

April 11 - 14, 2023

Portorož 2023

Rare b decays meet high-mass Drell-Yan

Aleks Smolkovic

Based on [2212.10497](#) with A. Greljo, J. Salko and P. Stangl

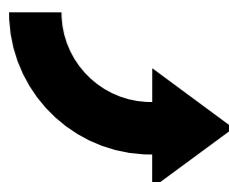
Outline

- **Intro:** framework, Drell-Yan, implementation in flavio
- **Results in EFT:** (semi)leptonic $b \rightarrow d$ and $b \rightarrow s$ meet high-mass DY
- **Model examples:** heavy Z's and LQs

SMEFT

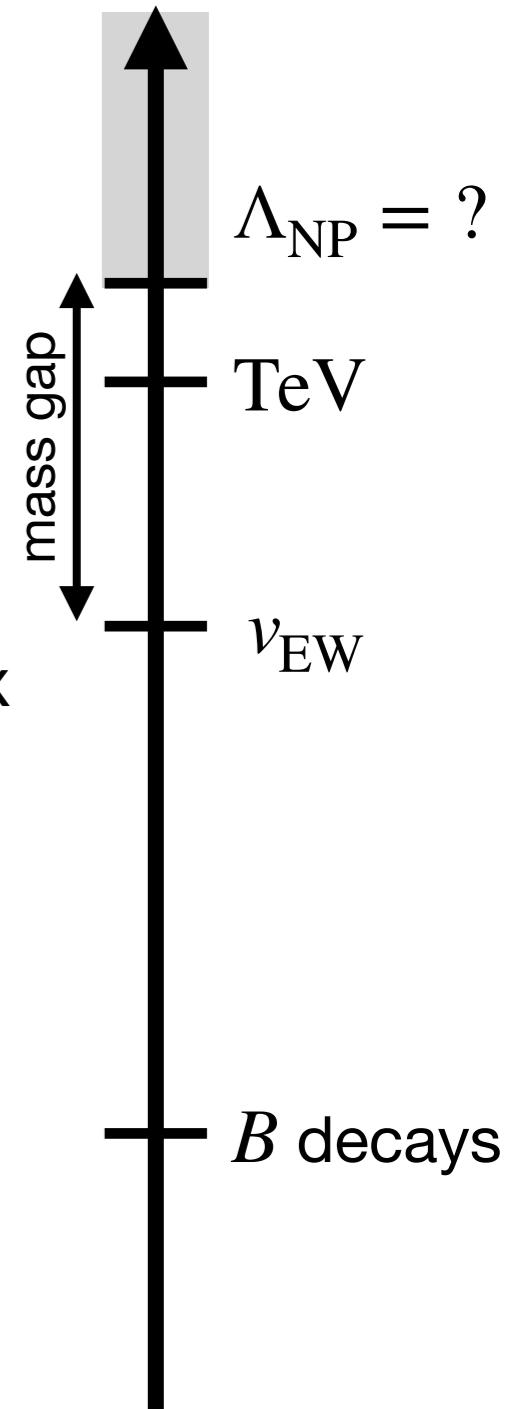
$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda^2} \sum_i C_i Q_i$$

- Model-independent description of heavy NP
- 59 operators for a single generation at dim. 6
- Flavour opens a huge parameter space: 1350 real + 1149 complex
- Correlates different classes of observables, non-trivial interplay
- Complicated data analyses done for $\{C_i\}$
-> bounds on C_i can be reinterpreted in many NP models



goal of e.g. flavio + wilson -> smelli

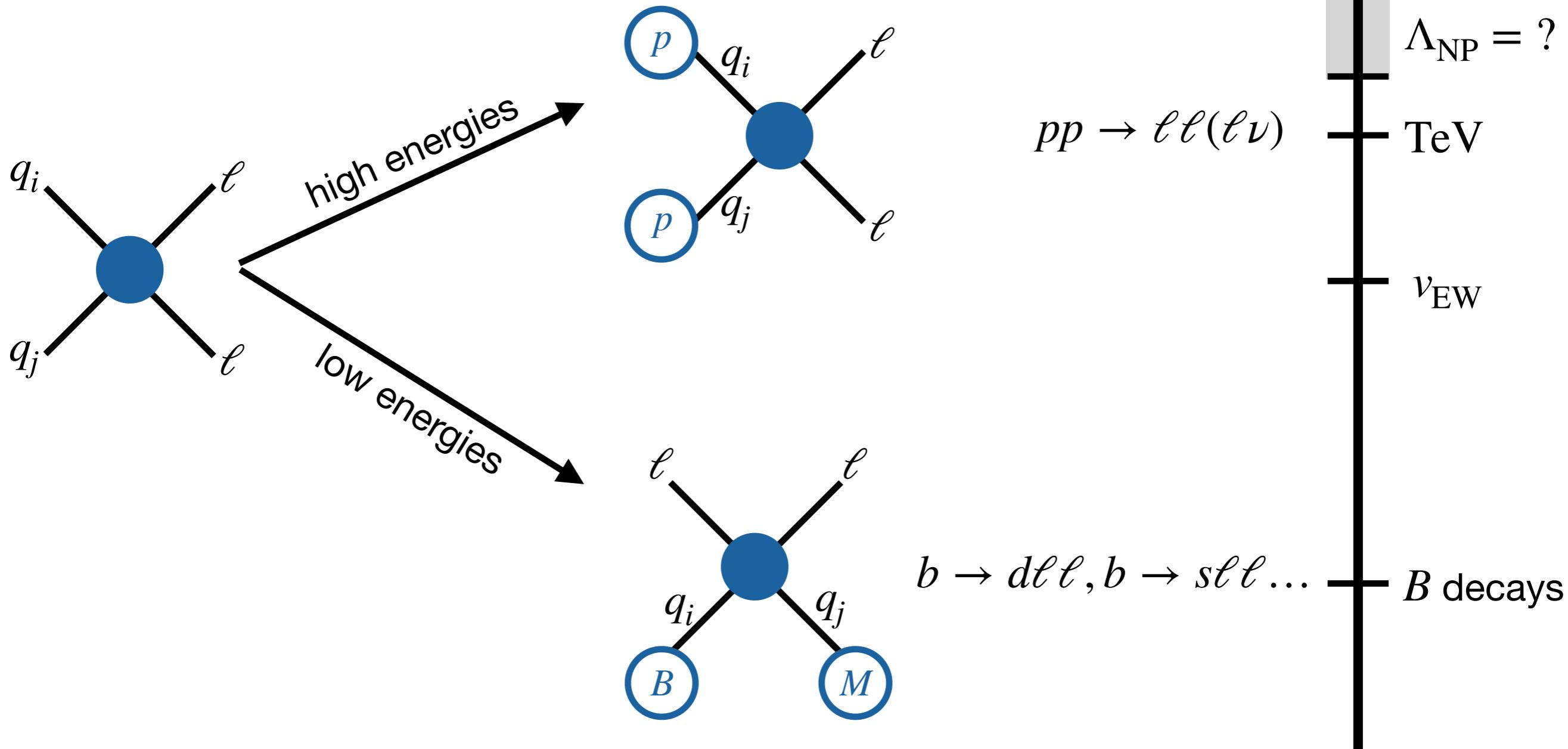
1810.08132, 1804.05033, 1810.07698



Low-energy processes meeting DY

1210.4553, 1605.07114, 1609.07138, 1704.09015, 1806.02370, 1809.01161,
1811.07920, 2002.05684, 2003.12421, 2008.07541, 2207.10714, 2303.07521, ...

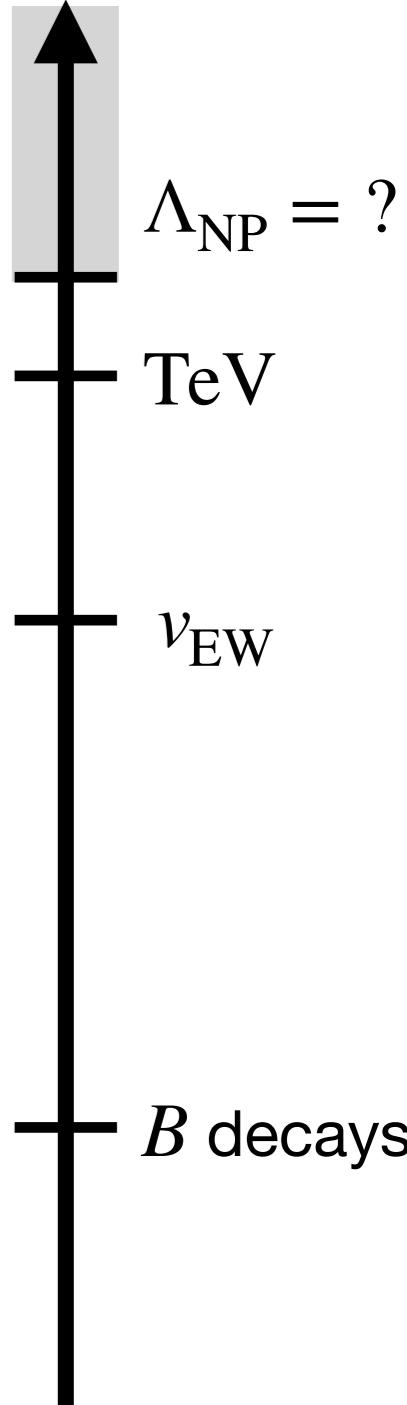
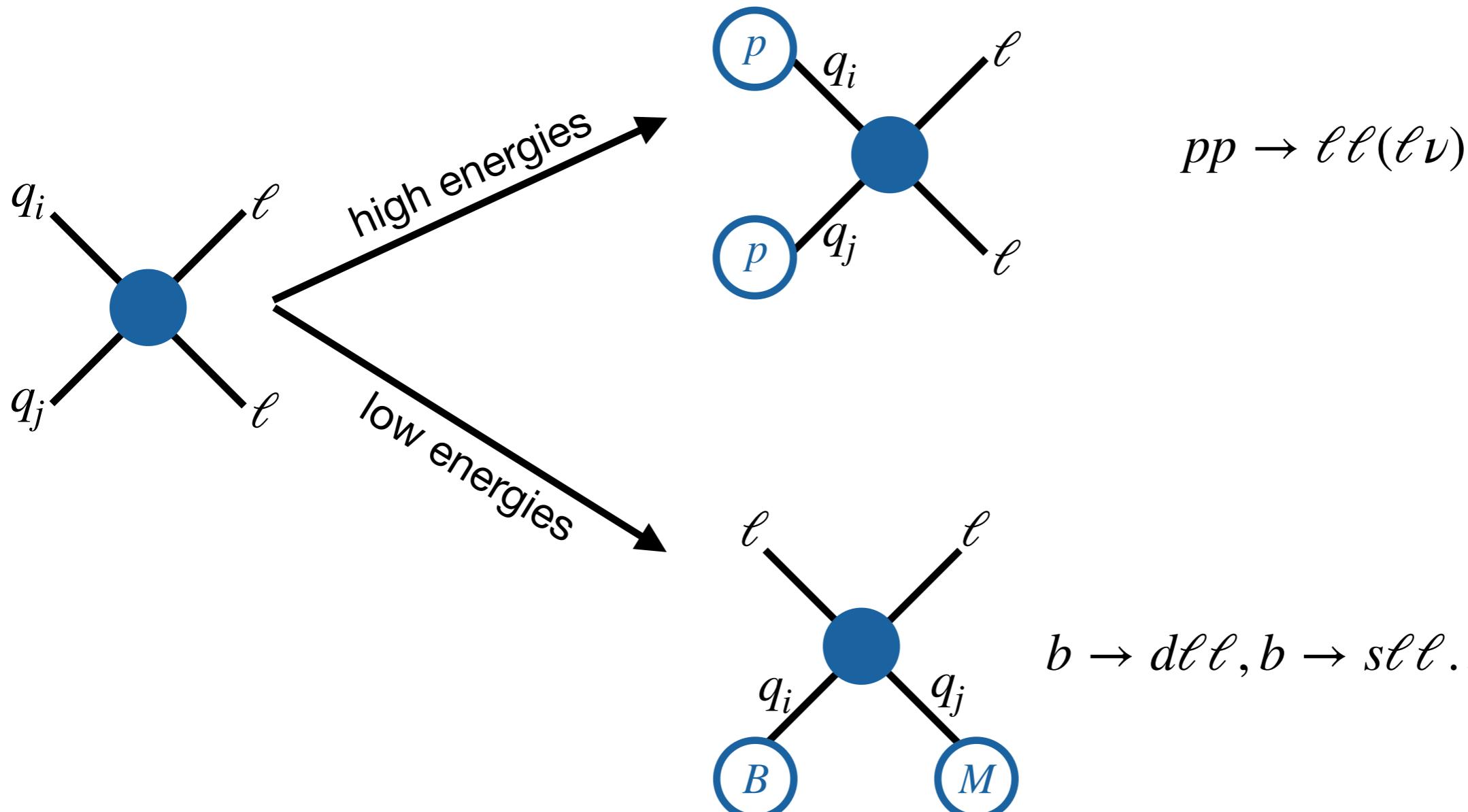
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$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda^2} \sum_i C_i Q_i$$



