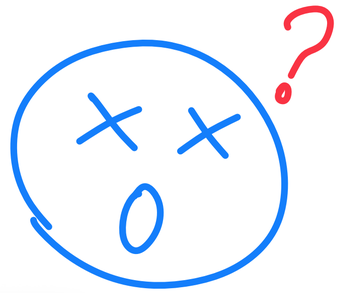

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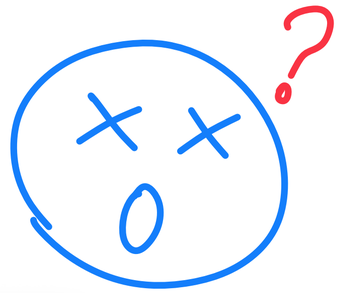

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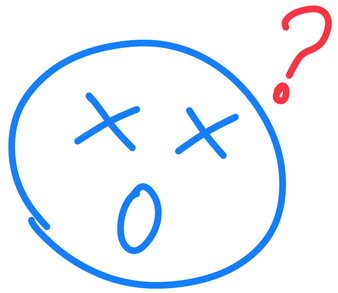

Simplify !

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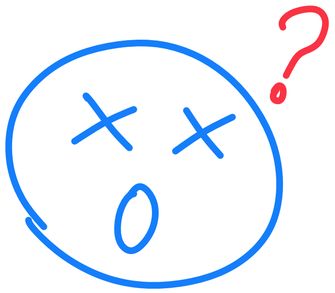

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Make flavor-symmetry assumptions

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

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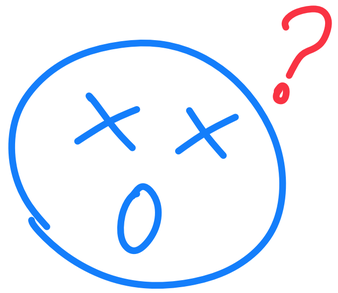

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EWPO + Higgs + top + some flavor...

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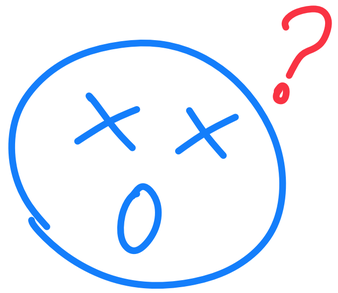

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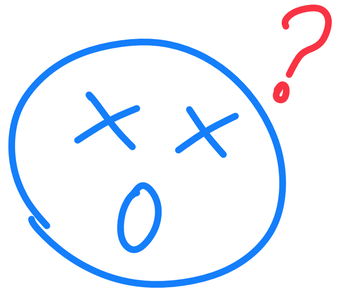

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Casefile: $U(3)^5$ + EWPO

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

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
$\hat{C}_{Hu}$	-0.02 ± 0.12
$\hat{C}_{Hd}$	-0.54 ± 0.25
C_Δ	-0.11 ± 0.069

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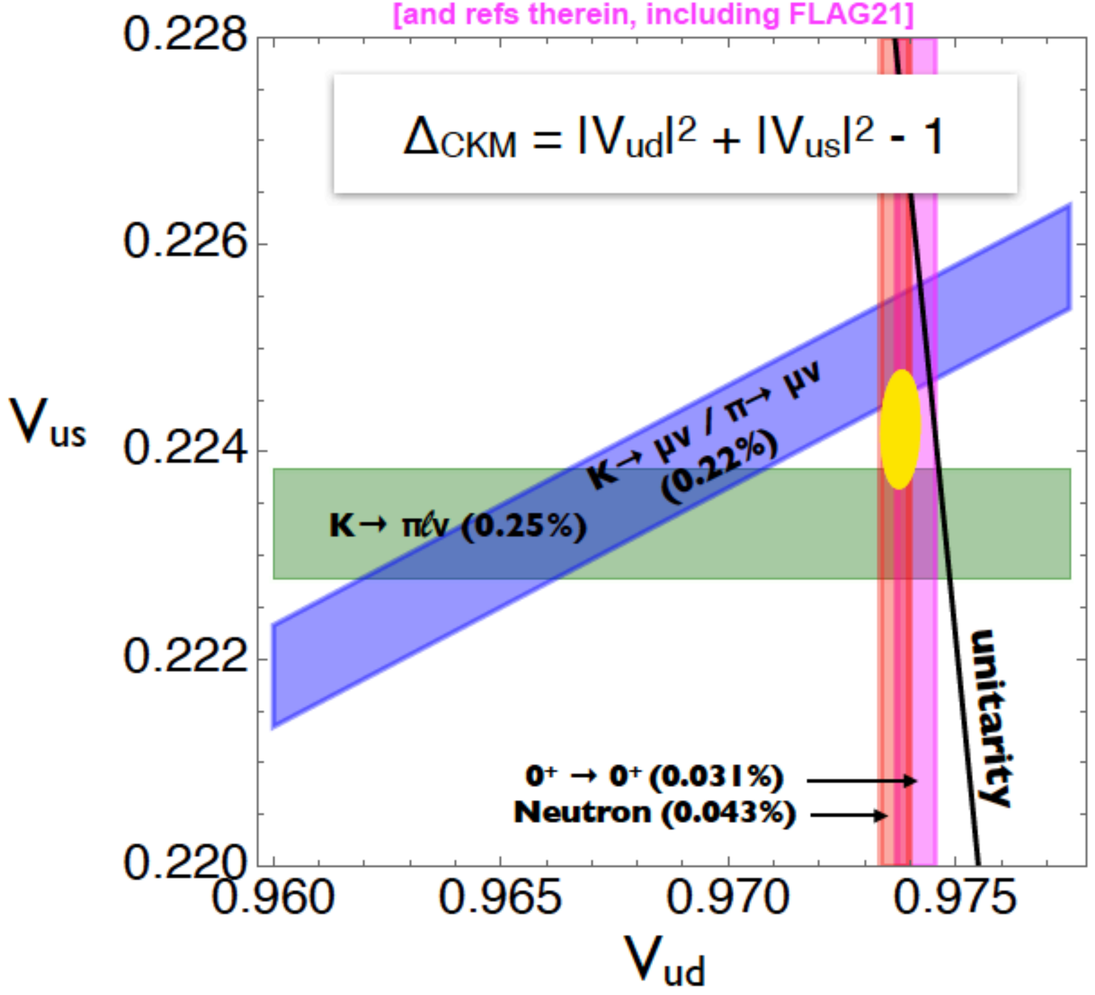
VC-Crivellin-Hoferichter-Moulson 2208.11707
[and refs therein, including FLAG21]



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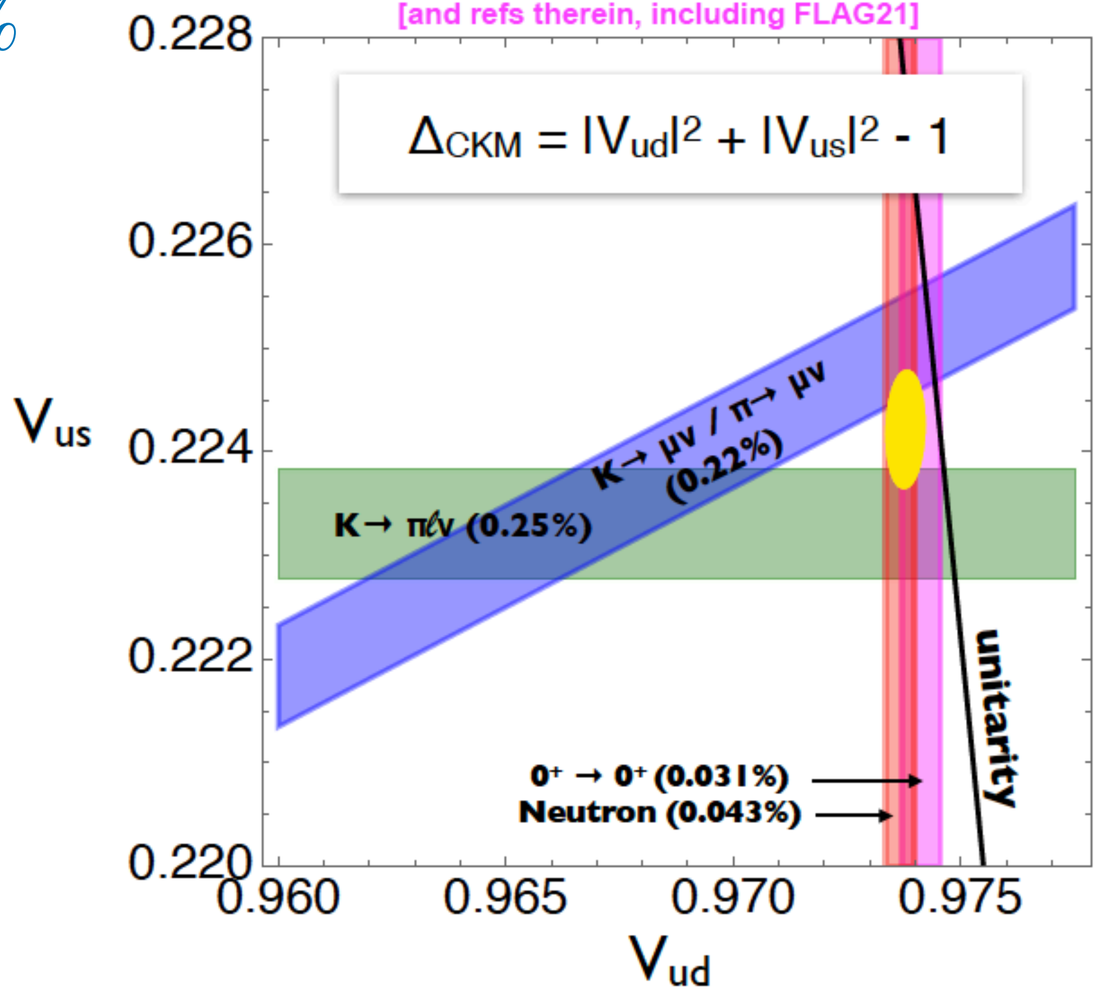

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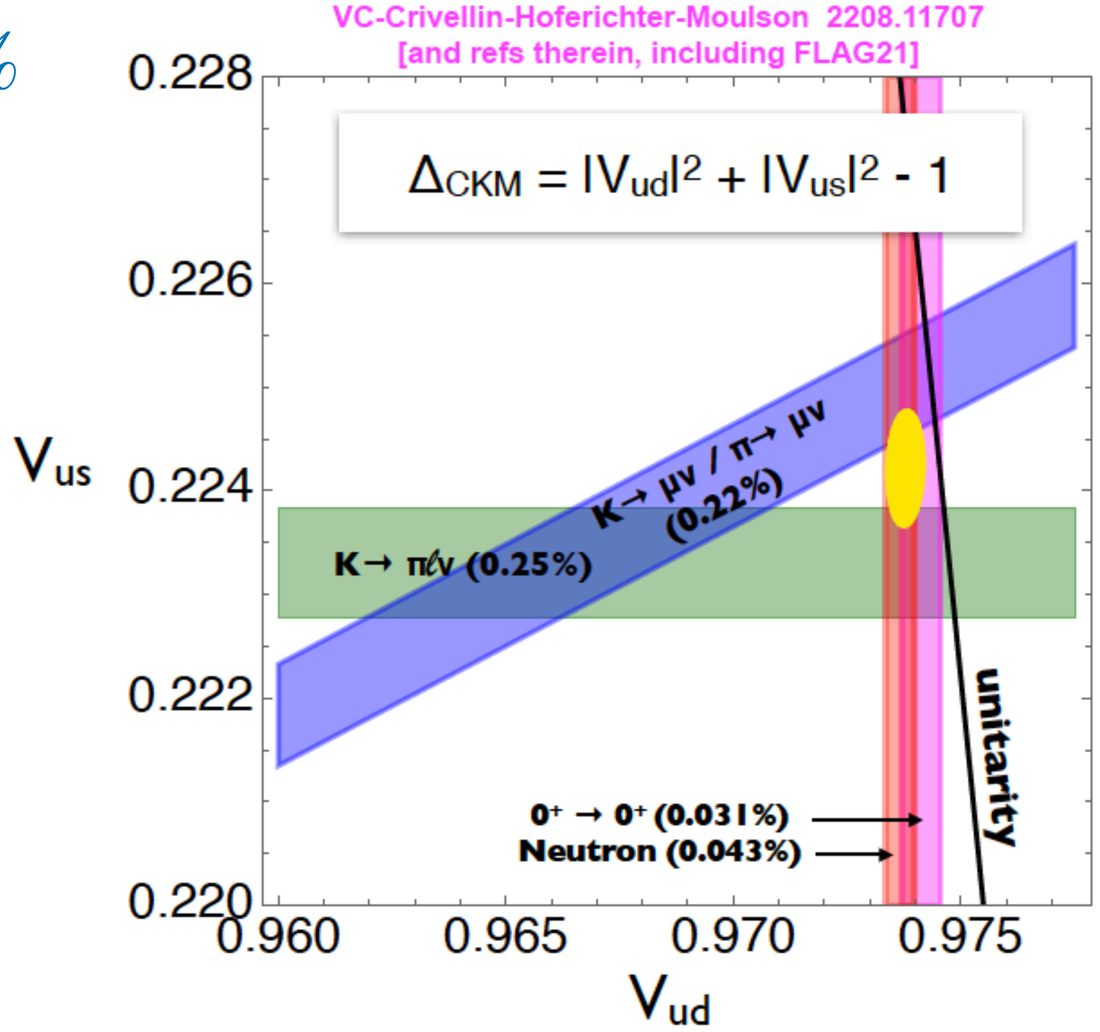

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~2σ at percent level

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

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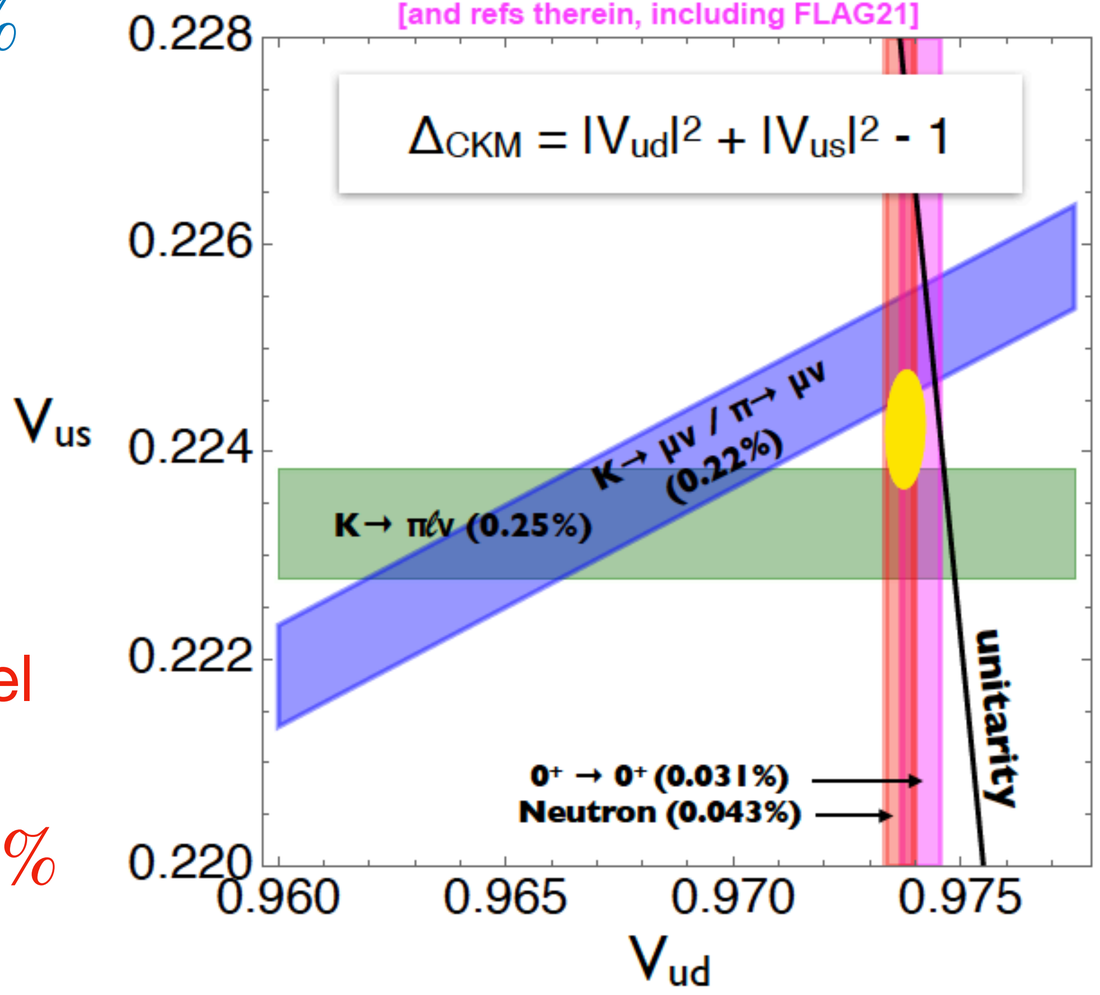

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Our paper 2204.08440

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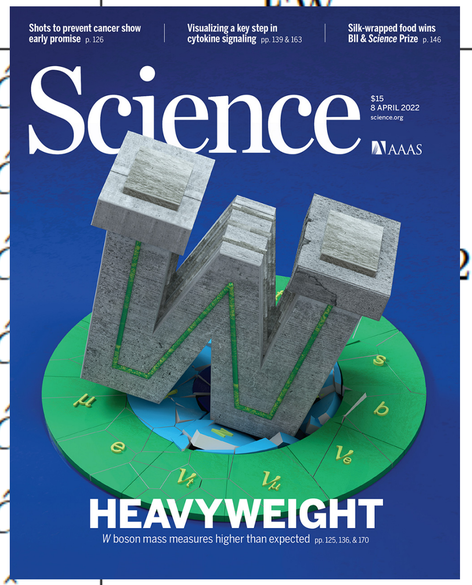

