New Frontiers in Lepton Flavor, Pisa

May 17, 2023

High-pT meets flavor

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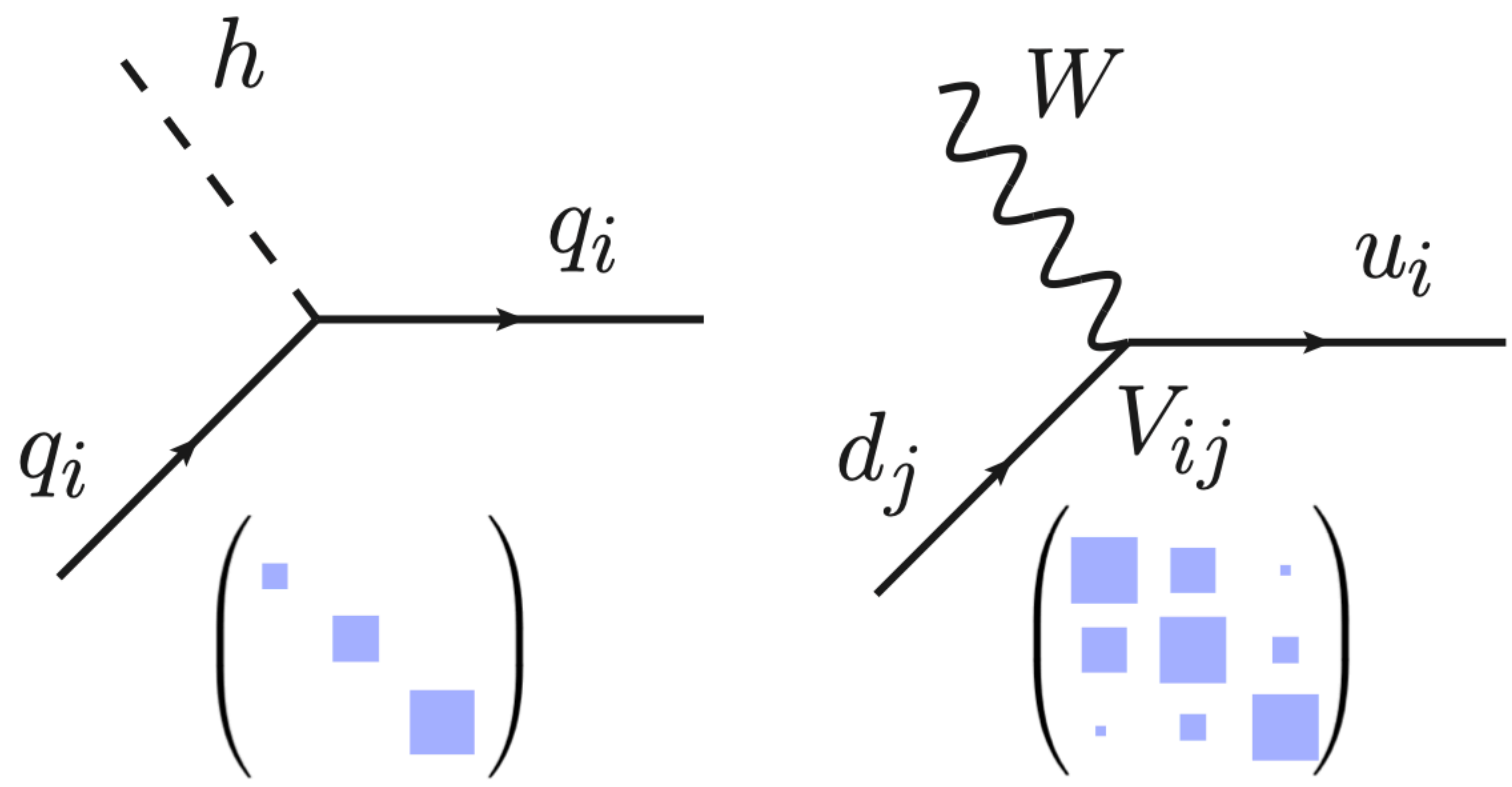
FOR FUNDAMENTAL PHYSICS

Outline

- **Intro:** heavy NP, SMEFT, high-mass Drell-Yan
- **Complementarity in EFT**
- **Complementarity in models**

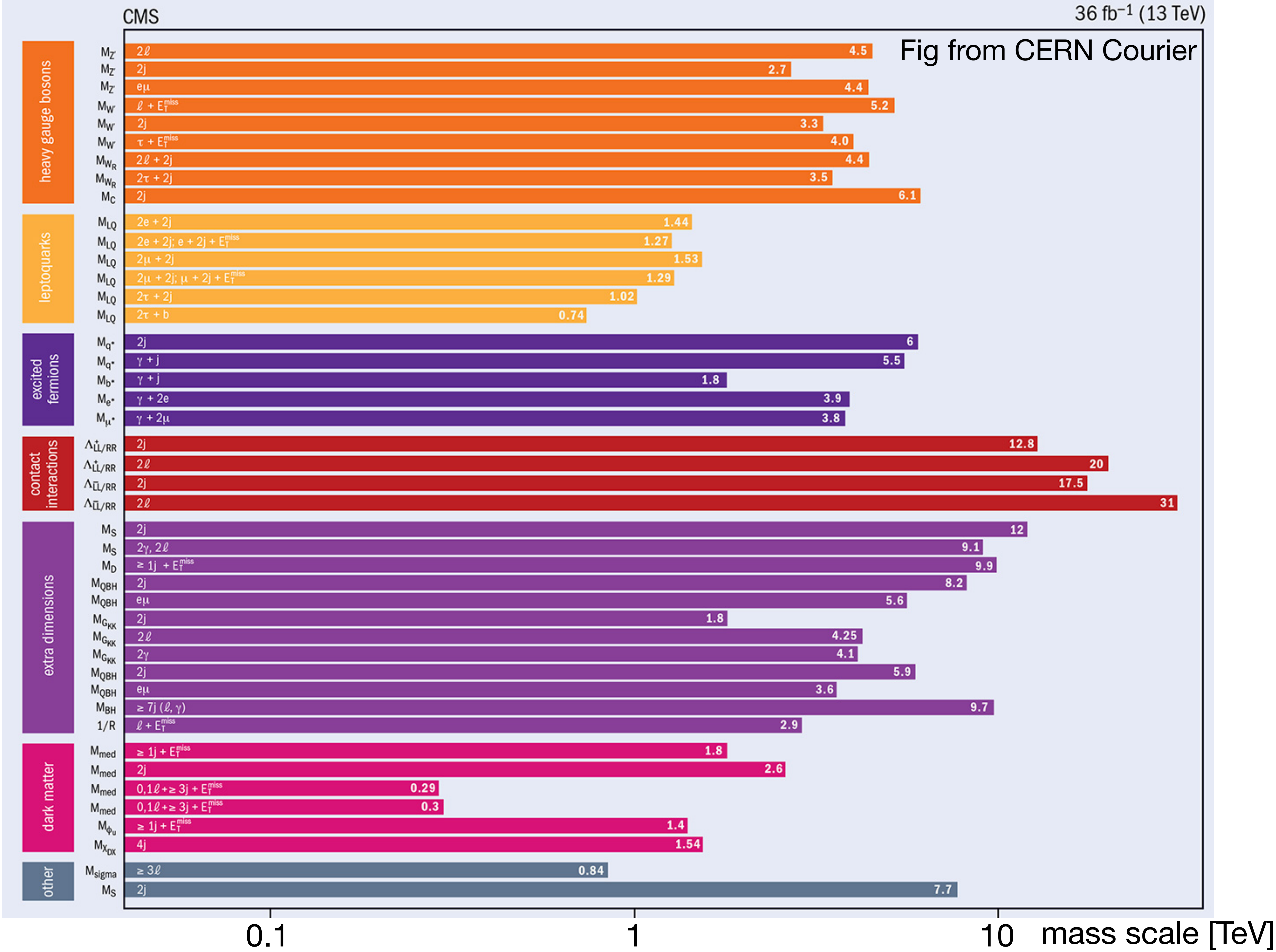
Heavy NP?

- Neutrino masses?
- Dark matter?
- Hierarchy problem?
- Flavor puzzle?
- CPV beyond the SM?

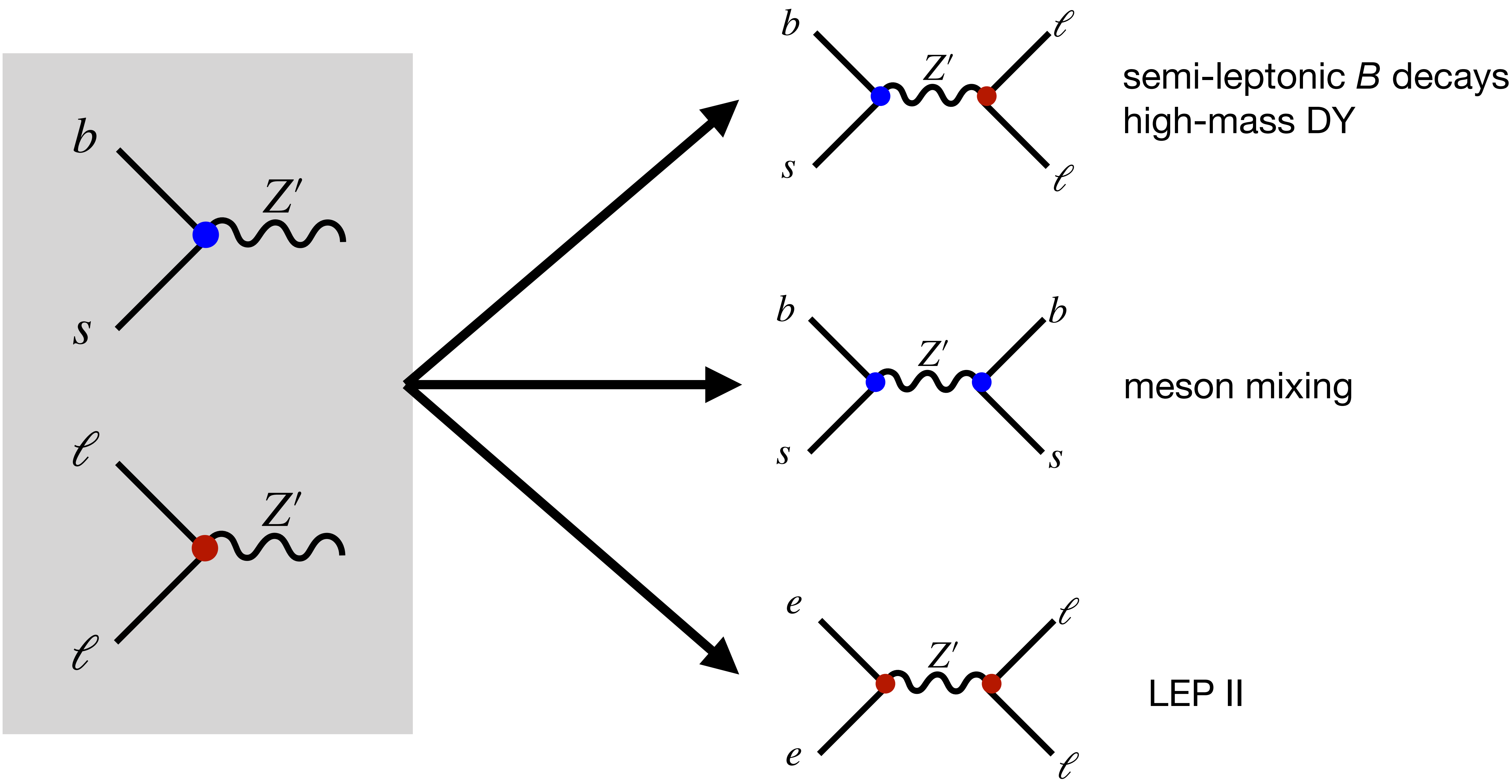


1903.05062

ATLAS&CMS are pushing the high-energy frontier, challenging many NP models


CMS
36 fb^{-1} (13 TeV)
Fig from CERN Courier
heavy gauge bosons
$M_{Z'}$ 2ℓ 4.5
$M_{Z'}$ 2j 2.7
$M_{Z'}$ eμ 4.4
$M_{W'}$ ℓ + E_T^{miss} 5.2
$M_{W'}$ 2j 3.3
$M_{W'}$ τ + E_T^{miss} 4.0
M_{W_R} 2ℓ + 2j 4.4
M_{W_R} 2τ + 2j 3.5
M_C 2j 6.1
leptoquarks
M_{LQ} 2e + 2j 1.44
M_{LQ} 2e + 2j; e + 2j + E_T^{miss} 1.27
M_{LQ} 2μ + 2j 1.53
M_{LQ} 2μ + 2j; μ + 2j + E_T^{miss} 1.29
M_{LQ} 2τ + 2j 1.02
M_{LQ} 2τ + b 0.74
excited fermions
M_{q^*} 2j 6
M_{q^*} γ + j 5.5
M_{b^*} γ + j 1.8
M_{e^*} γ + 2e 3.9
M_{μ^*} γ + 2μ 3.8
contact interactions
$\Lambda^{+}_{LL/RR}$ 2j 12.8
$\Lambda^{+}_{LL/RR}$ 2ℓ 20
$\Lambda^{-}_{LL/RR}$ 2j 17.5
$\Lambda^{-}_{LL/RR}$ 2ℓ 31
extra dimensions
M_S 2j 12
M_S 2γ, 2ℓ 9.1
M_D ≥ 1j + E_T^{miss} 9.9
M_{QBH} 2j 8.2
M_{QBH} eμ 5.6
$M_{G_{KK}}$ 2j 1.8
$M_{G_{KK}}$ 2ℓ 4.25
$M_{G_{KK}}$ 2γ 4.1
M_{QBH} 2j 5.9
M_{QBH} eμ 3.6
M_{BH} ≥ 7j (ℓ, γ) 9.7
1/R ℓ + E_T^{miss} 2.9
dark matter
M_{med} ≥ 1j + E_T^{miss} 1.8
M_{med} 2j 2.6
M_{med} 0,1ℓ+≥ 3j + E_T^{miss} 0.29
M_{med} 0,1ℓ+≥ 3j + E_T^{miss} 0.3
M_{ϕ_u} ≥ 1j + E_T^{miss} 1.4
$M_{X_{DX}}$ 4j 1.54
other
M_{sigma} ≥ 3ℓ 0.84
M_S 2j 7.7
0.1
1
10
mass scale [TeV]

Challenge: various NP models will in general impact several observables from vastly different classes



Global, model-independent approach?

SM(EFT)

SM gauge group:

$$SU(3)_C \times SU(2)_L \times U(1)_Y \to SU(3) \times U(1)_{\rm em}$$

Field content:

$$q_i, u_i, d_i, l_i, e_i \ \ (+H, \text{GBs}), \qquad i = 1,2,3$$

Wilson coefficient

Local operator

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

Cutoff scale

SM: $[Q] \leq 4$

flavor: 3 gen. -> 9 masses, 4 CKM par.

