Flavour News from my Homeoffice

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QCD@Work 2024

(Trani, 17-21 June, 2024)

Overture

News from the Homeoffice in Ottobrunn

Trani Symphony

1st Movement	:	Standard Model Predictions for Rare K and B Decays without New Physics Infection
2nd Movement	:	Z´ at Work
3rd Movement	:	Disentangling New Physics in $K \to \pi\nu\bar{\nu}$ and $B \to K(K^*)\bar{\nu}\nu$ Decays
4th Movement	:	More Flavour News

1st 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

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)

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.

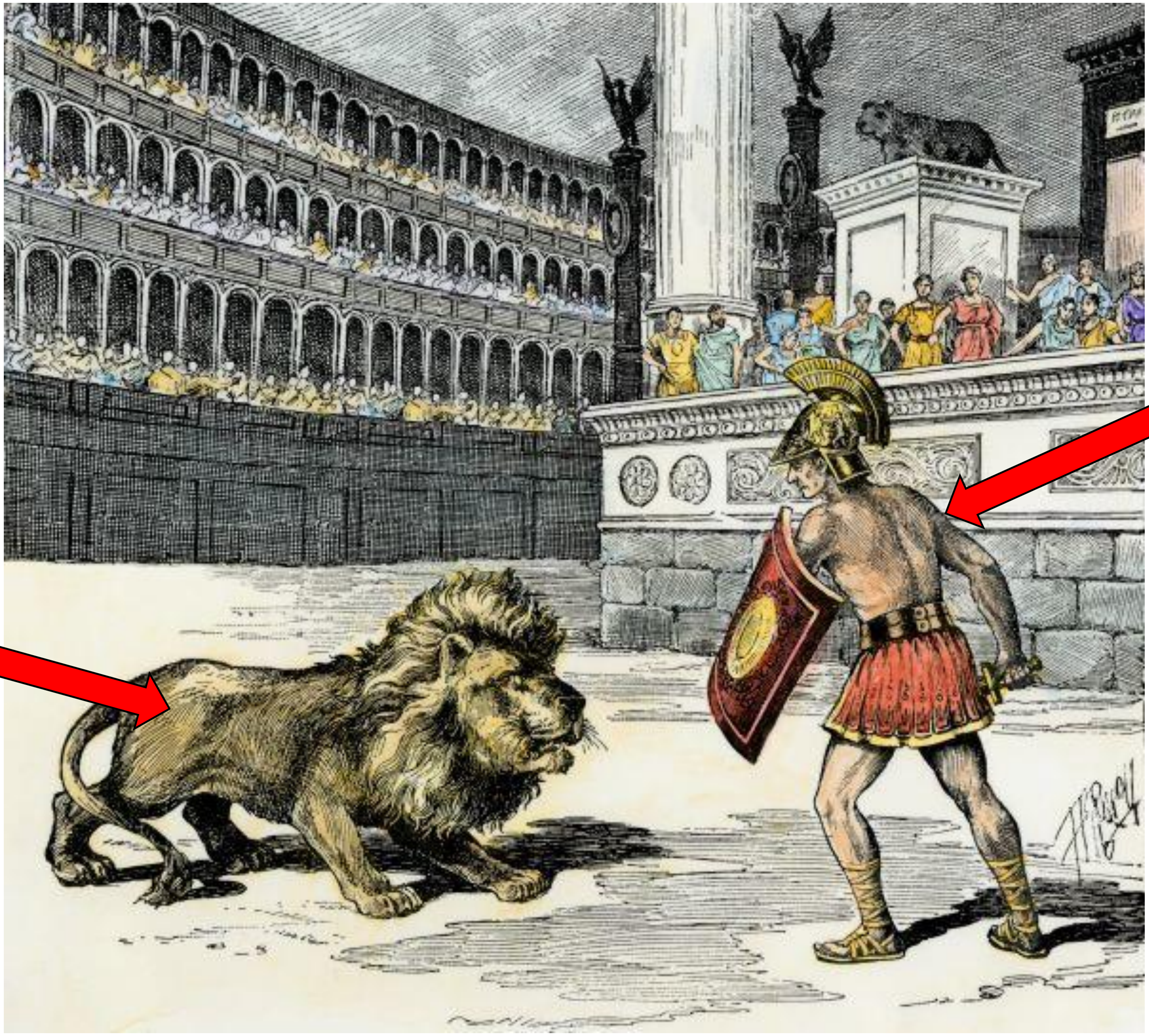
B. The remaining observables outside the "$\Delta F = 2$ archipelago" that could be infected by NP can be predicted within the SM and the pulls can be better estimated.

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

UT fitter
CKM fitter
PDG

AJB

Global Fitter



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

but with

E. Venturini

$|V_{cb}|$ Tension

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

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

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

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

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 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.

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 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

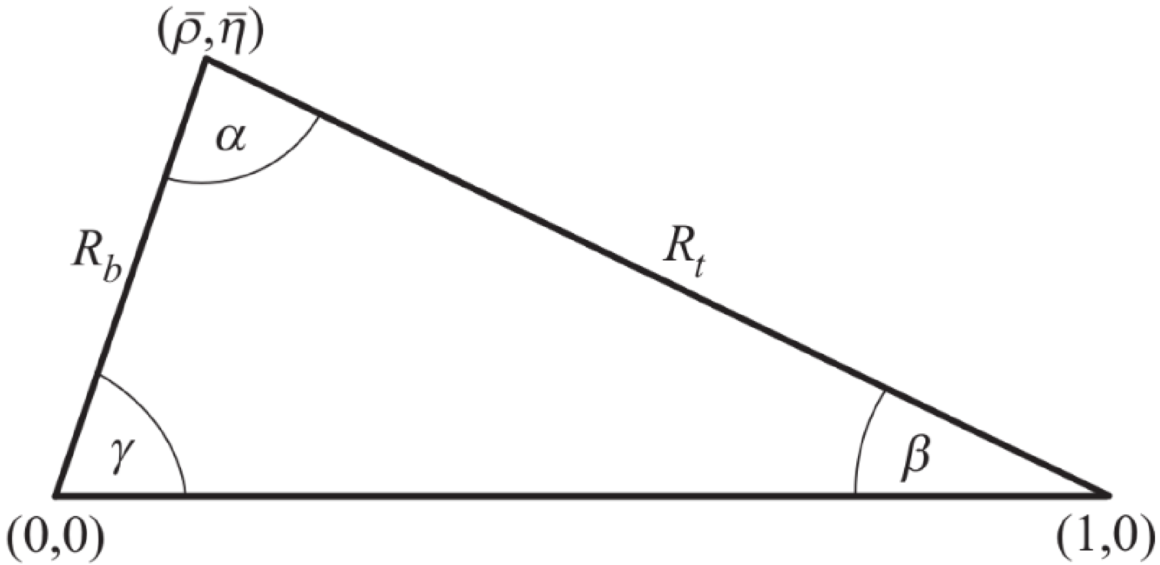
Recommended Parametrization of CKM Matrix

50th Anniversary in 2023

V_{us}, V_{cb}, β, γ

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)

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

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

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

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

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

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

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

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

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

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

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

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

AJB + E. Venturini (B-K Correlations)

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

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

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

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

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

C_i = CKM independent known factors

Important V_{cb} – Independent Formulae

AJB + E. Venturini (2109.11032)

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

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

Note: practically γ-independent

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

14 additional ratios in 2109.11032

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

Standard Model

(2024)

SM:

$$Br(K^+ \to \pi^+ \nu\bar{\nu}) = (8.6 \pm 0.4) \cdot 10^{-11}$$
$$Br(K_L \to \pi^0 \nu\bar{\nu}) = (2.94 \pm 0.15) \cdot 10^{-11}$$

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

$$Br(K^+ \to \pi^+ \nu\bar{\nu}) = (10.6 \pm 3.8) \cdot 10^{-11} \quad \text{(NA62)}$$
$$Br(K_L \to \pi^0 \nu\bar{\nu}) \leq 2.0 \cdot 10^{-9} \quad \text{(KOTO)}$$

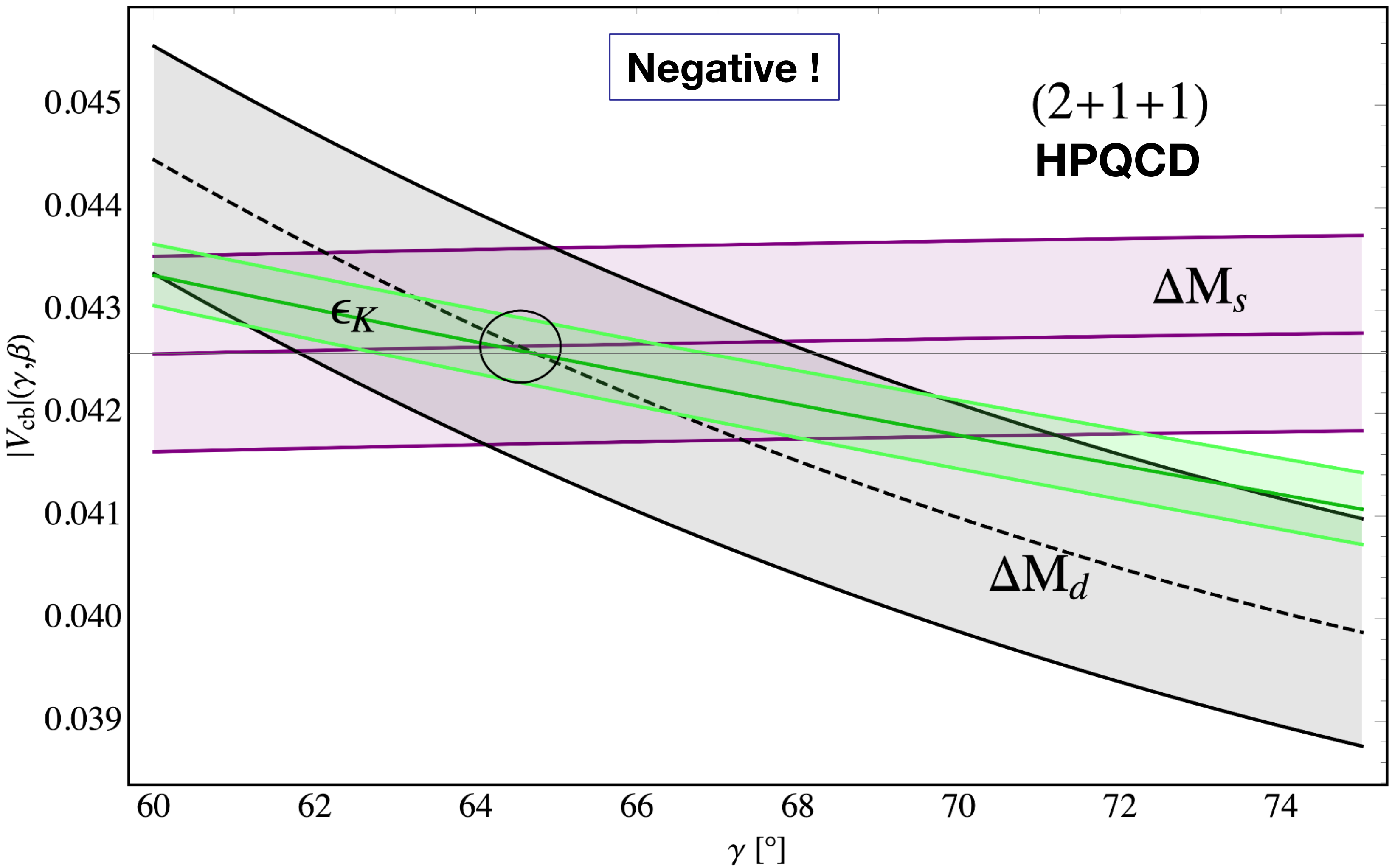
$$|V_{cb}| = 42.6(4) \cdot 10^{-3} \qquad |V_{cb}|_{inl} = 42.0(5) \cdot 10^{-3}$$

