Constraints on Z' solutions to the flavor anomalies with asymptotic safety

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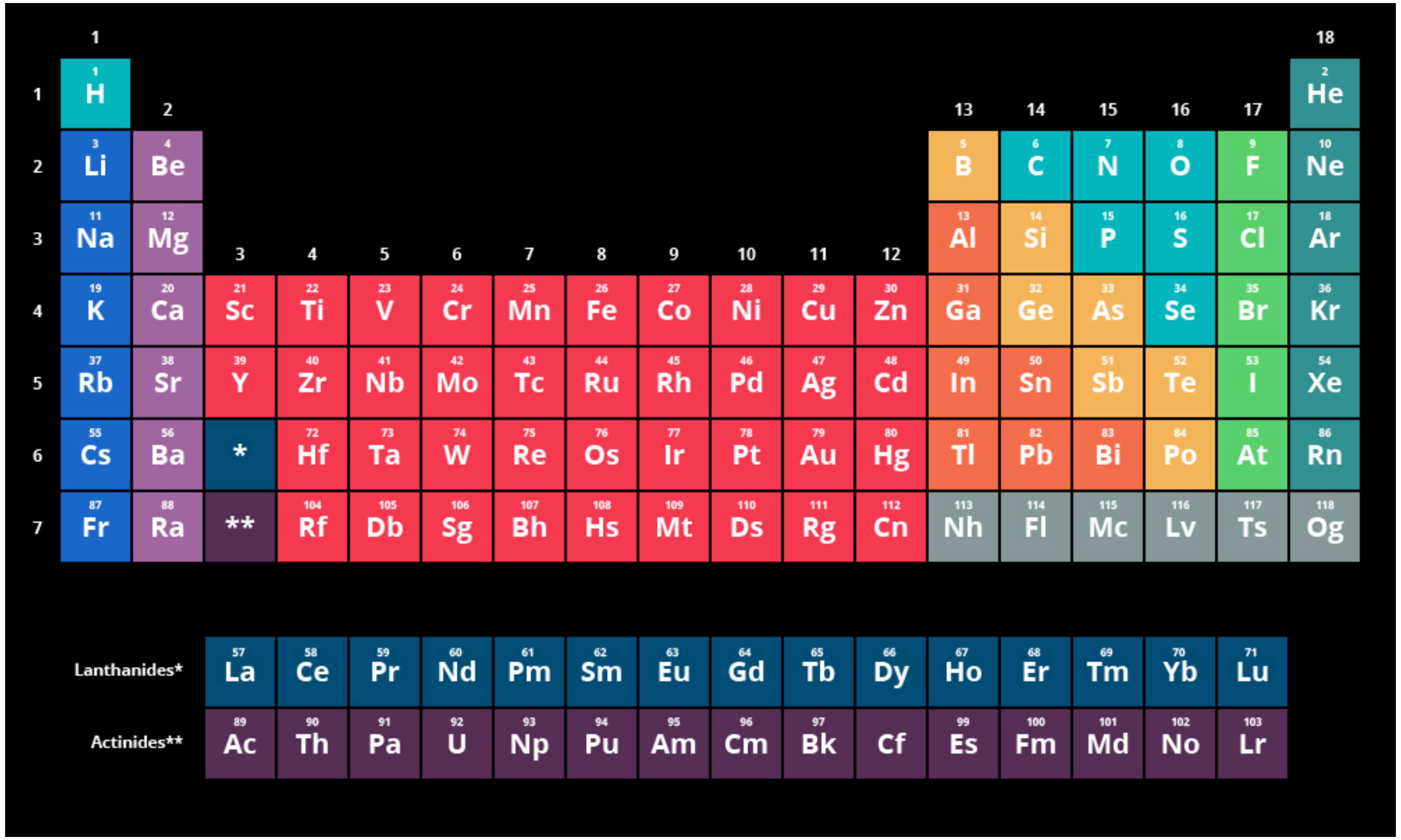
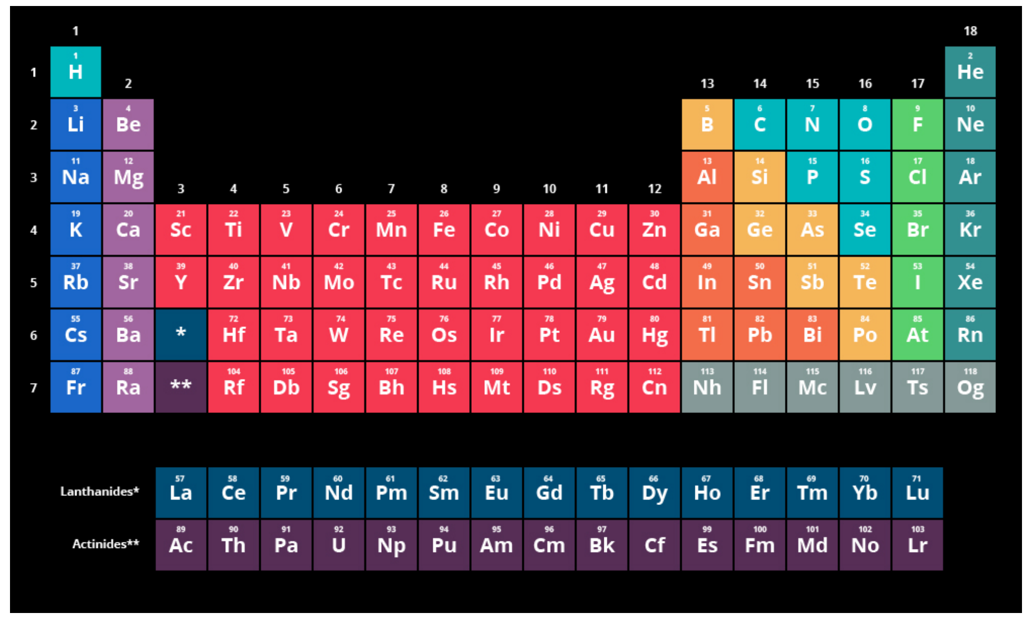
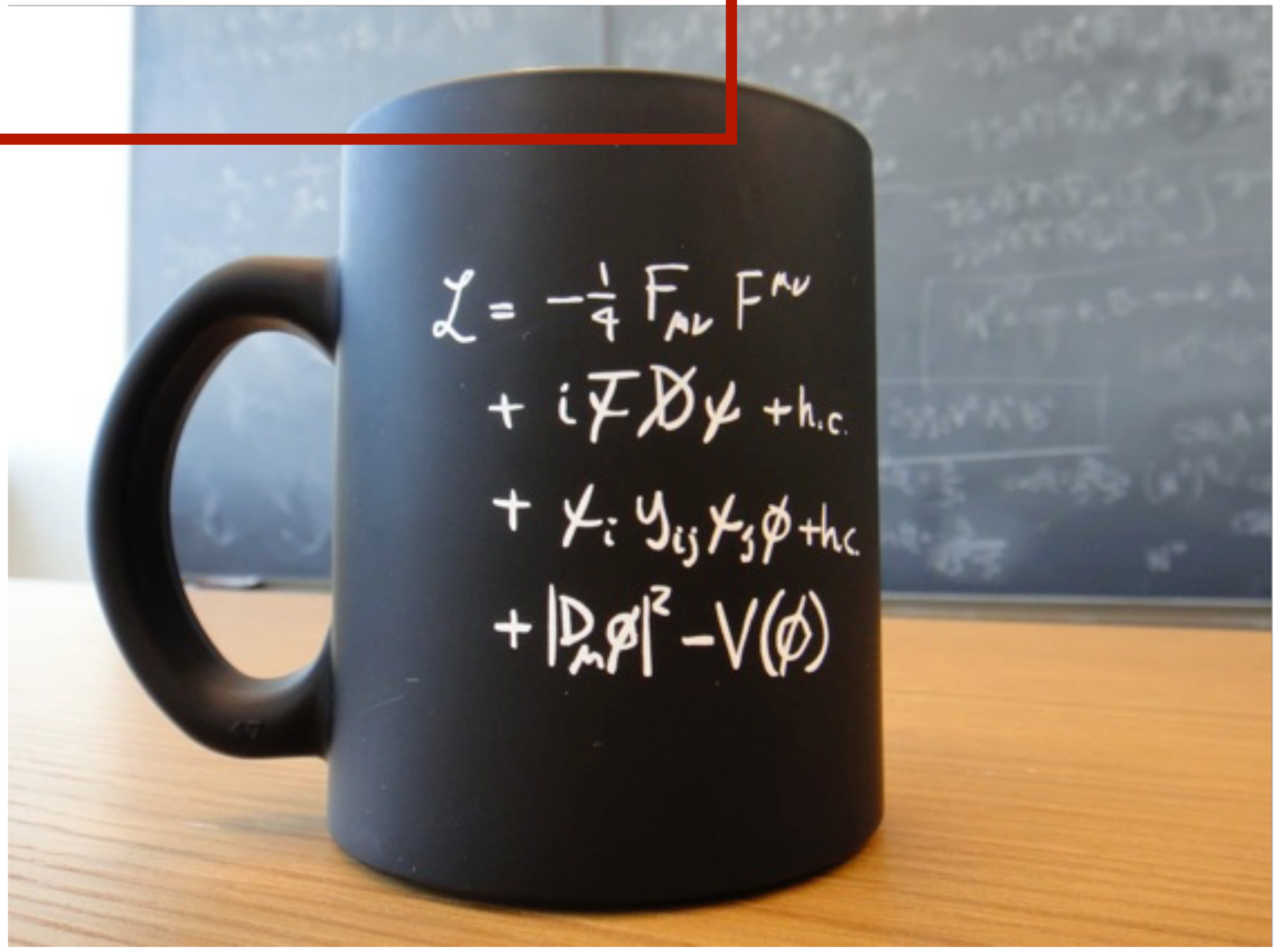
The Standard Model

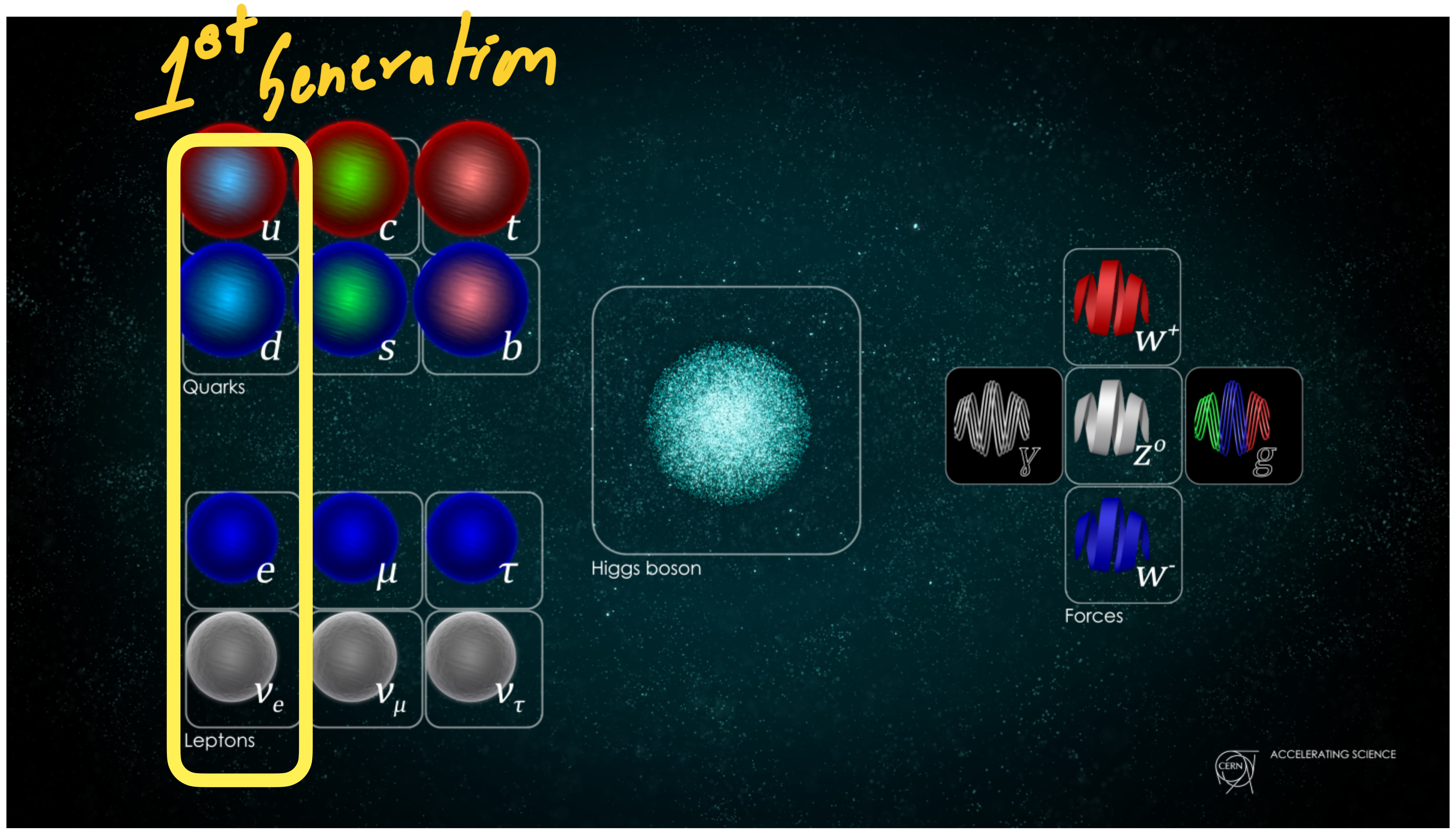


The Standard Model

- Fermions
    - 6 flavors of quarks and leptons
    - 3 generations
- Gauge bosons
    - Photon (γ), W^{+}, Z, g
- Scalar
    - Higgs



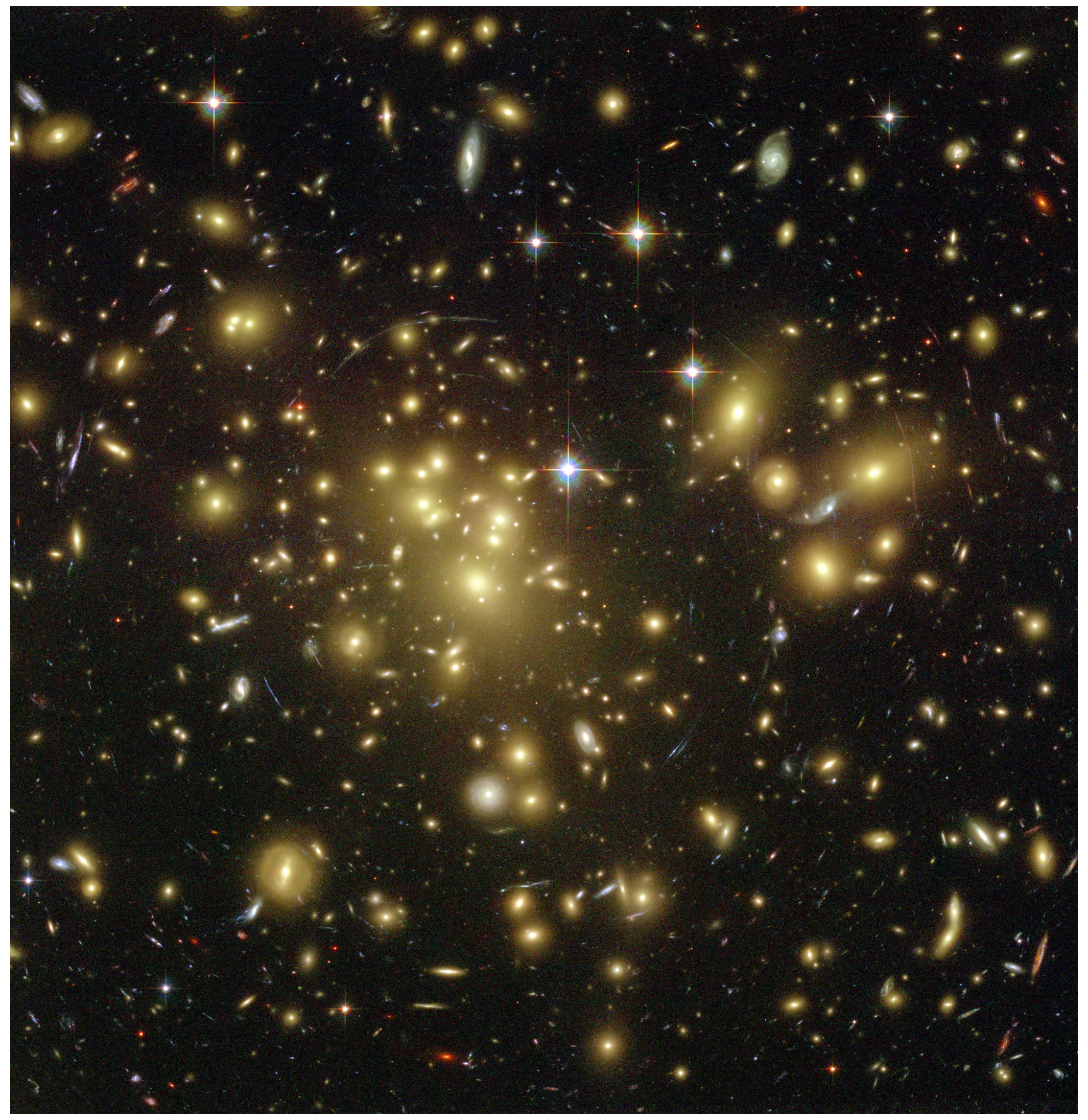




Is everything charted?

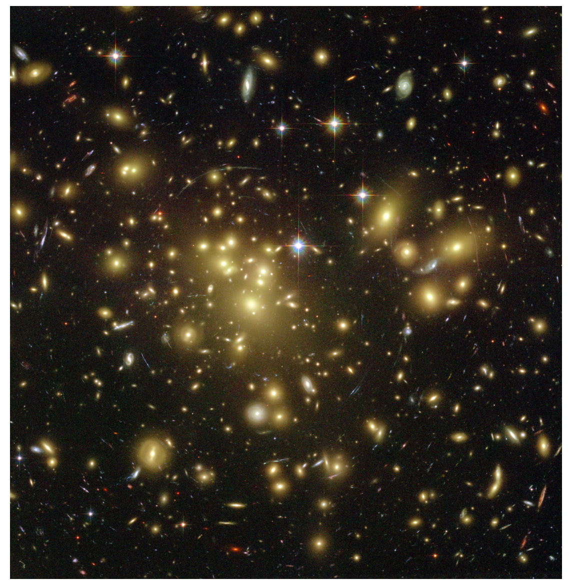
Source gallica.bnf.fr / Bibliothèque nationale de France

