Antonio Masiero fest

Padova, May 29, 2025

Reflections on BSM physics, about half a century later

Riccardo Barbieri
SNS, Pisa

Wondering about BSM, 1979/81

COSMOLOGICAL BARYON PRODUCTION THROUGH SUPERHEAVY FERMIONS

Riccardo Barbieri (CERN), Dimitri V. Nanopoulos (CERN), A. Masiero (Munich, Max Planck Inst.) (Oct, 1980)

Hierarchical Fermion Masses in E6

Riccardo Barbieri (CERN), Dimitri V. Nanopoulos (CERN), A. Masiero (Munich, Max Planck Inst.) (Mar, 1981)

Compositeness and a Left-Right Symmetric Electroweak Model Without Broken Gauge Interactions

Riccardo Barbieri (CERN), Rabindra N. Mohapatra (CERN), A. Masiero (Geneva U. and Munich, Max Planck Inst.) (May, 1981)

Supersymmetry forever, 1982 on

Gluino and Photino Masses in a Class of Locally Supersymmetric Models #

Riccardo Barbieri (Pisa U. and INFN, Pisa), L. Girardello (Milan U. and INFN, Milan), A. Masiero (INFN, Padua) (Mar, 1983)

Hierarchy of Fermion Masses in Supersymmetric Composite Models

Riccardo Barbieri (Pisa U. and INFN, Pisa), A. Masiero (INFN, Padua), G. Veneziano (CERN) (Apr, 1983)

Supersymmetric Models with Low-Energy Baryon Number Violation

Riccardo Barbieri (Ecole Normale Superieure), A. Masiero (INFN, Padua) (Aug, 1985)

Supersymmetry, R-parity breaking and the neutrino magnetic moment

Riccardo Barbieri (Pisa U. and CERN), M.M. Guzzo (SISSA, Trieste), A. Masiero (INFN, Padua), D. Tommasini (SISSA, Trieste) (Aug, 1990)

Point Reyes, CA, circa 1988

Supersymmetry forever
with well known contributions by Antonio

Large Muon and electron Number Violations in Supergravity Theories

Francesca Borzumati (New York U.), Antonio Masiero (New York U.) (May, 1986)

A Natural Solution to the mu Problem in Supergravity Theories

G.F. Giudice (SISSA, Trieste and INFN, Trieste), A. Masiero (INFN, Padua) (Feb, 1988)

Effects of supergravity induced electroweak breaking on rare B decays and mixings

S. Bertolini (DESY), Francesca Borzumati (Munich, Max Planck Inst.), A. Masiero (INFN, Padua), G. Ridolfi (INFN, Genoa) (Jul, 1990)

A Complete analysis of FCNC and CP constraints in general SUSY extensions of the standard model

F. Gabbiani (Massachusetts U., Amherst), E. Gabrielli (INFN, Rome), A. Masiero (Perugia U. and INFN, Perugia), L. Silvestrini (Rome U., Tor Vergata and INFN, Rome) (Apr, 1996)

... and flavour

All the SM in 1 page

1. Symmetry group $L \times \mathcal{G}$

L = Lorentz (space-time)

$\mathcal{G} = SU(3) \times SU(2) \times U(1)$ (local)

2. Particle content (rep.s of $L \times \mathcal{G}$**)**

	h	q_i	l_i	u_i	d_i	e_i
Lorentz	0	$1/2_L$	$1/2_L$	$1/2_R$	$1/2_R$	$1/2_R$
$SU(3)$	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{1}$
$SU(2)$	$\mathbf{2}$	$\mathbf{2}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$
$U(1)$	$-1/2$	$1/6$	$-1/2$	$2/3$	$-1/3$	-1

3. All local operators of dimension d≤4 in $\mathcal{L}$

Compare this with the catalogue of independent observables it explains, often with high numerical precision $10^{-3} \div 10^{-9}$

Observational

Questions from (problems for) the SM

Structural

0. Which rationale for matter quantum numbers?

E.g.: $|Q_n - Q_p - Q_e| < 10^{-21} e$

1. Phenomena unaccounted for

neutrino masses

matter-antimatter asymmetry

Dark matter

inflation?

2. Why $\theta \lesssim 10^{-10}$?

$\theta G_{\mu\nu} \tilde{G}^{\mu\nu}$

Axions? A discrete space-time symmetry?

3. $\mathcal{O}_i : d(\mathcal{O}_i) \leq 4$ only?

neutrino masses

Are the protons forever?

Gravity

What about individual L_i conservations?

4. Lack of calculability

Observational

Questions from (problems for) the SM

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neutrino masses

Gravity

Are the protons forever?

What about individual L_i conservations?

4. Lack of calculability

$\Rightarrow$ the hierarchy problem
the flavour puzzle $\Leftarrow$ none of the 15 masses predicted in the SM

A difference in the two sectors of the SM?

$$\mathcal{L}_{SM} = -\frac{1}{4} F^a_{\mu\nu} F^{a\mu\nu} + i\bar{\Psi} \not{D} \Psi$$

The "gauge sector"

$$+|D_\mu \phi|^2 + M^2|\phi|^2 - \lambda|\phi|^4 + \Lambda + \lambda_{ij}\phi\bar{\Psi}_i\Psi_j$$

The "Higgs sector"

1. An accumulation of problems in the Higgs sector

the hierarchy problem

the CC problem

the flavour puzzle

In EFT they look much the same

No particle mass calculable (15=17-2)

A difference in the two sectors of the SM?

$$\mathcal{L}_{SM} = -\frac{1}{4}F^a_{\mu\nu}F^{a\mu\nu} + i\bar{\Psi}\not{D}\Psi$$

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The "Higgs sector"

2. A different level of precision

(See specific models for precise comparisons)

De Blas et al, 2025

EWPT

	Result
$\delta\varepsilon_1$	0.0007 ± 0.0010
$\delta\varepsilon_2$	-0.0002 ± 0.0008
$\delta\varepsilon_3$	0.0007 ± 0.0009
$\delta\varepsilon_b$	0.0004 ± 0.0013

E.g. $M_W = M_W^{SM}(1 + a_i\delta\epsilon_i)$

$a_i = O(1)$ known

$\lesssim 1ppm$

Higgs couplings

	Result
κ_W	0.94 ± 0.10
κ_Z	1.03 ± 0.13
κ_ℓ	1.02 ± 0.15
κ_u	0.95 ± 0.13
κ_d	0.91 ± 0.22

$\mathcal{L}_Y = \frac{m}{v}k_f\bar{f}_L H f_R$ etc

$\gtrsim 10\%$

Flavour

see below

A difference in the two sectors of the SM

$$\mathcal{L}_{SM} = -\frac{1}{4}F^a_{\mu\nu}F^{a\mu\nu} + i\bar{\Psi}\not{D}\Psi$$

The "gauge sector"

$$+|D_\mu\phi|^2 + M^2|\phi|^2 - \lambda|\phi|^4 + \Lambda + \lambda_{ij}\phi\bar{\Psi}_i\Psi_j$$

The "Higgs sector"
(where the Fermi scale originates)

$\Lambda^h \equiv$ the physics scale that addresses the hierarchy problem and explains the origin of EWSB

$\Lambda^f \equiv$ the scale at which λ_{ij} originates (the flavour puzzle)

How far are Λ^h, Λ^f from the Fermi scale?

(None of the proposals to address the hierarchy problem
is exempt from the flavour problem)

Altogether : the relatively best motivation for BSM in the MultiTeV

(and a strong motivation for the next HE collider)

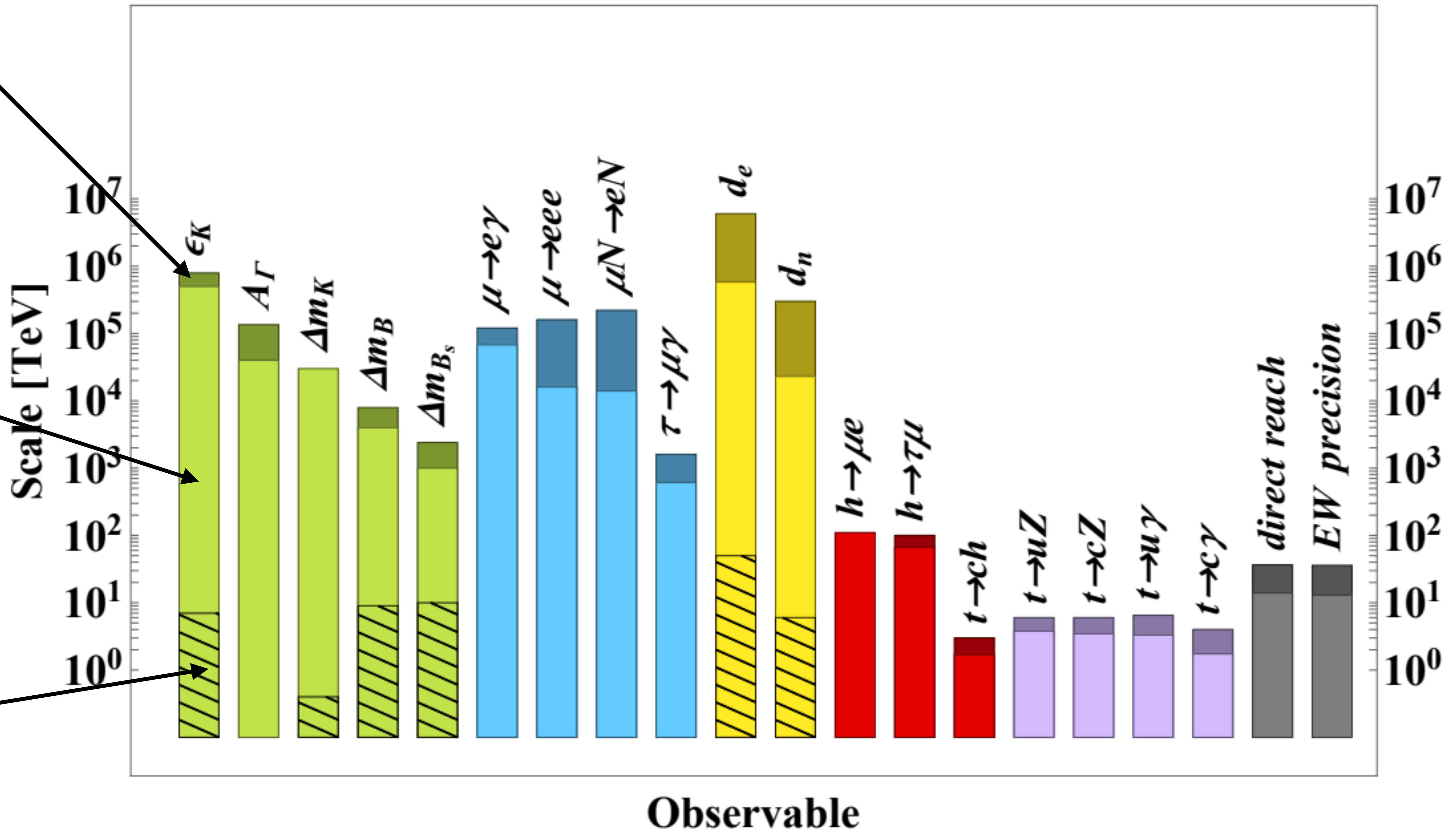
An extreme summary in precision measurements

(European Strategy for PP, 2020, under update)

"Mid-term" prospects:
All approved exp.s + LHCb II

current
$\mathcal{L} = \mathcal{L}_{SM} + \Sigma_i \frac{1}{\Lambda_i^2} \mathcal{O}_i$

current
$\mathcal{L} = \mathcal{L}_{SM} + \Sigma_i \frac{F_i^{SM}}{\Lambda_i^2} \mathcal{O}_i$



Flavour and EDMs (CPV) dominate

A more detailed plot

(from actually measured flavour quantities only, as opposed to bounds)

Bona et al, 2025

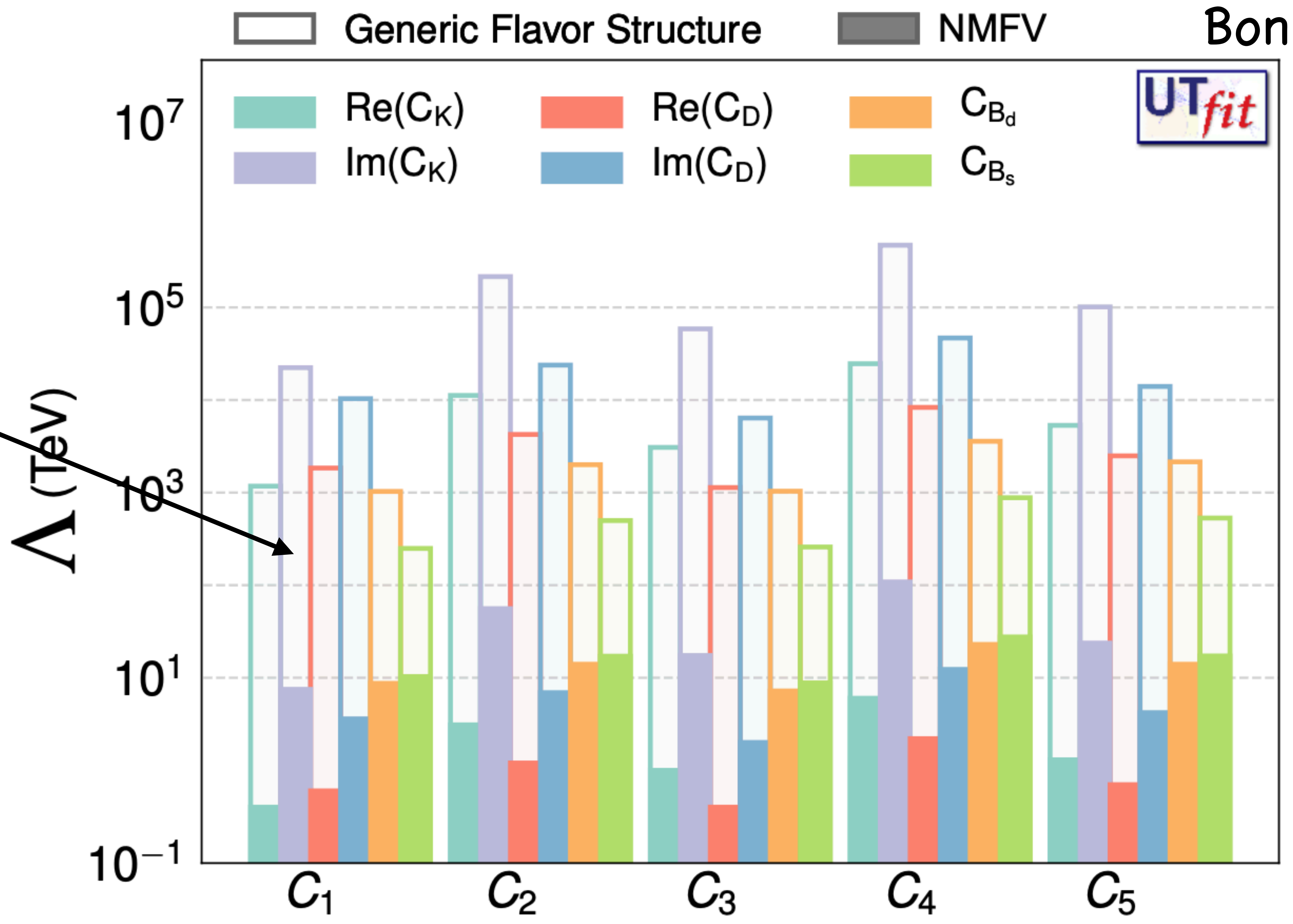
$$\mathcal{L} = \mathcal{L}_{SM} + \Sigma_i \frac{C_i}{\Lambda_i^2} \mathcal{O}_i$$

$\mathcal{C}_i = 1$

$$Q_1^{q_i q_j} = \bar{q}^\alpha_{jL} \gamma_\mu q^\alpha_{iL} \bar{q}^\beta_{jL} \gamma^\mu q^\beta_{iL} ,$$

$$Q_2^{q_i q_j} = \bar{q}^\alpha_{jR} q^\alpha_{iL} \bar{q}^\beta_{jR} q^\beta_{iL} , \qquad Q_4^{q_i q_j} = \bar{q}^\alpha_{jR} q^\alpha_{iL} \bar{q}^\beta_{jL} q^\beta_{iR} ,$$

$$Q_3^{q_i q_j} = \bar{q}^\alpha_{jR} q^\beta_{iL} \bar{q}^\beta_{jR} q^\alpha_{iL} , \qquad Q_5^{q_i q_j} = \bar{q}^\alpha_{jR} q^\beta_{iL} \bar{q}^\beta_{jL} q^\alpha_{iR} .$$



$\Lambda^f \gtrsim PeVs?$ Hence nothing to do with the Fermi scale?

