BSM Flavour Expedition (From the Attouniverse to the Zeptouniverse)

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

Herrmann Fest

(13th of September, 2022)

Happy Birthday to
Hermann Nicolai (70)

Overture

Elementary Particles and Forces

(2022)

The Standard Model

	Matter			Forces
QUARKS	**u** up ★	**c** charm	**t** top	**γ** photon ★
	d down ★	**s** strange ★	**b** bottom	**g** gluons
LEPTONS	**ν_e** ★	**ν_μ** ★	**ν_τ**	**Z** Z-boson
	e electron ★	**μ** muon ★	**τ** tau	**W** W-boson

Electromagnetic Force — **γ, Gluons massless**

Strong Force — ★ (2012) **Higgs** provides masses to **Quarks Leptons W, Z**

Weak Force

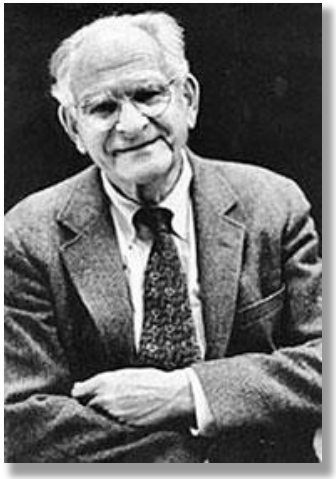
★ Known in 1970

Proton = u u d
Neutron = d d u

Masses of Proton and Neutron come from Strong Force, not Higgs !!

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

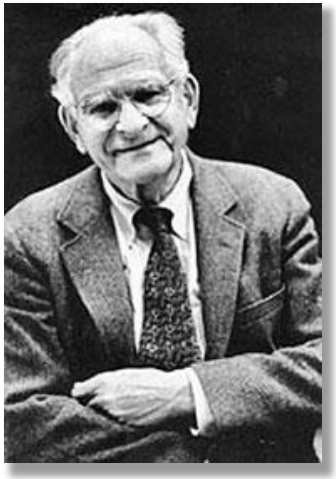
MPI (Munich) (1983)



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

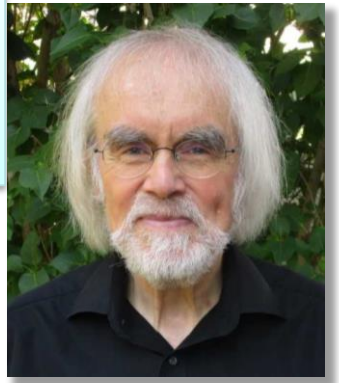
Victor Weisskopf (1908-2002) after $W^{\pm}$, Z^0 Discovery

MPI (Munich) (1983)



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

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



(2021)

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 before 2046

Reinhard Genzel

Flavour Strategy **allows to see them through**

Analogy : **Quantum Fluctuations**

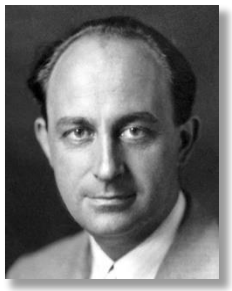
Le Verrier* predicted the existence of Neptune in 1846 through an anomaly in the orbit of the Uranus and predicted its position with an accuracy of 1°. Confirmed by Gottfried Galle.

***(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)

Allan Buras

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

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

Dual Picture **AJB (2009)**

10^{18}m →10^{21}m

Dual Picture of Nanouniverse

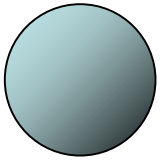
10^9m

3 light seconds

Earth

$0.4 \cdot 10^9$m

Moon



Nanouniverse

Dual Picture of Attouniverse

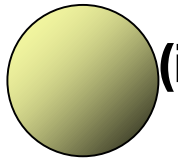
10^{18}m

105 light years

Earth

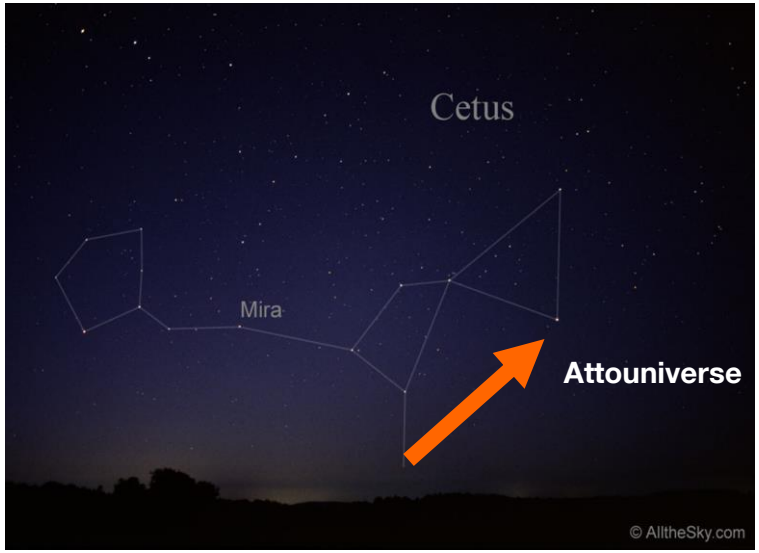
Beta Ceti

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**

Overture
finished

Hermann Symphony Nr. 25
(Premiere, MPI for Gravitational Physics, 13th September 2022)

1st Movement	:	Rare Processes: Technology to reach the Zeptouniverse
2nd Movement	:	DNA Charts
3rd Movement	:	Anomalies in Flavour Data
4th Movement	:	Finale Vivace

(1821)

1st Movement

Rare Processes: Technology to reach the Zeptouniverse

Main Players in Indirect Search: Mesons

Rare Decays of B_d^0, B_s^0, B^+, K^+, K_L

(quark-antiquark bound states)

$B_d^0 = (\bar{b}d)$ $B_s^0 = (\bar{b}s)$ $B^+ = (\bar{b}u)$

$K^+ = (\bar{s}u)$ $K_L = (\bar{s}d)$

Mass
5 GeV
0.5 GeV

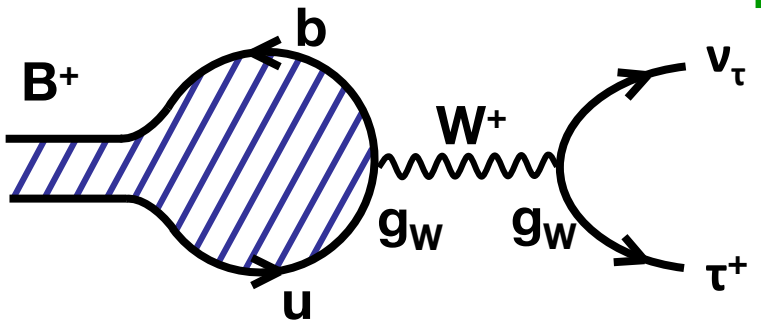
Step 1: Produced in high energy collisions

Step 2: Decay into lighter particles (through Quantum Fluctuations)

Step 3: Measurements of decay probabilities P_i
Calculations of P_i

Indirect Search: Precision Measurement of Decays of Mesons and Leptons

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

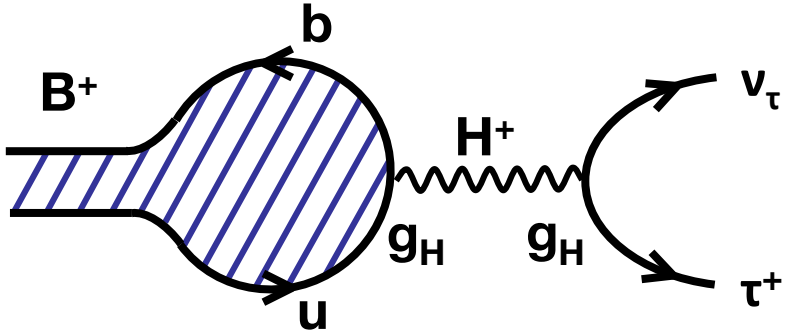


Standard Model

$$P\left(B^+ \to \tau^+ \nu_\tau\right)_{SM} = \left| A \frac{g_W^2}{M_W^2} \right|^2$$

$m_B \approx 5$ GeV

A, B – parameters of a given theory



Contribution of a new charged Heavy Particle

$$P\left(B^+ \to \tau^+ \nu_\tau\right) = \left| A \frac{g_W^2}{M_W^2} + B \frac{g_H^2}{M_H^2} \right|^2$$

Experiment

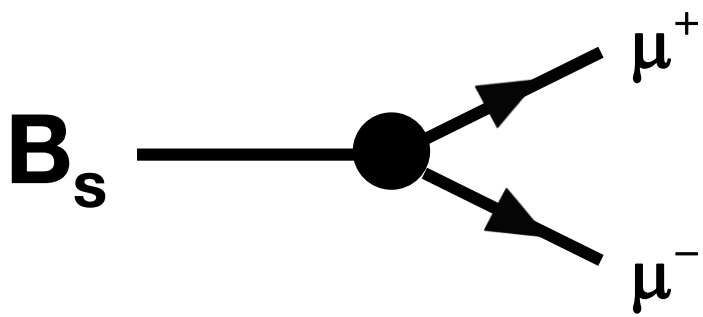
$$\Delta = P\left(B^+ \to \tau^+ \nu_\tau\right) - P\left(B^+ \to \tau^+ \nu_\tau\right)_{SM} \neq 0$$

