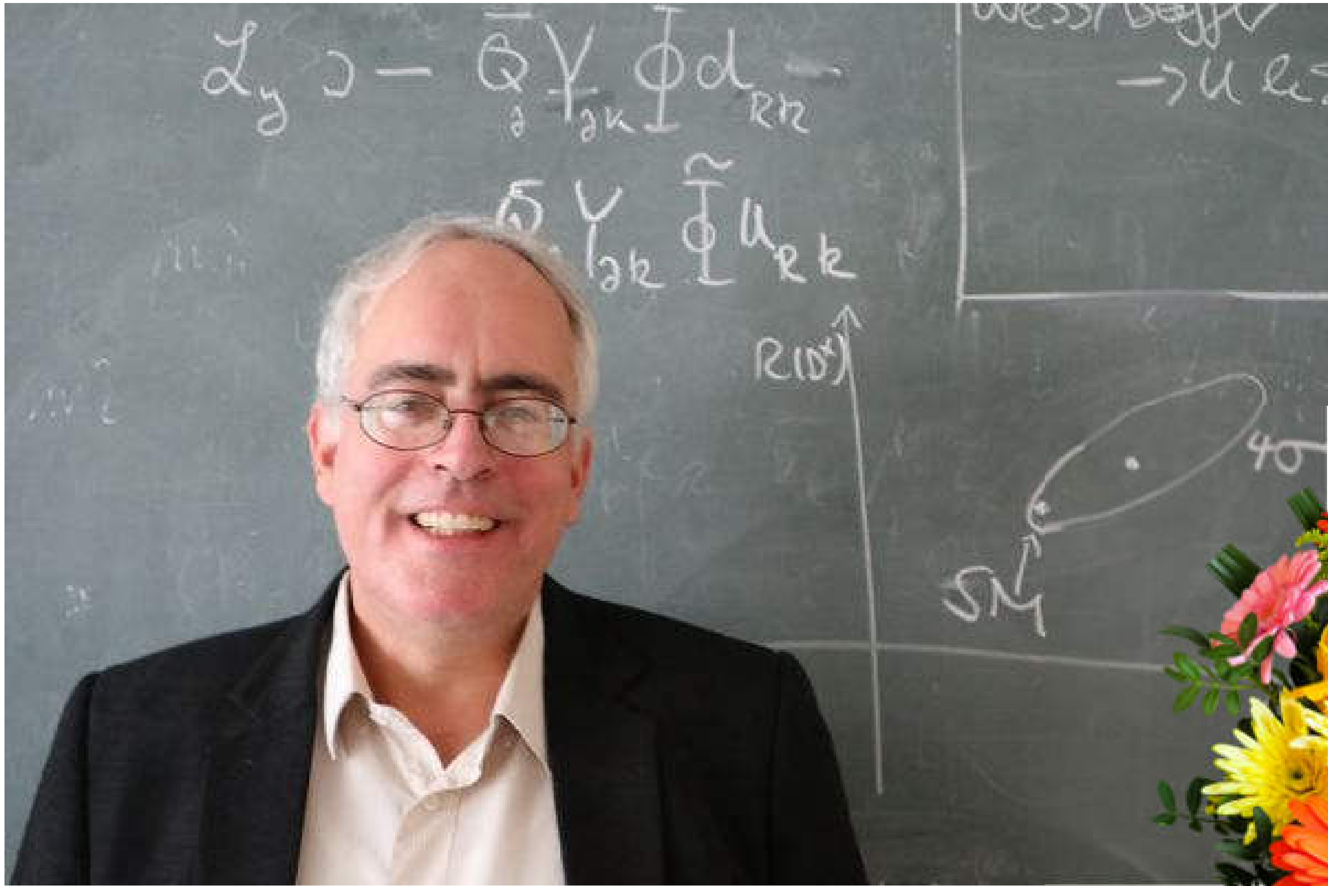
Hunting New Animalcula with Flavour Changing Processes

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

Uli Nierste 60th

(Karlsruhe, 2-3 July, 2026)



Happy Birthday Uli !

Overture

1676

A very important year for the humanity !

1676 : The Discovery of the Microuniverse (Animalcula) (The Empire of Bacteria)

10^{-6}m

Antoni van Leeuwenhoek
*24.10.1632 ✝27.08.1723

~500 Microscopes

(Magnification by ~300)

An Excursion towards 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

Most important Message from this Talk

Antoni van Leeuwenhook discovered in 1676

Animalcula

In the coming years we all expect to discover

New Animalcula beyond the Standard Model ones

with the help of **LHC** and

High Precision Experiments

Basic Question

How will these New Animalcula look like ?

New Gauge Bosons Z´, G´, W´

Vector-like Quarks and Leptons

New heavy Scalars (Supersymmetry?)

Leptoquarks: Dinosaurs of Particle Physics

Important Open Questions

1. Are there any other elementary particles and forces ?

2. What is the origin of vast differences of particle masses ? ("Flavour Problem")

$m_\nu \sim 10^{-9} m_{proton}$ $m_e \sim 10^{-3} m_{proton}$ $m_{top} \sim 10^{2} m_{proton}$

(and of the pattern of their interactions)

3. Naturalness of Electroweak Scale ?

Essential for our Existence !

4. Why is our universe dominated by matter ? (Violation of CP-Symmetry soon after BIG BANG !)

5. What is Dark Matter (25% of the Universe) ?

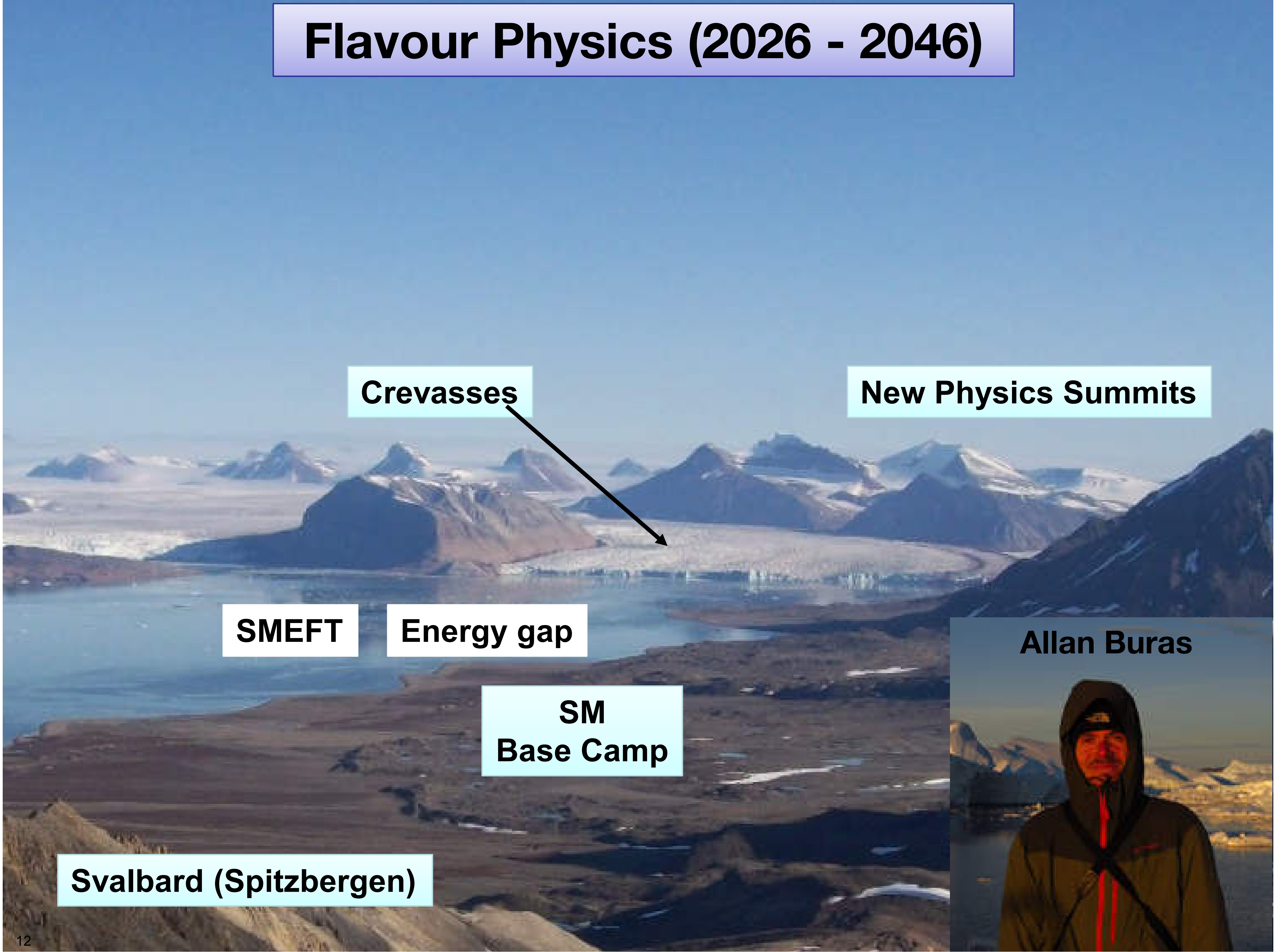
None of these questions can be answered within the Standard Model

New Physics beyond the SM must exist !!!

It is our duty to find it. If not at the LHC then through high precision experiments.

Quark Flavour Physics
Lepton Flavour Violation
EDMs + $(g-2)_{\mu,e}$

Flavour Physics (2026 - 2046)



Flavour Expedition
Attouniverse $\rightarrow$ Zeptouniverse
10^{-18}m $\rightarrow 10^{-21}$m

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

Overture Completed

Ulrich Symphony

1st Movement	:	Rare Processes: Technology to reach the Zeptouniverse
2nd Movement	:	Standard Model Predictions for Rare K and B Decays without New Physics Infection
3rd Movement	:	SMEFT at work
4th Movement	:	More Flavour News + ?

1st Movement

Rare Processes: Technology to reach the Zeptouniverse

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

Most recent

1012.1447
1204.5065

1306.3755

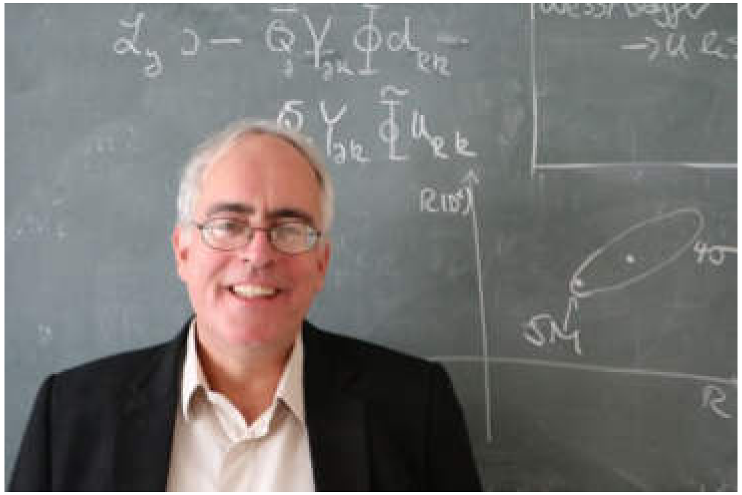
1505.00618 ⇐ Reviews

2601.03722

127 (22 F) Collaborators (18 Countries)

(Journal Papers) ⟨2⟩ per paper

(See some photos in the BACK UP)



Ulrich Nierste

Alexander Lenz
(Siegen)

Stefan Herrlich

Gaby Ostermaier

AJB+Lautenbacher+Ostermaier ($\bar{\rho}$ $\bar{\eta}$)

Many thanks for your supervision !

Charm quark contribution to K+ ---> pi+ nu anti-nu at next-to-next-to-leading order #1

Andrzej J. Buras (Munich, Tech. U.), Martin Gorbahn (Durham U., IPPP and Karlsruhe U., TTP), Ulrich Haisch (Fermilab and Zurich U.), Ulrich Nierste (Karlsruhe U., TTP and Fermilab) (Mar, 2006)

Published in: *JHEP* 11 (2006) 002, *JHEP* 11 (2012) 167 (erratum) • e-Print: hep-ph/0603079 [hep-ph]

pdf links DOI cite claim reference search 249 citations

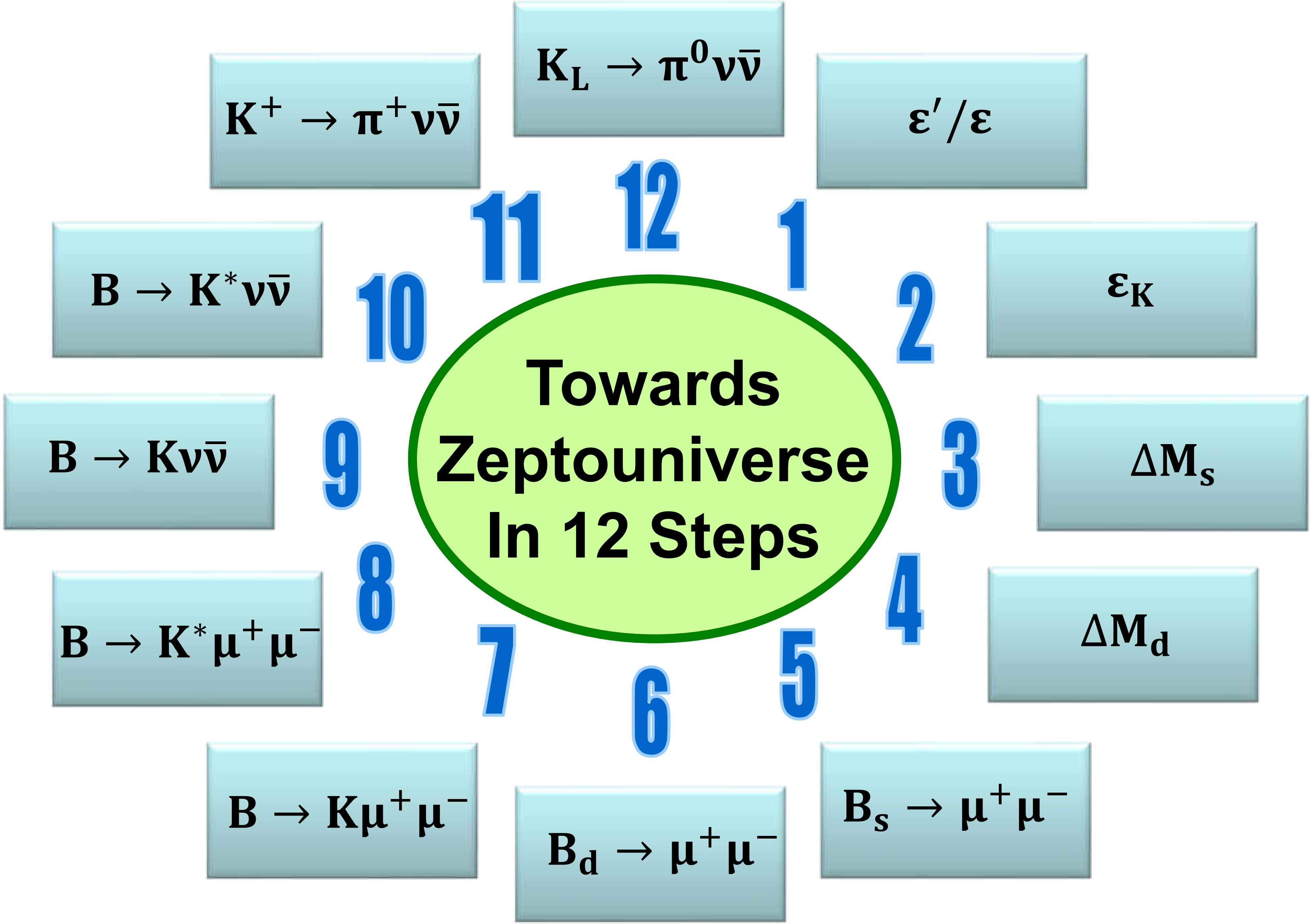
The Rare decay K+ ---> pi+ nu anti-nu at the next-to-next-to-leading order in QCD #2

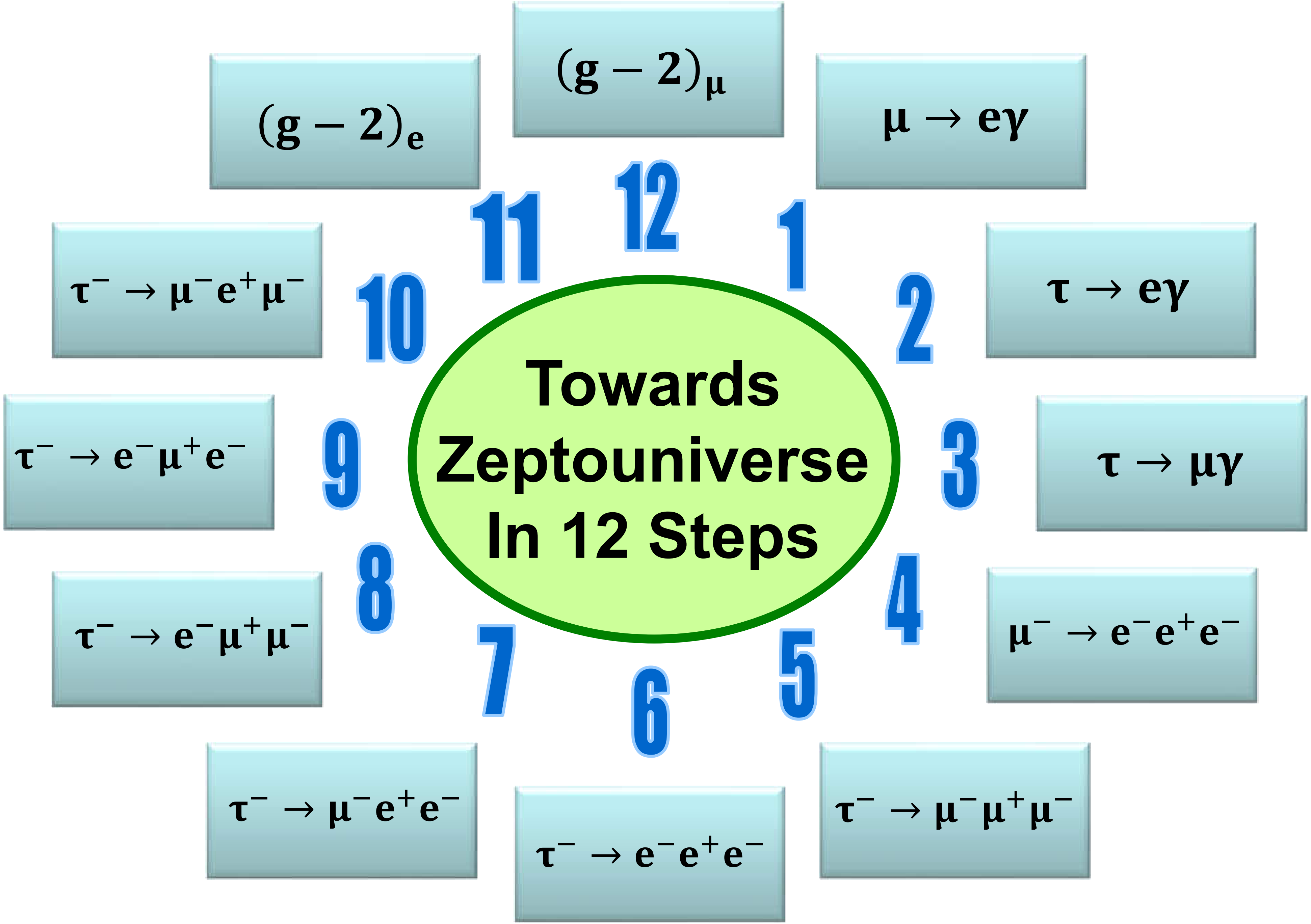
A.J. Buras (Munich, Tech. U.), M. Gorbahn (Durham U., IPPP), U. Haisch (Fermilab), U. Nierste (Fermilab) (Aug, 2005)

Published in: *Phys.Rev.Lett.* 95 (2005) 261805 • e-Print: hep-ph/0508165 [hep-ph]

pdf links DOI cite claim reference search 194 citations

Only two papers, but an important indirect impact on my research – to be presented soon !


