Standard Model Predictions for Rare K and B Decays without New Physics Infection and Z´ at Work

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10 Years MITP

Mainz, May, 2023

Happy Birthday to
Matthias Neubert (60)

MITP Symphony

1^{st} Movement	:	Standard Model Predictions for Rare K and B Decays without New Physics Infection
2^{nd} Movement	:	Z´ at Work
3^{rd} Movement	:	Footprints of Majorana Neutrinos in Rare K and B Decays
4^{th} Movement	:	Summary + Outlook

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 to appear 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 $|V_{cb}|$ and $|V_{ub}|$ 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.

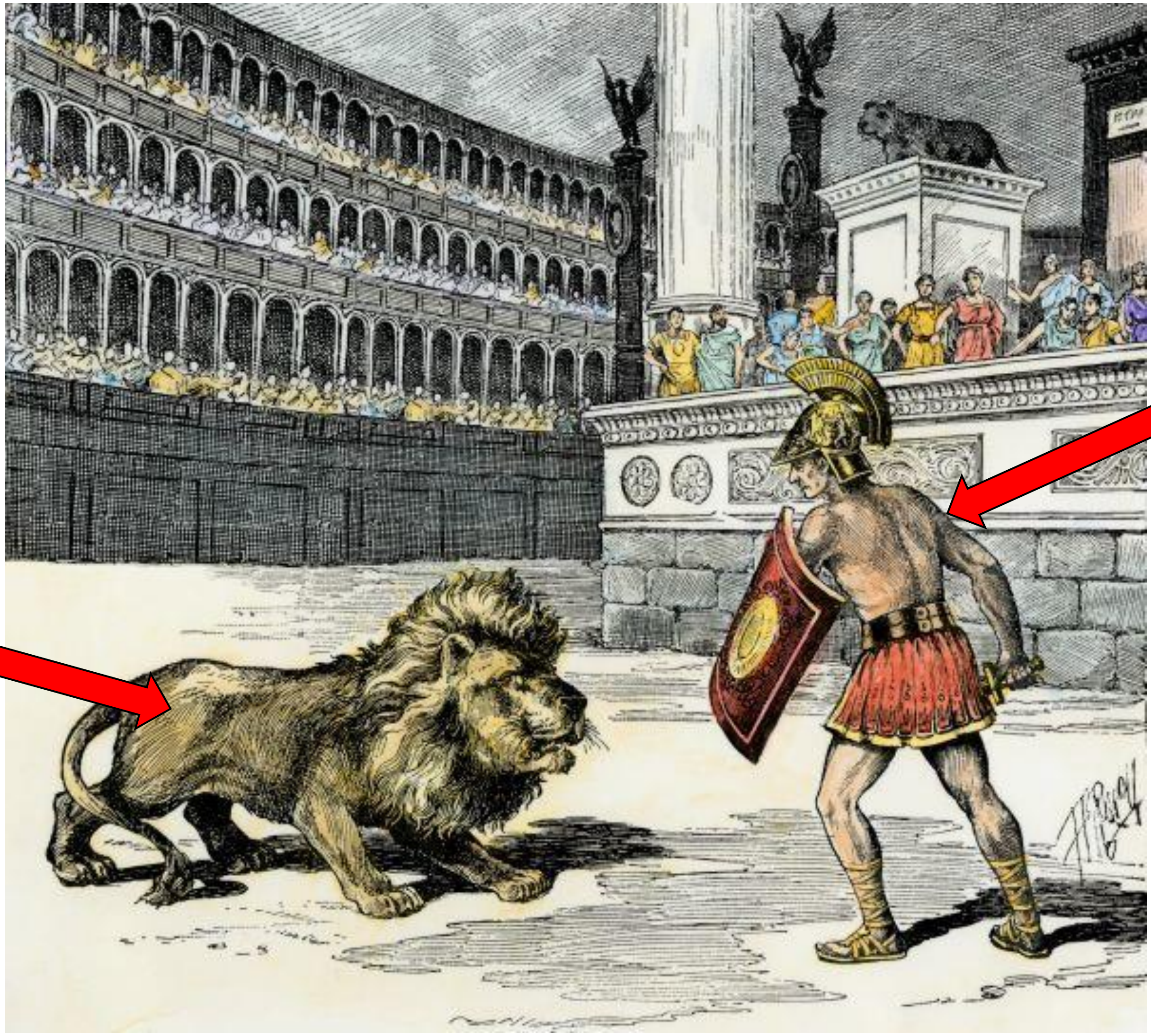
B. The remaining observables outside the "$\Delta F = 2$ archipelago" that could be infected by NP can be predicted within the SM and the pulls can be better estimated.

