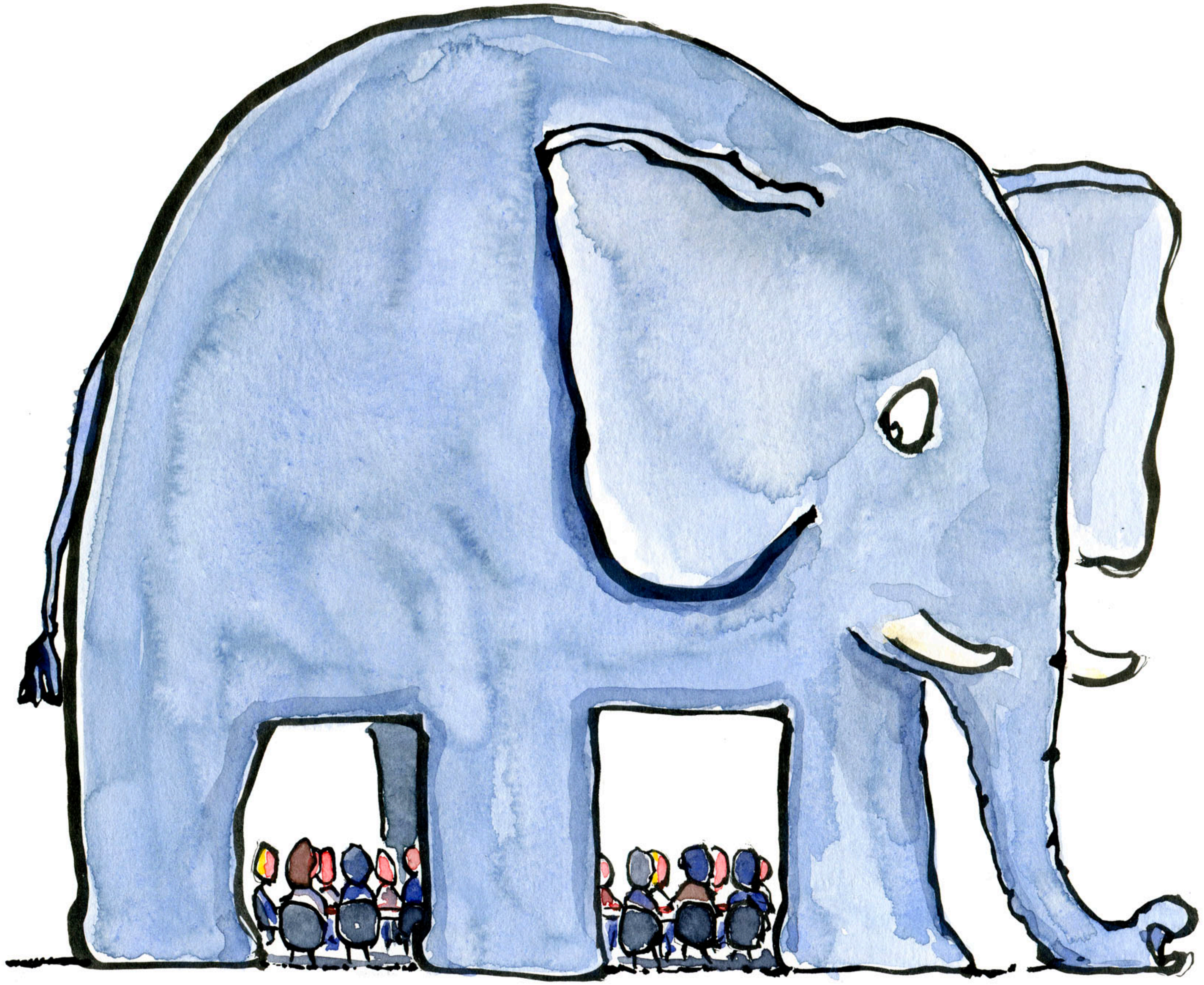
What did the Flavour Anomalies teach us?

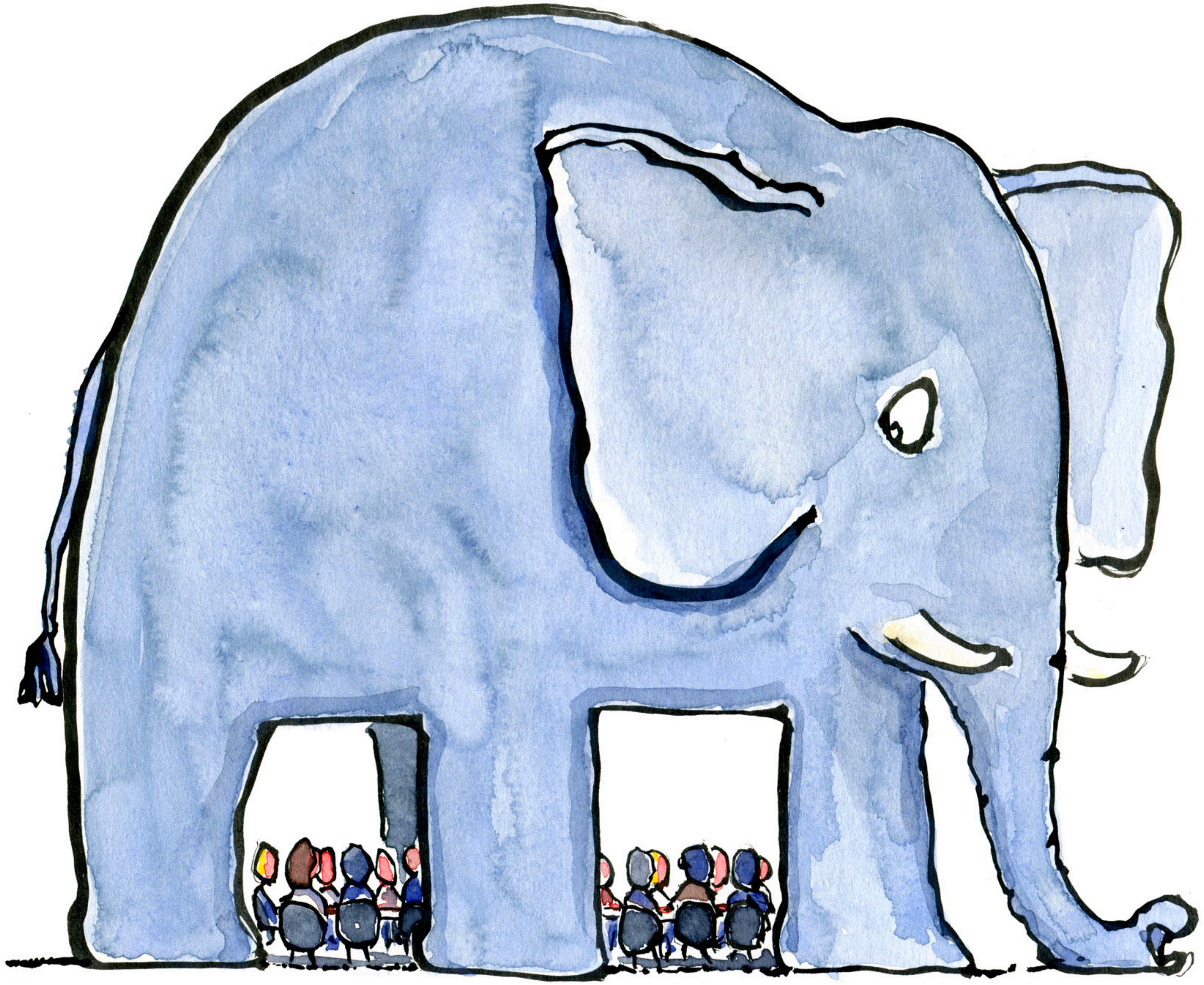
David Marzocca

INFN Trieste

HiDDeN ITN *29 - 11 - 2022*



Frits Ahlefeldt



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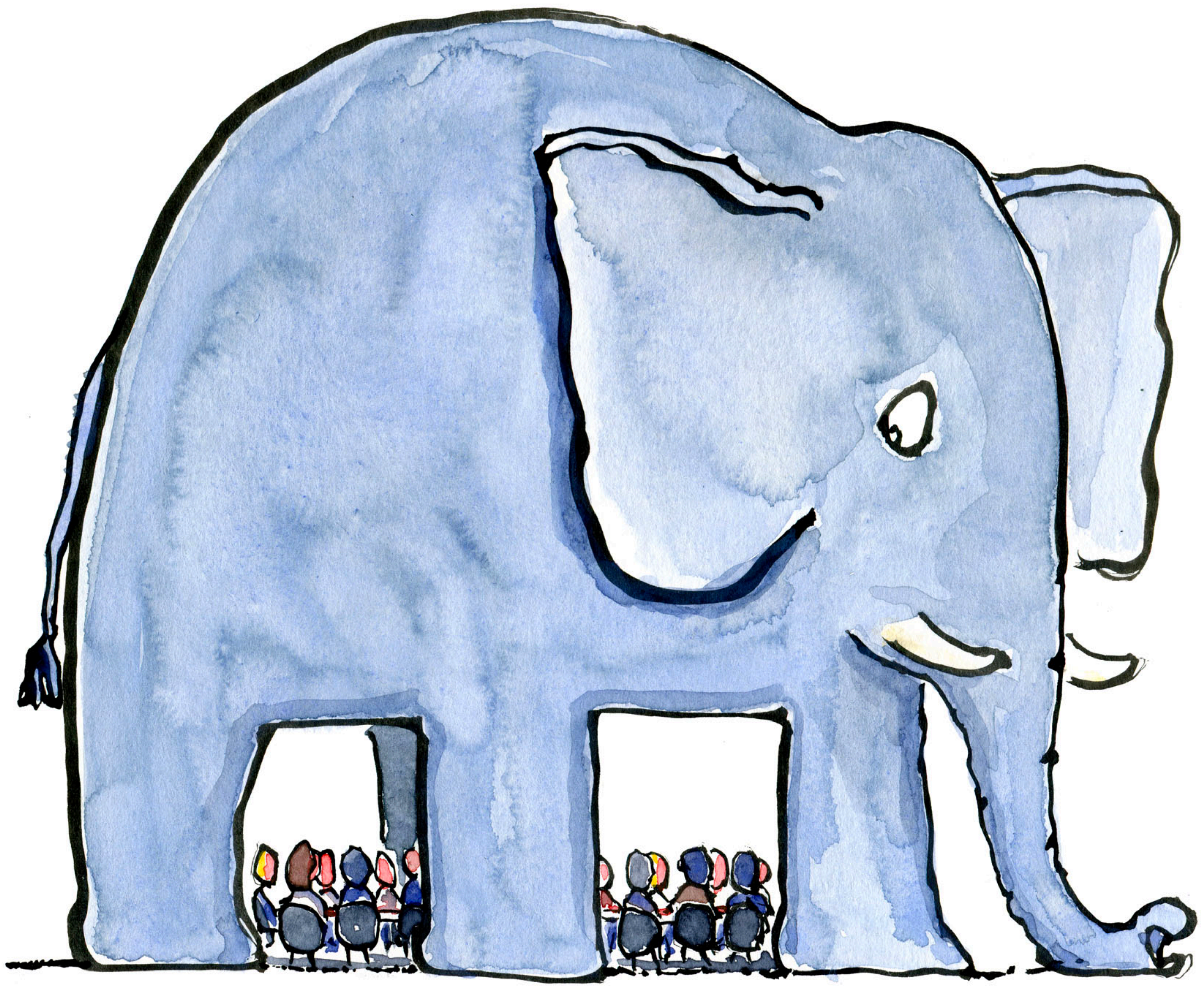
LHCb is now performing a combined measurement of **R_K** & **R_{K^*}** with the same dataset.

Wild rumours suggest that this new analysis now finds SM-like values for both observables…

Is the R_K anomaly going away?
Hopefully soon we will see this update.



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Meanwhile we can ask…

Was this all for naught?

In the worst-case scenario, what did we (or better, I) learn from the Flavour Anomalies?

1 - Judging anomalies

Why working on anomalies at all?

A physicist's job is to understand Nature in a mathematical model, using the scientific method.
An **anomaly** is just an **experimental phenomenon** we do not understand, it is thus worthwhile to try to gain insight and obtain a **possible explanation**, with correlated **predictions to be tested** experimentally.
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… but which one(s)?

Our time is limited and "anomalies" are abundant.
How does one choose?

- Field of interest
- Statistical significance
- Theoretical and experimental "robustness"
- Viability of a New Physics explanation + "beauty"
- Personal priors, biases, intuition, …

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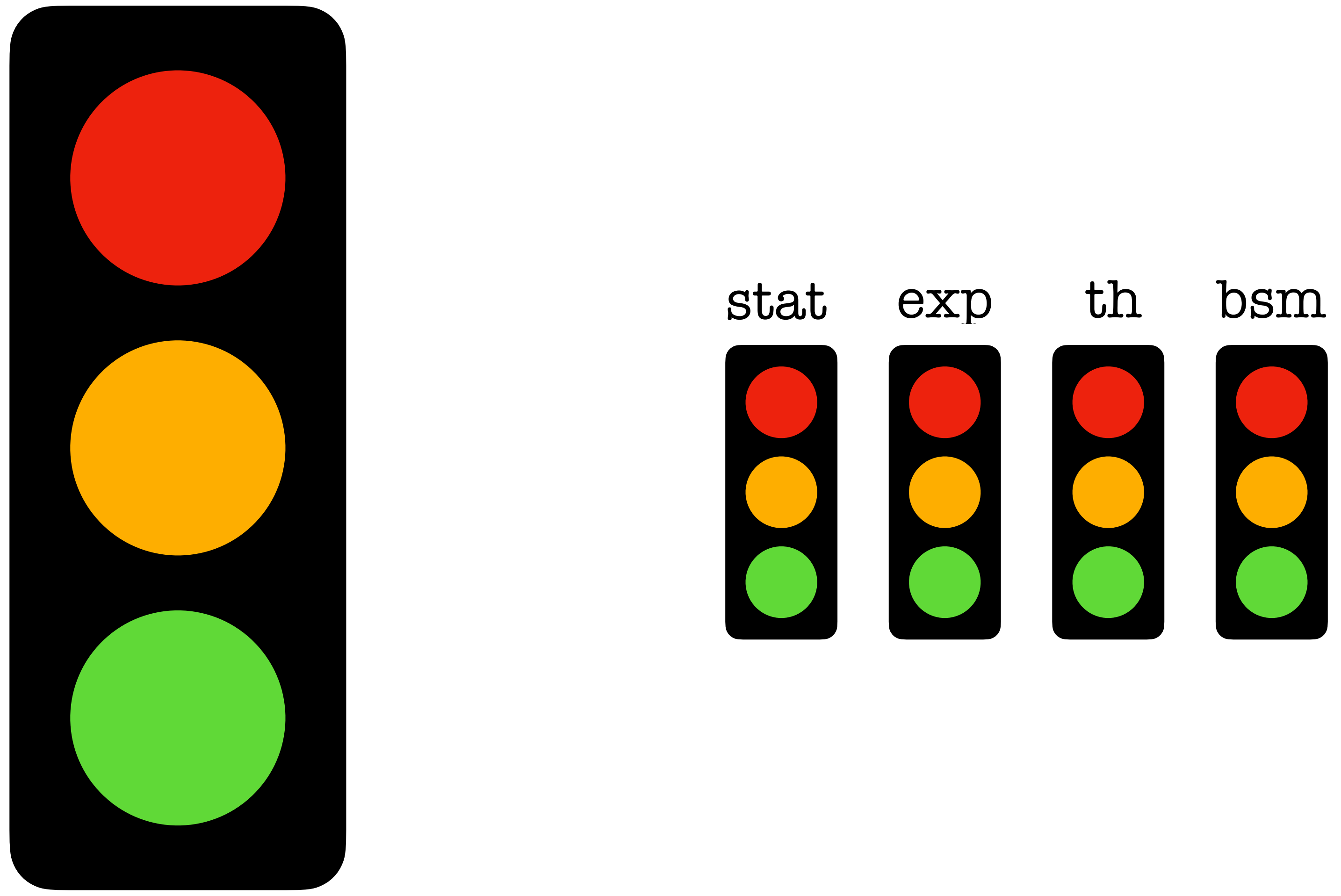
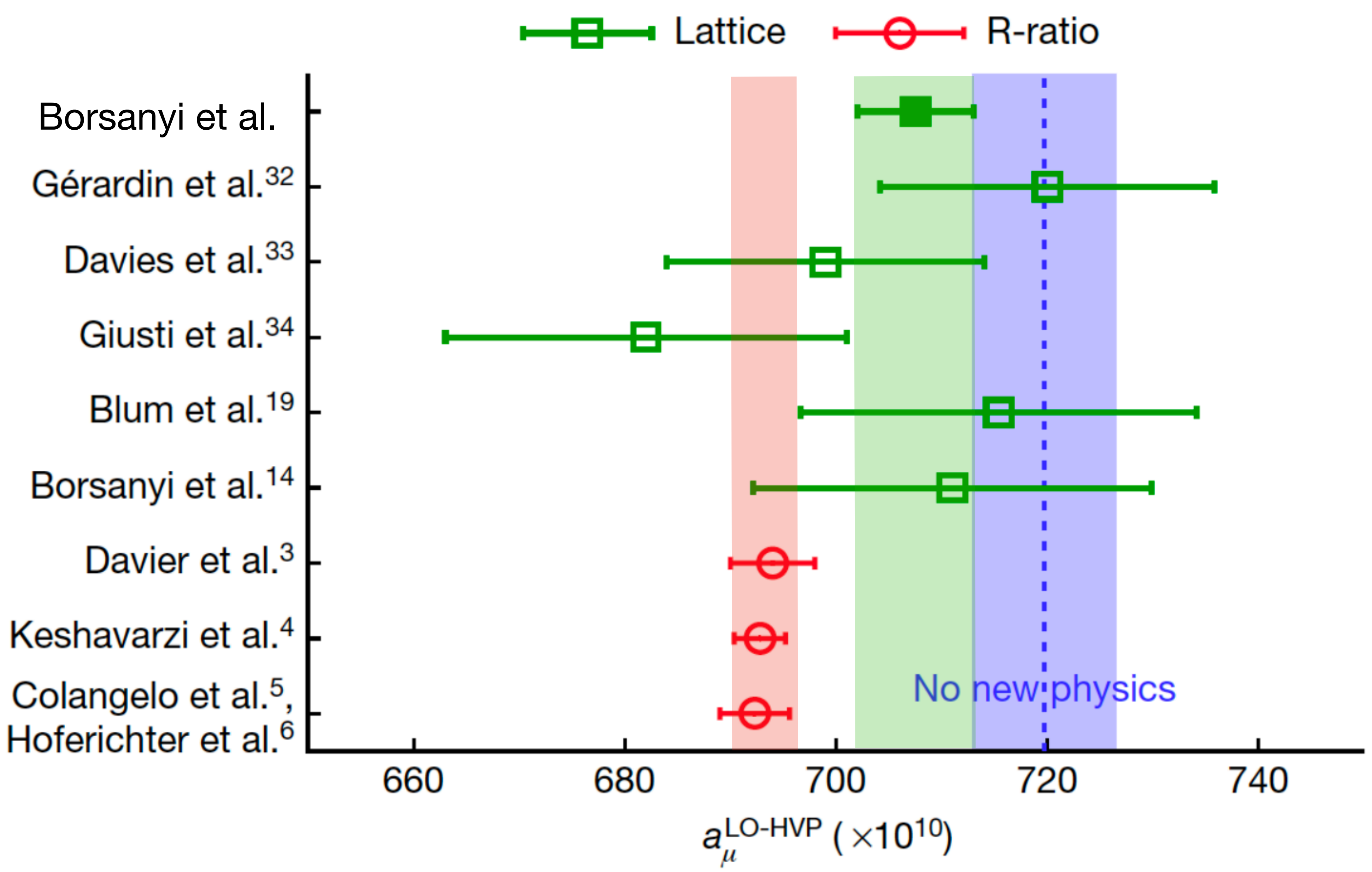
The anomaly traffic lights



Muon g-2



$a_\mu^{exp} = (11659\mathbf{2061} \pm \mathbf{41})\times 10^{-11}$ FNAL '21 + BNL '04

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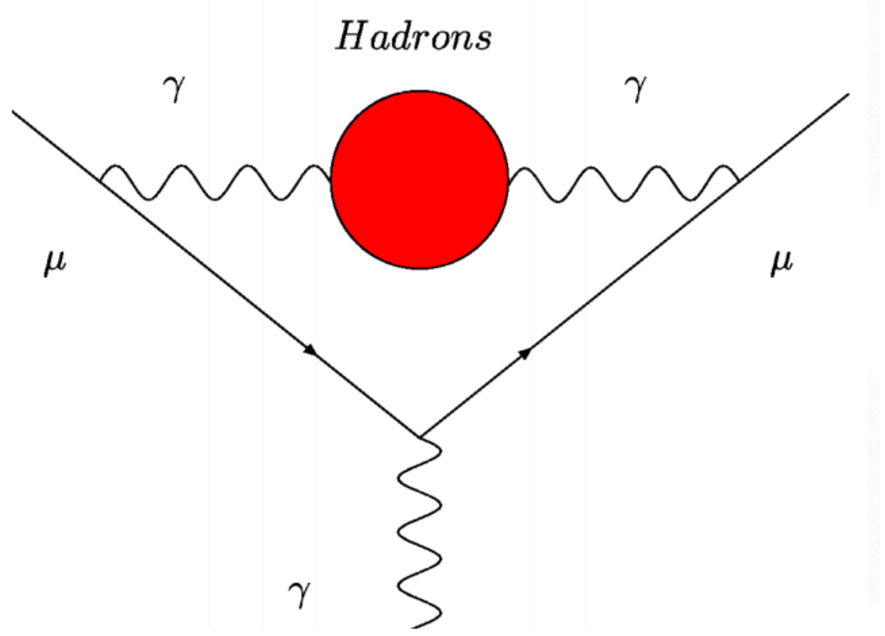
4.2σ or **1.6σ ??**

Main Th. uncertainty in HVP LO contribution:



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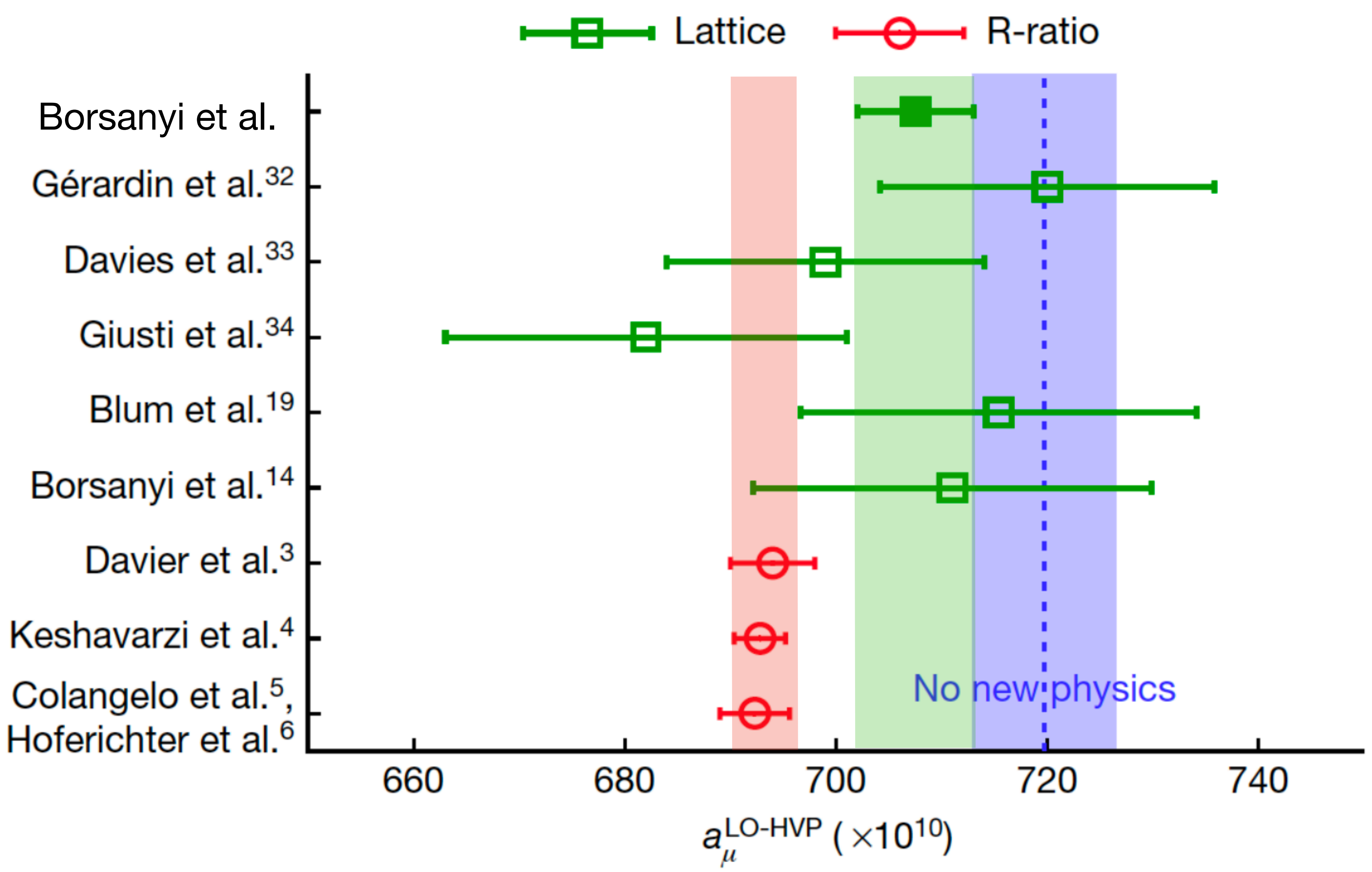

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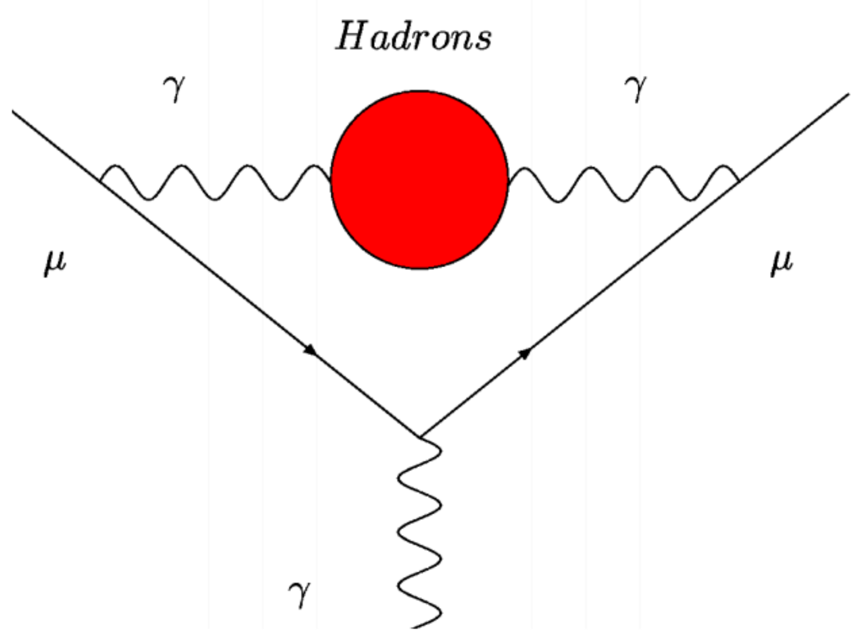
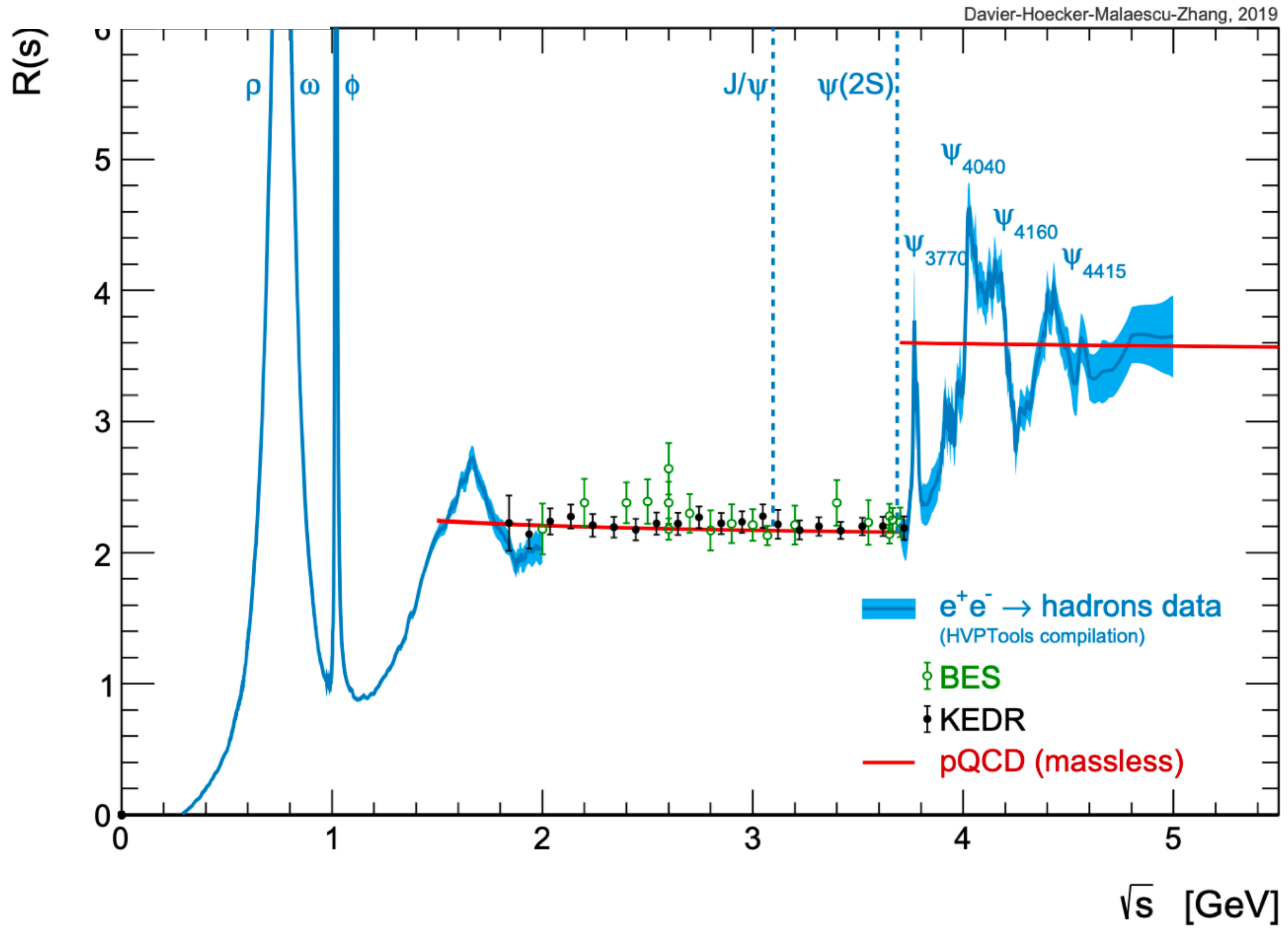


HVP via *dispersion relations*:

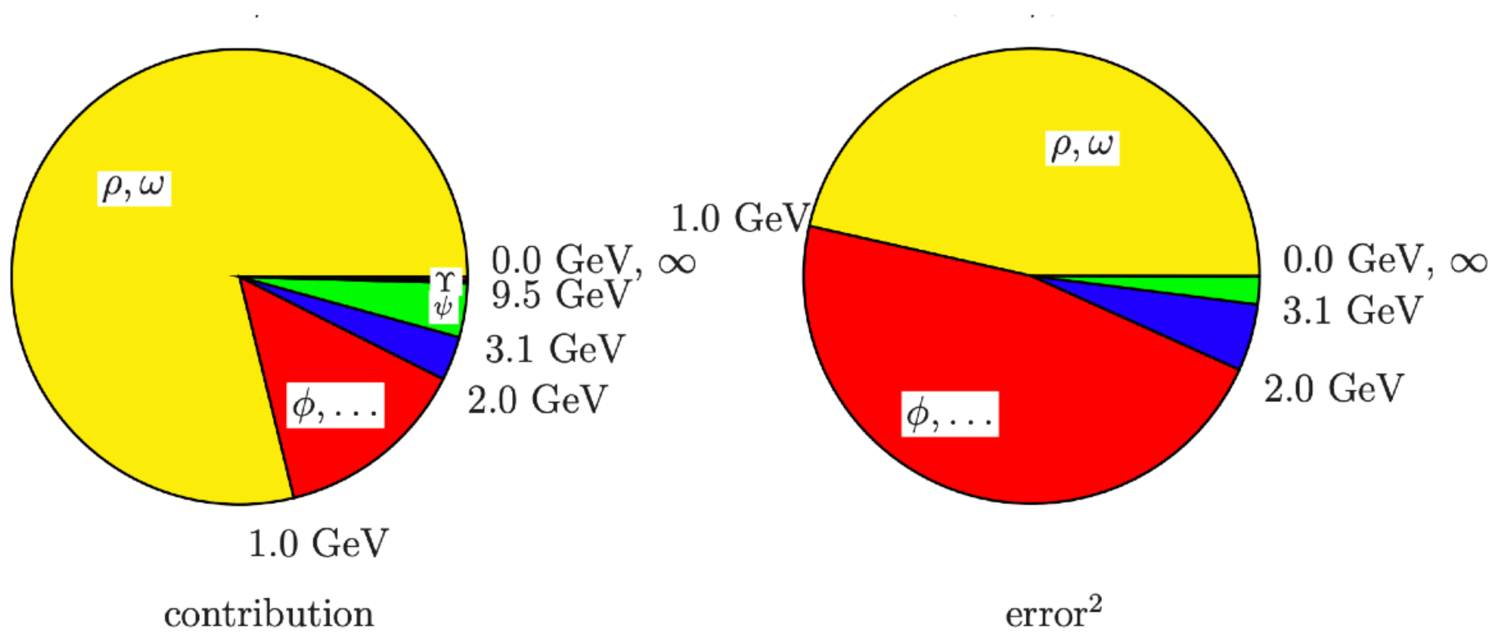
$$a_\mu^{\text{HVP, LO}} = \frac{\alpha^2}{3\pi^2}\int_{M_\pi^2}^{\infty}\frac{K(s)}{s}R(s)\,ds$$

$$R(s) = \frac{\sigma^0(e^+e^- \to \text{hadrons}(+\gamma))}{\sigma_{\text{pt}}}, \qquad \sigma_{\text{pt}} = \frac{4\pi\alpha^2}{3s}$$

$K(s)$: kernel function



Some discrepancies are present in the cross section data from different experiments.
In the WP of the g-2 theory initiative [2006.04822] a conservative combination was performed.



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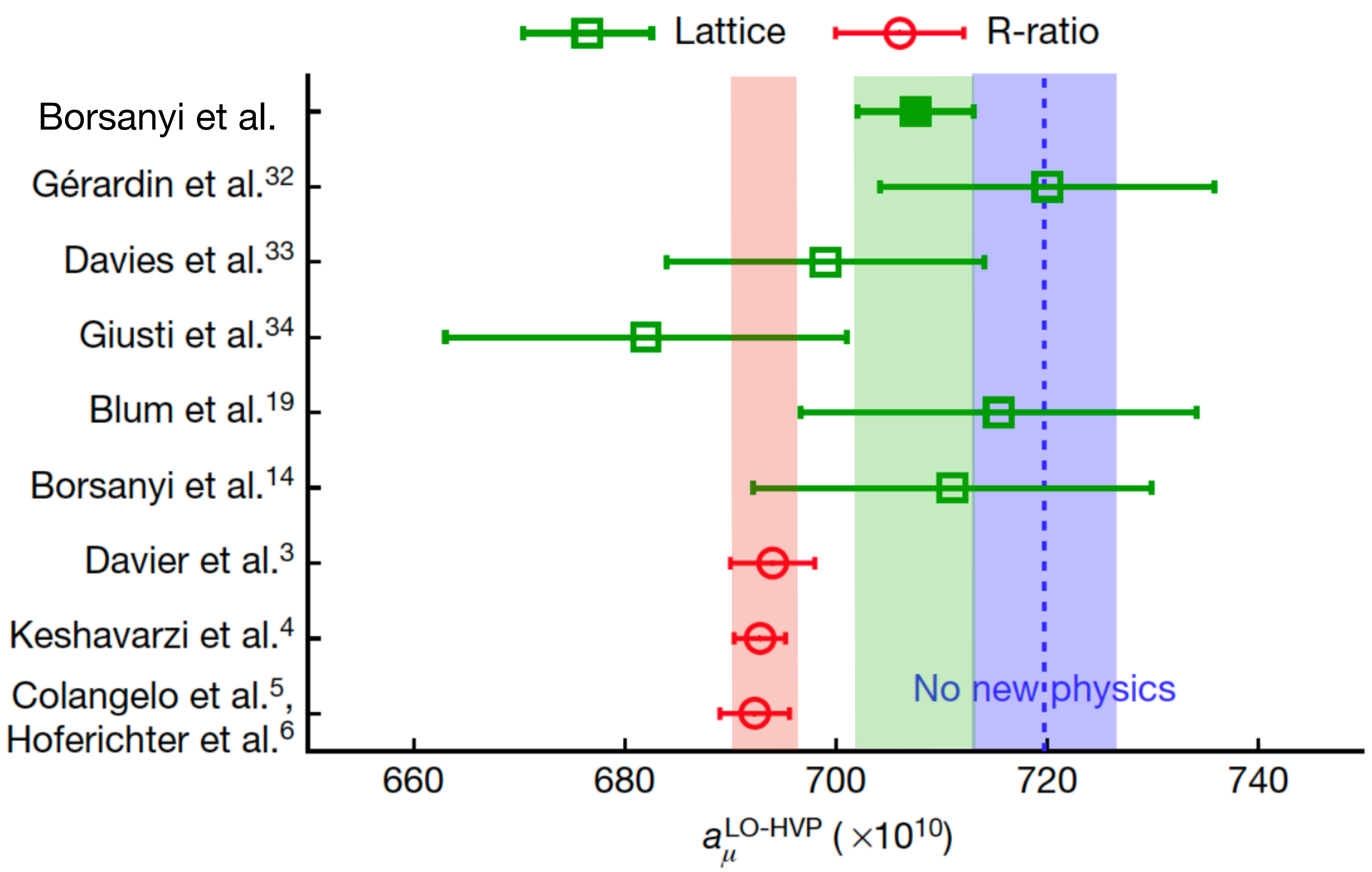

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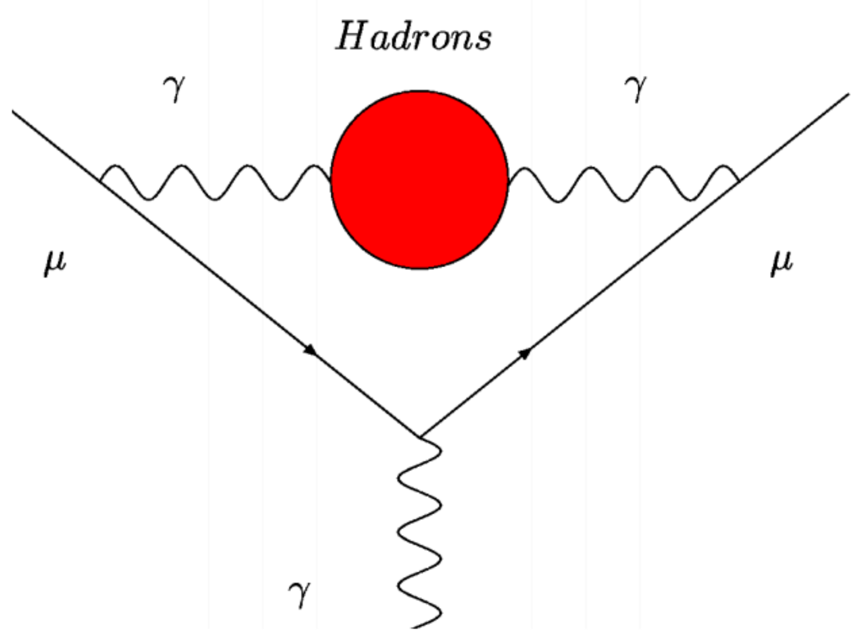

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HVP via *lattice calculations* (convolution of the Euclidean current-current correlator)

$$a_\mu^{\mathrm{LO-HVP}} = \alpha^2 \int_0^\infty dt\ K(t)\ G_{1\gamma\mathrm{I}}(t)$$

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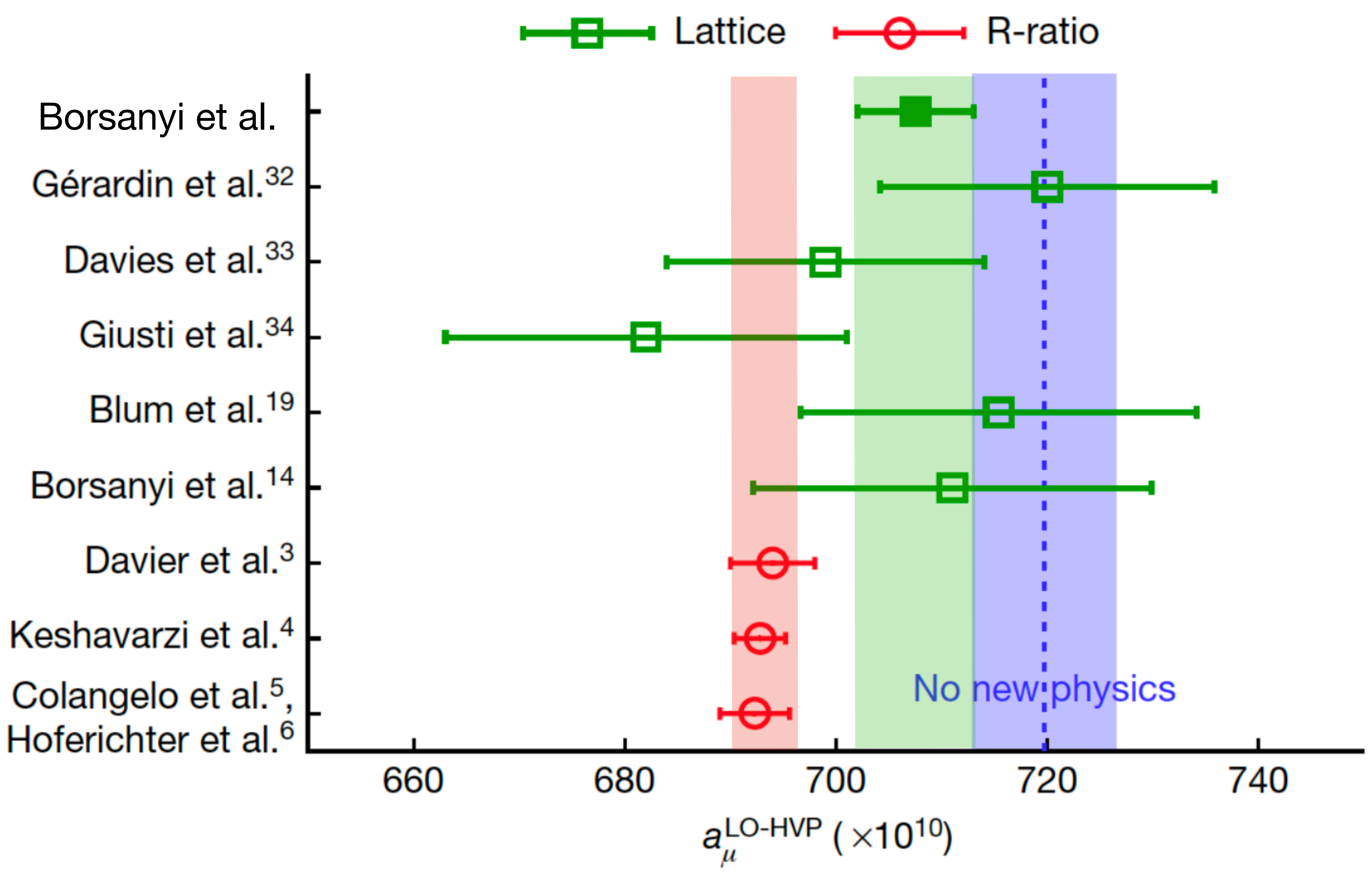