(In particular $\Lambda^f >> \Lambda^h$?)

(approximate) symmetries of the Yukawa couplings

$$Y_f = U_L^{f+} Y_f^{diag} U_R^f \qquad f = u, d, e$$

$$Y \propto U_L^+ \begin{pmatrix} m_1/m_3 & 0 & 0 \\ 0 & m_2/m_3 & 0 \\ 0 & 0 & 1 \end{pmatrix} U_R \qquad m_1/m_3 << m_2/m_3 << 1 \qquad U_L^u (U_L^d)^+ = V_{CKM} \approx \begin{pmatrix} 1 & \lambda & \lambda^3 \\ \lambda & 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix}_{\lambda \approx 0.2}$$

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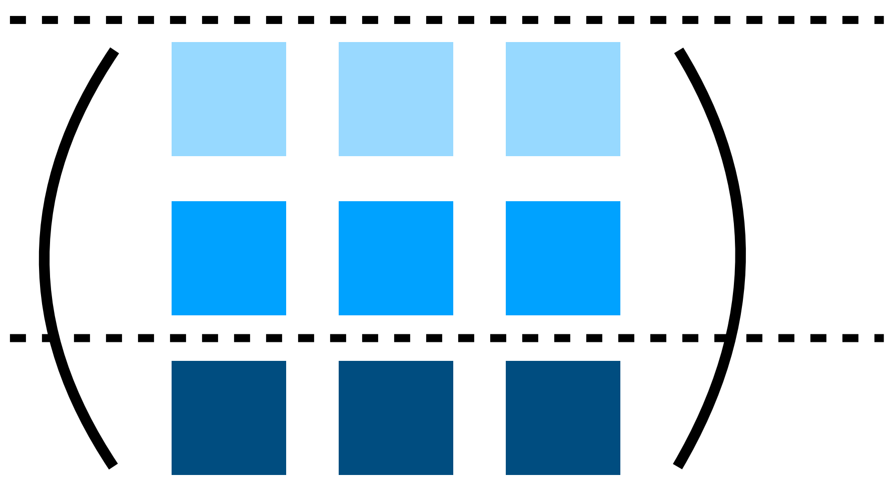
1 IF $[U_L^{u,d}]_{i \neq j} \lesssim [V_{CKM}]_{i \neq j}$

no special structure in $U_R^{u,d}$

$Y^{u,d} \propto$  $U(2)_q$

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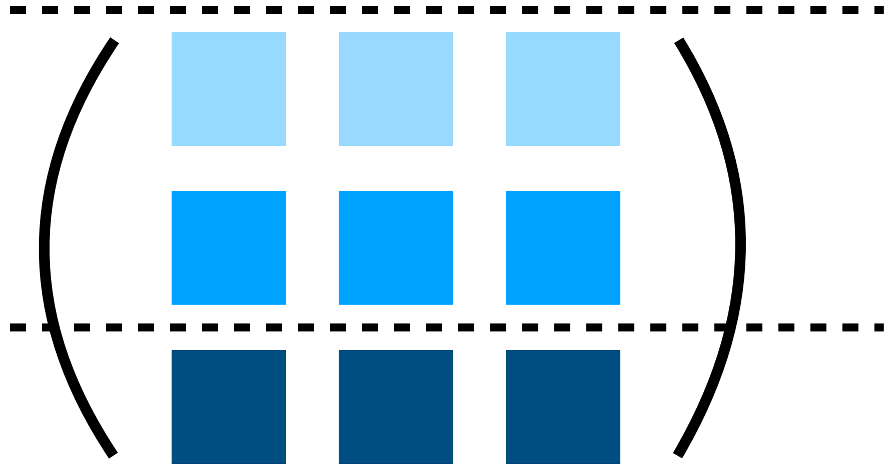


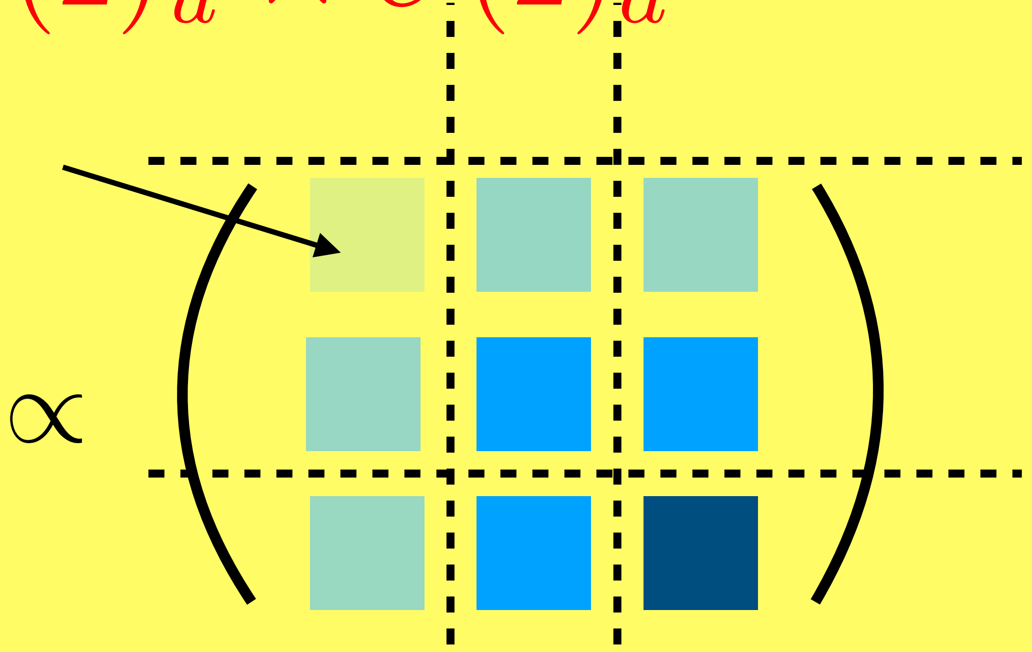
$U(2)_q$

2 IF 1 + $[U_R^{u,d}]_{i \neq j} \lesssim [U_L^{u,d}]_{i \neq j}$

$U(2)_u \times U(2)_d$

$U(1)_{u_1} \times U(1)_{d_1}$

$Y^{u,d} \propto$



$U(2)_q$

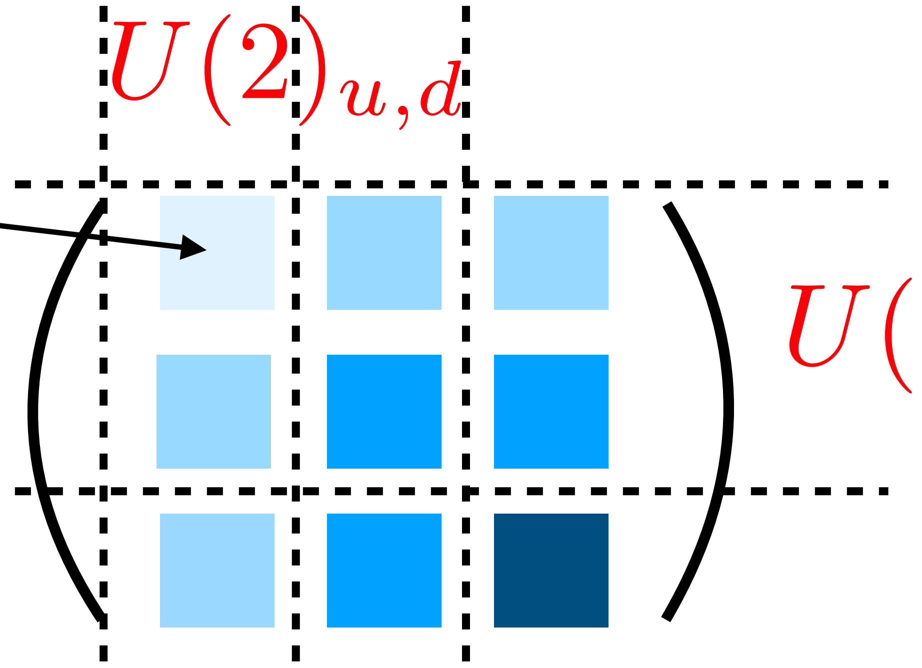
(approximate) symmetries of the Yukawa couplings

$$Y_f = U_L^{f+} Y_f^{diag} U_R^f$$

IF $[U_L^{u,d}]_{i\neq j} \lesssim [V_{CKM}]_{i\neq j}$ and $[U_R^{u,d}]_{i\neq j} \lesssim [U_L^{u,d}]_{i\neq j}$

$U(1)_{u_1} \times U(1)_{d_1}$

$Y^{u,d} \propto$



$\Rightarrow U(2)_q \times U(2)_u \times U(2)_d$

B, Isidori et al, 2011

Can $U(2)^n$ allow for Λ^f to be in the TeV?

YES, suitably broken (Froggatt-Nielsen would not)

Greljo et al, 2022
Allwicher et al, 2023

$\Rightarrow$ What is the origin of these symmetries? What breaks them? Which specific manifestations? $\Leftarrow$

(Deconstructed Susy models 2001)

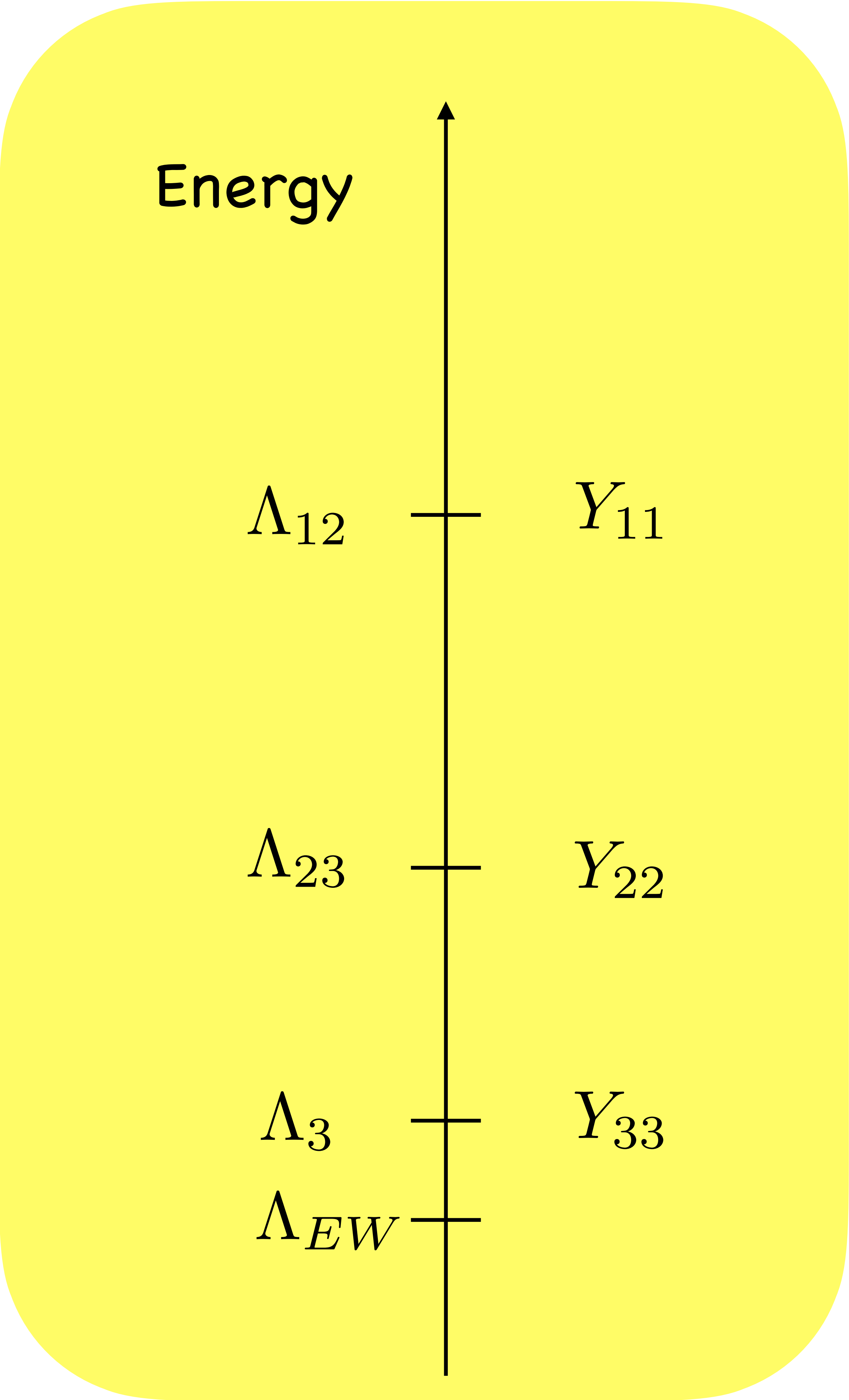
Flavour Deconstruction
(See Gino's talk)

Davighi, Isidori, 2023
Davighi et al, 2023
Fernando-Navarro, King 2023

1. The $SU(3) \times SU(2) \times U(1)$ gauge interactions are (fully or in part) flavour non-universal

Unlike $SU(3) \times SU(2) \times U(1) \times G^{[i]}$ gauged, global, discrete, etc

2. The flavour universal gauge interactions (observed so far) are a low energy manifestation of the step-wise breaking of the gauge group at different scales, responsible for the hierarchical structure of the Yukawa couplings



An explicit example, insisting on 4d, UV complete

B, Isidori, 2023

$$G = SU(3) \times SU(2) \times U(1)_Y^{[3]} \times U(1)_{B-L}^{[12]} \times U(1)_{T_{3R}}^{[2]} \times U(1)_{T_{3R}}^{[1]}$$