Towards Zeptouniverse In 12 Steps
12 $K_L \to \pi^0 \nu\bar{\nu}$
1 ε'/ε
2 ε_K
3 ΔM_s
4 ΔM_d
5 $B_s \to \mu^+\mu^-$
6 $B_d \to \mu^+\mu^-$
7 $B \to K\mu^+\mu^-$
8 $B \to K^*\mu^+\mu^-$
9 $B \to K\nu\bar{\nu}$
10 $B \to K^*\nu\bar{\nu}$
11 $K^+ \to \pi^+\nu\bar{\nu}$


Towards Zeptouniverse In 12 Steps
12
$(g-2)_\mu$
1
$\mu \to e\gamma$
2
$\tau \to e\gamma$
3
$\tau \to \mu\gamma$
4
$\mu^- \to e^- e^+ e^-$
5
$\tau^- \to \mu^- \mu^+ \mu^-$
6
$\tau^- \to e^- e^+ e^-$
7
$\tau^- \to \mu^- e^+ e^-$
8
$\tau^- \to e^- \mu^+ \mu^-$
9
$\tau^- \to e^- \mu^+ e^-$
10
$\tau^- \to \mu^- e^+ \mu^-$
11
$(g-2)_e$

Towards Zeptouniverse In 12 Steps

1. $K_S \rightarrow \mu^+\mu^-$
2. $K_L \rightarrow \mu^+\mu^-$
3. $K_L \rightarrow \pi^0\mu^+\mu^-$
4. $B \rightarrow X_S\gamma$
5. $B \rightarrow \pi\pi$
6. $B \rightarrow \pi K$
7. $B \rightarrow KK$
8. EDM
9. $K_L \rightarrow \mu^+e^-$
10. $B_s \rightarrow \tau^+e^-$
11. $B_d \rightarrow K\tau^+\mu^-$
12. $B_d \rightarrow K^*\tau^+\mu^-$

And now comes …

Indirect Impact of Uli on my Research

DNA of a Theory

Basic Idea

AJB + Jennifer Girrbach-Noe

Look at various observables and identify

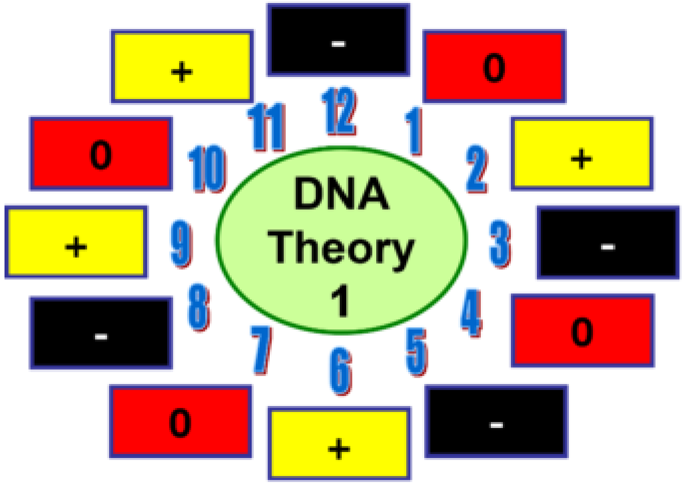
+	0	-
Increase of probability	No change	Decrease of probability

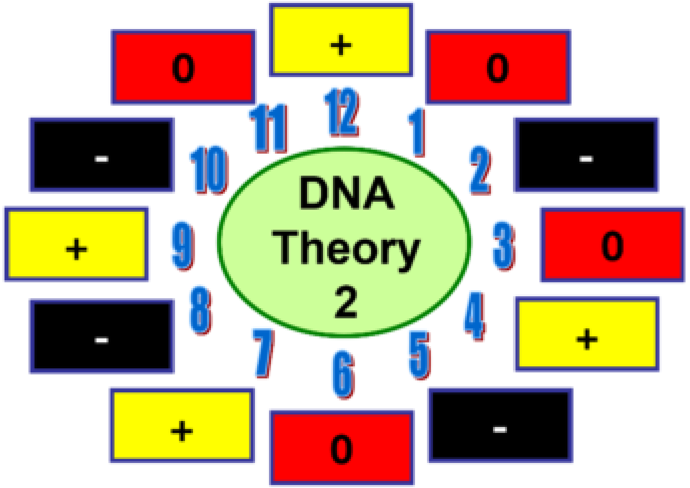
relative

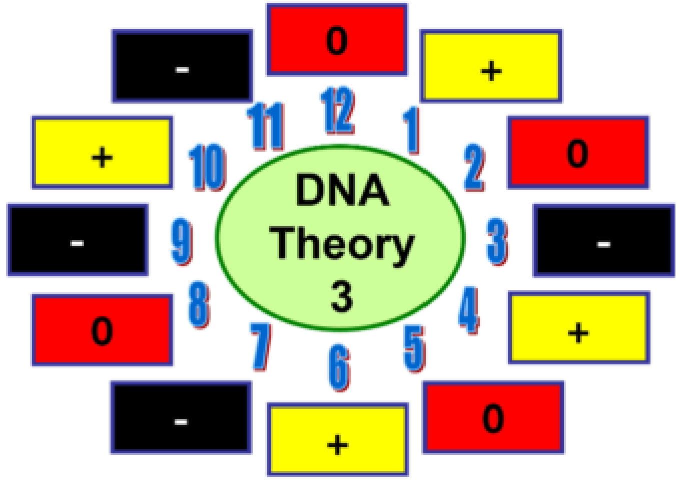
to the Standard Model

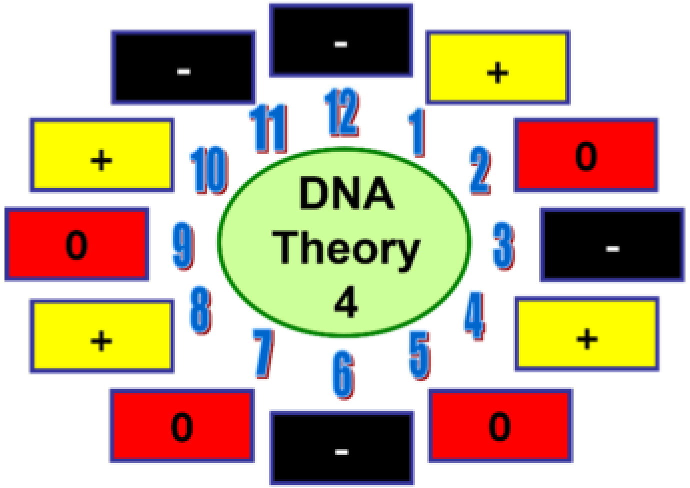
2013

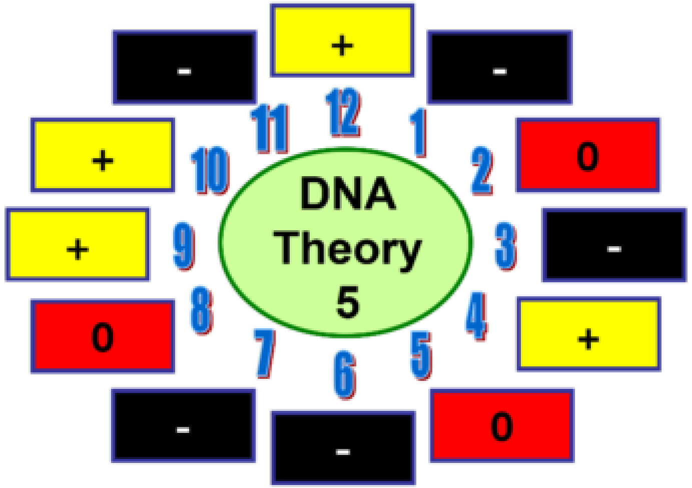
1306.3775
2403.02387

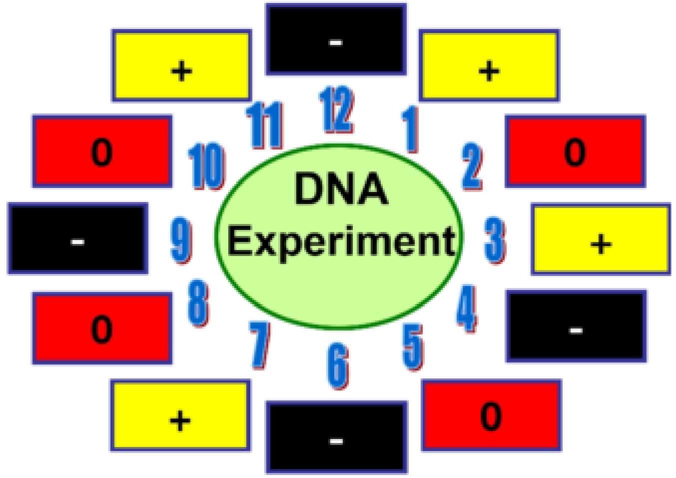

DNA
Theory
1


DNA
Theory
2

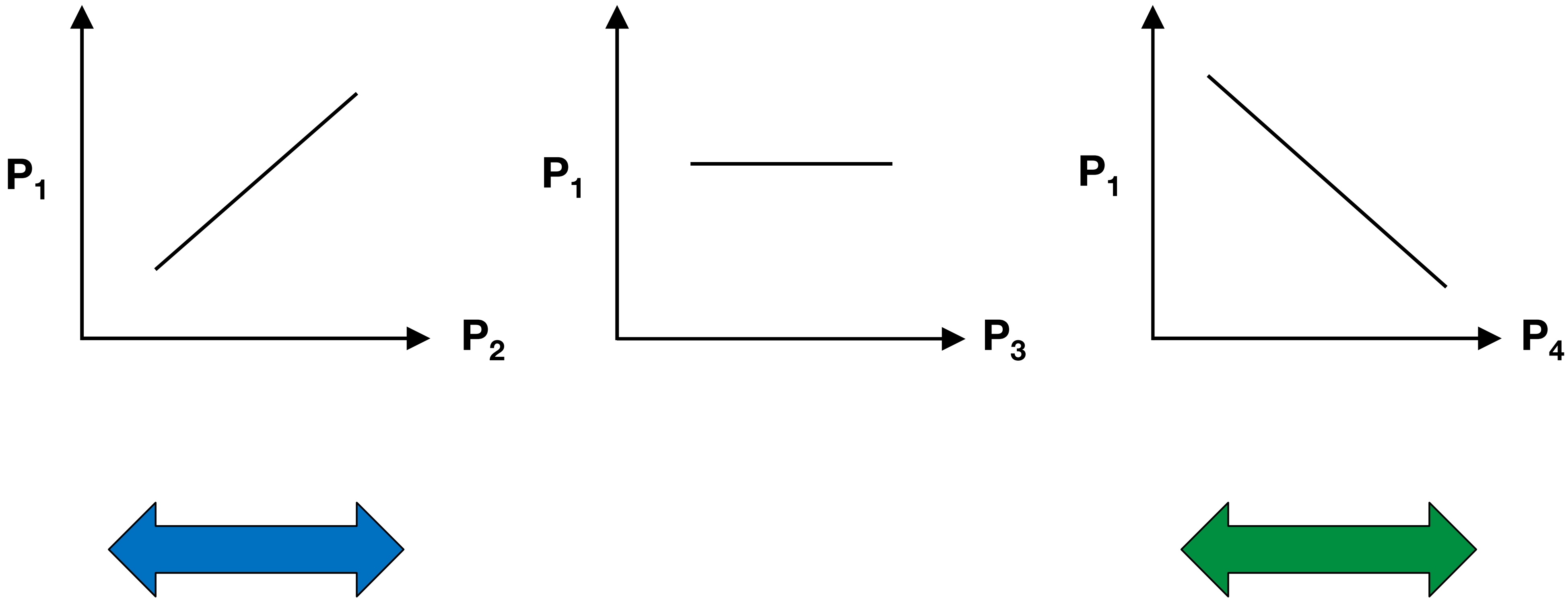

DNA
Theory
3


DNA
Theory
4


DNA
Theory
5

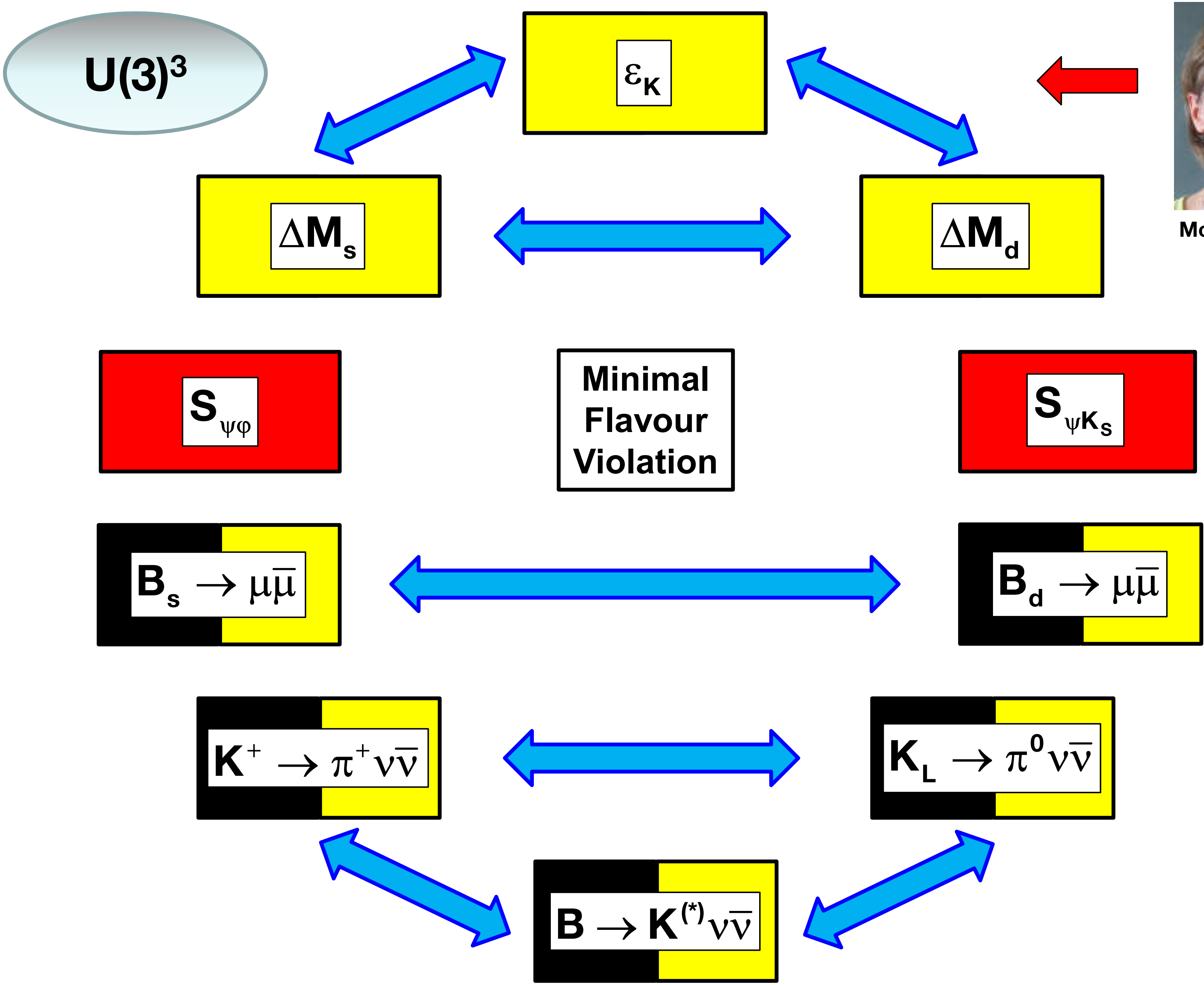

DNA
Experiment

Correlations and Anti-Correlations

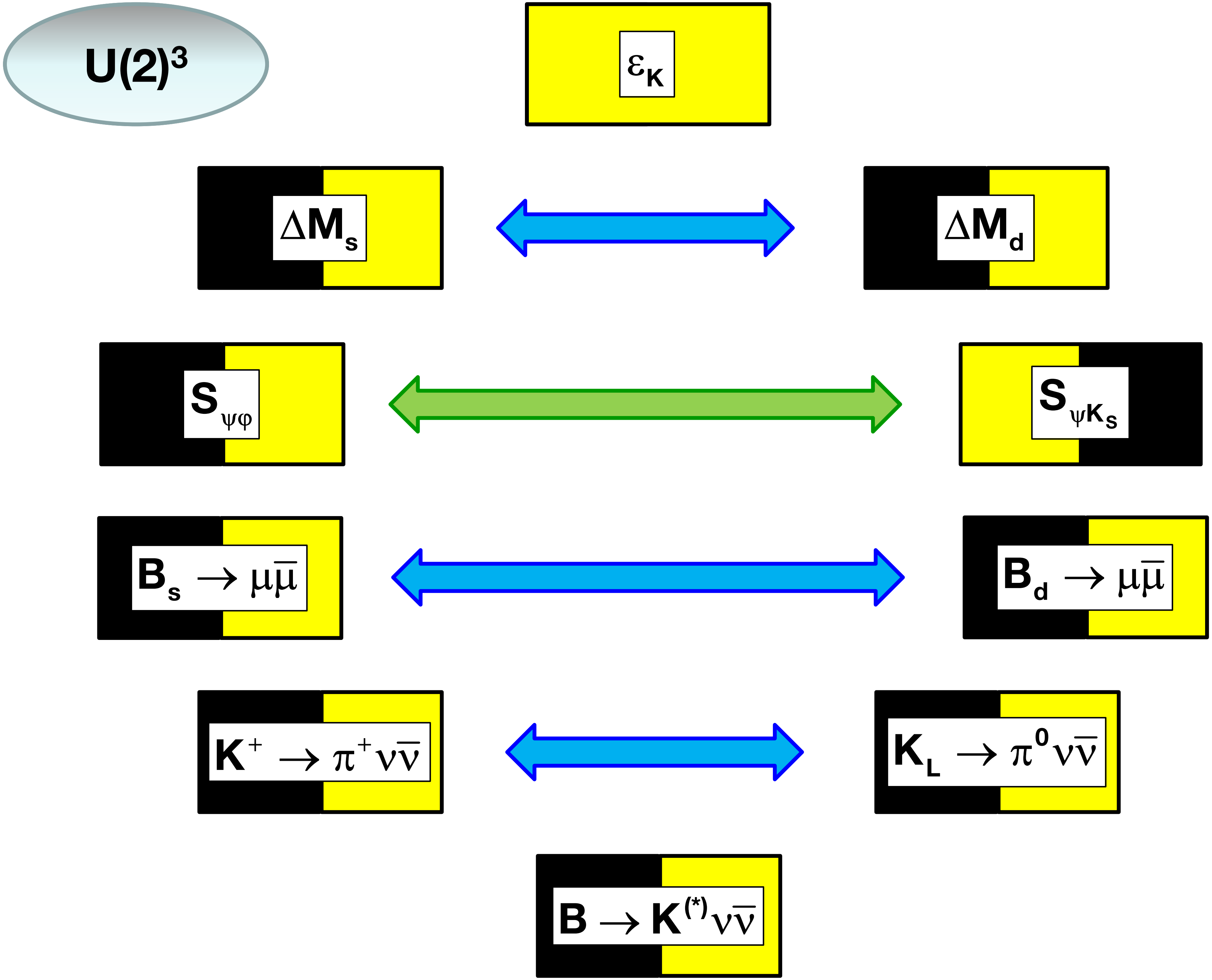


Correlation

Anti-Correlation

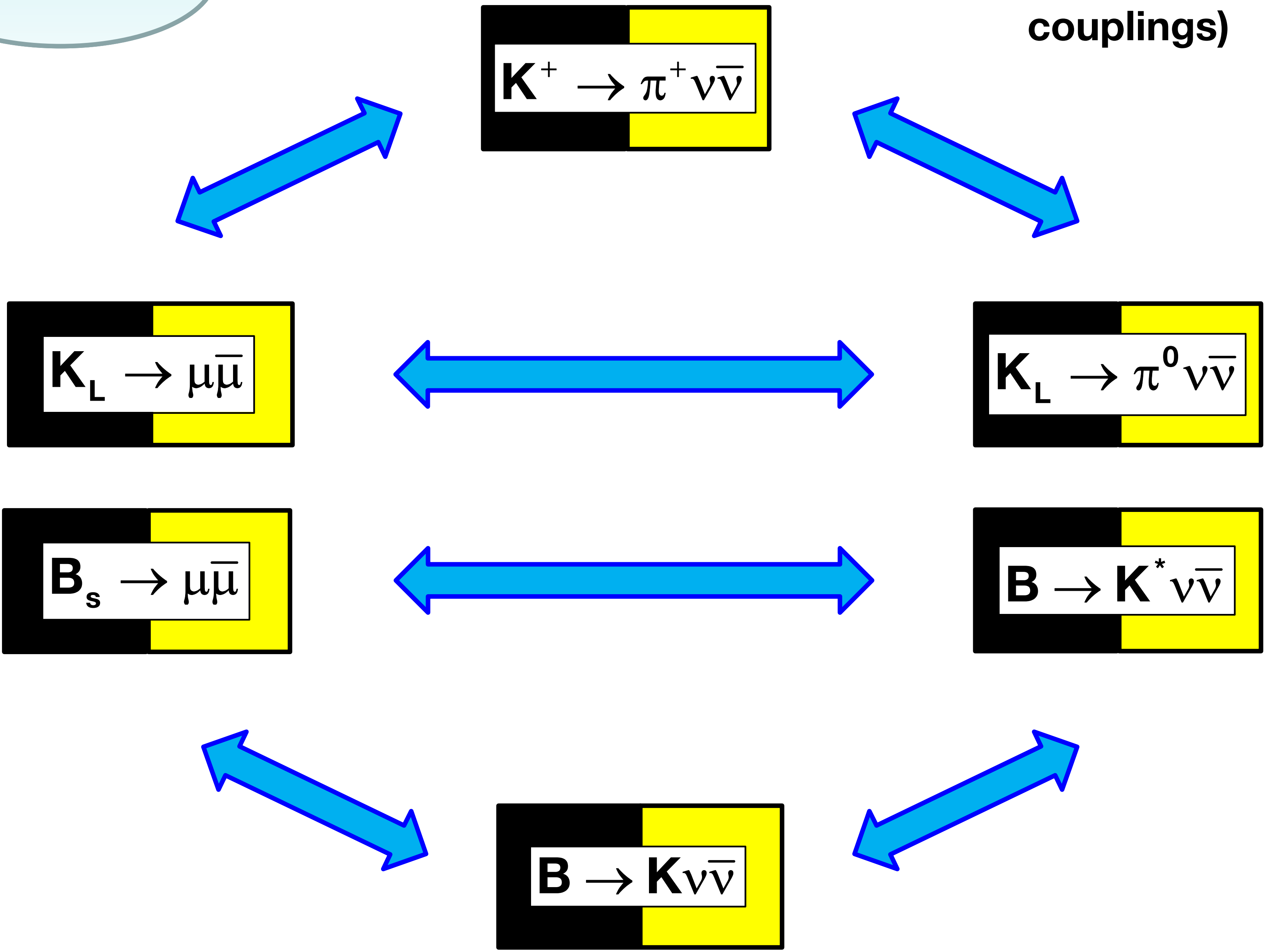


Monika Blanke


U(2)^3
ε_K
ΔM_s
ΔM_d
$S_{\psi\varphi}$
$S_{\psi K_S}$
$B_s \to \mu\bar{\mu}$
$B_d \to \mu\bar{\mu}$
$K^+ \to \pi^+ \nu\bar{\nu}$
$K_L \to \pi^0 \nu\bar{\nu}$
$B \to K^{(*)} \nu\bar{\nu}$