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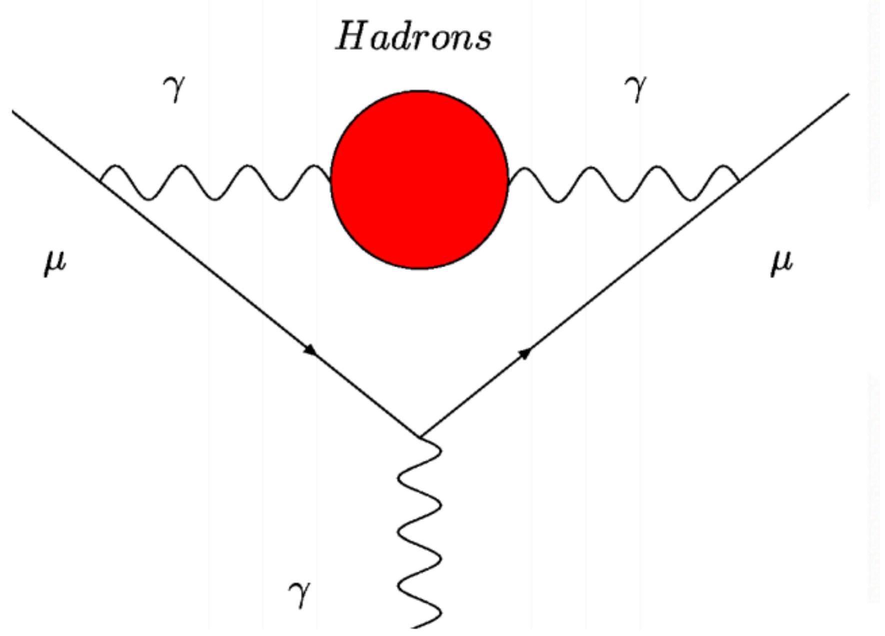

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Windows Approach for LQCD [1801.07224, 2206.06582, 2206.15084, 2207.04765]

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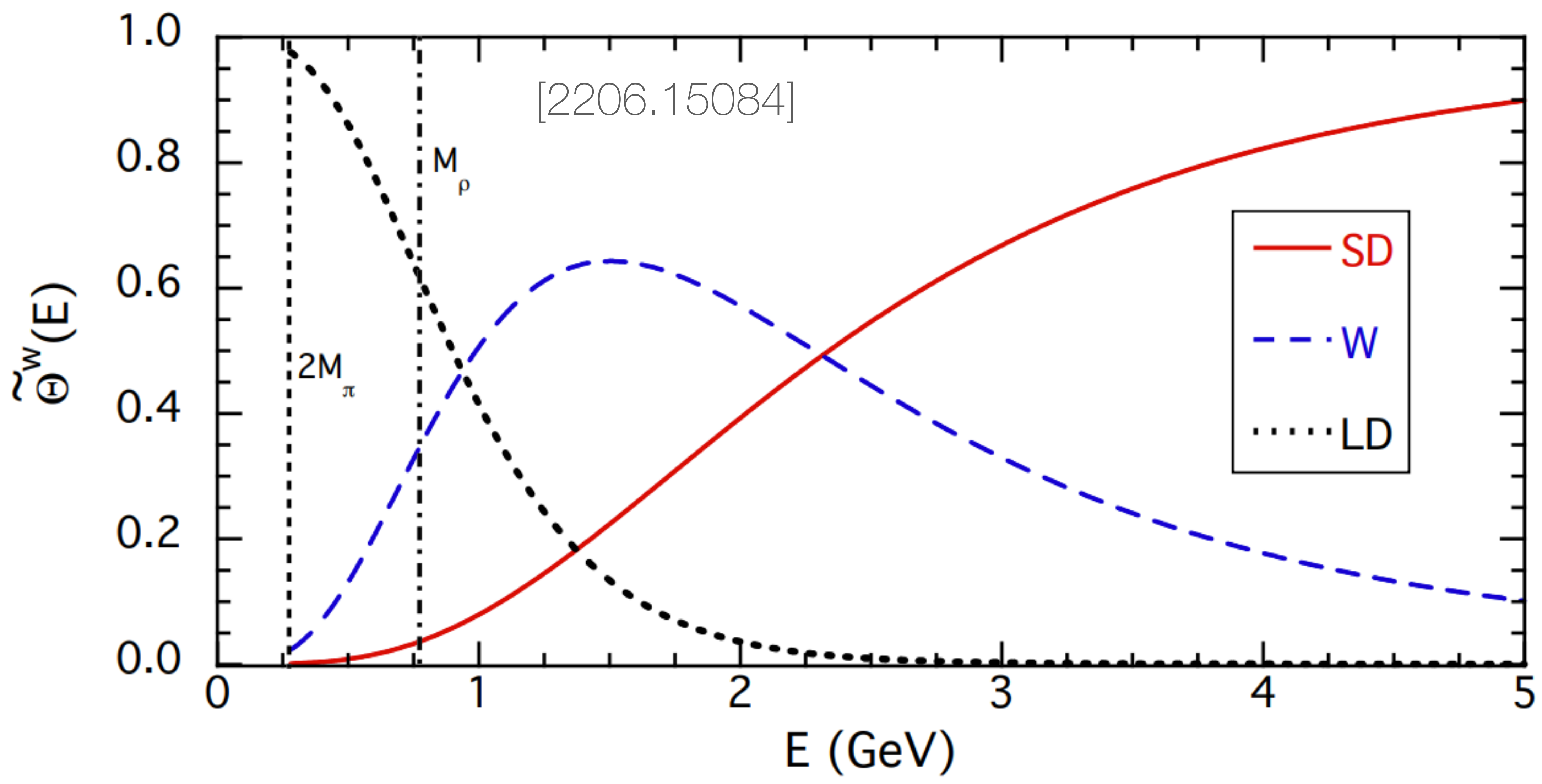

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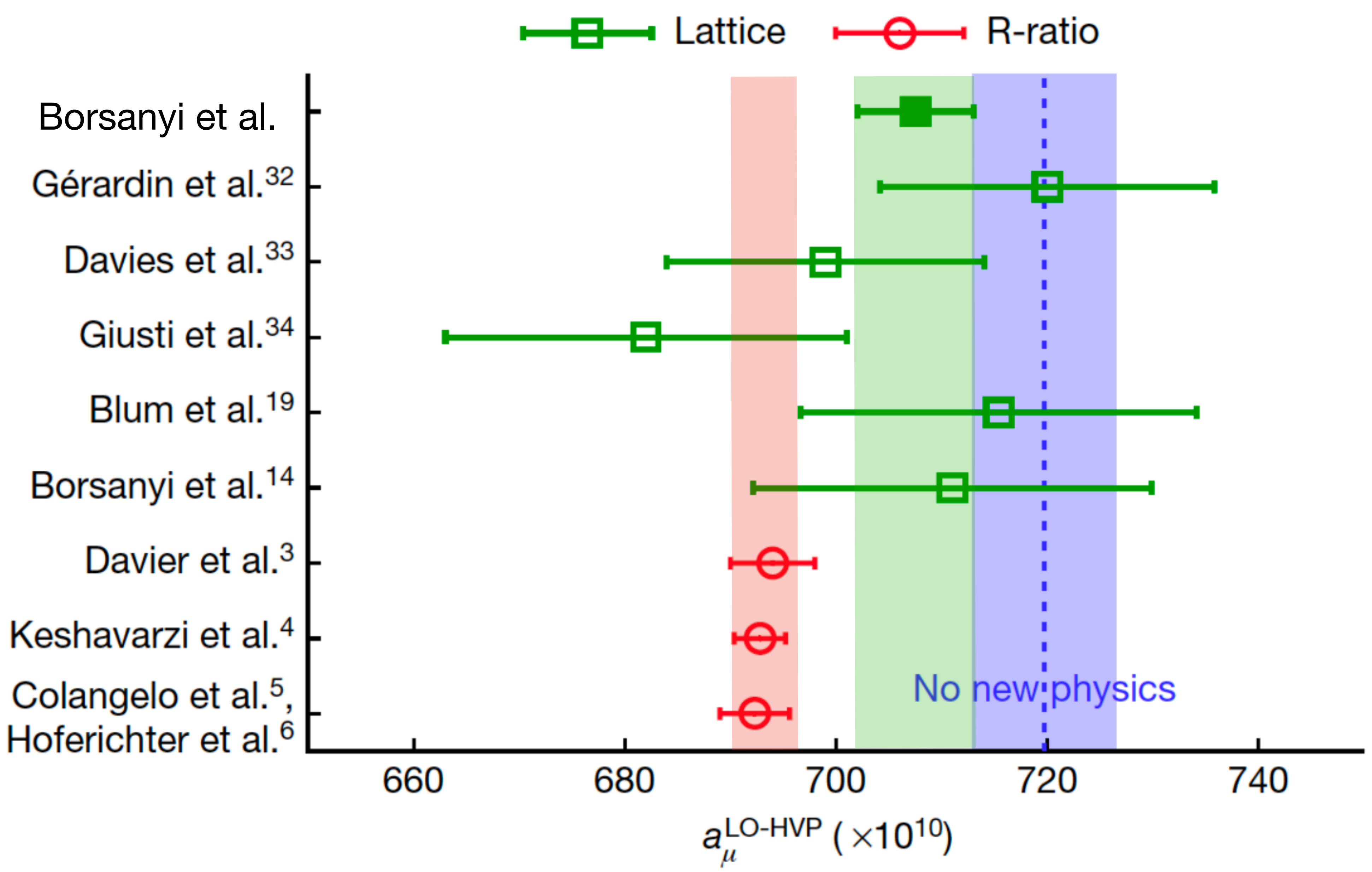

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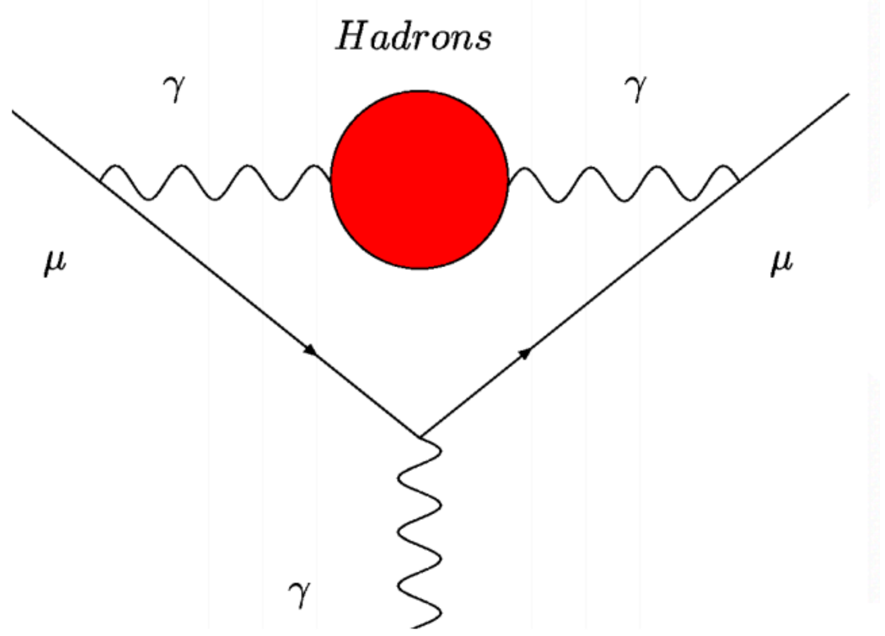

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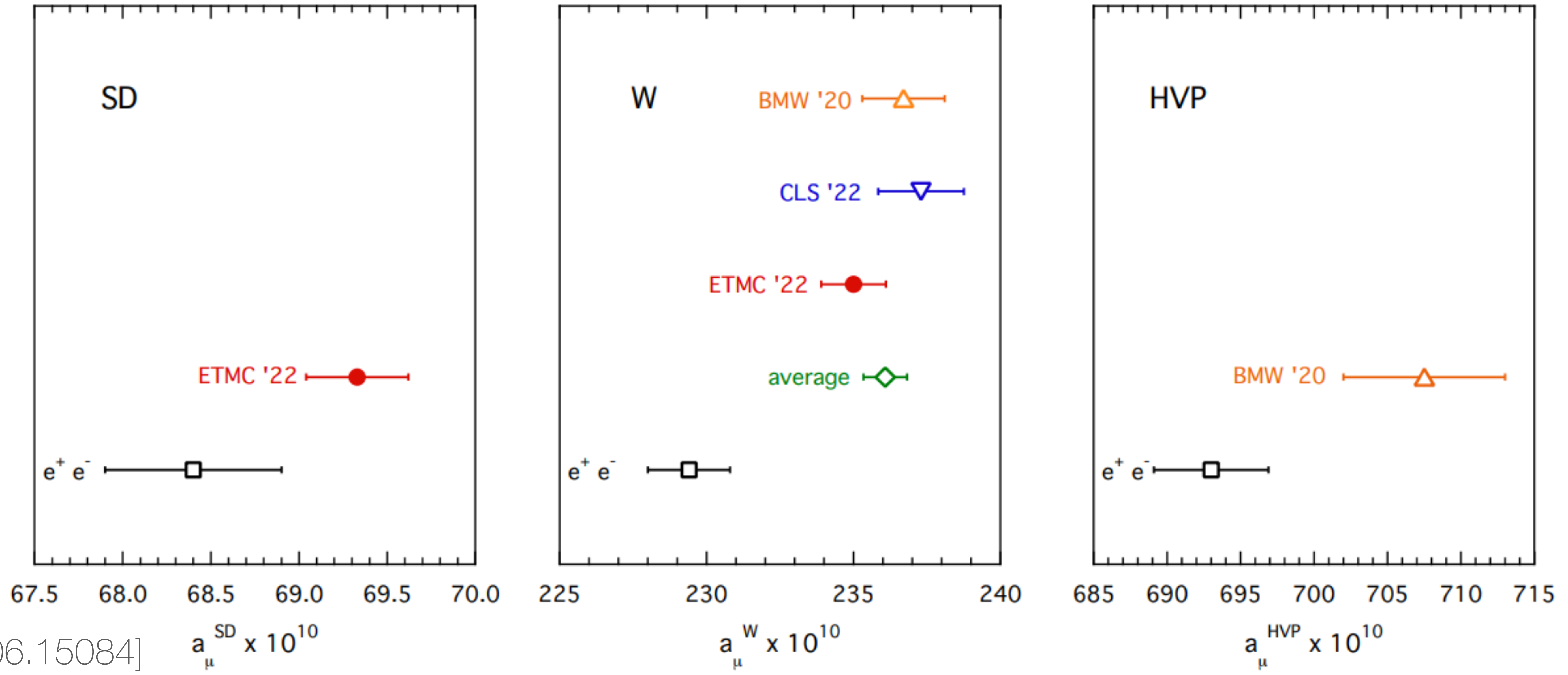

[ETMC 2206.15084]

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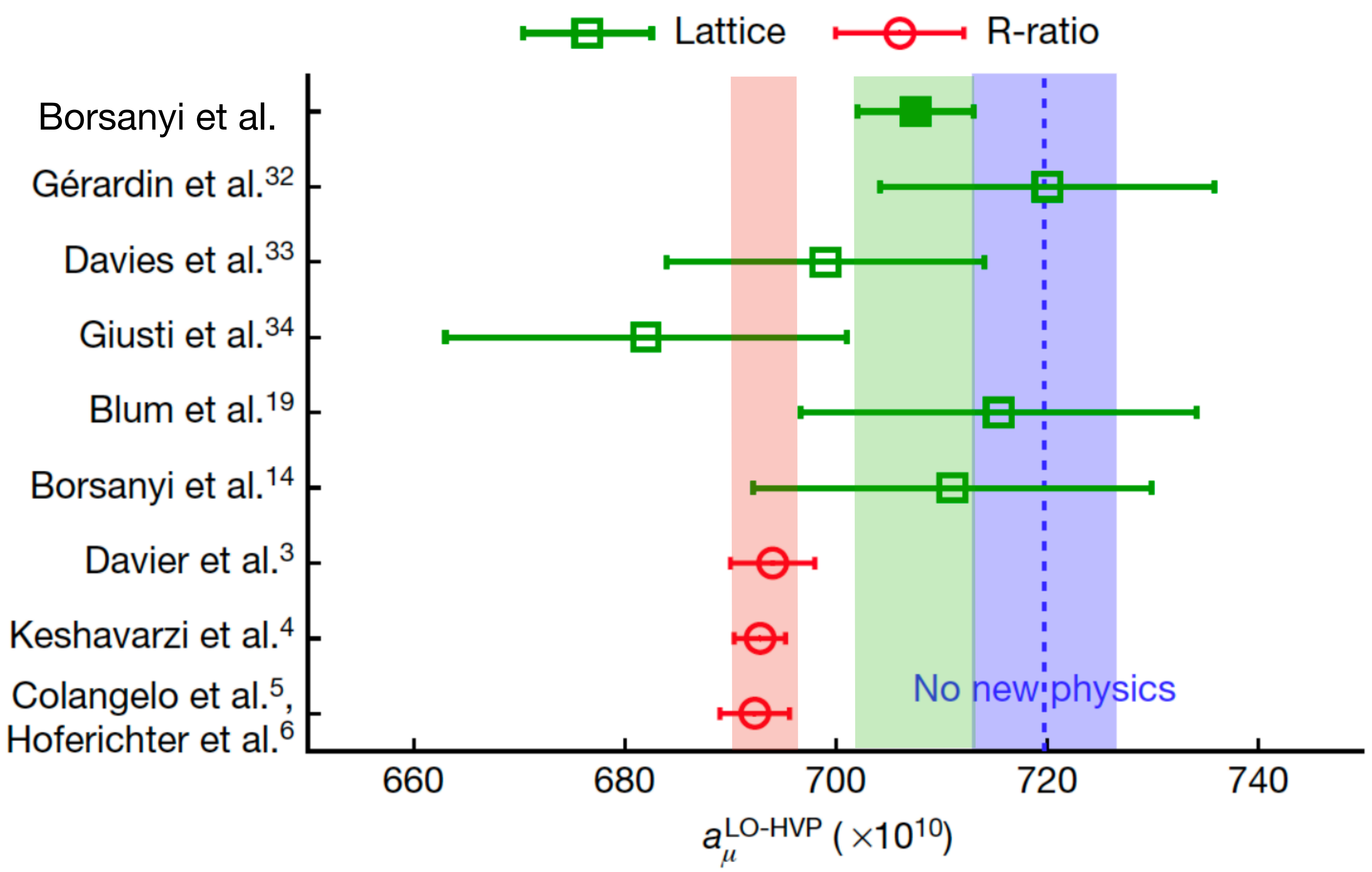

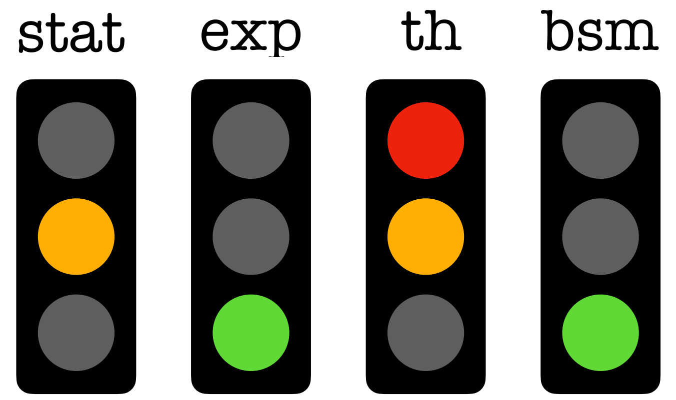

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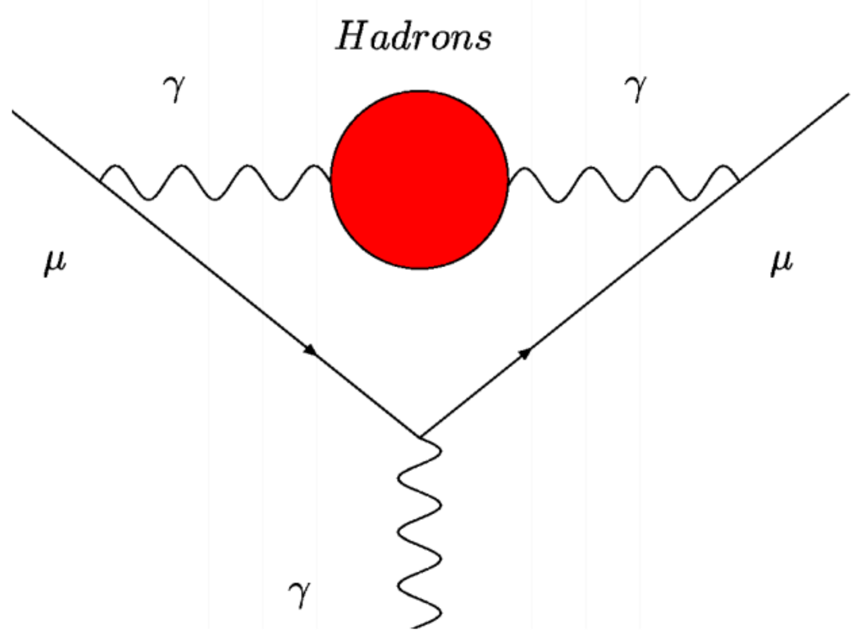

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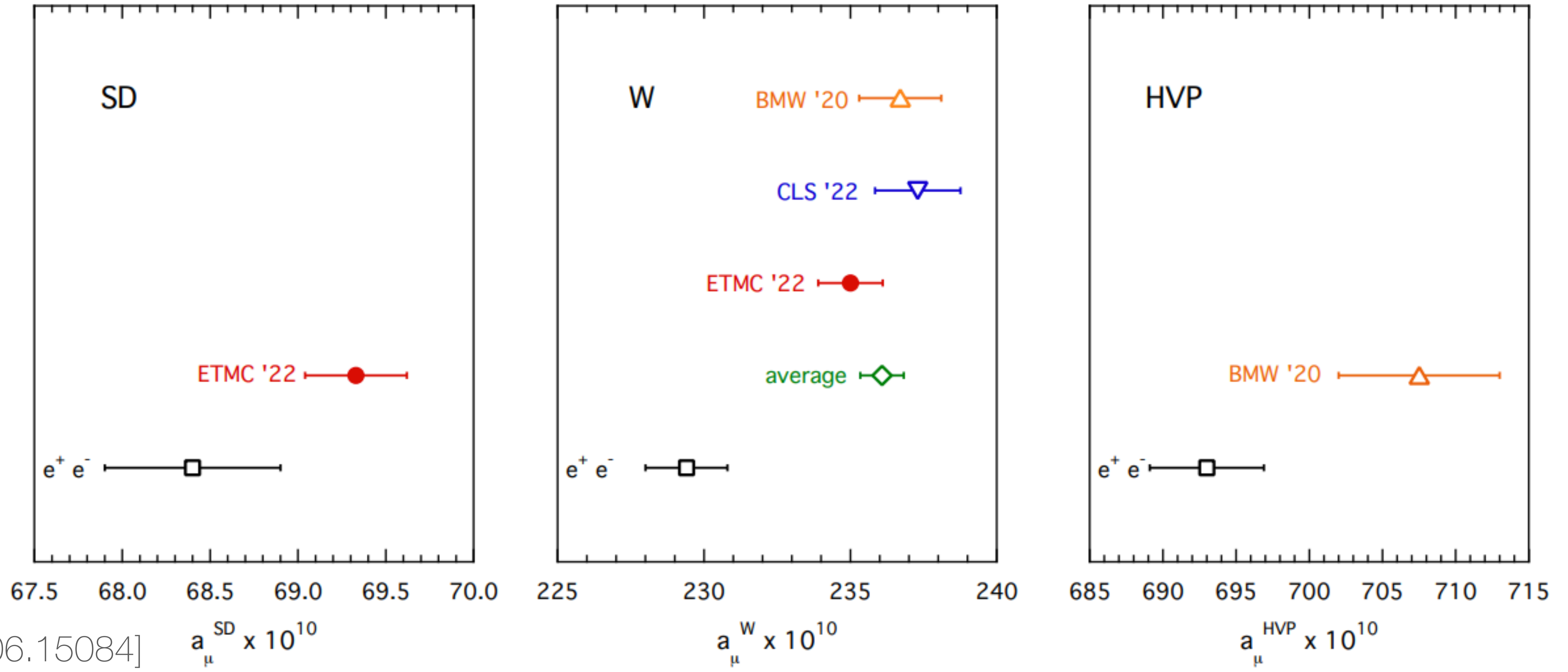


[ETMC 2206.15084]

B-anomalies

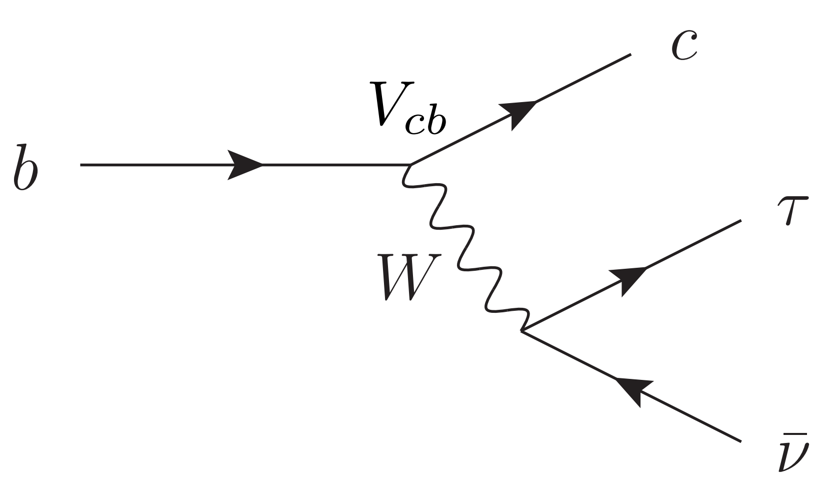
$b \to c\, \tau\, \overline{\nu}_\tau$

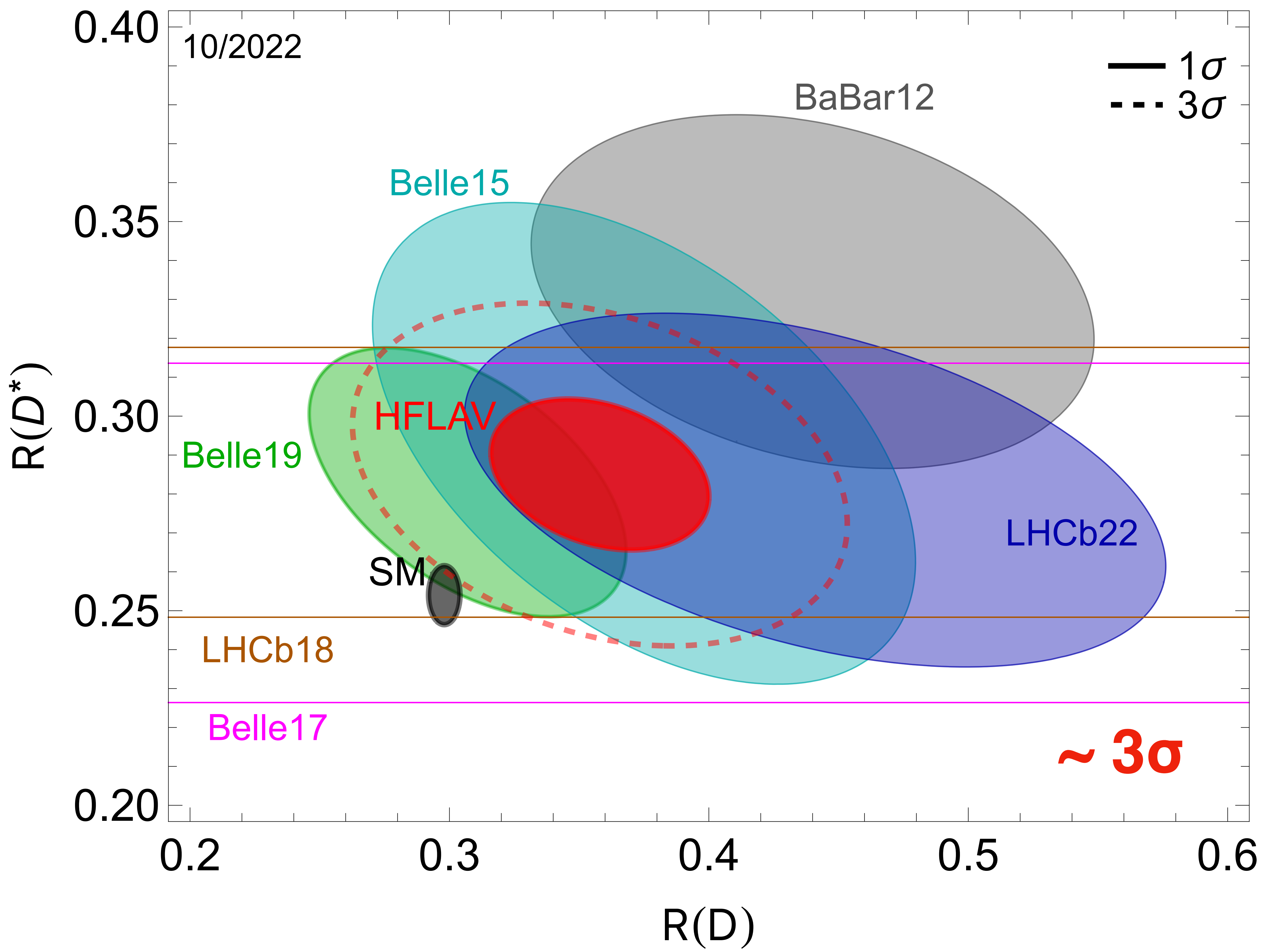
Lepton Flavour Universality

$$R(D^{(*)}) \equiv \frac{\mathcal{B}(B^0 \to D^{(*)+}\tau\nu)}{\mathcal{B}(B^0 \to D^{(*)+}\ell\nu)},$$

$$\ell = \mu, e$$

Tree-level SM process with V_{cb} suppression.





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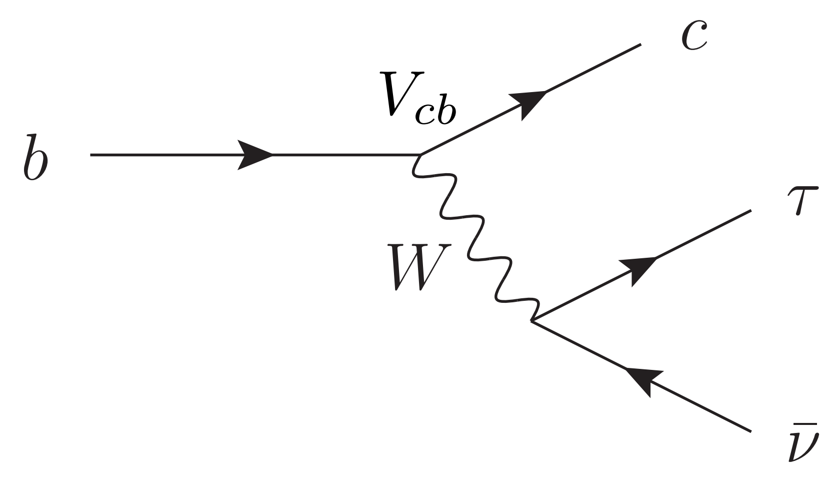

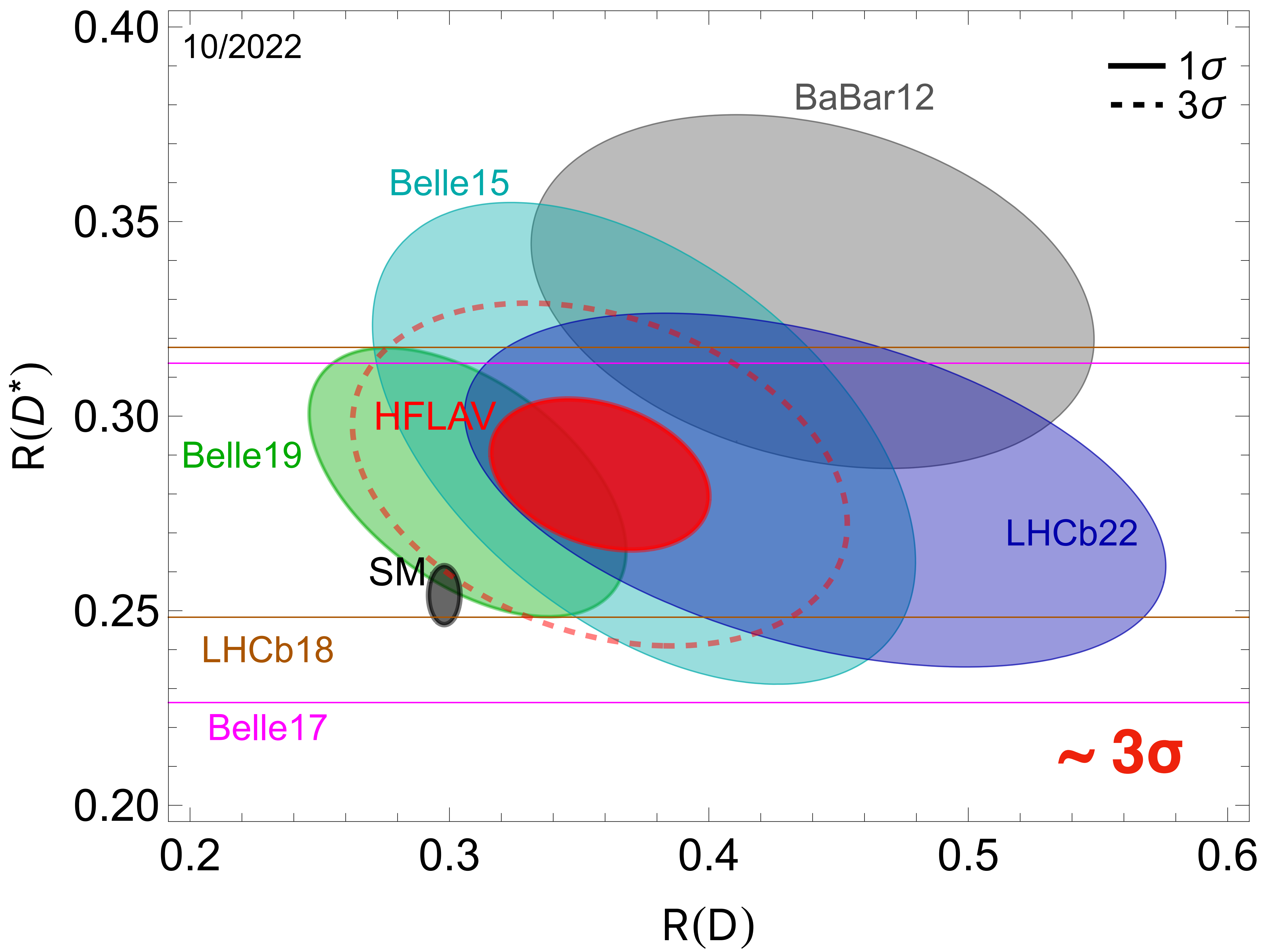

~13% enhancement from the SM amplitude

Requires a **New Physics scale** of

$$\boxed{C^{R(D^{(*)})}_{cb\tau\nu} \sim (4\,\mathrm{TeV})^{-2}}$$

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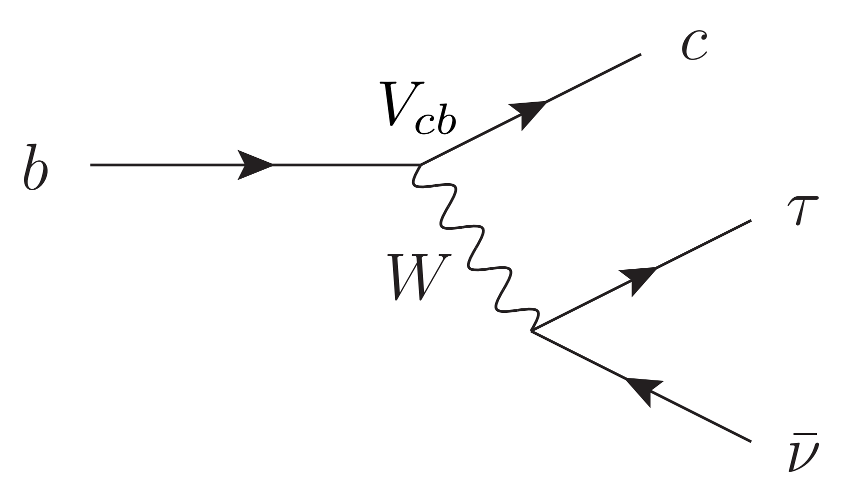

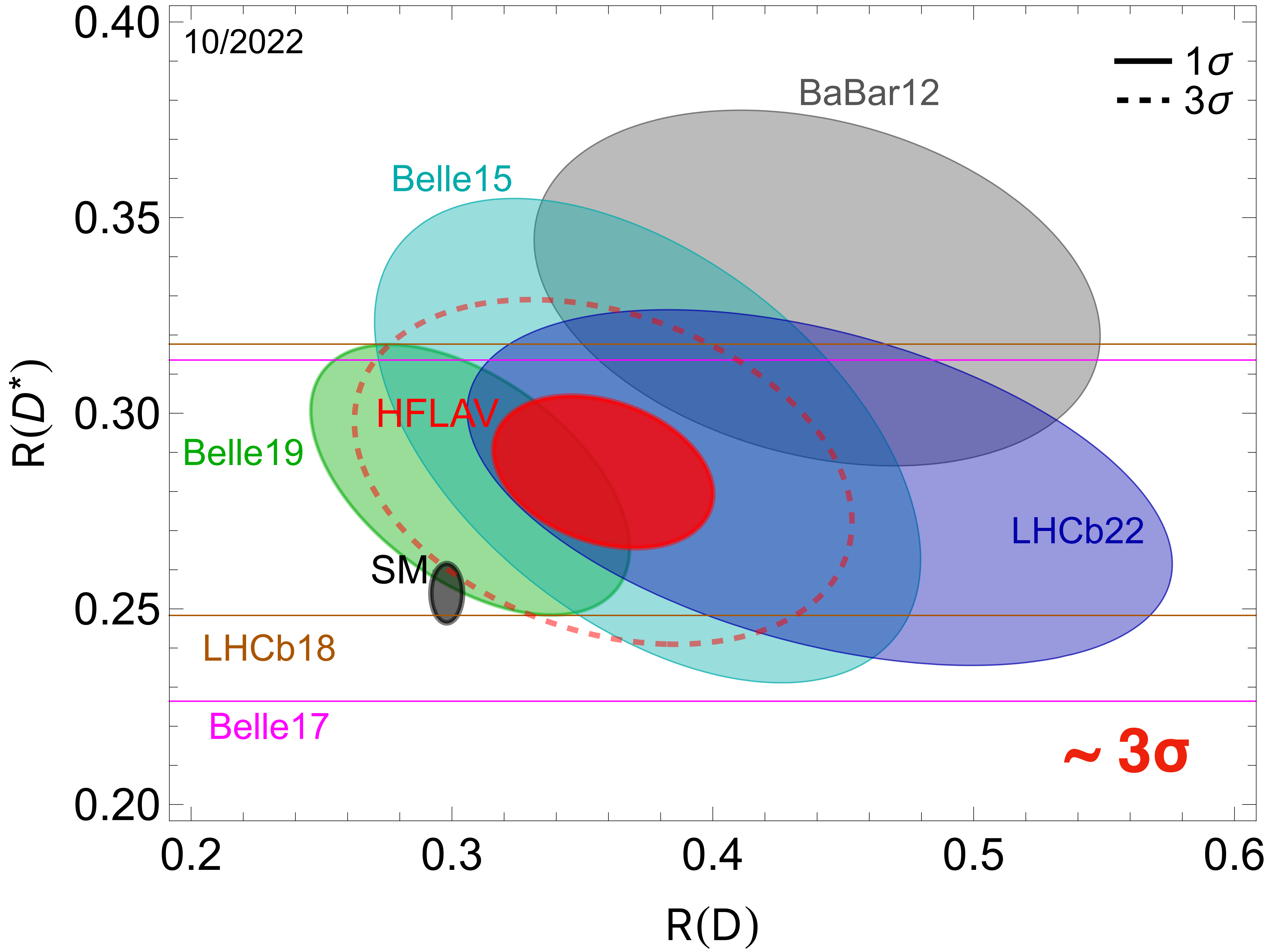

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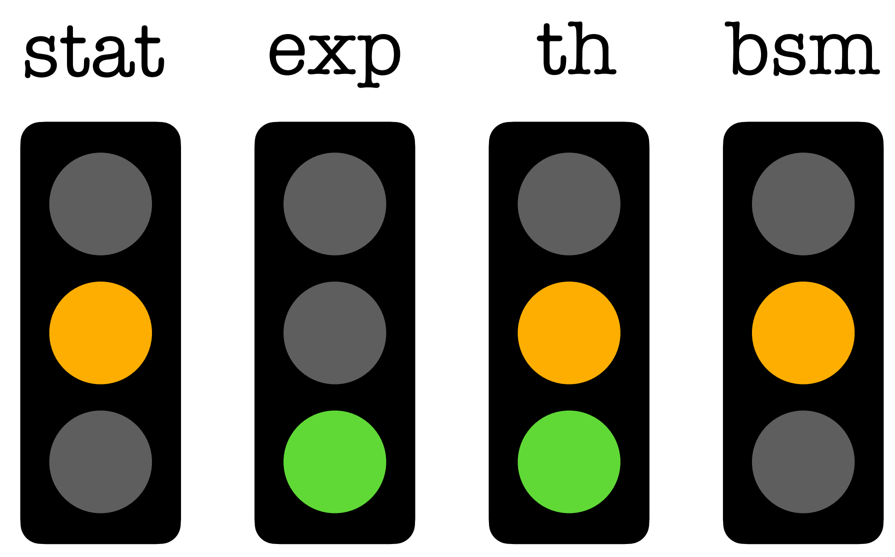
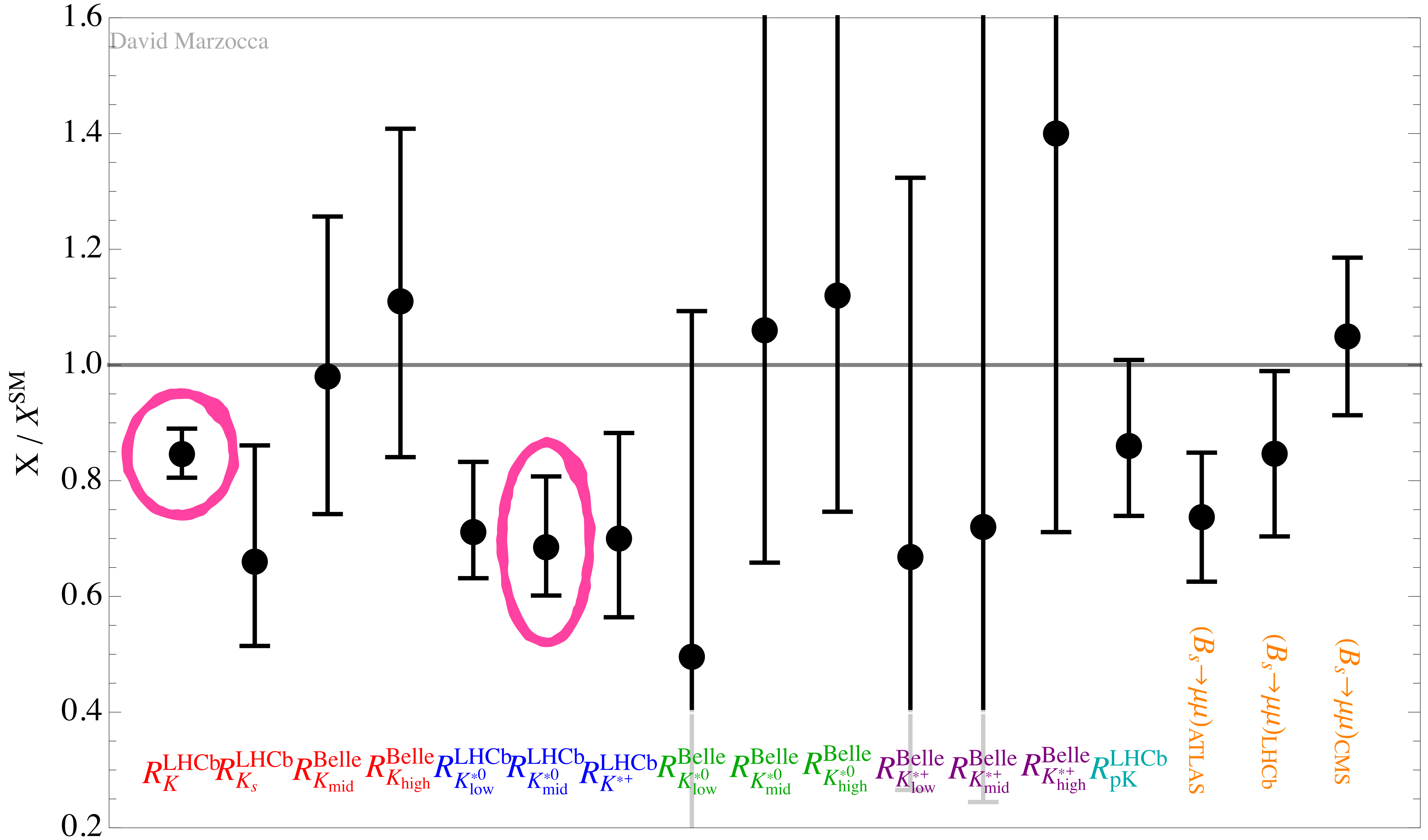