Standard 16-plet of chiral fermions, e.g. $q_3 = (3,2)_{(1/6,0,0,0)}$, including ν_{R1}, ν_{R2} (ν_{R3} fully neutral)

1 Breaking the gauge symmetry

Scalars

Field	$U(1)_Y^{[3]}$	$U(1)_{B-L}^{[12]}$	$U(1)_{T_{3R}}^{[2]}$	$U(1)_{T_{3R}}^{[1]}$	$SU(3)\times SU(2)$
σ	0	0	$1/2$	$-1/2$	$(\mathbf{1},\mathbf{1})$
χ^q	$-1/6$	$1/3$	0	0	$(\mathbf{1},\mathbf{1})$
χ^l	$1/2$	-1	0	0	$(\mathbf{1},\mathbf{1})$
ϕ	$1/2$	0	$-1/2$	0	$(\mathbf{1},\mathbf{1})$
$H_{u,d}$	$-1/2$	0	0	0	$(\mathbf{1},\mathbf{2})$

$\downarrow$ $<\sigma>$

$U(1)_Y^{[3]} \times U(1)_{B-L}^{[12]} \times U(1)_{T_{3R}}^{[12]}$

$\downarrow$ $<\phi, \chi>$

$U(1)_Y$

Most general $d \leq 4$ $\quad \mathcal{L}_Y = y_3^u \bar{q}_3 H_u u_3 + y_3^d \bar{q}_3 H_d^* d_3 + y_3^e \bar{l}_3 H_d^* e_3 + y_3^\nu \bar{l}_3 H_u^* \nu_3$

Symmetries of $\mathcal{L}_Y$ $\quad \Rightarrow \quad U(1)_{B_3} \times U(1)_{L_3} \times U(2)_q \times U(2)_l \times U(2)_u \times U(2)_d \times U(2)_e \times U(2)_\nu$

2 Breaking the global $U(2)^6$ in steps

Vector-like fermions
(a 16-plet/generation)

		$U(1)_Y^{[3]}$	$U(1)_{B-L}^{[12]}$	$U(1)_{T_{3R}}^{[2]}$	$U(1)_{T_{3R}}^{[1]}$	$SU(3)\times SU(2)$
light VL ($\alpha=1,2$)	U_α	$1/2$	$1/3$	0	0	$(\mathbf{3},\mathbf{1})$
	D_α	$-1/2$	$1/3$	0	0	$(\mathbf{3},\mathbf{1})$
	E_α	$-1/2$	-1	0	0	$(\mathbf{1},\mathbf{1})$
	N_α	$1/2$	-1	0	0	$(\mathbf{1},\mathbf{1})$
heavy VL	U_3	0	$1/3$	$1/2$	0	$(\mathbf{3},\mathbf{1})$
	D_3	0	$1/3$	$-1/2$	0	$(\mathbf{3},\mathbf{1})$
	E_3	0	-1	$-1/2$	0	$(\mathbf{1},\mathbf{1})$
	N_3	0	-1	$1/2$	0	$(\mathbf{1},\mathbf{1})$

M_α (light VL)

M_3 (heavy VL)

Most general $d \leq 4$

$$\mathcal{L}_Y^u = (y_3^u\, \bar{q}_3 u_3 H_u + y_{i\alpha}^u\, \bar{q}_i U_\alpha H_u + y_\alpha^{\chi_u}\, \bar{U}_\alpha u_3 \chi^q + y_{\alpha 2}^{\phi_u}\, \bar{U}_\alpha u_2 \phi + y_{\alpha 3}^{\phi_u}\, \bar{U}_{R\alpha} U_{L3}\phi + \hat{y}_{\alpha 3}^{\phi_u}\, \bar{U}_{L\alpha} U_{R3}\phi + y_1^{\sigma_u}\, \bar{U}_3 u_1 \sigma + \text{h.c.}) + M_{U_3}\, \bar{U}_3 U_3 + M_{U_\alpha}\, \bar{U}_\alpha U_\alpha$$

$$\Rightarrow \quad U(1)_B \times U(1)_L \xrightarrow{M_3\to\infty} U(1)_{B_{23}} \times U(1)_{L_{23}} \times U(1)_R^4 \xrightarrow{M_\alpha, M_3\to\infty} U(1)_{B_3} \times U(1)_{L_3} \times U(2)^6$$

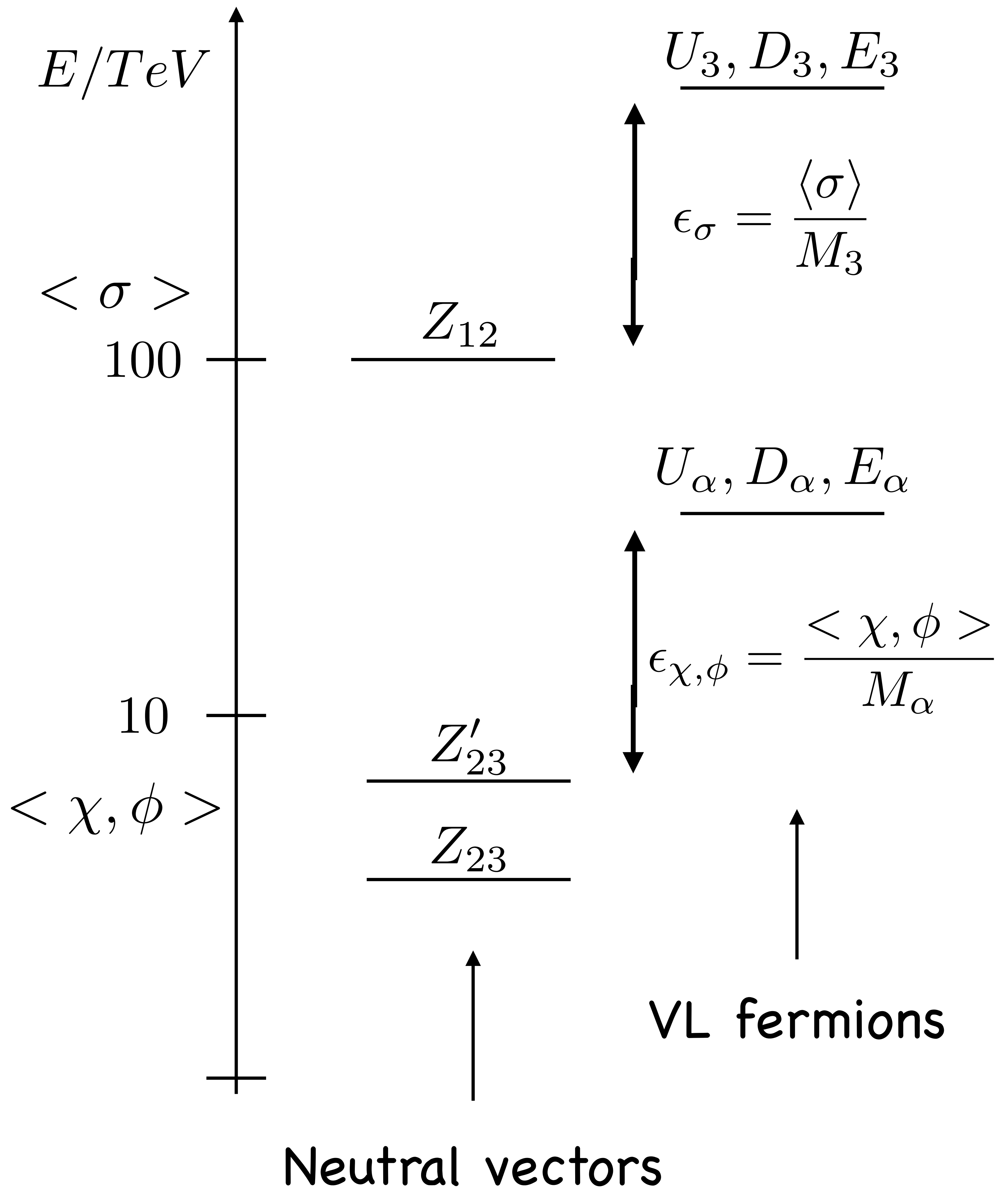
The overall picture

gauge

$$U(1)_Y^{[3]} \times U(1)_{B-L}^{[12]} \times U(1)_{T_{3R}}^{[2]} \times U(1)_{T_{3R}}^{[1]}$$

$$U(1)_Y^{(3)} \times U(1)_{B-L}^{[12]} \times U(1)_{T_{3R}}^{[12]}$$

$$U(1)_Y$$



approx global (accidental)

$$U(1)_{u_1} \times U(1)_{d_1} \times U(1)_{e_1}$$

$$U(2)_q \times U(2)_u \times U(2)_d \times U(2)_l \times U(2)_e$$

Universal $SU(3) \times SU(2)$ left understood

Universal $U(1)_B \times U(1)_L$ left understood

Yukawa couplings

By integrating out the VL fermions

$$\Rightarrow \quad Y_u \approx \begin{pmatrix} y^u_{1\alpha}\hat{y}^{\phi_u}_{\alpha 3} y^{\sigma_u}_1 \epsilon_\sigma \epsilon_\phi & y^u_{1\alpha} y^{\phi_u}_{\alpha 2} \epsilon_\phi & y^u_{12} y^{\chi_u}_2 \epsilon_\chi \\ y^u_{2\alpha}\hat{y}^{\phi_u}_{\alpha 3} y^{\sigma_u}_1 \epsilon_\sigma \epsilon_\phi & y^u_{2\alpha} y^{\phi_u}_{\alpha 2} \epsilon_\phi & y^u_{22} y^{\chi_u}_2 \epsilon_\chi \\ \approx 0 & \approx 0 & y^u_3 \end{pmatrix}$$

$$\epsilon_\chi = \frac{\langle \chi \rangle}{M_\alpha} \qquad \epsilon_\phi = \frac{\langle \phi \rangle}{M_\alpha} \qquad \epsilon_\sigma = \frac{\langle \sigma \rangle}{M_3}$$

And similarly for $Y_{d,e}$

All charged fermion masses and V_{CKM} reproduced with

$$\frac{v_u}{v_d} \approx 10 \qquad \epsilon_\chi, \epsilon_\phi, \epsilon_\sigma = (0.5 \div 2) \cdot 10^{-1} \quad \text{and} \quad y's = 0.1 \div 1$$

$$\Rightarrow \quad U_L^{u,d,e} \approx V_{CKM} \quad (U_L^u U_L^{d+} = V_{CKM}) \qquad [U_R^{u,d,e}]_{i\neq j} << [U_L^{u,d,e}]_{i \neq j}$$

“Mid term” prospects in precision on BSM

(Under current update)

De Blas et al, 2025

EWPT

Not expected to improve due to parametric uncertainties

$$\Delta\alpha_{had}(M_Z) \to \pm 3 \cdot 10^{-3}, \quad \alpha_S(M_Z) \to \pm 1 \cdot 10^{-3}$$

$$(FCC_{ee}: \quad \Delta\alpha_{had}(M_Z) \to \pm 5 \cdot 10^{-5}, \quad \alpha_S(M_Z) \to \pm 2 \cdot 10^{-4})$$

Higgs couplings

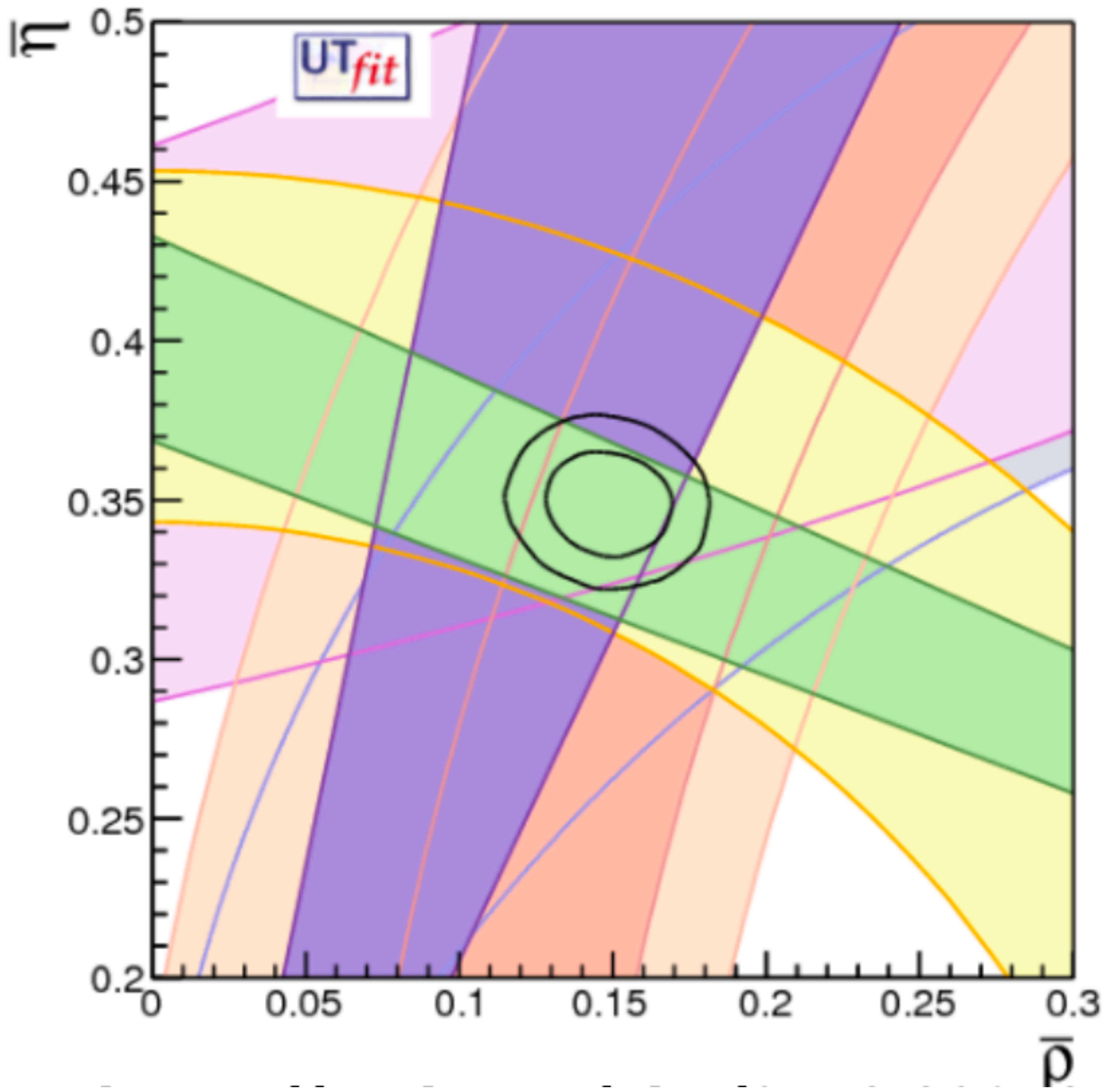
	$\approx 10\%$	$\Rightarrow$ $(1 \div 2)\%$
$\Delta\kappa_V\,[\times 10^{-4}]$	190	83
$\Delta\kappa_f\,[\times 10^{-4}]$	960	150
$\Delta\kappa_W[\times 10^{-4}]$	510	120
$\Delta\kappa_Z\,[\times 10^{-4}]$	1100	150
$\Delta\kappa_f\,[\times 10^{-4}]$	1100	160
$\Delta\kappa_V\,[\times 10^{-4}]$	210	120
$\Delta\kappa_u\,[\times 10^{-4}]$	1200	170
$\Delta\kappa_d\,[\times 10^{-4}]$	1400	230
$\Delta\kappa_\ell\,[\times 10^{-4}]$	1300	270