We implement predictions and latest measurements of **neutral and charged current high-mass Drell-Yan** with $\ell = e, \mu$ in **flavio** [See also talk by Jaffredo]

Implementation of Drell-Yan

Greljo, Salko, AS, Stangl; 2212.10497

Experimental measurements:

	$pp \rightarrow \ell\ell$	$pp \rightarrow \ell\nu$
CMS	2103.02708	2202.06075
ATLAS	2006.12946	1906.05609

(~140fb⁻¹)

Likelihood: Poisson convolved with Gaussian (systematics)

Predictions:

We reweigh the reported expected number of DY events with $N_{DY}^{\text{NP+SM}} = \frac{\sigma^{\text{SM+NP}}}{\sigma^{\text{SM}}} N_{DY}^{\text{SM}}$

A. Greljo and D. Marzocca: 1704.09015

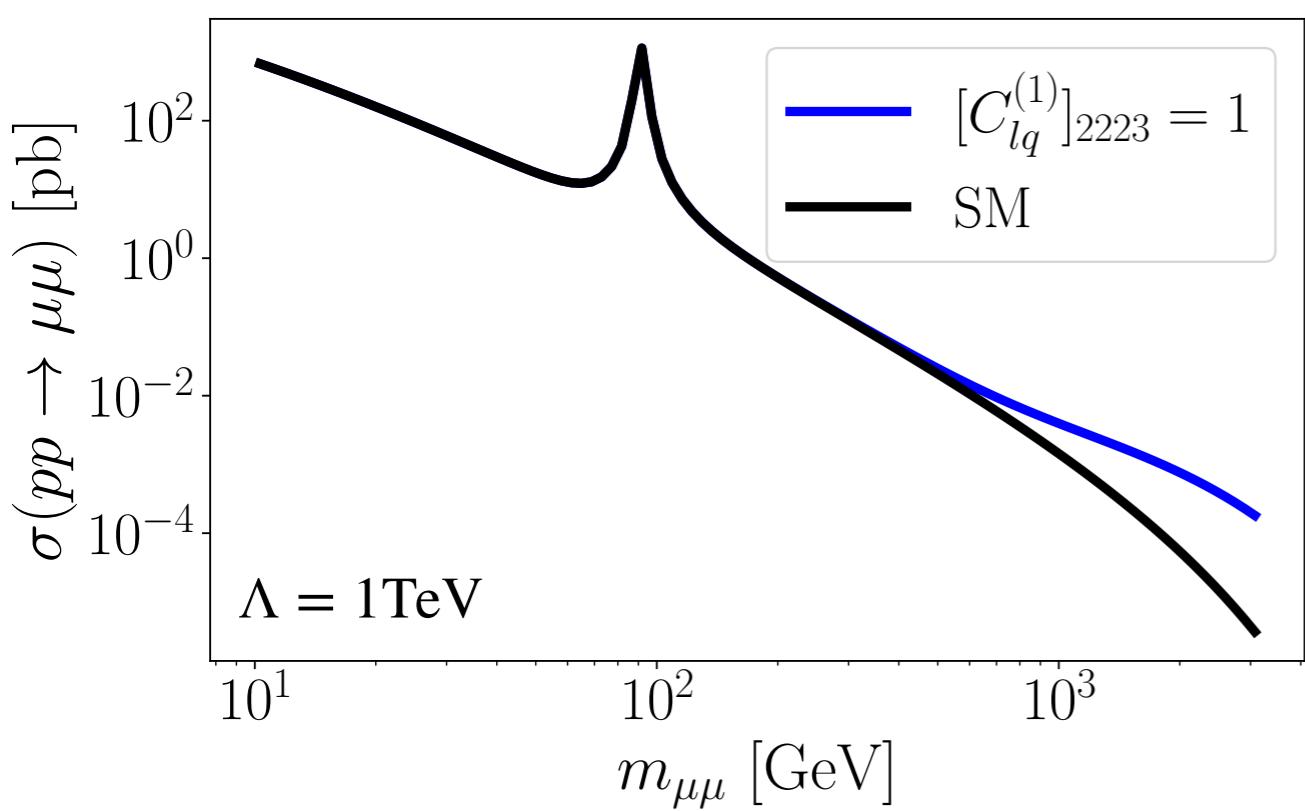
$$\sigma_{\text{part}}^{q\bar{q}} \sim \left| \sum_{\substack{\text{chiralities,} \\ \text{Lorentz}}} \left(\begin{array}{c} q_i \\ \gamma/Z/W \\ q_j \end{array} \right) + \begin{array}{c} q_i \\ \text{blue circle} \\ q_j \end{array} \right|^2$$

$$\sigma_{\text{had}} \sim \sum_{q\bar{q}} \mathcal{L}_{q\bar{q}} * \sigma_{\text{part}}^{q\bar{q}}$$

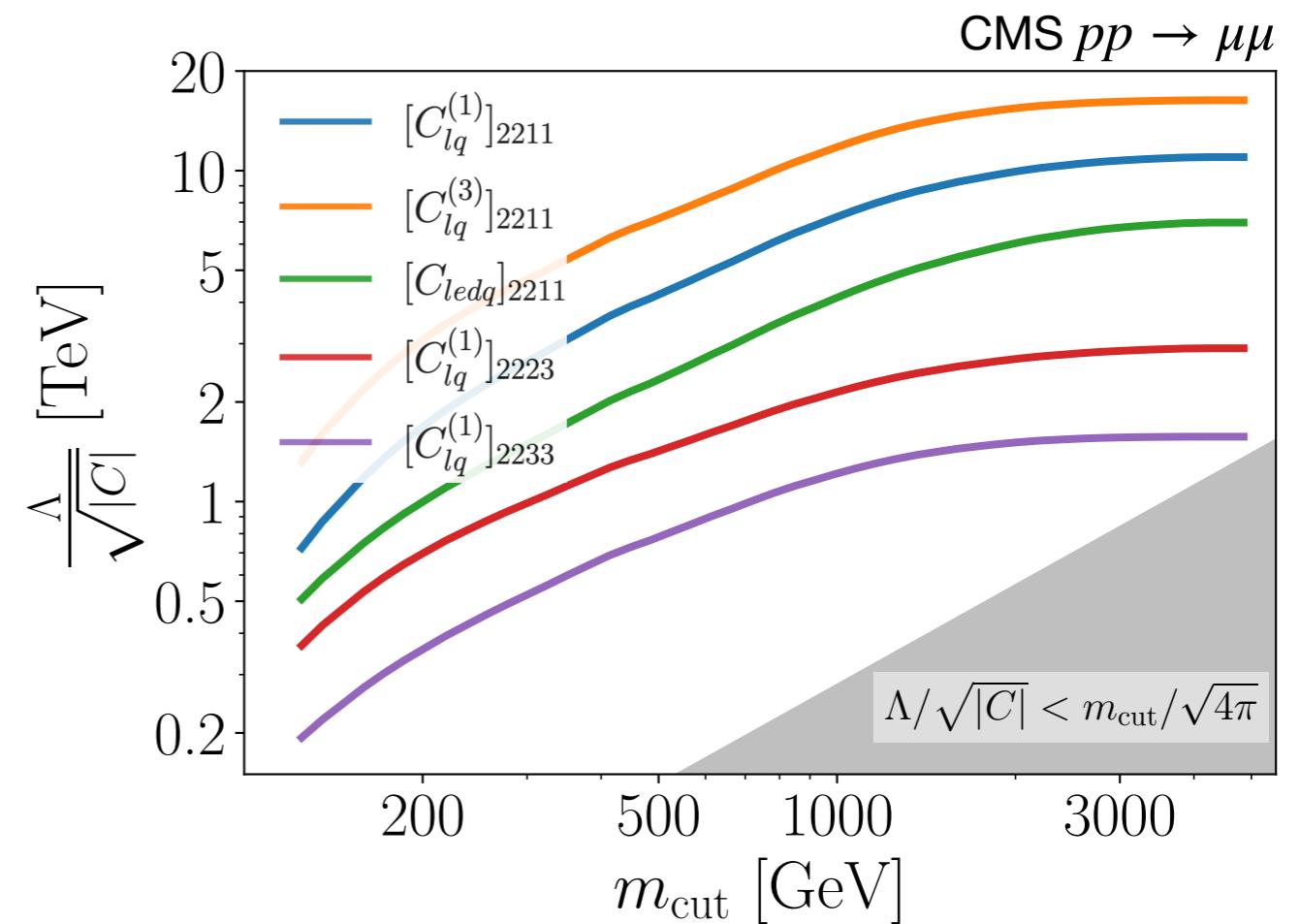
$Q_{lq}^{(1)}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{q}_s \gamma^\mu q_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p \gamma_\mu \sigma^i l_r)(\bar{q}_s \gamma^\mu \sigma^i q_t)$
Q_{lu}	$(\bar{l}_p \gamma_\mu l_r)(\bar{u}_s \gamma^\mu u_t)$
Q_{ld}	$(\bar{l}_p \gamma_\mu l_r)(\bar{d}_s \gamma^\mu d_t)$
Q_{qe}	$(\bar{q}_p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

Sensitivity of DY to CI

Greljo, Salko, AS, Stangl; 2212.10497



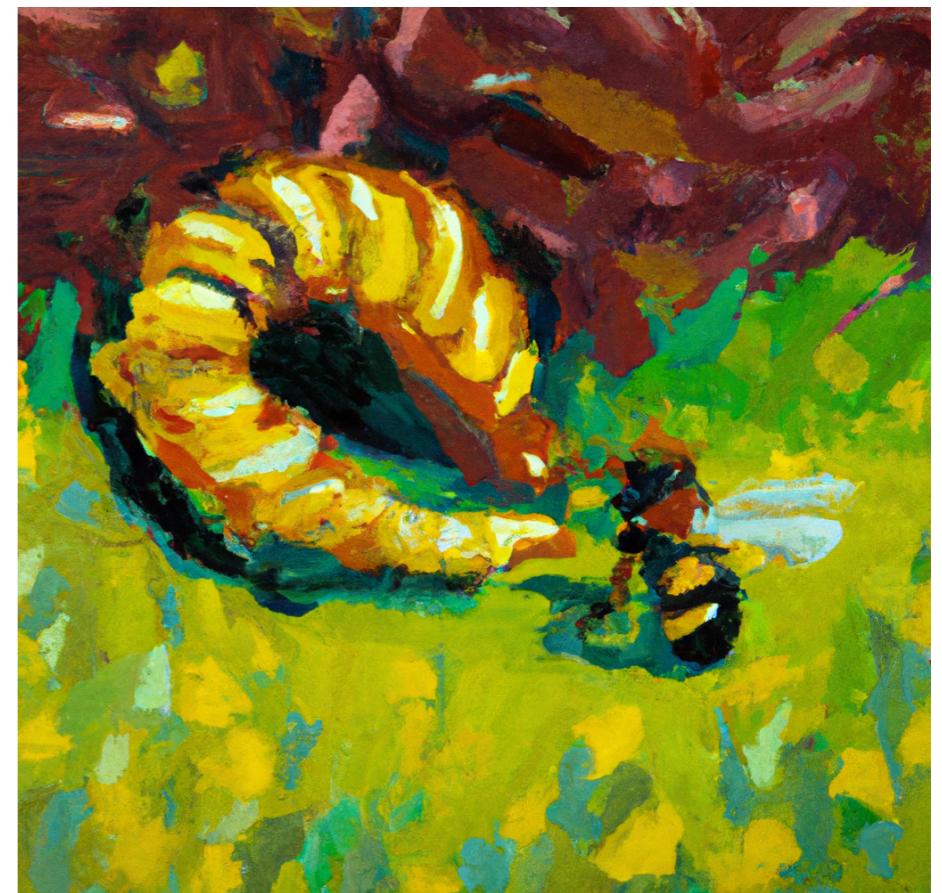
EFT CI enhanced at high energies



Bound saturates at bins of \sim TeV

Also e.g. 1811.07920, 2207.10714

Results in EFT: $b \rightarrow d$ and $b \rightarrow s^*$ meet high-mass DY



*assuming non-local effects under control (2110.10126, 2206.03797, ...)