B-anomalies

$b \to s\, \mu^+ \mu^-$

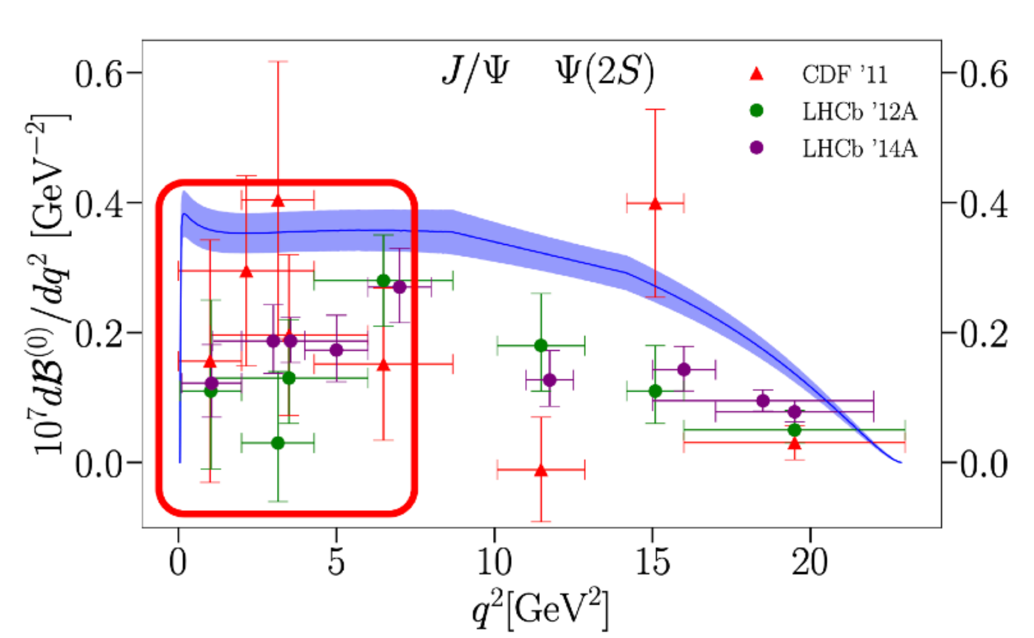
"Clean" observables

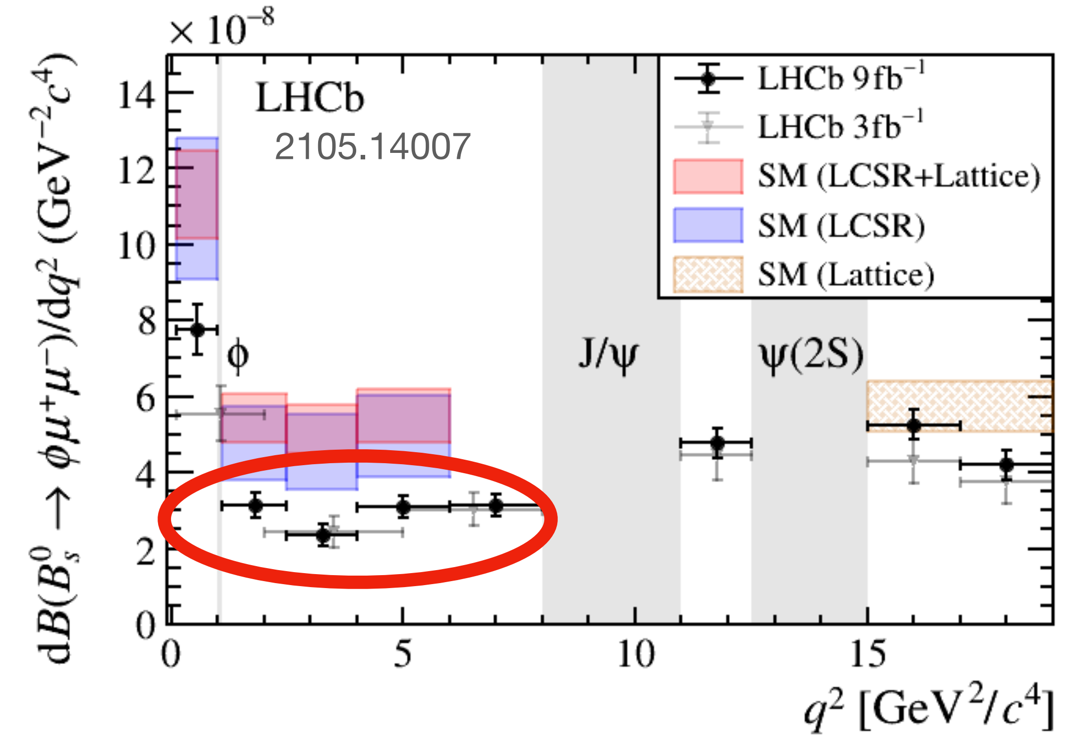
Compilation of clean observables testing the b→sμμ transition. 08/2022



Branching ratios

Lattice $B^0 \to K^0\mu^+\mu^-$ [arXiv:2207.13371]





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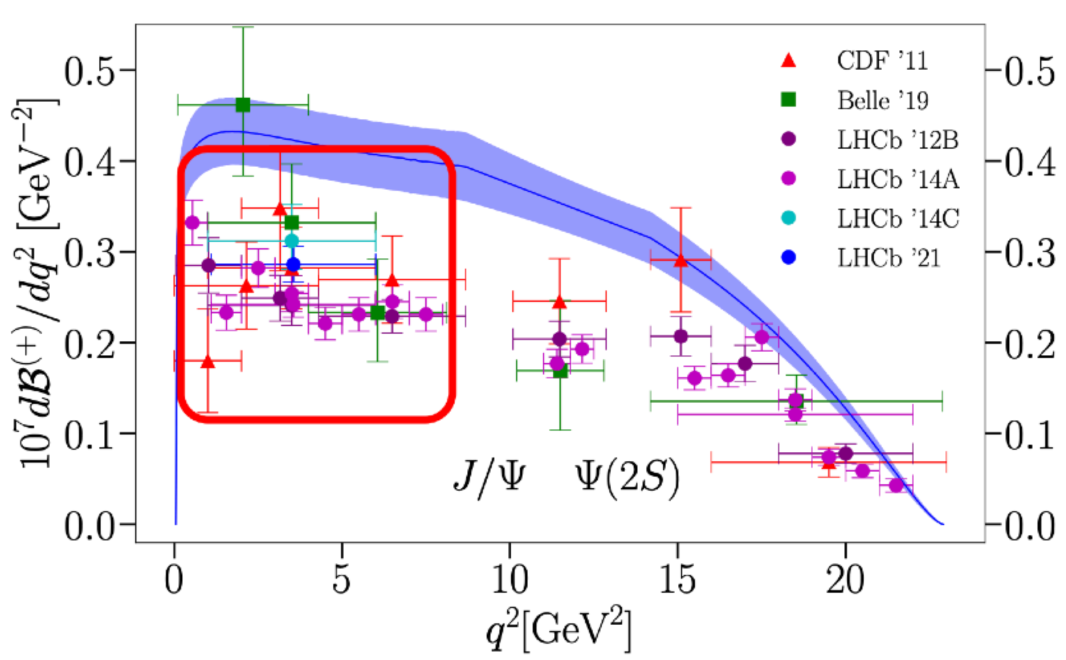
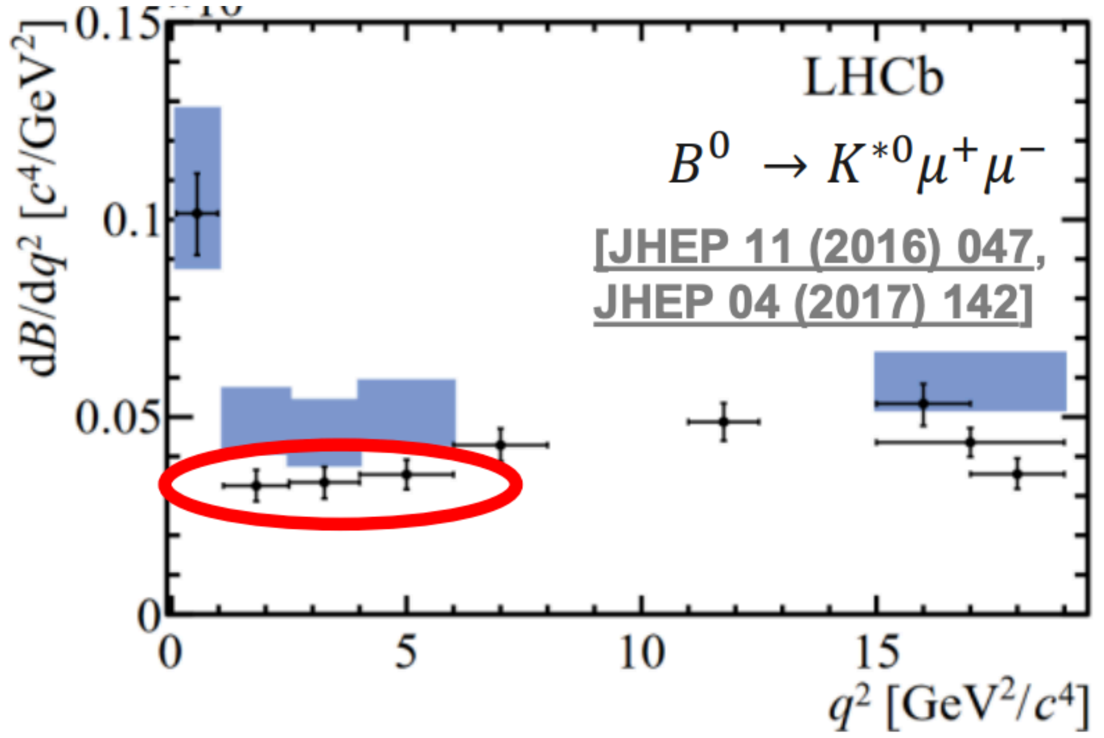
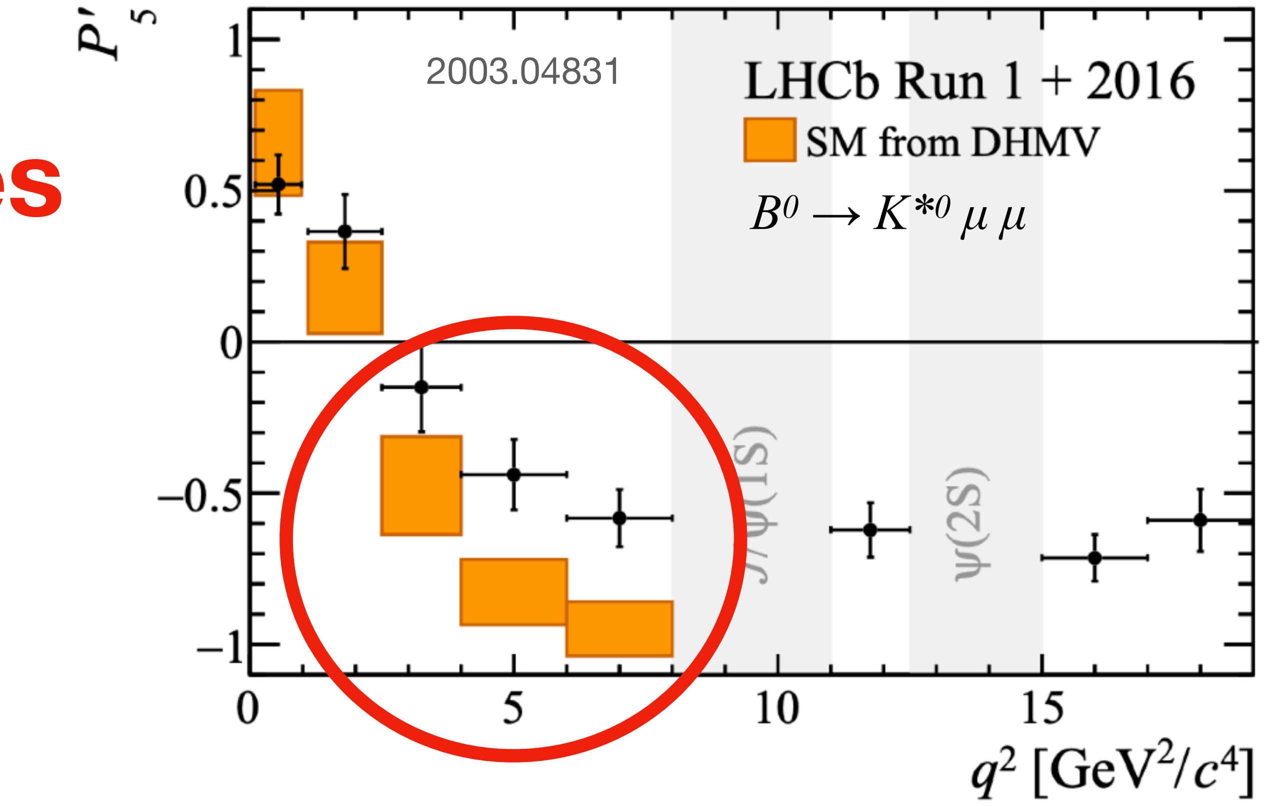




Angular observables



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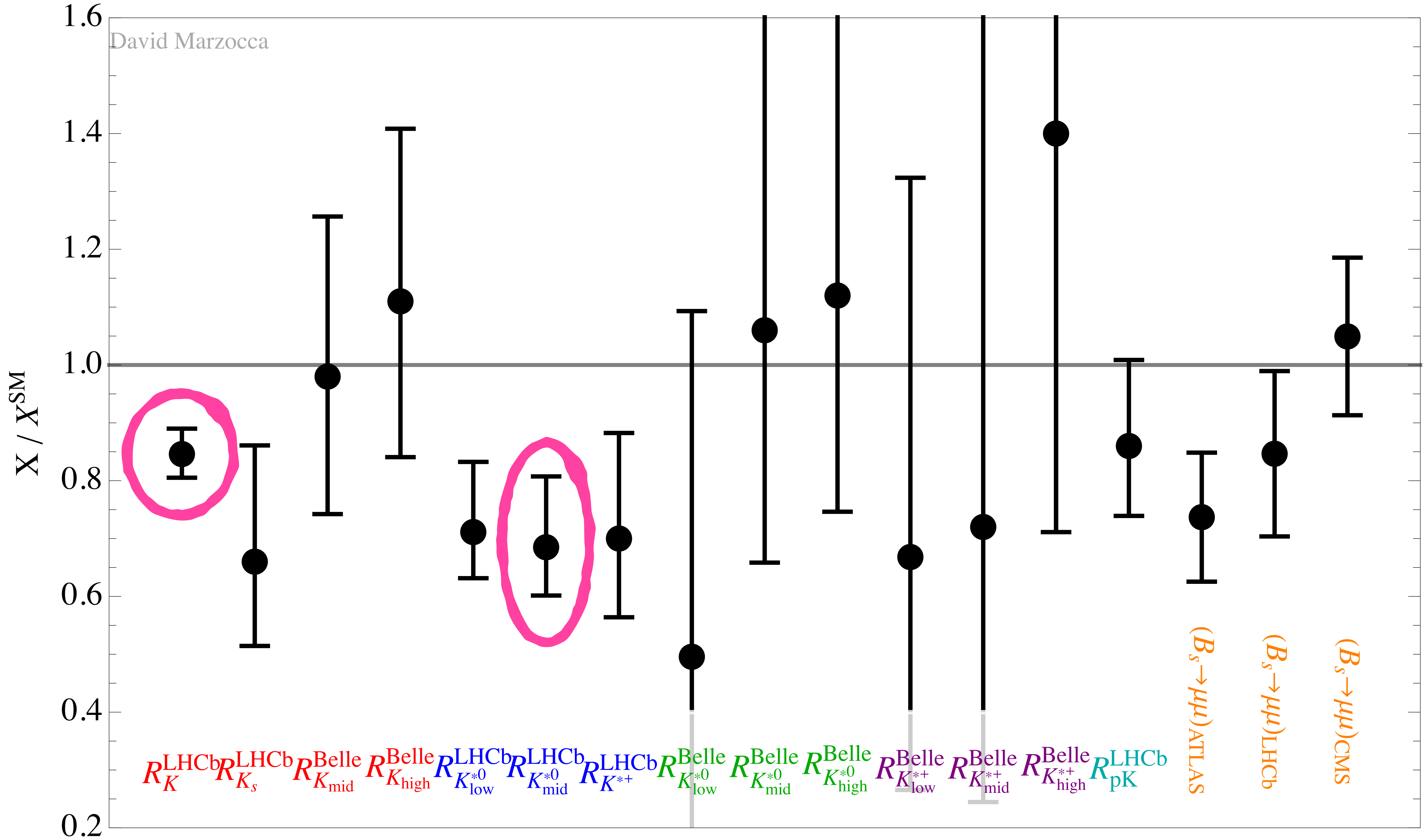

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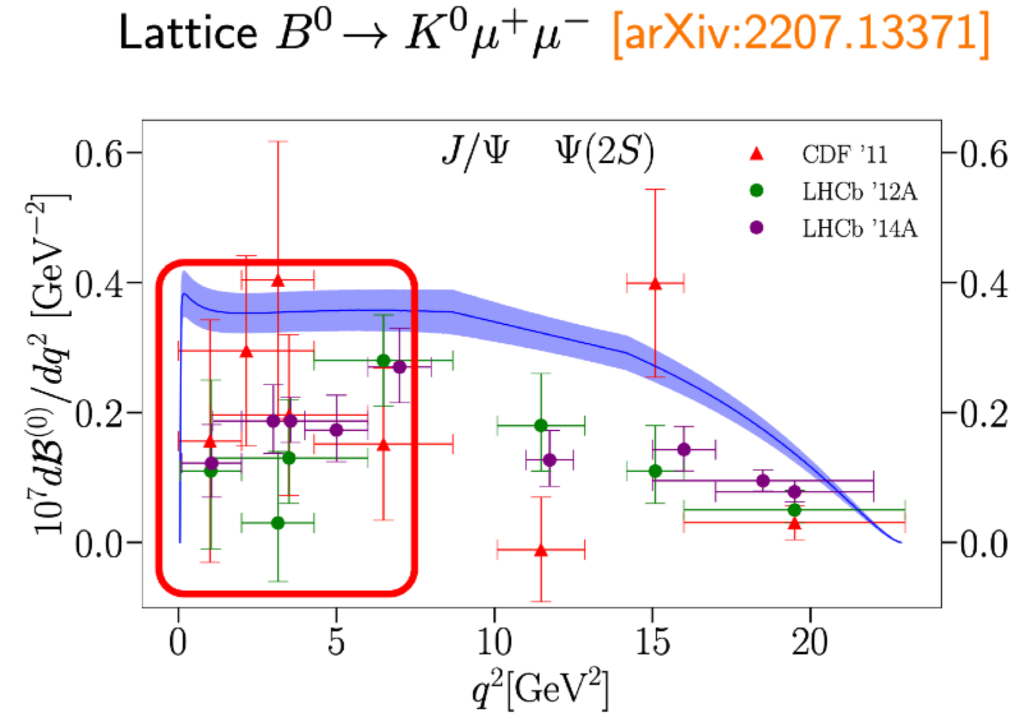

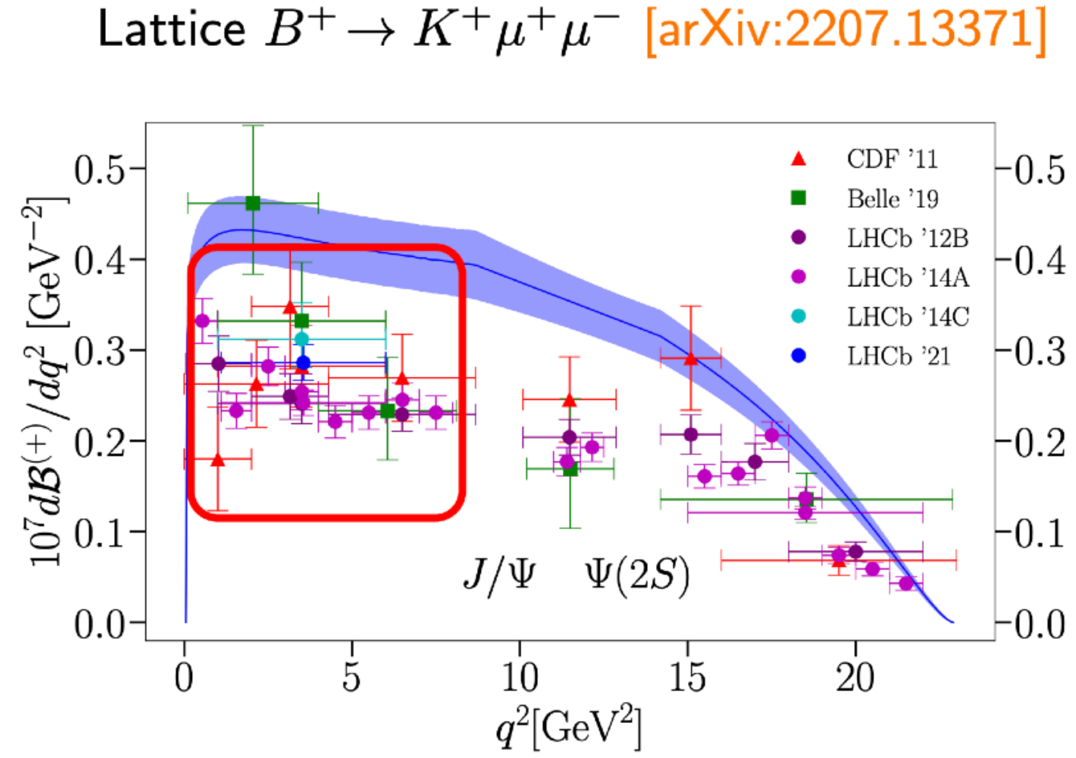

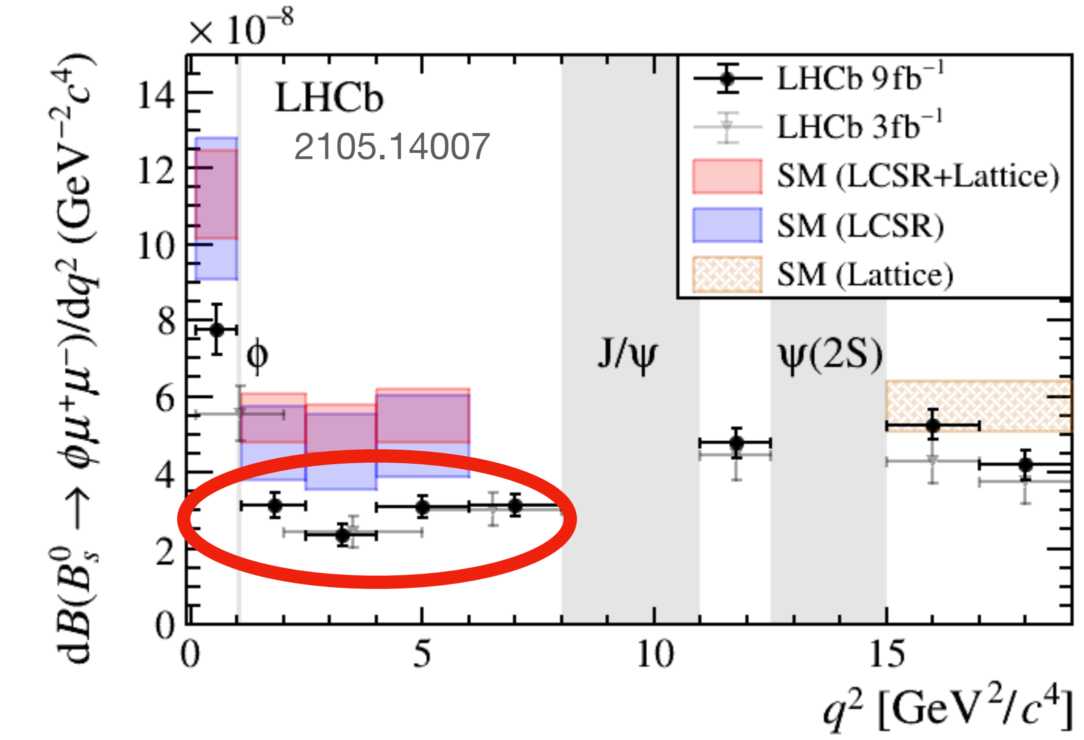

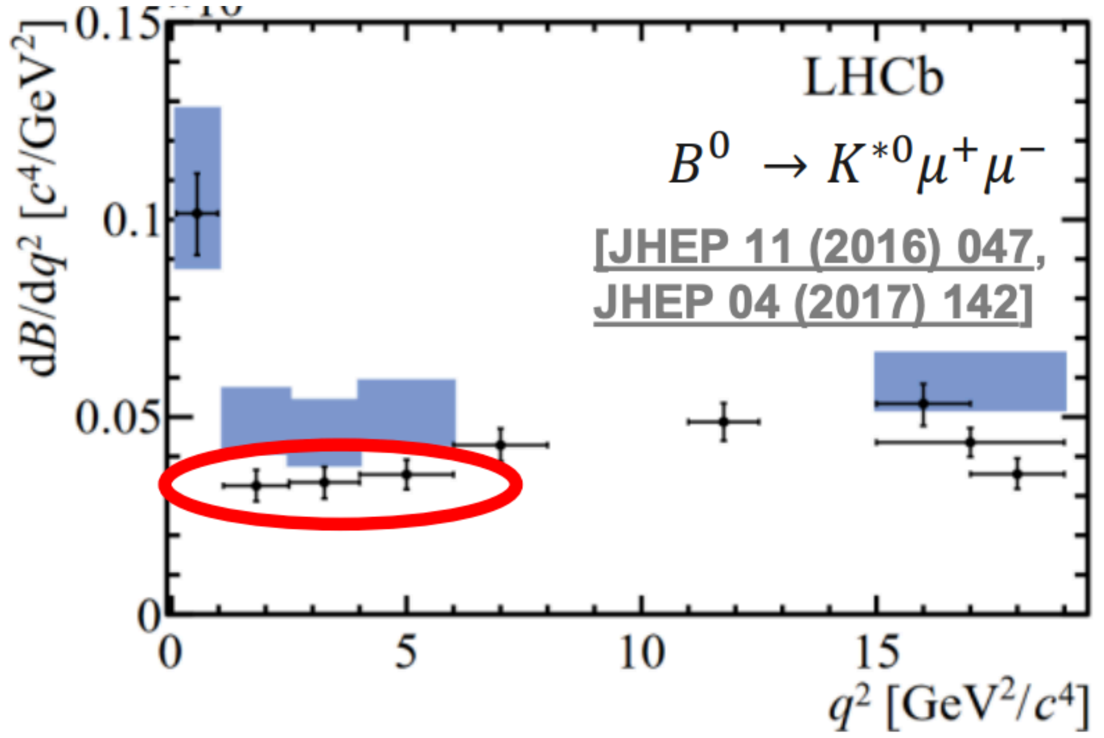

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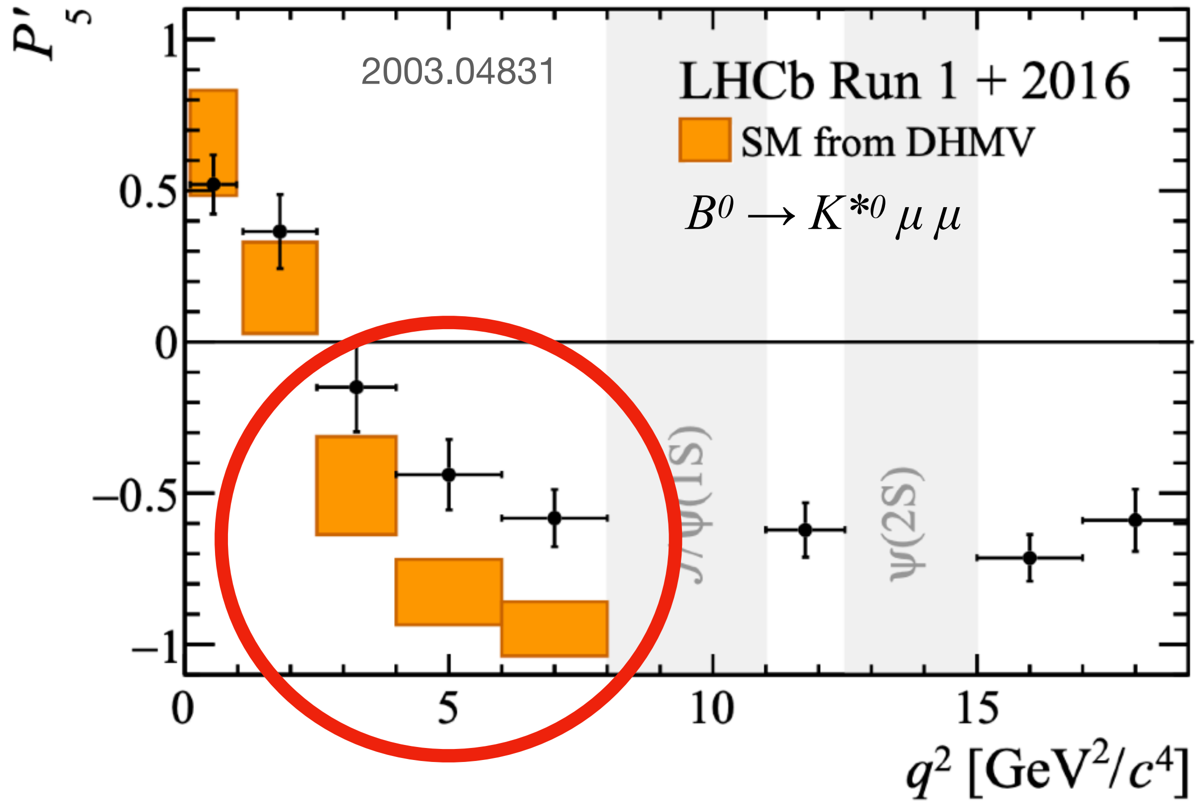

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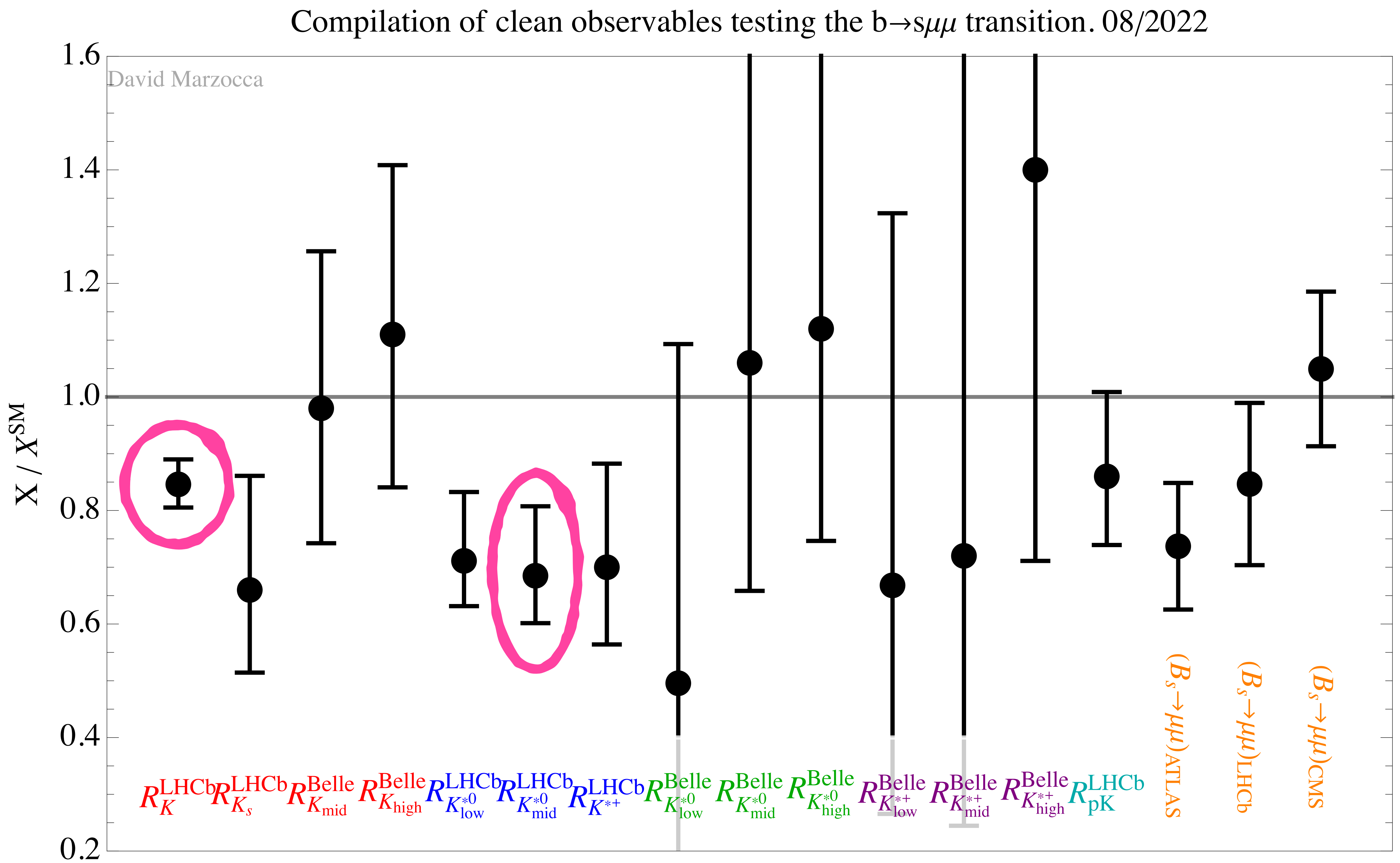

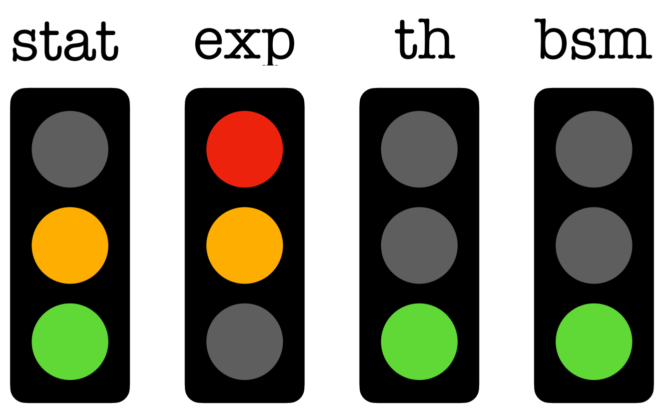

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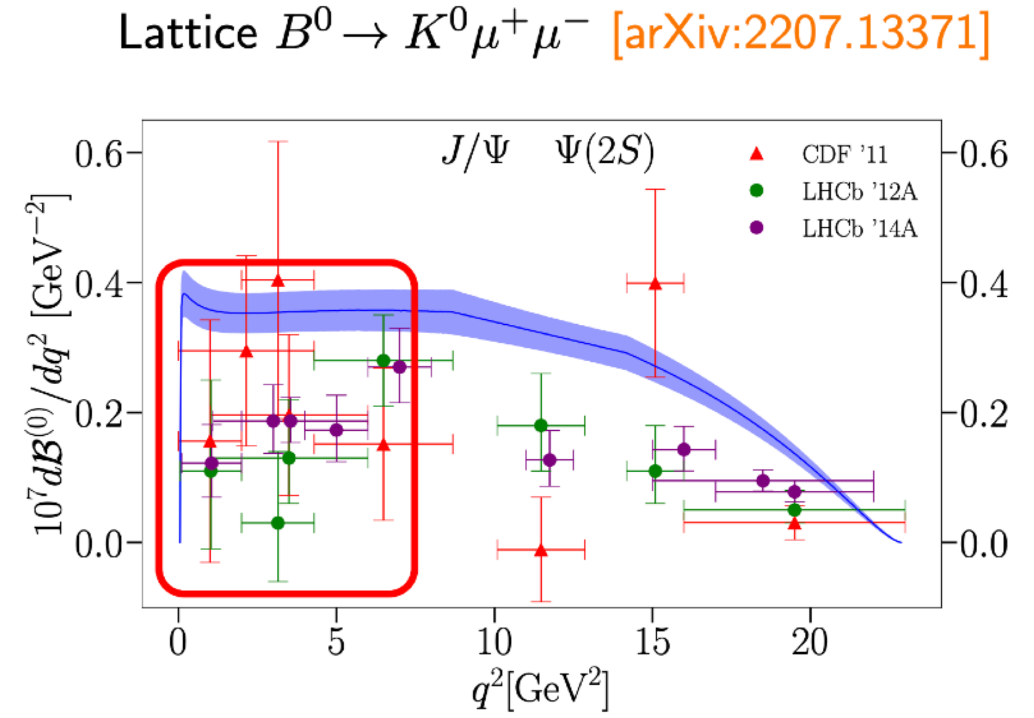
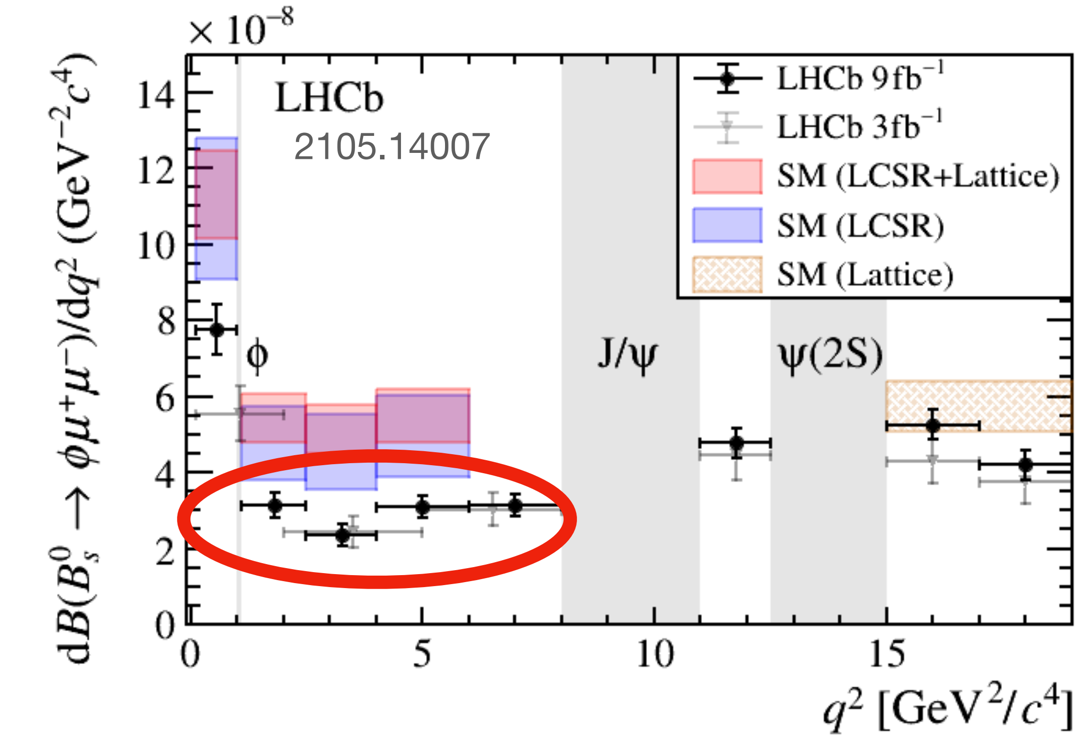
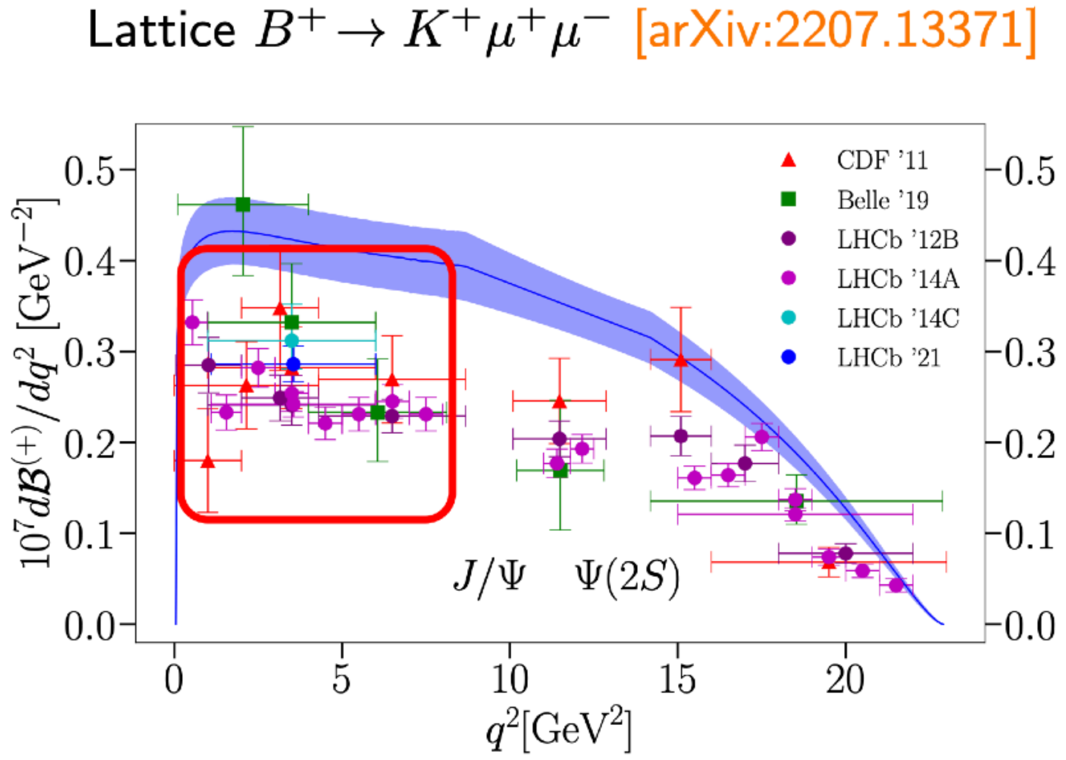
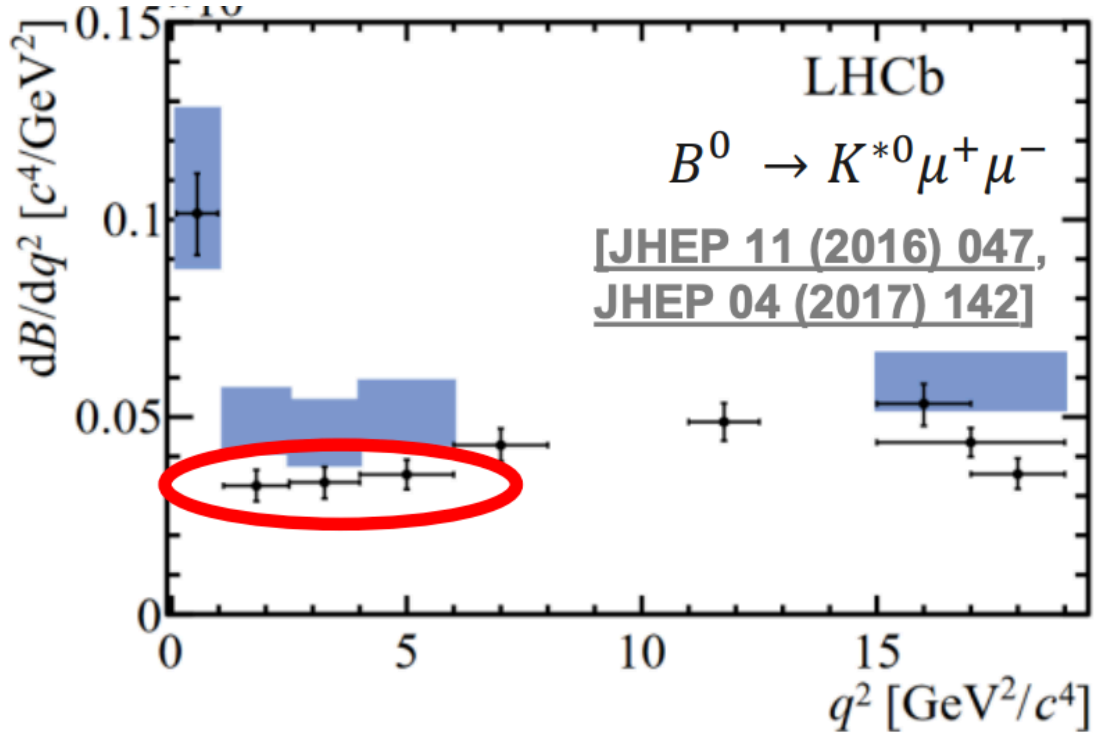
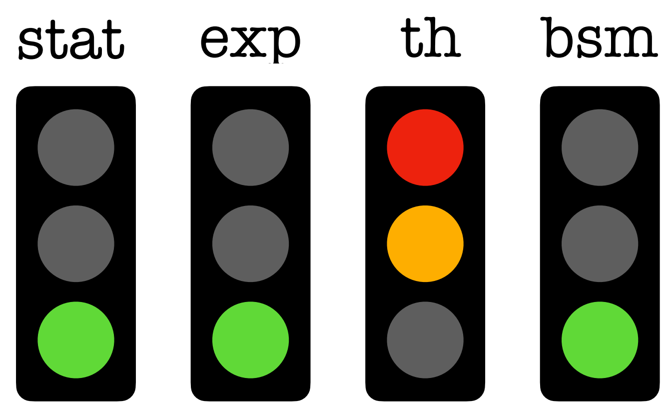