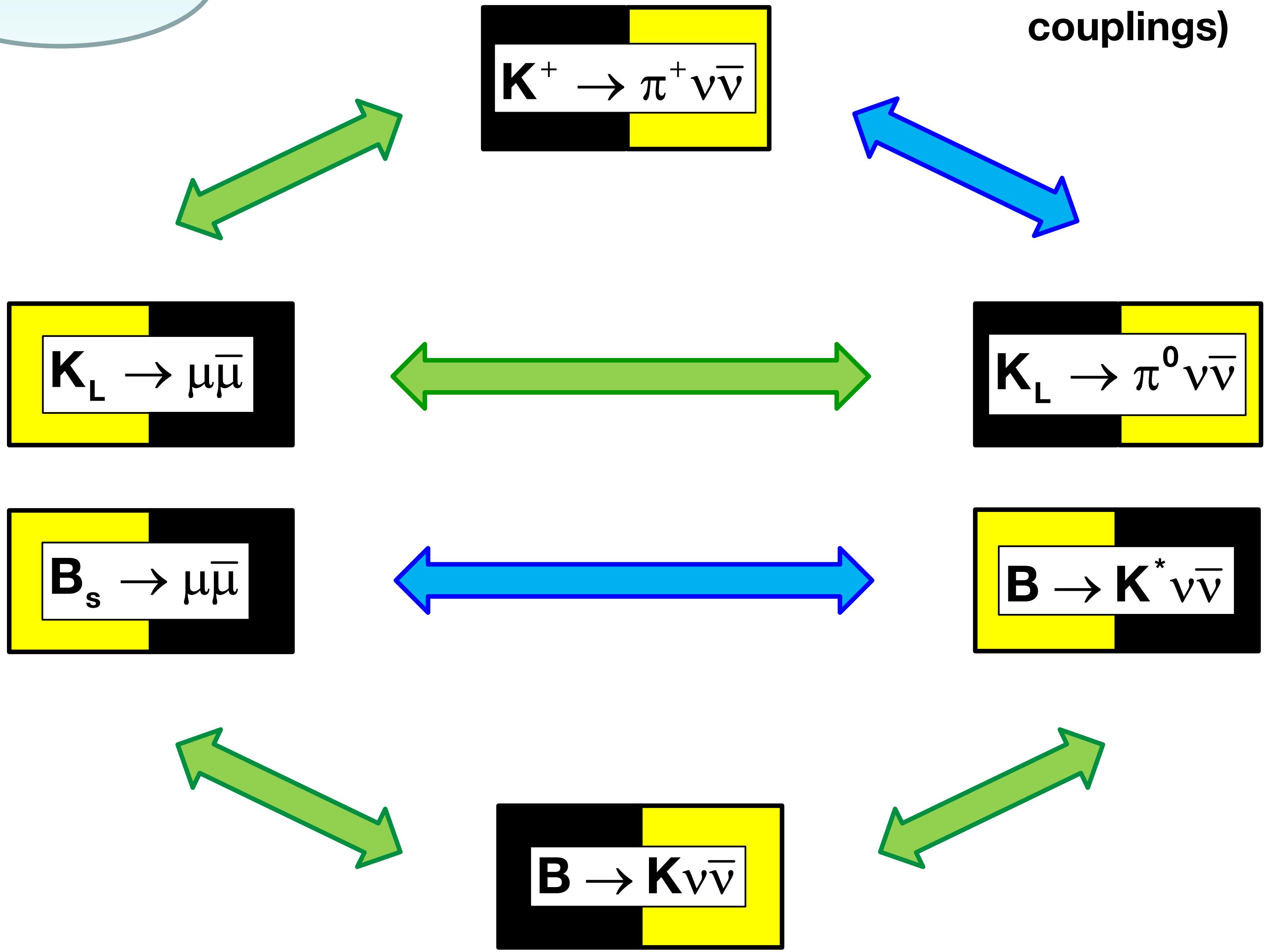
Z′ LHS

(Left-handed couplings)



Z´ RHS

(Right-handed couplings)



2nd Movement: Standard Model Predictions for Rare K and B Decays without New Physics Infection

General Expression for Branching Ratios in the Standard Model

Calculable in the SM

Br (Decay) = [CKM factor] · [Hadronic Matrix Element] · [Perturbative Calculation LO, NLO, NNLO]

Not predicted by SM

Lattice QCD
HQEFT
Dual QCD
ChPT

Presently known with high precision

AJB: Book, Review in Physics Reports (1102.5650v6)

If CKM parameters are determined in a global fit that includes processes which are infected by New Physics, the resulting BR cannot be considered as genuine SM predictions.

AJB: 2209.03968

Suggested Strategy

AJB	0303060
AJB+E.Venturini	2109.11032
"	2203.11960
AJB	2209.03968

Step 1

Remove CKM dependence by calculating suitable ratios of branching ratios to ΔM_d, ΔM_s, $|\varepsilon_k|$

⇒ **CKM can be fully eliminated for all rare B decays. For K decays only the dependence on β remains. (γ dependence irrelevant!!)**

Step 2

β

No New Physics!

Set ΔM_d, ΔM_s, ε_k and $S_{\psi K_S}$ to experimental values ($\Delta F=2$)

⇒ **Very precise predictions for rare decays branching ratios independent of CKM parameters!**

Step 3

Rapid test of New Physics infection in the $\Delta F=2$ sector using $|V_{cb}|$ - γ plots

BV1 + BV2
+
AJB 2204.10337

Step 4

Determination of CKM parameters from $\Delta F=2$ only.

Advantages over full global fits

A. $\Delta F = 2$ sector appears to be free of NP infection:
NP is not required.

B. The remaining observables outside the "$\Delta F = 2$ archipelago" that could be infected by NP can be predicted within the SM and the pulls can be better estimated.

C. $|V_{cb}|$ and $|V_{ub}|$ tensions can be avoided.

Standard Model Predictions for Rare K and B Decays without $|V_{cb}|$ uncertainties and New Physics Infection

but with

E. Venturini

$|V_{cb}|$ Tension

$|V_{cb}|_{inclusive} = (41.97 \pm 0.48) \cdot 10^{-3}$ Finauri & Gambino (2310.20234)

$|V_{cb}|_{exclusive} = (39.21 \pm 0.62) \cdot 10^{-3}$ (FLAG) (2022)

(see also Bordone, Gubernari, van Dyk, Jung (1912.09335)
Bordone, Capdevilla, Gambino (2107.00604)

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% $\left(K_L \to \pi^0\nu\bar{\nu}, K_S \to \mu^+\mu^-\right)$

$|V_{cb}|$ tension is a $\boxed{\text{disaster}}$ 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 $\boxed{\text{disaster}}$ 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.

Basic Strategy for Rare B and K Decays

AJB + E. Venturini (2109.11032)

1. **Use as basic parameters**

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

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

3. **16 Ratios involving**

$$\left.\begin{array}{l} B_s \to \mu^+\mu^-,\ B_d \to \mu^+\mu^- \\ B^+ \to K^+\nu\bar{\nu},\ B^0 \to K^{0*}\nu\bar{\nu} \\ K^+ \to \pi^+\nu\bar{\nu},\ K_L \to \pi^0\nu\bar{\nu},\ K_S \to \mu^+\mu^- \\ |\varepsilon_K|,\ \Delta M_d,\ \Delta M_s \end{array}\right\}$$

★

Once γ and β will be precisely measured very good test of SM

Additional ratios with $B \to K(K^*)\mu^+\mu^-$, $B_s \to \varphi\mu^+\mu^-$ in 2209.03968

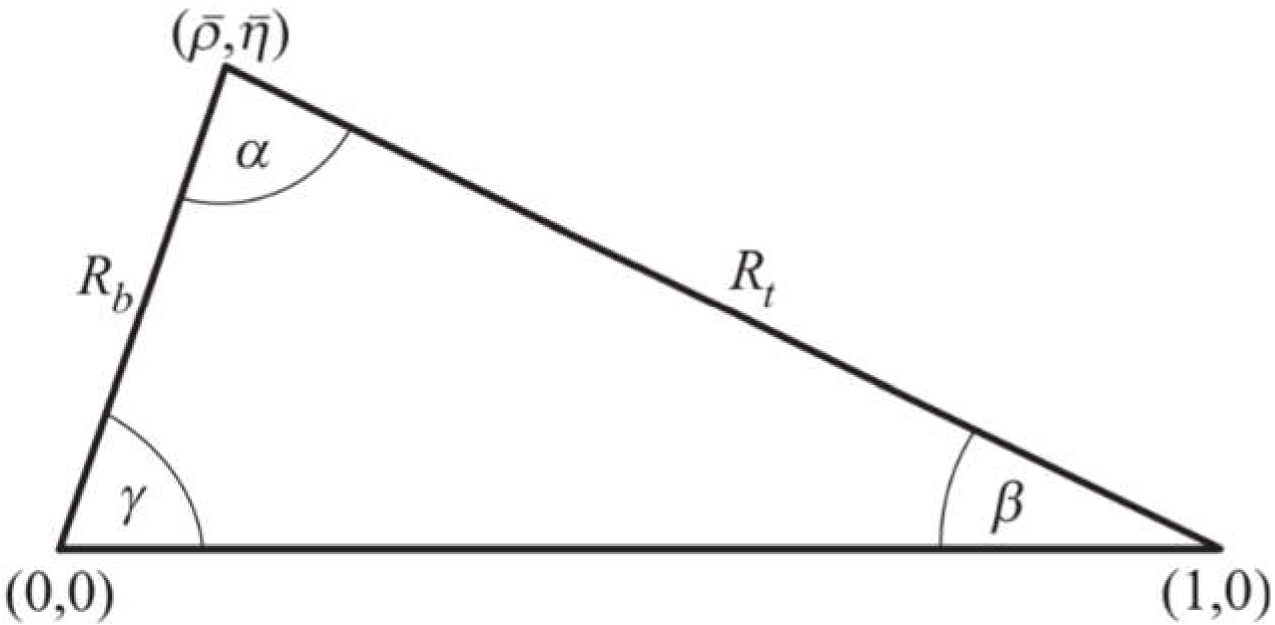
Recommended Parametrization of CKM Matrix

50th Anniversary in 2023

$V_{us}, \ V_{cb}, \ \beta, \ \gamma$

AJB, Parodi, Stocchi (0207101)

(β, γ) Strategy: Most efficient to find UT



$$\bar{\rho} = \frac{\sin\beta \ \cos\gamma}{\sin(\beta+\gamma)}$$

$$\bar{\eta} = \frac{\sin\beta \ \sin\gamma}{\sin(\beta+\gamma)}$$

AJB: 2305.00021

"Critical Exponents" of Flavour Physics

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

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

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

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

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

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

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

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

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

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

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

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

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

AJB + E. Venturini (B-K Correlations)

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

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

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

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

V_{cb}-independent correlations between K and B Decays

C_i = CKM independent known factors

The Story of $B_s \to \mu^+\mu^-$ continues (SM)

$$\overline{\mathrm{Br}}(B_s \to \mu^+\mu^-) = (3.78 \pm 0.12) \cdot 10^{-9}$$

AJB + Venturini
2203.11960

$$\overline{\mathrm{Br}}(B_s \to \mu^+\mu^-) = (3.45 \pm 0.29) \cdot 10^{-9}$$

HFLAV
(CMS, LHCb, ATLAS)

$$\overline{\mathrm{Br}}(B_s \to \mu^+\mu^-) = (3.47 \pm 0.14) \cdot 10^{-9}$$

UTfitter
2212.1051

Theory SM :

Buchalla + AJB (1993, 1998)
Misiak + Urban (1998)
} NLO QCD

Bobeth, Gorbahn, Stamou (2013) NLO EW
Hermann, Misiak, Steinhauser (2013) NNLO QCD
Beneke, Bobeth, Szafron (2017, 2019) QED

Important V_{cb} – Independent Formulae

AJB + E. Venturini (2109.11032)

$$\frac{Br(K^+\to\pi^+\nu\bar\nu)}{|\varepsilon_K|^{0.82}} = (1.\mathbf{27}\pm 0.06)\cdot 10^{-8}\left[\frac{\sin 22.\mathbf{6}}{\sin\beta}\right]^{0.71}\left[\frac{\sin\gamma}{\sin 64.\mathbf{6}\,°}\right]^{0.015}$$

$$\frac{Br(K_L\to\pi^0\nu\bar\nu)}{|\varepsilon_K|^{1.18}} = (\mathbf{4.03}\pm 0.\mathbf{21})\cdot 10^{-8}\left[\frac{\sin\beta}{\sin 22.\mathbf{6}}\right]^{0.98}\left[\frac{\sin\gamma}{\sin 64.\mathbf{6}\,°}\right]^{0.030}$$

Note: practically γ-independent

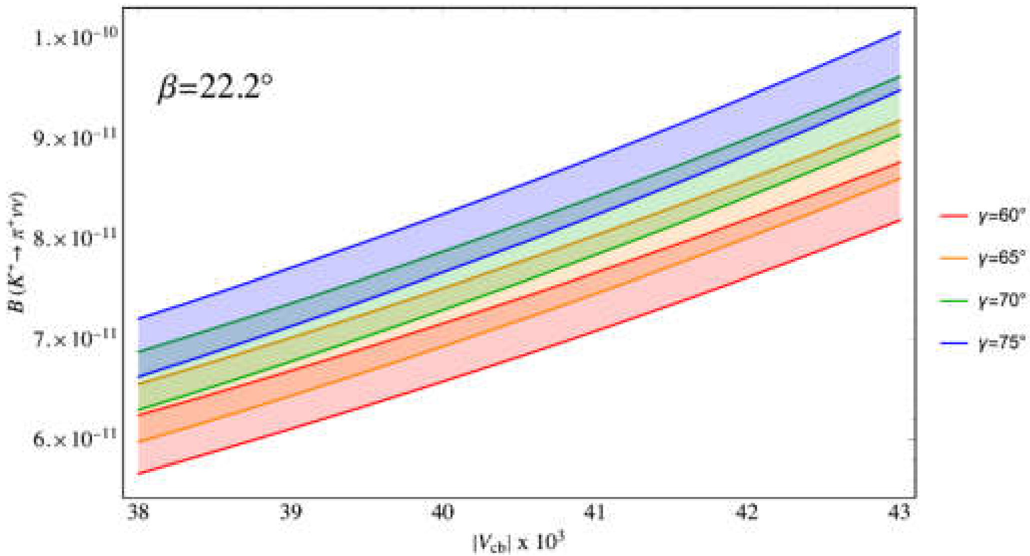
$$\left\{\left|\varepsilon_K\right|_{\rm exp},\, S^{\rm exp}_{\psi K_s} = \sin 2\beta\right\} \Rightarrow \left\{\begin{array}{l}\text{Most accurate}\\ \text{Predictions to}\\ \text{date}\end{array}\right\}$$

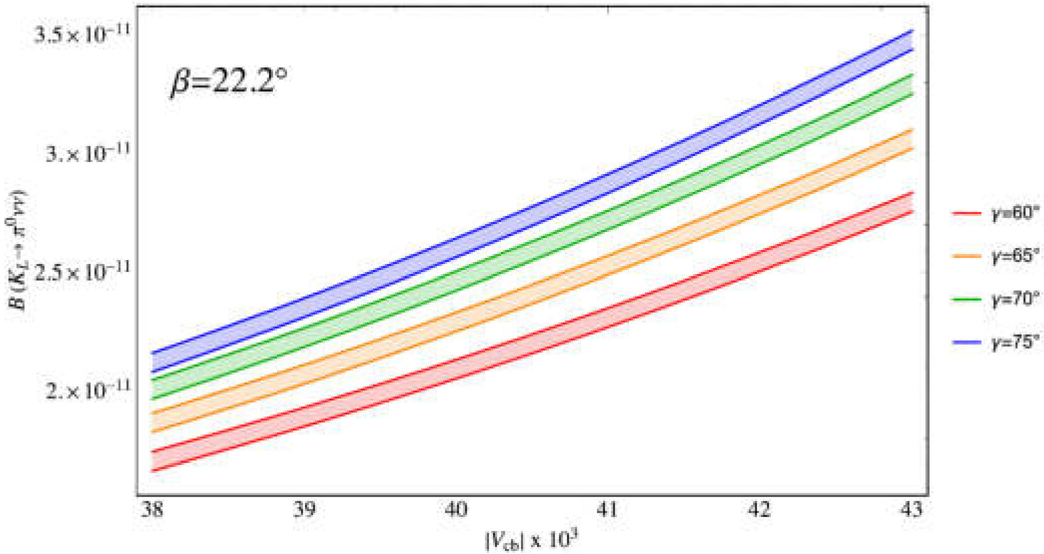
14 additional ratios in 2109.11032

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

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

AJB + E. Venturini (2109.11032) (Update 2026)





$$Br(K^+ \to \pi^+ \nu\bar{\nu})_{\mathrm{exp}} = \left(9.6^{+1.9}_{-1.8}\right) \cdot \mathbf{10^{-11}}$$

NA62

$$\boldsymbol{Br\left(K_L \to \pi^0 \nu\bar{\nu}\right)_{exp} \leq 2.0 \cdot 10^{-9}}$$

KOTO

$$\mathbf{Br}\left(\mathbf{K}^+ \to \pi^+ \nu\bar{\nu}\right)_{\mathbf{SM}} = \left(\mathbf{8.65 \pm 0.42}\right) \cdot \mathbf{10^{-11}}$$

V_{cb} and γ independent

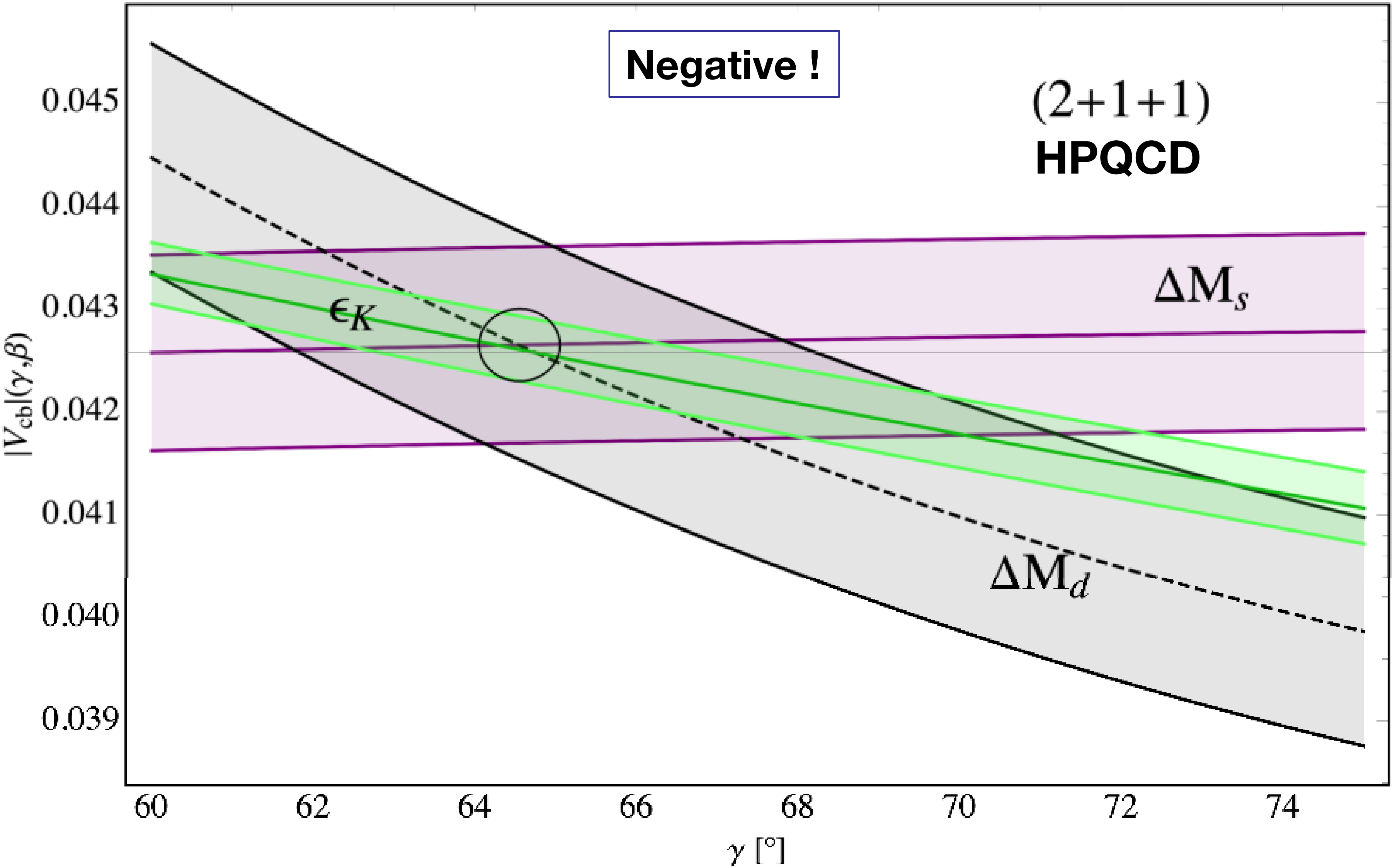
See also Gorbahn, Stamou et al Kaon 25

$$\boldsymbol{Br\left(K_L \to \pi^0 \nu\bar{\nu}\right)_{SM} = (3.05 \pm 0.17) \cdot 10^{-11}}$$