Observed anomalies



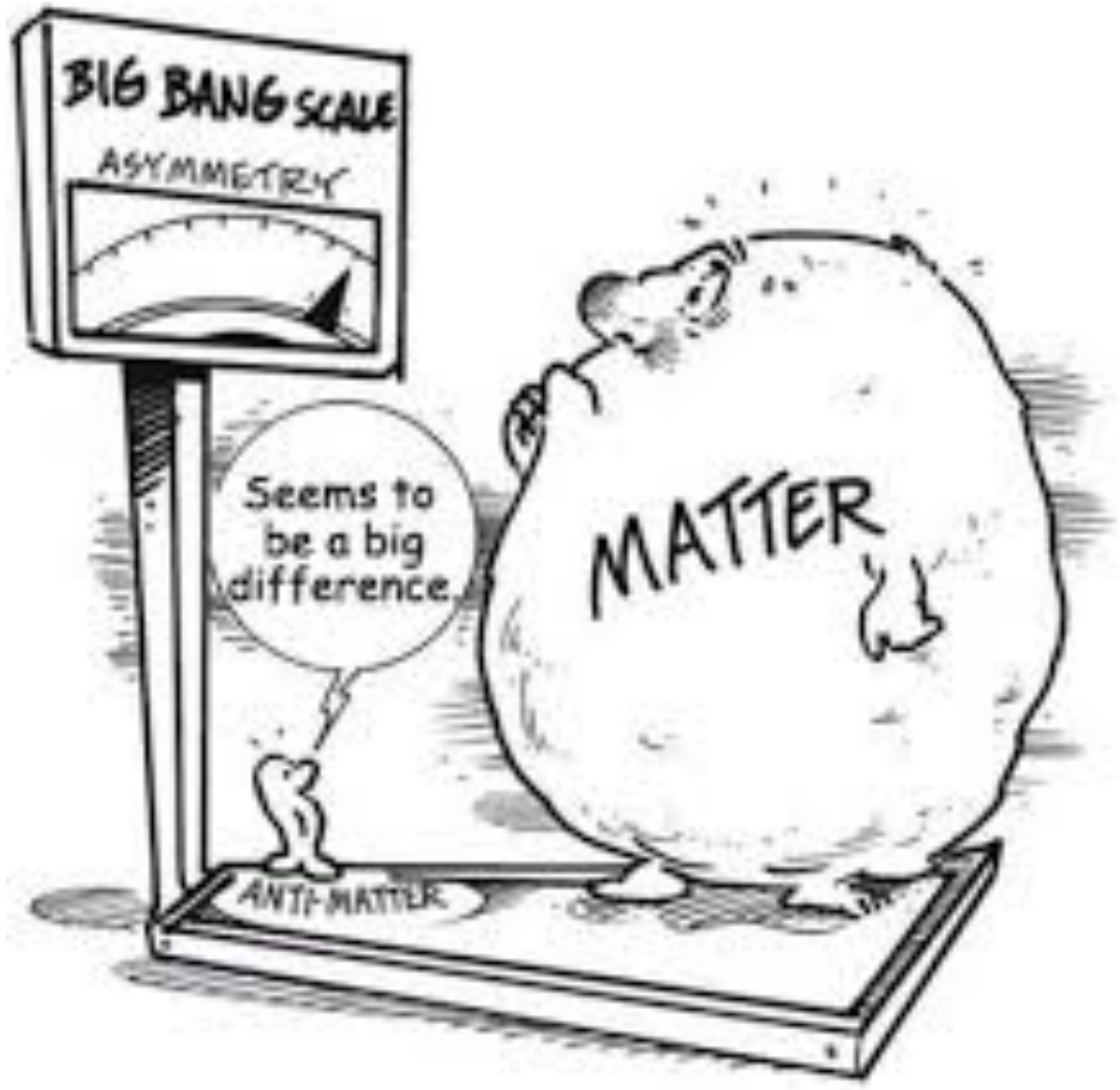
Dark matter

Observed anomalies



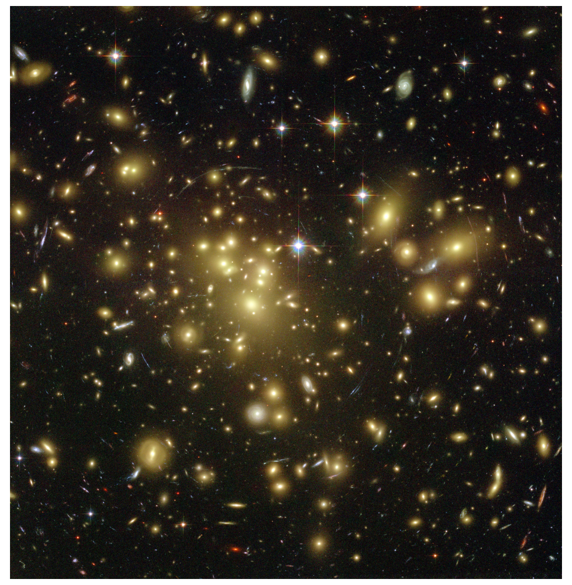
Dark matter

Romulus Godang talk



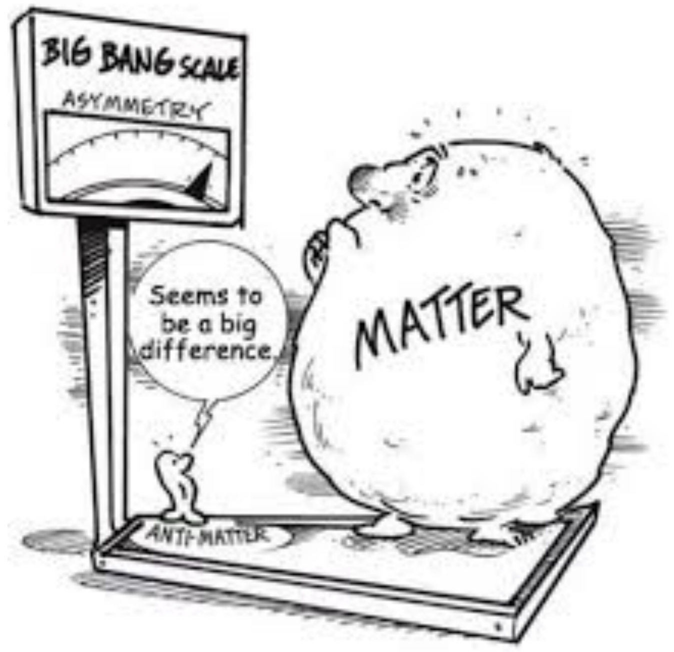
Matter-antimatter asymmetry

Observed anomalies



Dark matter

Romulus

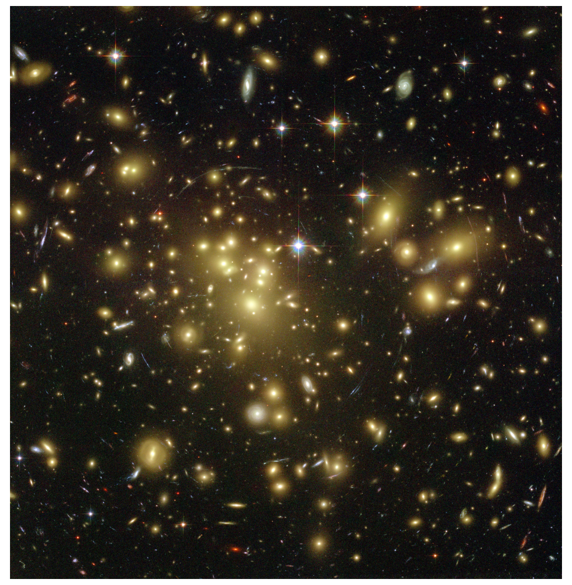


Matter-antimatter asymmetry

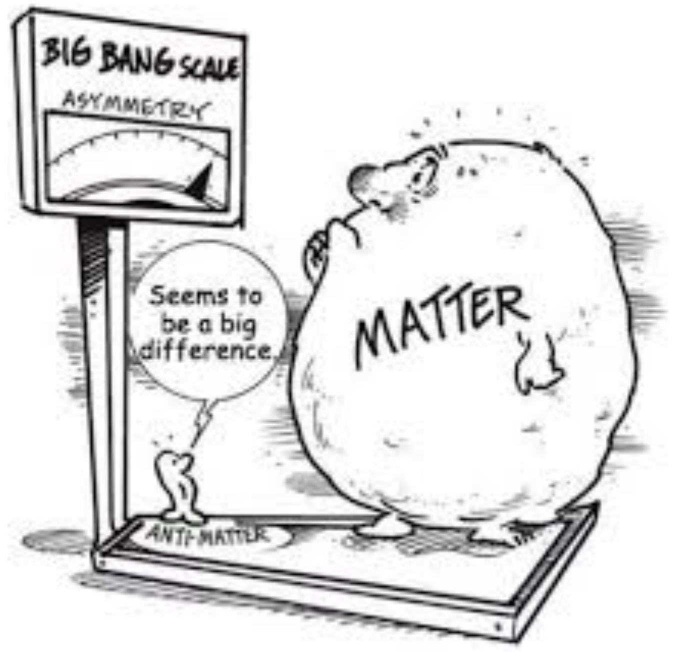
Symmetry magazine

Neutrino mass

Observed anomalies



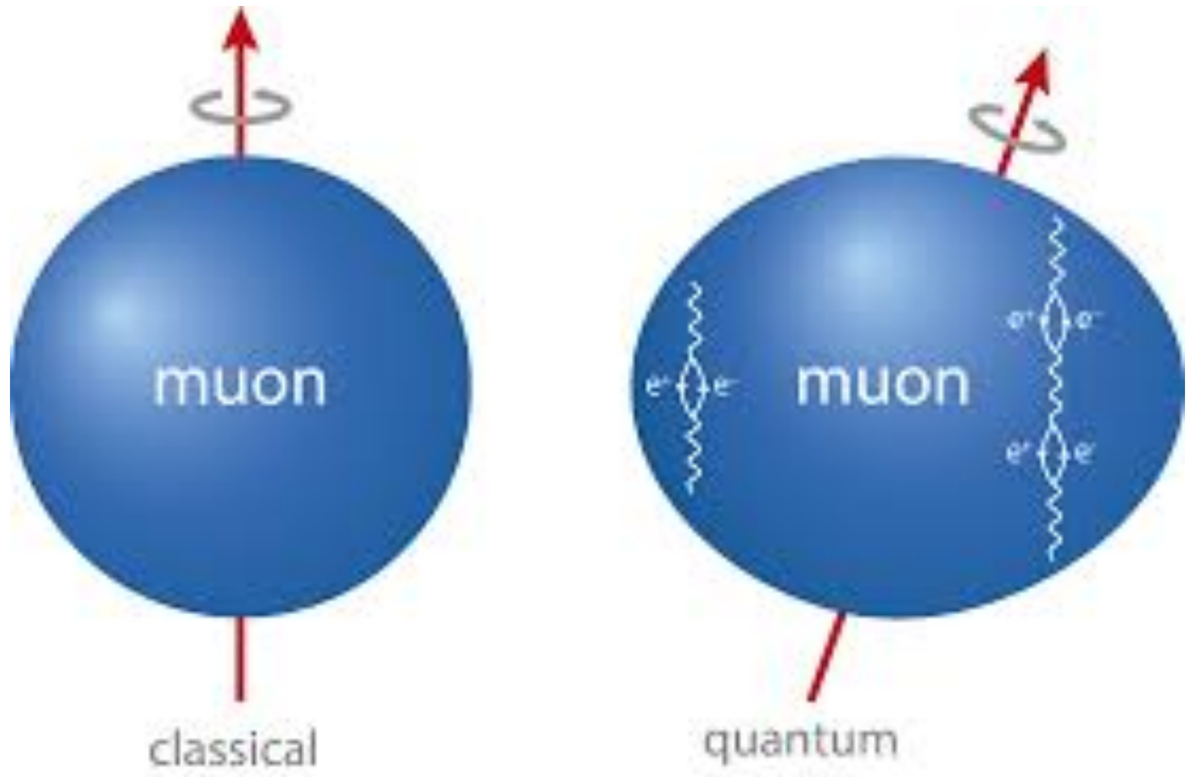
Dark matter



Matter-antimatter asymmetry

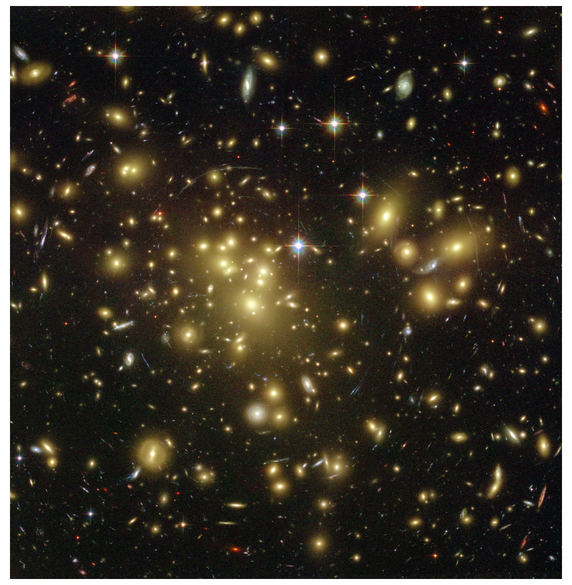
Neutrino mass

Jansen, NIC Symposium

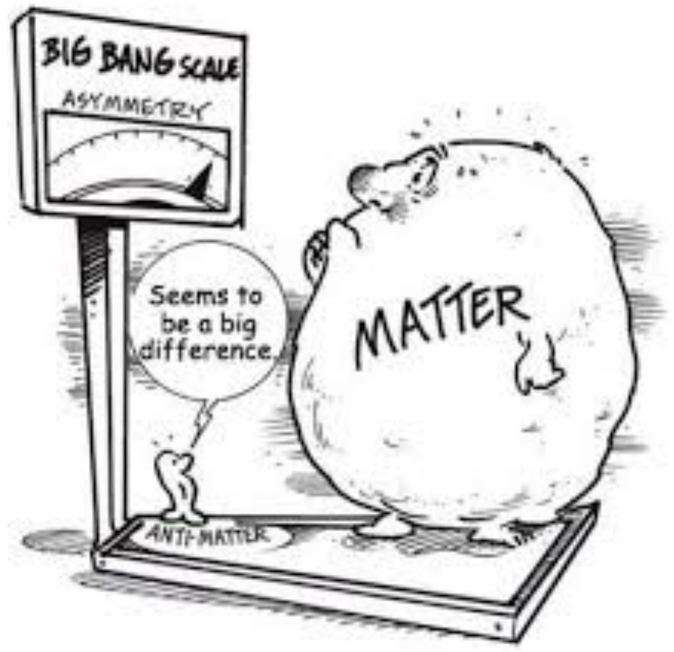


Muon anomalous magnetic moment

Observed anomalies



Dark matter



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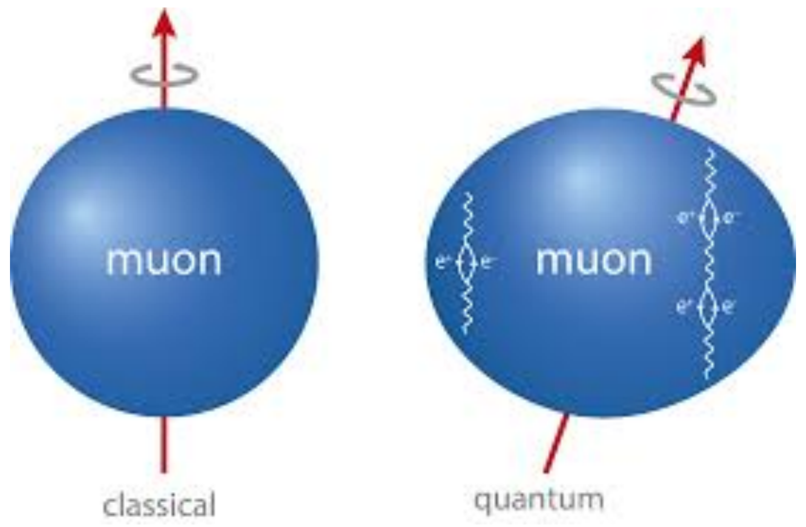
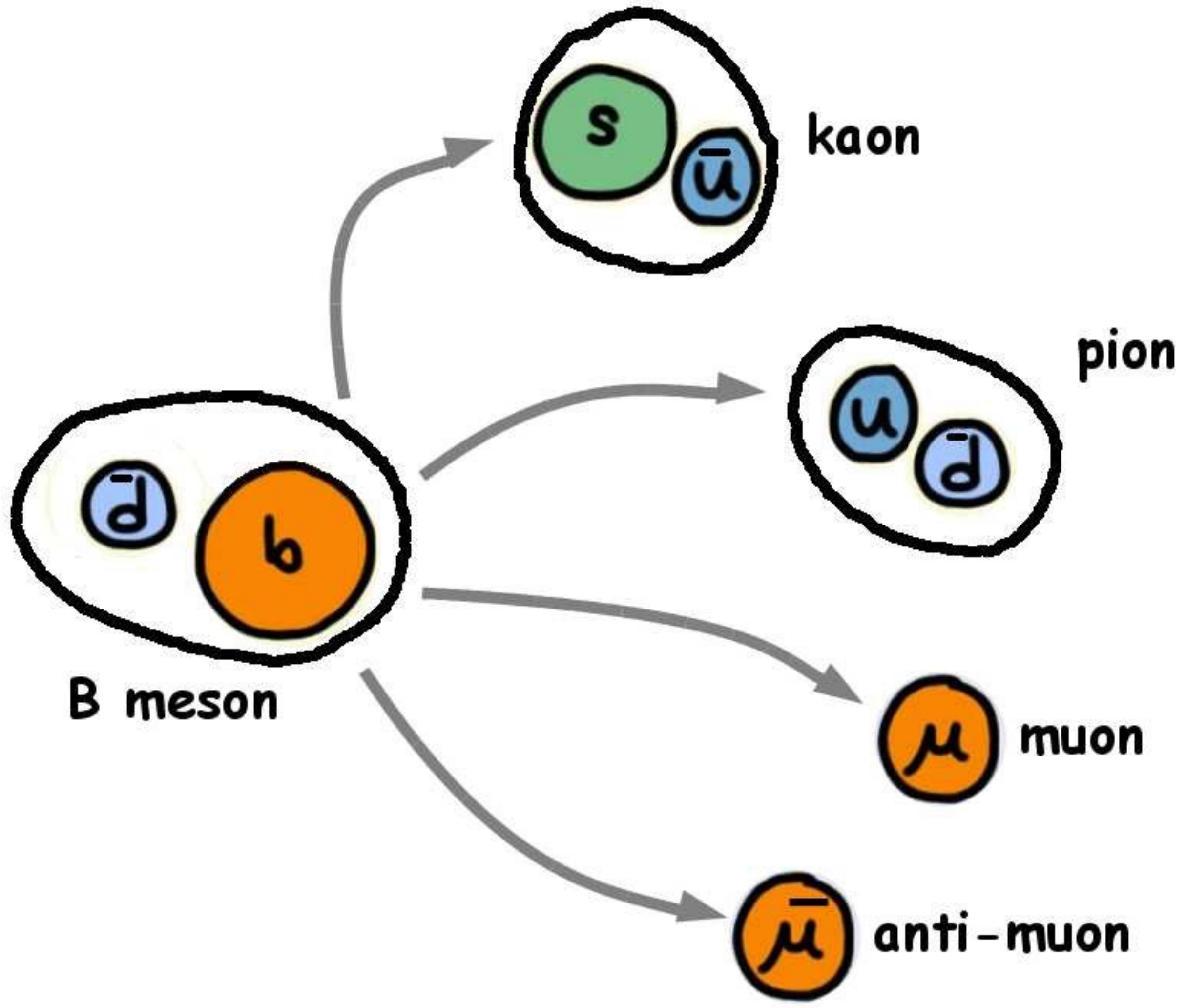


