BSM in rare b decays

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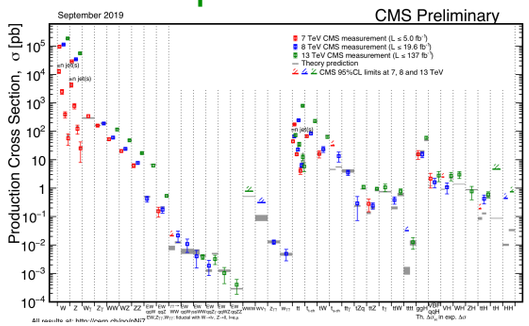
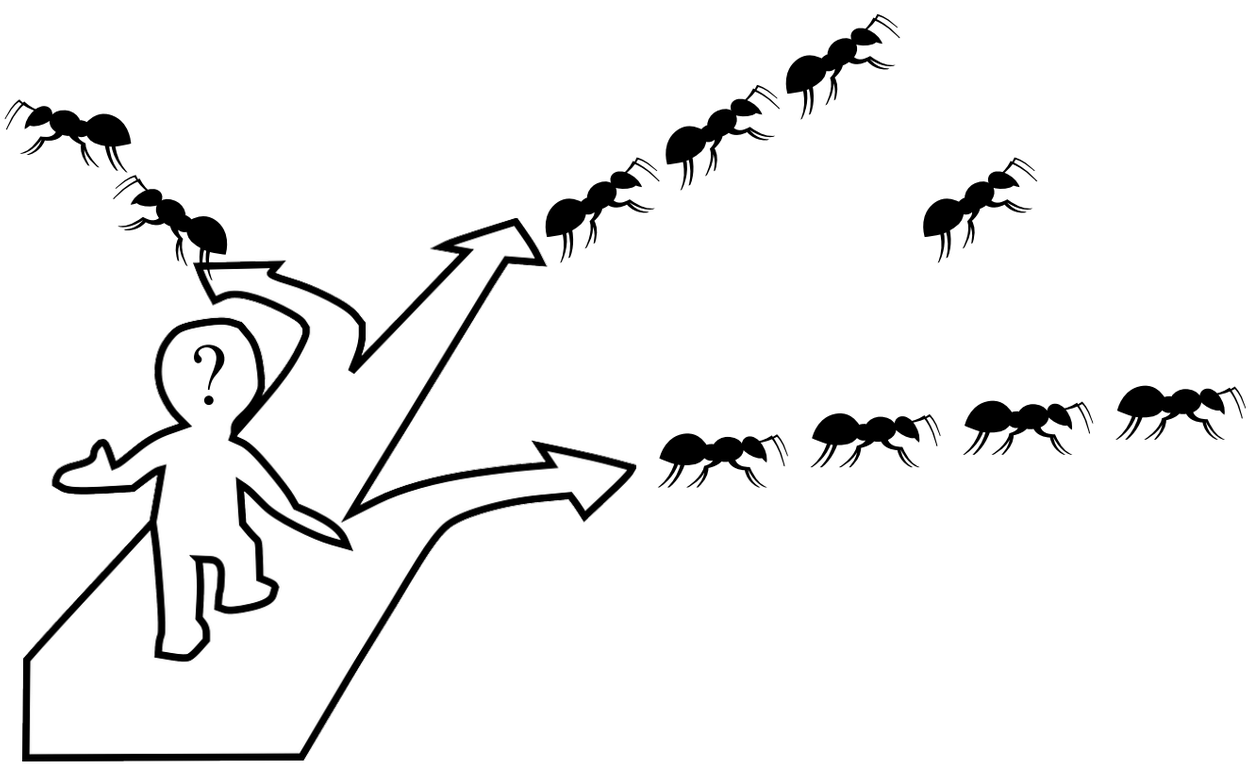
Confusing situation?!

1. The SM: Experimental success!



2. Yet, many open questions:

Hierarchy problem
Flavour puzzle
Strong CP problem
Charge quantization
Dark matter
Baryon asymmetry
Neutrino masses
Inflation
Dark energy
Quantum gravity
….

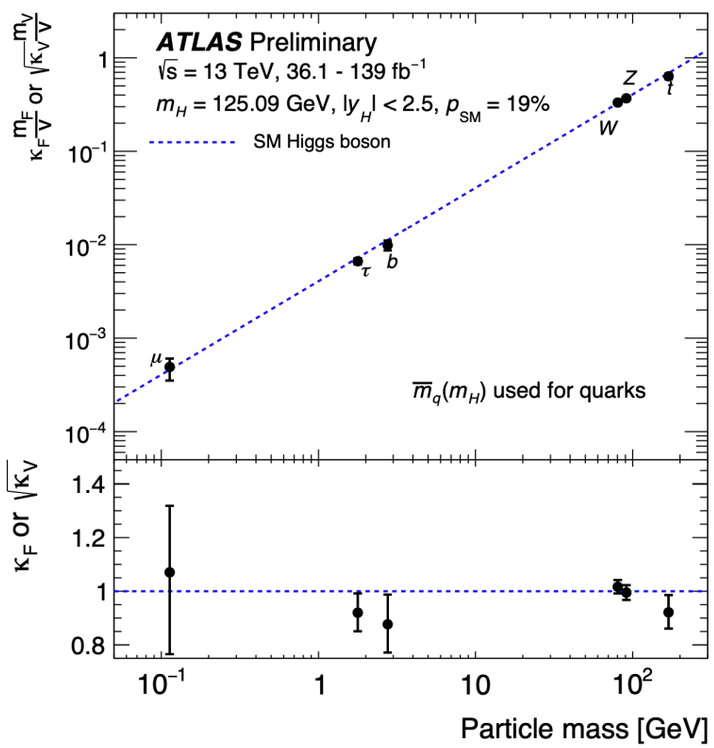


Beyond the SM

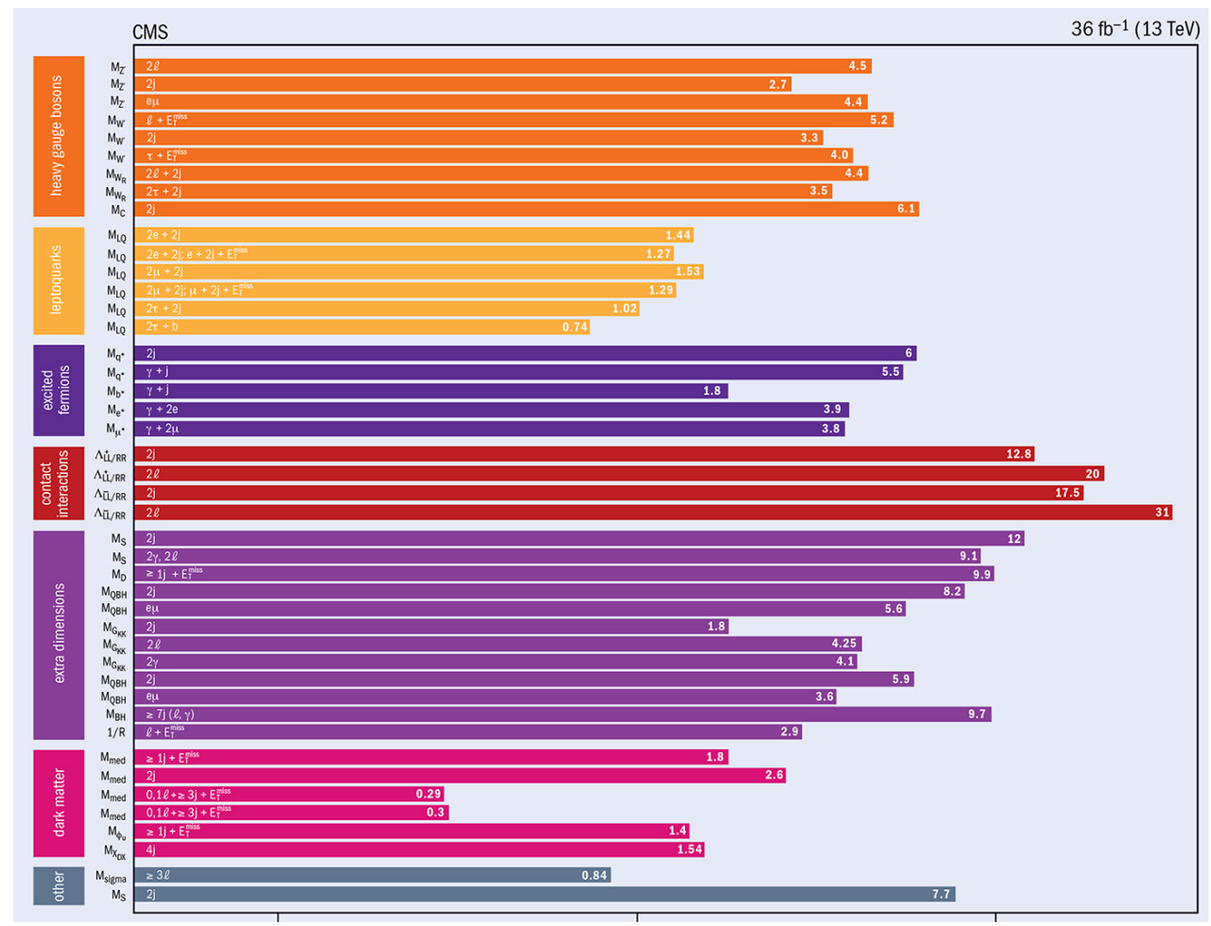
Solid QFT principles

- SM fields & symmetries
- Scale separation $\Lambda_{\rm Q} \gg v_{\rm EW}$
- Higher-dimensional operators encode short-distance physics:

$$\mathscr{L} = \sum_{Q} \frac{C_Q}{\Lambda_Q^{[Q]-4}} Q$$

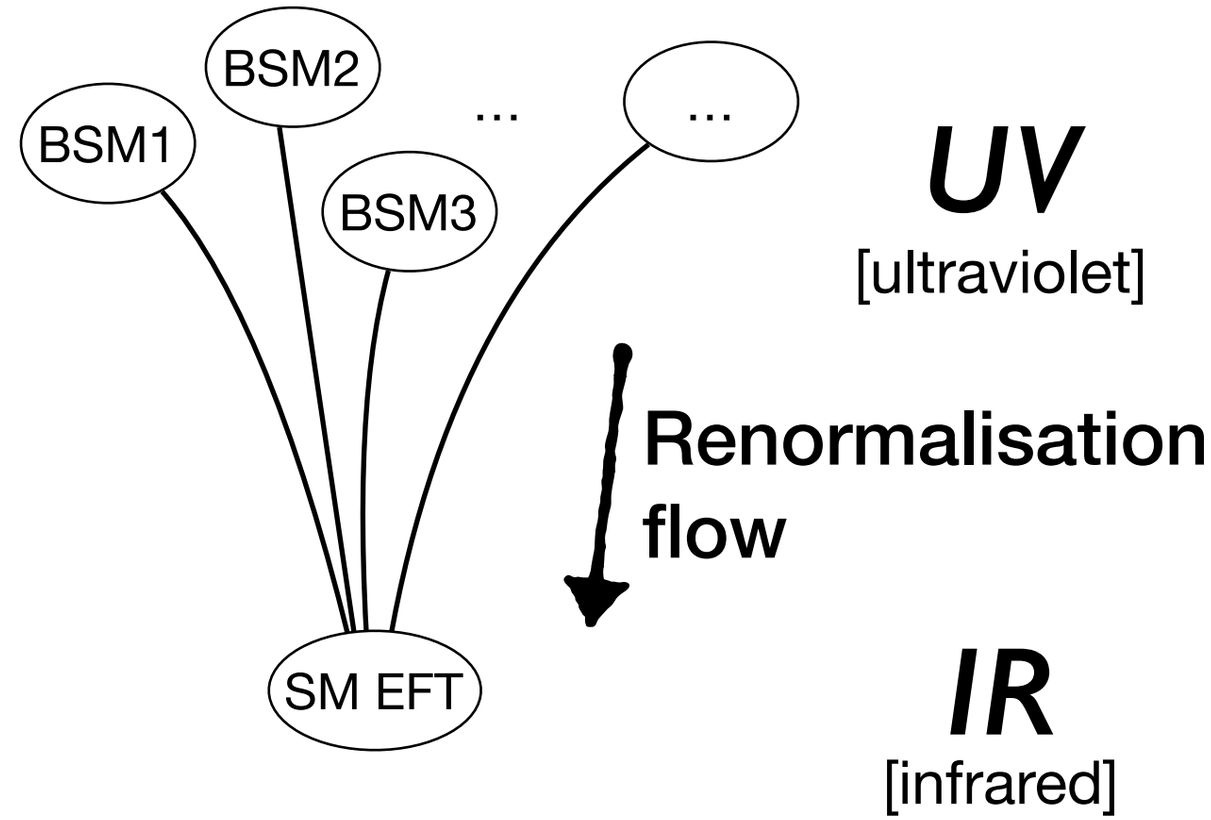


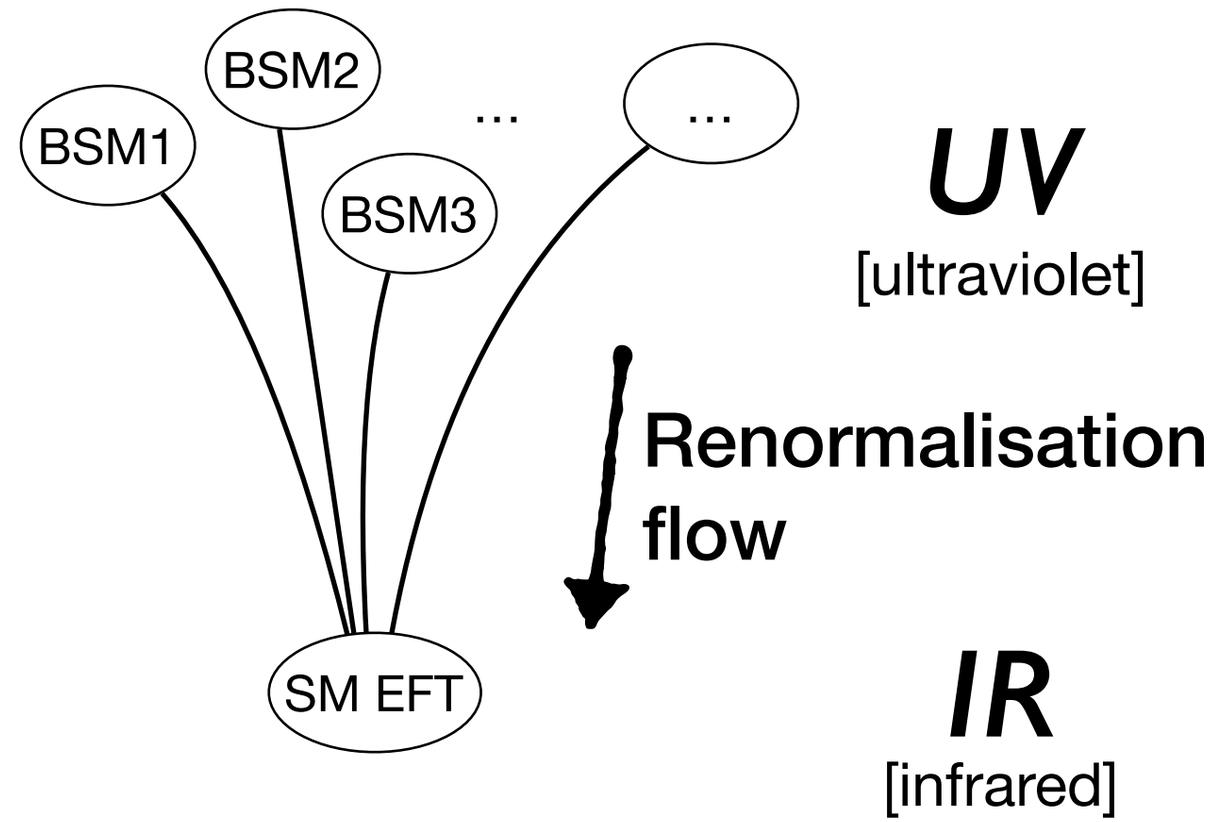
Linear EWSB?



NP mass gap?