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

UT fitter
CKM fitter
PDG

AJB

Global Fitter



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

but with

E. Venturini

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

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

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

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

(FLAG) (2022)

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

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

(Belle 2021) (larger values before 2010)

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

(FLAG)

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

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

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

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

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

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

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

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

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

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 $R_i\ (\beta,\gamma)$**

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

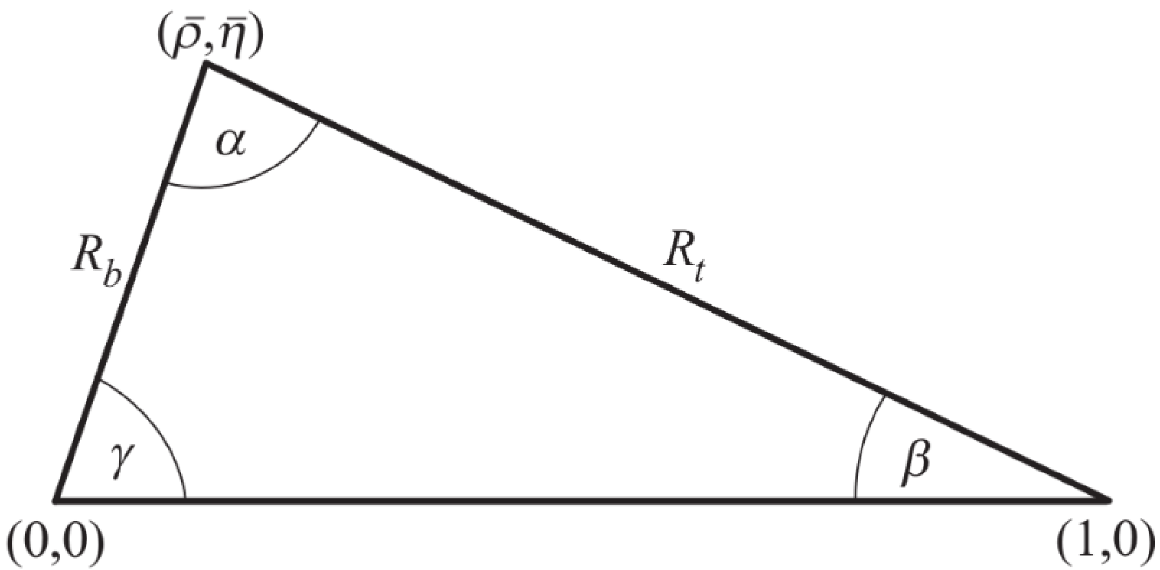
Additional ratios with $B \to K(K^*)\mu^+\mu^-$, $B_s \to \varphi\mu^+\mu^-$ in 2209.03968

Recommended Parametrization of CKM Matrix

50th Anniversary in 2023

V_{us}, V_{cb}, 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

Italian Experimental Collaborators

The CKM Matrix and the UT: another look (2002)

Achille Stocchi

Fabrizio Parodi

“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)

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

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

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

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

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

C_i = CKM independent known factors

(2003)

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

(q=d,s)

Numerical Constant

AJB 0303060

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

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

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

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

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

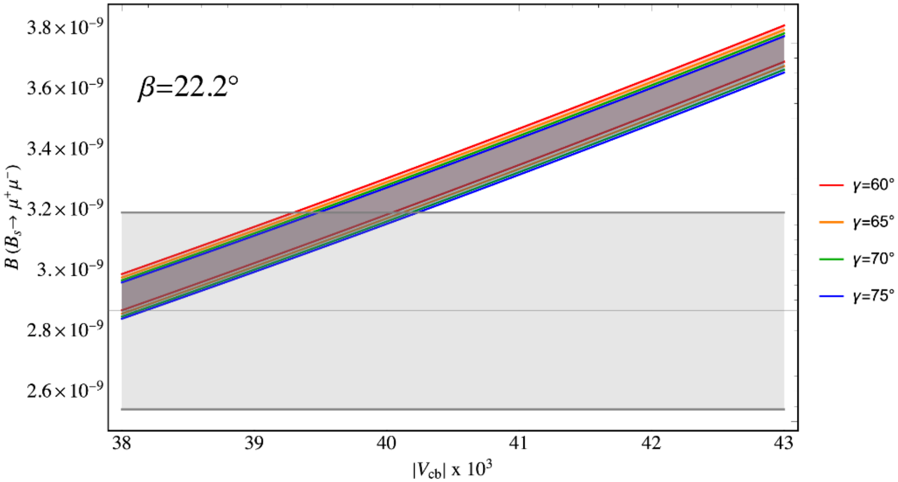
$$\boxed{[R_{s\mu}]_{exp} = \left(1.94 \pm 0.16\right)\cdot 10^{-10}\,\text{ps}}$$