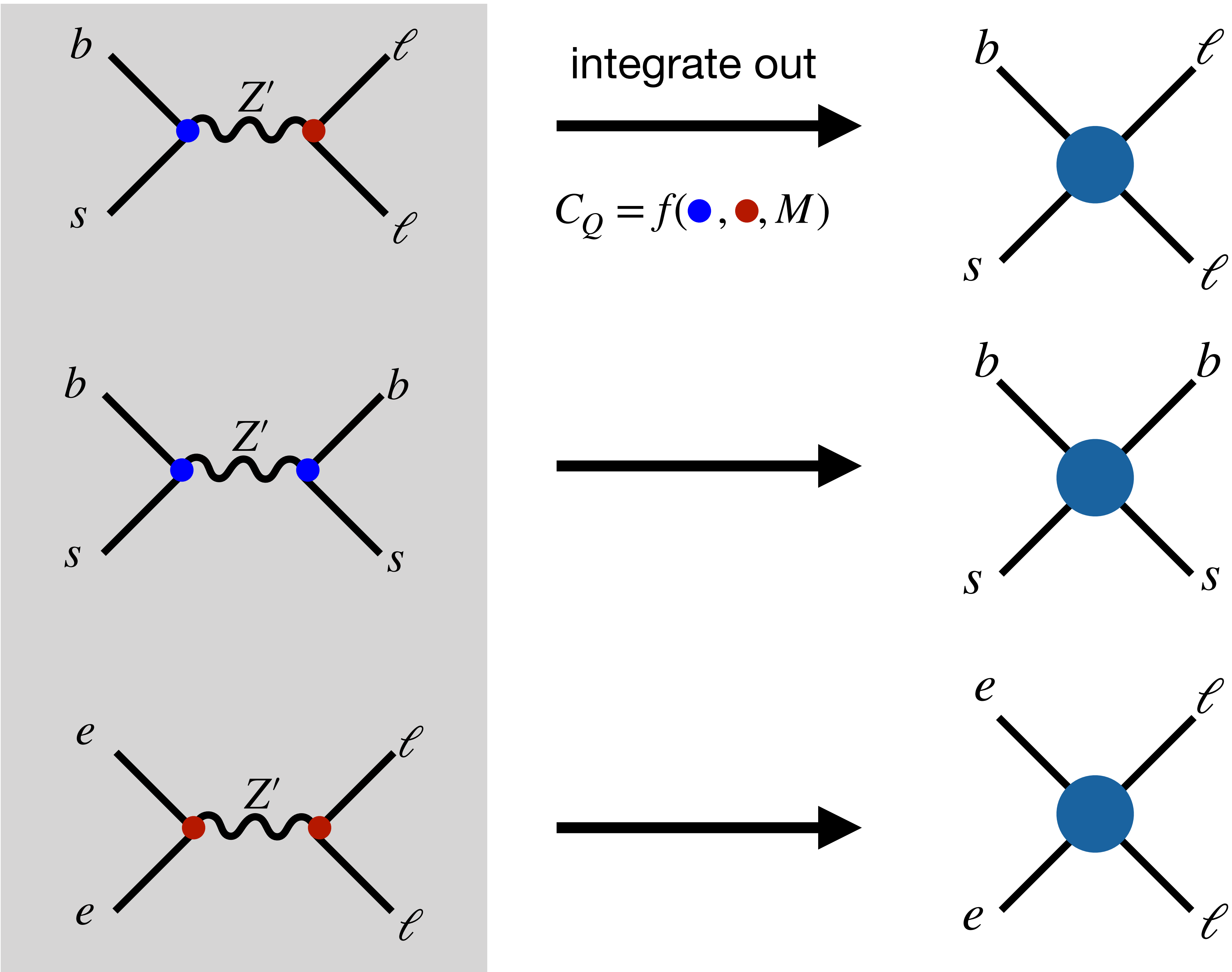
$$\text{e.g.}\ [Y^d]_{ij} \bar{q}_i H d_j, \ \ [Y^u]_{ij} \bar{q}_i \tilde{H} u_j$$

SMEFT: include $[Q] > 4$, truncate at dim. 6, $\Delta B = 0$ most parameters from flavor (59 -> 2499 for 3 gen)

$$\text{e.g.}\ \frac{[C_{lq}^{(1)}]_{prst}}{\Lambda^2} (\bar{l}_p \gamma_\mu l_r)(\bar{q}_s \gamma^\mu q_t)$$

8 classes of operators, 2499 parameters (e.g. 1008.4884)

Concrete models will generate operators with particular structure



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

...

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

...

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

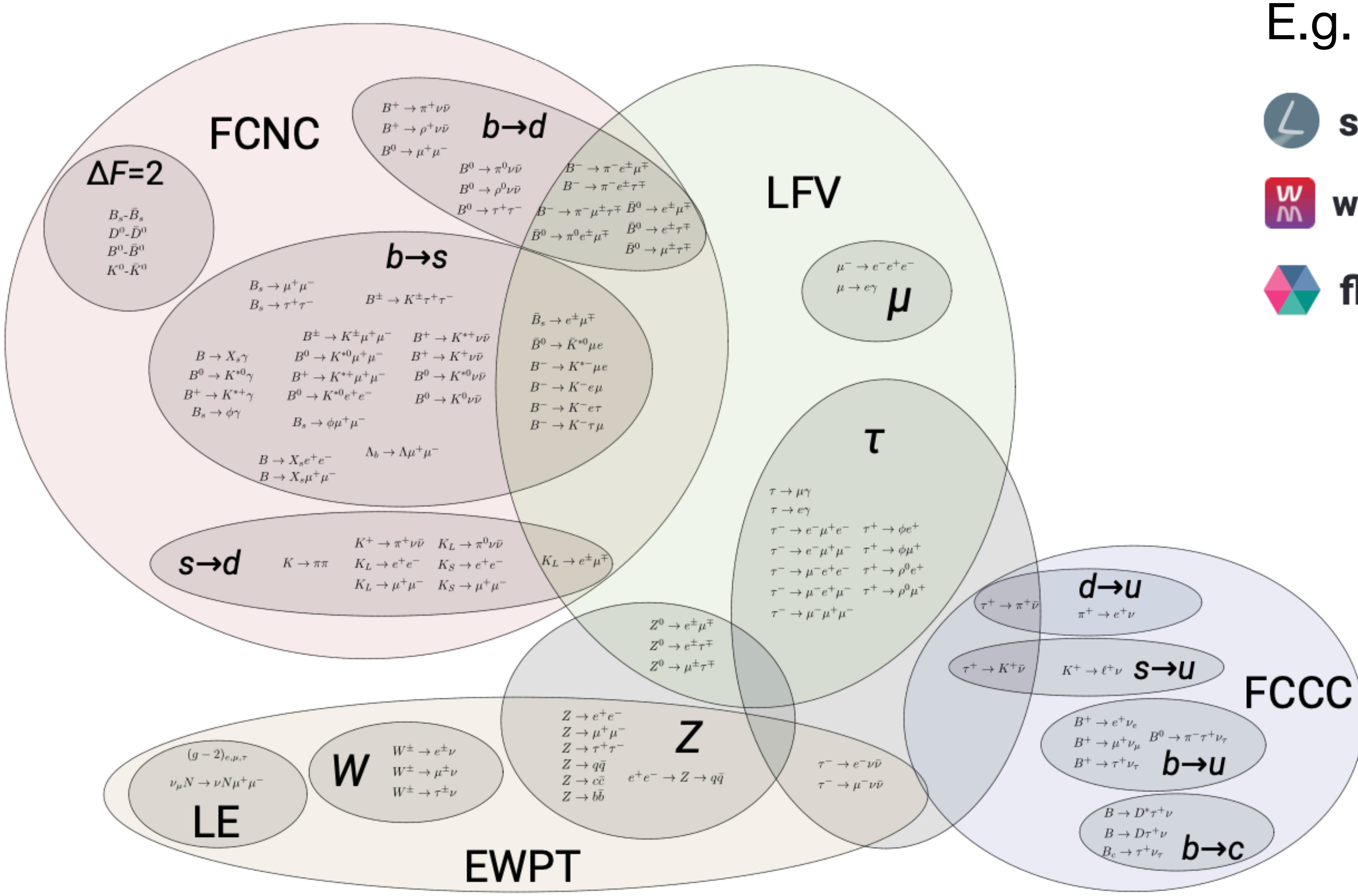
...

prst - flavor

e.g. 1711.10391, 2305.08898

Challenge: various SMEFT operators will impact observables from vastly different classes

For a model independent approach, study the *global* SMEFT likelihood



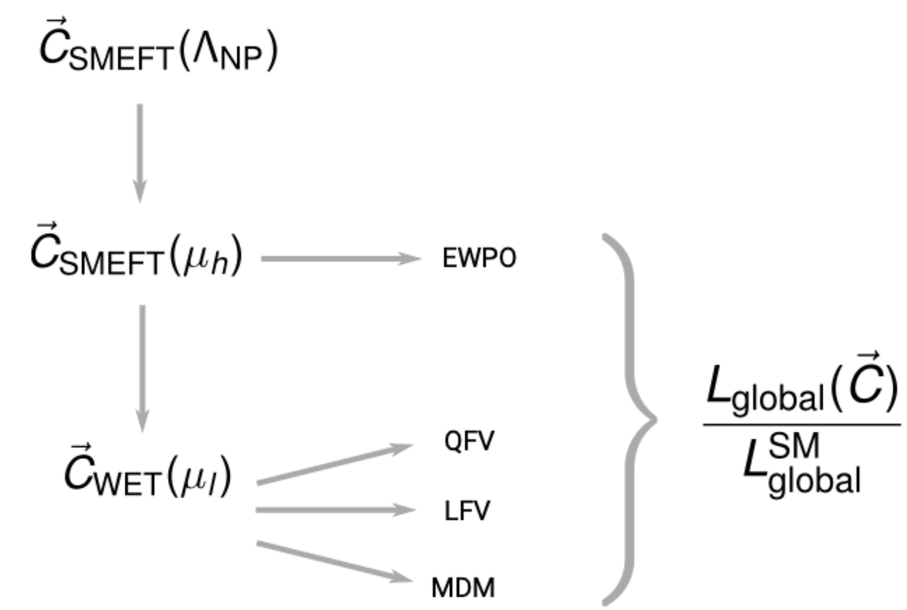
E.g.

smelli Aebischer, Kumar, Stangl, Straub, 1810.07698

wilson Aebischer, Kumar, Straub, 1804.05033

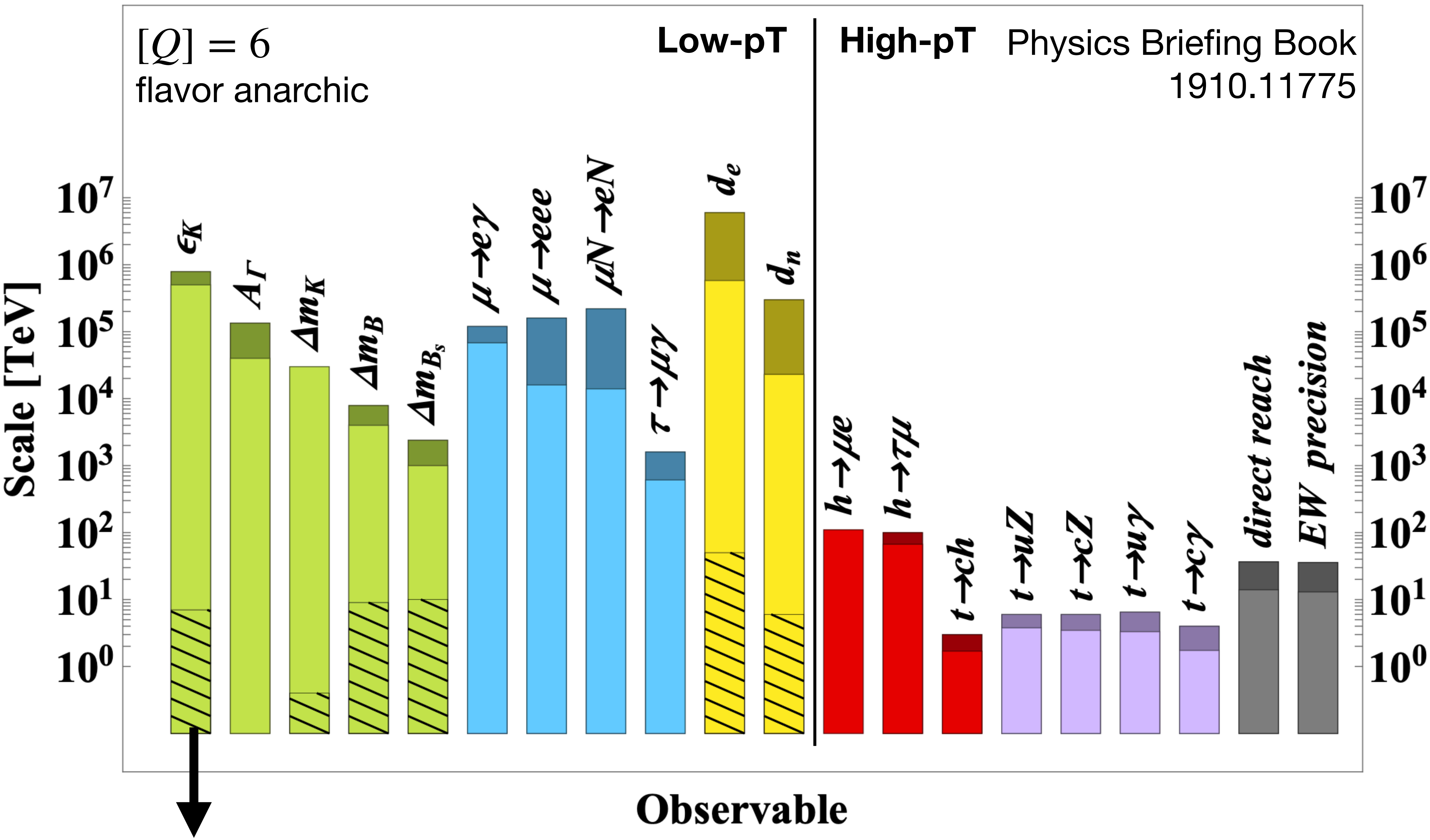
flavio Straub, 1810.08132

Also: `HEPfit`, SMEFiT, EOS, …



Crucially relies on RGE&matching computations
1308.2627, 1310.4838, 1312.2014, 1709.04486, 1908.05295, …

Importance of flavor violation



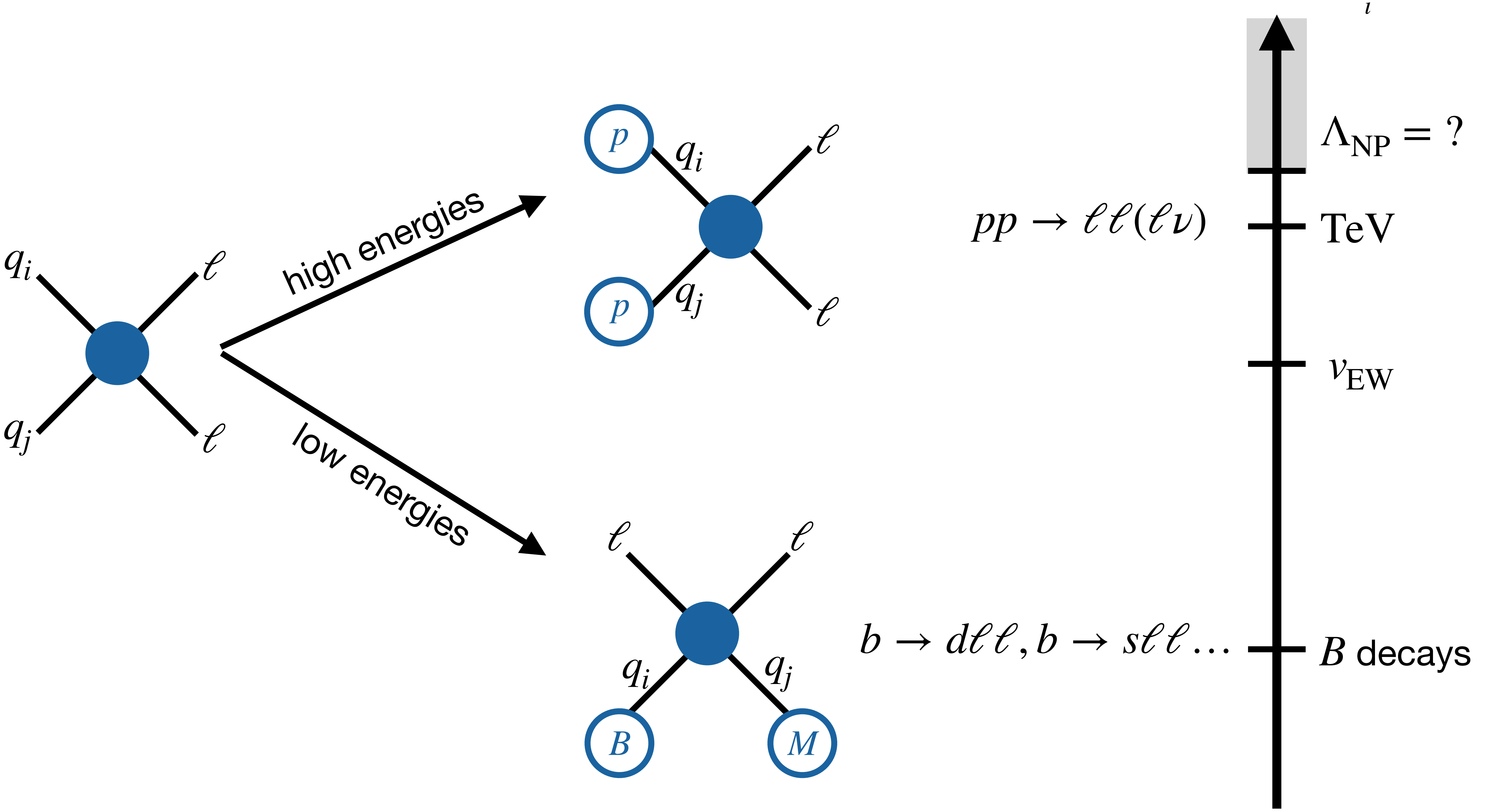
Minimal flavor violation
hep-ph/0207036

Anarchy is highly unlikely
e.g. 2005.05366, 2203.09561

Focus for remainder of the talk:

Interplay between low-energy meson decays and high-mass Drell-Yan

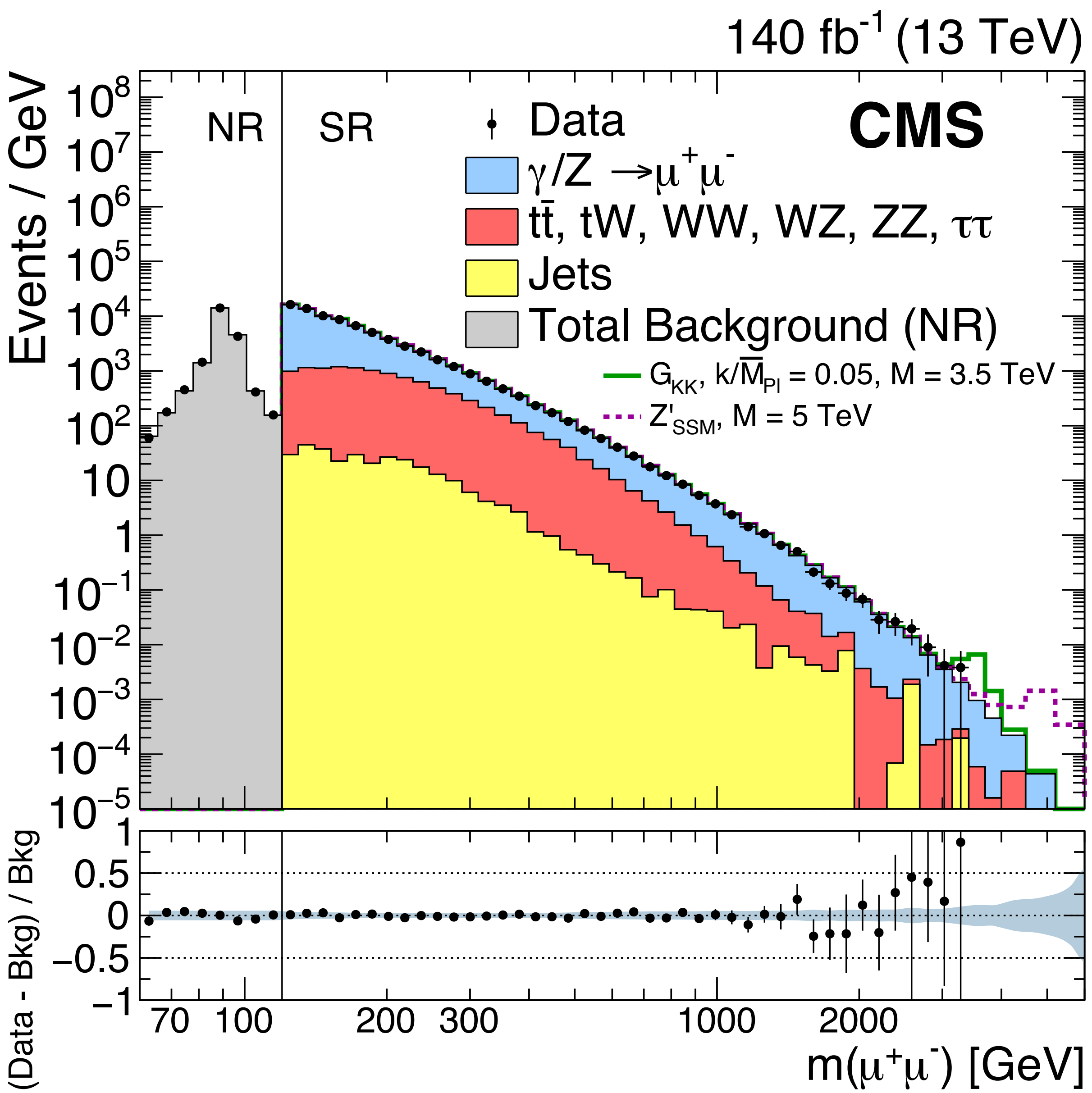
$$\mathscr{L} = \mathscr{L}_{\rm SM} + \frac{1}{\Lambda^2}\sum_i C_i Q_i$$



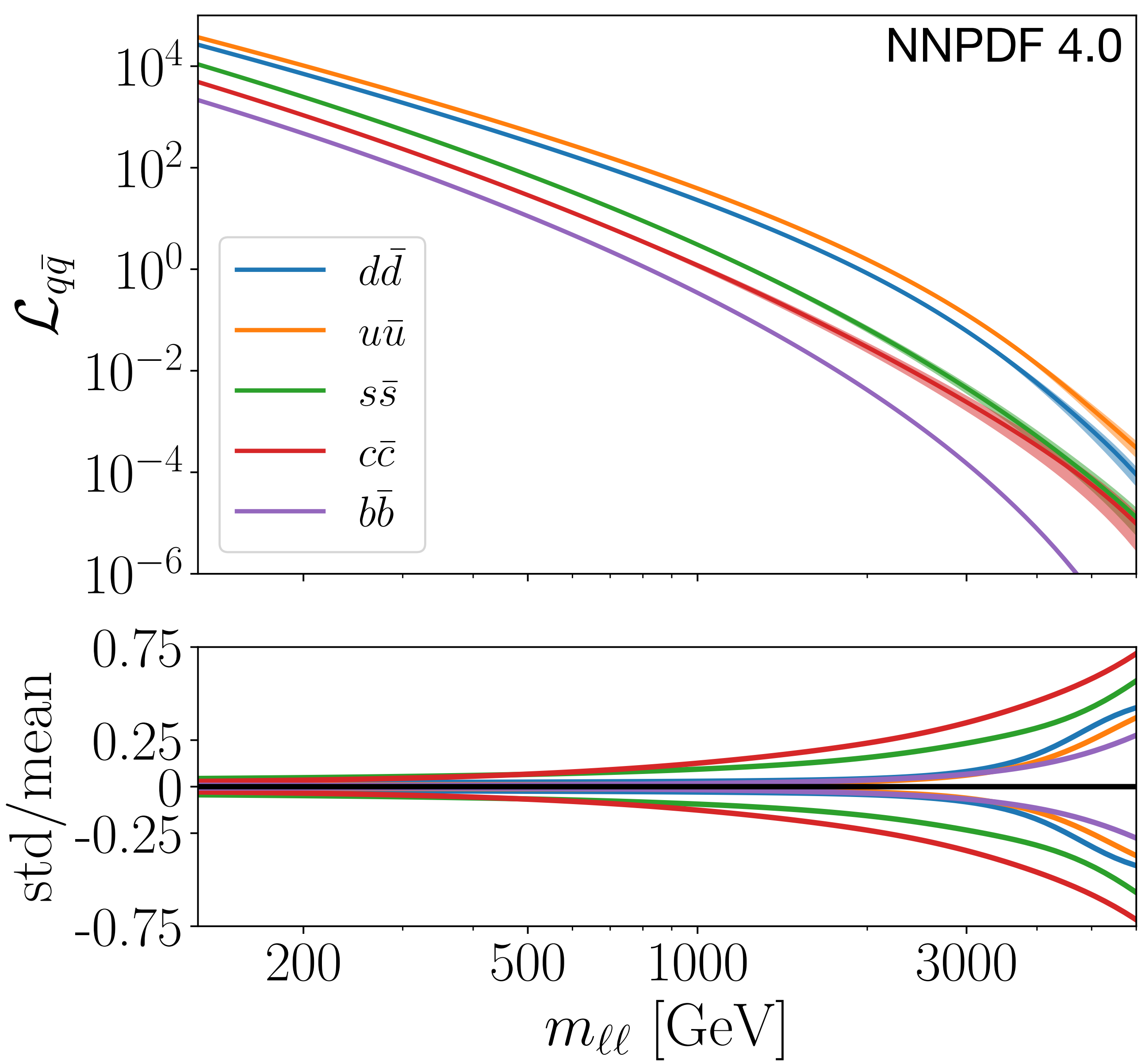
Why high-mass Drell-Yan?

5 flavors in the proton

$$\mathscr{L}_{\bar{q}q}(\tau,\mu_F) = \int_\tau^1 \frac{dx}{x} f_{\bar{q}}(x,\mu_F) f_q(\tau/x,\mu_F)\,, \quad \tau = m_{\ell\ell}^2/s$$



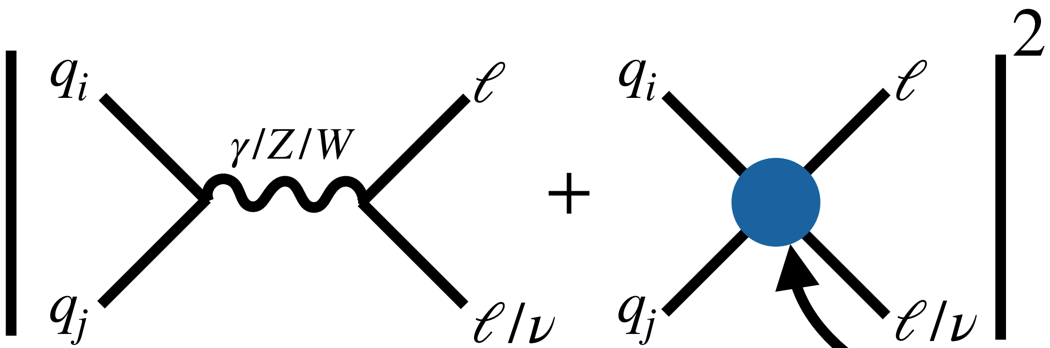
[m_T in CC]



Why high-mass Drell-Yan?

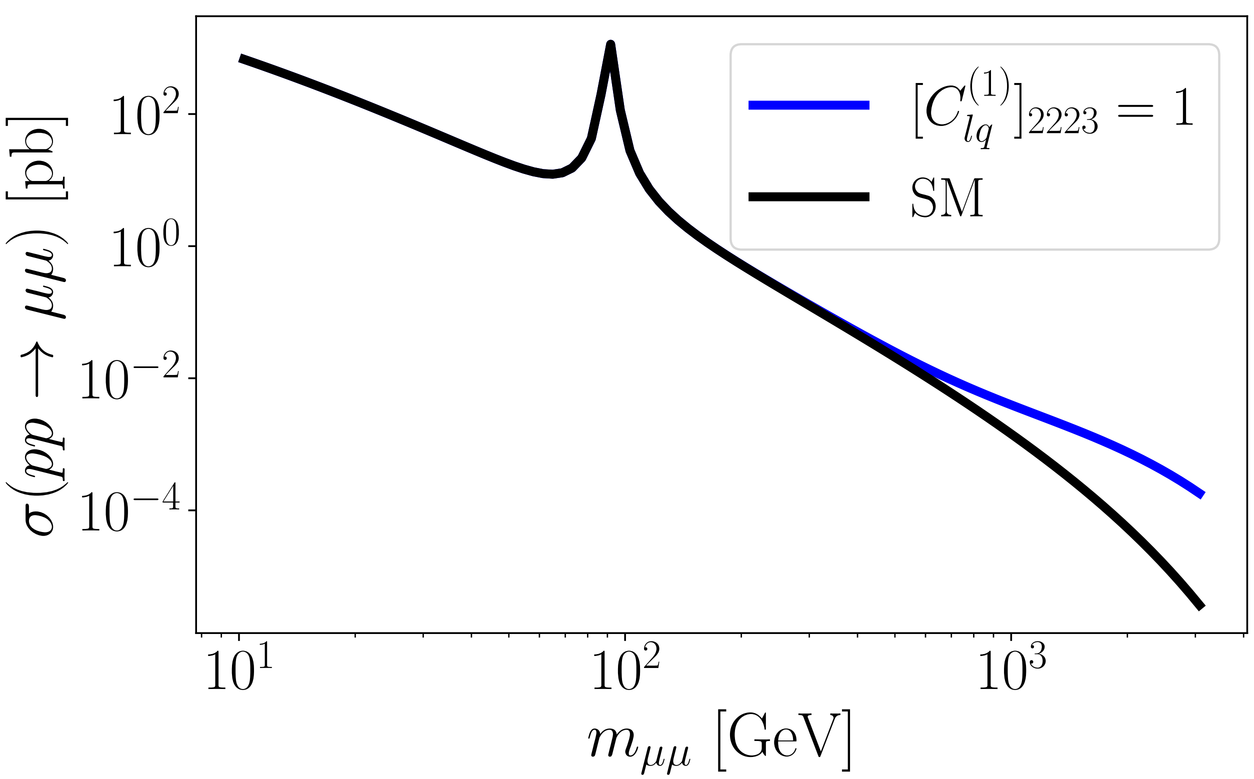
Many operators contribute, especially sensitive to contact interactions

$\sigma^{q\bar{q}}_{\text{part}} \sim$



$$\sigma_{\text{had}} \sim \mathscr{L}_{q\bar{q}} * \sigma^{q\bar{q}}_{\text{part}}$$

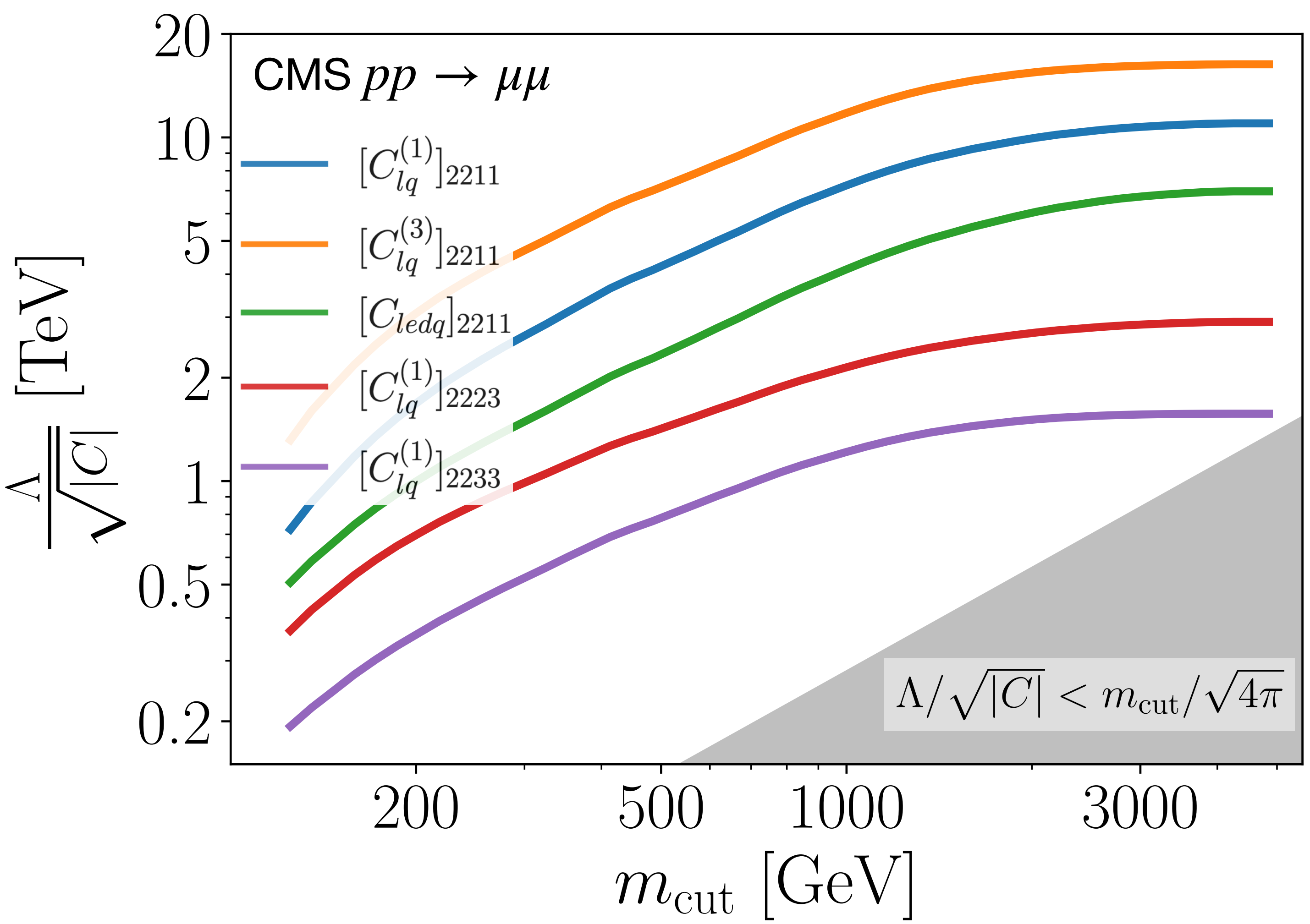
$Q^{(1)}_{lq}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t)$
$Q^{(3)}_{lq}$	$(\bar{l}_p\gamma_\mu\sigma^i l_r)(\bar{q}_s\gamma^\mu\sigma^i q_t)$
Q_{lu}	$(\bar{l}_p\gamma_\mu l_r)(\bar{u}_s\gamma^\mu u_t)$
Q_{ld}	$(\bar{l}_p\gamma_\mu l_r)(\bar{d}_s\gamma^\mu d_t)$
Q_{qe}	$(\bar{q}_p\gamma_\mu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