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~3σ at permil level

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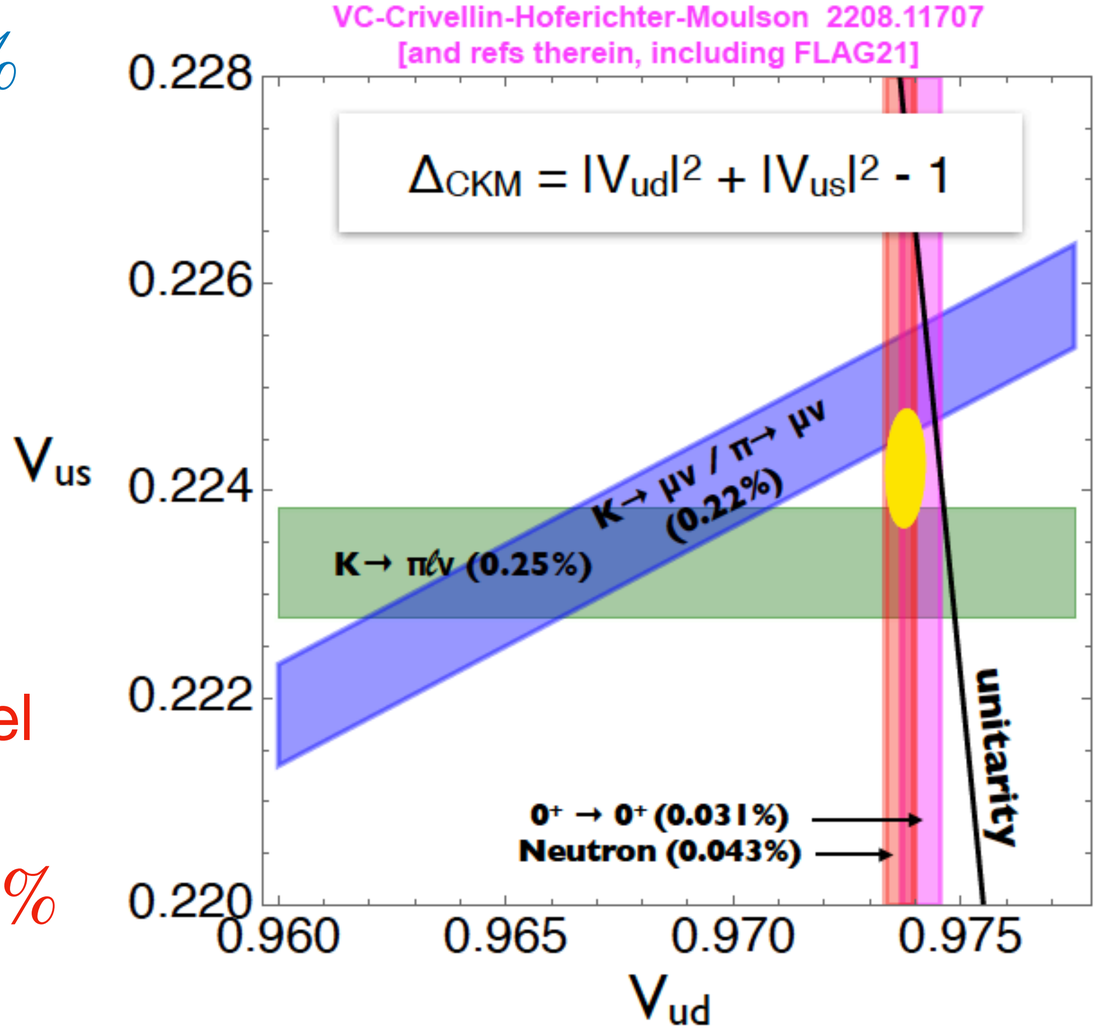
$$2v^2\left[C^{(3)}_{Hq} - C^{(3)}_{Hl} + C_{ll} - C^{(3)}_{lq}\right] = \Delta^{fit}_{CKM} \approx -0.91\,\%$$



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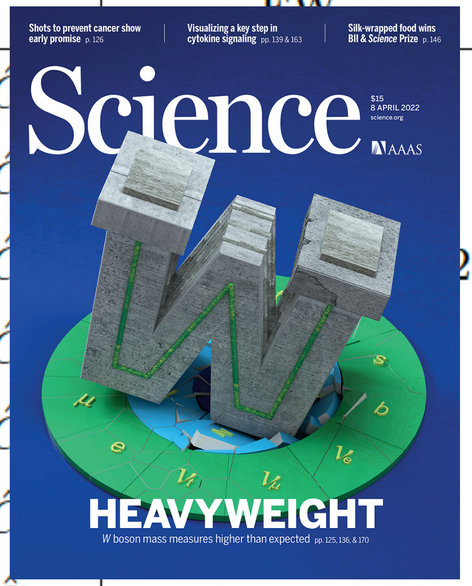

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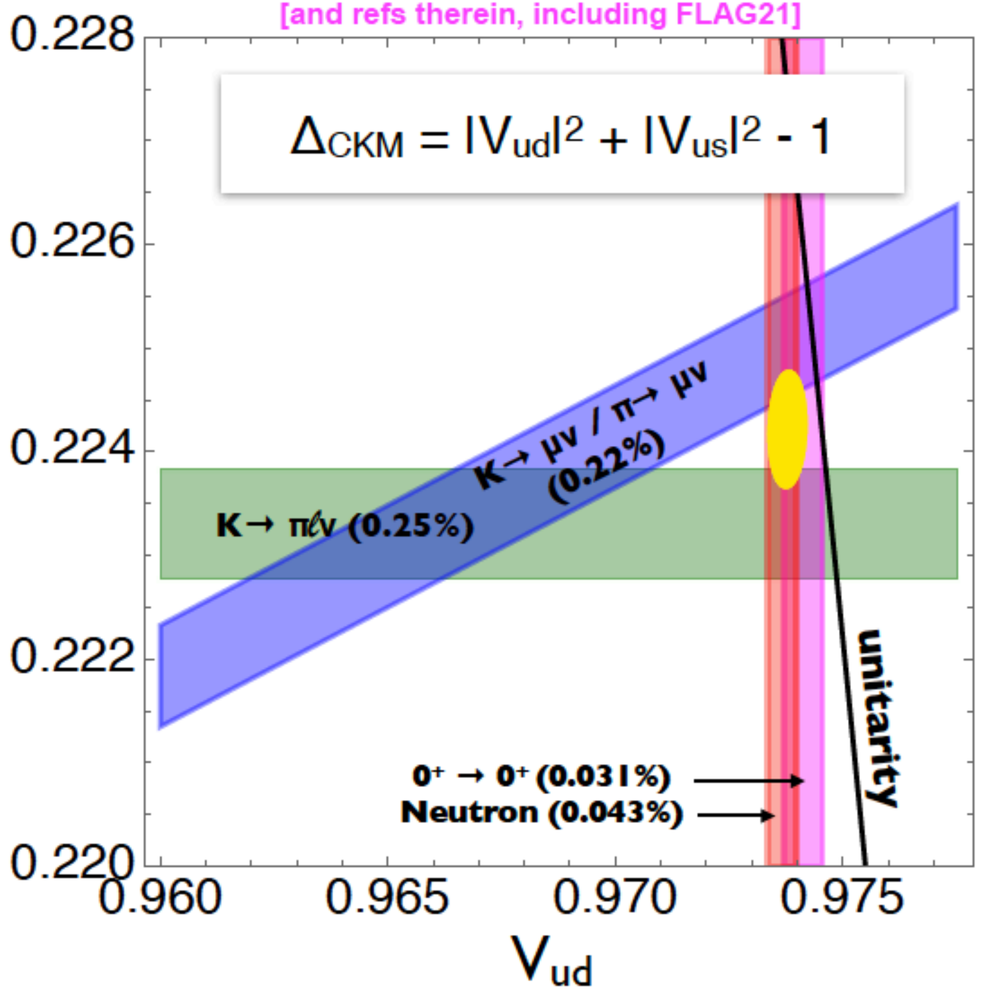

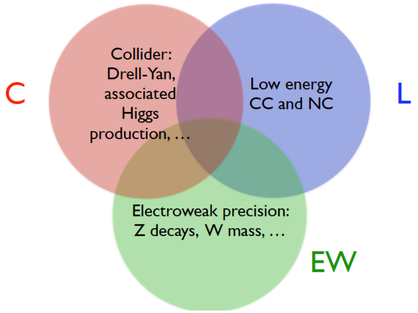

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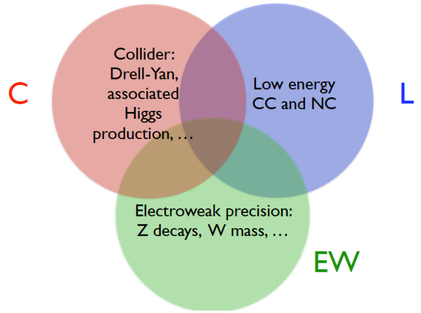

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EW

	EW
$\hat{C}_{Hl}^{(1)}$	-0.0091 ± 0.011
$\hat{C}_{Hl}^{(3)}$	-0.057 ± 0.015
$\hat{C}_{He}$	-0.024 ± 0.0086
$\hat{C}_{Hq}^{(1)}$	-0.029 ± 0.043
$\hat{C}_{Hq}^{(3)}$	-0.095 ± 0.032
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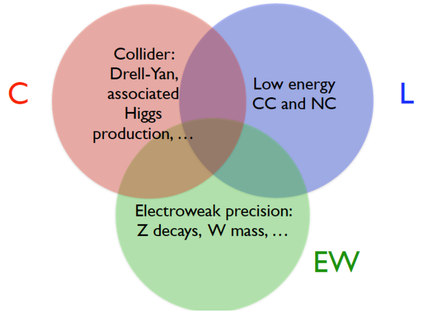

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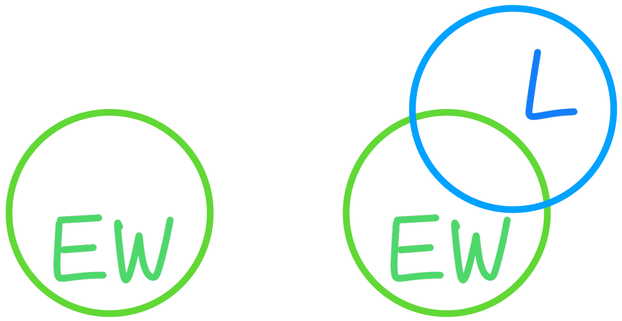
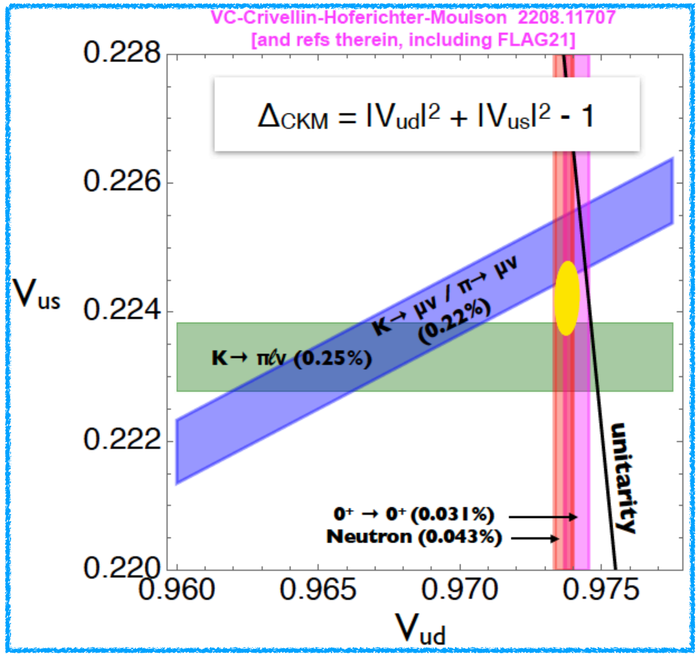
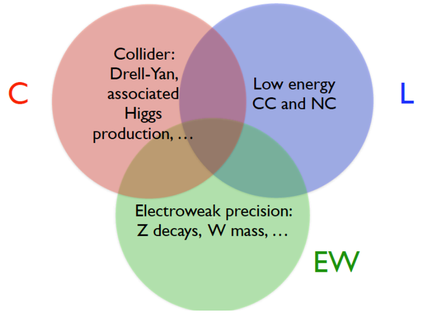


	EW	LEW_1
$\hat{C}_{Hl}^{(1)}$	-0.0091 ± 0.011	-0.016 ± 0.011
$\hat{C}_{Hl}^{(3)}$	-0.057 ± 0.015	-0.046 ± 0.014
$\hat{C}_{He}$	-0.024 ± 0.0086	-0.027 ± 0.0085
$\hat{C}_{Hq}^{(1)}$	-0.029 ± 0.043	-0.045 ± 0.042
$\hat{C}_{Hq}^{(3)}$	-0.095 ± 0.032	-0.041 ± 0.014
$\hat{C}_{Hu}$	-0.0046 ± 0.12	-0.12 ± 0.098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





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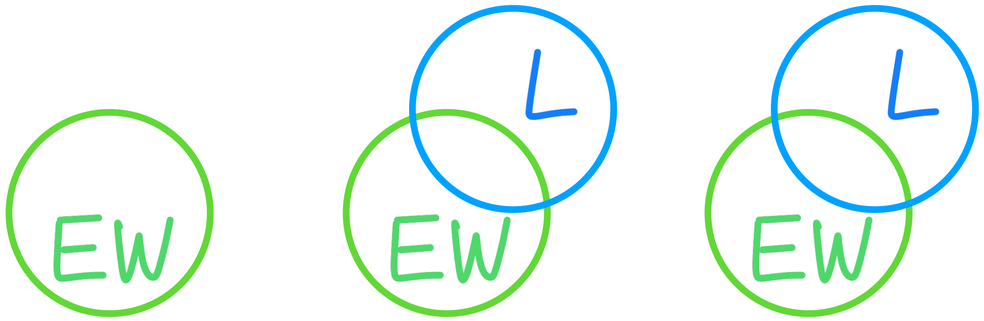
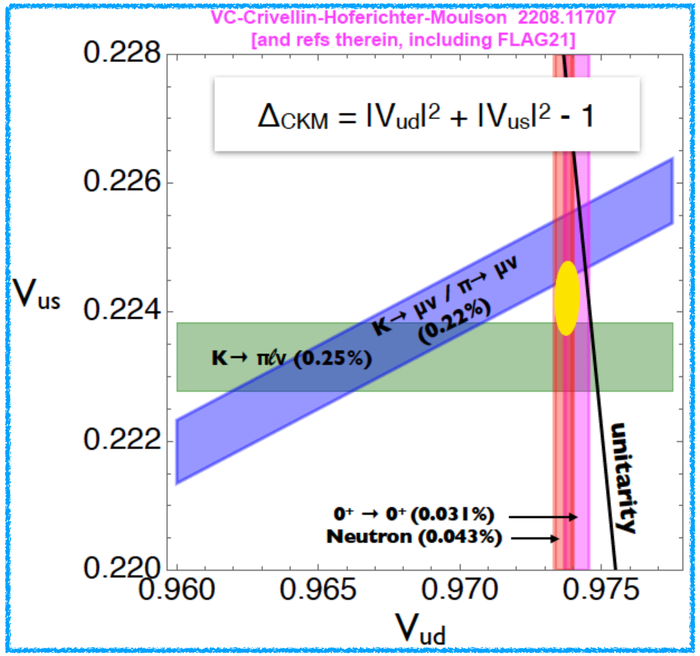
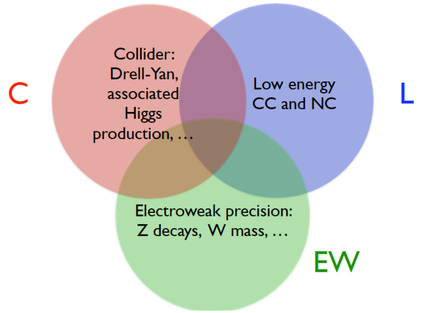
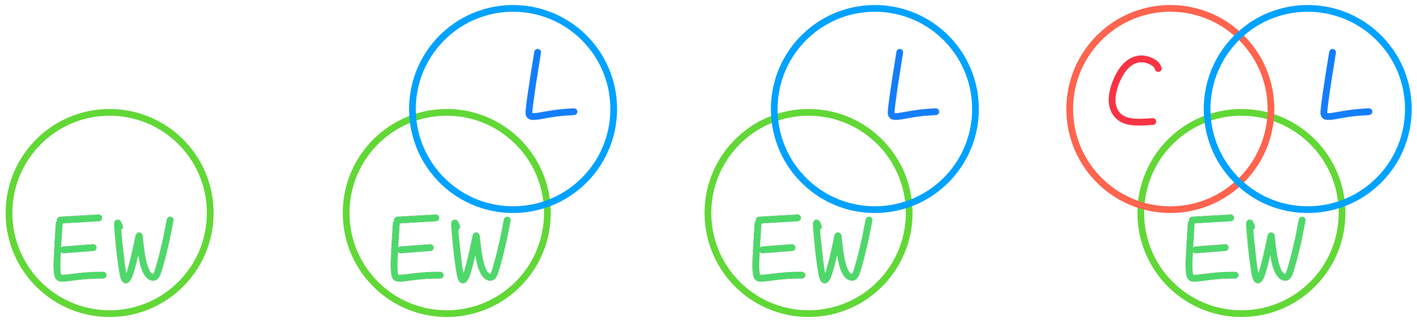