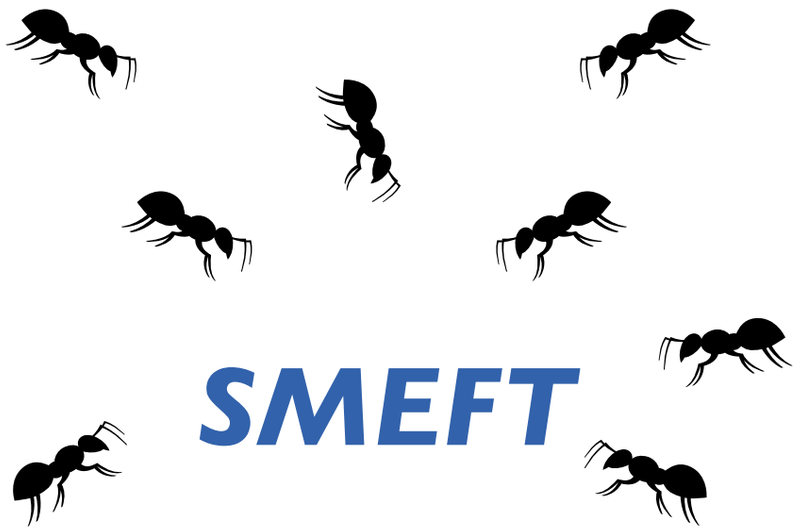

SMEFT


BSM1
BSM2
...
BSM3
...
UV
[ultraviolet]
Renormalisation flow
SM EFT
IR
[infrared]



<u>Reinforced by the current state of affairs</u>

1. No clear preferred BSM: Short-distance direction still the most compelling
2. SMEFT explains why SM works well: limited luminosity and energy so far
3. Experiments headed towards the precision era



- Challenge: **A large number of independent parameters!**
- 2499 $\dim[\mathcal{O}] = 6$ $\Delta B = \Delta L = 0$ independent operators
- Why? **3 flavours**
- For a single generation, this would be 59

SMEFT $\mathcal{O}(1)$ terms (dim-6, $\Delta B = 0$)		Lepton sector							
		MFV_L	$\mathrm{U}(3)_V$	$\mathrm{U}(2)^2 \times \mathrm{U}(1)$	$\mathrm{U}(2)^2$	$\mathrm{U}(2)_V$	$\mathrm{U}(1)^6$	$\mathrm{U}(1)^3$	No symm.
Quark sector	MFV_Q	47	54	65	71	80	87	111	339
	$\mathrm{U}(2)^2 \times \mathrm{U}(3)_d$	82	93	105	115	128	132	168	450
	$\mathrm{U}(2)^3 \times \mathrm{U}(1)_{b_\mathrm{R}}$	96	107	121	128	144	150	186	480
	$\mathrm{U}(2)^3$	110	123	135	147	162	164	206	512
	No symm.	1273	1334	1347	1407	1470	1425	1611	2499

AG, Thomsen, Palavric; 2203.09561
See also: AG, Palavric; 2305.08898

Theory of weak decays

[See talk by Gambino]

Effective Field Theory
Factorisation

$$\langle \mathscr{H}_{eff} \rangle \propto \langle Q(\mu) \rangle \; C(\mu)$$

long-distance contributions $E < \mu$

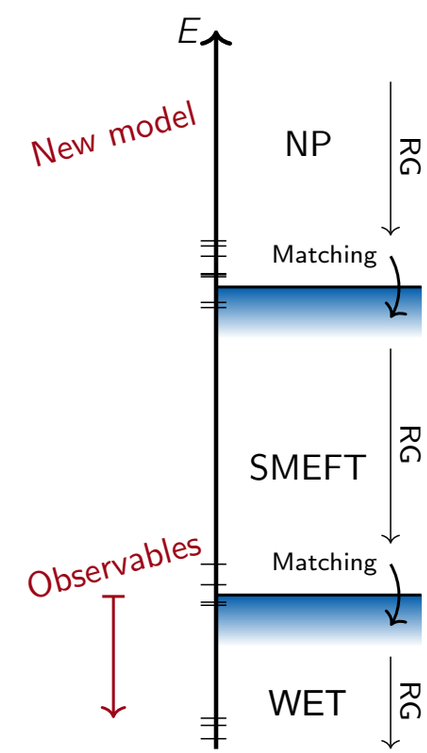
short-distance contributions $E > \mu$

Hadronic matrix elements

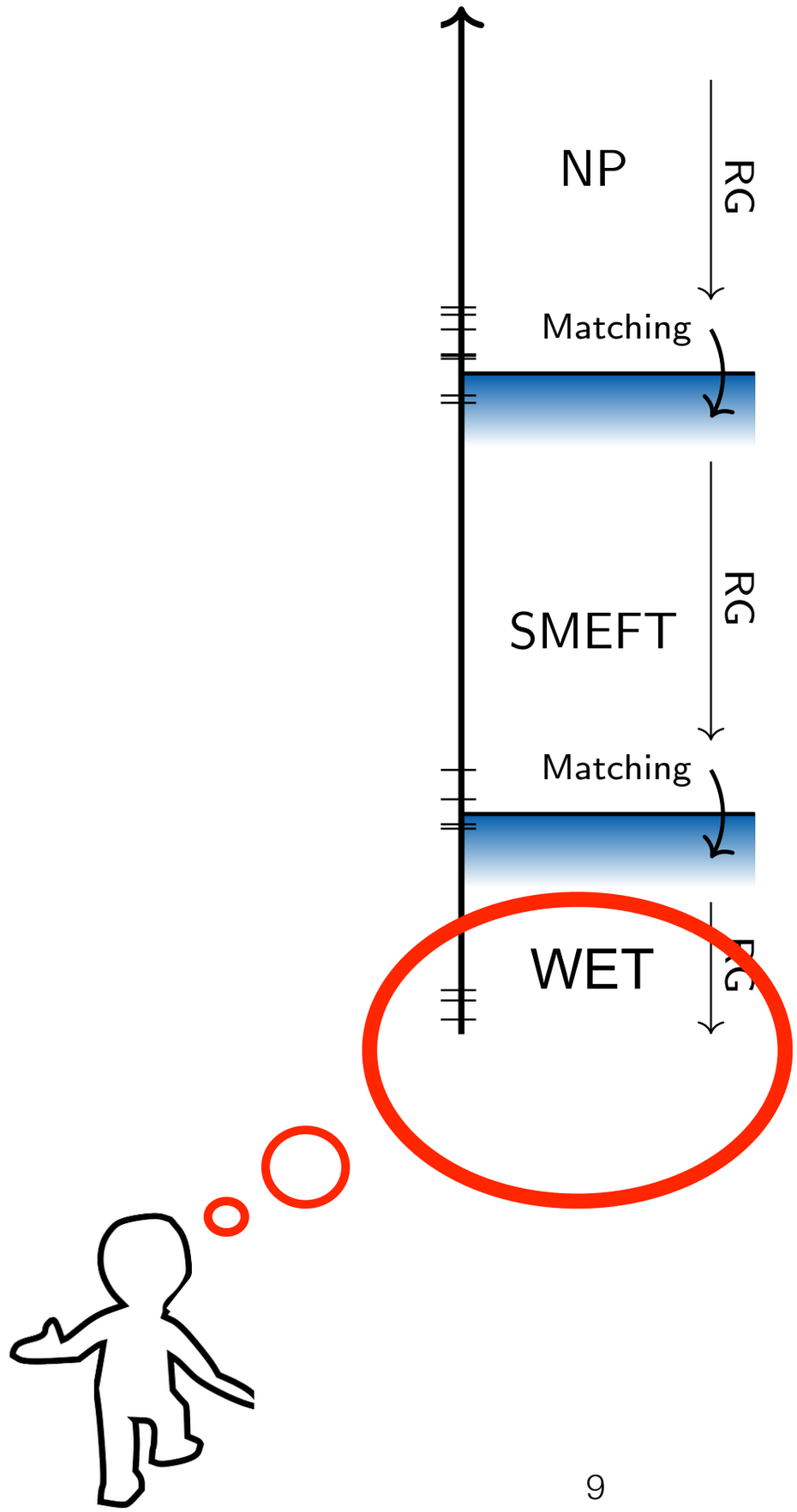
2205.15373, 2205.13952, 2204.09091, 2108.05589, 1904.08731, 1902.09553, 1908.09398, 1912.09335, 1908.07011, 2002.00020, 2006.07287, 2101.12028, 2105.09330, 2106.12168, 2112.07685, 2206.11281, …

Lattice QCD, http://flag.unibe.ch/2021/
Heavy quark effective theory,
Heavy quark expansion,
QCD factorisation,
SCET,
ChPT,
QCD sum rules,
Light-cone sum rules,
…

Wilson coefficients



1308.2627, 1310.4838, 1312.2014, 1709.04486, 1711.05270, 1711.10391, 1710.06445, 1804.05033, 1908.05295, 2010.16341, 2012.08506, 2012.07851, …



[See talk by Capdevila:
WET interpretation of $b \to s\ell\ell$]

The EFT at LHCb, Belle II, BESIII, …

- Remarkably, short-distance NP enters weak decays through a handful of parameters (Wilson coefficients in the WET)
- It is important to take this opportunity, and exploit it maximally!
  More can be done…

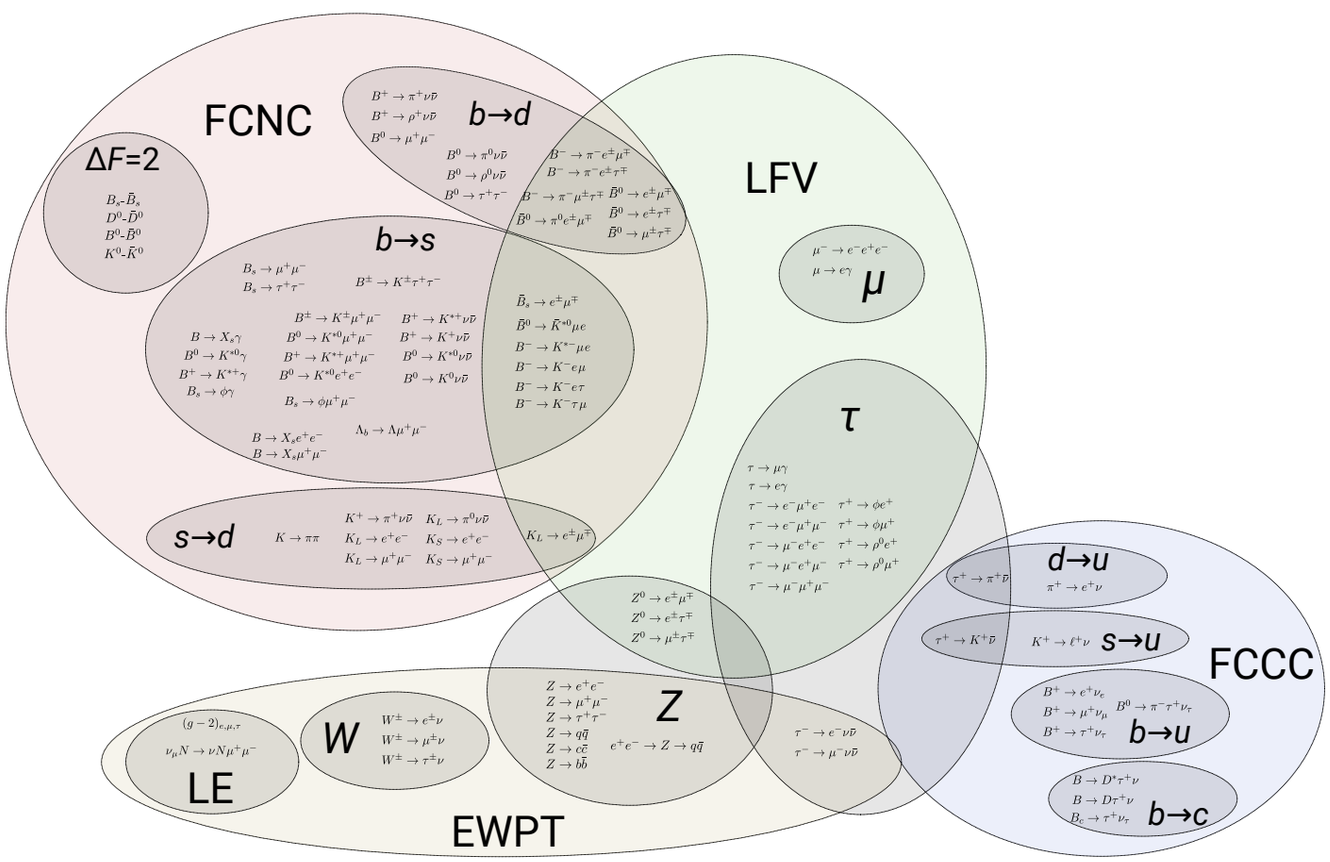
[See the LHC EFT WG at the LPCC. LHCb is a part of it.]

Why?

- EFT interpretation of an analysis informs model builders about its importance relative to the global data!
- Construction of the global SMEFT likelihood an ideal format to report particle physics experiments if NP is short-distance.

Towards a global SMEFT likelihood

- **SMEFT** - the low-energy limit of a generic microscopic new physics
- Correlated deviations expected — **global approach** needed

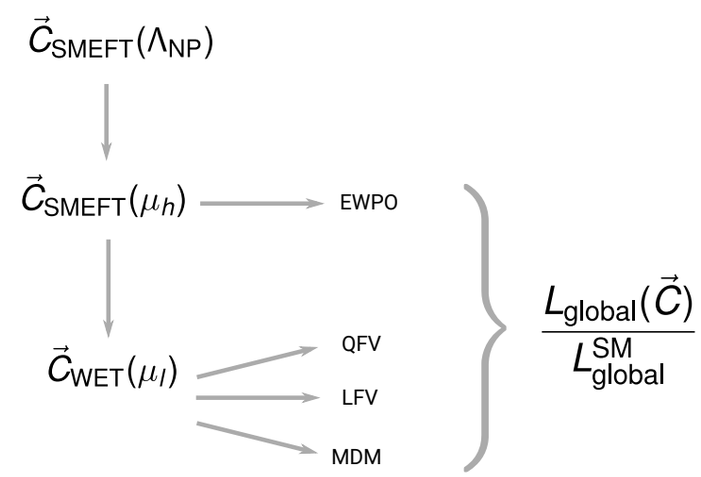


smelli Aebischer, Kumar, Stangl, Straub, 1810.07698

wilson Aebischer, Kumar, Straub, 1804.05033

flavio Straub, 1810.08132

$$L(\vec{C}) \approx \prod_i L^i_{\text{exp}}(\vec{O}_{\text{th}}(\vec{C},\vec{\theta}_0)) \times \tilde{L}_{\text{exp}}(\vec{O}_{\text{th}}(\vec{C},\vec{\theta}_0))$$



See also:
https://hepfit.roma1.infn.it
Blas et al, 1910.14012
https://eos.github.io
van Dyk et al, 2111.15428
...

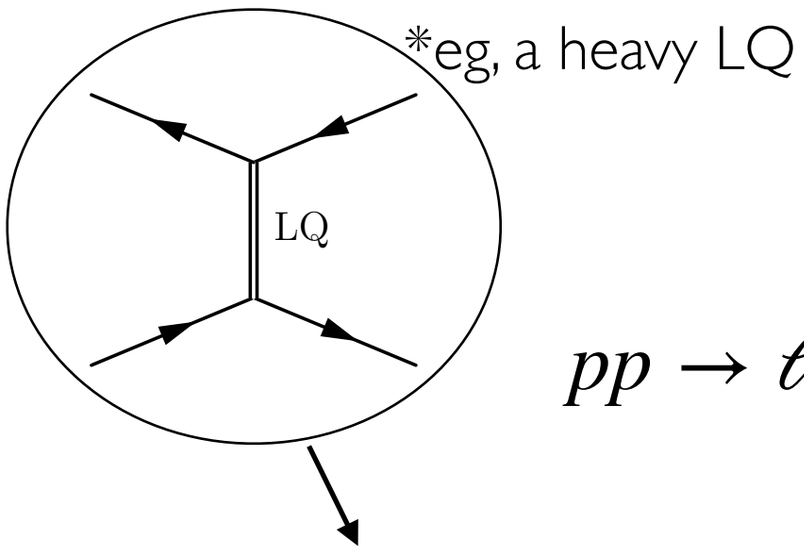
The SMEFT correlations

- How realistic is it to discover short-distance NP in a given observable given the global data?

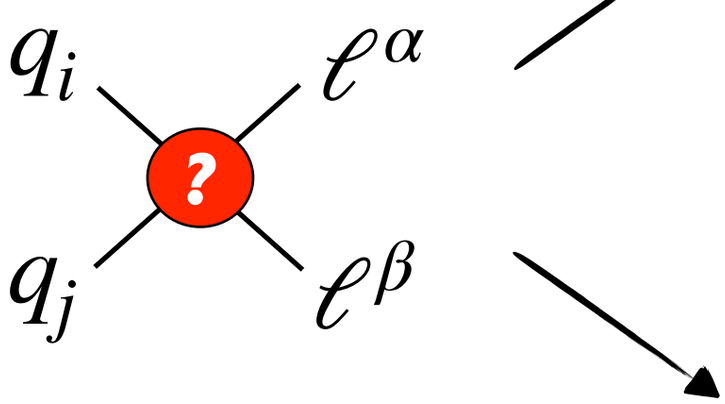
[See Gudrun's talk: SMEFT bounds from charged lepton processes on $c \to u\nu\nu$]

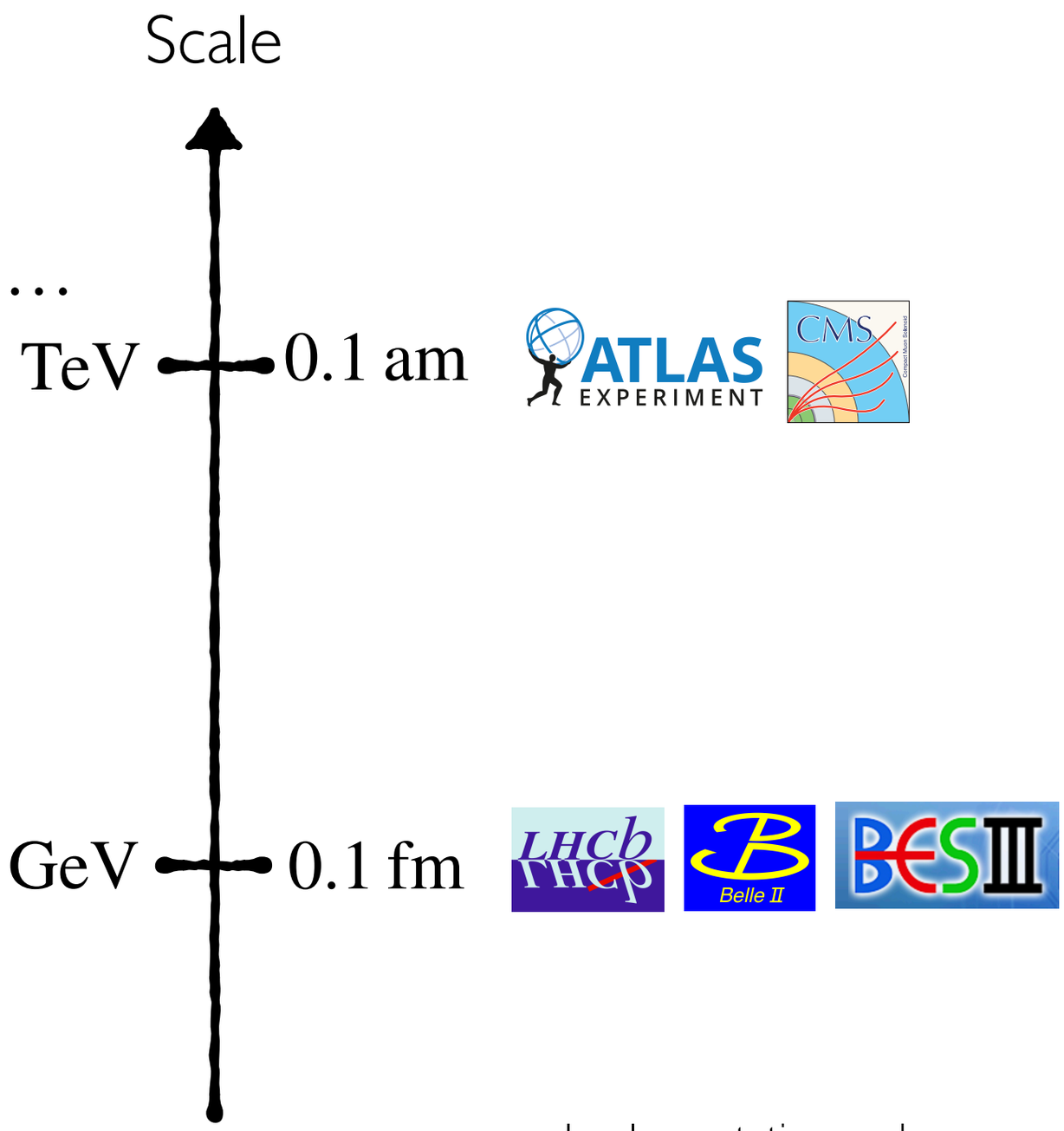
An example on the next slide =>

Drell-Yan versus Weak Decays



$$pp \to \ell^+_\alpha \ell^-_\beta (j), \ \ldots$$





Example: $b \to s\mu\mu$ vs Drell-Yan

AG, Marzocca; 1704.09015

Implementation and systematic study in `flavio`

AG, Salko, Smolkovic, Stangl; 2212.10497

SMEFT example

$$[C_{lq}^{(1)}]_{st}^{(l)}(\bar{l}_l\gamma_\mu l_l)(\bar{q}_s\gamma^\mu q_t)$$

$$[C_{lq}^{(1)}]^{(\ell)} \equiv [C_{lq}^{(1)}]^{(e)} = [C_{lq}^{(1)}]^{(\mu)}$$

$$Q_{lq}^{(1)} = (\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t)$$

AG, Salko, Smolkovic, Stangl; 2212.10497

SMEFT example

MFV expansion

$$[C_{lq}^{(1)}]_{st}^{(l)}(\bar{l}_l\gamma_\mu l_l)(\bar{q}_s\gamma^\mu q_t) \to [C_{lq}^{(1)}]_{st}^{(l)} = \delta_{st}[C_{lq}^{(1)}]_{\delta}^{(l)} + (Y_u Y_u^\dagger)_{st}[C_{lq}^{(1)}]_{Y_u Y_u^\dagger}^{(l)} + \ldots$$

$$[C_{lq}^{(1)}]^{(\ell)} \equiv [C_{lq}^{(1)}]^{(e)} = [C_{lq}^{(1)}]^{(\mu)}$$

$$\sim y_t^2 \begin{pmatrix} V_{td}V_{td}^* & V_{ts}V_{td}^* & V_{tb}V_{td}^* \\ V_{td}V_{ts}^* & V_{ts}V_{ts}^* & V_{tb}V_{ts}^* \\ V_{td}V_{tb}^* & V_{ts}V_{tb}^* & V_{tb}V_{tb}^* \end{pmatrix}$$