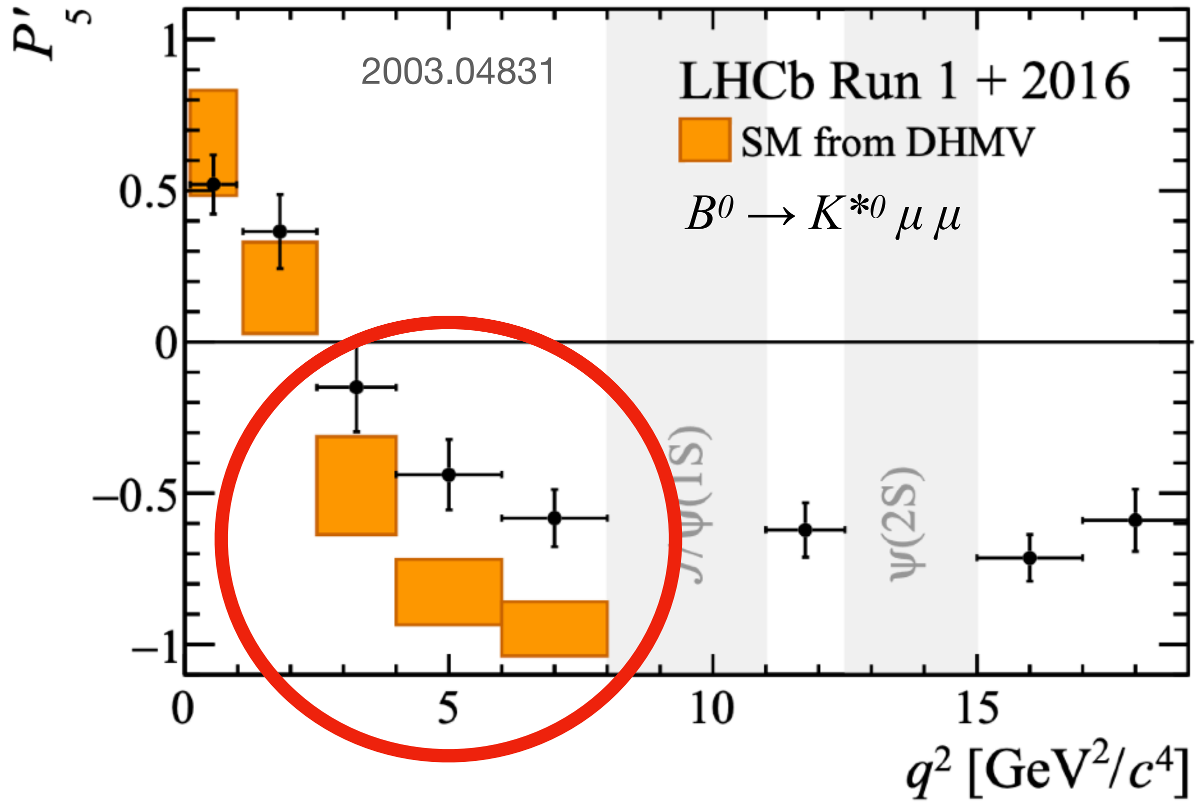






Angular observables

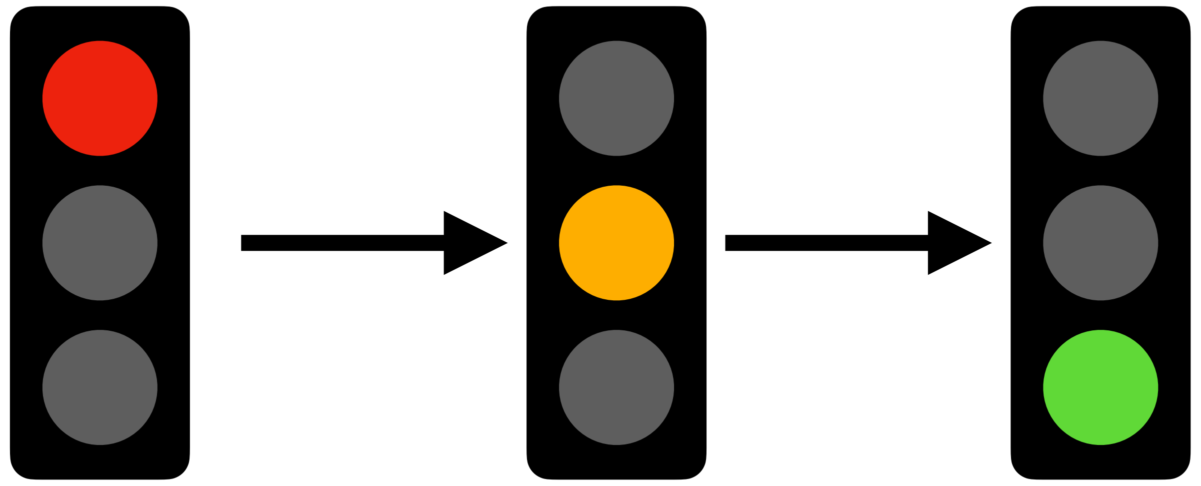




2 - Combining them

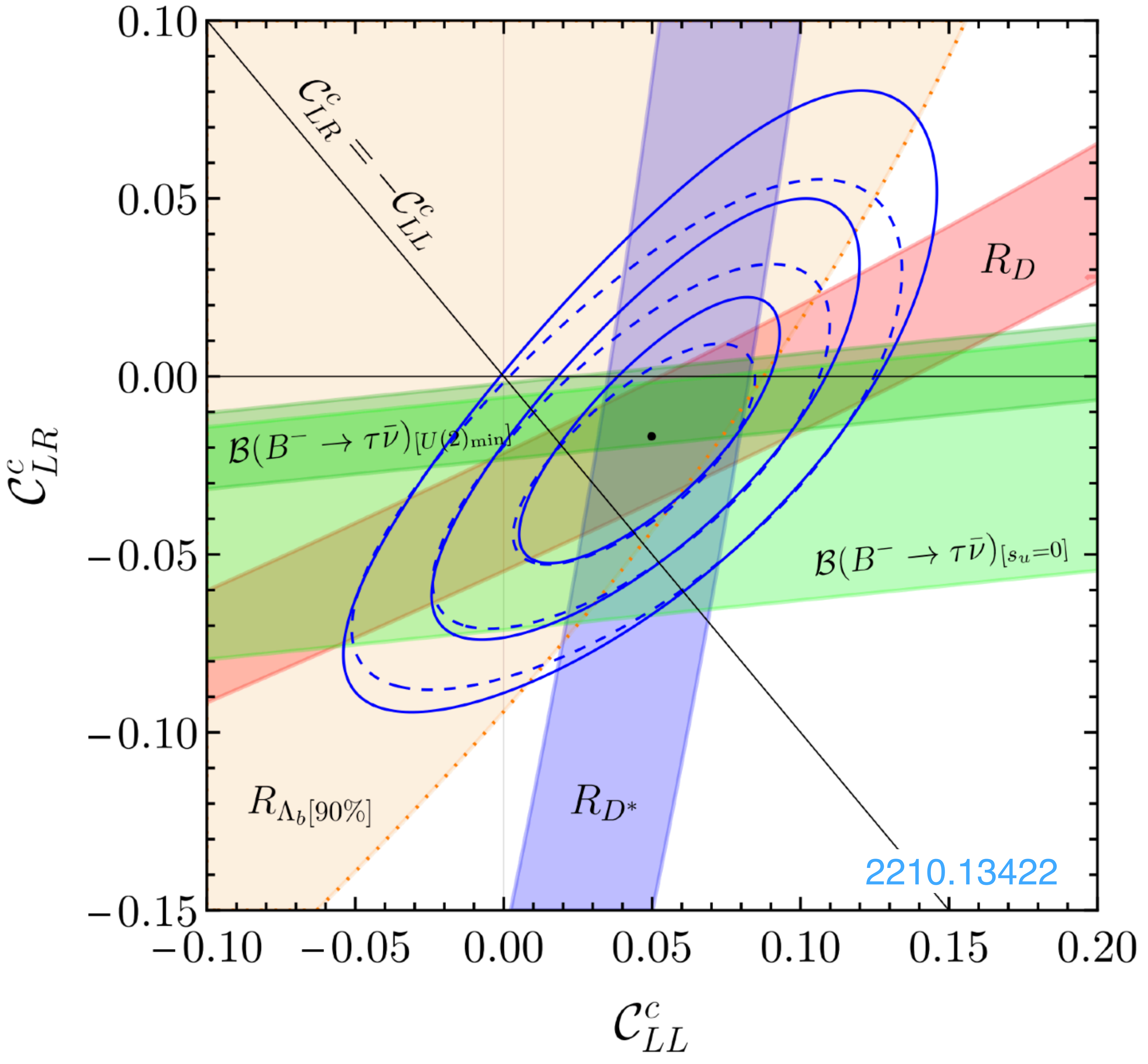
Two anomalies are better than one [cit.]

If several anomalies can be coherently explained in a single unified framework,
with interesting correlations arising among them,
they become collectively more interesting as possible NP signals.



Coherent EFT interpretation

$b \to c\, \tau\, \bar{\nu}_\tau$



$$[O^{(1)}_{\ell q}]_{\alpha\beta ij} = (\bar{\ell}^\alpha_L \gamma_\mu \ell^\beta_L)(\bar{q}^i_L \gamma^\mu q^j_L)\,,$$

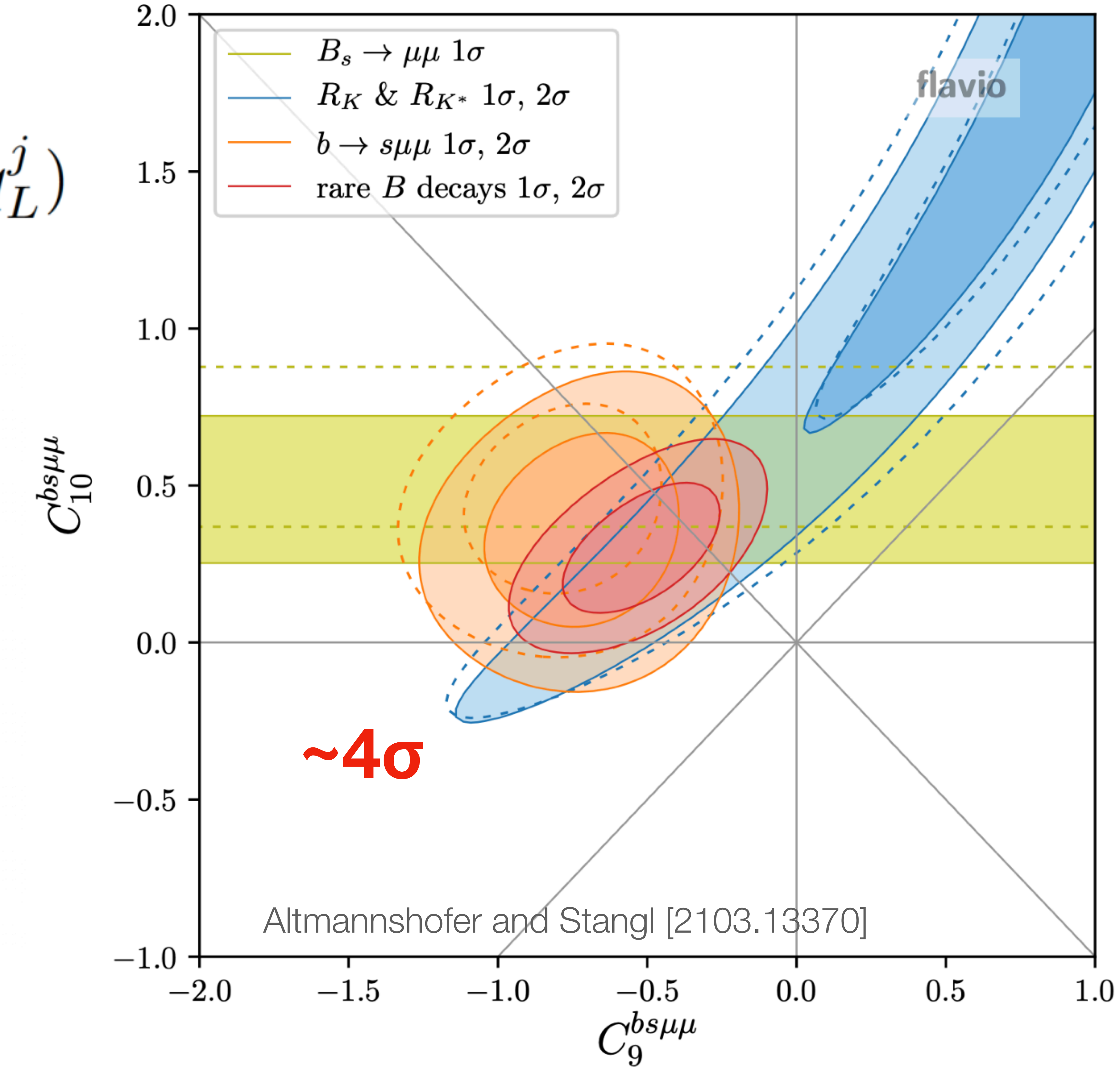
$$[O^{(3)}_{\ell q}]_{\alpha\beta ij} = (\bar{\ell}^\alpha_L \sigma^I \gamma_\mu \ell^\beta_L)(\bar{q}^i_L \sigma^I \gamma^\mu q^j_L)$$

$3_q \to 2_q\, 3_\ell\, 3_\ell \qquad 3_q \to 2_q\, 2_\ell\, 2_\ell$

$$\sim \frac{1}{(4\,\text{TeV})^2} \gg \sim \frac{1}{(40\,\text{TeV})^2}$$

$$\sim c_q \frac{V_{cb}(\lambda_\tau)^2}{\Lambda^2} \qquad \sim c_\mu \frac{V_{ts}(\lambda_\mu)^2}{\Lambda^2}$$

$b \to s\, \mu^+ \mu^-$



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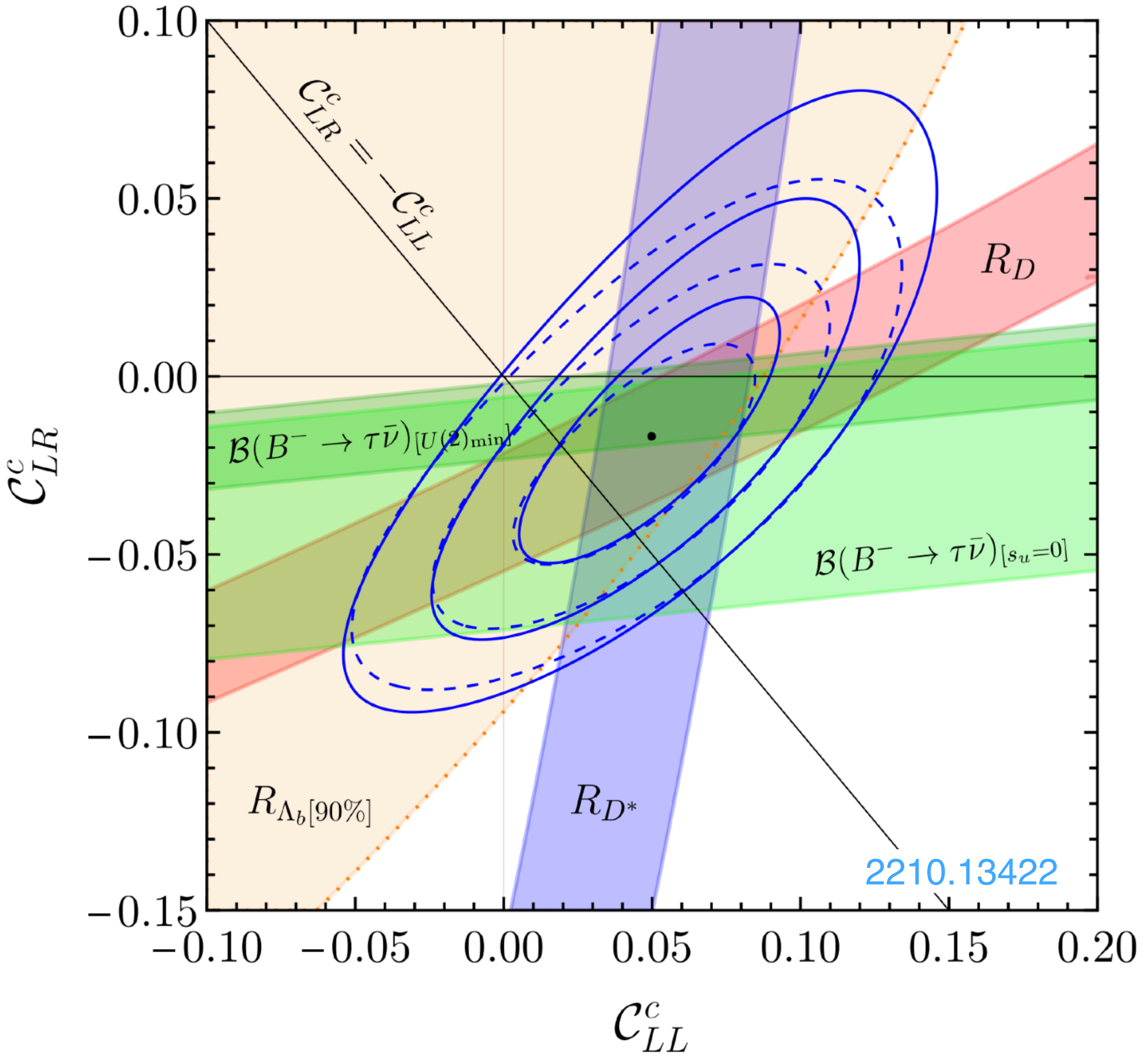

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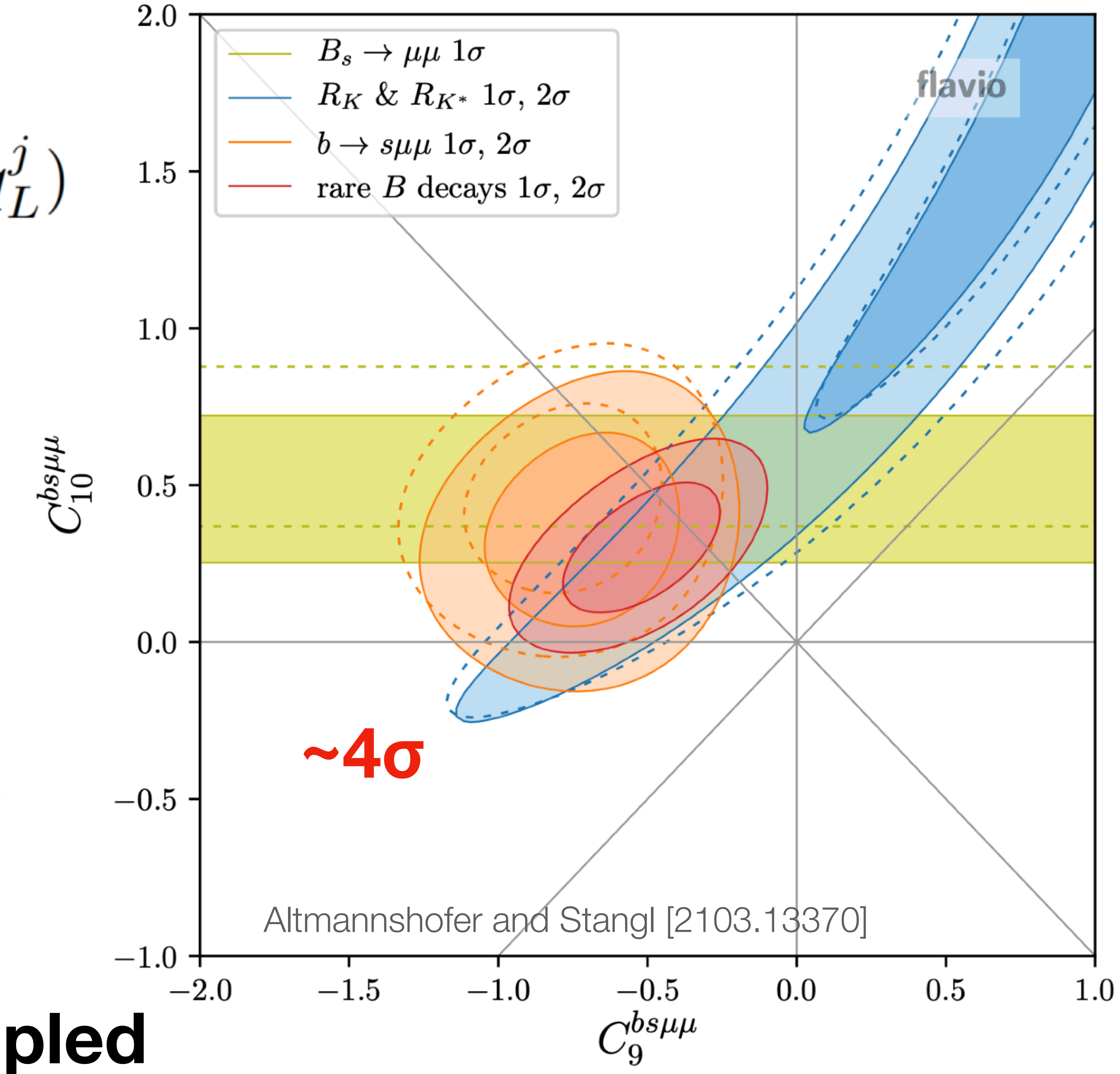
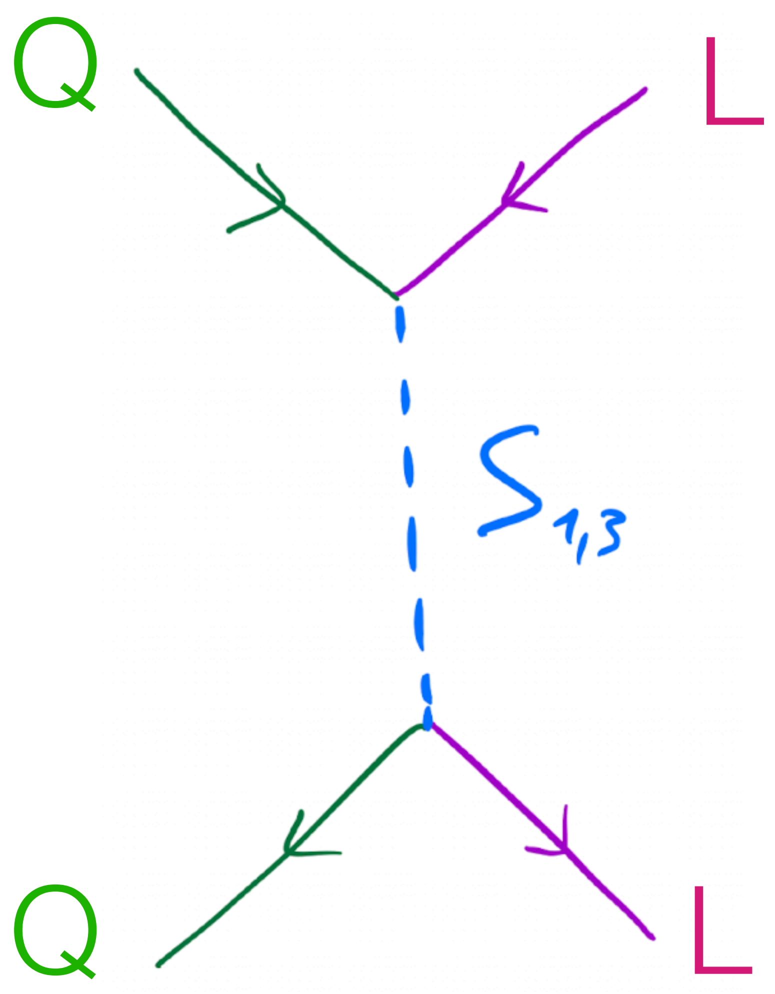


$$\Rightarrow \begin{cases} \lambda_\tau = 1, \quad \lambda_\mu \sim 0.1 \iff \dfrac{\lambda_\mu}{\lambda_\tau} \sim \dfrac{m_\mu}{m_\tau} \\ \Lambda \sim 1\,\mathrm{TeV} \\ c_{\mu,\tau} \gtrsim \mathcal{O}(1) \end{cases}$$

New Physics mainly coupled to the 3rd generation.

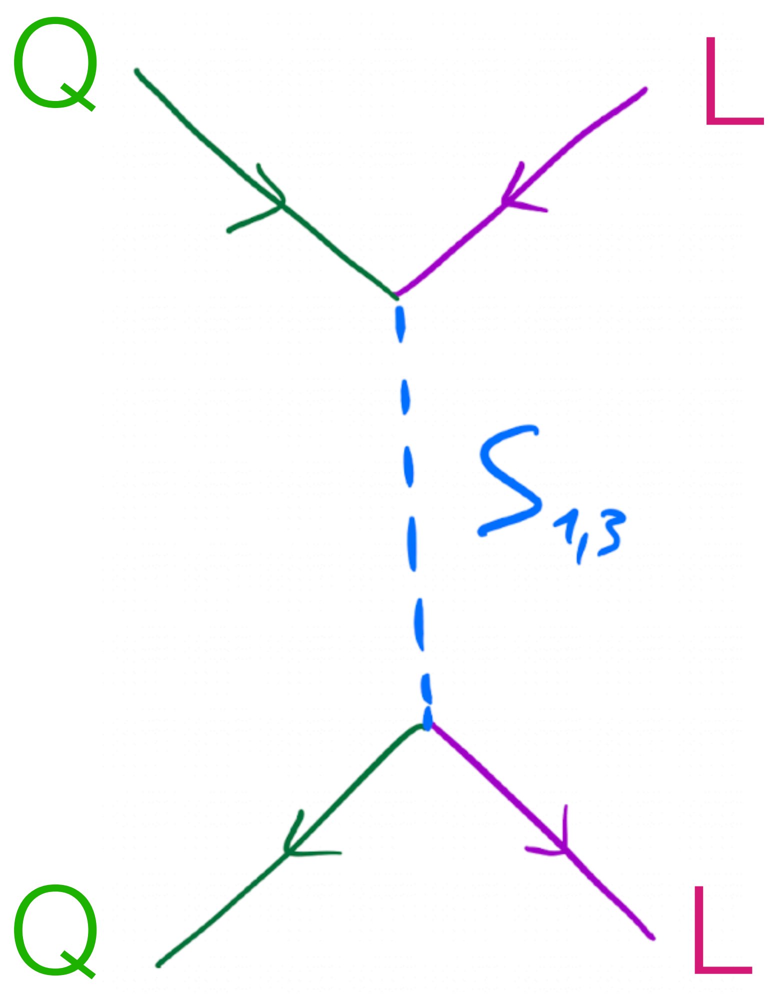
R(D$^{(*)}$) anomalies drive most new physics requirements

Leptoquarks and B-anomalies



LQ induce semileptonic @ tree level,
4-quark & 4-lepton only at loop level.

Leptoquarks and B-anomalies



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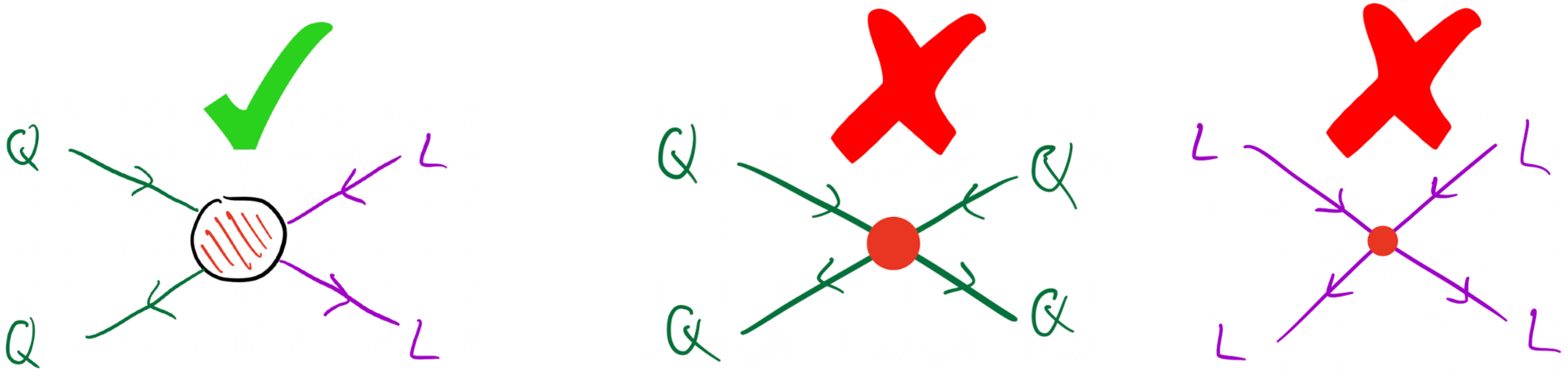
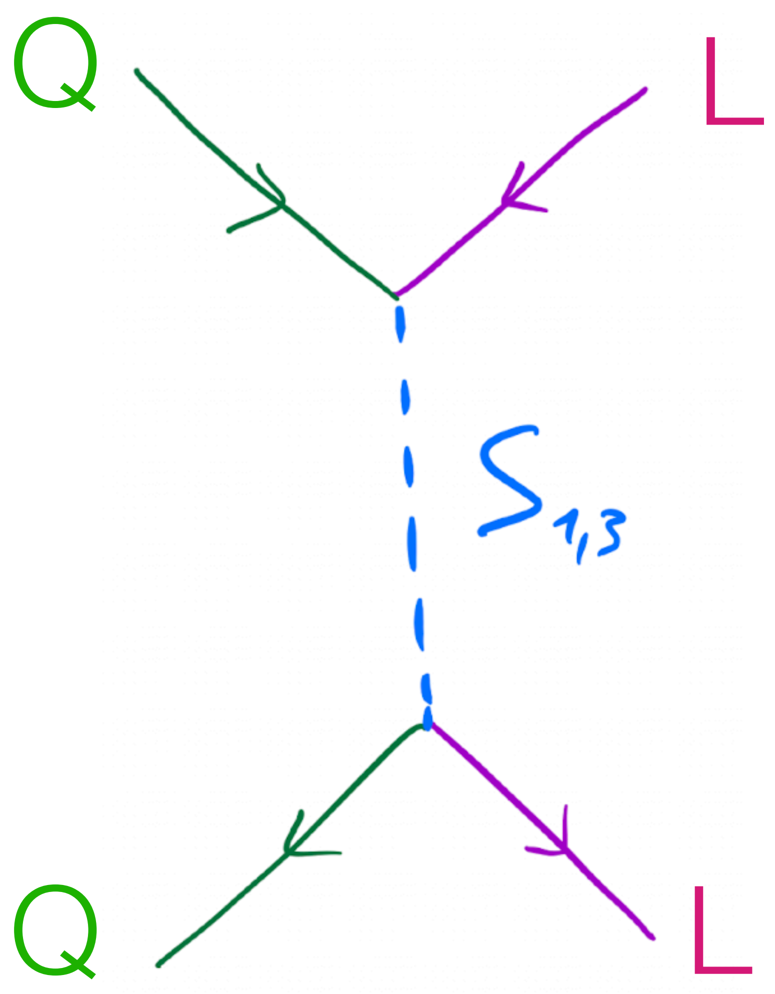
Deviations in **semileptonic** processes,
strong bounds from $\Delta F=2$ & CLFV processes.



Leptoquarks and B-anomalies



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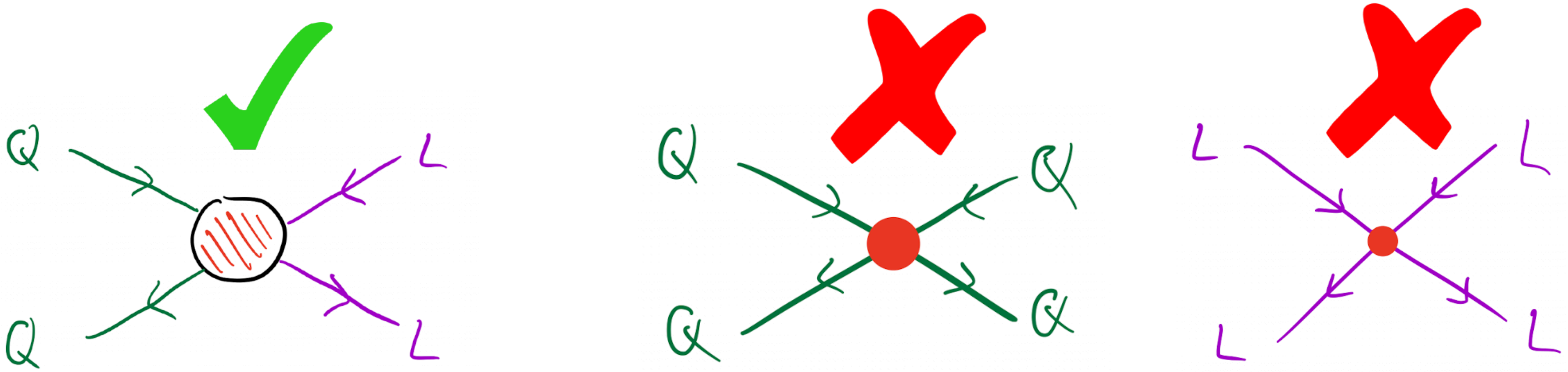
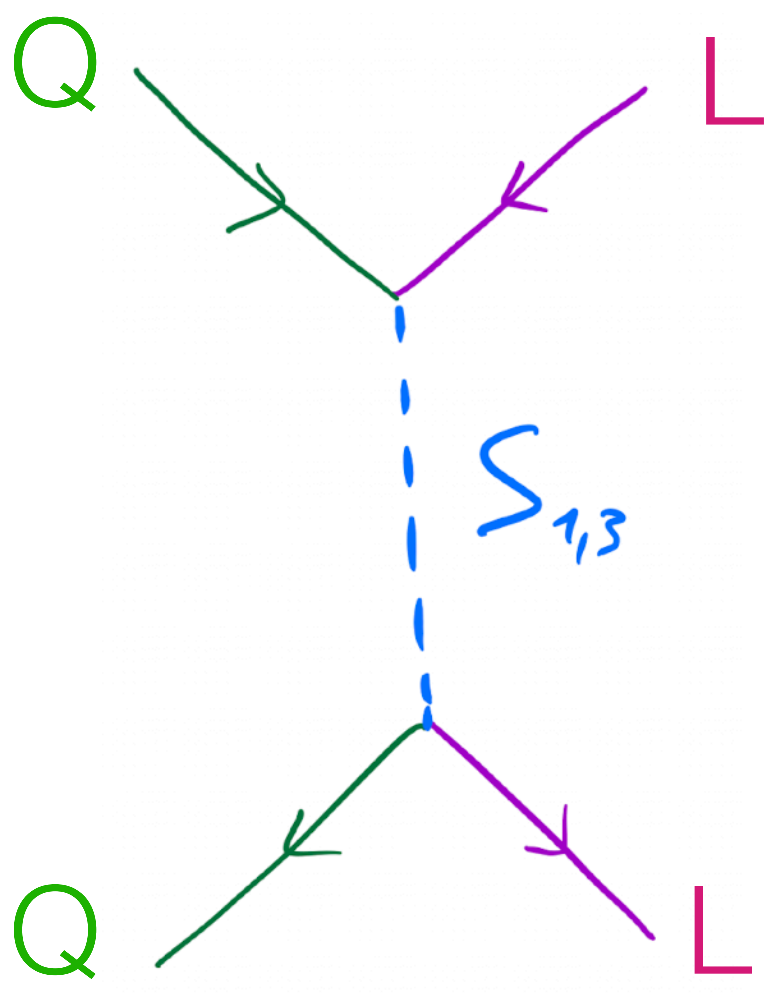


>> Very strong bounds on LQ couplings to 1st generation fermions, e.g. $K_L \to \mu e$, etc..

Leptoquarks and B-anomalies



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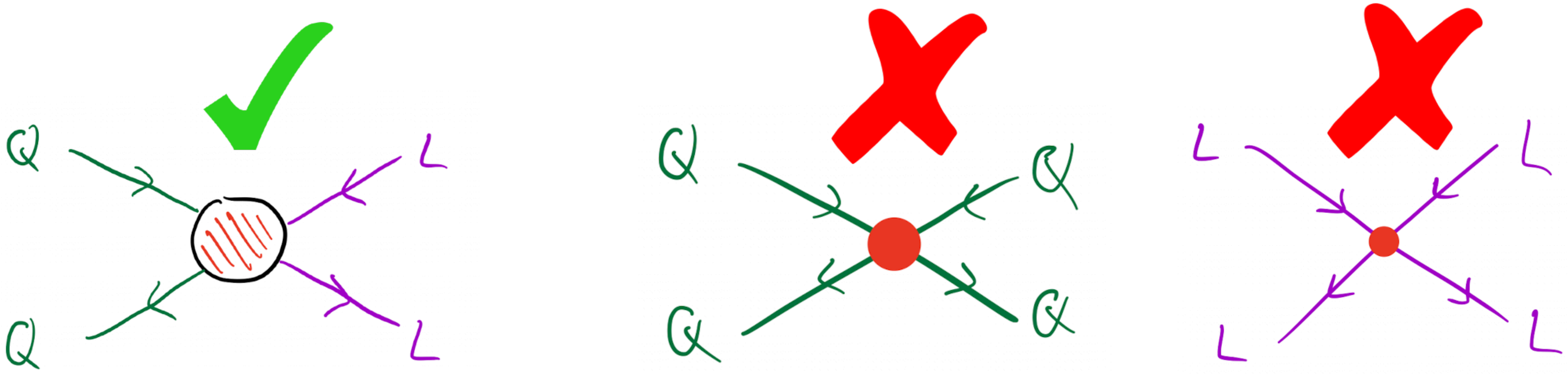
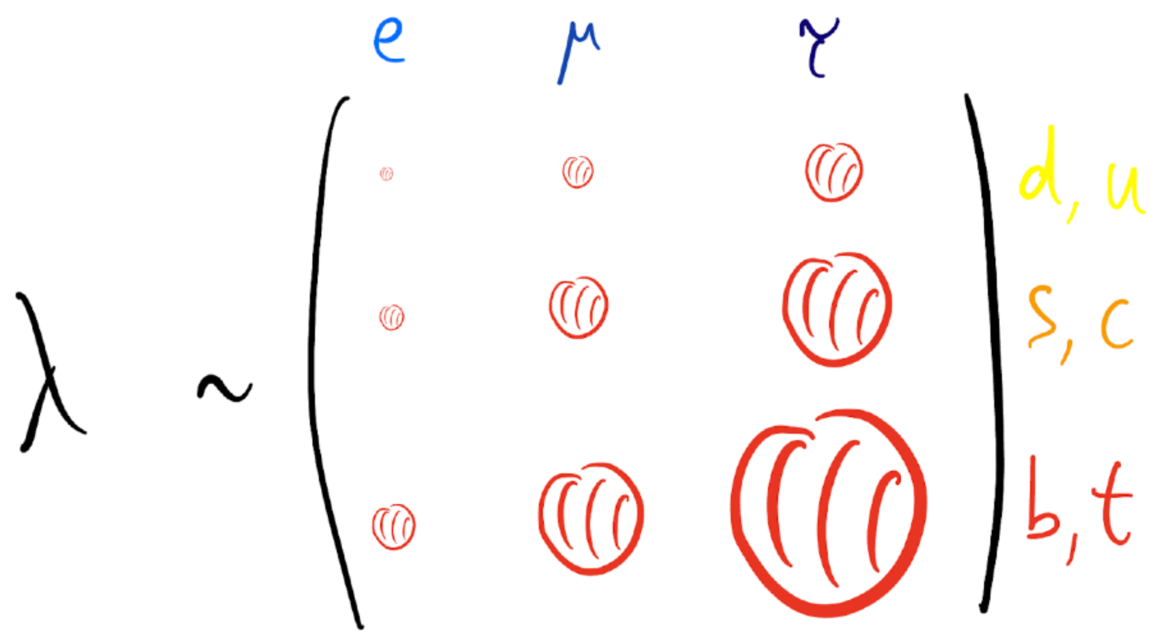


>> Very strong bounds on LQ couplings to 1st generation fermions, e.g. $K_L \to \mu\, e$, etc..