Signal of a new particle

2013

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

$B_s = (\bar{b}s)$



Quantum fluctuations at very short distance scales

The probability for this decay to occur depends on the dynamics hidden in ● : particles and forces at short distance scales

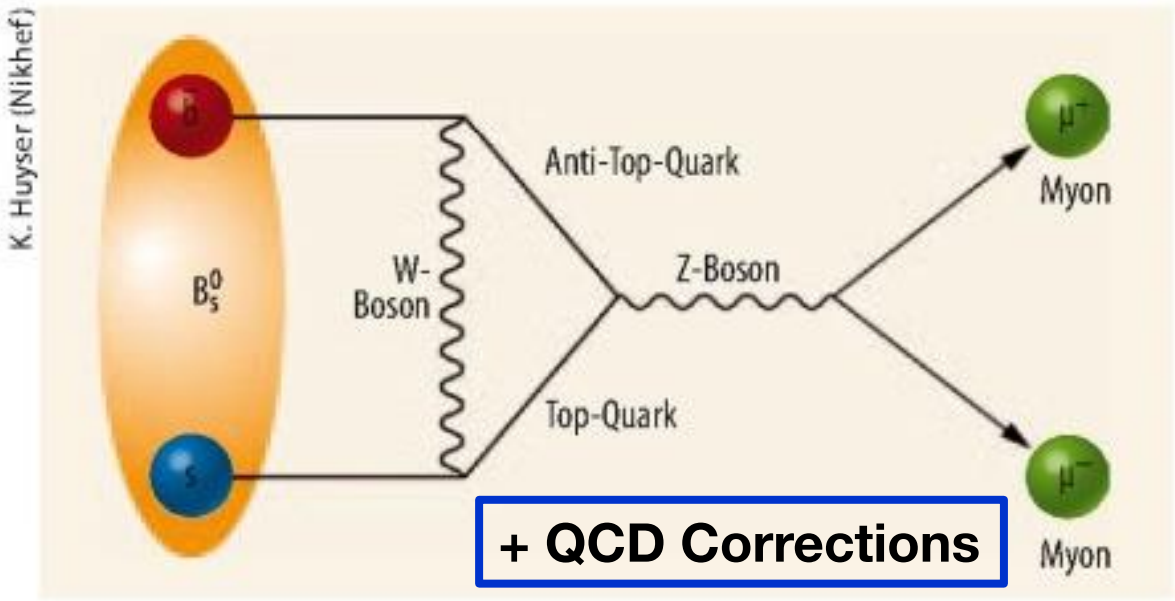
Searching for New Particles through Rare Processes

$B_s^0 \rightarrow \mu^+\mu^-$

Standard Model

G. Buchalla + AJB (1993)

Correcting literature by factor 2



What is the Probability for this Decay to occur?

100% ↔ P = 1

$B_s \to \mu^+\mu^-$ in the Standard Model

$B_s \equiv (\bar{b}s)$

1993 Buchalla + AJB $P = (3.5 \pm 1.2) \cdot 10^{-9}$ (NLO)

Note: Only about 3 among 1 Billion produced B_s^0 mesons are predicted to decay into $\mu^+\mu^-$

LHC: proton + proton (13 TeV) $\Rightarrow$ B_s, $\bar{B}_s^0$, ... + many other particles

$B_s \to \mu^+\mu^-$, $\bar{B}_s^0 \to \mu^+\mu^-$

1993-2022

Improved calculations

AJB **2003**, AJB Girrbach-Noe, Guadagnoli, Isidori **2012**

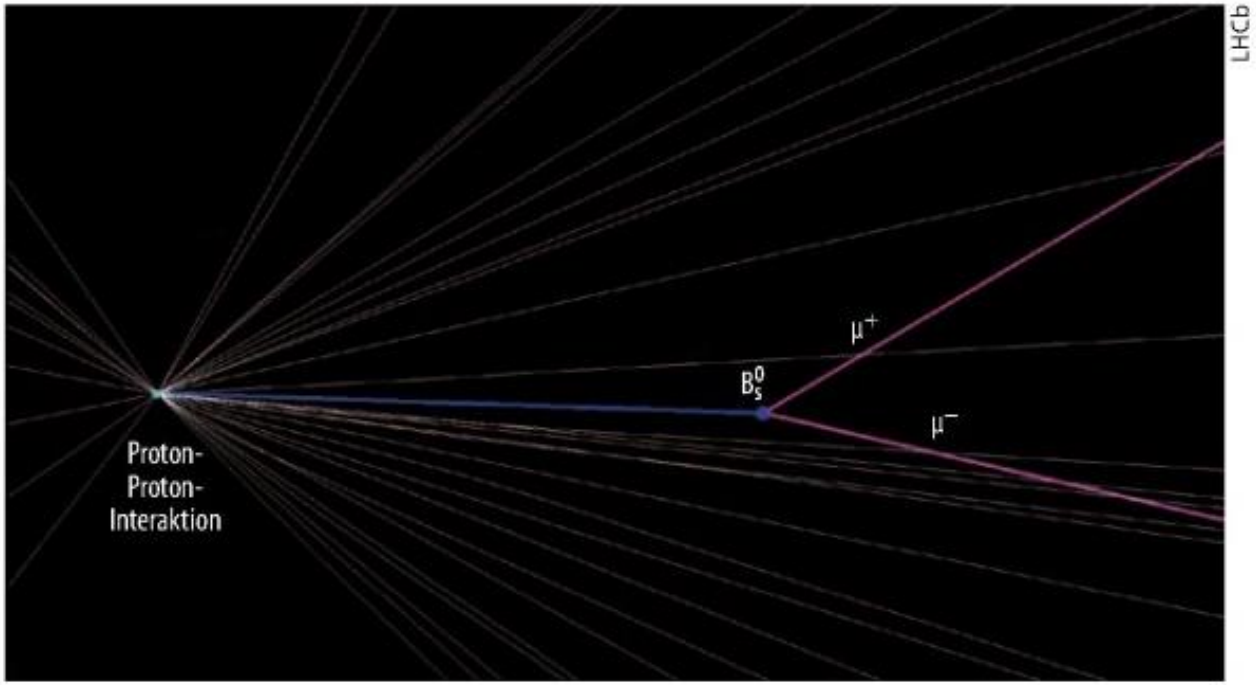
Bobeth, Gorbahn, Hermann, Misiak, Stamou, Steinhauser **2013**

Beneke, Bobeth, Szafron **2019**

Messages from the LHC

July 2013

EPS Stockholm



20 years later

LHCb

CMS

$$P_{exp} = (3.0 \pm 0.6) \cdot 10^{-9}$$

ATLAS

$B_s \to \mu^+\mu^-$ and $B_d \to \mu^+\mu^-$ (2022)

(LHCb, CMS, ATLAS Experiment)

$$P\left(B_s \to \mu^+\mu^-\right)_{SM} = \left(3.78 \pm 0.11\right)\cdot 10^{-9} \qquad \left(2.86 \pm 0.33\right)\cdot 10^{-9}$$

$$P\left(B_d \to \mu^+\mu^-\right)_{SM} = \left(1.02 \pm 0.04\right)\cdot 10^{-10} \qquad \left(\quad ? \quad\right)\cdot 10^{-10}$$

AJB + Venturini (2022) 2203.11960

2.7σ – Anomaly in $B_s \to \mu^+\mu^-$

E. Venturini

However: on the basis of one decay it is impossible to find out which NEW PHYSICS is responsible for it

Superstars of 2010 – 2030 (Flavour Physics)

$S_{\psi\varphi}$

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

$(B_s \to \varphi\varphi)$

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

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)

