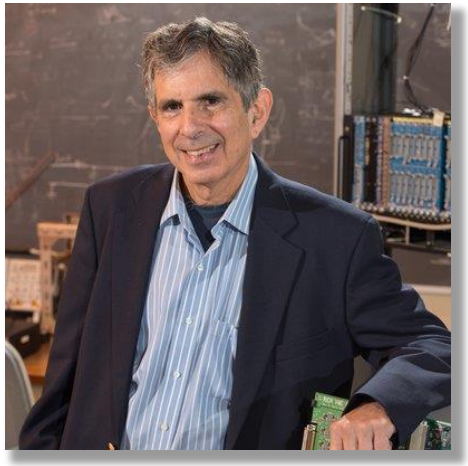
BSM Flavour Expedition (From the Attouniverse to the Zeptouniverse)

Andrzej J. Buras
(Technical University Munich TUM-IAS)

Implications of LHCb Measurements and Future Prospects 2021

Overture 1

Great Flavour physicist and a wonderful person



with a special sense of humour!

Sheldon Stone (1946-2021)

Vienna 2015 EPS

Overture 2

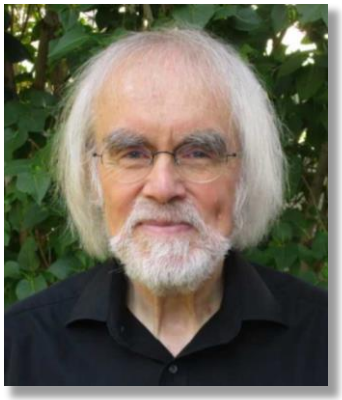
1981 - 2021

40 years later

1981 - 2021

(1981)

40 years later

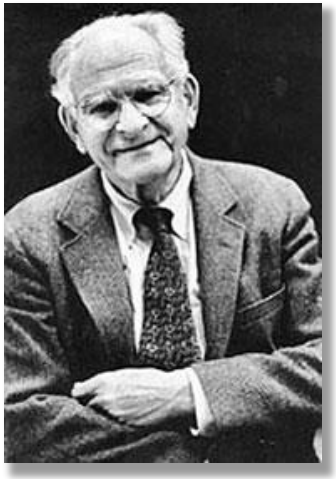


(2021)

Victor Weisskopf (1908-2002) after $W^{\pm}$, Z^0 Discovery

MPI (Munich) (1983)

MPM (1956)

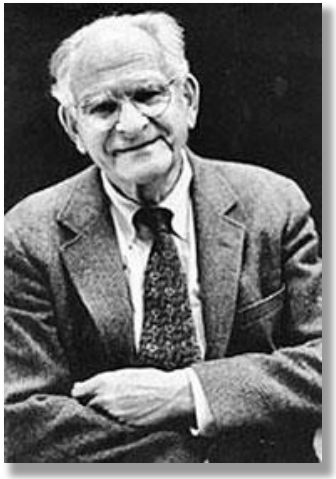


“If experiment agrees with theory (SM) there is no progress !”

Victor Weisskopf (1908-2002) after $W^{\pm}$, Z^0 Discovery

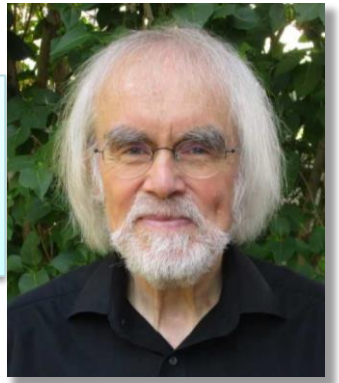
MPI (Munich) (1983)

MPM (1956)



"If experiment agrees with theory (SM) there is no progress !"

MPM (2020)



"If theory (SM) agrees with experiment there is no progress !"

(2021)

Present Anomalies

Violation of
μ-e Universitality
R(K), R(K*)

(-) B

Anomaly in
Angular Distribution
$B \to K^* \mu^+ \mu^-$ (P_5')

(-) B

Violation of
$\mu - \tau$ Universality
R(D*), R(D*)

(+) B

$B_s \to \mu^+ \mu^-$

(-) B

$(g-2)_\mu$ (+)

$(g-2)_e$ (-)

$\frac{\varepsilon'}{\varepsilon}$ (+) K

ΔA_{CP} (-) C

ΔM_K (-) K

Violation of
CKM Unitarity
V_{us}, V_{ud}

Violation of
$\mu - e$ Universality
τ – Decays

(+)

$B_d^0 \to \pi^0 K_S$
CPV – Anomaly

Neutrino
Anomalies

(+) (-) : Action of New Physics

B-Physics Anomalies (2013-2021)

B-Physics Anomalies (2013-2021)

Altmannshofer
Straub
Stangl
Crivellin

Kaon Flavour Physics

(2016 -)

Foto by Gurli Buras

Physik Journal 18 (2019) Nr. 8/9

Christof Wetterich

Gentner-Kastler-Prize 2019

Where do we go from here?

(Collider physics view)

(2046?) New Physics Summits

John Ellis

Pampa (Argentina)

European Strategy for High Energy Physics will not allow us to see directly new particles with masses above 10 TeV

Flavour Strategy **allows to see them through**

Analogy : **Quantum Fluctuations**

Le Verrier* predicted the existence of Neptune in 1846 through an anomaly in the orbit of the Uranus and predicted its position with an accuracy of 1°. Confirmed by Gottfried Galle.

***(See also John Couch Adams)**

Black Hole

Nobel Prize 2020

Dark Matter searches

Enrico Fermi

Enrico Fermi (MPM 1954)

$W^{\pm}$, Z° were also seen indirectly well before their discovery in 1983

Flavour Physics (2020 -)

Crevasses

New Physics Summits

SMEFT

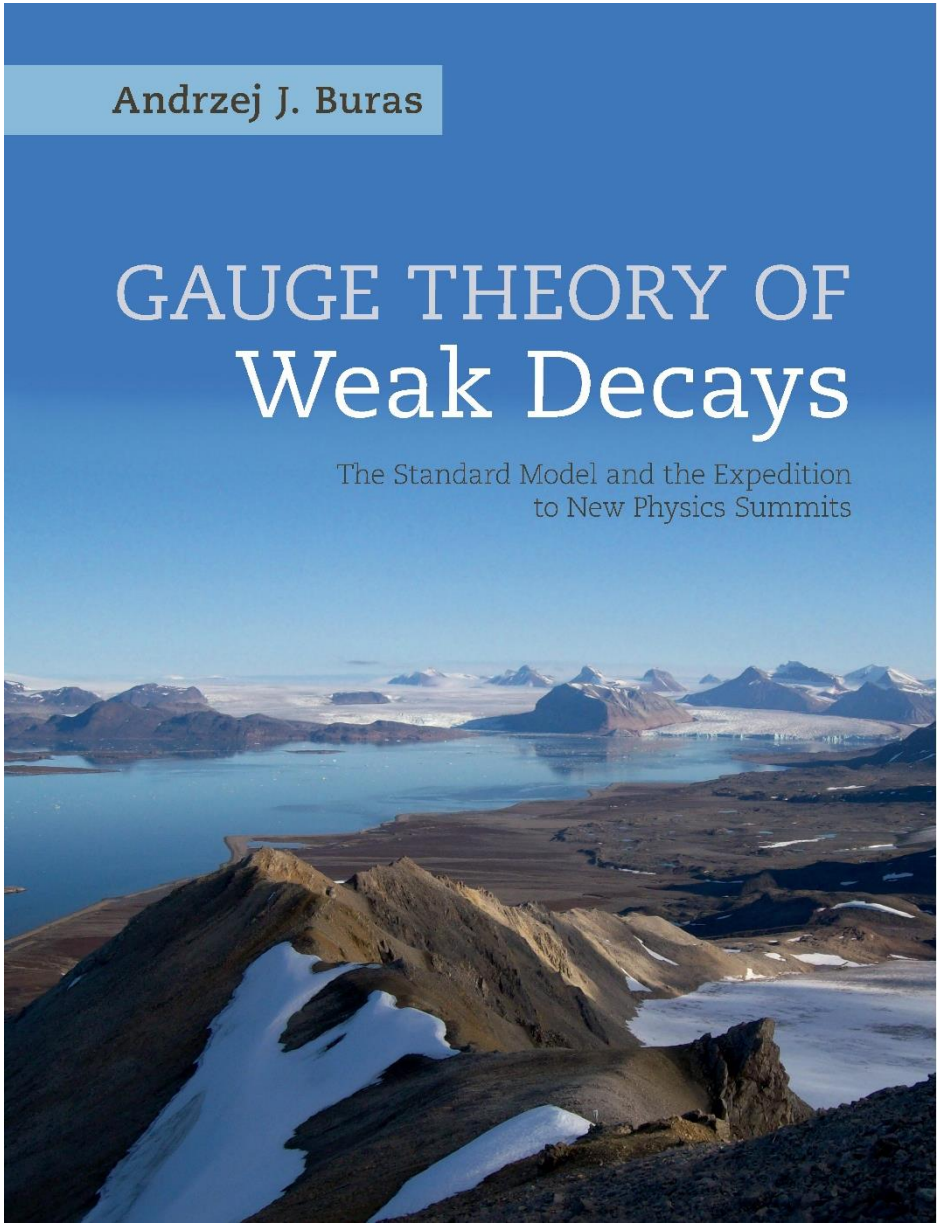
Energy gap

SM
Base Camp

Svalbard (Spitzbergen)

Zeptouniverse Guide

Published July 2020



739 pages
1350 references

Cambridge University Press

But this is not the Whole Story !!

The Search for Feebly-Interacting Particles with masses below GeV

(Axions, Axinos, Dark Matter, ...)

Light but very weakly interacting with the ordinary matter we know.

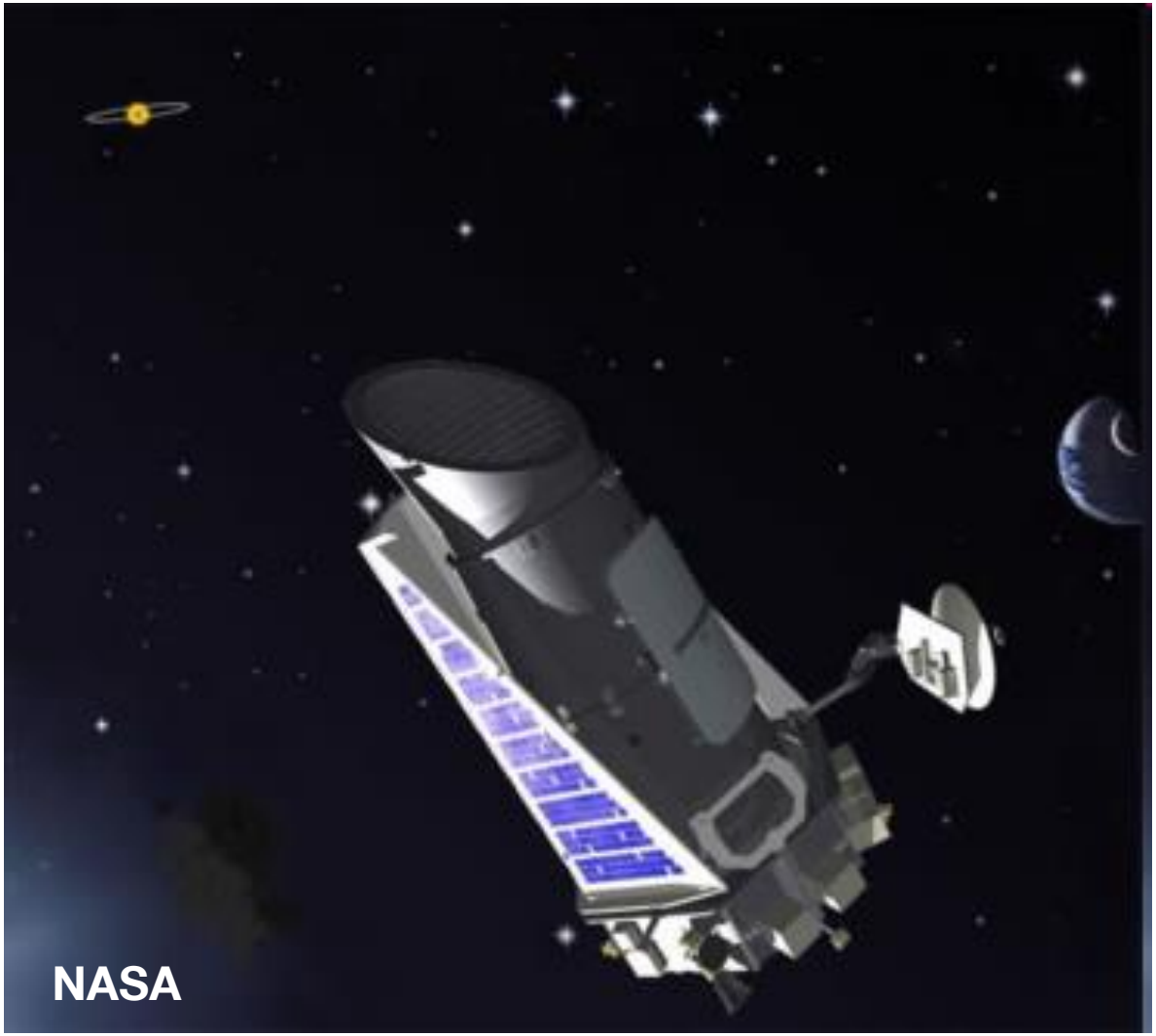
(2011.02157, Lanfranchi, Pospelov, Schuster)

Expedition
Attouniverse → Zeptouniverse
10^{-18}m → 10^{-21}m

Usual Picture of the Month

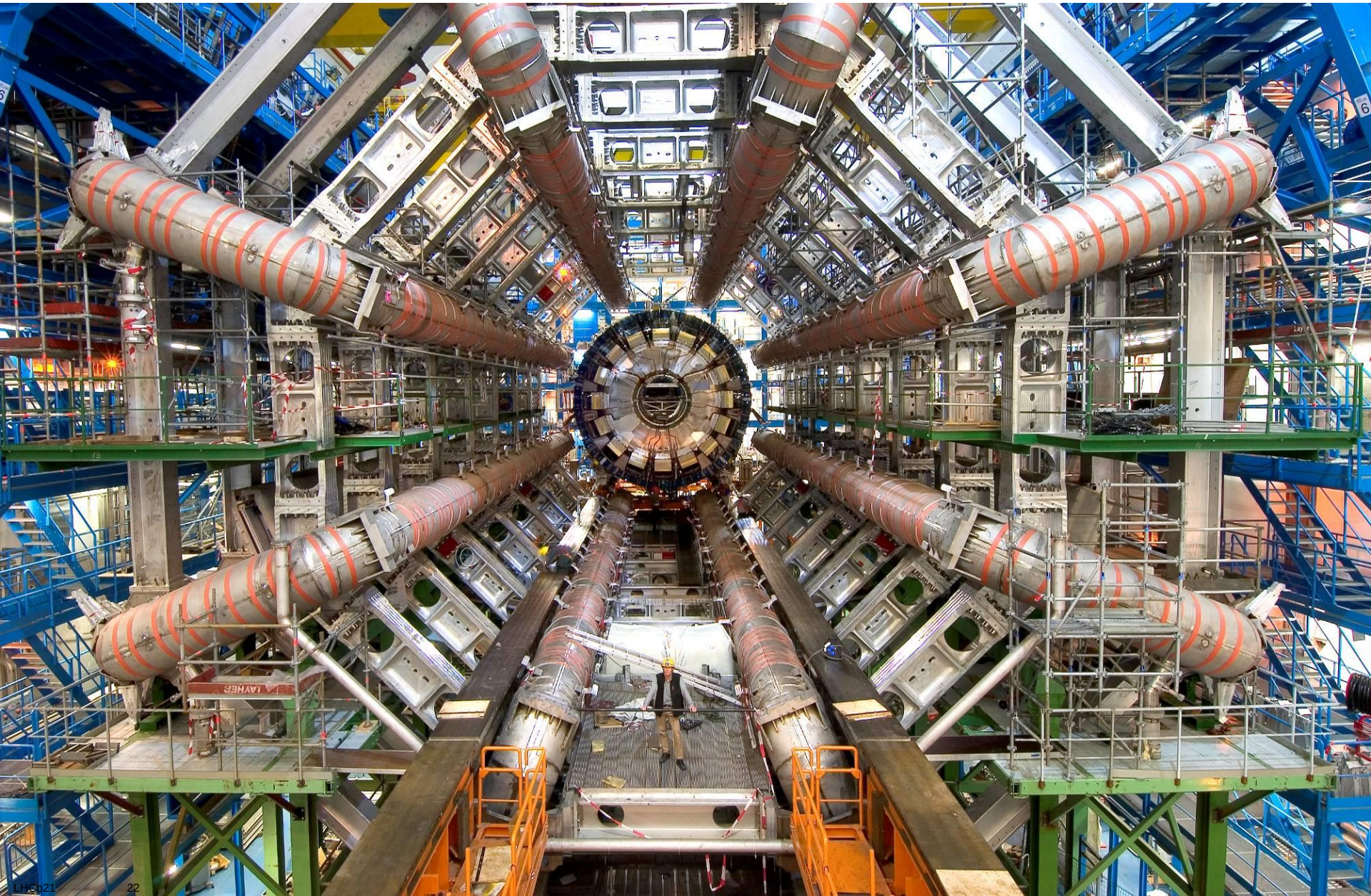
(CERN Courier)

Kepler Searching for new Planetary Systems and New Lifes



March 2009

Technology to go beyond the Attouniverse



Expedition
Attouniverse → Zeptouniverse
10^{-18}m → 10^{-21}m

Dual Picture AJB (2009)

10^{18}m → 10^{21}m

Dual Picture of Nanouniverse

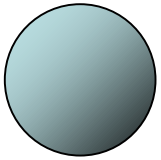
10^9m

3 light seconds

Earth

$0.4 \cdot 10^9$m

Moon



Nanouniverse

Dual Picture of Attouniverse

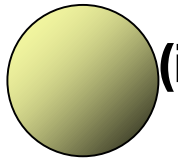
10^{18}m

105 light years

Earth

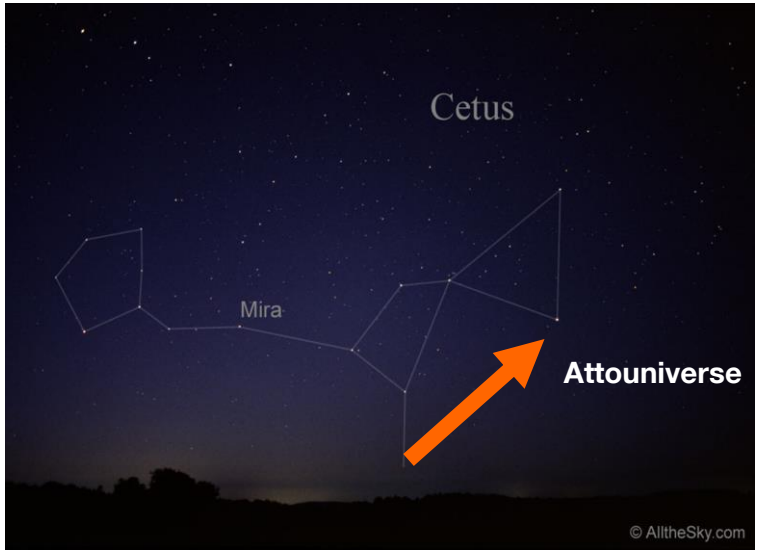
Beta Ceti

97 light years



(in the constellation Cetus)

2026 ← → 1929



Dual Picture of Zeptouniverse

10^{21}m

100.000 light years

Earth

170.000 light years

Large Magellanic Cloud

170.000 Years ago...

170.000 Years ago...

Flavour Expedition to the Zeptouniverse = **True Mammoth Project**

A Journey to the Very Short Distance Scales:

1676 - 2046

Microuniverse	10^{-6}m	Bacteriology Microbiology
Nanouniverse	10^{-9}m	Nanoscience
Femtouniverse	10^{-15}m	Nuclear Physics Low Energy Elementary Particle Physics
Attouniverse	10^{-18}m	High Energy Particle Physics (present)
High Energy Proton-Proton Collisions at the LHC	$5 \cdot 10^{-20}$m	Frontiers of Elementary Particle Physics in 2020´s
High Precision Measurements of Rare Processes (Europe, Japan, USA)	10^{-21}m	Zeptouniverse

Basic Questions in Flavour Physics

New Flavour violating CPV phases?