AG, Salko, Smolkovic, Stangl; 2212.10497

SMEFT example

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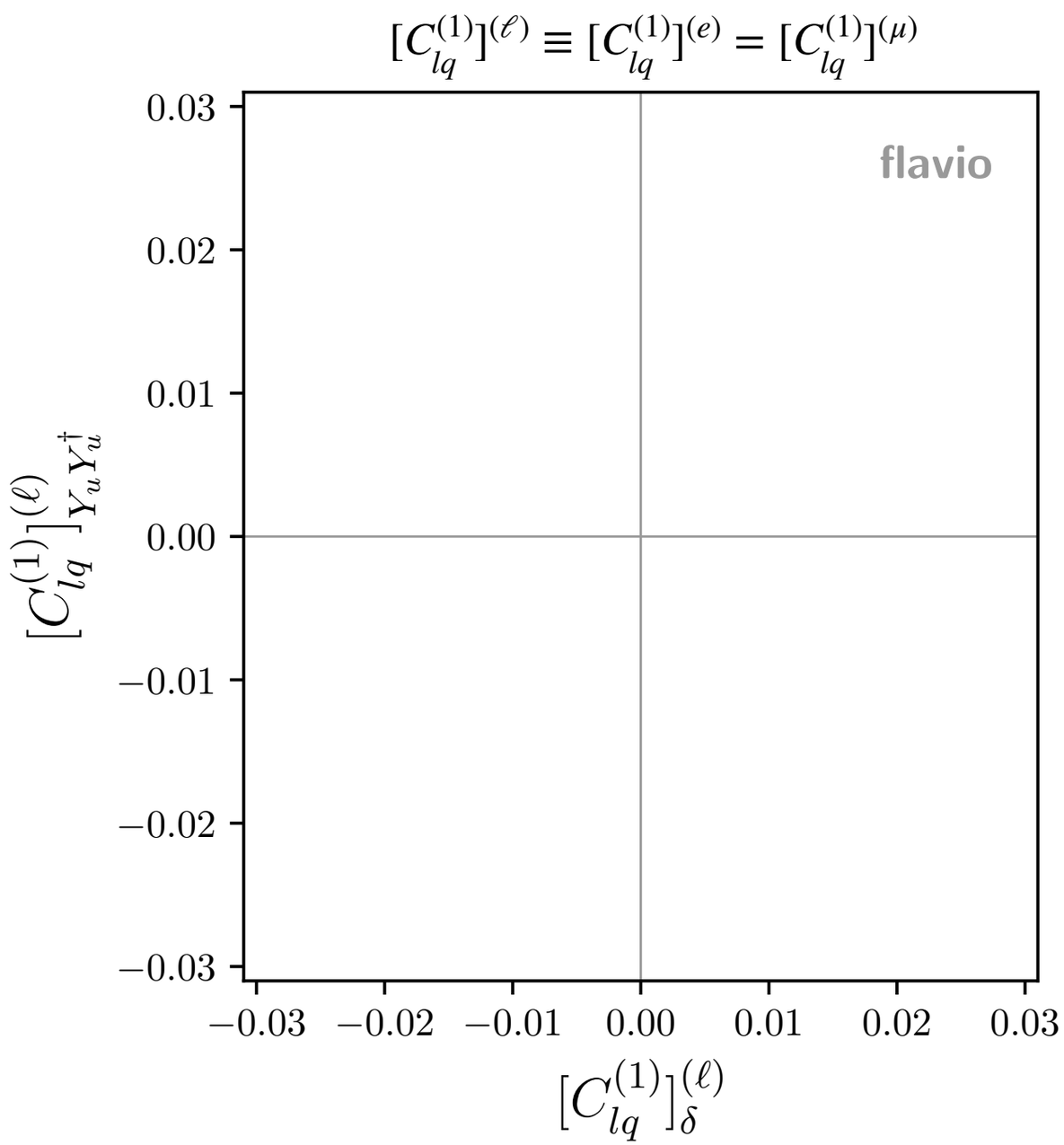

AG, Salko, Smolkovic, Stangl; 2212.10497

SMEFT example

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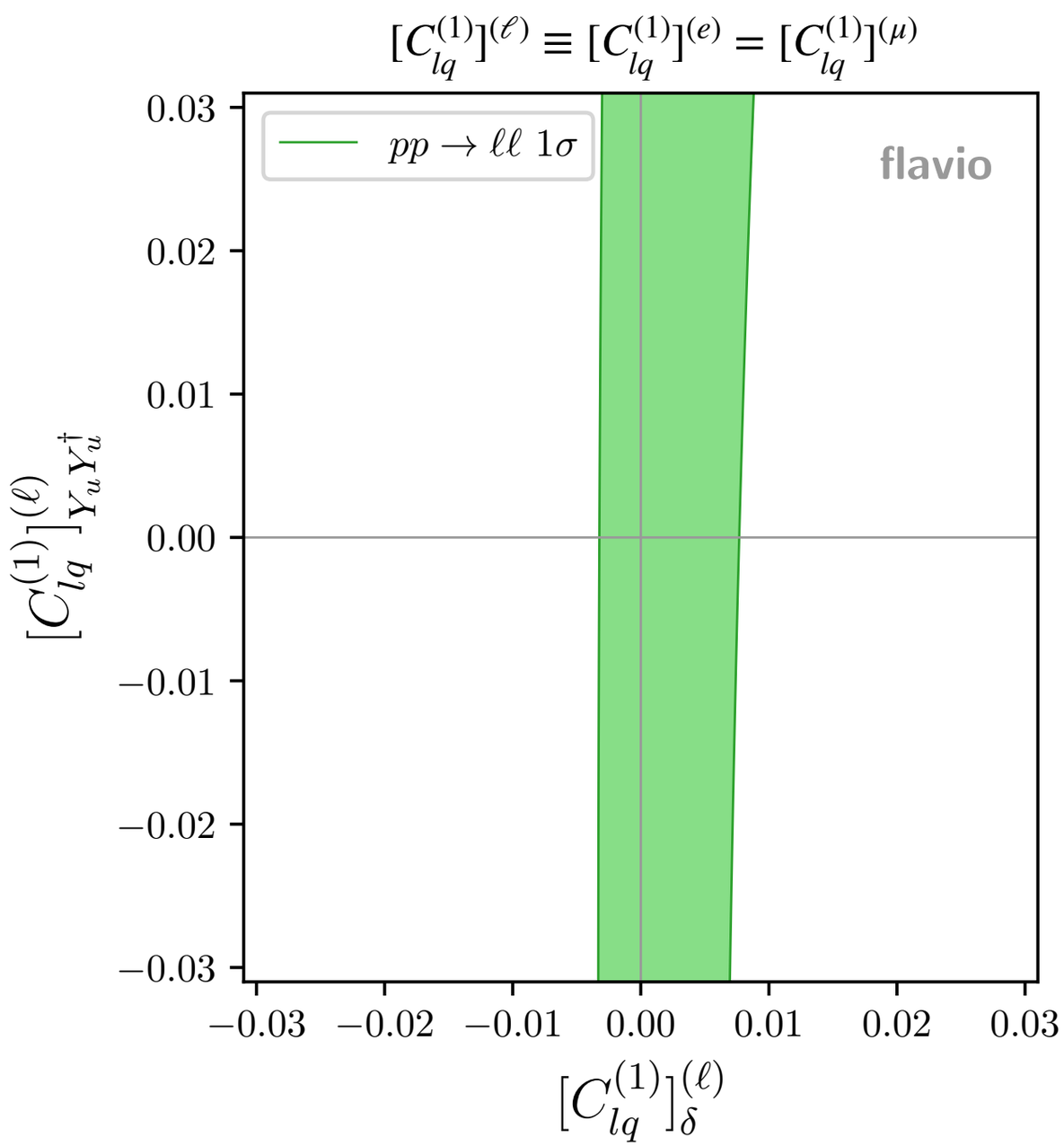

AG, Salko, Smolkovic, Stangl; 2212.10497

SMEFT example

MFV expansion

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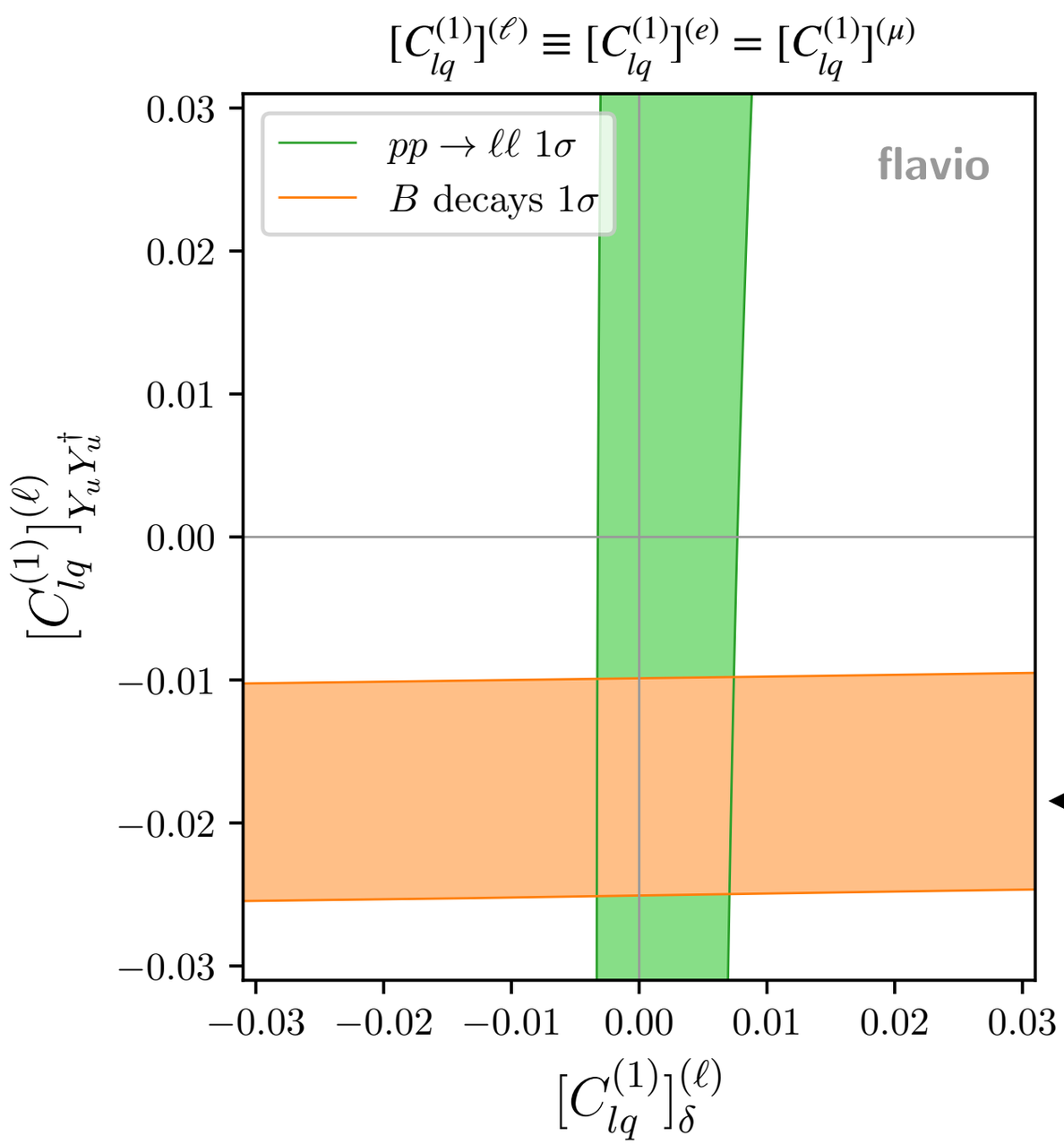


Dominated by $b \to s\mu\mu$

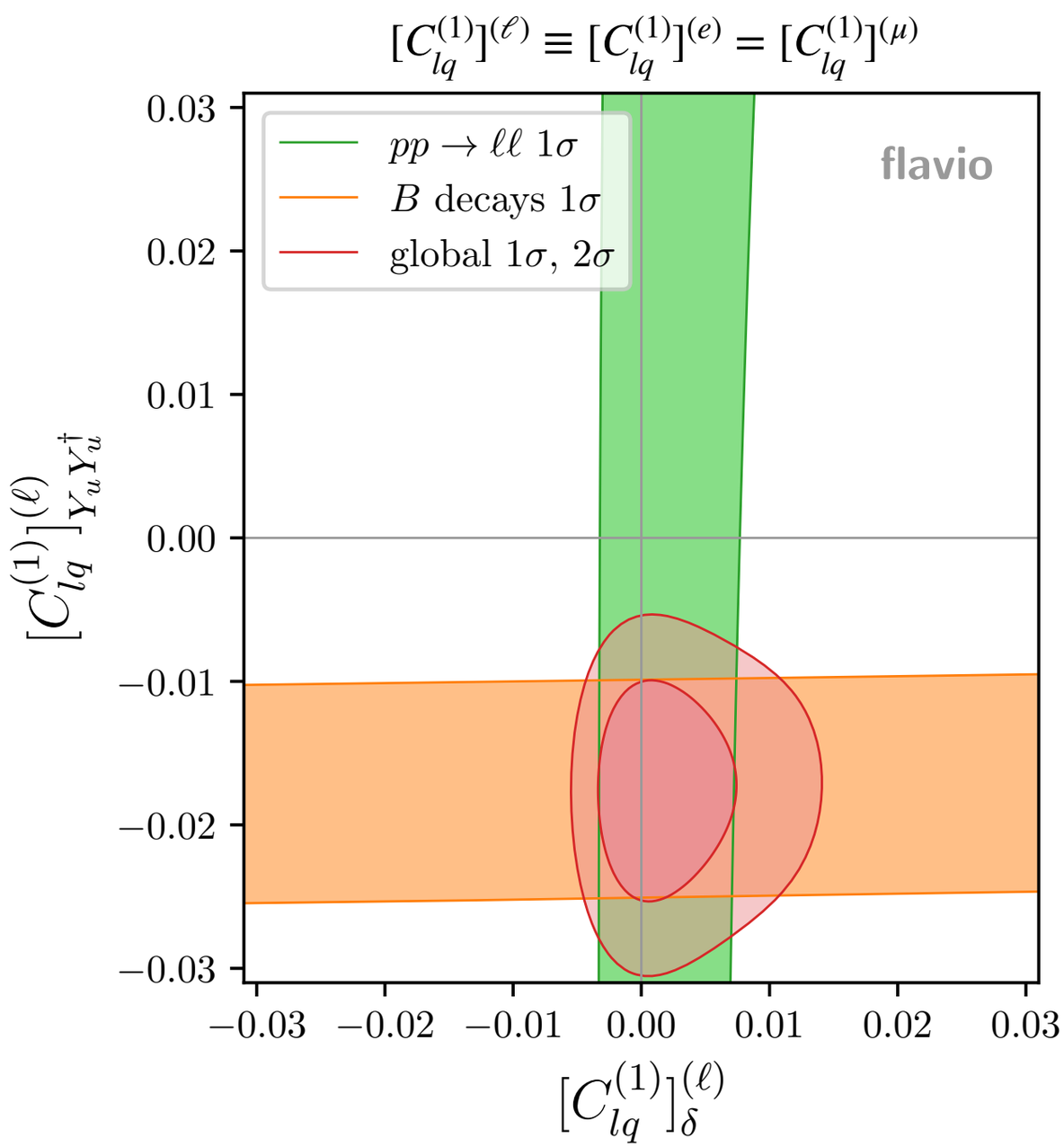
AG, Salko, Smolkovic, Stangl; 2212.10497

SMEFT example

MFV expansion

$$[C_{lq}^{(1)}]_{st}^{(l)}(\bar{l}_l\gamma_\mu l_l)(\bar{q}_s\gamma^\mu q_t) \to [C_{lq}^{(1)}]_{st}^{(l)} = \delta_{st}[C_{lq}^{(1)}]_{\delta}^{(l)} + (Y_u Y_u^\dagger)_{st}[C_{lq}^{(1)}]_{Y_u Y_u^\dagger}^{(l)} + \dots$$

$$\sim y_t^2 \begin{pmatrix} V_{td}V_{td}^* & V_{ts}V_{td}^* & V_{tb}V_{td}^* \\ V_{td}V_{ts}^* & V_{ts}V_{ts}^* & V_{tb}V_{ts}^* \\ V_{td}V_{tb}^* & V_{ts}V_{tb}^* & V_{tb}V_{tb}^* \end{pmatrix}$$