2nd Movement

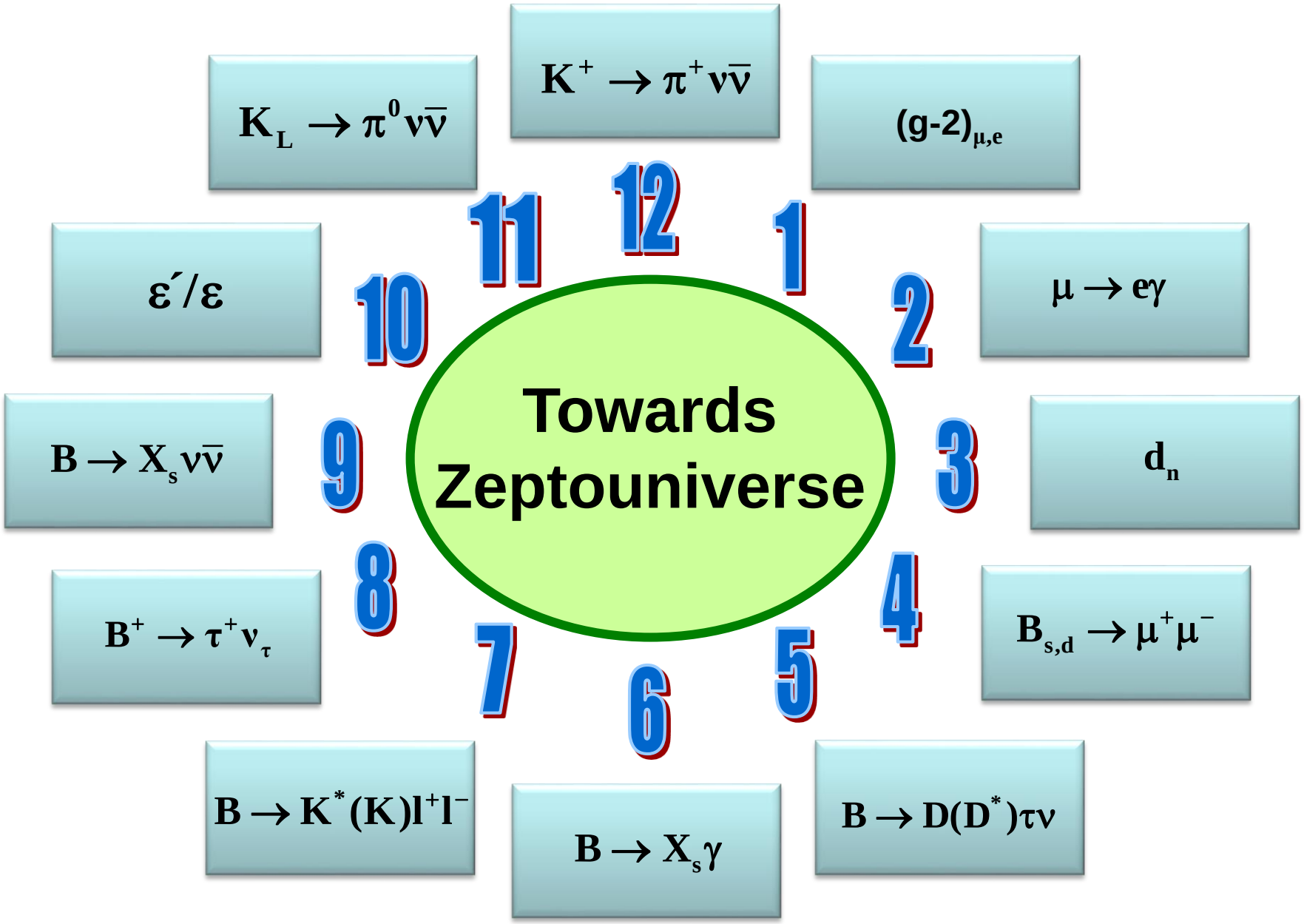
DNA Charts

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).


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

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

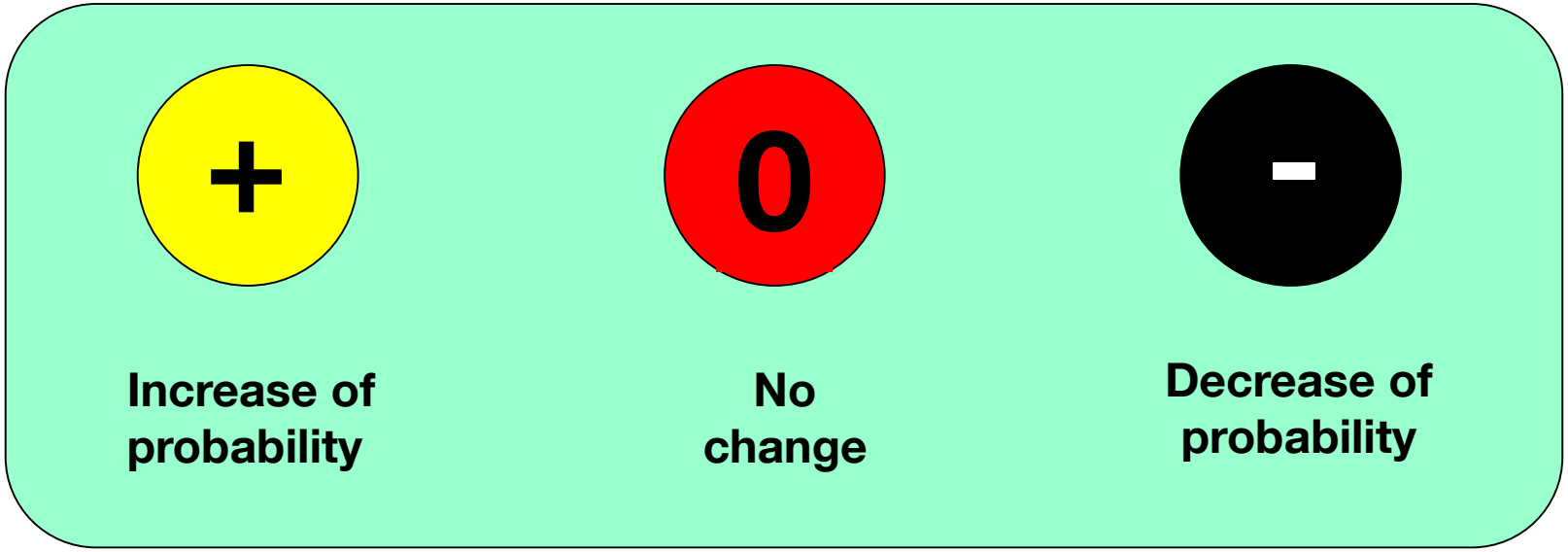
1505.00618 ⇦ Reviews

DNA of a Theory

AJB + Jennifer Girrbach-Noe

Basic Idea

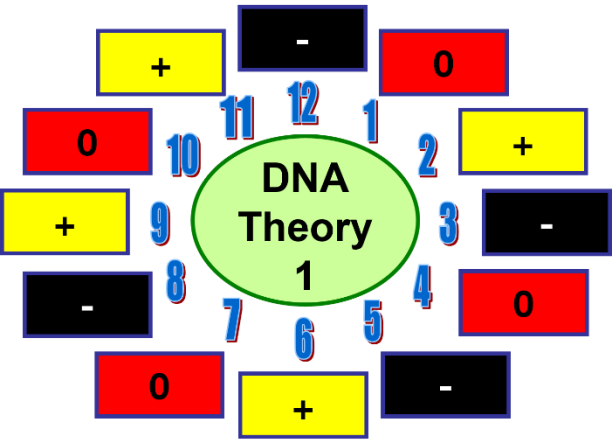
Look at various observables and identify