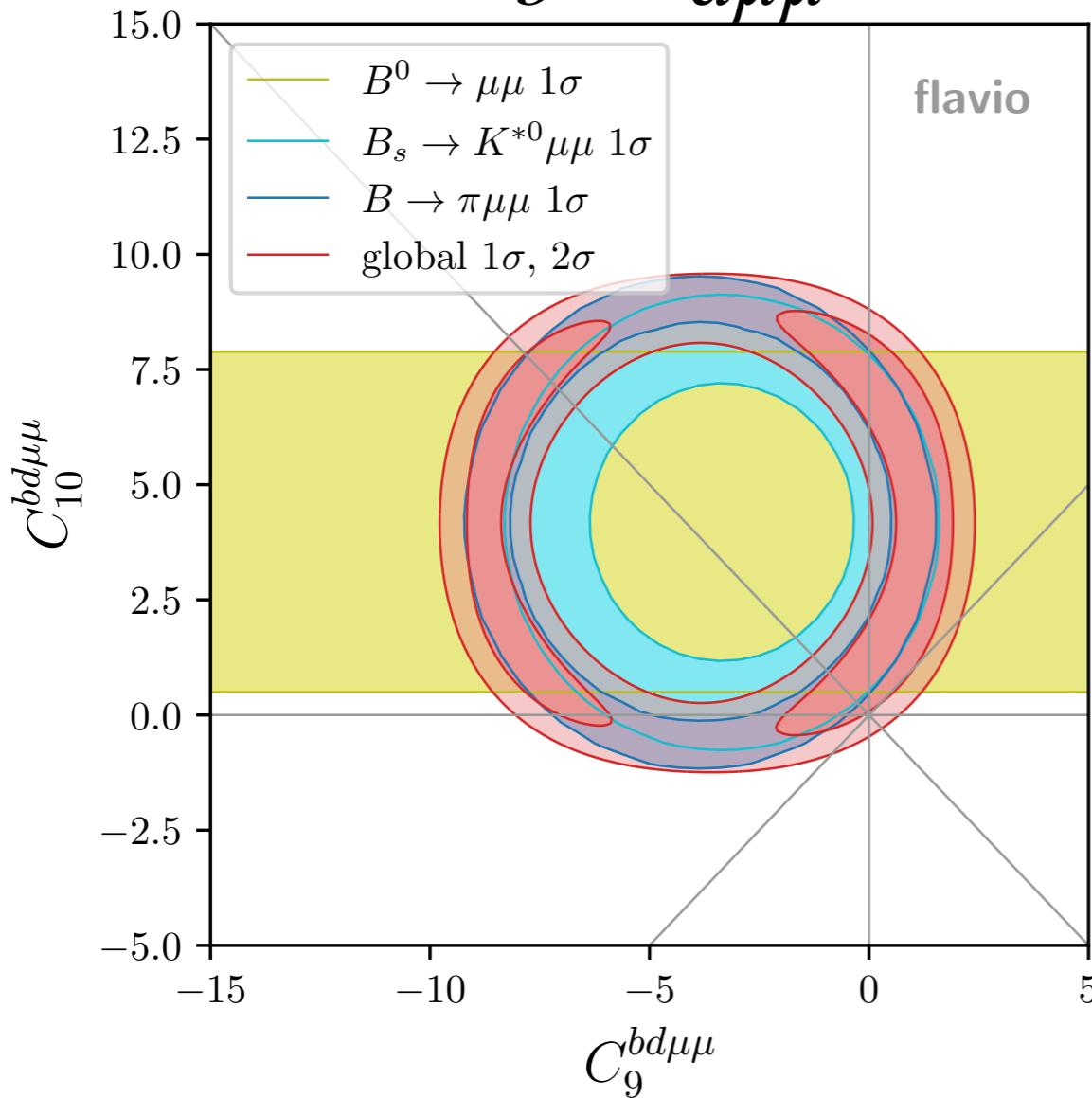
$b \rightarrow d, s$ in WET

Greljo, Salko, AS, Stangl; 2212.10497

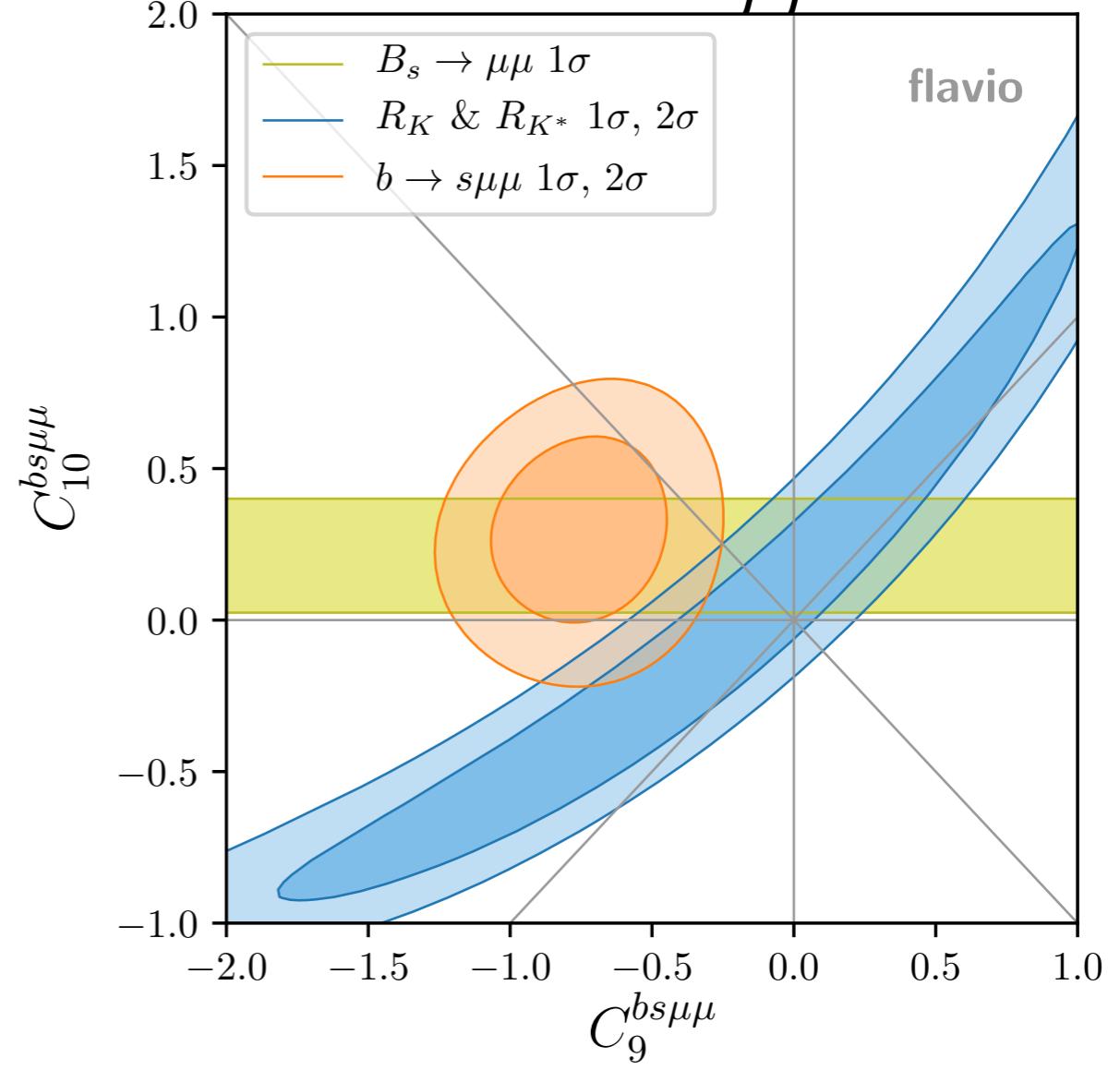
$$O_9^{bq\ell\ell} = (\bar{q}\gamma^\mu P_L b)(\bar{\ell}\gamma_\mu \ell)$$

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

$b \rightarrow d\mu\mu$



$b \rightarrow s\mu\mu$



$B \rightarrow \pi$ FFs from 2102.07233

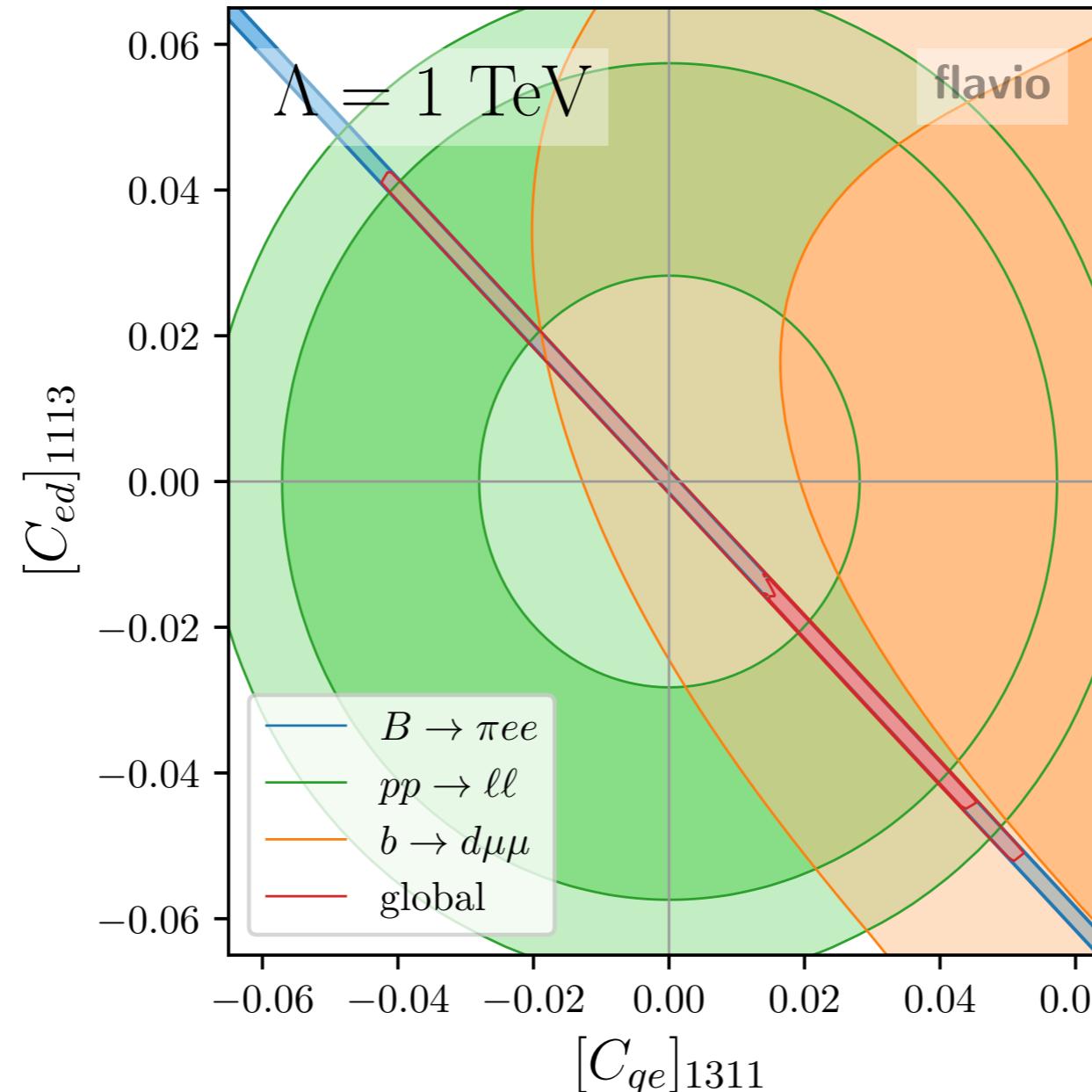
Also e.g. R. Bause et al (2209.04457), M. Ciuchini et al (2212.10516)

SMEFT: minimalistic flavor

Closing flat directions with complementary constraints:

Greljo, Salko, AS, Stangl; 2212.10497

Example assuming NP only in $bdee$



$$Q_{ed} = (\bar{e}\gamma_\mu e)(\bar{d}\gamma^\mu d), \quad Q_{qe} = (\bar{q}\gamma_\mu q)(\bar{e}\gamma^\mu e)$$

SMEFT: interplay in MFV

Greljo, Salko, AS, Stangl; 2212.10497

$$[C_{lq}^{(1)}]_{st}^{(l)} \bar{L}_l \gamma_\mu L_l \bar{Q}_s \gamma^\mu Q_t \rightarrow [C_{lq}^{(1)}]_{st}^{(l)} = \delta_{st} [C_{lq}^{(1)}]_{\delta}^{(l)} + (Y_u Y_u^\dagger)_{st} [C_{lq}^{(1)}]_{Y_u Y_u^\dagger}^{(l)} + \dots$$