$$\approx \left(\frac{140 fb^{-1}}{3ab^{-1}}\right)^{1/2}$$

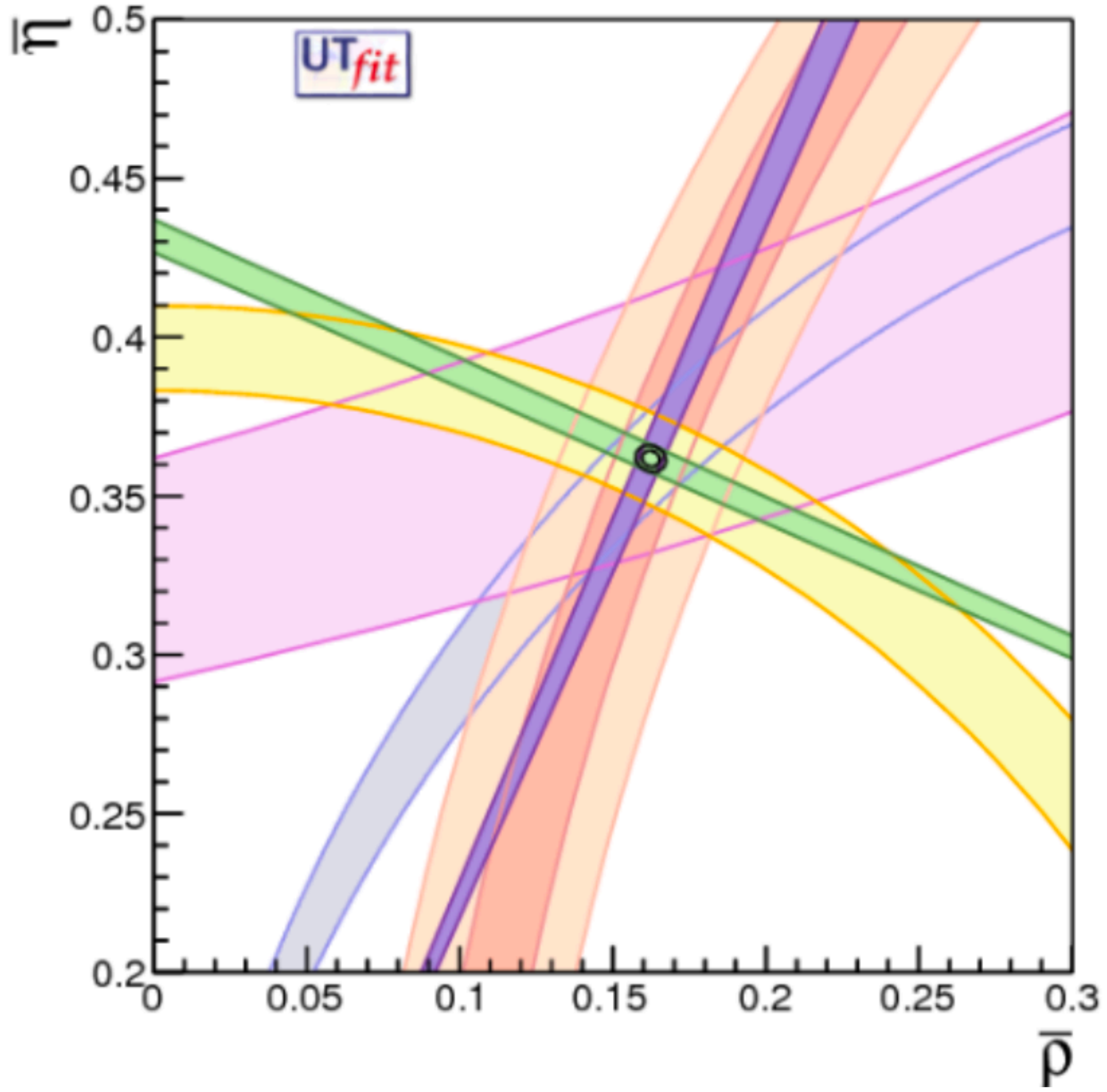
"Mid term" prospects in precision on BSM

Flavour

Unitarity triangle



$\Rightarrow$



A much too synthetic description!

A FlavourPT Table long awaited!

(See Martinelli's talk!?)

Flavour Precision Tests, a partial list (2022)

Input	Reference	Measurement	UTfit Prediction	Pull
$\sin 2\beta$	[22], UTfit	0.688(20)	0.736(28)	−1.4
γ	[22]	66.1(3.5)	64.9(1.4)	+0.29
α	UTfit	94.9(4.7)	92.2(1.6)	+0.6
$\varepsilon \cdot 10^3$	[38]	2.228(1)	2.00(15)	+1.56
$\lvert V_{ud}\rvert$	UTfit	0.97433(19)	0.9738(11)	+0.03
$\lvert V_{ub}\rvert \cdot 10^3$ •	UTfit	3.77(24)	3.70(11)	+0.25
$\lvert V_{ub}\rvert \cdot 10^3$ (excl)	[39]	3.74(17)		
$\lvert V_{ub}\rvert \cdot 10^3$ (incl)	[22]	4.32(29)		
$\lvert V_{cb}\rvert \cdot 10^3$ •	UTfit	41.25(95)	42.22(51)	−0.59
$\lvert V_{cb}\rvert \cdot 10^3$ (excl)	UTfit	39.44(63)		
$\lvert V_{cb}\rvert \cdot 10^3$ (incl)	[40]	42.16(50)		
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$	[39]	0.0844(56)		
$\Delta M_d \times 10^{12}\,\mathrm{s}^{-1}$	[38]	0.5065(19)	0.519(23)	−0.49
$\Delta M_s \times 10^{12}\,\mathrm{s}^{-1}$	[38]	17.741(20)	17.94(69)	−0.30
$\mathrm{BR}(B_s \to \mu\mu) \times 10^9$	[38]	3.41(29)	3.47(14)	−0.14
$\mathrm{BR}(B \to \tau\nu) \times 10^4$	[38]	1.06(19)	0.869(47)	+0.96
$\mathrm{Re}\,(\varepsilon'/\varepsilon) \times 10^4$	[38]	16.6(3.3)	15.2(4.7)	+0.27
$(\lvert q/p\rvert_D - 1) \times 10^2$		0.05(2.50)	0.8(4.0)	−0, 15
$BR(B^+ \to K^+\nu\nu)10^6$		23(7)	5.58(37)	+2.5
$BR(K^+ \to \pi^+\nu\nu)10^{11}$		10.6(4.0)	9.31(76)	+0, 3
R_D		0.344(26)	0.298(4)	+1.7
R_{D^*}		0.285(12)	0.254(5)	+2.3

UTfit Collaboration
with some little integration

(No EDM's, $\mu \to e\gamma$, etc.)

Current precision

Input	Reference	Measurement	UTfit Prediction	Pull	current
$\sin 2\beta$	[22], UTfit	0.688(20)	0.736(28)	−1.4	4%th/exp
γ	[22]	66.1(3.5)	64.9(1.4)	+0.29	5%exp
α	UTfit	94.9(4.7)	92.2(1.6)	+0.6	5%exp
$\varepsilon \cdot 10^3$	[38]	2.228(1)	2.00(15)	+1.56	8%th
$\lvert V_{ud}\rvert$	UTfit	0.97433(19)	0.9738(11)	+0.03	0.1%th
$\lvert V_{ub}\rvert \cdot 10^3$ •	UTfit	3.77(24)	3.70(11)	+0.25	8%exp/th
$\lvert V_{ub}\rvert \cdot 10^3$ (excl)	[39]	3.74(17)			
$\lvert V_{ub}\rvert \cdot 10^3$ (incl)	[22]	4.32(29)			
$\lvert V_{cb}\rvert \cdot 10^3$ •	UTfit	41.25(95)	42.22(51)	−0.59	2%exp/th
$\lvert V_{cb}\rvert \cdot 10^3$ (excl)	UTfit	39.44(63)	Ciao.		
$\lvert V_{cb}\rvert \cdot 10^3$ (incl)	[40]	42.16(50)			
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$	[39]	0.0844(56)			
$\Delta M_d \times 10^{12}\,\mathrm{s}^{-1}$	[38]	0.5065(19)	0.519(23)	−0.49	5%th/exp
$\Delta M_s \times 10^{12}\,\mathrm{s}^{-1}$	[38]	17.741(20)	17.94(69)	−0.30	4%th
$\mathrm{BR}(B_s \to \mu\mu) \times 10^9$	[38]	3.41(29)	3.47(14)	−0.14	9%exp
$\mathrm{BR}(B \to \tau\nu) \times 10^4$	[38]	1.06(19)	0.869(47)	+0.96	20%exp
$\mathrm{Re}\,(\varepsilon'/\varepsilon) \times 10^4$	[38]	16.6(3.3)	15.2(4.7)	+0.27	30%th
$(\lvert q/p\rvert_D - 1) \times 10^2$		0.05(2.50)	0.8(4.0)	−0,15	100%th*
$BR(B^+ \to K^+\nu\nu)10^6$		23(7)	5.58(37)	+2.5	35%exp
$BR(K^+ \to \pi^+\nu\nu)10^{11}$		10.6(4.0)	9.31(76)	+0,3	40%exp
R_D		0.344(26)	0.298(4)	+1.7	8%exp
R_{D^*}		0.285(12)	0.254(5)	+2.3	4%exp

Conceivable progress in the "mid-term" of flavour

Input	Reference	Measurement	UTfit Prediction	Pull	current	mid-term
$\sin 2\beta$	[22], **UTfit**	0.688(20)	0.736(28)	−1.4	4%th/exp	0.6%
γ	[22]	66.1(3.5)	64.9(1.4)	+0.29	5%exp	0.8%
α	**UTfit**	94.9(4.7)	92.2(1.6)	+0.6	5%exp	0.4%
$\varepsilon \cdot 10^3$	[38]	2.228(1)	2.00(15)	+1.56	8%th	
$\|V_{ud}\|$	**UTfit**	0.97433(19)	0.9738(11)	+0.03	0.1%th	
$\|V_{ub}\| \cdot 10^3$ •	**UTfit**	3.77(24)	3.70(11)	+0.25	8%exp/th	1%
$\|V_{ub}\| \cdot 10^3$ (excl)	[39]	3.74(17)				
$\|V_{ub}\| \cdot 10^3$ (incl)	[22]	4.32(29)				
$\|V_{cb}\| \cdot 10^3$ •	**UTfit**	41.25(95)	42.22(51)	−0.59	2%exp/th	0.5%
$\|V_{cb}\| \cdot 10^3$ (excl)	**UTfit**	39.44(63)				
$\|V_{cb}\| \cdot 10^3$ (incl)	[40]	42.16(50)				
$\|V_{ub}\|/\|V_{cb}\|$	[39]	0.0844(56)				
$\Delta M_d \times 10^{12}\,\mathrm{s}^{-1}$	[38]	0.5065(19)	0.519(23)	−0.49	5%th/exp	2%
$\Delta M_s \times 10^{12}\,\mathrm{s}^{-1}$	[38]	17.741(20)	17.94(69)	−0.30	4%th	1.5%
$BR(B_s \to \mu\mu) \times 10^9$	[38]	3.41(29)	3.47(14)	−0.14	9%exp	4%
$BR(B \to \tau\nu) \times 10^4$	[38]	1.06(19)	0.869(47)	+0.96	20%exp	4%
$\mathrm{Re}\,(\varepsilon'/\varepsilon) \times 10^4$	[38]	16.6(3.3)	15.2(4.7)	+0.27	30%th	
$(\|q/p\|_D - 1) \times 10^2$		0.05(2.50)	0.8(4.0)	−0,15	100%th*	30%*
$BR(B^+ \to K^+\nu\nu)10^6$		23(7)	5.58(37)	+2.5	35%exp	10%
$BR(K^+ \to \pi^+\nu\nu)10^{11}$		10.6(4.0)	9.31(76)	+0,3	40%exp	20%
R_D		0.344(26)	0.298(4)	+1.7	8%exp	3%
R_{D^*}		0.285(12)	0.254(5)	+2.3	4%exp	2%

with strong correlations!

(No EDM's, $\mu \to e\gamma$, etc.)

Summary

0. No lack of Questions opened by the SM
   and needing a wide front of attach

0'. An accumulation of problems in the Higgs sector of the SM

How far are Λ^h, Λ^f from the Fermi scale?

1. Flavour symmetries ($U(2)^n$) can:
   - be related to the pattern of $Y^{u,d,e}$ and arise accidentally
   - allow for flavour changing $\frac{1}{\Lambda^{n-4}}\mathcal{O}^{n>4}$ with $\Lambda \approx$ MultiTeV

2. While preparing for the next high energy collider,
   the "mid term" of precision physics can find evidence
   for motivated new physics in the MultiTeV

3. Can one address/solve the "little hierarchy" problem
   and the "flavour puzzle" at the same MultiTeV scale?

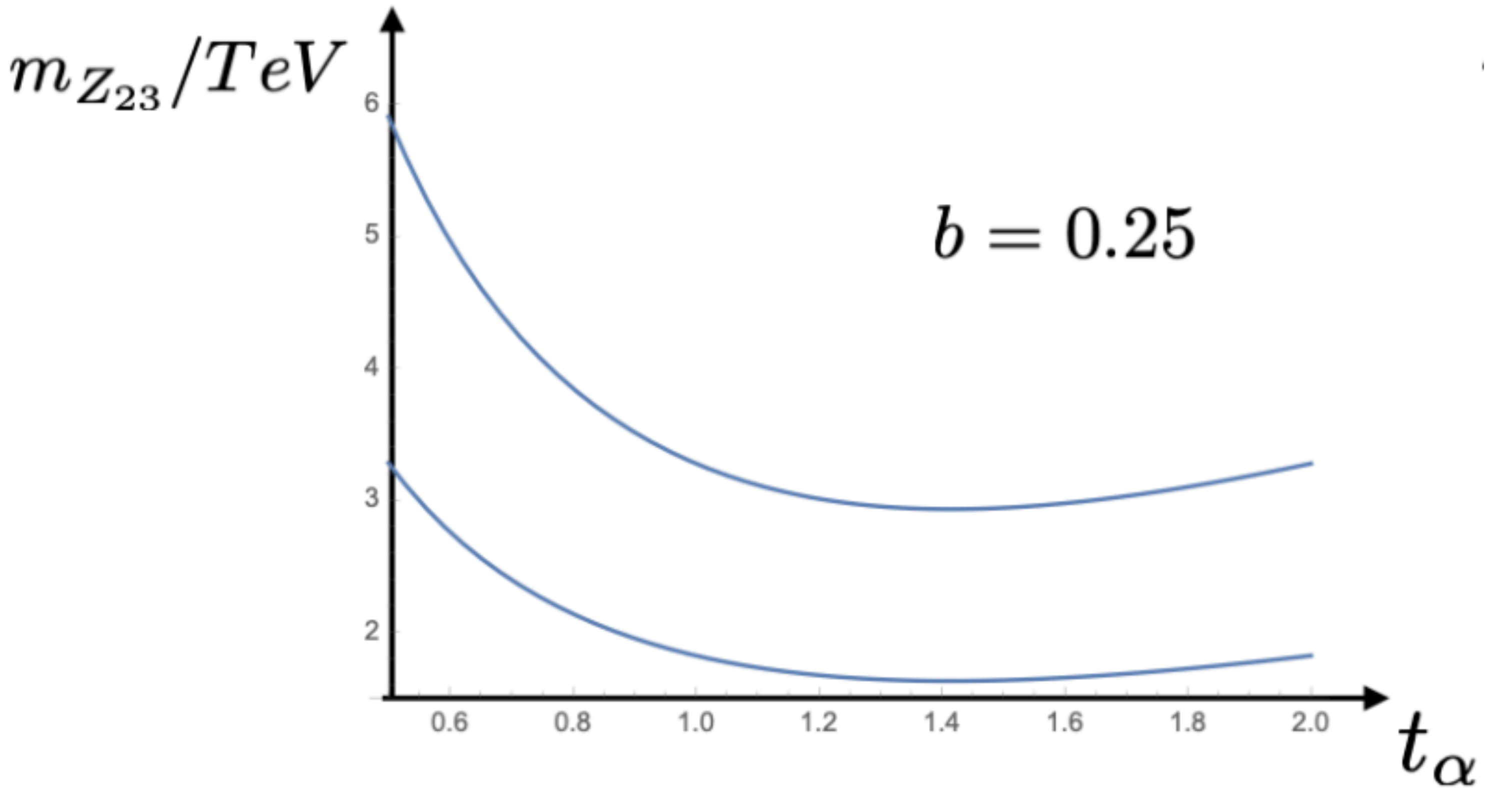
When and where the next trip?