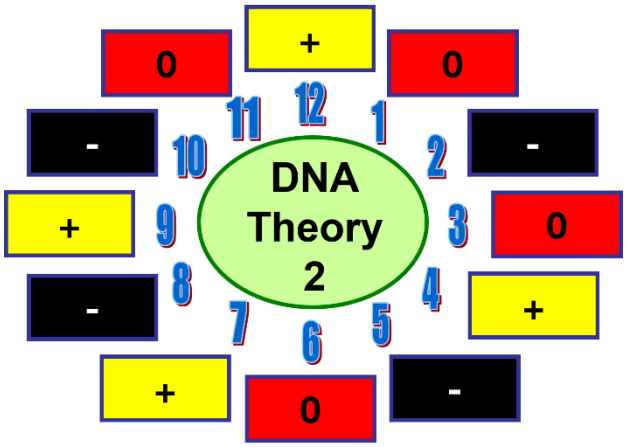


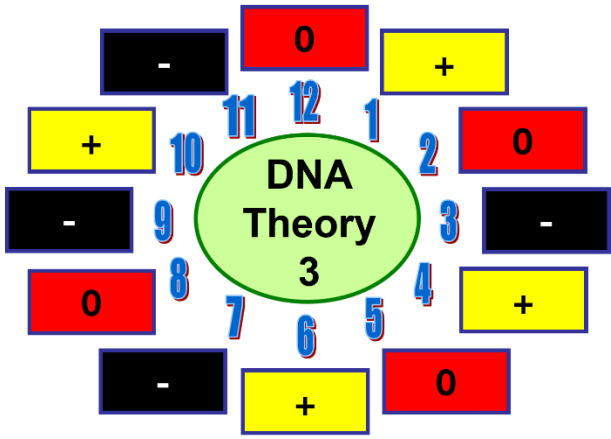
2013

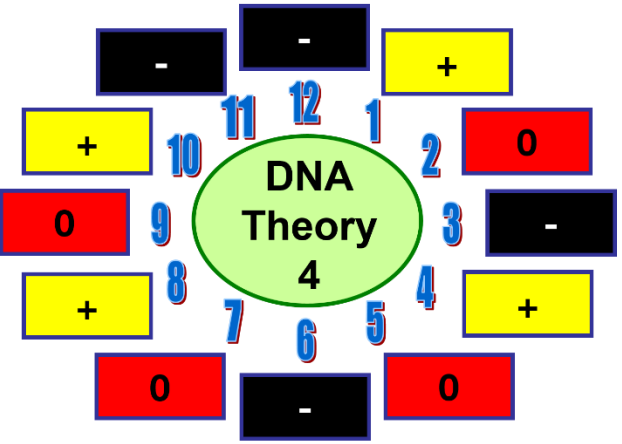
relative

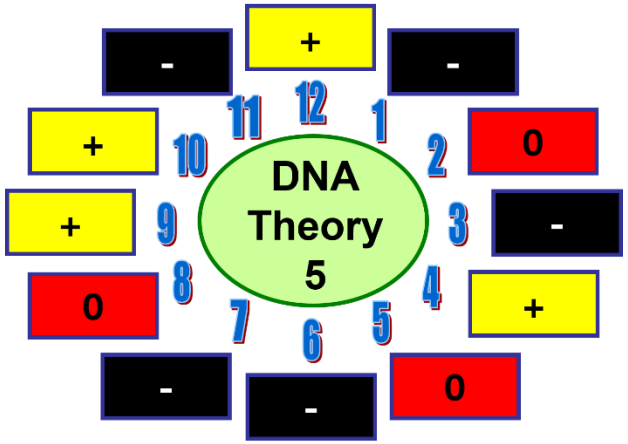
to the Standard Model

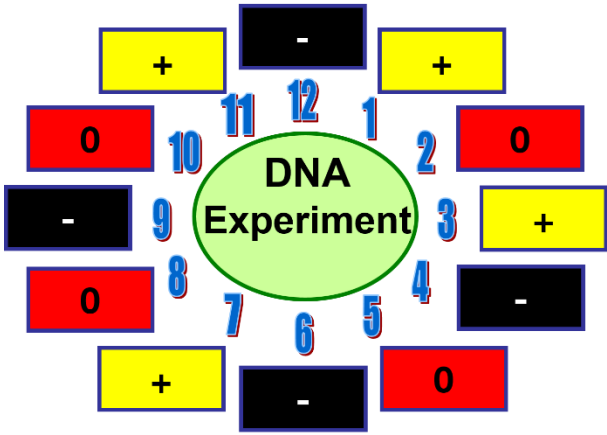

DNA
Theory
1


DNA
Theory
2

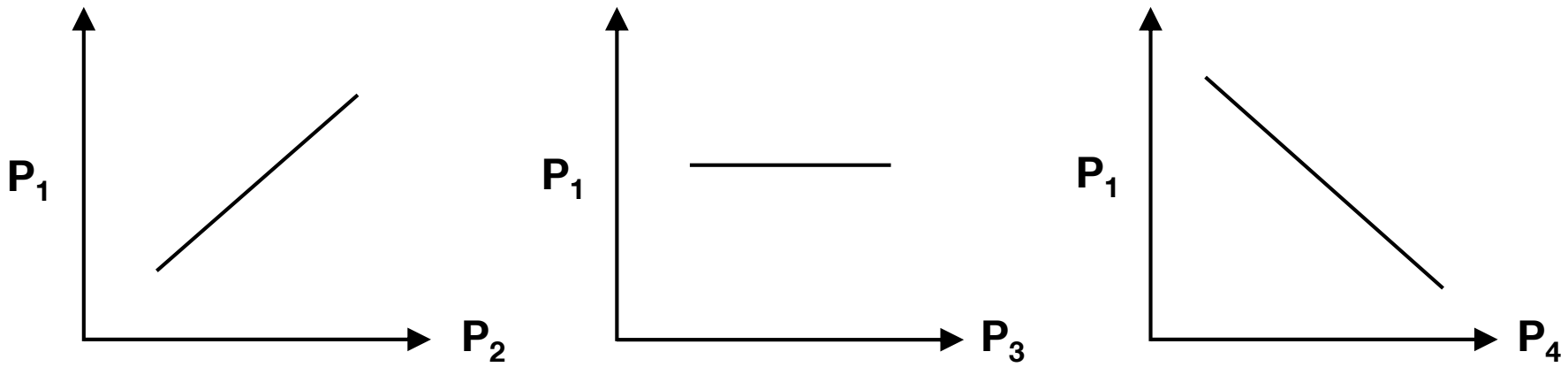

DNA
Theory
3


DNA
Theory
4


DNA
Theory
5


DNA
Experiment

Correlations and Anti-Correlations



Correlation

Anti-Correlation


Monika Blanke

$U(3)^3$

ε_K

ΔM_s

ΔM_d

$S_{\psi\varphi}$

Minimal Flavour Violation

$S_{\psi K_S}$

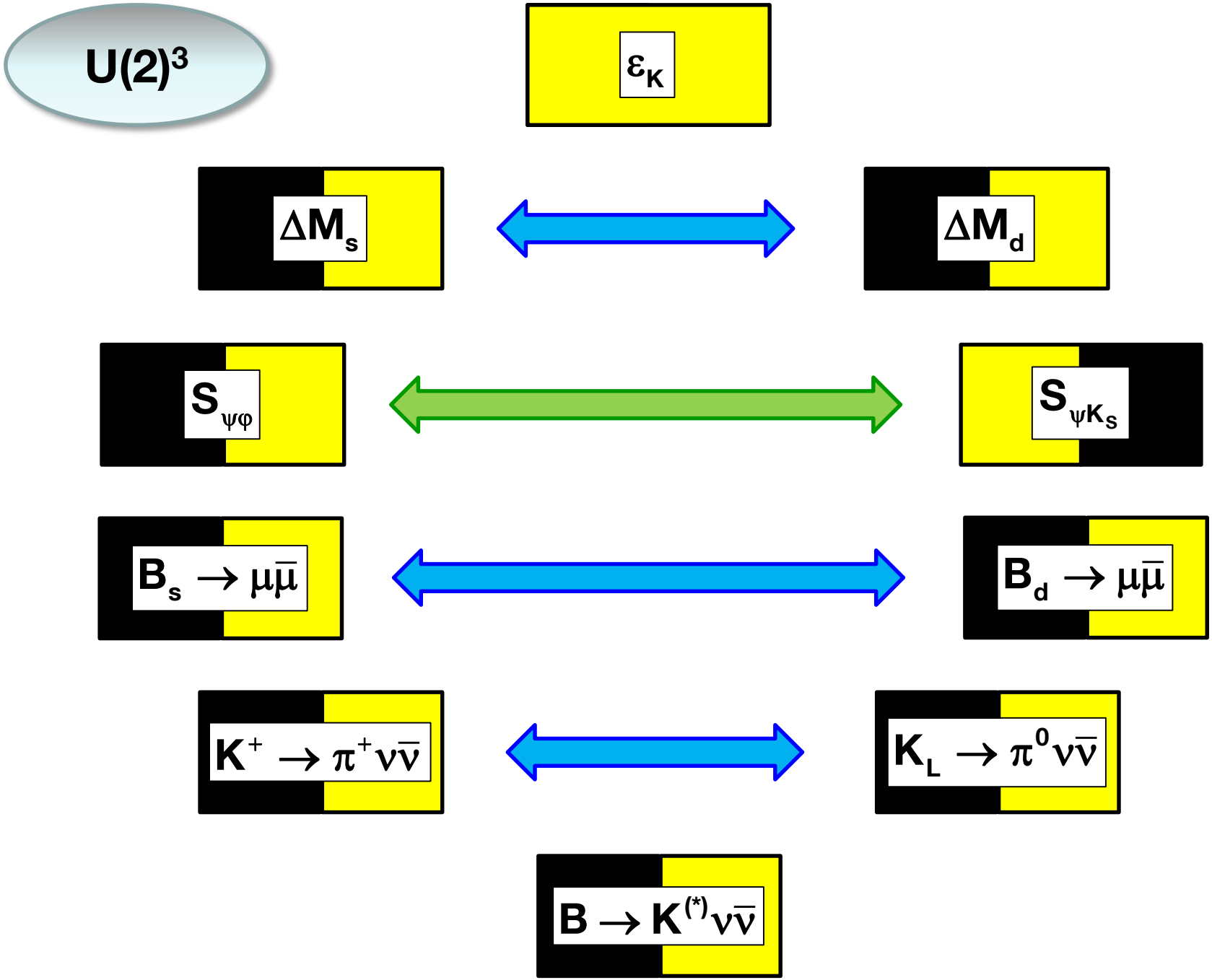
$B_s \to \mu\bar{\mu}$

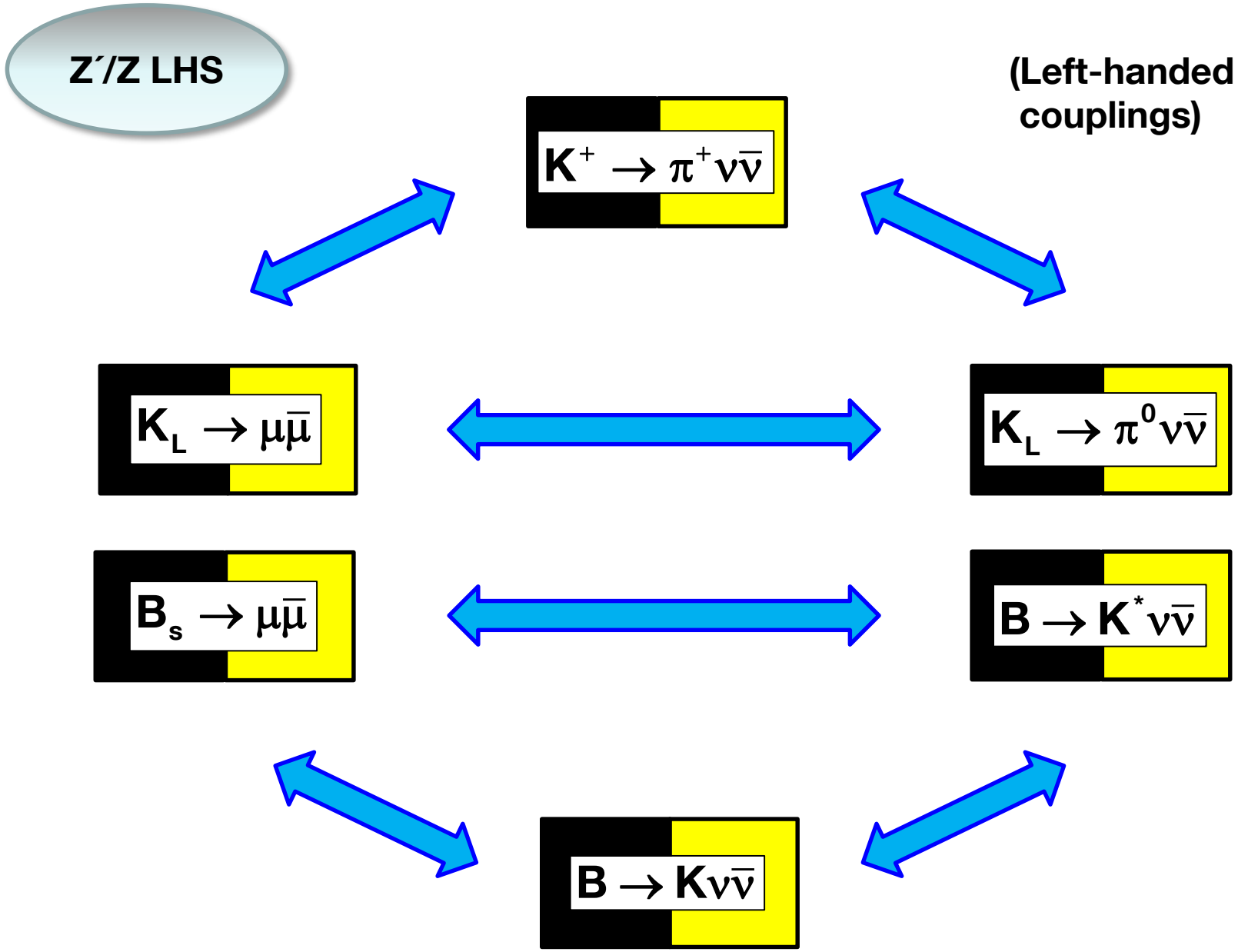
$B_d \to \mu\bar{\mu}$

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

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

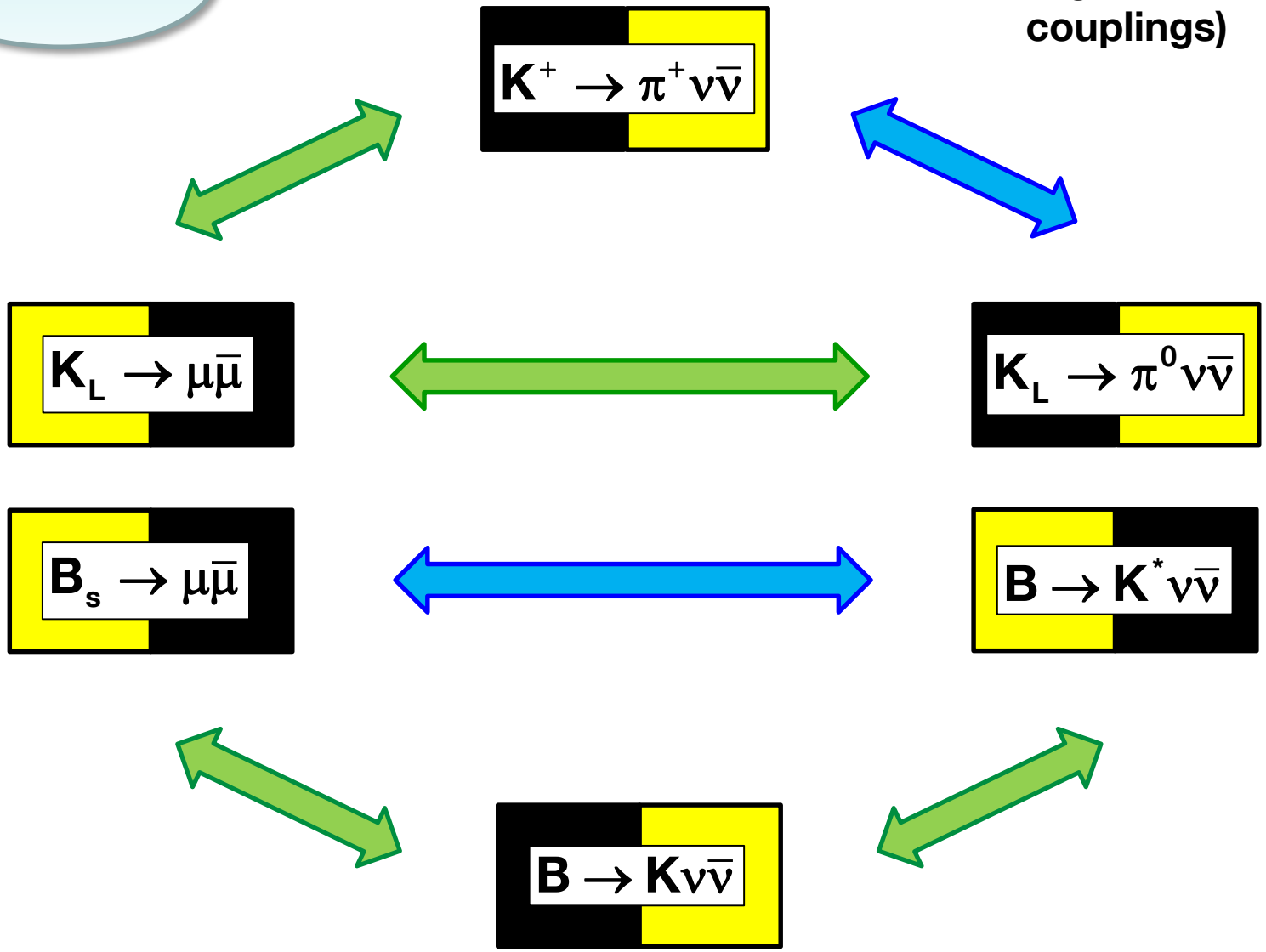
$B \to K^{(*)} \nu\bar{\nu}$


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)



3rd Movement

Anomalies in Flavour Data

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

B-Physics Anomalies (2013-2022)

Altmannshofer
Straub
Stangl
Crivellin

B Physics Anomalies

(2013 - 2022)
Lepton Flavour Universality Violation

1.

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

BaBar, LHCb, Belle

$$R(D) = 0.340(27)(13)_{syst} \qquad 0.300 \pm 0.008$$
$$R(D^*) = 0.295(11)(8)_{syst} \qquad 0.258 \pm 0.003$$

(Standard Model)

2.

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

(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.

$$B \to K\left(K^*\right)\mu^+\mu^- \qquad (5.1\sigma)$$
$$\left(B_s \to \varphi\mu^+\mu^-\right) \quad (4.8\ \sigma)$$

(hadronic uncertainties)

P_5'

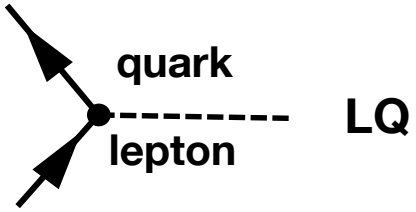
New Particles behind B-Physics Anomalies