AG, Salko, Smolkovic, Stangl; 2212.10497

SMEFT example

MFV expansion

$$[C_{lq}^{(1)}]_{st}^{(l)}(\bar{l}_l\gamma_\mu l_l)(\bar{q}_s\gamma^\mu q_t) \to [C_{lq}^{(1)}]_{st}^{(l)} = \delta_{st}[C_{lq}^{(1)}]_{\delta}^{(l)} + (Y_uY_u^\dagger)_{st}[C_{lq}^{(1)}]_{Y_uY_u^\dagger}^{(l)} + \dots$$

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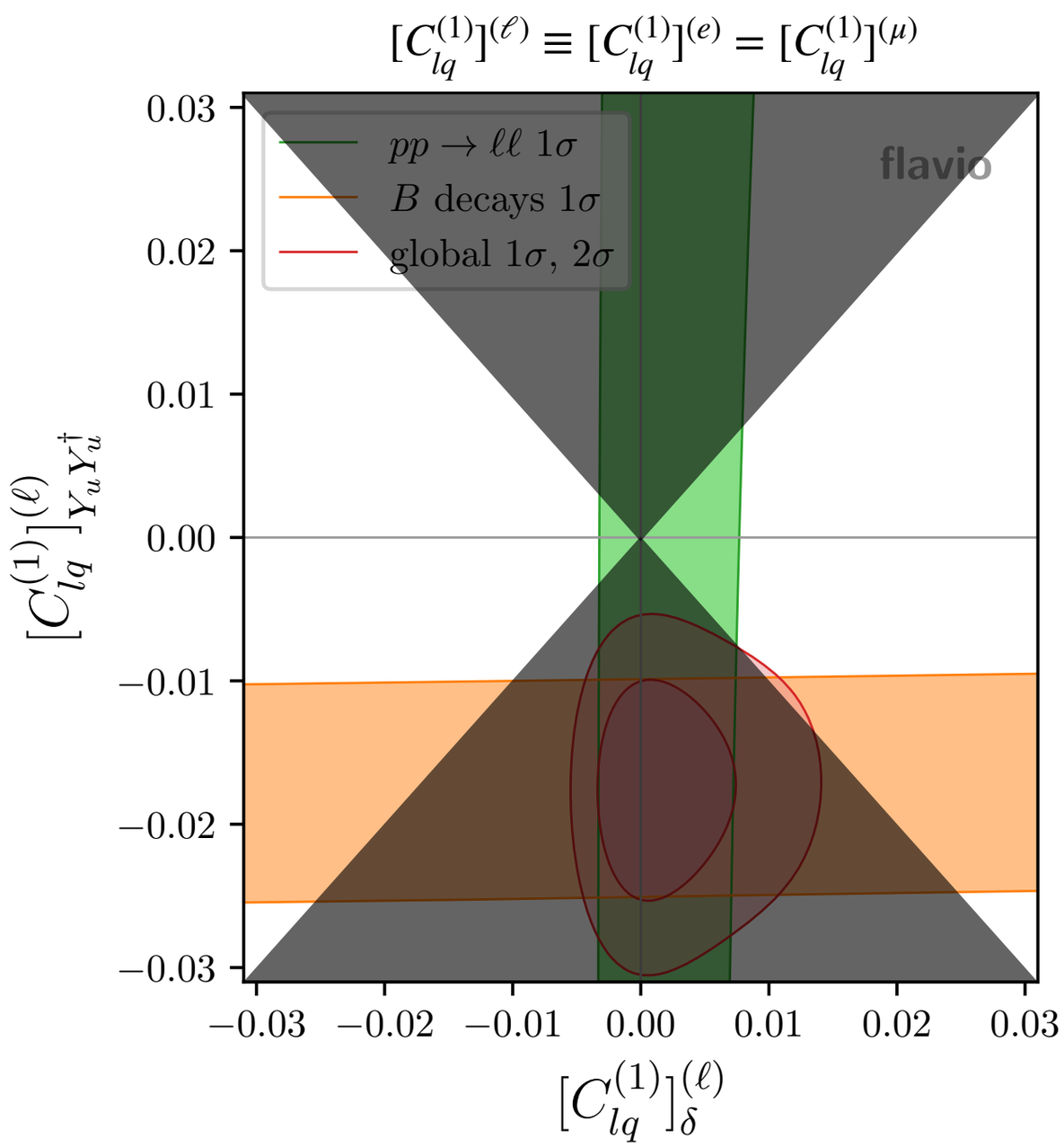


MFV Expansion validity?

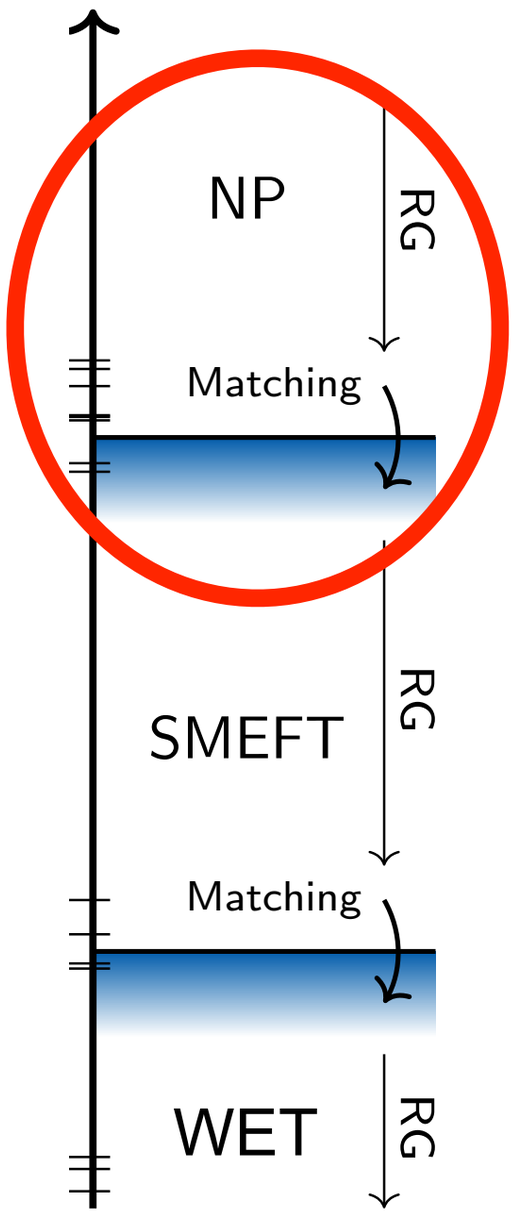
Linear MFV: $|[C_{lq}^{(1)}]_{Y_uY_u^\dagger}| \ll |[C_{lq}^{(1)}]_{\delta}|$ 0903.1794

A large class of models ruled out!

AG, Marzocca; 1704.09015

AG, Salko, Smolkovic, Stangl; 2212.10497

SMEFT: Systematic BSM



New Physics

- Strongly coupled

  Yet, SMEFT works provided the mass gap

- Perturbative

  1. Tree-level

     Finite number of topologies, classified at dim-6.

  2. Loop-level

     Infinite but countable.

To get a large effect in weak decays:

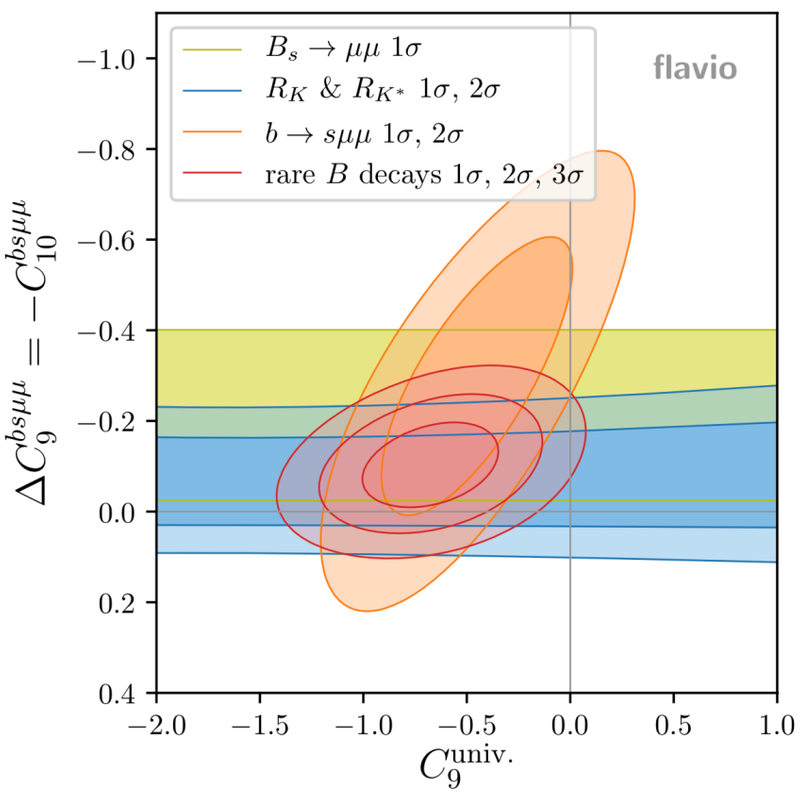
- a large coupling

  Perturbativity

- a small mass

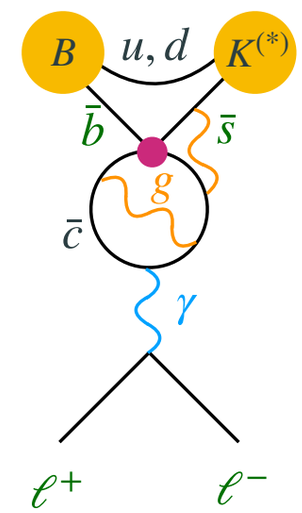
  Direct searches

AG, Salko, Smolkovic, Stangl; 2212.10497



[See talk by Capdevila]

- The $b \to s\ell\ell$ global fits prefer universal C_9
- Based on the symmetries, looks like a QCD, but the size of the effect is (maybe) too big?



[See talk by Gubernari]

Q: LFU NP in $b \to s\ell\ell$?

"If it looks like a duck, walks like a duck and quacks like a duck, then it just may be a ~~duck.~~"
leptoquark

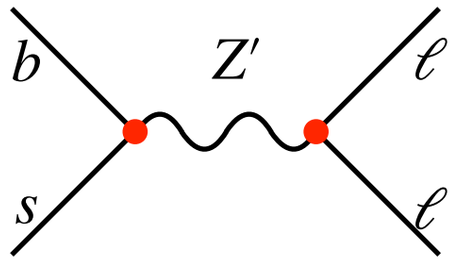
Disclaimer: My exercises is academic — NP in P_5' and co while $R_K = 1$ — there is still a room for LFUV, …

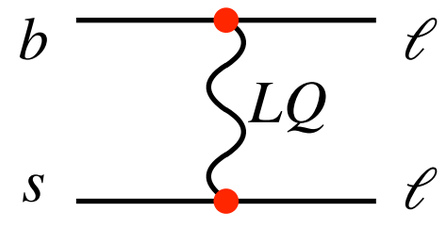
Systematic approach

Perturbative UV completion:

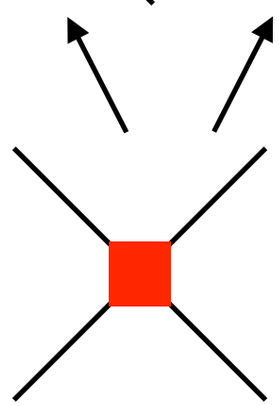
1. Tree-level models (leading operator)

NP:



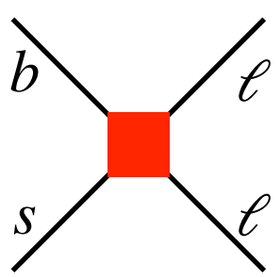


SMEFT:



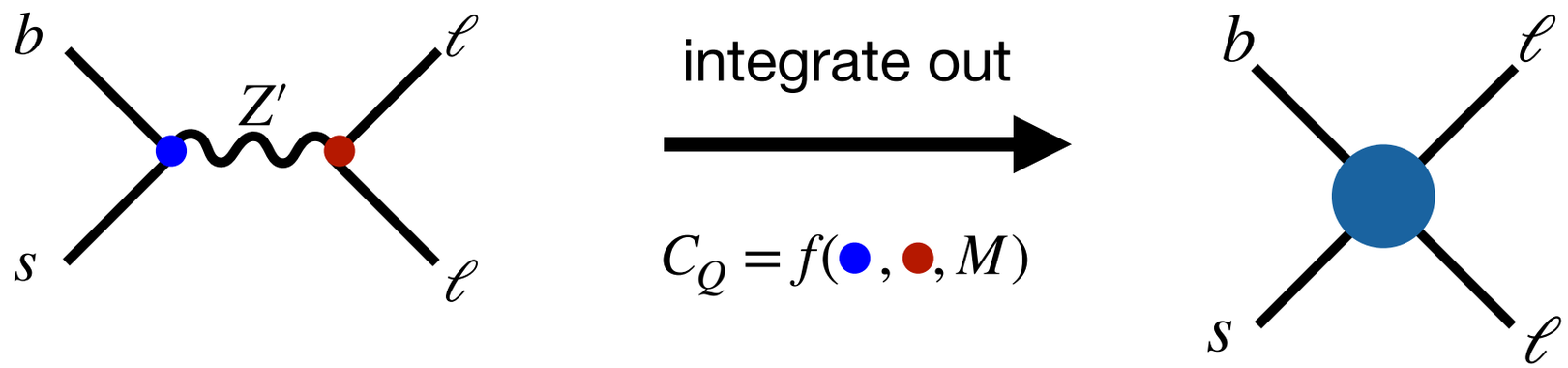
Or ~~Z vertex corrections~~

WET:



$$O_9^{bq\ell\ell} = (\bar{q}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell)$$

LFU models: Z'



$$Q_{lq}^{(1)} = (\bar{l}_p \gamma_\mu l_r)(\bar{q}_s \gamma^\mu q_t)$$

...

$$Q_{qq}^{(1)} = (\bar{q}_p \gamma_\mu q_r)(\bar{q}_s \gamma^\mu q_t)$$

...

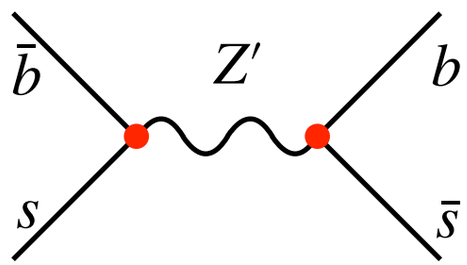
$$Q_{ll} = (\bar{l}_p \gamma_\mu l_r)(\bar{l}_s \gamma^\mu l_t)$$

...

prst - flavor

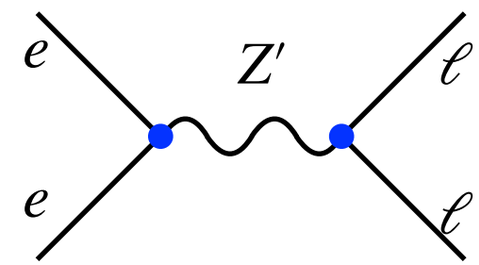
LFU models: Z'

- The bounds from



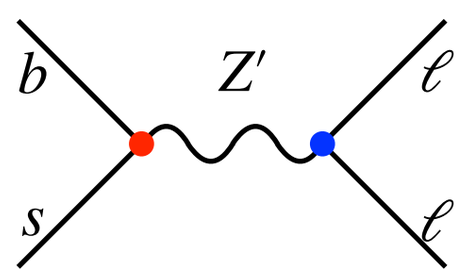
Meson mixing

+



LEP II

are too constraining



!