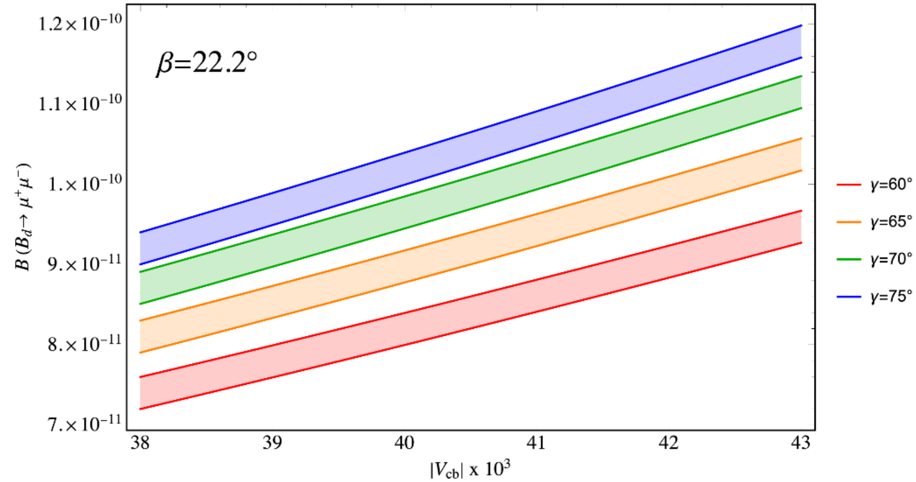
(1.1 σ tension)
(Independent of CKM parameters!!)

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

AJB + E. Venturini (2109.11032)

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





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

LHCb
CMS
ATLAS

CMS + FLAG22

Averages from: 2103.12738, 2103.13370, 2104.10058

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

CKM Independent !

(1.1 σ)

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)

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

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

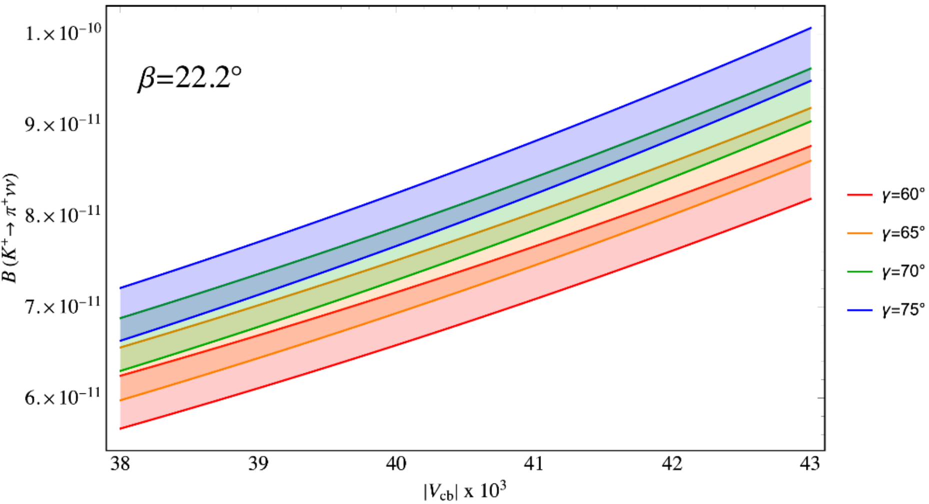
Note: practically γ-independent

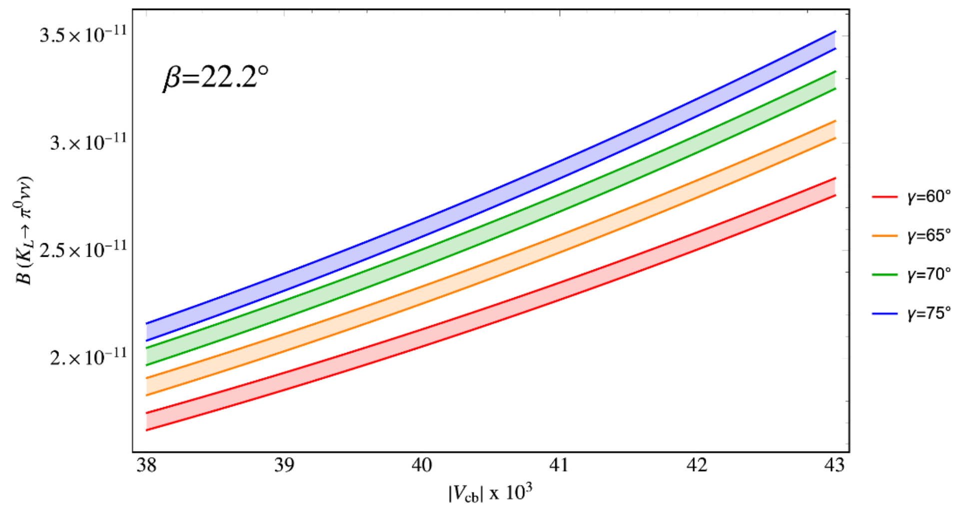
$$\left\{|\varepsilon_K|_{exp}, S^{exp}_{\psi K_s} = \sin 2\beta\right\} \Rightarrow \left\{\begin{array}{l}\text{Most accurate} \\ \text{Predictions to} \\ \text{date}\end{array}\right\}$$