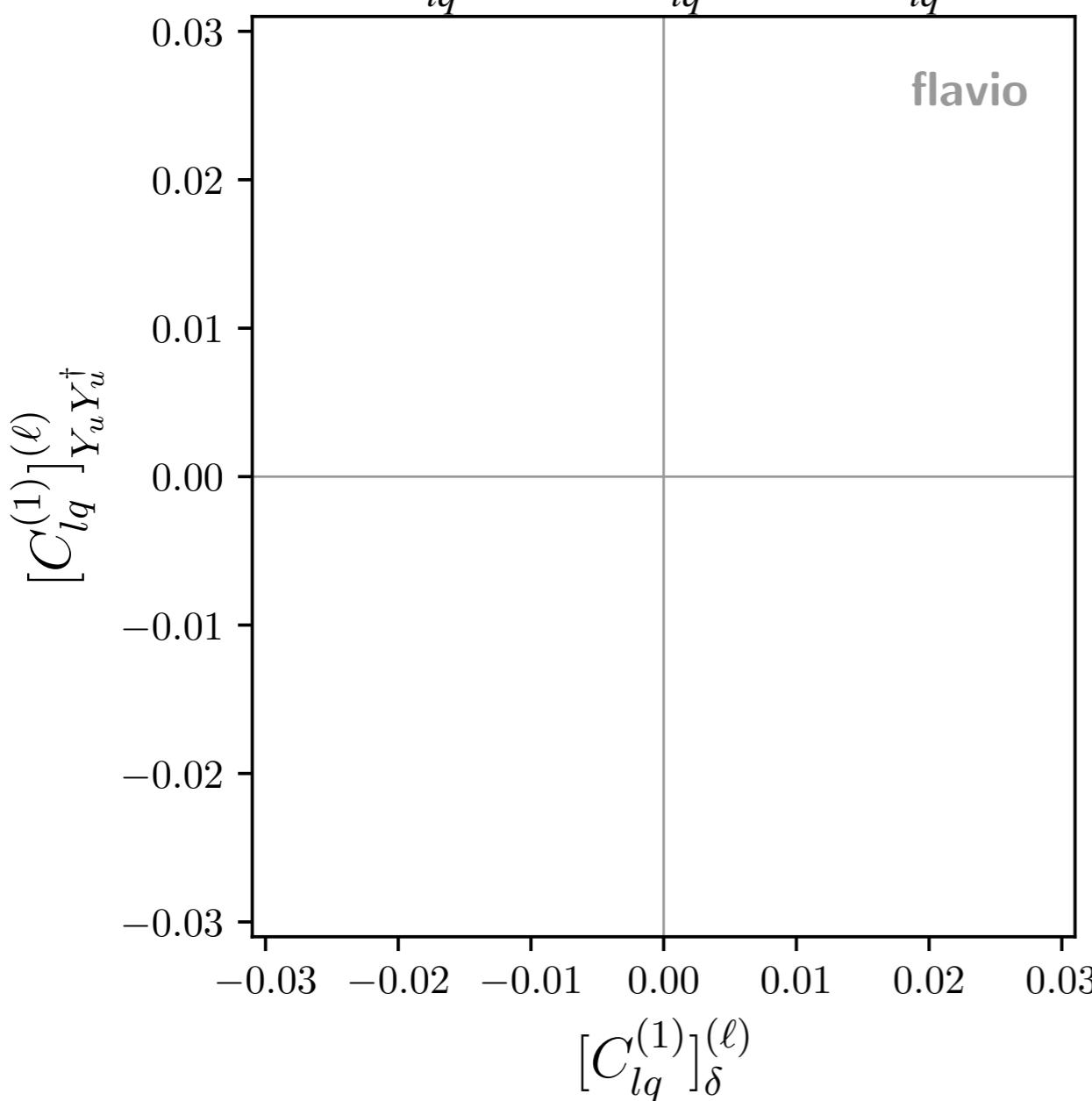
$$\sim y_t^2 \begin{pmatrix} V_{td} V_{td}^* & V_{ts} V_{td}^* & V_{tb} V_{td}^* \\ V_{td} V_{ts}^* & V_{ts} V_{ts}^* & V_{tb} V_{ts}^* \\ V_{td} V_{tb}^* & V_{ts} V_{tb}^* & V_{tb} V_{tb}^* \end{pmatrix}$$

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



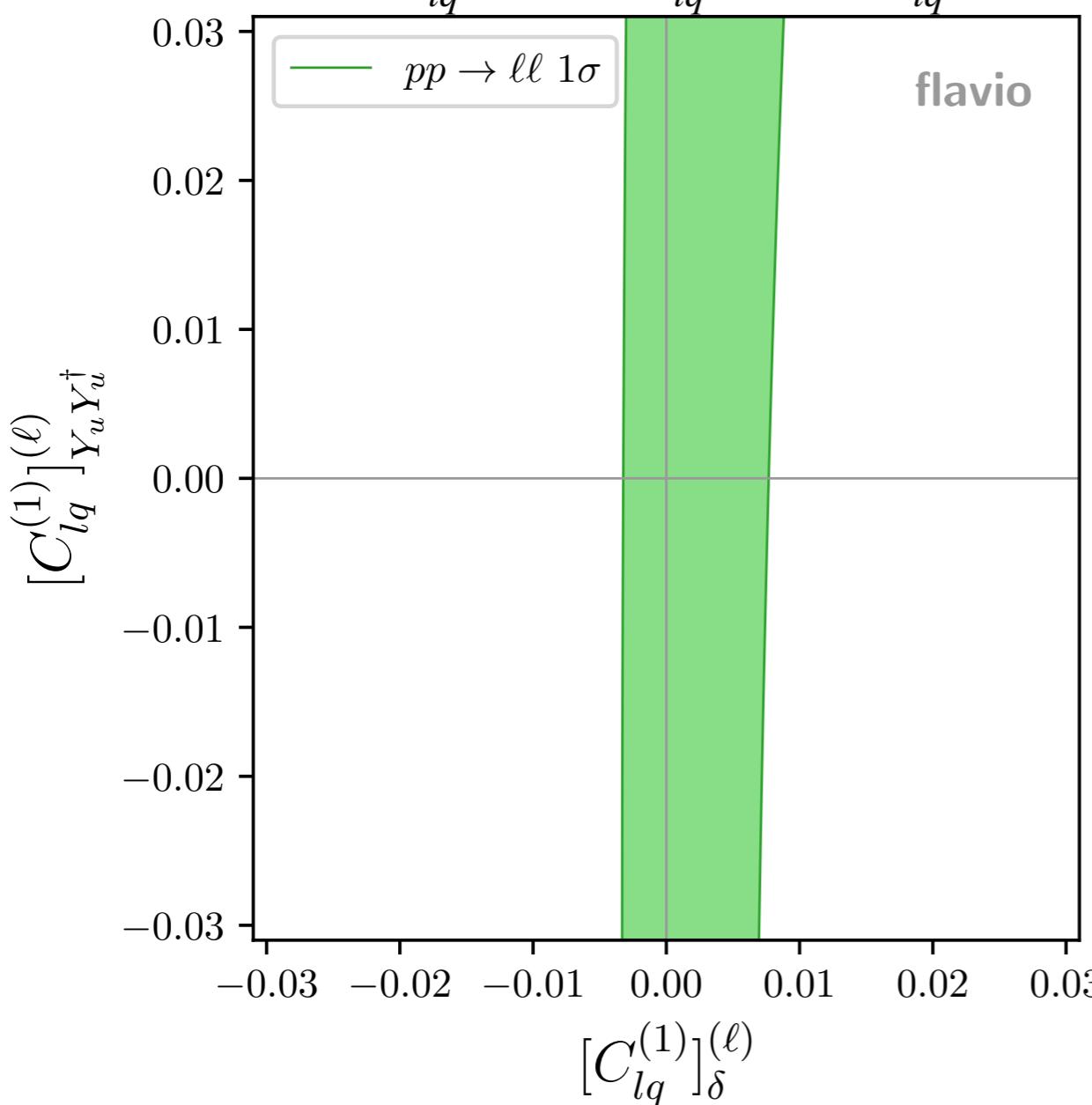
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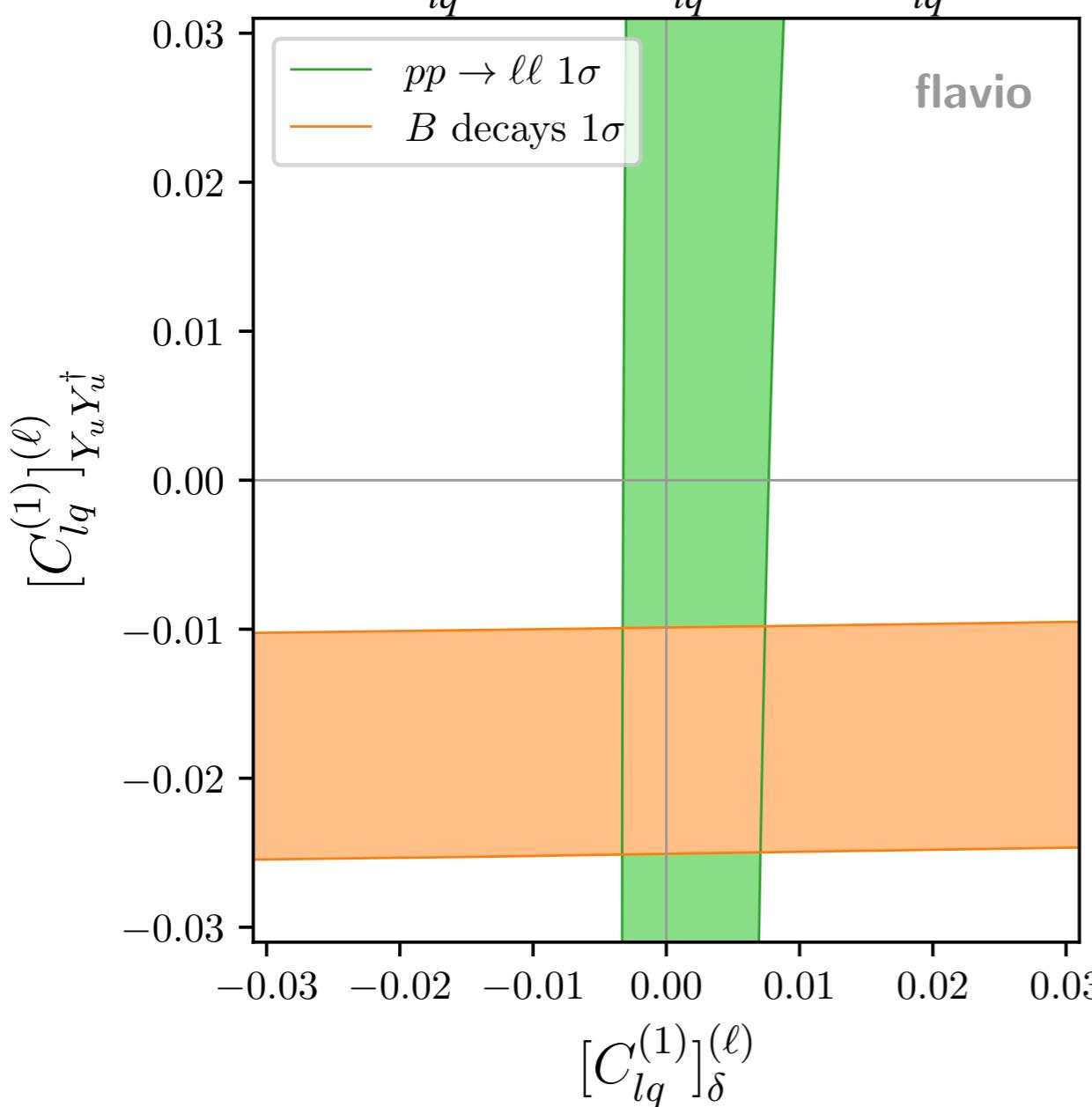
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Curved arrow pointing from the text above to the matrix equation.