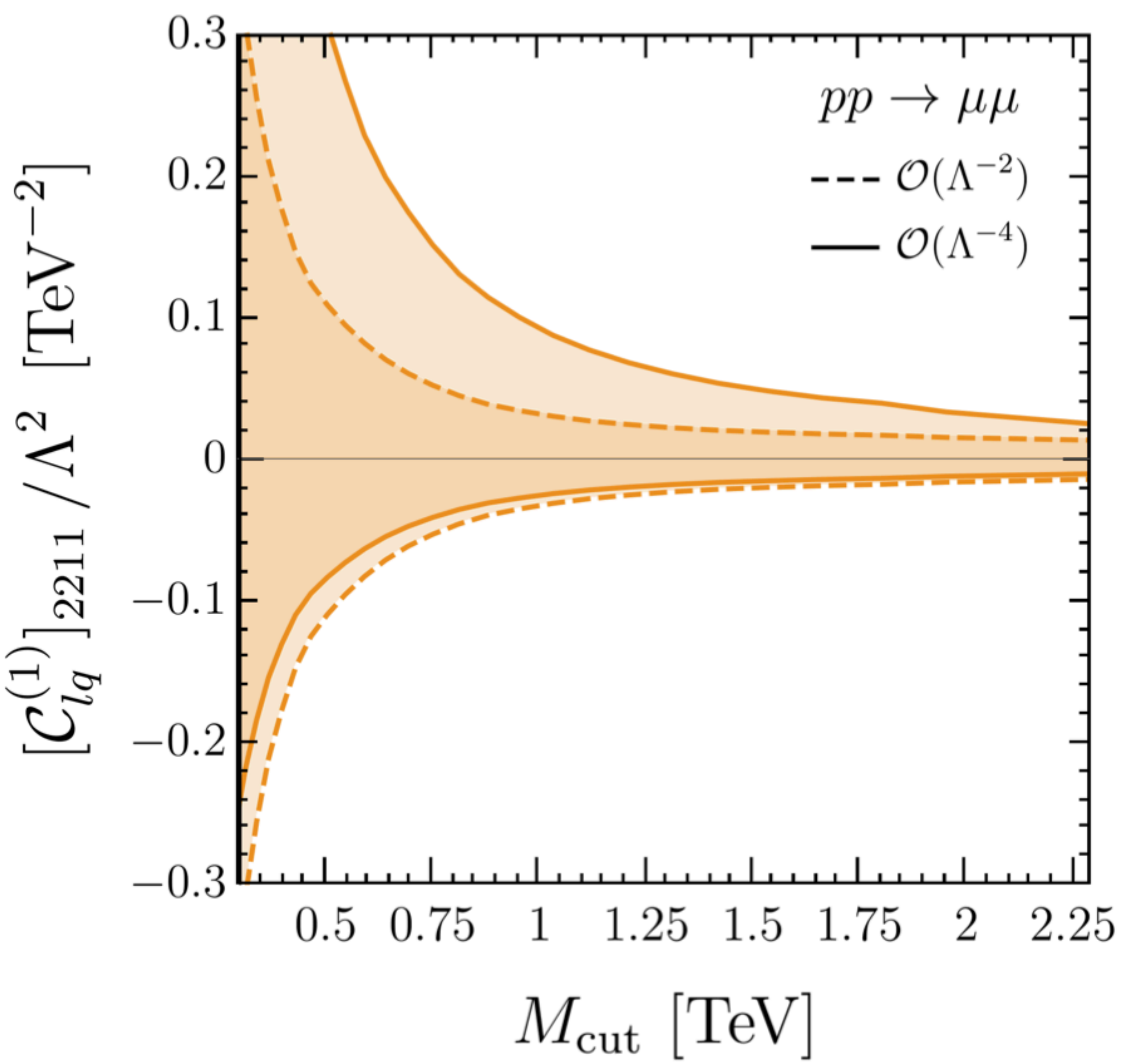
PDF suppression compensated by energy enhancement

Sensitivity of DY to CIs

Bound saturates at bins of ~TeV



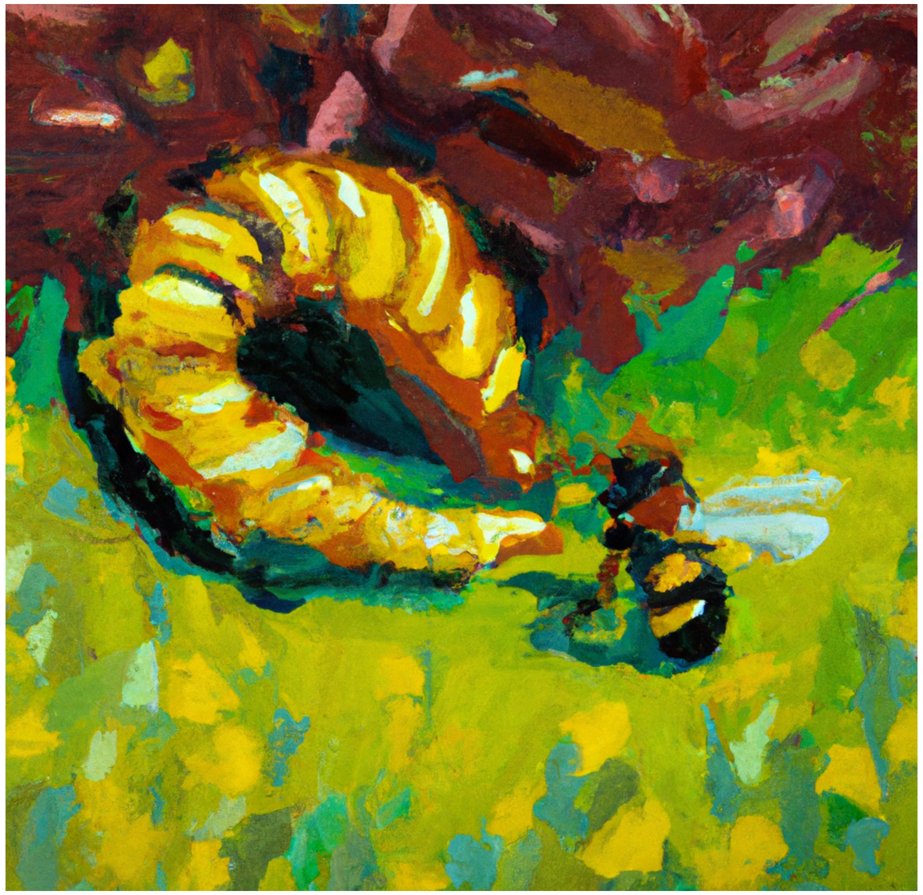
Greljo, Salko, AS, Stangl; 2212.10497



Allwicher, Faroughy, Jaffredo, Sumensari, Wilsch; 2207.10714

Selected examples in EFT and models

(not a complete review by far)

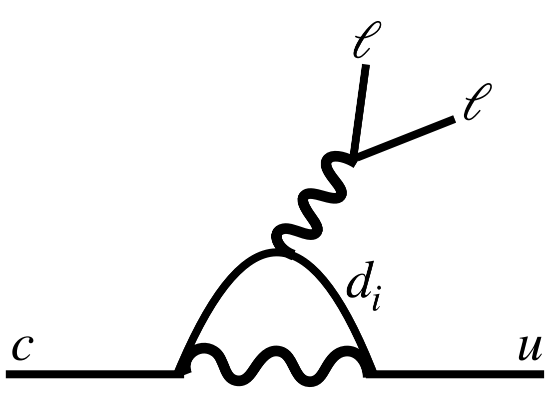


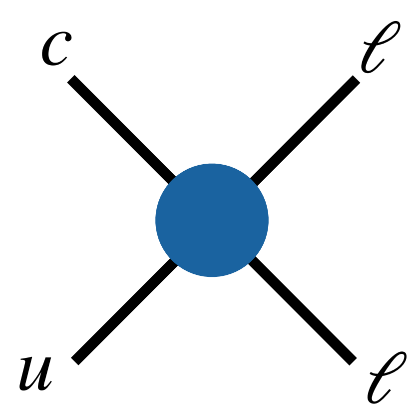
Charm Physics Confronts High-pT Lepton Tails

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

Rare $c \to u\ell\ell$ decays

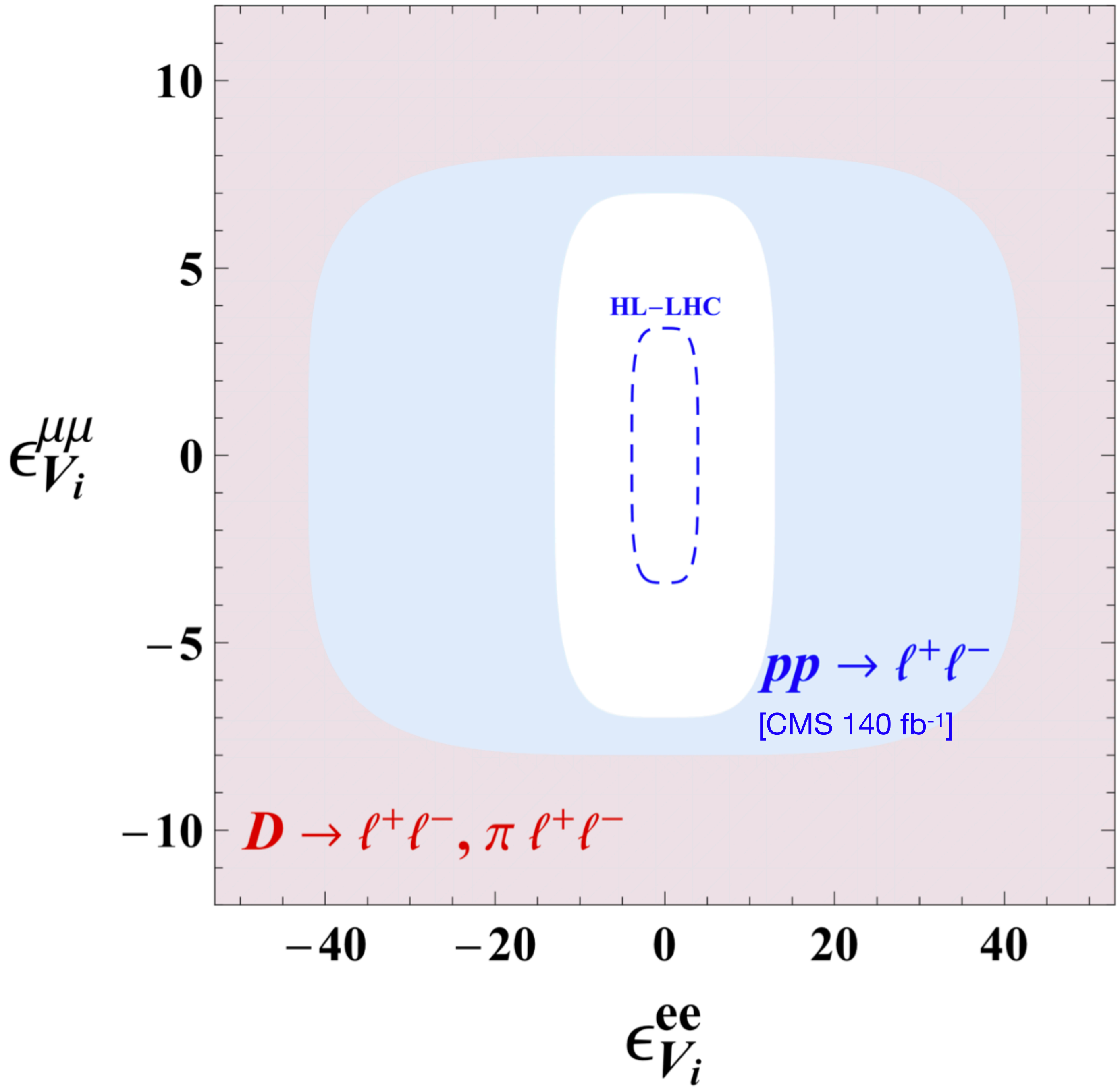
- Efficient GIM suppression
- long-distance dominated





$$\mathscr{L}_{NP}^{\Delta C=1} \approx \frac{\epsilon_V^{\ell\ell}}{(15\mathrm{TeV})^2} \left(\bar{u}\gamma^\mu c\right)\left(\bar{\ell}\gamma_\mu \ell\right)$$

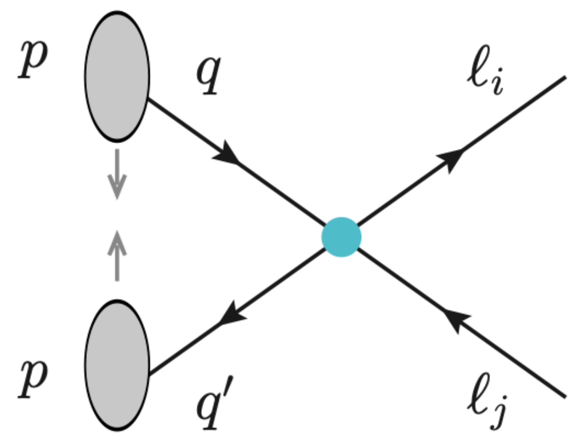
High-mass DY leads to compatible/ stronger constraints

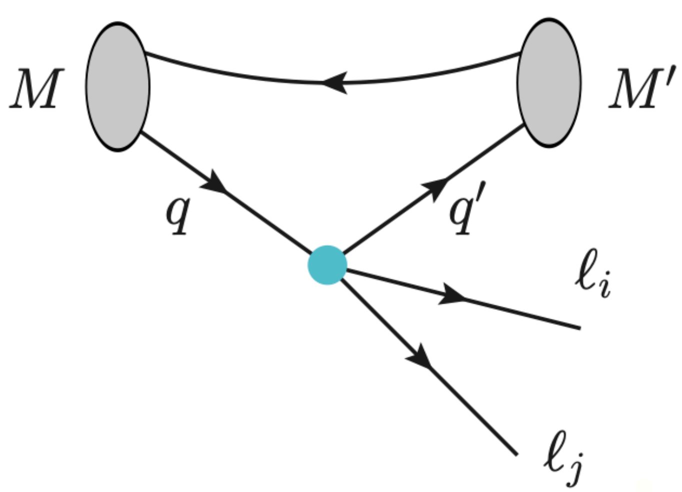


Probing LFV in Meson Decays with LHC Data

Descotes-Genon, Faroughy, Plakias, Sumensari; 2303.07521

Comparing $pp \to \ell_i \ell_j$ (CMS, 140 fb^{-1}) to LFV meson decays





See also 2002.05684

LHC competitive

LHC only constraint

Observable	LHC (140 fb^{-1})	HL-LHC (3 ab^{-1})	Exp. limit
$\mathcal{B}(B^0 \to \mu^\pm\tau^\mp)$	8×10^{-4}	1.7×10^{-4}	1.4×10^{-5}
$\mathcal{B}(B^+ \to \pi^+\mu^\pm\tau^\mp)$	1.1×10^{-4}	2×10^{-5}	9.4×10^{-5}
$\mathcal{B}(B_s \to K_S^0\mu^\pm\tau^\mp)$	4×10^{-5}	8×10^{-6}	–
$\mathcal{B}(B^0 \to \rho\mu^\pm\tau^\mp)$	7×10^{-5}	1.5×10^{-5}	–
$\mathcal{B}(B_s \to \mu^\pm\tau^\mp)$	8×10^{-3}	1.7×10^{-3}	4.2×10^{-5}
$\mathcal{B}(B^+ \to K^+\mu^\pm\tau^\mp)$	9×10^{-4}	1.9×10^{-4}	3.9×10^{-5}
$\mathcal{B}(B^0 \to K^{*0}\mu^\pm\tau^\mp)$	4×10^{-4}	1.0×10^{-4}	–
$\mathcal{B}(B_s \to \phi\mu^\pm\tau^\mp)$	5×10^{-4}	1.0×10^{-4}	–
$\mathcal{B}(B^0 \to e^\pm\tau^\mp)$	1.7×10^{-3}	4×10^{-4}	2.1×10^{-5}
$\mathcal{B}(B^+ \to \pi^+e^\pm\tau^\mp)$	2×10^{-4}	5×10^{-5}	9.8×10^{-5}
$\mathcal{B}(B_s \to K_Se^\pm\tau^\mp)$	8×10^{-5}	1.7×10^{-5}	–
$\mathcal{B}(B^0 \to \rho e^\pm\tau^\mp)$	1.4×10^{-4}	3×10^{-5}	–
$\mathcal{B}(B_s \to e^\pm\tau^\mp)$	1.8×10^{-2}	4×10^{-3}	7.3×10^{-4}
$\mathcal{B}(B^+ \to K^+e^\pm\tau^\mp)$	2×10^{-3}	4×10^{-4}	3.9×10^{-5}
$\mathcal{B}(B^0 \to K^{*0}e^\pm\tau^\mp)$	1.1×10^{-3}	2×10^{-4}	–
$\mathcal{B}(B_s \to \phi e^\pm\tau^\mp)$	1.2×10^{-3}	2×10^{-4}	–