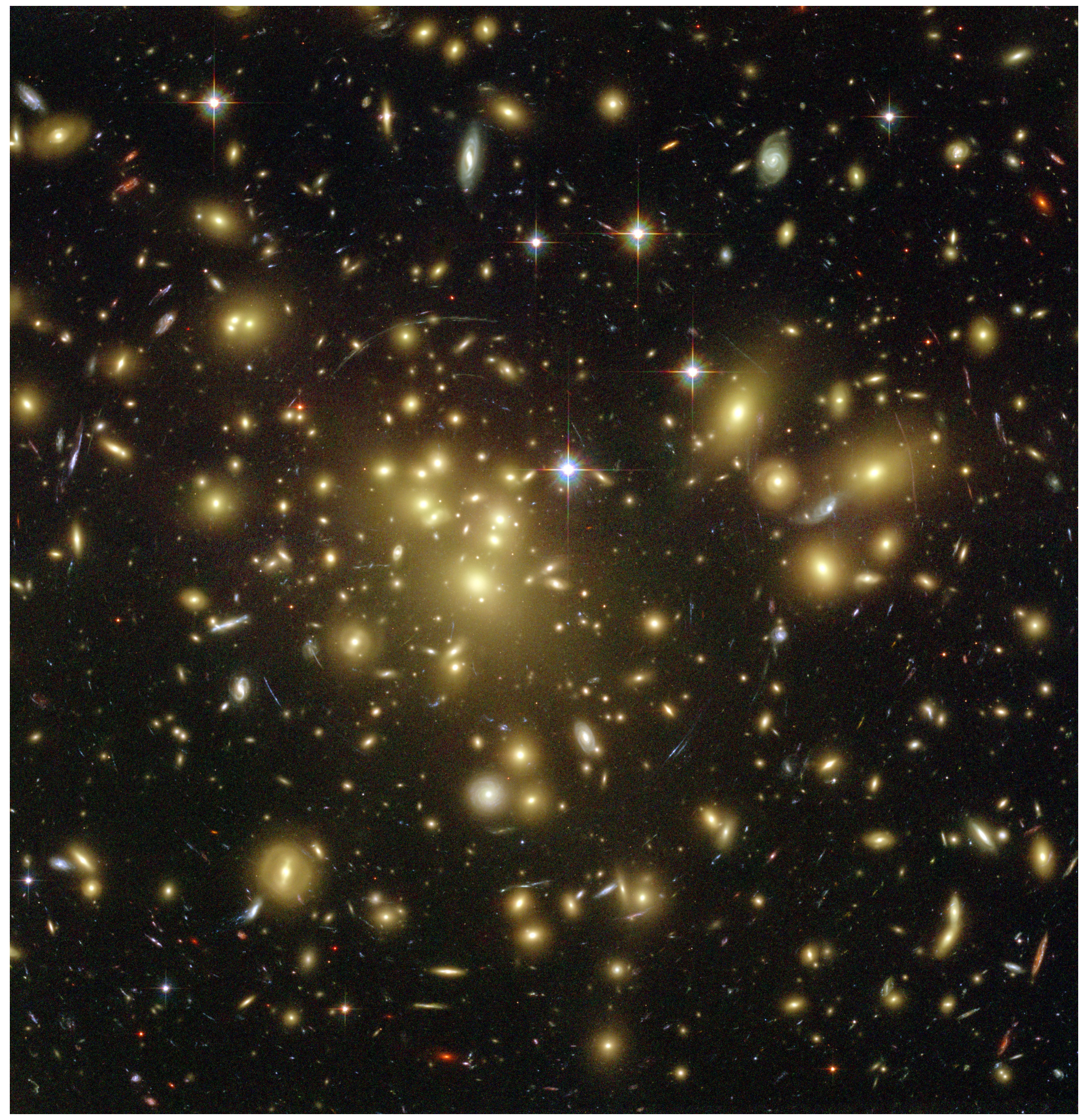
Muon anomalous magnetic moment

Altmannshofer



Flavor anomalies

Observed anomalies



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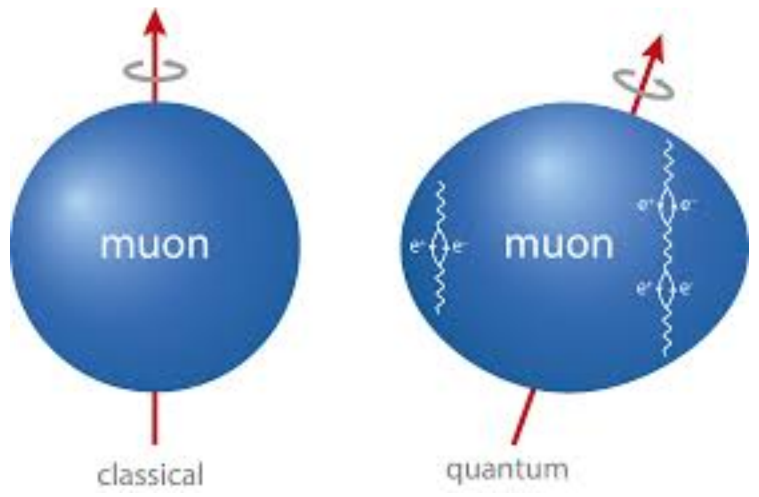
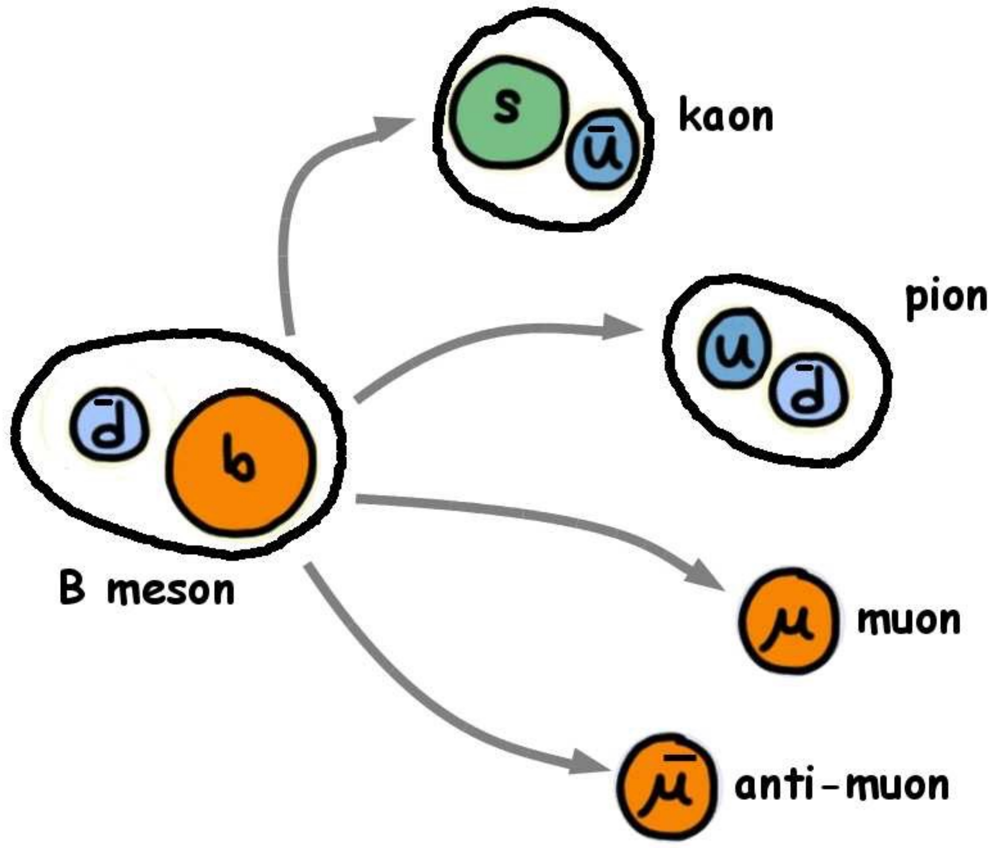


Muon anomalous magnetic moment

Altmannshofer



Flavor anomalies

Flavor structure in the SM

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i \bar{\psi} \not{D} \psi + h.c.$$

the quarks and leptons interaction with the gauge bosons

Parameterized by g_Y, g_2, g_3

$$+ |D_\mu \phi|^2 - V(\phi)$$

Breaks electro-weak symmetry $SU(2)_L \times U(1)_Y$

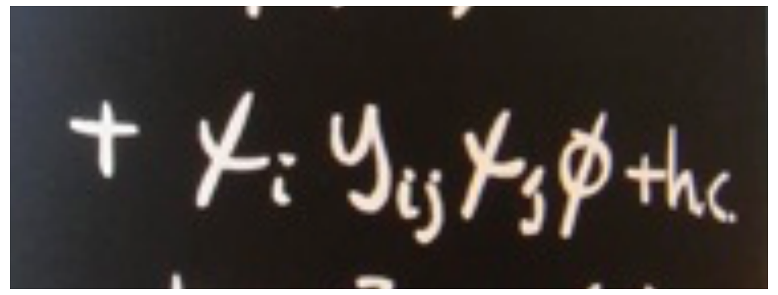
Generates mass to $W^{\pm}, Z$

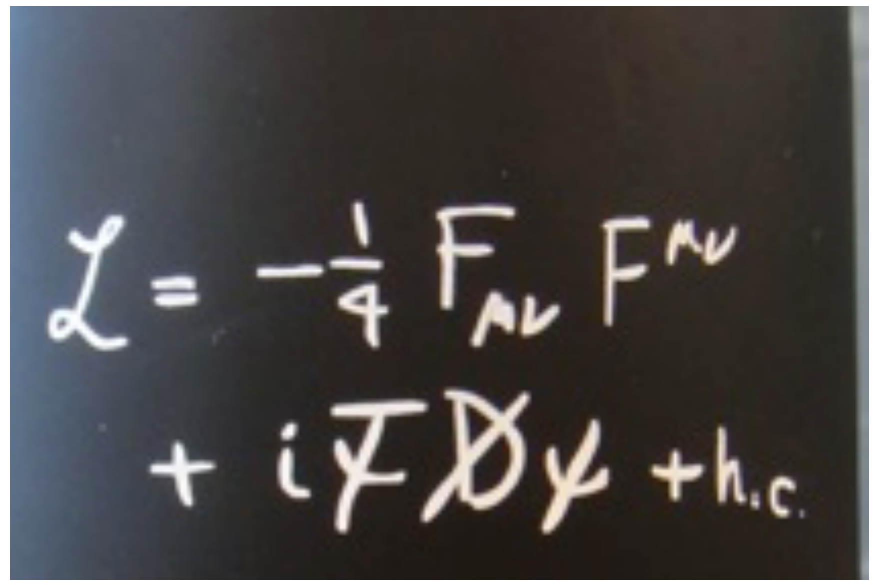
$$+ \bar{\psi}_i y_{ij} \psi_j \phi + h.c.$$

Generates mass to the quarks and leptons

Mixing of quarks

Flavor structure in the SM: quarks





Physical basis are the mass basis

$$|u\rangle_f = U_{uu}|u\rangle_m + U_{uc}|c\rangle_m + U_{ut}|t\rangle_m$$

$$|d\rangle_f = D_{dd}|d\rangle_m + D_{ds}|s\rangle_m + D_{db}|b\rangle_m$$

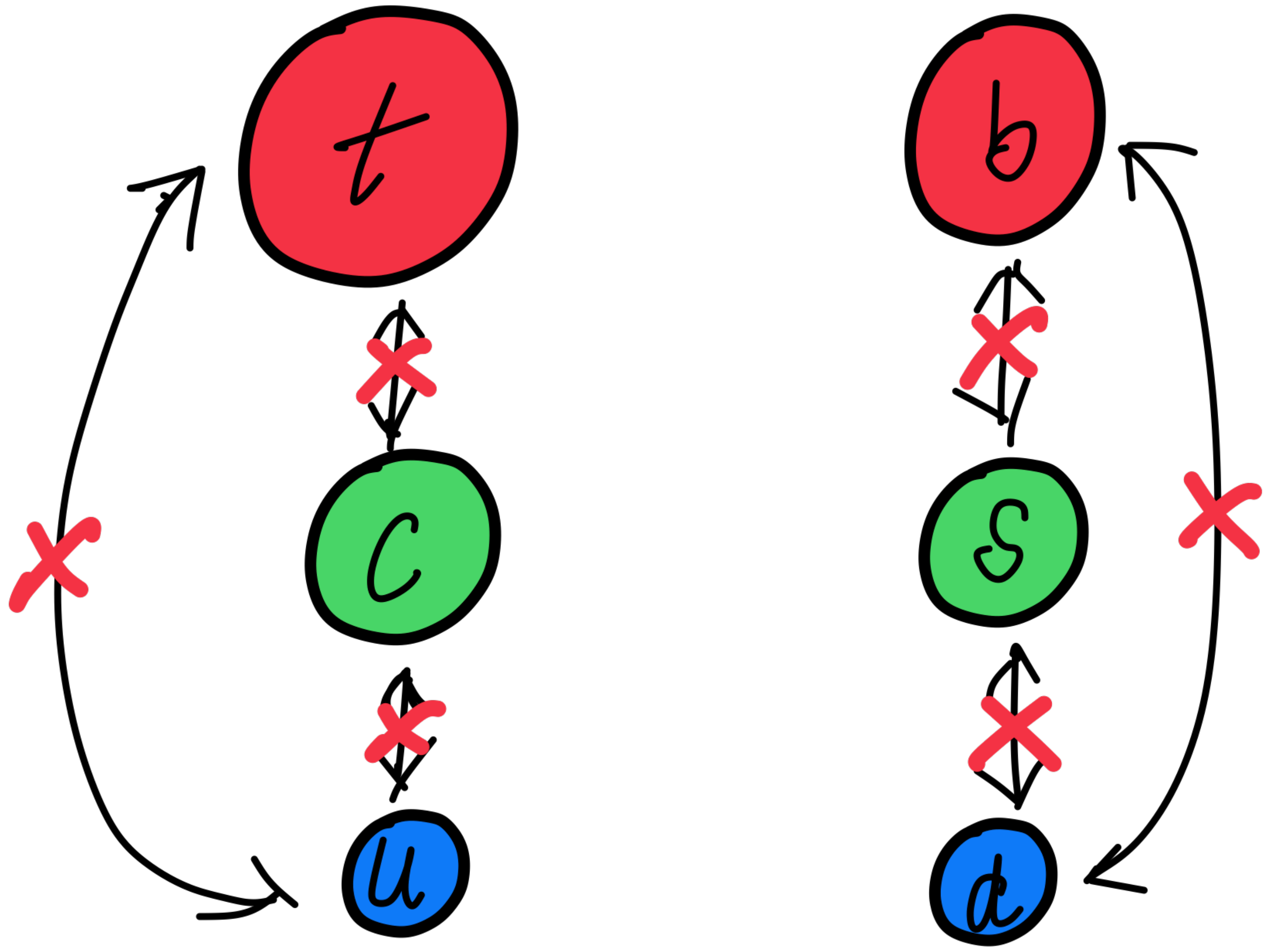
$$u_{f,i} = U_{ij}\, u_{m,j}\,, \quad d_{f,i} = D_{ij}\, d_{m,j}$$

$$i = 1,2,3$$

$$\frac{g_2}{\sqrt{2}} W^+ (U^\dagger D)_{ij} \bar{u}_i \gamma^\mu d_j + h.c$$

$$+ \frac{g_2}{\sqrt{2}} Z (U^\dagger U)_{ij} \bar{u}_i \gamma^\mu u_j + \frac{g_2}{\sqrt{2}} Z (D^\dagger D)_{ij} \bar{d}_i \gamma^\mu d_j$$

Flavour changing neutral current are absent at the tree level



Flavor structure in the SM: quarks

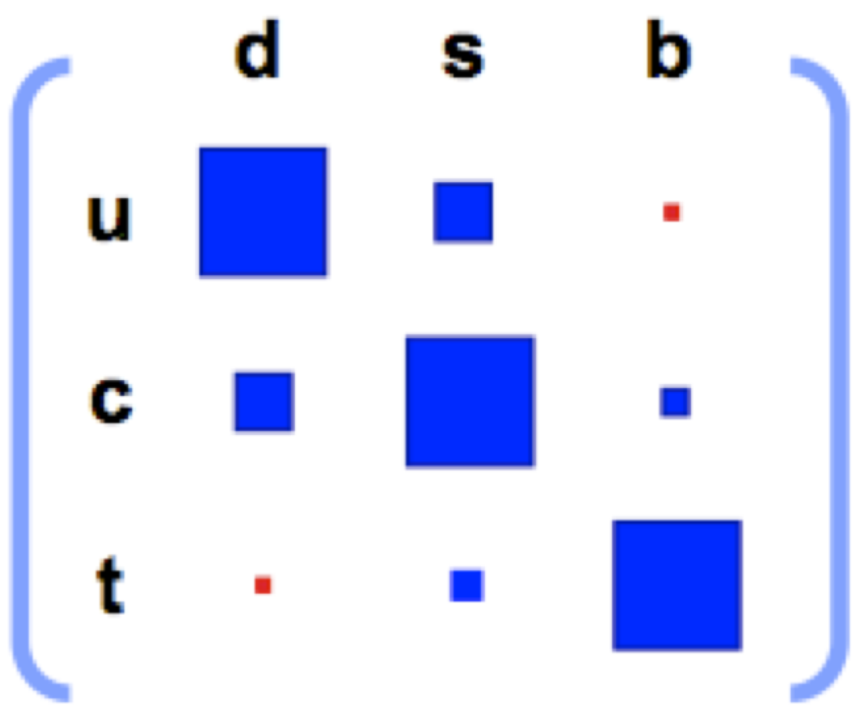
$$\frac{g_2}{\sqrt{2}} W^+ (U^\dagger D)_{ij} \bar{u}_i \gamma^\mu d_j + h.c$$

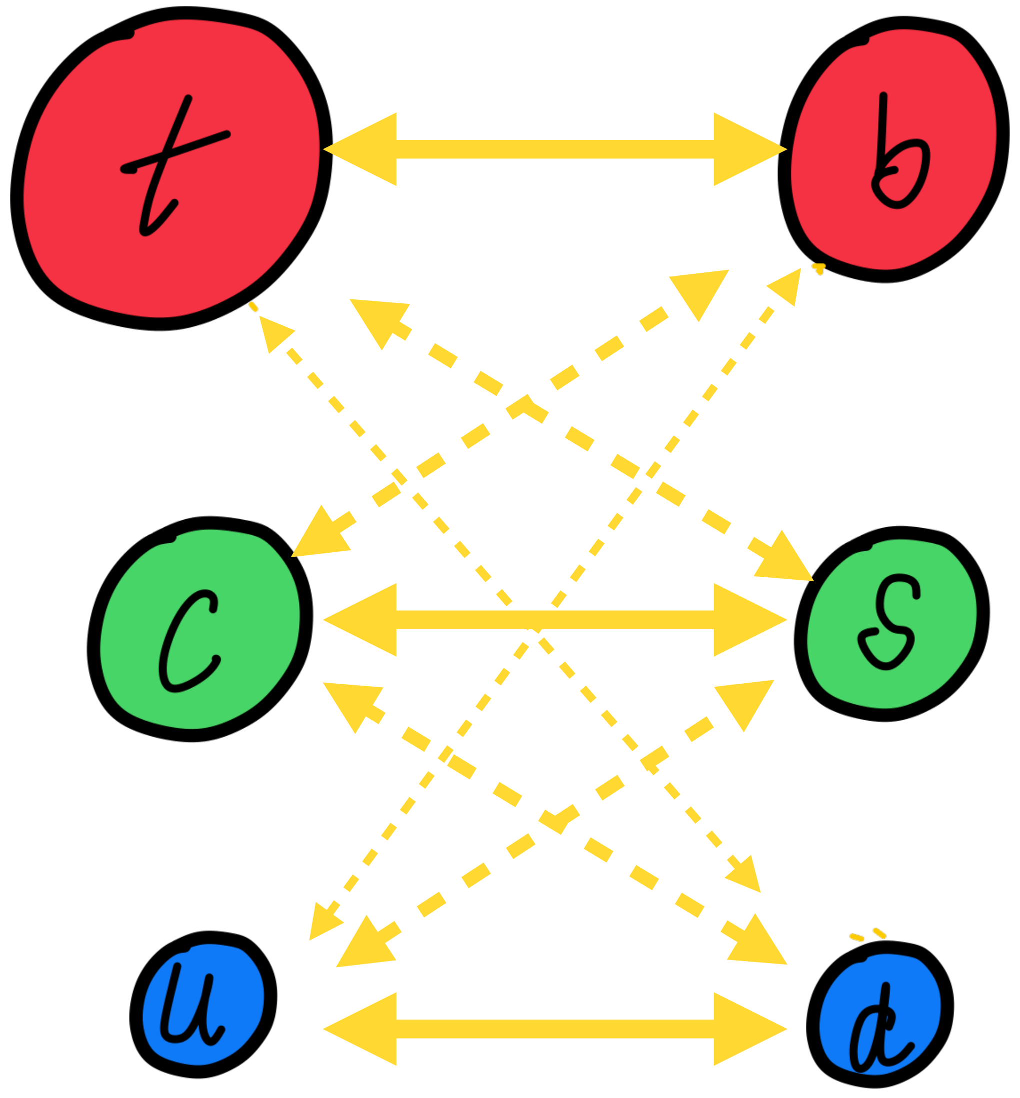
$$+ \frac{g_2}{\sqrt{2}} Z (U^\dagger U)_{ij} \bar{u}_i \gamma^\mu u_j + \frac{g_2}{\sqrt{2}} Z (D^\dagger D)_{ij} \bar{d}_i \gamma^\mu d_j$$

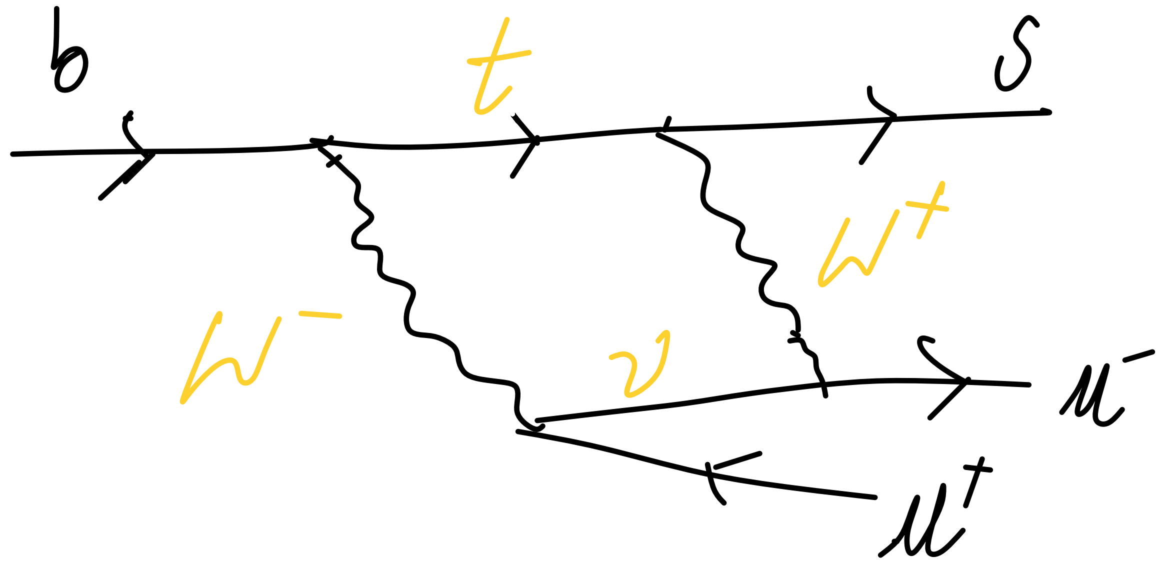
$W^\pm$ can induce flavor change among the quarks

V_{CKM} is the source of flavor violation among the quarks

$$V_{CKM} \equiv U^\dagger D$$







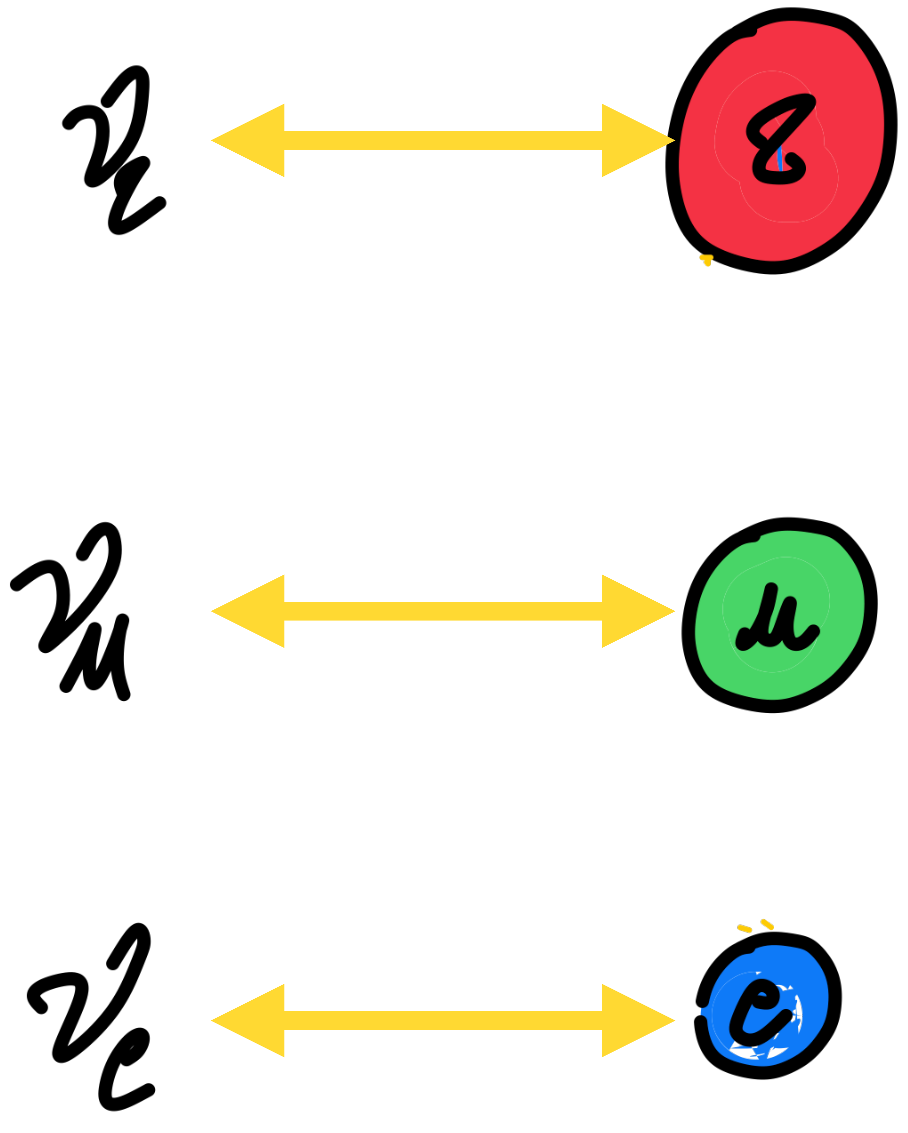
Flavor structure in the SM: leptons vs quarks