	EW	LEW_1	LEW_2
$\hat{C}_{Hl}^{(1)}$	-0.0091 ± 0.011	-0.016 ± 0.011	-0.0091 ± 0.011
$\hat{C}_{Hl}^{(3)}$	-0.057 ± 0.015	-0.046 ± 0.014	-0.057 ± 0.015
$\hat{C}_{He}$	-0.024 ± 0.0086	-0.027 ± 0.0085	-0.024 ± 0.0086
$\hat{C}_{Hq}^{(1)}$	-0.029 ± 0.043	-0.045 ± 0.042	-0.029 ± 0.043
$\hat{C}_{Hq}^{(3)}$	-0.095 ± 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

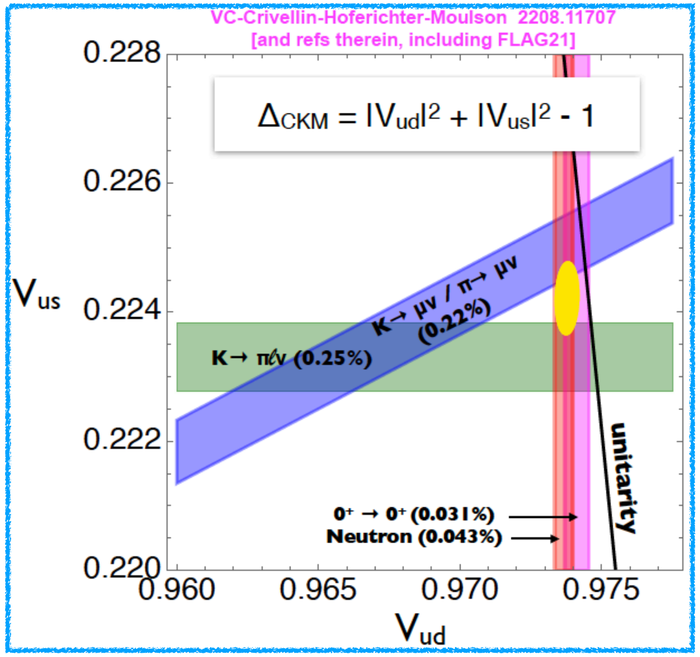




Casefile: $U(3)^5$ + CLEW



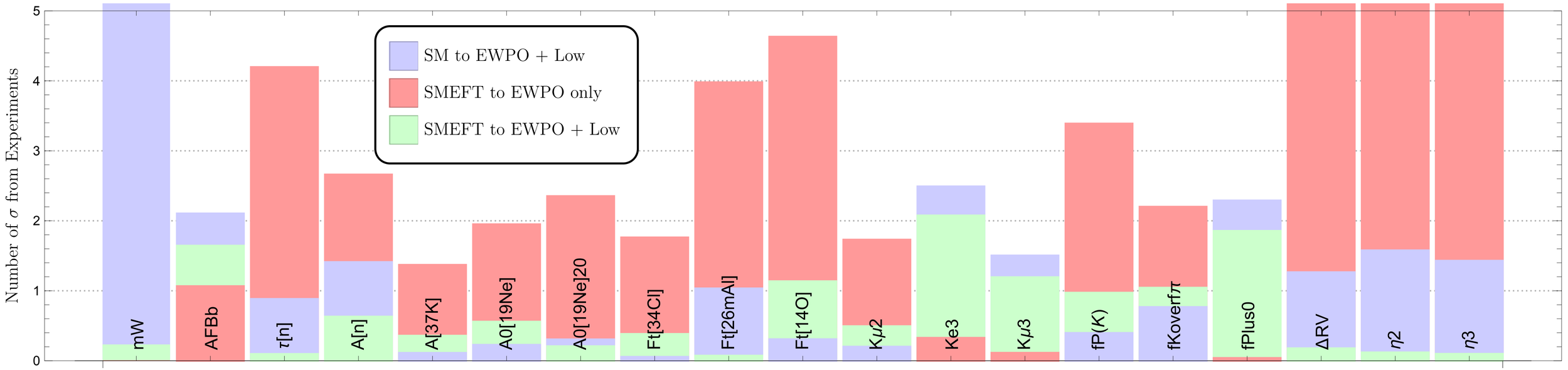
	EW	LEW_1	LEW_2	CLEW
$\hat{C}_{Hl}^{(1)}$	-0.0091 ± 0.011	-0.016 ± 0.011	-0.0091 ± 0.011	-0.016 ± 0.011
$\hat{C}_{Hl}^{(3)}$	-0.057 ± 0.015	-0.046 ± 0.014	-0.057 ± 0.015	-0.046 ± 0.014
$\hat{C}_{He}$	-0.024 ± 0.0086	-0.027 ± 0.0085	-0.024 ± 0.0086	-0.027 ± 0.0085
$\hat{C}_{Hq}^{(1)}$	-0.029 ± 0.043	-0.045 ± 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

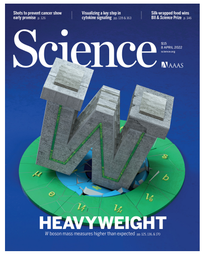


CLEW *versus* No-CLEW

CLEW *versus* No-CLEW

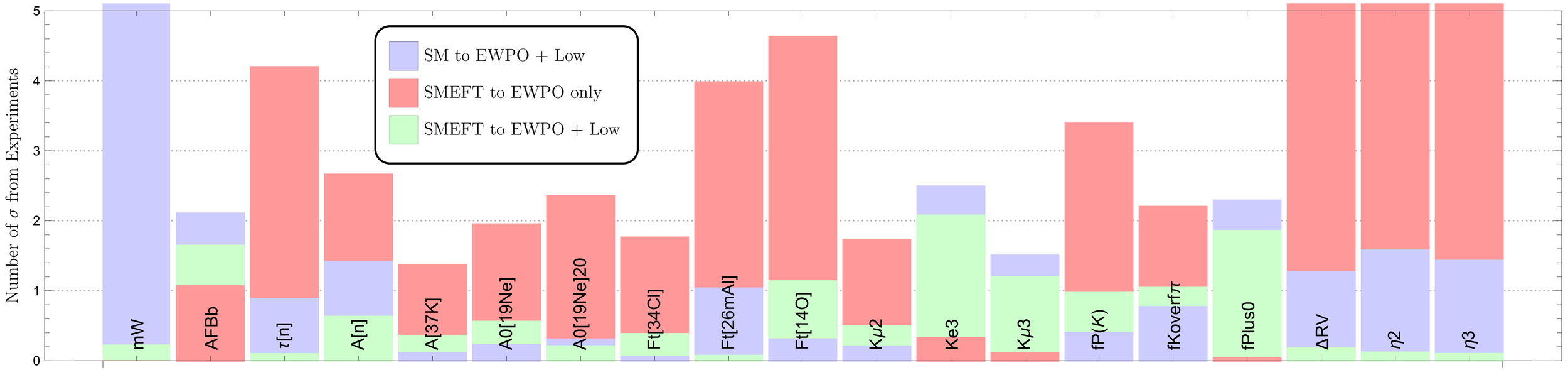
SM

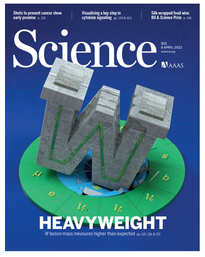




CLEW *versus* No-CLEW

SM

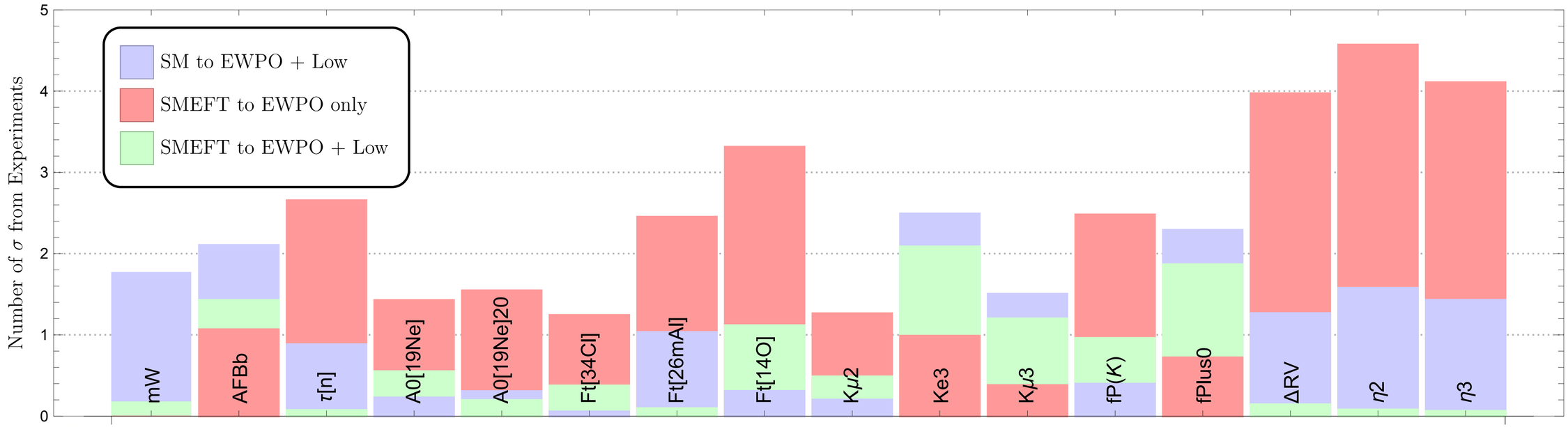




With out a CLEW, SMEFT could be worse than the SM!

CLEW *versus* No-CLEW

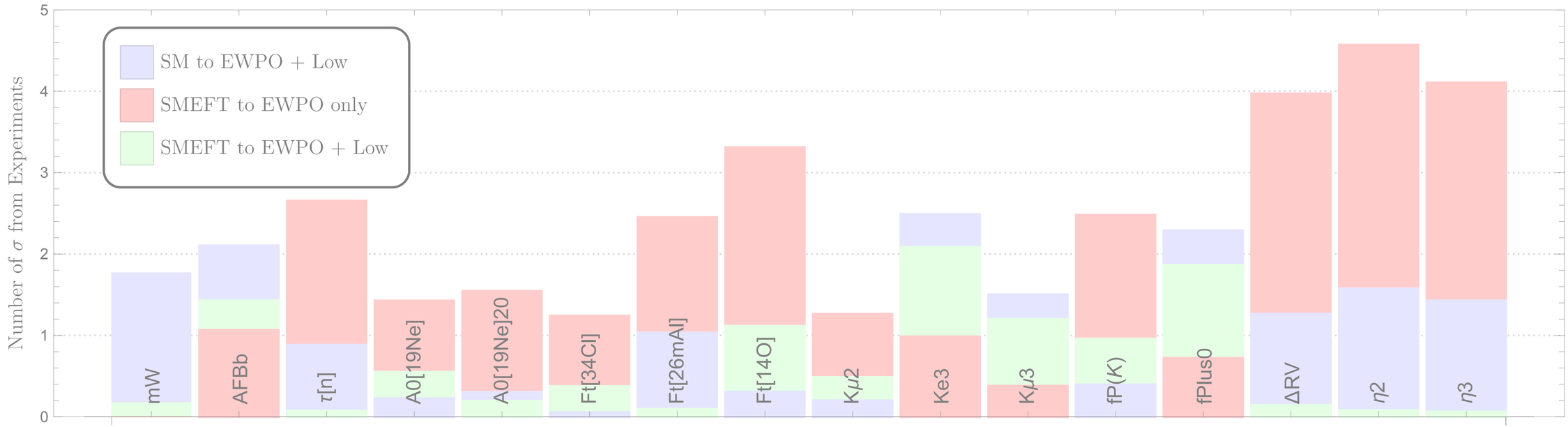
SM



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

CLEW *versus* No-CLEW

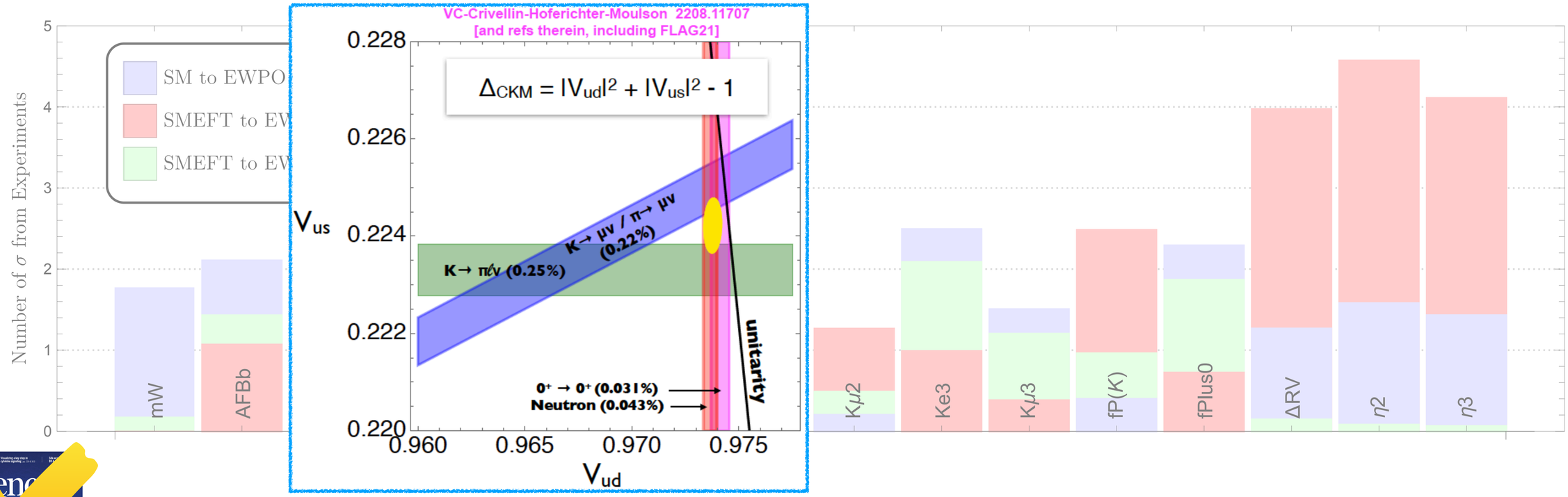
SM



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

CLEW *versus* No-CLEW

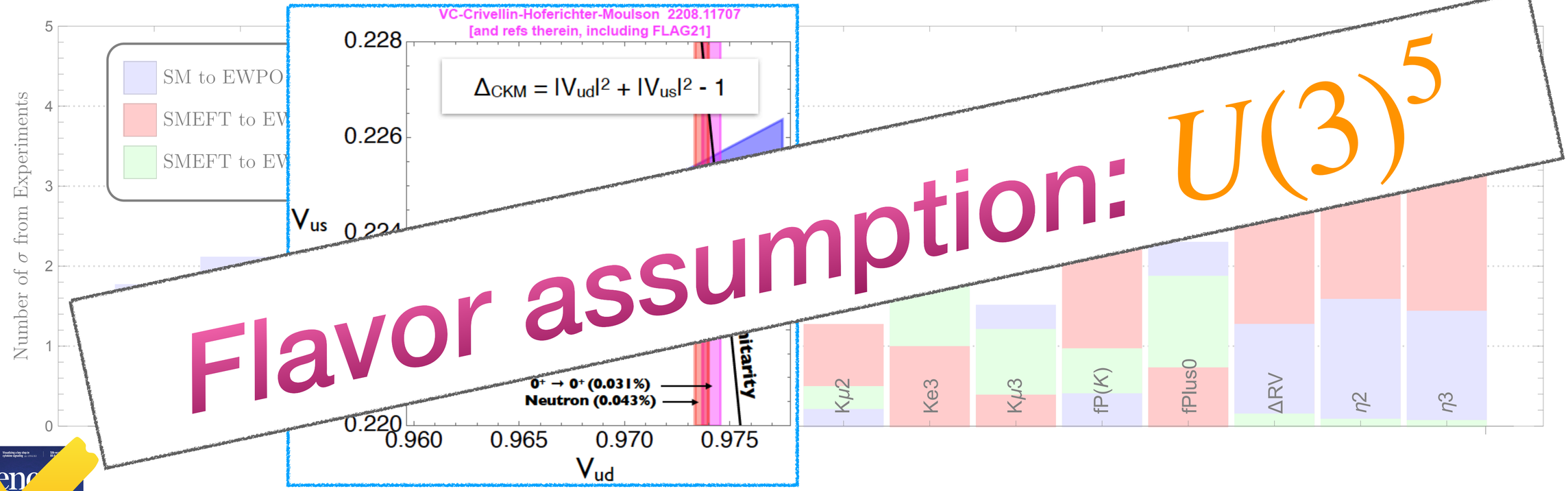
SM



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

CLEW *versus* No-CLEW

SM



Flavor assumption: $U(3)^5$

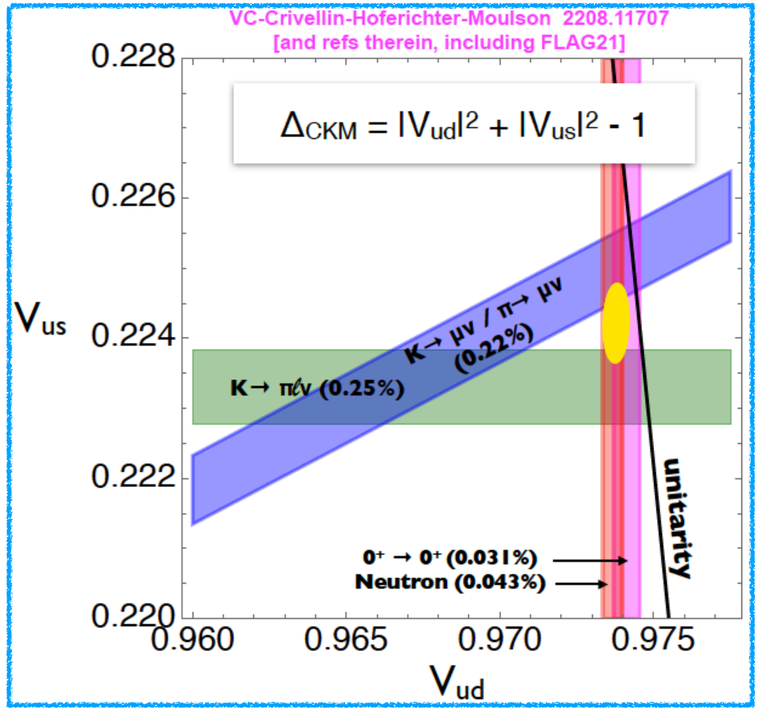
Even with a CLEW, there's another BIG problem to fix!