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

$|V_{cb}|$ - γ Plot = Rapid Test

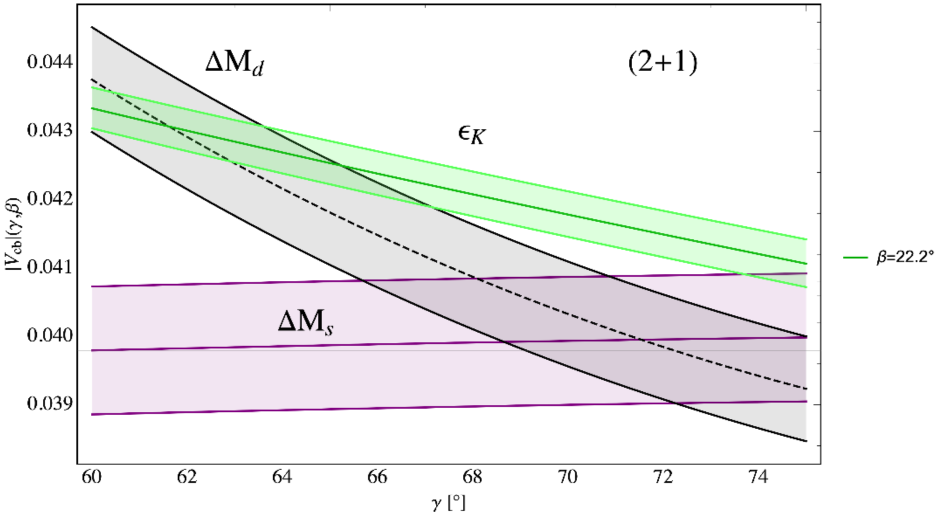
Perfect consistency between ΔM_s, ΔM_d, ε_K, $S_{\psi K}$

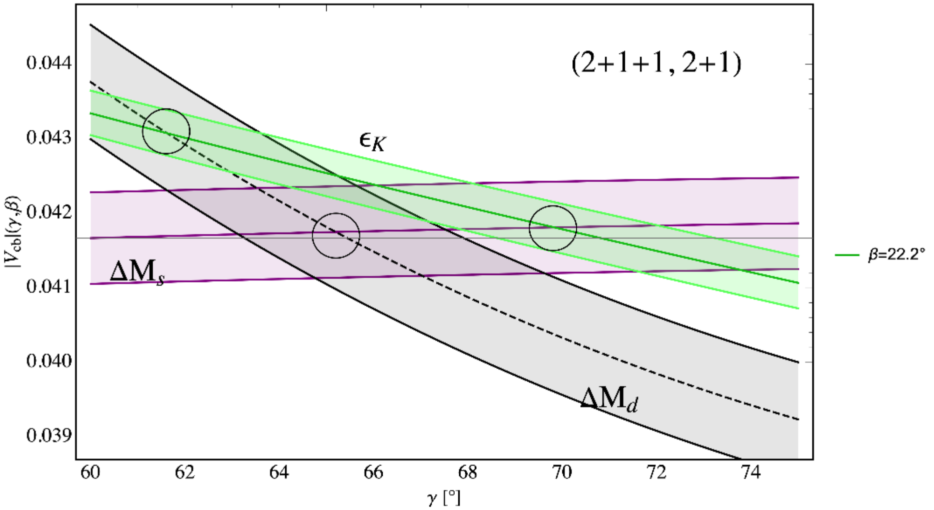
AJB + Venturini 2203.11960



Positive Tests

AJB + Venturini 2203.11960





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

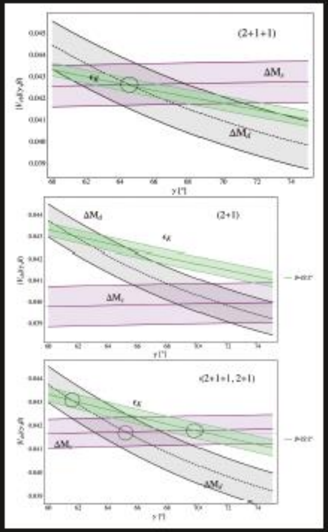
<u>Rapid Test</u>: cover picture of EPJC Vol. 83 number 1, January 2023

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

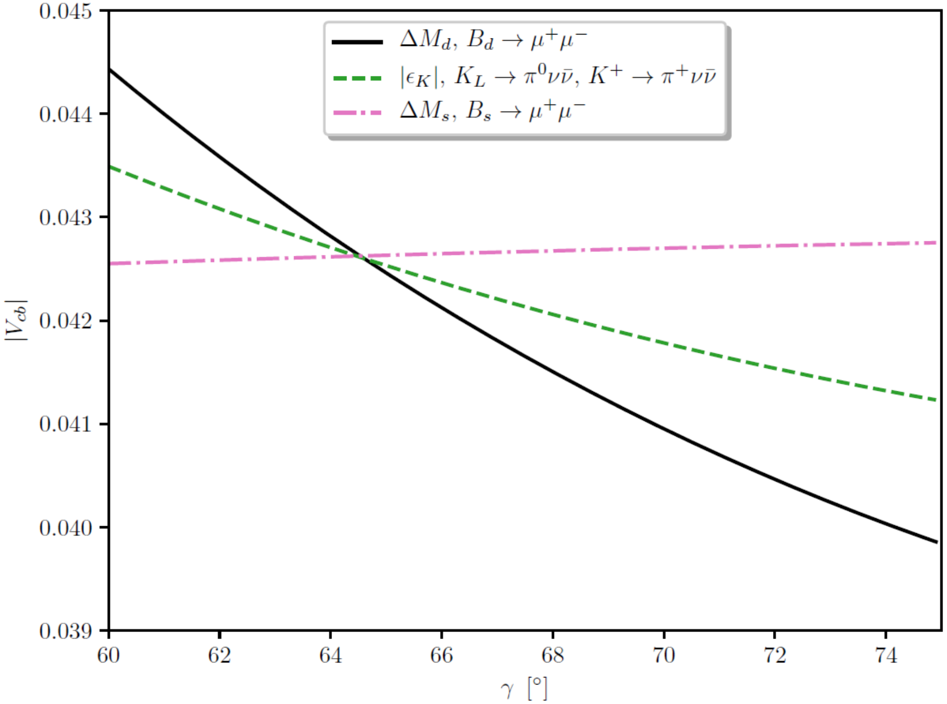
From Andrzej J. Buras on: Standard Model predictions for rare K and B decays without new physics infection. Eur. Phys. J. C 83, 66 (2023).

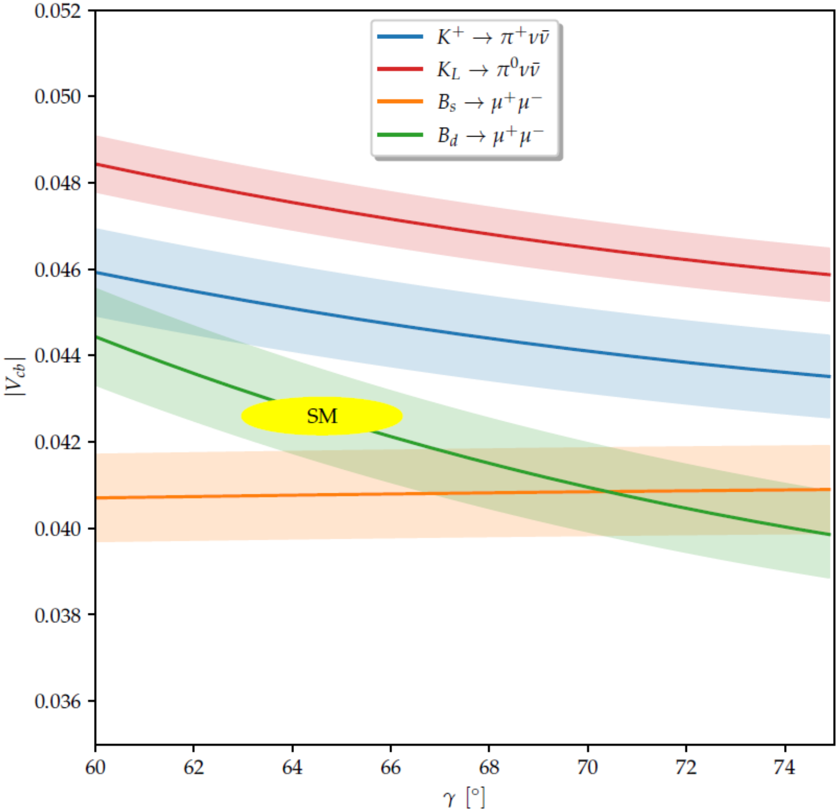
Società Italiana di Fisica
Springer

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

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

AJB 2209.03968

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

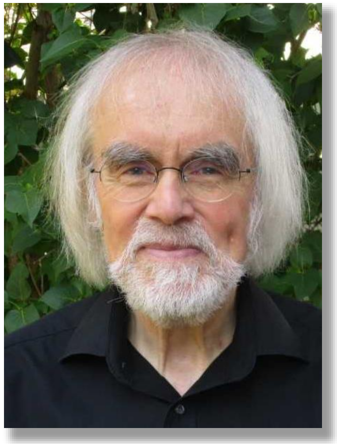
$$\frac{\mathrm{Br}(K^+ \to \pi^+ \nu\bar{\nu})}{[\mathrm{Br}(B^+ \to K^+ \nu\bar{\nu})]^{1.4}} = (1.90 \pm 0.13) \cdot 10^{-3}$$

Many other results in 2209.03968

2nd Movement:
Z´ at Work

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 ΔM_s, $S_{\psi\varphi}$, ...