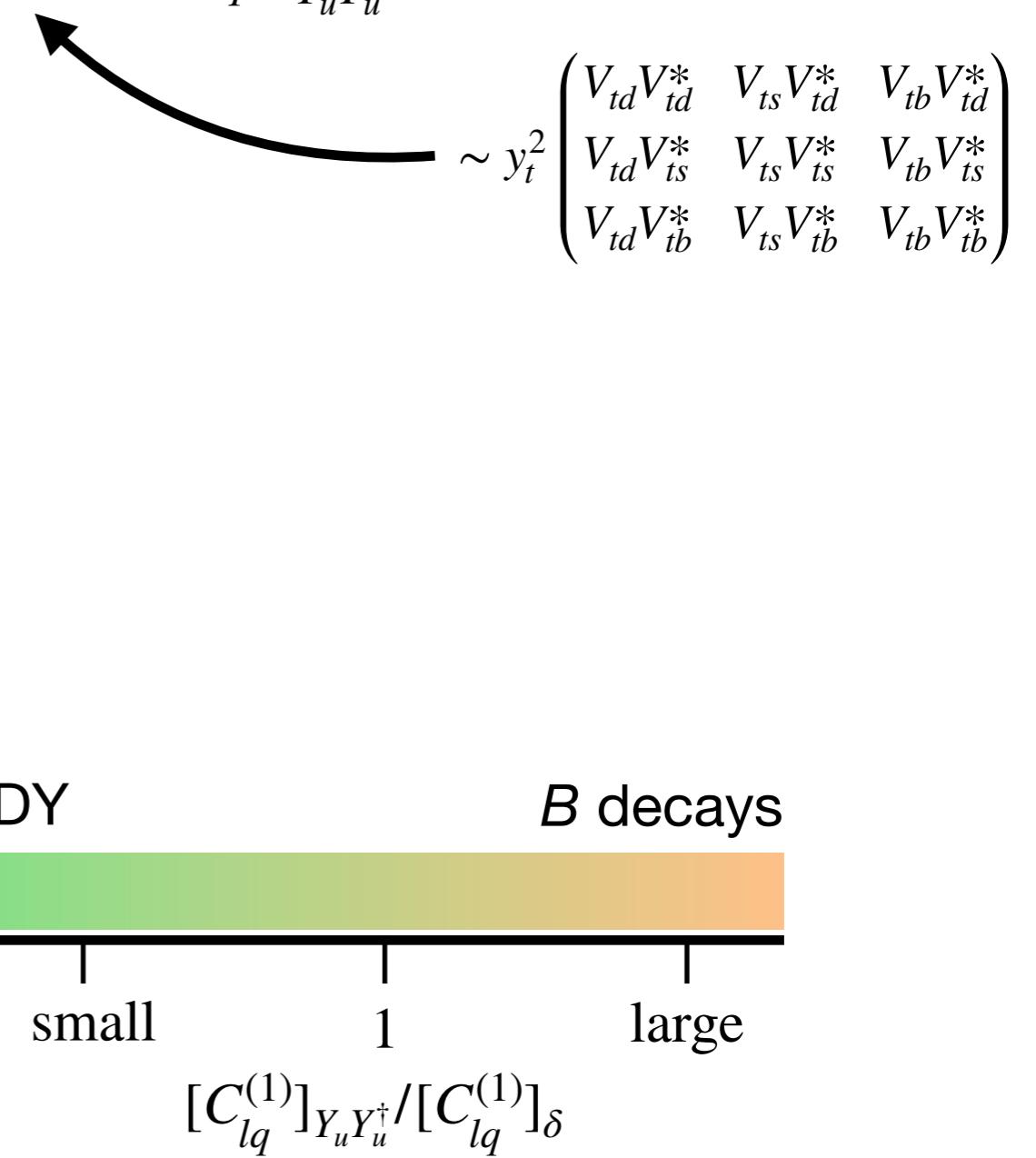
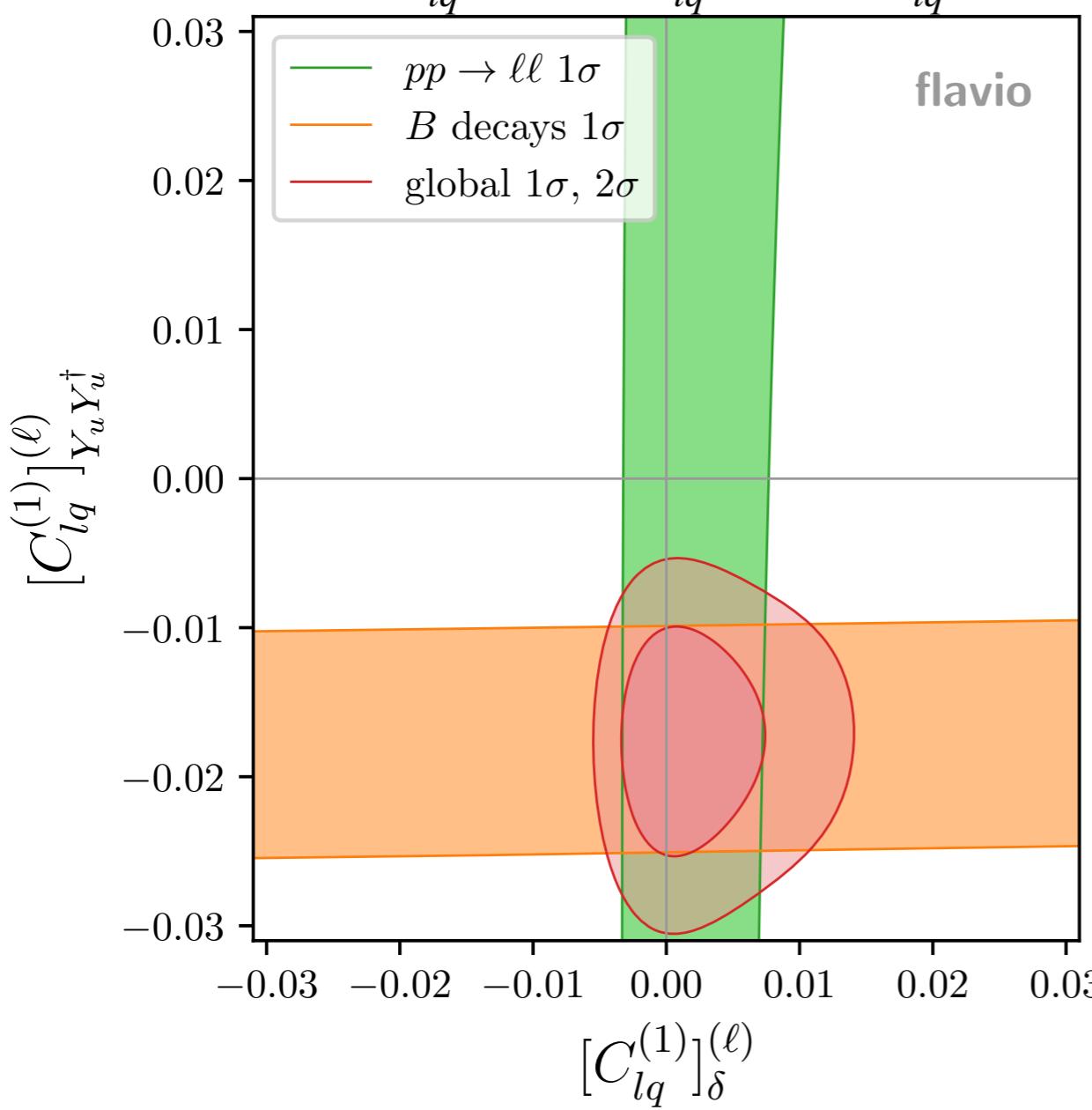
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Greljo, Salko, AS, Stangl; 2212.10497

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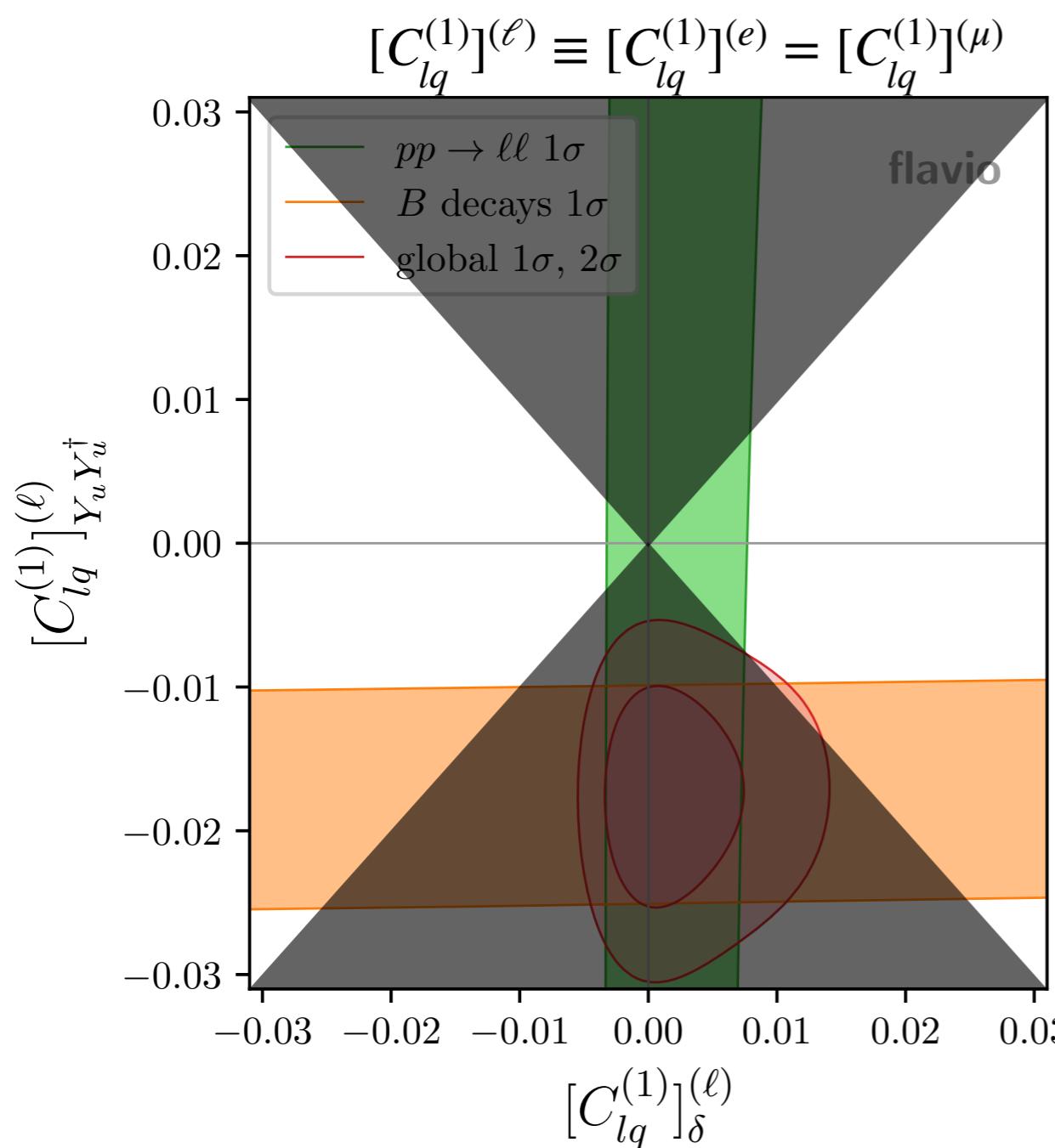
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SMEFT: interplay in MFV

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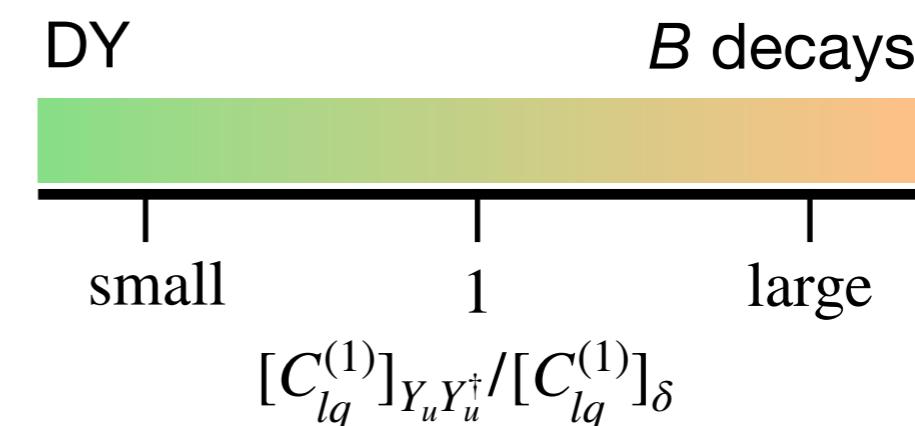
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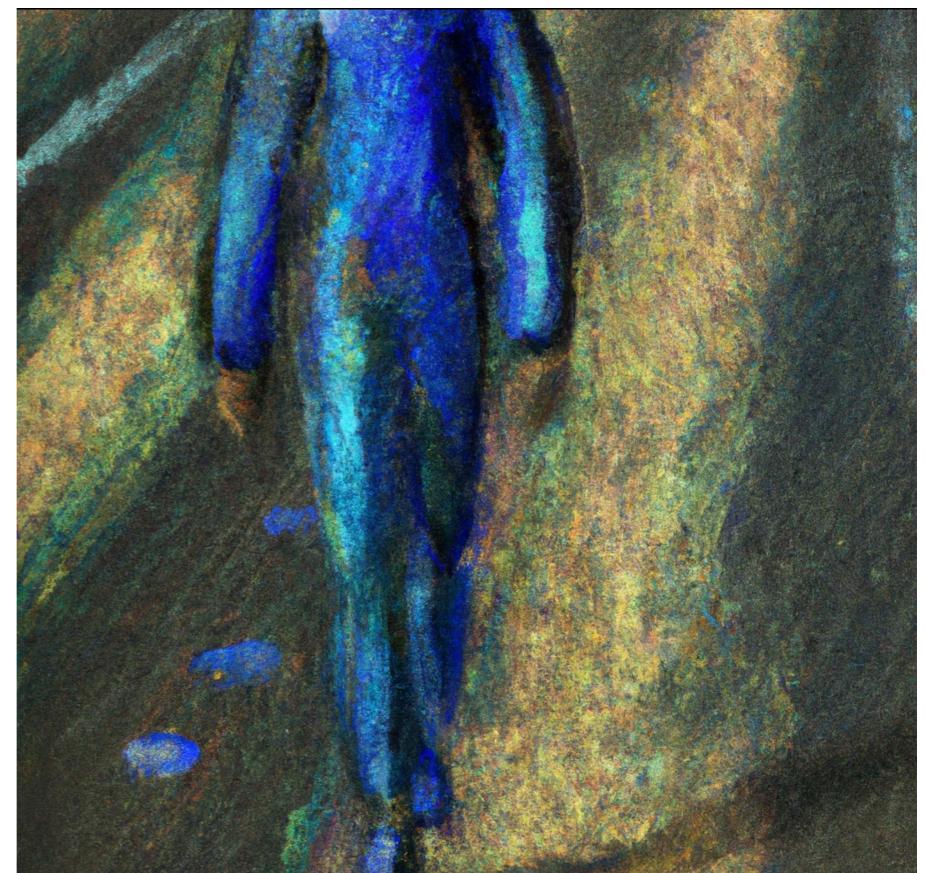
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Expansion validity?