$|V_{cb}|$ - γ Plot = Rapid Test

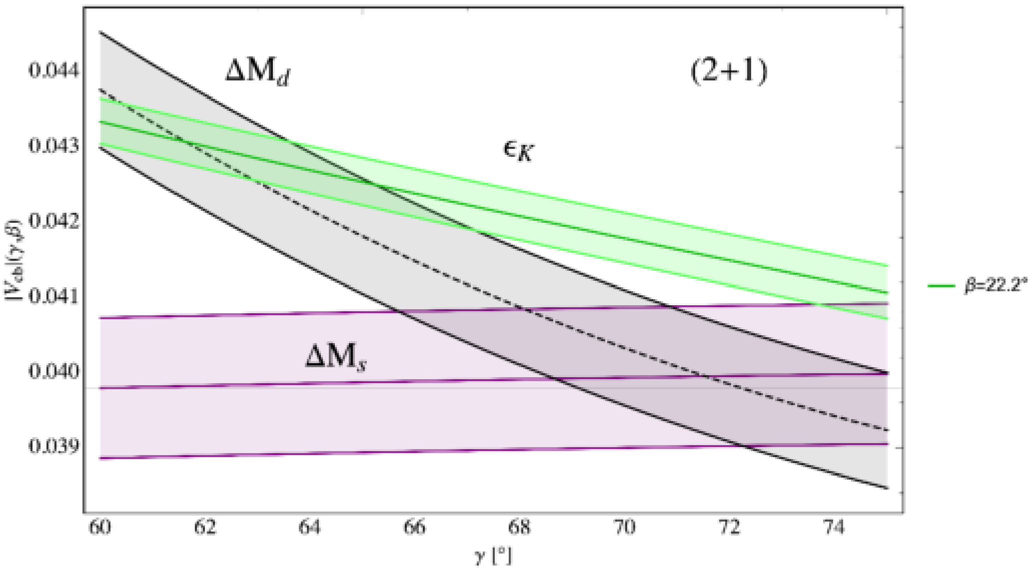
Perfect consistency between ΔM_s, ΔM_d, ε_K, $S_{\psi K}$

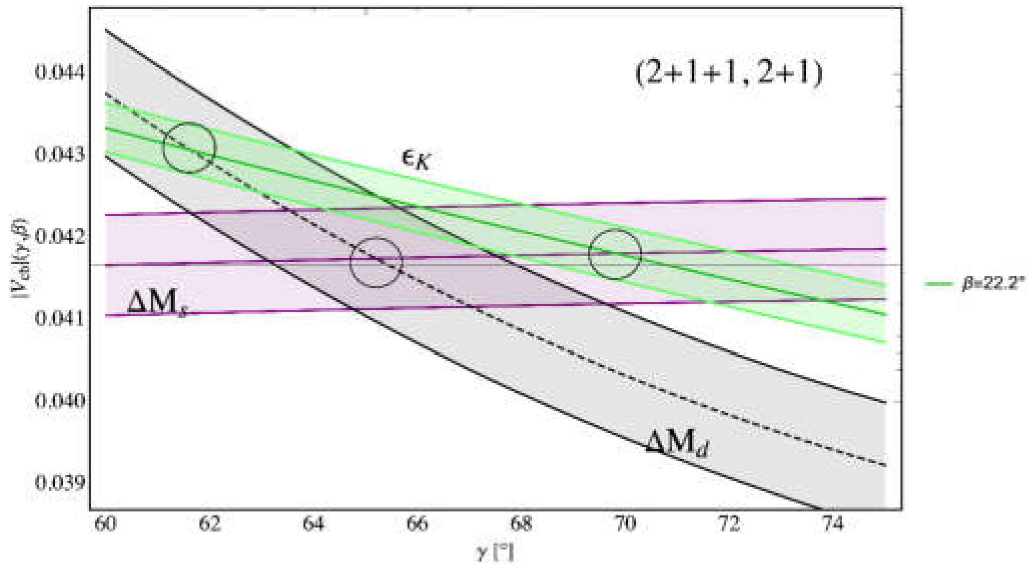
AJB + Venturini 2203.11960



Positive Tests

AJB + Venturini 2203.11960





Precise Lattice QCD and higher order QCD calculations are necessary to make the rapid tests reliable!

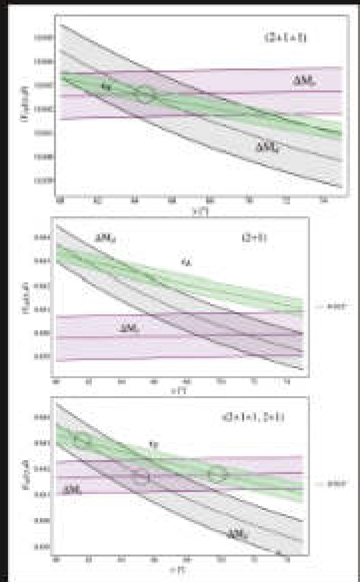
<u>Rapid Test</u>: cover picture of EPJC Vol. 83 number 1, January 2023

The European Physical Journal volume 83 · number 1 · january · 2023

EPJ C

Recognized by European Physical Society

Particles and Fields



Three rapid tests of NP infection in the $\Delta F = 2$ sector as explained in the text. The values of $|V_{cb}|$ extracted from ε_K, ΔM_d and ΔM_s as functions of γ. 2 + 1 + 1 flavours (top), 2 + 1 flavours (middle), average of 2 + 1 + 1 and 2 + 1 cases (bottom). The green band represents experimental $S_{\psi K_S}$ constraint on β

From Andrzej J. Buras on: Standard Model predictions for rare K and B decays without new physics infection. Eur. Phys. J. C 83, 66 (2023).

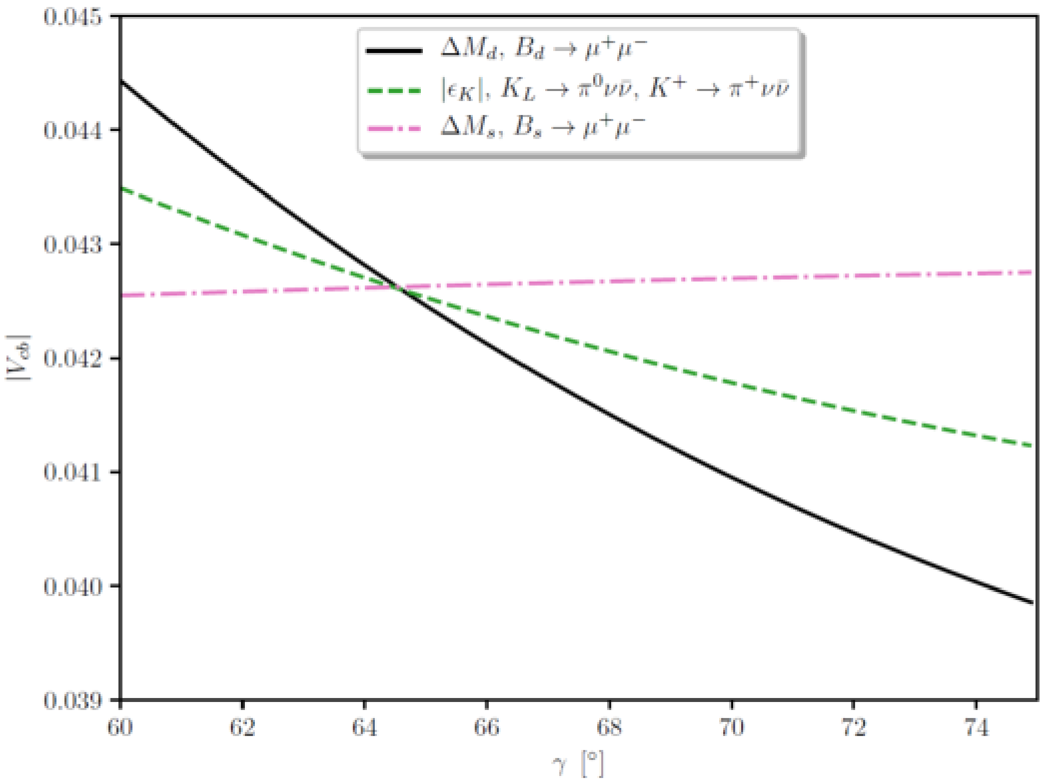
Società Italiana di Fisica

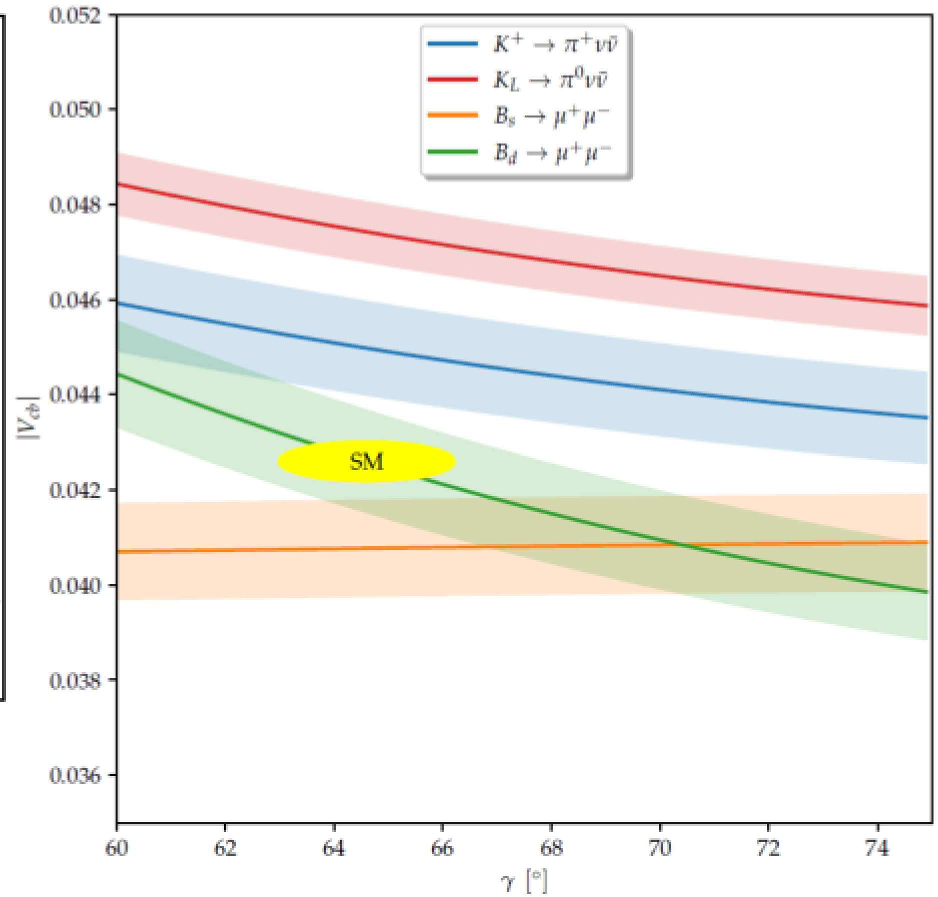
Springer

SM without uncertainties

Impact of New Physics

V_{cb} - γ Plot





Superior over UT-triangle plots: $|V_{cb}|$ seen, γ better exposed
AJB 2204.10337

See CERN Courier July/Aug 2024
AJB

3rd Movement

SMEF at Work

Recent Review: J. Aebischer, AJB, J. Kumar
2507.05926

NLO QCD in WET and SMEFT (in Homeoffice)

WET $\mu \leq \mathrm{EW}$ $SU(3)_c \otimes U(1)_{QED}$

SM + New Physics Operators

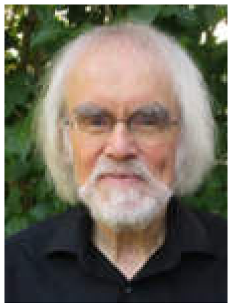
$\Delta F = 1$ (Non-Leptonic) J. Aebischer, C. Bobeth, AJB, J. Kumar, M. Misiak
(2107.10262) (2107.12391) (ε'/ε)

$\Delta F = 2$ (Non-Leptonic) J. Aebischer, C. Bobeth, AJB, J. Kumar
(2009.07276)

SMEFT $\mu \geq \mathrm{EW}$

$\Delta F = 2$ (Non-Leptonic) J. Aebischer, AJB, J. Kumar
(2203.11224) (2202.01225)


J. Aebischer


AJB


J. Kumar


Christoph Bobeth


M. Misiak

Main Activities in the Homeoffice in Ottobrunn

B Physics without NP in Quark Mixing

Fine tuning in ΔM_q q=d,s

suppression factor

$$\mathbf{M_{12}(Z')} \sim \left[1 + \left(\frac{\Delta_R^{bq}(Z')}{\Delta_L^{bq}(Z')}\right)^2 + 2K_{bq}\frac{\Delta_R^{bq}}{\Delta_L^{bq}}\right]\frac{\Delta_L^{bq}(Z')}{M_{Z'}^2}$$

$$K_{bq} = \frac{\left\langle \hat{Q}_1^{LR}(M_{Z'})\right\rangle^{bq}}{\left\langle \hat{Q}_1^{VLL}(M_{Z'})\right\rangle^{bq}} \approx -5$$

$$\boxed{\Delta_R^{bq}(Z') \approx 0.1\,\Delta_L^{bq}(Z')}$$

AJB, De Fazio, Girrbach-Noe 1404.3824
AJB, Buttazzo, Girrbach-Noe 1408.0728
Crivellin, Hofer, Matias, Nierste, Pokorski, Rosiek 1504.07928

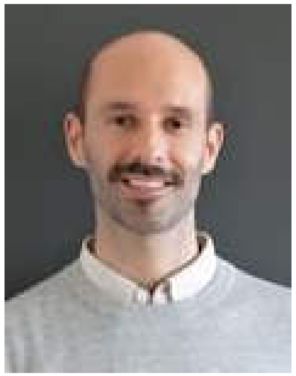
Strong Suppression of Z′ to $B_s - \bar{B}_s$ Mixing

Requires $\boxed{\Delta_R^{bs}(Z') \approx 0.1\, \Delta_L^{bs}(Z')}$ **Non-negligible RH couplings**

Implications for rare B-Decays

- **Suppression of** $B^+ \to K^+\mu^+\mu^-, B_s \to \varphi\mu^+\mu^-, B \to K^*\mu^+\mu^-$

+ **Enhancement of** $B^+ \to K^+\nu\bar{\nu}, B^0 \to K^0\nu\bar{\nu}$ **up to 20%**

AJB +  **(2412.14254)**

Peter Stangl

News from Belle II

(2311.14647)

$$\mathbf{Br(B^+ \to K^+ \nu\bar{\nu}) = (13 \pm 4) \cdot 10^{-6}}$$

*)

+

$$\mathbf{Br(B^+ \to K^+ \nu\bar{\nu})_{SM} = (4.92 \pm 0.30) \cdot 10^{-6}}$$

AJB + Stangl (2024)

News from CERN (LHCb, CMS, ATLAS)

-

$$\overline{\mathbf{Br}}(\mathbf{B_s \to \mu^+\mu^-}) = \mathbf{(3.45 \pm 0.29) \cdot 10^{-9}}$$

$$\overline{\mathbf{Br}}(B_s \to \mu^+\mu^-)_{\mathbf{SM}} = \mathbf{(3.78 \pm 0.12) \cdot 10^{-9}}$$

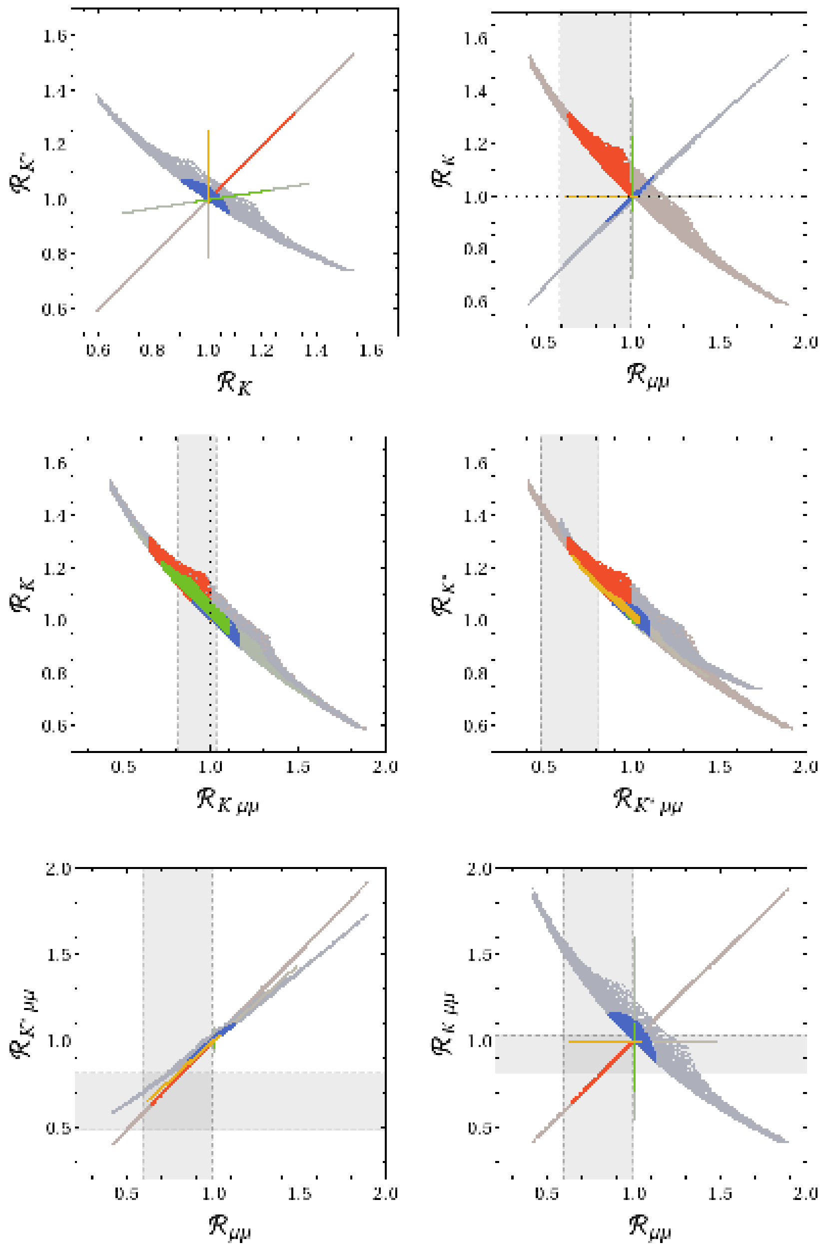
AJB + Venturini (2022)

*) Many analyses:

Bause et al. (2309.00075)
Becirevic et al. (2301.06990, 2309.02246)
Dreiner et al. (2309.03727)
He et al. (2309.12741)

Testing Z´ Couplings (1409.4557) 2014

AJB, J. Girrbach-Noe, C. Niehoff, D. Straub



Left-handed

Right-handed

Excluded

$$R_K = \frac{Br(B \to K\nu\bar{\nu})}{Br(B \to K\nu\bar{\nu})_{SM}}$$

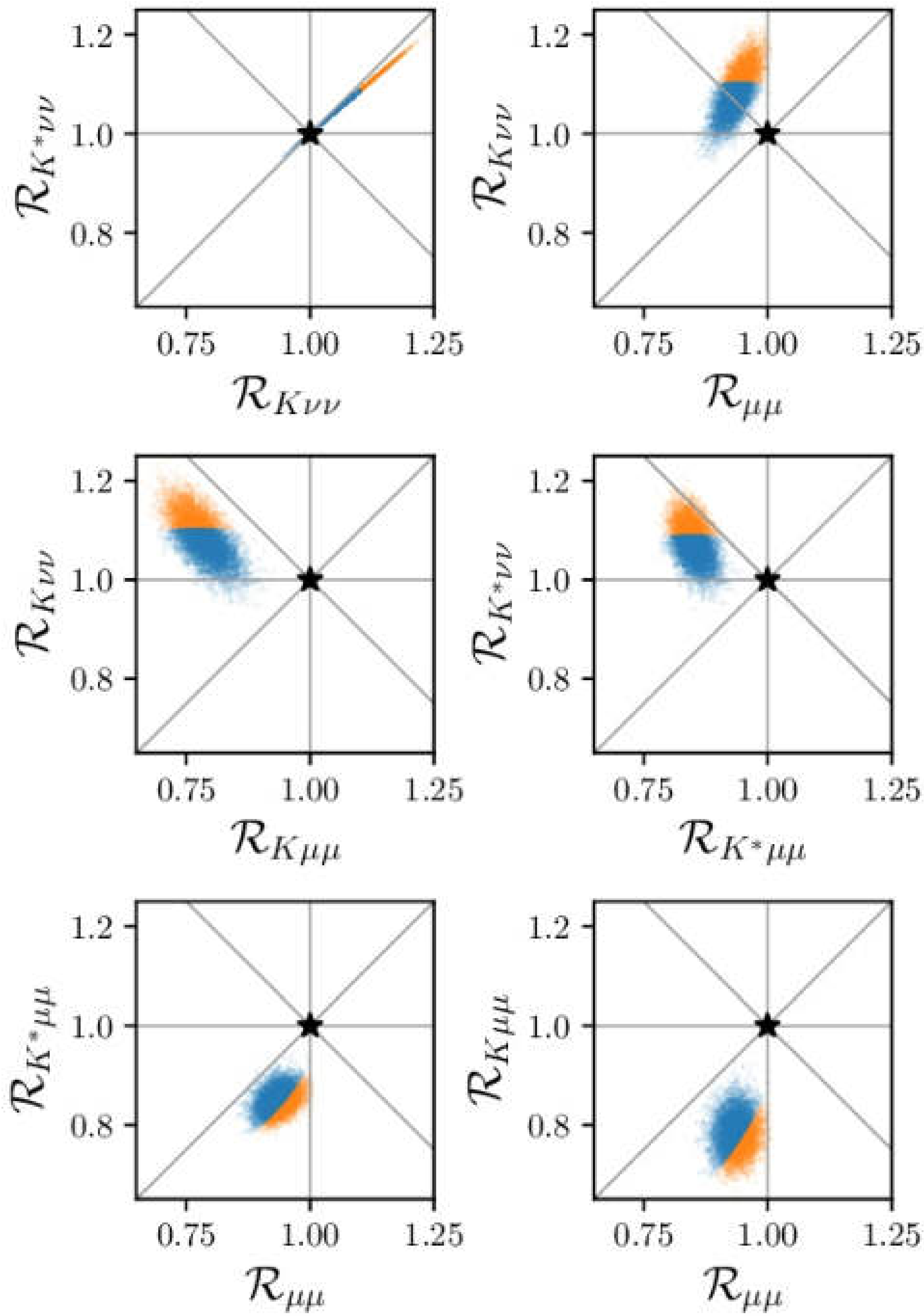
$$R_{K^*} = \frac{Br(B \to K^*\nu\bar{\nu})}{Br(B \to K^*\nu\bar{\nu})_{SM}}$$