To address both B-anomalies:

TeV-scale leptoquark coupled to **3rd** and **2nd** generation

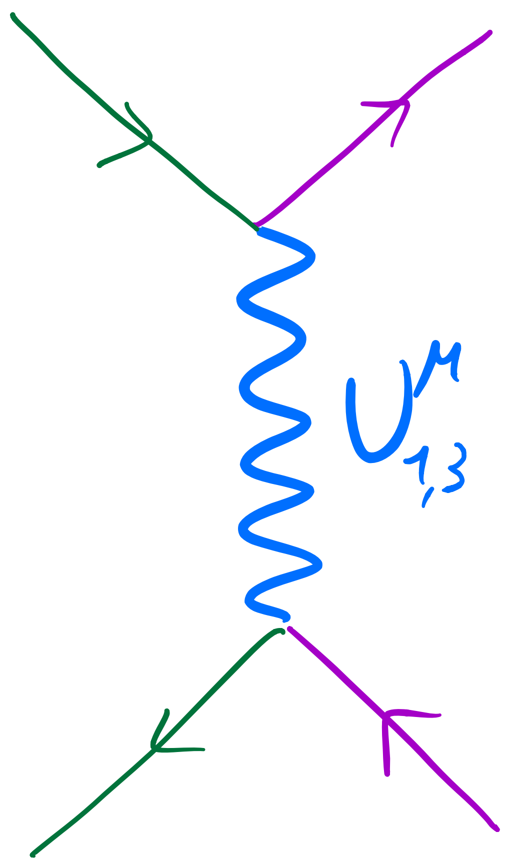
$$g(3rd) > g(2nd) > g(1st)$$



Leptoquarks and B-anomalies

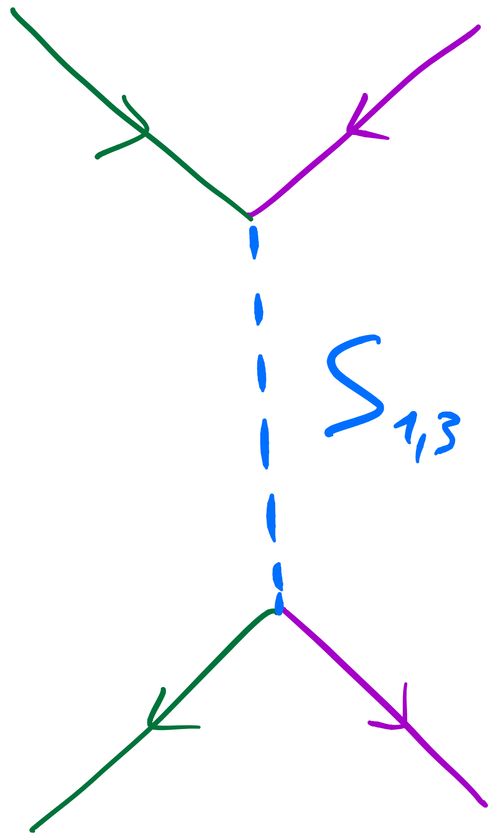
Vector Leptoquark

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



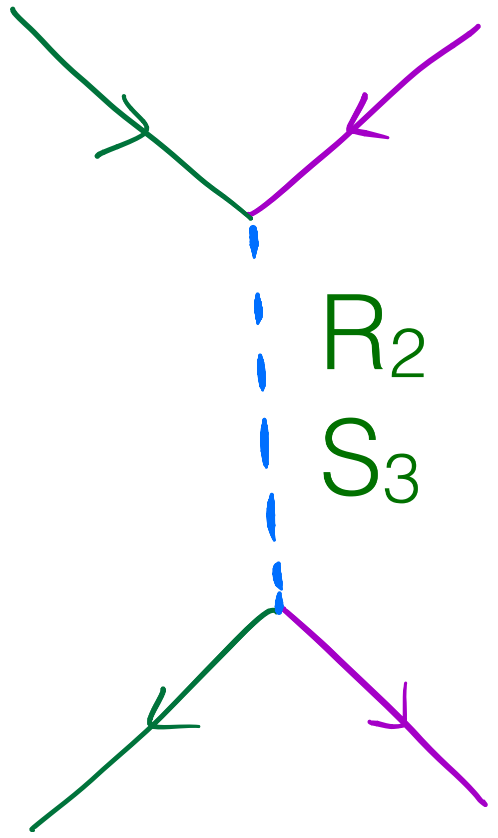
Scalar Leptoquarks

$S_1 = (\bar{\mathbf{3}}, \mathbf{1}, 1/3)$,
$S_3 = (\bar{\mathbf{3}}, \mathbf{3}, 1/3)$,



Scalar Leptoquarks

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



Leptoquarks and B-anomalies

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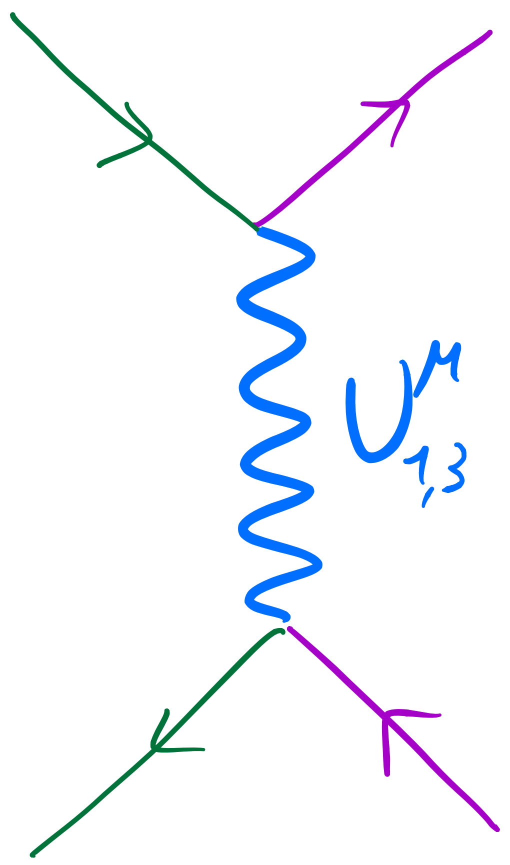

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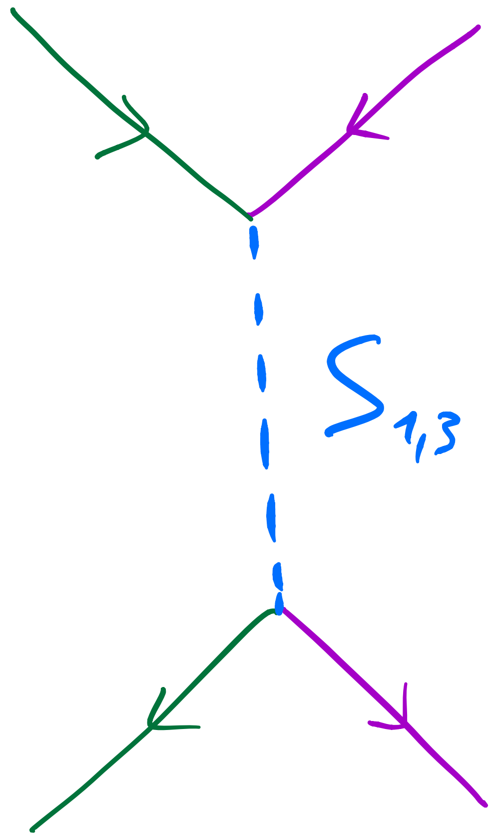

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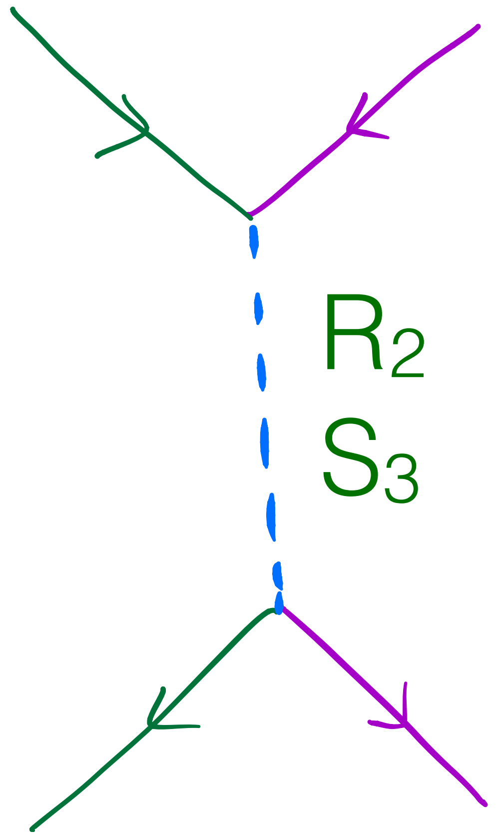
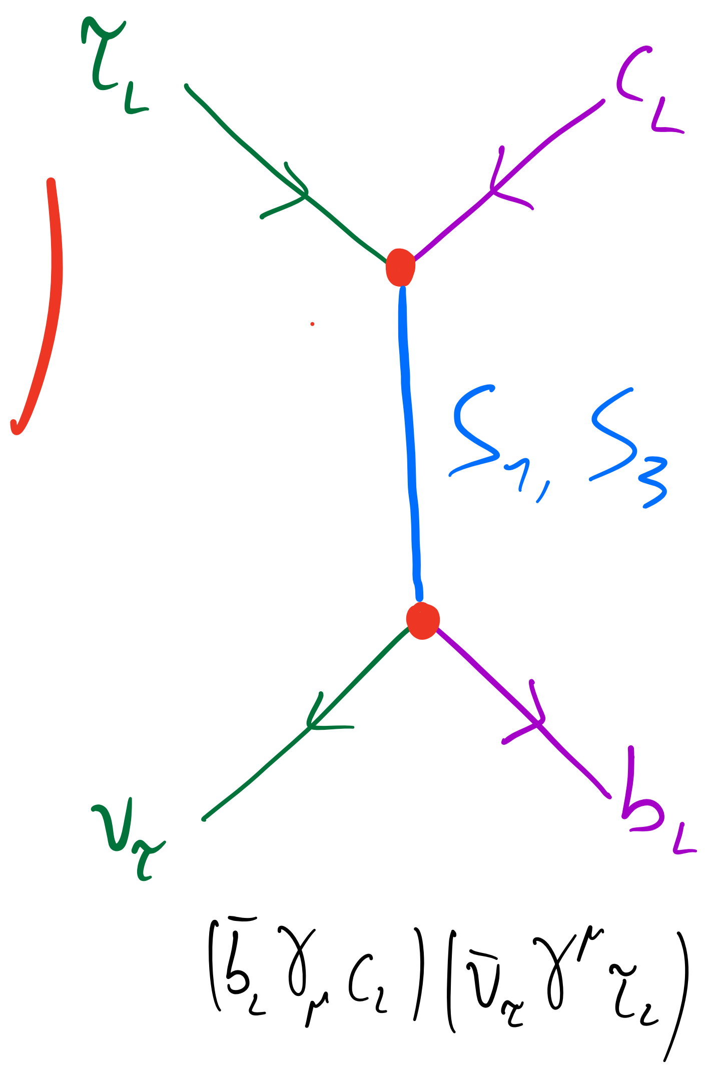


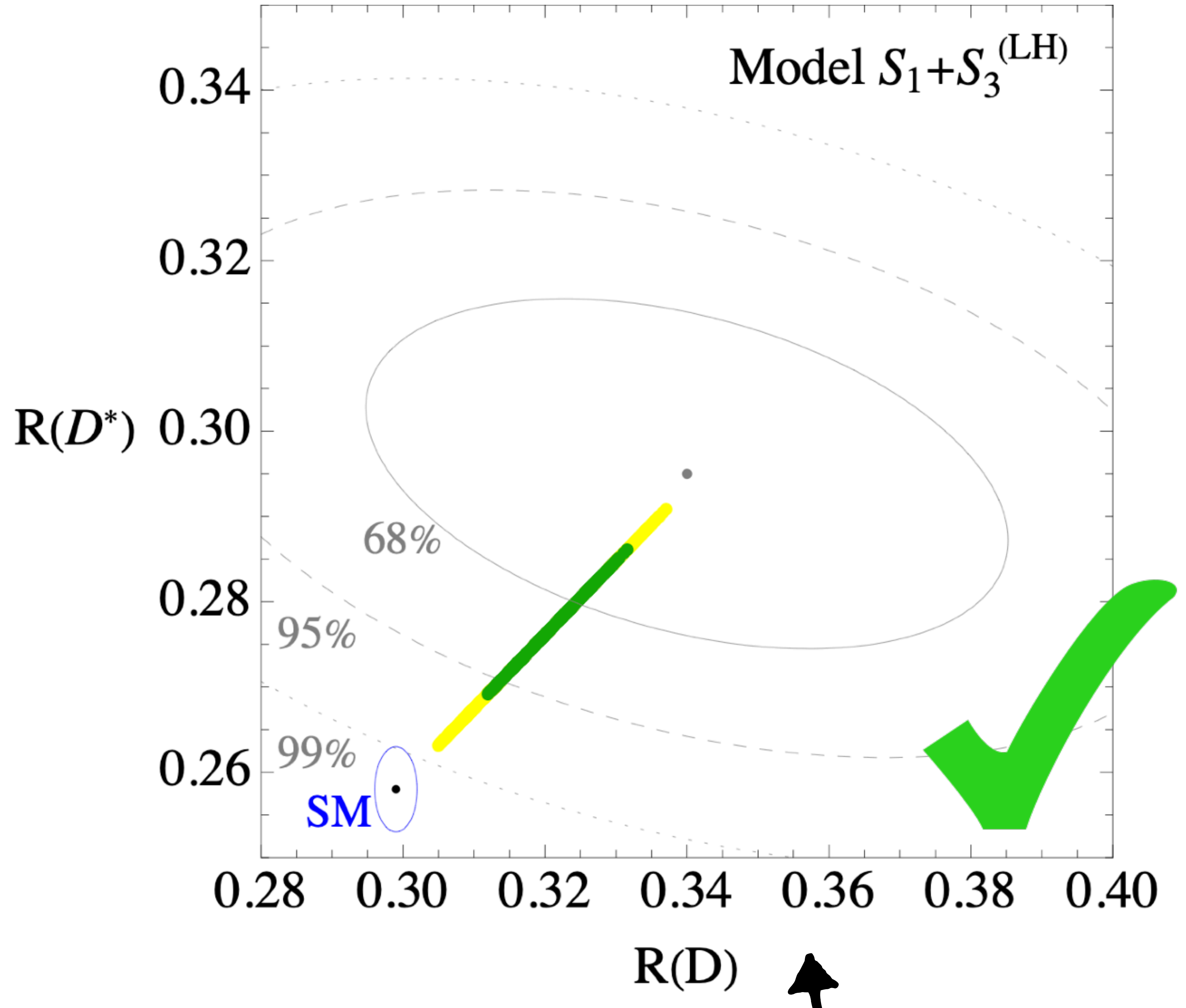
TeV-scale leptoquark coupled to **3rd** and **2nd** generation

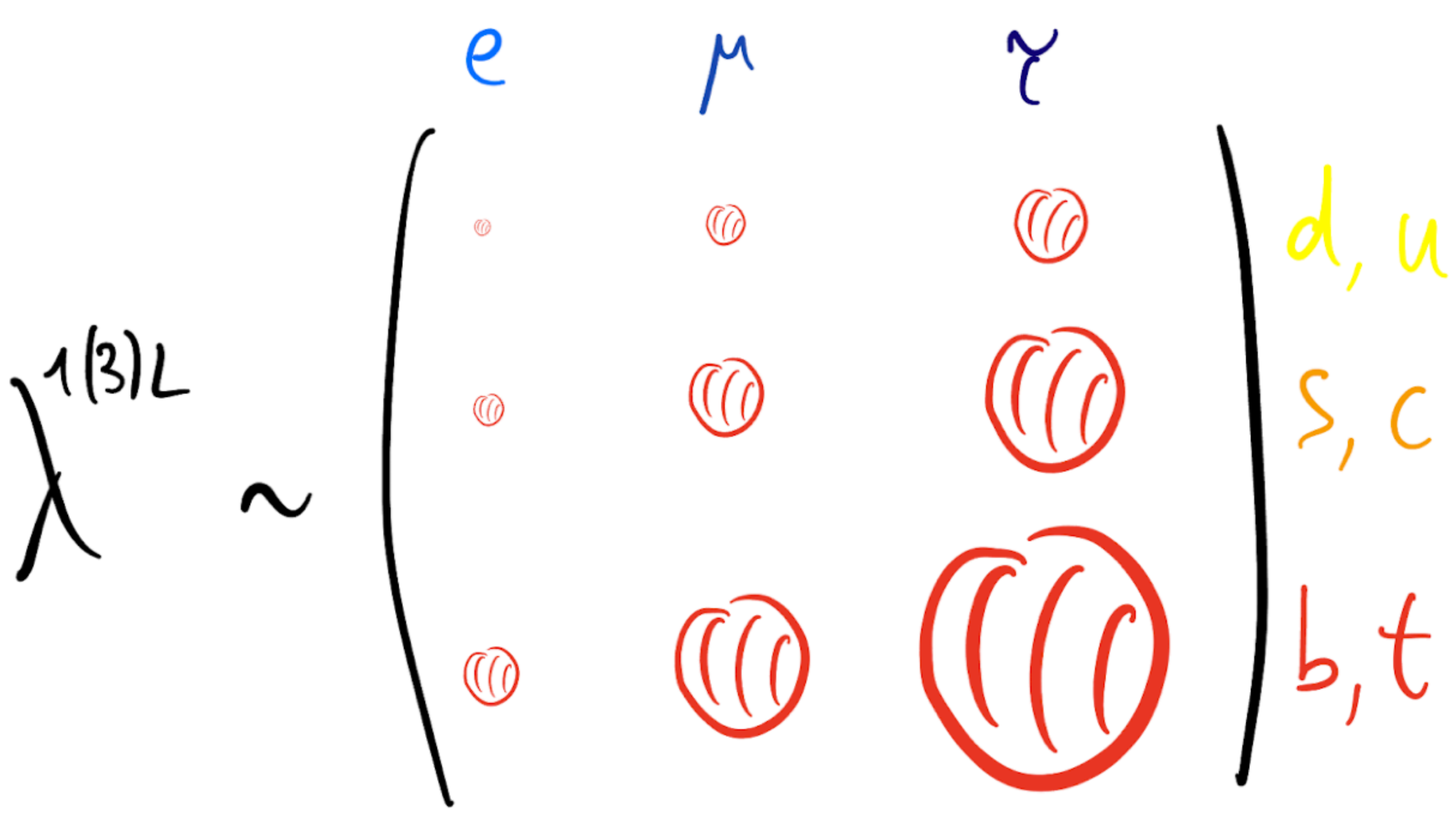
g(3rd) > g(2nd) > g(1st)

S_1 and S_3 - contributions to anomalies

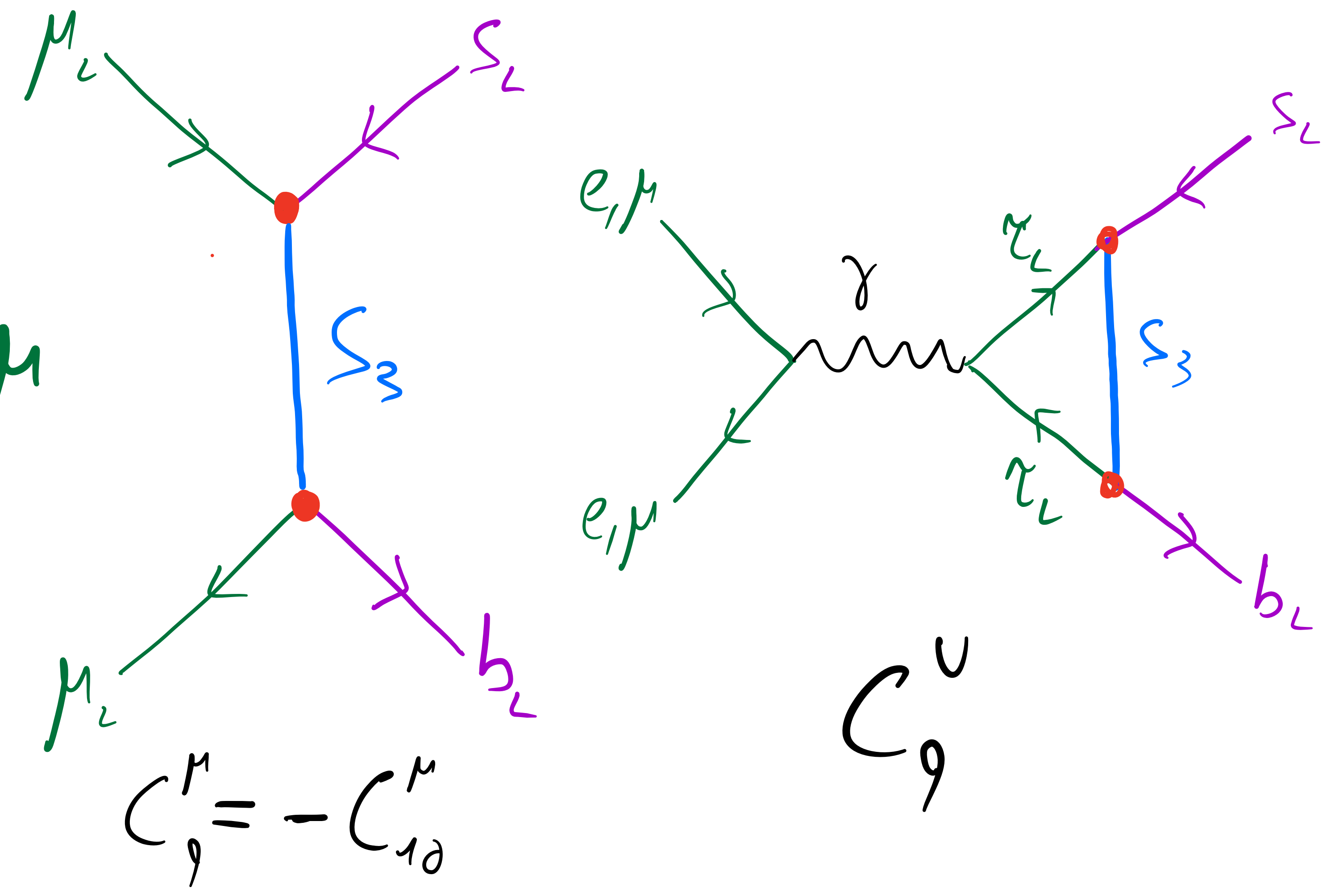
$R(D^{(*)})$



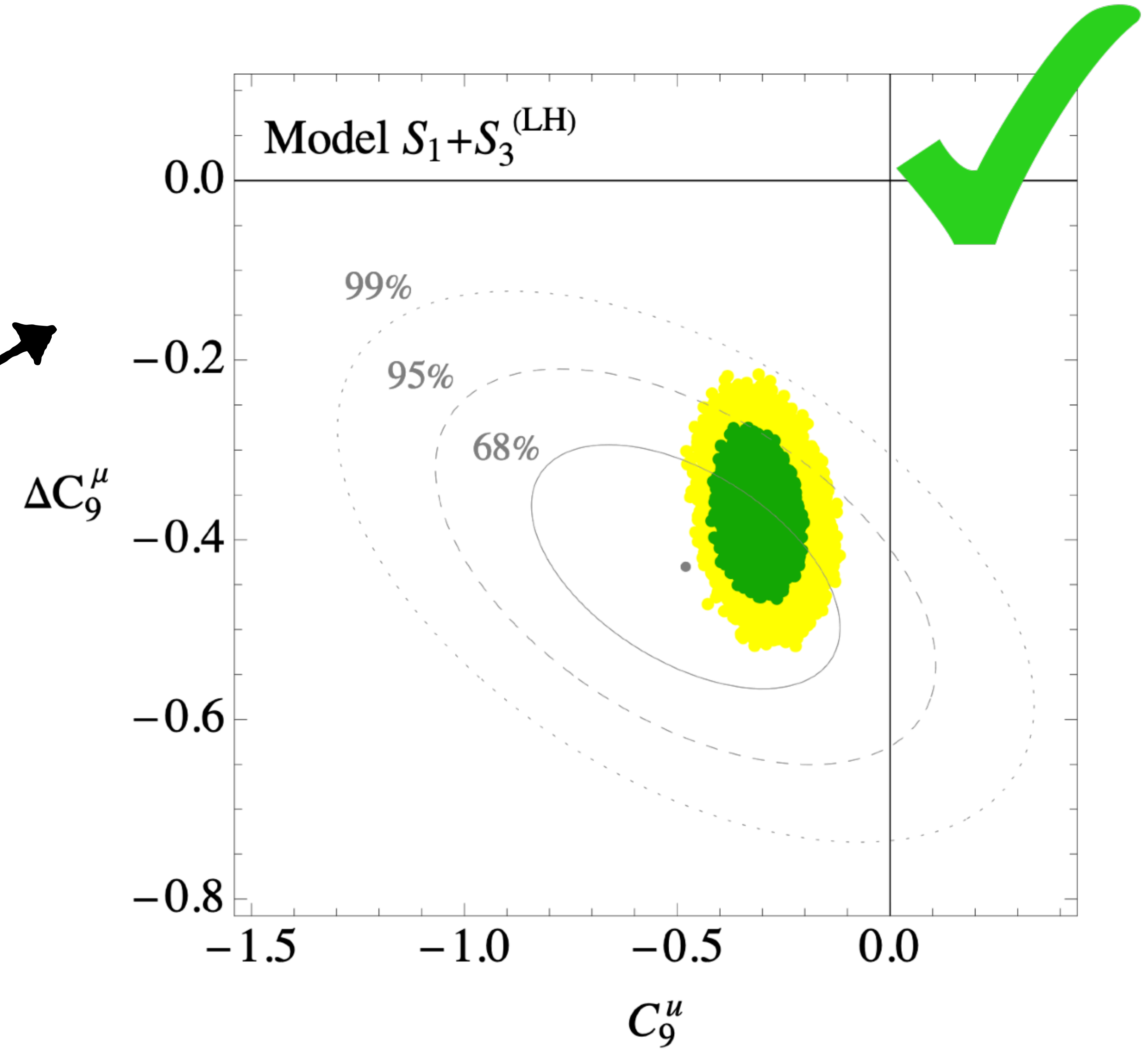




$b \to s\mu\mu$



Global fit with all relevant **flavour**, **EW**, and **collider** constraints.
(details in backup)



V. Gherardi, E. Venturini, D.M. [2008.09548]

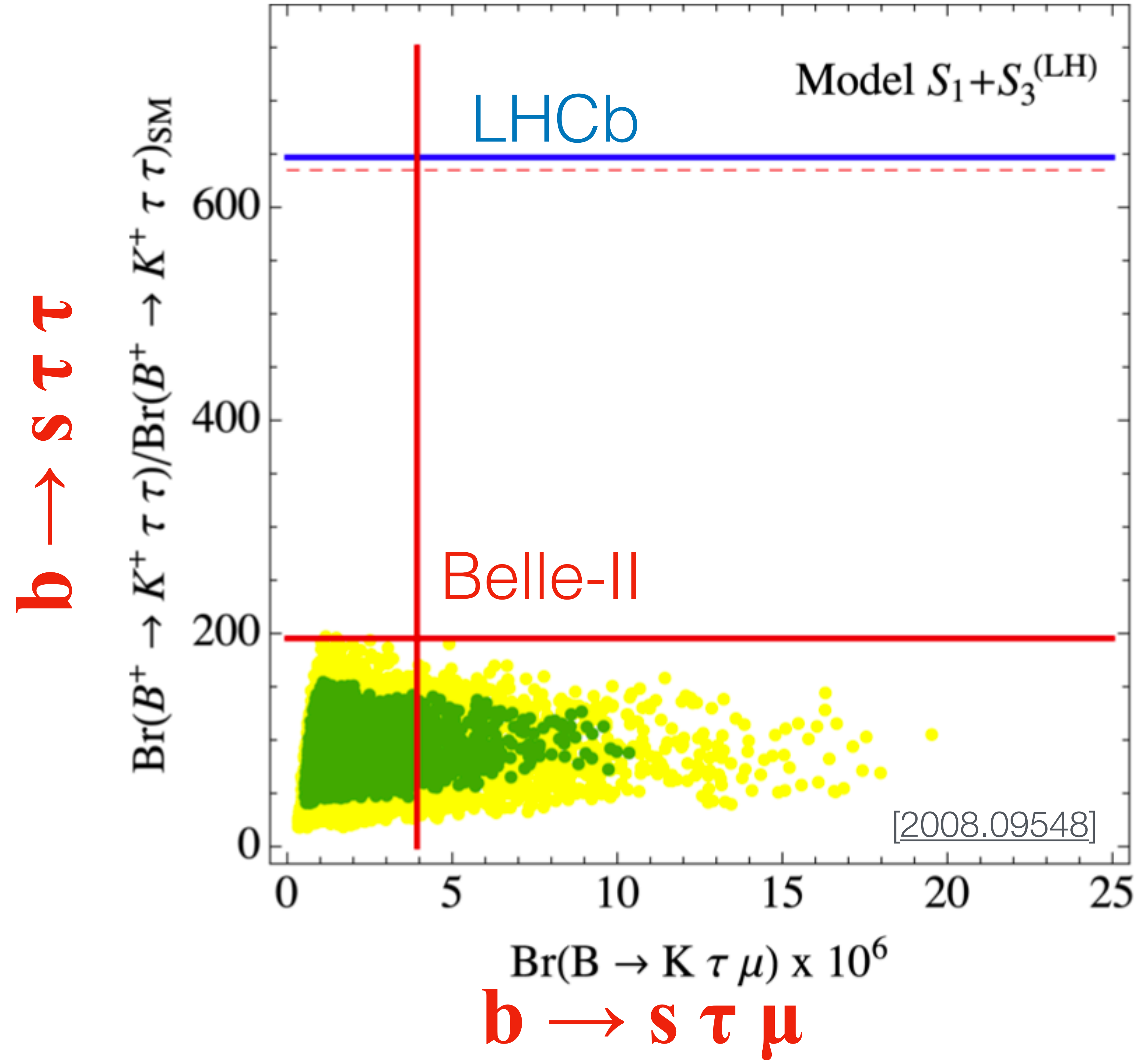
Predictions!

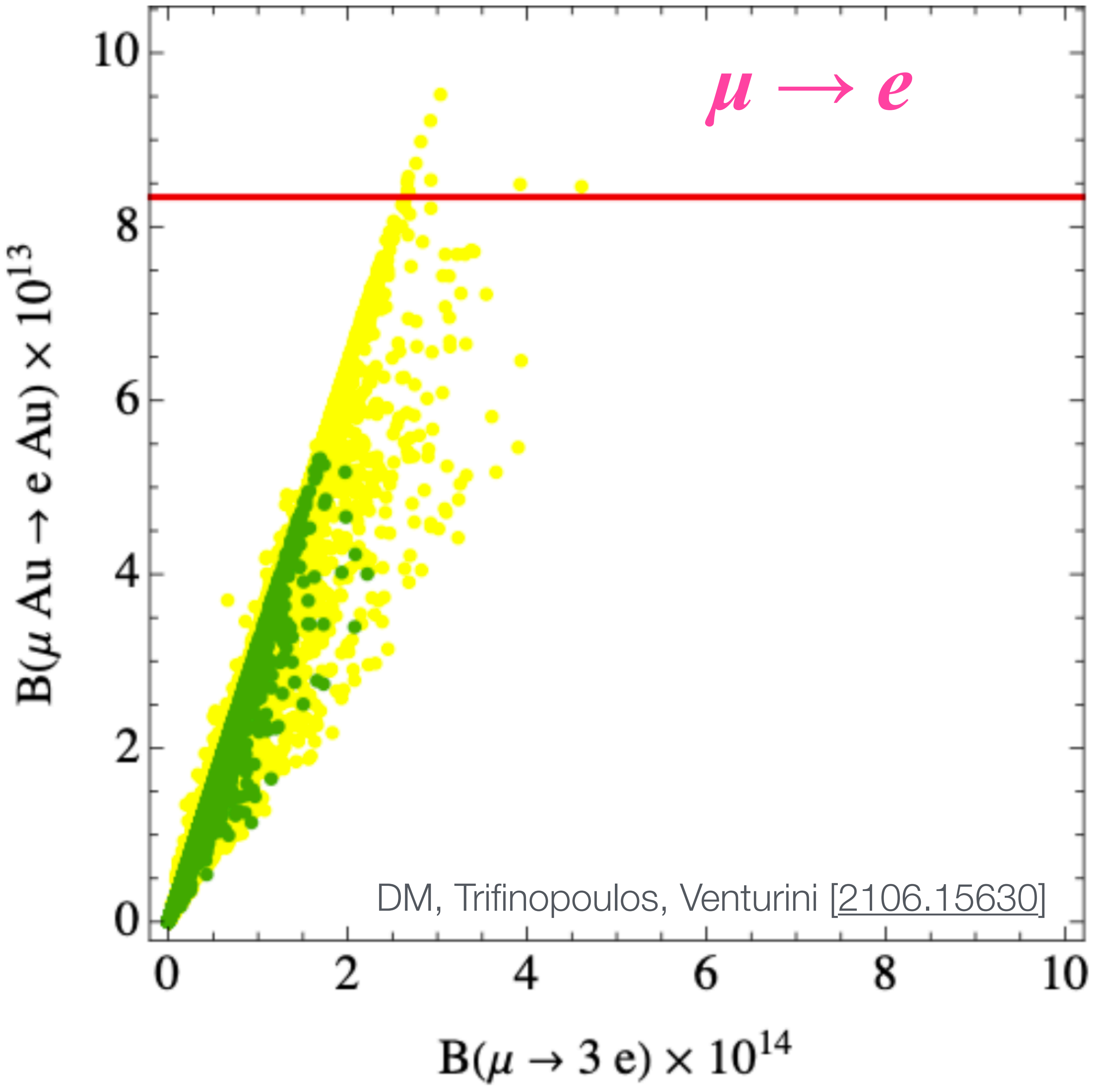
Better to be wrong than “not even wrong”

Predictions

Typical for all models addressing R(D(*)) ⟶ The large couplings to τ imply signatures in DY tails of $pp \to \tau\,\tau$, deviations in **τ LFU** tests and **τ → μ LFV** tests (Belle-II). Also **B_s-mixing** and **B→ K* ν ν̄** are close to present bounds.

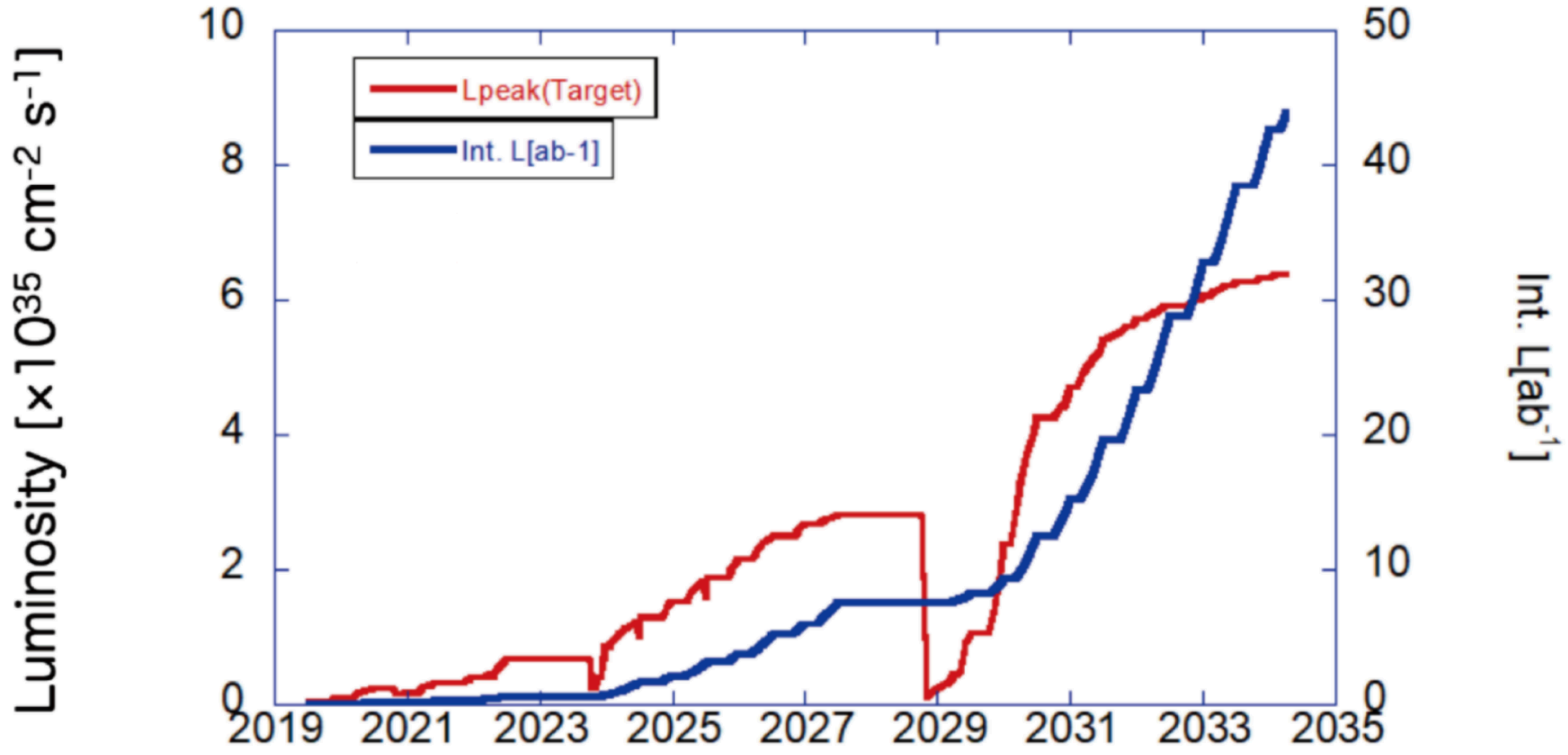
Large effects are also expected in $\mathbf{b \to s\,\tau\,\tau}$ and $\mathbf{b \to s\,\tau\,\mu}$ transitions, as well as in $\mu \to e$:





Near Future Prospects in Flavour

Belle-II



Belle-II will be able to **completely test R(D$^{(*)}$) with 5ab^{-1}**.

Measuring R(K$^{(*)}$) with 3% precision requires 50ab^{-1}.

Discover SM value of $B^0 \to K^{*0}\, \nu\, \bar{\nu}$ with ~5ab^{-1}.

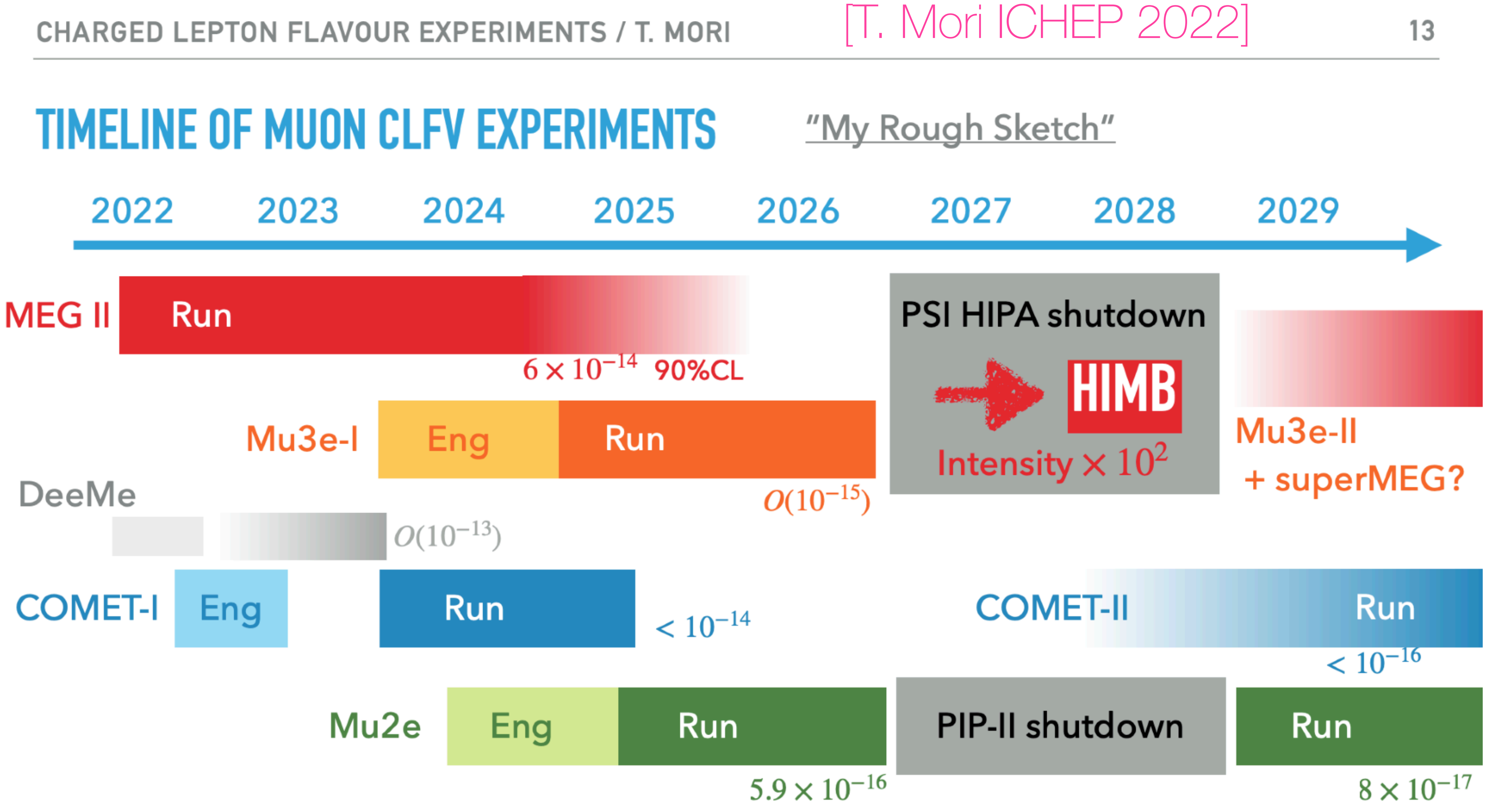
Bound on $Br(\tau \to \mu\, \gamma\ (3\ \mu)\ )$ will **improve by a factor of 6 (60)**.

μ → e LFV

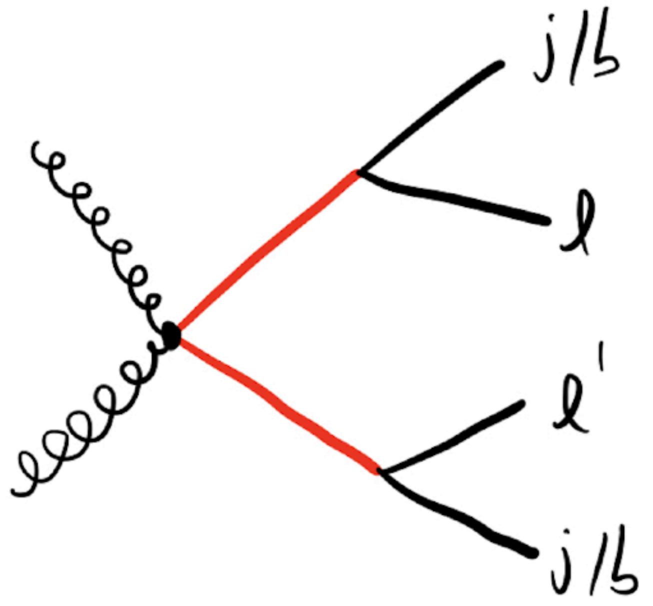
today:

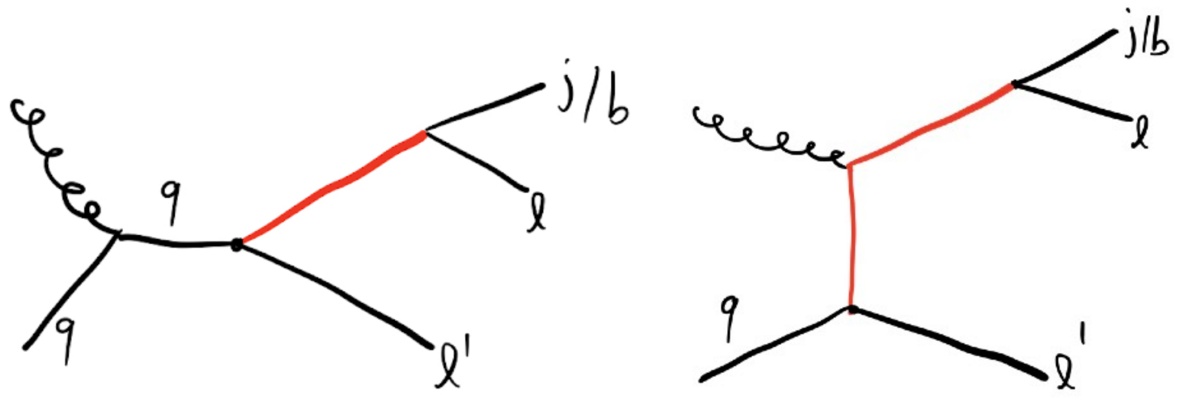
$\mathcal{B}(\mu \to e\gamma)$	$< 5.0 \times 10^{-13}$
$\mathcal{B}(\mu \to 3e)$	$< 1.2 \times 10^{-12}$
$\mathcal{B}^{(\mathrm{Ti})}_{\mu e}$	$< 5.1 \times 10^{-12}$
$\mathcal{B}^{(\mathrm{Au})}_{\mu e}$	$< 8.3 \times 10^{-13}$

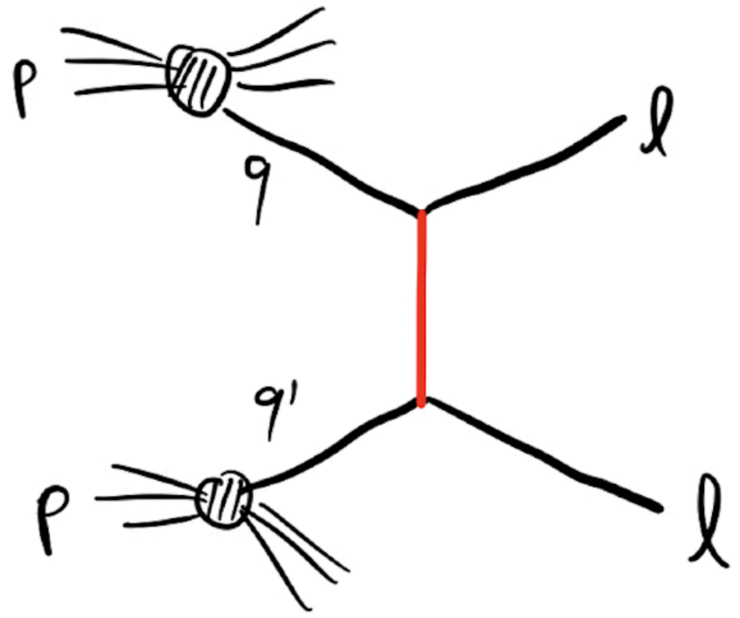
[T. Mori ICHEP 2022]