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

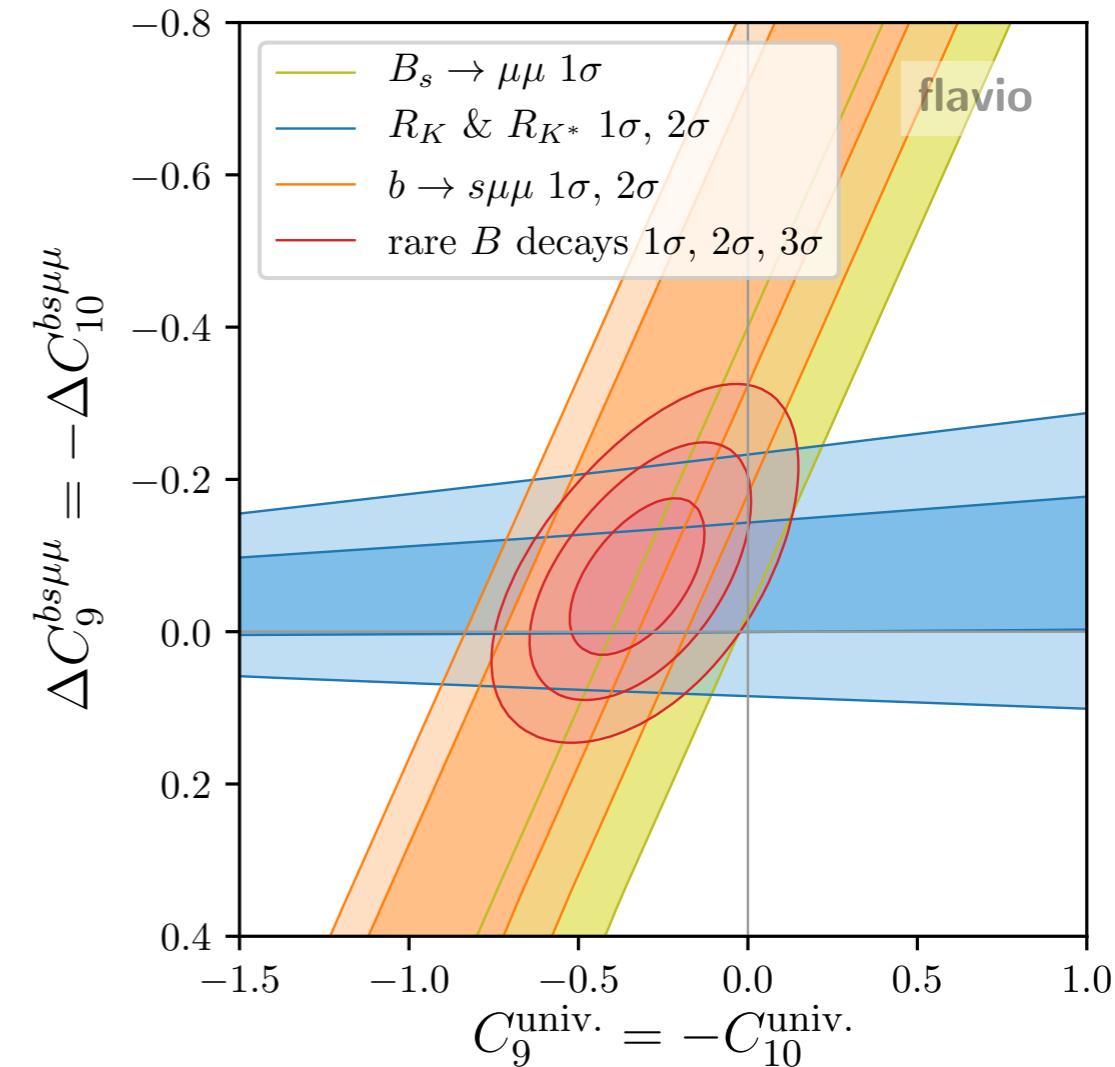
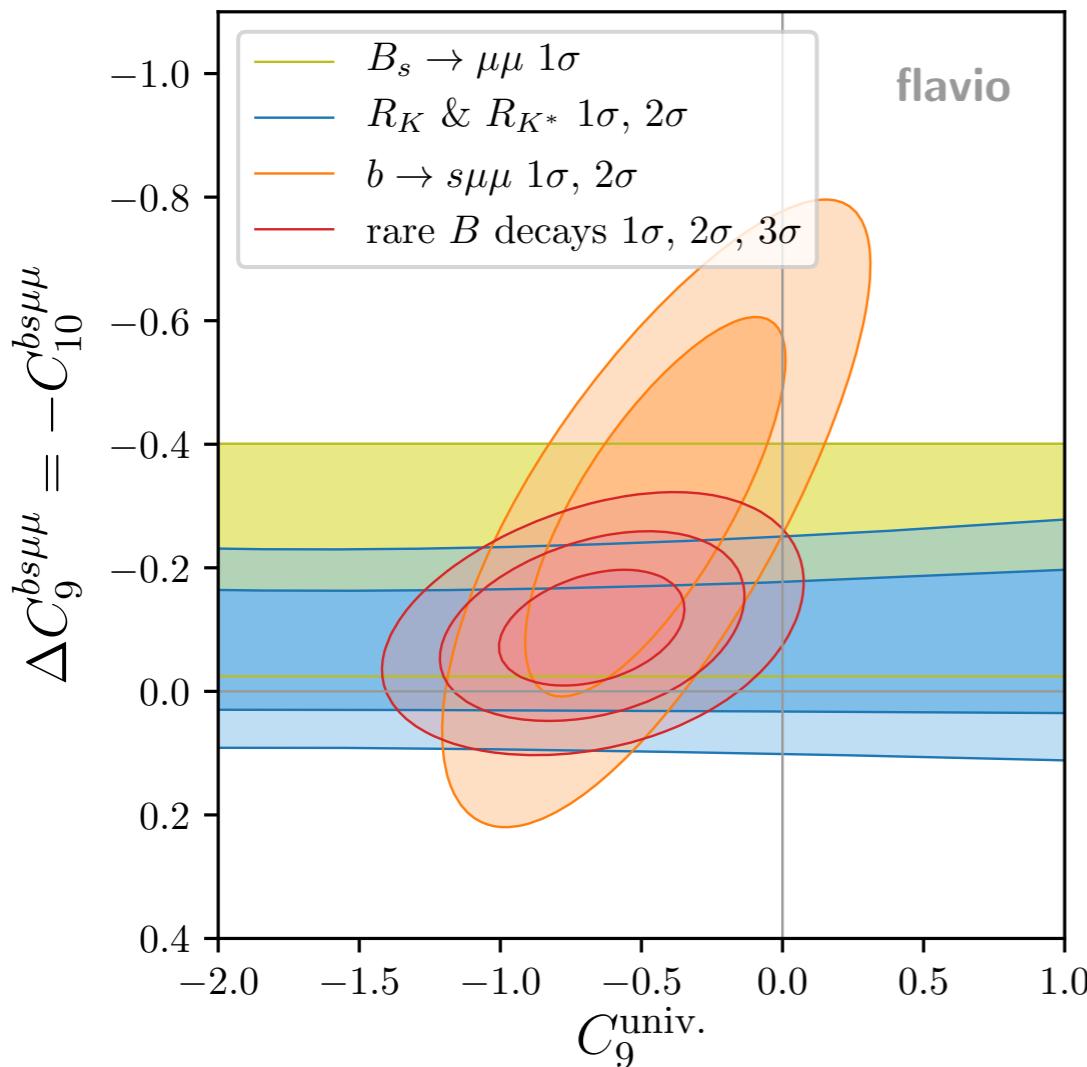


Model examples: heavy Z's and LQs



LFU vs LFUV

Greljo, Salko, AS, Stangl; 2212.10497

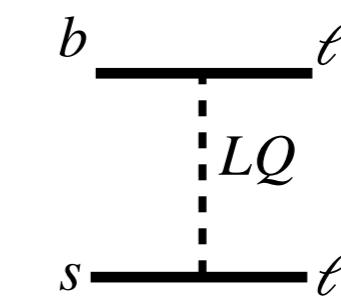
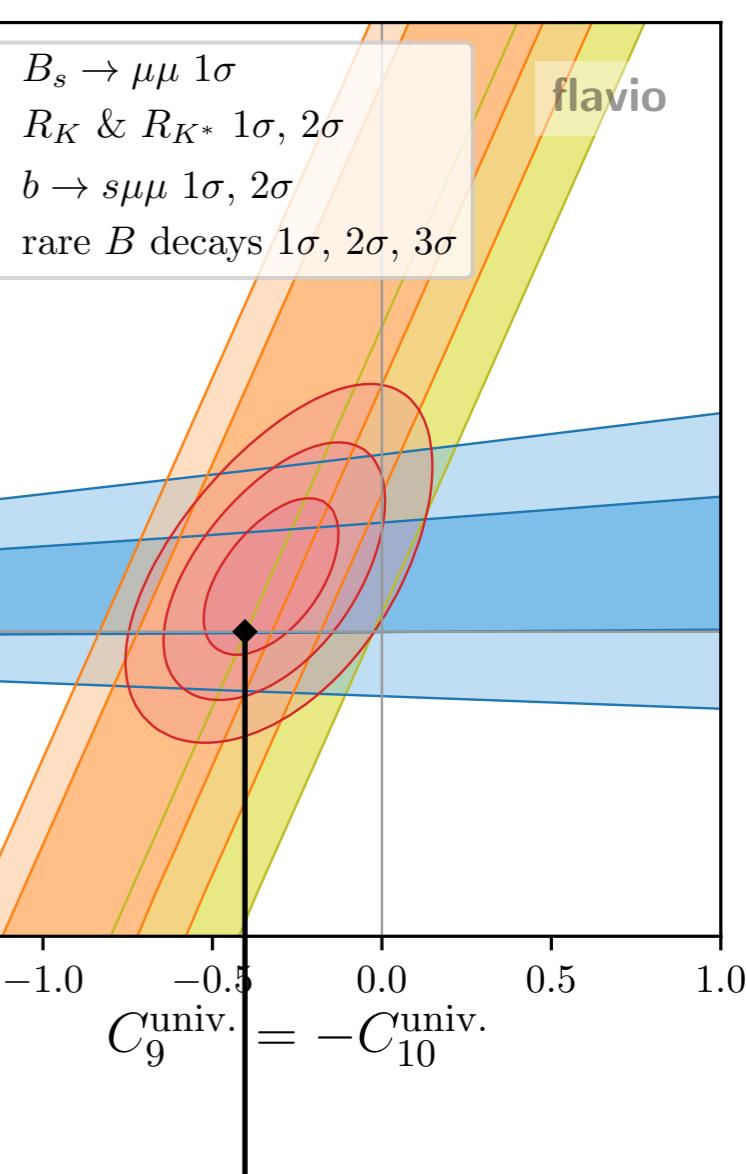
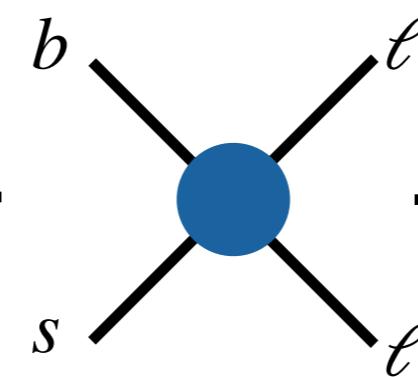
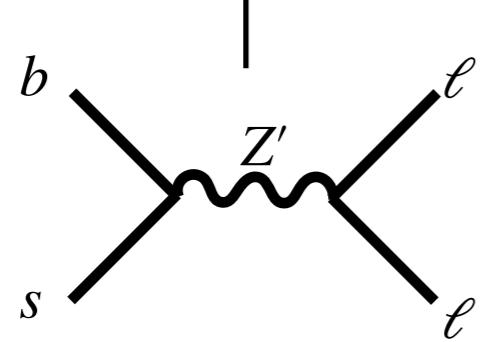
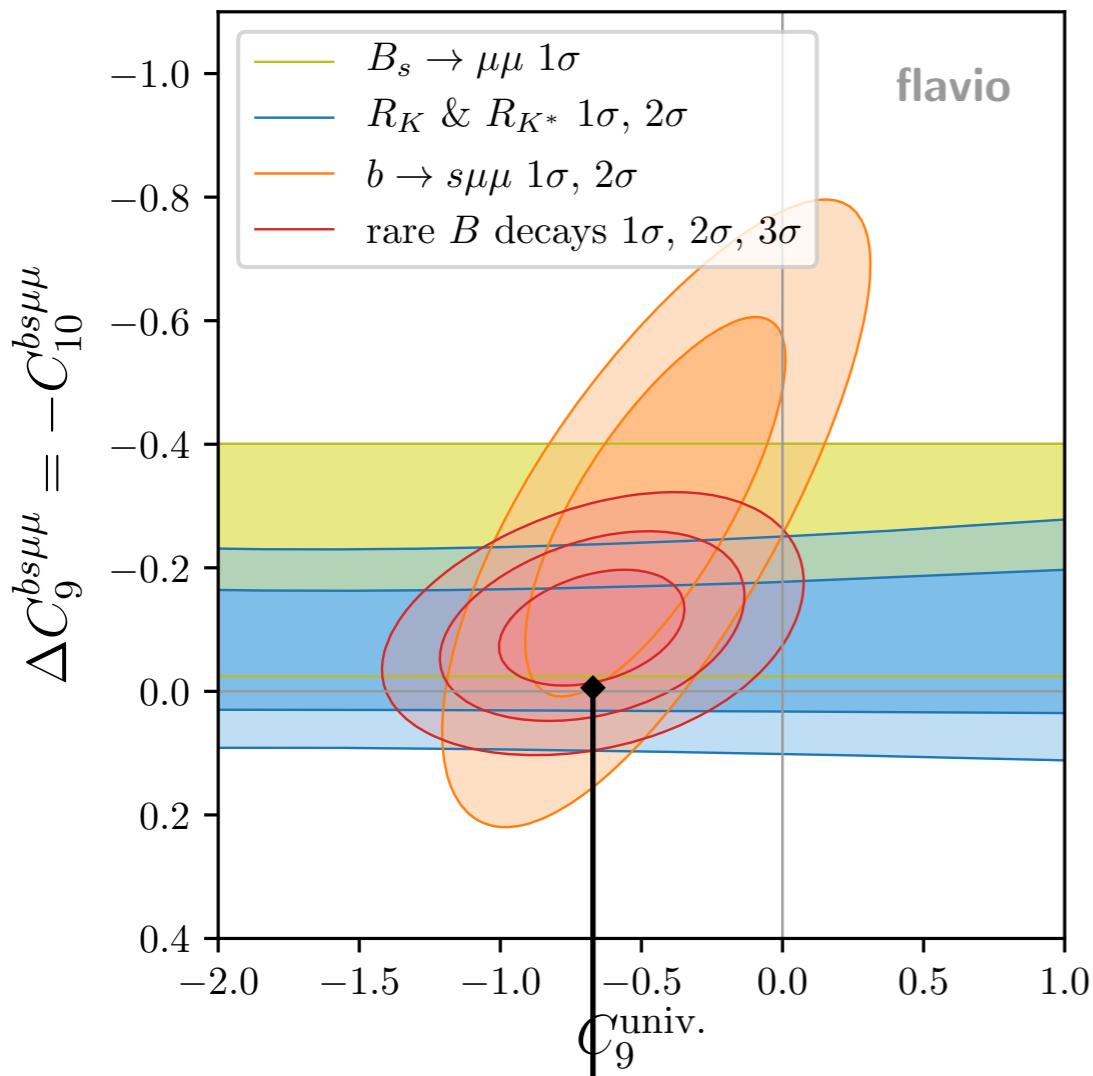