Phenomenological summary

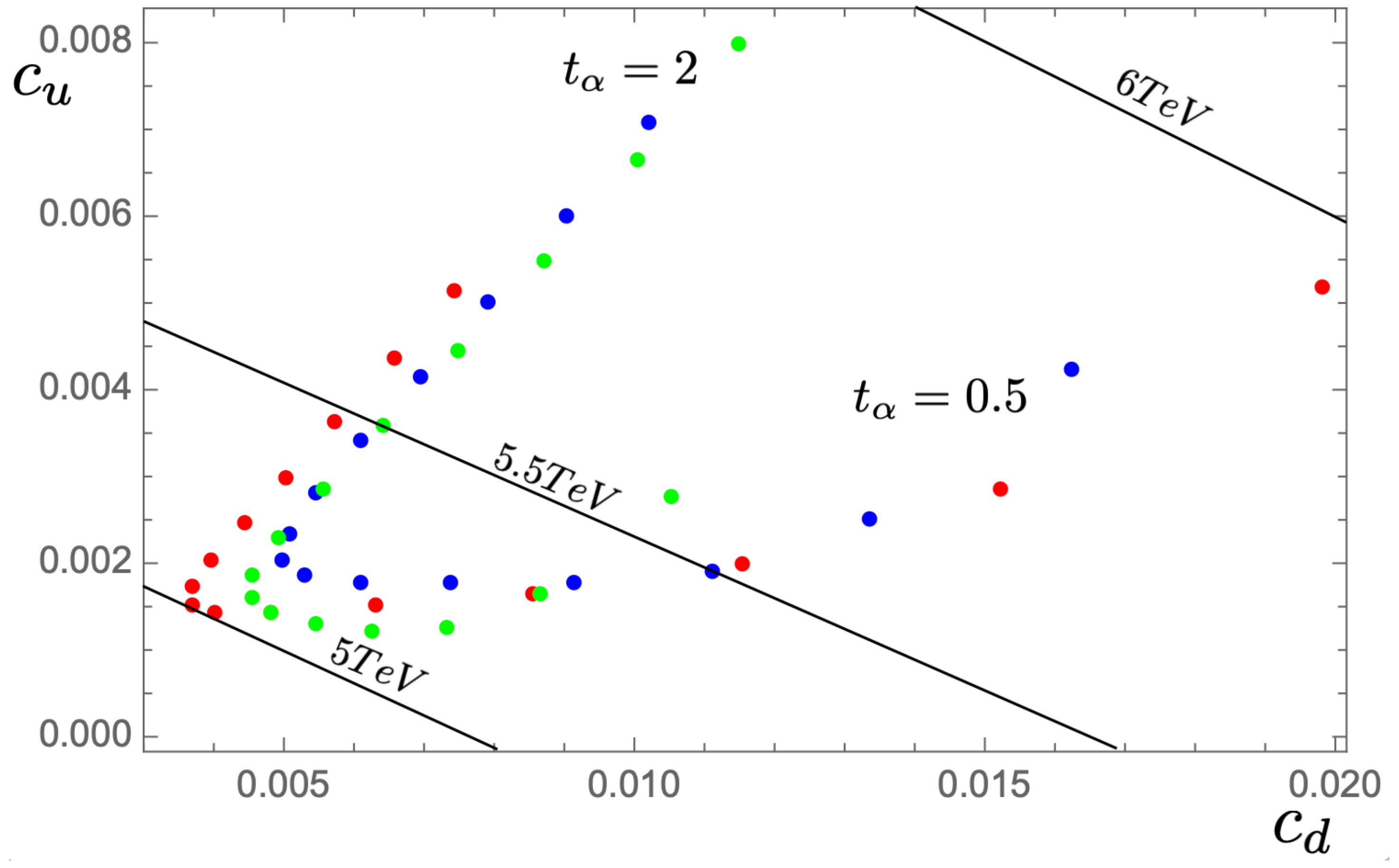
B, 2024

1. EWPT

$$\frac{\delta m_Z^2}{m_Z^2} = (\frac{m_Z(SM)}{m_Z(exp)})^2 - 1 = (38 \pm 20)$$

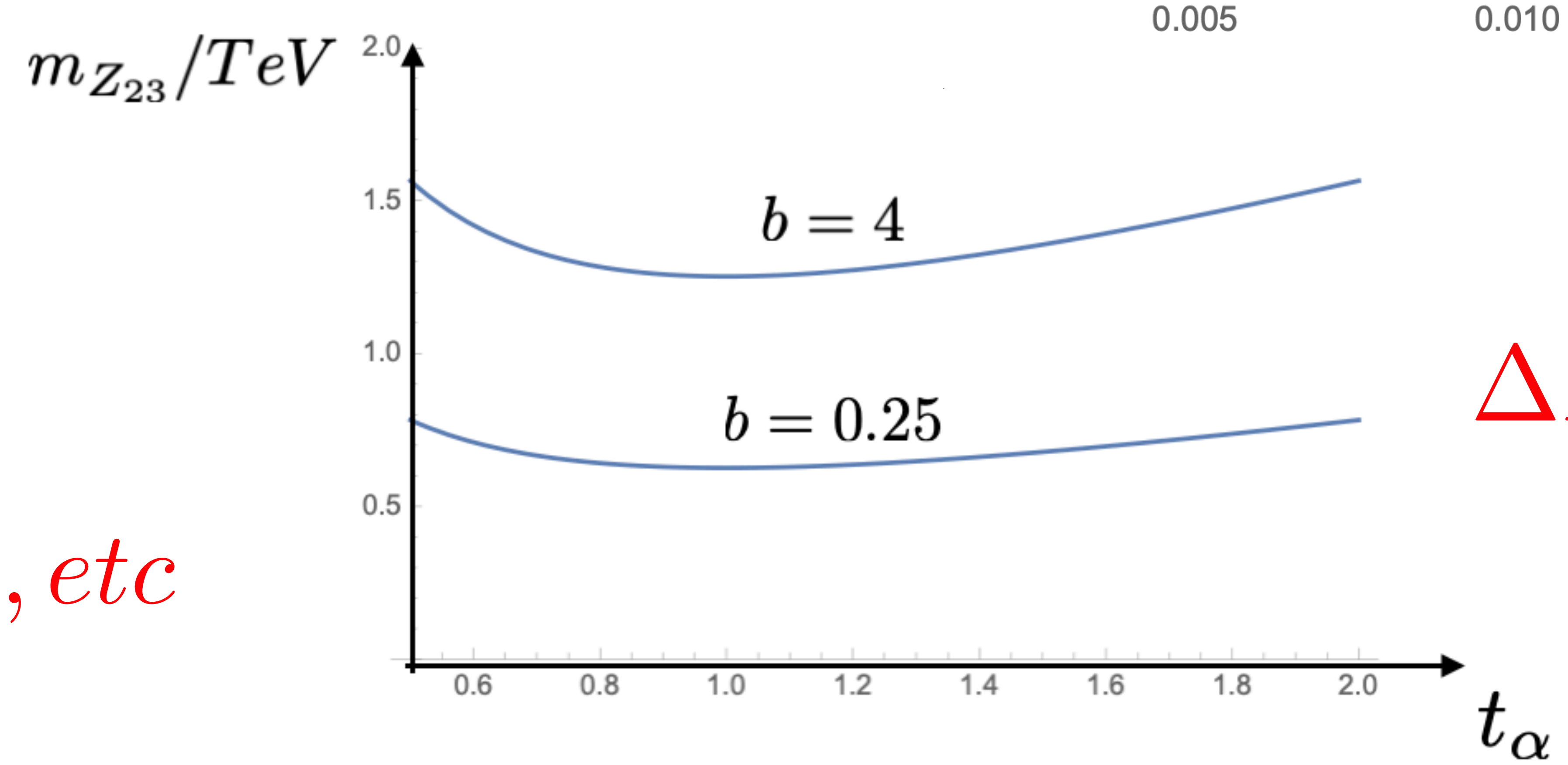


2. Drell-Yan $pp \to l^+ l^-, \quad l = e, \mu$



3. Flavour changing effects

$\Delta F = 2, b \to sll, K \to \pi\nu\nu, \tau \to 3\mu, \mu \to 3e, etc$



ΔM_{B_s}

A comment on charge quantisation

SM, 1 family: No non-anomalous global charge

$$Q = T_{3L} + Y \quad \text{not a convention}$$

SM, 3 families: $L_i - L_j$ non anomalous

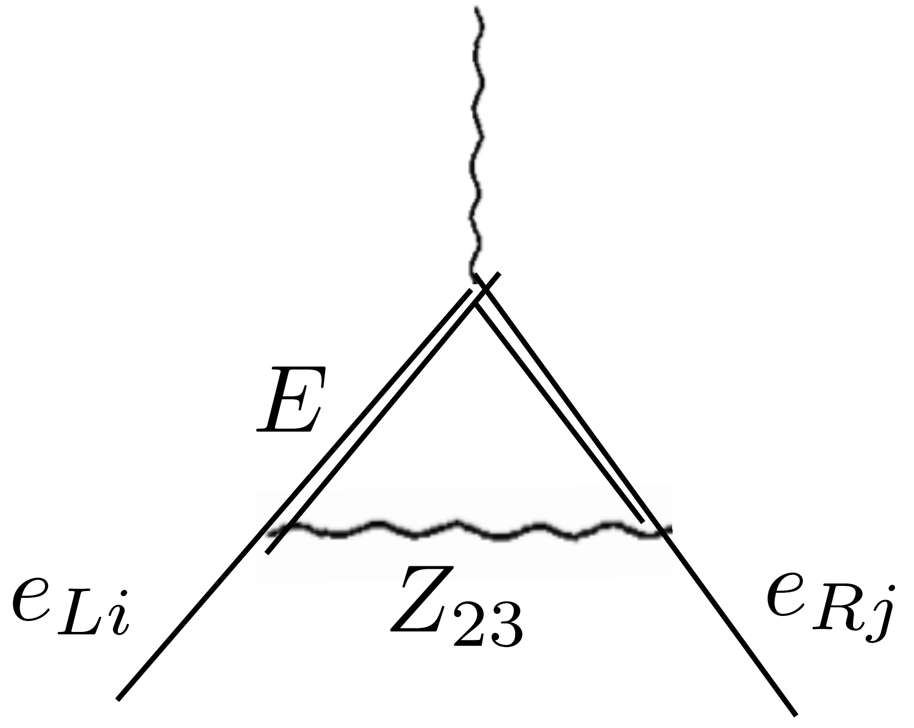
$$\Rightarrow Q = T_{3L} + Y + \epsilon(L_i - L_j)$$

FD Model: No non-anomalous global charge

$$Q = T_{3L} + Y^{[3]} + (B-L)^{[12]}/2 + T_{3R}^{[2]} + T_{3R}^{[1]} \equiv T_{3L} + Y \quad \text{not a convention}$$

Dipole moments

Loop effects from $e-E$ mixings



$$\mathcal{L}^{dip} = \frac{e}{32\pi^2}\frac{g'^2}{m^2_{Z_{23\mu}}}\Sigma_{Q,Q'}a_Q a_{Q'}(\bar{e}_L\sigma^{\mu\nu}\hat{\epsilon}_L(Q)M\hat{\epsilon}^\dagger_R(Q')e_R)F_{\mu\nu}$$

$$\hat{\epsilon}_L(Q)M\hat{\epsilon}^\dagger_R(Q') = \frac{v_1}{4}\begin{pmatrix} -y_1^\sigma y^e_{1\alpha}\hat{y}^{\phi_e}_{\alpha 3}\epsilon_\phi\epsilon_\sigma & y^e_{1\alpha}y^{\phi_e}_{\alpha 2}\epsilon_\phi & -y^e_{12}y_2^{\chi_e}\epsilon_{\chi^l} \\ -y_1^\sigma y^e_{2\alpha}\hat{y}^{\phi_e}_{\alpha 3}\epsilon_\phi\epsilon_\sigma & y^e_{2\alpha}y^{\phi_e}_{\alpha 2}\epsilon_\phi & -y^e_{22}y_2^{\chi_e}\epsilon_{\chi^l} \\ 0 & 0 & 0 \end{pmatrix}$$

$\Rightarrow$ An exact alignment with the Yukawa coupling Y_e in the 12 sector

$$\mathcal{L}^{dip} = \frac{ev_1}{32\pi^2}\frac{g'^2}{m^2_{Z_{23\mu}}}\bar{e}_L(a_Y Y_e + \tilde{a}_Y\tilde{Y}_e)e_R F_{\mu\nu}$$

$\Rightarrow$ No significant effects in: electron EDM, $\Delta a_\mu, \tau \to \mu\gamma$ relative to the tree level effects already discussed

Neutrino masses

	$U(1)_Y^{[3]}$	$U(1)_{B-L}^{[12]}$	$U(1)_{T_{3R}}^{[2]}$	$U(1)_{T_{3R}}^{[1]}$
ν_1	0	-1	0	$1/2$
ν_2	0	-1	$1/2$	0
ν_3	0	0	0	0
N_α	$1/2$	-1	0	0
N_3	0	-1	$1/2$	0

Taking

$$M_{N_\alpha} \approx < \chi, \phi > \Rightarrow \epsilon_{\chi,\phi} \approx 1$$

$$M_{N_3} \approx < \sigma > \Rightarrow \epsilon_\sigma \approx 1$$

1. Integrating out $N_{\alpha,3}$ $\Rightarrow$ $Y_\nu \approx \begin{pmatrix} y^3 & y^2 & y^2 \\ y^3 & y^2 & y^2 \\ 0 & 0 & y \end{pmatrix}$