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

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

AJB + E. Venturini (2109.11032)





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

NA62

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

KOTO

$$Br\left(K^+ \to \pi^+ \nu\bar{\nu}\right)_{SM} = \left(8.60 \pm 0.42\right) \cdot 10^{-11}$$

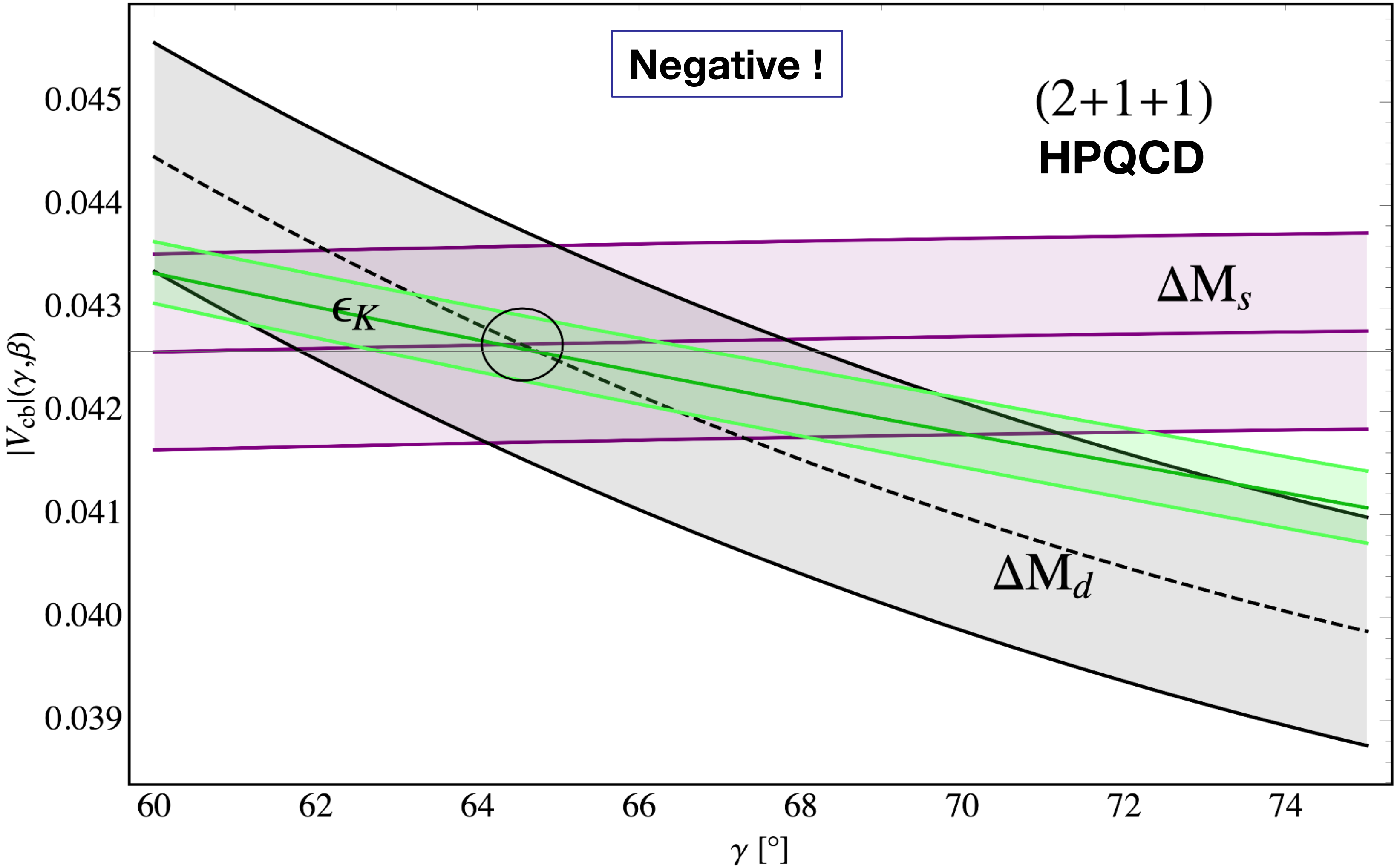
V_{cb} and γ independent