CLEW *versus* No-CLEW

SM

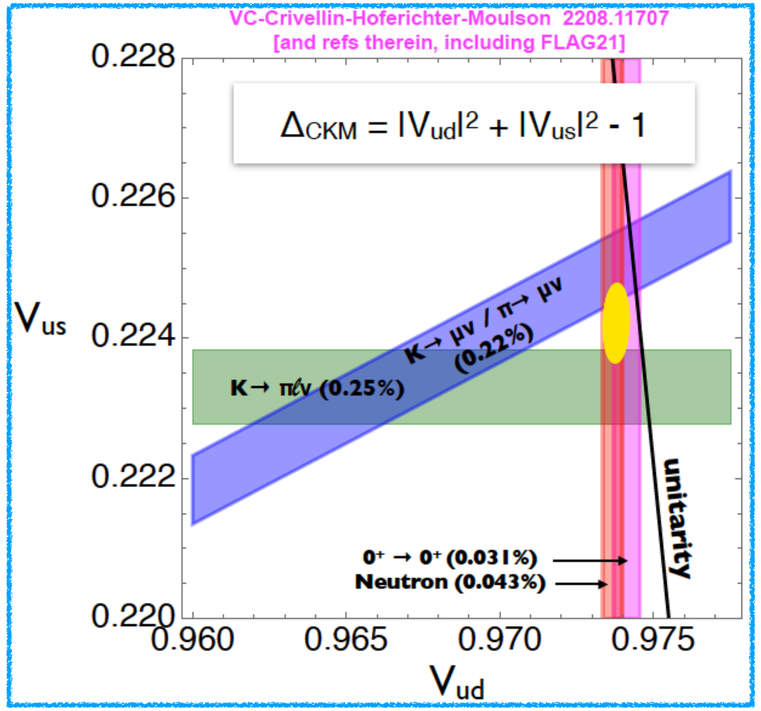
Even with a CLEW, there's another BIG problem to fix!

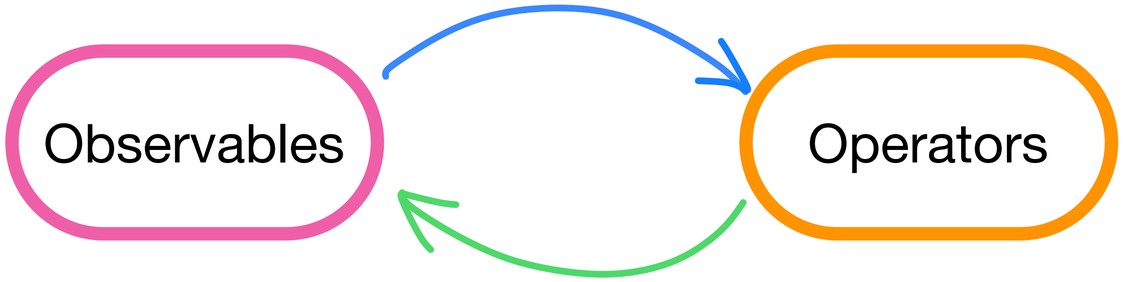
List all the relevant operators



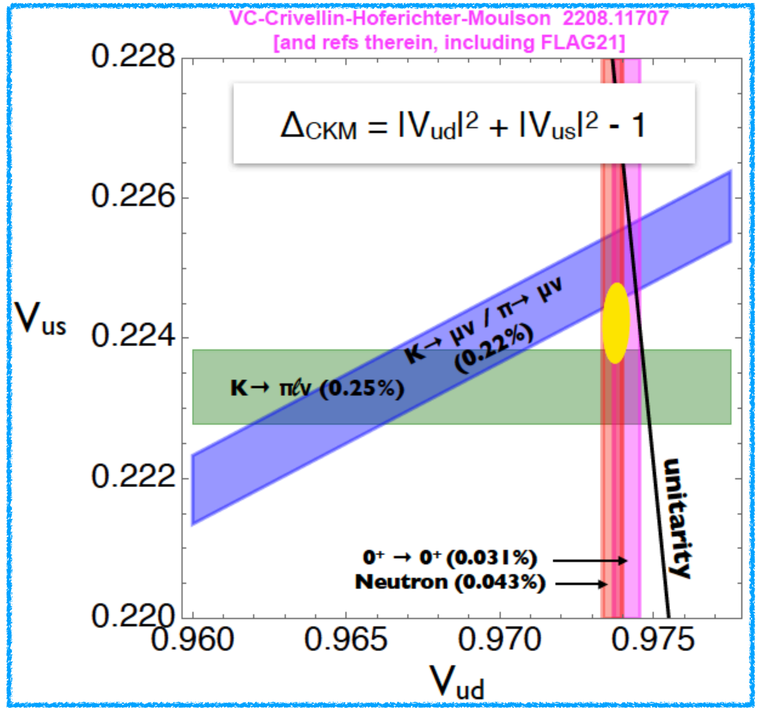
Observables

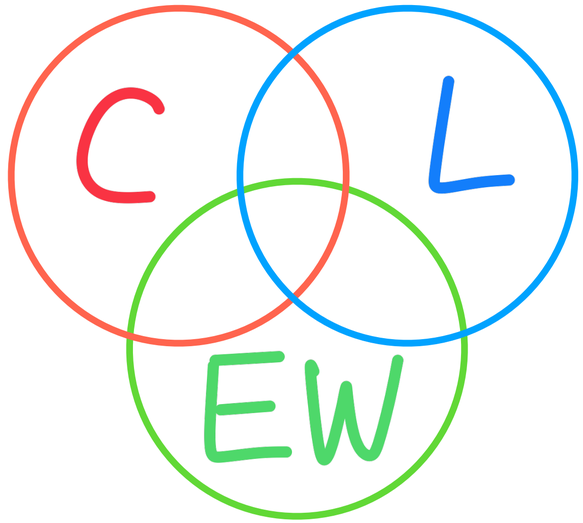
List all the relevant operators

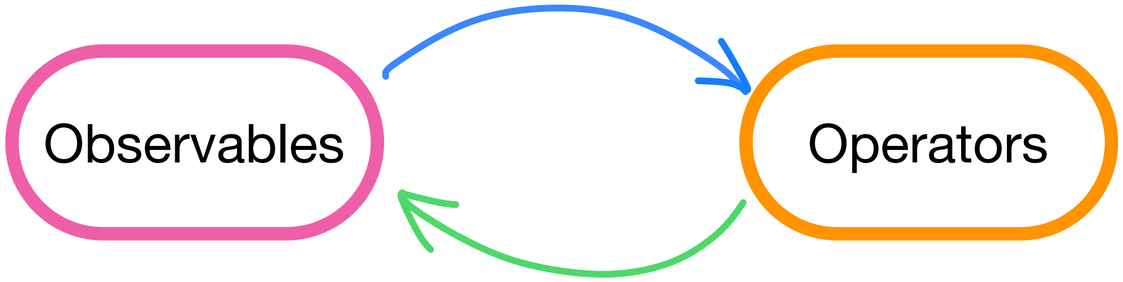




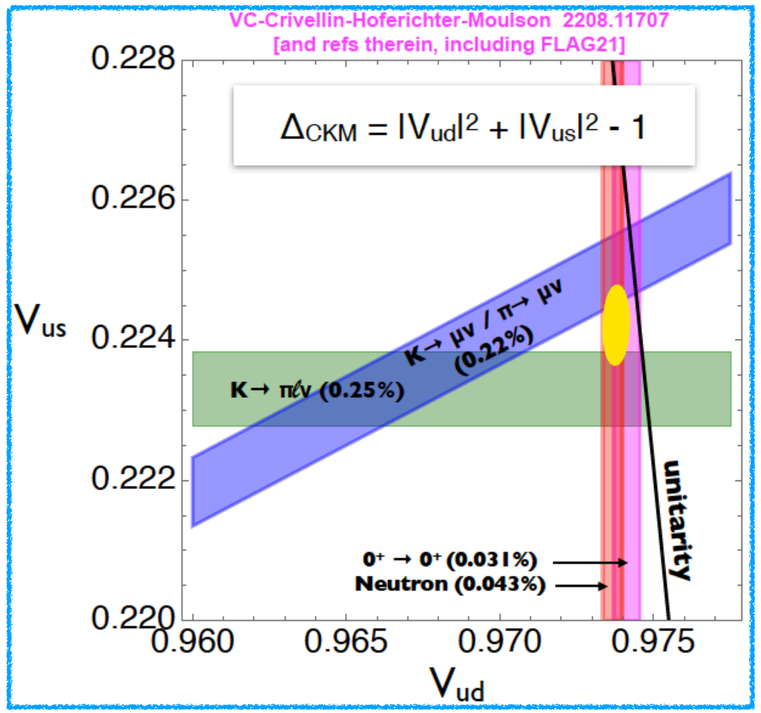
List all the relevant operators

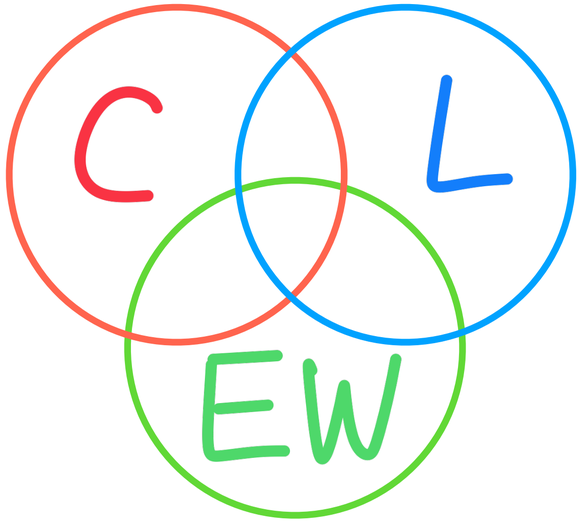


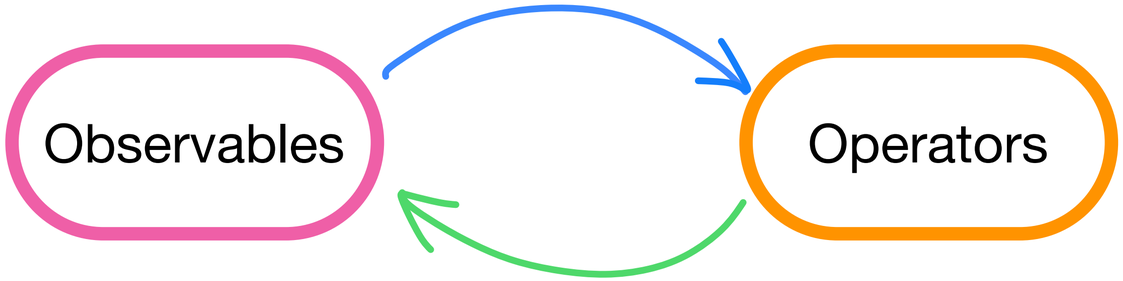




List all the relevant operators



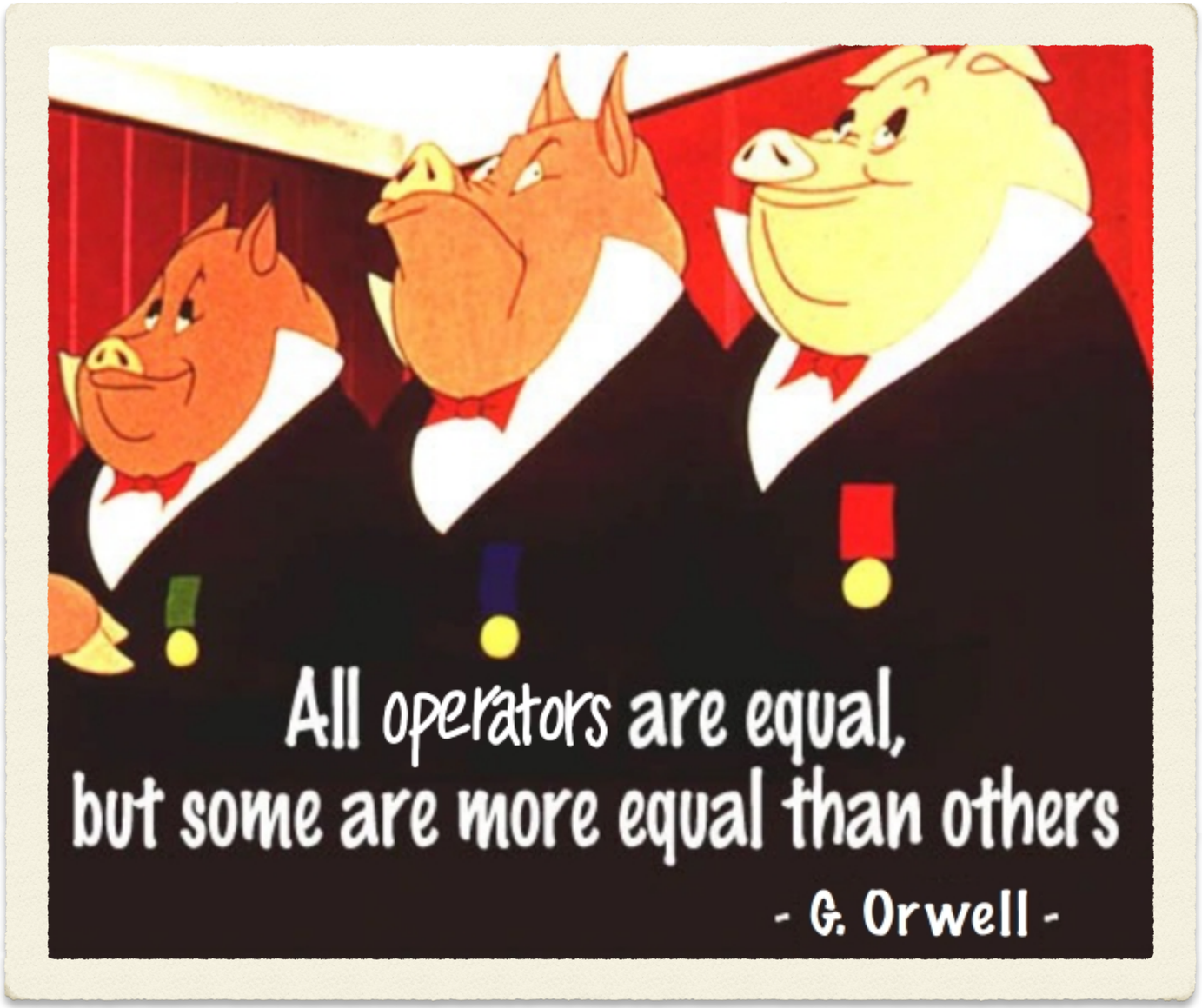




Operators		Low energy CC	EWPO	LHC
H^4D^2				
Q_{HD}	$(H^\dagger D^\mu H)^* (H^\dagger D_\mu H)$	parameter shift (m_Z)		
X^2H^2				
Q_{HWB}	$H^\dagger \tau^I H W^I_{\mu\nu} B^{\mu\nu}$			
		✗	✓	✓
	$i D^I_\mu H)(\bar{l}_p \tau^I \gamma^\mu l_r)$	✓	✓	✓
Q_{He}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{e}_p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

With all flavor indices

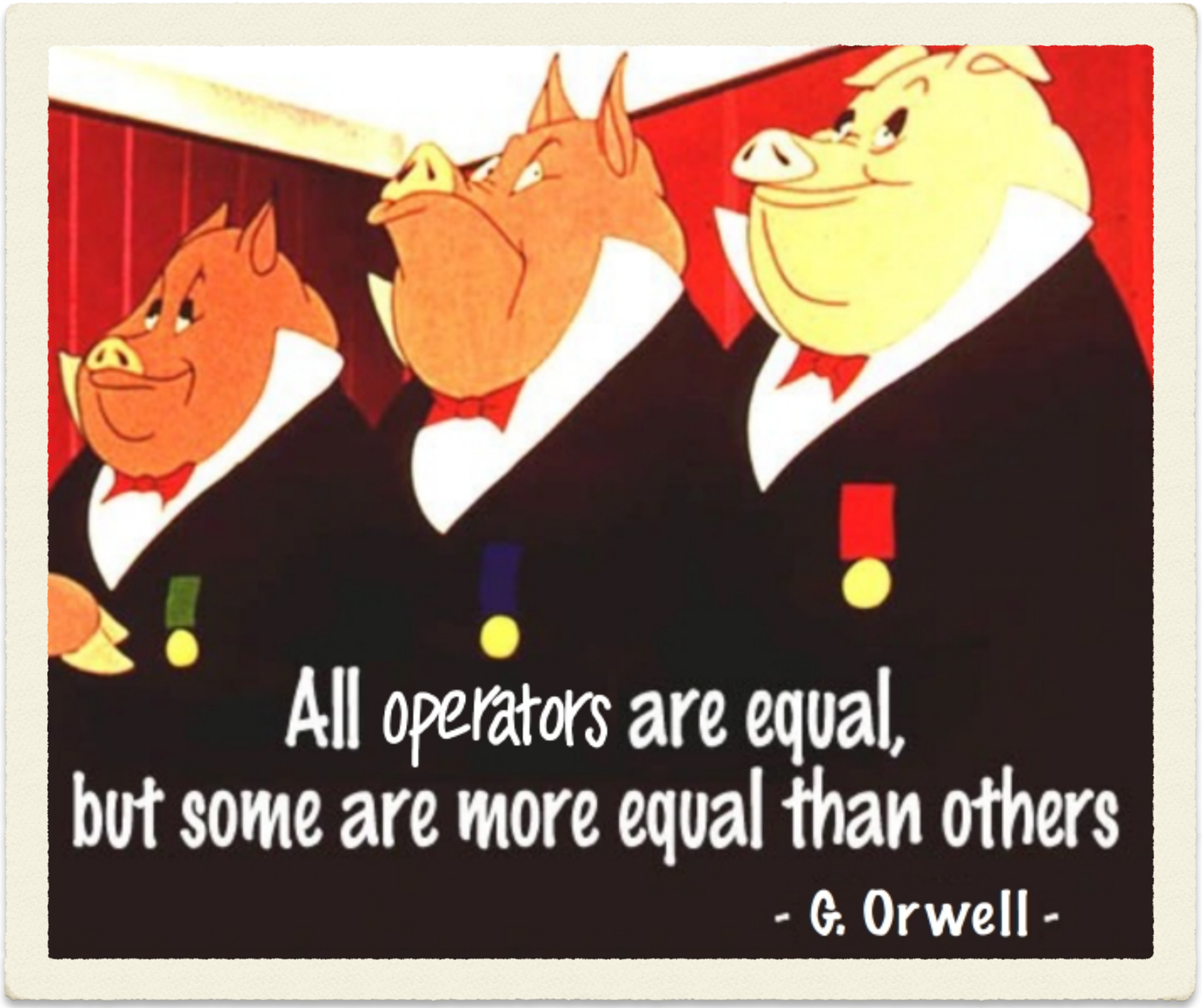
All operators are equal, but...