$$C_{9,10}^{\text{bs}\mu\mu} = C_{9,10}^{\text{univ.}} + \Delta C_{9,10}^{\text{bs}\mu\mu}$$

$$C_{9,10}^{\text{bsee}} = C_{9,10}^{\text{univ.}}$$

LFU tree level models

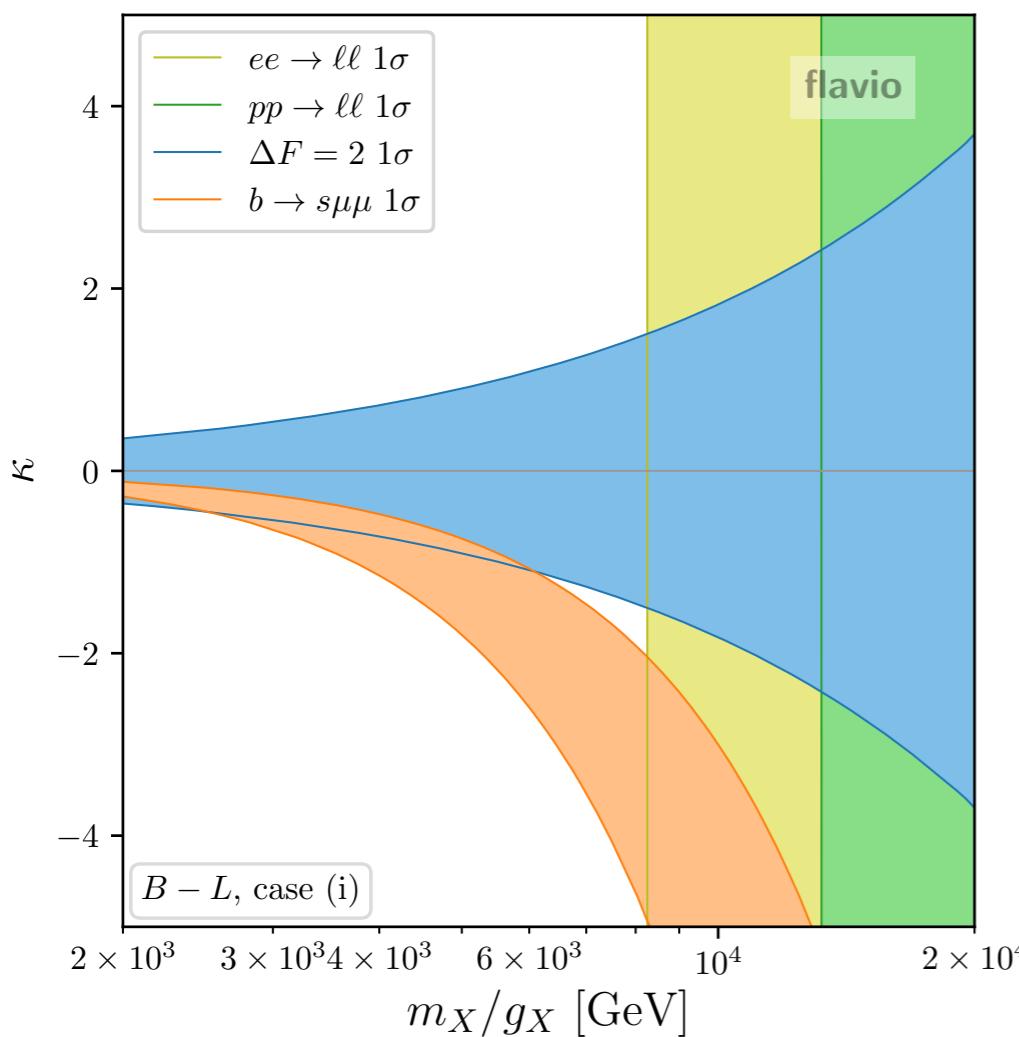
Greljo, Salko, AS, Stangl; 2212.10497



LFU Z'

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

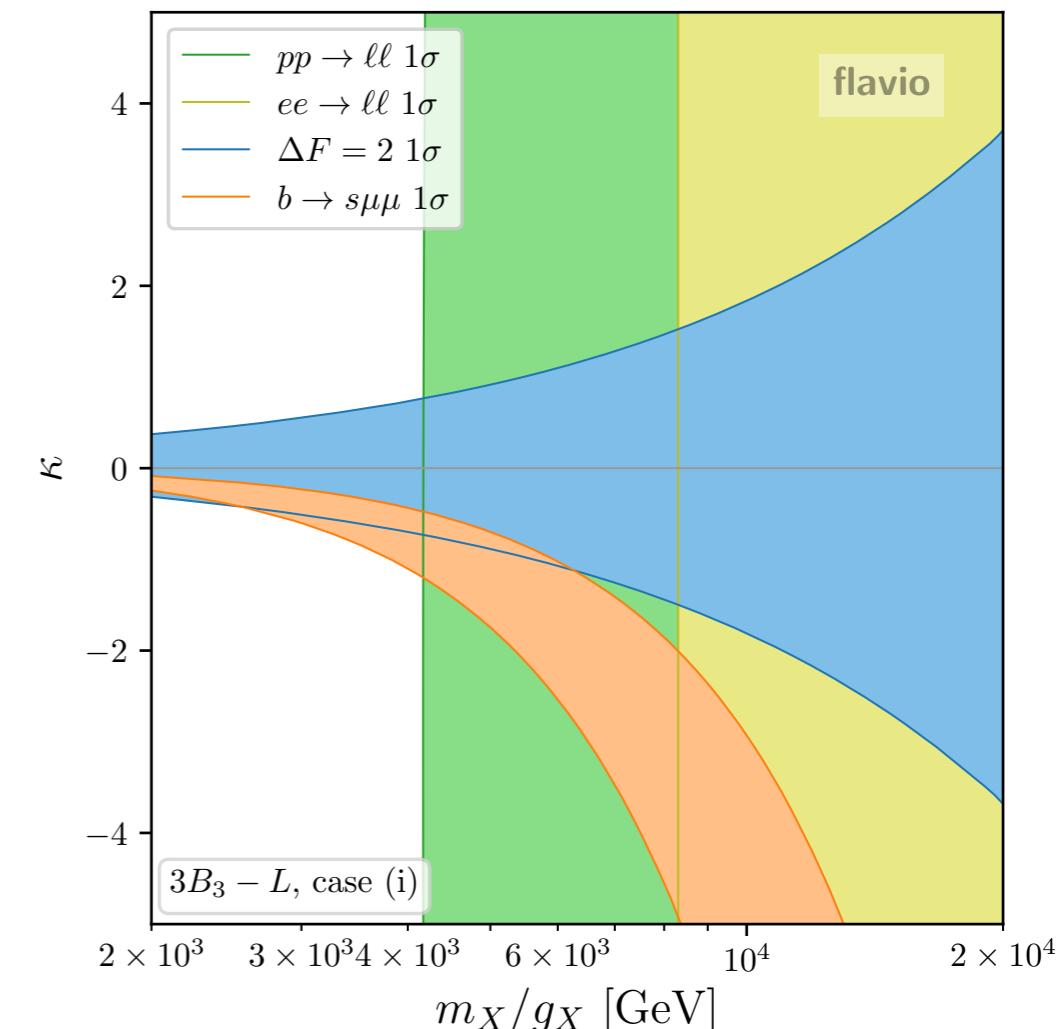
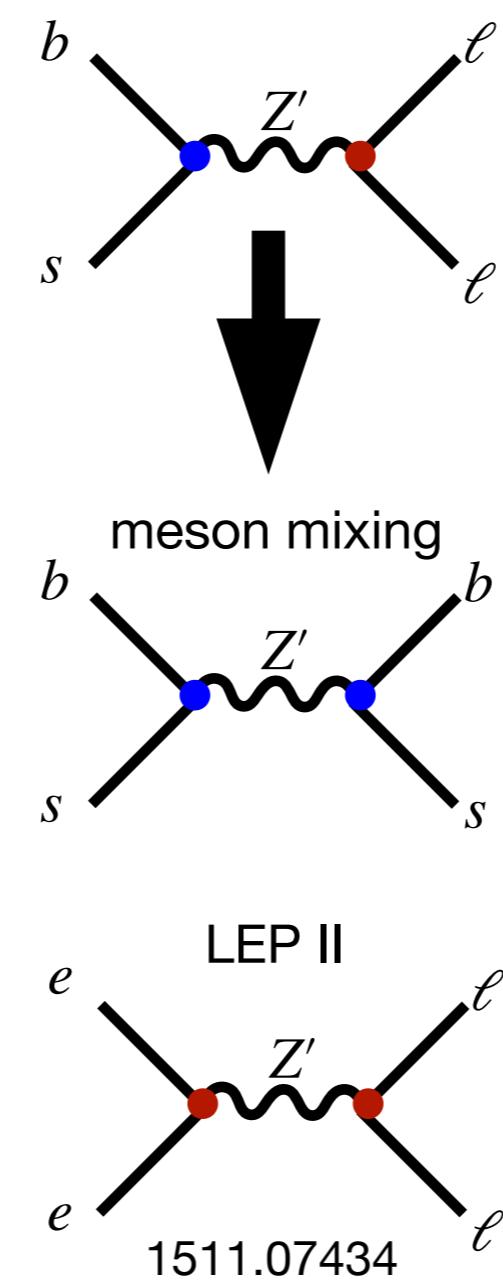
$$J^\mu = J^\mu_{B-L} + \frac{1}{3}\epsilon_{ij}\bar{q}_i\gamma^\mu q_j$$