Which NP scenario can reproduce this pattern ?

ε_K, ε'/ε, ΔM_K, $K^+ \to \pi^+\nu\bar{\nu}$, $K_L \to \pi^0\nu\bar{\nu}$

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

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

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

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

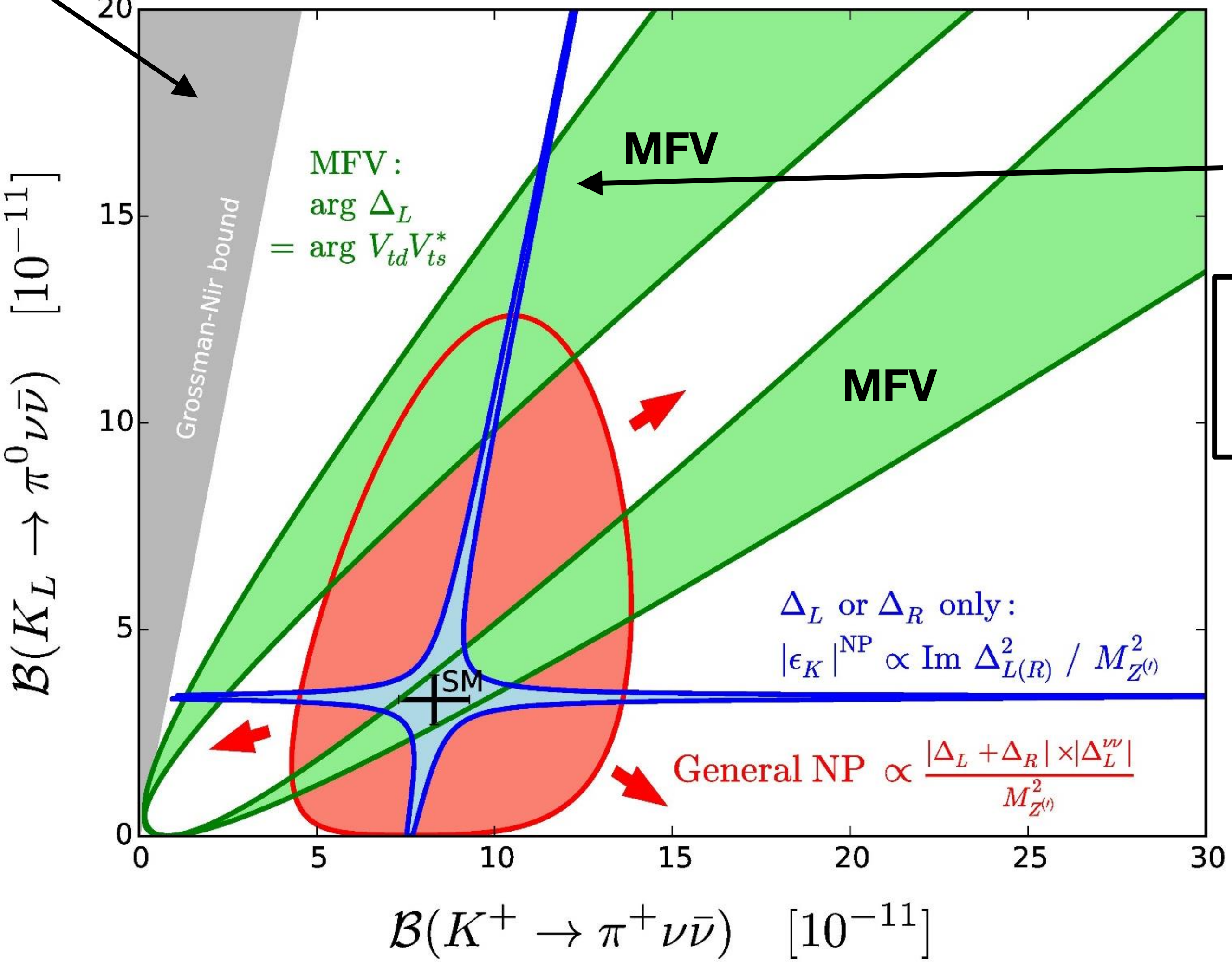
With $\mathrm{Re}\Delta_L^{sd}(Z') \ll \mathrm{Im}\Delta_L^{sd}(Z')$ **(Imaginary coupling)**

$\varepsilon_K^{NP} \simeq 0$ $\quad (\varepsilon'/\varepsilon)^{NP}$ **can be enhanced**
ΔM_K **can be suppressed + Interesting implications**
(possibly required by Lattice QCD) **for** $K \to \pi\nu\bar{\nu}$

Aebischer
AJB
Kumar
2302.00013

GN bound

Buttazzo, AJB, Knegjens, 1507.08672



MB branch

Action only on the MB branch

Monika Blanke

Based on the insights from Monika Blanke (0904.1545)

Kaon Physics without New Physics in ε_K

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

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

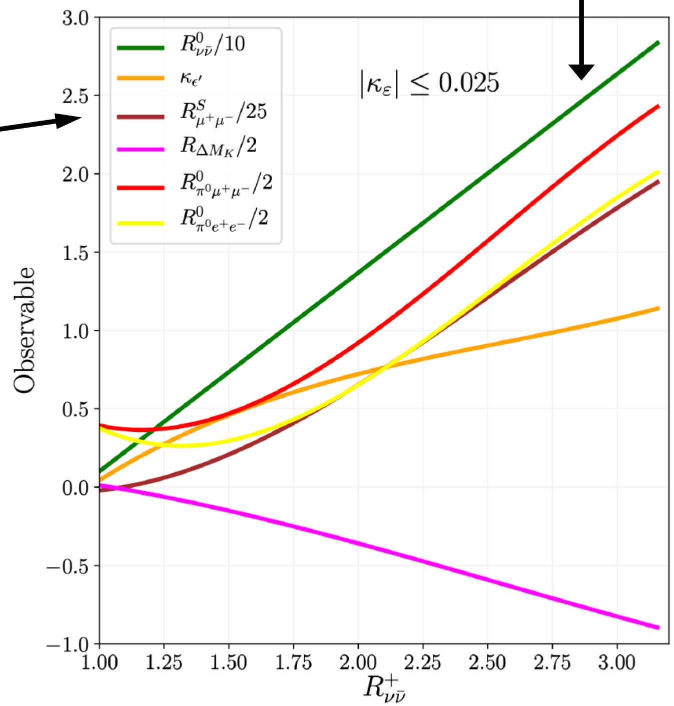
$$R_{\Delta M_K} = \frac{\Delta M_K^{BSM}}{\Delta M_K^{exp}}, \quad \Delta\left(\frac{\varepsilon'}{\varepsilon}\right) = \kappa_{\varepsilon'}\cdot 10^{-3}, \quad \Delta(\varepsilon_K) = \kappa_\varepsilon \cdot 10^{-3}$$

MB branch

$\kappa_\varepsilon \le 0.02$

Dery, Ghosh, Grossman, Schacht (2104.06427)

(Z´ at work)



Aebischer, AJB, Kumar 2302.00013

J. Aebischer

J. Kumar

Left-handed couplings

B Physics without NP in Quark Mixing

Fine tuning in ΔM_q q=d,s

suppression factor

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

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

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

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 $\Delta_R^{bs}(Z') \approx 0.1\, \Delta_L^{bs}(Z')$ **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 +  **(2407.xxx)**

Peter Stangl

News from Belle II

(2311.14647)

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

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

*)

+

AJB + Stangl (2024)

News from CERN (LHCb, CMS, ATLAS)

-

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

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

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)

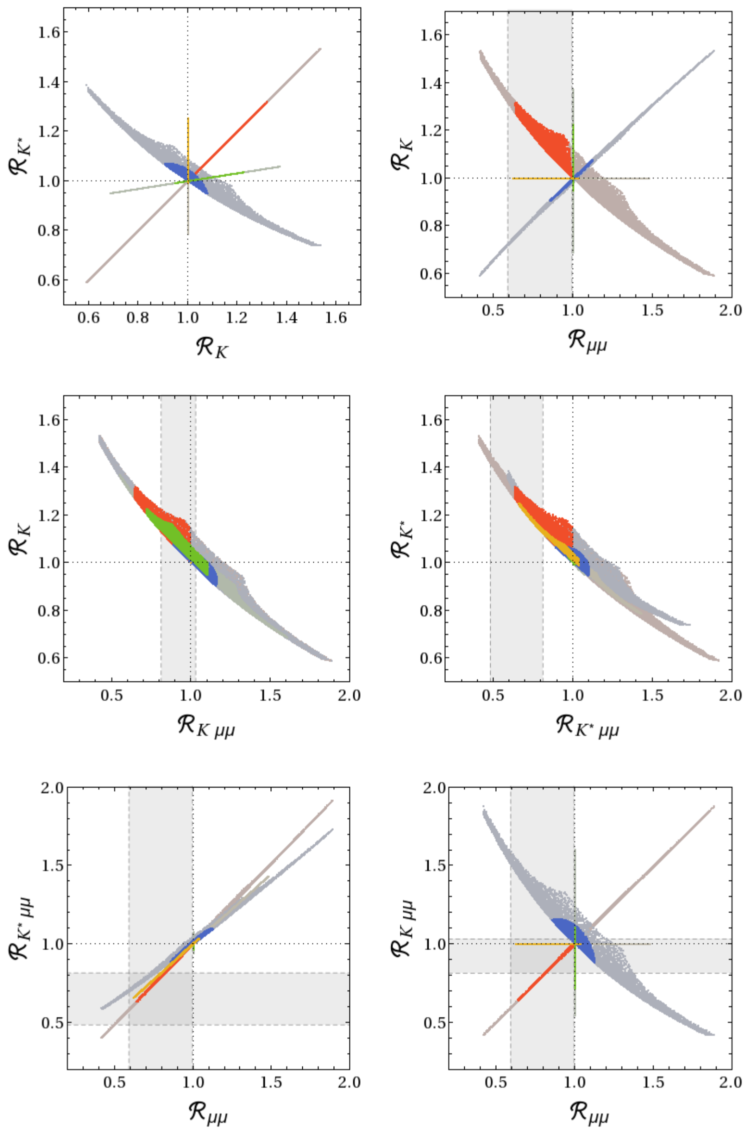
Testing Z´ Couplings (1409.4557)