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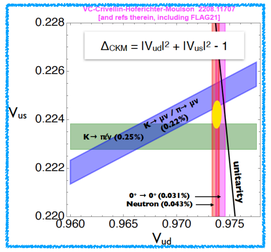
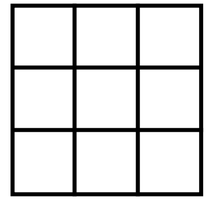
Q_{HD}	$\left(H^\dagger D^\mu H\right)^* \left(H^\dagger D_\mu H\right)$	parameter shift (m_Z)		
X^2H^2				
Q_{HWB}	$H^\dagger \tau^I H W^I_{\mu\nu} B^{\mu\nu}$			
		✗	✓	✓
	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{l}_p \tau^I \gamma^\mu l_r)$	✓	✓	✓
Q_{He}	$(H^\dagger i\overleftrightarrow{D}_\mu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

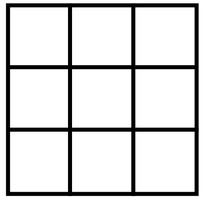


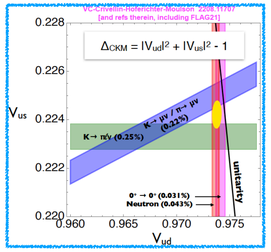
All operators are equal, but...

$C_{Hq}^{(1)}$ 3×3



$C_{Hq}^{(3)}$ 3×3





All operators are equal, but...

Basis rotation

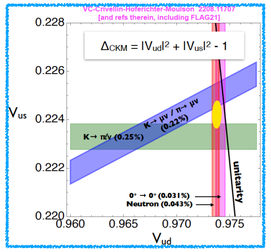
$$C_{Hq}^{(u)} = V\left[C_{Hq}^{(1)} - C_{Hq}^{(3)}\right]V^\dagger, \qquad C_{Hq}^{(d)} = C_{Hq}^{(1)} + C_{Hq}^{(3)},$$

$C_{Hq}^{(1)}$ 3×3

$C_{Hq}^{(3)}$ 3×3

$C_{Hq}^{(u)}$ 3×3 X

$C_{Hq}^{(d)}$ 3×3



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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})

$C_{Hq}^{(1)}$ 3×3

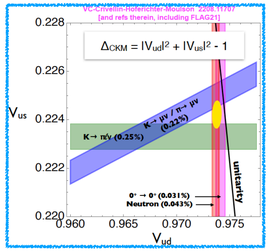
$C_{Hq}^{(3)}$ 3×3

$C_{Hq}^{(u)}$ 3×3 (X)

$C_{Hq}^{(d)}$ 3×3

$C_{Hq}^{(u)}$ 3×3 (X, X, X, X, X)

$C_{Hq}^{(d)}$ 3×3 (X, X)



All operators are equal, but...

Basis rotation

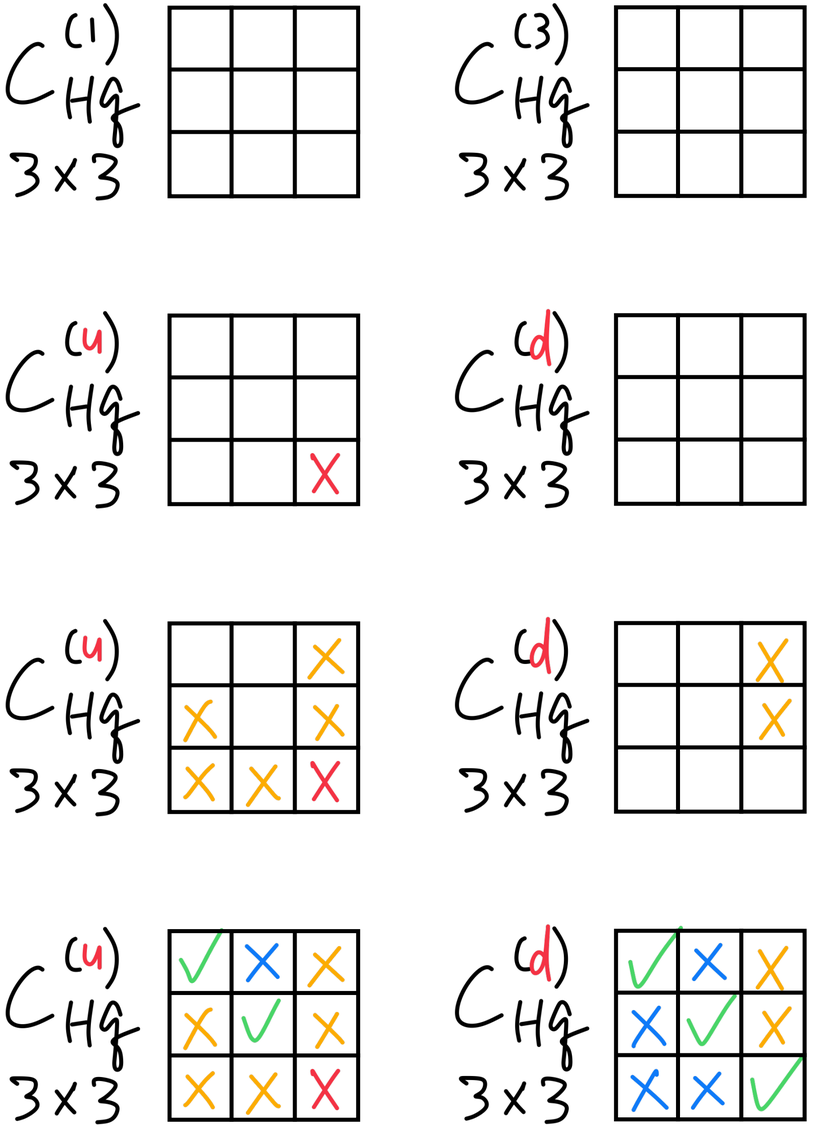
$$C_{Hq}^{(u)} = V\left[C_{Hq}^{(1)} - C_{Hq}^{(3)}\right]V^\dagger, \qquad C_{Hq}^{(d)} = C_{Hq}^{(1)} + C_{Hq}^{(3)},$$

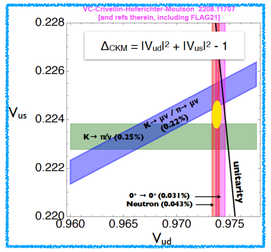
Relative contribution

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

Pheno constraints

FCNC decays of B, D and K mesons





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Basis rotation

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Relative contribution

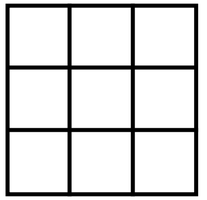
Suppressed by $|V_{us}|^2$ or (V_{ts}/V_{us})

Pheno constraints

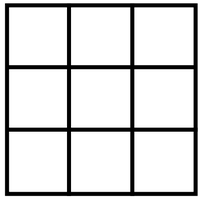
FCNC decays of B, D and K mesons

"More-equal" operators

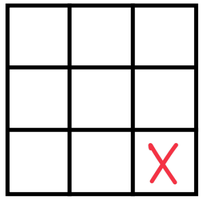
$C_{Hq}^{(1)}$ 3×3



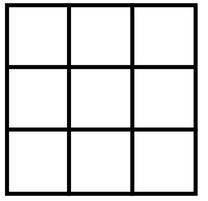
$C_{Hq}^{(3)}$ 3×3



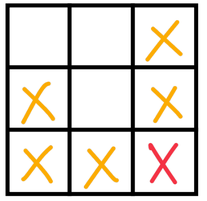
$C_{Hq}^{(u)}$ 3×3



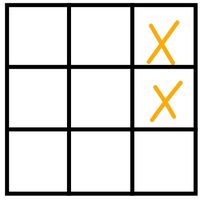
$C_{Hq}^{(d)}$ 3×3



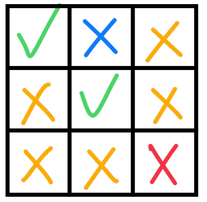
$C_{Hq}^{(u)}$ 3×3



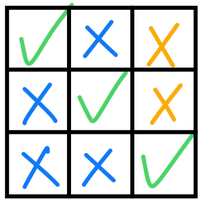
$C_{Hq}^{(d)}$ 3×3



$C_{Hq}^{(u)}$ 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}	$H^\dagger \tau^I H W^I_{\mu\nu} B^{\mu\nu}$			
		✗	✓	✓
	$(H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar{l}_p \tau^I \gamma^\mu l_r)$	✓	✓	✓
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

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

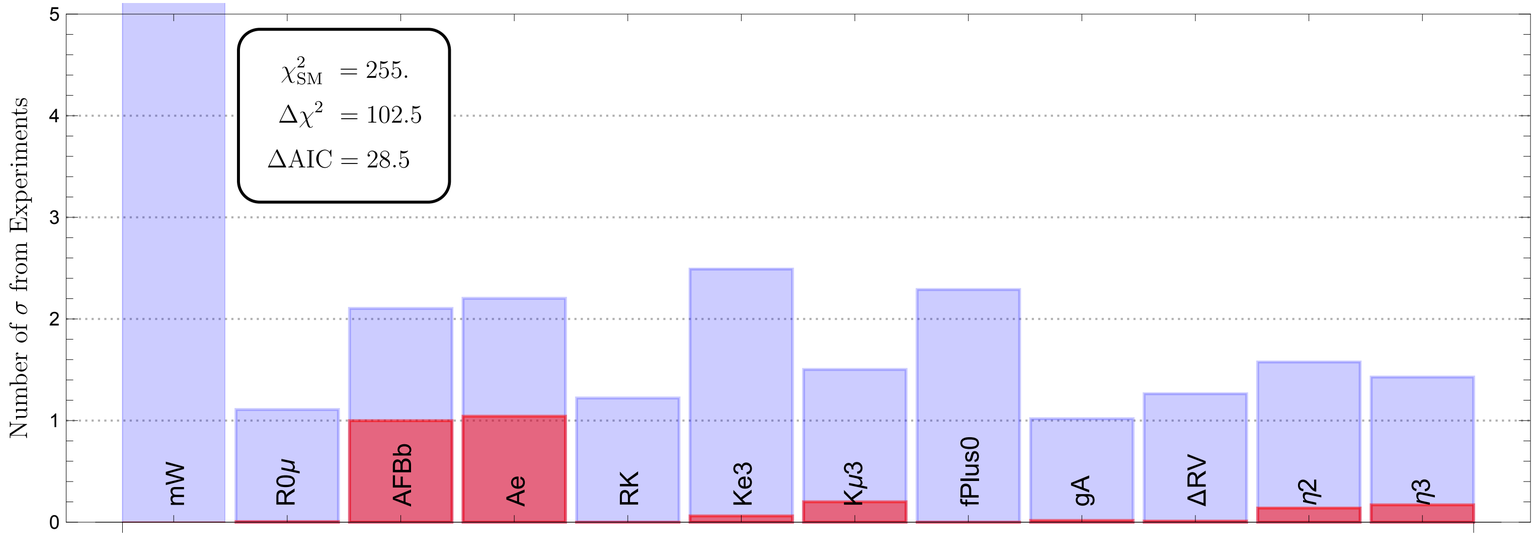
With all flavor indices

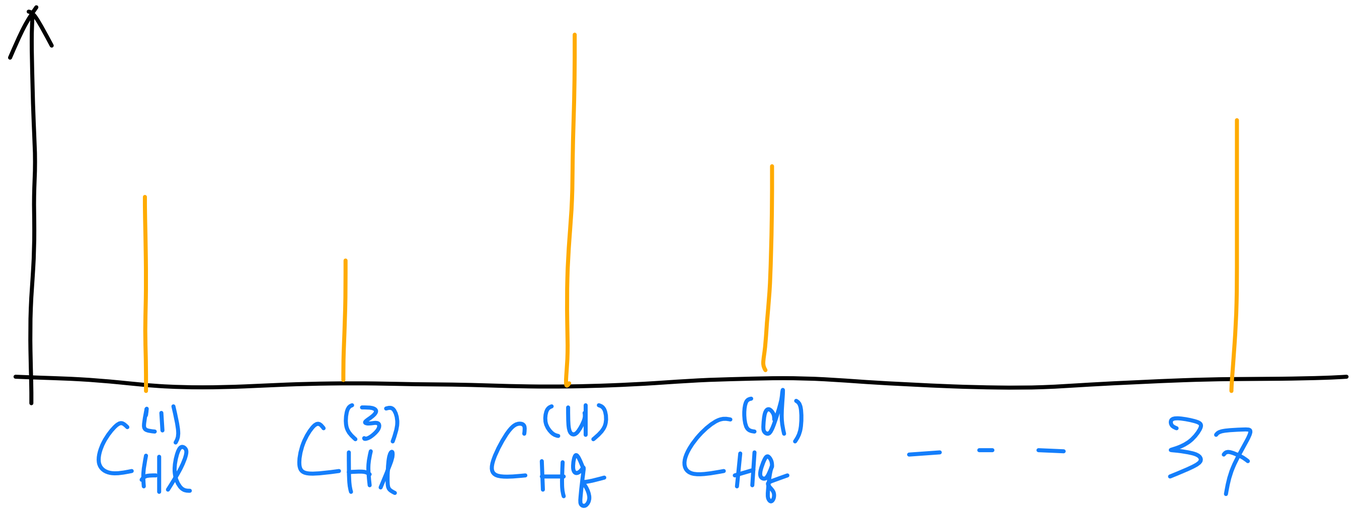
Operators		Low energy CC	EWPO	LHC
H^4D^2				
Q_{HD}	$(H^\dagger D^\mu H)^* (H^\dagger D_\mu H)$	parameter shift (m_Z)		
X^2H^2				
Q_{HWB}	$H^\dagger \tau^I H W^I_{\mu\nu} B^{\mu\nu}$			
		✗	✓	✓
	$i D^I_\mu H)(\bar{l}_p \tau^I \gamma^\mu l_r)$	✓	✓	✓
Q_{He}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{e}_p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