Flavour Conserving CPV phases?

Non-MFV Interactions?

Right-Handed Charged Currents?

Scalars H^0, $H^{\pm}$ and related FCNC´s?

New Fermions? New Gauge Bosons?

How to explain dynamically 22 free Parameters in the Flavour Sector ?

More Basic Questions

1. Can Quark Flavour Physics give us insight into the dynamics at very SD scales if no direct clear signal of NP will be seen at the LHC? No new particles below 6 TeV.

2. Can we reach Zeptouniverse 10^{-21}m (~ 200 TeV) by means of Quark Flavour Physics?

3. Can we reach even higher scales well beyond any collider in the coming centuries (like 1000 TeV) ?

Overture Finished

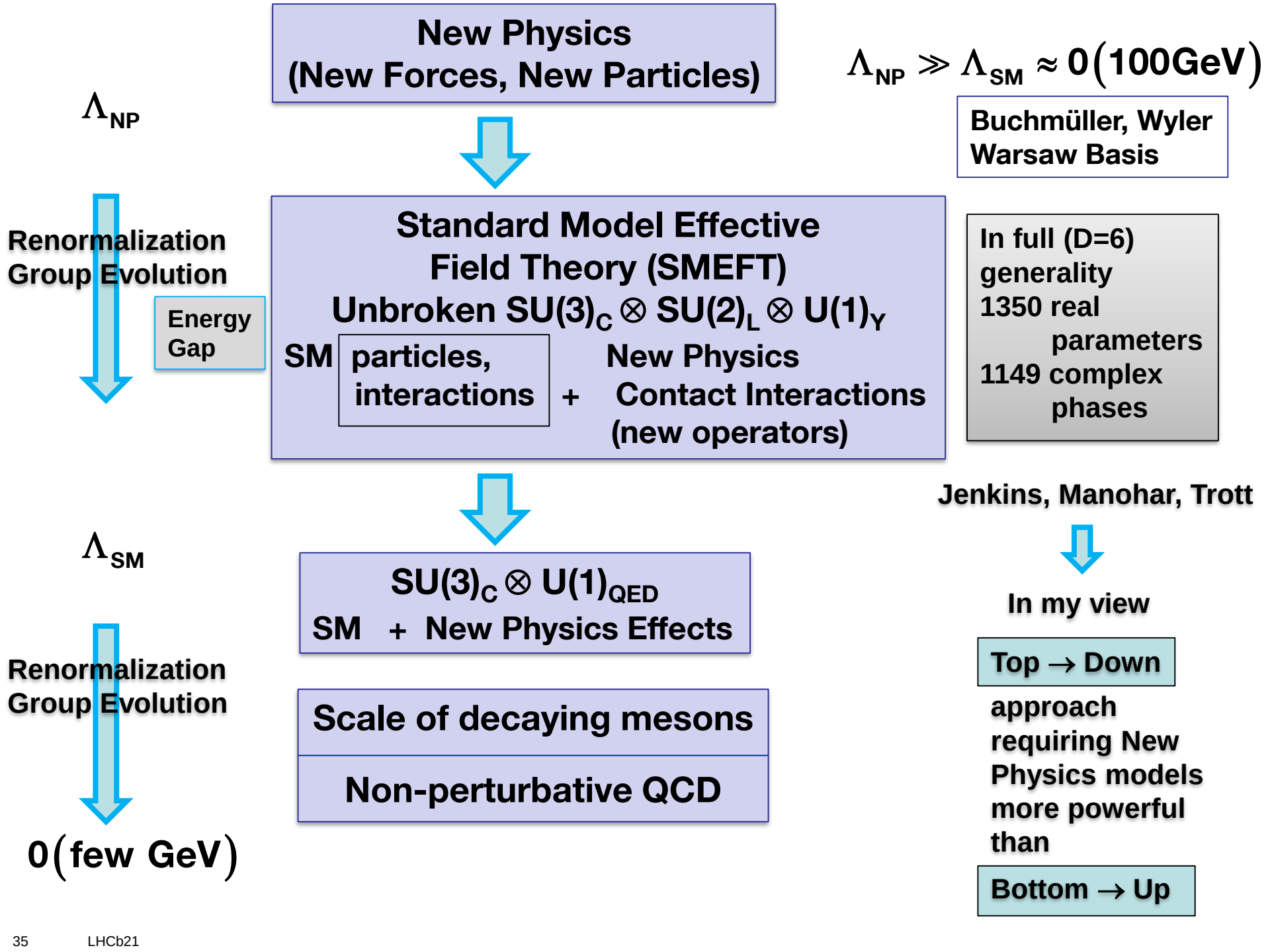
LHCb Symphony Nr. 19
(Premiere, CERN 22.10.2021)

1st Movement	:	Bottom-Up vs Top Down SMEFT at Work
2nd Movement	:	Beyond Global Fits: Correlations and DNAs
3rd Movement	:	Searching for New Physics in Rare B and K Decays without $\|V_{cb}\|$ and $\|V_{ub}\|$ Uncertainties
4th Movement	:	Flavour Messages and Shopping List

(1821)

1st Movement

Bottom-Up vs Top Down
SMEFT at Work



New Physics
(New Forces, New Particles)

$\Lambda_{NP} \gg \Lambda_{SM} \approx 0(100\text{GeV})$

Buchmüller, Wyler
Warsaw Basis

Λ_{NP}

Renormalization
Group Evolution

Energy
Gap

Standard Model Effective
Field Theory (SMEFT)
Unbroken $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$

SM particles, interactions + New Physics Contact Interactions (new operators)

In full (D=6)
generality
1350 real parameters
1149 complex phases

Jenkins, Manohar, Trott

Λ_{SM}

$SU(3)_C \otimes U(1)_{QED}$
SM + New Physics Effects

In my view

Renormalization
Group Evolution

Scale of decaying mesons

Non-perturbative QCD

Top → Down

approach requiring New Physics models more powerful than

Bottom → Up

$0(\text{few GeV})$

General Structure

$$\left\{ A = \sum_i C_i^{LEFT}(\mu_{had}) \langle O_i^{LEFT}(\mu_{had}) \rangle \right\} \Rightarrow \left\{ \begin{array}{l} \text{Observables :} \\ \text{Branching} \\ \text{Ratios, Asymmetries} \end{array} \right\}$$

LEFT = Low Energy Effective Theory

$$\vec{C} = [C_1, C_2, \ldots]^T$$

Step 1

$$\vec{C}^{SMEFT}(\mu_{ew}) = \hat{U}_{SMEFT}(\mu_{ew}, \Lambda)\vec{C}_{SMEFT}(\Lambda)$$

From some UV Model

Renormalization Group Evolution: α_s, α_2, α_1, Y_i

Step 2

$$\vec{C}^{LEFT}(\mu_{ew}) = \hat{M}(\mu_{ew})\vec{C}^{SMEFT}(\mu_{ew})$$ (Matching)

Step 3

$$\vec{C}^{LEFT}(\mu_{had}) = \hat{U}_{LEFT}(\mu_{had}, \mu_{ew})\vec{C}^{LEFT}(\mu_{ew})$$

Renormalization Group Evolution: α_s, α_{QED}

Numerical Codes $(\hat{U}, \hat{M})$

Running and/or Matching: Dixtools, Wilson, Matching Tools
WCxf, Matchmaker, SuperTracer, STrEM

Flavour Observables: flavio, EOS, FlavorKit, Spheno,
Formflavor, SuperIso, HEPfit, FlavBit

SMEFT related: SMEFTsim, CodEx, BasisGen

Known fully in LO of RG improved perturbation theory.

J. Aebischer

J. Kumar

C. Bobeth

NLO requires : One-Loop matching ✓

Necessary to get scheme independent answers { Two-Loop anomalous Dimensions (only partly known)

(2006.01138, 2009.07276, 2107.12391, 2107.10262)

M. Misiak

Present Status of RG Analysis

$\vec{C}_{SMEFT}(\Lambda)$: Tree-Level Matching known
Examples of one-loop matching
VLQs (Bobeth et al. 1609.04783)

De Blas et al. (1711.10391)
Gherardi, Marzocca Venturini, (2008.09548 (LQs) 2003.12525)

$\hat{U}_{SMEFT}(\mu_{ew}, \Lambda)$: Leading Order (one-loop ADMs) known (San Diego)
NLO (two-loop ADMs) partly known

$\hat{M}(\mu_{ew})$: Tree-Level and one-loop matching known

Jenkins, Manohar, Stoffer (1709.04486)
Aebischer et al. (1512.02830)
Dekens + Stoffer (1908.05295)

$\hat{U}_{LEFT}(\mu_{had}, \mu_{ew})$: LO known (San Diego, Aebischer et al)

(2107.10262, 2107.12391) NLO known for $\Delta F=1$ non-leptonic decays (Munich)

(2009.07276) NLO known for $\Delta F=2$ mixing

Question to Bottom-Up Supporters

How can you identify New Physics at Λ from $\vec{C}_{LEFT}(\mu_{had})$?

Please tell me, how you can do it !

Hopefully an answer by next LHCb workshop

Analyses with one or two Wilson Coefficients, even if useful to get the first messages from Nature can only be considered as a first look !

$$C_{9\mu}^{NP} = -C_{10\mu}^{NP}$$

$$C_{9}^{NP}, C_{9\mu}^{'} = -C_{10\mu}^{'}$$

$$C_{9}^{NP}, C_{10\mu}^{'}$$

$$C_{9\mu}^{NP}, C_{10}^{NP}$$

(see Anomaly Workshop)

Questions in Top-Down Approach

Assume we have a concrete model with couplings and masses.

How should we present the results of a given numerical analysis?

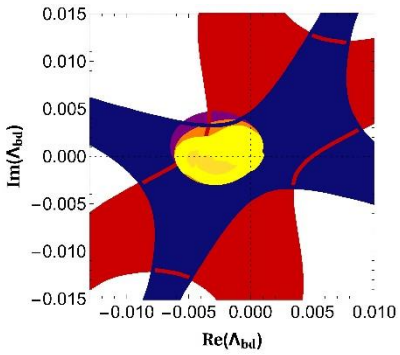
A. **In terms of constraints on parameters from experiment demonstrating that a given model survives in some range of couplings.**

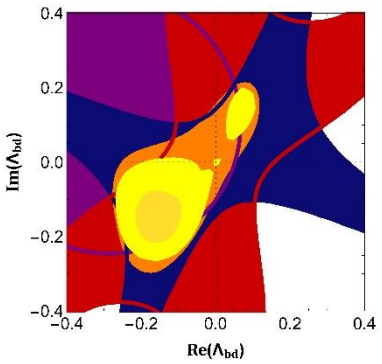
B. **In terms of Wilson Coefficients and correlations between them characteristic for a given model.**

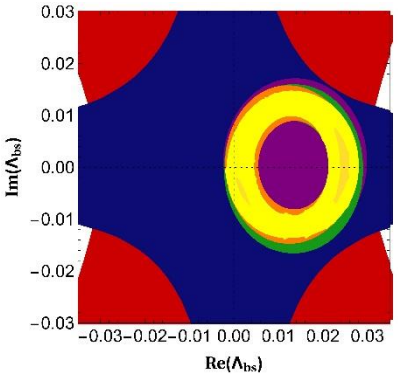
Could be useful for model builders

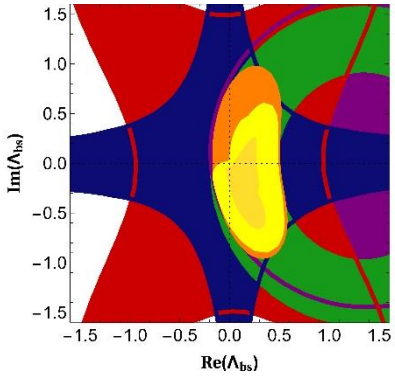
C. **In terms of observables: branching ratios, asymmetries and correlations between them.**

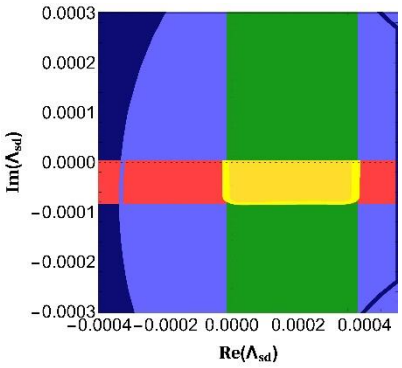
C. Bobeth, AJB, A. Celis, M. Jung
Vector-Like Quark Models 1609.04783

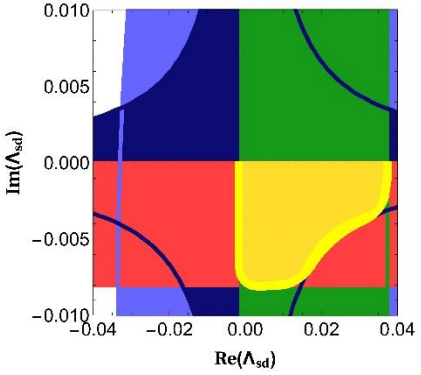


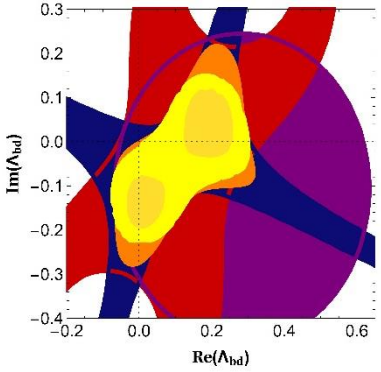


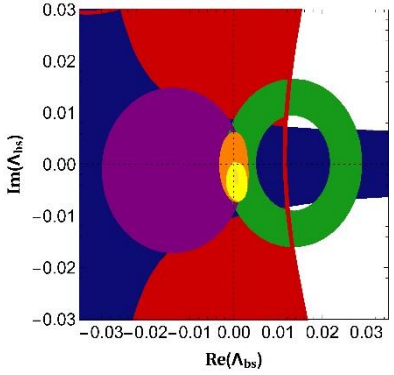


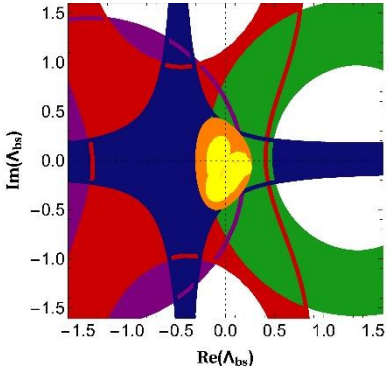


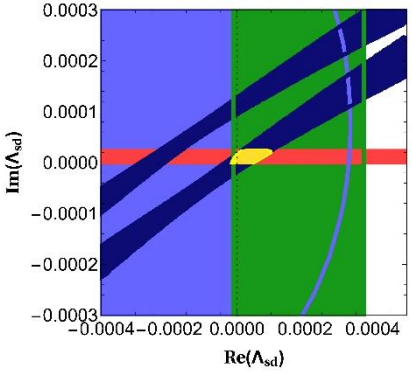


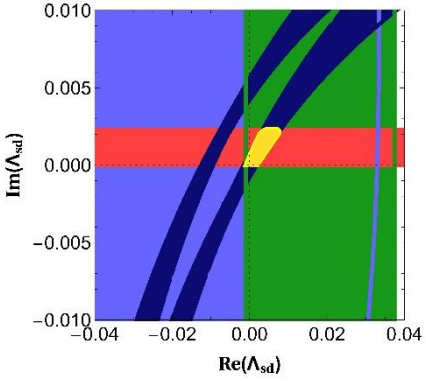






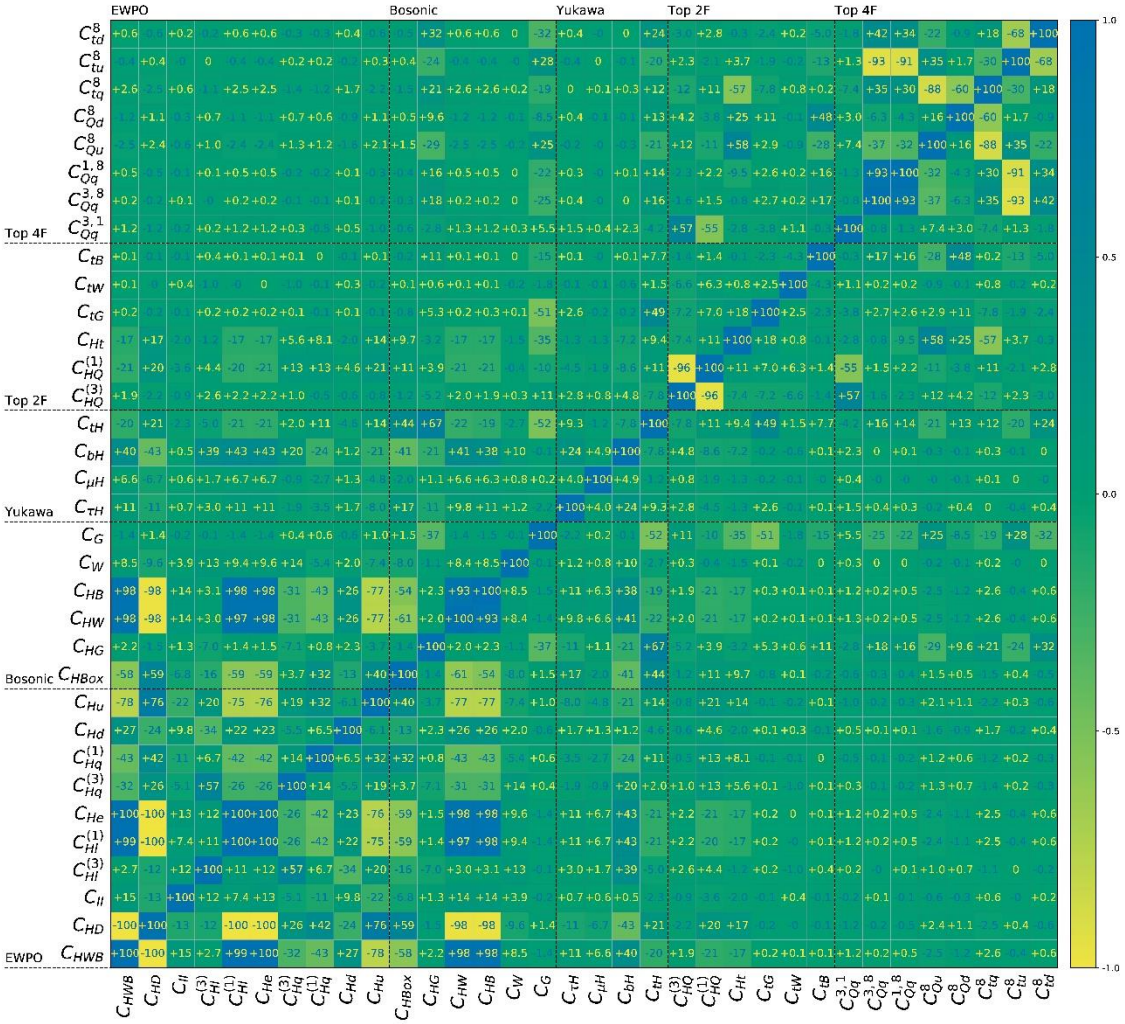






Painter:
Martin Jung

John Ellis at Work
2105.14942



J. Ellis
M. Madigan
K. Mimasu
V. Sanz
T. You
[2012.02779]

2nd Movement

Beyond Global Fits (Correlations and DNAs)

In Order to identify New Physics through Flavour Physics

We need

1. Many precision measurements of many observables and precise theory.

2. Study Patterns on Flavour Violation in various New Physics models (correlations between many flavour observables).

Study of Flavour Violation in NP Models

RS_c	Gauged Flavour Models	CMFV, MFV
L-R Models	Vector-like Fermions	$2HDM_{\overline{MFV}}$
Z, Z´	331, $U(2)^3$	LHT
Leptoquarks	SO(10)-GUT $SSU(5)_{RN}$	SUSY Flavour

All studied at TUM

1012.1447
1204.5065

1306.3755

1505.00618 ⇦ Reviews

Global Fits

S_1 and S_3 - global analysis

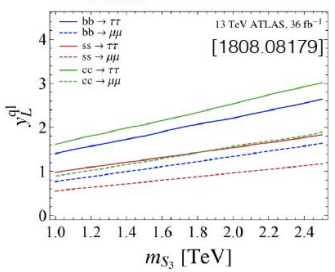
Using the complete one-loop matching to SMEFT, we include in our analysis the following observables.