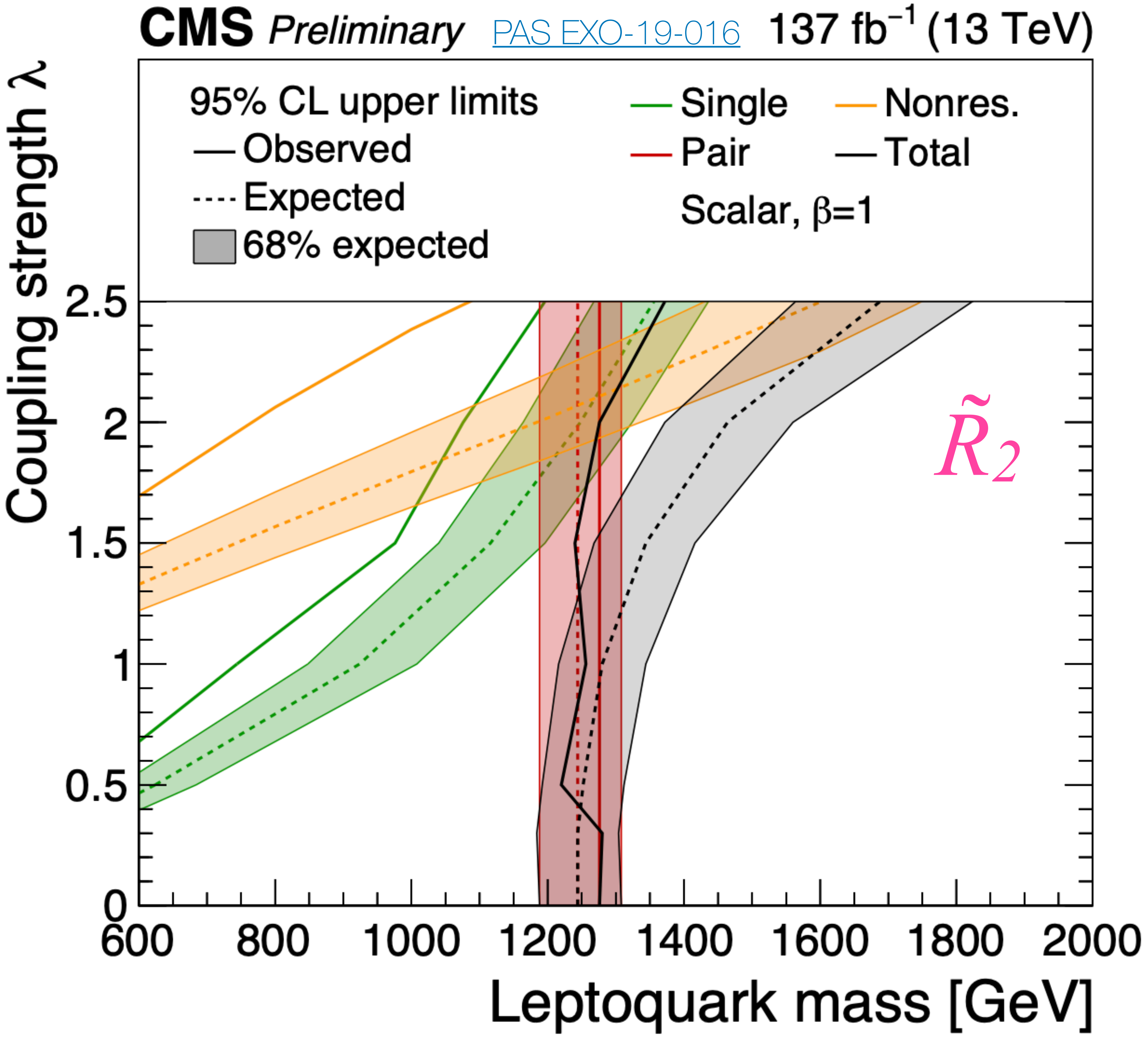


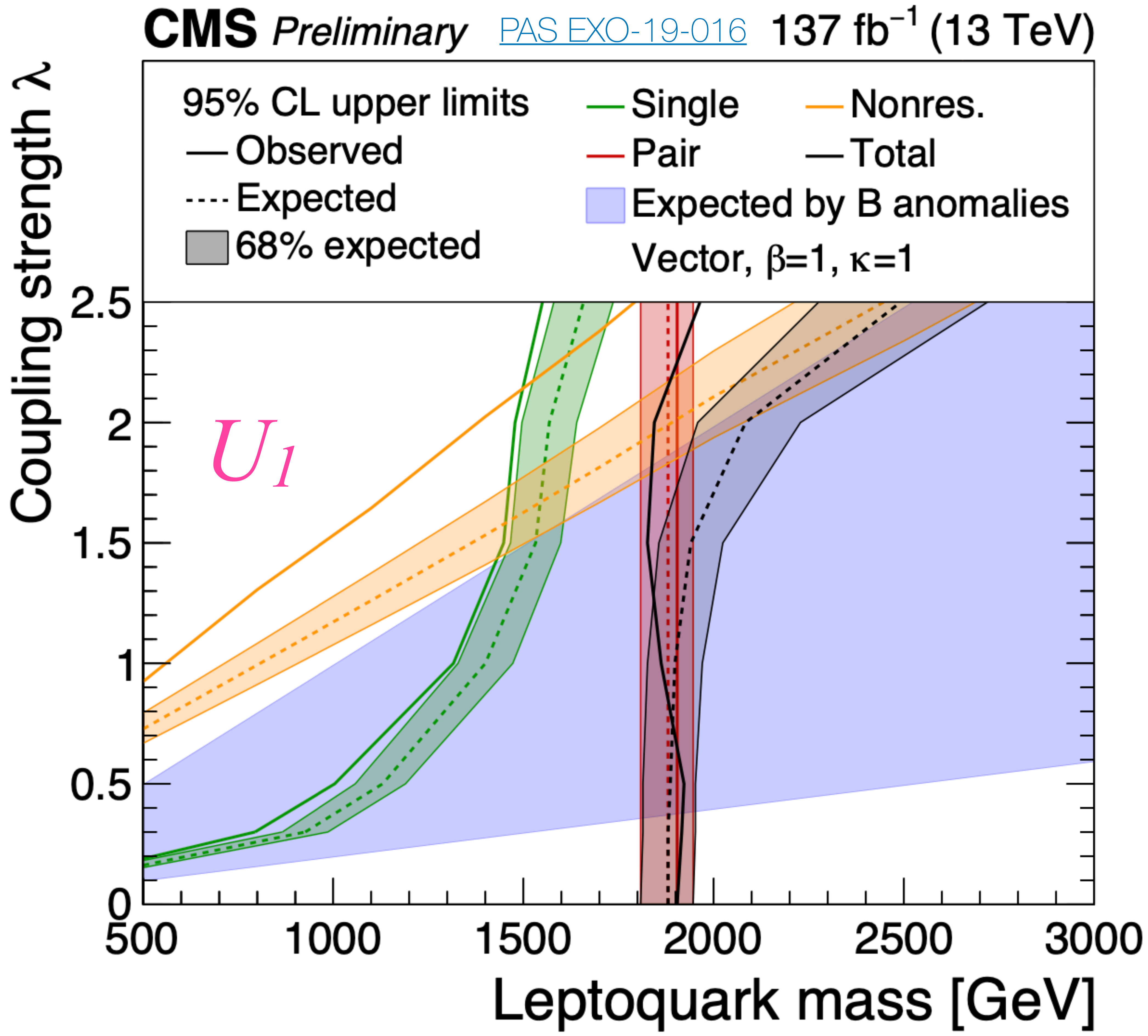
3rd gen LQ searches







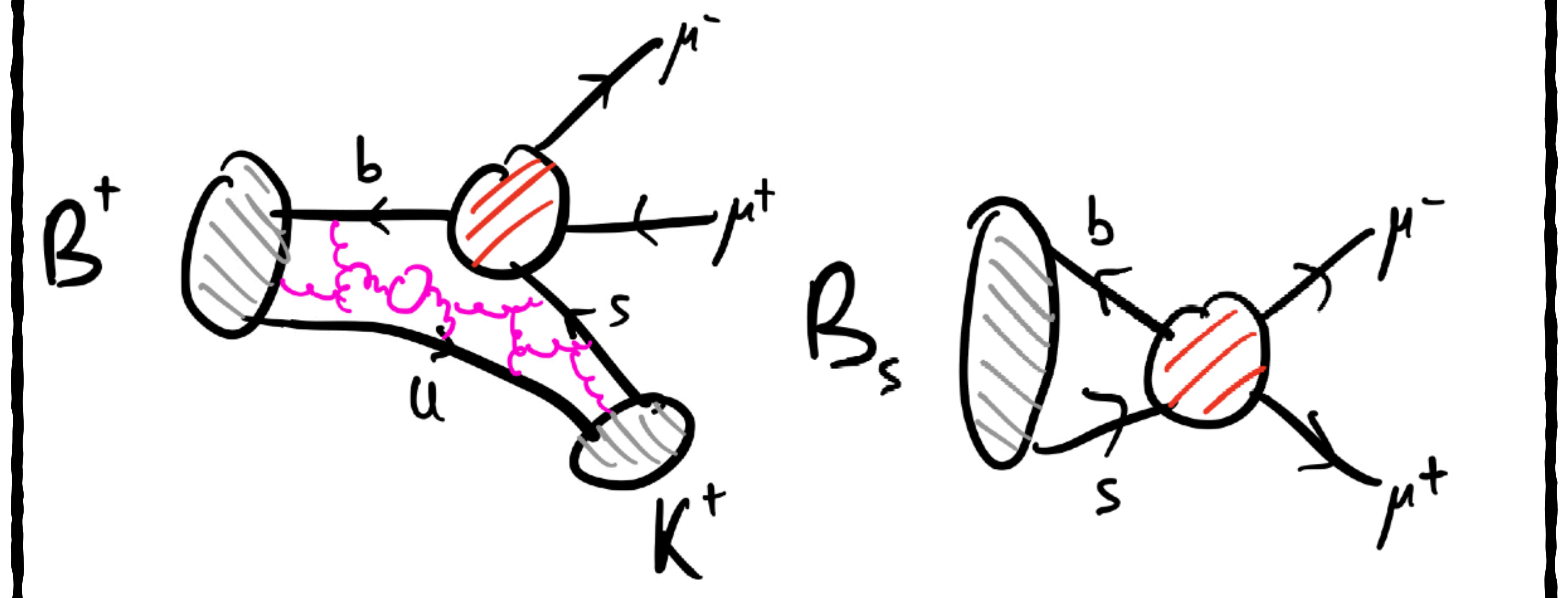




scalar $M_{LQ} \gtrsim 1.3$ TeV **vector $M_{LQ} \gtrsim 1.9$ TeV**

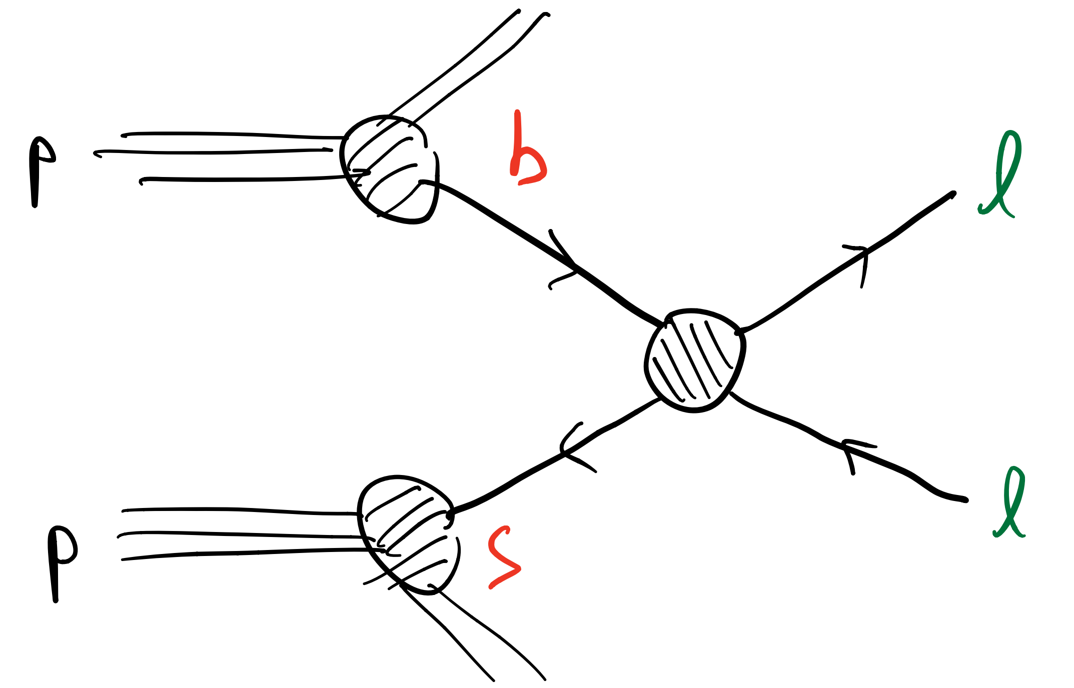
High-p_T tails

Meson decays



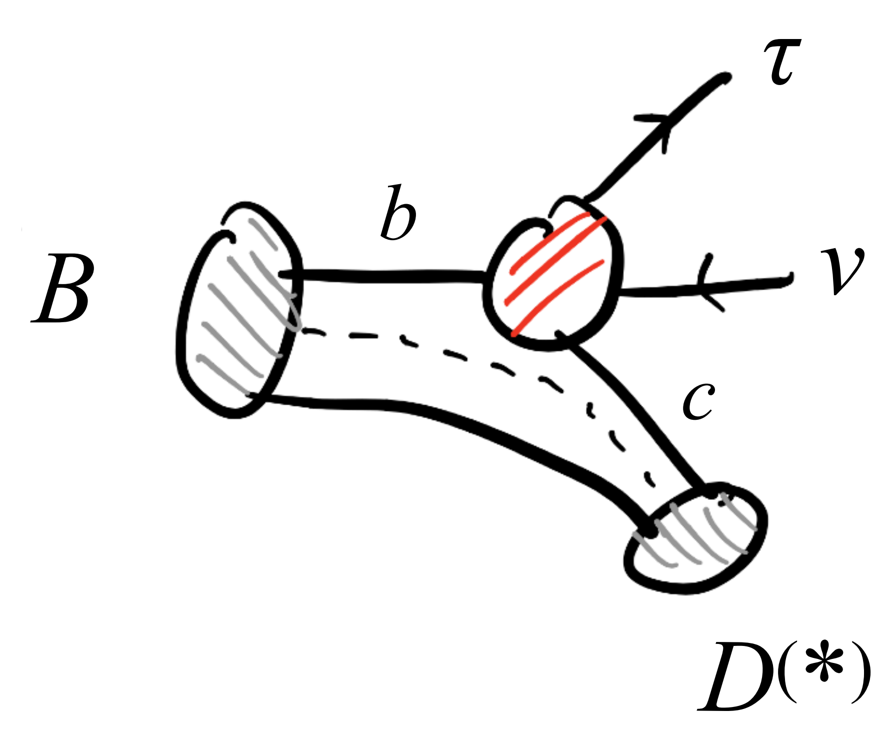
Crossing symmetry

Drell-Yan tail



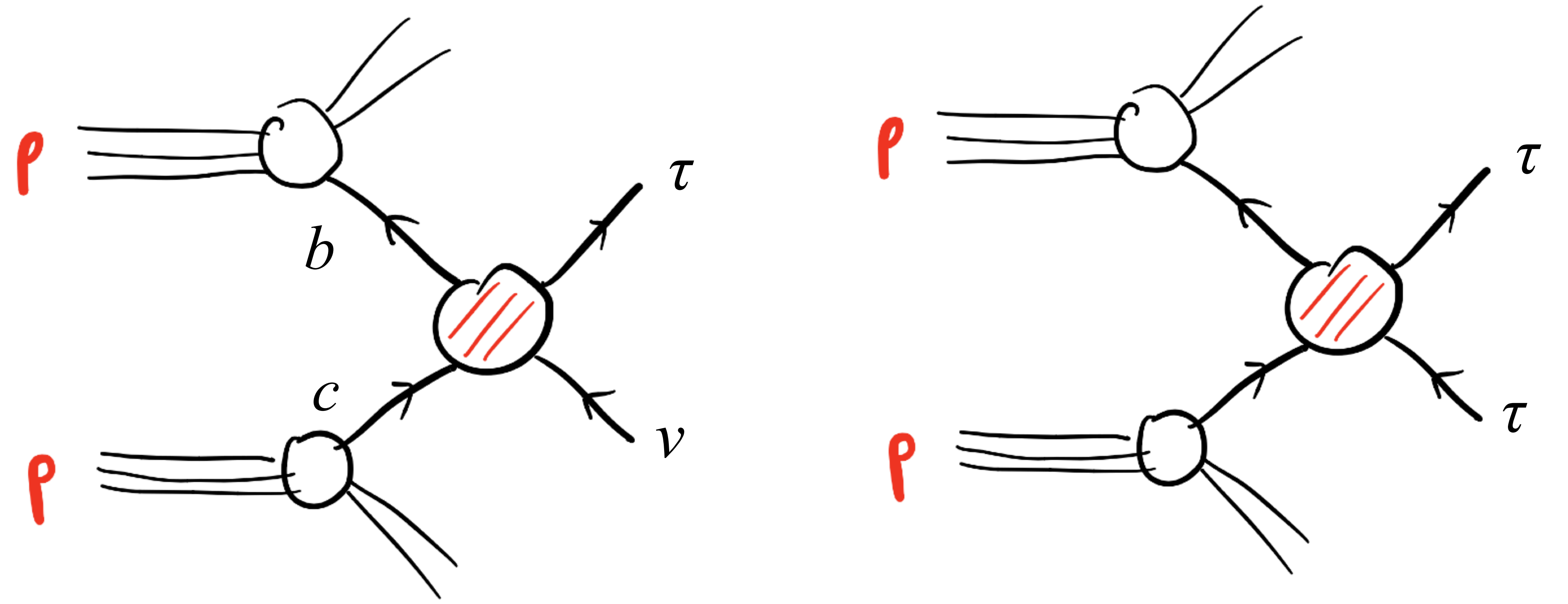
[Greljo, DM 1704.09015]

If $m_{EW} < E_{\mu\mu} \ll M_{NP}$ we can use an EFT approach



Crossing symmetry

Drell-Yan tail

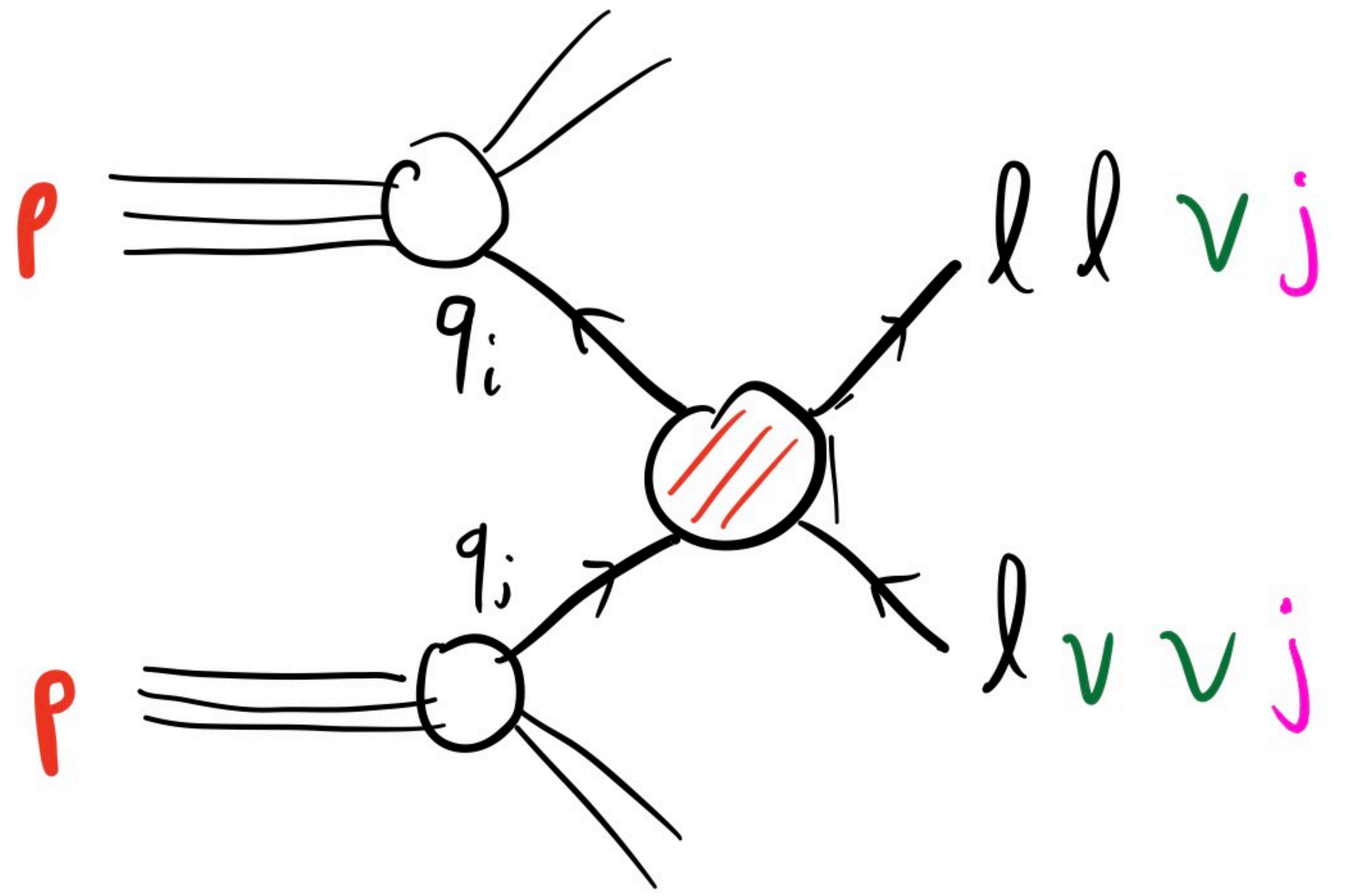


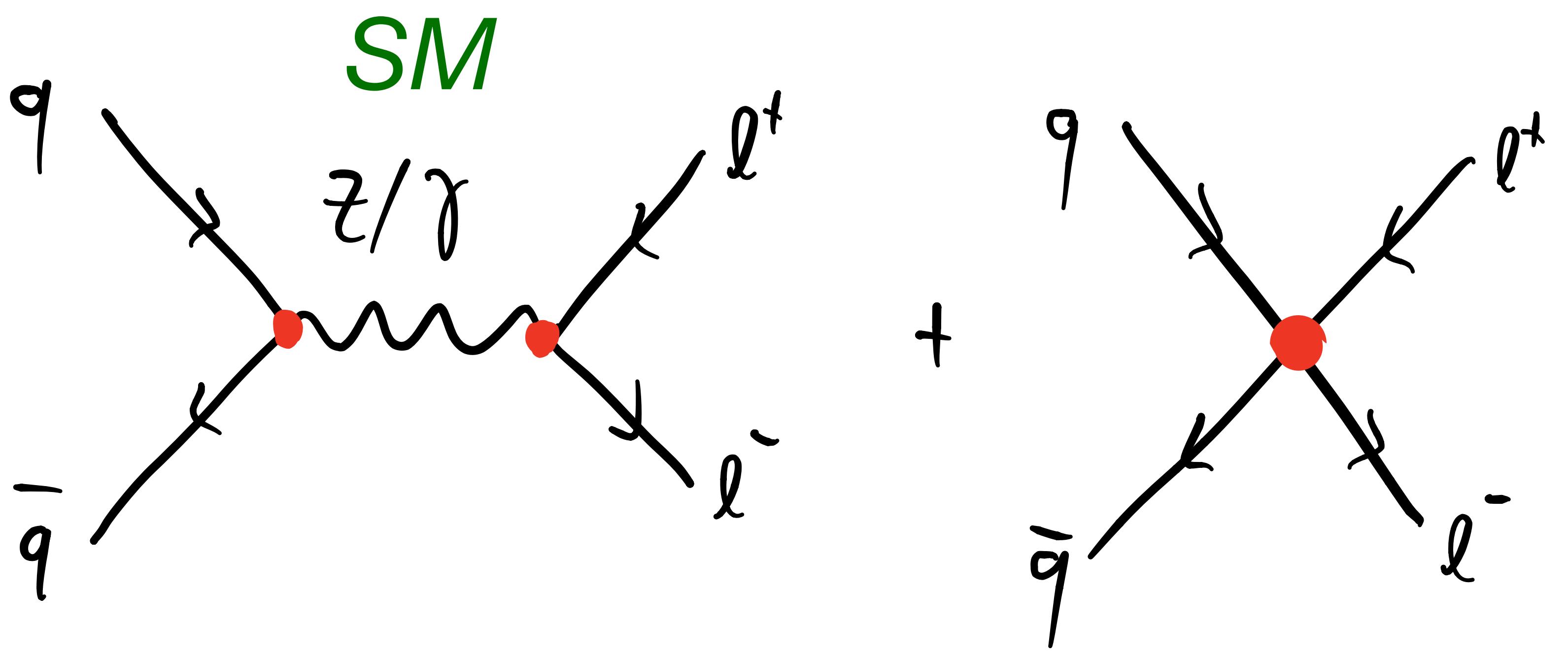
[Greljo, Camalich, Ruiz-Alvarez 1811.07920]
[DM, Min, Son, 2008.07541]

[Faroughy, Greljo, Kamenik 1609.07138]

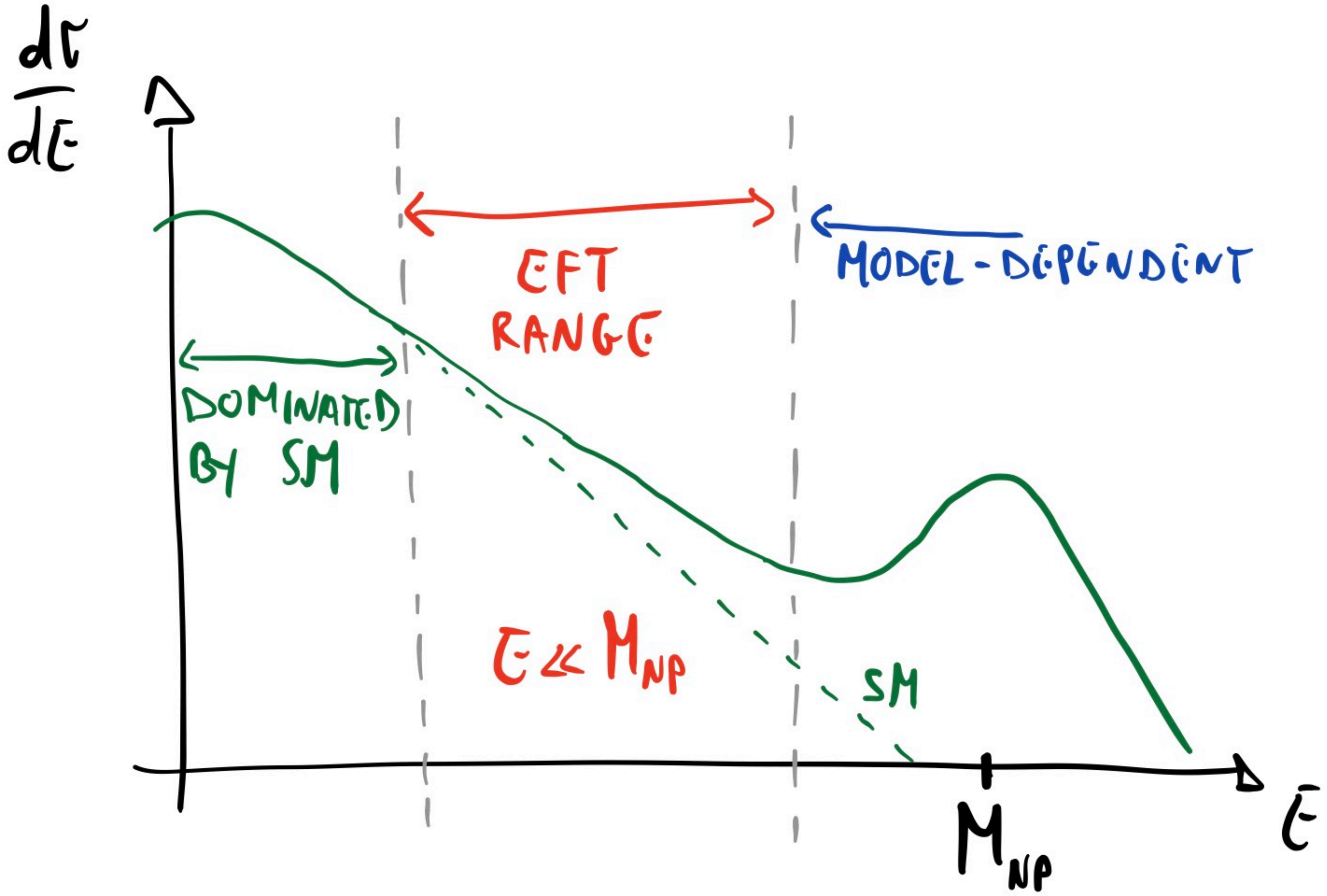
Now also a public tool: *HighpT*: [2207.10714, 2207.10756]

High-p_T tails





The **EFT contributions** to the amplitude grow with the energy, compared to the SM.



$E \gg m_{EW}$

$$\mathcal{A} \sim \frac{g_{SM}^2}{E^2} + \frac{c_{ij}}{M_{NP}^2} \sim \mathcal{A}_{SM}\left(1 + \frac{c_{ij}}{g_{SM}^2}\frac{E^2}{M_{NP}^2}\right)$$

EFT enhancement in high-pT tails

Lessons Learned (part 1)

Broadening of experimental analyses

- Broader range of processes studied to test $b \to s\,(d)\,\ell\,\ell$ and $b \to c\,(u)\,\tau\,\nu$ transitions.
- Renewed focus on LFU ratios (also at high-p_T)!
- Development of a leptoquark search program at ATLAS and CMS
- Interest in high-p_T tails at LHC: SMEFT, simplified models.
  These are some of the most interesting searches to look for from HL-LHC.

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SM theory improvements and BSM perspectives

- Improvements in SM understanding of hadronic matrix elements
- Renaissance of leptoquarks as possible BSM scenarios
- New Physics models built around (vs against) flavour

3 - Do they help us address SM problems?

How do these leptoquarks fit in a bigger picture?
Are they involved in answers to the big puzzles of the Standard Model?

From Leptoquarks to the Higgs, and back

From B-anomalies

$$M_{LQ} \sim \text{TeV}$$

Hierarchical couplings to SM fermions

$$g(3rd) > g(2nd) > g(1st)$$

From Leptoquarks to the Higgs, and back

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$M_{LQ} \sim$ TeV

Hierarchical couplings to SM fermions

$g(\mathbf{3rd}) > g(\mathbf{2nd}) > g(\mathbf{1st})$

Higgs & EW hierarchy

$M_{BSM} \lesssim$ TeV

Hierarchical Yukawa couplings

$y(\mathbf{3rd}) > y(\mathbf{2nd}) > y(\mathbf{1st})$

From Leptoquarks to the Higgs, and back

From B-anomalies

$\mathbf{M_{LQ} \sim TeV}$

Hierarchical couplings to SM fermions

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Higgs & EW hierarchy

$\mathbf{M_{BSM} \lesssim TeV}$

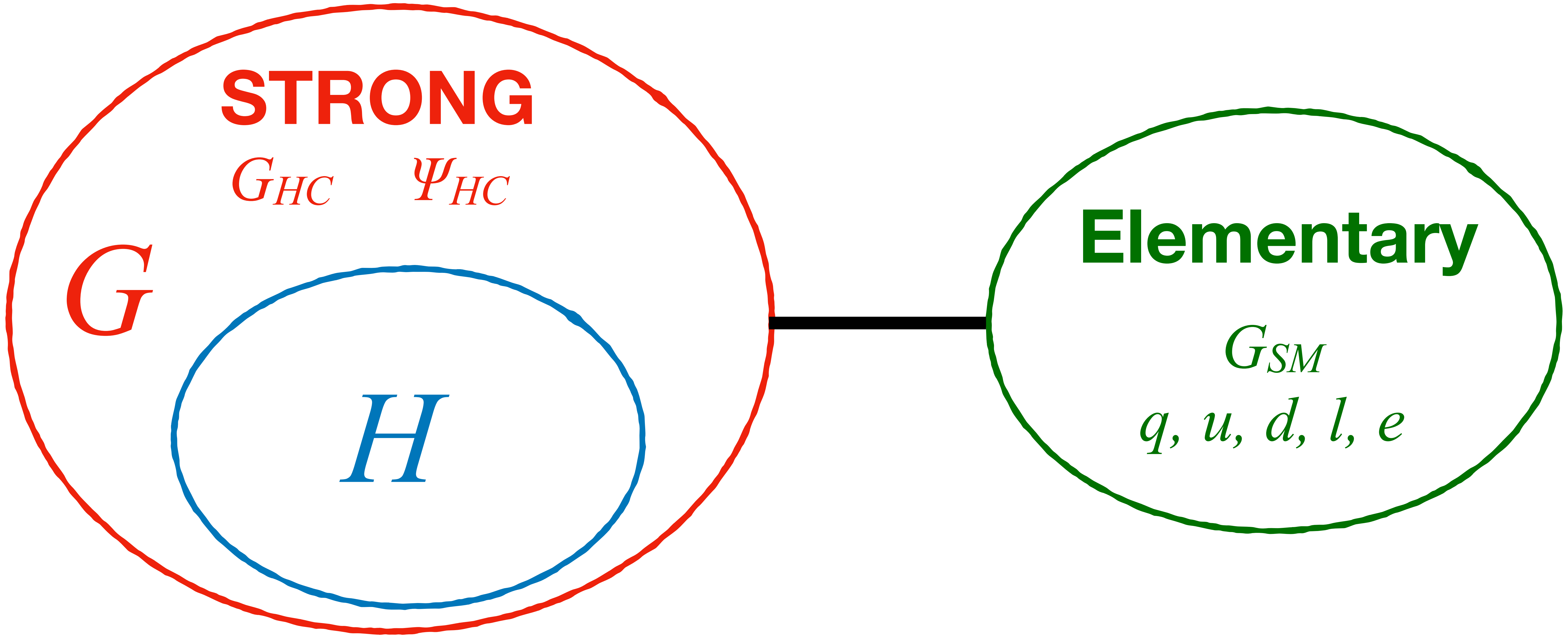
Hierarchical Yukawa couplings

$\mathbf{y(3rd) > y(2nd) > y(1st)}$

LQ from same UV responsible for the EW scale,
connection between LQ couplings and Yukawa couplings.

Scalar LQ & Higgs: both pseudo-Goldstones?

In Composite Higgs models the Higgs arises as a pseudo-Goldstone (pNGB) of a spontaneously broken global symmetry G → H of a TeV-scale strong sector



Spontaneous global symmetry breaking at the $f \sim 1\ \mathrm{TeV}$ scale

$$G \to H$$

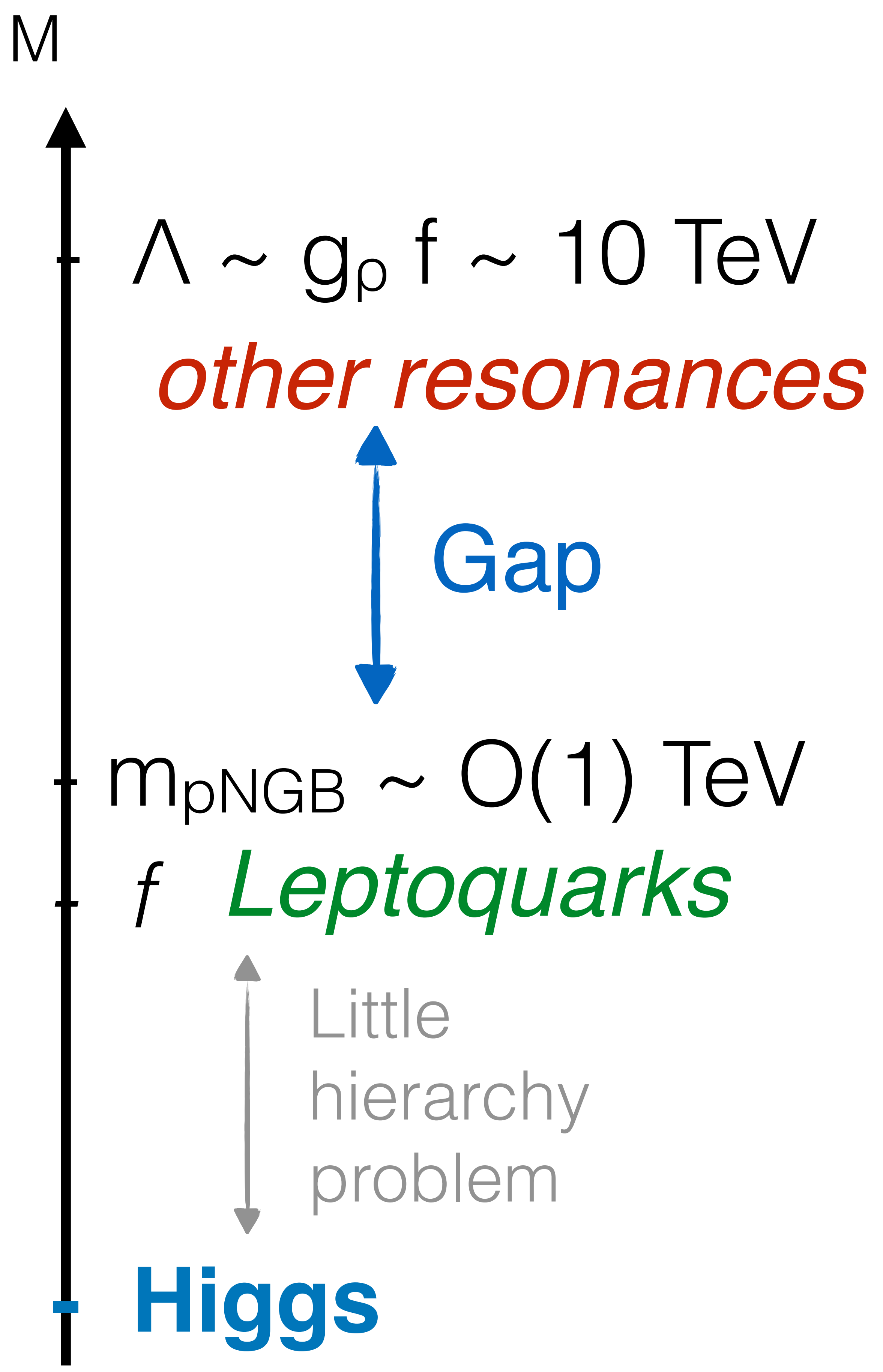
One obtains naturally

$$m_{PNGB} \ll M_{Resonances}$$

Scalar LQ & Higgs: both pseudo-Goldstones?

Scalar LQs could arise as pNGB together with the Higgs from the same G/H of the strong sector.

[Gripaios 0910.1789, Gripaios, Nardecchia, Renner 1412.1791]



Low-energy phenomenology dominated by the LQs

$$m_{SLQ} \ll \Lambda$$

Having the same origin, it is expected that LQ couplings have same structure as Higgs Yukawa couplings:

possible connection with flavour structure

A Fundamental Composite Higgs + LQ Model

D.M. 1803.10972

Gauge group: $\mathrm{SU}(N_{HC}) \times \mathrm{SU}(3)_c \times \mathrm{SU}(2)_w \times \mathrm{U}(1)_Y$

"HyperColor"

Extra vectorlike fermions charged under SU(N_{HC}):

QCD-like!!

	$\mathrm{SU}(N_{HC})$	$\mathrm{SU}(3)_c$	$\mathrm{SU}(2)_w$	$\mathrm{U}(1)_Y$
Ψ_L	$\mathbf{N_{HC}}$	$\mathbf{1}$	$\mathbf{2}$	Y_L
Ψ_N	$\mathbf{N_{HC}}$	$\mathbf{1}$	$\mathbf{1}$	$Y_L + 1/2$
Ψ_E	$\mathbf{N_{HC}}$	$\mathbf{1}$	$\mathbf{1}$	$Y_L - 1/2$
Ψ_Q	$\mathbf{N_{HC}}$	$\mathbf{3}$	$\mathbf{2}$	$Y_L - 1/3$

For similar constructions see:
Shmaltz et al 1006.1356,
Vecchi 1506.00623,
Ma, Cacciapaglia 1508.07014

SU(N_{HC}) confines at $\Lambda_{\mathrm{HC}} \sim 10$ TeV

A Fundamental Composite Higgs + LQ Model

D.M. 1803.10972

Gauge group: $SU(N_{HC}) \times SU(3)_c \times SU(2)_w \times U(1)_Y$

"HyperColor"

Extra vectorlike fermions charged under SU(N_{HC}):

QCD-like!!

	$SU(N_{HC})$	$SU(3)_c$	$SU(2)_w$	$U(1)_Y$
Ψ_L	$\mathbf{N_{HC}}$	$\mathbf{1}$	$\mathbf{2}$	Y_L
Ψ_N	$\mathbf{N_{HC}}$	$\mathbf{1}$	$\mathbf{1}$	$Y_L + 1/2$
Ψ_E	$\mathbf{N_{HC}}$	$\mathbf{1}$	$\mathbf{1}$	$Y_L - 1/2$
Ψ_Q	$\mathbf{N_{HC}}$	$\mathbf{3}$	$\mathbf{2}$	$Y_L - 1/3$

For similar constructions see:
Shmaltz et al 1006.1356,
Vecchi 1506.00623,
Ma, Cacciapaglia 1508.07014

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Approximate global symmetry, spontaneously broken (as chiral symm. in QCD)

$$G = SU(10)_L \times SU(10)_R \times U(1)_V \xrightarrow[\langle \bar{\Psi}_i \Psi_j \rangle = -B_0 f^2 \delta_{ij}]{f \sim 1\text{TeV}} H = SU(10)_V \times U(1)_V$$

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Ψ_N	$\mathbf{N_{HC}}$	$\mathbf{1}$	$\mathbf{1}$	$Y_L + 1/2$
Ψ_E	$\mathbf{N_{HC}}$	$\mathbf{1}$	$\mathbf{1}$	$Y_L - 1/2$
Ψ_Q	$\mathbf{N_{HC}}$	$\mathbf{3}$	$\mathbf{2}$	$Y_L - 1/3$

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The **Higgs and leptoquarks** arise together as **pNGB**: close partners.

Yukawas and LQ couplings from the same origin → possible U(2)^5 flavour structure

Vector Leptoquark

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

Needs to couple not universally to SM fermions:

Di Luzio et al 1708.08450; Bordone et al. 1712.01368; Calibbi et al. '17; Blanke, Crivellin '18; Cornella et al 2103.16558

4321 models: $SU(4) \times SU(3)' \times SU(2)_L \times U(1) \rightarrow SU(3)_C \times SU(2)_L \times U(1)_Y$

SM fermions have different embedding between SU(4) and SU(3)', or mix with vectorlike fermions.