LFU models: Z'

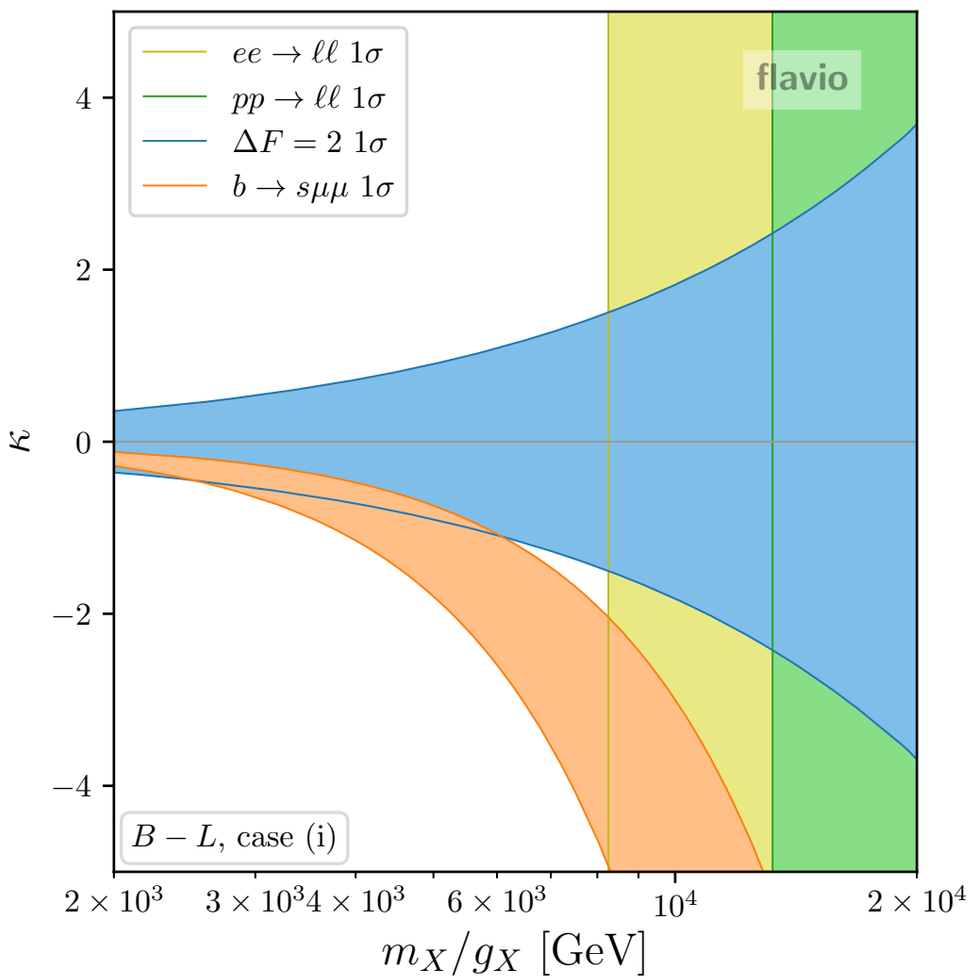
$$U(1)_{B-L}$$

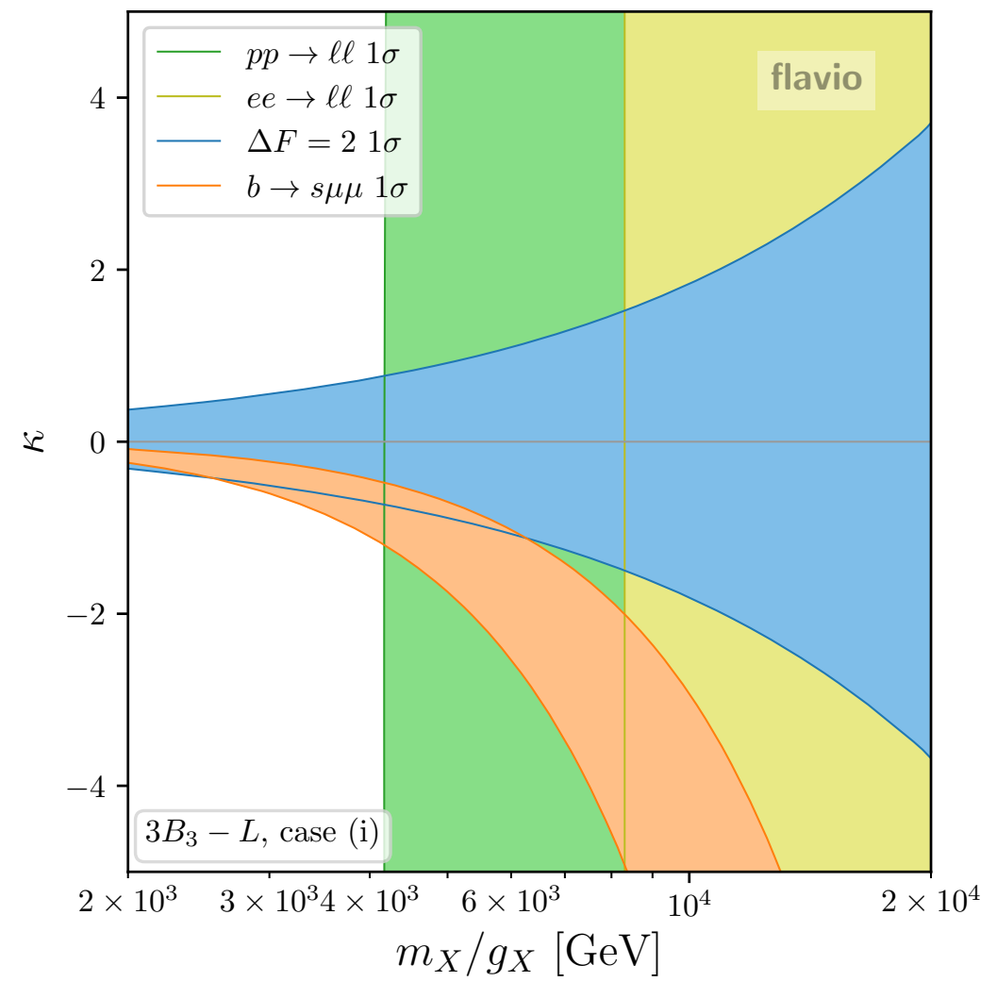
$$J^\mu = J^\mu_{B-L} + \frac{1}{3}\epsilon_{ij}\,\bar{q}_i\gamma^\mu q_j$$

$$\epsilon_{ij} = -\,\kappa\,|\,V_{ts}\,|\,(\delta_{i2}\delta_{j3} + \delta_{i3}\delta_{j2})$$

$$U(1)_{3B_3-L}$$

$$J^\mu = J^\mu_{3B_3-L} + \frac{1}{3}\epsilon_{ij}\,\bar{q}_i\gamma^\mu q_j$$





Tension!

AG, Salko, Smolkovic, Stangl; 2212.10497

LFU leptoquark

- First of all, no single leptoquark representation gives C_9 only

Doršner, Fajfer, AG, Kamenik, Košnik; 1603.04993

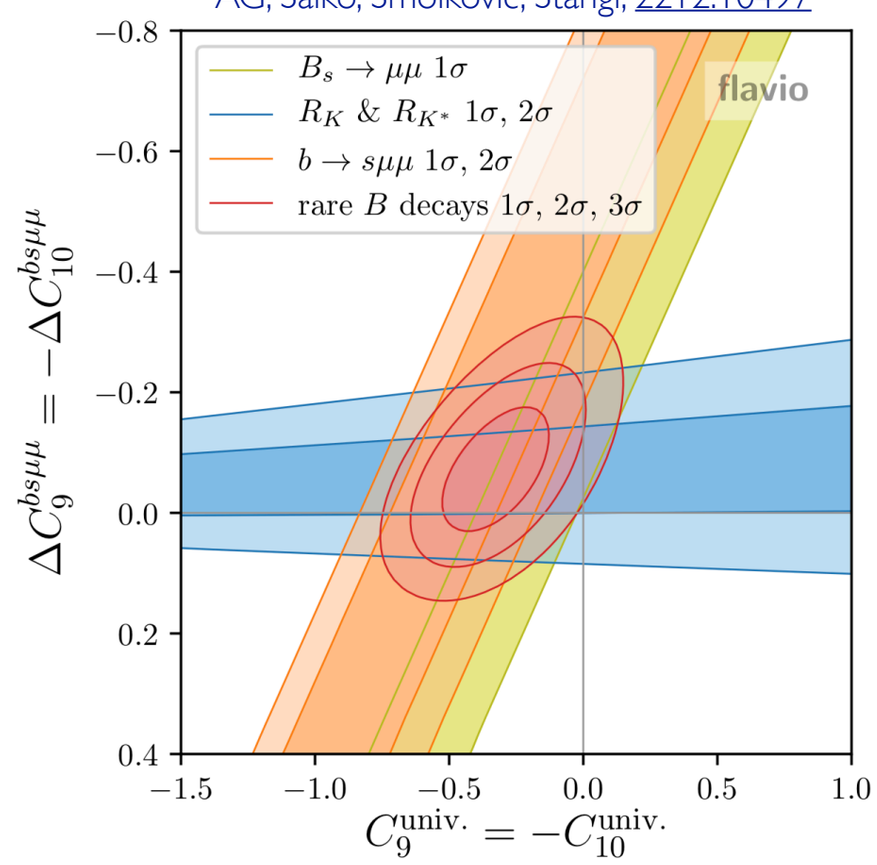
$$R_2 = (\mathbf{3}, \mathbf{2}, 7/6) \quad + \quad S_3 = (\overline{\mathbf{3}}, \mathbf{3}, 1/3)$$

$$\bar{e}_R^i R_2^{a\,*} Q_L^{j,a} \qquad\qquad \bar{Q}_L^{C\,i,a} \epsilon^{ab} (\tau^k S_3^k)^{bc} L_L^{j,c}$$

$$O_9^{bq\ell\ell} = (\bar{q}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell)$$

- Perhaps:

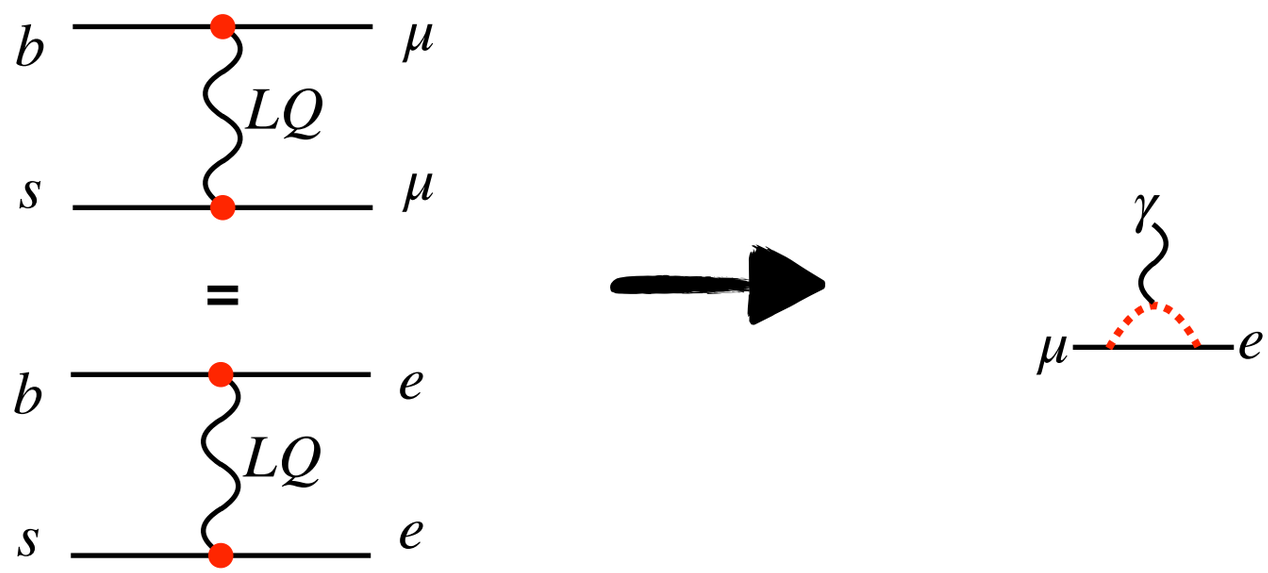
AG, Salko, Smolkovic, Stangl; 2212.10497



[See talk by Capdevila]

LFU leptoquark

- In addition, excluded by cLFV!



+ other cLFV

LFU leptoquark

- Solution: Leptoquark as $SU(2)$ flavor multiplet

$$(\bar{\mathbf{3}}, \mathbf{3}, 1/3) \times 2 = LQ_e + LQ_\mu$$

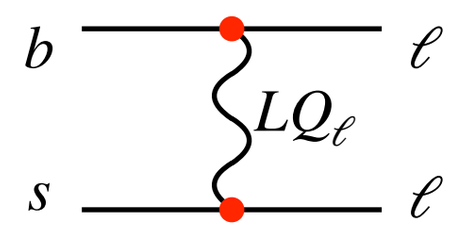
$$U(1)_e \times U(1)_\mu \times Z_2^{\mathrm{LFU}}$$

$$\downarrow$$

$$LQ_e \leftrightarrow LQ_\mu$$

$$e \leftrightarrow \mu$$

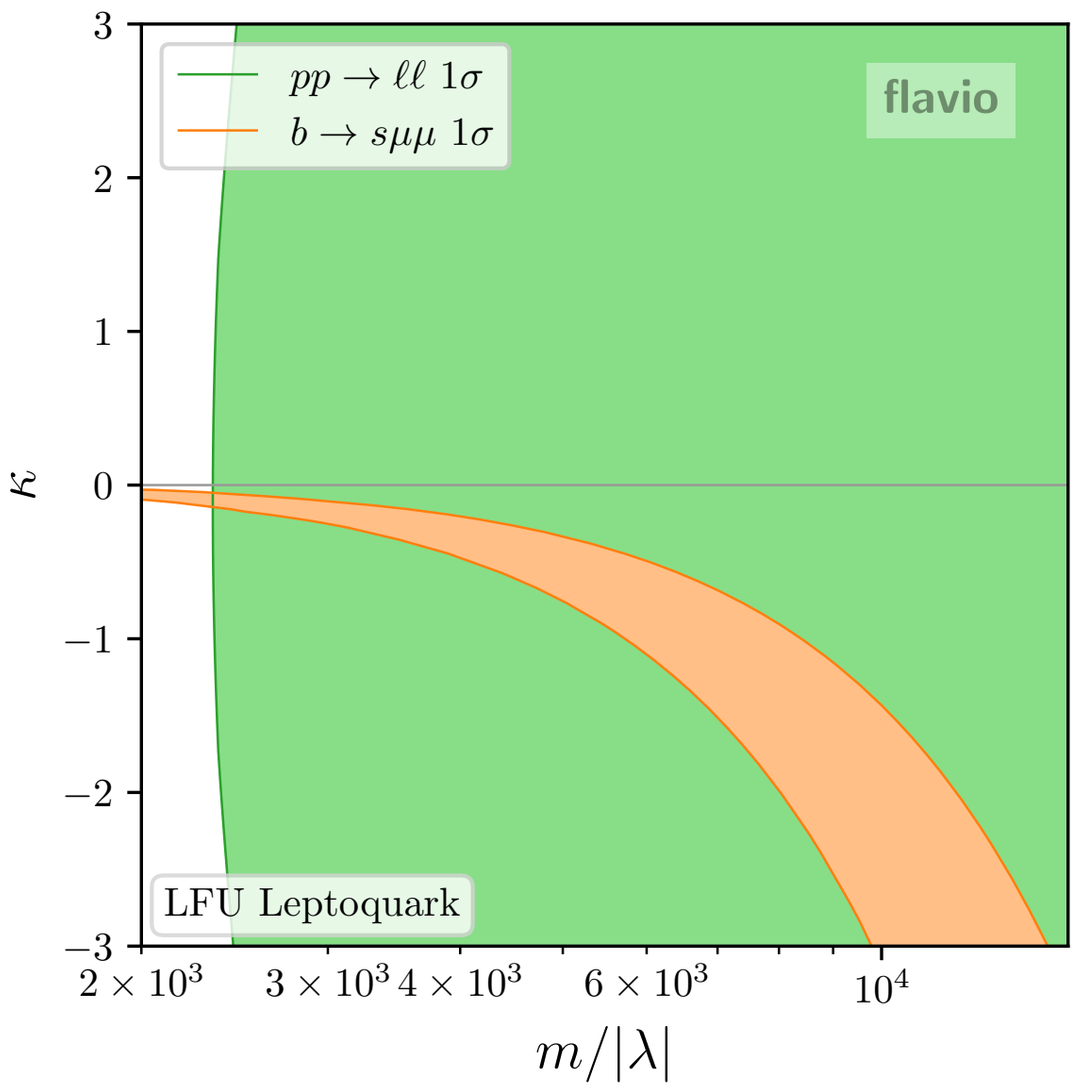
Mass/Coupling degeneracy

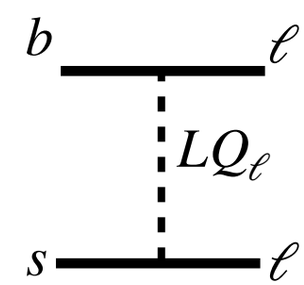


LFU leptoquark

$$\mathscr{L} \supset (D_\mu S^\alpha)^\dagger (D^\mu S^\alpha) - m^2 S^{\alpha\dagger} S^\alpha - (\lambda_i \, \bar{q}_i^c l_\alpha S^\alpha + \mathrm{h.c.})$$

$$\lambda_i = \lambda \, (\kappa V_{td}, \kappa V_{ts}, 1)$$





$2q2\ell$ at tree level

$4q$ and 4ℓ loop suppressed ✓

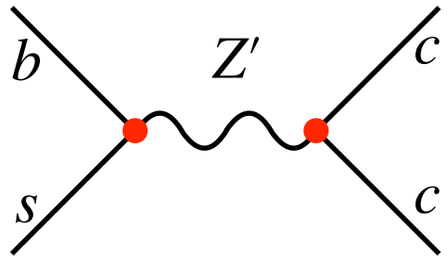
AG, Salko, Smolkovic, Stangl; 2212.10497

Systematic approach

Perturbative UV completion:

1. Tree-level models (but subleading operator)

NP:

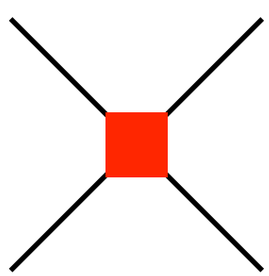


- Direct searches for a dijet resonance?