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

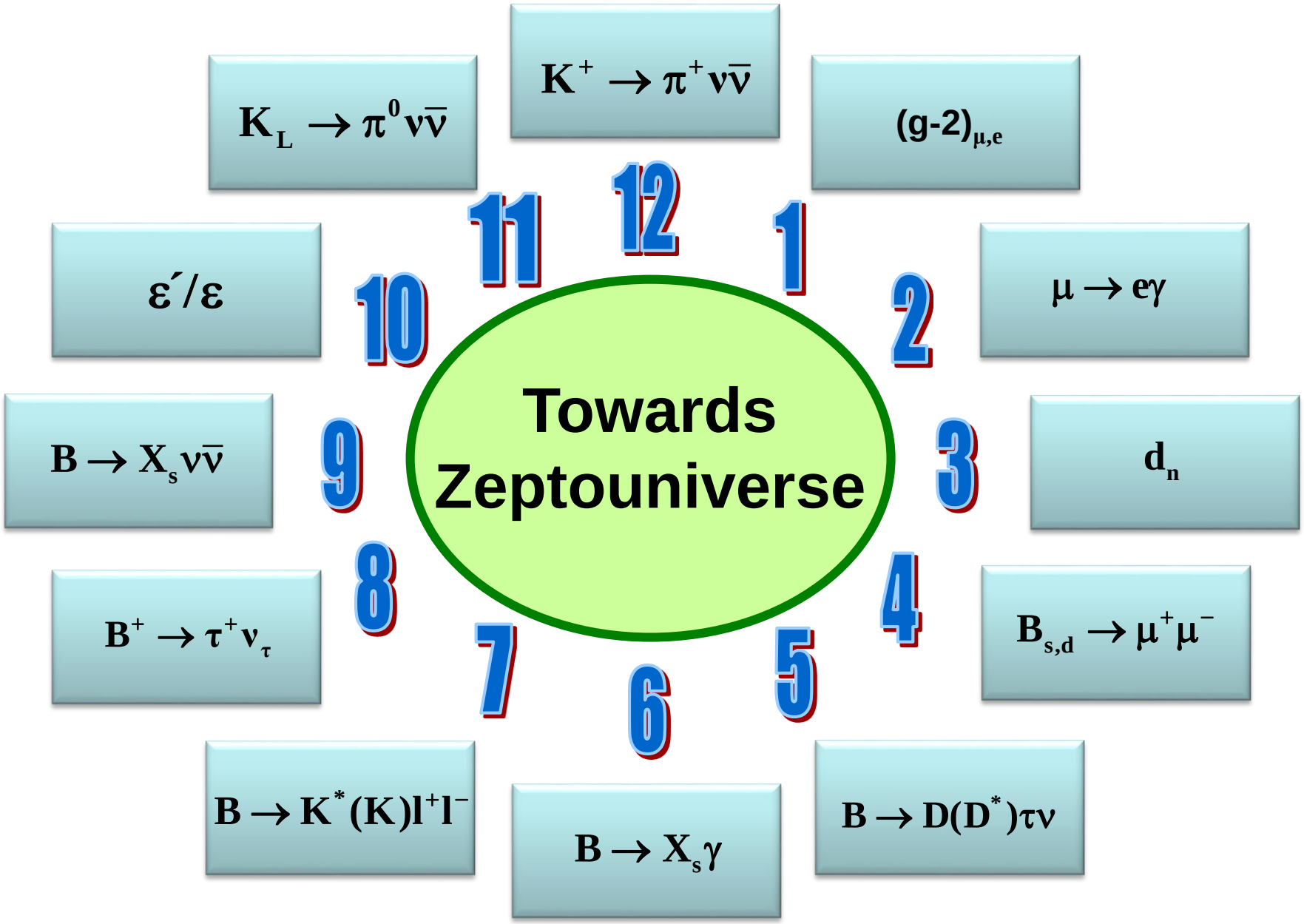


Observable	SM prediction	Experimental bounds
$b \to s\ell\ell$ observables		[37]
$\Delta C_9^{sb\mu\mu}$	0	-0.43 ± 0.09 [79]
$\mathcal{C}_9^{\rm univ}$	0	-0.48 ± 0.24 [79]
$b \to c\tau(\ell)\nu$ observables		[37]
R_D	0.299 ± 0.003 [12]	$0.34 \pm 0.027 \pm 0.013$ [12]
R_{D^*}	0.258 ± 0.005 [12]	$0.295 \pm 0.011 \pm 0.008$ [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]
$\mathcal{B}(K_L \to \pi^0ee)$	$(3.2^{+1.2}_{-0.8}) \times 10^{-11}$ [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]
$B_s^0 - \overline{B}_s^0$: $\lvert C^1_{B_s}\rvert$	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 $\cdot$ cm [124, 125]	$< 1.3 \times 10^{-29}$ e $\cdot$ cm [126]
$\lvert d_\mu\rvert$	$< 10^{-42}$ e $\cdot$ cm [125]	$< 1.9 \times 10^{-19}$ e $\cdot$ cm [127]
d_τ	$< 10^{-41}$ e $\cdot$ cm [125]	$(1.15 \pm 1.70) \times 10^{-17}$ e $\cdot$ cm [37]
d_n	$< 10^{-33}$ e $\cdot$ cm [128]	$< 2.1 \times 10^{-26}$ e $\cdot$ 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]

David Marzocca (Talk at Portoroz 2021)


$K^+ \to \pi^+ \nu\bar{\nu}$
$K_L \to \pi^0 \nu\bar{\nu}$
$(g\text{-}2)_{\mu,e}$
12
1
11
ε'/ε
10
2
$\mu \to e\gamma$
Towards Zeptouniverse
$B \to X_s \nu\bar{\nu}$
9
3
d_n
8
4
$B^+ \to \tau^+ \nu_\tau$
$B_{s,d} \to \mu^+\mu^-$
7
5
6
$B \to K^*(K) l^+ l^-$
$B \to X_s \gamma$
$B \to D(D^*)\tau\nu$

DNA of a Theory

AJB + Jennifer Girrbach-Noe

Basic Idea

1306.3755

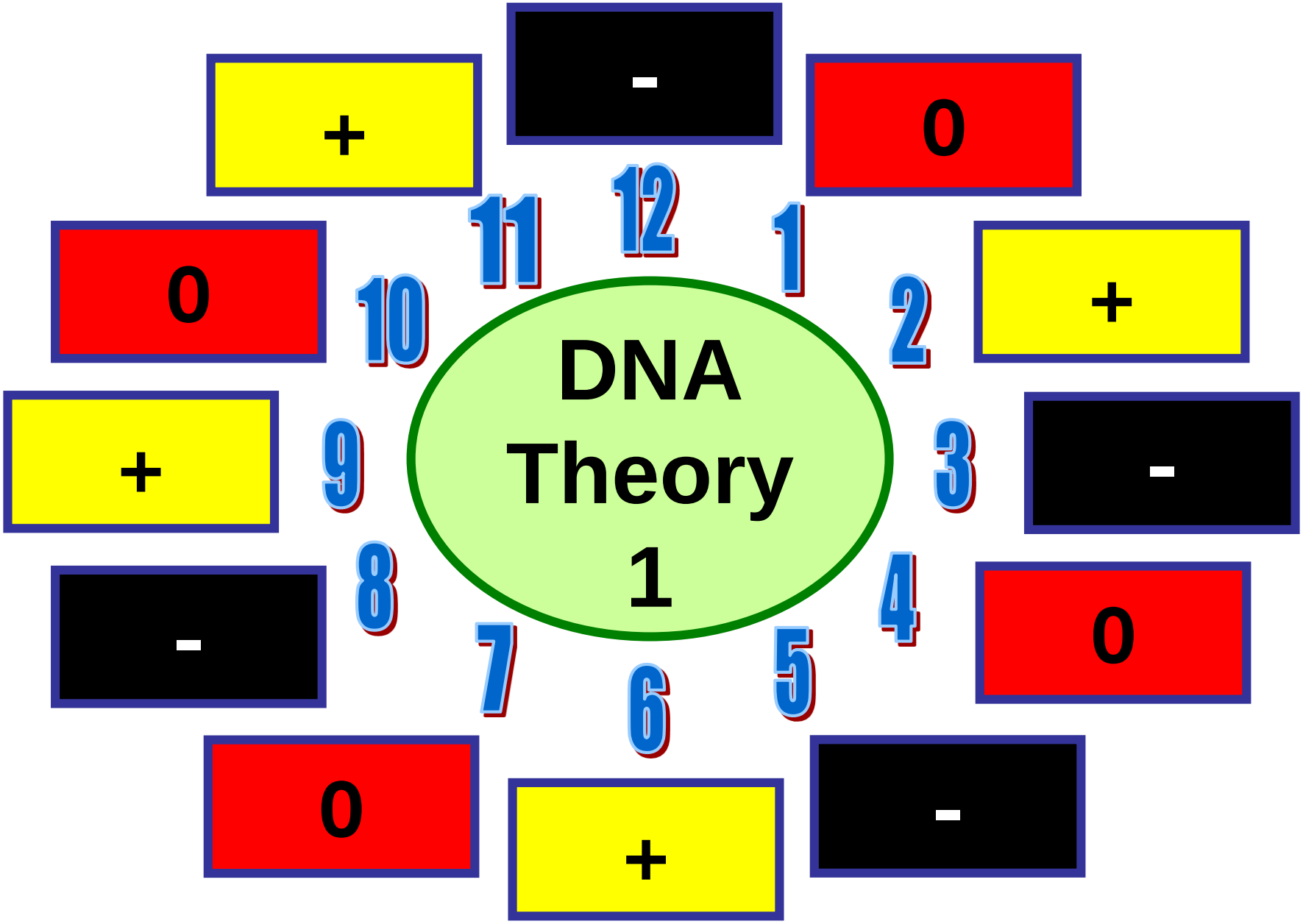
Look at various observables and identify

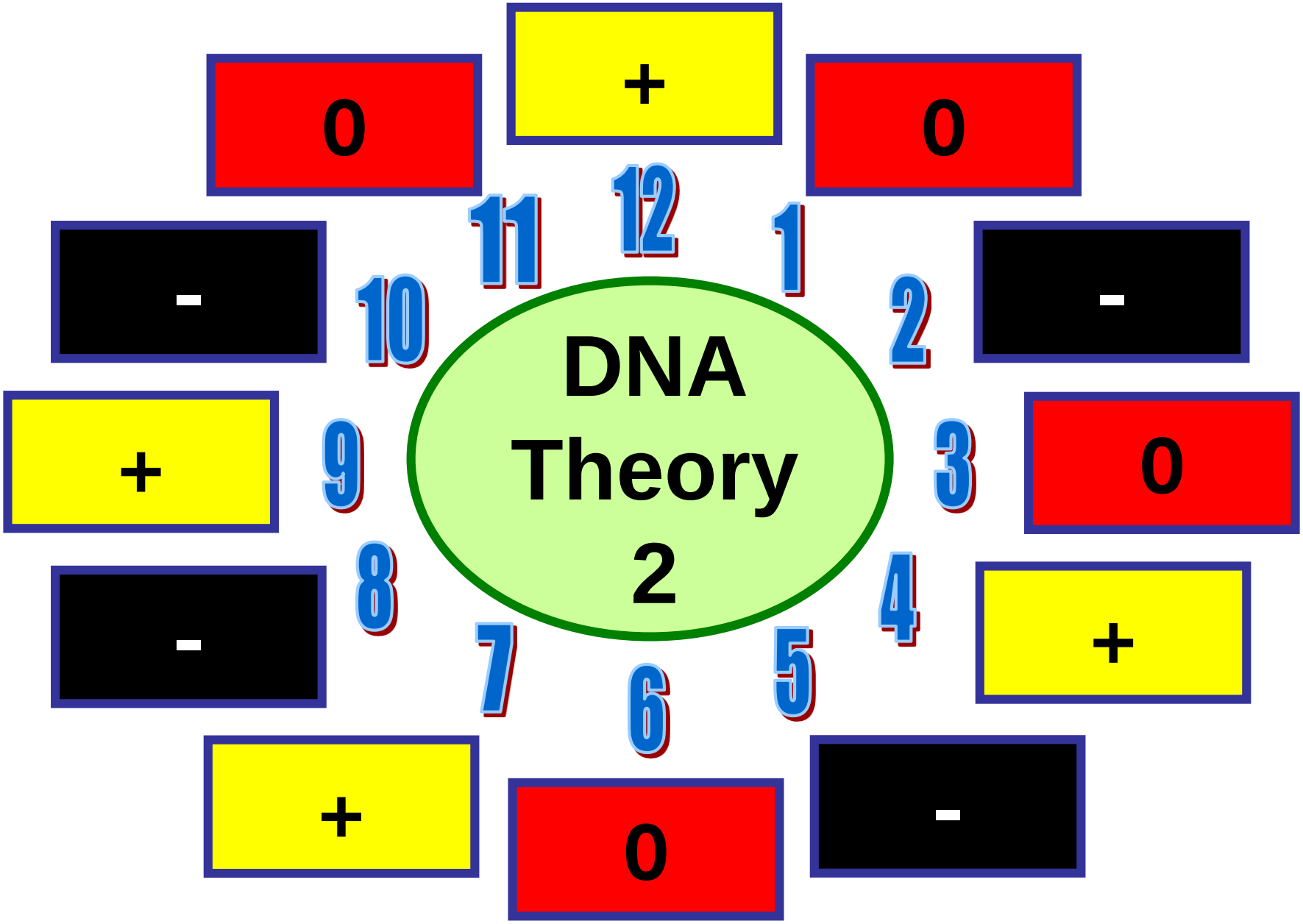
+	0	-
Increase of Br	No Br	Decrease of Br

2013

relative

to the Standard Model


DNA
Theory
1
12
1
2
3
4
5
6
7
8
9
10
11
+
-
0
+
0
+
-
0
+
-
0
+
-


DNA
Theory
2
12
1
2
3
4
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6
7
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9
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+
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+
0
+
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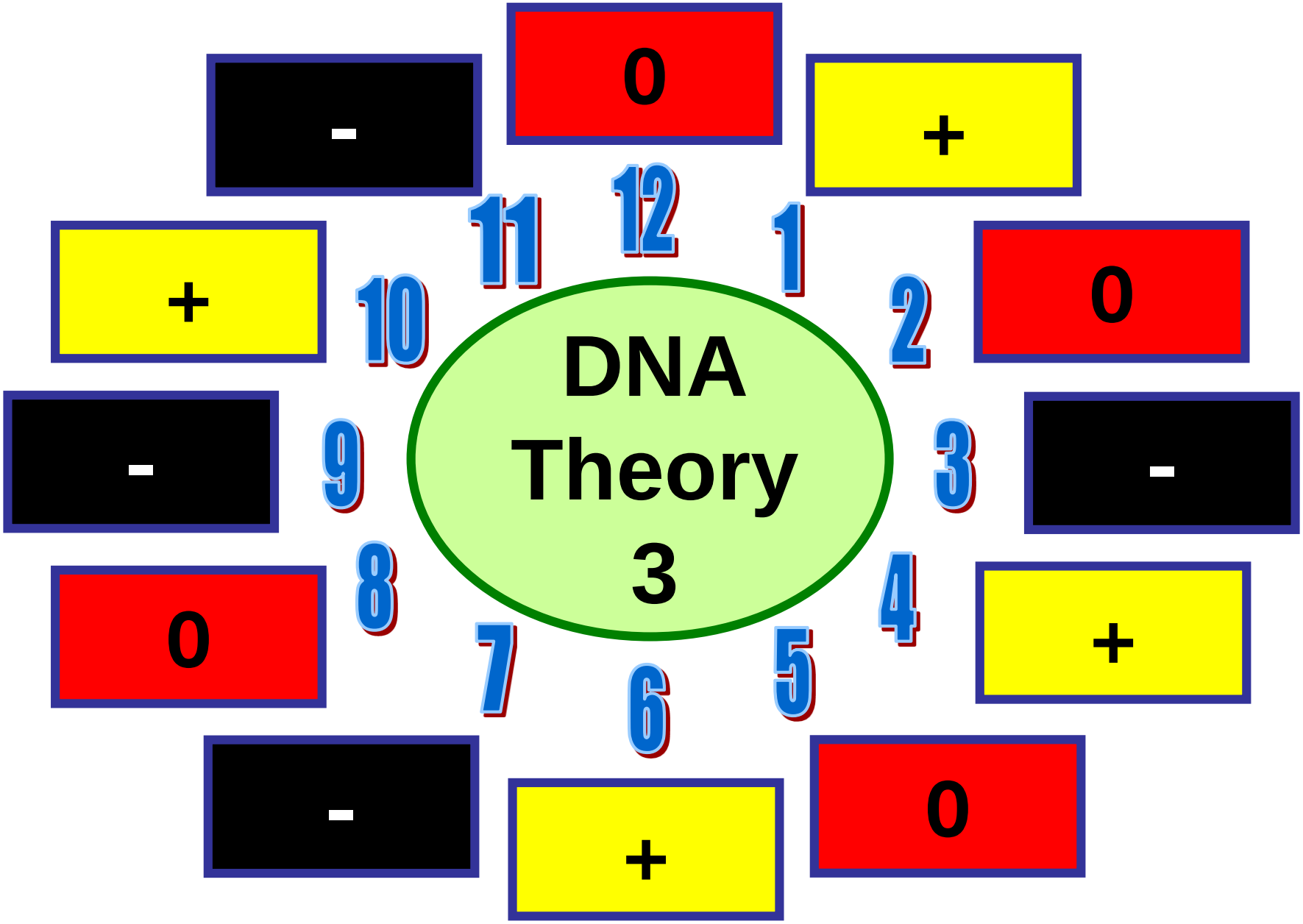
-
+
0
-