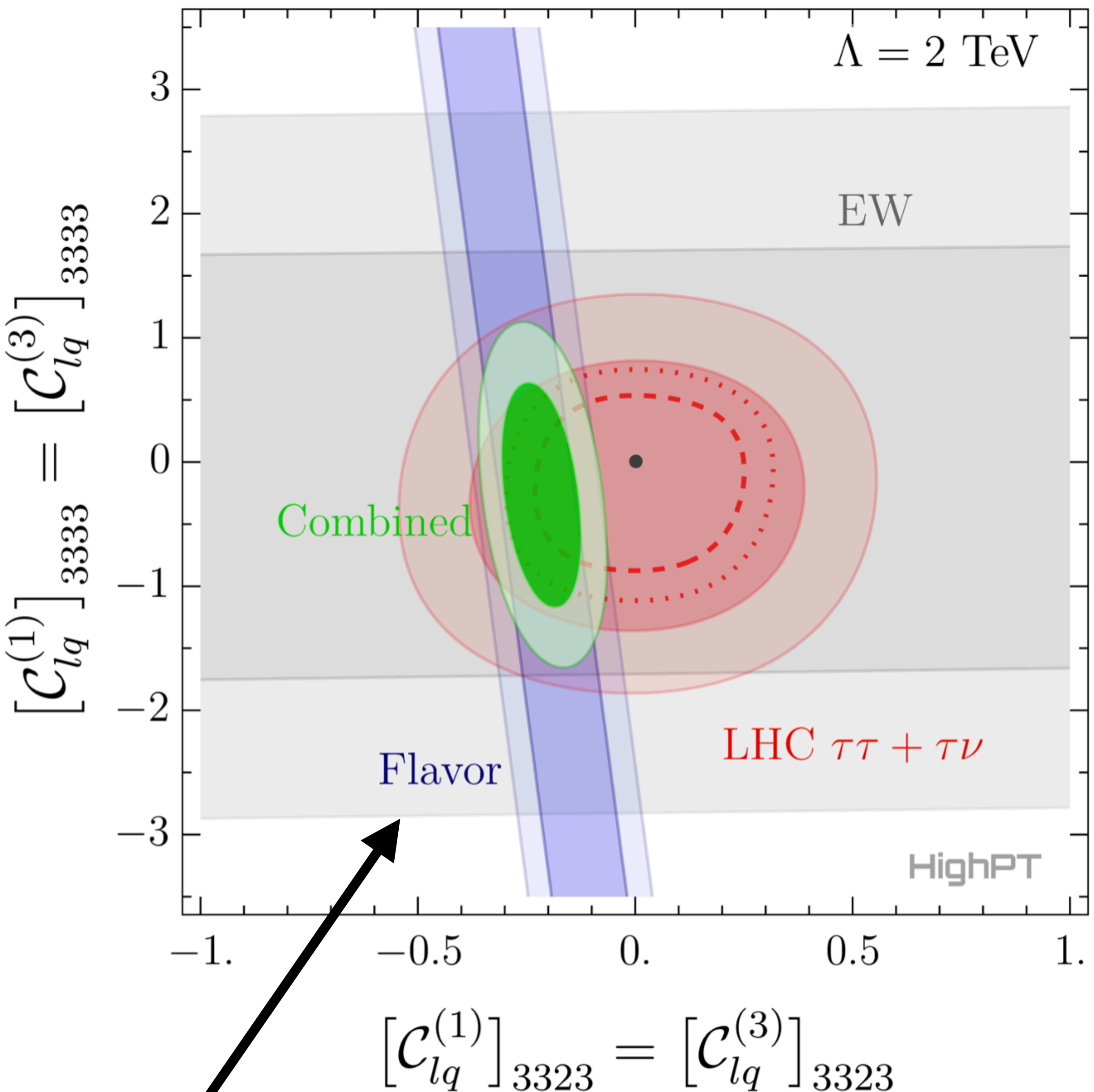
Drell-Yan Tails Beyond the Standard Model

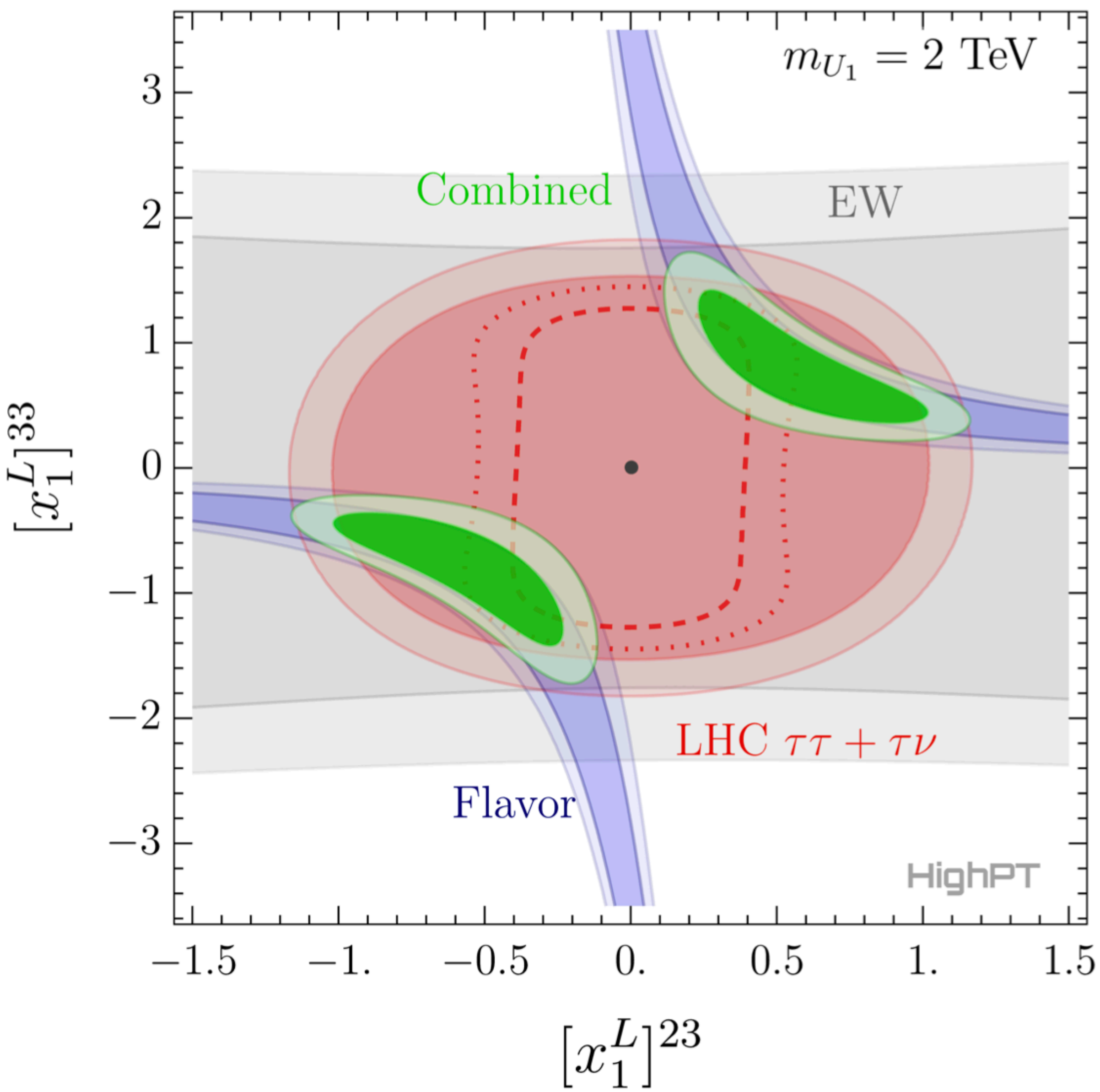
Allwicher, Faroughy, Jaffredo, Sumensari, Wilsch; 2207.10714

See also 1609.07138

Study of $pp \to \ell\ell, \ell\nu$ in SMEFT (up to d=8)
+ concrete UV mediators

$U_1 \sim (\mathbf{3}, \mathbf{1}, 2/3)$





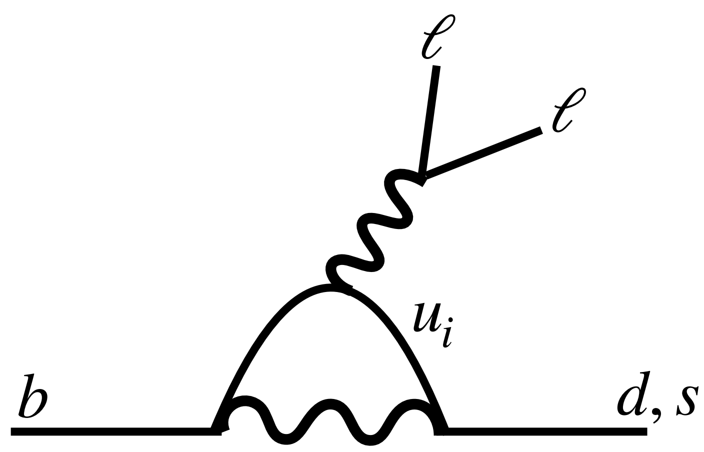
Dominated by $b \to c\tau\nu$

Released HighPT Mathematica package
(2207.10756, **github.com/HighPT**)

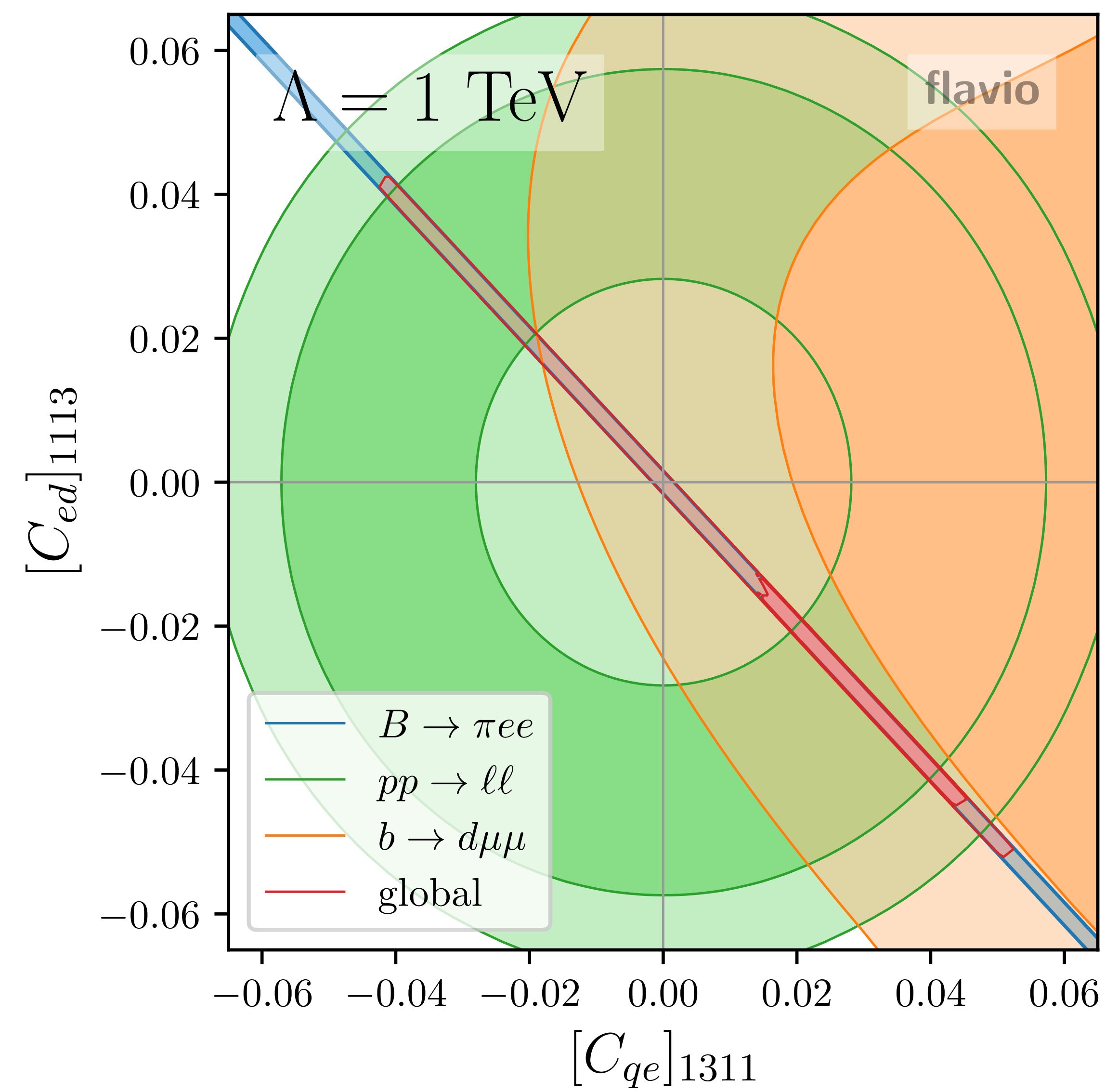
Rare b decays meet high-mass Drell-Yan

Greljo, Salko, AS, Stangl; 2212.10497

Complementarity with rare b decays



NP in $bdee$



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

$pp \to \ell\ell, \ell\nu$ now available in flavio

flav-io.github.io

Data:

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

Rare b decays meet high-mass Drell-Yan

Greljo, Salko, AS, Stangl; 2212.10497

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

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

Rare b decays meet high-mass Drell-Yan

Greljo, Salko, AS, Stangl; 2212.10497

MFV expansion

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

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

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

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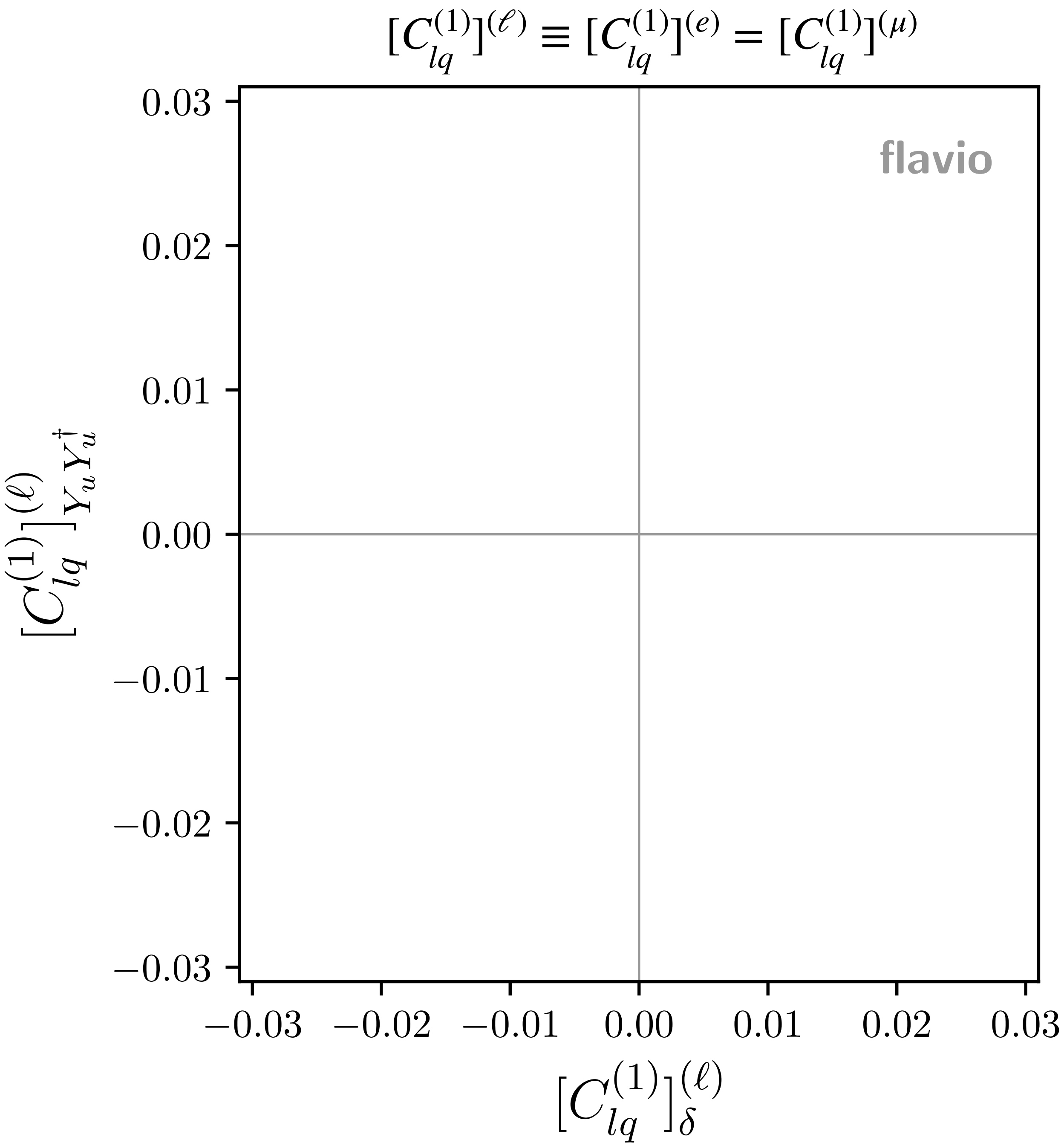