  See, e.g., Bordone, AG, Marzocca; 2103.10332

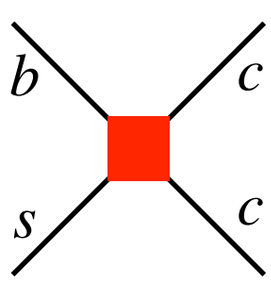
  (Likely end up as Gudrun's model for U-spin breaking) See Gudrun's talk

SMEFT:



Jäger et al, 1701.09183, 1910.12924

WET:



Systematic approach

Perturbative UV completion:

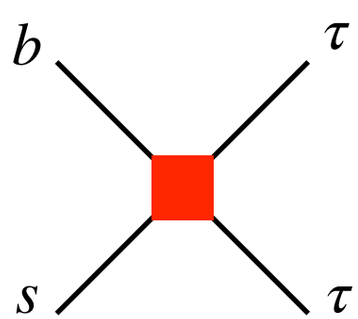
1. Loop-level (large RGE effects)

NP: U_1 vector leptoquark

$$\Delta C_9^{\rm eff}(0) \approx -0.3.$$

Aebischer et al, 2210.13422v2

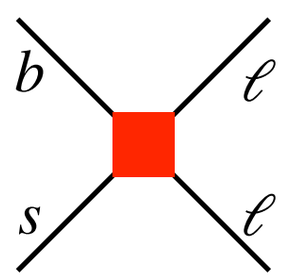
SMEFT:



RGE

Crivellin et al, 1807.02068

WET:



$$O_9^{bq\ell\ell} = (\bar{q}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell)$$

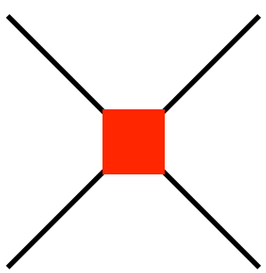
Systematic approach

Perturbative UV completion:

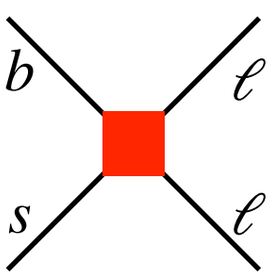
1. Loop-level

NP: Box diagrams, again LFV, lower scale, direct searches, …

SMEFT:



WET:



$$O_9^{bq\ell\ell} = (\bar{q}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell)$$

Etc…

Thank you for your attention

Backup

The WET analysis

- WET at the b scale

AG, Salko, Smolkovic, Stangl; 2212.10497

$$\mathcal{H}_{\rm eff} = \mathcal{H}_{\rm eff}^{\rm SM} - \frac{4G_F}{\sqrt{2}}\frac{e^2}{16\pi^2}\sum_{q=s,d}\sum_{\ell=e,\mu}\sum_{i=9,10,S,P} V_{tb}V_{tq}^*(C_i^{bq\ell\ell}O_i^{bq\ell\ell} + C_i'^{bq\ell\ell}O_i'^{bq\ell\ell}) + \text{h.c.}\,.$$

- Operators:

$$O_9^{bq\ell\ell} = (\bar{q}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell)\,,$$
$$O_{10}^{bq\ell\ell} = (\bar{q}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu\gamma_5 \ell)\,,$$
$$O_S^{bq\ell\ell} = m_b(\bar{q}P_R b)(\bar{\ell}\ell)\,,$$
$$O_P^{bq\ell\ell} = m_b(\bar{q}P_R b)(\bar{\ell}\gamma_5 \ell)\,,$$

$$O_9'^{bq\ell\ell} = (\bar{q}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu \ell)\,,$$
$$O_{10}'^{bq\ell\ell} = (\bar{q}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu\gamma_5 \ell)\,,$$
$$O_S'^{bq\ell\ell} = m_b(\bar{q}P_L b)(\bar{\ell}\ell)\,,$$
$$O_P'^{bq\ell\ell} = m_b(\bar{q}P_L b)(\bar{\ell}\gamma_5 \ell)\,.$$

WET fit: 1D

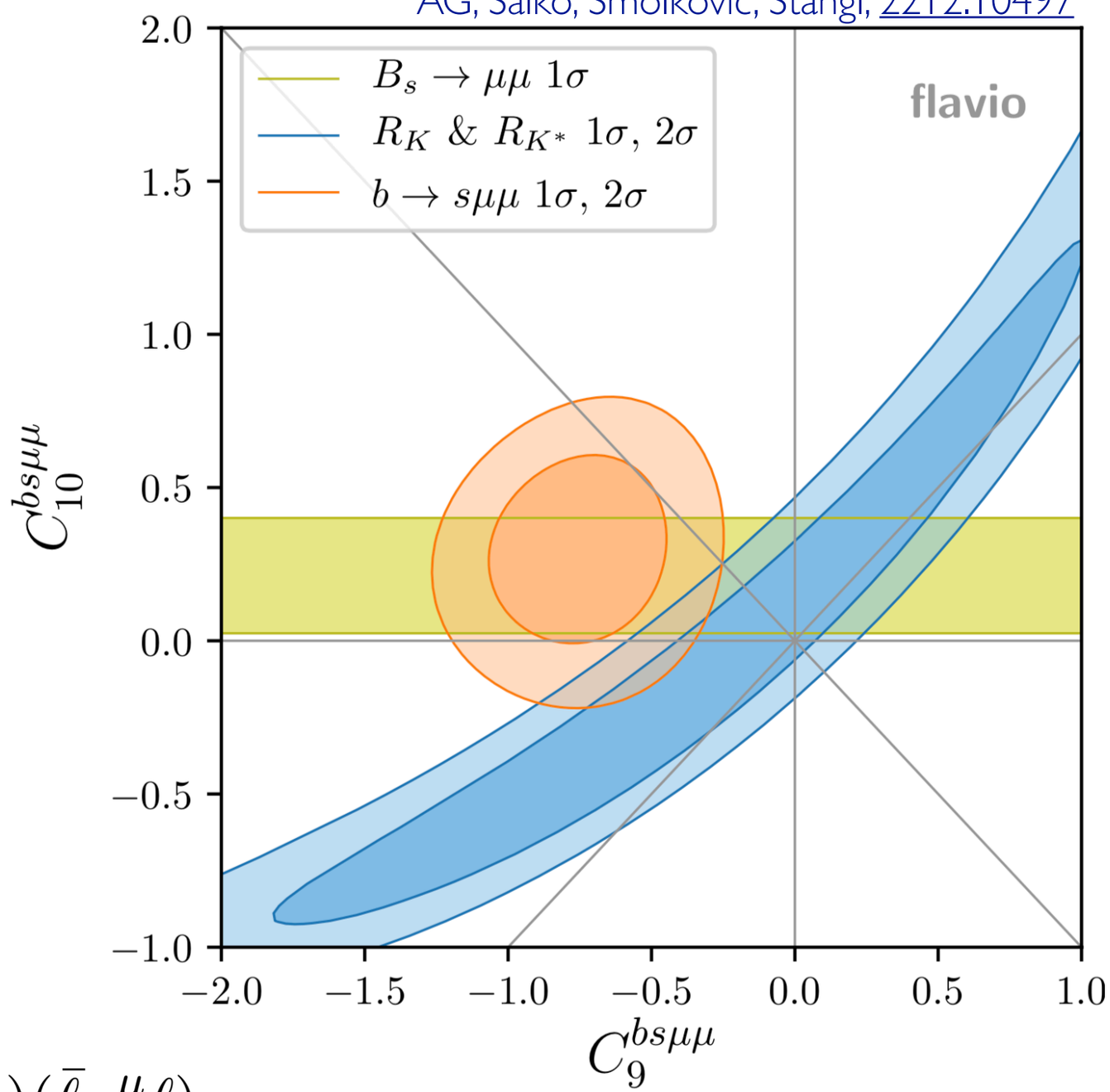
AG, Salko, Smolkovic, Stangl; 2212.10497

Wilson coefficient	$b \to s\mu\mu$ best fit	$b \to s\mu\mu$ pull	LFU, $B_s \to \mu\mu$ best fit	LFU, $B_s \to \mu\mu$ pull	all rare B decays best fit	all rare B decays pull
$C_9^{bs\mu\mu}$	$-0.77^{+0.21}_{-0.21}$	3.6σ	$-0.21^{+0.17}_{-0.19}$	1.2σ	$-0.42^{+0.13}_{-0.14}$	3.2σ
$C_9'^{bs\mu\mu}$	$+0.29^{+0.25}_{-0.25}$	1.2σ	$-0.22^{+0.17}_{-0.18}$	1.3σ	$-0.04^{+0.13}_{-0.13}$	0.3σ
$C_{10}^{bs\mu\mu}$	$+0.33^{+0.24}_{-0.24}$	1.3σ	$+0.16^{+0.12}_{-0.11}$	1.4σ	$+0.17^{+0.10}_{-0.10}$	1.8σ
$C_{10}'^{bs\mu\mu}$	$-0.05^{+0.16}_{-0.15}$	0.3σ	$+0.04^{+0.11}_{-0.12}$	0.3σ	$+0.02^{+0.09}_{-0.09}$	0.2σ
$C_9^{bs\mu\mu} = C_{10}^{bs\mu\mu}$	$-0.27^{+0.15}_{-0.15}$	1.7σ	$+0.17^{+0.18}_{-0.18}$	1.0σ	$-0.08^{+0.11}_{-0.11}$	0.7σ
$C_9^{bs\mu\mu} = -C_{10}^{bs\mu\mu}$	$-0.53^{+0.13}_{-0.13}$	3.6σ	$-0.10^{+0.07}_{-0.07}$	1.4σ	$-0.17^{+0.06}_{-0.06}$	2.7σ
$C_9^{bs\ell\ell}$	$-0.77^{+0.21}_{-0.21}$	3.6σ			$-0.78^{+0.21}_{-0.21}$	3.7σ
$C_9'^{bs\ell\ell}$	$+0.29^{+0.25}_{-0.25}$	1.2σ			$+0.30^{+0.25}_{-0.25}$	1.2σ
$C_{10}^{bs\ell\ell}$	$+0.33^{+0.24}_{-0.24}$	1.3σ	$+0.21^{+0.19}_{-0.19}$	1.1σ	$+0.23^{+0.15}_{-0.15}$	1.6σ
$C_{10}'^{bs\ell\ell}$	$-0.05^{+0.16}_{-0.15}$	0.3σ	$-0.21^{+0.19}_{-0.19}$	1.1σ	$-0.08^{+0.11}_{-0.12}$	0.7σ
$C_9^{bs\ell\ell} = C_{10}^{bs\ell\ell}$	$-0.27^{+0.15}_{-0.15}$	1.7σ	$+0.21^{+0.19}_{-0.19}$	1.1σ	$-0.09^{+0.11}_{-0.11}$	0.8σ
$C_9^{bs\ell\ell} = -C_{10}^{bs\ell\ell}$	$-0.53^{+0.13}_{-0.13}$	3.6σ	$-0.21^{+0.19}_{-0.19}$	1.1σ	$-0.40^{+0.11}_{-0.11}$	3.5σ
$\left(C_S^{bs\mu\mu} = -C_P^{bs\mu\mu}\right) \times \text{GeV}$			$-0.002^{+0.001}_{-0.002}$	1.1σ	$-0.001^{+0.001}_{-0.001}$	0.7σ
$\left(C_S'^{bs\mu\mu} = C_P'^{bs\mu\mu}\right) \times \text{GeV}$			$-0.002^{+0.001}_{-0.002}$	1.1σ	$-0.001^{+0.001}_{-0.001}$	0.7σ

LFU

WET fit: 2D μ

AG, Salko, Smolkovic, Stangl; 2212.10497



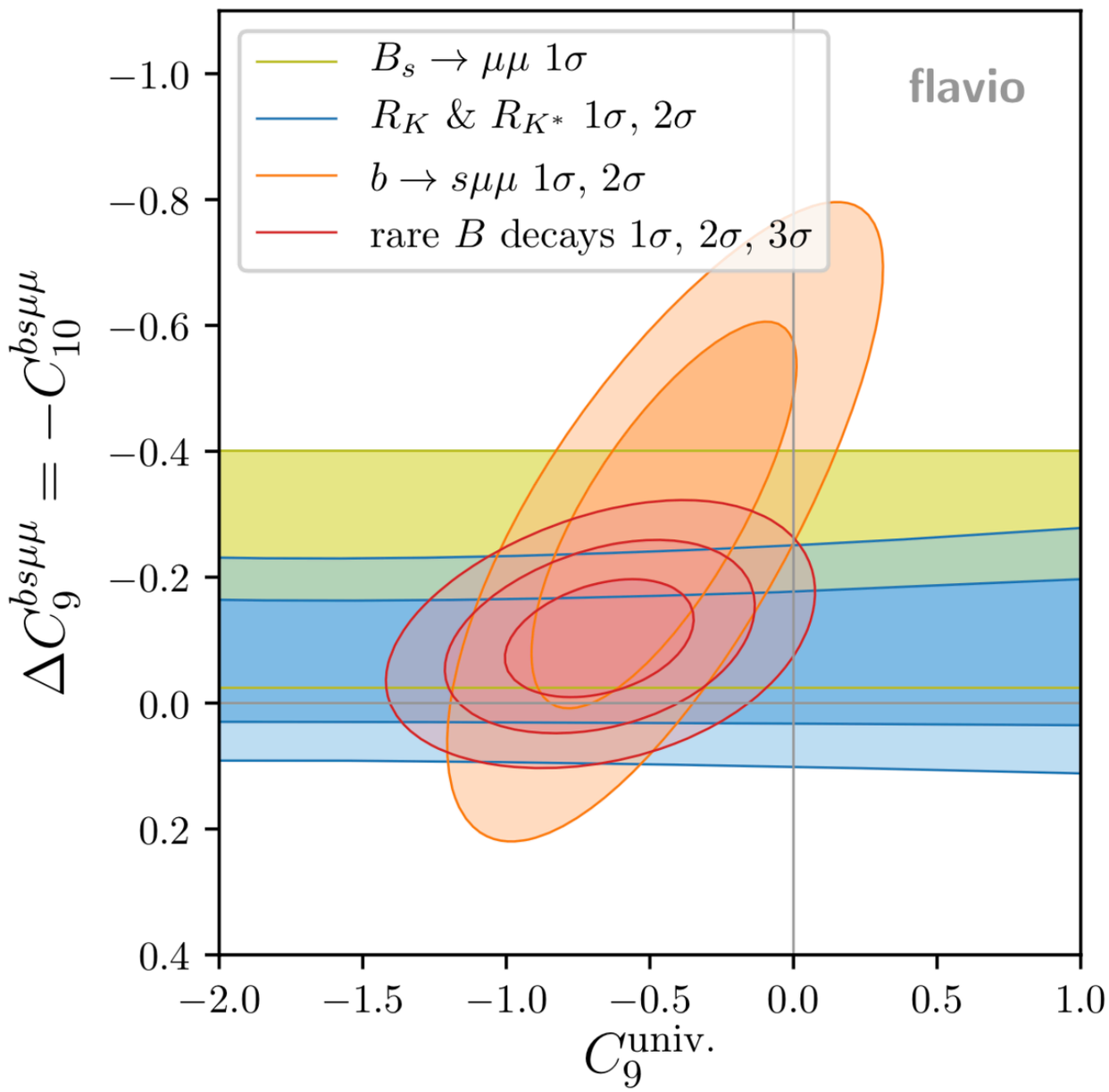
(Slight) tension!

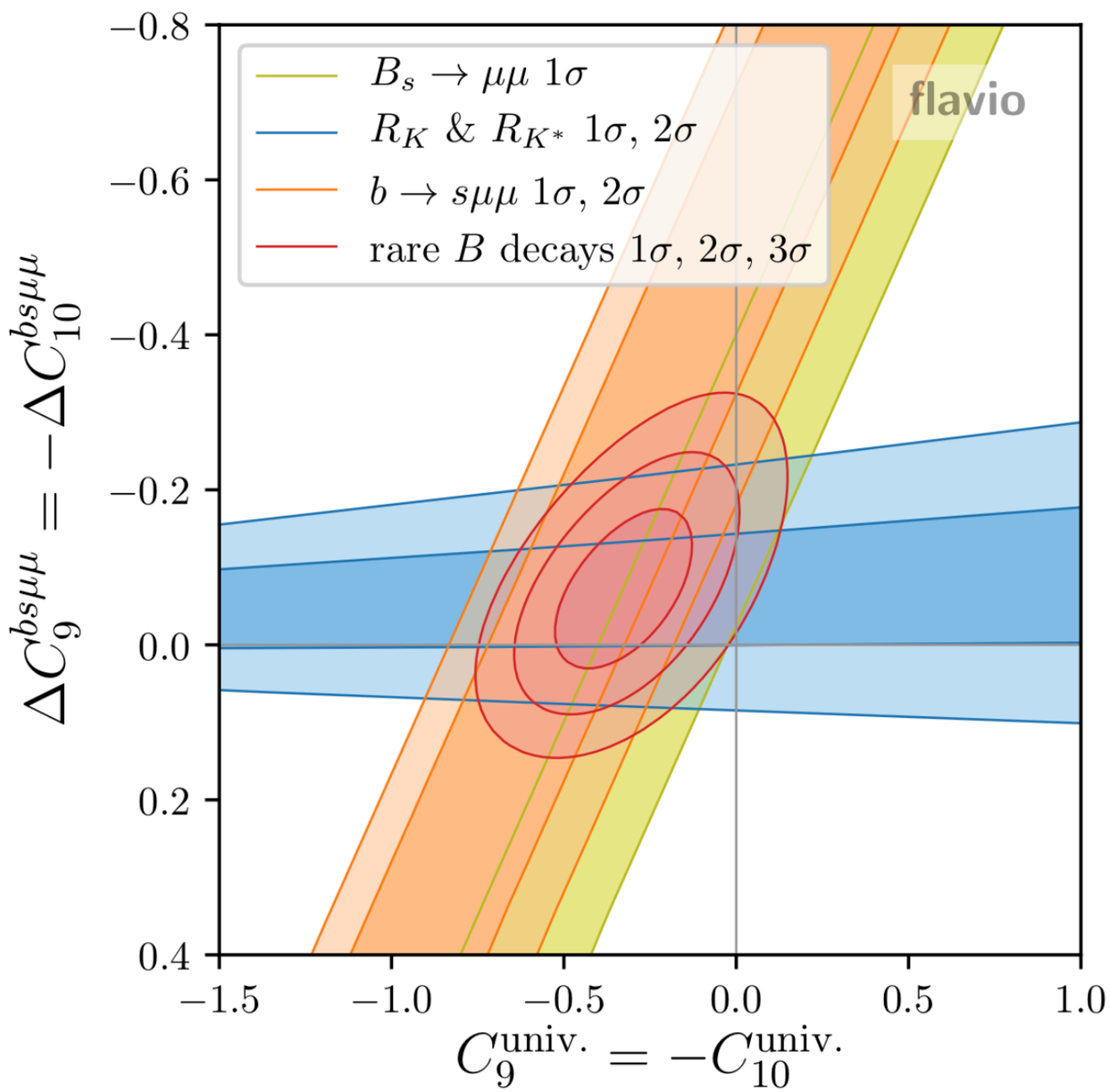
$$O_9^{bq\ell\ell} = (\bar{q}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell)\,,$$

$$O_{10}^{bq\ell\ell} = (\bar{q}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$$