DNA
Theory
3
0
+
0
-
+
-
0
+
-
0
+
-
12
1
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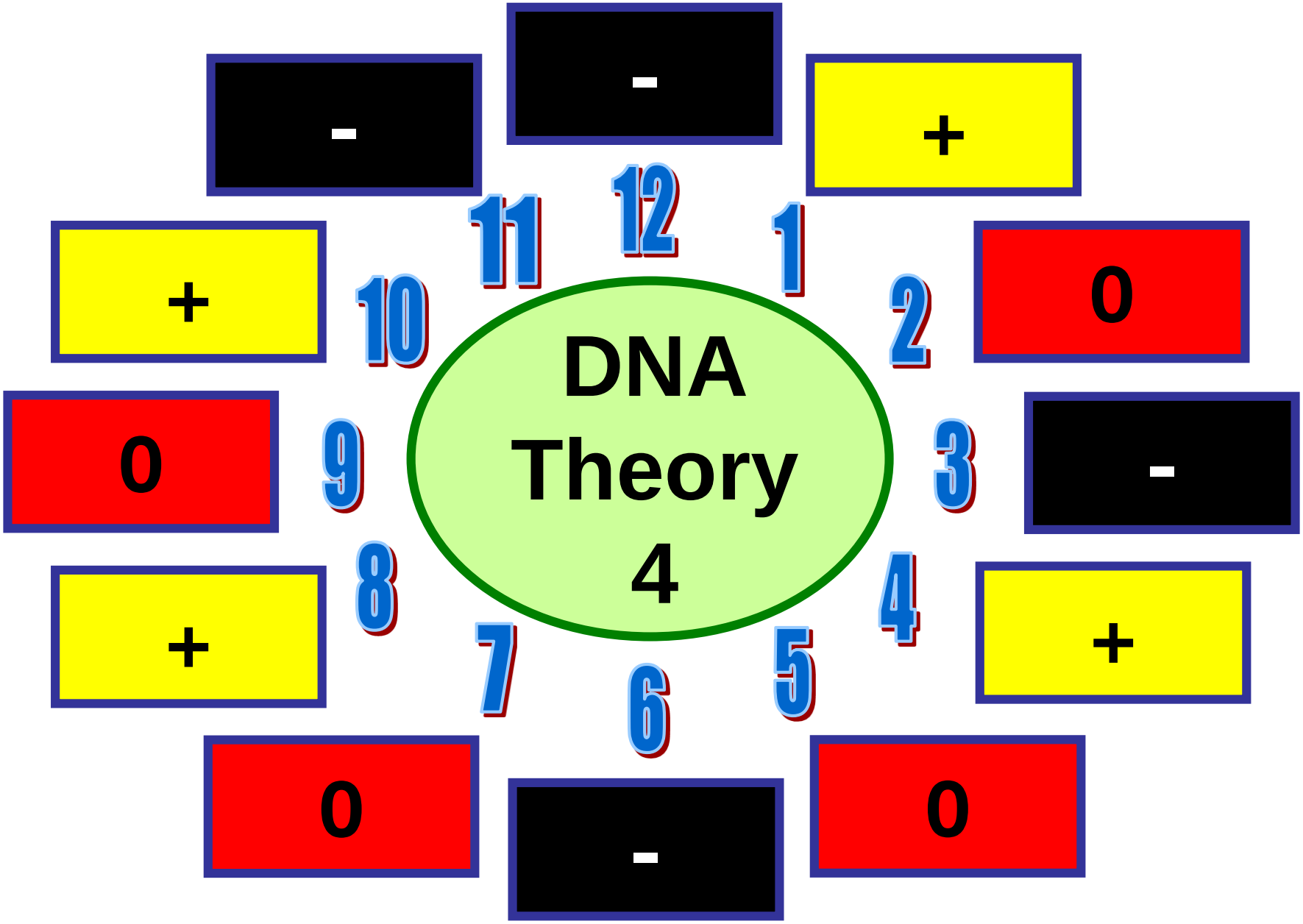
5
6
7
8
9
10
11


-
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11
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2
DNA
Theory
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9
3
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+
+
7
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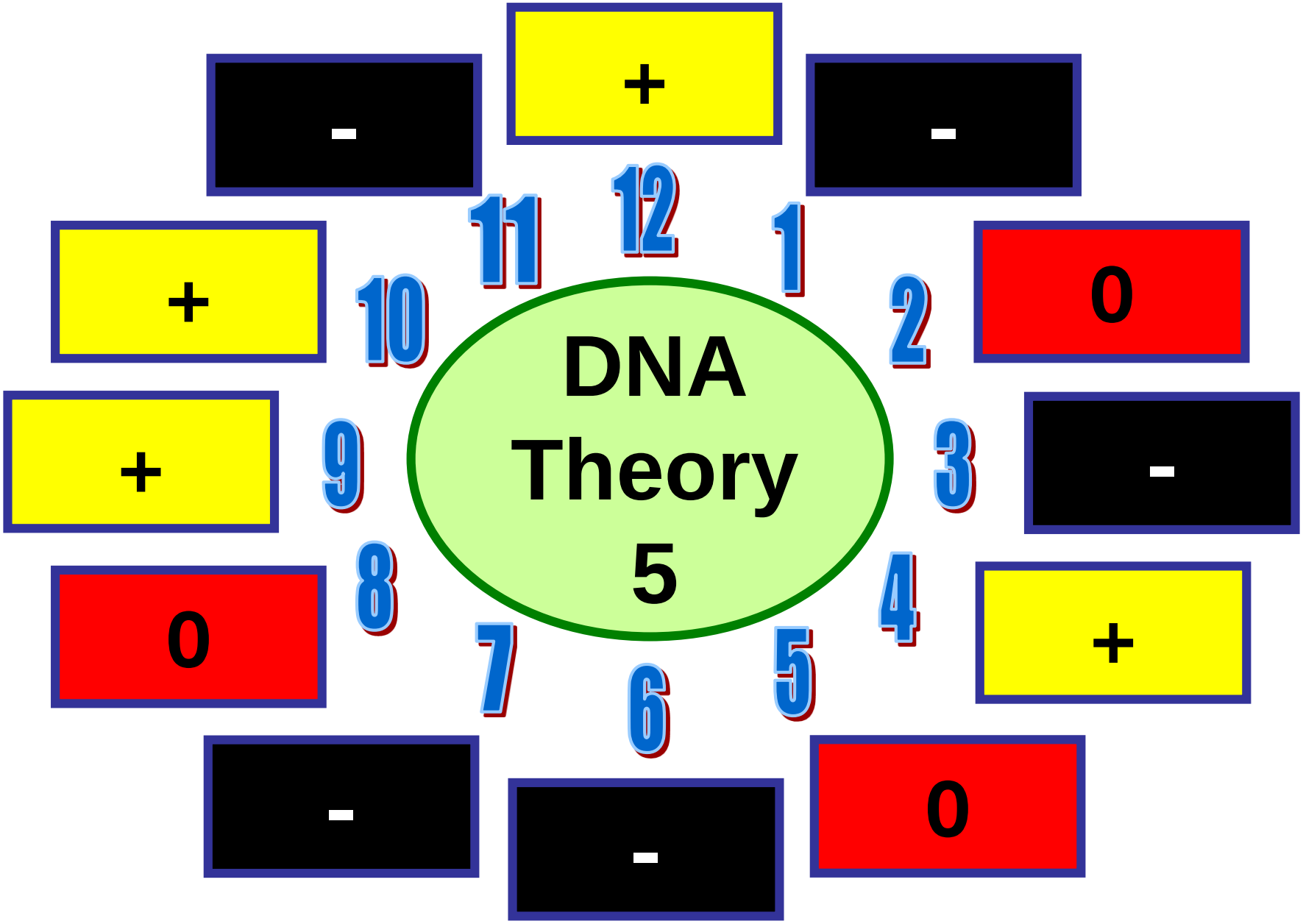
6
0
-
0


DNA
Theory
5
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+
-
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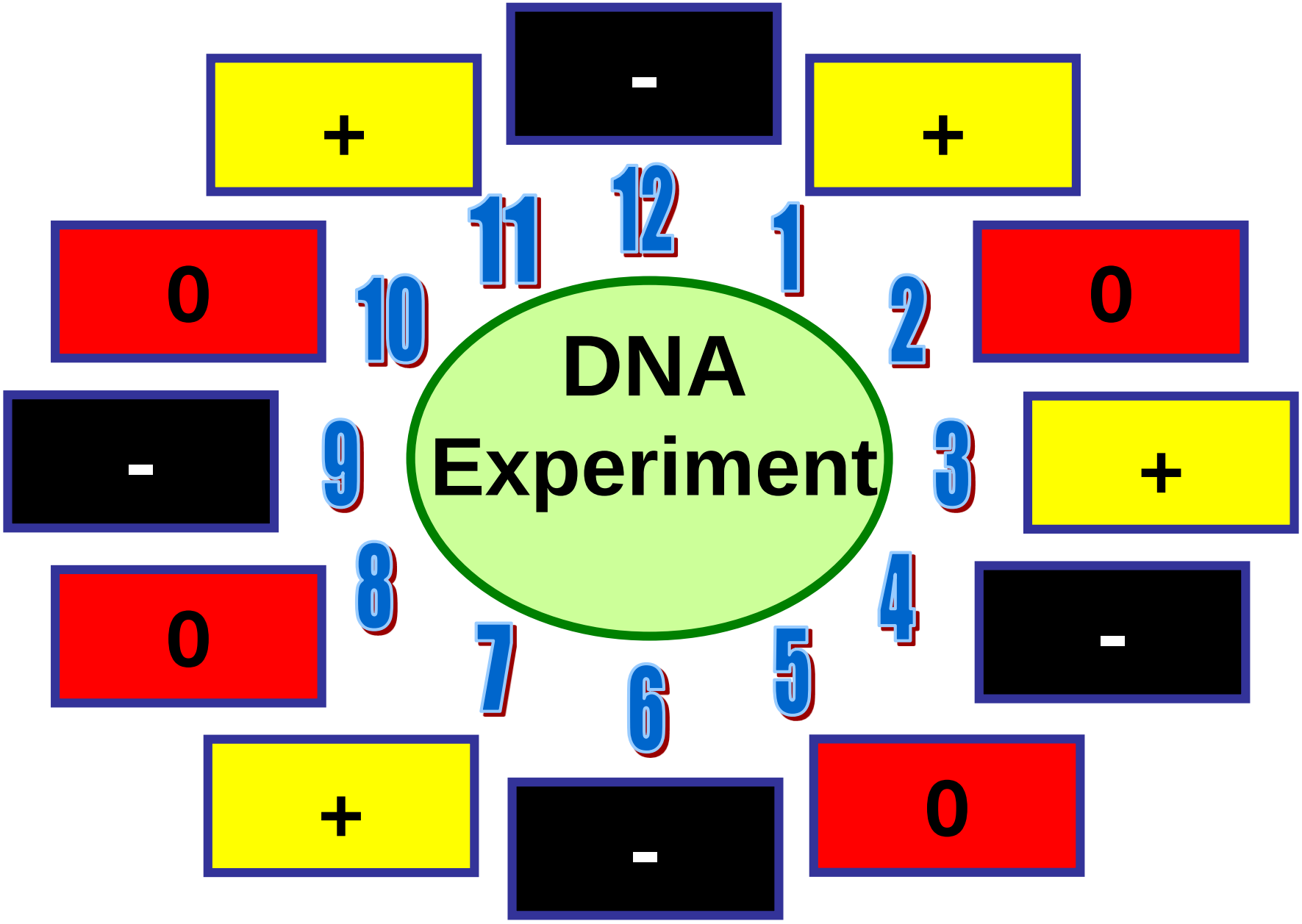
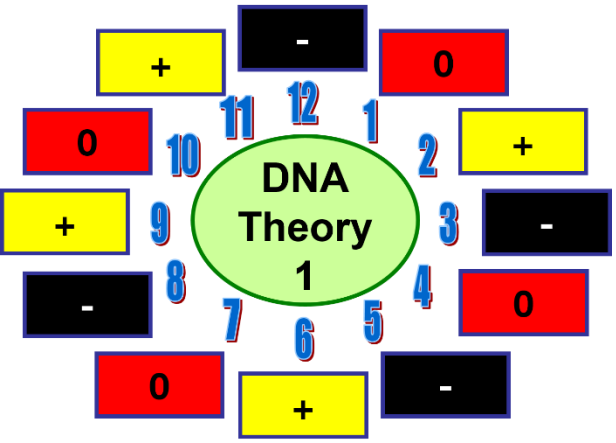
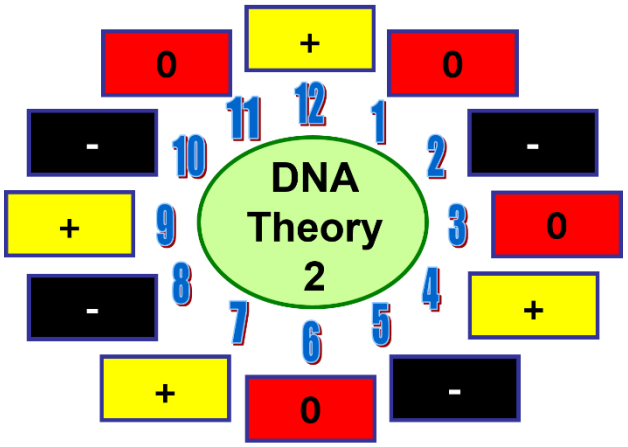
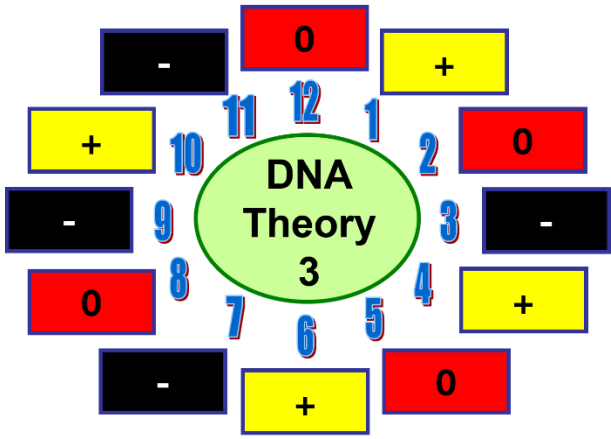
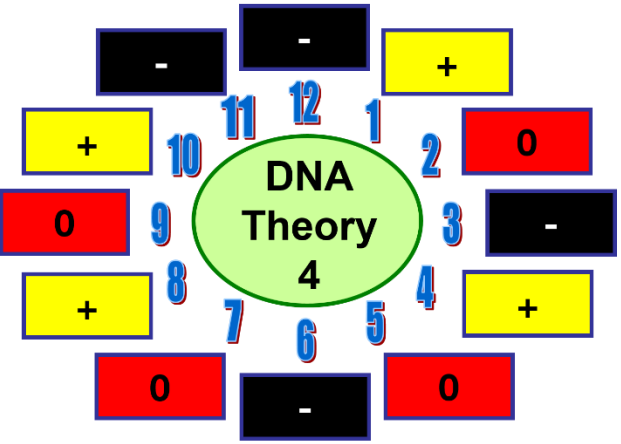
-
-
0
+