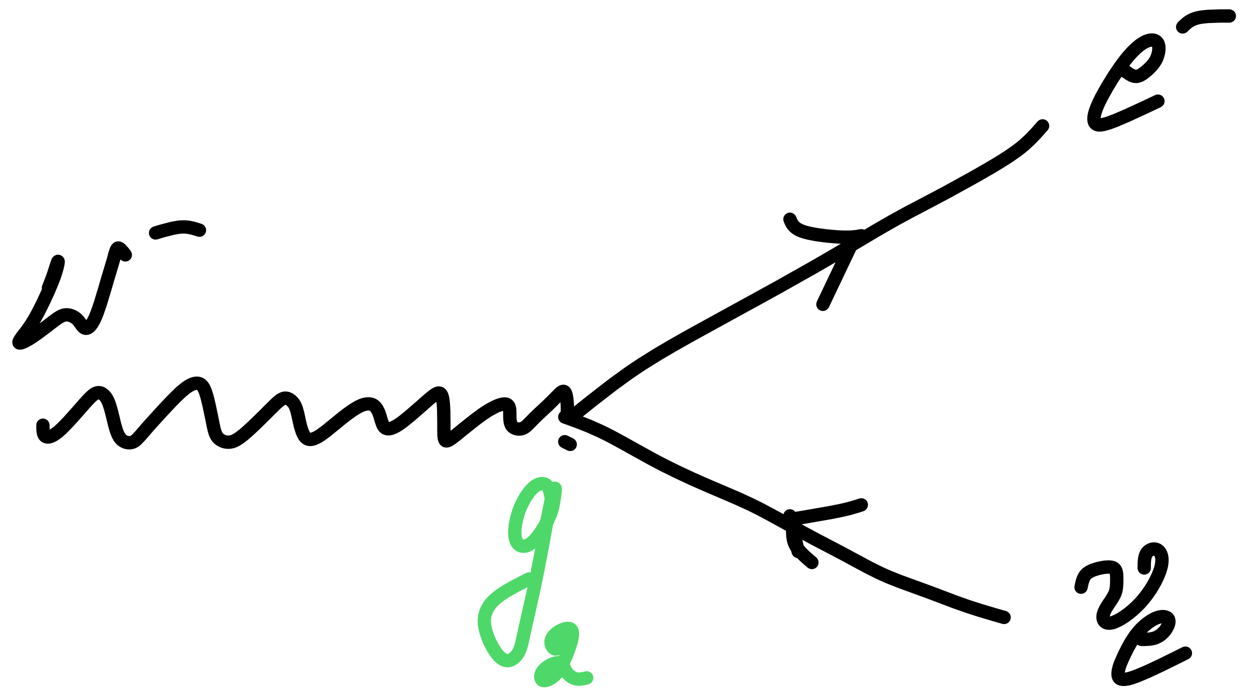
Right handed neutrinos are absent

$\Longrightarrow$ Only 1 Yukawa matrix

$\Longrightarrow$ Does not mix different family

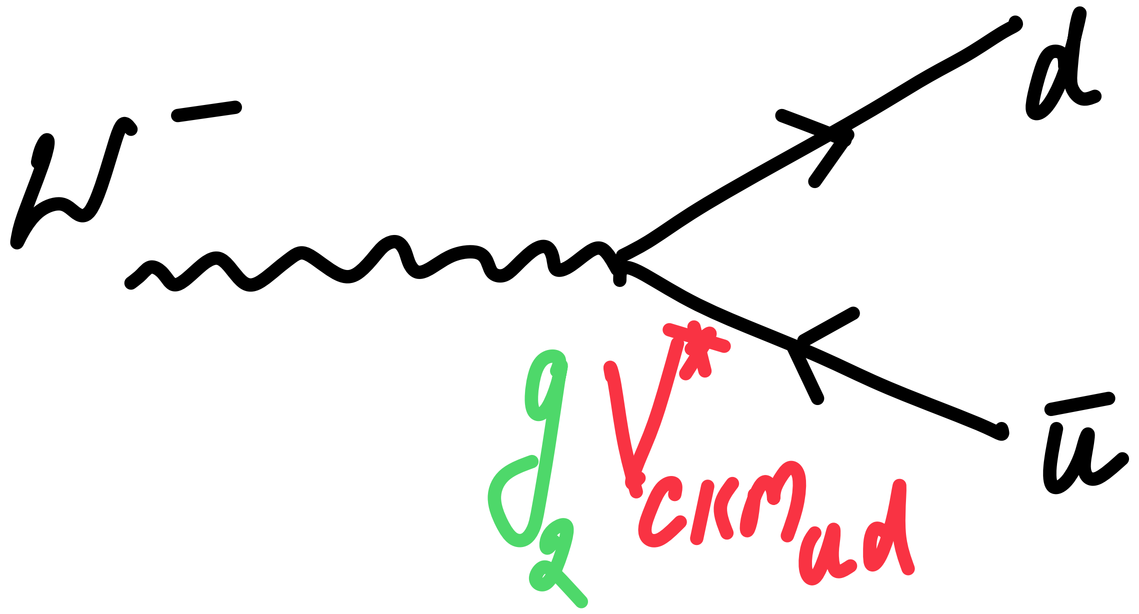
$$\frac{g_2}{\sqrt{2}} W^+ \delta_{ij}\bar{e}_i\gamma^\mu\nu_j + h.c$$





$\Longrightarrow$ Lepton Flavor Universality (LFV)

$$g_{2,e} = g_{2,\mu} = g_{2,\tau}$$



Lepton Flavor Universality Test

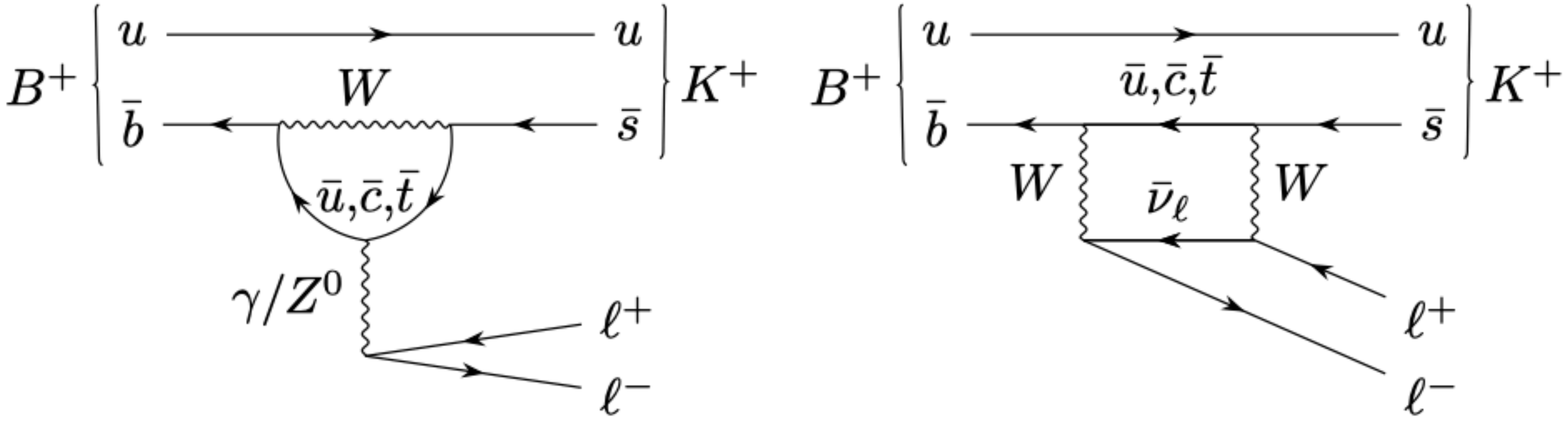
Confinement: hadronization of quarks

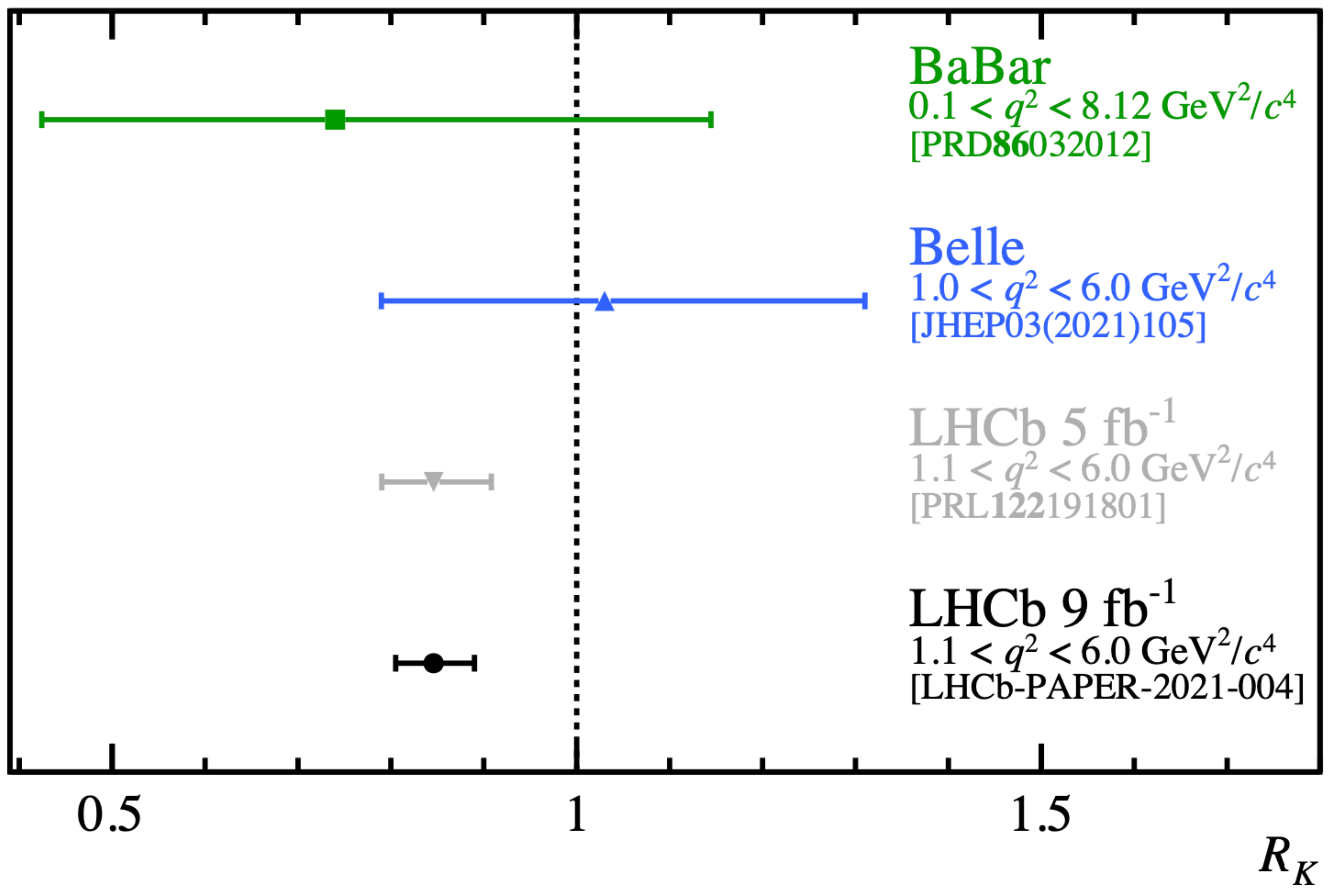
⇒ Observables during rare decays of meson

$$R_K = \frac{BR(B^+ \to K^+\mu^-\mu^+)}{BR(B^+ \to K^+e^-e^+)}$$

SM prediction: $R_K = 1$

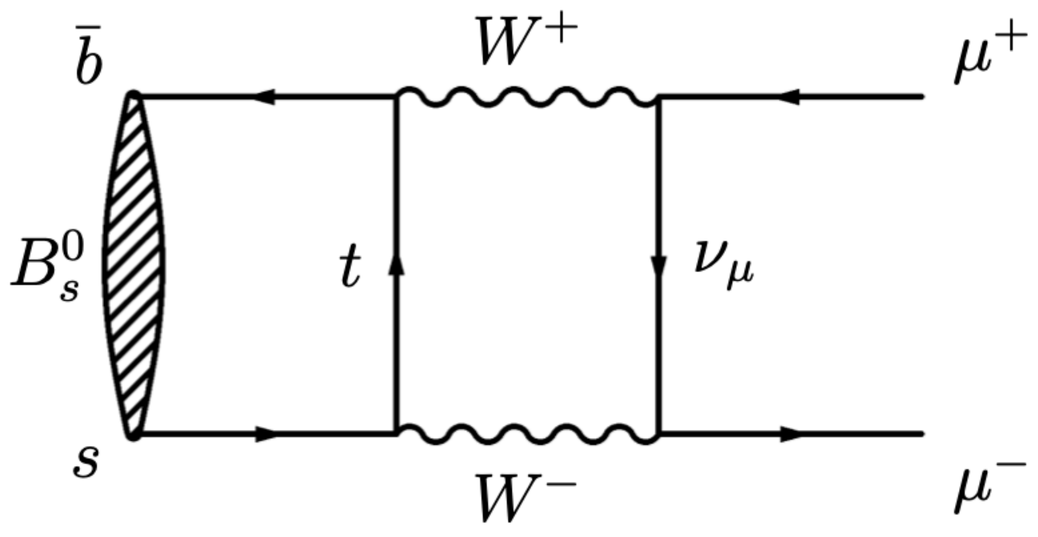
Up to phase space corrections

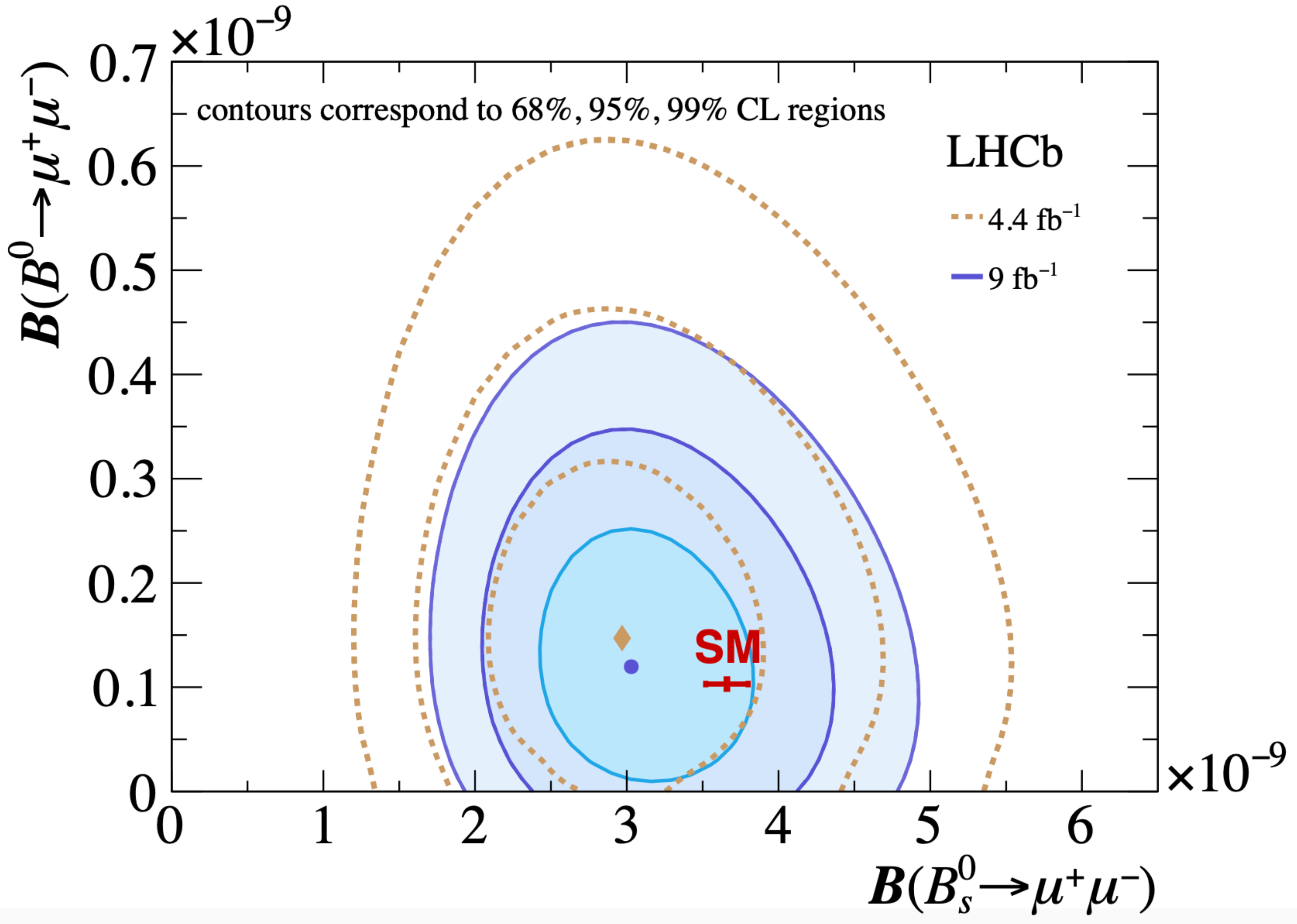




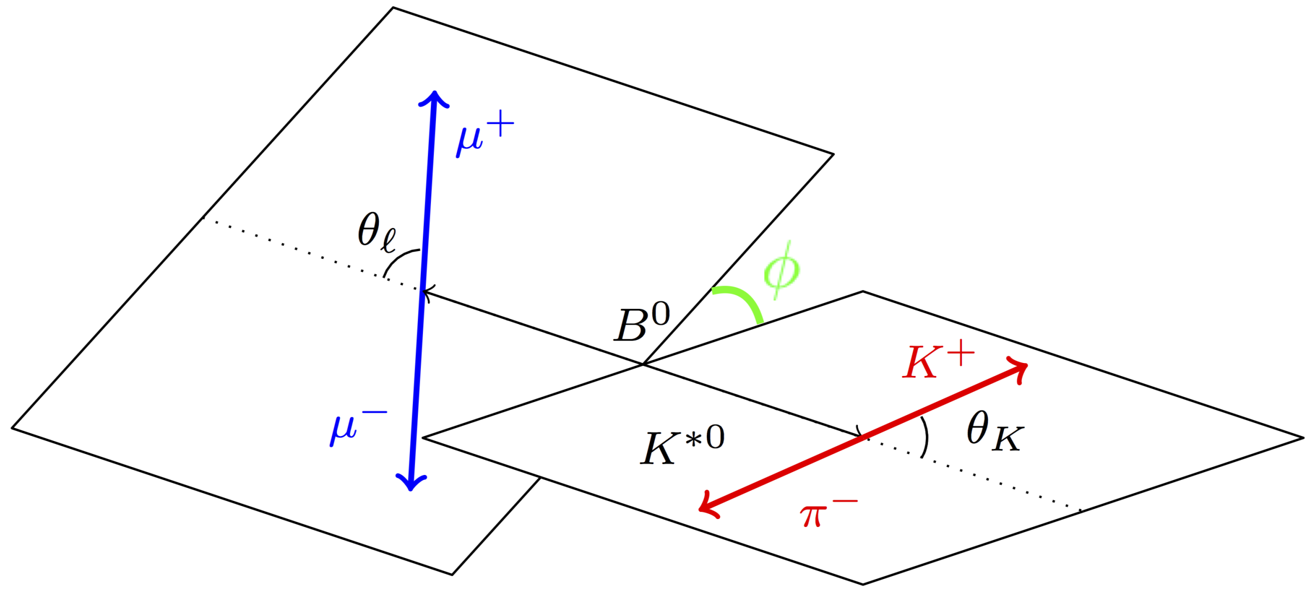
Other observables

Branching Fractions: $B(B_s \to \mu^-\mu^+)$





Angular observables



Model-independent approach

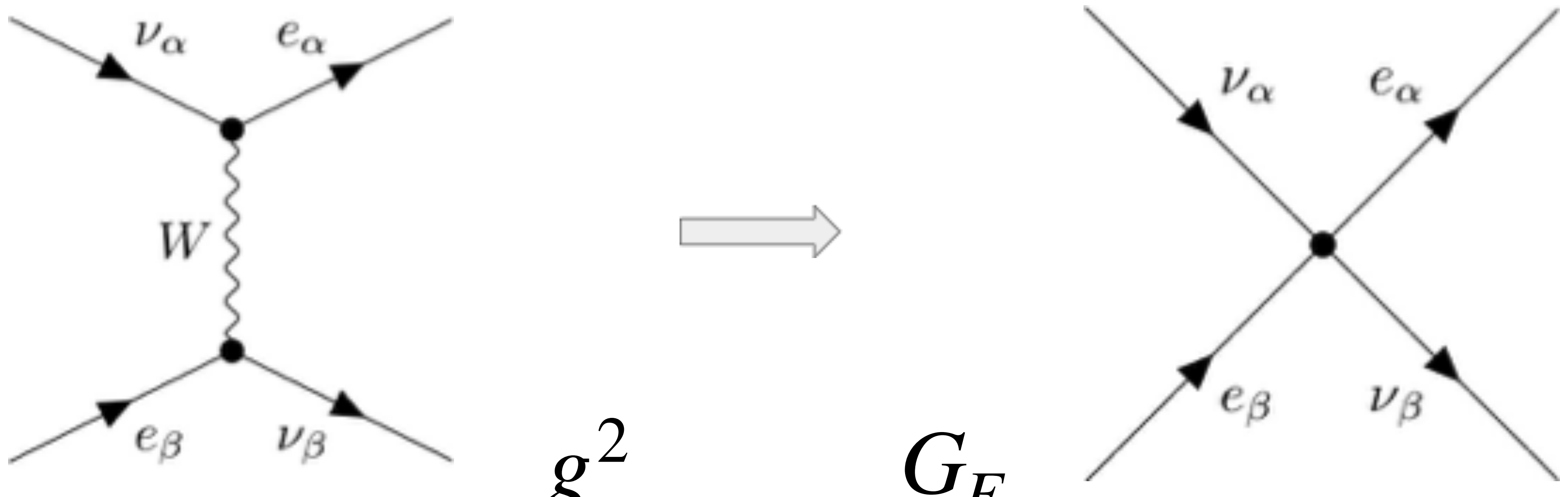
Anomalies caused by the New Physics (NP)