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From $SU(4) \times SU(3)' \rightarrow SU(3)_c$ one gets:

$U_1 = (\mathbf{3}, \mathbf{1}, 2/3)$ Vector LQ

$G' = (\mathbf{8}, \mathbf{1}, 0)$ Coloron

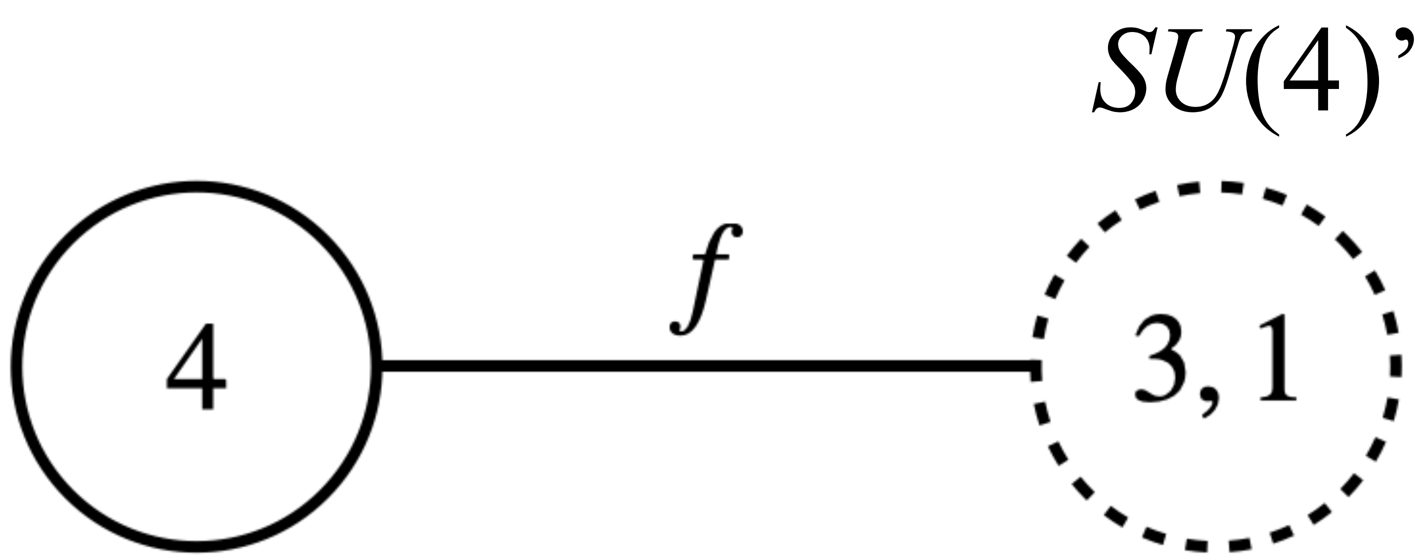
$Z' = (\mathbf{1}, \mathbf{1}, 0)$ Z'

$\rightarrow$ FCNC @ tree-level+ strong collider bounds

… result in several years of challenging model building…

Composite Higgs + Vector LQ [2004.11376]

The vector U_1 LQ gets mass from the strong sector, as W,Z bosons do in technicolor.



$$\langle \bar{\zeta}_L^\alpha \, \zeta_R^\beta \rangle = -\frac{1}{2} B_\zeta \, f_\zeta^2 \, \delta_{\alpha\beta}$$

$\longrightarrow$ $SU(4)_{\mathrm{D}}$

$SU(4) \quad \times \quad SU(3)' \times U(1)'$

Heavy fermions

Light fermions

15 eaten NGB:
- heavy coloron
- U_1 LQ
- Z'

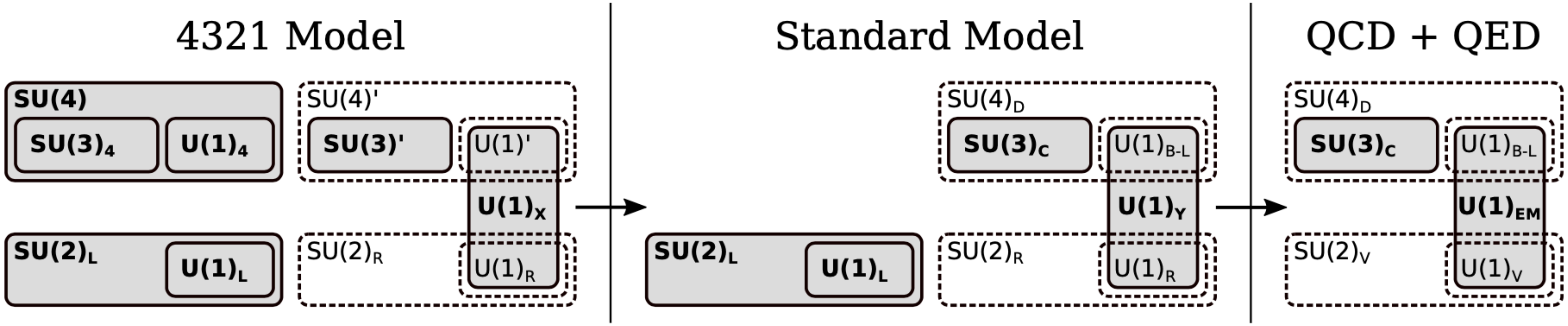
$$M_U \sim g_4 \, f_\zeta$$

For the Composite Higgs part:

$$\langle \bar{\xi}_L^{i\,c} \, \xi_L^j \rangle = \langle \bar{\xi}_R^{i\,c} \, \xi_R^j \rangle = -\frac{1}{2} B_\xi \, f_\xi^2 \, \epsilon_{ij}$$

$$SU(4)_{\mathrm{EW}} \times U(1)_A \to Sp(4)_{\mathrm{EW}}$$

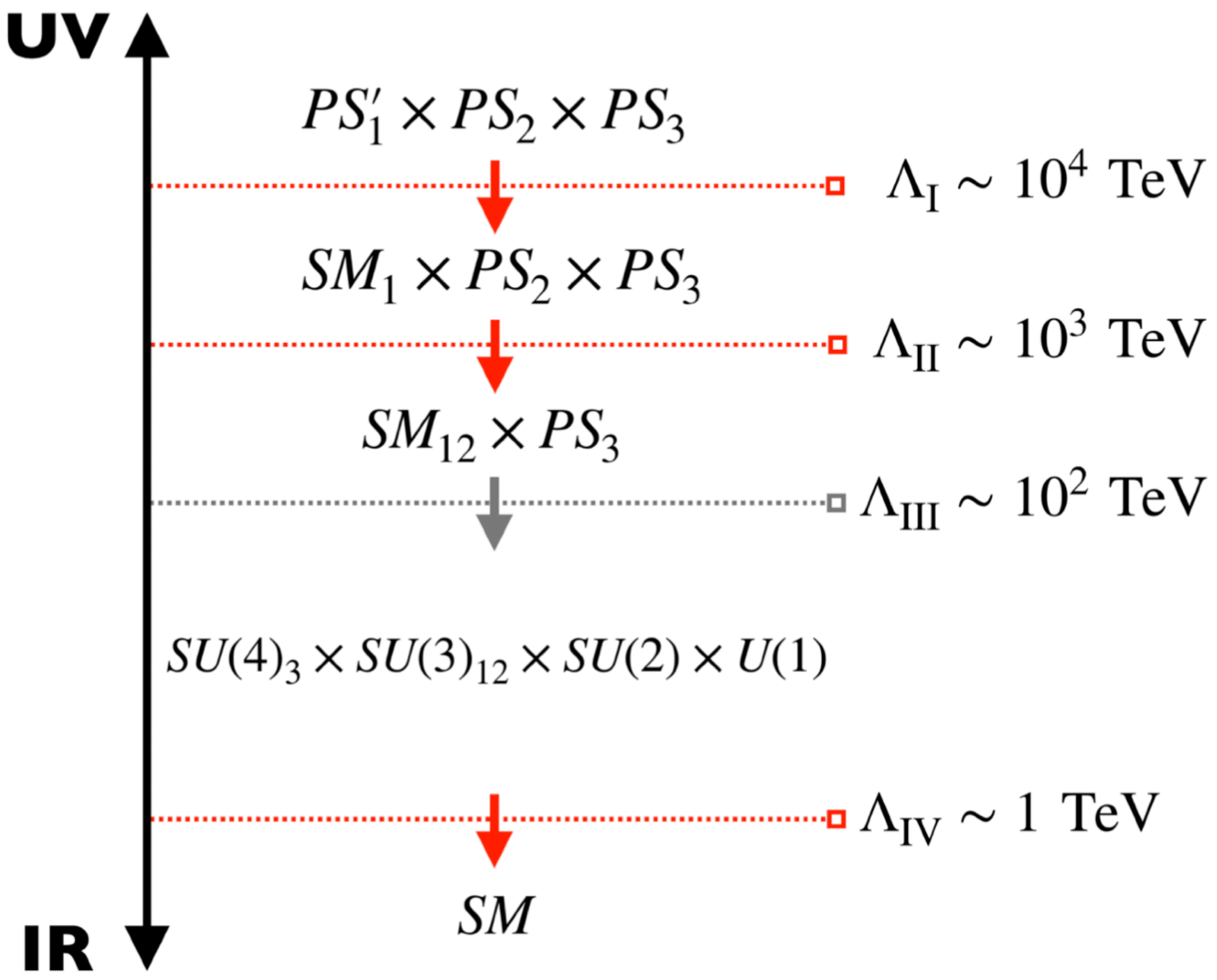
6 pNGB:
- Higgs doublet
- 2 singlets



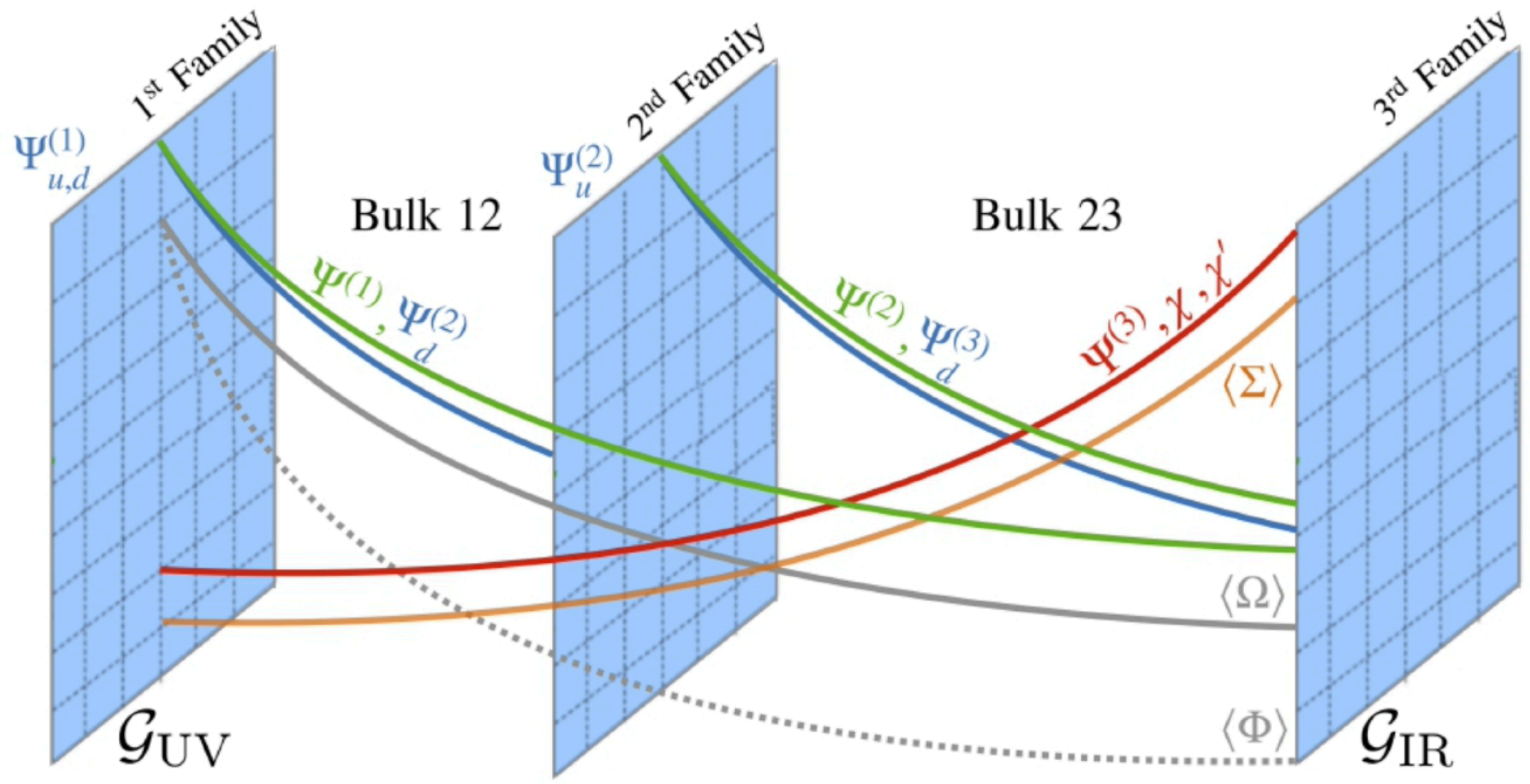
Vector leptoquark UV models: PS^3

The **vector U_1 LQ** comes from a UV structure **(Pati-Salam)^3**,
where each fermion generation is charged under its own Pati-Salam gauge group:
Lepton-Flavour-Universality is an emergent feature at low energies (like Parity in the SM).

Bordone, Cornella, Fuentes-Martin, Isidori; 1712.01368



This picture can be embedded in a warped 5D compactification



Fuentes-Martin et al; 2203.01952

Flavour hierarchy $\leftrightarrow$ Hierarchy of scales (RG stable)

Accidental **approximate U(2)^5 at low energy!**

EW hierarchy problem can be addressed by adding a further Planck brane.

Lessons Learned (part 2)

Broadening of experimental analyses

- Broader range of processes studied to test $b \to s\,(d)\,\ell\,\ell$ and $b \to c\,(u)\,\tau\,\nu$ transitions.
- Renewed focus on LFU ratios (also at high-p_T)!
- Development of a leptoquark search program at ATLAS and CMS
- Interest in high-p_T tails at LHC: SMEFT, simplified models: These are some of the most interesting searches to look at from HL-LHC.

SM theory improvements and BSM perspectives

- Improvements in SM understanding of hadronic matrix elements
- Renaissance of leptoquarks as possible BSM scenarios
- New Physics models built around (vs against) flavour

Model building

- Challenging model building to have large flavour violation at few TeV, consistently with all flavour + collider bounds.
- The hierarchy problem can still be addressed with TeV-scale New Physics
- NP models do not necessarily have to satisfy our minimality criteria: the SM is non minimal!
- Addressing flavour pushed to develop new ideas, e.g. PS^3

Conclusions

Still too early to conclude anything…

Conclusions

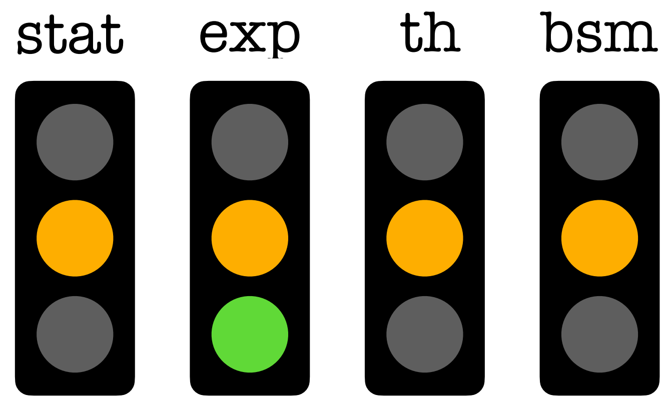
Still too early to conclude anything…

better…

Questions?

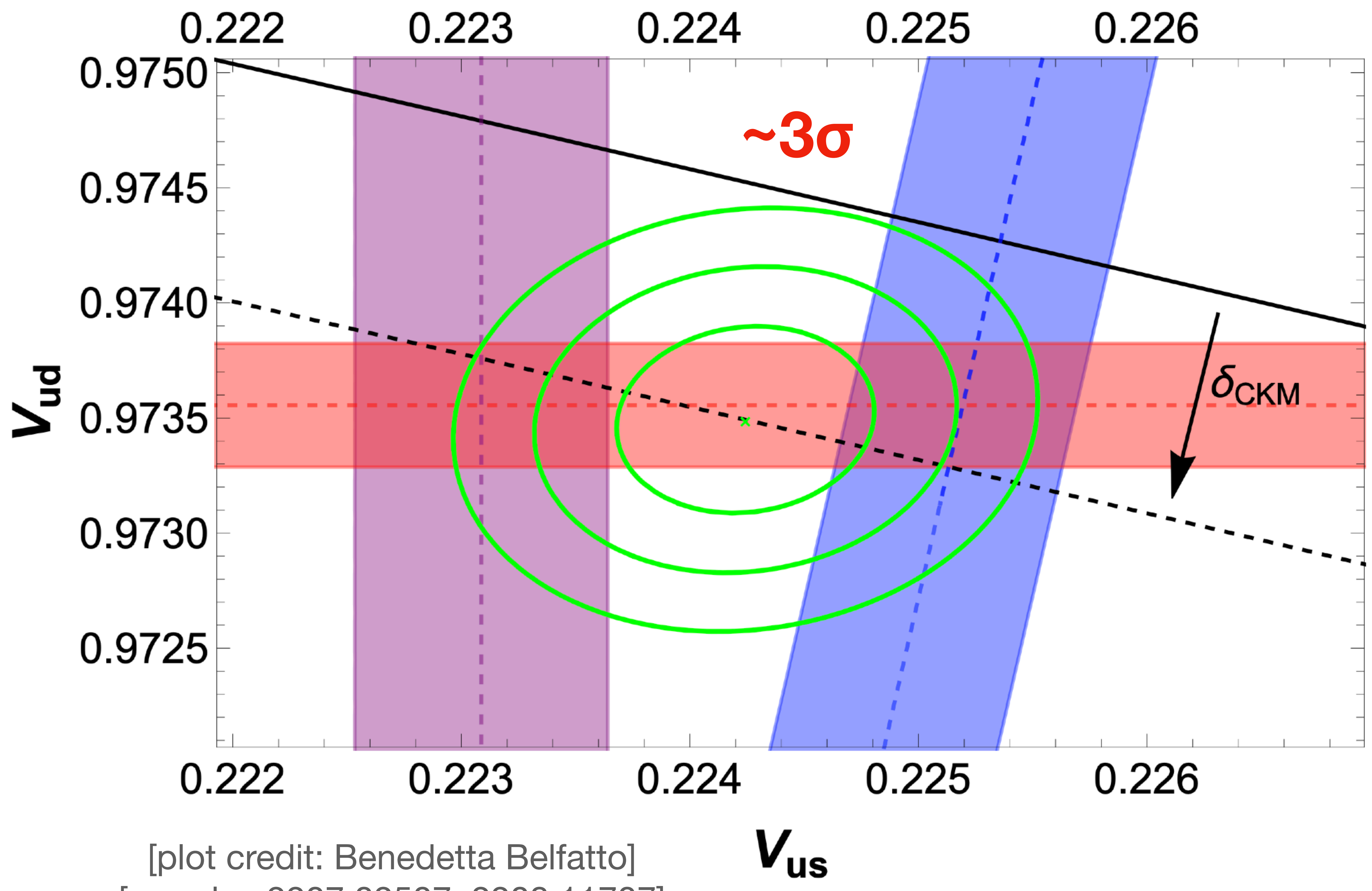
Cabibbo Angle Anomaly

SGPR 1807.10197,
Belfatto, Beradze, Berezhiani 1906.02714,
Grossmann, Passermar, Schacht 1911.07821



Unitarity of the first row of the CKM matrix: $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$

Neglecting the very small V_{ub}: $V_{ud}^2 + V_{us}^2 = 1$



[plot credit: Benedetta Belfatto]
[see also 2207.02507, 2208.11707]

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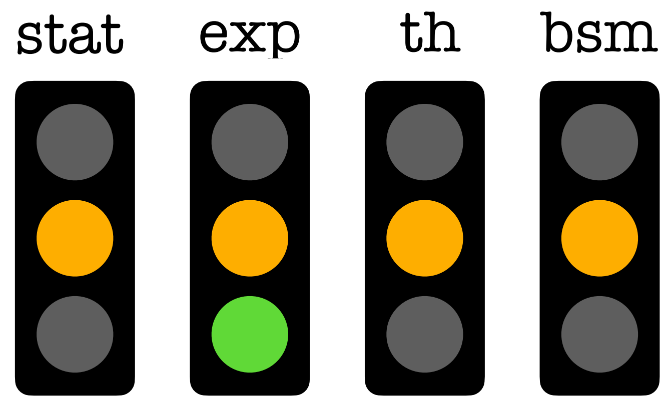

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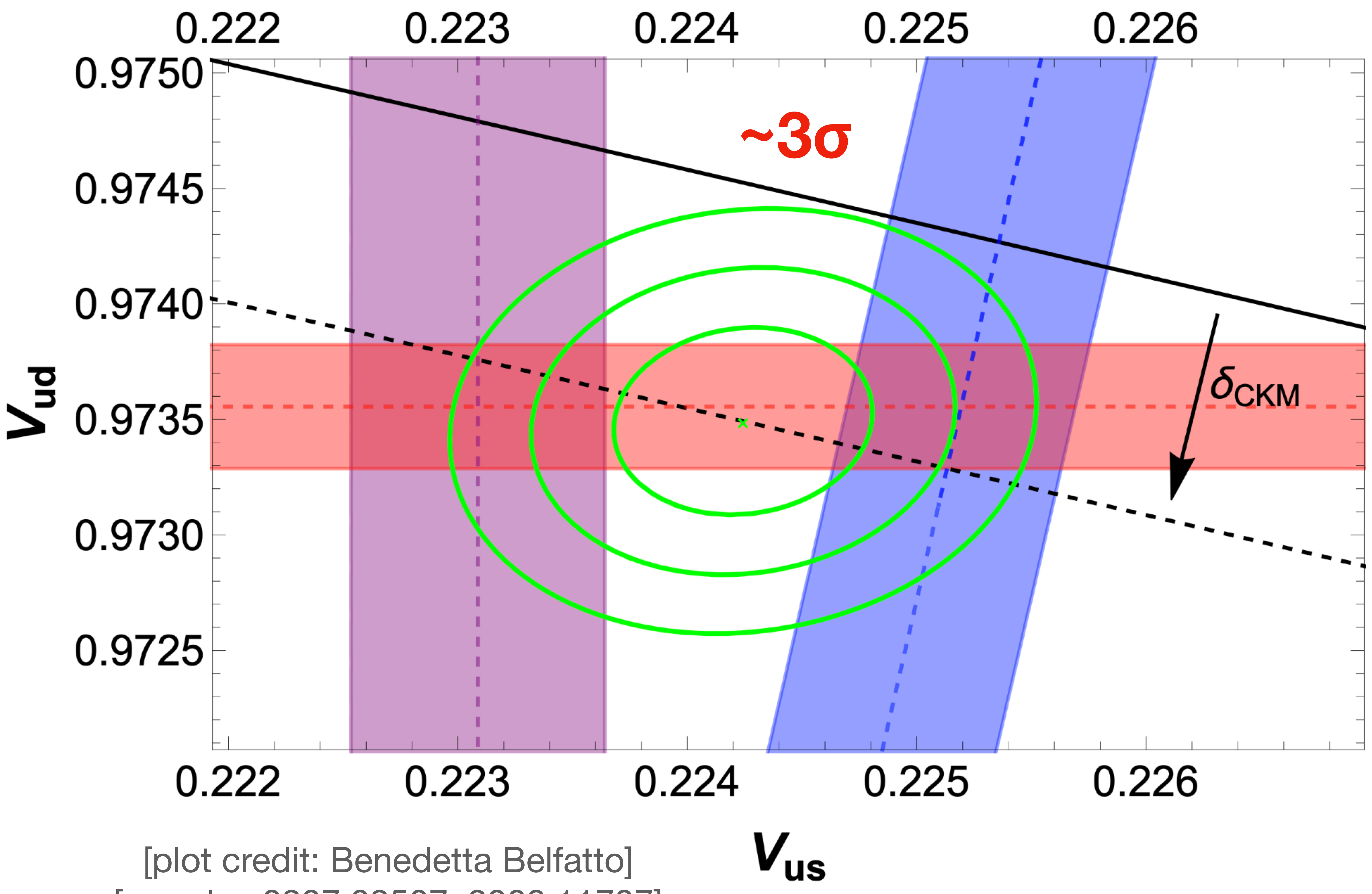


[plot credit: Benedetta Belfatto]
[see also 2207.02507, 2208.11707]

Possible New Physics scenarios:

- four fermion operators in $d \to u\, e\, \nu$
- four fermion operator in $\mu \to e\, \nu\, \nu$
- modified $W \to \mu\, \nu$ or $W \to u\, d$ couplings
- vectorlike quarks, rescaling of G_F vs G_μ, …

See [2207.02507] for review on possible UV models

S_1 and S_3 - global analysis

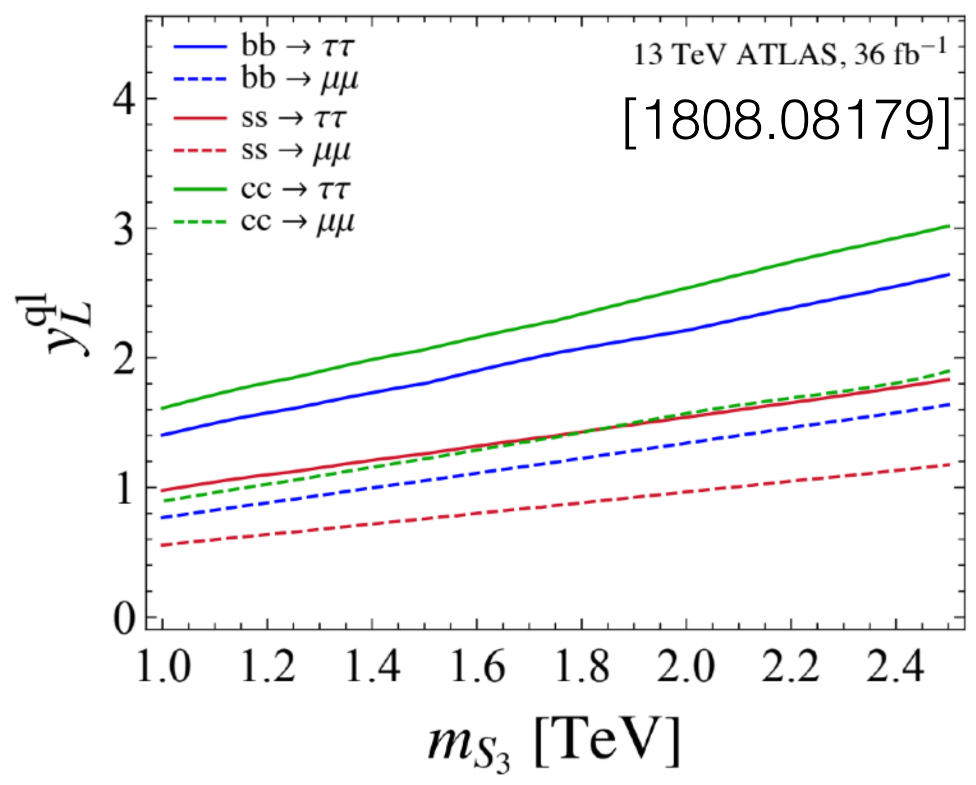
Using the complete one-loop matching to SMEFT, we include in our analysis the following observables.

All these are used to build a **global likelihood**.

$$-2\log\mathcal{L} \equiv \chi^2(\lambda_x, M_x) = \sum_i \frac{(\mathcal{O}_i(\lambda_x, M_x) - \mu_i)^2}{\sigma_i^2}$$

Observable	Experimental bounds
Z boson couplings	App. A.12
$\delta g^Z_{\mu_L}$	$(0.3 \pm 1.1)10^{-3}$ [99]
$\delta g^Z_{\mu_R}$	$(0.2 \pm 1.3)10^{-3}$ [99]
$\delta g^Z_{\tau_L}$	$(-0.11 \pm 0.61)10^{-3}$ [99]
$\delta g^Z_{\tau_R}$	$(0.66 \pm 0.65)10^{-3}$ [99]
$\delta g^Z_{b_L}$	$(2.9 \pm 1.6)10^{-3}$ [99]
$\delta g^Z_{c_R}$	$(-3.3 \pm 5.1)10^{-3}$ [99]
N_ν	2.9963 ± 0.0074 [100]

Drell-Yan



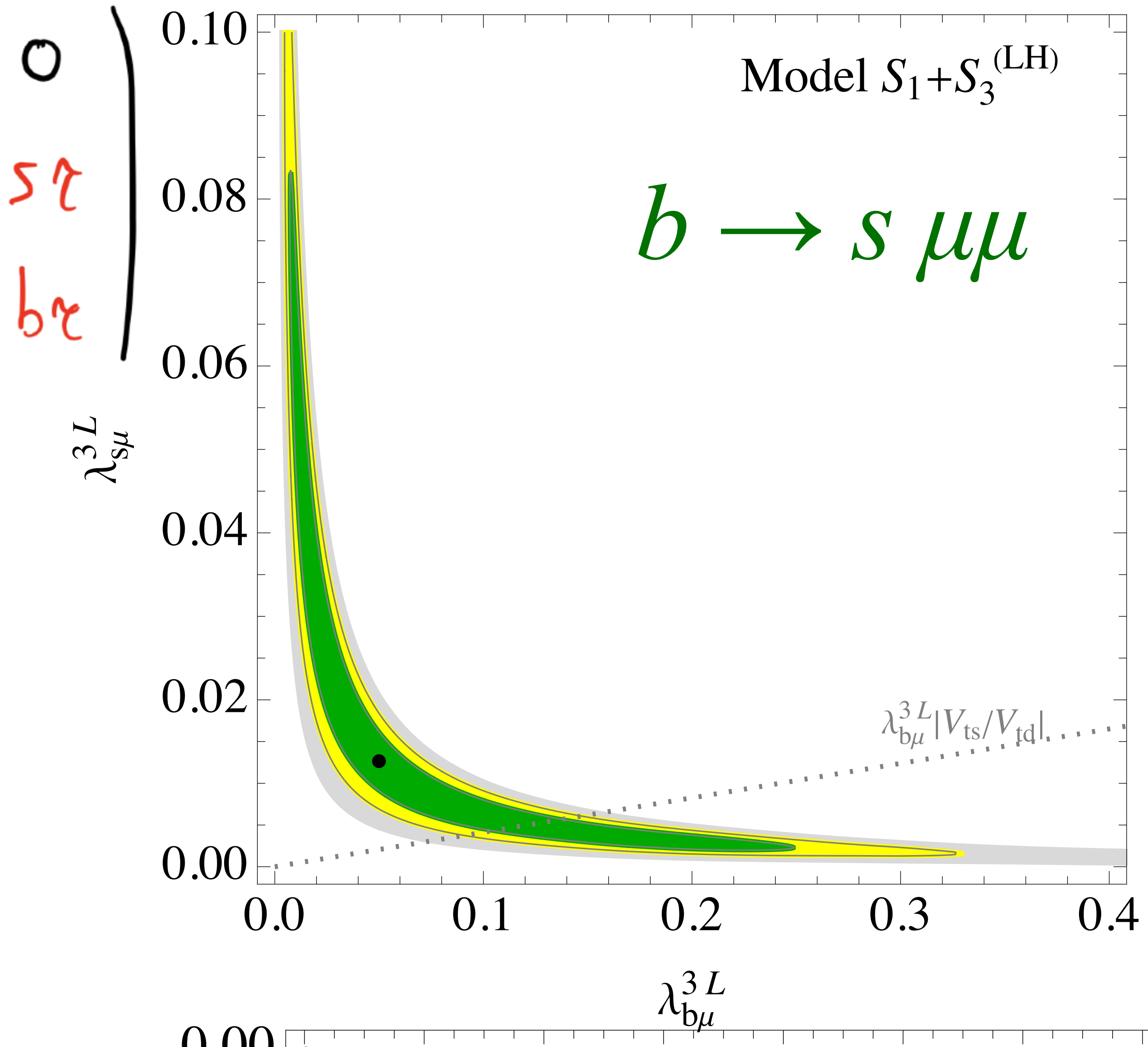
Observable	SM prediction	Experimental bounds
$b \to s\ell\ell$ observables		[37]
$\Delta\mathcal{C}_9^{sb\mu\mu}$	0	-0.43 ± 0.09 [79]
$\mathcal{C}_9^{\rm univ}$	0	-0.48 ± 0.24 [79]
$b \to c\tau(\ell)\nu$ observables		[37]
R_D	0.299 ± 0.003 [12]	$0.34 \pm 0.027 \pm 0.013$ [12]
R_D^*	0.258 ± 0.005 [12]	$0.295 \pm 0.011 \pm 0.008$ [12]
$P_\tau^{D^*}$	-0.488 ± 0.018 [80]	$-0.38 \pm 0.51 \pm 0.2 \pm 0.018$ [7]
F_L	0.470 ± 0.012 [80]	$0.60 \pm 0.08 \pm 0.038 \pm 0.012$ [81]
$\mathcal{B}(B_c^+ \to \tau^+\nu)$	2.3%	$<10\%$ (95% CL) [82]
$R_D^{\mu/e}$	1	0.978 ± 0.035 [83, 84]
$b \to s\nu\nu$ and $s \to d\nu\nu$		[37]
R_K^ν	1 [85]	< 4.7 [86]
$R_{K^*}^\nu$	1 [85]	< 3.2 [86]
$b \to d\mu\mu$ and $b \to dee$		App. A.5
$\mathcal{B}(B^0 \to \mu\mu)$	$(1.06 \pm 0.09) \times 10^{-10}$ [87, 88]	$(1.1 \pm 1.4) \times 10^{-10}$ [89, 90]
$\mathcal{B}(B^+ \to \pi^+\mu\mu)$	$(2.04 \pm 0.21) \times 10^{-8}$ [87, 88]	$(1.83 \pm 0.24) \times 10^{-8}$ [89, 90]
$\mathcal{B}(B^0 \to ee)$	$(2.48 \pm 0.21) \times 10^{-15}$ [87, 88]	$< 8.3 \times 10^{-8}$ [51]
$\mathcal{B}(B^+ \to \pi^+ee)$	$(2.04 \pm 0.24) \times 10^{-8}$ [87, 88]	$< 8 \times 10^{-8}$ [51]
B LFV decays		[37]
$\mathcal{B}(B_d \to \tau^\pm\mu^\mp)$	0	$< 1.4 \times 10^{-5}$ [91]
$\mathcal{B}(B_s \to \tau^\pm\mu^\mp)$	0	$< 4.2 \times 10^{-5}$ [91]
$\mathcal{B}(B^+ \to K^+\tau^-\mu^+)$	0	$< 5.4 \times 10^{-5}$ [92]
$\mathcal{B}(B^+ \to K^+\tau^+\mu^-)$	0	$< 3.3 \times 10^{-5}$ [92] $< 4.5 \times 10^{-5}$ [93]

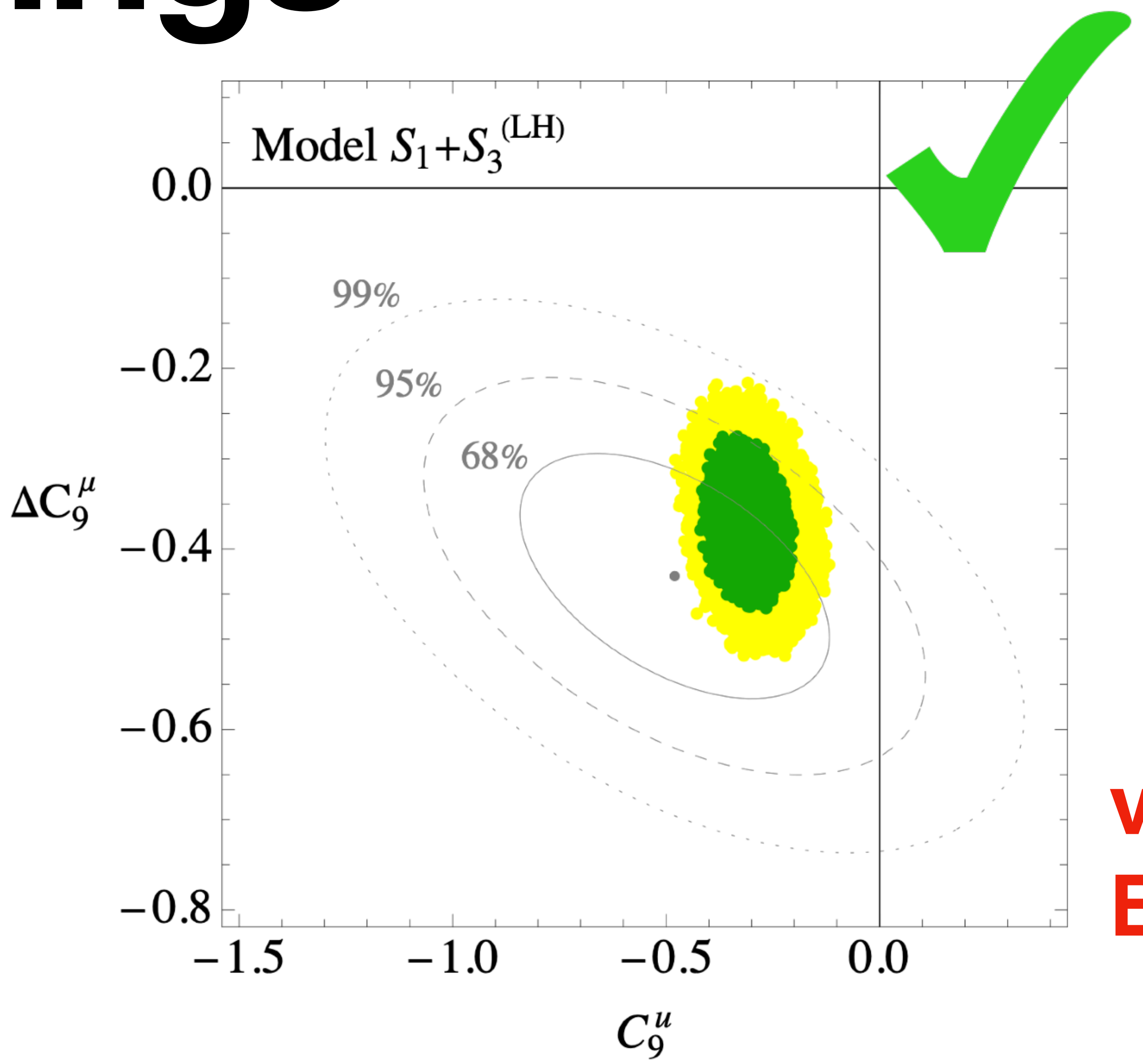
Observable	SM prediction	Experimental bounds
D leptonic decay		[37] and App. A.4
$\mathcal{B}(D_s \to \tau\nu)$	$(5.169 \pm 0.004) \times 10^{-2}$ [94]	$(5.48 \pm 0.23) \times 10^{-2}$ [51]
$\mathcal{B}(D^0 \to \mu\mu)$	$\approx 10^{-11}$ [95]	$< 7.6 \times 10^{-9}$ [96]
$\mathcal{B}(D^+ \to \pi^+\mu\mu)$	$\mathcal{O}(10^{-12})$ [97]	$< 7.4 \times 10^{-8}$ [98]
Rare Kaon decays ($\nu\nu$)		App. A.1
$\mathcal{B}(K^+ \to \pi^+\nu\nu)$	8.64×10^{-11} [99]	$(11.0 \pm 4.0) \times 10^{-11}$ [100]
$\mathcal{B}(K_L \to \pi^0\nu\nu)$	3.4×10^{-11} [99]	$< 3.6 \times 10^{-9}$ [101]
Rare Kaon decays ($\ell\ell$)		App. A.3 and A.2
$\mathcal{B}(K_L \to \mu\mu)_{SD}$	8.4×10^{-10} [102]	$< 2.5 \times 10^{-9}$ [76]
$\mathcal{B}(K_S \to \mu\mu)$	$(5.18 \pm 1.5) \times 10^{-12}$ [76, 103, 104]	$< 2.5 \times 10^{-10}$ [105]
$\mathcal{B}(K_L \to \pi^0\mu\mu)$	$(1.5 \pm 0.3) \times 10^{-11}$ [106]	$< 4.5 \times 10^{-10}$ [107]
$\mathcal{B}(K_L \to \pi^0 ee)$	$(3.2^{+1.2}_{-0.8}) \times 10^{-11}$ [108]	$< 2.8 \times 10^{-10}$ [109]
LFV in Kaon decays		App. A.3 and A.2
$\mathcal{B}(K_L \to \mu e)$	0	$< 4.7 \times 10^{-12}$ [110]
$\mathcal{B}(K^+ \to \pi^+\mu^-e^+)$	0	$< 7.9 \times 10^{-11}$ [111]
$\mathcal{B}(K^+ \to \pi^+e^-\mu^+)$	0	$< 1.5 \times 10^{-11}$ [112]
CP-violation		App. A.8
ϵ'_K/ϵ_K	$(15 \pm 7) \times 10^{-4}$ [113]	$(16.6 \pm 2.3) \times 10^{-4}$ [51]

Observable	SM prediction	Experimental bounds
$\Delta F = 2$ processes		[37]
$B^0 - \overline{B}^0$: $\lvert C^1_{B_d}\rvert$	0	$< 9.1 \times 10^{-7}$ TeV^{-2} [114, 115]
$B^0_s - \overline{B}^0_s$: $\lvert C^1_{B_s}\rvert$	0	$< 2.0 \times 10^{-5}$ TeV^{-2} [114, 115]
$K^0 - \overline{K}^0$: Re$[C^1_K]$	0	$< 8.0 \times 10^{-7}$ TeV^{-2} [114, 115]
$K^0 - \overline{K}^0$: Im$[C^1_K]$	0	$< 3.0 \times 10^{-9}$ TeV^{-2} [114, 115]
$D^0 - \overline{D}^0$: Re$[C^1_D]$	0	$< 3.6 \times 10^{-7}$ TeV^{-2} [114, 115]
$D^0 - \overline{D}^0$: Im$[C^1_D]$	0	$< 2.2 \times 10^{-8}$ TeV^{-2} [114, 115]
$D^0 - \overline{D}^0$: Re$[C^4_D]$	0	$< 3.2 \times 10^{-8}$ TeV^{-2} [114, 115]
$D^0 - \overline{D}^0$: Im$[C^4_D]$	0	$< 1.2 \times 10^{-9}$ TeV^{-2} [114, 115]
$D^0 - \overline{D}^0$: Re$[C^5_D]$	0	$< 2.7 \times 10^{-7}$ TeV^{-2} [114, 115]
$D^0 - \overline{D}^0$: Im$[C^5_D]$	0	$< 1.1 \times 10^{-8}$ TeV^{-2} [114, 115]
LFU in τ decays		[37]
$\lvert g_\mu/g_e\rvert^2$	1	1.0036 ± 0.0028 [116]
$\lvert g_\tau/g_\mu\rvert^2$	1	1.0022 ± 0.0030 [116]
$\lvert g_\tau/g_e\rvert^2$	1	1.0058 ± 0.0030 [116]
LFV observables		[37]
$\mathcal{B}(\tau \to \mu\phi)$	0	$< 1.00 \times 10^{-7}$ [117]
$\mathcal{B}(\tau \to 3\mu)$	0	$< 2.5 \times 10^{-8}$ [118]
$\mathcal{B}(\tau \to \mu\gamma)$	0	$< 5.2 \times 10^{-8}$ [119]
$\mathcal{B}(\tau \to e\gamma)$	0	$< 3.9 \times 10^{-8}$ [119]
$\mathcal{B}(\mu \to e\gamma)$	0	$< 5.0 \times 10^{-13}$ [120]
$\mathcal{B}(\mu \to 3e)$	0	$< 1.2 \times 10^{-12}$ [121]
$\mathcal{B}^{\rm (Ti)}_{\mu e}$	0	$< 5.1 \times 10^{-12}$ [122]
$\mathcal{B}^{\rm (Au)}_{\mu e}$	0	$< 8.3 \times 10^{-13}$ [123]
EDMs		[37]
$\lvert d_e\rvert$	$< 10^{-44}$ e · cm [124, 125]	$< 1.3 \times 10^{-29}$ e · cm [126]
$\lvert d_\mu\rvert$	$< 10^{-42}$ e · cm [125]	$< 1.9 \times 10^{-19}$ e · cm [127]
d_τ	$< 10^{-41}$ e · cm [125]	$(1.15 \pm 1.70) \times 10^{-17}$ e · cm [37]
d_n	$< 10^{-33}$ e · cm [128]	$< 2.1 \times 10^{-26}$ e · cm [129]
Anomalous Magnetic Moments		[37]
$a_e - a_e^{SM}$	$\pm 2.3 \times 10^{-13}$ [130, 131]	$(-8.9 \pm 3.6) \times 10^{-13}$ [132]
$a_\mu - a_\mu^{SM}$	$\pm 43 \times 10^{-11}$ [42]	$(279 \pm 76) \times 10^{-11}$ [40, 42]
$a_\tau - a_\tau^{SM}$	$\pm 3.9 \times 10^{-8}$ [130]	$(-2.1 \pm 1.7) \times 10^{-7}$ [133]

S_1 and S_3 — only LH couplings

$$\lambda^{1L} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & s\tau \\ 0 & 0 & b\tau \end{pmatrix} \quad \lambda^{3L} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & s\mu & s\tau \\ 0 & b\mu & b\tau \end{pmatrix}$$