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 $SU(2)_L$**

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

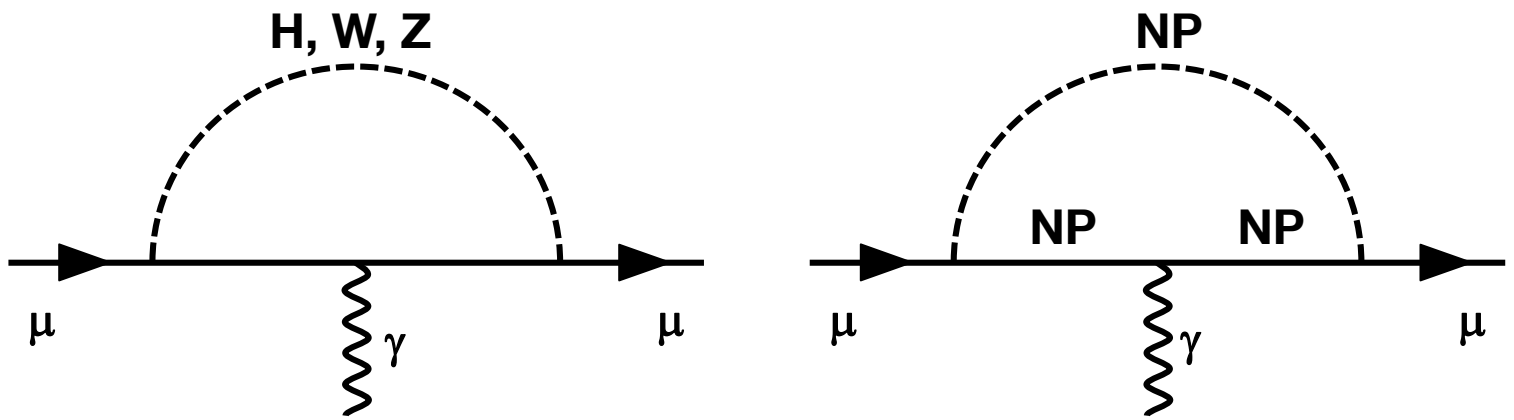
$$a_\mu^{SM} = \frac{(g-2)_\mu}{2} = (116591810 \pm 43) \cdot 10^{-11}$$

$$a_\mu^{EXP} = (116592061 \pm 41) \cdot 10^{-11} \quad \text{(BNL, Fermilab)}$$

$$a_\mu^{EXP} - a_\mu^{SM} = (251 \pm 59) \cdot 10^{-11}$$

(4.2 σ Anomaly)

SM



$\Delta I = 1/2$ 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)

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

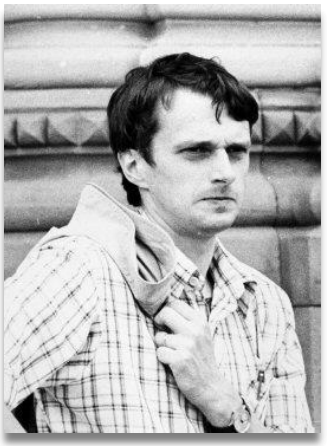
Dual QCD Approach for Weak Decays

Successful low energy approximation of QCD for $K \to \pi\pi$ K^0-K^0 mixing

1986

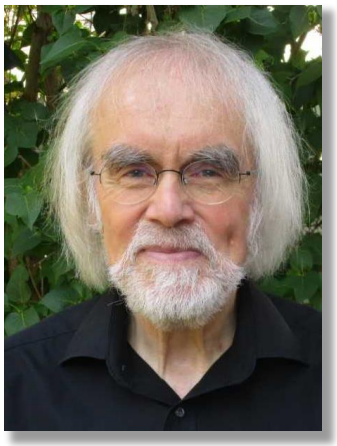
W. Bardeen

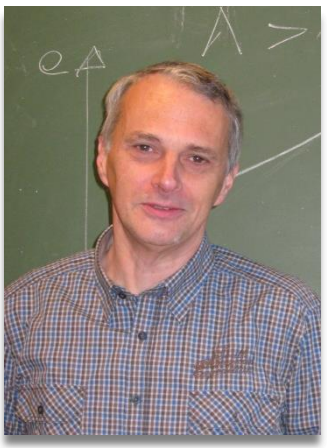
AJB



J.-M. Gérard

2016





(2021) Age Sum Rule

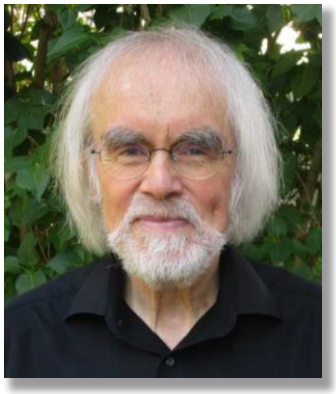
Accurate to 1‰ !

N. Christ

+

C. Sachrajda

$$\frac{\text{N. Christ} + \text{C. Sachrajda}}{2} = \text{AJB} = 75$$



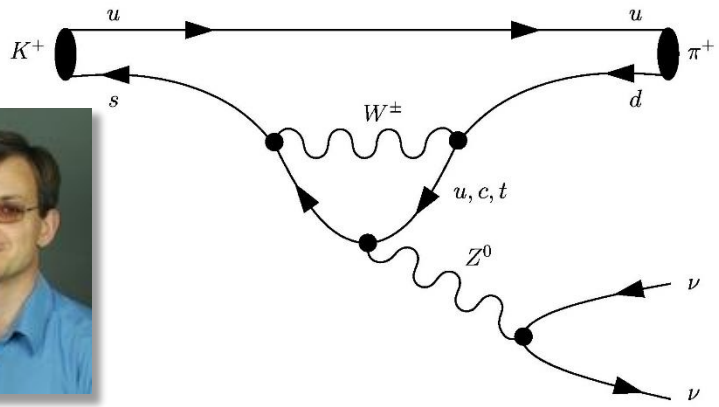
AJB

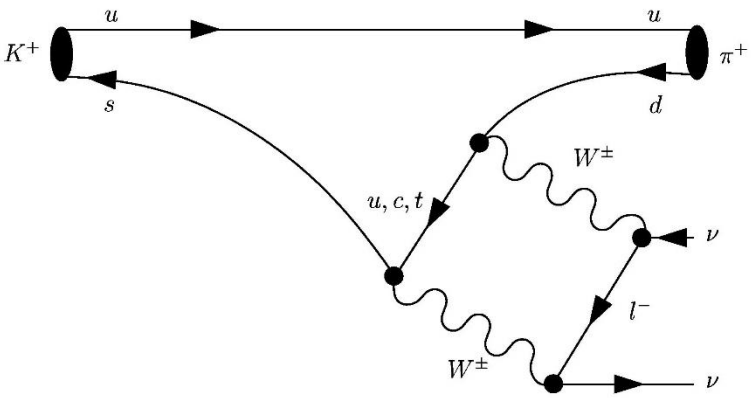
A. Pich

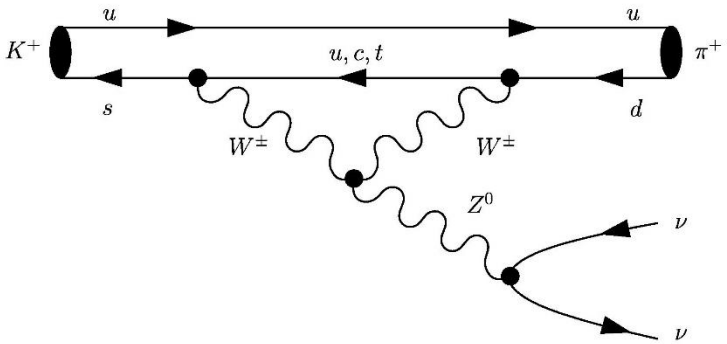
★ **Good health for us 4 the full decade**

Waiting for $K^+ \to \pi^+ \nu\bar{\nu}$ and $K_L \to \pi\nu\bar{\nu}$

G. Buchalla
+ AJB
(1993)







28 years!

NA62 (2019)
KOTO (2019)

SM:

$$P\left(K^+ \to \pi^+ \nu\bar{\nu}\right) = \left(8.4 \pm 1.0\right) \cdot 10^{-11}$$
$$P\left(K_L \to \pi^0 \nu\bar{\nu}\right) = \left(3.4 \pm 0.6\right) \cdot 10^{-11}$$

NLO Buchalla, AJB; Misiak, Urban (93, 98)
NNLO AJB, Gorbahn, Haisch, Nierste (2005)
AJB, Buttazzo, Girrbach-Noe, Knejgens (2015)

Standard Model (2022)

SM:

$$P\left(K^+ \to \pi^+ \nu\bar{\nu}\right) = (8.60 \pm 0.42)\cdot 10^{-11}$$
$$P\left(K_L \to \pi^0 \nu\bar{\nu}\right) = (2.94 \pm 0.15)\cdot 10^{-11}$$

AJB + E. Venturini (2109.11032)

E. Venturini

Reduction of uncertainties:
In $K^+ \to \pi^+ \nu\bar{\nu}$ by factor 2.4
$K_L \to \pi^0 \nu\bar{\nu}$ by factor 4.0

News from NA62 and KOTO

$$P\left(K^+ \to \pi^+ \nu\bar{\nu}\right) = (10.6 \pm 3.8)\cdot 10^{-11} \quad \text{(NA62)}$$
$$P\left(K_L \to \pi^0 \nu\bar{\nu}\right) \leq 3.0\cdot 10^{-9} \quad \text{(KOTO)}$$
$$P\left(K_L \to \pi^0 \nu\bar{\nu}\right) = \left(2.1^{+4.6}_{-2.0}\right)\cdot 10^{-9} \quad \text{(KOTO)}$$

But what if neutrinos are Majorana particles?

AJB + J. Harz (soon)

4th Movement

Finale Vivace

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

Exciting Times are just ahead of us !!!