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

$$R_{K\mu\mu} \leftrightarrow B^+ \to K^+\mu\bar{\mu}$$

$$R_{K^*\mu\mu} \leftrightarrow B^0 \to K^{0*}\mu\bar{\mu}$$

10 Years Later



$$\Delta C_9(\Lambda_{NP}) \neq 0$$
$$\Delta C_{10}(\Lambda_{NP}) = 0$$

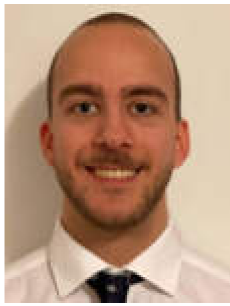
AJB + Stangl (2412.14254)

4th Movement
More Flavour News

Disentangling New Physics in $K \to \pi\nu\bar{\nu}$ and $B \to K(K^*)\bar{\nu}\nu$ Decays

AJB +

J. Harz



M. Mojahed

2405.06742

For $K \to \pi\nu\bar{\nu}$ see also Gorbahn, Stamou et al 2312.06494

Goal: Disentangling different New Physics contributions to the rare decays $K \to \pi + \not{E}$ and $B \to K(K^*) + \not{E}$ through kinematic distributions in the missing energy $\not{E}$

Step 1: WET with active or sterile neutrinos including Lepton Number violating operators with scalar and tensor currents

Step 2: Dark WET: new invisible particles in the final state: two dark scalars, two dark fermions, two dark vectors

Main Results

A. Vector, scalar and tensor quark currents can be uniquely determined from experimental data of kinematic distributions

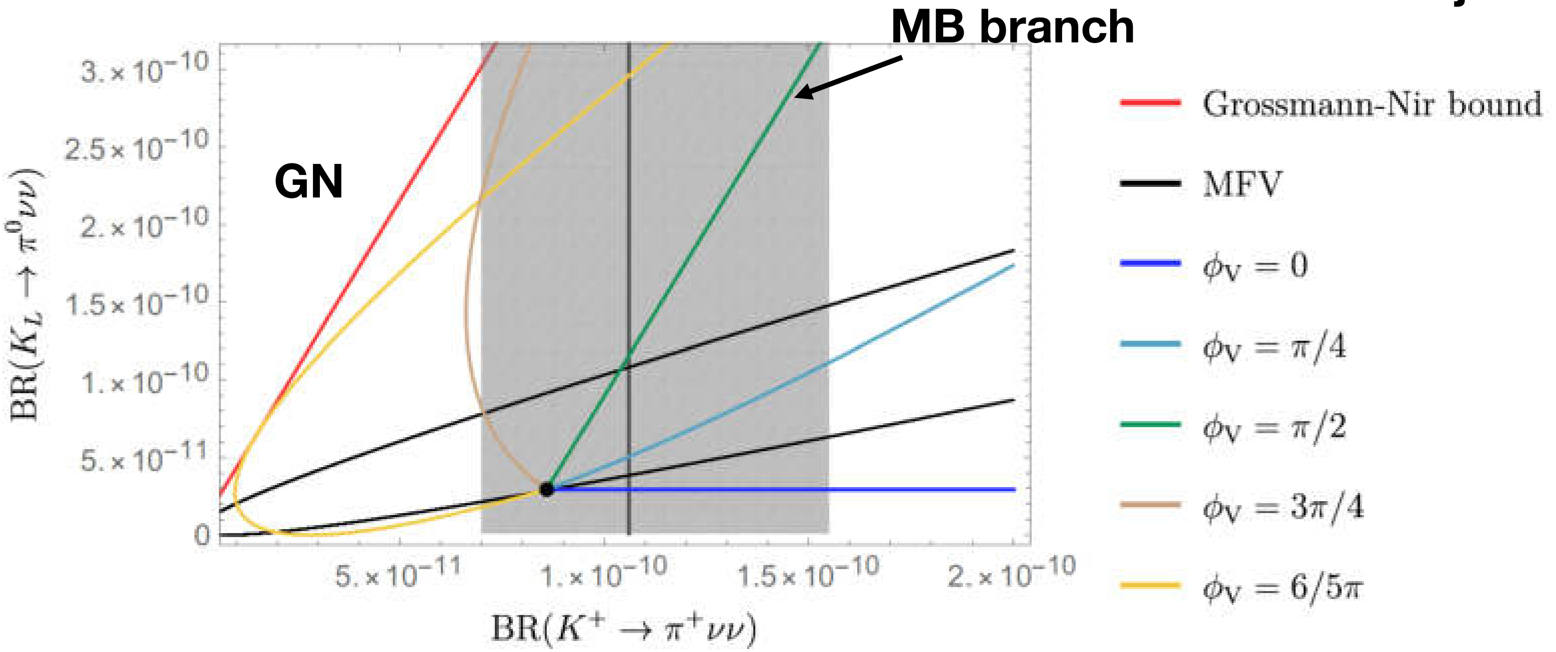
B. Measurements of kinematic distributions make it possible to disentangle the contributions of WET operators from most of the dark-sector operators

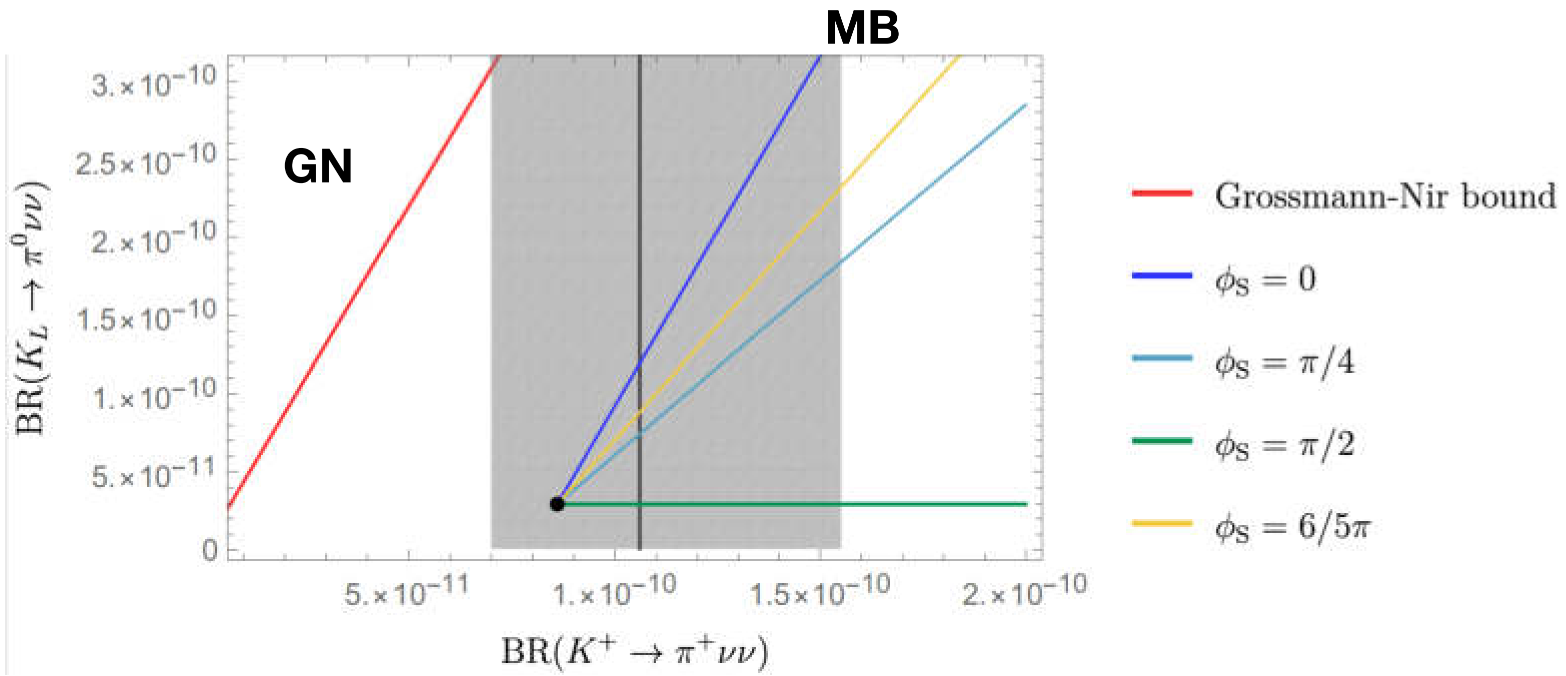
C. Sum Rules for vector currents in WET are also satisfied in some new dark-physics scenarios that mimic WET

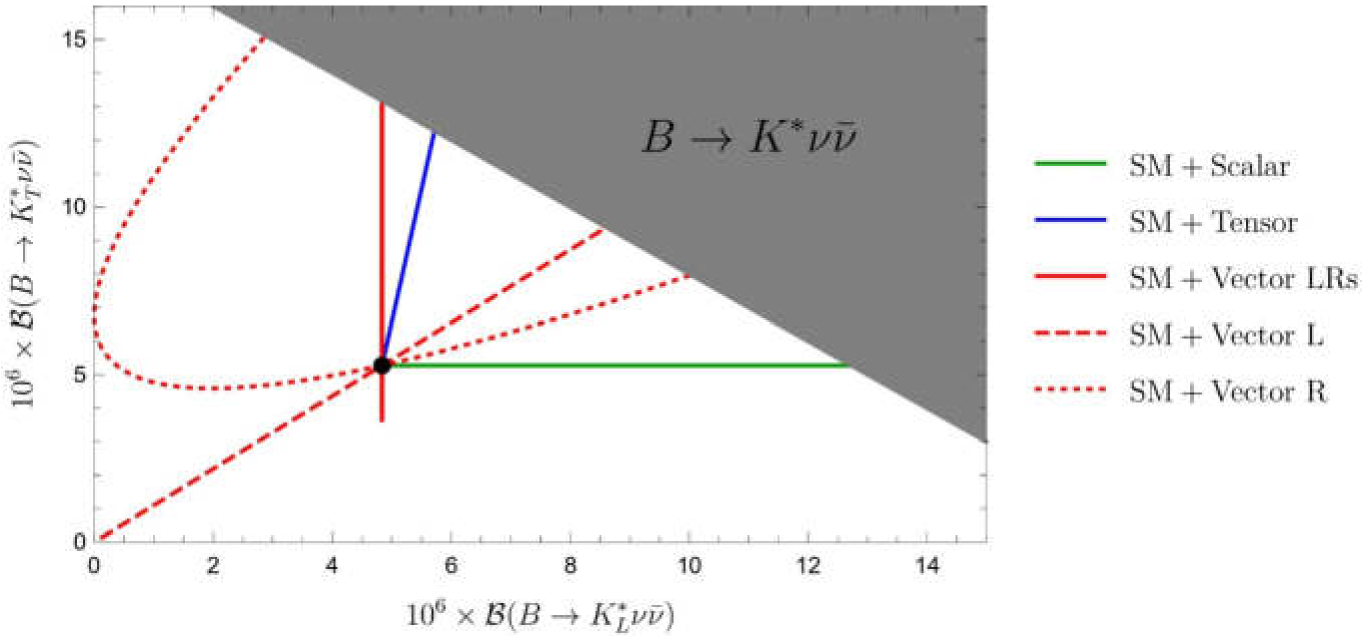
$$\boxed{\Delta C_V = \left|C_V^{NP}\right| e^{i\varphi_V} \qquad C_S = |C_S| e^{i\varphi_S}}$$

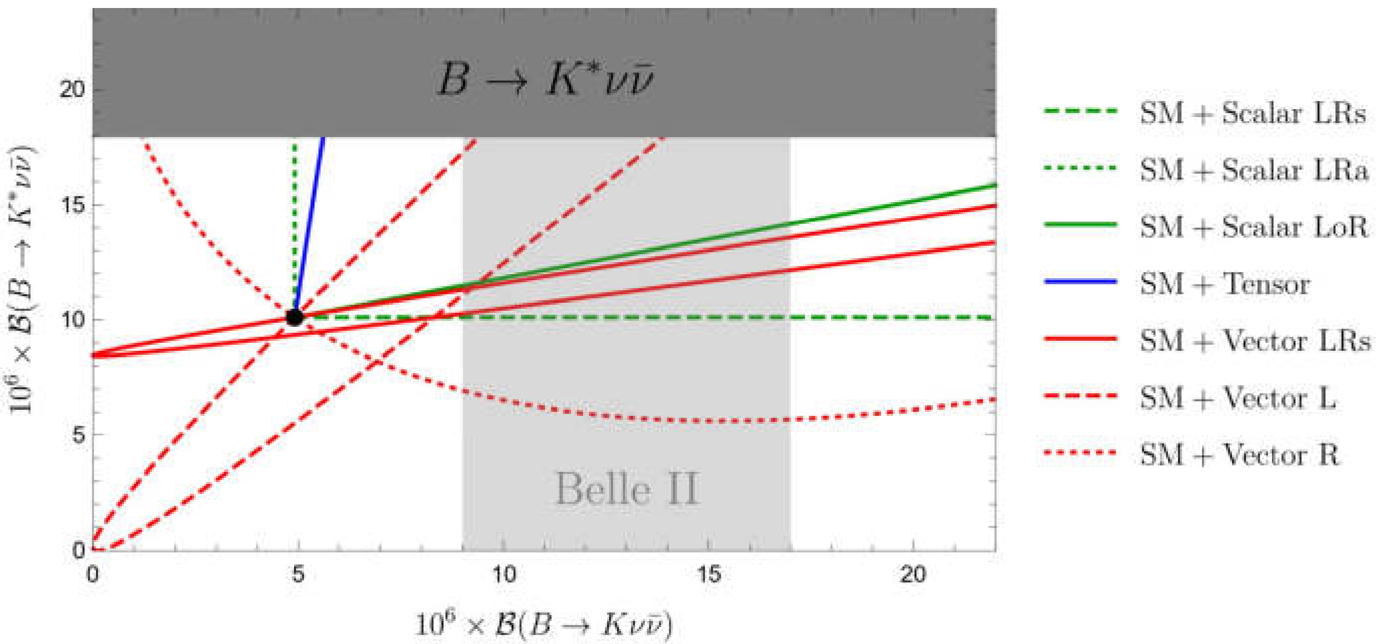
$K_L \to \pi^0 \nu\bar{\nu} - K^+ \to \pi^+ \nu\bar{\nu}$ Correlation

AJB + J.Harz + M. Mojahed

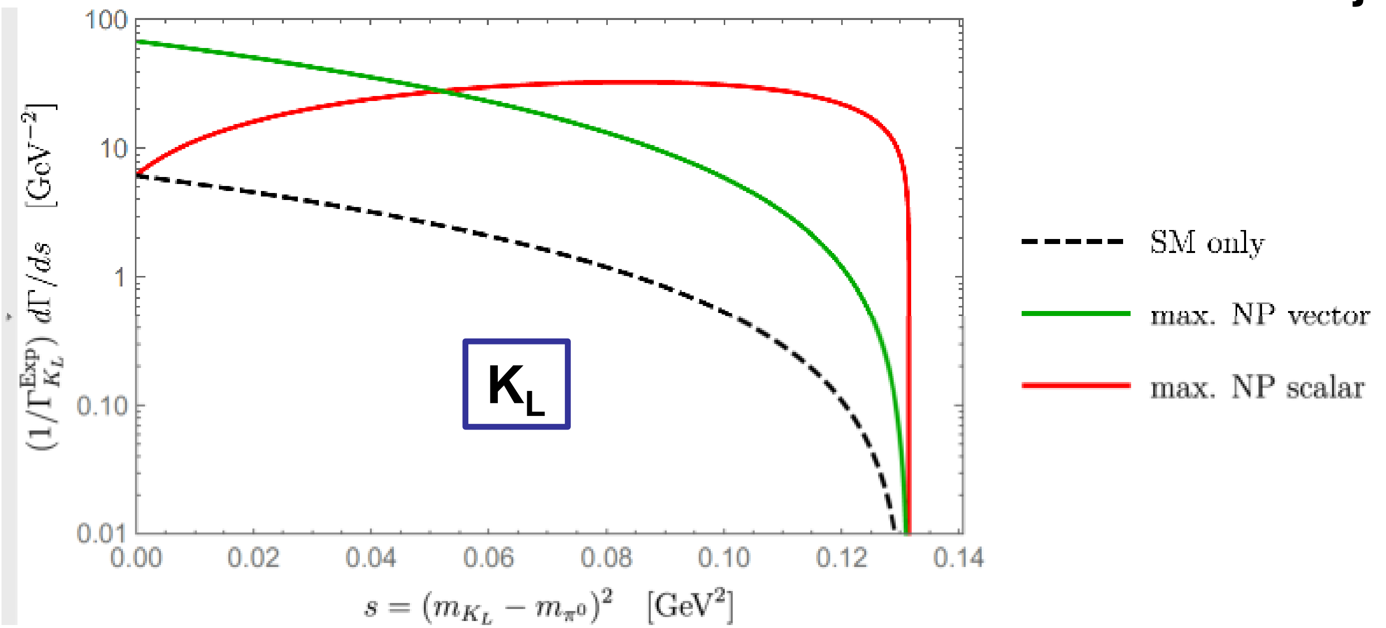


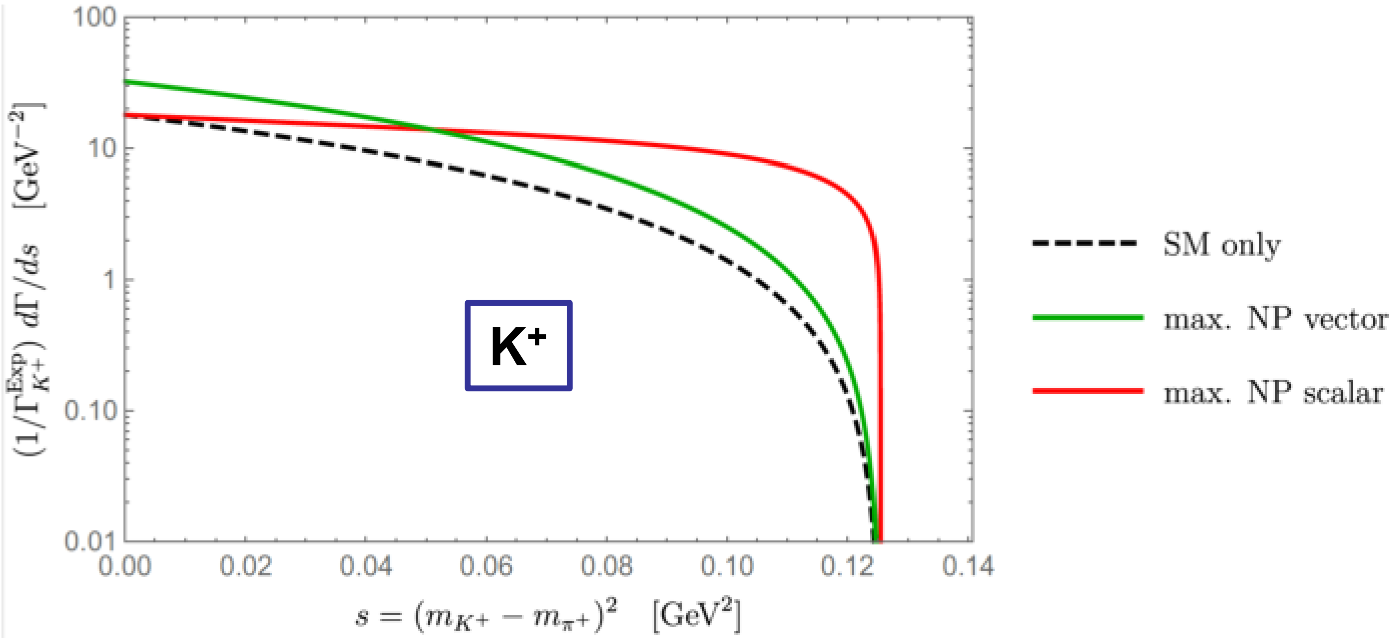



$B \to K^* \nu\bar{\nu}$
SM + Scalar
SM + Tensor
SM + Vector LRs
SM + Vector L
SM + Vector R
$10^6 \times \mathcal{B}(B \to K_T^* \nu\bar{\nu})$
$10^6 \times \mathcal{B}(B \to K_L^* \nu\bar{\nu})$


$B \to K^* \nu\bar{\nu}$
Belle II
SM + Scalar LRs
SM + Scalar LRa
SM + Scalar LoR
SM + Tensor
SM + Vector LRs
SM + Vector L
SM + Vector R
$10^6 \times \mathcal{B}(B \to K^* \nu\bar{\nu})$
$10^6 \times \mathcal{B}(B \to K \nu\bar{\nu})$

AJB + J.Harz
+ M. Mojahed

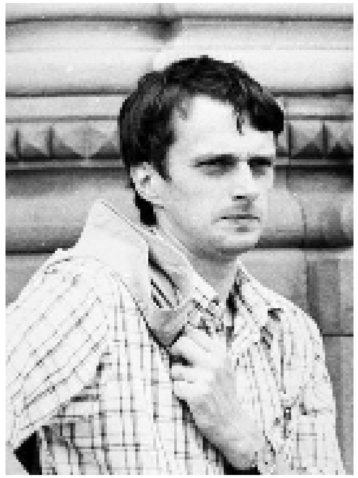




Dual QCD Approach for Weak Decays

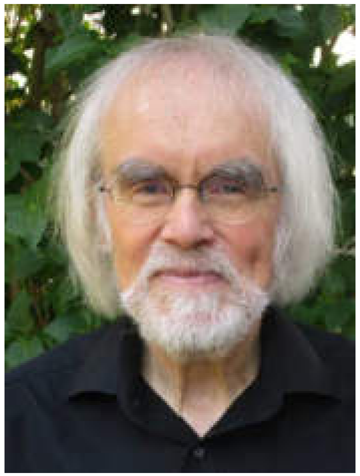
Successful low energy approximation of QCD
for $K \to \pi\pi$ K^0-$\bar{K}^0$ mixing (Large N framework)

1986



W. Bardeen | **AJB** | **J.-M. Gérard**

2024



$\Delta I = 1/2$ 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

$\boxed{R = 16 \pm 2}$

Dual
QCD

Bardeen, AJB, Gérard
(Current-Current Operators)

2020

$\boxed{R = 19.19 \pm 4.8}$

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

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

(NA48, KTeV) (2000)

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

Chiral Perturbation Theory (Pich et al) — No Anomaly

★

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

Hep-arxiv: 2101.00020

Insight from Dual QCD + NNLO QCD

(AJB + Gérard) — Anomaly

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

RBC – UKQCD — No Anomaly

Hopefully this controversy will be clarified in this decade

Reviews AJB: 2101.00020, 2203.12632
2307.15737

Good News on ε'/ε

ε'/ε = QCD Penguins – Electroweak Penguin

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

Perfect Agreement!