Parameterizing the new physics (NP) in terms of four-fermion contact interaction

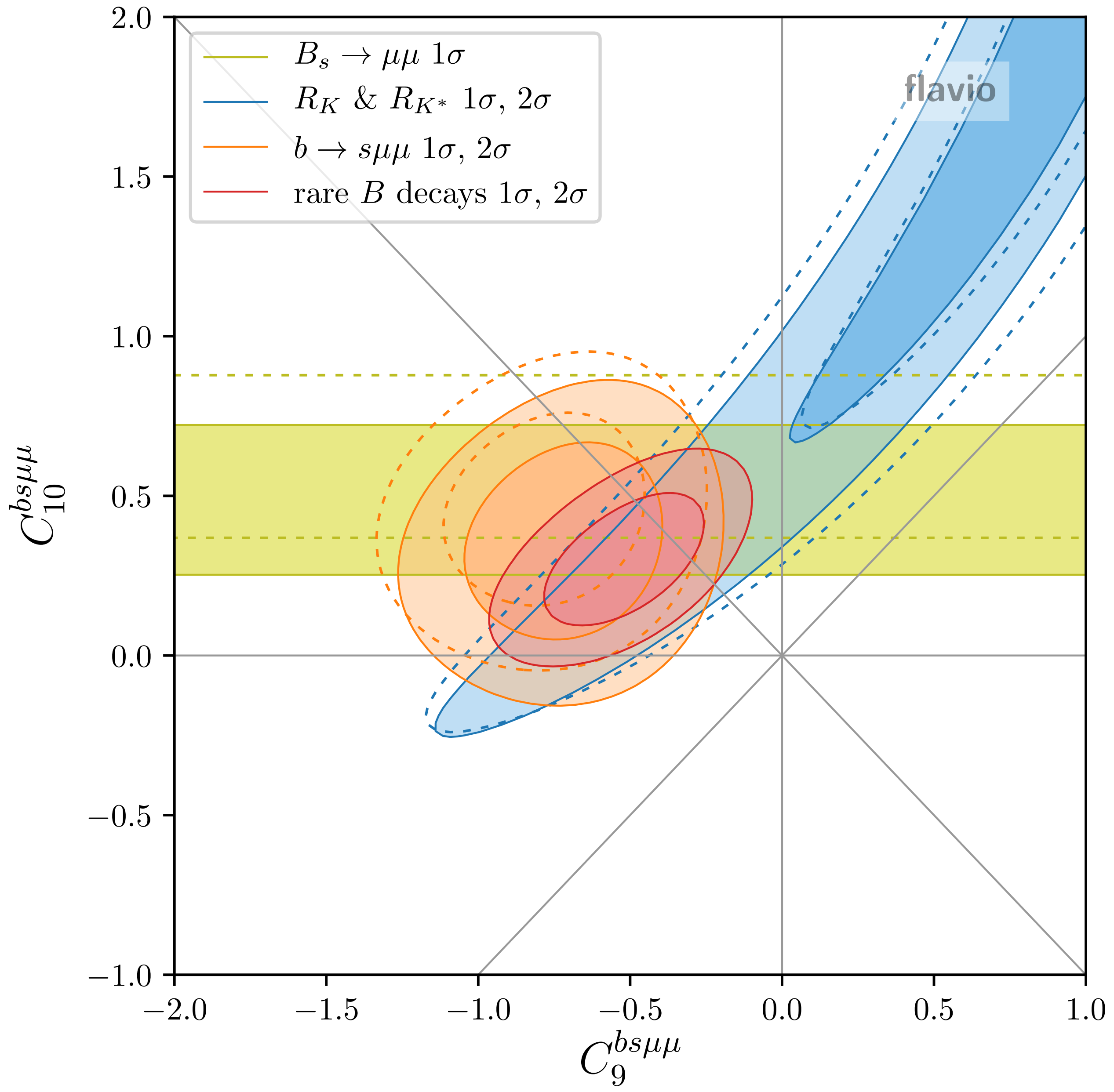
$$\mathscr{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_{i,l} (C_i^l O_i^l + C_i'^l O_i'^l) + \text{H.c.}\,,$$

$$O_9^{(\prime)\mu} = \frac{e^2}{16\pi^2}(\bar{s}\gamma^\rho P_{L(R)} b)(\bar{\mu}\gamma_\rho \mu),$$

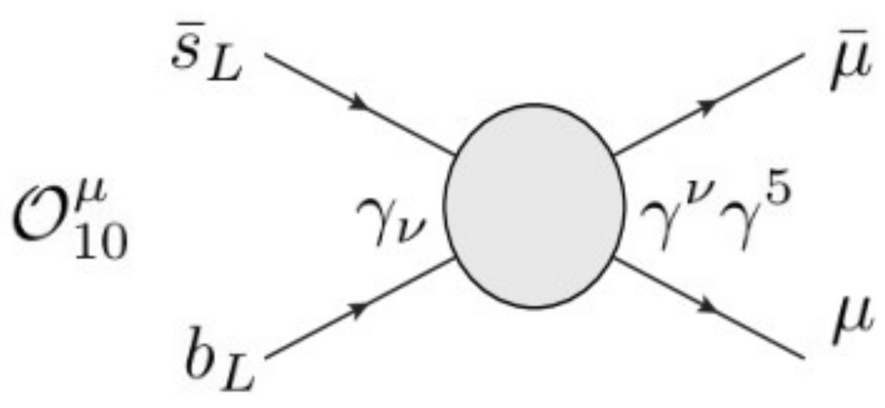
$$O_{10}^{(\prime)\mu} = \frac{e^2}{16\pi^2}(\bar{s}\gamma^\rho P_{L(R)} b)(\bar{\mu}\gamma_\rho \gamma_5 \mu)$$

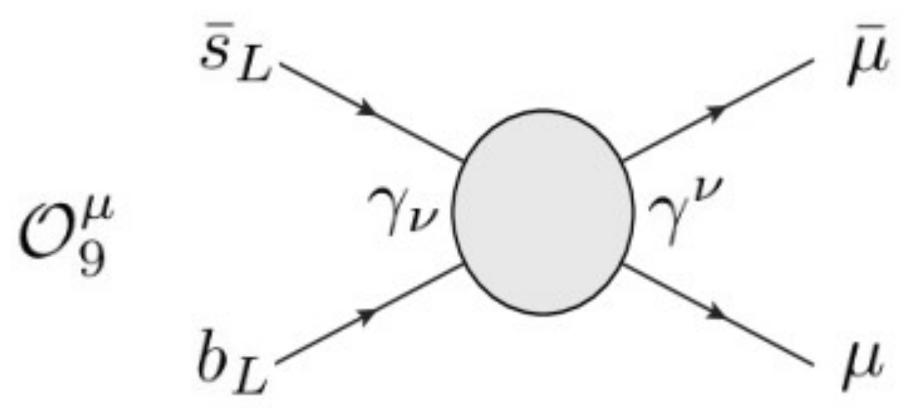


$$\frac{g^2}{8m_W^2} \longrightarrow \frac{G_F}{\sqrt{2}}$$



Altmannshofer, Stangl arXiv: 2103.13370





Minimal Z' models

Generic Z' coupling for the flavor anomalies

$$\mathscr{L} \supset Z'_\rho \left(g_L^{sb}\, \bar{s}\gamma^\rho P_L\, b + g_R^{sb}\, \bar{s}\gamma^\rho P_R\, b + g_L^{\mu\mu}\, \bar{\mu}\gamma^\rho P_L\, \mu + g_R^{\mu\mu}\, \bar{\mu}\gamma^\rho P_R\, \mu \right) + \text{H.c.}$$

$$C^\mu_{9,\text{NP}} = -2\frac{g_L^{sb} g_V^{\mu\mu}}{V_{tb}V_{ts}^*}\left(\frac{\Lambda_v}{m_{Z'}}\right)^2 \quad C^\mu_{10,\text{NP}} = -2\frac{g_L^{sb} g_A^{\mu\mu}}{V_{tb}V_{ts}^*}\left(\frac{\Lambda_v}{m_{Z'}}\right)^2$$

$$g_V^{\mu\mu} = (g_L^{\mu\mu} + g_R^{\mu\mu})/2\,, \quad g_A^{\mu\mu} = (g_R^{\mu\mu} - g_L^{\mu\mu})/2\,, \quad \Lambda_v = \left(\frac{\pi}{\sqrt{2}G_F\alpha_{\text{em}}}\right)^{1/2}$$

Only marginal improvement in the fit with C_9' and C_{10}'

Kowalska, Kumar, Sessolo, arXiv: 1903.10932

g_L^{sb} is an effective coupling:

$$\mathscr{L} \supset -\lambda_{Q,i} S Q' q_i - m_Q\, Q'Q + \text{H.c.}$$

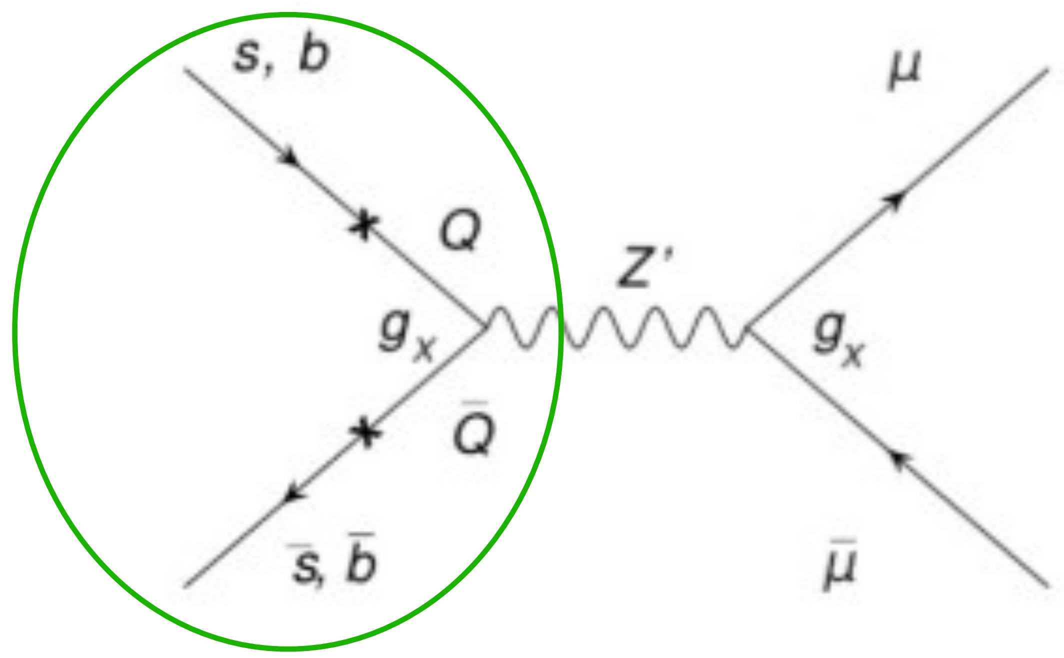
$$\Rightarrow g_L^{sb} \approx \pm\, g_X Q_S \frac{\sqrt{2}\, m_Q\, \lambda_{Q,2}\, \lambda_{Q,3}\, v_S^2}{\left(2m_Q^2 + \lambda_{Q,2}^2\, v_S^2\right)\sqrt{2\, m_Q^2 + \left(\lambda_{Q,2}^2 + \lambda_{Q,3}^2\right) v_S^2}}\,,$$

$$g_R^{sb} \approx 0$$

$$SU(3) \times SU(2)_W \times U(1)_Y \times U(1)_X$$

$$S : (\mathbf{1}, \mathbf{1}, 0, Q_S)\,,$$
$$Q : (\mathbf{3}, \mathbf{2}, 1/6, Q_S) \qquad Q' : (\bar{\mathbf{3}}, \bar{\mathbf{2}}, -1/6, -Q_S)\,,$$

$g_L^{sb} \sim$



Minimal Z' models

Model 1: VL Lepton mixing

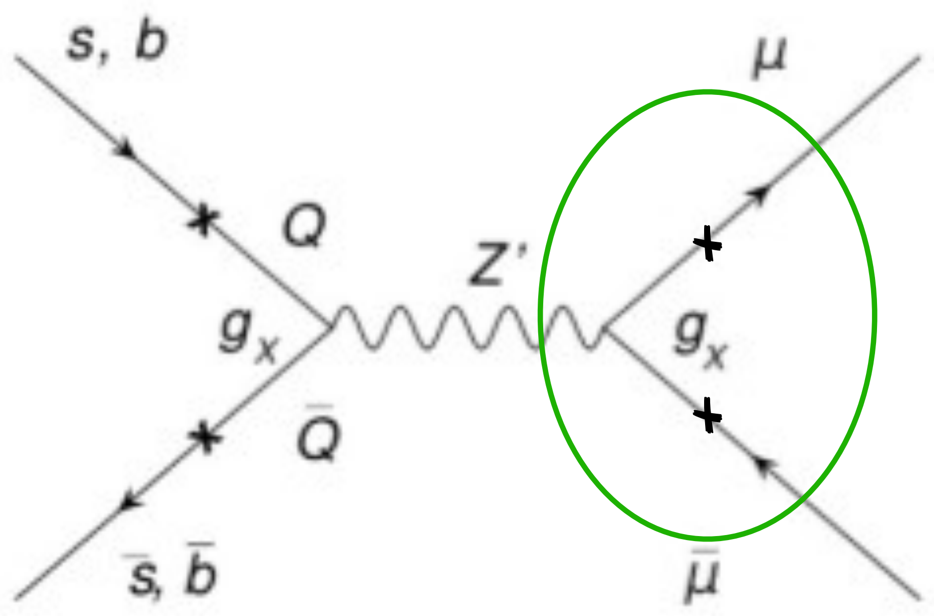
$$\mathcal{L} \supset \lambda_{L,i}^{(*)} S^{(*)} L' l_i + m_L L' L + \text{H.c.}$$

$$g_L^{\mu\mu} \approx g_X Q_L \frac{\lambda_{L,2}^2 v_S^2}{2m_L^2 + \lambda_{L,2}^2 v_S^2}, \qquad g_R^{\mu\mu} \approx 0$$

$L : (\mathbf{1}, \mathbf{2}, -1/2, Q_L) \qquad L' : (\mathbf{1}, \bar{\mathbf{2}}, 1/2, -Q_L)$

Model 1A: $Q_L = Q_S$

Model 1B: $Q_L = -Q_S$



$\sim g_L^{\mu\mu}$

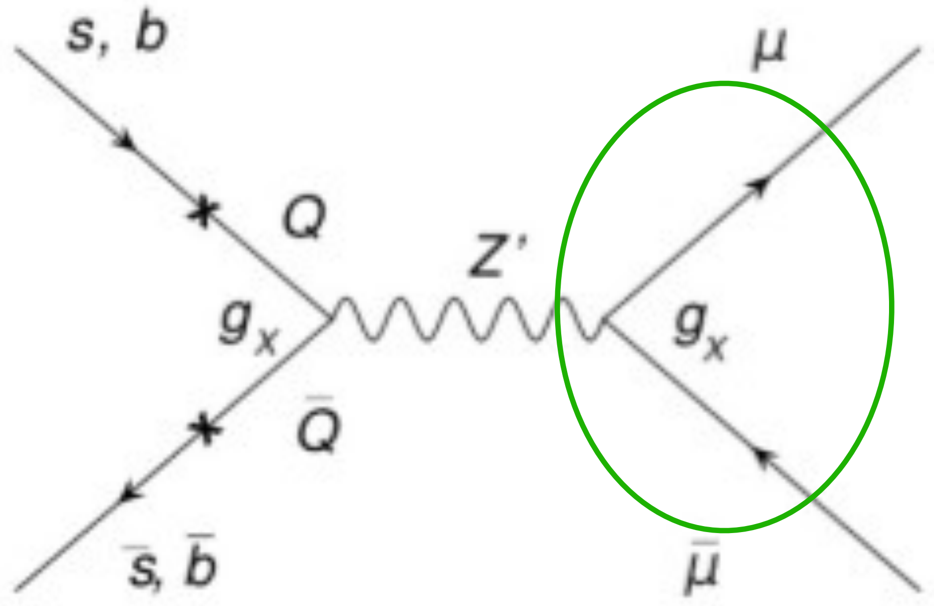
Model 2: Direct lepton coupling with $L_\mu - L_\tau$ Symmetry

$$g_V^{\mu\mu} = g_X \qquad g_A^{\mu\mu} = 0$$

$l_1 : (\mathbf{1}, \mathbf{2}, -1/2, 0) \quad e_R : (\mathbf{1}, \mathbf{1}, 1, 0)$

$l_2 : (\mathbf{1}, \mathbf{2}, -1/2, 1) \quad \mu_R : (\mathbf{1}, \mathbf{1}, 1, -1)$

$l_3 : (\mathbf{1}, \mathbf{2}, -1/2, -1) \quad \tau_R : (\mathbf{1}, \mathbf{1}, 1, 1)$