Coming Years : Flavour Precision Era

LHC Upgrade
E = 14 TeV
(CERN)

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

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

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

2015-2046 : Expedition Attouniverse → Zeptouniverse

10^{-18}m → 10^{-21}m

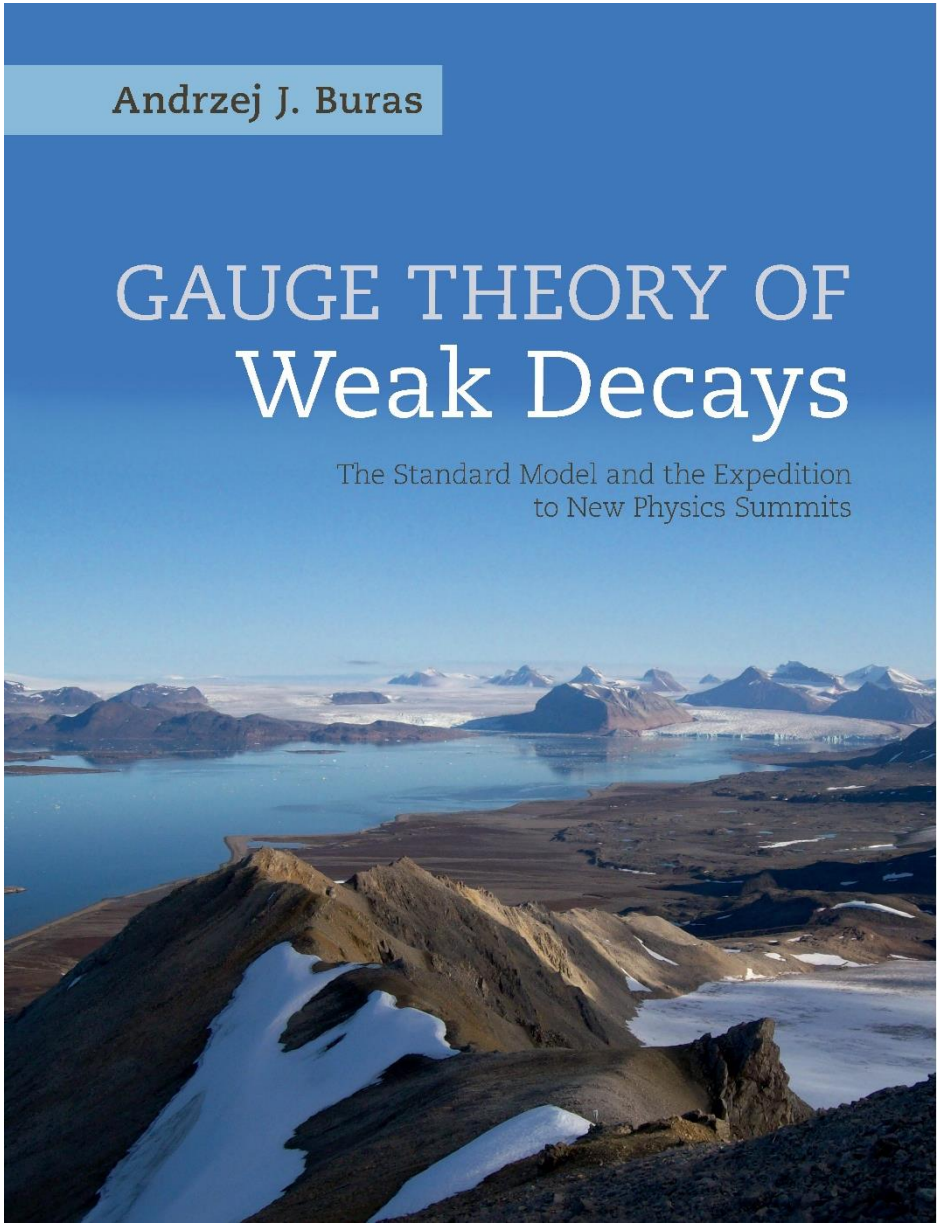
Advanced ERC Grant at the TUM Institute for Advanced Study
Zeptouniverse Base Camp (2011-2016) ⇨ 2046

Homeoffice in Ottobrunn

March 2020 →

Zeptouniverse Guide

Published July 2020

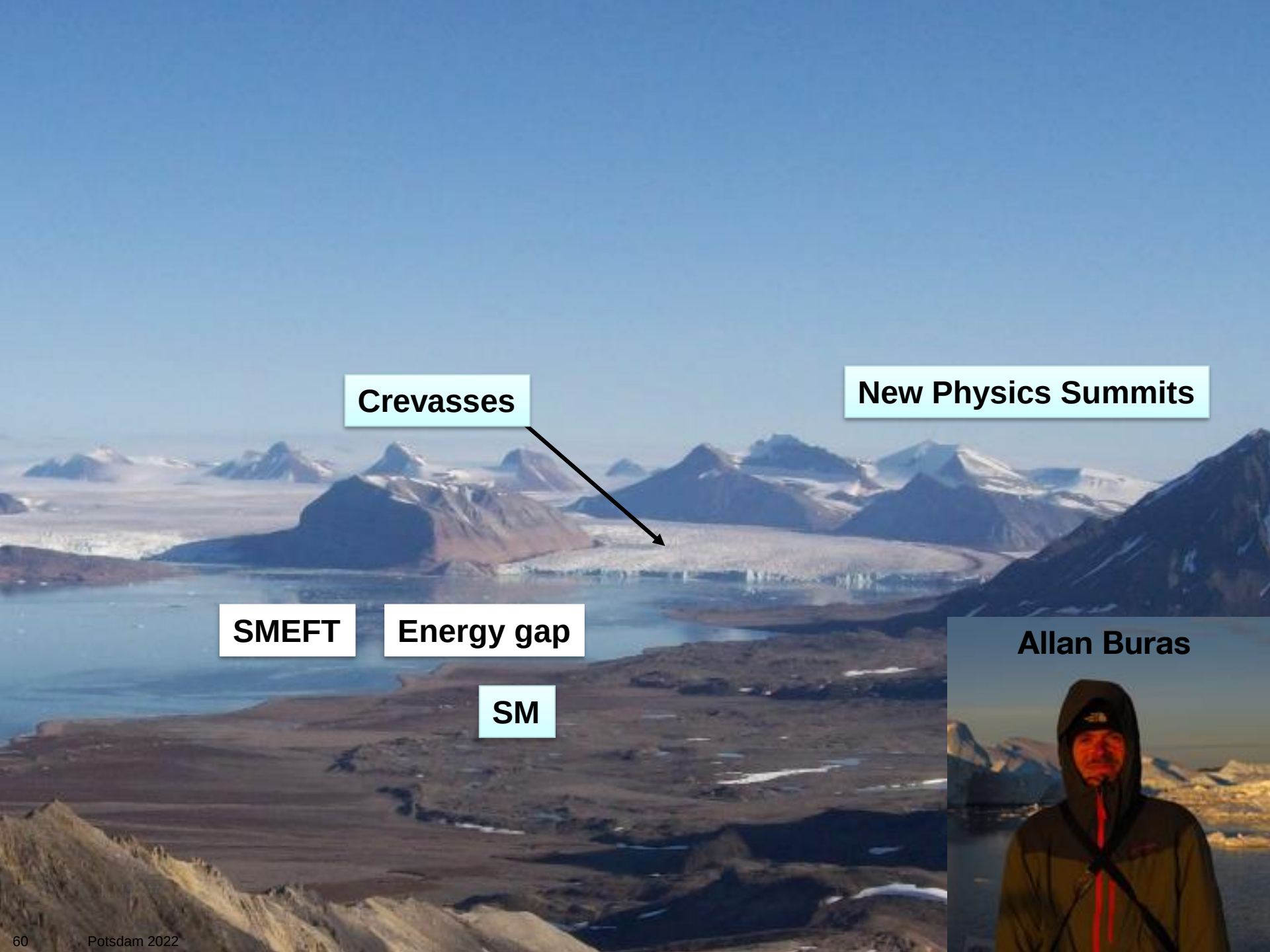


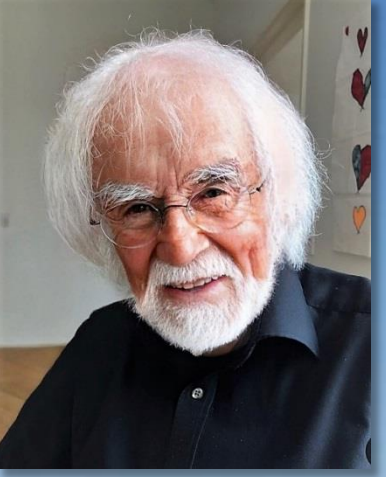
739 pages
1350 references

Cambridge University Press

7

Exciting Years !