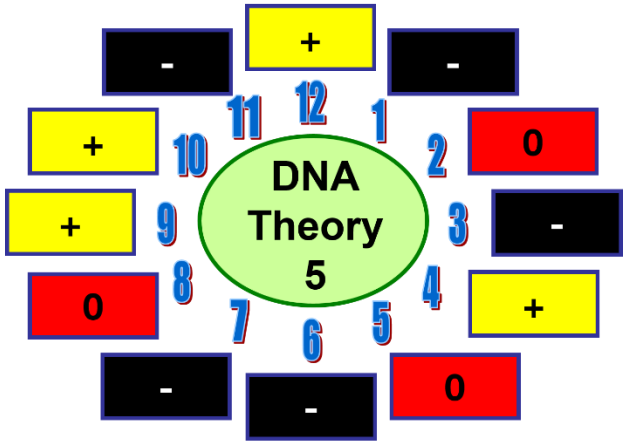

-
+
+
12
1
11
0
0
10
2
DNA
Experiment
-
9
3
+
8
4
0
-
7
5
6
+
-
0

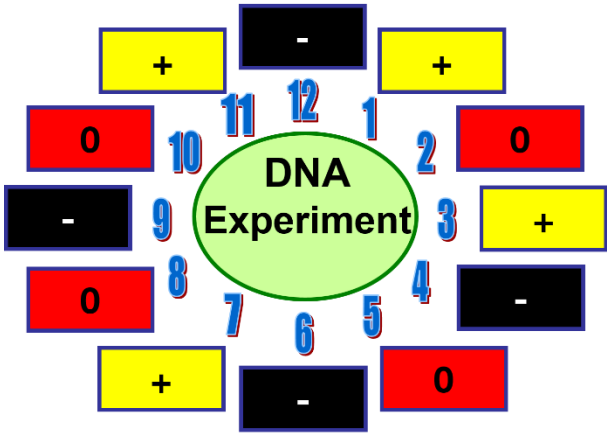

DNA
Theory
1


DNA
Theory
2

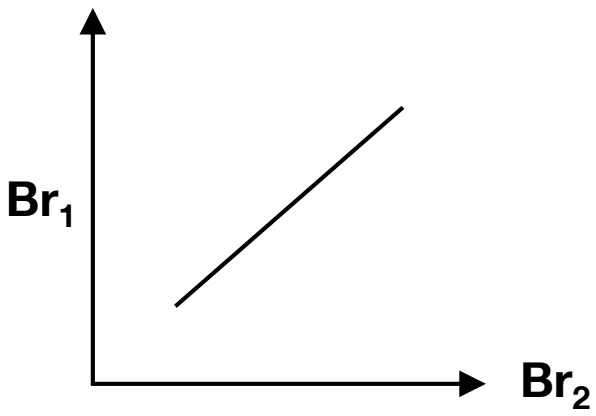

DNA
Theory
3

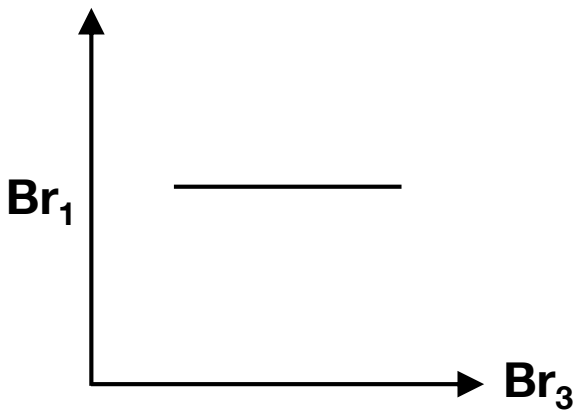

DNA
Theory
4

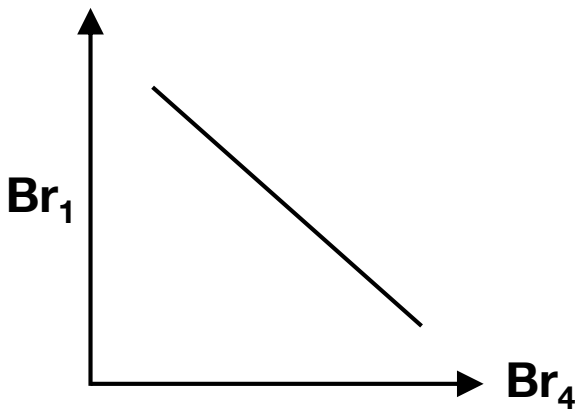

DNA
Theory
5


DNA
Experiment

Correlations and Anti-Correlations

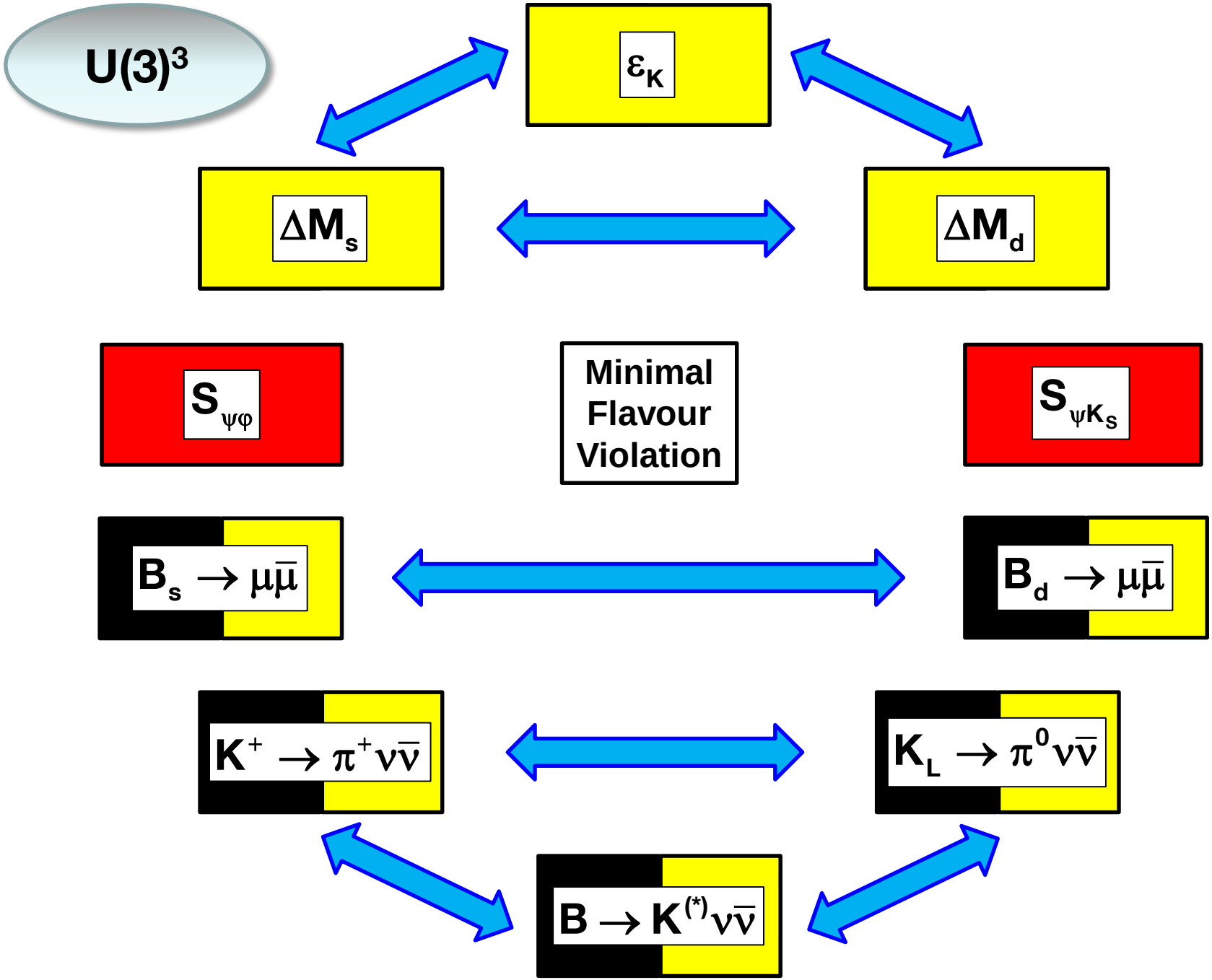


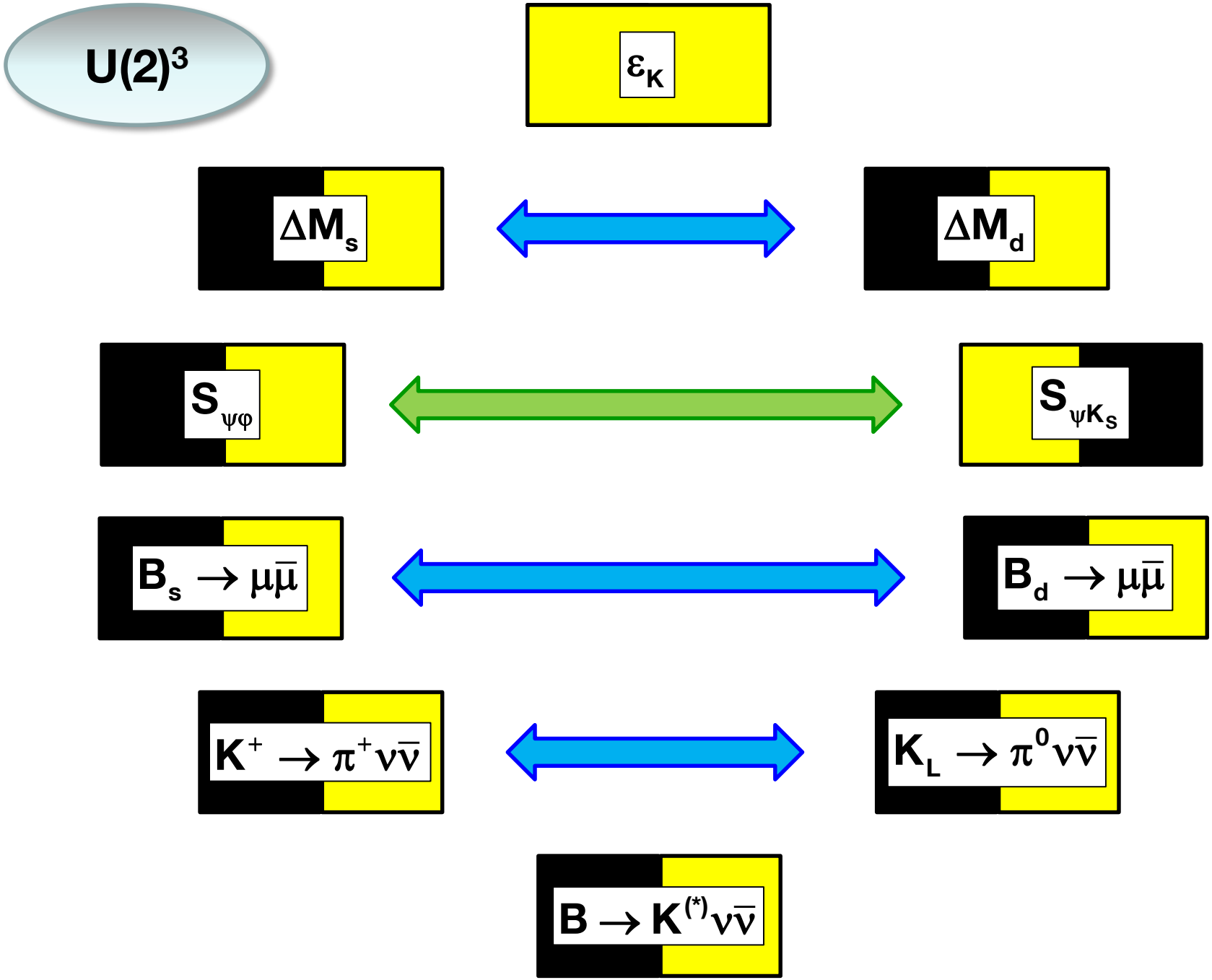


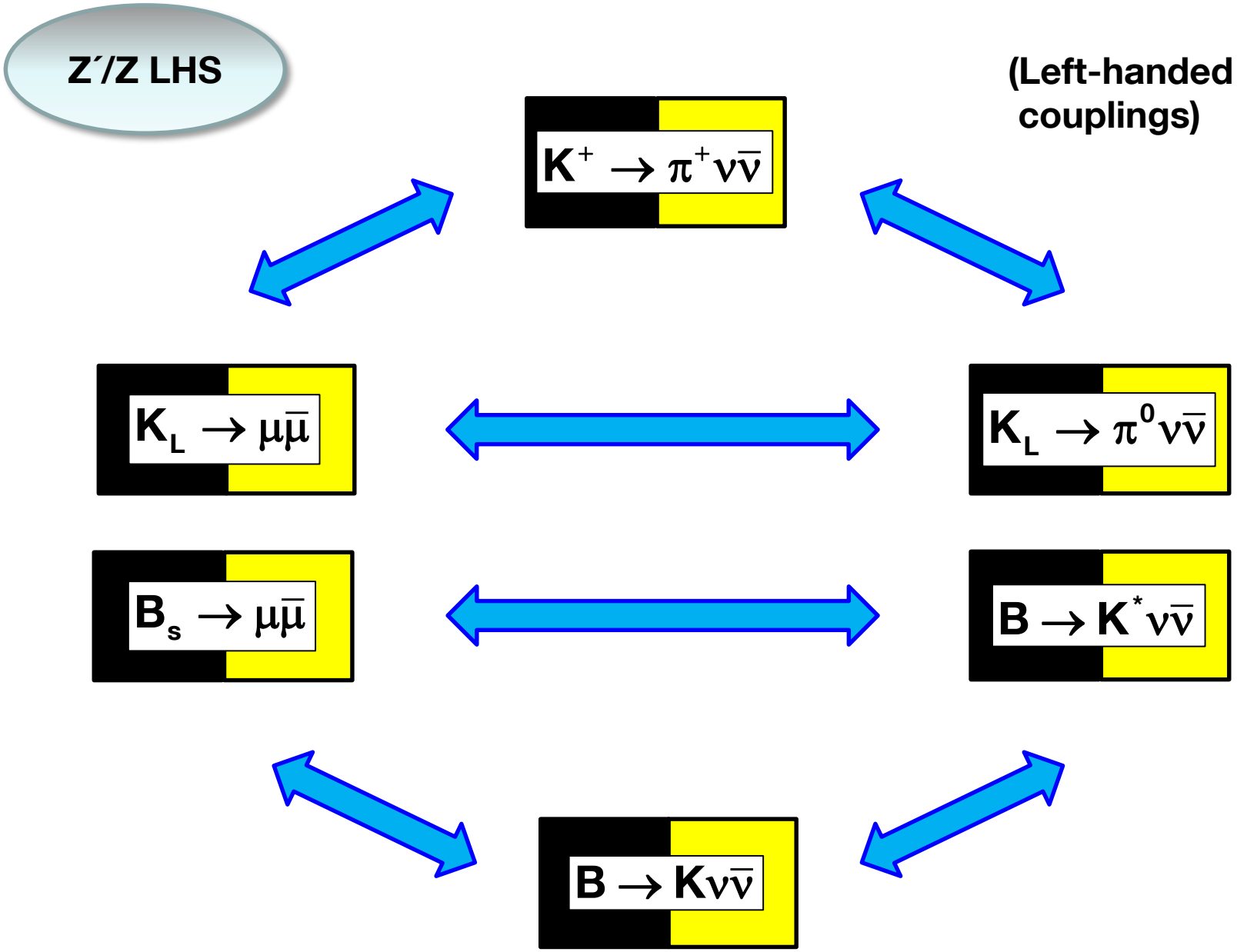


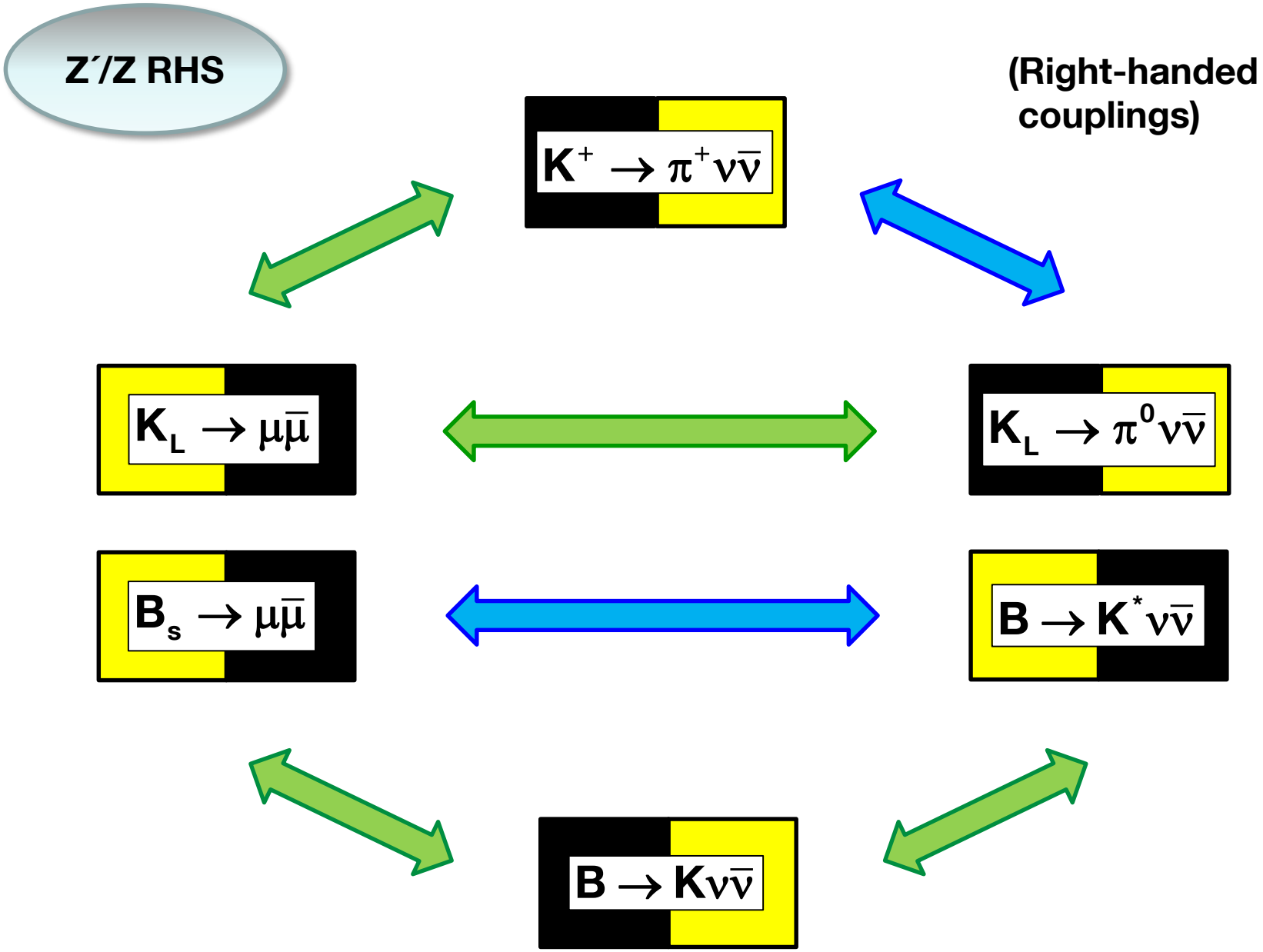
Correlation

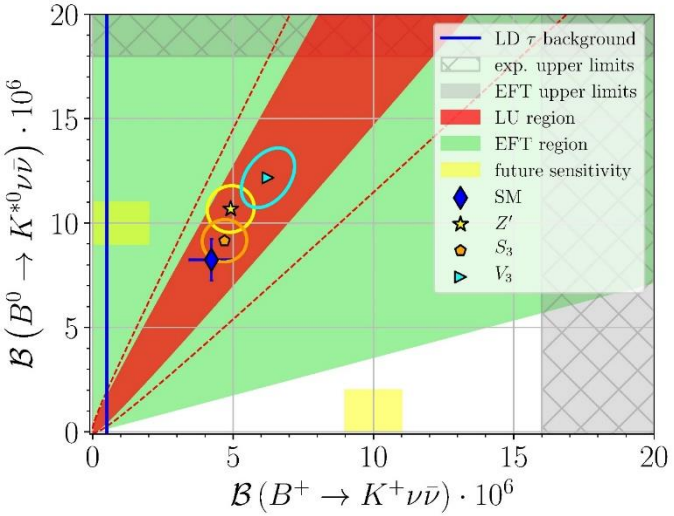
Anti-Correlation


U(3)3
εK
ΔMs
ΔMd
Sψφ
Minimal Flavour Violation
SψKS
Bs → μμ̄
Bd → μμ̄
K+ → π+νν̄
KL → π0νν̄
B → K(*)νν̄

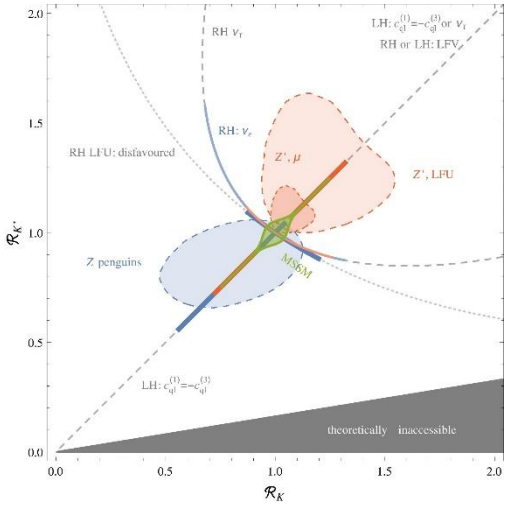

U(2)3
εK
ΔMs
ΔMd
Sψφ
SψKs
Bs → μμ̄
Bd → μμ̄
K+ → π+νν̄
KL → π0νν̄
B → K(*)νν̄


Z´/Z LHS
(Left-handed couplings)
$K^+ \to \pi^+ \nu\bar{\nu}$
$K_L \to \mu\bar{\mu}$
$K_L \to \pi^0 \nu\bar{\nu}$
$B_s \to \mu\bar{\mu}$
$B \to K^* \nu\bar{\nu}$
$B \to K \nu\bar{\nu}$

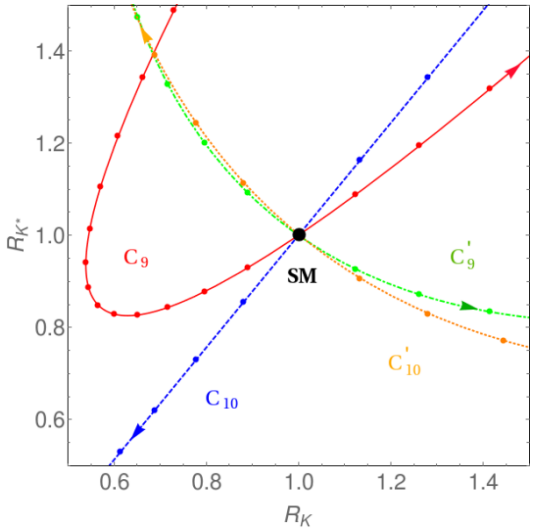

Z´/Z RHS
(Right-handed couplings)
$K^+ \to \pi^+ \nu\bar{\nu}$
$K_L \to \mu\bar{\mu}$
$K_L \to \pi^0 \nu\bar{\nu}$
$B_s \to \mu\bar{\mu}$
$B \to K^* \nu\bar{\nu}$
$B \to K\nu\bar{\nu}$



Bause, Gisbert, Goltz, Hiller
2109.01675

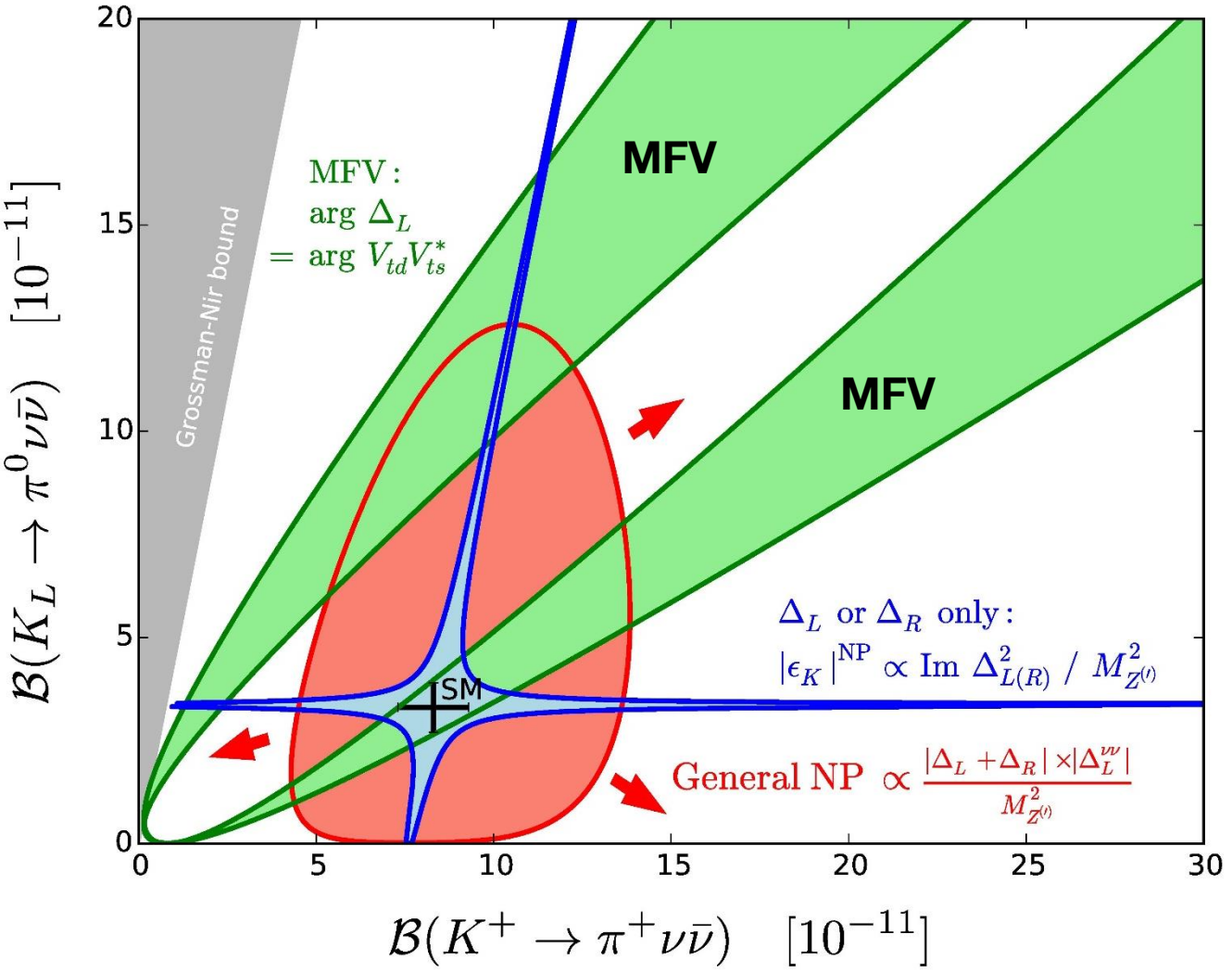


AJB, J. Girbach-Noe, C. Niehoff, D. Straub 1409.4577



Geng, Grinstein, Jäger, Camalich, Ren, Shi
1704.05446

Buttazzo, AJB, Knegjens, 1507.08672



Monika Blanke

Based on the insights from Monika Blanke (0904.1545)