2. Standard Seesaw: Lepton number broken at $< \sigma_1 > \approx < \sigma_2 > \approx < \sigma > \approx m_3$

$$\mathcal{L}^\nu_{L-\text{breaking}} = y^{\sigma_1}\sigma_1 \nu_R^1 \nu_R^1 + y^{\sigma_2}\sigma_2 \nu_R^2 \nu_R^2 + m_3 \nu_R^3 \nu_R^3 \equiv \nu^T \Sigma \nu$$

$m_\nu \approx v^2 Y_\nu \frac{1}{\Sigma} Y_\nu^T$ anarchic $< \sigma > \approx 10^{-13} GeV$

3. Inverse Seesaw: Lepton number broken at $\mu << M_{N_{\alpha,3}}$

$$\mathcal{L}^\nu_{L-\text{breaking}} = \phi_1 S_1 \nu_1^c + \phi_2 S_2 \nu_2^c + m_3 S_3 \nu_3^c + S^T \mu S \equiv S^T M v^c + S^T \mu S$$

$< \phi_1 > \approx < \phi_2 > \approx m_3 \approx < \phi, \chi >$

$m_\nu \approx v^2 Y_\nu \frac{1}{M} \mu \frac{1}{M^T} Y_\nu^T$ anarchic $\mu \approx 1 keV,$ $< \phi, \chi > \approx 10 TeV,$ $< \sigma > \approx 10^{2\div 3} TeV$

A more detailed plot

(from actually measured flavour quantities only, as opposed to bounds)

$$\mathcal{L} = \mathcal{L}_{SM} + \Sigma_i \frac{C_i}{\Lambda_i^2} \mathcal{O}_i$$

$$Q_1^{q_i q_j} = \bar{q}_{jL}^{\alpha} \gamma_\mu q_{iL}^{\alpha} \bar{q}_{jL}^{\beta} \gamma^\mu q_{iL}^{\beta} \,,$$

$$Q_2^{q_i q_j} = \bar{q}_{jR}^{\alpha} q_{iL}^{\alpha} \bar{q}_{jR}^{\beta} q_{iL}^{\beta} \,, \qquad Q_4^{q_i q_j} = \bar{q}_{jR}^{\alpha} q_{iL}^{\alpha} \bar{q}_{jL}^{\beta} q_{iR}^{\beta} \,,$$

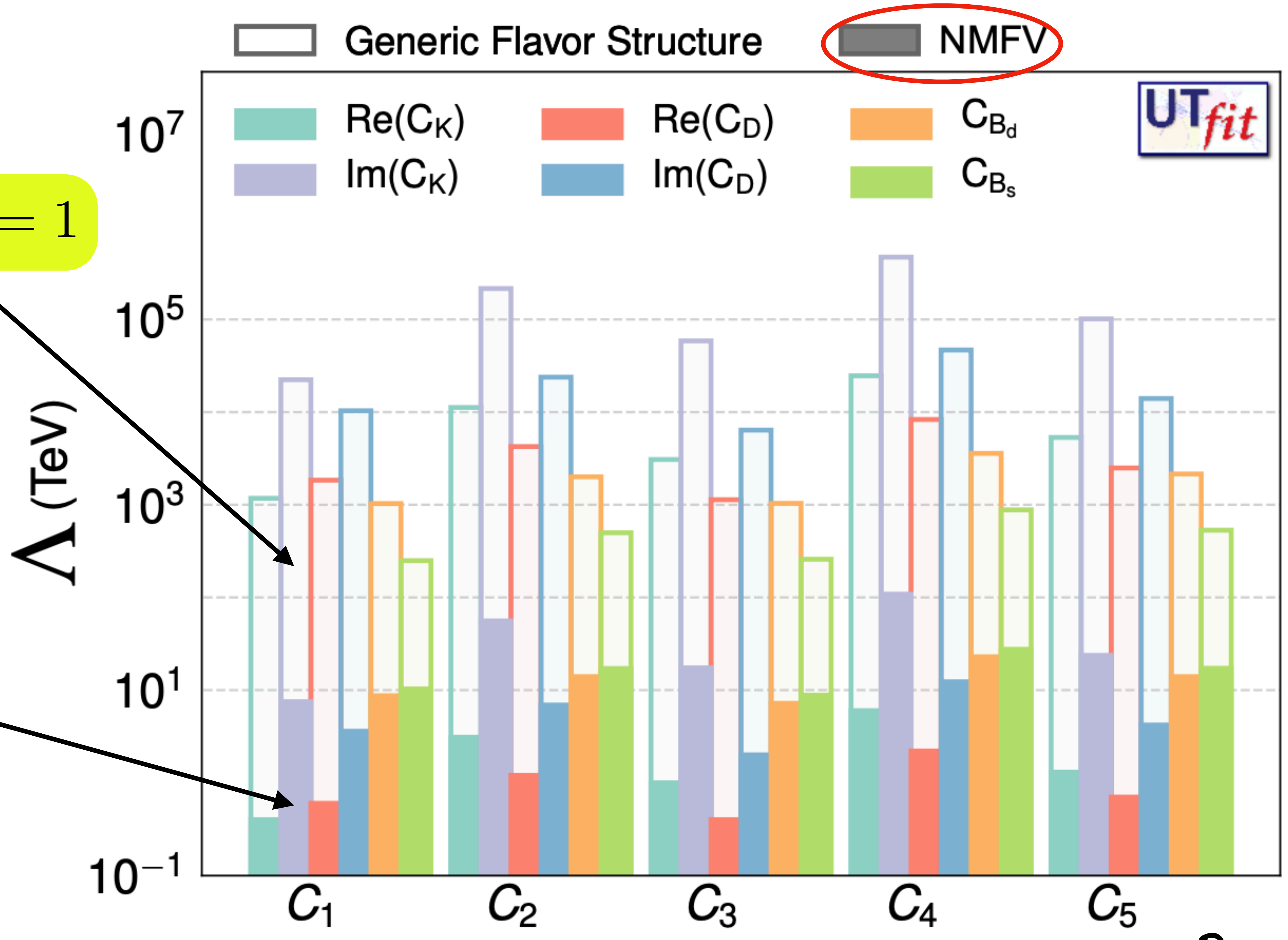
$$Q_3^{q_i q_j} = \bar{q}_{jR}^{\alpha} q_{iL}^{\beta} \bar{q}_{jR}^{\beta} q_{iL}^{\alpha} \,, \qquad Q_5^{q_i q_j} = \bar{q}_{jR}^{\alpha} q_{iL}^{\beta} \bar{q}_{jL}^{\beta} q_{iR}^{\alpha} \,.$$

$\mathcal{C}_i = 1$

NMFV $$\mathcal{L} = \mathcal{L}_{SM} + \Sigma_i \frac{F_i^{SM}}{\Lambda_i^2} \mathcal{O}_i$$

$$F^{SM}(C_{K,D}) = (V_{td} V_{ts}^*)^2 e^{i\phi_{K,D}}$$

$$F^{SM}(C_{B_q}) = (V_{tq} V_{tb}^*)^2 e^{i\phi_{B_q}}$$



Bona et al, 2025

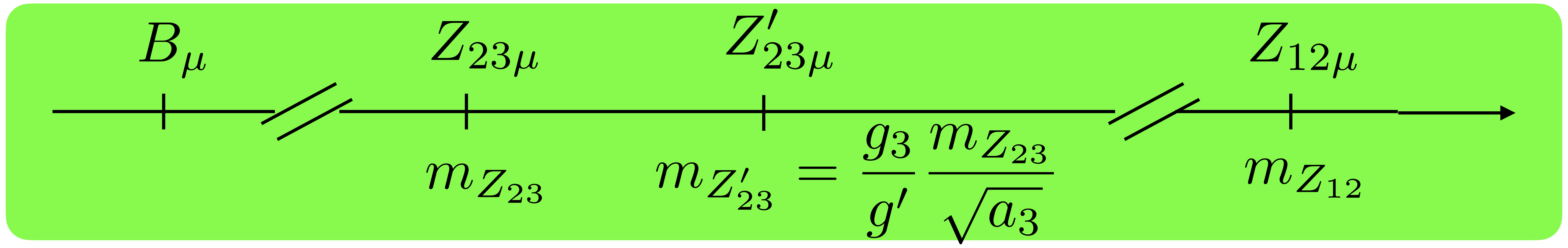
Vector masses and couplings

B, 2024

$$D_\mu \equiv \partial_\mu - i(g_3 Y^{[3]} A_{3\mu} + g_B \frac{(B-L)^{[12]}}{2} A_{B\mu} + g_2 T_{3R}^{[2]} A_{2\mu} + g_1 T_{3R}^{[1]} A_{1\mu})$$

Take $\langle\sigma\rangle >> \langle\chi\rangle, \langle\phi\rangle \equiv \sqrt{b}\langle\chi\rangle$ and $g_3 >> g_B, g_2, g_1$ Define $\frac{g_B\sqrt{g_1^2+g_2^2}}{g_1 g_2} = \tan\alpha \equiv t_\alpha$

Before EWSB



$$a_3 = \frac{b(1+t_\alpha^2)^2}{t_\alpha^2(1+b)^2}$$

$$a_{23} = \frac{1-bt_\alpha^2}{t_\alpha(1+b)}$$

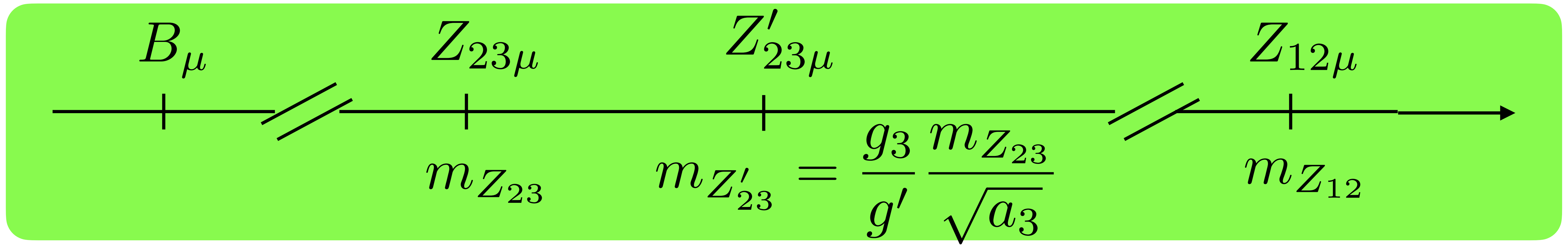
$$D_\mu(B, Z_{23}, Z'_{23}) = -i[g' B_\mu Y + g' Z_{23\mu}(a_{23} Y^{[3]} + \frac{1}{t_\alpha}\frac{(B-L)^{[12]}}{2} - t_\alpha T_{3R}^{[12]}) + g_3 Z'_{23\mu} Y^{[3]}]$$

Parameters at the lowest new scale $m_{Z_{23}}; \quad t_\alpha, b$

Vector masses and couplings

B, 2024

Before EWSB



$$D_\mu(B, Z_{23}, Z'_{23}) = -i[g' B_\mu Y + g' Z_{23\mu}(a_{23} Y^{[3]} + \frac{1}{t_\alpha}\frac{(B-L)^{[12]}}{2} - t_\alpha T_{3R}^{[12]}) + g_3 Z'_{23\mu} Y^{[3]}]$$

$$a_3 = \frac{b(1+t_\alpha^2)^2}{t_\alpha^2(1+b)^2} \qquad a_{23} = \frac{1-bt_\alpha^2}{t_\alpha(1+b)}$$

After EWSB

$$\mathcal{L}_H^{gauge} = |(\partial_\mu - ig\vec{T}\cdot\vec{W}_\mu - ig_3 Y^{[3]} A_{3\mu})H|^2$$

$$\frac{\delta m_Z^2}{m_Z^2} \equiv s_W^2 \frac{m_Z^2}{m_{Z_{23}}^2}(a_{23}^2 + a_3)$$

and

$$\delta D_\mu(Z) = -iZ_\mu g' s_W \frac{m_Z^2}{m_{Z_{23}}^2}[(a_{23}^2 + a_3)Y^{[3]} + a_{23}(\frac{1}{t_\alpha}\frac{(B-L)^{[12]}}{2} - t_\alpha T_{3R}^{[12]})]]$$

Parameters at the lowest new scale $m_{Z_{23}}$; t_α, b

Quoting Weinberg
Changing attitudes and the SM, 1992

I remember how exciting it was when we first realised that the most general renormalizable YM theory of quark and gluons automatically conserves C, P, strangeness and, for small quark masses, it also has an SU(3)xSU(3) symmetry...

From then on we would be suspicious of any approximate symmetry that could not be explained as an accidental consequence of the constraints imposed by renormalizability and the various exact symmetries