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

$|V_{cb}|$ - γ Plot = Rapid Test

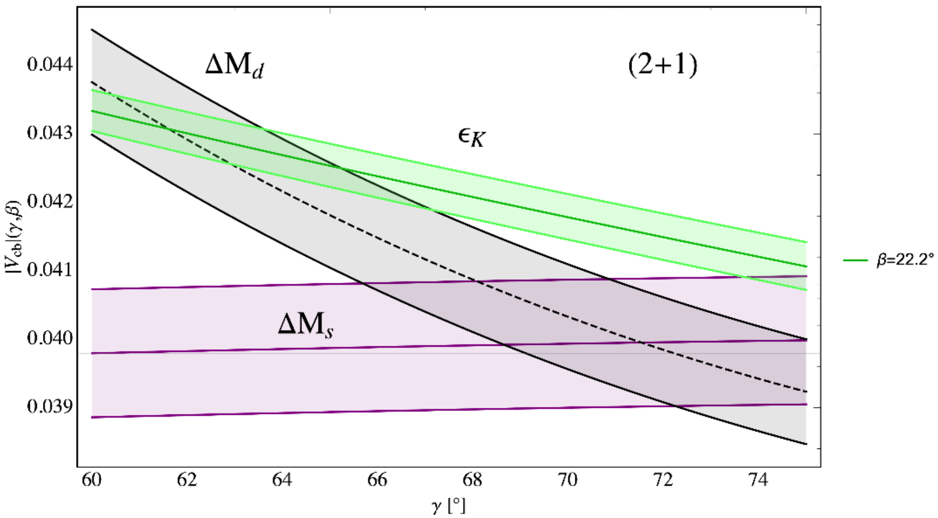
Perfect consistency between ΔM_s, ΔM_d, ε_K, $S_{\psi K}$

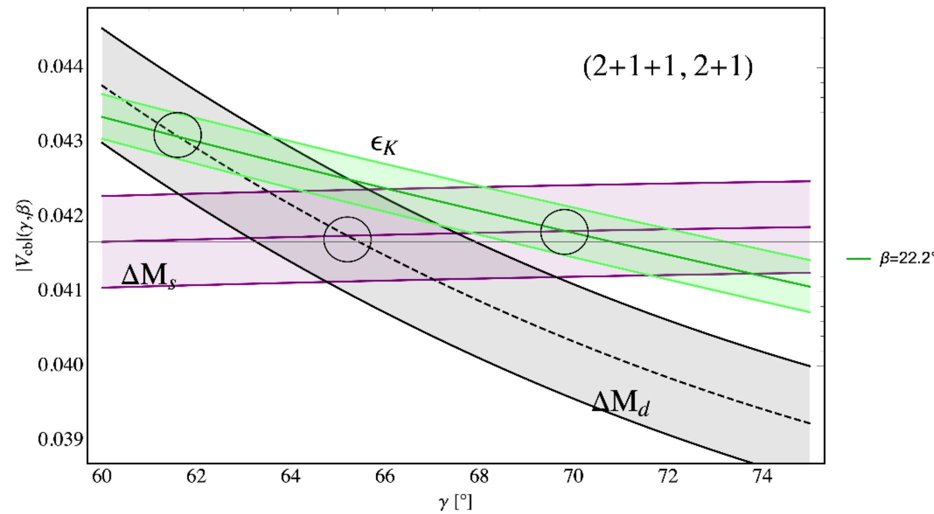
AJB + Venturini 2203.11960



Positive Tests

AJB + Venturini 2203.11960





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

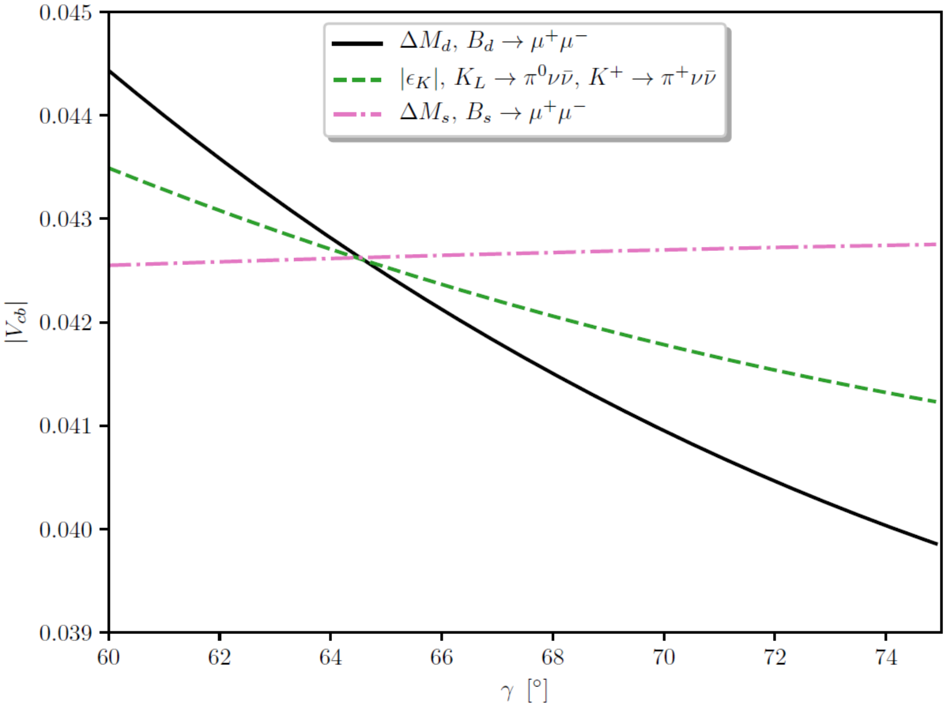
<u>Rapid Test</u>: cover picture of EPJC Vol. 83 number 1, January 2023