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

Disagreements on QCD Penguin contribution.

Good news on $\hat{B}_K$

$\hat{B}_K = 0.73 \pm 0.02$ **Dual QCD (2014)**

$\hat{B}_K = 0.76 \pm 0.01$ **RBC-UKQCD (2024)**

(Relevant for ε_K)

Coming Years : Flavour Precision Era

LHC Upgrade
E = 14 TeV
(CERN)

Precision
$B_{d,s}$ – Meson Decays
LHCb, CMS
ATLAS, Belle II

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

Improved Lattice Gauge Theory Calculations

Neutrinos

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

ε'/ε

$\Delta I = 1/2$ Rule, ΔM_K

2026-2046 : Expedition
Attouniverse → Zeptouniverse
10^{-18}m →10^{-21}m

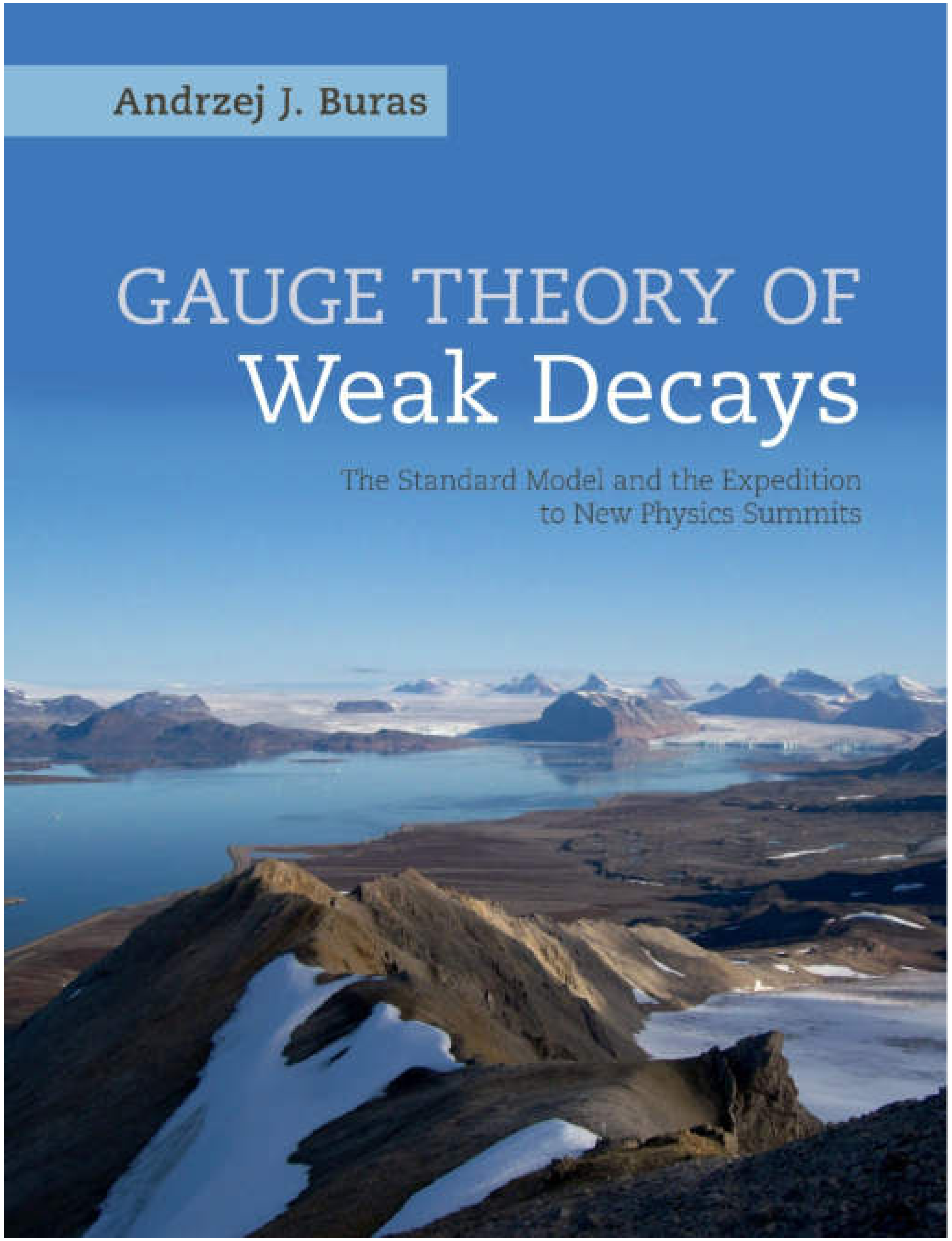
Hopefully meeting Z´, Leptoquarks,
Vector-Like Quarks and Leptons

Zeptouniverse Guide

Published July 2020

7

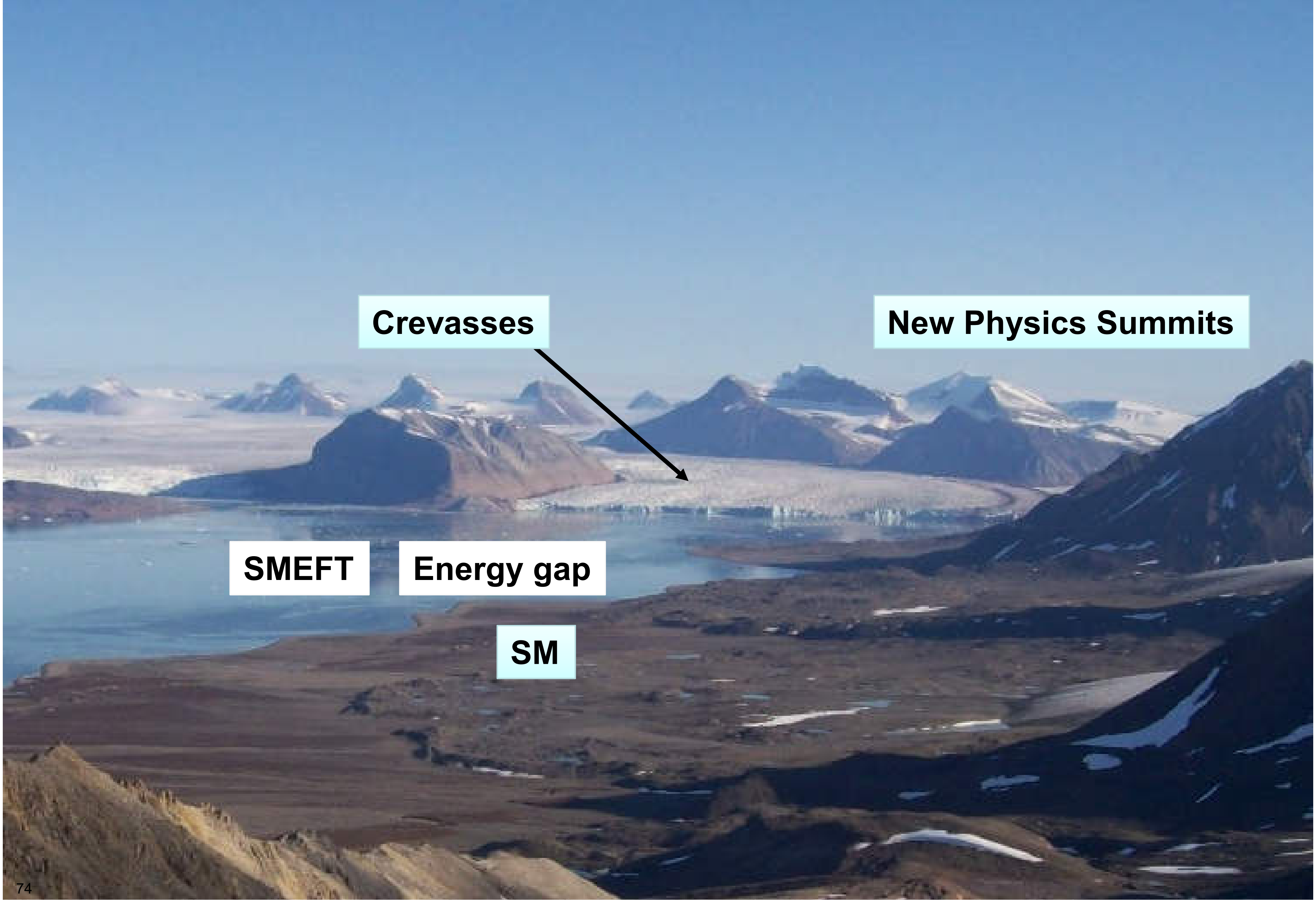
Exciting Years !

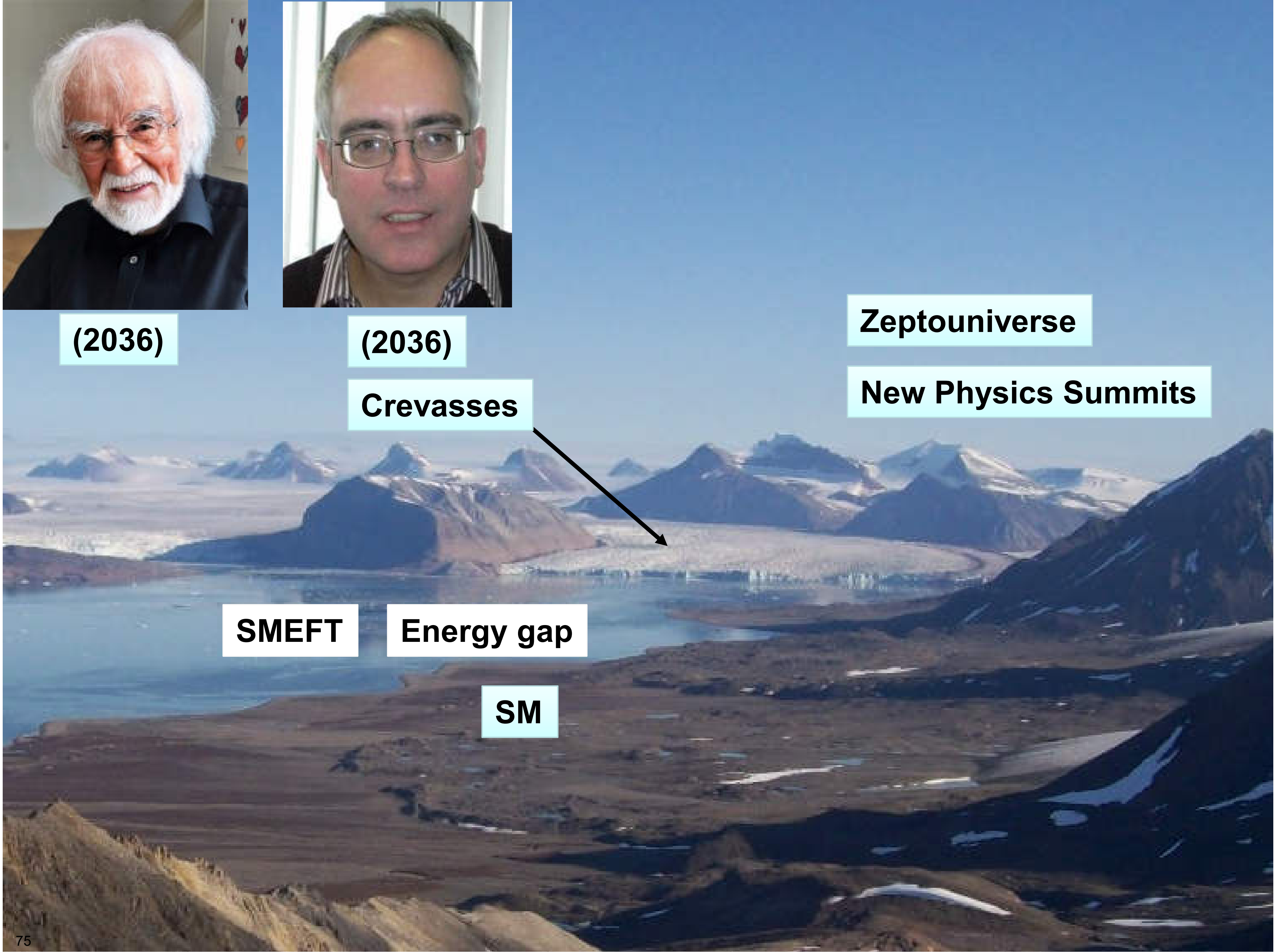


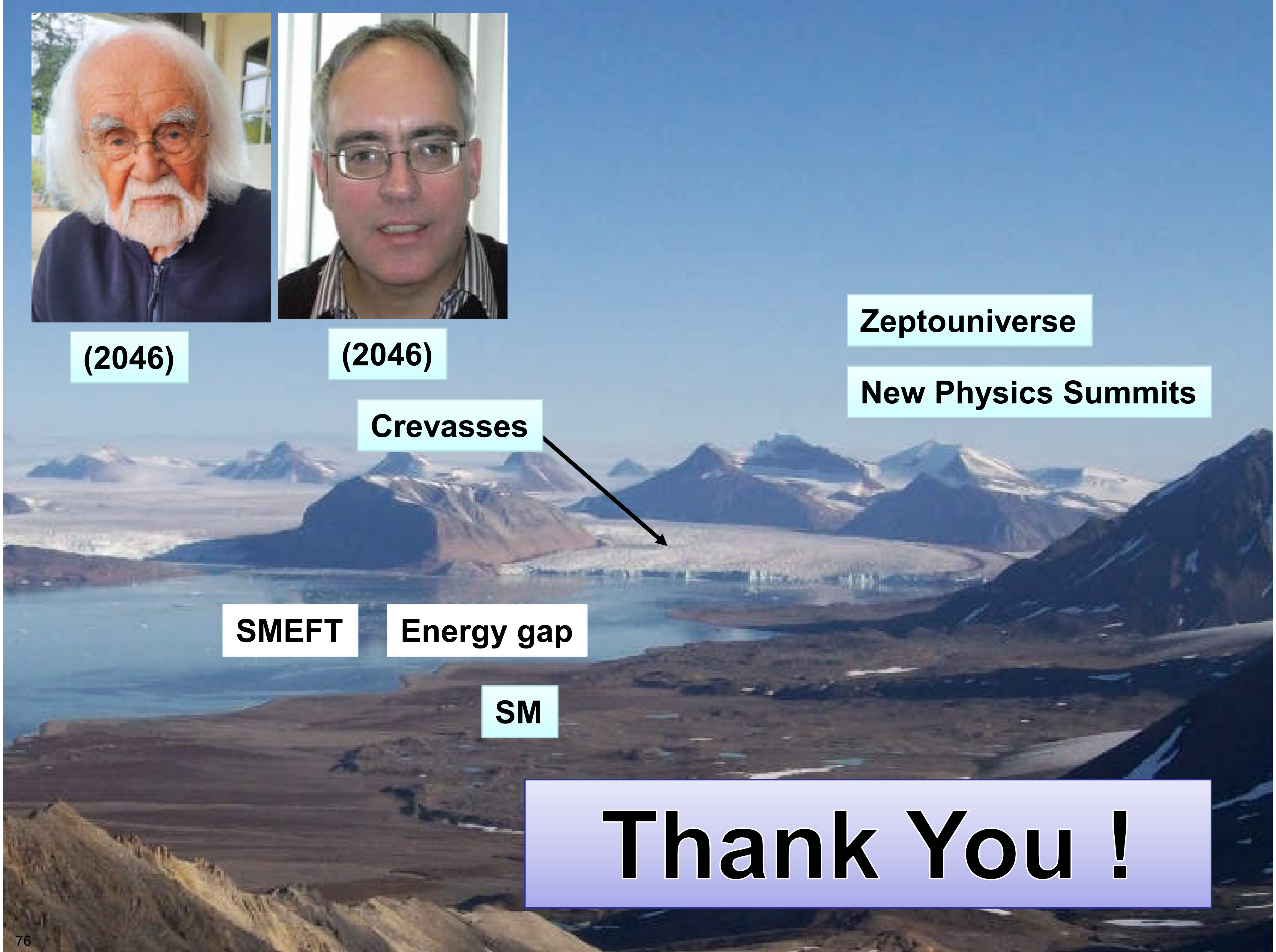
739 pages
1350 references

Cambridge University Press

Flavour Physics (2026-2046)




(2036)
(2036)
Crevasses
Zeptouniverse
New Physics Summits
SMEFT
Energy gap
SM


(2046)
(2046)
Zeptouniverse
New Physics Summits
Crevasses
SMEFT
Energy gap
SM
Thank You !

Backup

Present Anomalies (2024)

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

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

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

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

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

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

ΔA_{CP} - C

ΔM_K - K

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

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

$B_d^0 \to \pi^0 K_S$
CPV – Anomaly -

Neutrino Anomalies

Footprints of Majorana Neutrinos in Rare K and B Decays

AJB + Julia Harz

All existing calculations of $K^+ \to \pi^+ \nu\bar{\nu}$ and $K_L \to \pi^0 \nu\bar{\nu}$ assumed until recently that neutrinos are of Dirac type.

What if neutrinos are Majorana neutrinos?
First pioneering studies:


J. Harz

1912.10433	T. Li, X.-D. Ma, M. A. Schmidt
2009.04494	F. Deppisch, K. Fridell, J. Harz

Main Goals of AJB – JH Collaboration

AJB + Julia Harz

A. Closer look at the impact of Majorana neutrinos on the $K^+ \to \pi^+\nu\bar{\nu}$ - $K_L \to \pi^0\nu\bar{\nu}$ plane

B. Generalization to $B \to K\nu\bar{\nu}$, $\boxed{B \to K^*\nu\bar{\nu},}$ $B \to X\nu\bar{\nu}$

C. Efficient strategies that would allow NA62, KOTO and Belle II to find possible footprints of Majorana neutrinos in their data.

D. Strategies valid in the presence of right-handed currents, LFUV and LFV

$$\Delta C_V = \left|C_V^{NP}\right| e^{i\varphi_V} \qquad\qquad C_S = |C_S| e^{i\varphi_S}$$

Main Messages from these Studies

1.

Lepton Number Violating operators

$$\left(\bar{d}^i_R d^j_L\right)\left(\bar{\nu}^c_\alpha \nu_\beta\right) \qquad \left(\bar{d}^i_L d^j_R\right)\left(\bar{\nu}^c_\alpha \nu_\beta\right) \qquad (\mathrm{LNV}) \quad (\Delta L = 2)$$

Enter L_{eff} as dim=7 operators. $\nu \equiv P_L \nu$

dim6 $$\left(\bar{d}^i_L \gamma^\mu d^j_L\right)\left(\bar{\nu}^c_\alpha \gamma^\mu \nu_\beta\right) \qquad \left(\bar{d}^i_R \gamma^\mu d^j_R\right)\left(\bar{\nu}^c_\alpha \gamma^\mu \nu_\beta\right) \qquad (\mathrm{LNC}) \quad (\Delta L = 0)$$

2.

**Difference between LNV and LNC seen in s-distributions,
s = the invariant mass² of $\nu\bar{\nu}$**

3.

Scale $\Lambda^{LNV}_{NP} \approx$ 20TeV can be probed

4.