B Physics Anomalies

(2013 - 2020)

1.

$$R_{D^{(*)}} = \frac{Br\left(B \to D^{(*)}\tau\nu_\tau\right)}{Br\left(B \to D^{(*)}\mu\nu_\mu\right)} \qquad (3.1\sigma)$$

BaBar, LHCb, Belle

$$R(D) = 0.340(27)(13)_{syst} \qquad 0.293 \pm 0.008$$
$$R(D^*) = 0.295(11)(8)_{syst} \qquad 0.258 \pm 0.003$$

(Standard Model)

2.

$$R_K = \frac{Br\left(B \to K\mu\mu\right)}{Br\left(B \to Kee\right)} = 0.846(42)$$

(3.1σ)

LHCb

SM

$$R_{K^*} = 0.685 \pm \begin{matrix}0.113\\0.069\end{matrix} \pm 0.047$$

$R_K \approx 1.0 \pm 0.01$

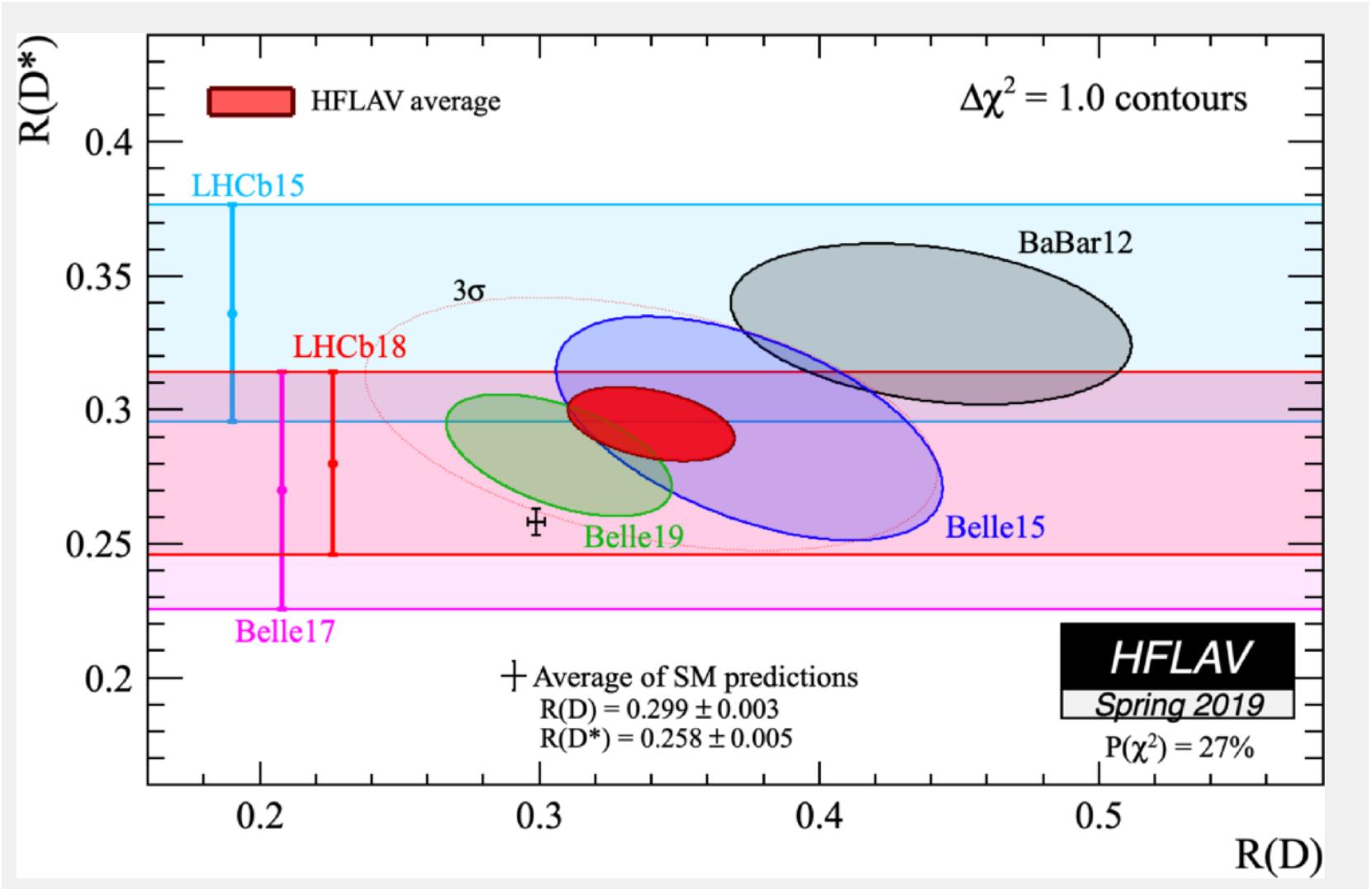
$R_{K^*} \approx 1.0$

3.

$$\frac{B \to K(K^*)\mu^+\mu^-}{\left(B \to \varphi\mu^+\mu^-\right)} \qquad (4.5\sigma)$$

(hadronic uncertainties)

P_5'


HFLAV average
$\Delta\chi^2 = 1.0$ contours
R(D*)
0.4
0.35
0.3
0.25
0.2
LHCb15
BaBar12
3σ
LHCb18
Belle19
Belle15
Belle17
Average of SM predictions
R(D) = 0.299 ± 0.003
R(D*) = 0.258 ± 0.005
HFLAV
Spring 2019
P(χ^2) = 27%
0.2
0.3
0.4
0.5
R(D)

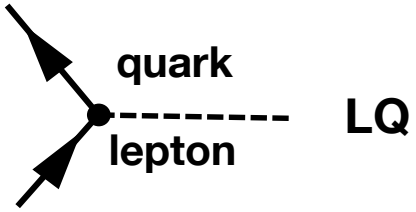
New Particles behind B-Physics Anomalies

Top candidates

Supersymmetry ?

Z´ boson : **heavy neutral gauge boson (Spin 1)** ★

Leptoquarks : **Spin 0 or Spin 1** ★
(provide interactions between quarks and leptons)



Vector-like quarks : **Left and right components transform identically under $SU(2)_L$** ★

Other Anomalies

Anomalous Magnetic Moment of the muon

(Since 2000)

$$a_\mu = \left(\frac{1}{2}\right)(g-2)_\mu$$

$$a_\mu^{exp} - a_\mu^{th} = (25.1 \pm 5.9)\cdot 10^{-10}$$

$$4.2\ \sigma$$

Brookhaven (2000) Fermilab (2021)

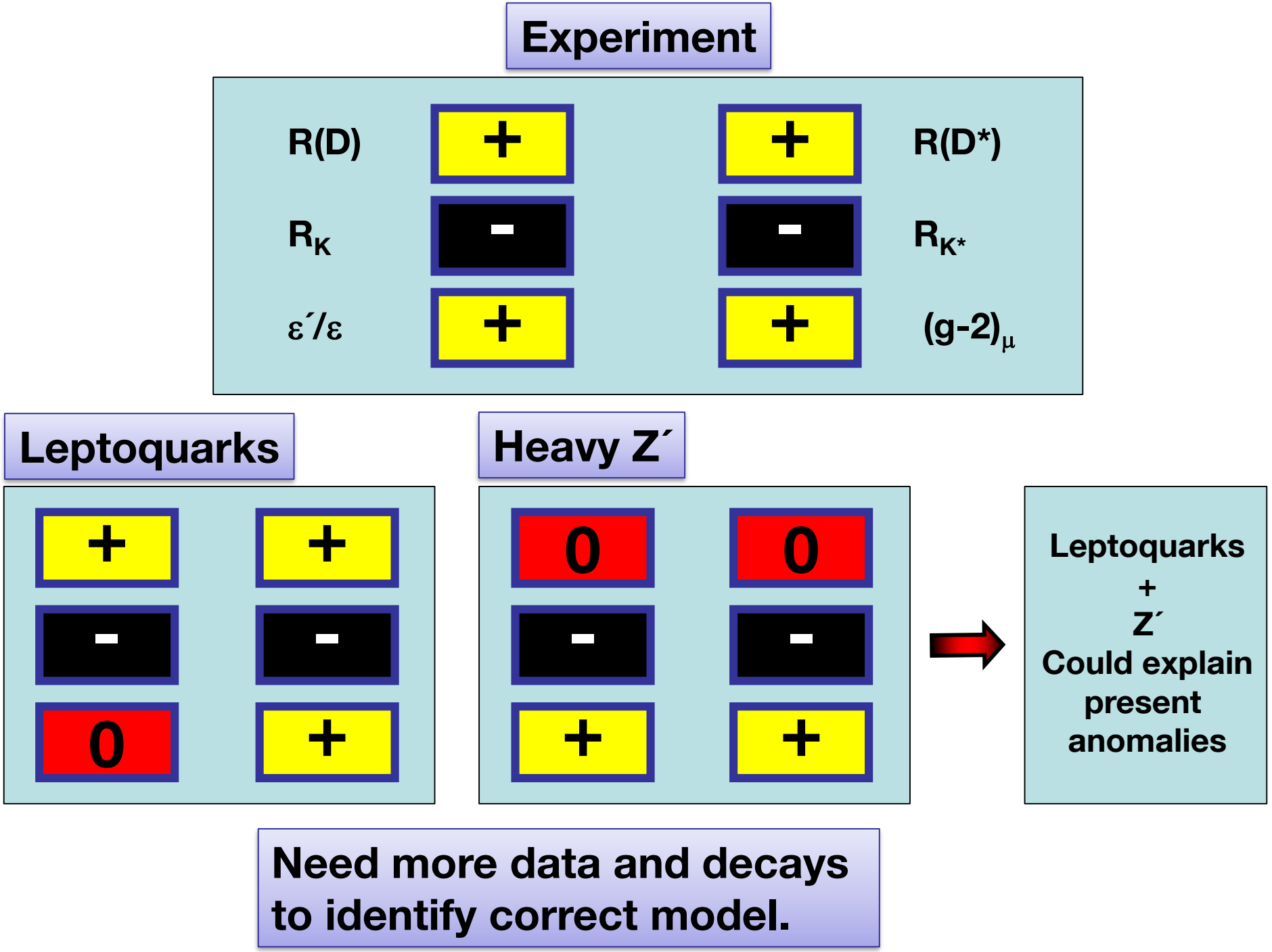
Yet also anomaly in CP-violation in K-physics (ε'/ε)

ε' = CP-violation in Decay $(K_L \to \pi\pi)$ (2000)

ε = CP-violation in $K^0 - \bar{K}^0$ Mixing (1964)

$\varepsilon \sim 2\cdot 10^{-3}$ (ok in SM)

Discovery


Experiment
R(D)
+
+
R(D*)
R_K
-
-
R_{K^*}
ε´/ε
+
+
$(g-2)_\mu$
Leptoquarks
+
+
-
-
0
+
Heavy Z´
0
0
-
-
+
+
Leptoquarks
+
Z´
Could explain
present
anomalies
Need more data and decays
to identify correct model.

Most Popular Models

LQs

Sophie A. Renner

S_1+S_3	Yan, Yang, Yuan Buttazzo, Greljo, Isidori, Marzocca Crivellin, Müller, Ota Gherardi, Marzocca, Venturini Marzocca, Trafinopoulos, Venturini
S_3+R_2	Becirevic, Drosner, Fajfer
U_1	Buttazzo, Greljo, Isidori, Marzocca Bhattacharya, London, ...

Pati-Salam SU(4)

Di Luzio, Fuentes-Martin, Greljo, Nardecchia, Renner
Cornella, Fuentes-Martin, Isidori

ε'/ε

Bobeth + AJB (except for U_1(?) LQs cannot explain possible anomaly)

Review of LQs, VLQs, Z´ models, ... See chapters 15 and 16
AJB: "Gauge Theory of Weak Decays"

3rd Movement

Searching for New Physics in Rare B and K Decays without $|V_{cb}|$ and $|V_{ub}|$ Uncertainties

$|V_{cb}|$ and $|V_{ub}|$ Tensions

$$|V_{cb}|_{\text{inclusive}} = (42.16 \pm 0.50) \cdot 10^{-3}$$

Bordone, Capdevilla, Gambino (2107.00604) (see Keri Voss, Portoroz)

$$|V_{cb}|_{\text{exclusive}} = (39.09 \pm 0.68) \cdot 10^{-3}$$

(FLAG) (1902.0819)

(see also Bordone, Gubernari, van Dyk, Jung (1912.09335)

$$|V_{ub}|_{\text{inclusive}} = (4.10 \pm 0.28) \cdot 10^{-3}$$

(Belle 2021) (larger values before 2010)

$$|V_{ub}|_{\text{exclusive}} = (3.73 \pm 0.14) \cdot 10^{-3}$$

(FLAG)

$$|V_{ub}|_{\text{exclusive}} = (3.77 \pm 0.15) \cdot 10^{-3}$$

(Light-cone Sum Rules) Leljak, Melic, van Dyk (2102.07233)

$|V_{cb}|$ and $|V_{ub}|$ Tensions are a disaster for those who spent decades to calculate NLO and NNLO QCD Corrections to basically all important rare K and B decays.

Achieving the reduction of TH uncertainties to 1% - 2% level.

Similar disaster for Lattice QCD which for ΔM_s, ΔM_d, ε_K and weak decay constants achieved accuracy below 5%. Moreover experimental data are very precise for them.

Note: Changing $|V_{cb}|$: $\boxed{39 \cdot 10^{-3} \Rightarrow 42 \cdot 10^{-3}}$

changes $|V_{cb}|^2$: by 16% $\left(B_{s,d} \to \mu^+\mu^-,\ \Delta M_{s,d}\right)$

$|V_{cb}|^3$: by 25% $\left(K^+ \to \pi^+ \nu\bar{\nu}, \varepsilon_K\right)$

$|V_{cb}|^4$: by 35% $\left(K_L \to \pi^0 \nu\bar{\nu}, K_S \to \mu^+\mu^-\right)$

(2003)

$$R_{q\mu} \equiv \frac{\bar{B}r\left(B_q \to \mu^+\mu^-\right)}{\Delta M_q} = C\,\frac{\tau_{B_q}}{\hat{B}_q}\left[F\left(x_t\right)\right]$$

(q=d,s)

Numerical Constant

Known with NLO QCD

AJB 0303060

a) $|V_{cb}|^2$ dependence (in fact all CKM dependence) cancels out.

b) $F_{B_q}^2$ dependence cancels out.

c) $\hat{B}_q$ enter linearly, are already precisely known (LQCD) and do not depend on NP!

$$\left[R_{s\mu}\right]_{SM} = \left(2.04^{+0.08}_{-0.06}\right)\cdot 10^{-10}\,\text{ps}$$

(2104.095219) C. Bobeth + AJB

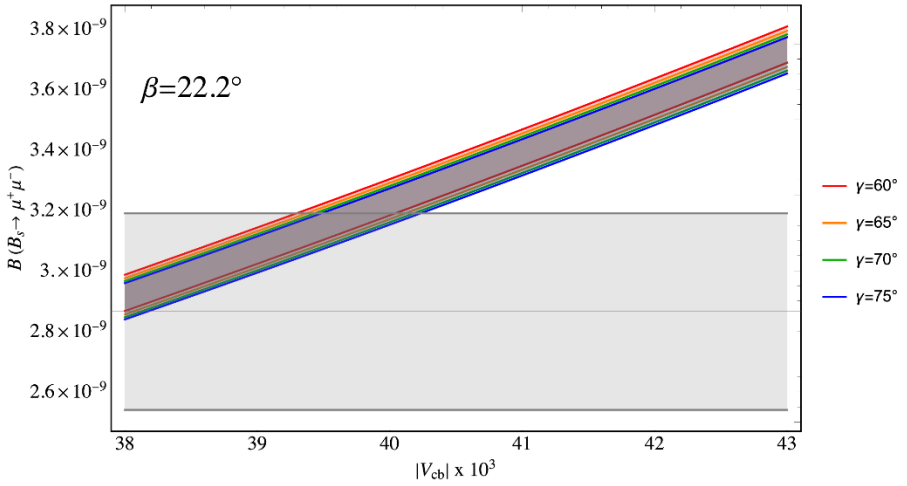
$$\left[R_{s\mu}\right]_{exp} = \left(1.61^{+0.19}_{-0.17}\right)\cdot 10^{-10}\,\text{ps}$$

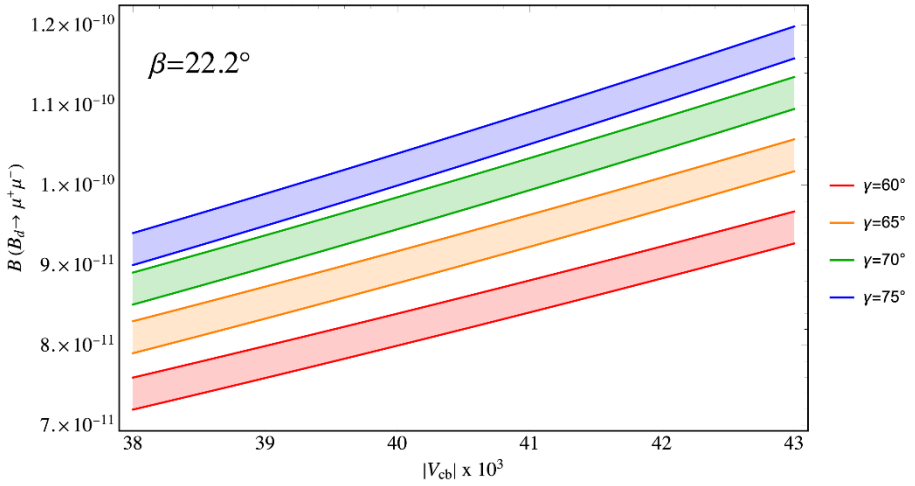
(2.1 σ tension)
(Independent of CKM parameters!!)

$$Br\left(B_{s,d} \to \mu^+\mu^-\right)_{SM} = F\left(\beta, \gamma, V_{cb}\right)$$

AJB + E. Venturini (2109.11032)

$$|V_{ub}| = \lambda |V_{cb}| \frac{\sin\beta}{\left(1 - \lambda \frac{2}{2}\right)}$$





$$\bar{Br}\left(B_s \to \mu^+\mu^-\right)_{exp} = \left(2.85^{+0.34}_{-0.31}\right) \cdot 10^{-9}$$

LHCb
CMS
ATLAS

Averages from: 2103.12738, 2103.13370, 2104.10058

$$\bar{Br}\left(B_s \to \mu^+\mu^-\right)_{SM} = \left(3.62^{+0.15}_{-0.10}\right) \cdot 10^{-9}$$

CKM Independent !