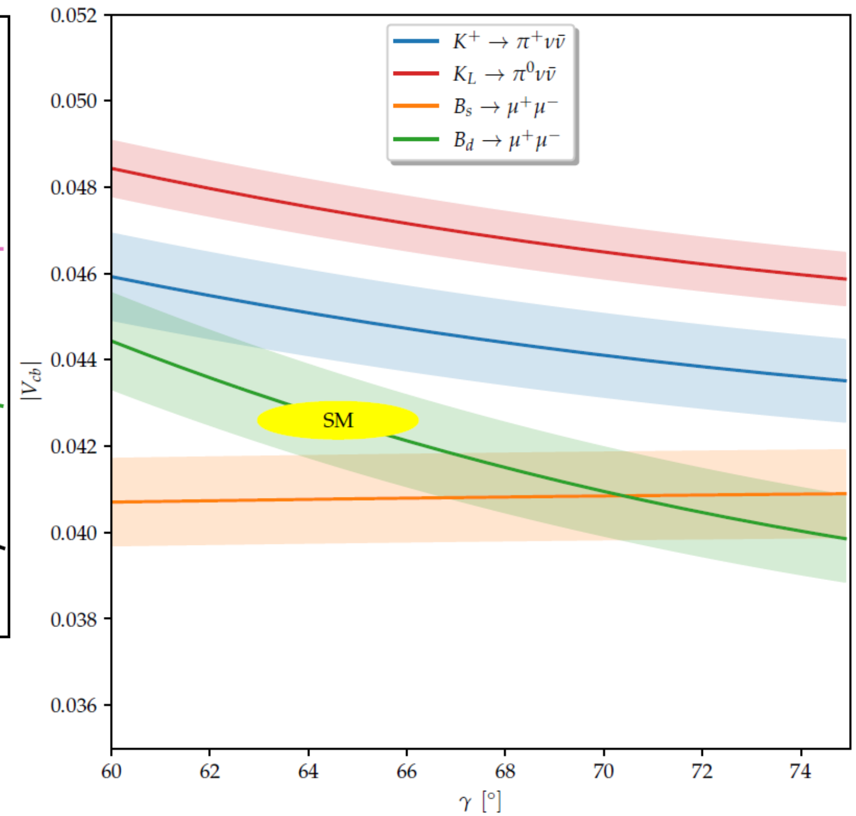
The European Physical Journal
volume 83 · number 1 · january · 2023
EPJ C
Recognized by European Physical Society
Particles and Fields
Three rapid tests of NP infection in the $\Delta F = 2$ sector as explained in the text. The values of $|V_{cb}|$ extracted from ε_K, ΔM_d and ΔM_s as functions of γ. 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

CKM Matrix from ε_K, ΔM_s, ΔM_d, $S_{\psi K_S}$

AJB + Venturini (2203.11960)

$|V_{us}| = 0.2243(8)$ $|V_{cb}| = 42.6(4)\cdot 10^{-3}$ $|V_{ub}| = 3.72(11)\cdot 10^{-3}$

$|V_{ts}| = 41.9(4)\cdot 10^{-3}$ $|V_{td}| = 8.66(14)\cdot 10^{-3}$

$\gamma = 64.6(16)^\circ$ $\beta = 22.2(7)^\circ$ $\mathrm{Im}\,(V^*_{ts}V_{td}) = 1.43(5)\cdot 10^{-4}$

$|V_{cb}| = 42.2(5)\cdot 10^{-3}$

(Inclusive: Gambino et al)

$|V_{ub}| = 3.61(13)\cdot 10^{-3}$

FLAG

$\gamma = 63.8(36)^\circ$

LHCb

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

Utfitter (22)

$|V_{cb}| = 41.8(8)\cdot 10^{-3}$

PDG (22)

$|V_{cb}| = 41.5(5)\cdot 10^{-3}$

CKMfitter (22)