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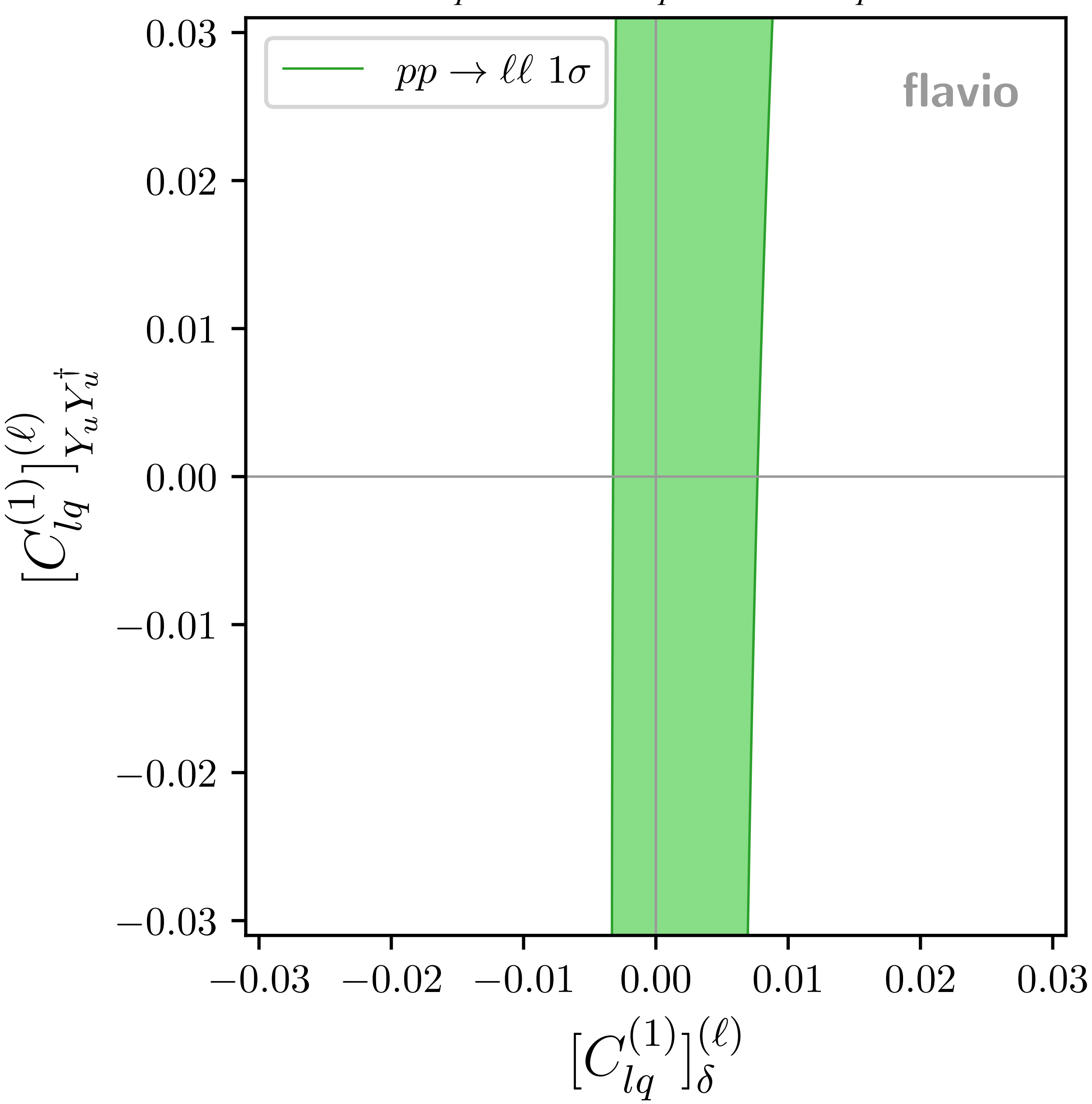
$$\sim y_t^2 \begin{pmatrix} V_{td}V_{td}^* & V_{ts}V_{td}^* & V_{tb}V_{td}^* \\ V_{td}V_{ts}^* & V_{ts}V_{ts}^* & V_{tb}V_{ts}^* \\ V_{td}V_{tb}^* & V_{ts}V_{tb}^* & V_{tb}V_{tb}^* \end{pmatrix}$$