WET fit: LFU vs LFUV

AG, Salko, Smolkovic, Stangl; 2212.10497



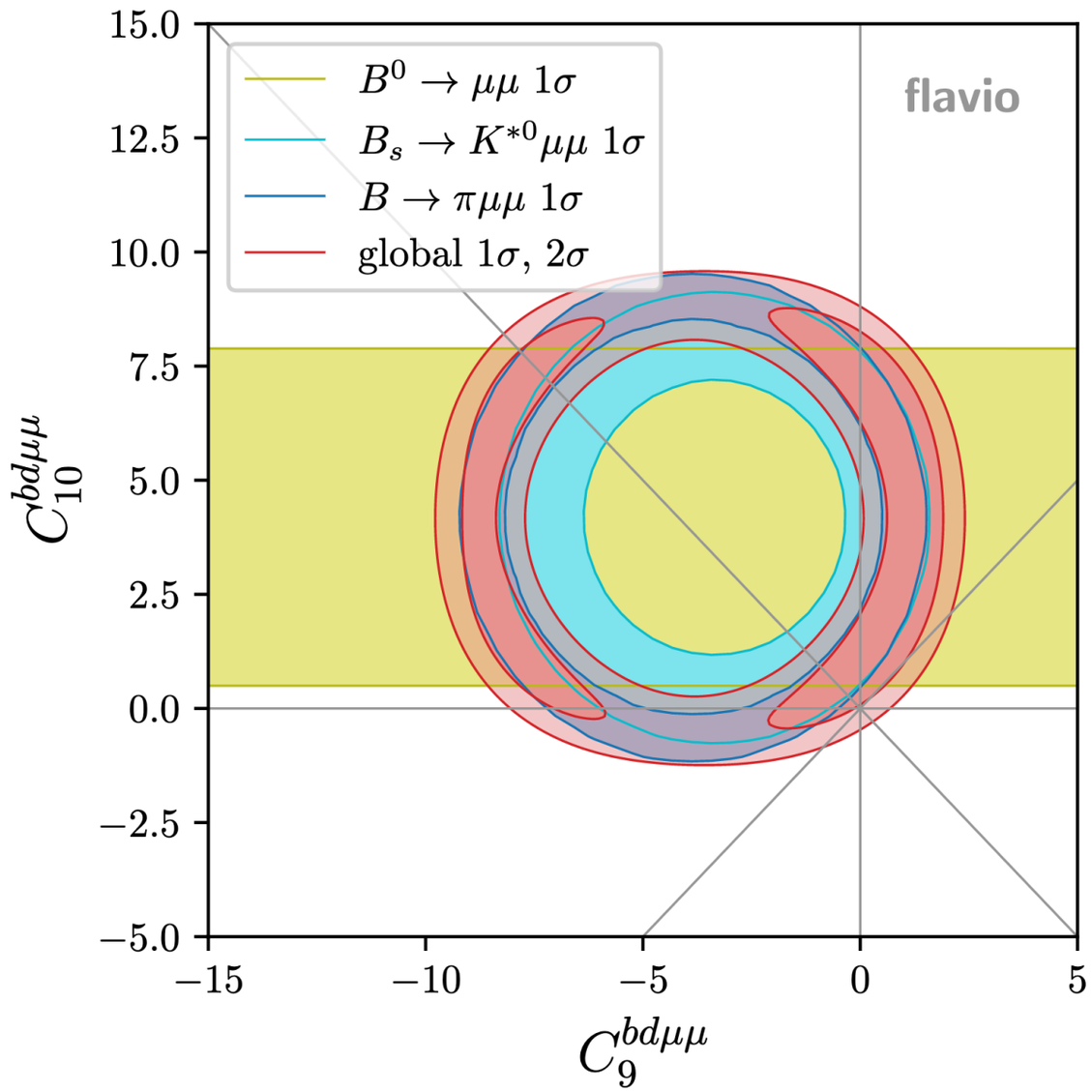


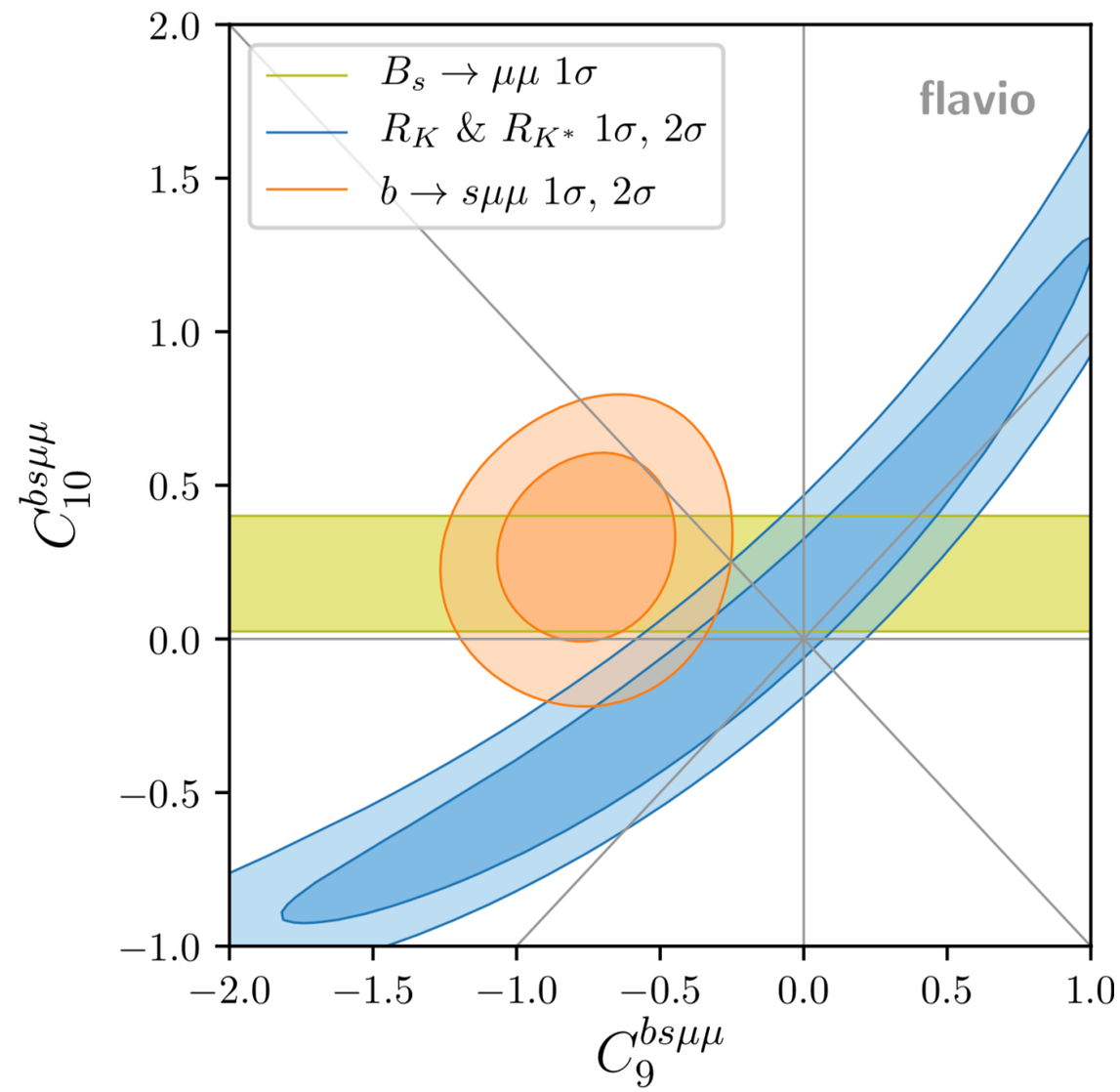
- LFU Z'
- LFU LQ

[For other fits see the paper]

WET fit: $b \to d$ versus $b \to s$

AG, Salko, Smolkovic, Stangl; 2212.10497

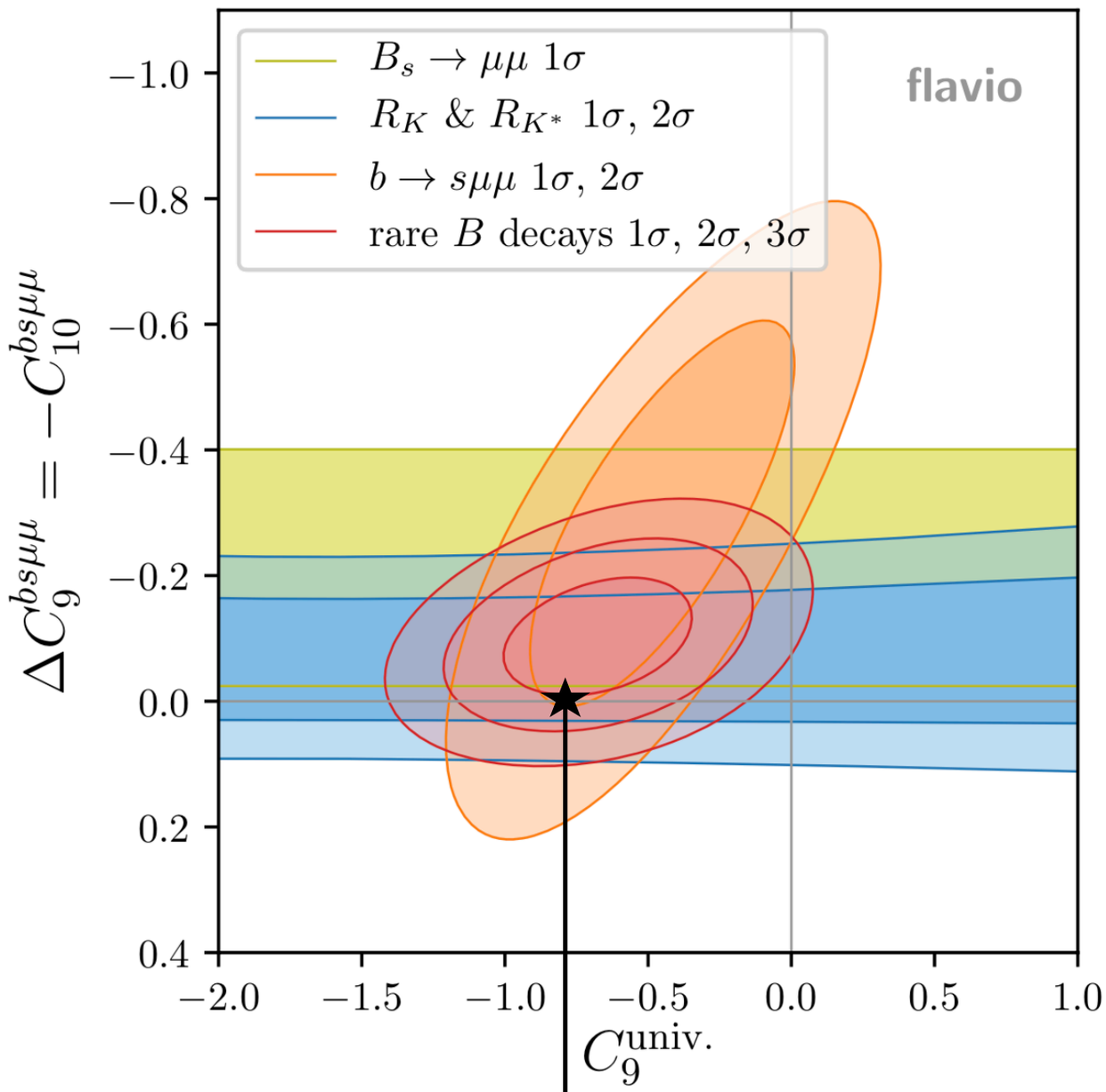


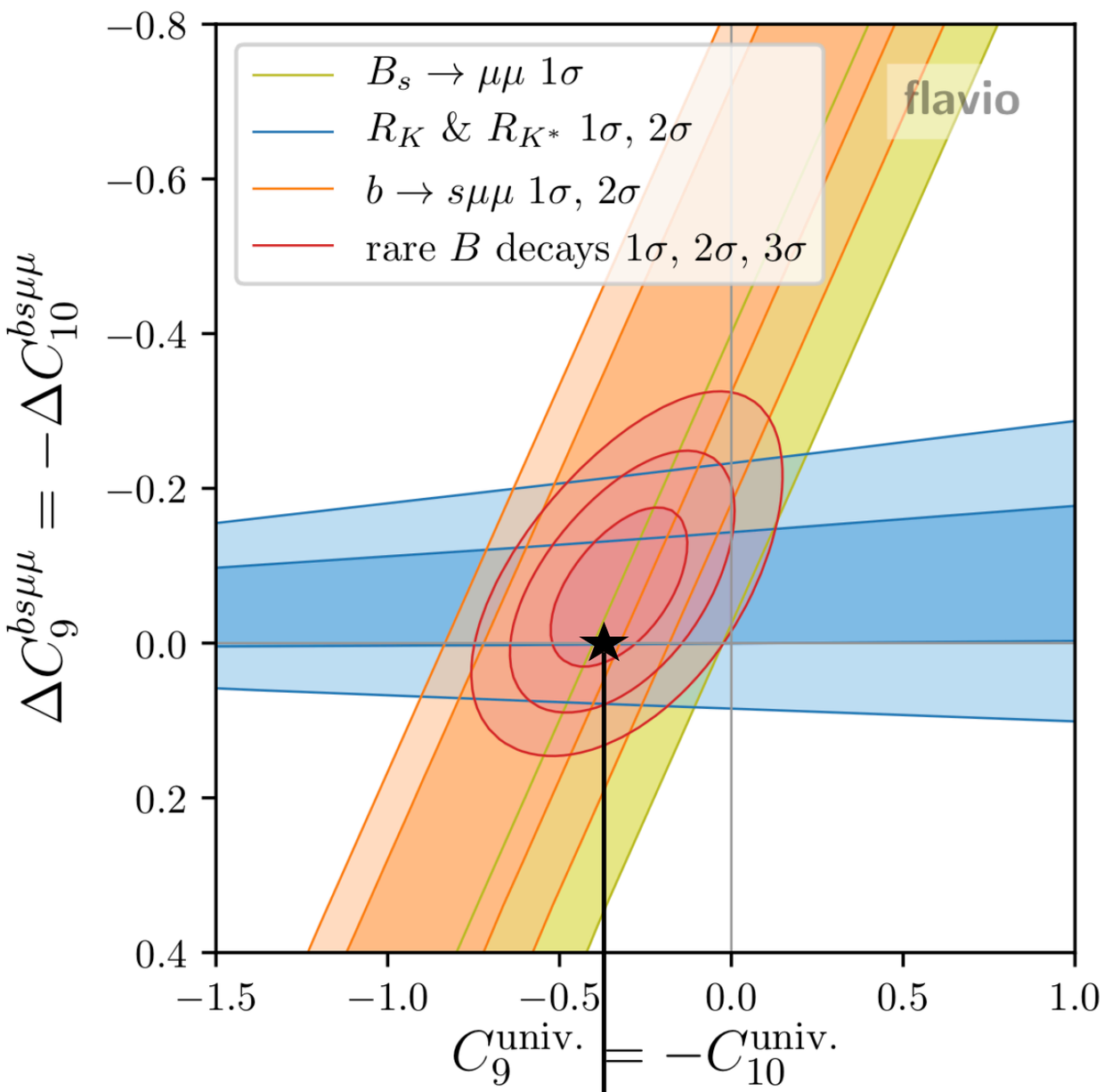


[For other fits see the paper]

LFU models for $b \to s\ell\ell$

AG, Salko, Smolkovic, Stangl; 2212.10497



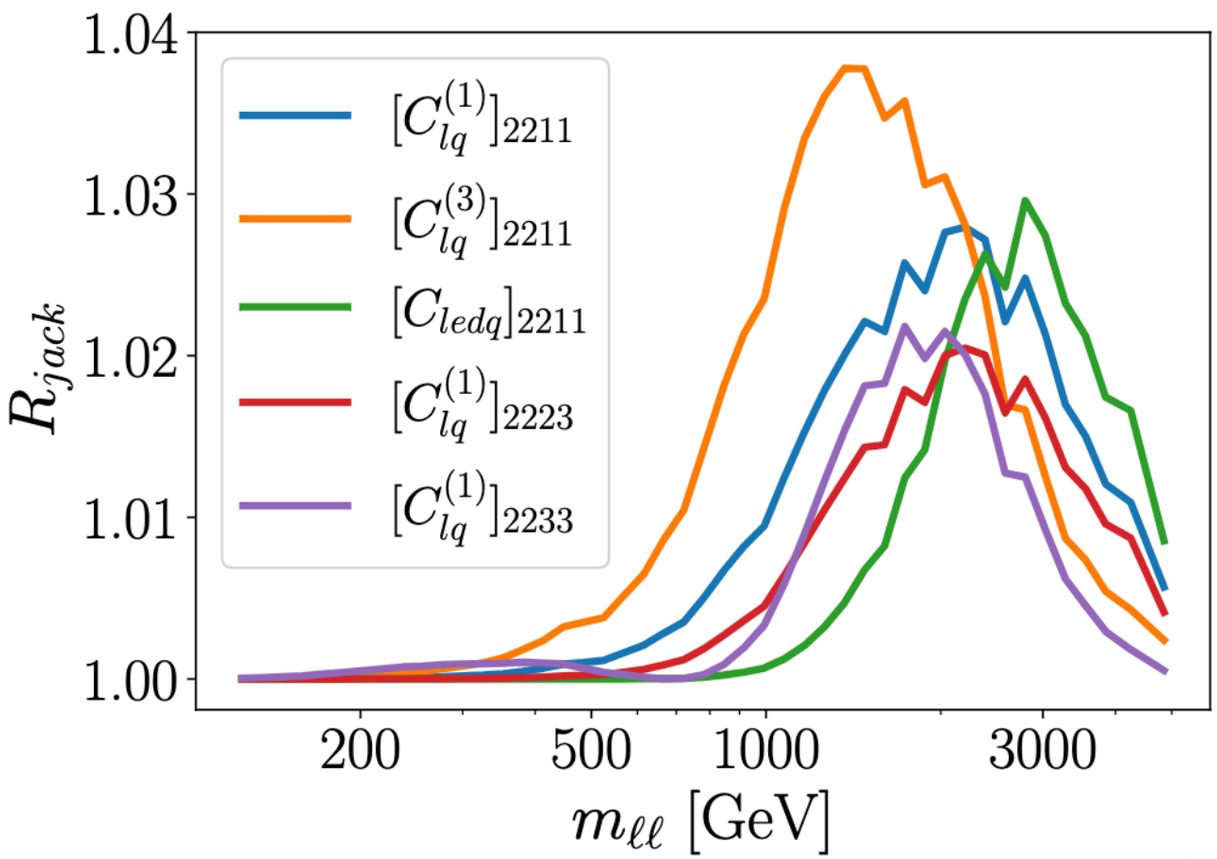


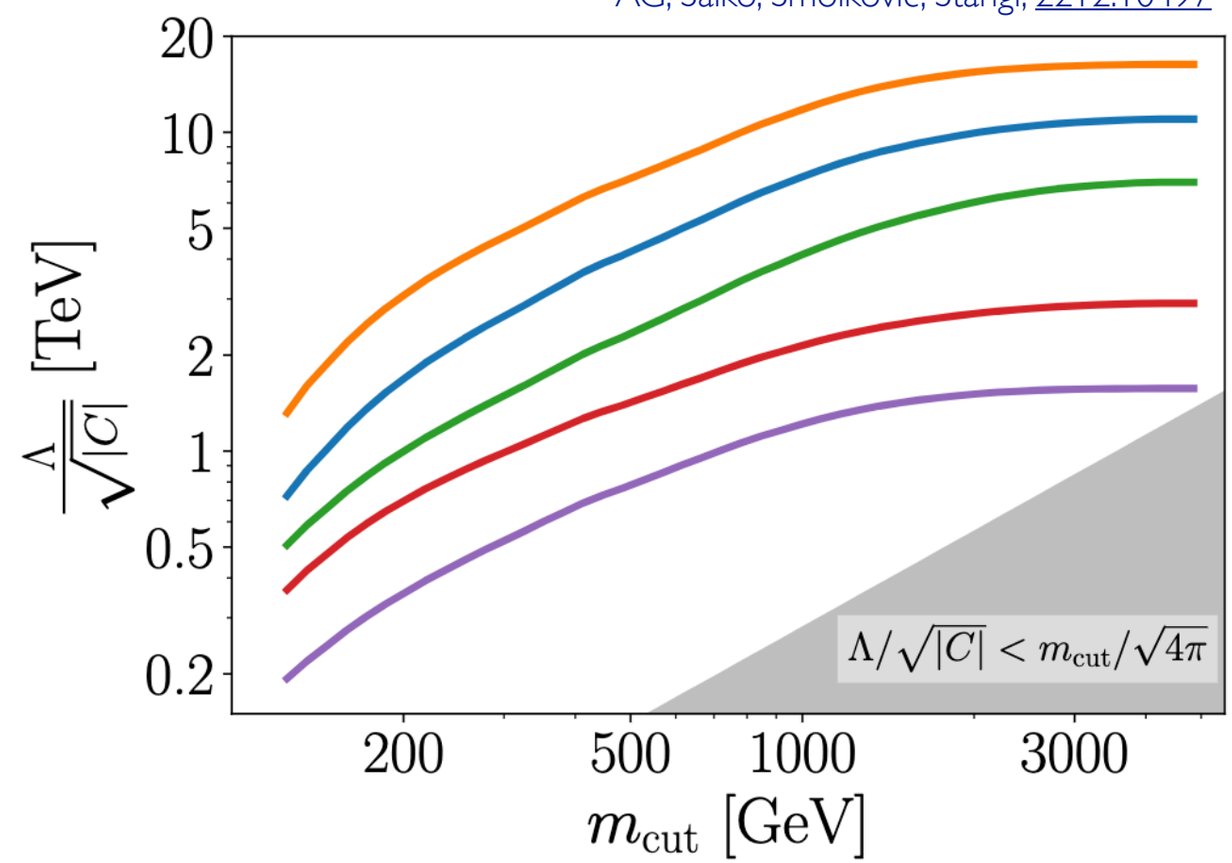
- LFU Z'