Basic Strategy for Rare B and K Decays

AJB + E. Venturini (2109.11032)

1. Use as basic parameters

$$\lambda,\ |V_{cb}|,\ \beta,\ \gamma$$

2. Construct $|V_{cb}|$ independent Ratios R_i (β,γ)

3. 16 Ratios involving

$B_s \to \mu^+\mu^-,\ B_d \to \mu^+\mu^-$

$B^+ \to K^+\nu\bar{\nu},\ B^0 \to K^{0*}\nu\bar{\nu}$

$K^+ \to \pi^+\nu\bar{\nu},\ K_L \to \pi^0\nu\bar{\nu},\ K_s \to \mu^+\mu^-$

$|\varepsilon_K|,\ \Delta M_d,\ \Delta M_s$

Once γ will be precisely measured very good test of SM

E. Venturini

"Critical Exponents" of Flavour Physics

AJB + Venturini (2109.11032) (All decays TH clean)

$$Br\left(K^+ \to \pi^+ \nu\bar{\nu}\right) \sim |V_{cb}|^{2.8} \left[\sin\gamma\right]^{1.4}$$

$$Br\left(K_L \to \pi^0 \nu\bar{\nu}\right) \sim |V_{cb}|^{4} \left[\sin\gamma\right]^{2} \left[\sin\beta\right]^{2}$$

$$Br\left(K_s \to \mu^+\mu^-\right)_{SD} \sim |V_{cb}|^{4} \left[\sin\gamma\right]^{2} \left[\sin\beta\right]^{2}$$

$$|\varepsilon_K| \sim |V_{cb}|^{3.4} \left[\sin\gamma\right]^{1.67} \left[\sin\beta\right]^{0.87}$$

$$Br\left(B_s \to \mu^+\mu^-\right) \sim |V_{cb}|^{2}$$

$$Br\left(B_d \to \mu^+\mu^-\right) \sim |V_{cb}|^{2} \left[\sin\gamma\right]^{2}$$

$$Br\left(B^+ \to K^+ \nu\bar{\nu}\right) \sim |V_{cb}|^{2}$$

$$Br\left(B^0 \to K^{0*} \nu\bar{\nu}\right) \sim |V_{cb}|^{2}$$

$$\Delta M_s \sim |V_{cb}|^{2}$$

$$\Delta M_d \sim |V_{cb}|^{2} \left[\sin\gamma\right]^{2}$$

In contrast to B→K(K*)$\mu^+\mu^-$
Basically no hadronic uncertainties
Isidori et al. 2110.09882
Ciuchini et al. 2110.10126

$$S_{\psi K_s} = \sin 2\beta$$

$|V_{cb}|$ Independent Ratios in the SM

AJB + E. Venturini

$$R_1(\beta,\gamma) = \frac{Br\left(K^+ \to \pi^+ \nu\bar{\nu}\right)}{\left[\bar{Br}\left(B_s \to \mu^+\mu^-\right)\right]^{1.4}} = C_1 \left(\sin\gamma\right)^{1.4} \left(F_{B_s}\right)^{-2.8}$$

$$R_2(\beta,\gamma) = \frac{Br\left(K^+ \to \pi^+ \nu\bar{\nu}\right)}{\left[Br\left(B_d \to \mu^+\mu^-\right)\right]^{1.4}} = C_2 \left(\sin\gamma\right)^{-1.4} \left(F_{B_d}\right)^{-2.8}$$

$$R_3(\beta,\gamma) = \frac{Br\left(K_L \to \pi^0 \nu\bar{\nu}\right)}{\left[\bar{Br}\left(B_s \to \mu^+\mu^-\right)\right]^{2}} = C_3 \left[\sin\beta \sin\gamma\right]^2 \left(F_{B_s}\right)^{-4}$$

$$R_4(\beta,\gamma) = \frac{Br\left(K_L \to \pi^0 \nu\bar{\nu}\right)}{\left[\bar{Br}\left(B_d \to \mu^+\mu^-\right)\right]^{2}} = C_4 \left[\frac{\sin\beta}{\sin\gamma}\right]^2 \left(F_{B_d}\right)^{-4}$$

Important V_{cb} – Independent Formulae

AJB + E. Venturini (2109.11032)

$$\frac{Br\left(K^+ \to \pi^+ \nu\bar{\nu}\right)}{\left|\varepsilon_K\right|^{0.82}} = \left(1.31 \pm 0.05\right) \cdot 10^{-8} \left[\frac{\sin 22.2}{\sin\beta}\right]^{0.71} \left[\frac{\sin\gamma}{\sin 67°}\right]^{0.015}$$

$$\frac{Br\left(K_L \to \pi^0 \nu\bar{\nu}\right)}{\left|\varepsilon_K\right|^{1.18}} = \left(3.87 \pm 0.06\right) \cdot 10^{-8} \left[\frac{\sin\beta}{\sin 22.2}\right]^{0.98} \left[\frac{\sin\gamma}{\sin 67°}\right]^{0.030}$$

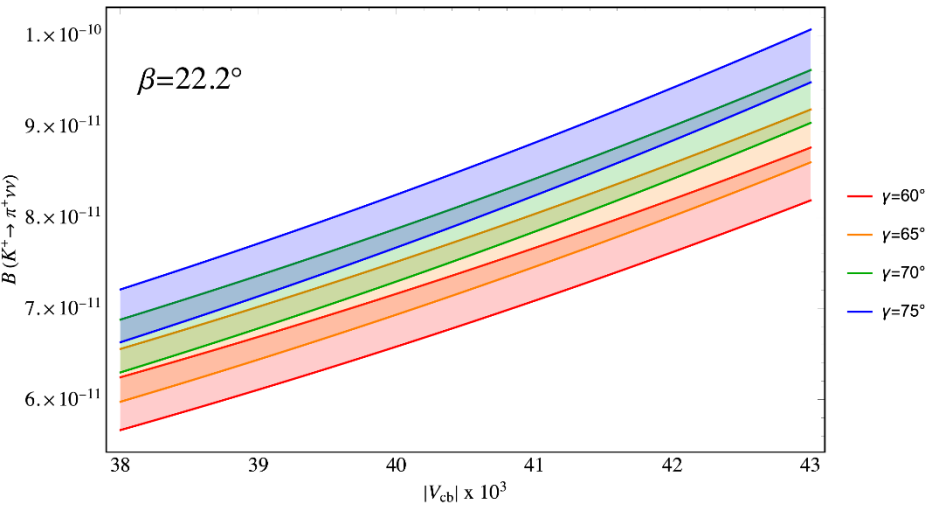
Note: practically γ-independent

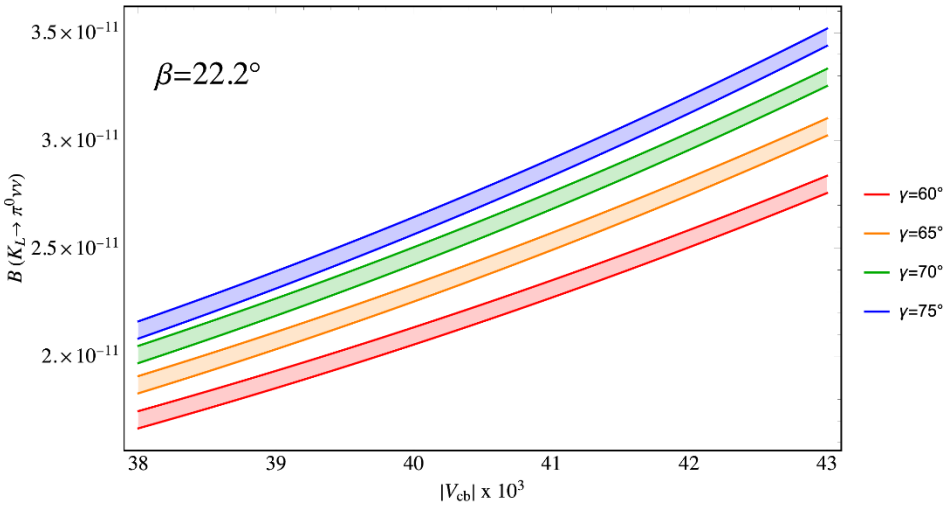
$$\left\{\left|\varepsilon_K\right|_{exp}, S^{exp}_{\psi K_s} = \sin 2\beta\right\} \Rightarrow \left\{\begin{array}{l}\text{Most accurate}\\ \text{Predictions to}\\ \text{date}\end{array}\right\}$$

Important reduction of TH uncertainties in ε_K
(Brod, Gorbahn, Stamou, 1911.06822)

$Br\left(K^+ \to \mu^+ \nu\bar{\nu}\right)_{SM}$ and $Br\left(K_L \to \pi^0 \nu\bar{\nu}\right)_{SM}$

AJB + E. Venturini (2109.11032)





$$Br\left(K^+ \to \pi^+ \nu\bar{\nu}\right)_{exp} = \left(10.6^{+4.0}_{-3.5}\right) \cdot 10^{-11}$$

NA62

$$Br\left(K_L \to \pi^0 \nu\bar{\nu}\right)_{exp} \leq 3.0 \cdot 10^{-9}$$

KOTO

$$Br\left(K^+ \to \pi^+ \nu\bar{\nu}\right)_{SM} = \left(8.6 \pm 0.42\right) \cdot 10^{-11}$$

V_{cb} and γ independent

$$Br\left(K_L \to \pi^0 \nu\bar{\nu}\right)_{SM} = \left(2.94 \pm 0.15\right) \cdot 10^{-11}$$

Most Precise V_{cb} – Independent Estimates

(SM)

BV: 2109.11032

$$Br\left(K^+ \to \pi^+ \nu\bar{\nu}\right) = \left(8.62 \pm 0.42\right) \cdot 10^{-11}$$

$$Br\left(K_L \to \pi^0 \nu\bar{\nu}\right) = \left(2.94 \pm 0.15\right) \cdot 10^{-11}$$

Only β-dependent (γ-dependence very weak)

$$Br\left(B_s \to \mu^+\mu^-\right) = \left(3.62 \pm 0.12\right) \cdot 10^{-9}$$

$$Br\left(B_d \to \mu^+\mu^-\right) = \left(0.99 \pm 0.04\right) \cdot 10^{-10}$$

CKM-independent

(use $\Delta M_{s,d}$)

Based on ε_K, $S_{\psi K_s}$, ΔM_s, ΔM_d

Supersede the usual quoted values (with $V_{cb} \approx (V_{cb})_{incl}$)

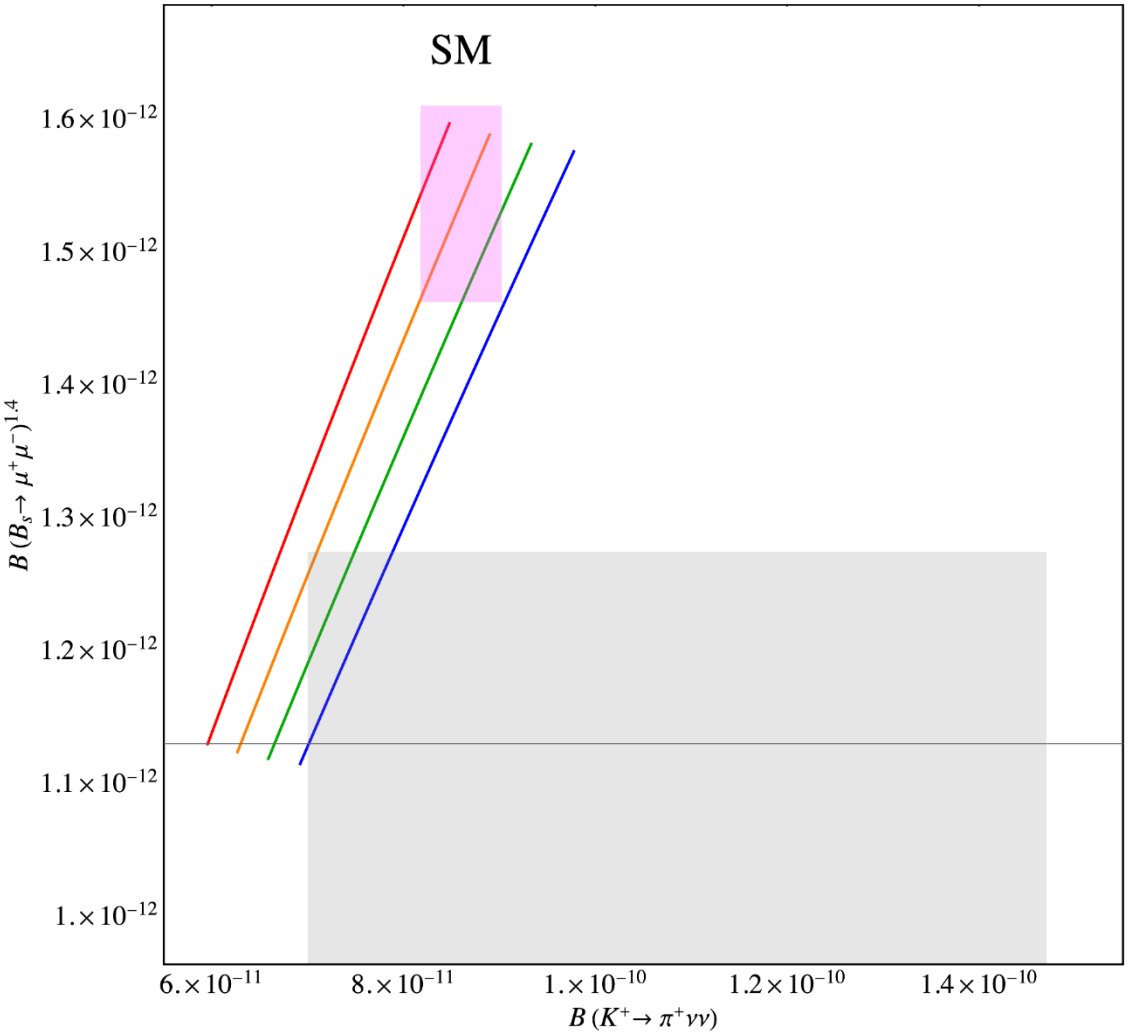
$$Br\left(K^+\right) = \left(8.4 \pm 1.0\right) \cdot 10^{-11} \qquad Br\left(K_L\right) = \left(3.4 \pm 0.6\right) \cdot 10^{-11} \quad \left(1503.02693\right)$$

$$Br\left(B_s\right) = \left(3.66 \pm 0.14\right) \cdot 10^{-9} \qquad Br\left(B_s\right) = \left(1.03 \pm 0.05\right) \cdot 10^{-10}$$

(Bobeth et al.)

$\left[\mathrm{Br}\left(B_s \to \mu^+\mu^-\right)\right]^{1.4}$ vs $\mathrm{Br}\left(K^+ \to \pi^+\nu\bar{\nu}\right)$

AJB + E. Venturini (2109.11032)



SM: independent of V_{cb} and γ

Interesting for LHCb, Belle II, NA62

$|V_{cb}|$ from ε_K, ΔM_s, ΔM_d (SM)

AJB + E. Venturini (2109.11032)

$$\varepsilon_K \Rightarrow |V_{cb}| = F_1(\beta,\gamma) \qquad \left(\hat{B}_K\right)$$

$$\Delta M_s \Rightarrow |V_{cb}| \approx \beta \text{ and } \gamma \text{ independent} \qquad \left(\sqrt{\hat{B}_s} F_{B_s}\right)$$

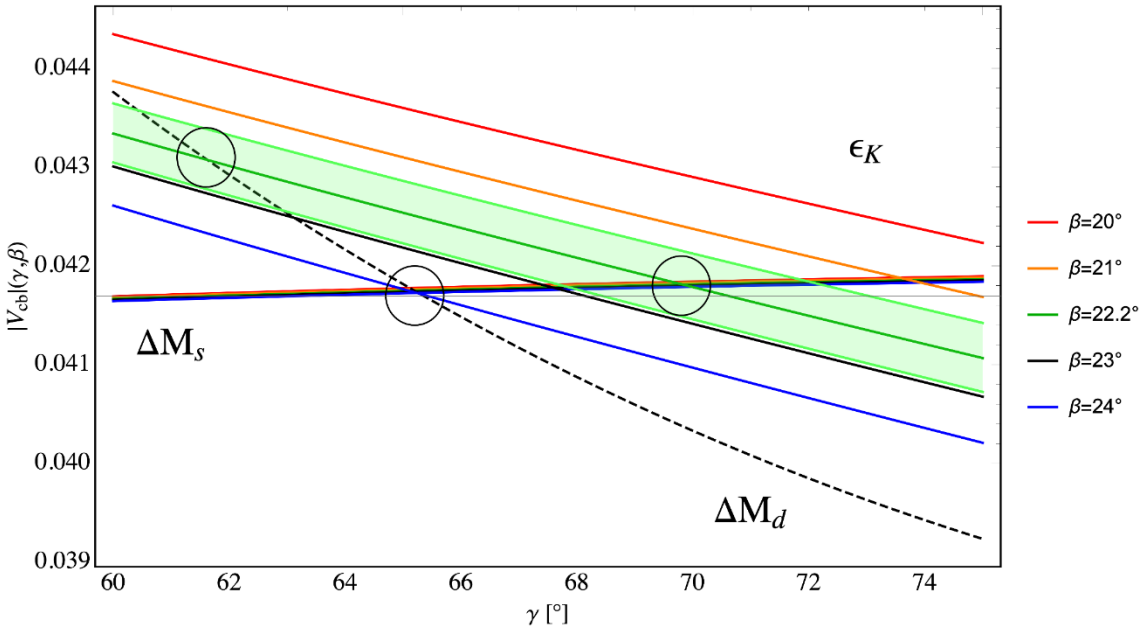
$$\Delta M_d \Rightarrow |V_{cb}| = F_3(\gamma) \qquad \left(\sqrt{\hat{B}_d} F_{B_d}\right)$$

$$R_9(\beta,\gamma) = \frac{|\varepsilon_K|}{(\Delta M_d)^{1.7}}$$

$$R_{10}(\beta,\gamma) = \frac{|\varepsilon_K|}{(\Delta M_s)^{1.7}}$$

The only existing FCNC processes in which TH and EXP uncertainties are very small (except $B \to X_s\gamma$)

Tensions



$$\left\{\varepsilon_K,\ \Delta M_s,\ \Delta M_d\right\} \Rightarrow \left\{\beta = 24.1(14)^\circ,\ \gamma = 65.2(28)^\circ,\ |V_{cb}| = 41.6(6)\cdot 10^{-3}\right\}$$

$$\left\{S_{\psi K_s},\ \varepsilon_K,\ \Delta M_d\right\} \Rightarrow \left\{\beta = 22.2(7)^\circ,\ \gamma = 61.3(16)^\circ,\ |V_{cb}| = 43.1(10)\cdot 10^{-3}\right\}$$

$$\left\{S_{\psi K_s},\ \varepsilon_K,\ \Delta M_s\right\} \Rightarrow \left\{\beta = 22.2(7)^\circ,\ \gamma = 70.3(26)^\circ,\ |V_{cb}| = 41.7(6)\cdot 10^{-3}\right\}$$

$$\left\{\Delta M_s,\ S_{\psi K_s}\right\} \Rightarrow \boxed{|V_{cb}| = 41.7(6)\cdot 10^{-3},\ |V_{ub}| = 3.64(12)\cdot 10^{-3}}$$

alone !!