Phenomenology at the lowest new scale 1

B, 2024

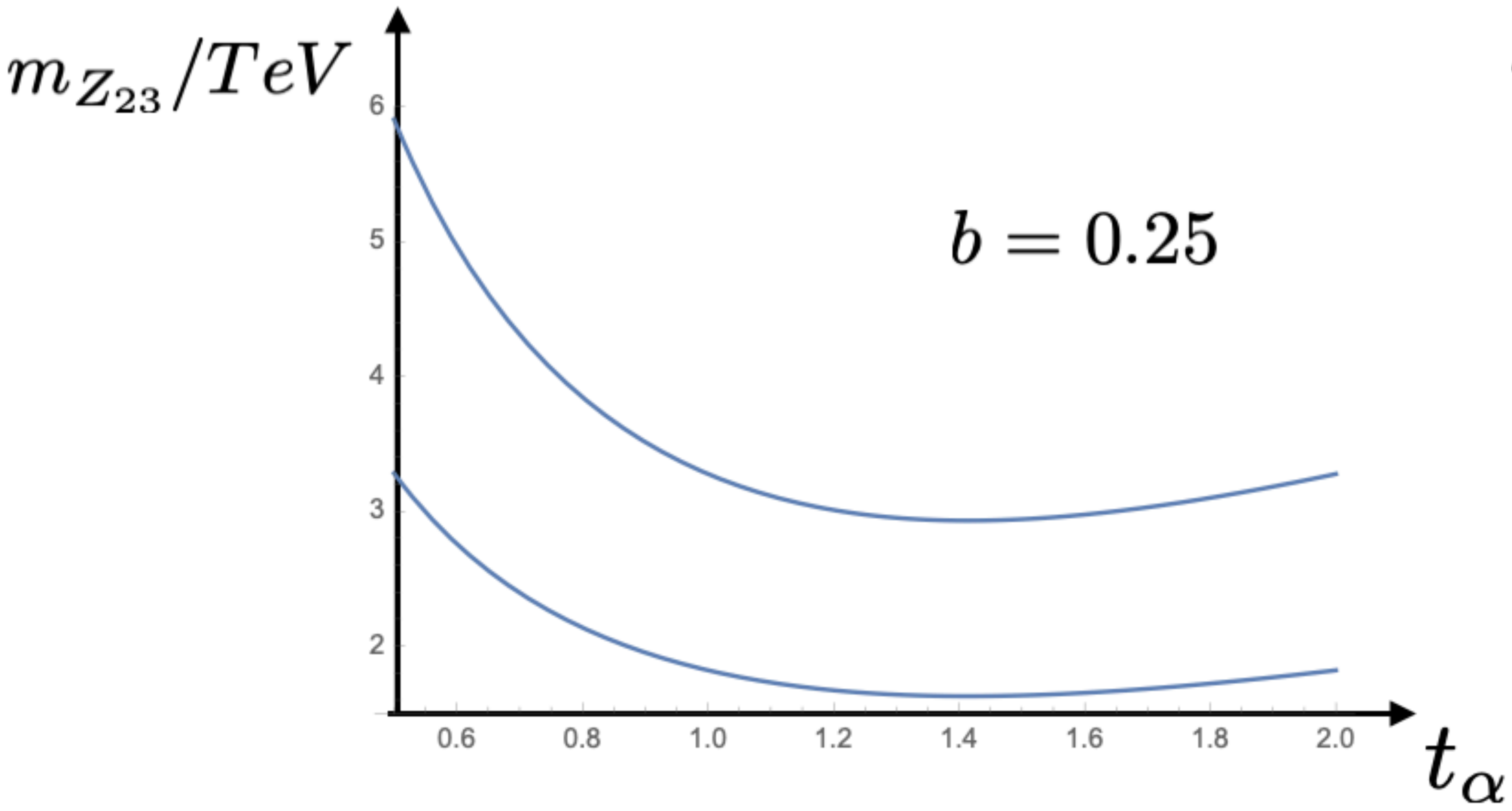
EWPT

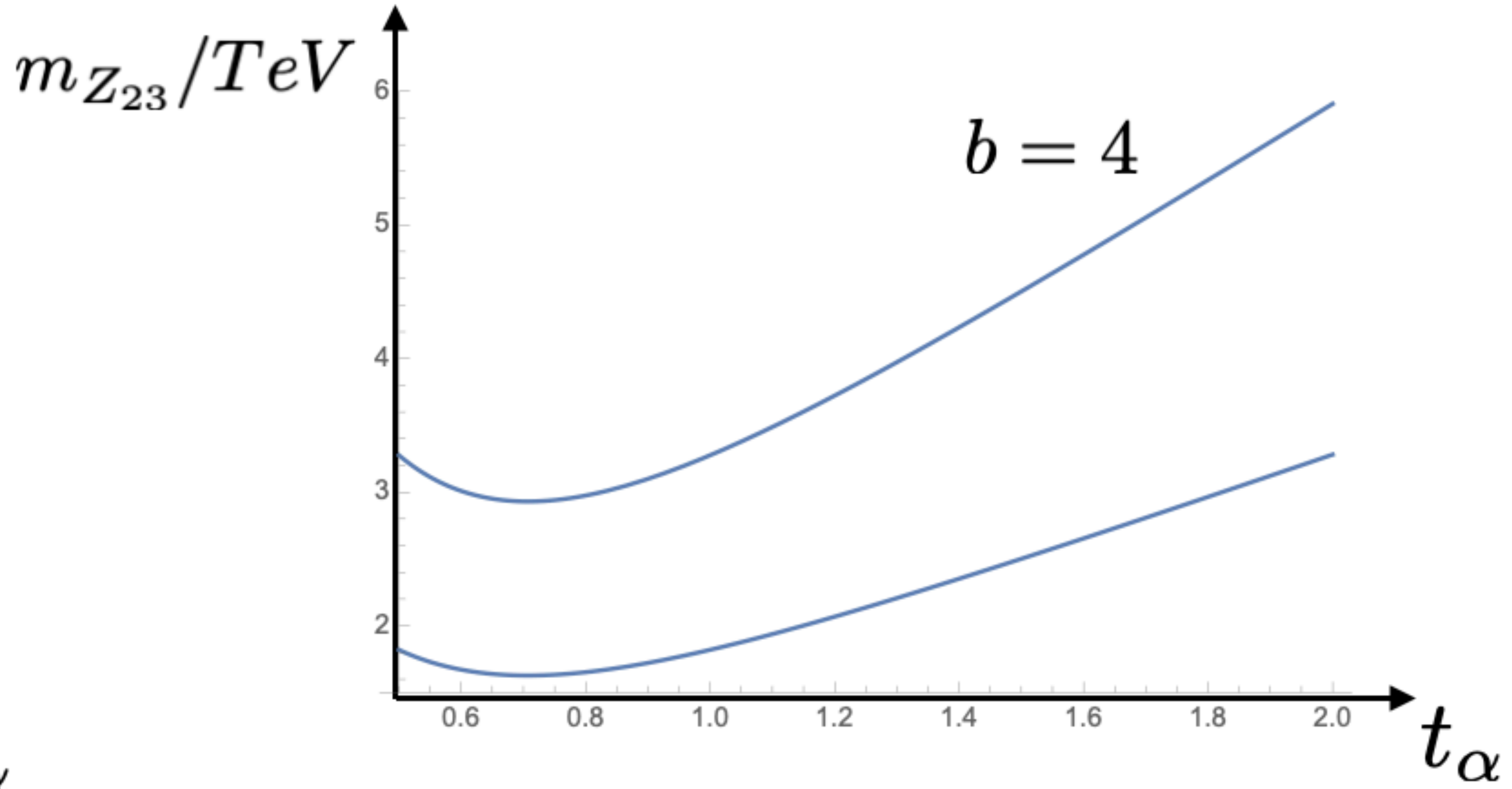
$$\frac{\delta m_Z^2}{m_Z^2} \equiv s_W^2 \frac{m_Z^2}{m_{Z_{23}}^2}(a_{23}^2 + a_3)$$

$$\frac{\delta m_Z^2}{m_Z^2} = (\frac{m_Z(SM)}{m_Z(exp)})^2 - 1 = (38 \pm 20) \cdot 10^{-5}$$

De Blas et al, 2022

To reproduce the 1σ interval above





Phenomenology at the lowest new scale 2

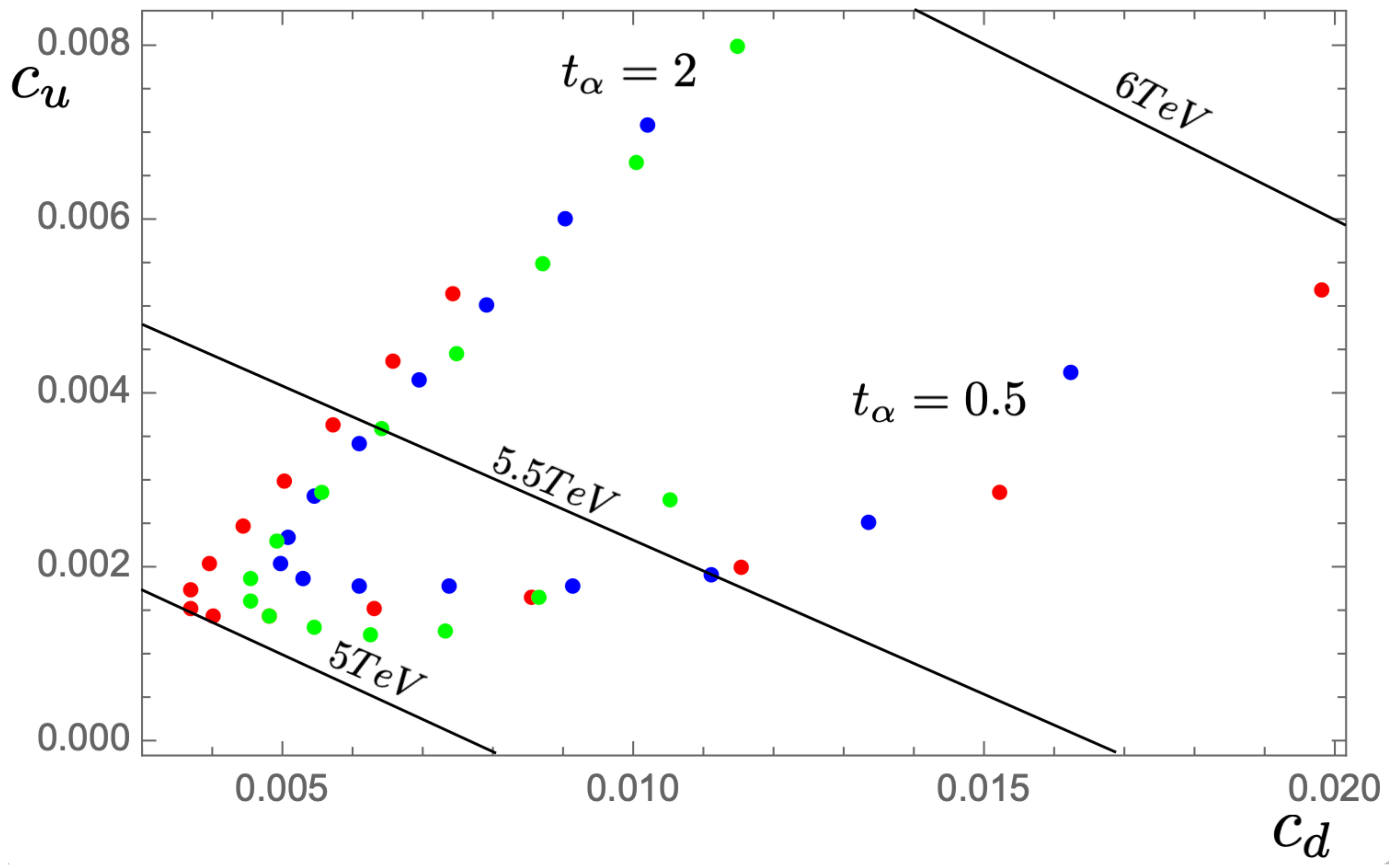
High-p_T Drell-Yan $pp \to l^+ l^-, \quad l = e, \mu$

$$\mathcal{L}_{Z_{23}} = g' Z_{23\mu}(g_L^f \bar{f}_L \gamma^\mu f_L + g_R^f \bar{f}_R \gamma^\mu f_R)$$

from Z_{23} exchange $\quad c_u w_u + c_d w_d = \frac{6}{\pi} \sigma_{l^+ l^-}$

$$c_u = g'^2 (g_L^{u2} + g_R^{u2}) Br_{Z_{23}}(l^+ l^-), \quad c_d = g'^2 (g_L^{d2} + g_R^{d2}) Br_{Z_{23}}(l^+ l^-)$$

Current lower bound on $m_{Z_{23}}$



ATLAS, CMS $140 fb^{-1}$

b=0.25

b=1

b=4

Phenomenology at the lowest new scale 3

Flavour Changing effects $\Delta F = 2, b \to sll, K \to \pi\nu\nu, \tau \to 3\mu, \mu \to 3e, etc$

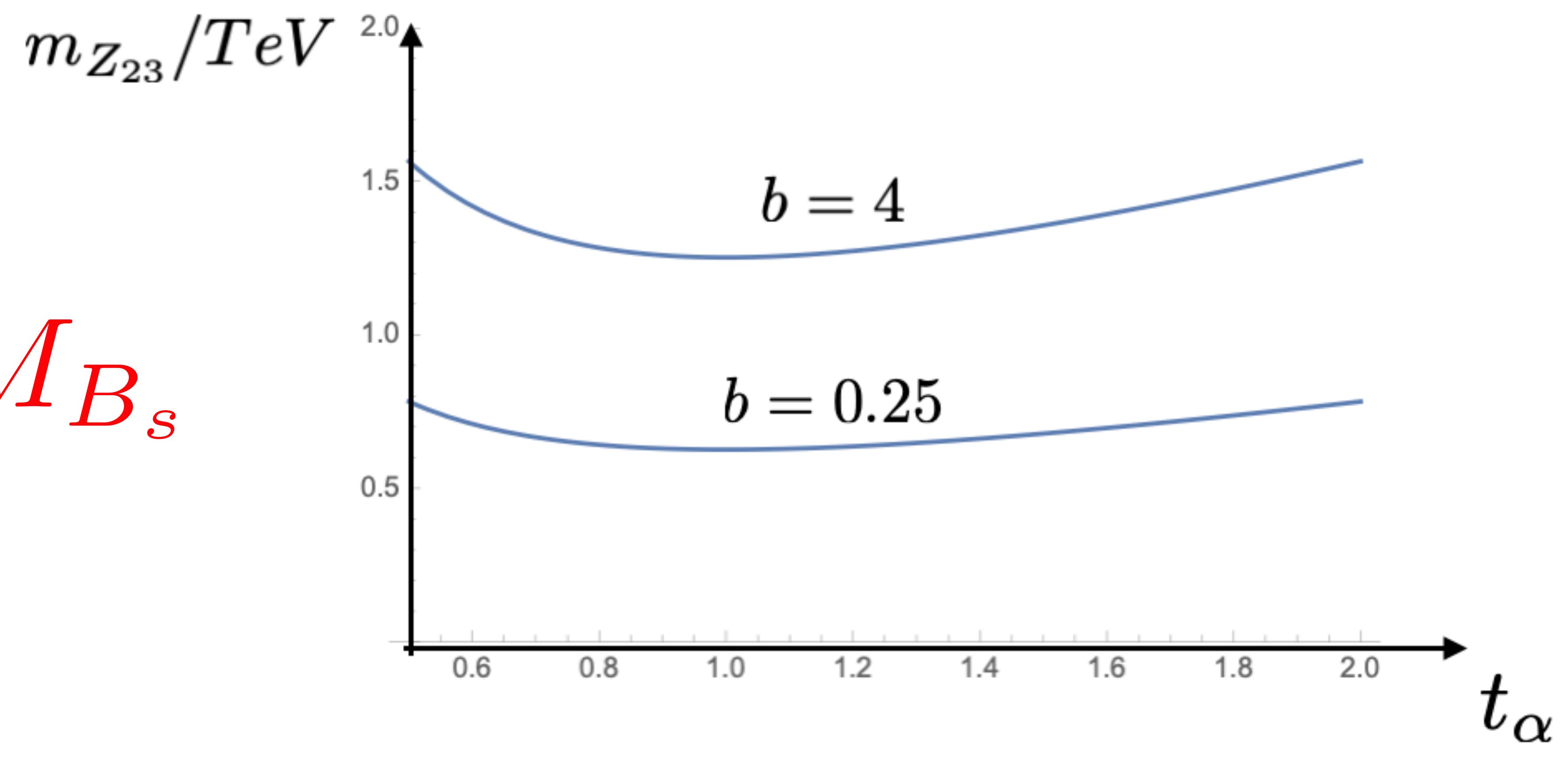
From the different couplings of Z, Z_{23}, Z'_{23} to the third generation versus the first two, after going to the mass basis: $f_L = U_L^f f_L^{(0)}, f_R \approx f_R^{(0)}$