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



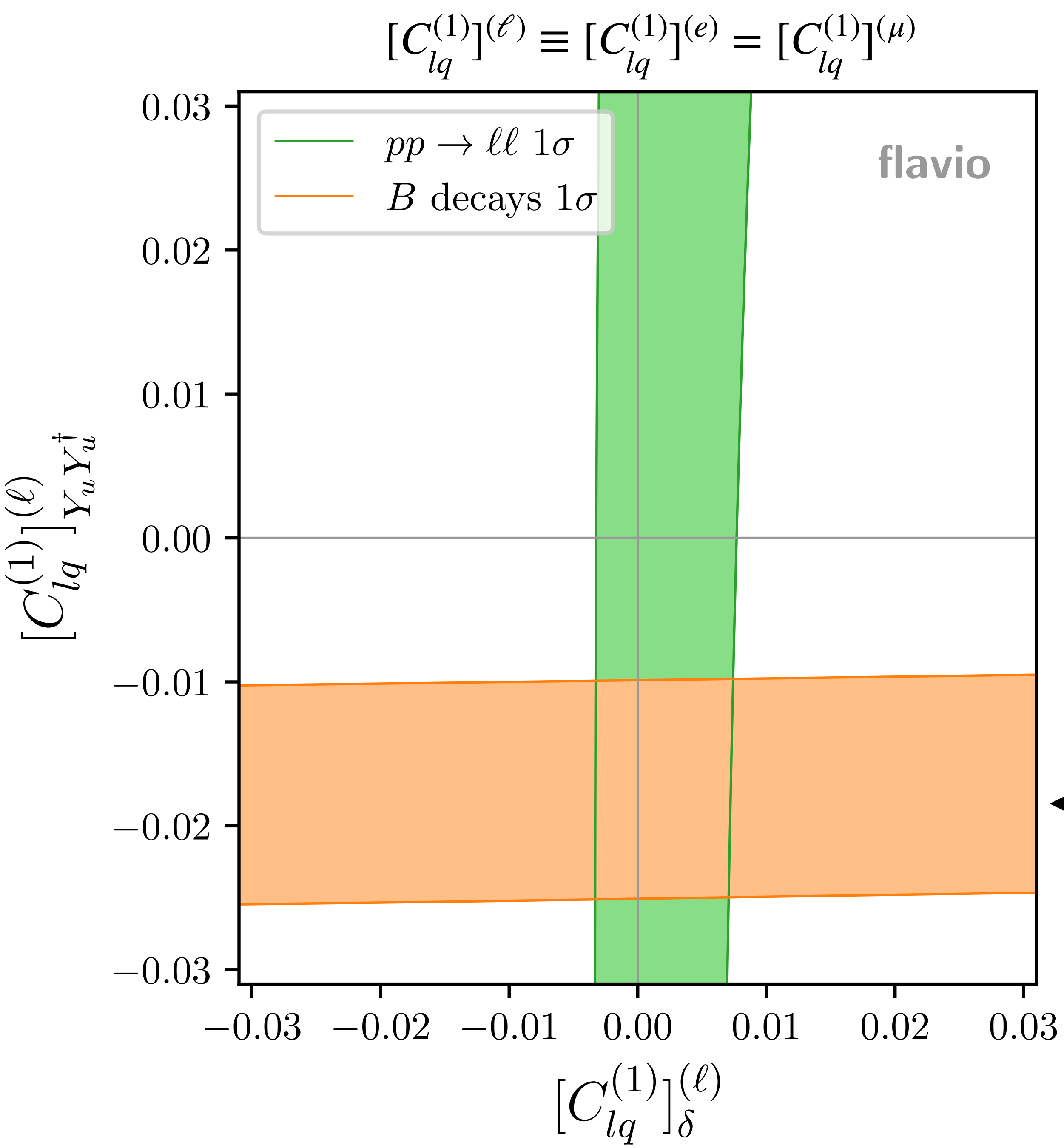
Rare b decays meet high-mass Drell-Yan

Greljo, Salko, AS, Stangl; 2212.10497

MFV expansion

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

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



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

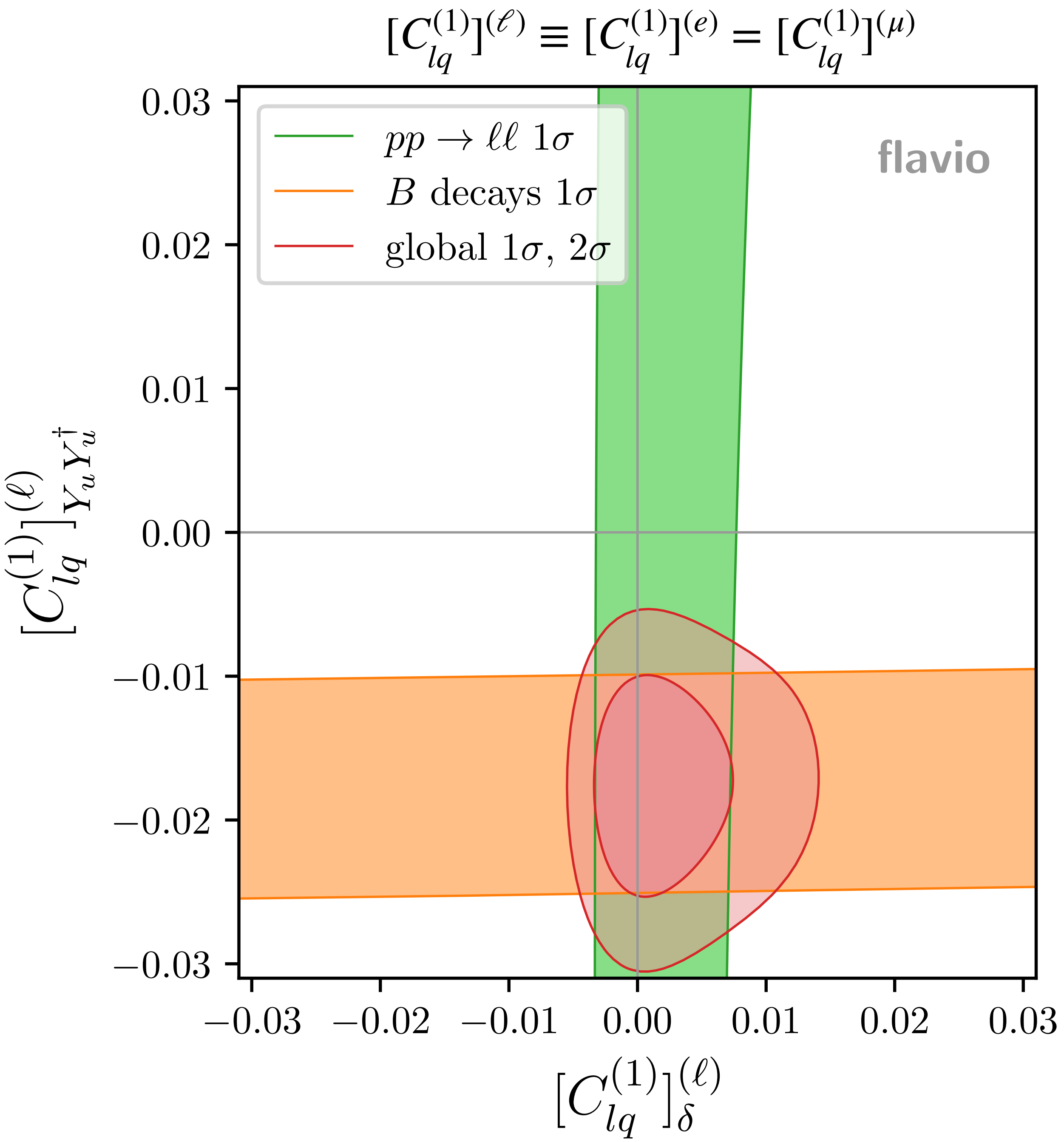
Rare b decays meet high-mass Drell-Yan

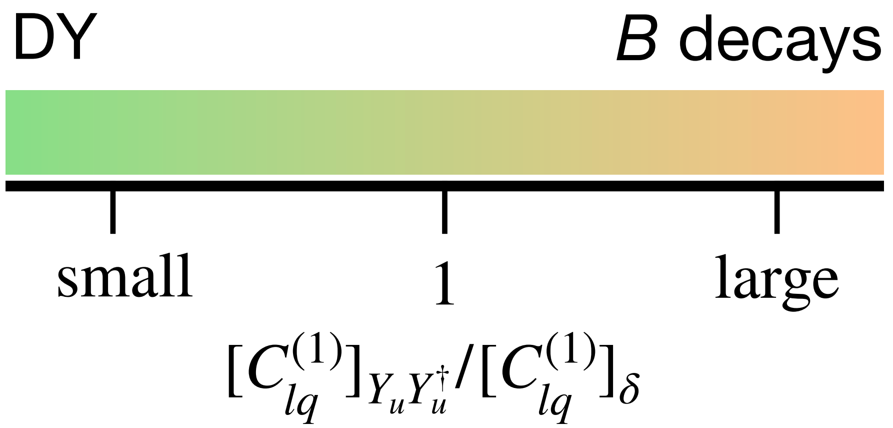
Greljo, Salko, AS, Stangl; 2212.10497

MFV expansion

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

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





Rare *b* decays meet high-mass Drell-Yan

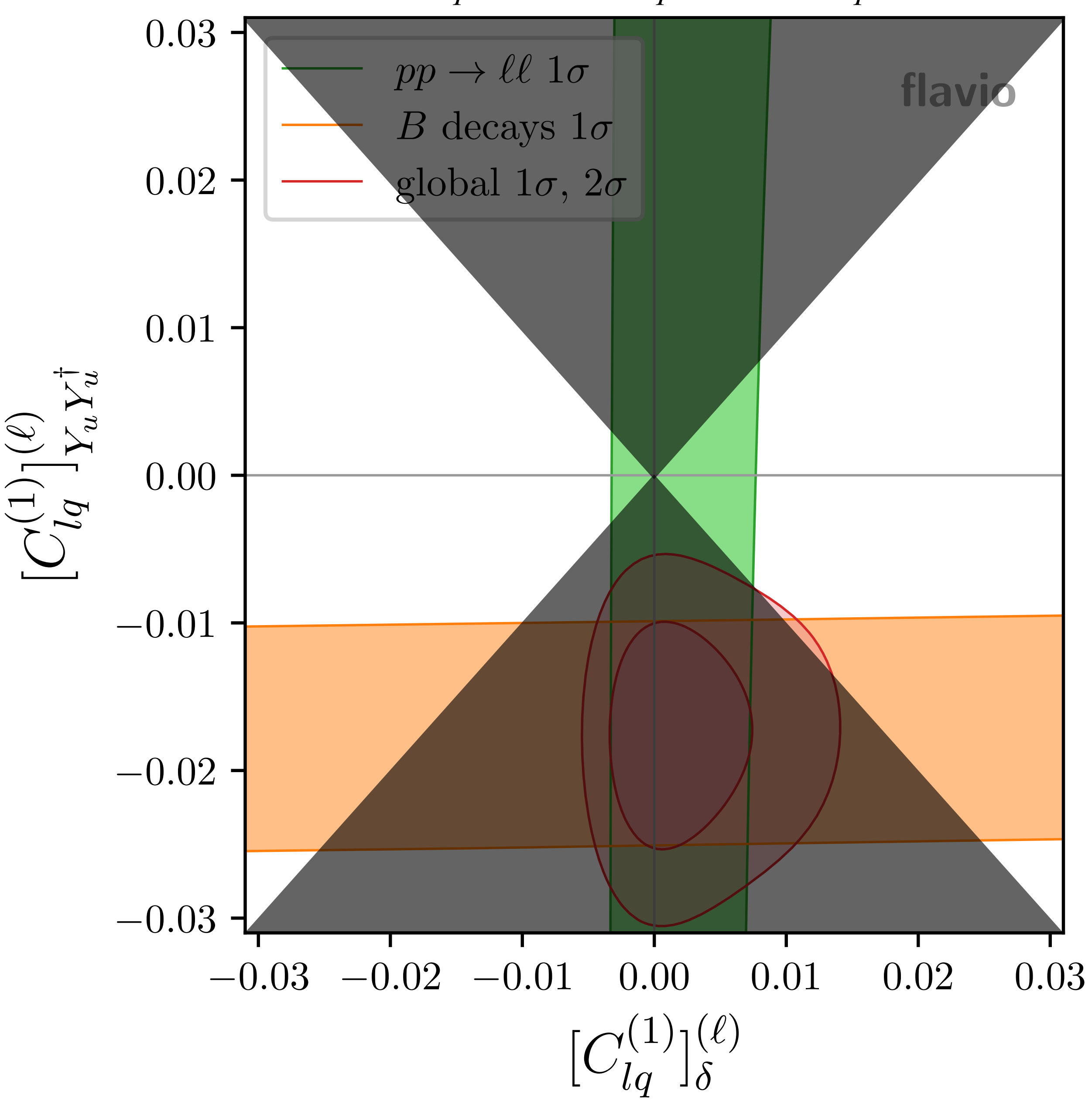
Greljo, Salko, AS, Stangl; 2212.10497

MFV expansion

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

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

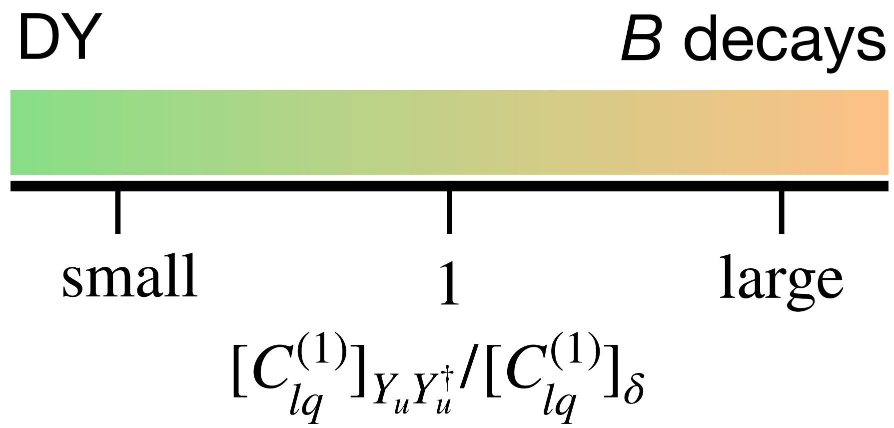
$[C_{lq}^{(1)}]^{(\ell)} \equiv [C_{lq}^{(1)}]^{(e)} = [C_{lq}^{(1)}]^{(\mu)}$



Expansion validity?

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

0903.1794



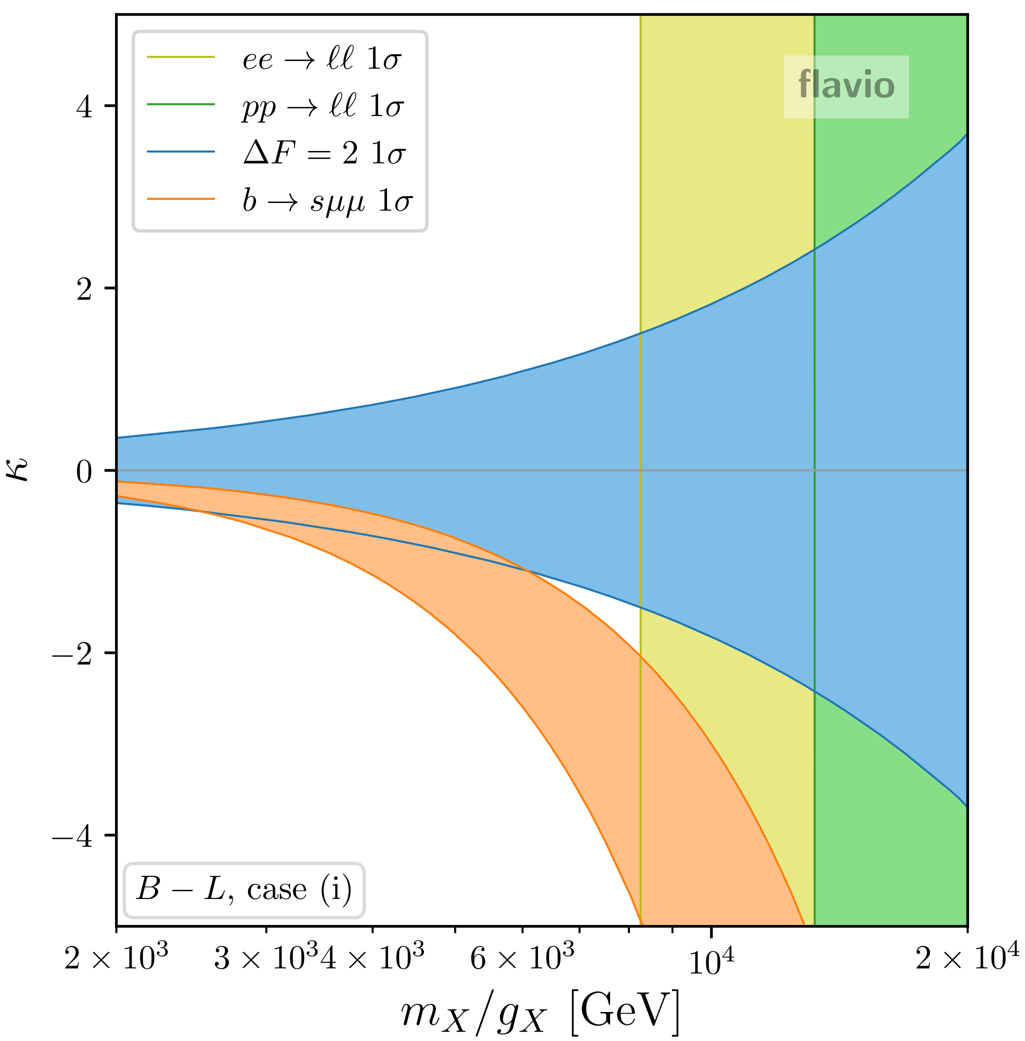
See also 1704.09015

Greljo, Salko, AS, Stangl; 2212.10497

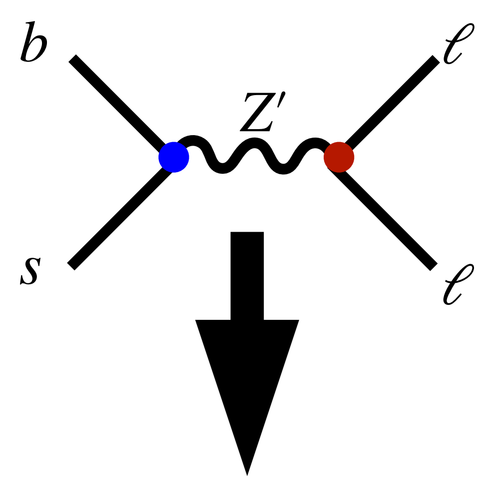
LFU Z'

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

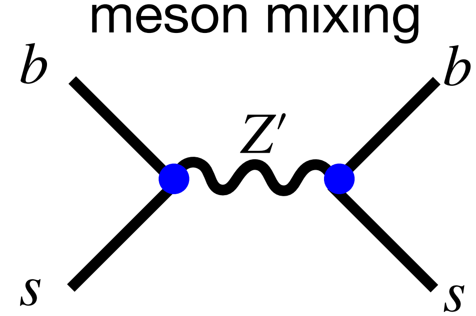
$$J^\mu = J^\mu_{B-L} + \frac{1}{3}\epsilon_{ij}\,\bar{q}_i\gamma^\mu q_j$$



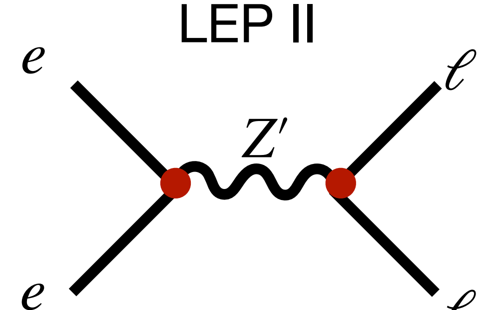
$$\epsilon_{ij} = -\kappa\,|V_{ts}|\,(\delta_{i2}\delta_{j3} + \delta_{i3}\delta_{j2})$$



meson mixing



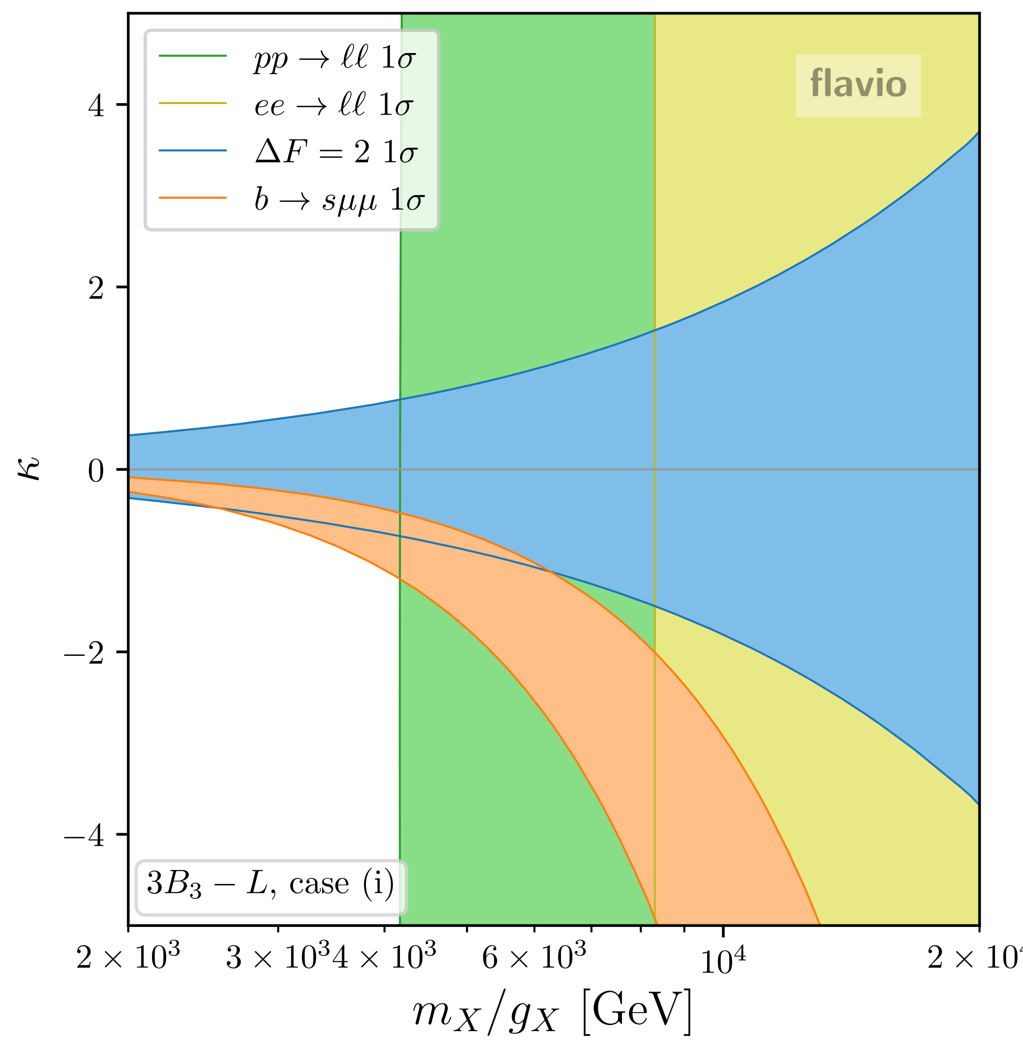
LEP II



1511.07434

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

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



Tension

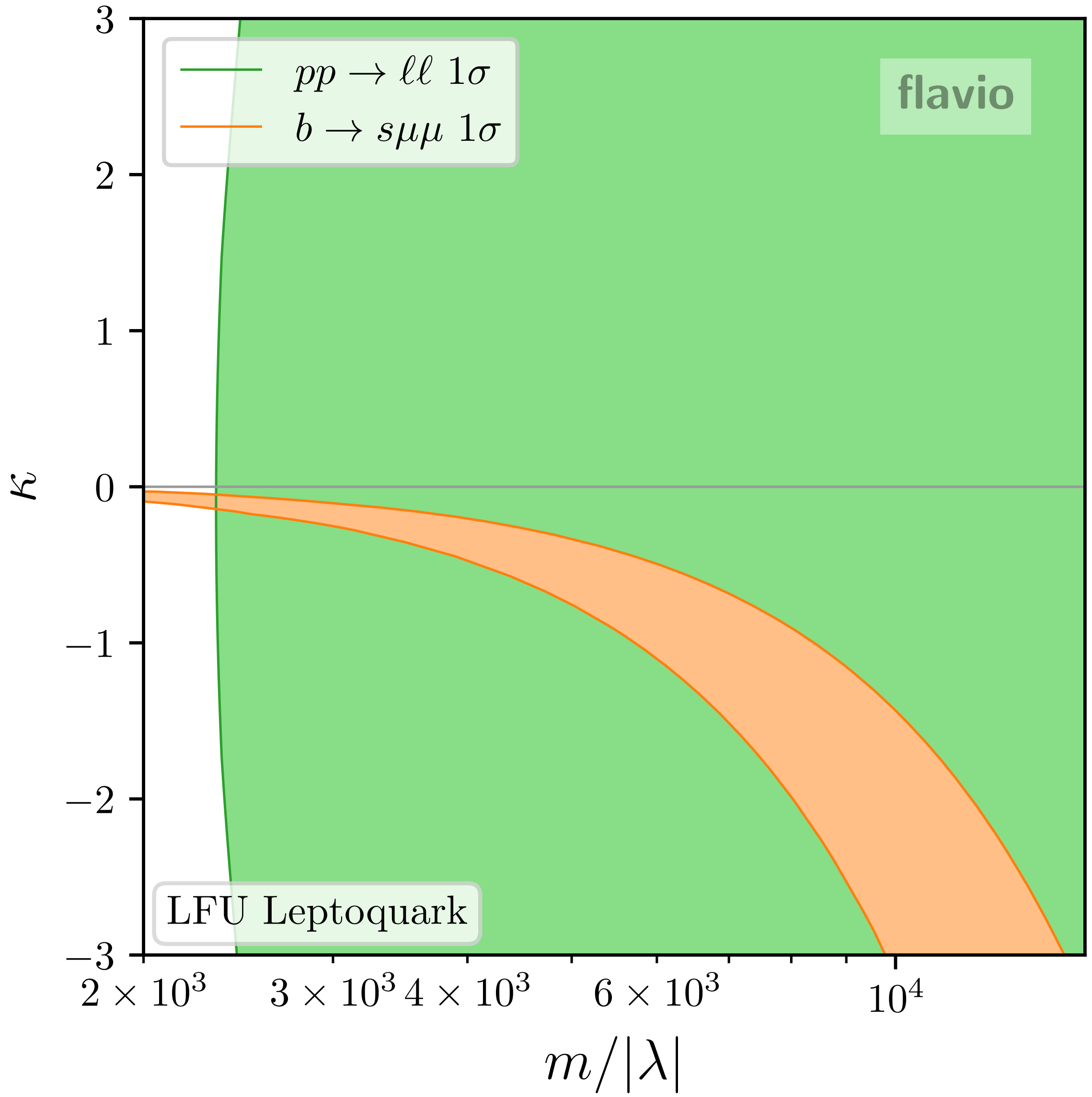
Greljo, Salko, AS, Stangl; 2212.10497

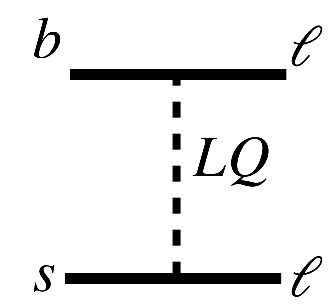
LFU LQ

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

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

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





$2q2\ell$ at tree level

$4q$ and 4ℓ loop suppressed

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

Summary

- Model-independent approach to heavy NP
  -> tools for global analyses indispensable