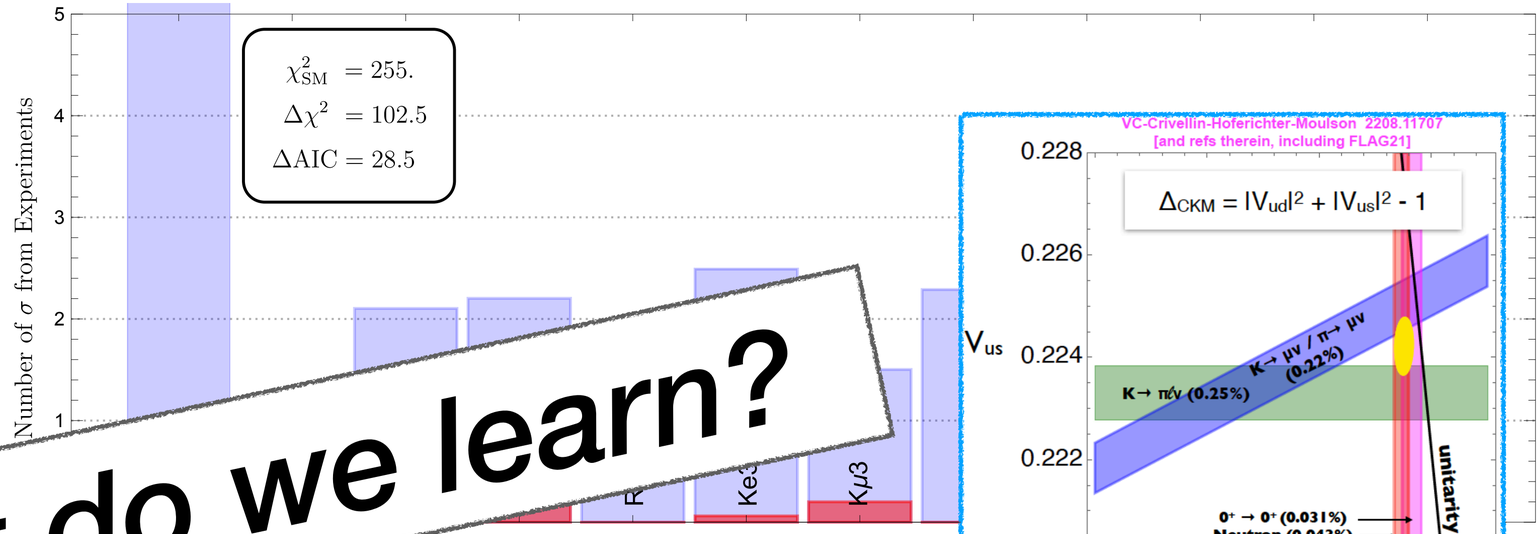


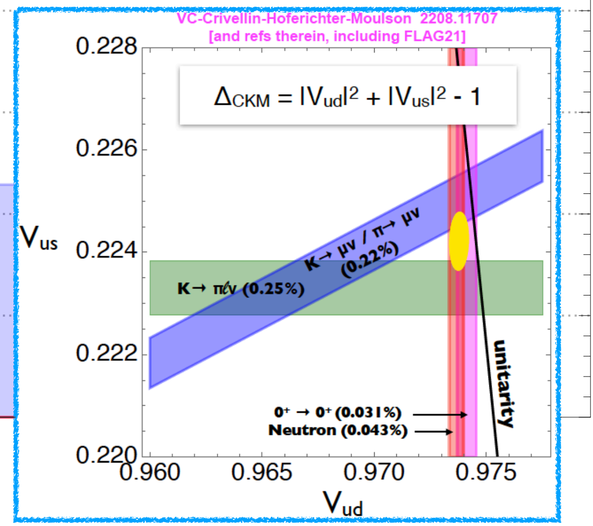


Let's fit these 37 operators

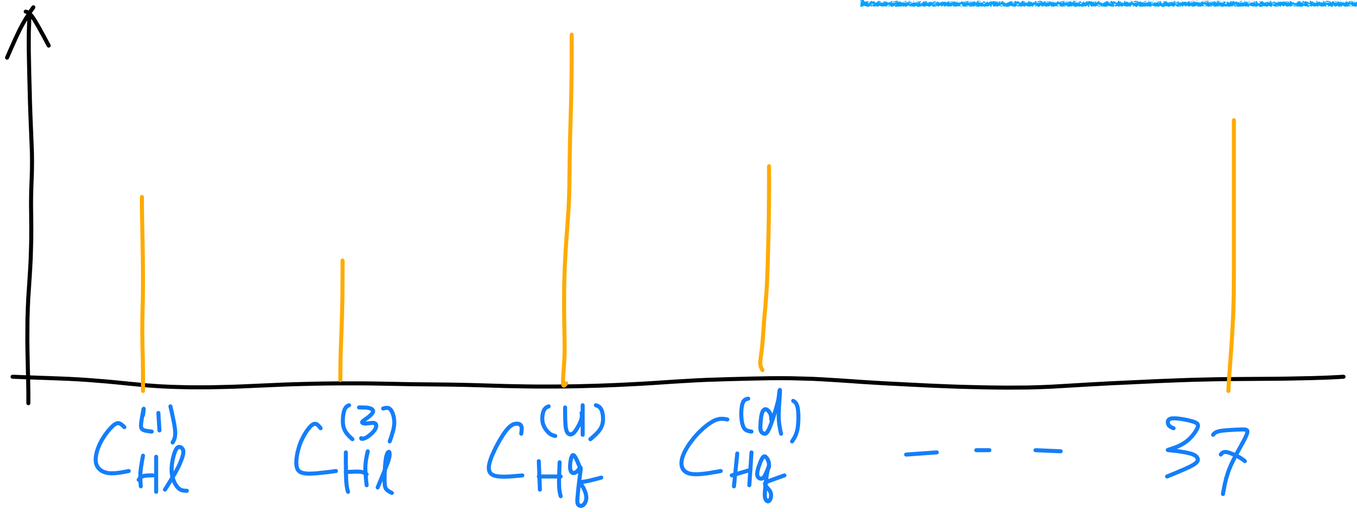
Global analysis	Indices
$C_{Hl\,pr}^{(1,3)}$, $C_{He\,pr}$	$pr \in \{ee,\ \mu\mu,\ \tau\tau\}$
$C_{Hq\,pr}^{(d)}$, $C_{Hd\,pr}$	$pr \in \{11, 22, 33\}$
$C_{Hq\,pr}^{(u)}$, $C_{Hu\,pr}$	$pr \in \{11, 22\}$
$C_{Hud\,pr}$	$pr \in \{11, 12\}$
$C_{lq\,\ell\ell pr}^{(d)}$, $C_{ledq\,\ell\ell pr}$	$\ell \in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

37 in total





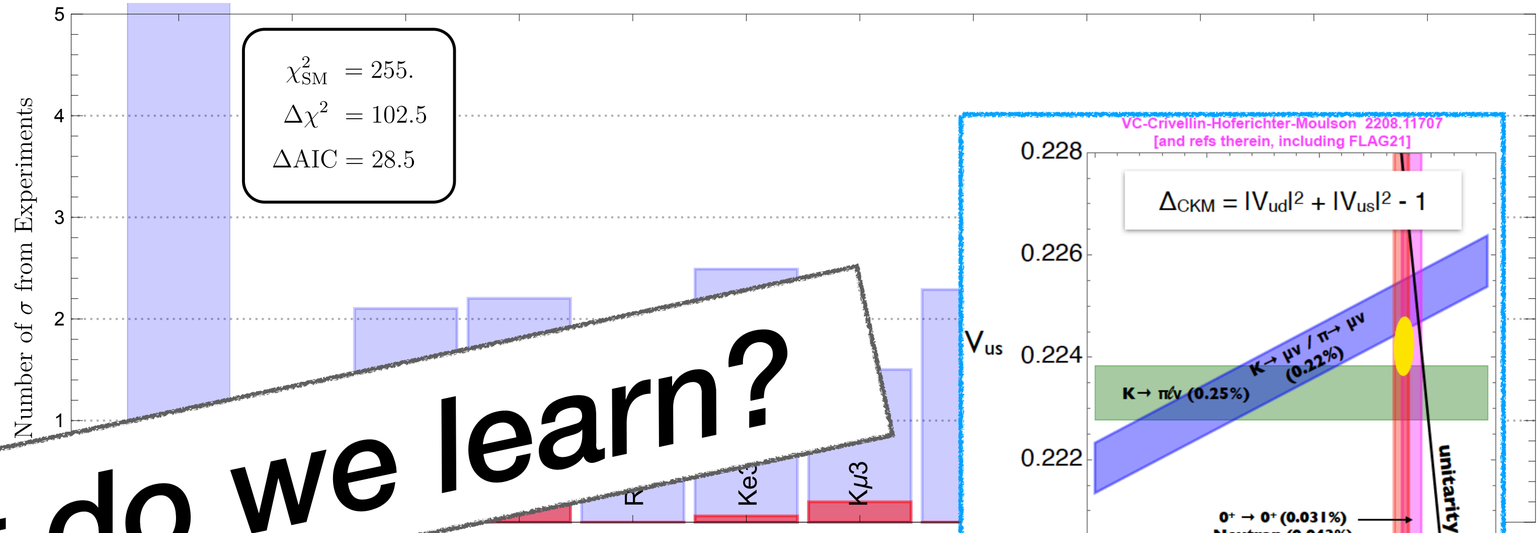
What do we learn?

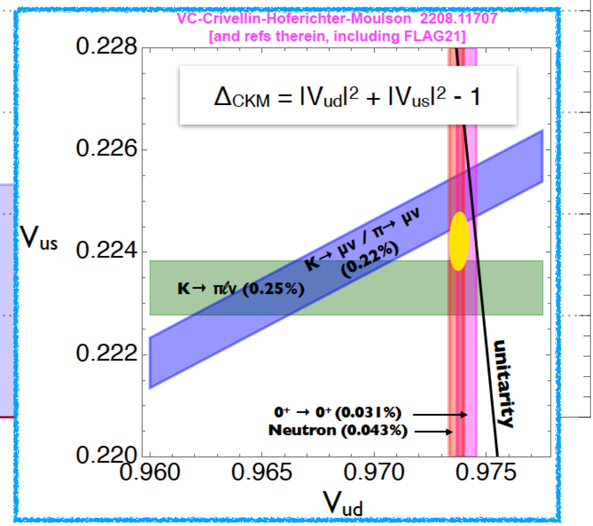


Let's fit these 37 operators

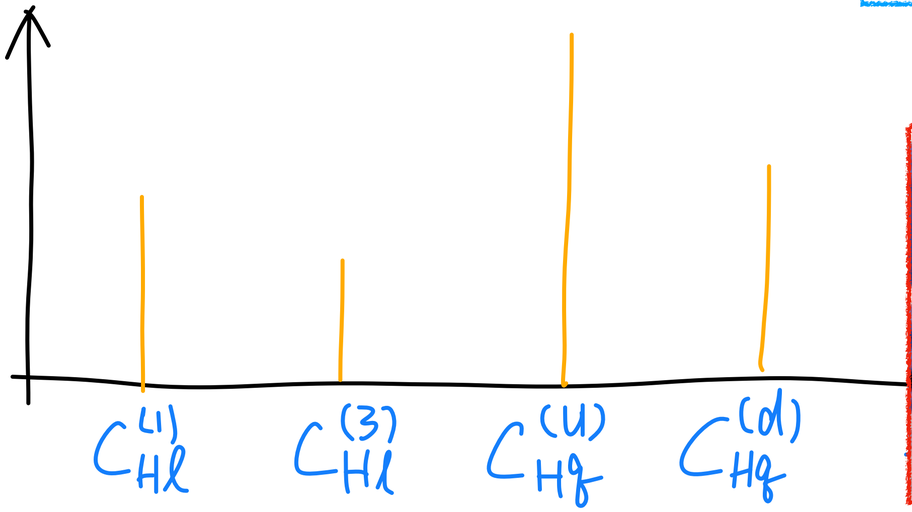
Global analysis	Indices
$C_{Hl\,pr}^{(1,3)}$, $C_{He\,pr}$	$pr \in \{ee,\ \mu\mu,\ \tau\tau\}$
$C_{Hq\,pr}^{(d)}$, $C_{Hd\,pr}$	$pr \in \{11, 22, 33\}$
$C_{Hq\,pr}^{(u)}$, $C_{Hu\,pr}$	$pr \in \{11, 22\}$
$C_{Hud\,pr}$	$pr \in \{11, 12\}$
$C_{lq\,\ell\ell pr}^{(d)}$, $C_{ledq\,\ell\ell pr}$	$\ell \in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

37 in total





What do we learn?



Not all 37 are 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}	
$C_{\substack{ll \\ 2112}}$		

Not all 37 are equal...

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

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

Not all 37 are equal...

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

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

Group them into 10 families

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!

	operators	class	WC
1.	C_{Hud}	RH charged-currents	2
2.	$C^{(1)}_{Hl}$, $C^{(3)}_{Hl}$	LH leptonic vertex corrections	6
3.	C_{He}	RH leptonic vertex corrections	3
4.	$C^{(u)}_{Hq}$, $C^{(d)}_{Hq}$	LH quark vertex corrections	5
5.	C_{Hu}, C_{Hd}	RH quark vertex corrections	5
6.	C_{ll}	LH leptonic four-fermion ops.	1
7.	$C^{(u)}_{lq}$, $C^{(d)}_{lq}$	LH semileptonic four-fermion ops.	6
8.	C_{ledq}, $C^{(1)}_{lequ}$	scalar four-fermion ops.	6
9.	$C^{(3)}_{lequ}$	tensor four-fermion ops.	2
10.	C_{HD}, C_{HWB}	oblique corrections	1

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

AIC and one thousand fits

Akaike Information Criterion

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

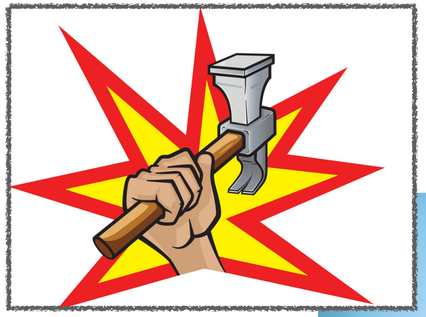
	operators	class	WC
1.	C_{Hud}	RH charged-currents	2
2.	$C_{Hl}^{(1)}$, $C_{Hl}^{(3)}$	LH leptonic vertex corrections	6
3.	C_{He}	RH leptonic vertex corrections	3
4.	$C_{Hq}^{(u)}$, $C_{Hq}^{(d)}$	LH quark vertex corrections	5
5.	C_{Hu}, C_{Hd}	RH quark vertex corrections	5
6.	C_{ll}	LH leptonic four-fermion ops.	1
7.	$C_{lq}^{(u)}$, $C_{lq}^{(d)}$	LH semileptonic four-fermion ops.	6
8.	C_{ledq}, $C_{lequ}^{(1)}$	scalar four-fermion ops.	6
9.	$C_{lequ}^{(3)}$	tensor four-fermion ops.	2
10.	C_{HD}, C_{HWB}	oblique corrections	1

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

AIC and one thousand fits

Akaike Information Criterion

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



	operators	class	WC
1.	C_{Hud}	RH charged-currents	2
2.	$C_{Hl}^{(1)}$, $C_{Hl}^{(3)}$	LH leptonic vertex corrections	6
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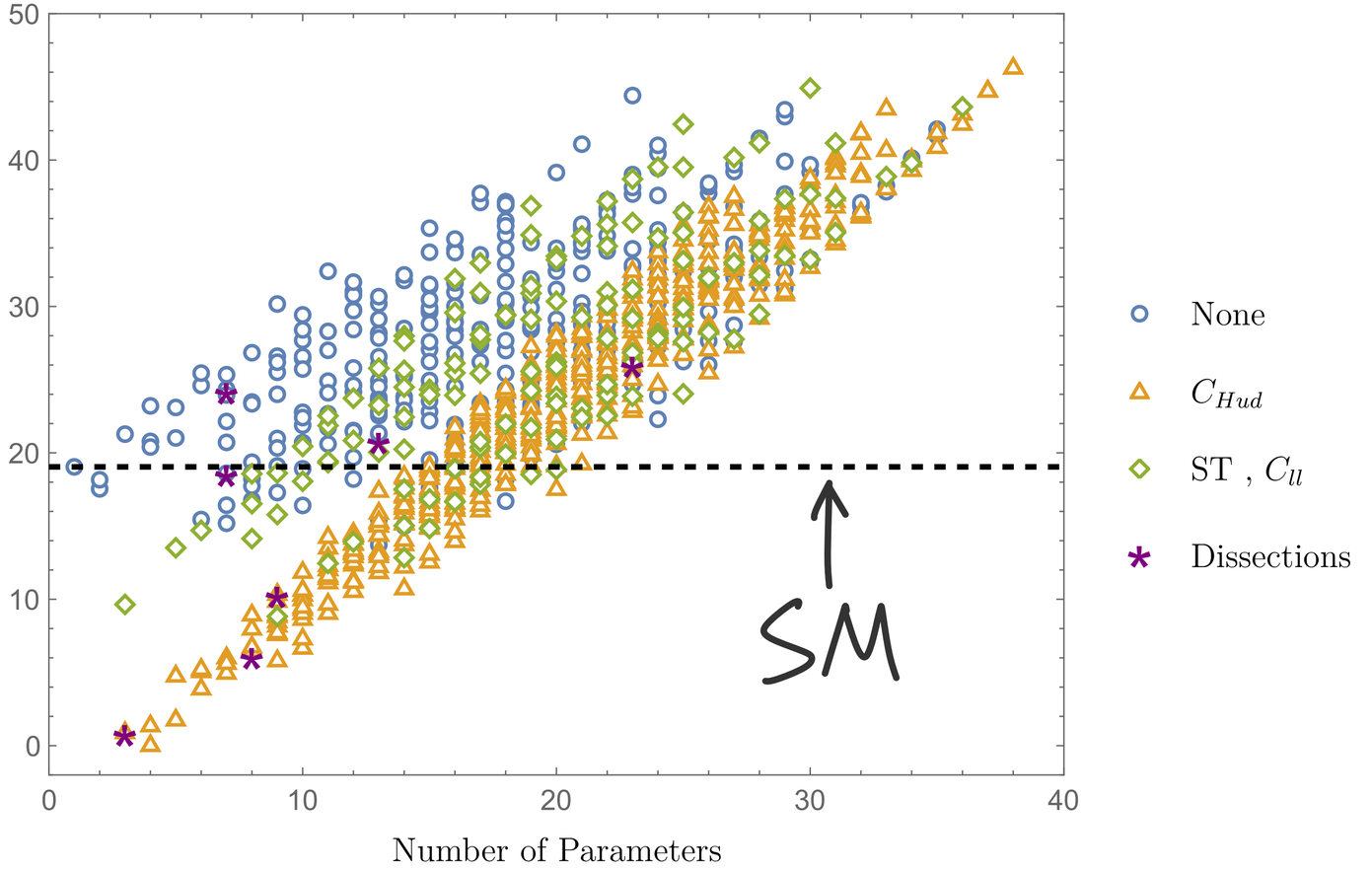
5.	C_{Hu}, C_{Hd}	RH quark vertex corrections	5
6.	C_{ll}	LH leptonic four-fermion ops.	1
7.	$C_{lq}^{(u)}$, $C_{lq}^{(d)}$	LH semileptonic four-fermion ops.	6
8.	C_{ledq}, $C_{lequ}^{(1)}$	scalar four-fermion ops.	6
9.	$C_{lequ}^{(3)}$	tensor four-fermion ops.	2
10.	C_{HD}, C_{HWB}	oblique corrections	1