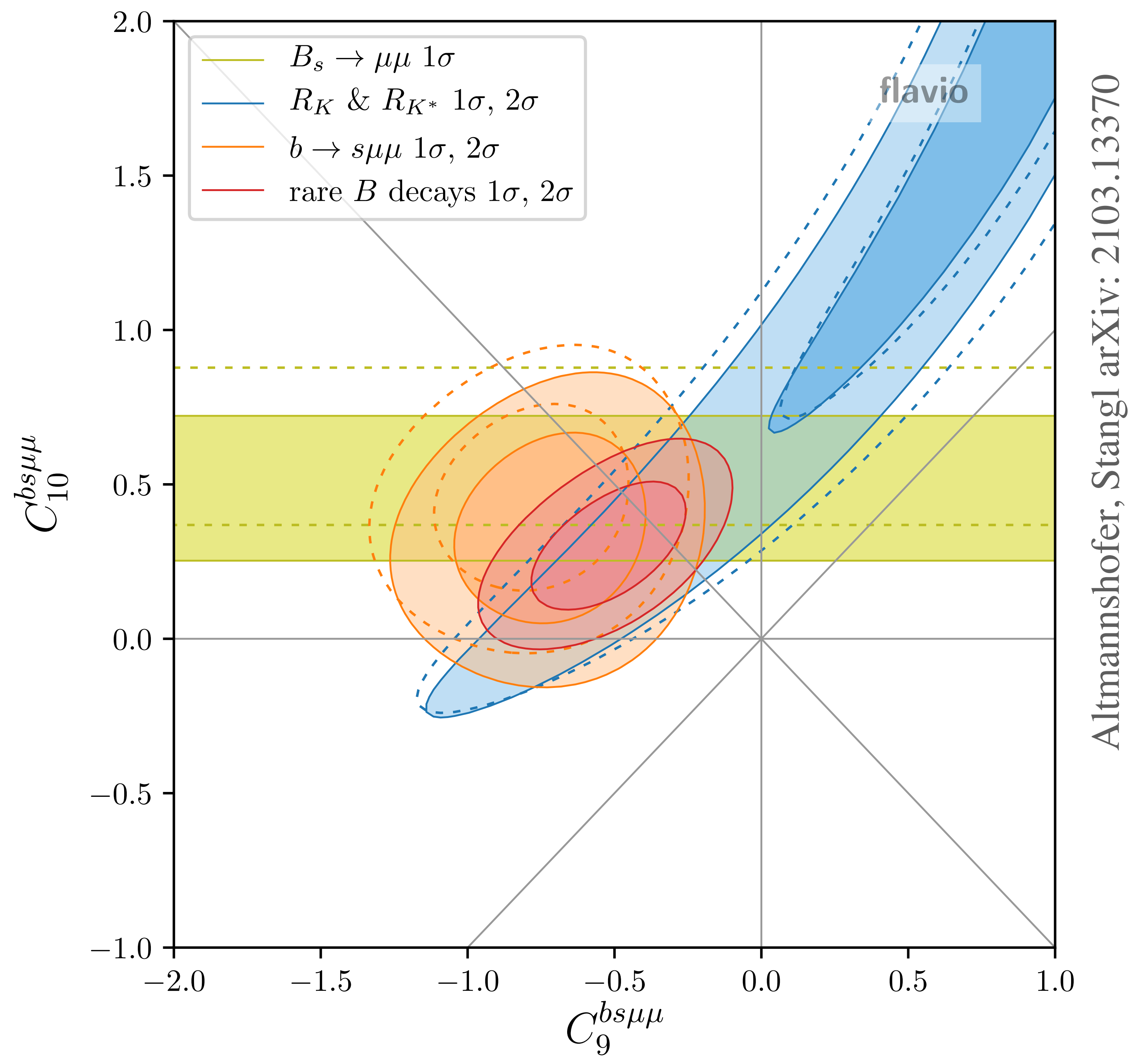


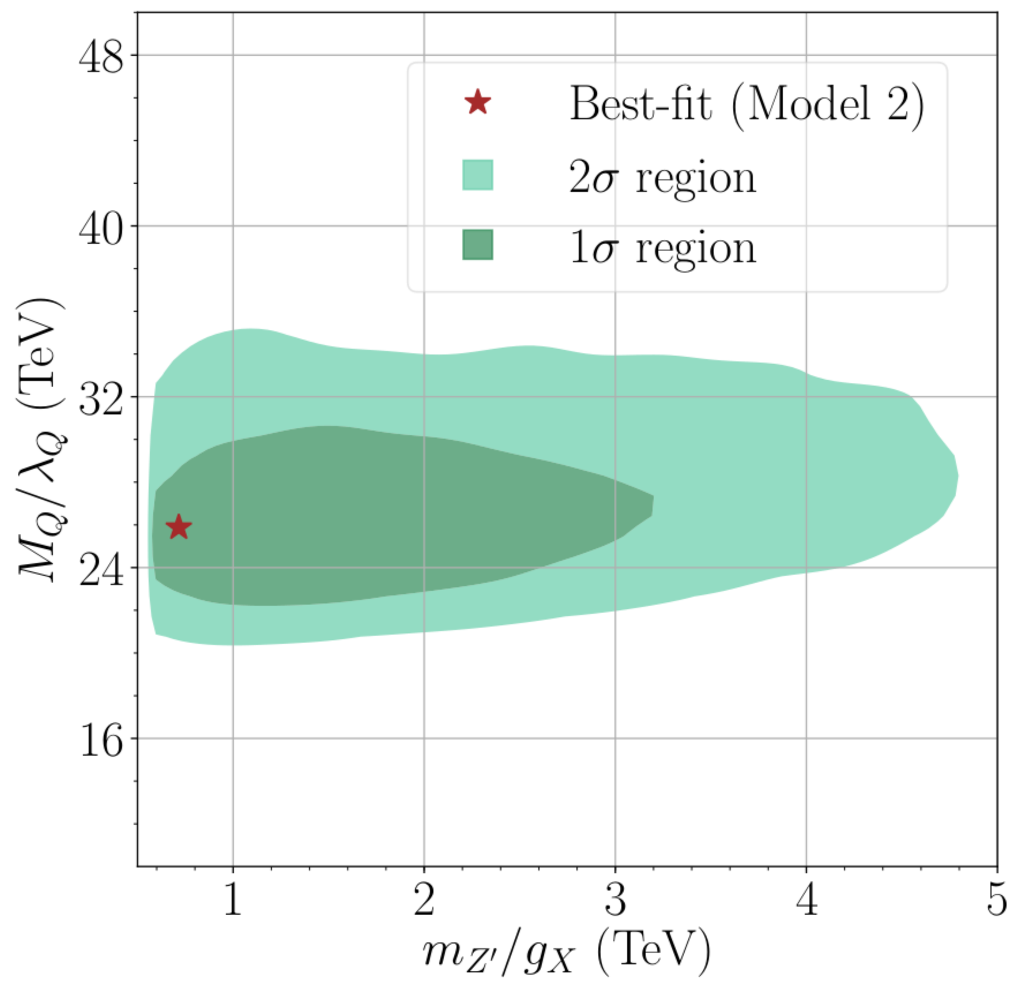
$\sim g_L^{\mu\mu} = g_X$

Minimal Z' models

Model 1: $-0.53 \leq C_9^\mu (= - C_{10}^\mu) \leq -0.25$

Model 2: $-1.03 \leq C_9^\mu \leq -0.43$





Problem: The constraints are only on the ratios of mass/couplings?

→ No prediction for the NP scale

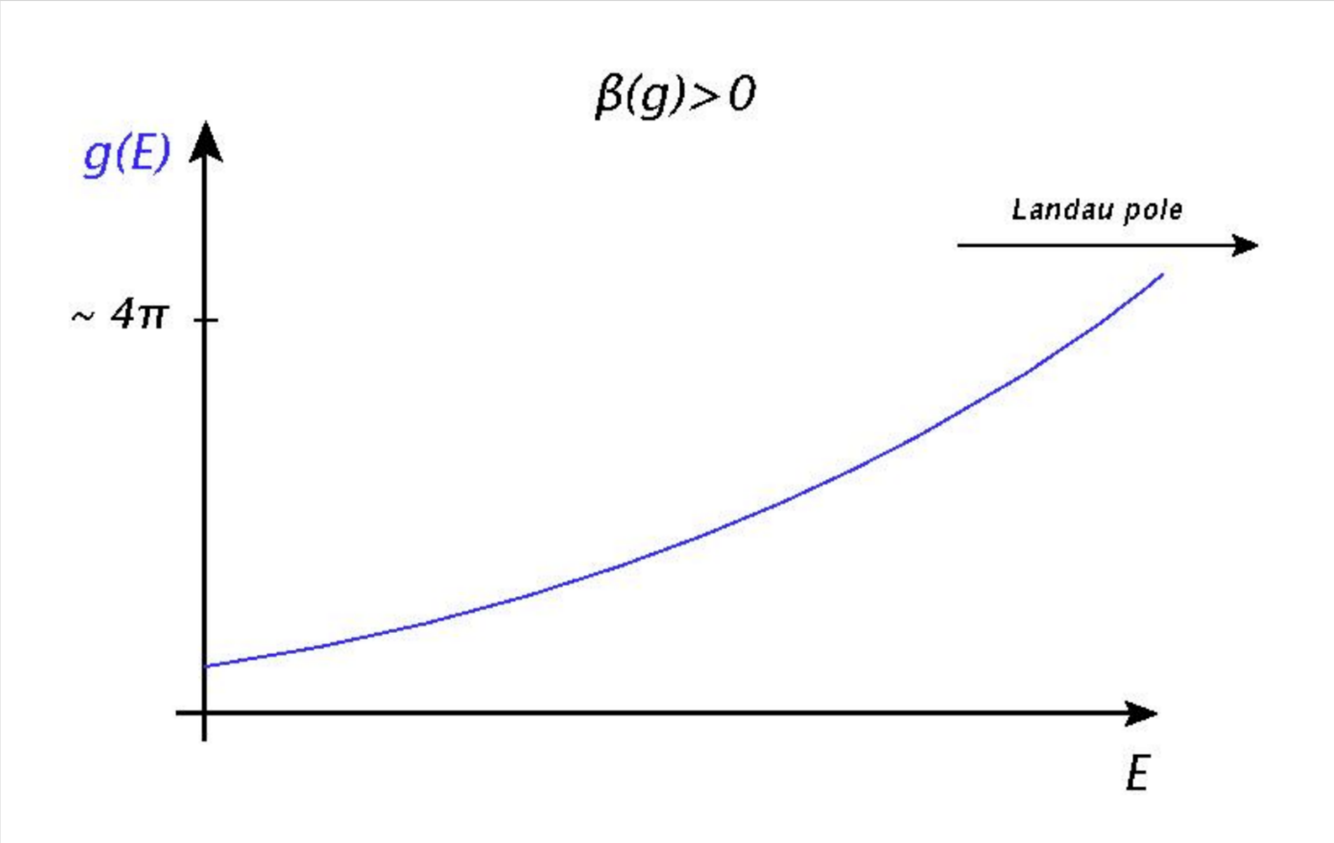
Solution: Asymptotic safety?

Asymptotic Safety

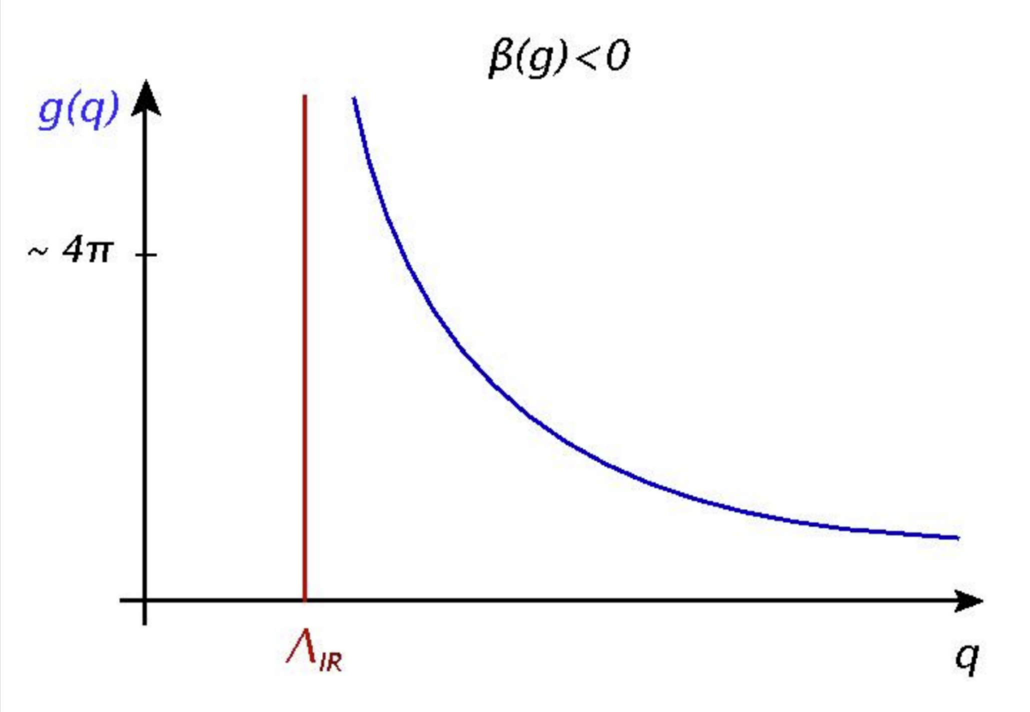
Coupling constants are scale dependent

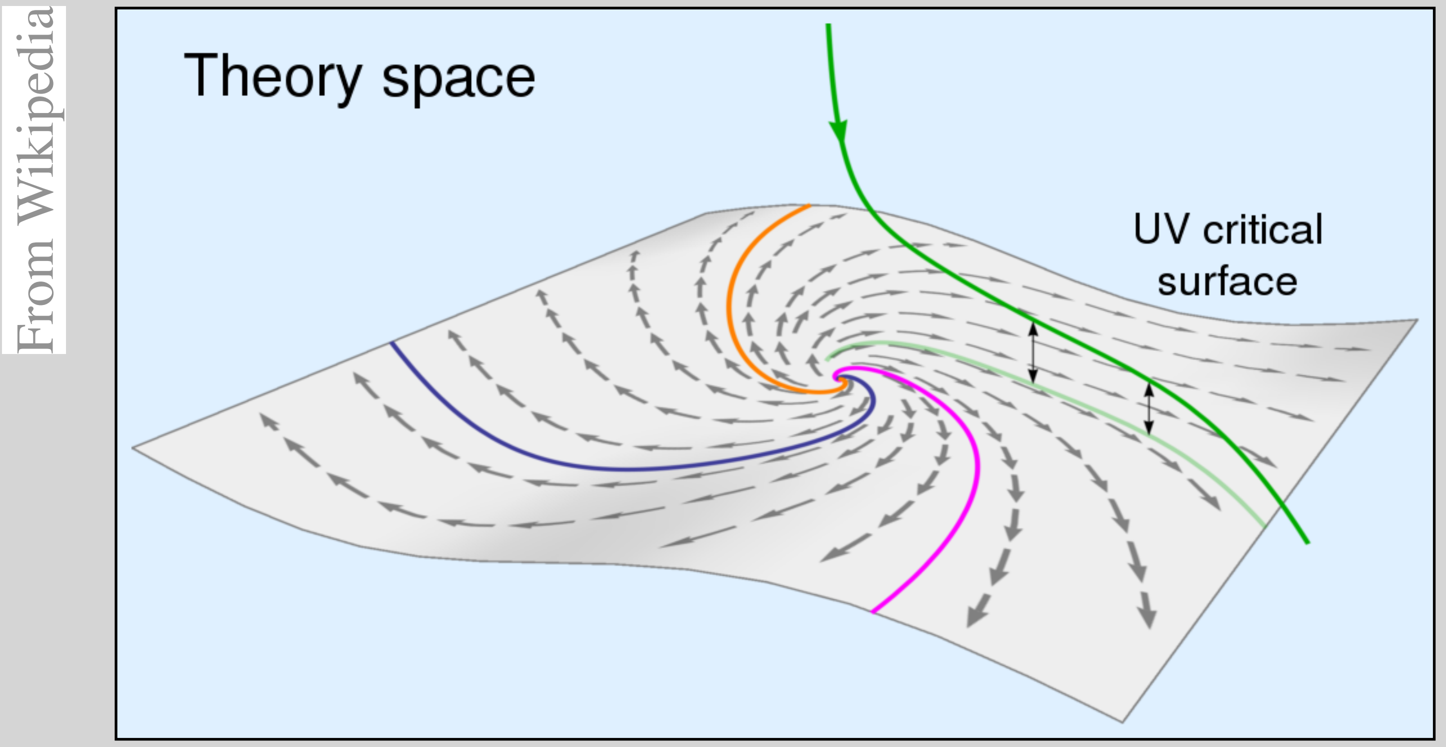
Landau pole: $g(q) \to \infty$ as $q \to q_0$

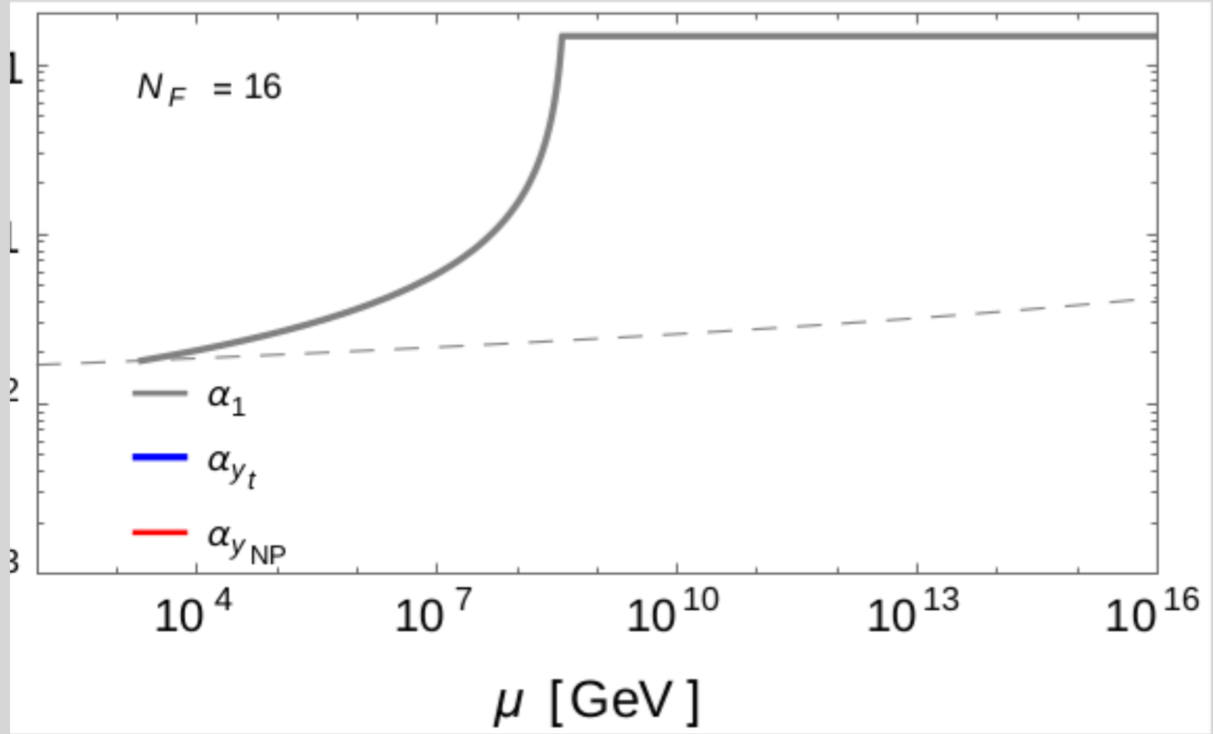
Needs UV completion



Asymptotic freedom: $g(q) \to 0$ as $q \to \infty$







Asymptotic safety: $\{g_i\} \to \{g_i^*\}$ as $q \to \infty$

Asymptotic safety with gravity

Gauge coupling: $\beta_g = \beta_g^{SM+NP} - f_g g$

Yukawa coupling: $\beta_y = \beta_y^{SM+NP} - f_y y$

Quantum-Gravitational contribution

In principle via FRG

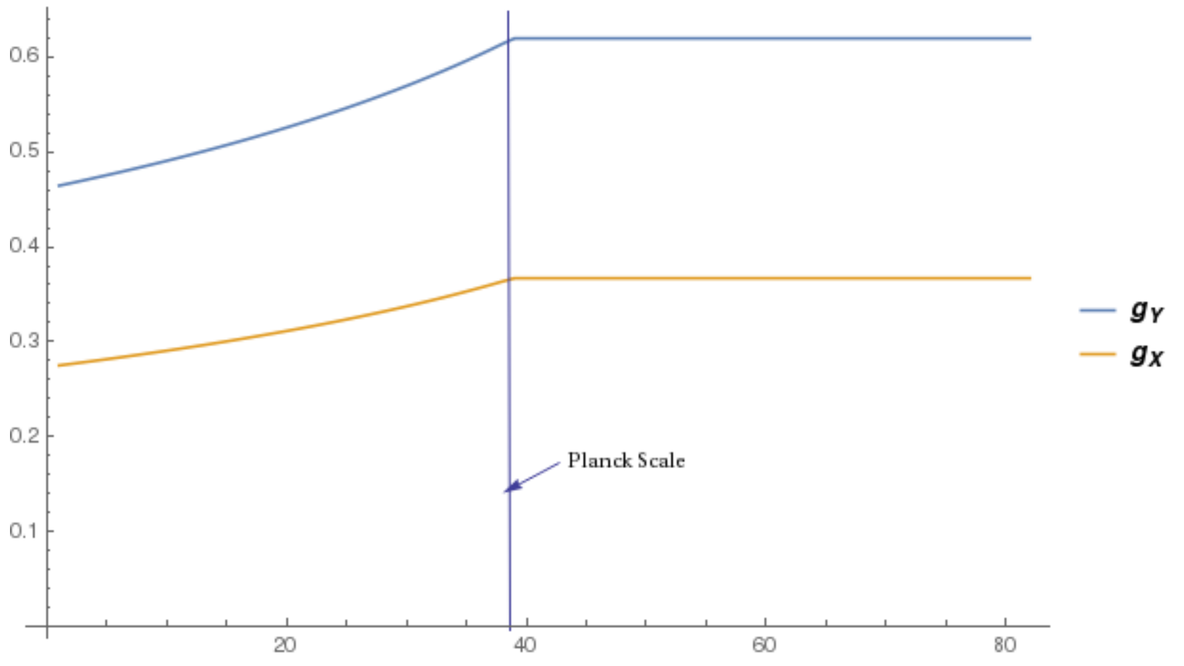
Universal: Does not distinguish internal symmetry

Daum, Harst, Reuter '09, Folkerst, Litim, Pawlowski '11, Harst, Reuter '11, Christiansen, Eichhorn '17, Eichhorn, Versteegen '17, Zanusso *et al*. '09, Oda, Yamada '15, Eichhorn, Held, Pawlowski '16, ...

f_g and f_y are free parameters determined by matching low-energy data

Eg: $\beta_{g_Y} = \frac{139}{30} g_Y^3 - f_g g_Y \qquad \beta_{g_X} = 11 g_X^3 - f_g g_X$