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

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

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



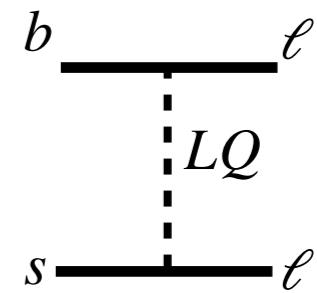
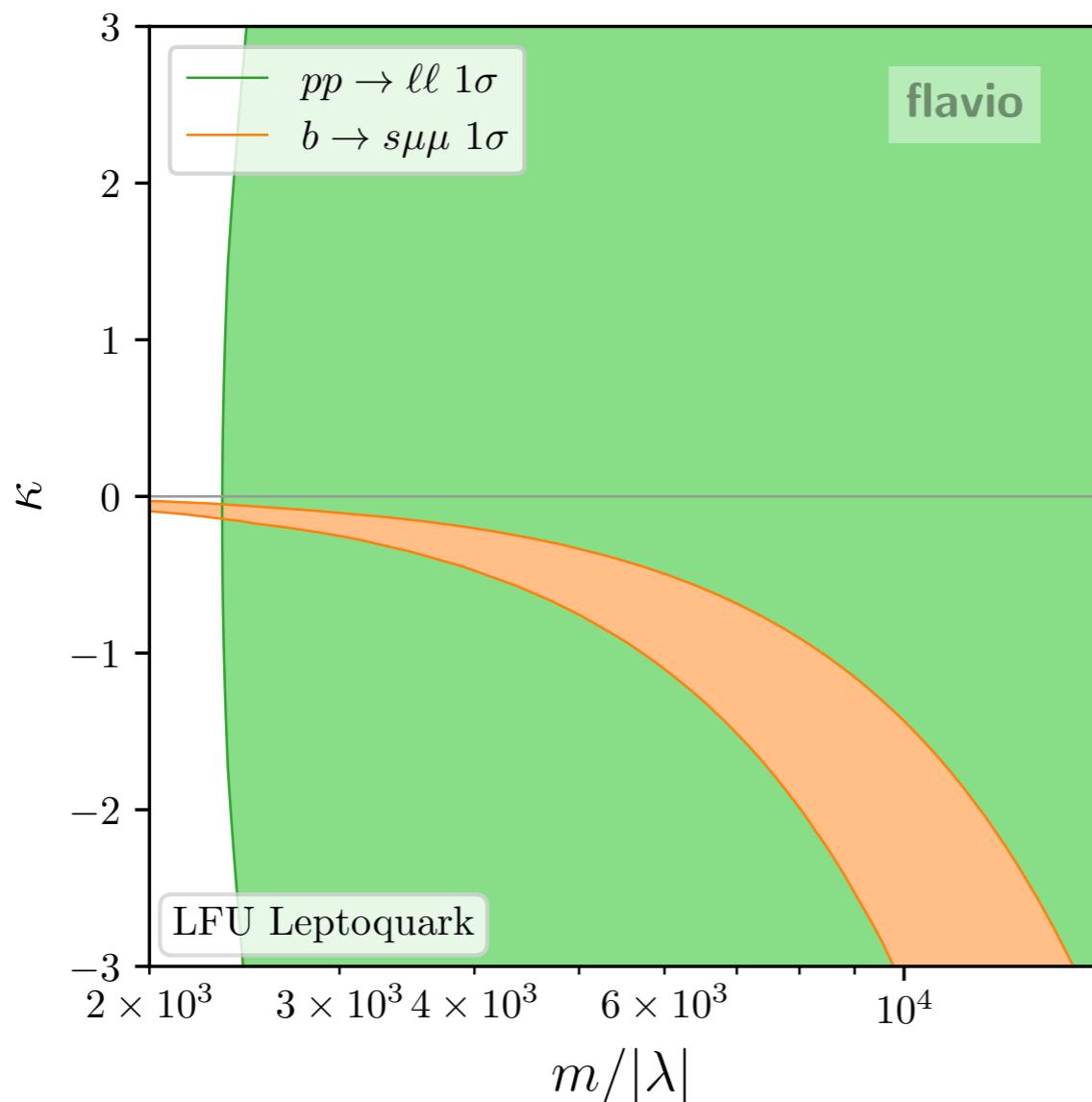
Tension

LFU leptoquark

Triplet of scalar S_3 LQs: $S^\alpha \sim (\bar{\mathbf{3}}, \mathbf{3}, 1/3)$, LQs form a $\bar{\mathbf{3}}$ under $U(3)_l$ ^{*}

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

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



2q2 ℓ at tree level
4q and 4 ℓ loop suppressed

* could be more minimal, i.e. $U(2)_l$ or $U(1)_e \times U(1)_\mu \times Z_2^{e \leftrightarrow \mu}$

Summary

- Implement neutral and charged current high-mass Drell-Yan tails with light leptons into the flavio+smelli framework*
available on flav-io.github.io
- Analyse the interplay between low-energy B -meson decays into light leptons and high-mass Drell-Yan constraints in the SMEFT and beyond
- Demonstrate high complementarity between Drell-Yan and meson decays in realistic flavour scenarios, and concrete models

*shoutout to HighPT (see talk by Jaffredo)

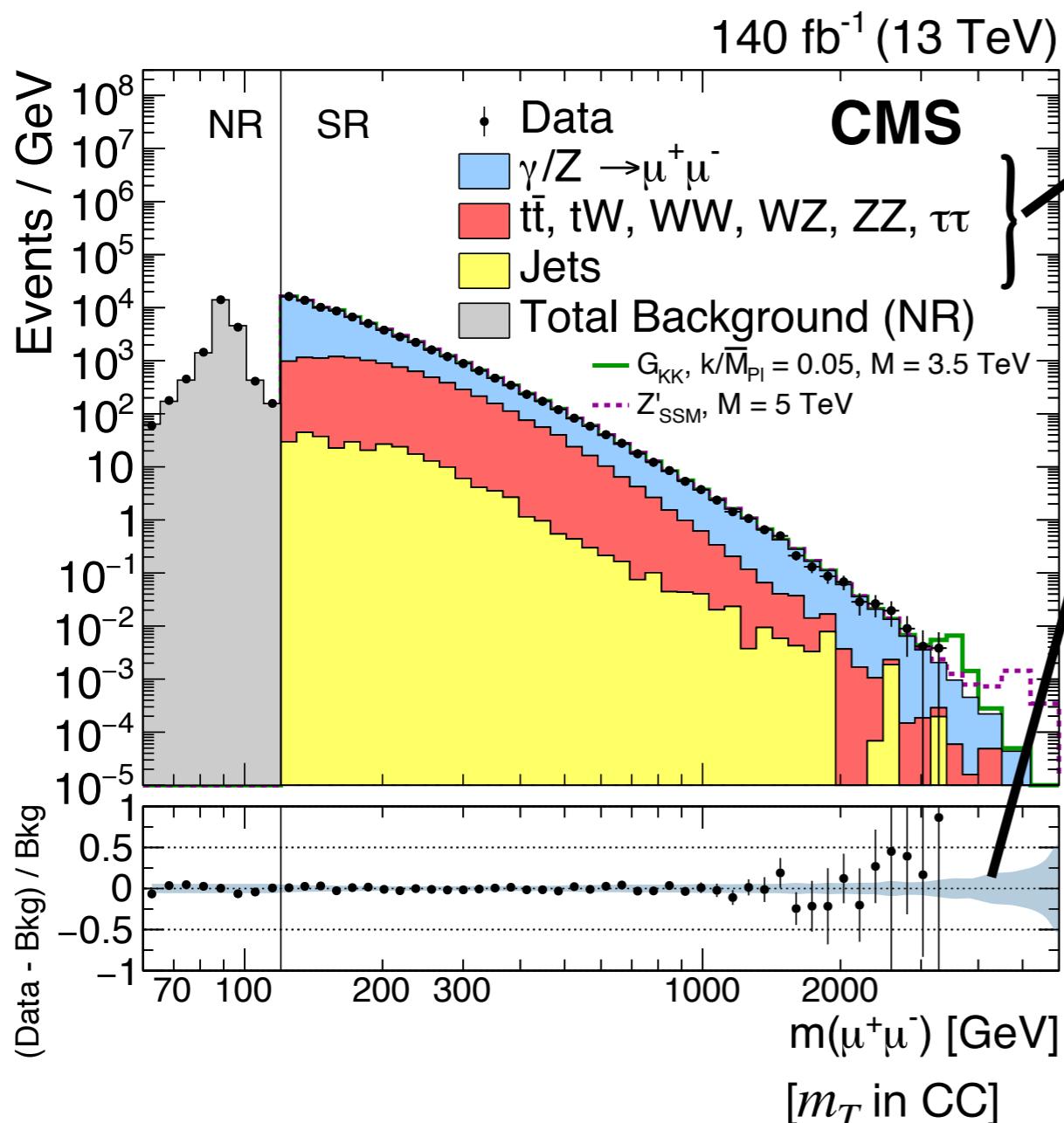
Thank you

Additional slides

Implementation of Drell-Yan

Experimental measurements:

We implement data ($\sim 140\text{fb}^{-1}$) from latest CMS and ATLAS searches:



	$pp \rightarrow \ell\ell$	$pp \rightarrow \ell\nu$
CMS	2103.02708	2202.06075
ATLAS	2006.12946	1906.05609

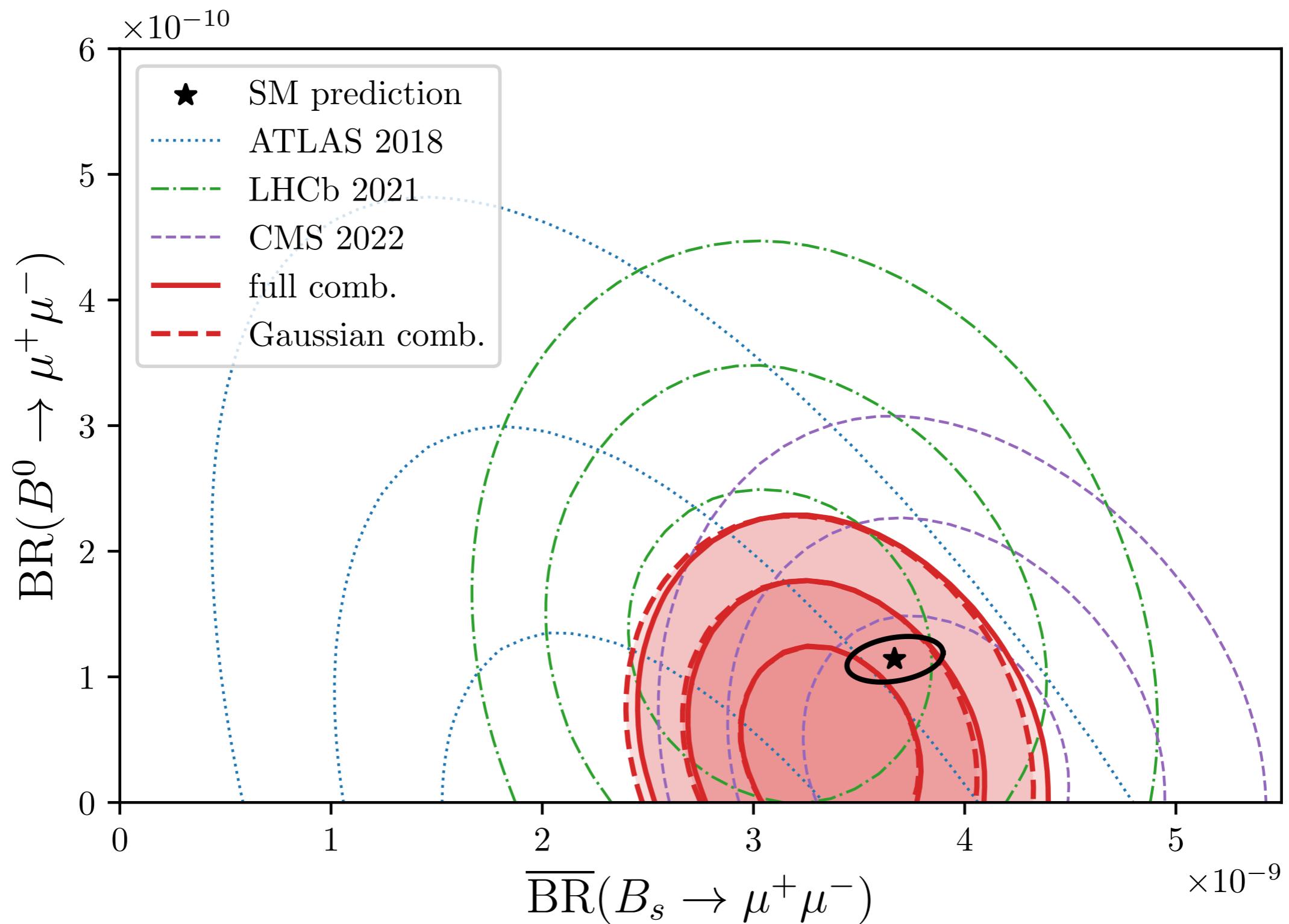
For predictions:
 We reweigh the reported expected number of DY events with ratio

$$N_{DY}^{\text{NP+SM}} = \frac{\sigma^{\text{SM+NP}}}{\sigma^{\text{SM}}} N_{DY}^{\text{SM}}$$

⇒ implement analytical predictions
 of $d\sigma(pp \rightarrow \ell\ell, \ell\nu)/dm$

A. Greljo and D. Marzocca: 1704.09015

Wilson coefficient	$b \rightarrow s\mu\mu$		LFU, $B_s \rightarrow \mu\mu$		all rare B decays	
	best fit	pull	best fit	pull	best fit	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
$(C_S^{bs\mu\mu} = -C_P^{bs\mu\mu}) \times \text{GeV}$			$-0.002^{+0.001}_{-0.002}$	1.1σ	$-0.001^{+0.001}_{-0.001}$	0.7σ
$(C_S'^{bs\mu\mu} = C_P'^{bs\mu\mu}) \times \text{GeV}$			$-0.002^{+0.001}_{-0.002}$	1.1σ	$-0.001^{+0.001}_{-0.001}$	0.7σ



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