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

AIC and one thousand fits

Akaike Information Criterion

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

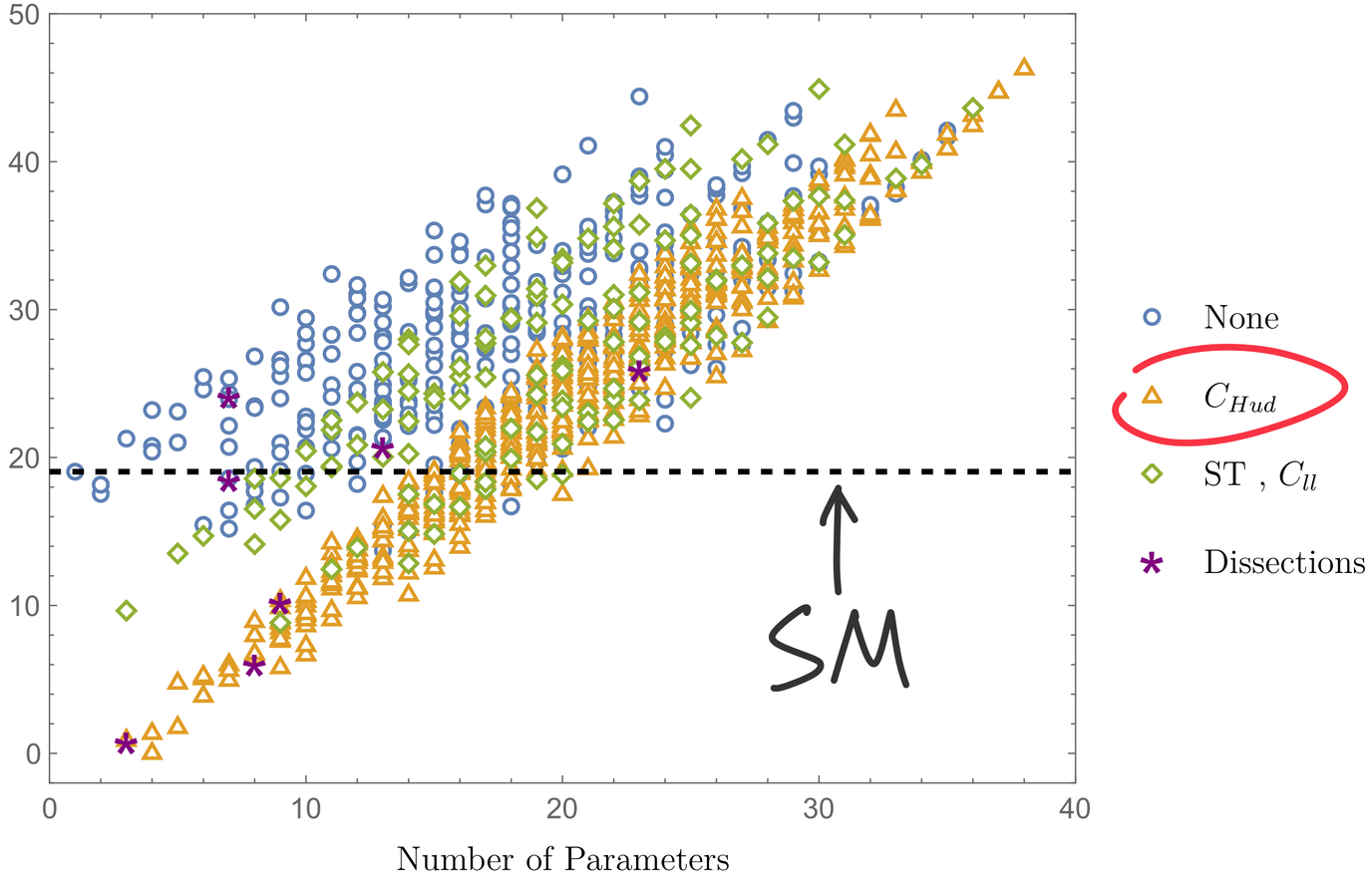


Lower the AIC, better the model

AIC and one thousand fits

Akaike Information Criterion

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

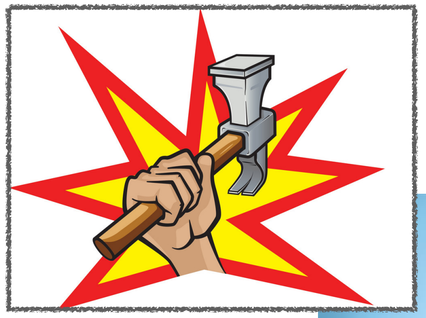


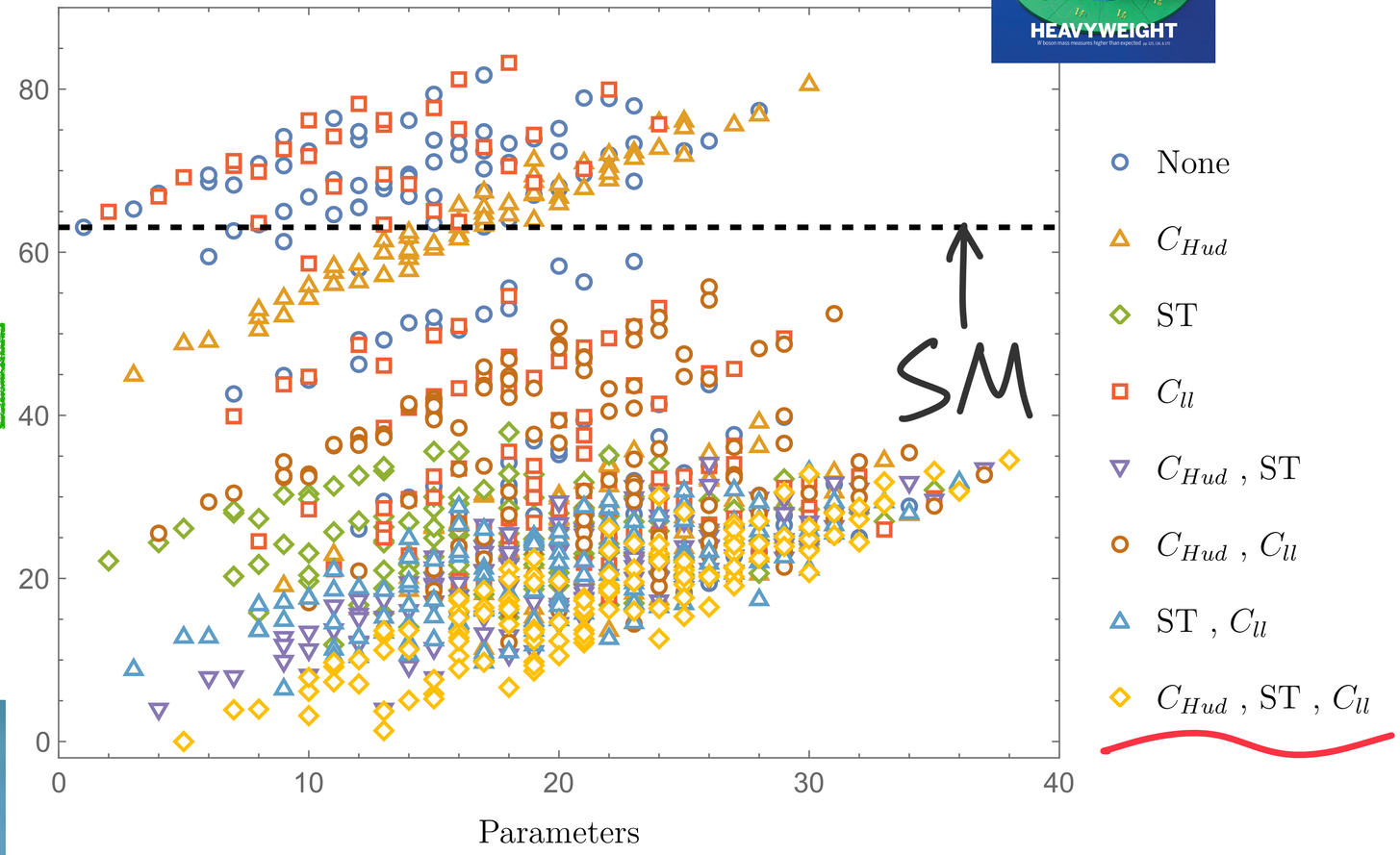
Lower the AIC, better the model

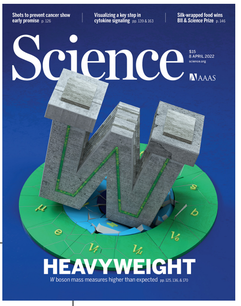
AIC and one thousand fits

Akaike Information Criterion

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

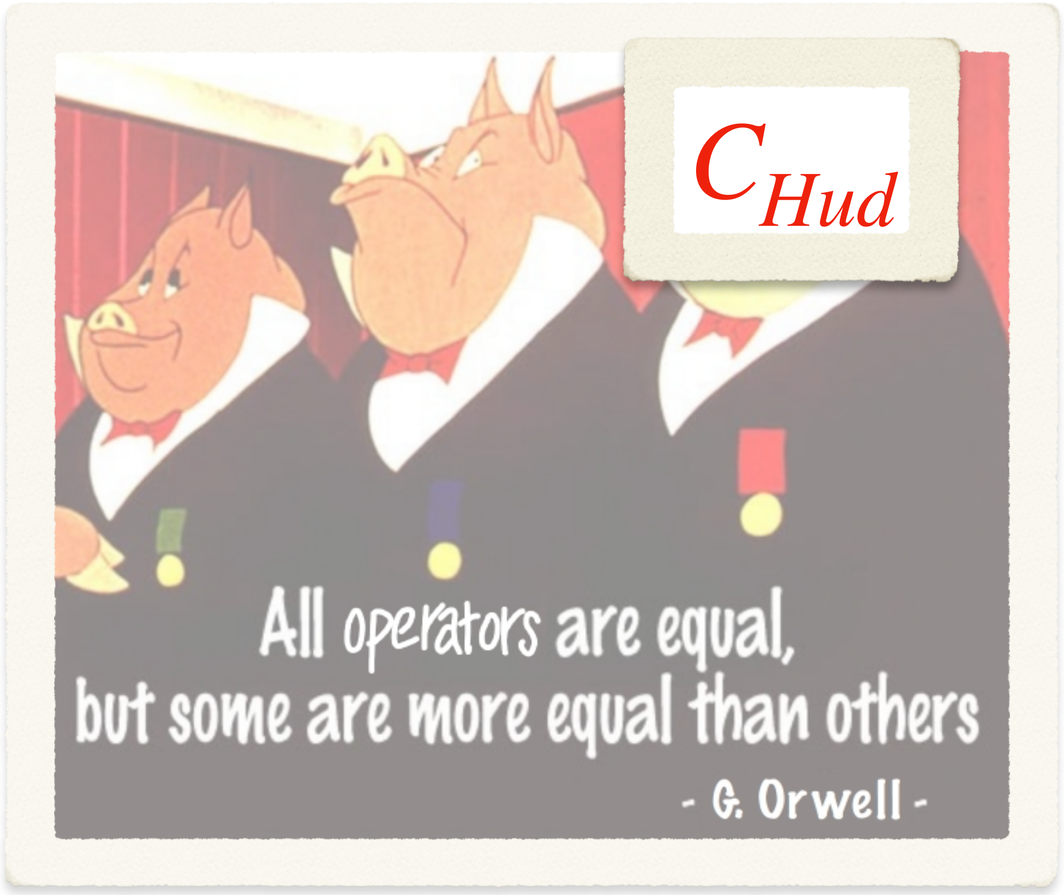


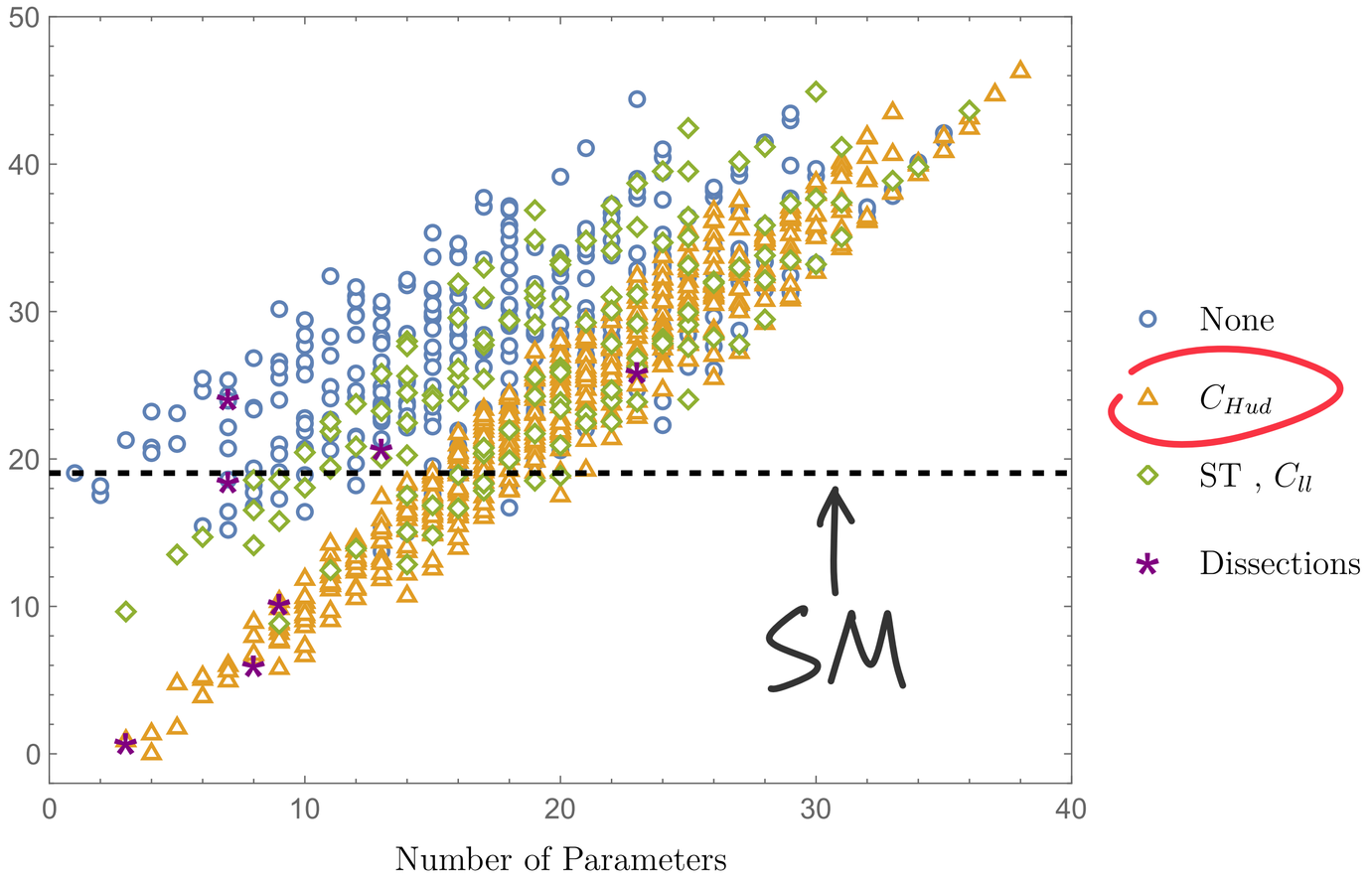




Lower the AIC, better the model

Who is this C_{Hud}



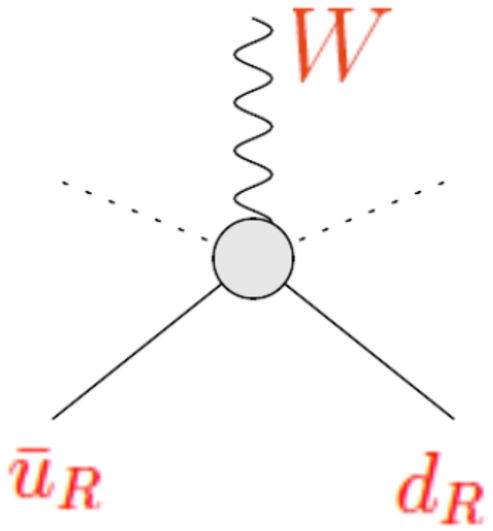


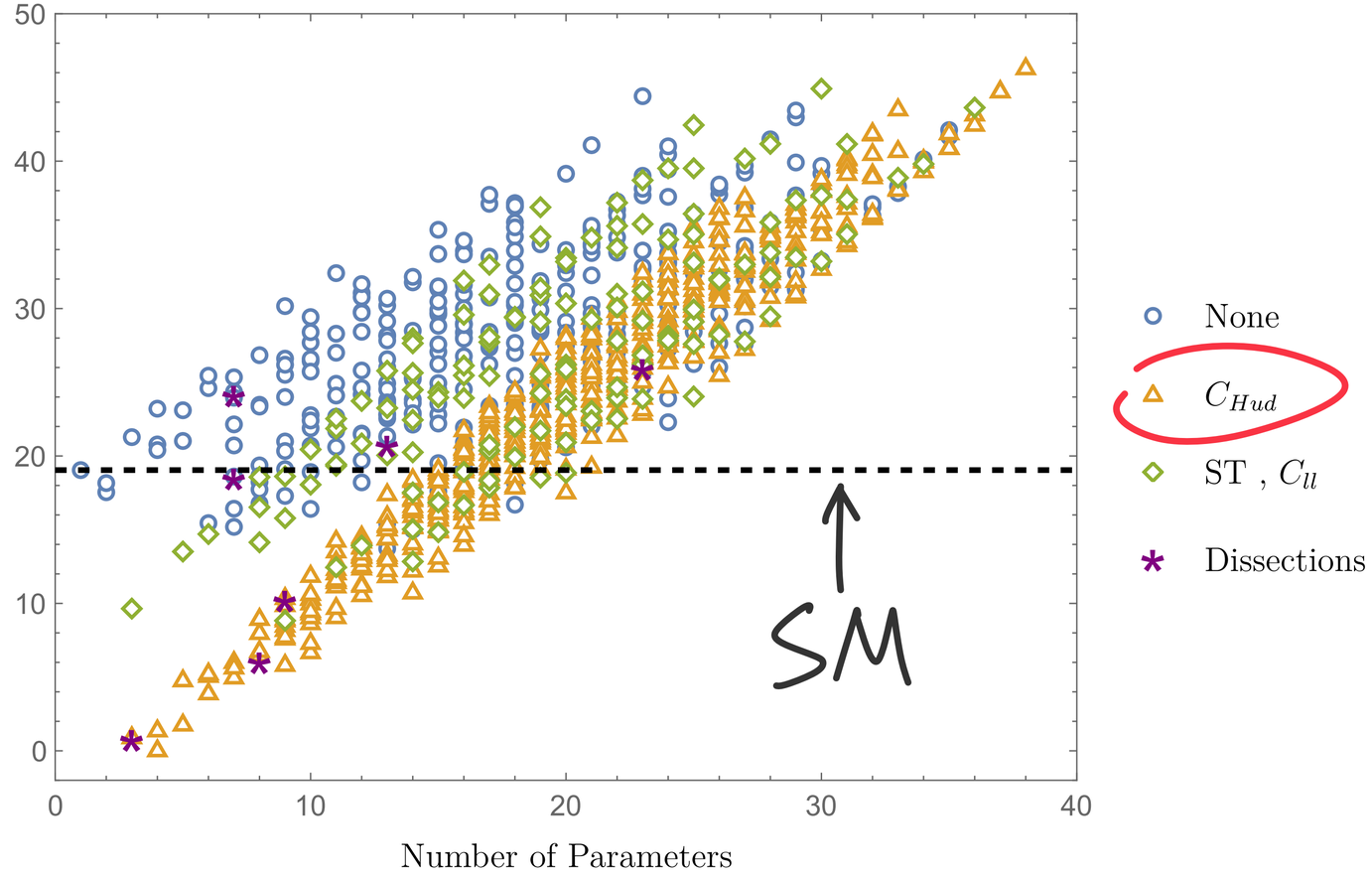
Lower the AIC, better the model

Who is this C_{Hud}

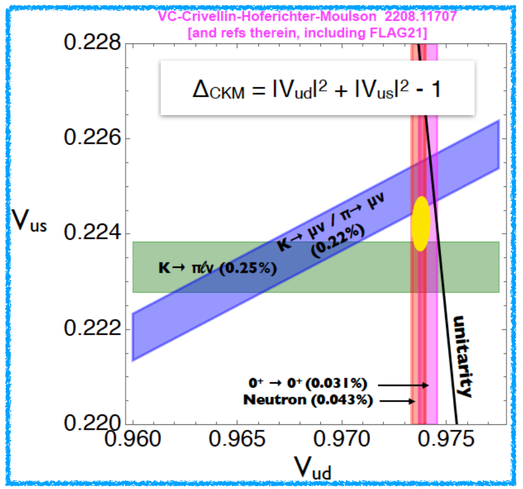
C_{Hud}

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



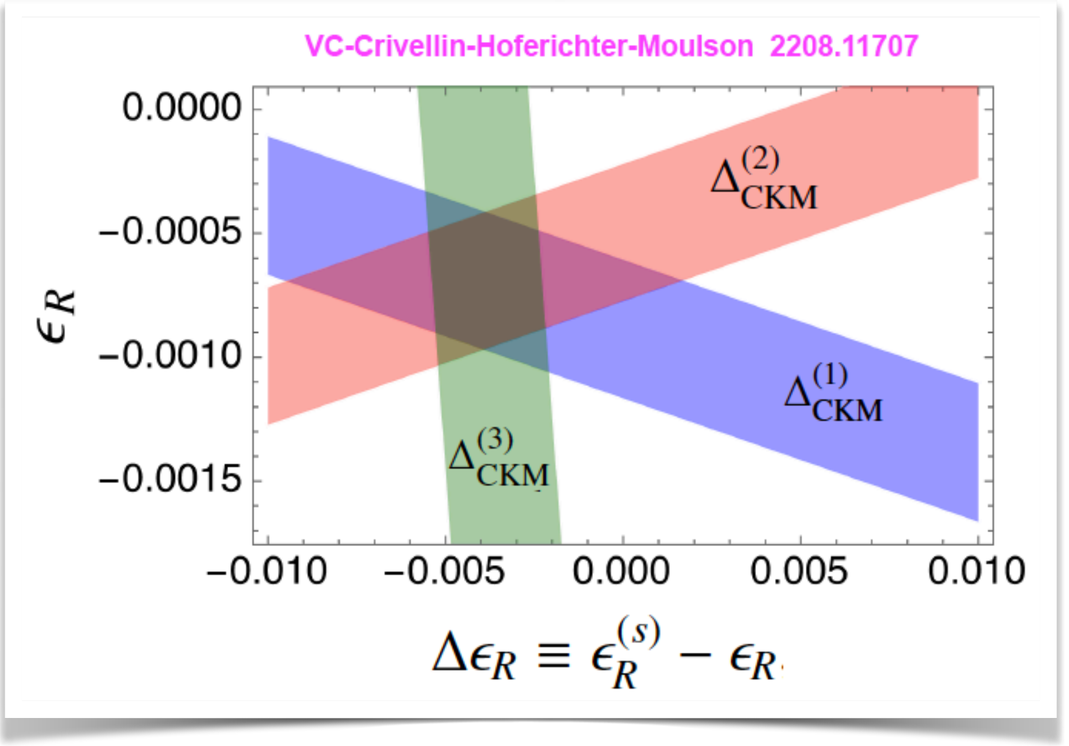


Lower the AIC, better the model

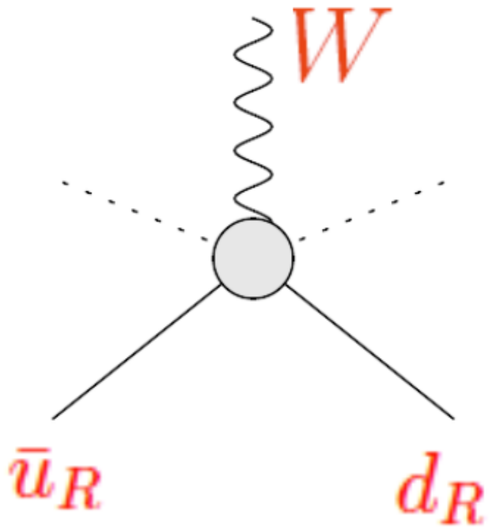


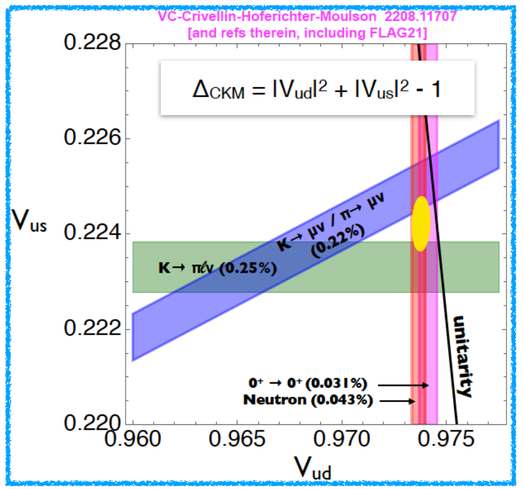
C_{Hud} solves Cabibbo

C_{Hud}