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

AJB 2209.03968

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

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

Many other results in 2209.03968

Largest Anomalies in Single Branching Ratios following from this Strategy

(AJB: 2209.03968)

	$[q^2_{min}, q^2_{max}]$	
$B^+ \to K^+\mu^+\mu^-$	[1.1, 6]	-5.1σ
$B^+ \to K^+\mu^+\mu^-$	[15, 22]	-3.6σ
$B_s \to \varphi\ \mu^+\mu^-$	[1.1, 6]	-4.8σ

New Formfactors from HPQCD (2207.13371, 2207.12468)

ε'/ε Controversy

2015-2020

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

(NA48, KTeV)

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

Chiral Perturbation Theory
(Pich et al)

No Anomaly

★

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

Hep-arxiv: 2101.00020

Insight from Dual QCD + NNLO QCD

(AJB + Gérard)

Anomaly

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

RBC – UKQCD

No Anomaly

Good News on ε´/ε

ε´/ε = QCD Penguins – Electroweak Penguin

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

Perfect Agreement!

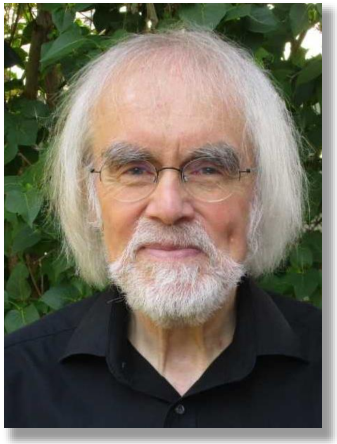
Chiral Pert Th: $\approx (-3.5 \pm 2.0) \cdot 10^{-4}$

Disagreements on QCD Penguin contribution.

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 ?

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

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

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

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

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

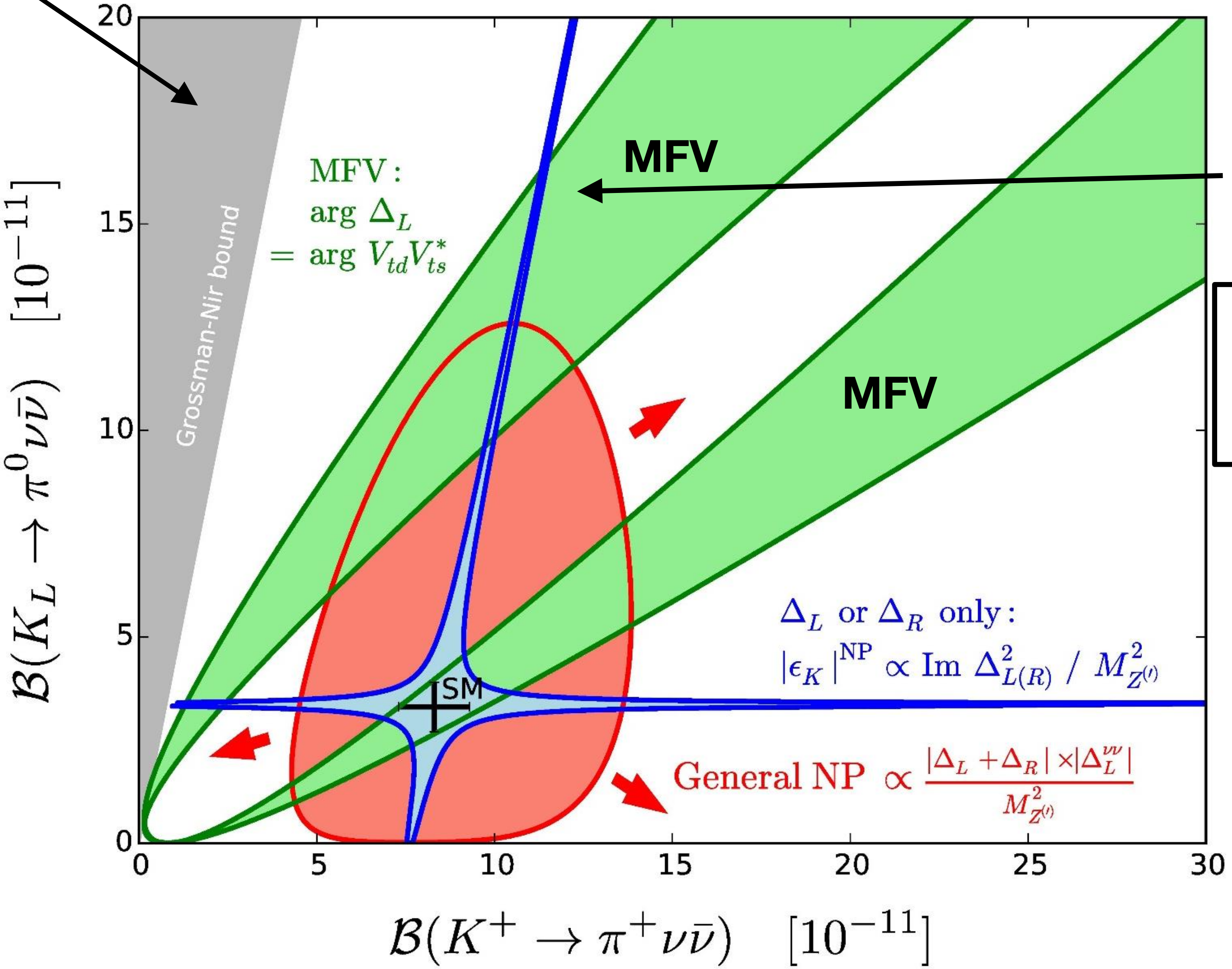
With $\mathrm{Re}\Delta_L^{sd}(Z') \ll \mathrm{Im}\Delta_L^{sd}(Z')$ **(Imaginary coupling)**