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

Left-handed

Right-handed

Excluded



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

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

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

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

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

3rd Movement:

Distangling 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

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

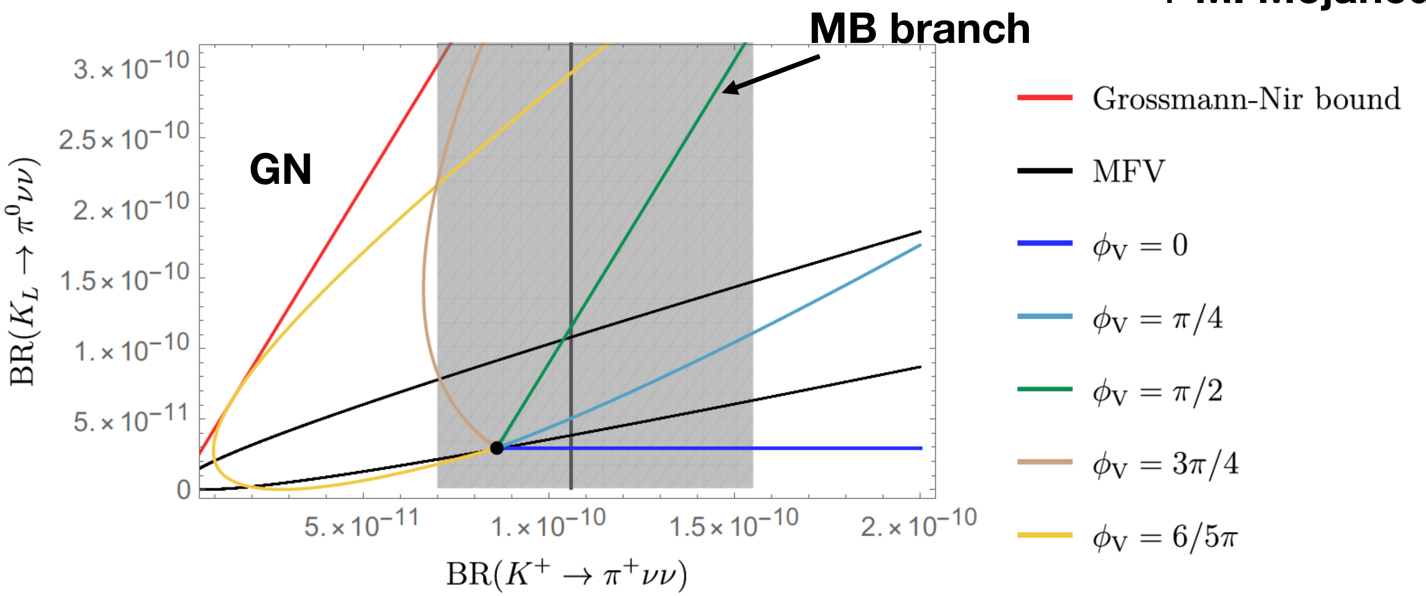
A. **Vector, scalar and tensor quark currents can be uniquely determined from experimental data of kinematic distributions**

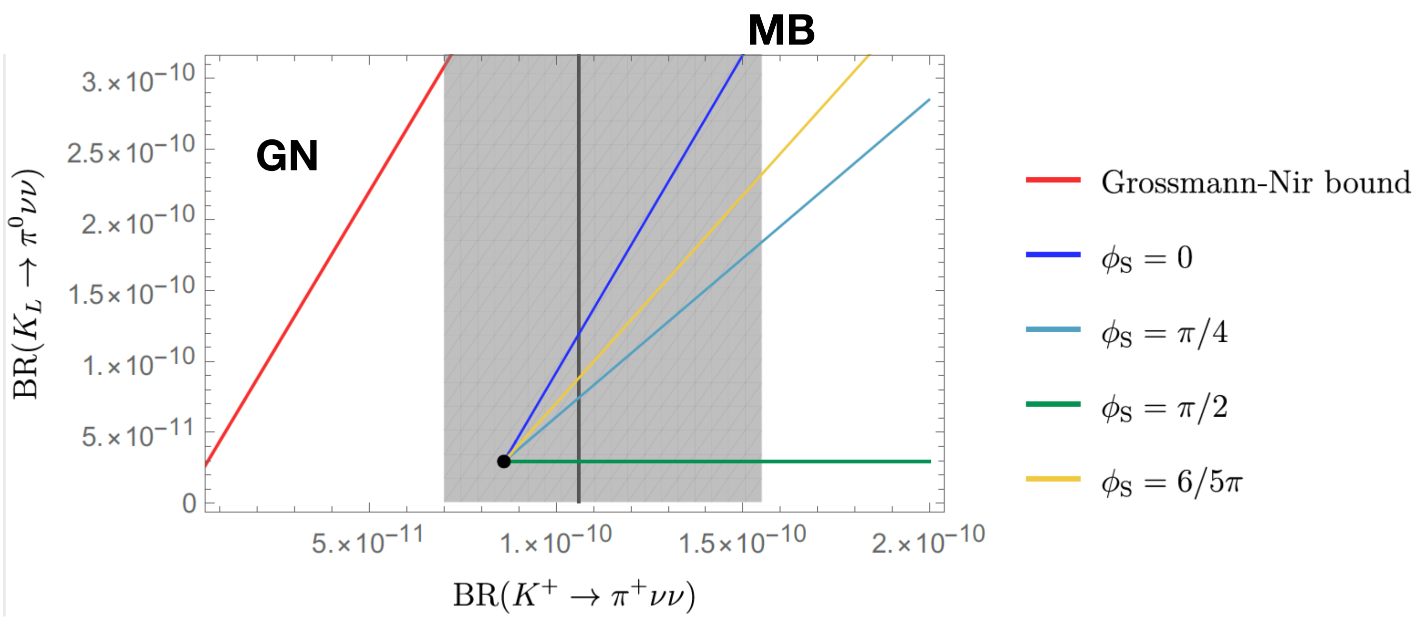
B. **Measurements of kinematic distributions make it possible to disentangle the contributions of WET operators from most of the dark-sector operators**

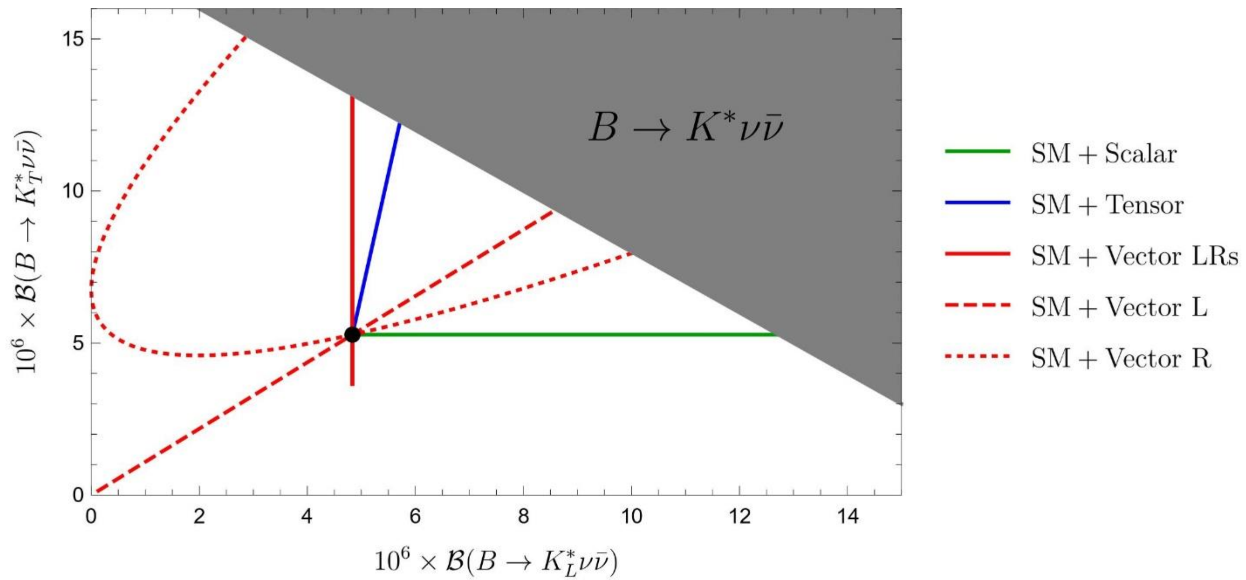
C. **Sum Rules for vector currents in WET are also satisfied in some new dark-physics scenarios that mimic WET**