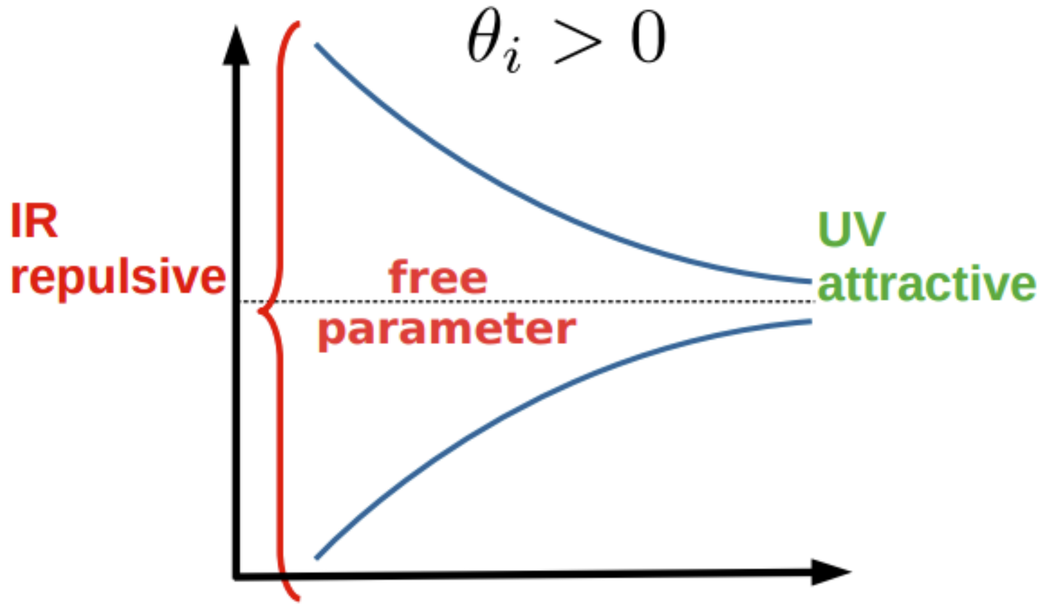
FP: $\beta_i(\{g_i\})\Big|_{g_i^*} = 0; \implies g_Y^* = \sqrt{\frac{30}{139} f_g} \qquad g_X^* = \sqrt{11 f_g}$



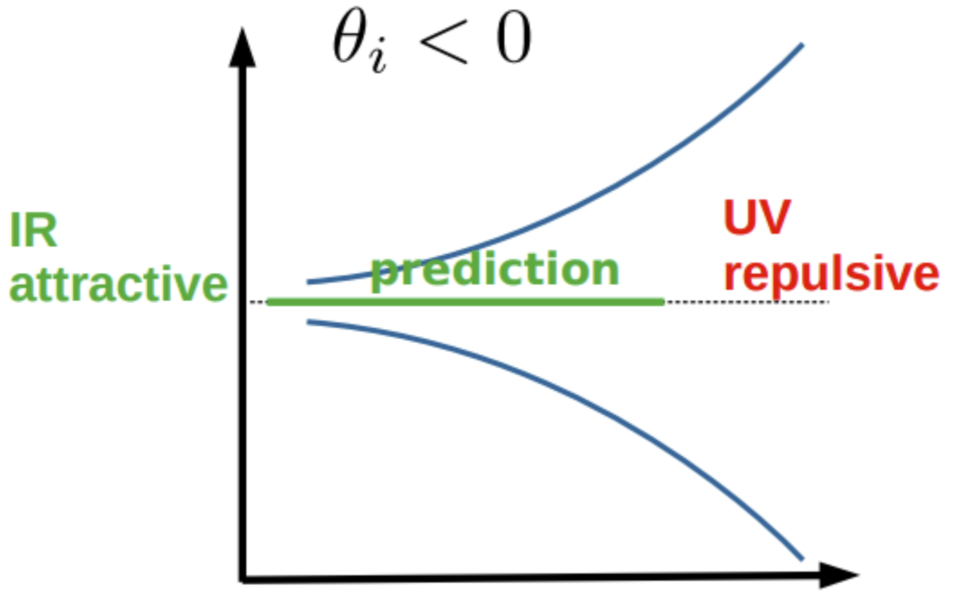
Fixed point properties:

$$\beta_i(\{g_i\}) = 0 \longrightarrow M_{ij} = \frac{\partial \beta_i}{\partial g_j}\Bigg|_{\{g_i^*\}} \longrightarrow \{\theta_i\}$$

Stability Matrix — Critical Exponents



Relevant couplings are free parameters of the theory



Irrelevant couplings provide predictions

Fixed Point Analysis

Couplings pertinent to flavor anomalies:

SM: $g_3,\ g_2,\ g_Y,\ y_b,\ y_t,\ V_{33}$

NP: $g_D,\ g_\epsilon,\ \lambda_{Q,2},\ \lambda_{Q,3},\ \lambda_{L,2}$

With 2 family approximation

Irrelevant couplings

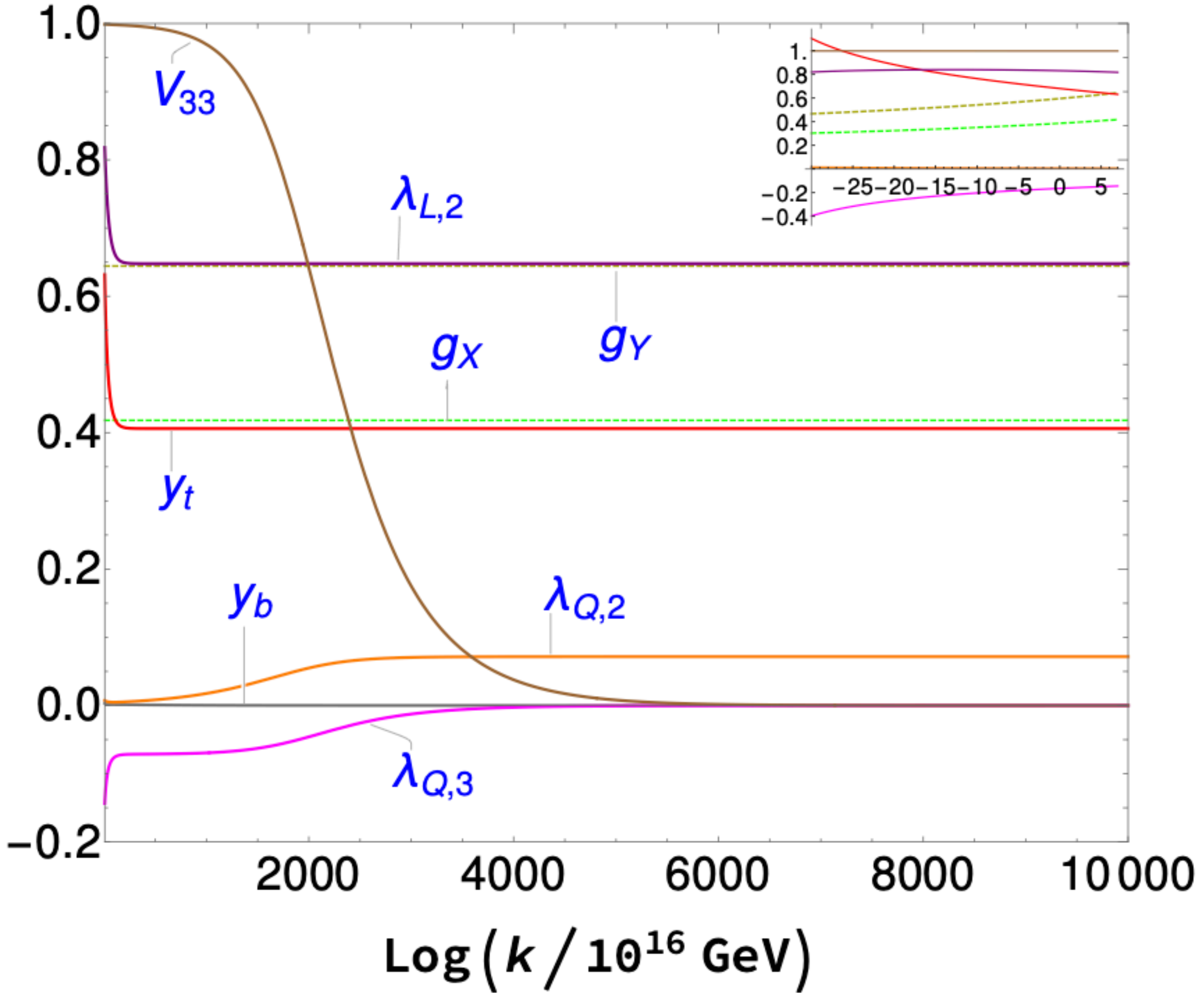
$$g_Y^* \neq 0,\ y_t^* \neq 0$$

$$g_D^* \neq 0,\ g_\epsilon^* \neq 0$$

$$\lambda_{Q,i}^* \neq 0,\ \lambda_{L,2}^* \neq 0$$

Relevant couplings

$$g_3^* = g_2^* = y_b^* = V_{33}^* = 0$$



Predictions vary based on the models and the fixed points

	$g_Y(k_0)$	$g_D(k_0)$	$g_\epsilon(k_0)$	$y_t(k_0)$	$\lambda_{Q,3}(k_0)$	$\lambda_{Q,2}(k_0)$	$\lambda_{L,2}(k_0)$
$FP_{1A,a}$	0.364	0.305	0	1.08	-0.381	0.016	0.823
$FP_{1A,b}$	0.364	0.305	0	1.09	0.034	0.803	0.606
$FP_{1B,a}$	0.363	0.318	0.110	1.05	-0.612	0.296	0.652
$FP_{1B,b}$	0.363	0.318	0.110	1.08	0.004	0.874	0.499
$FP_{2,a}$	0.363	0.277	0.052	1.03	-0.700	0.638	–
$FP_{2,b}$	0.363	0.277	0.052	1.10	0.040	0.988	–

CC values at $k_0 = 2\,TeV$

Phenomenology

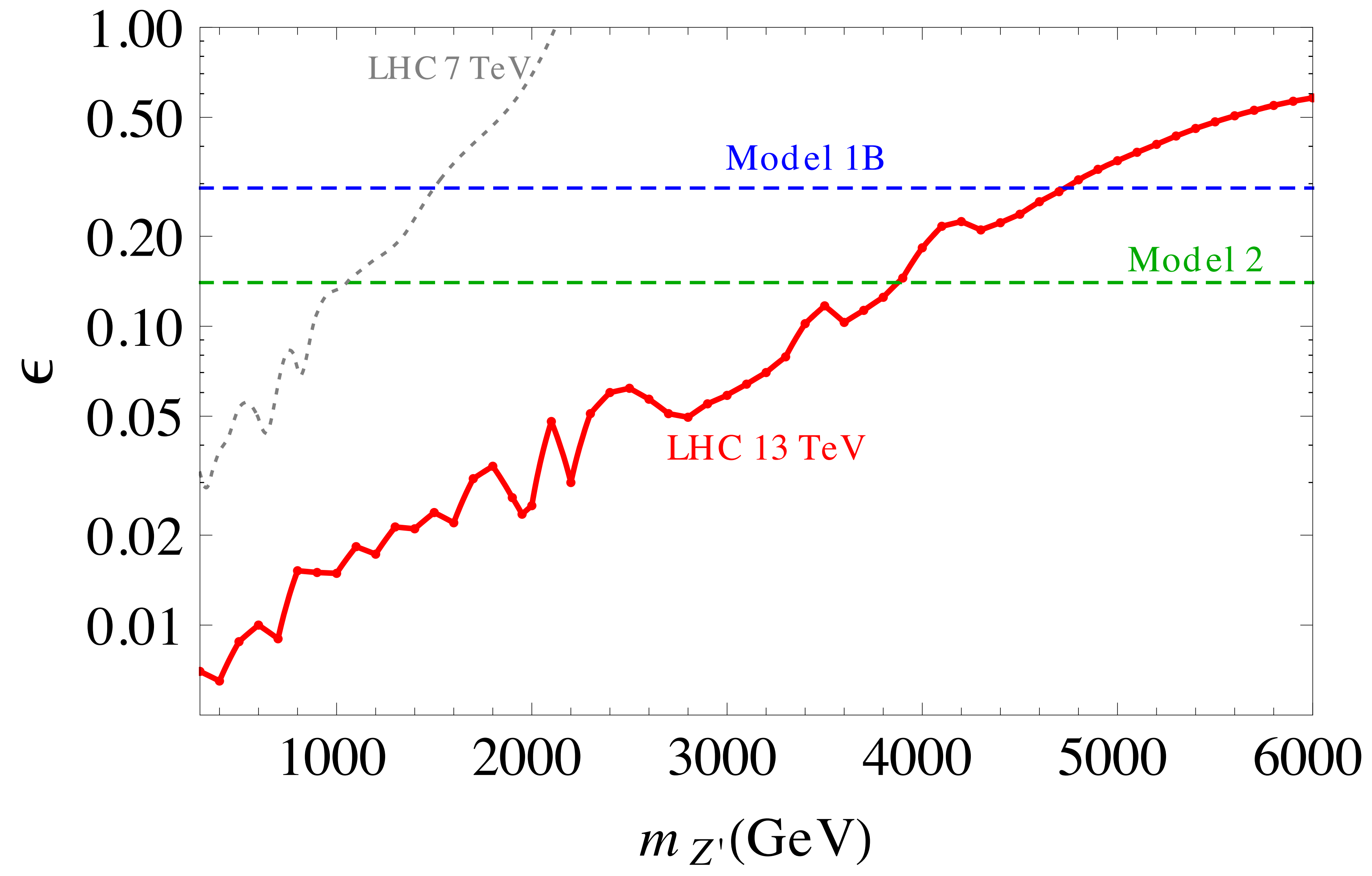
Kinetic terms of gauge coupling:

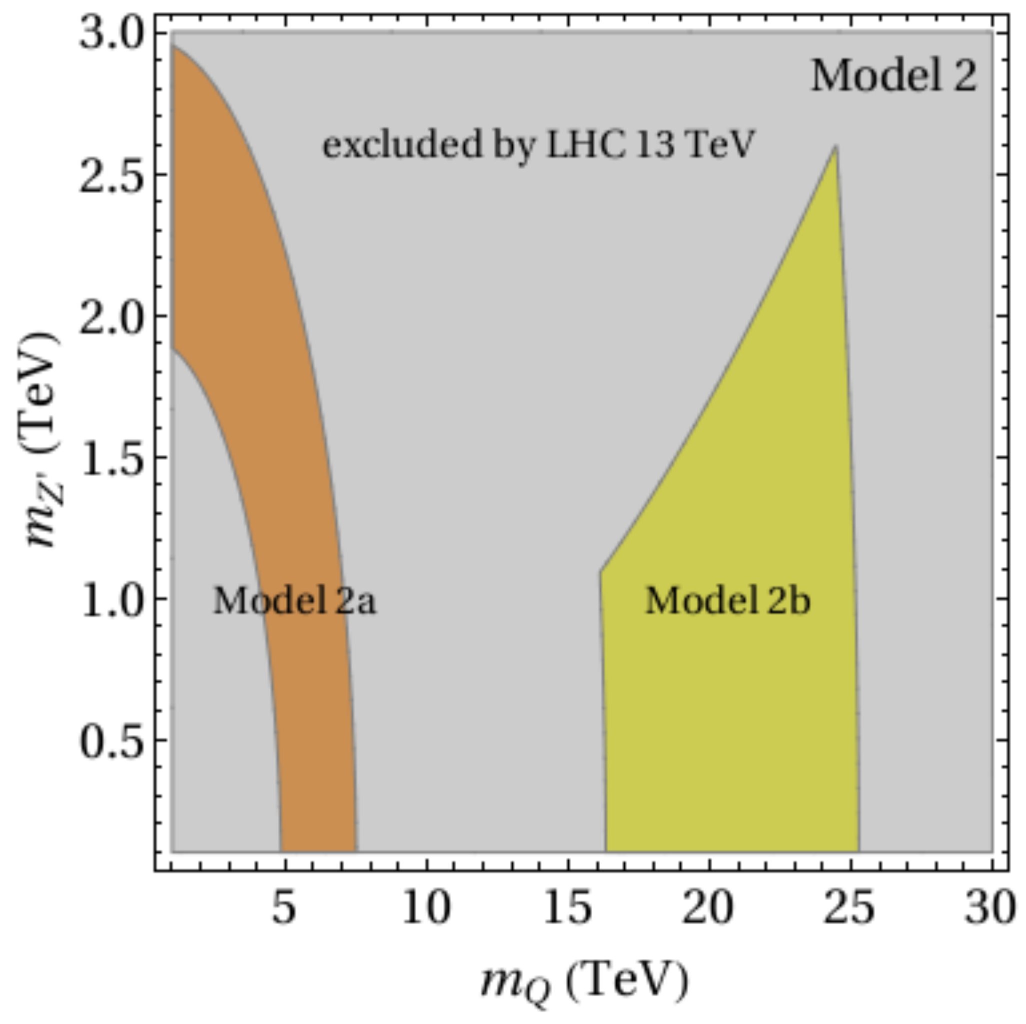
$$\mathscr{L} \supset -\frac{1}{4}W^i_{\mu\nu}W^{i\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}X_{\mu\nu}X^{\mu\nu} - \frac{1}{2}\epsilon\, B_{\mu\nu}X^{\mu\nu}$$

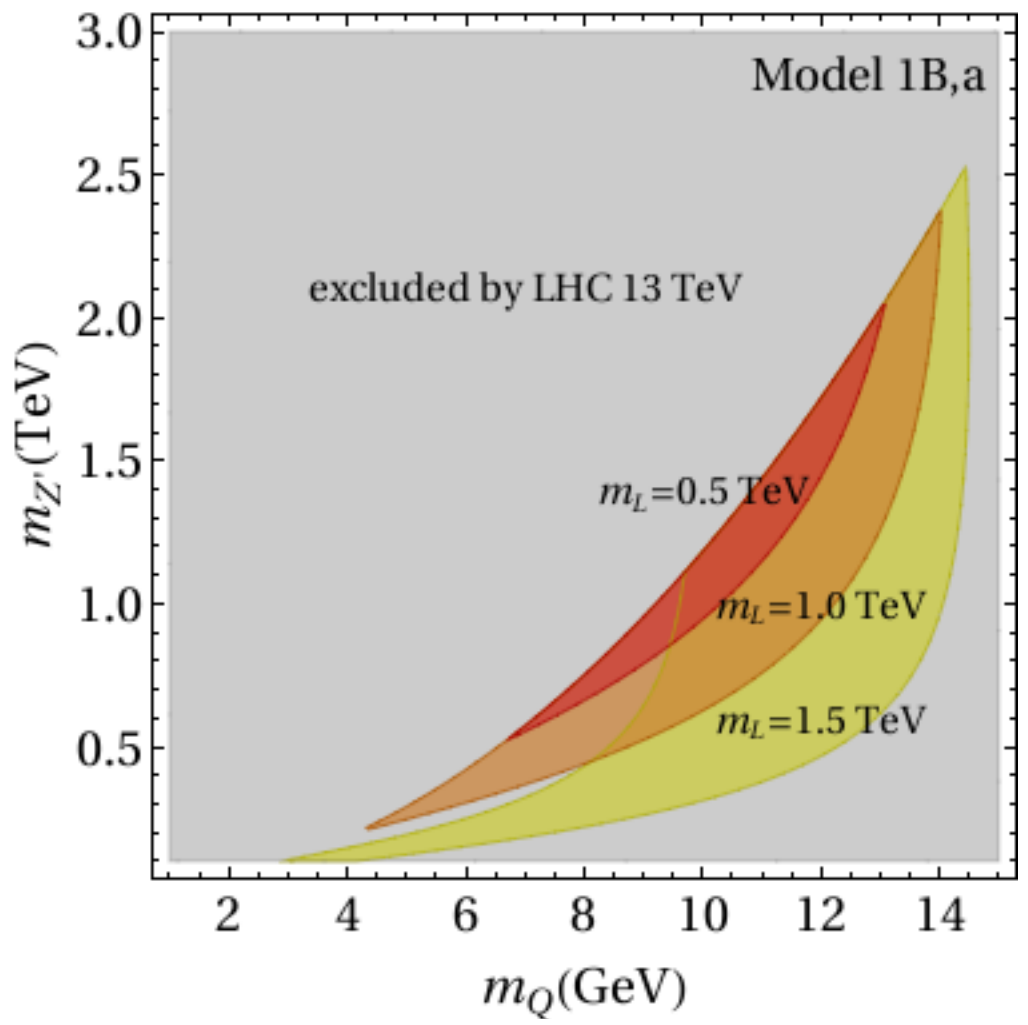
$$\epsilon = \frac{g_\epsilon}{\sqrt{g_y^2 + g_\epsilon^2}}$$