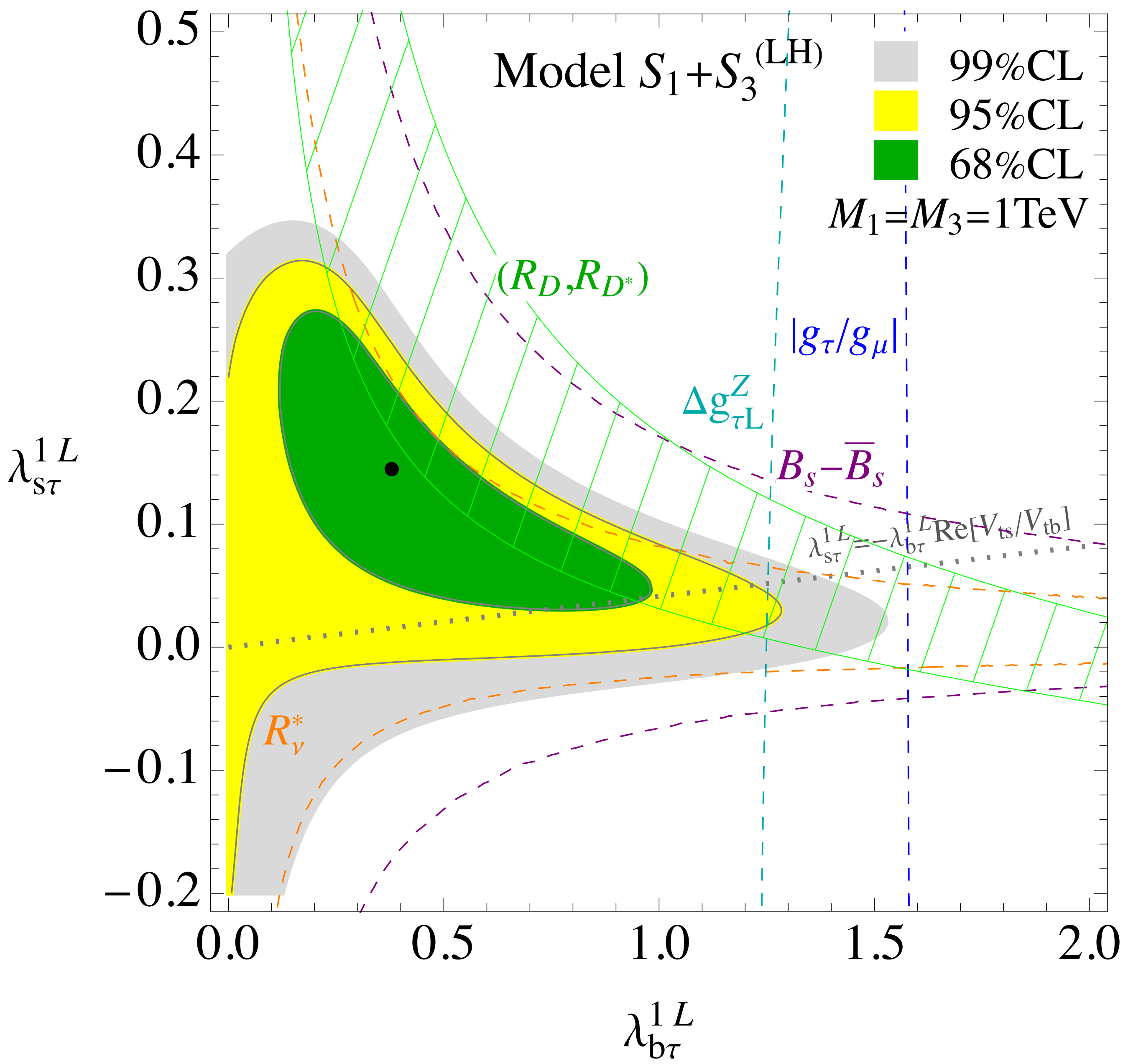


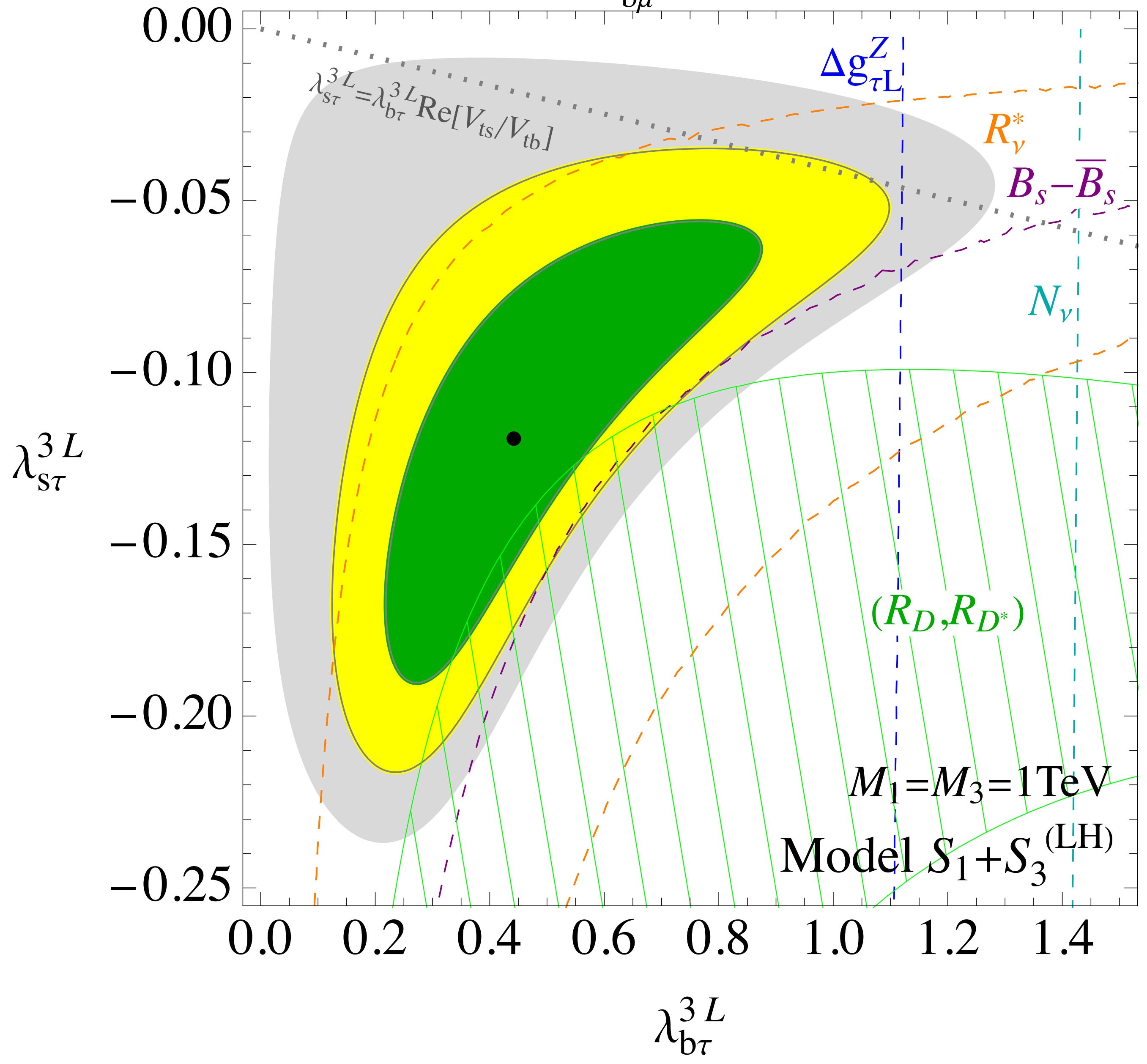
very good fit of B-anomalies

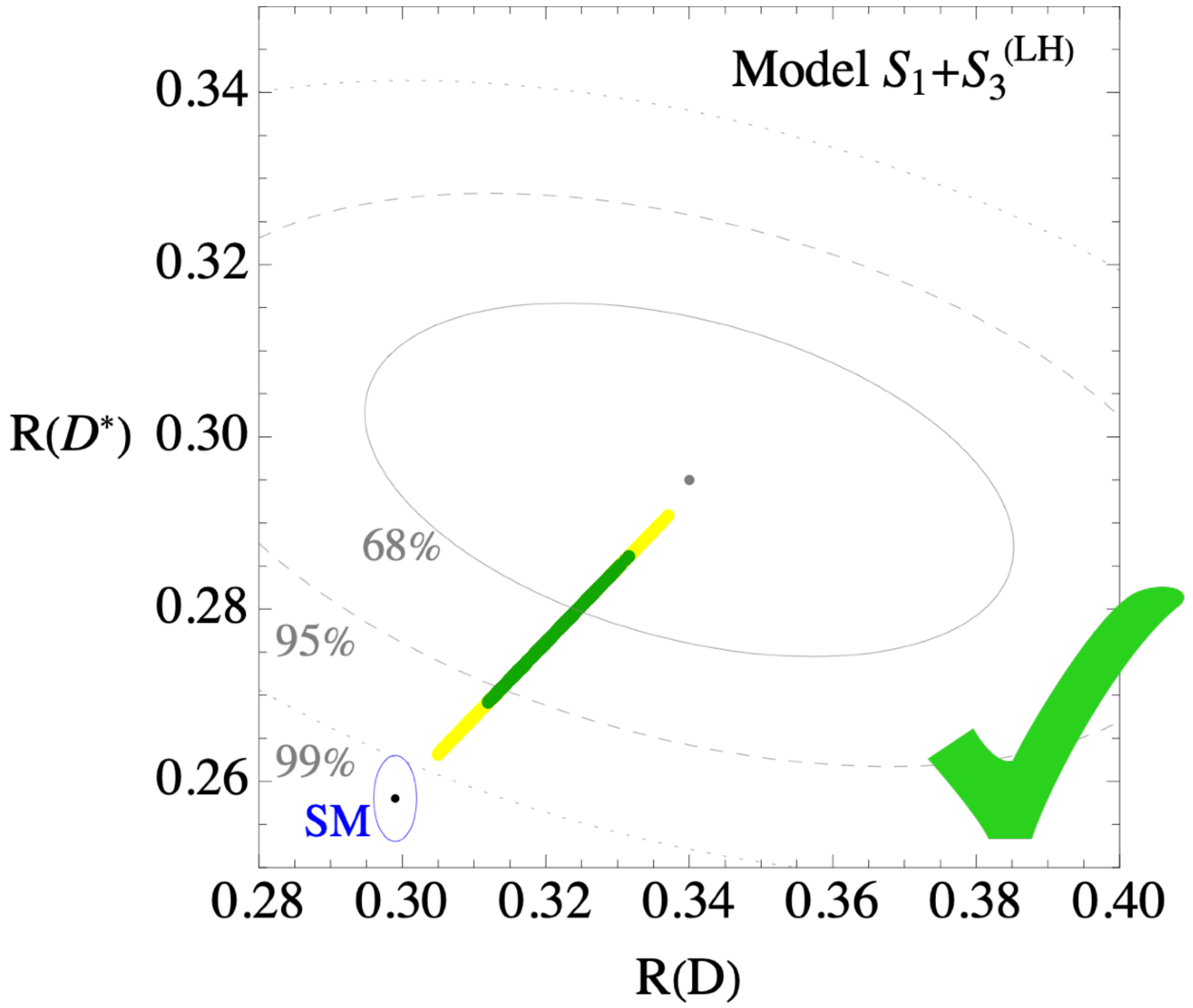
$\lambda^{1R} = 0$ → Cannot fit $(g-2)_\mu$

(see backup slides for a S_1+S_3 scenario that addresses also the muon magnetic moment)

R(D(*))







Plots updated w.r.t. [v3:2008.09548]

S_1 and S_3 — only LH couplings

$$\lambda^{1L} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & s\tau \\ 0 & 0 & b\tau \end{pmatrix} \quad \lambda^{3L} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & s\mu & s\tau \\ 0 & b\mu & b\tau \end{pmatrix}$$

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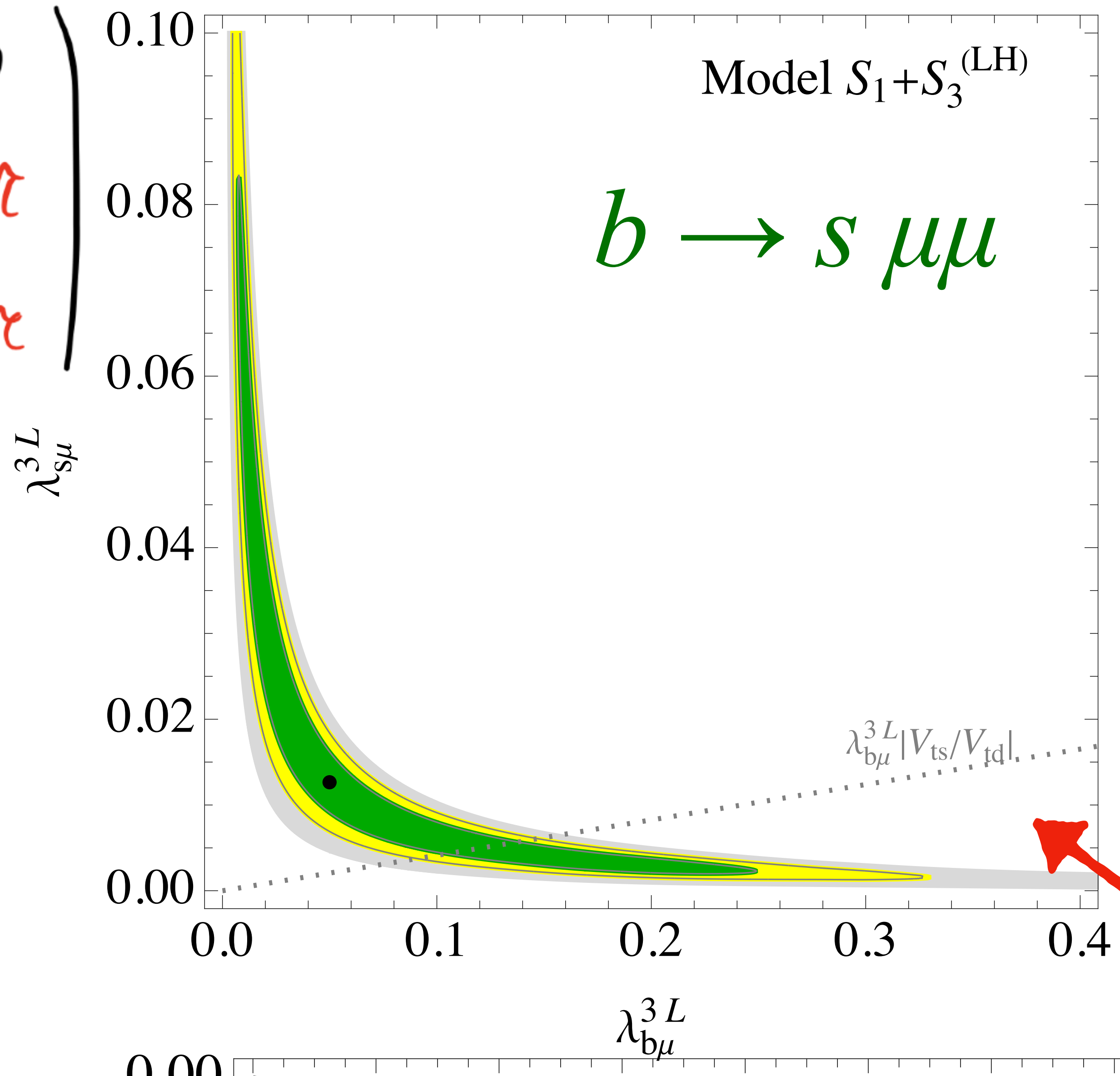

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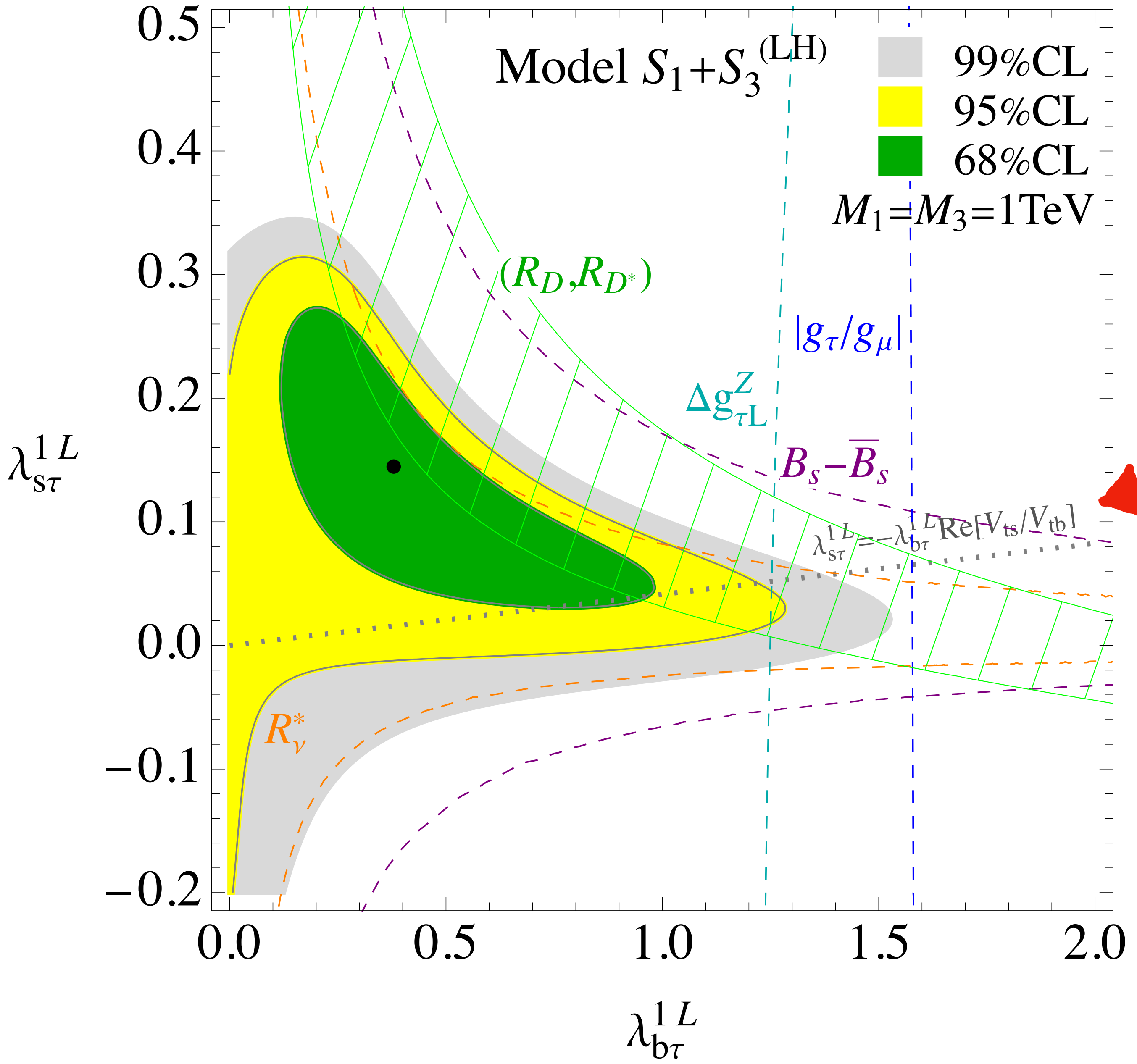
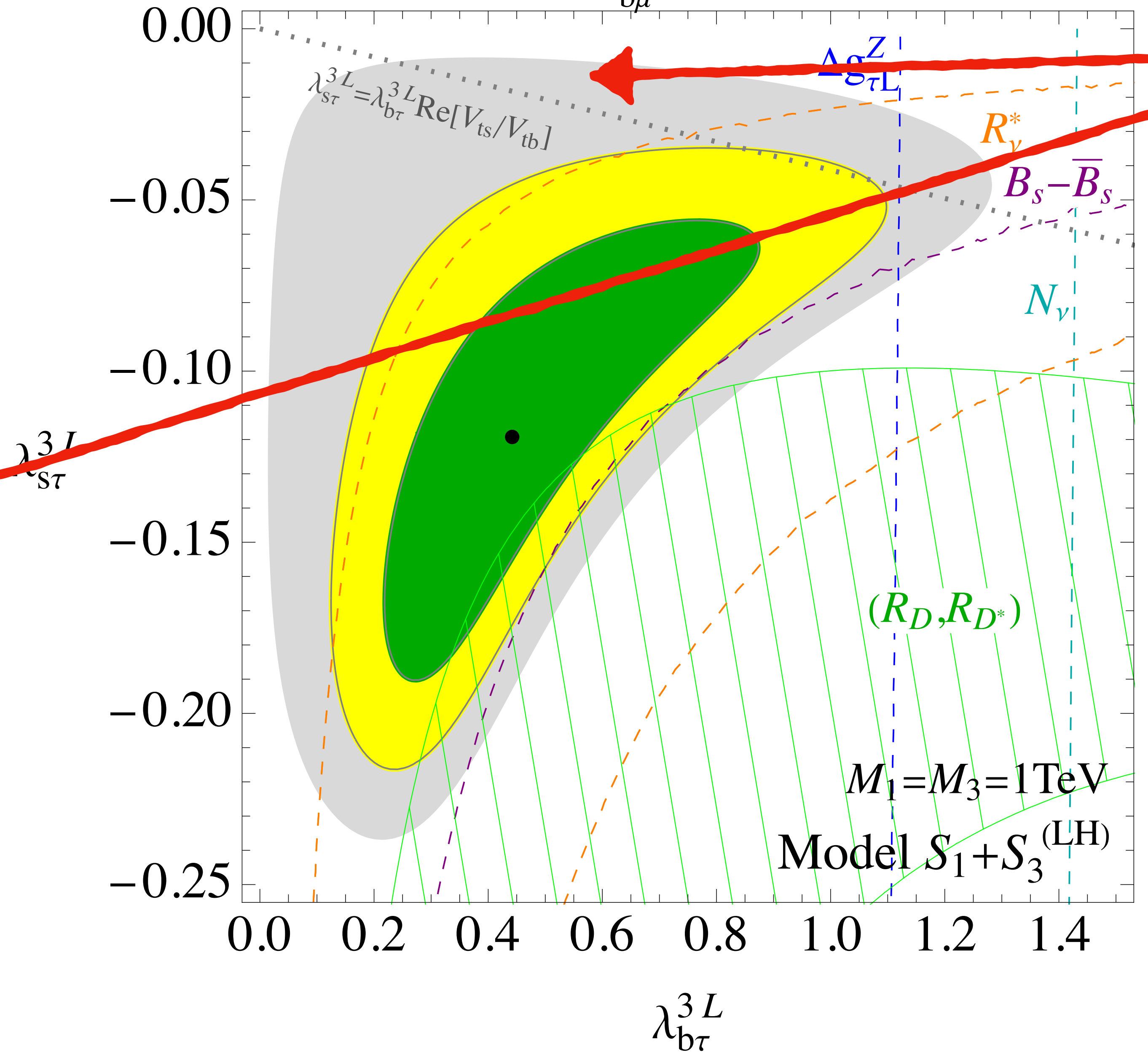




The relation between couplings to s-quark and b-quark is compatible with a U(2)⁵ flavour symmetry, that would predict:

$$\lambda_{s\alpha} = c_{U(2)} V_{ts} \lambda_{b\alpha}$$

$c_{U(2)} = 1$

$c_{U(2)} \sim \mathcal{O}(1)$ e.g. 3 - 5

See also Buttazzo, Greljo, Isidori, D.M. 1706.07808

Plots updated w.r.t. [v3:2008.09548]

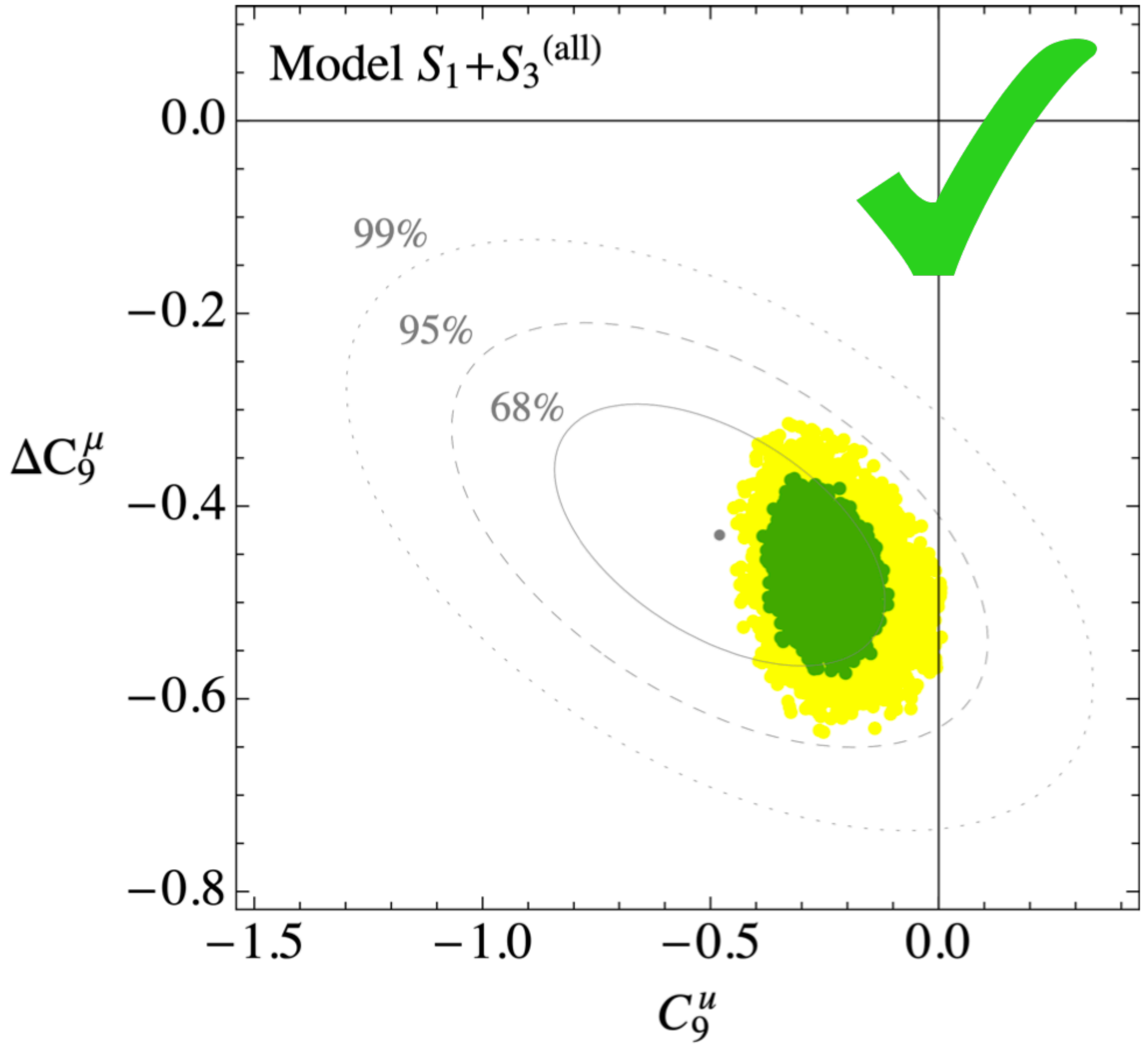
S_1 and S_3 : $R(K^{(*)})$ + $R(D^{(*)})$ + $(g-2)_\mu$

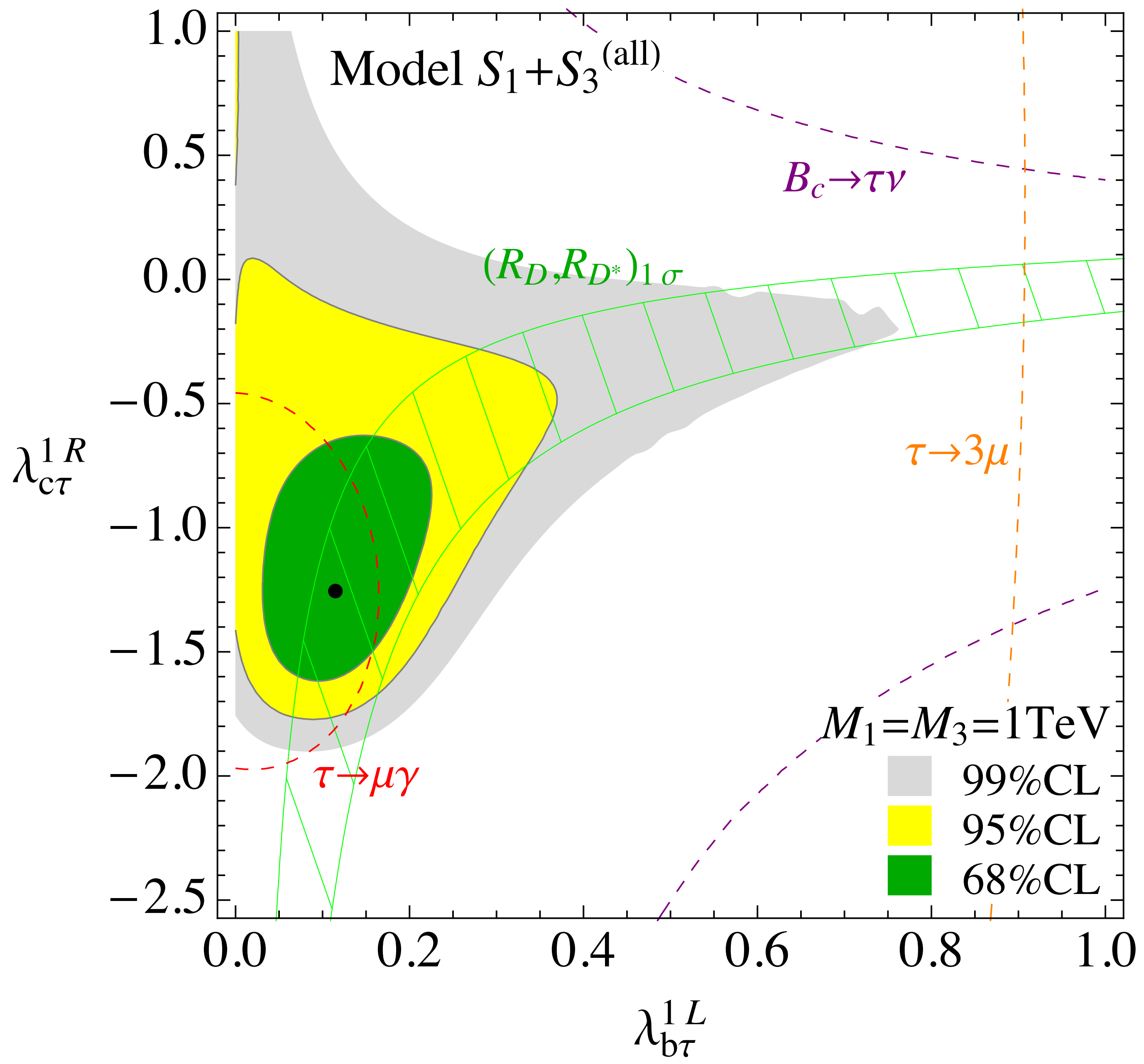
No a-priori flavour structure imposed

$$\lambda^{1L} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & s\tau \\ 0 & b\mu & b\tau \end{pmatrix} \qquad \lambda^{3L} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & s\mu & s\tau \\ 0 & b\mu & b\tau \end{pmatrix}$$

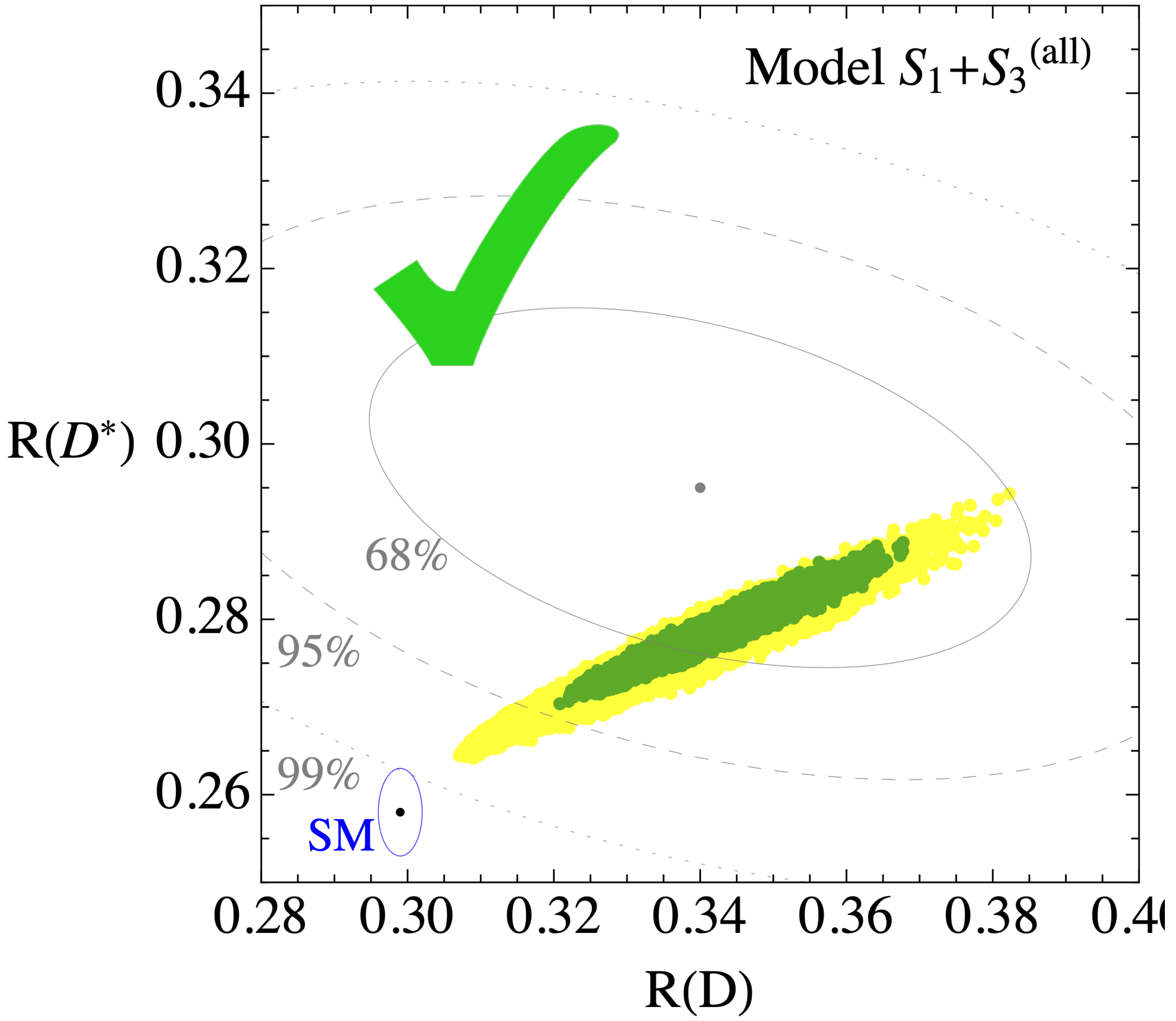
$$\lambda^{1R} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & c\tau \\ 0 & t\mu & t\tau \end{pmatrix}$$

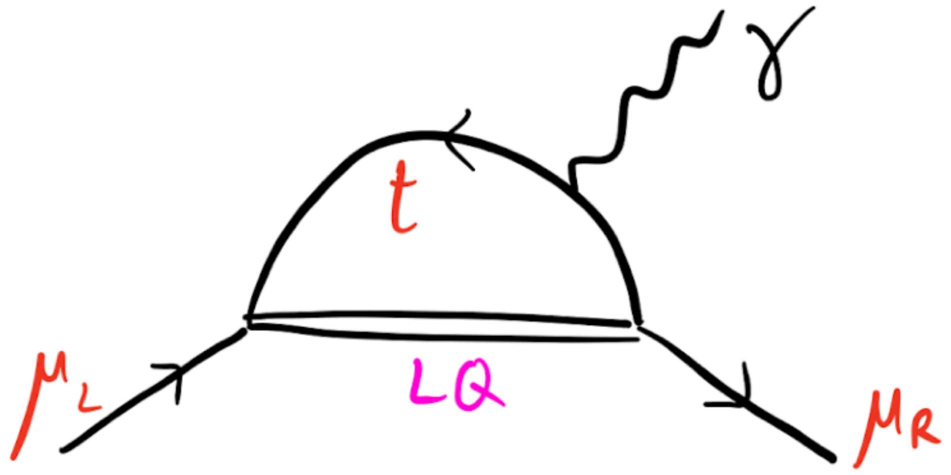
$b \rightarrow s\,\ell\,\ell$



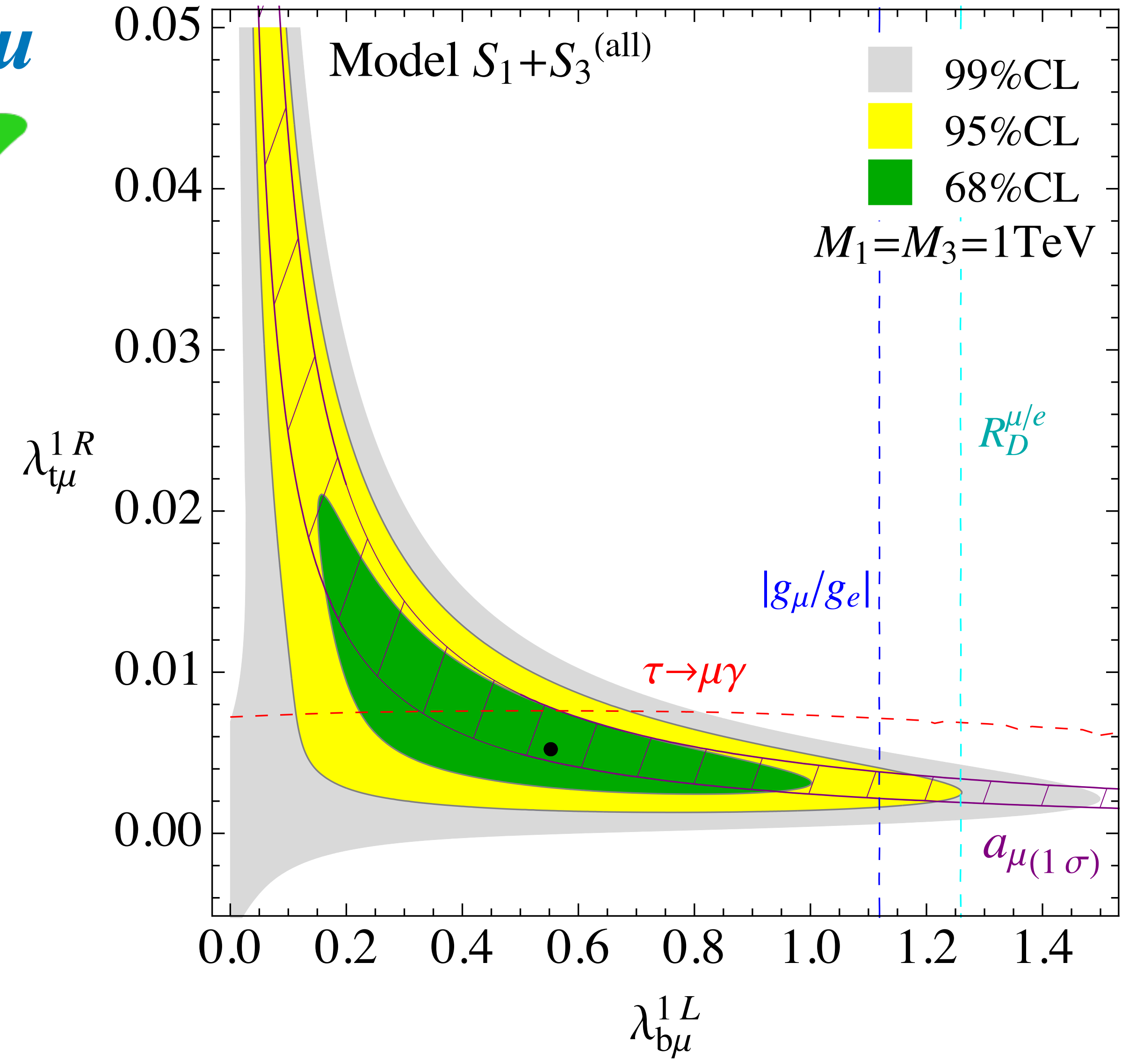


$R(D^{(*)})$





$(g-2)_\mu$



Very good fit of all anomalies!

A Fundamental Composite Higgs + LQ Model

$$G = SU(10)_L \times SU(10)_R \times U(1)_V \xrightarrow{\langle \bar{\Psi}_i \Psi_j \rangle = -B_0 f^2 \delta_{ij}} H = SU(10)_V \times U(1)_V$$

Like QCD pions, the pNGB are composite states of HC-fermion bilinears: $\bar{\Psi}\Psi$

Several states are present at the **TeV scale** as pNGB, including

Two Higgs doublets: $H_{SM}\,,\ \tilde{H}_2 \sim \mathbf{(1,2)}_{1/2}$

Singlet and Triplet LQ: $S_1 \sim \mathbf{(3,1)}_{-1/3} \quad + \quad S_1 \sim \mathbf{(3,3)}_{-1/3}$

H and LQ are close partners!!

$$H_1 \sim i\sigma^2(\bar{\Psi}_L \Psi_N)$$
$$H_2 \sim (\bar{\Psi}_E \Psi_L)$$
$$S_1 \sim (\bar{\Psi}_Q \Psi_L)$$
$$S_3 \sim (\bar{\Psi}_Q \sigma^a \Psi_L)$$

Coupling with SM fermions from 4-fermion operators

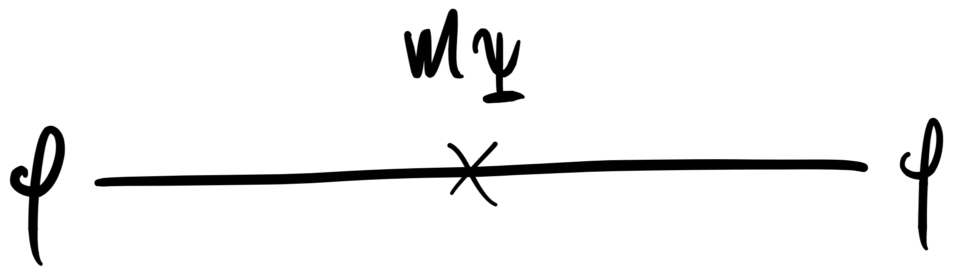
$$\mathcal{L}_{4-\mathrm{Fermi}} \sim \frac{c_{\psi\Psi}}{\Lambda_t^2} \bar{\psi}_{\mathrm{SM}} \psi_{\mathrm{SM}} \bar{\Psi}\Psi \quad \xrightarrow{E \lesssim \Lambda_{HC}} \quad \sim y_{\psi\phi}\, \bar{\psi}_{\mathrm{SM}} \psi_{\mathrm{SM}}\, \phi + \ldots$$

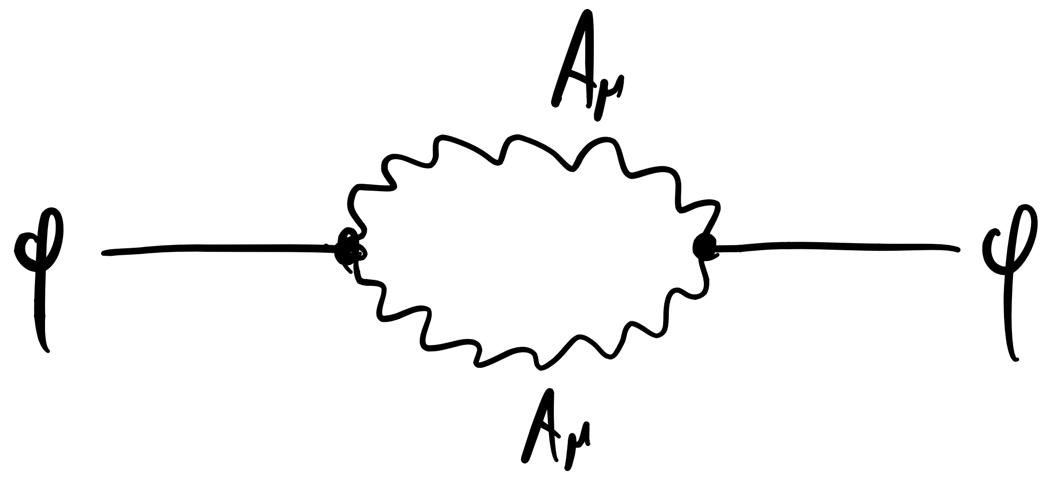
Yukawas & LQ couplings

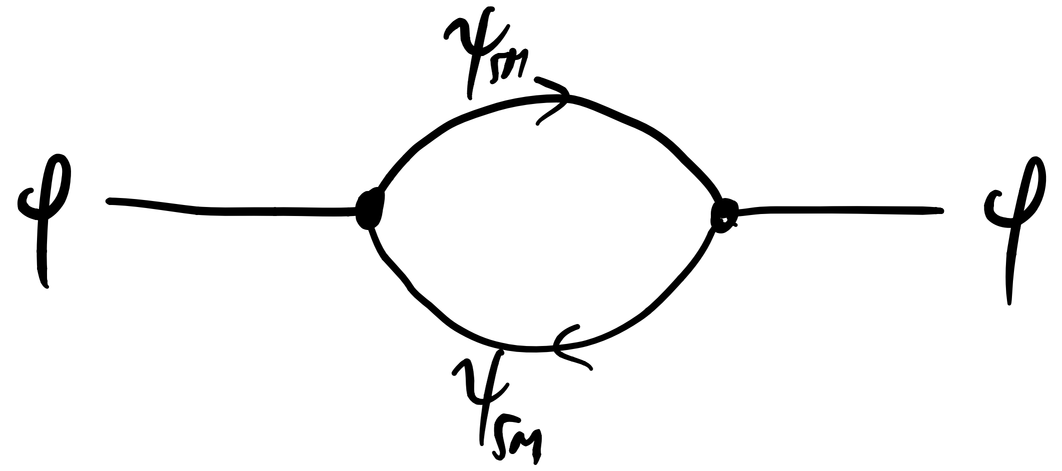
+ approximate $U(2)^5$ flavor symmetry to protect from unwanted flavor violation

Scalar Potential: NDA + symmetry

The pNGB potential arises at 1-loop from all the explicit breaking terms







NDA + spurion analysis

$$m^2_{(\bar\Psi_i \Psi_j)} = B_0 (m_i + m_j)$$

$$V_{\mathcal{G}} = -\frac{3 f^2 \Lambda^2_{HC}}{16\pi^2} \sum_X c_X \mathrm{Tr}\left[\mathcal{G}^L_X U \mathcal{G}^R_X U^\dagger\right]$$

$$V_t = -\frac{c_t y_t^2 N_c \Lambda^2_{HC}}{16\pi^2} |H_1 - H_2|^2$$

$$V_{\mathrm{LQ}} = -\frac{(c_1 g_1^2 + c_1^u g_1^{u2})\Lambda^2_{HC}}{8\pi^2}|S_1|^2 - \frac{c_3 g_3^2 \Lambda^2_{HC}}{8\pi^2}|S_3|^2$$

valence	irrep.	valence	irrep.
$H_1 \sim i\sigma^2(\bar\Psi_L \Psi_N)$	$(\mathbf{1},\mathbf{2})_{1/2}$	$H_2 \sim (\bar\Psi_E \Psi_L)$	$(\mathbf{1},\mathbf{2})_{1/2}$
$S_1 \sim (\bar\Psi_Q \Psi_L)$	$(\bar{\mathbf{3}},\mathbf{1})_{1/3}$	$S_3 \sim (\bar\Psi_Q \sigma^a \Psi_L)$	$(\bar{\mathbf{3}},\mathbf{3})_{1/3}$
$\omega^\pm \sim (\bar\Psi_N \Psi_E)$	$(\mathbf{1},\mathbf{1})_{-1}$	$\Pi_L \sim (\bar\Psi_L \sigma^a \Psi_L)$	$(\mathbf{1},\mathbf{3})_0$
$\tilde R_2 \sim (\bar\Psi_E \Psi_Q)$	$(\mathbf{3},\mathbf{2})_{1/6}$	$T_2 \sim (\bar\Psi_Q \Psi_N)$	$(\bar{\mathbf{3}},\mathbf{2})_{5/6}$
$\tilde\pi_1 \sim (\bar\Psi_Q T^A \Psi_Q)$	$(\mathbf{8},\mathbf{1})_0$	$\tilde\pi_3 \sim (\bar\Psi_Q T^A \sigma^a \Psi_Q)$	$(\mathbf{8},\mathbf{3})_0$
$\Pi_Q \sim (\bar\Psi_Q \sigma^a \Psi_Q)$	$(\mathbf{1},\mathbf{3})_0$	$\eta_i \sim 3 \times c_i^a(\bar\Psi_a \Psi_a)$	$(\mathbf{1},\mathbf{1})_0$

pNGB spectrum: example