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

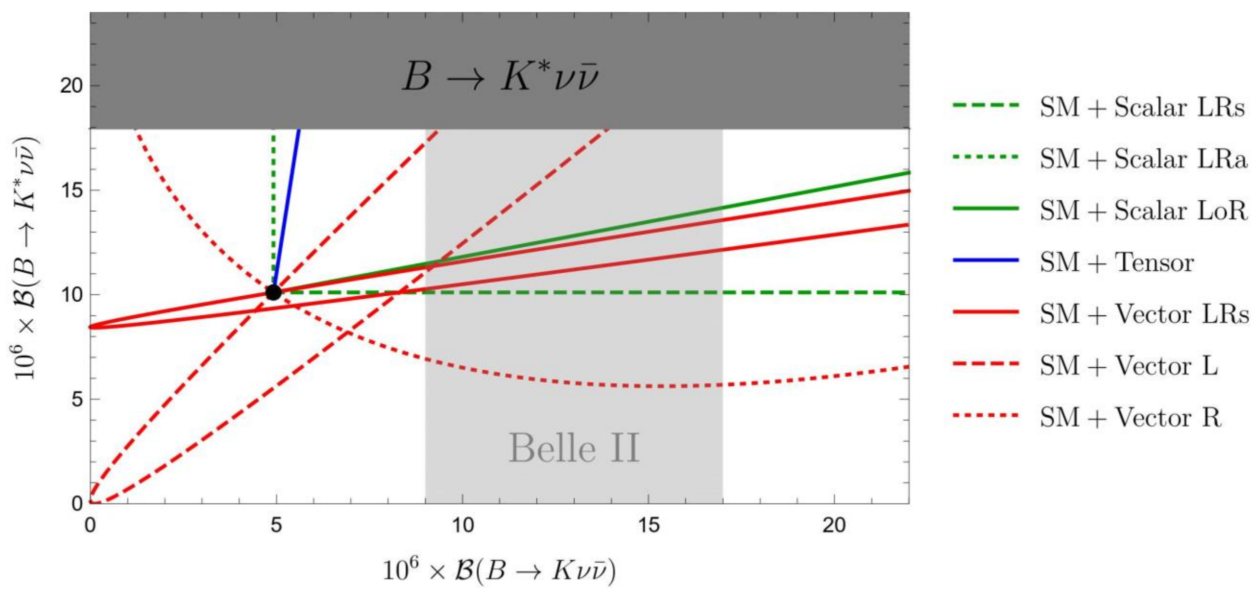
AJB + J.Harz + M. Mojahed





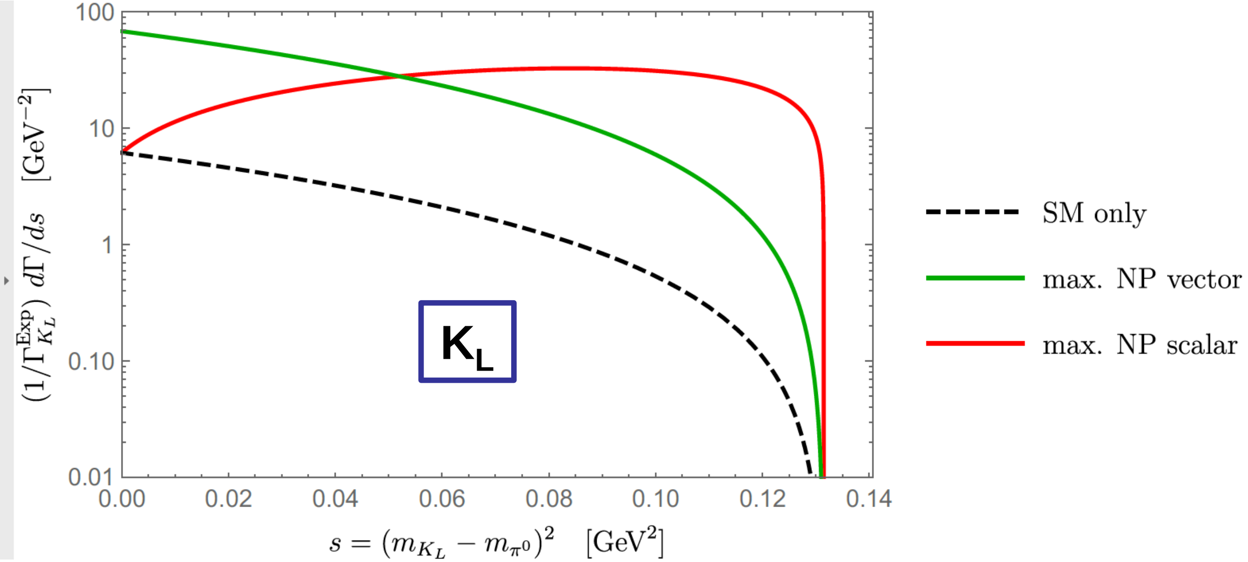


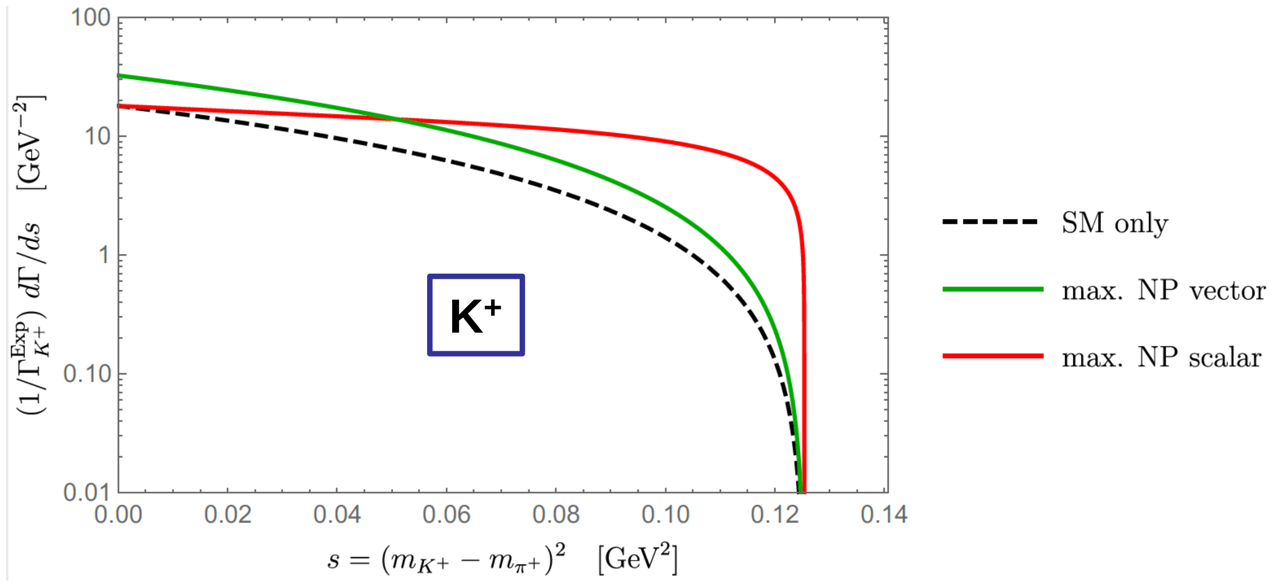
15
10
5
0
0
2
4
6
8
10
12
14
$B \to K^* \nu \bar{\nu}$
SM + Scalar
SM + Tensor
SM + Vector LRs
SM + Vector L
SM + Vector R
$10^6 \times \mathcal{B}(B \to K_T^* \nu \bar{\nu})$
$10^6 \times \mathcal{B}(B \to K_L^* \nu \bar{\nu})$



20
15
10
5
0
0
5
10
15
20
$B \to K^* \nu \bar{\nu}$
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



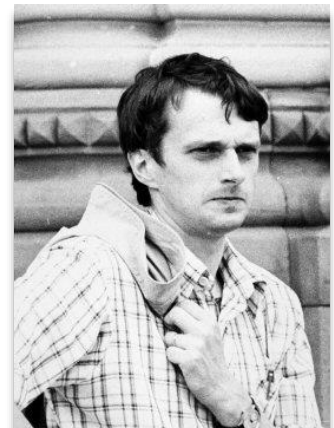


4th Movement
More Flavour News

Dual QCD Approach for Weak Decays

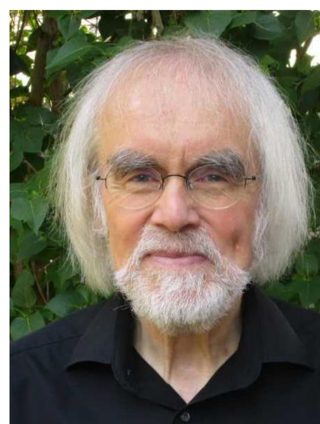
Successful low energy approximation of QCD
for $K \to \pi\pi$ K^0-K^0 mixing (Large N framework)

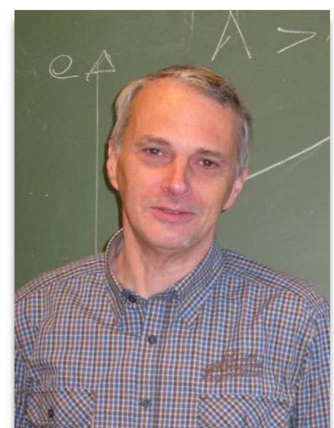
1986



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 $R = 16 \pm 2$ **Dual QCD** — **Bardeen, AJB, Gérard (Current-Current Operators)**

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) (2000)

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

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

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

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

Perfect Agreement!

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

Disagreements on QCD Penguin contribution.