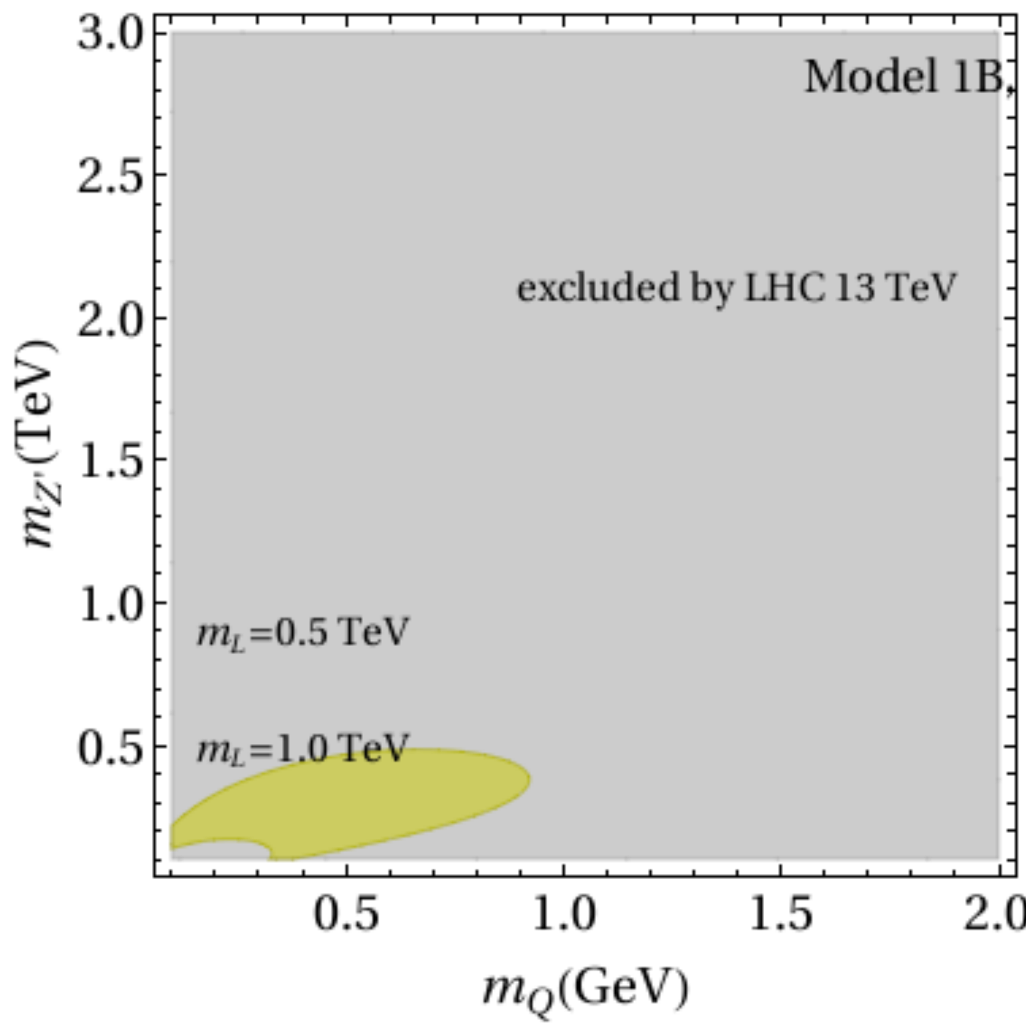
$\implies m_{Z'} > 3.9$ TeV Model 2

$m_{Z'} > 4.7$ TeV Model 1B







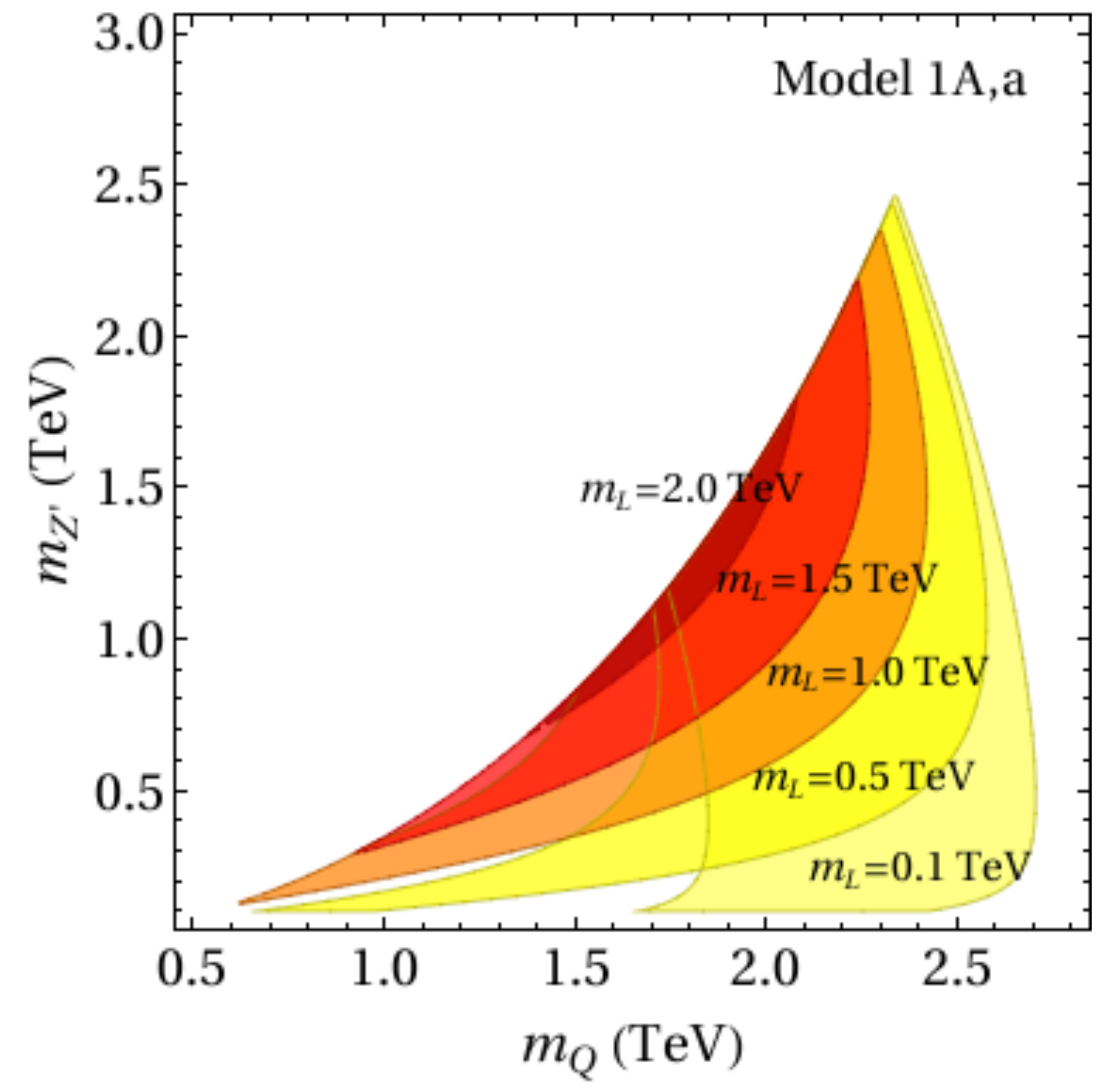


Phenomenology

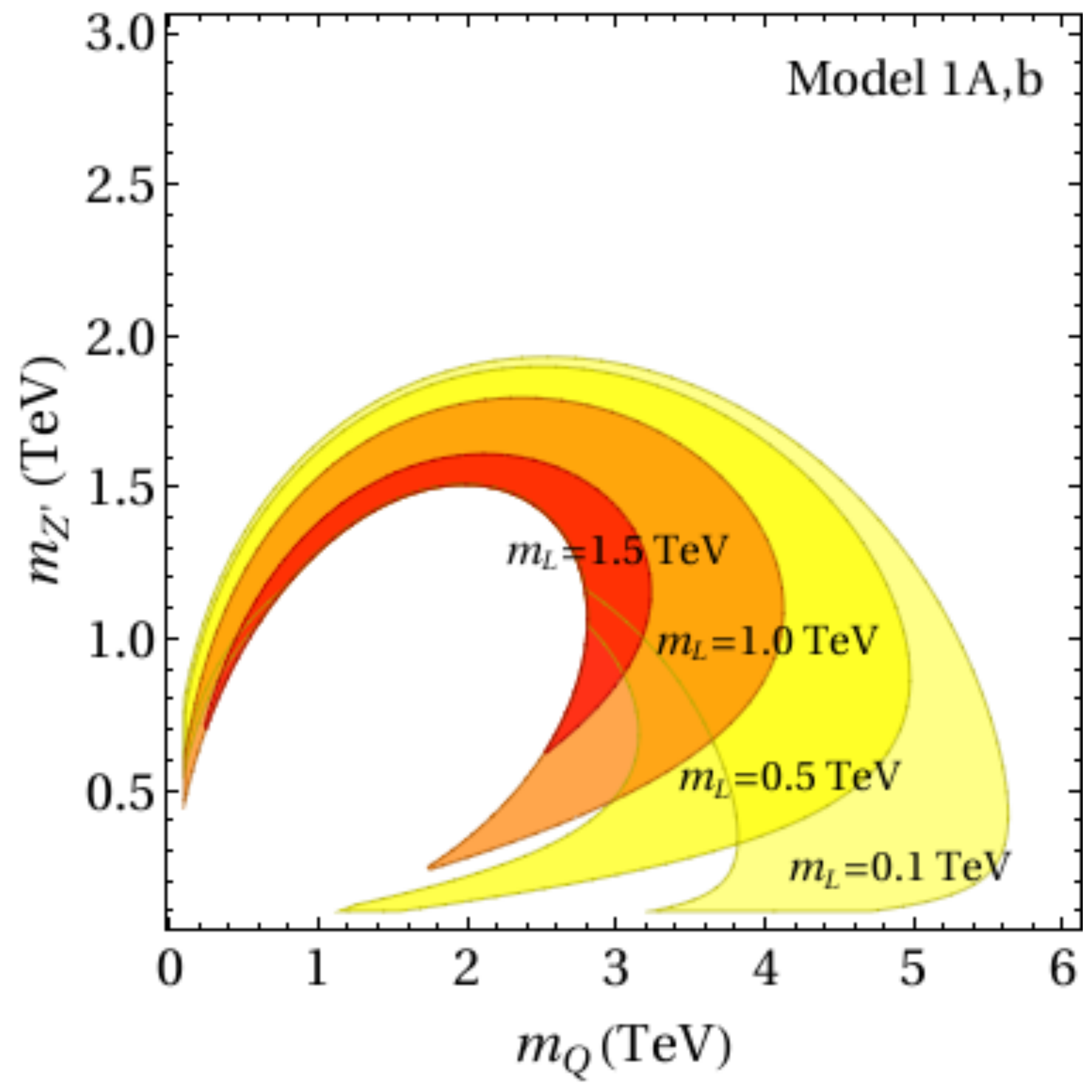
Model 1A:

No direct constraint from kinetic mixing

$\lambda_{Q2} = 0.016$



$\lambda_{Q2} = 0.803$



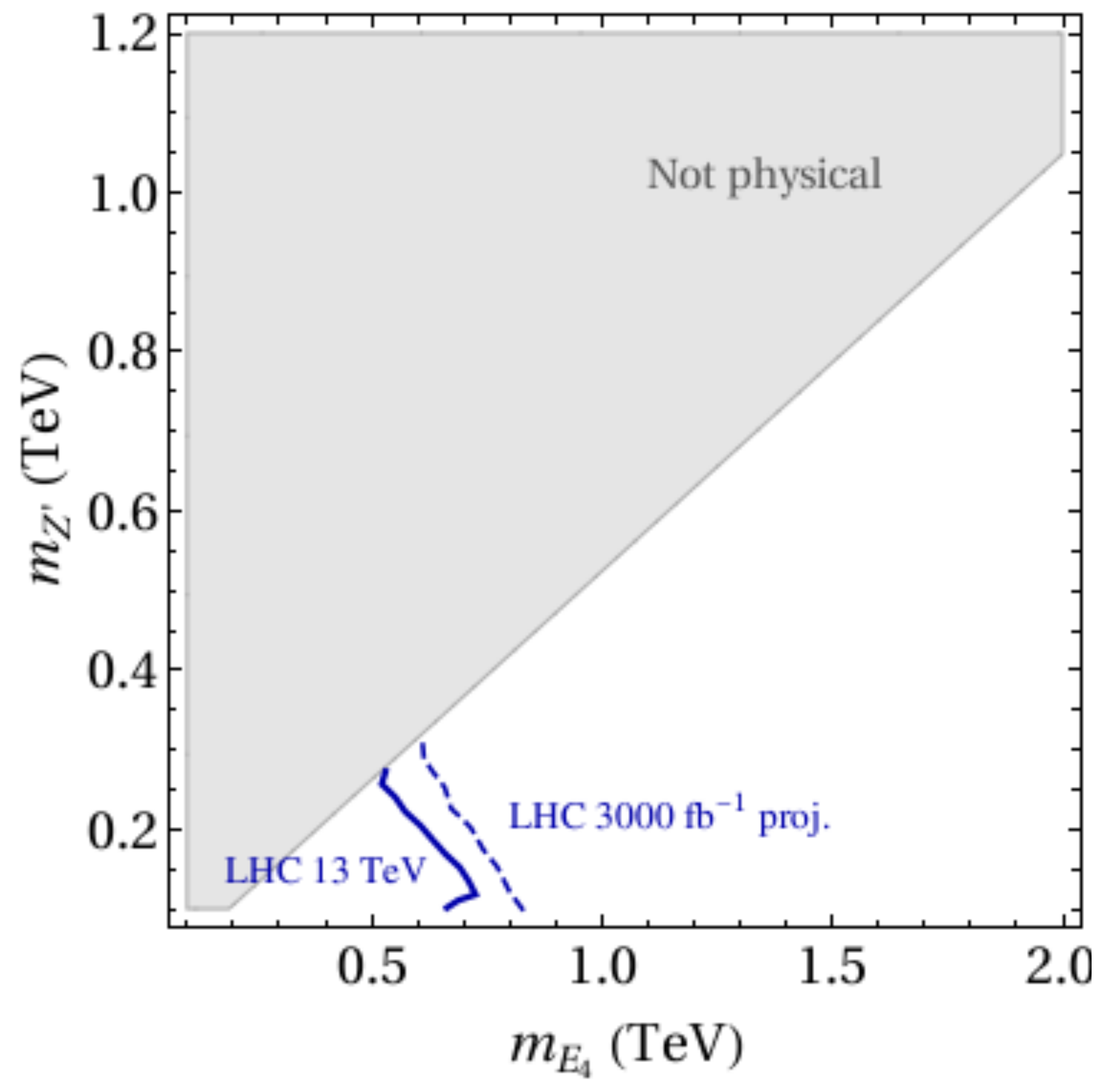
Model 1A,b:

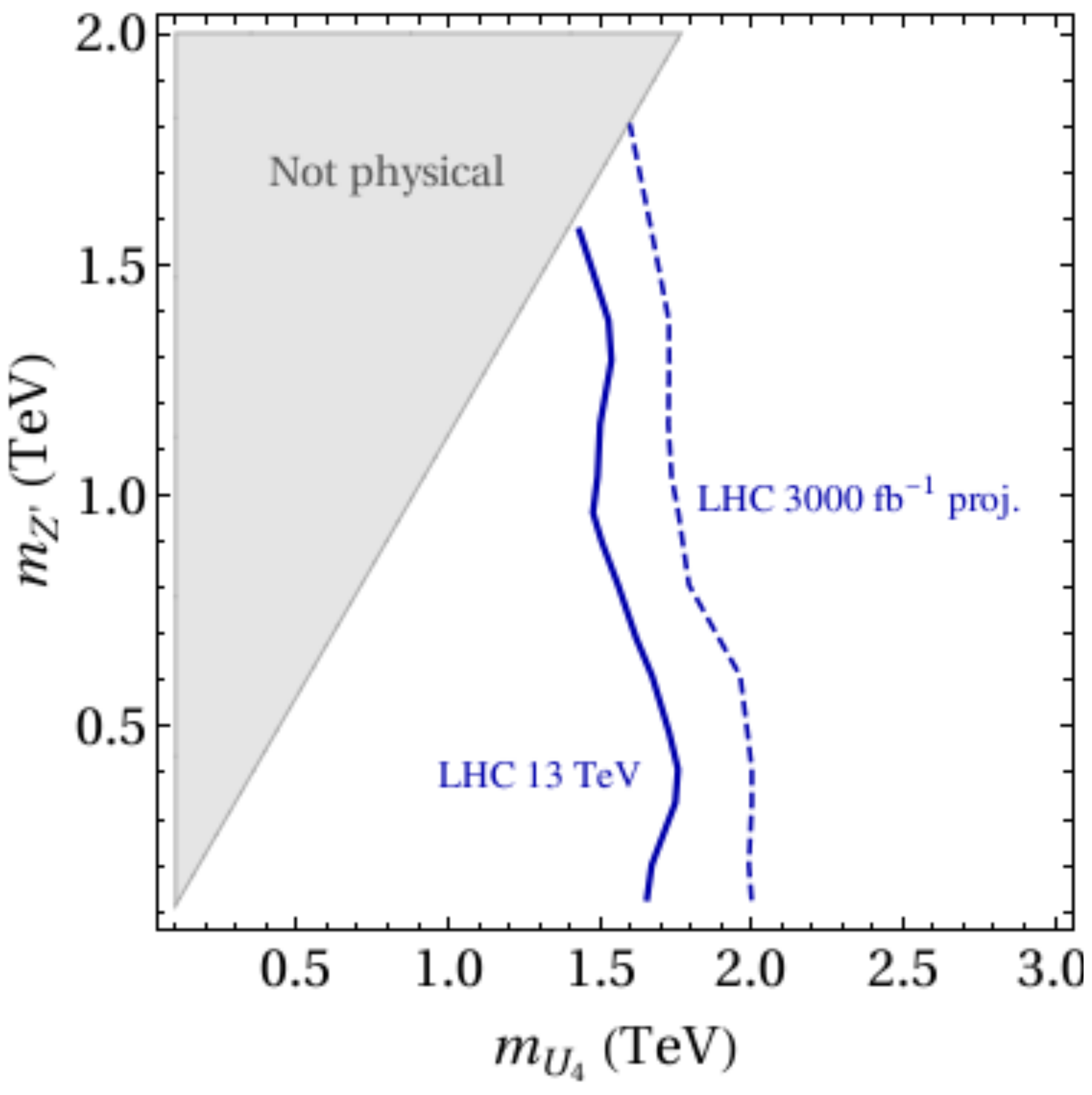
Collider searches: $m_{Z'} > 5$ TeV

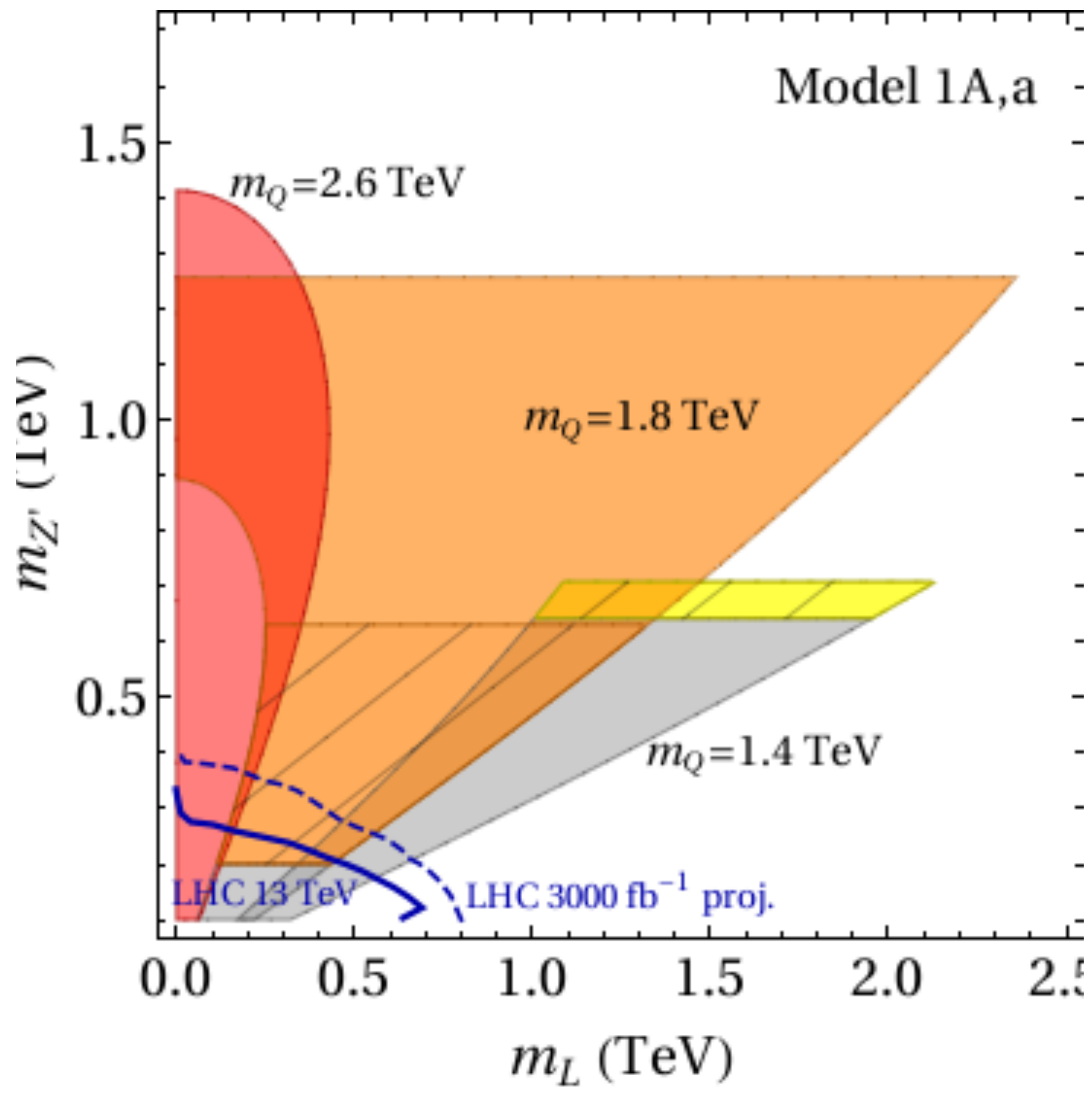
Phenomenology

Model 1A,a:

Constraints by recasting SUSY particle searches







Conclusion

- U(1)' solutions to NC flavor anomalies embedded in a UV completion with asymptotic safety
- The RGE flow of "irrelevant" couplings from a UV fixed point gives IR predictions -> U(1) gauge couplings, kinetic mixing, Yukawa couplings
- Comparison with operators of the EFT restricts allowed mass ranges for Z' + VL fermions
- Enhanced predictive power w.r.t. pure pheno models -- direct LHC constraints bite deeply in parameter space
- Enticing detection prospects at Hi-Luminosity LHC

Thank you