**All neutrino generations involved as opposed
to neutrinoless double beta decay**

SM Relation for ΔM_s, ΔM_d, $|\varepsilon_K|$, β

AJB: 2209.03968

$$\boxed{\mathbf{R} \equiv \frac{|\boldsymbol{\varepsilon}_{\mathbf{K}}|^{1.18}}{\Delta \mathbf{M}_{\mathbf{d}} \Delta \mathbf{M}_{\mathbf{s}}} = (\mathbf{8.22} \pm \mathbf{0.18}) \cdot \mathbf{10}^{-5} \left(\frac{\mathbf{sin}\boldsymbol{\beta}}{\mathbf{sin22.2°}}\right)^{1.027} \mathbf{K}\,\mathbf{ps}^2}$$

$$\boxed{\mathbf{K} = \left(\frac{\hat{\mathbf{B}}_{\mathbf{K}}}{\mathbf{0.7625}}\right)^{1.18} \left[\frac{\mathbf{210.6\ MeV}}{\sqrt{\hat{\mathbf{B}}_{\mathbf{B_d}}}\,\mathbf{F}_{\mathbf{B_d}}}\right]^2 \left[\frac{\mathbf{256.1\ MeV}}{\sqrt{\hat{\mathbf{B}}_{\mathbf{B_s}}}\,\mathbf{F}_{\mathbf{B_s}}}\right]^2}$$

HPQCD

$$\boxed{\mathbf{R}_{\mathbf{exp}} = (\mathbf{8.26} \pm \mathbf{0.06}) \cdot \mathbf{10}^{-5}\mathbf{ps}^2}$$

$$\boxed{\mathbf{K} = \mathbf{1.00} \pm \mathbf{0.07}}$$

Searching for Majorana Footprints through LNC Sum Rules

LNC Sum Rules

AJB, J. Girrbach-Noe, C. Niehoff, D. Straub (1409.4557)

$$\left(r_1^{LNC} = r_2^{LNC} = 1\right)$$

$$F_L = F_L^{SM}\left[\frac{\left(\kappa_\eta - 2\right)R_K + 4R_{K^*}}{\left(\kappa_\eta + 2\right)R_{K^*}}\right]r_1^{LNV}$$

$$\boxed{\begin{aligned} r_1^{LNV} &\neq 1 \\ r_2^{LNV} &\neq 1 \end{aligned}}$$

$$Br\left(B \to X_s \nu\bar{\nu}\right) = Br\left(B \to X_s \nu\bar{\nu}\right)_{SM}\left[\frac{\kappa_\eta R_K + 2R_{K^*}}{\kappa_\eta + 2}\right]r_2^{LNV}$$

$$R_K = \frac{Br\left(B \to K\nu\bar{\nu}\right)}{B_{SM}\left(B \to K\nu\bar{\nu}\right)} \qquad R_{K^*} = \frac{Br\left(B \to K^*\nu\bar{\nu}\right)}{Br\left(B \to K^*\nu\bar{\nu}\right)_{SM}}$$

$\kappa_\eta = 1.33 \pm 0.05$ (formfactor) $\qquad F_L^{SM} = 0.49 \pm 0.04$

K^* longitudinal polarization fraction

Strong Suppression of Z′ to ΔF = 2 Process

K-System

$$\mathrm{Re}\Delta_L^{sd}(Z') \ll \mathrm{Im}\Delta_L^{sd}(Z')$$

Negligible RH couplings

$B_{s,d}$-Systems

$$\Delta_R^{bq}(Z') \approx 0.1\,\Delta_L^{bq}(Z')$$

Non-negligible RH couplings

Basic Questions for Flavour Physics

New Flavour violating CPV phases?

Flavour Conserving CPV phases?

Non-MFV Interactions?

(Non-CKM)

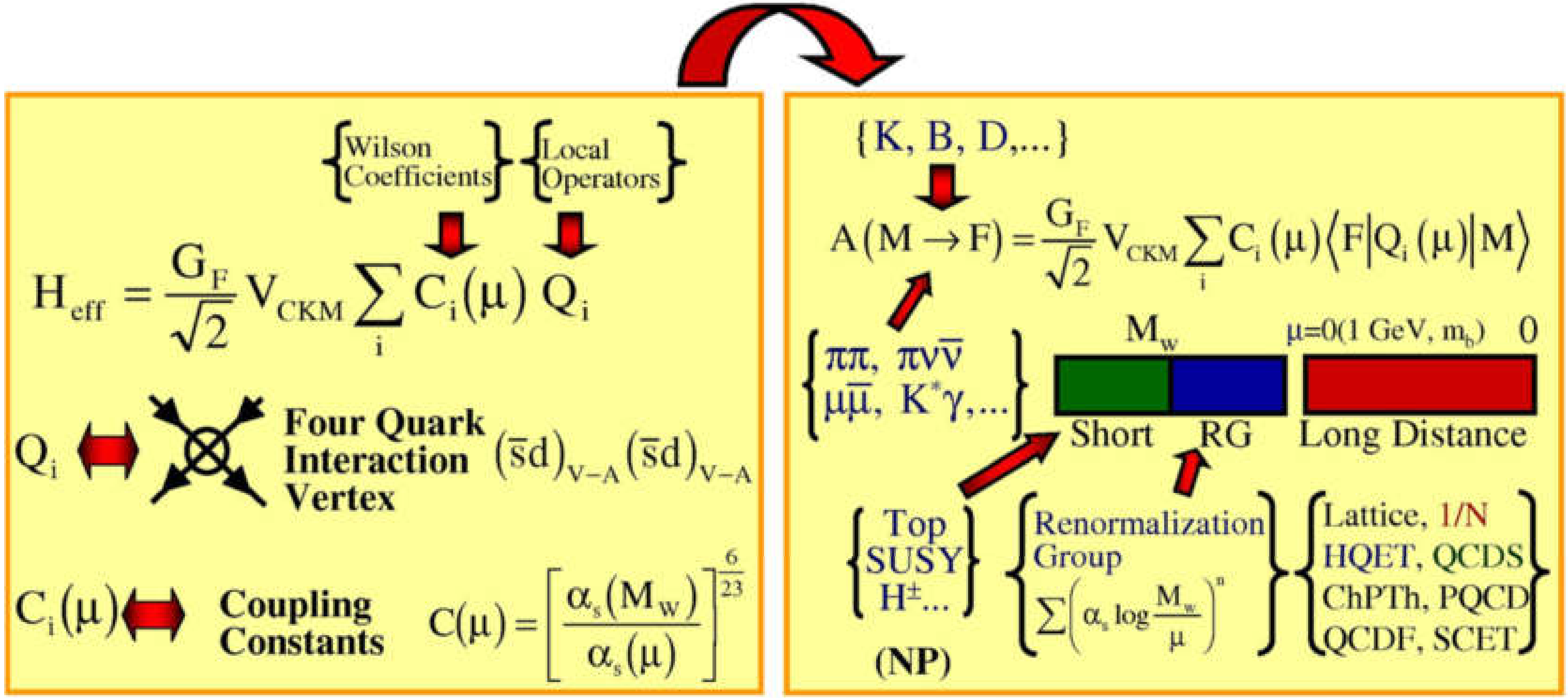
Right-Handed Charged Currents?

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 ?

Operator Product Expansion



$$\langle \bar{K}^0 | (\bar{s}d)_{V-A}(\bar{s}d)_{V-A} | K^0 \rangle = \frac{8}{3} \hat{B}_K\, F_K^2\, m_K^2 [\alpha_s(\mu)]^{2/9}$$

Master Formula for Weak Decays

AJB (2001)
hep-ph/0101336

Non-Perturbative Factors in the SM	QCD RG Factors	Short Distance Loop Functions (Penguins, Boxes)	New Flavour-Changing Parameters

Represent different Dirac and Colour Stuctures

$$A(\text{Decay}) = B_i\ \eta^i_{QCD}\ V^i_{CKM}\left[F^i_{SM} + F^i_{New}\right] + B^{New}_i \left[\eta^i_{QCD}\right]^{New} V^i_{New}\left[G^i_{New}\right]$$

(Summation over i)

$\boxed{\text{New} \equiv \text{NP}}$

Non-Perturbative Factors beyond SM	Short Distance Loop Functions Penguins, Boxes

F^i_{SM}, F^i_{New}, G^i_{New} : **Fully calculable in Perturbation Theory**

η^i_{QCD}, $\left[\eta^i_{QCD}\right]^{New}$: **Fully calculable in RG improved Perturbation Theory**

B_i, B^{New}_i : **Require Non-Perturbative Methods or can be extracted from leading decays**

(represent $\langle Q \rangle$)

Fully calculable in the SM

Higher Order QCD Corrections (Flavour Physics)


Gerhard Buchalla
(LMU)


Markus Lautenbacher


Manfred Münz


Ulrich Nierste
(Karlsruhe)


Stefan Herrlich


Alexander Lenz
(Siegen)


Christoph Bobeth


Martin Gorbahn
(Liverpool)


Ulrich Haisch
(MPI Munich)


J.Girrbach-
Noe


Thorsten Ewerth


Sebastian Jäger
(Sussex)

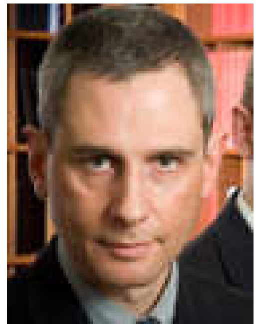

P. Weisz


M. Jamin

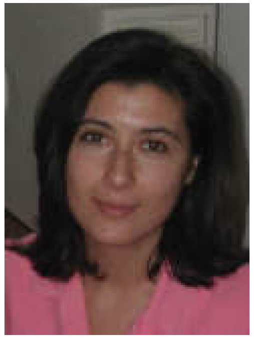

M. Misiak


J. Urban


P. Gambino


A. Czarnecki

Italian Collaborators (BSM Flavour Physics)

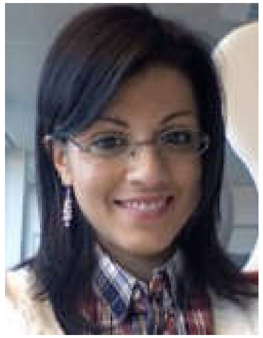


F. de Fazio

C.Tarantino

S.Gori
(Santa Cruz)

E. Venturini



M.V.Carlucci

P. Colangelo

G. Isidori

L. Silvestrini

P. Gambino

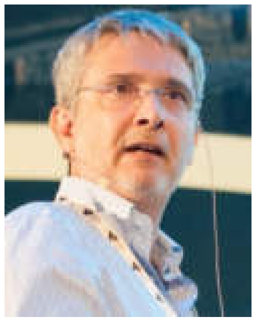
A. Romanino

G. Colangelo

D. Guadagnoli

P. Paradisi

D. Buttazzo



M. Ciuchini

G. Martinelli

E. Franco

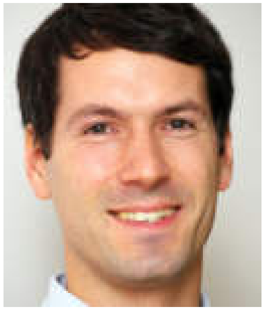
L. Merlo

Non-Italian Collaborators I (BSM Flavour Physics)


Andreas Weiler
(TUM)


Robert Fleischer
(Nikhef, Amsterdam)


Wolfgang Altmannshofer
(Santa Cruz)

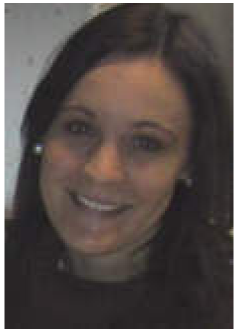

David Straub

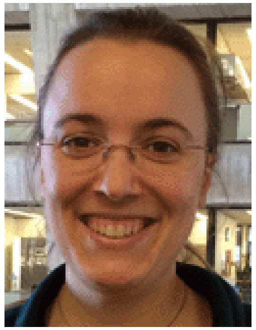

Björn Duling


Emmanuel Stamou
(Dortmund)


Monika Blanke
(Karlsruhe)


J.Girrbach-
Noe


Selma Uhlig


Katrin Gemmler


Michaela Albrecht

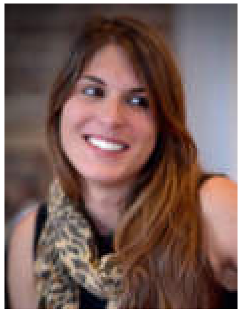

P.Ball


Anton Poschenrieder


Michael Spranger


Gaby Ostermaier


Michaela Harlander

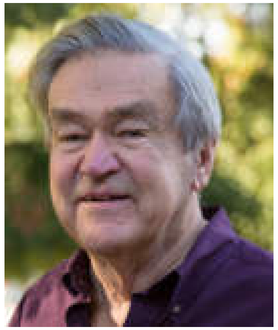

M. Cerdà-Sevilla


A.Bharucha

Non-Italian Collaborators II (BSM Flavour Physics)


S. Pokorski


P.Q. Hung


J. Bjorken


I. Bigi


G. Branco


T. Feldmann


T. Mannel


J. Rosiek


R. Ziegler

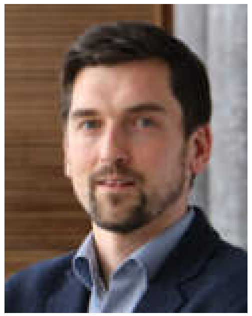

B. Schellekens

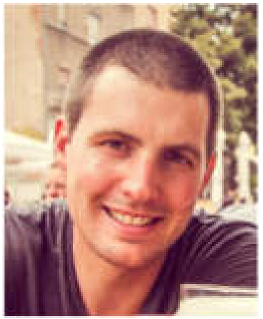

S. Dawson

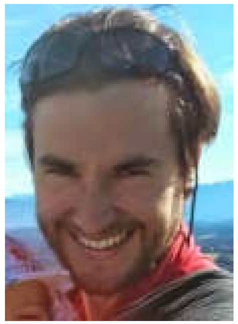

S. Recksiegel


M. Jung


Tillmann Heidsieck


Michael Wick


R. Knegjens


Christoph Promberger


A. Celis

Most Recent Collaborators (BSM Flavour in Homeoffice)


J. Aebischer


J. Kumar


Christoph Bobeth

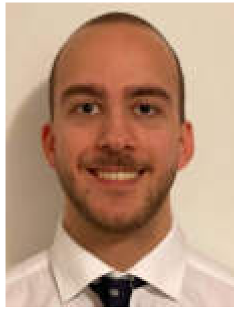

E. Venturini

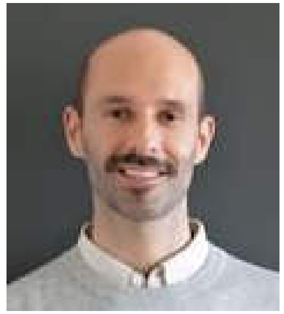

J. Harz


F. de Fazio


P. Colangelo

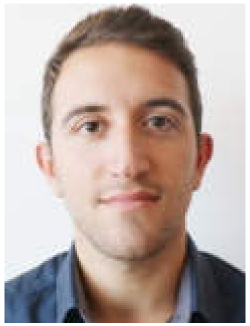

F. Loparco


M. Mojahed


Peter Stangl


A. Crivellin


F. Kirk


C. A. Manzari

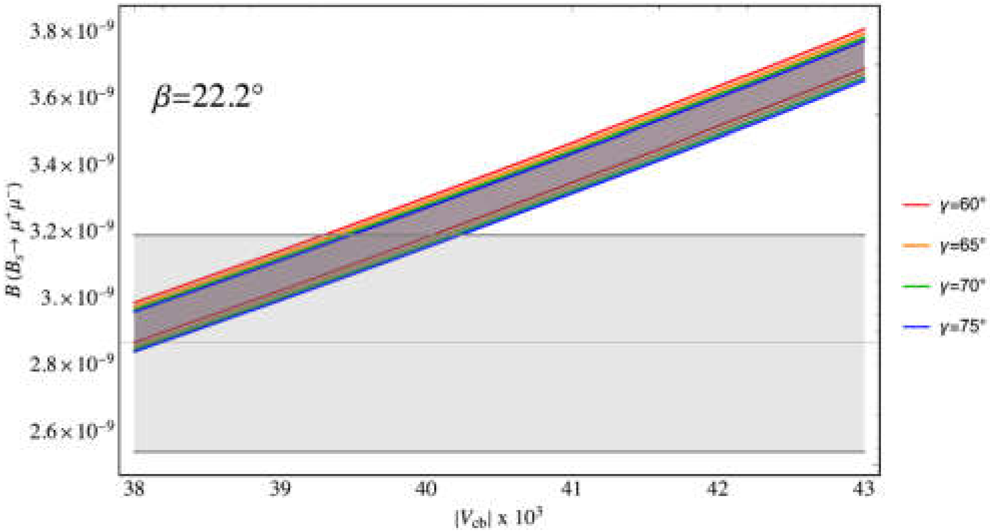

M. Montull

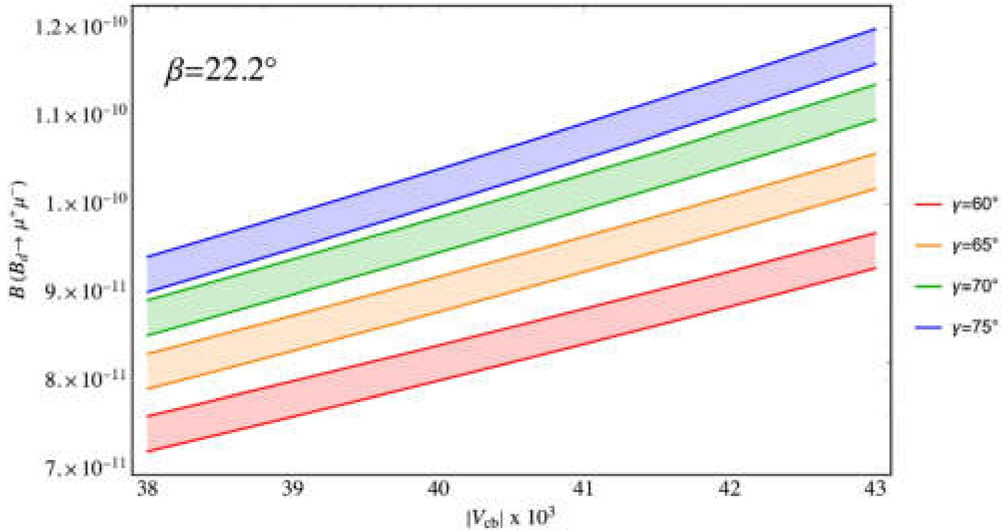

P. Niehoff

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

AJB + E. Venturini (2109.11032)

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





$$\overline{Br}\left(B_s \to \mu^+\mu^-\right)_{exp} = (3.45 \pm 0.29)\cdot 10^{-9}$$

LHCb
CMS
ATLAS

CMS + FLAG22

Averages from: 2103.12738, 2103.13370, 2104.10058

$$\overline{Br}\left(B_s \to \mu^+\mu^-\right)_{SM} = \left(3.78\,^{+0.15}_{-0.10}\right)\cdot 10^{-9}$$

CKM Independent !

(1.1 σ)

R_i (β, γ) can now be predicted in the SM

AJB 2209.03968

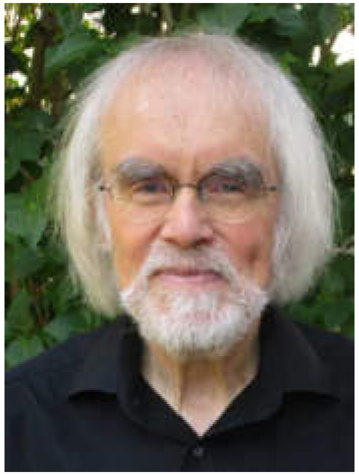
$$\frac{\mathrm{Br}(K^+ \to \pi^+ \nu\bar{\nu})}{[\overline{\mathrm{Br}}(B_s \to \mu^+\mu^-)]^{1.4}} = 53.69 \pm 2.75$$

$$\frac{\mathrm{Br}(K^+ \to \pi^+ \nu\bar{\nu})}{[\mathrm{Br}(B^+ \to K^+ \nu\bar{\nu})]^{1.4}} = (1.90 \pm 0.13) \cdot 10^{-3}$$

Many other results in 2209.03968

10 Years Anniversary (Z´, 331)

AJB – Fulvia de Fazio – Jennifer Girrbach-Noe Collaboration



AJB

Fulvia

Jennifer

1211.1896
1211.1237
1303.3723
1311.6729
1404.3824
1405.3850

1512.02869
1604.02344
1912.09308
2301.02649

Without Jennifer

10 papers

Peculiar Pattern of Flavour Data

$\Delta\varepsilon_K^{NP} = 0$
Indirect CP Violation

but

$\Delta\left(\frac{\varepsilon'}{\varepsilon}\right)^{NP} > 0$ (significant)
Direct CP Violation

Direct CP Violation

Required $\bar{s}$d coupling from New Physics
$\Rightarrow$ Impact on ε_K

$\Delta M_s, \Delta M_d$
$S_{\psi K_S}, S_{\psi\varphi}$
SM-Like

but

$Br(B^+ \to K^+\mu^+\mu^-)$ (pull -5.1 σ)
$Br(B_s \to \varphi\mu^+\mu^-)$ (pull -4.8 σ)

[1.1, 6]

Required $\bar{b}$s coupling from New Physics
$\Rightarrow$ Impact on $\Delta M_s, S_{\psi\varphi}, \ldots$

Which NP scenario can reproduce this pattern ?

$\varepsilon_K, \varepsilon'/\varepsilon, \Delta M_K, K^+ \to \pi^+\nu\bar{\nu}, K_L \to \pi^0\nu\bar{\nu}$

New heavy gauge boson Z′: $\Delta_L^{sd}(Z') = |\Delta_L^{sd}(Z')| e^{i\varphi}$

$$\varepsilon_K^{NP} \backsim \mathrm{Im}\left(\Delta_L^{sd}(Z')\right)^2 \backsim \left[\mathrm{Re}\Delta_L^{sd}(Z')\right]\left[\mathrm{Im}\Delta_L^{sd}(Z')\right]$$

$$(\varepsilon'/\varepsilon)^{NP} \backsim \mathrm{Im}\Delta_L^{sd}(Z')$$

$$\Delta M_K^{NP} \backsim \left(\mathrm{Re}\Delta_L^{sd}(Z')\right)^2 - \left(\mathrm{Im}\Delta_L^{sd}(Z')\right)^2 \qquad (K^0 - \bar{K}^0)$$

With $\mathrm{Re}\Delta_L^{sd}(Z') \ll \mathrm{Im}\Delta_L^{sd}(Z')$ **(Imaginary coupling)**

$\varepsilon_K^{NP} \simeq 0$ $\quad (\varepsilon'/\varepsilon)^{NP}$ **can be enhanced**

ΔM_K **can be suppressed + Interesting implications**

(possibly required by **for** $K \to \pi\nu\bar{\nu}$

Lattice QCD)

Aebischer
AJB
Kumar
2302.00013

New Particles behind Anomalies

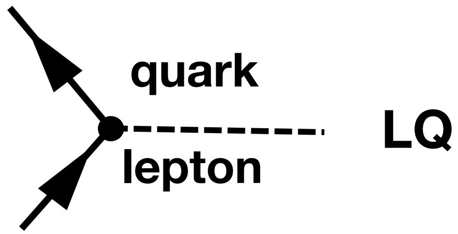
Top candidates

Review:
Capdevilla, Crivellin, Matias
2309.01311

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

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

Dinosaurs of
Flavour Physics?