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

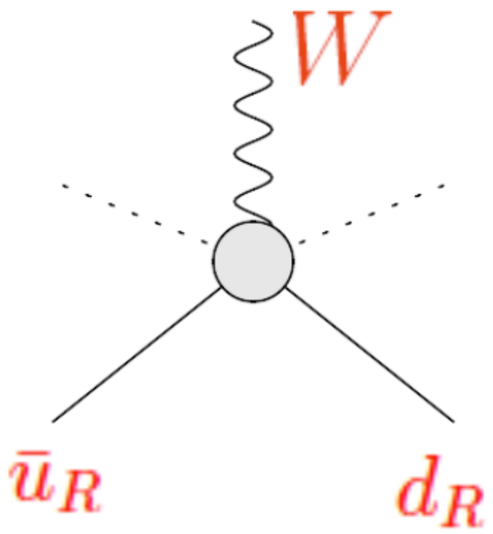


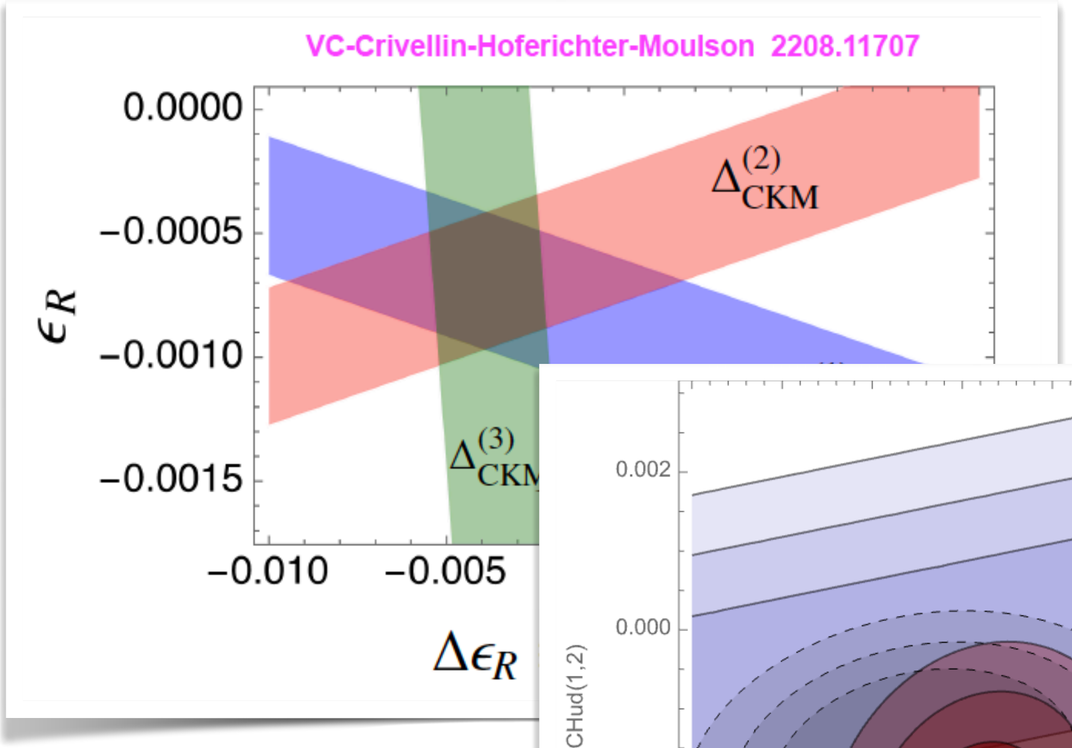


Falsifying C_{Hud}

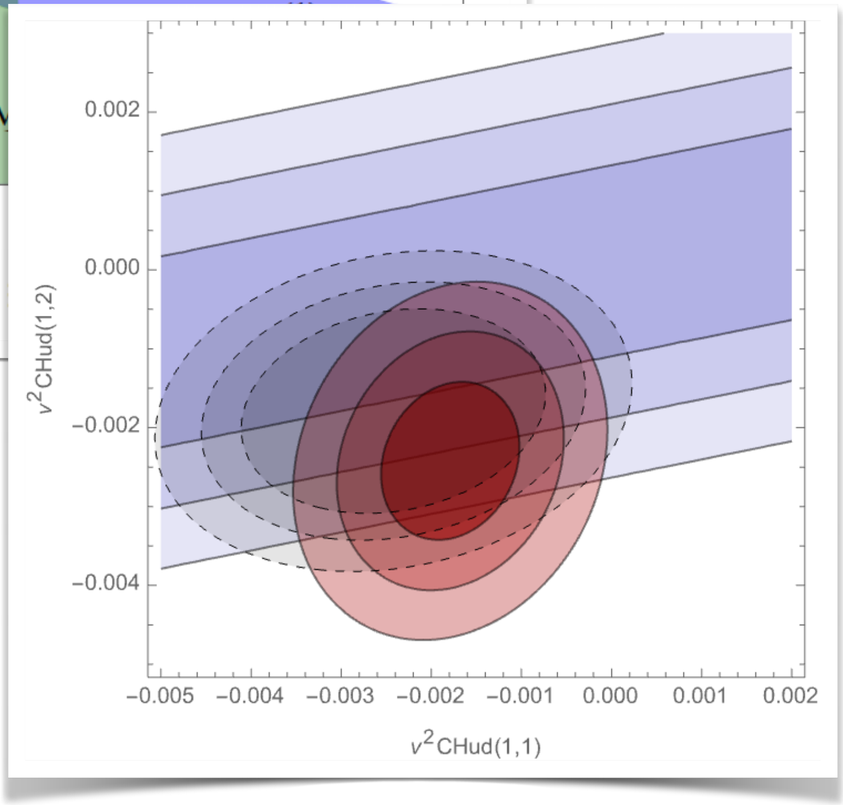
C_{Hud}

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





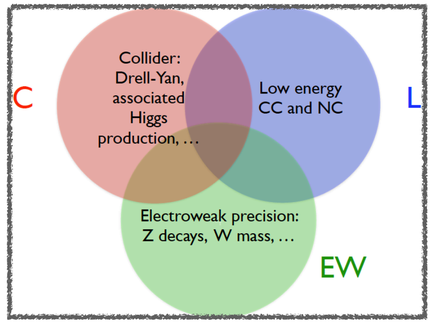
$K \to \pi\pi$

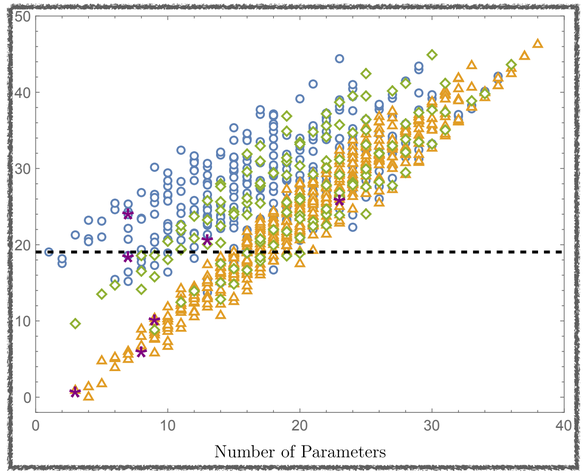


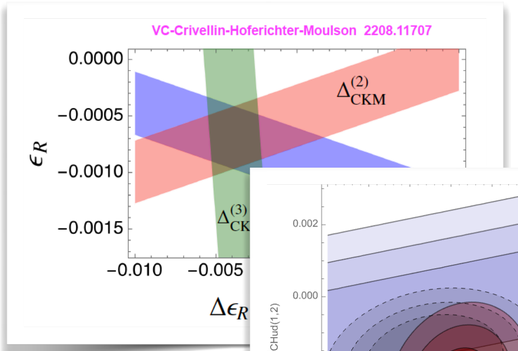
Summary: the CLEW framework

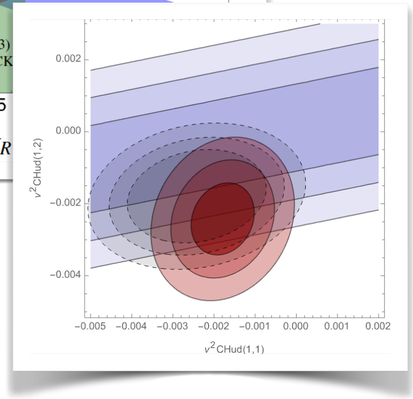
Global analysis	Indices
$C_{Hl\,pr}^{(1,3)}$, $C_{He\,pr}$	$pr \in \{ee,\ \mu\mu,\ \tau\tau\}$
$C_{Hq\,pr}^{(d)}$, $C_{Hd\,pr}$	$pr \in \{11, 22, 33\}$
$C_{Hq\,pr}^{(u)}$, $C_{Hu\,pr}$	$pr \in \{11, 22\}$
$C_{Hud\,pr}$	$pr \in \{11, 12\}$
$C_{lq\,\ell\ell pr}^{(d)}$, $C_{ledq\,\ell\ell pr}$	$\ell \in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

C_{Hud}









Finale

Merriam-Webster | Dictionary | Thesaurus | clew

Dictionary

Definition

- noun
- verb

clew 1 of 2 noun

'klü

1 : a ball of thread, yarn, or cord

Definition

- noun
- verb

- Did you know?
- Word History
- Podcast
- Entries Near

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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. Also, *clew* is the only choice for the sailing senses.