Good news on $\hat{B}_K$

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

$\hat{B}_K = 0.74 \pm 0.01$ RBC-UKQCD (2024)

Main Activities in the Homeoffice in Ottobrunn

NLO QCD in WET and SMEFT (in Homeoffice)

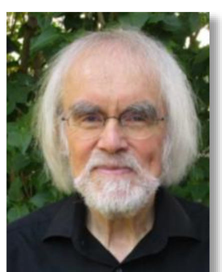
WET $\mu \leq \mathrm{EW}$ $SU(3)_c \otimes U(1)_{QED}$
SM + New Physics Operators

$\Delta F = 1$ (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 $\mu \geq \mathrm{EW}$ J. Aebischer, AJB, J. Kumar
$\Delta F = 2$ (Non-Leptonic) (2203.11224) (2202.01225)


J. Aebischer


AJB


J. Kumar


Christoph Bobeth


M. Misiak

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

Top → Down

approach requiring New Physics models more powerful than

Bottom → Up

Renormalization Group Evolution

Scale of decaying mesons

Non-perturbative QCD

$0(\text{few GeV})$

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

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

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, $\Delta I = 1/2$ rule with 2 + 1 + 1 flavours

Coming Years : Flavour Precision Era

LHC Upgrade
E = 14 TeV
(CERN)

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

★

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

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

Lepton Flavour Violation
$\mu \rightarrow e\gamma$
$\mu \rightarrow eee$
$\tau \rightarrow \mu\gamma$, $\tau \rightarrow 3\mu$

Electric Dipole Moments

Improved Lattice Gauge Theory Calculations

Neutrinos

★ $(g\text{-}2)_\mu$

★ ε'/ε

$\Delta I = ½$ Rule, ΔM_K

2024-2046 : Expedition
Attouniverse → Zeptouniverse
10^{-18}m →10^{-21}m

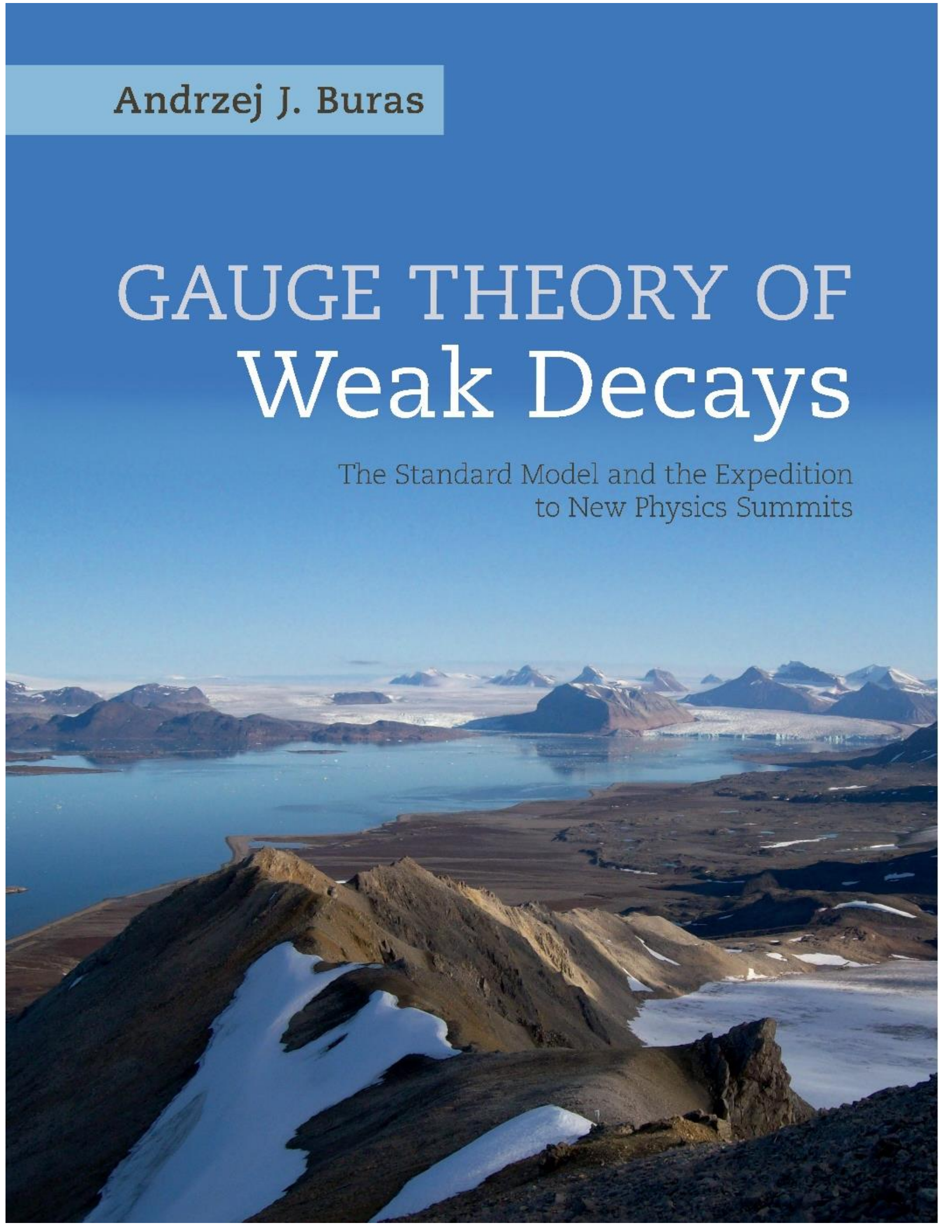
Hopefully meeting Z´, Leptoquarks, Vector-Like Quarks and Leptons

Zeptouniverse Guide

Published July 2020

7

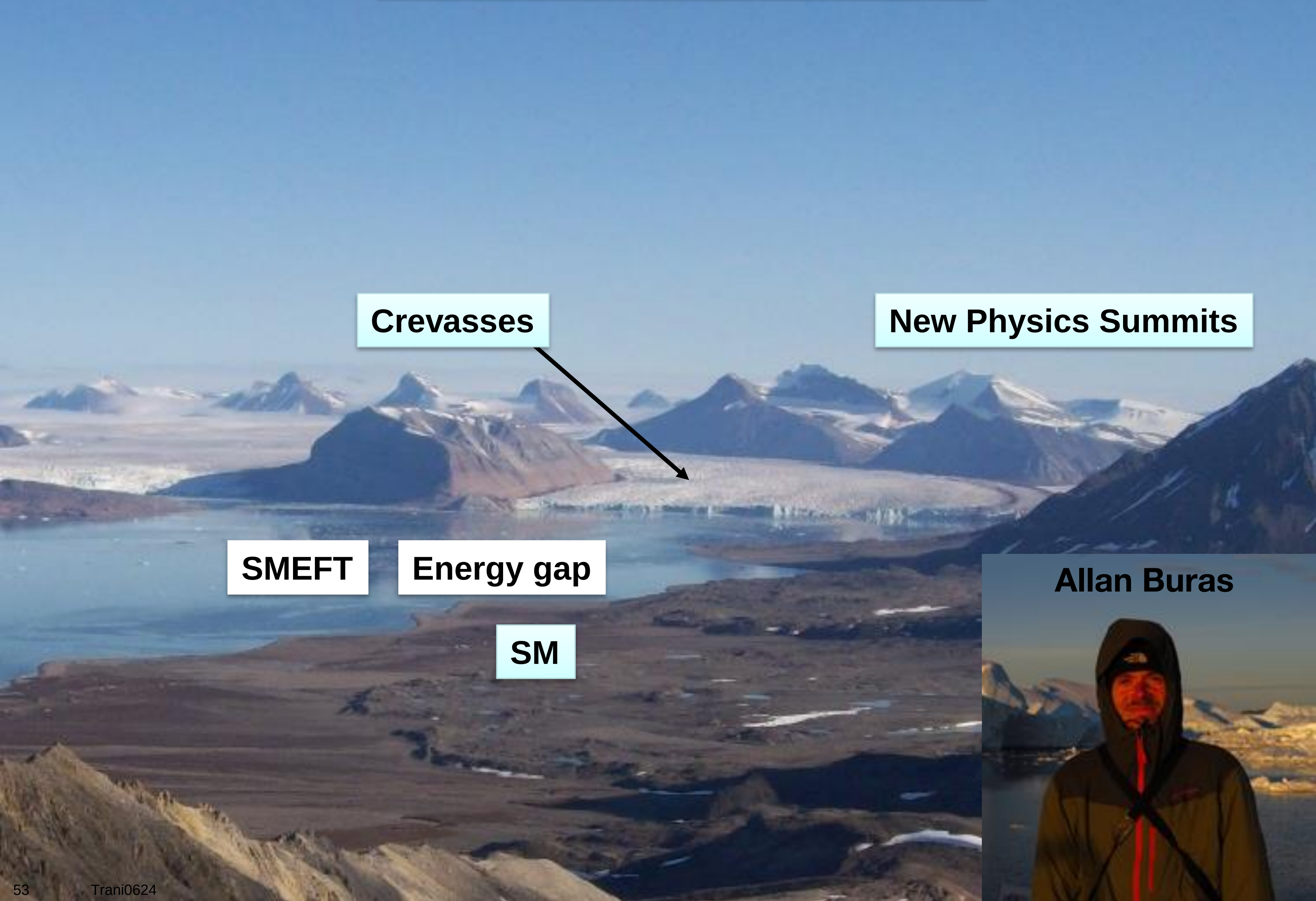
Exciting Years !