- Complicated data analyses can be done “once and for all”
  -> reinterpretation in concrete heavy NP models possible

- Flavor responsible for the vast majority of parameters
  -> interesting correlations between observables from different classes

- High complementarity between high-mass DY and meson decays
  especially in realistic flavor scenarios and concrete models

Thank you

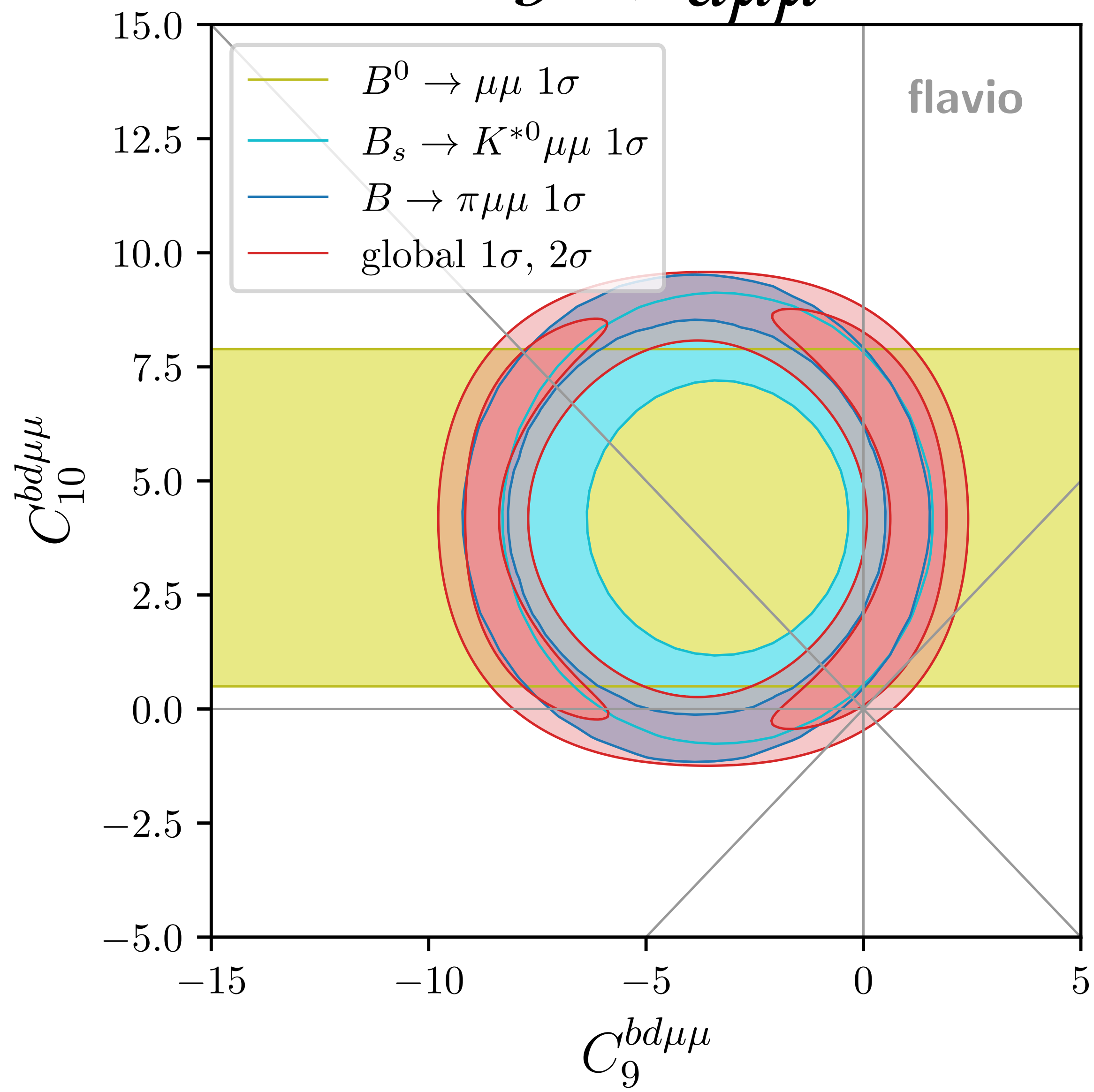
Additional slides

$b \to d, s$ in WET

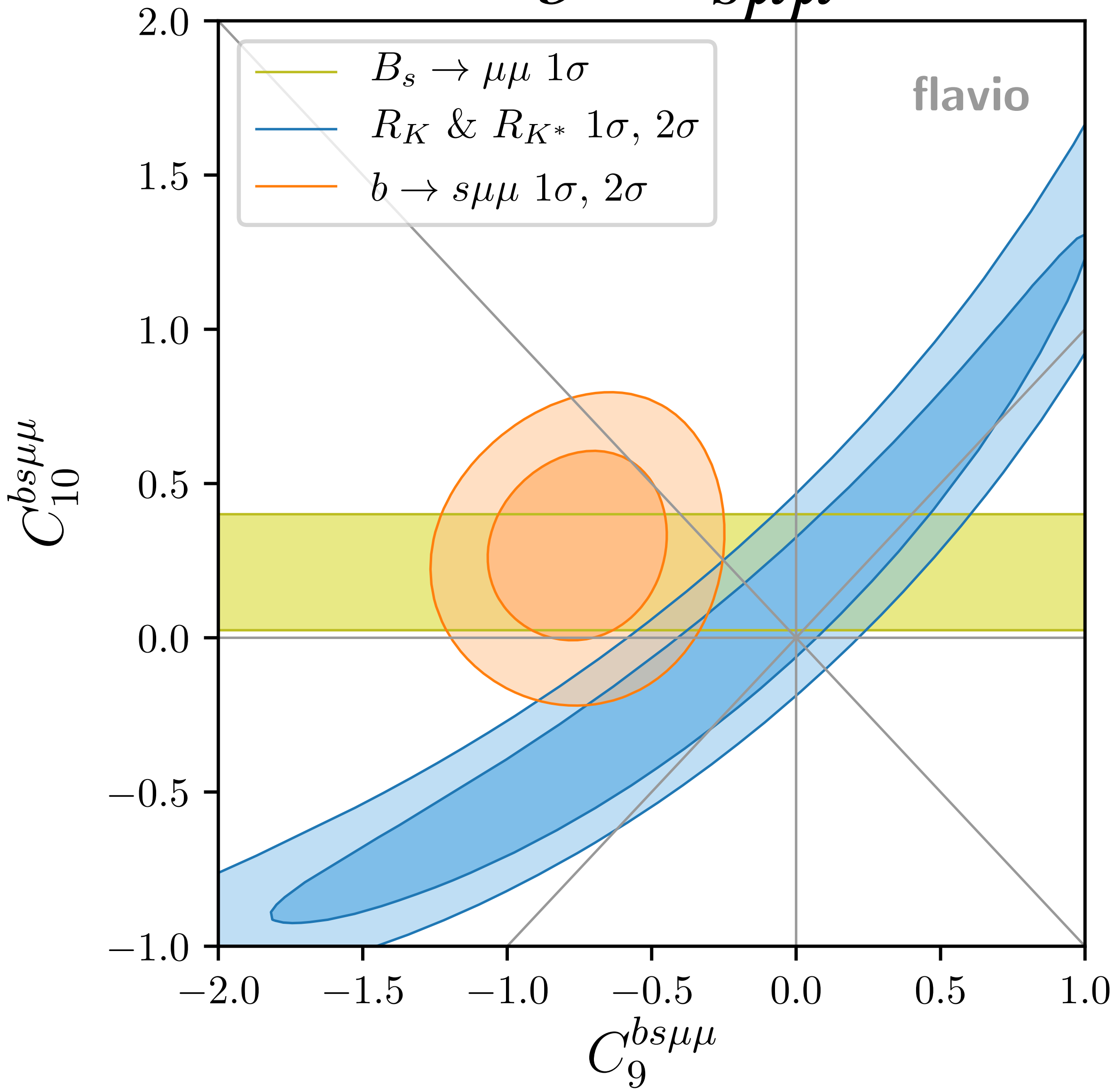
Greljo, Salko, AS, Stangl; 2212.10497

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

$b \to d\mu\mu$



$b \to s\mu\mu$

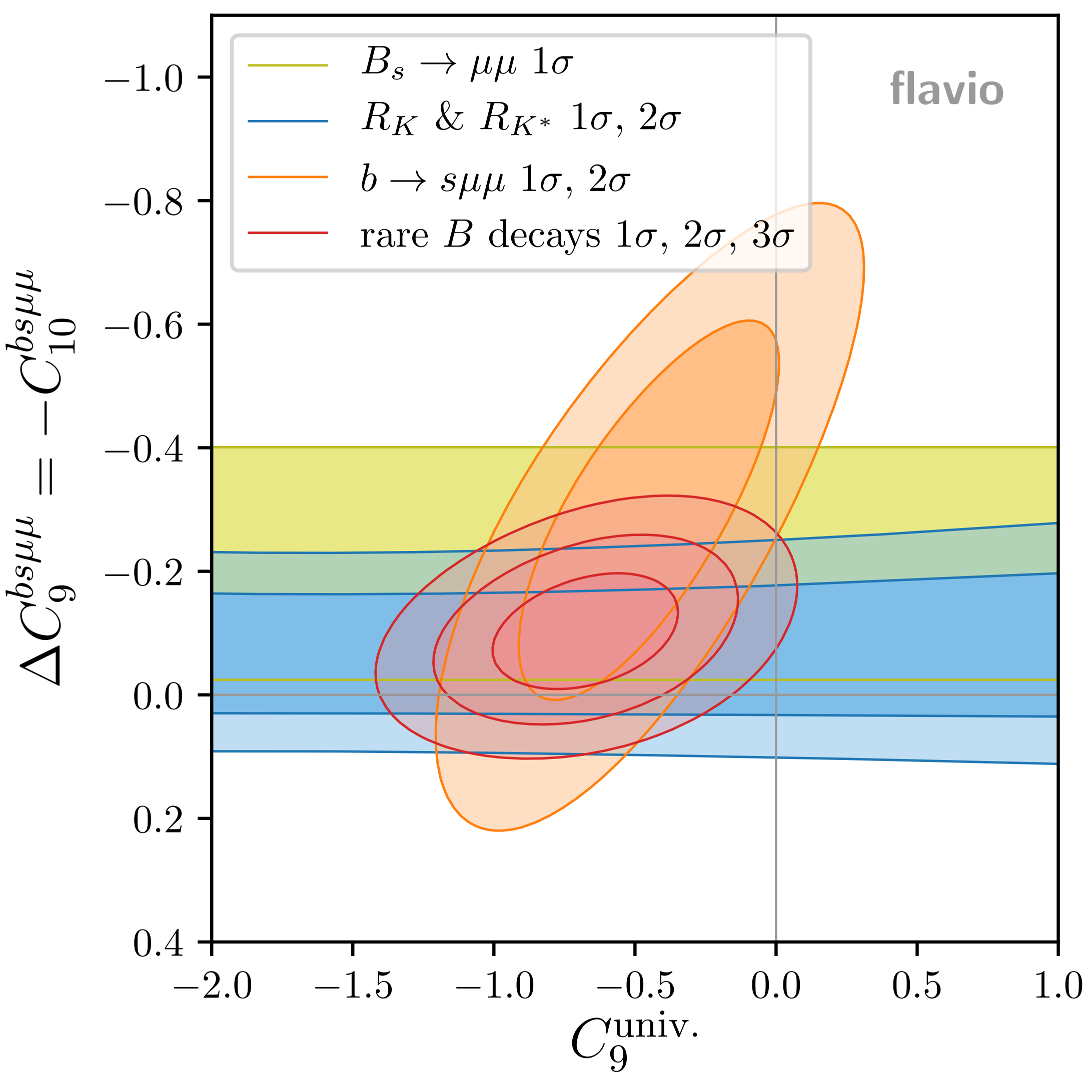


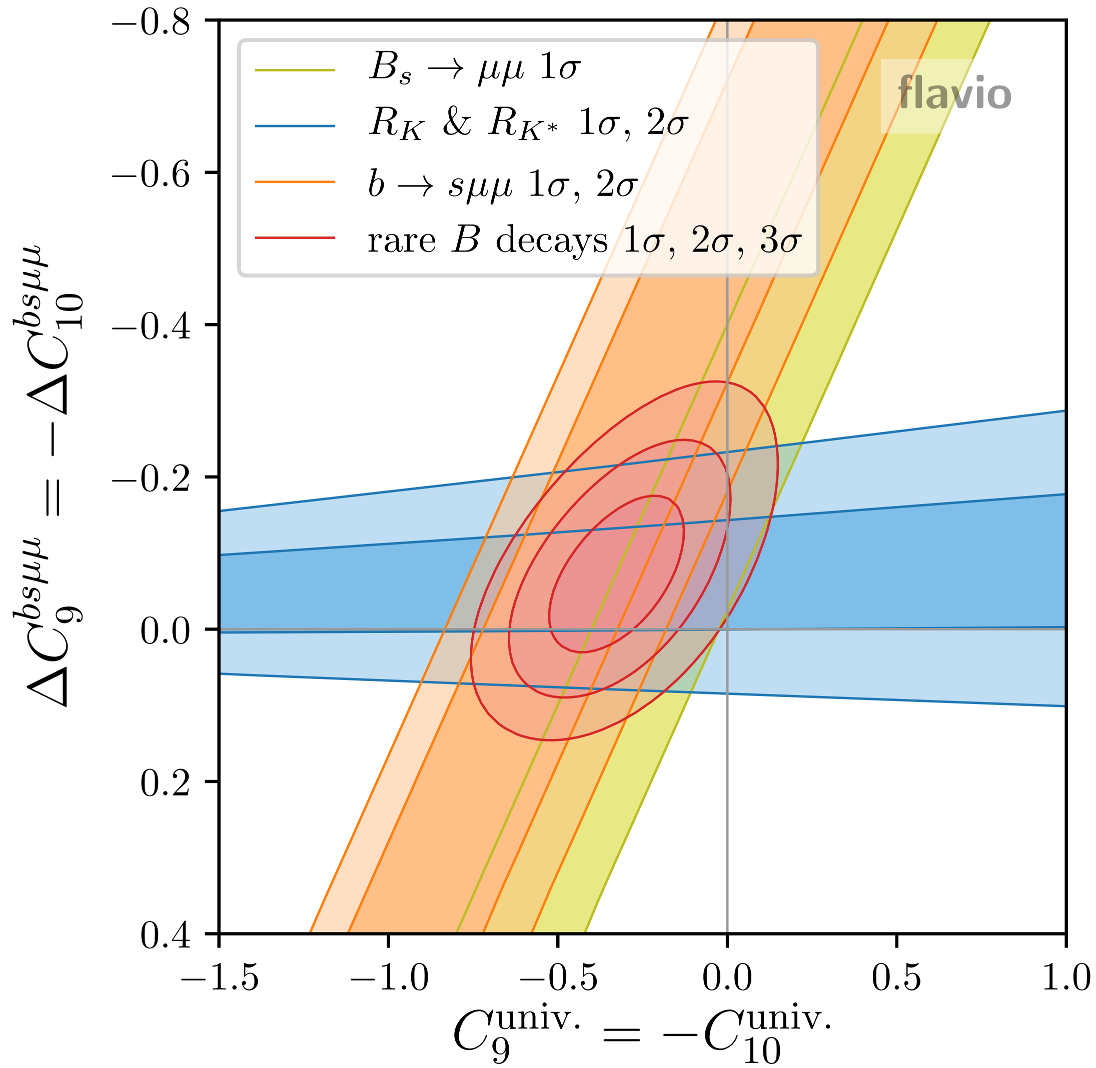
$B \to \pi$ FFs from 2102.07233

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

LFU vs LFV in $b \to s$

Greljo, Salko, AS, Stangl; 2212.10497





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

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

LFU tree level models

Greljo, Salko, AS, Stangl; 2212.10497