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

(2003)

$$R_{q\mu} \equiv \frac{\bar{\mathrm{Br}}\left(B_q \to \mu^+\mu^-\right)}{\Delta M_q} = C\,\frac{\tau_{B_q}}{\hat{B}_q}\underbrace{\left[F\left(x_t\right)\right]}_{\text{Known with NLO QCD}}$$

(q=d,s)

Numerical Constant

AJB 0303060

a) $\left|V_{cb}\right|^2$ 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!

$$\left[R_{s\mu}\right]_{SM} = \left(2.13\,^{+0.08}_{-0.06}\right)\cdot 10^{-10}\,\mathrm{ps}$$

(2104.095219) C. Bobeth + AJB
(2203.11960) AJB + E. Venturini

$$\left[R_{s\mu}\right]_{exp} = \left(1.94 \pm 0.16\right)\cdot 10^{-10}\,\mathrm{ps}$$

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

Standard Model

(2024)

SM:

$$Br(K^+ \to \pi^+ \nu\bar{\nu}) = (8.6 \pm 0.4) \cdot 10^{-11}$$
$$Br\left(K_L \to \pi^0 \nu\bar{\nu}\right) = (3.05 \pm 0.17) \cdot 10^{-11}$$

AJB + Venturini (2109.11032)

Relativ to 1503.02693 (AJB, Buttazzo, Girrbach-Noe, Knegjens)

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

$$Br(K^+ \to \pi^+ \nu\bar{\nu}) = \left(9.6 \, \frac{+1.9}{-1.8} \, 3.8\right) \cdot 10^{-11}$$ (NA62)

$$Br\left(K_L \to \pi^0 \nu\bar{\nu}\right) \leq 2.0 \cdot 10^{-9}$$ (KOTO)

$$|V_{cb}| = 42.5(5) \cdot 10^{-3} \qquad |V_{cb}|_{inl} = 42.0(5) \cdot 10^{-3}$$

$$\gamma = 64.6(16)^\circ \qquad \gamma = 63.8(36)^\circ \quad \text{LHCb}$$

Problems with SM Predictions for TH “clean” Rare K and B Decays

(AJB 2209.03968)

1. **In a global fit New Physics can infect them through CKM parameters.**

2. **Tensions in the determination of $|V_{cb}|$ from inclusive vs exclusive tree level decays. (Lower the precision and should be presently avoided)**

3. **Hadronic uncertainties in some observables included in the fit are much larger than in many rare K and B decays. (Lower the precision and should be presently avoided)**

Standard Model Predictions without NP Infection

SM

$\mathbf{B^0_{s,d} - \overline{B}^0_{s,d}}$ **mixing**

$\boldsymbol{\varepsilon_K, S_{\psi K_s}}$

No NP infection

Determination of CKM parameters without NP infection

True SM predictions to be compared with Flavour Observables

Clean determination of anomalies

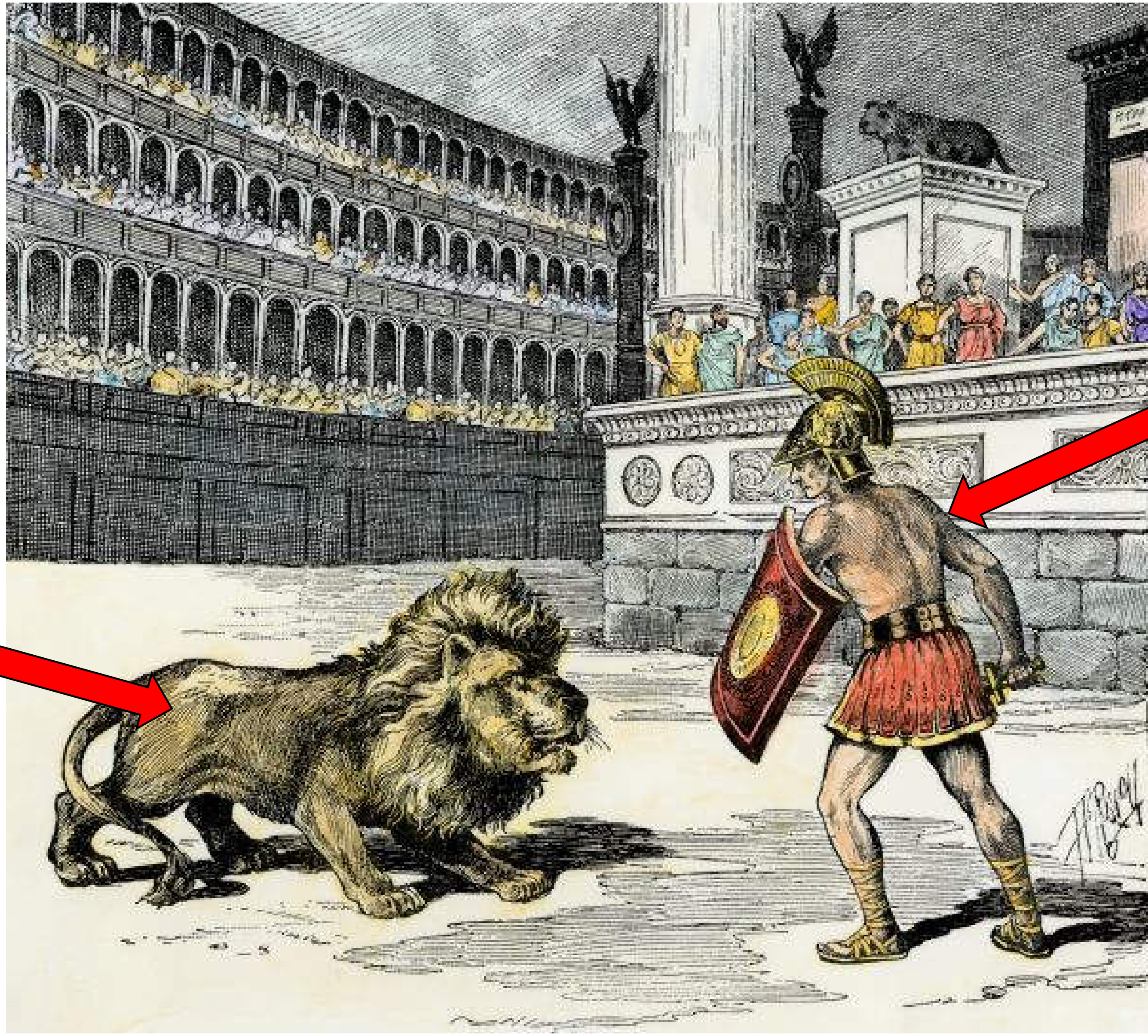
Present outcome:

AJB + Venturini 2203.11960
AJB 2209.03968
Aebischer, AJB, Kumar 2302.00013
AJB + Stangl 2412.14254

UT fitter
CKM fitter
PDG

AJB

Global Fitter



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

Reinhard Genzel

Flavour Strategy allows to see them through

Analogy :

Quantum Fluctuations

Black Hole

Nobel Prize 2020

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)

Dark Matter searches

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

Enrico Fermi

Enrico Fermi ~ 1935

First Effective Field Theory

Kaon Physics without New Physics in ε_K

$$R^+_{\nu\bar\nu} = \frac{\mathcal{B}(K^+\to\pi^+\nu\bar\nu)}{\mathcal{B}(K^+\to\pi^+\nu\bar\nu)_{SM}}, \quad R^0_{\nu\bar\nu} = \frac{\mathcal{B}(K_L\to\pi^0\nu\bar\nu)}{\mathcal{B}(K_L\to\pi^0\nu\bar\nu)_{SM}},$$

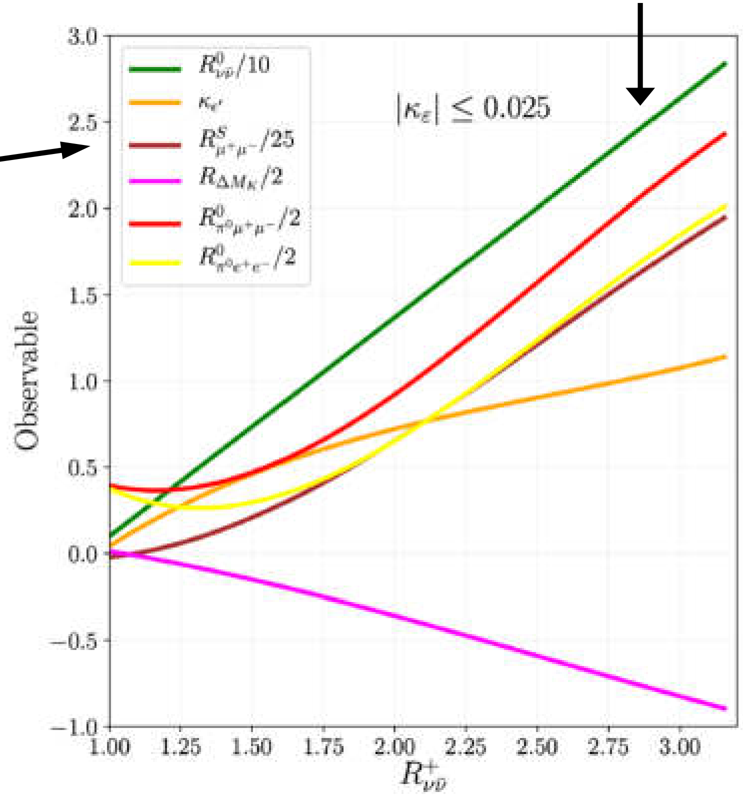
$$R^S_{\mu^+\mu^-} = \frac{\mathcal{B}(K_S\to\mu^+\mu^-)_{\rm SD}}{\mathcal{B}(K_S\to\mu^+\mu^-)^{SD}_{SM}}, \quad R^0_{\pi\ell^+\ell^-} = \frac{\mathcal{B}(K_L\to\pi^0\ell^+\ell^-)}{\mathcal{B}(K_L\to\pi^0\ell^+\ell^-)_{SM}},$$

$$R_{\Delta M_K} = \frac{\Delta M_K^{BSM}}{\Delta M_K^{exp}}, \quad \Delta\left(\frac{\varepsilon'}{\varepsilon}\right) = \kappa_{\varepsilon'}\cdot 10^{-3}, \quad \Delta(\varepsilon_K) = \kappa_\varepsilon \cdot 10^{-3}$$

MB branch

$\boxed{\kappa_\varepsilon \lesssim 0.02}$

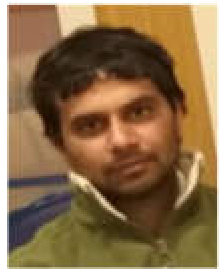
Dery, Ghosh, Grossman, Schacht (2104.06427)



(Z´ at work)

Aebischer, AJB, Kumar 2302.00013

J. Aebischer

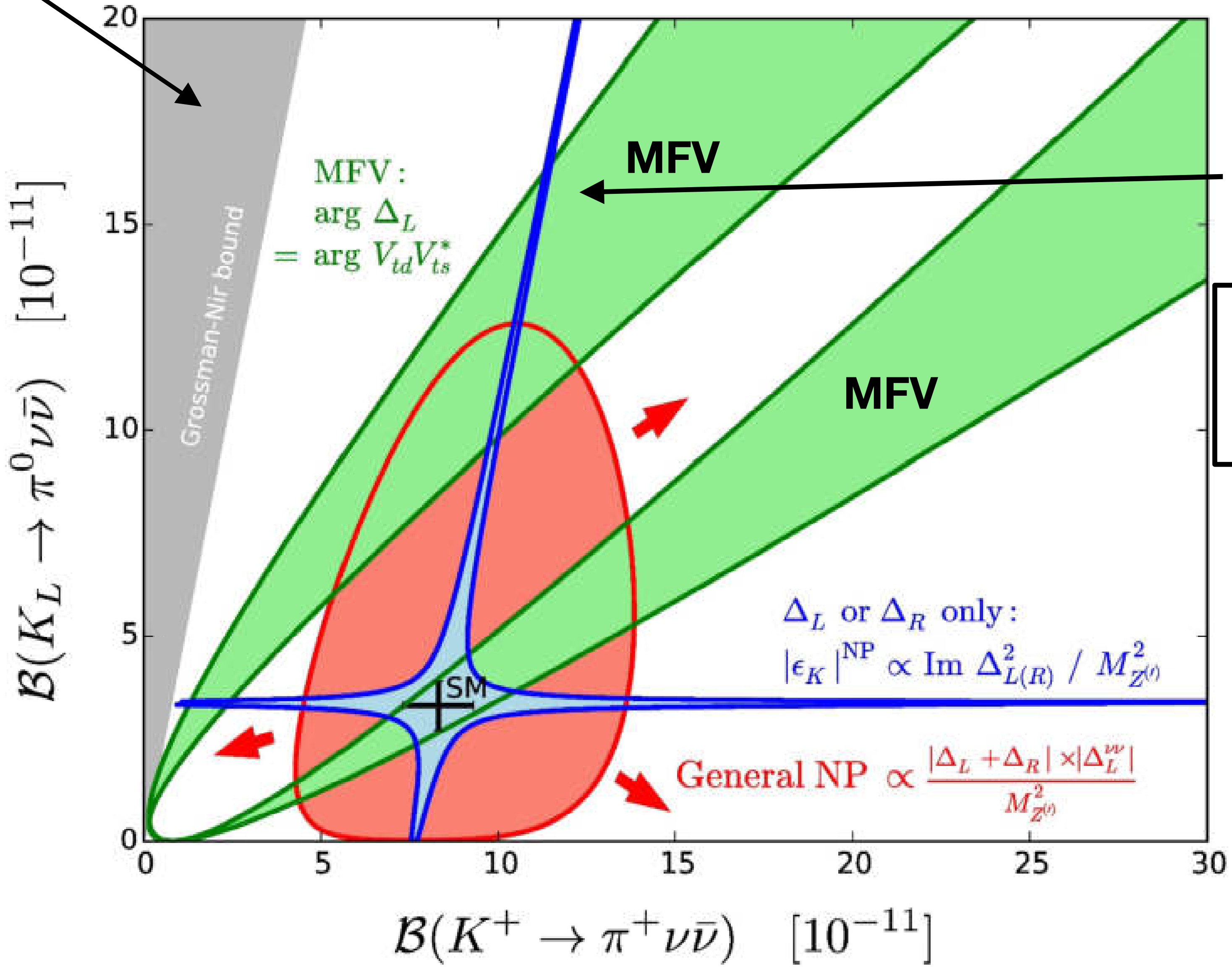


J. Kumar

Left-handed couplings

Buttazzo, AJB, Knegjens,   1507.08672

GN bound

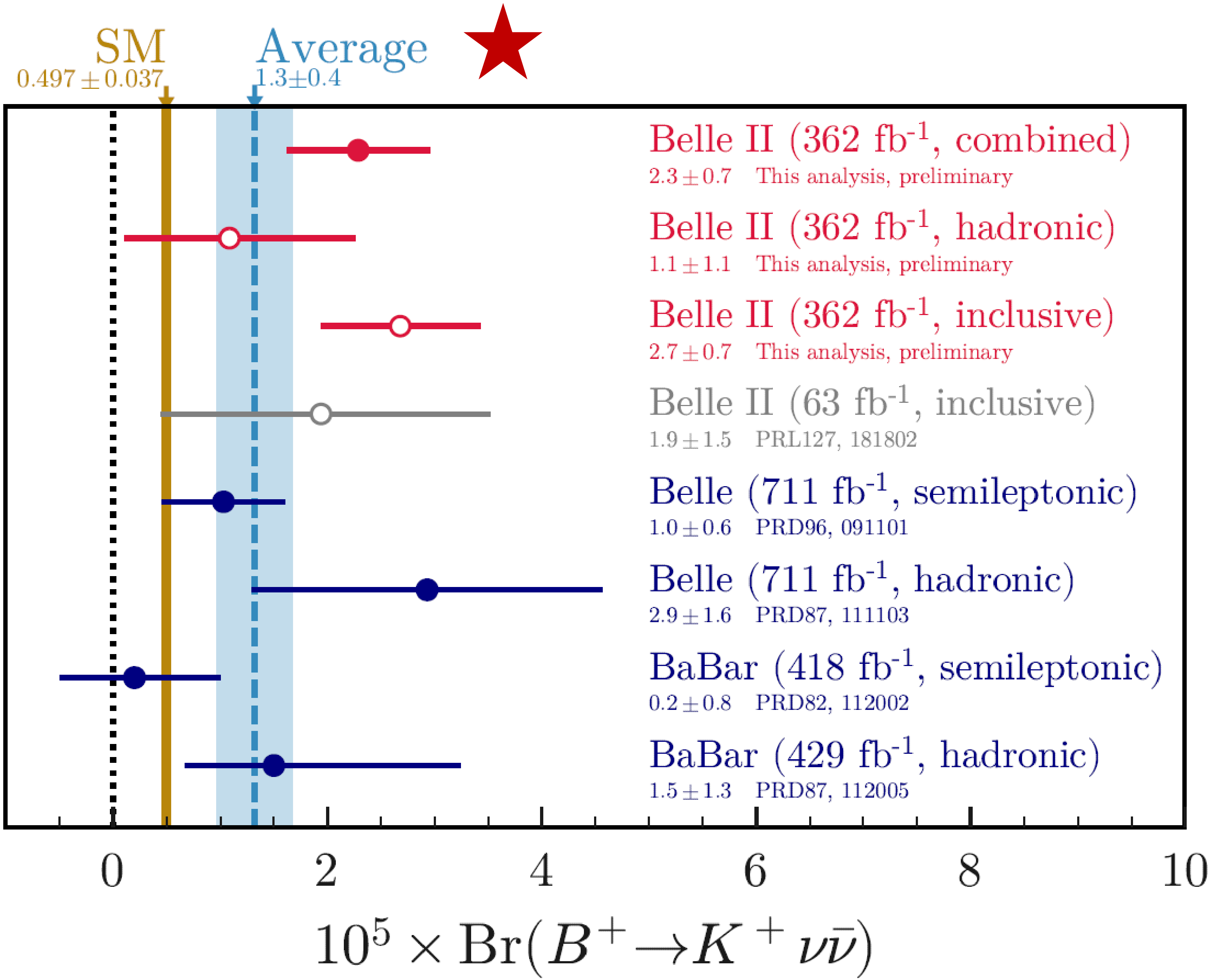


MB branch

Action only on the MB branch

Monika Blanke

Based on the insights from Monika Blanke (0904.1545)


SM
0.497 ± 0.037
Average
1.3±0.4
Belle II (362 fb-1, combined)
2.3 ± 0.7 This analysis, preliminary
Belle II (362 fb-1, hadronic)
1.1 ± 1.1 This analysis, preliminary
Belle II (362 fb-1, inclusive)
2.7 ± 0.7 This analysis, preliminary
Belle II (63 fb-1, inclusive)
1.9 ± 1.5 PRL127, 181802
Belle (711 fb-1, semileptonic)
1.0 ± 0.6 PRD96, 091101
Belle (711 fb-1, hadronic)
2.9 ± 1.6 PRD87, 111103
BaBar (418 fb-1, semileptonic)
0.2 ± 0.8 PRD82, 112002
BaBar (429 fb-1, hadronic)
1.5 ± 1.3 PRD87, 112005
0
2
4
6
8
10
$10^5 \times \mathrm{Br}(B^+ \to K^+ \nu\bar{\nu})$

Messages to take to your Homeoffice

1. V_{cb} – independent ratios and V_{cb} - γ plots will play important roles in the search for New Physics

2. The sextet

$$\boxed{\begin{array}{l} K^+ \to \pi^+ \nu\bar{\nu}, K_L \to \pi^0 \nu\bar{\nu}, B \to K\nu\bar{\nu} \\ B \to K^*\nu\bar{\nu}, B_s \to \mu^+\mu^-, B_d \to \mu^+\mu^- \end{array}}$$

can reveal NP easier than

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

(smaller long-distance uncertainties)

3. It is crucial that several lattice QCD groups calculate ΔM_d, ΔM_s, ε'/ε, $\Delta I = ½$ rule with 2 + 1 + 1 flavours

Basic Structure of DQCD for $K \rightarrow \pi\pi$, $K^0 - \bar{K}^0$ mixing

(ε'/ε, ε, $\Delta I = 1/2$ Rule, ΔM_K)

SM and BSM Operators

Reviews: 1401.1385, 1408.4820, 1809.02616

Λ_{NP}

EW

1 GeV

$\Lambda_{DQCD} \approx 0.8$ GeV

m_π, m_K

SMEFT with SM and BSM Operators

QCD + QED with SM and BSM Operators (Quark-Gluon Evolution)

DQCD: Meson Evolution (1/N)

$0(m_\pi, m_K) \rightarrow \Lambda_{DQCD} \approx 0.8$ GeV

RG Evolution

α_s, α_2, α_1

top Yukawa

α_s, α_{QED}

Non-Factorizable contributions

SM and BSM operators

Factorization Scale

for hadronic matrix elements

($N \rightarrow \infty$)

★ Crucial strong dynamics
Responsible for $\Delta I = 1/2$ Rule, ε'/ε, ε, ΔM_K, $K \rightarrow \pi\pi$ in general.

★ Very different philosophy from Chiral PTh in which meson evolution not included (Possibly hidden in LECs L_i).

Λ_{NP}

New Physics
(New Forces, New Particles)

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

Buchmüller, Wyler
Warsaw Basis

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

Top $\rightarrow$ Down

approach
requiring New
Physics models
more powerful
than

Bottom $\rightarrow$ Up

Renormalization
Group Evolution

Scale of decaying mesons

Non-perturbative QCD

$0(\text{few GeV})$