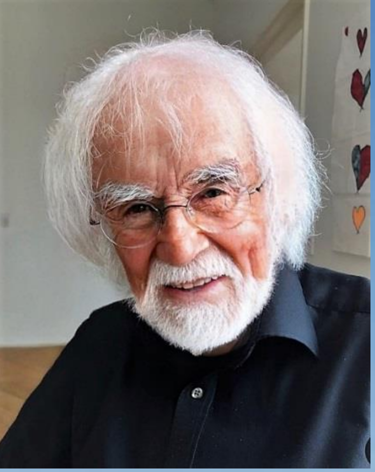
739 pages
1350 references

Cambridge University Press

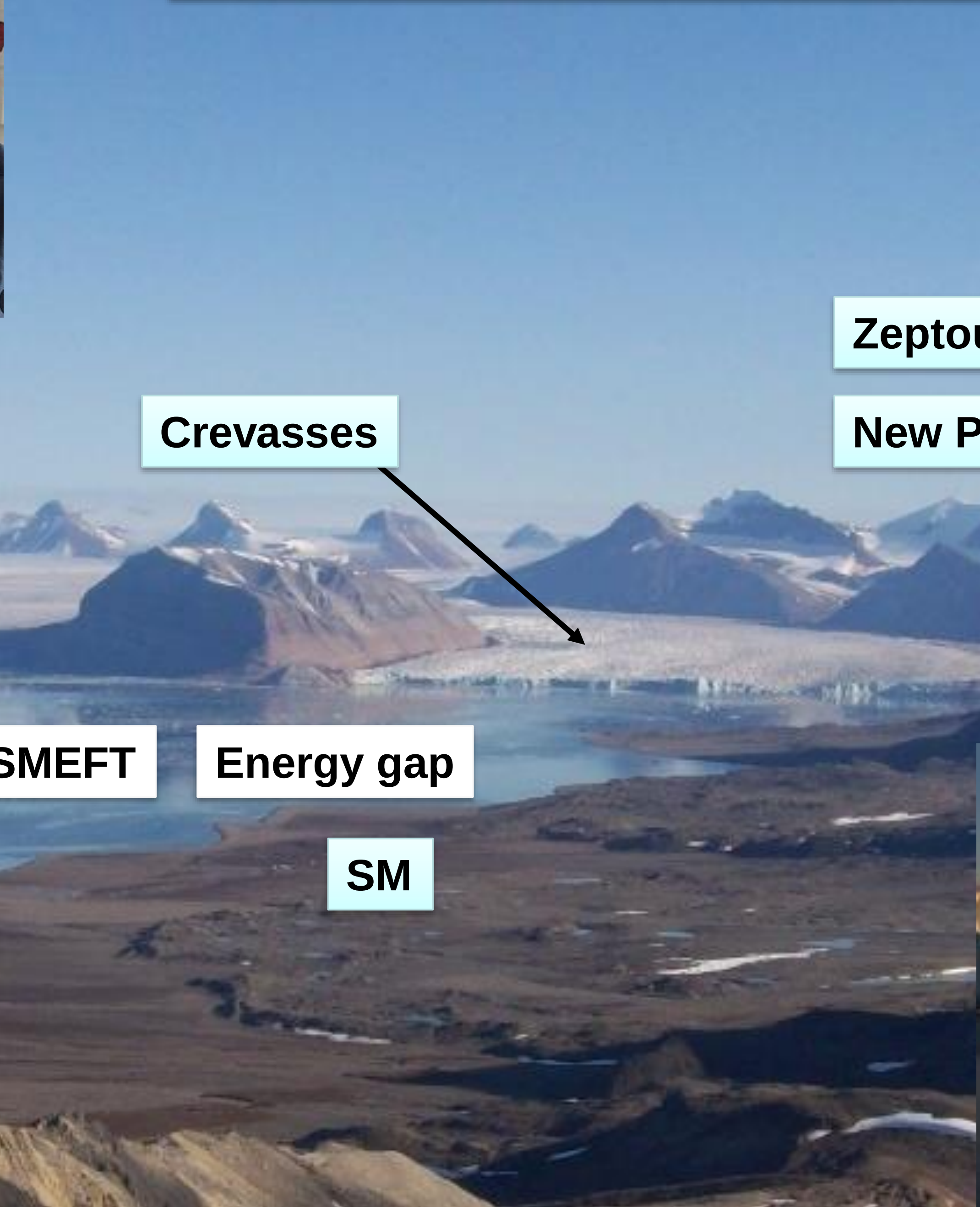
Flavour Physics (2024-)



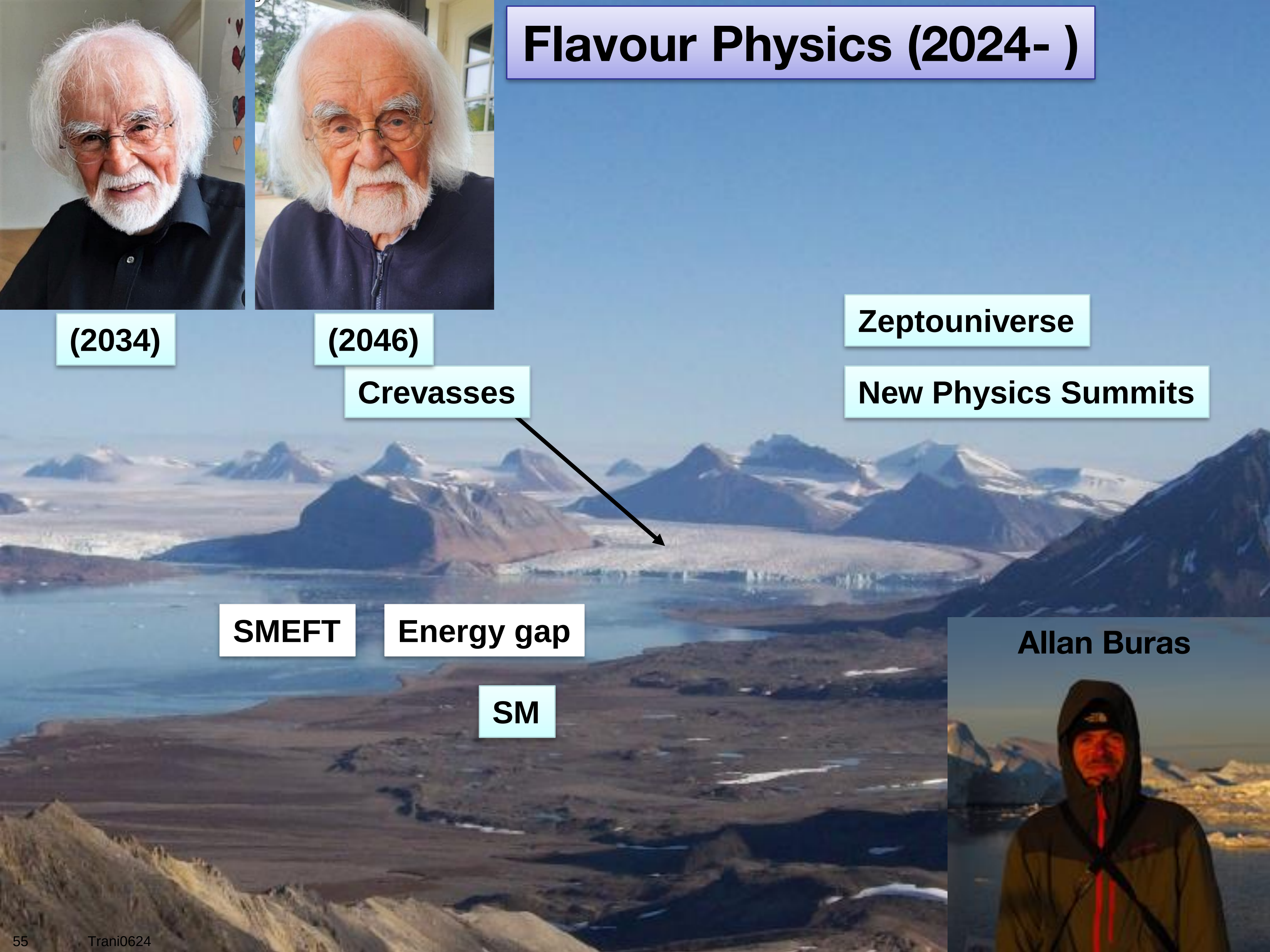
Flavour Physics (2024-)



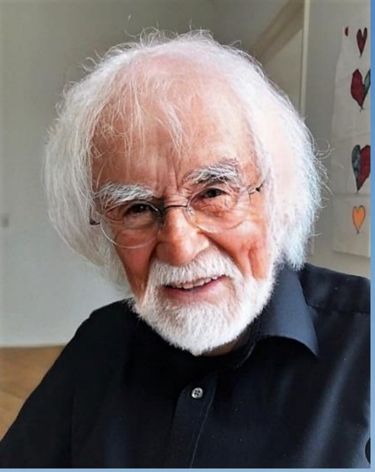
(2034)



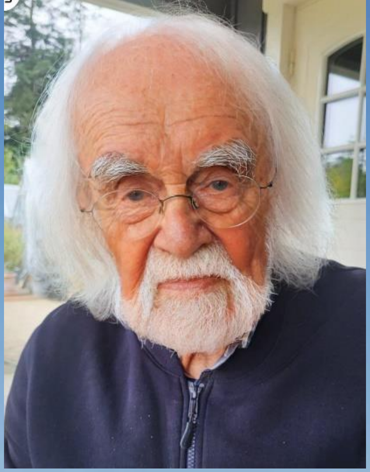
Flavour Physics (2024-)



Flavour Physics (2024-)



(2034)



(2046)

Allan Buras

Thank You !

Backup

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 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 mass^2 of $\nu\bar{\nu}$

3.

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

4.

All neutrino generations involved as opposed to neutrinoless double beta decay

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

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**

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

Present Anomalies (2024)

- $B^+ \to K^+ \nu\bar{\nu}$ — + — B
- Anomaly in Angular Distribution $B \to K^* \mu^+\mu^-$ (P_5^I) — - — 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