4th Movement Flavour Messages and Shopping List

Violation of Lepton Flavour Universality although very interesting does not help us to explain our existence.

We have to search for new sources of CPV!

CP – Asymmetries in $B \to K^* \bar{l}l$

ΔA_{CP} (Charm)

$K_S \to \mu^+\mu^-$
$K_L \to \pi^0 \nu\bar{\nu}$

Bobeth, Hiller, Piranishuili 0805.2525

$B \to \pi K$

$K_L \to \pi\pi$
ε'/ε

Could provide distiction between various LQ, VLQ, Z´ models

Series of papers by R. Fleischer et al.

$\Delta I = 1/2$ Rule

$$R_{exp} = \frac{A\left(K \to (\pi\pi)_{I=0}\right)}{A\left(K \to (\pi\pi)_{I=2}\right)} = 22.4$$

Puzzle since
1954 (Gell-Mann + Pais)

$R_{th} = \sqrt{2}$ (without QCD)

1986, 2014: $R = 16 \pm 2$ — Dual QCD — Bardeen, AJB, Gérard

2020: $R = 19.19 \pm 4.8$ — RBC-UKQCD Lattice Collaboration

QCD dynamics dominate this rule
but New Physics could still contribute

AJB
F. de Fazio
J. Girrbach-Noe
(1404.3824)

Note: Relative to no QCD case must
enhance A_0 by 7.5
suppress A_2 by 2.1

Hep-arxiv: 2101.00020

ε'/ε Controversy

2015-2020

$$\left(\varepsilon'/\varepsilon\right)_{exp} = \left(16.6 \pm 2.3\right) \cdot 10^{-4}$$

(NA48, KTeV)

$$\left(\varepsilon'/\varepsilon\right)_{SM} = \left(14 \pm 5\right) \cdot 10^{-4}$$

Chiral Perturbation Theory
(Pich et al)

No Anomaly

$$\left(\varepsilon'/\varepsilon\right)_{SM} = \left(5 \pm 2\right) \cdot 10^{-4}$$

Hep-arxiv: 2101.00020

Insight from Dual QCD + NNLO QCD

(AJB + Gérard)

Anomaly

$$\left(\varepsilon'/\varepsilon\right)_{SM} = \left(21.7 \pm 8.4\right) \cdot 10^{-4}$$

RBC – UKQCD

No Anomaly

Good News on ε´/ε

ε´/ε = QCD Penguins – Electroweak Penguin

$$\left(\frac{\varepsilon'}{\varepsilon}\right)^{EWP}_{SM} = -(7 \pm 1)\cdot 10^{-4} \quad \text{(RBC – UKQCD and DQCD)}$$

Perfect Agreement!

Chiral Pert Th: $\approx (-3.5 \pm 2.0) \cdot 10^{-4}$

Disagreements on QCD Penguin contribution.

Anomalies in Kaon Flavour Physics

(2016)

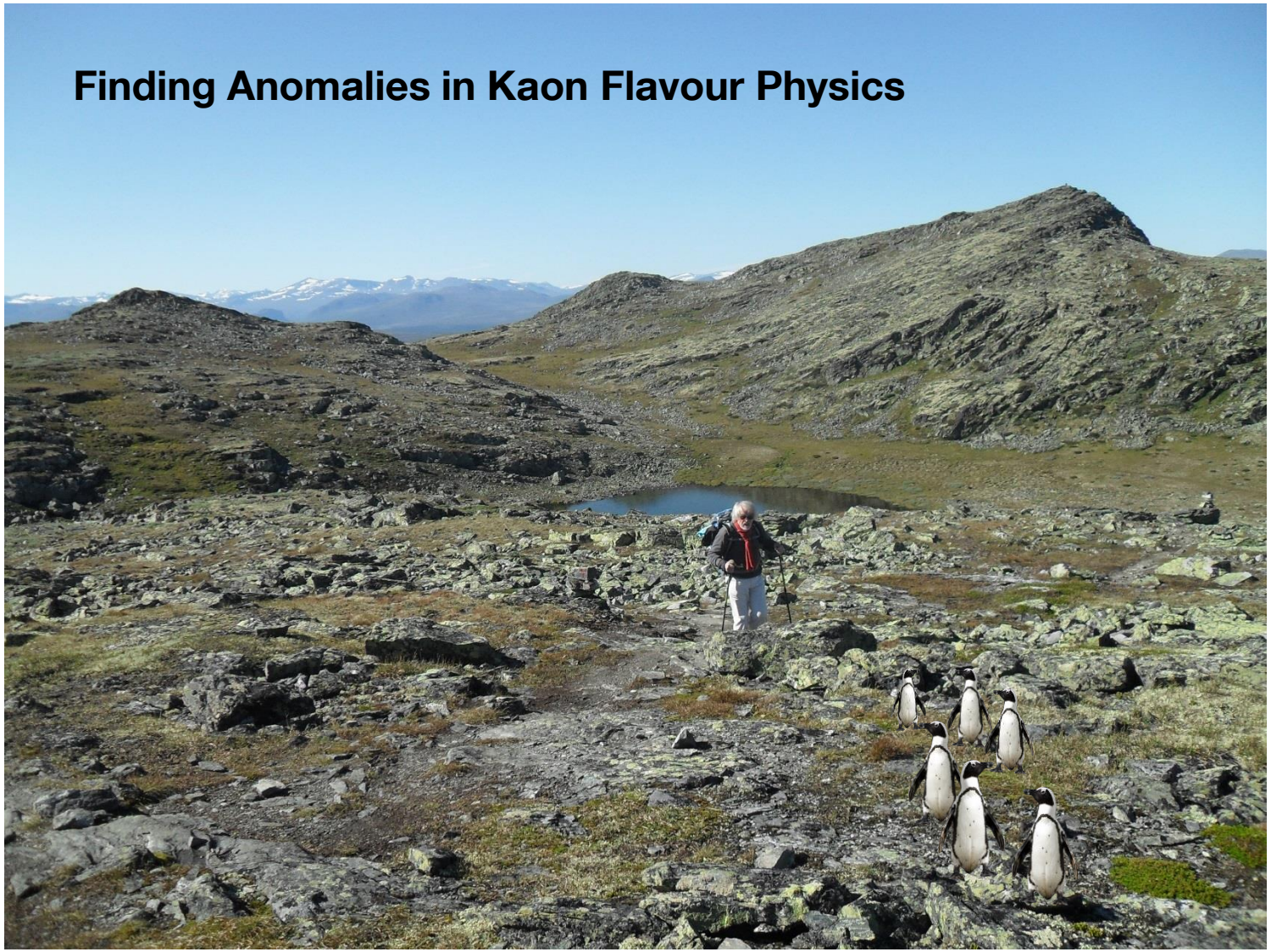


Photo: Gurli Buras

Present Anomalies

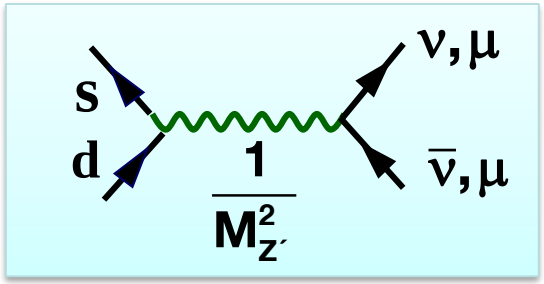
Violation of μ-e Universitality R(K), R(K*) (-) B	Anomaly in Angular Distribution $B \to K^* \mu^+\mu^-$ (P_5^l) (-) B	Violation of $\mu - \tau$ Universality R(D*), R(D*) (+) B	$B_s \to \mu^+\mu^-$ (-) B
$(g-2)_\mu$ (+) $(g-2)_e$ (-)	$\frac{\varepsilon'}{\varepsilon}$ (+) K	ΔA_{CP} (-) C	ΔM_K (-) K
Violation of CKM Unitarity V_{us}, V_{ud}	Violation of $\mu - e$ Universality $\tau -$ Decays (+)	$B_d^0 \to \pi^0 K_S$ CPV – Anomaly	Neutrino Anomalies

(+) (-) : Action of New Physics

Can we reach Zeptouniverse through Rare K and B Decays?

AJB, Buttazzo, Girrbach-Noe, Knegjens, 1407.0728

Heavy Gauge Boson (Z′)



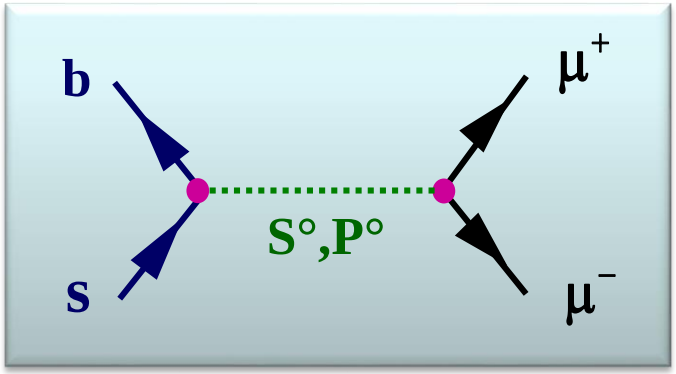
:

$K \to \pi\nu\bar{\nu}$: $\Lambda_{NP}^{max} \simeq 2000$ TeV

B_d : $\Lambda_{NP}^{max} \simeq 160$ TeV

B_s : $\Lambda_{NP}^{max} \simeq 160$ TeV

Heavy Scalar Boson (S) or Pseudoscalar Boson (P)



$B_{s,d} \to \mu^+\mu^-$

S : ≈ 350 TeV

P : ≈ 700 TeV

Main Message

Rare K, B_s, B_d Decays will play crucial role in identifying New Physics hopefully present on the route

Attouniverse → Zeptouniverse

Also Lepton Flavour Violation and EDMs

Shopping List 1

Observable	EXP	TH (SM)
R_K^μ, $R_{K^*}^\mu$	★	✓
$R(D)$, $R(D^*)$	★	★
P_5'	★	★
CP – Asymmetries in $b \to s\mu^+\mu^-$	★	★
$B \to K(K^* \nu\bar{\nu})$	★	✓
$B_{s,d} \to \mu^+\mu^-$	★	✓
V_{us}, V_{cb}, V_{ub}, γ	★	★

Shopping List 2

Observable	EXP	TH (SM)
$K^+ \to \pi^+ \nu\bar{\nu}$	☆	✓
$K_L \to \pi^0 \nu\bar{\nu}$	☆	✓
$\left(K_s \to \mu^+\mu^-\right)_{SM}$	☆	✓
$\varepsilon'/\varepsilon,\ \Delta I = 1/2$ Rule	✓	☆
$B \to \pi K,\ KK,\ \Delta A_{CP}$	☆	☆
$(g-2)_{\mu,e}$	☆	☆
Lepton Flavour Violation	☆	✓
Electric Dipole Moments	☆	✓

Exciting Times are just ahead of us !!!

Superstars of 2010 – 2030 (Flavour Physics)

$S_{\psi\varphi}$

~~CP~~ in $B_s^0 - \bar{B}_s^0$

$(B_s \to \varphi\varphi)$

$B \to D(D^*)\tau\nu_\tau$

γ, V_{ub} from Tree Level Decays

$B_s \to \mu^+\mu^-$

$(B_d \to \mu^+\mu^-)$

$B \to K^* \mu^+\mu^-$

$B \to K\mu^+\mu^-$

$\mu \to e\gamma$

$\tau \to \mu\gamma$

$\tau \to e\gamma$

$\mu \to 3e$

$\tau \to 3$ leptons

$K^+ \to \pi^+ \nu\bar{\nu}$

$(K_L \to \pi^0 \nu\bar{\nu})$

$B \to K^* \nu\bar{\nu}$

$B \to K\nu\bar{\nu}$

$B^+ \to \tau^+ \nu_\tau$

EDM´s

$(g-2)_\mu$

ε'/ε

(Lattice)

2015-2030 : Expedition Attouniverse → Zeptouniverse

10^{-18}m → 10^{-21}m

Flavour Physics (2020 -)

Crevasses

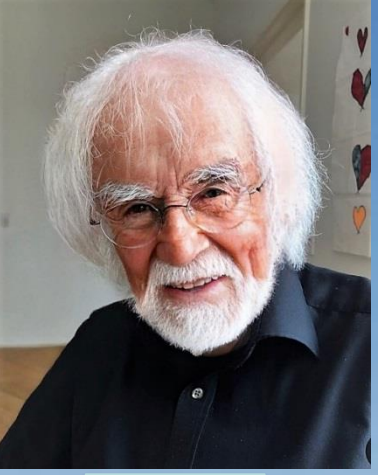
New Physics Summits

SMEFT

Energy gap

SM

Flavour Physics (2020 -)



(2031)

Zeptouniverse

New Physics Summits

Crevasses

SMEFT

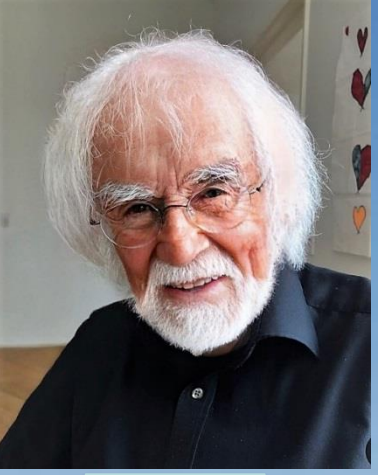
Energy gap

SM

Allan Buras

Flavour Physics (2020 -)

Thank You !



(2031)

Zeptouniverse

New Physics Summits

Crevasses

SMEFT

Energy gap

SM

Allan Buras

Backup

Dual QCD Approach

Bardeen, AJB, Gérard

High Energy Scale

Wilson Coefficients

Standard Renormalization Group Evolution within Quark + Gluon Phase

Short-Distances

0 (1 GeV)

Hadronic Matrix Elements

Evolution within Meson Phase of QCD (Meson Evolution)

Long-Distance Scales

Large N Limit

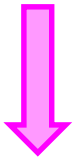
Factorization Scale

The only analytic approach allowing matching of short distance and long-distance contributions

AJB, Gérard 2016

Meson evolution (hidden in lattice QCD) is crucial strong dynamics responsible for $\Delta I=1/2$ rule, ε'/ε, ε, $K\to\pi\pi$ in general

Lattice QCD	Dual QCD	Chiral Perturbation Theory
New Physics	New Physics	New Physics
Short Distance RG Evolution	Short Distance RG Evolution	Short Distance RG Evolution
Numerical sophisticated and demanding calculations lasting many years. (from first principles)	Meson Evolution: The only analytic approach allowing matching with short distance	Problems with matching with short distance, L_i (No meson evolution)
		Based on global symmetries of QCD



0(1GeV)

$0(m_K)$

Meson evolution (hidden in lattice QCD) is crucial strong dynamics responsible for $\Delta I=1/2$ rule , ε'/ε , ε , $K\to\pi\pi$ in general

Basic CKM Parameters

$|V_{us}|$, $|V_{cb}|$, β, γ

- $|V_{us}| = \lambda$, precisely known (Cabibbo anomaly irrelevant here)
- $\beta = (22.2 \pm 0.7)^\circ$ from $S_{\psi K_s} = 0.699$ (17)
- $\gamma = \left(65.4\,^{+3.8}_{-4.2}\right)^\circ$ (LHCb)

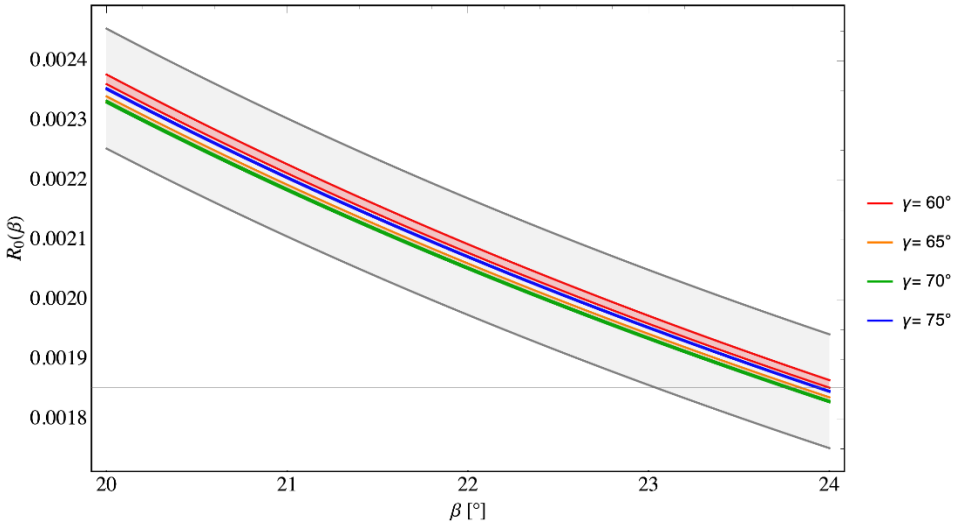
  $\gamma = (64.7 \pm 1.6)^\circ$ (ΔM_s / ΔM_d + FLAG)

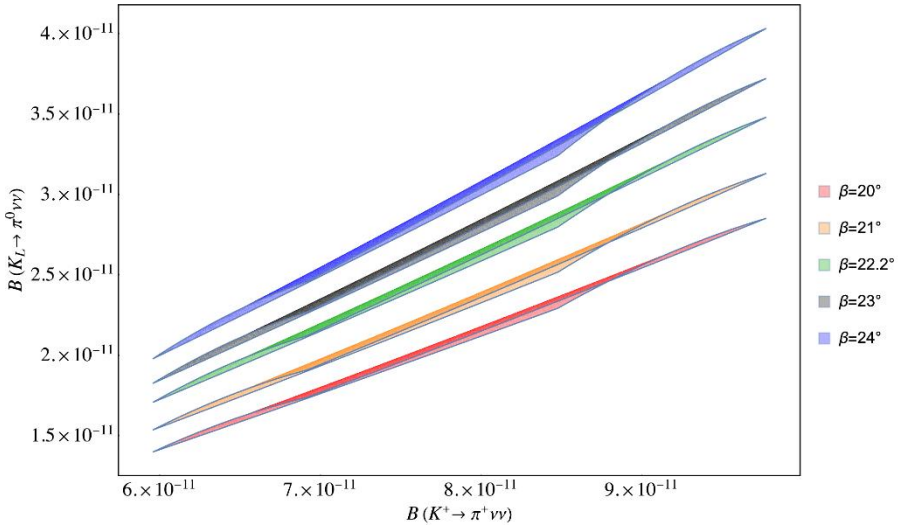
$$\mathrm{Br}\left(K^+ \to \pi^+ \nu\bar{\nu}\right) \leftrightarrow \mathrm{Br}\left(K_L \to \pi^0 \nu\bar{\nu}\right)$$

AJB + E. Venturini

$$R_0(\beta) = \frac{\mathrm{Br}\left(K^+ \to \pi^+ \nu\bar{\nu}\right)}{\left[\mathrm{Br}\left(K_L \to \pi^0 \nu\bar{\nu}\right)\right]^{0.7}} = (2.03 \pm 0.11) \cdot 10^{-3}$$

(V_{cb} and γ independent)





Coming Years : Flavour Precision Era

LHC Upgrade
E = 14 TeV
(CERN)

Precision
$B_{d,s}$ – Meson Decays
LHCb, CMS
KEK (Japan)

$K^+ \to \pi^+ \nu\bar{\nu}$ ($\sim 10^{-10}$) (CERN)

$K_L \to \pi^0 \nu\tilde{\nu}$ ($\sim 3 \cdot 10^{-11}$) J-PARC (Japan)

Lepton Flavour Violation

$\mu \to e\gamma$

$\mu \to eee$

$\tau \to \mu\gamma$, $\tau \to 3\mu$

Electric Dipole Moments

$(g\text{-}2)_\mu$

Improved Lattice Gauge Theory Calculations

ε'/ε

$\Delta I = ½$ Rule, ΔM_K

Neutrinos