Crevasses
New Physics Summits
SMEFT
Energy gap
SM
Allan Buras



(2032)

Zeptouniverse

New Physics Summits

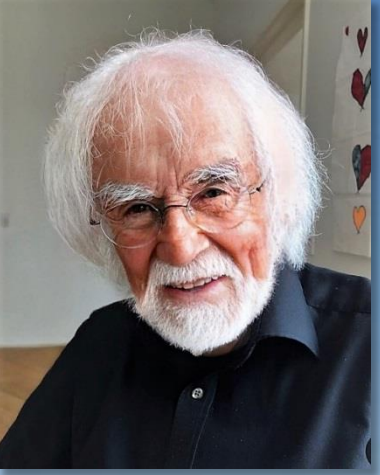
Crevasses

SMEFT

Energy gap

SM

Allan Buras



(2032)

(2032)

Crevasses

Zeptouniverse

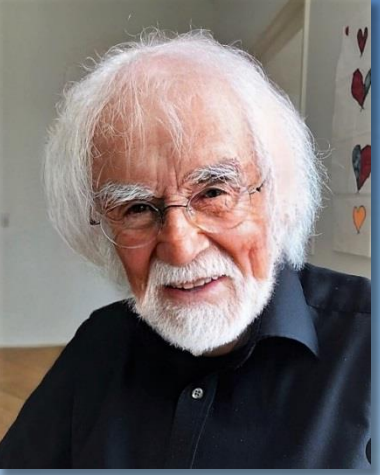
New Physics Summits

SMEFT

Energy gap

SM

Allan Buras



(2032)

(2032)

80

Zeptouniverse

New Physics Summits

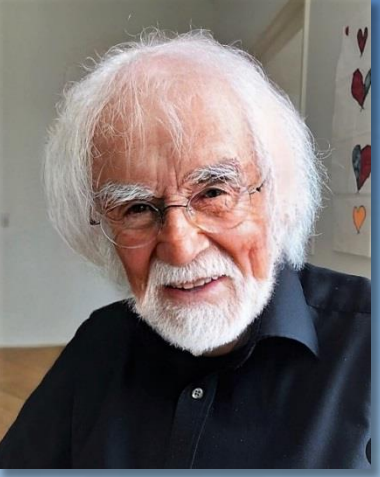
Crevasses

SMEFT

Energy gap

SM

Allan Buras



(2032)

(2032)

80

Zeptouniverse

New Physics Summits

Crevasses

SMEFT

Energy gap

SM

Allan Buras

Thank You !

Backup

Good News on ε'/ε

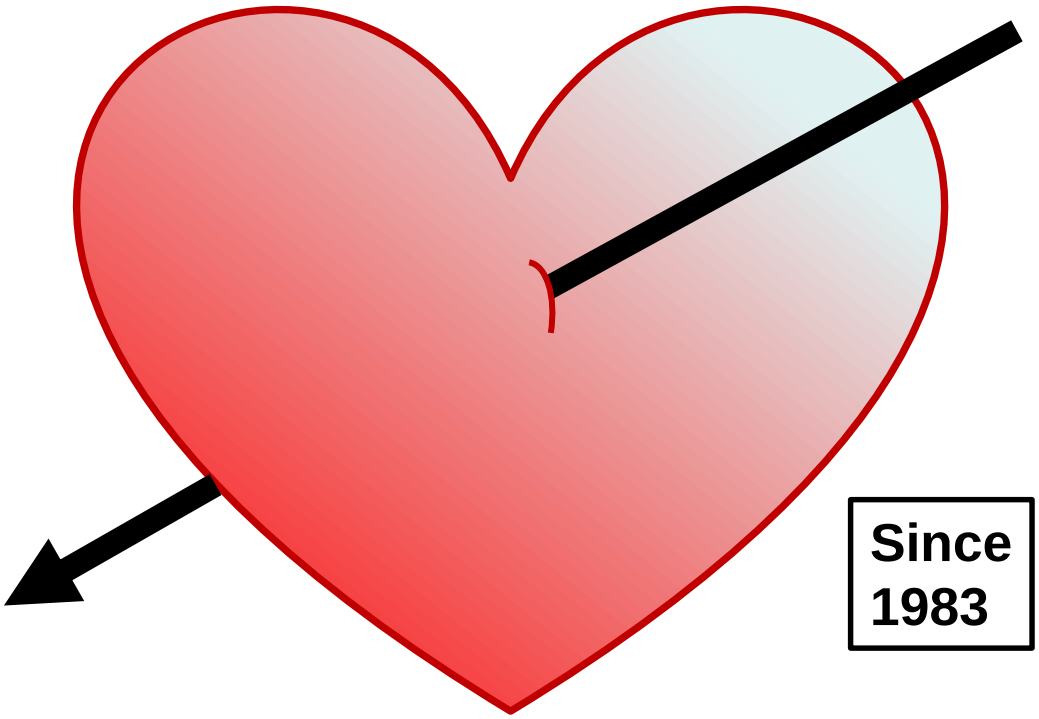
ε'/ε = QCD Penguins – Electroweak Penguin

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

Perfect Agreement!

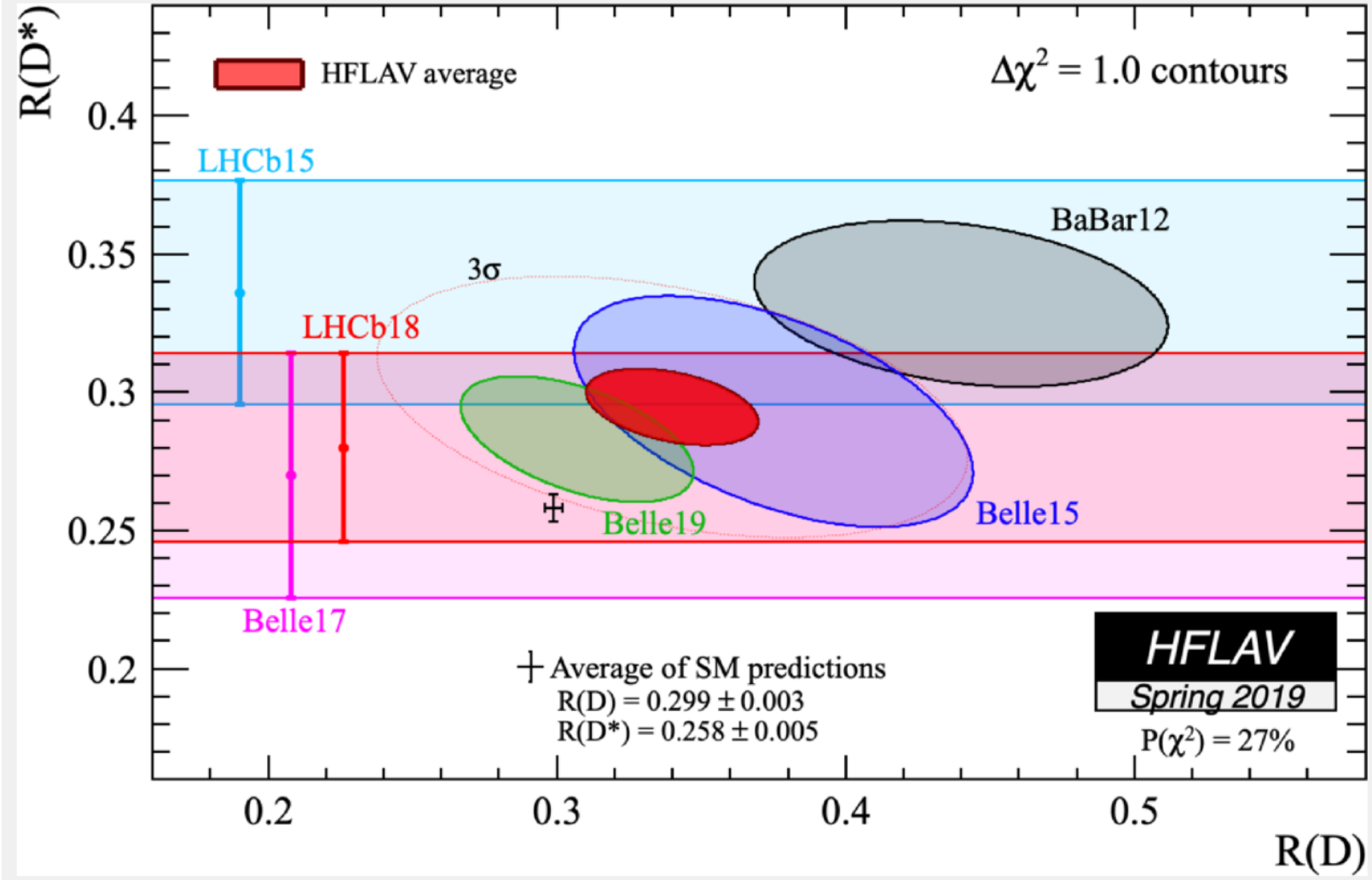
Chiral Pert Th: $\approx (-3.5 \pm 2.0) \cdot 10^{-4}$

Disagreements on QCD Penguin contribution.



$\varepsilon'/\varepsilon,\ \Delta I = 1/2$ Rule

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


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)

Kaon Flavour Physics

(2016 -)

Foto by Gurli Buras

Usual Picture of the Month

(CERN Courier)

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)