New Particles behind Anomalies

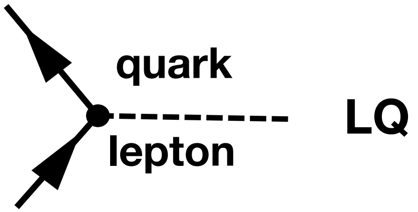
Top candidates

Review:
Capdevilla, Crivellin, Matias
2309.01311

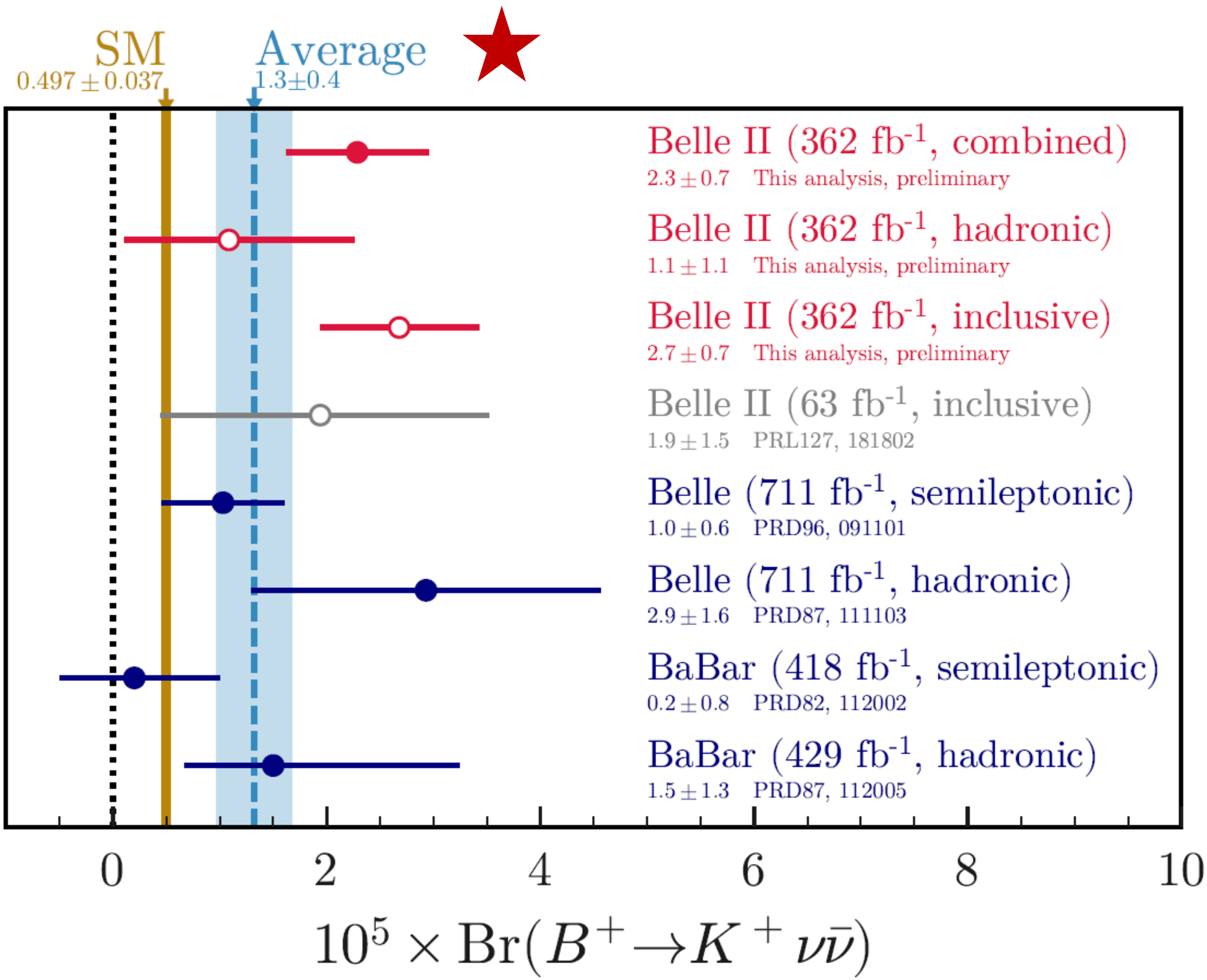
Z´ boson : heavy neutral gauge boson (Spin 1)

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 $SU(2)_L$



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
$10^5 \times \mathrm{Br}(B^+ \to K^+ \nu\bar{\nu})$

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

AJB: 2209.03968

$$R \equiv \frac{|\varepsilon_K|^{1.18}}{\Delta M_d \Delta M_s} = (8.22 \pm 0.18) \cdot 10^{-5} \left(\frac{\sin\beta}{\sin 22.2^\circ}\right)^{1.027} K\,\mathrm{ps}^2$$

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

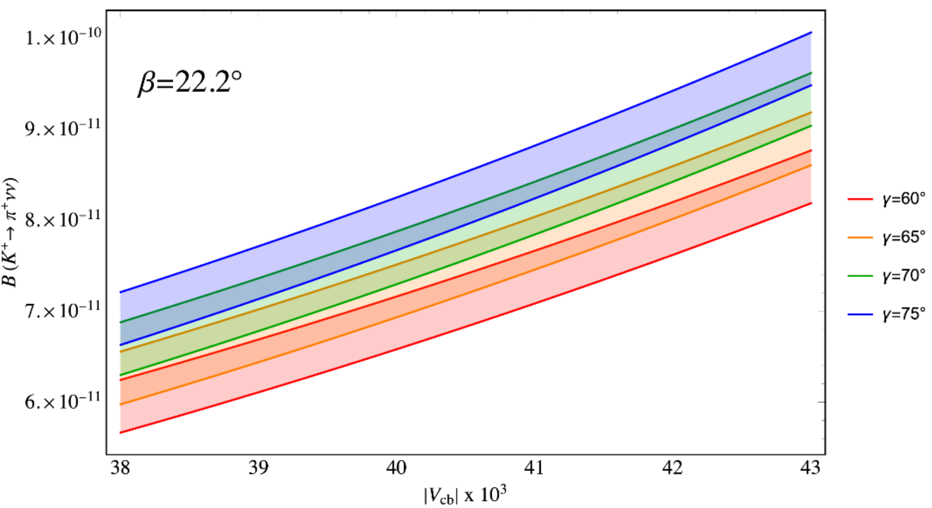
HPQCD

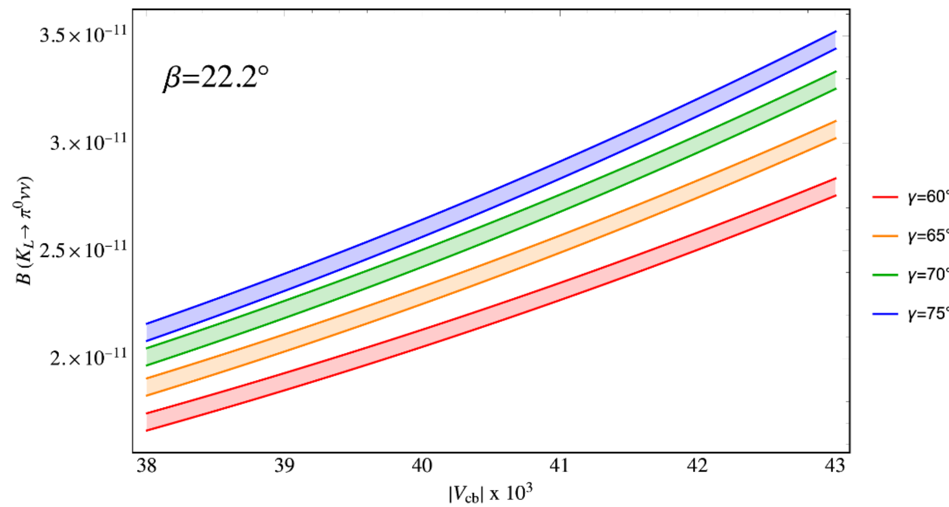
$$R_{exp} = (8.26 \pm 0.06) \cdot 10^{-5}\mathrm{ps}^2$$

$$K = 1.00 \pm 0.07$$

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

$$Br\left(K^{+} \to \pi^{+}\nu\bar{\nu}\right)_{SM} = \left(8.60\pm0.42\right)\cdot 10^{-11}$$

V_{cb} and γ independent

$$Br\left(K_{L} \to \pi^{0}\nu\bar{\nu}\right)_{SM} = \left(2.94\pm0.15\right)\cdot 10^{-11}$$

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

Searching for Majorana Footprints through LNC Sum Rules

LNC Sum Rules

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

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

$$r_1^{LNV} \neq 1$$

$$r_2^{LNV} \neq 1$$

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

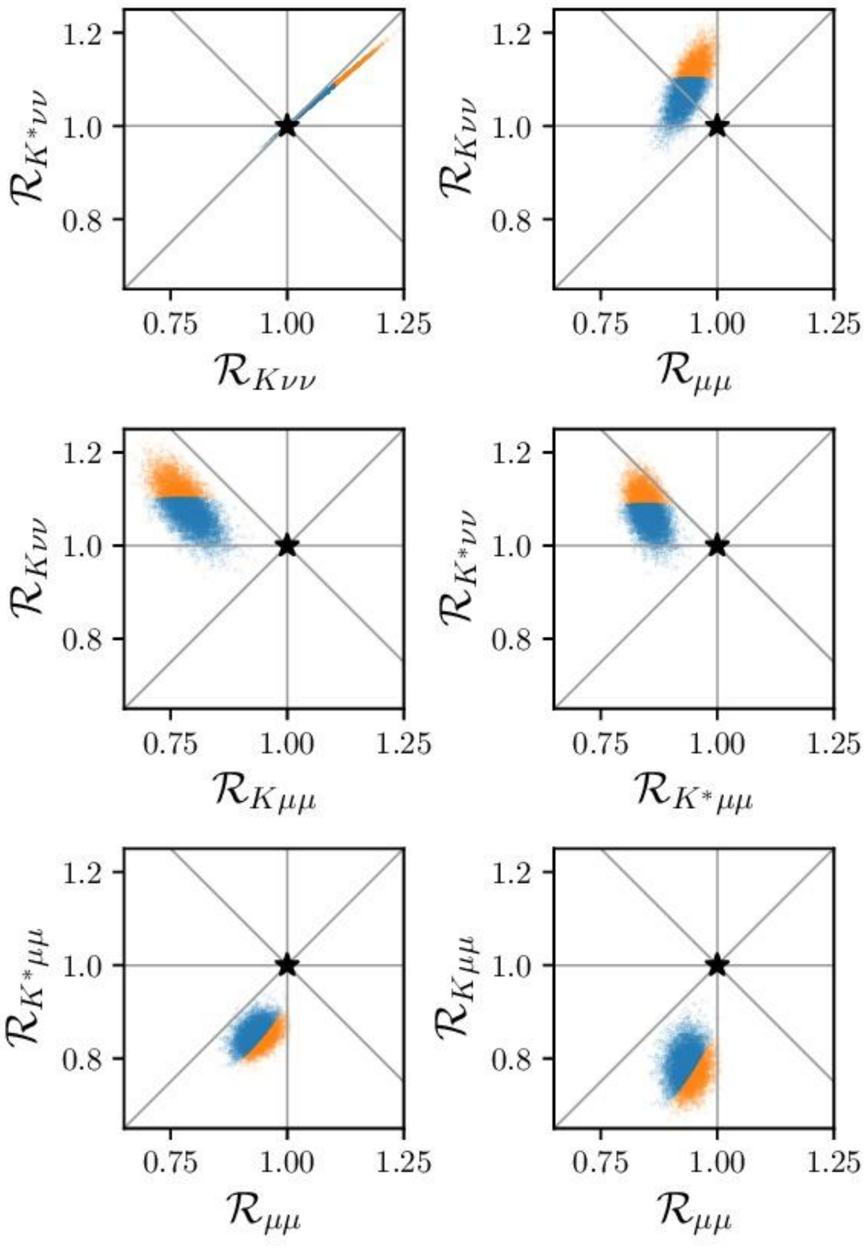
$$Br\left(B \to X_s \nu\bar{\nu}\right) = Br\left(B \to X_s \nu\bar{\nu}\right)_{SM}\left[\frac{\kappa_\eta R_K + 2R_{K^*}}{\kappa_\eta + 2}\right] r_2^{LNV}$$

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

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

K* longitudinal polarization fraction

Vector Z' Couplings to Leptons



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

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

AJB + Stangl (2407.xxx)

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