- LFU LQ

NP in the Drell-Yan Tails

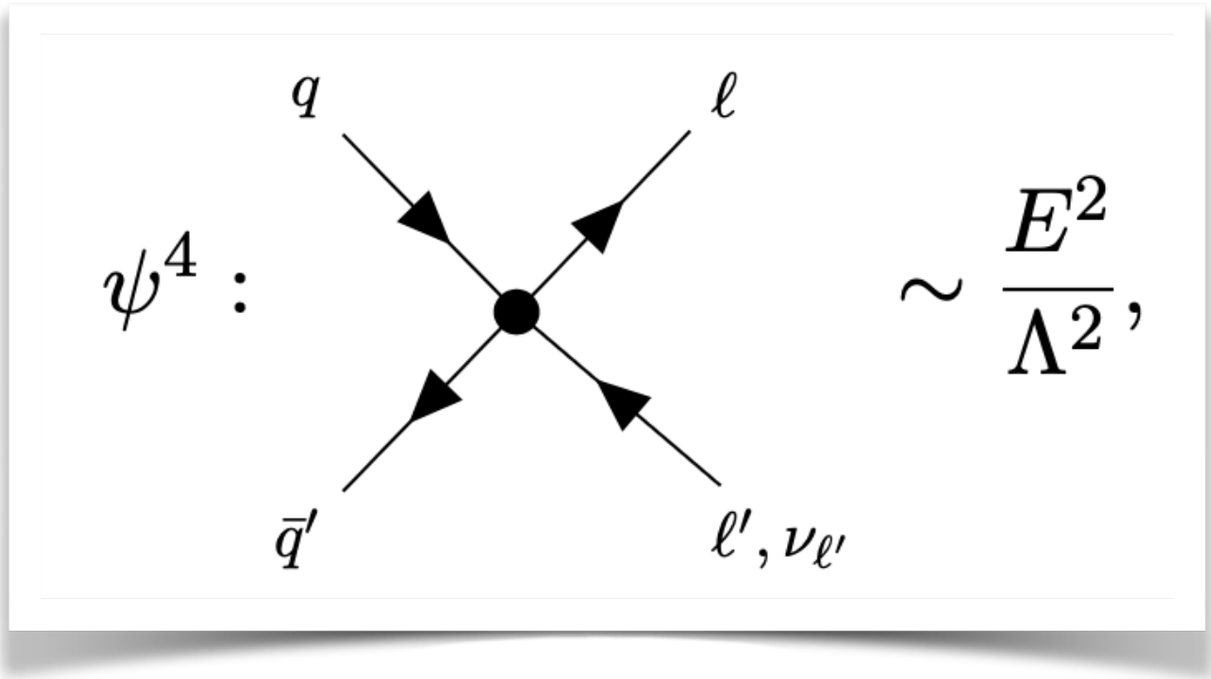
AG, Salko, Smolkovic, Stangl; 2212.10497

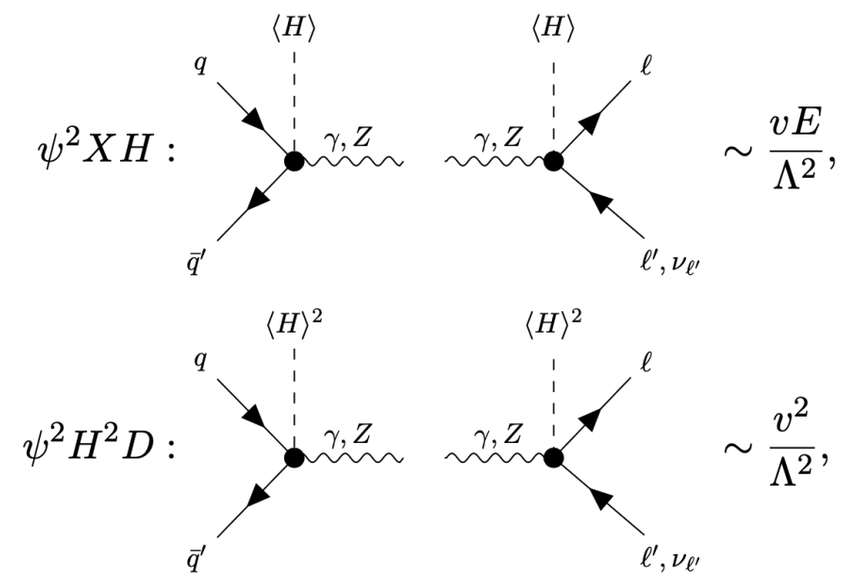




Search	Ref.	Channel	Luminosity
ATLAS	[45]	$pp \to ee$	139 fb^{-1}
		$pp \to \mu\mu$	139 fb^{-1}
CMS	[46]	$pp \to ee$	137 fb^{-1}
		$pp \to \mu\mu$	140 fb^{-1}
ATLAS	[47]	$pp \to e\nu$	139 fb^{-1}
		$pp \to \mu\nu$	139 fb^{-1}
CMS	[48]	$pp \to e\nu$	138 fb^{-1}
		$pp \to \mu\nu$	138 fb^{-1}

Drell-Yan in the SMEFT





AG, Palavric; wip

DY dim-6 ψ^4 $\mathcal{O}(1)$ terms		Lepton sector					
		MFV_L	$U(2)^2 \times U(1)_{\tau_R}$	$U(2)^2$	$U(1)^6$	$U(1)^3$	No symmetry
Quark sector	MFV_Q	7	14	14	21	21	63
	$U(2)_q \times U(2)_u \times U(3)_d$	10	20	20	30	30	90
	$U(2)^3 \times U(1)_{b_R}$	12	24	24	36	36	108
	$U(2)^3$	12	24	26	36	42	126
	No symmetry	53	106	148	159	285	855

Table 3: Flavor counting of the dimension-6 operators of the type ψ^4 which contribute to Drell-Yan scattering.

SMEFT fit: 1D

4F SMEFT operators with arbitrary flavor

$Q_{lq}^{(1)}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p\gamma_\mu\sigma^i l_r)(\bar{q}_s\gamma^\mu\sigma^i q_t)$
Q_{lu}	$(\bar{l}_p\gamma_\mu l_r)(\bar{u}_s\gamma^\mu u_t)$
Q_{ld}	$(\bar{l}_p\gamma_\mu l_r)(\bar{d}_s\gamma^\mu d_t)$
Q_{qe}	$(\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t)$
Q_{eu}	$(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$
Q_{ed}	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_{tj})$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\varepsilon_{jk}(\bar{q}_s^k u_t)$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j\sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar{q}_s^k\sigma^{\mu\nu} u_t)$

Drell-Yan data used

Search	Ref.	Channel	Luminosity
ATLAS	[45]	$pp \to ee$	139 fb^{-1}
		$pp \to \mu\mu$	139 fb^{-1}
CMS	[46]	$pp \to ee$	137 fb^{-1}
		$pp \to \mu\mu$	140 fb^{-1}
ATLAS	[47]	$pp \to e\nu$	139 fb^{-1}
		$pp \to \mu\nu$	139 fb^{-1}
CMS	[48]	$pp \to e\nu$	138 fb^{-1}
		$pp \to \mu\nu$	138 fb^{-1}

Table 4: The 2σ bounds on different flavor structures of single Wilson coefficients at $\Lambda = 1$ TeV. See Sec. 5.1 for details.

		Drell-Yan tails		B decays	
Operator	Flavor	NC	CC	$b \to q\ell\ell$	$b \to q\nu\nu$
$\mathcal{O}_{lq}^{(1)}$	1113	[-0.068, 0.068]	-	[-0.005, 0.002]	[-0.035, 0.039]
	2213	[-0.031, 0.032]	-	[-4.96, 0.78]$\times10^{-4}$	[-0.035, 0.039]
	1123	[-0.145, 0.152]	-	[-4.26, 0.98]$\times10^{-4}$	[-0.038, 0.017]
	2223	[-0.066, 0.071]	-	[7.71, 51.86]$\times10^{-5}$	[-0.038, 0.017]
$\mathcal{O}_{lq}^{(3)}$	1113	[-0.068, 0.068]	[-0.017, 0.017]	[-0.005, 0.002]	[-0.037, 0.033]
	2213	[-0.032, 0.031]	[-0.029, 0.029]	[-4.85, 0.7]$\times10^{-4}$	[-0.037, 0.033]
	1123	[-0.152, 0.145]	[-0.054, 0.051]	[-4.26, 0.98]$\times10^{-4}$	[-0.015, 0.035]
	2223	[-0.071, 0.066]	[-0.089, 0.089]	[7.71, 51.86]$\times10^{-5}$	[-0.015, 0.035]
$\mathcal{O}_{ld}$	1113	[-0.068, 0.068]	-	[-0.005, 0.002]	[-0.038, 0.038]
	2213	[-0.032, 0.032]	-	[-2.79, 2.43]$\times10^{-4}$	[-0.038, 0.038]
	1123	[-0.149, 0.149]	-	[-4.04, 1.09]$\times10^{-4}$	[-0.007, 0.023]
	2223	[-0.069, 0.069]	-	[-1.68, 2.14]$\times10^{-4}$	[-0.007, 0.023]
$\mathcal{O}_{qe}$	1311	[-0.068, 0.068]	-	[-0.003, 0.004]	-
	1322	[-0.032, 0.032]	-	[-3.35, 7.56]$\times10^{-4}$	-
	2311	[-0.148, 0.149]	-	[-0.003, 0.001]	-
	2322	[-0.068, 0.069]	-	[-2.39, 4.97]$\times10^{-4}$	-
$\mathcal{O}_{ed}$	1113	[-0.068, 0.068]	-	[-0.003, 0.004]	-
	2213	[-0.032, 0.032]	-	[-7.03, 3.76]$\times10^{-4}$	-
	1123	[-0.149, 0.149]	-	[-0.002, 0.002]	-
	2223	[-0.069, 0.069]	-	[-4.05, 4.37]$\times10^{-4}$	-
$\mathcal{O}_{ledq}$	1113	[-0.079, 0.079]	-	[-1.19, 1.18]$\times10^{-4}$	-
	1131	[-0.079, 0.079]	[-0.037, 0.037]	[-1.18, 1.18]$\times10^{-4}$	-
	2213	[-0.037, 0.037]	-	[-3.48, 0.67]$\times10^{-5}$	-
	2231	[-0.037, 0.037]	[-0.061, 0.061]	[-3.49, 0.68]$\times10^{-5}$	-
	1123	[-0.173, 0.173]	-	[-1.78, 1.79]$\times10^{-4}$	-
	1132	[-0.173, 0.173]	[-0.113, 0.113]	[-1.77, 1.78]$\times10^{-4}$	-
	2223	[-0.08, 0.08]	-	[-6.82, 16.57]$\times10^{-6}$	-
	2232	[-0.08, 0.08]	[-0.194, 0.194]	[-6.8, 16.48]$\times10^{-6}$	-

AG, Salko, Smolkovic, Stangl; 2212.10497

Example

Example:

$$\mathscr{L}_{NP}^{\Delta C=1} \approx \frac{\epsilon_V^{\ell\ell}}{(15\,\text{TeV})^2}\,(\bar{u}_R\gamma^\mu c_R)(\bar{\ell}_R\gamma^\mu \ell_R)$$

Rare $c \to u\ell^+\ell^-$ decays

Theory:

$BR(D^0 \to \mu^+\mu^-)_{SM} \sim \mathcal{O}(10^{-13})$

- Efficient GIM suppression
- Long-distance dominated

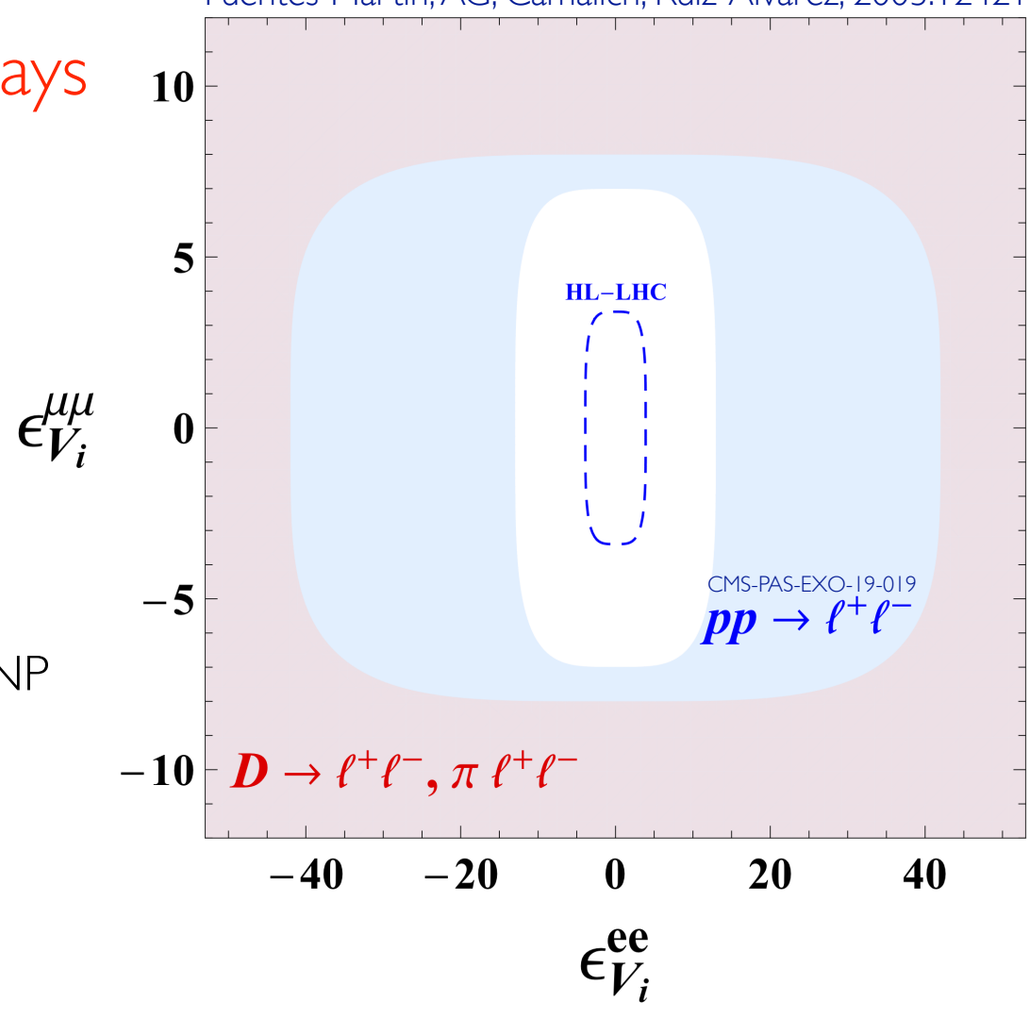
Experiment:

$BR(D^0 \to \mu^+\mu^-) \lesssim 6 \times 10^{-9}$

LHCb, 1305.5059

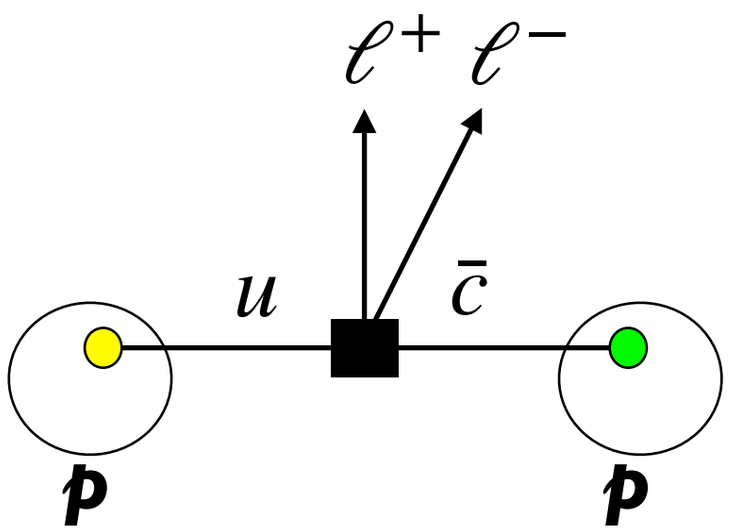
Null test of the SM sensitive to NP

Fuentes-Martin, AG, Camalich, Ruiz-Alvarez; 2003.12421



Drell-Yan $cu \to \ell^+\ell^-$

- Energy enhancement
- PDF suppression



Systematic exploration of the low-p_T / high-p_T interplay

1609.07138, 1704.09015, 1811.07920, 1805.11402, 1912.00425, 2002.05684, 2008.07541, 2104.02723, 2111.04748, …