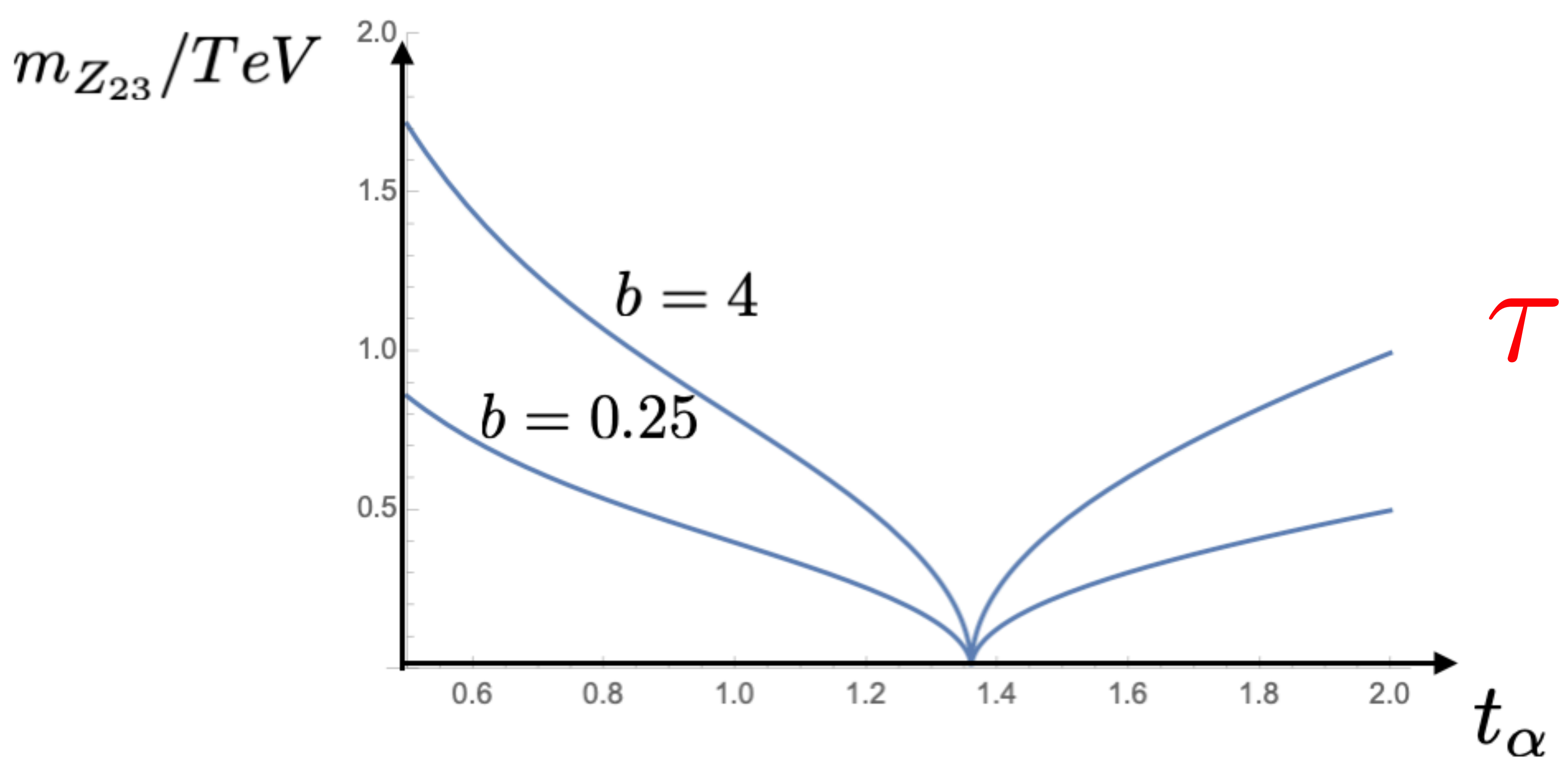
$$\mathcal{L}^{(FC)} = [g'(a_{23} - \frac{1}{t_\alpha})Z_{23\mu} + g_3 Z'_{23\mu} + s_W g' \frac{m_Z^2}{m_{Z_{23}}^2}(a_{23}^2 - \frac{a_{23}}{t_\alpha} + a_3)Z_\mu]J^\mu,$$

$$J^\mu = \frac{1}{6}J_u^\mu + \frac{1}{6}J_d^\mu - \frac{1}{2}J_e^\mu, \qquad J_f^\mu = \Sigma_{i\neq j}[U_L^f]_{i3}[U_L^f]_{j3}^* \bar{f}_{Li}\gamma^\mu f_{Lj}$$

Current lower bounds on $m_{Z_{23}}$ with $U_L^e = U_L^d = V_{CKM}^+$

ΔM_{B_s}





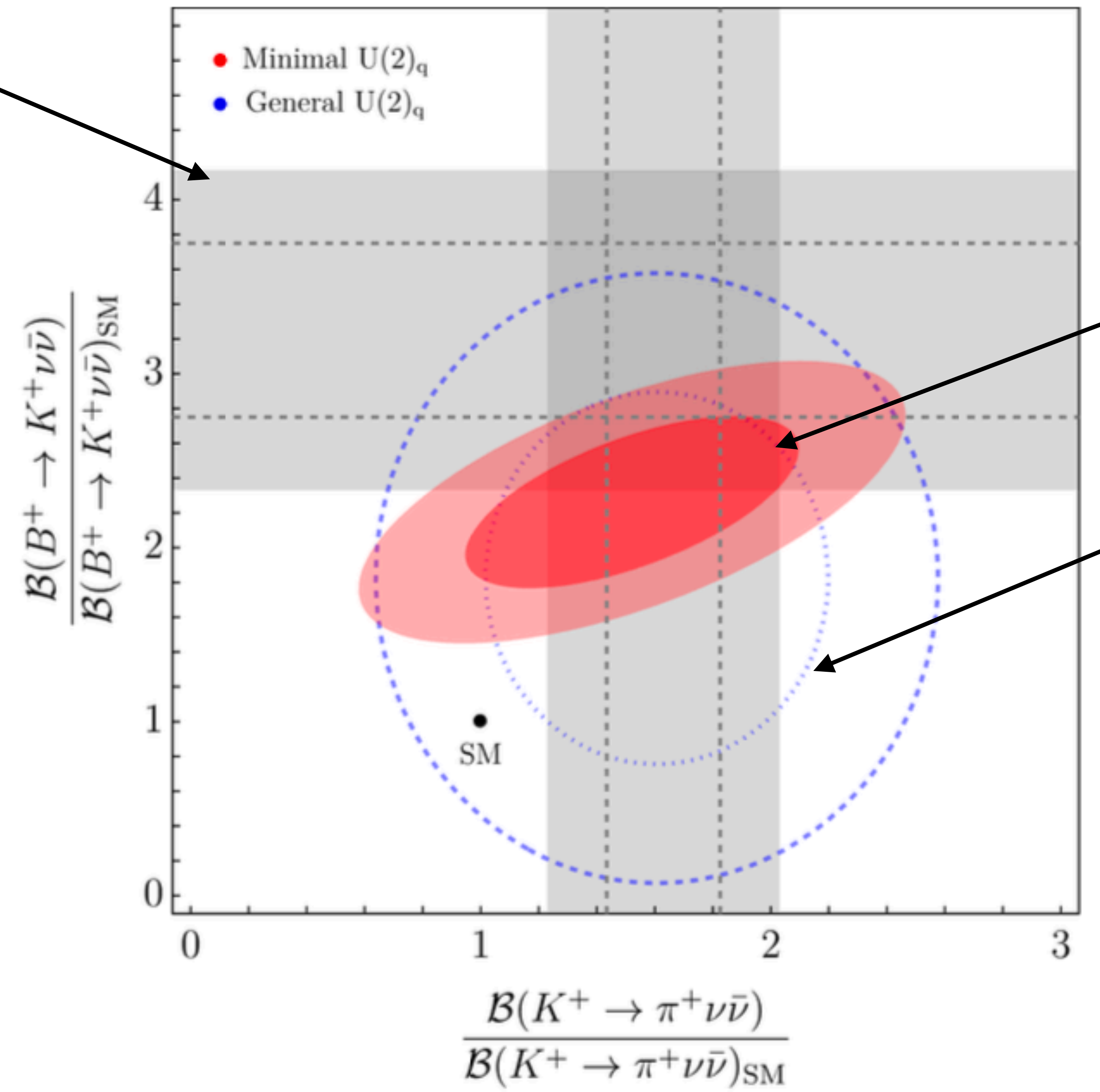
$\tau \to 3\mu$

Phenomenology at the lowest new scale 3

Flavour Changing effects $\Delta F = 2, b \to sll, K \to \pi\nu\nu, \tau \to 3\mu, \mu \to 3e, etc$

Current exp. constraint

An example of correlation



$U_L^d = V_{CKM}^+$

$U_L^d \approx V_{CKM}^+$

Allwicher et al, 2024

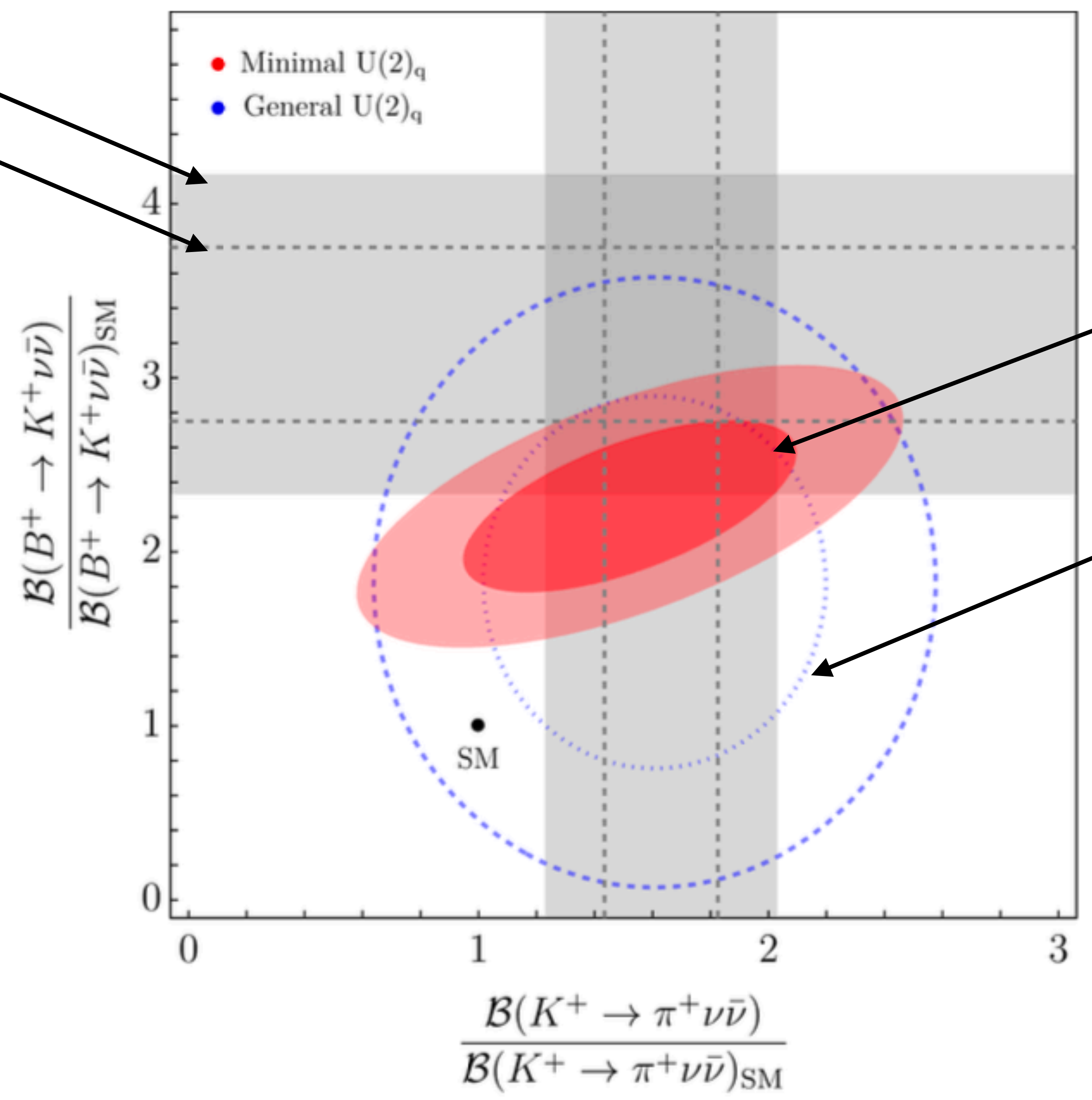
Phenomenology at the lowest new scale 3

Flavour Changing effects $\Delta F = 2, b \to sll, K \to \pi\nu\nu, \tau \to 3\mu, \mu \to 3e, etc$

Current exp. constraint

Mid term exp. expected

An example of correlation



$U_L^d = V_{CKM}^+$

"$U_L^d \approx V_{CKM}^+$"

Allwicher et al, 2024

For so far unobserved transitions

$BR(\tau \to 3\mu) \lesssim 10^{-8} \longrightarrow 10^{-10}$	Belle II
$BR(\mu \to 3e) \lesssim 10^{-12} \longrightarrow 10^{-15}$	Mu3e

De Blas et al, 2025

	Current	HL-LHC	ILC		FCCee								CepC	
					Z (no pol)		Z (pol)		WW		$t\bar{t}$			
ΔS $[\times 10^{-3}]$	100	99	99	99	12	7.8	11	6.4	11	6.4	11	6.3	21	19
ΔT $[\times 10^{-3}]$	120	120	120	120	13	8.1	13	7.9	13	7.9	12	5.8	28	26
ΔU $[\times 10^{-3}]$	95	87	83	82	32	31	32	31	9.8	5.4	9.6	5.2	21	20
ΔS $[\times 10^{-3}]$	91	81	79	79	12	7.8	11	6.4	9.5	6.1	9.5	6	14	12
ΔT $[\times 10^{-3}]$	72	63	52	52	13	8.1	13	7.9	10	7.4	6.8	3.6	16	15
$(U = 0)$														
$\Delta\varepsilon_1^{\rm NP}[\times 10^{-5}]$	96	96	96	95	11	7.3	11	7.2	11	7.2	9.5	4.7	25	23
$\Delta\varepsilon_2^{\rm NP}[\times 10^{-5}]$	86	81	77	76	29	28	28	28	8.6	4.8	8.5	4.7	21	19
$\Delta\varepsilon_3^{\rm NP}[\times 10^{-5}]$	91	87	88	87	9.9	6.6	9.3	5.5	9.2	5.5	9.3	5.5	20	18
$\Delta\varepsilon_b^{\rm NP}[\times 10^{-5}]$	130	130	130	130	15	12	15	12	15	12	14	11	41	37
$\Delta\delta g_L^b$ $[\times 10^{-4}]$	14	14	14	14	1.5	1.3	1.2	1.1	1.2	1.1	1.2	1.1	2.4	2.2
$\Delta\delta g_R^b$ $[\times 10^{-4}]$	72	70	70	70	7.1	6.6	5.3	5.3	5.3	5.3	5.3	5.3	8.9	8.6
$\Delta\kappa_V$ $[\times 10^{-3}]$	22	14	4.5	4.4	4.6	3.9	4.4	3.7	4.1	3.7	1.8	1.3	5	4.7

Table 22. Comparison of the current and expected sensitivities, Δ, to the different NP scenarios at the future colliders considered in this study. In this table, the future projections for the sensitivity to κ_V has been computed considering only the improvements in EWPO. (See table 23 for the projections using EWPO and Higgs-boson observables.) For the case of future lepton colliders we quote results that also include the expected future theoretical errors given in table 21 (dark background), as well as results in which the theoretical errors have been neglected (white background).