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

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

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

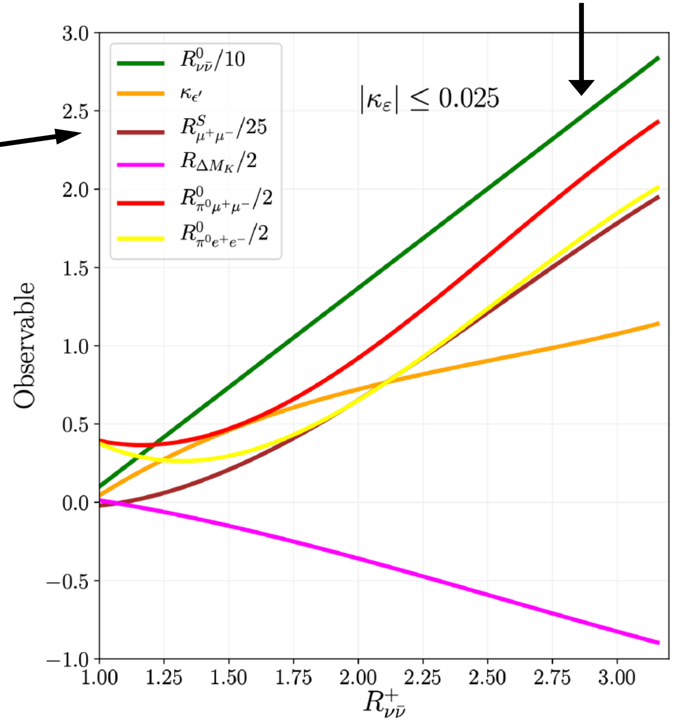
$$R^S_{\mu^+\mu^-} = \frac{\mathcal{B}(K_S\to\mu^+\mu^-)_{\rm SD}}{\mathcal{B}(K_S\to\mu^+\mu^-)^{SD}_{SM}}, \quad R^0_{\pi\ell^+\ell^-} = \frac{\mathcal{B}(K_L\to\pi^0\ell^+\ell^-)}{\mathcal{B}(K_L\to\pi^0\ell^+\ell^-)_{SM}},$$

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

MB branch

Dery, Ghosh, Grossman, Schacht (2104.06427)

(Z´ at work)



Aebischer, AJB, Kumar
2302.00013

J. Aebischer

J. Kumar

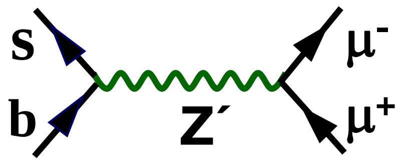
December 2022

μ-e Universality Violation 0.2 σ

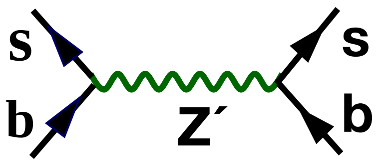
(LHCb)

Heavy Z´ gauge boson remains an important candidate behind suppressed branching ratios for $B \to K(K^*)\mu^+\mu^-$, $B_s \to \varphi\, \mu^+\mu^-$

But how a Z´ can explain these anomalies without destroying $(\Delta M_s)_{exp} = (\Delta M_s)_{SM}$?



Explaining $b \to s\mu^-\mu^+$ anomalies



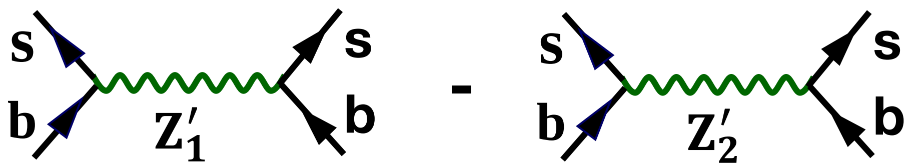
Contributing to ΔM_s

New Physics Scenario : Z´ -Tandem

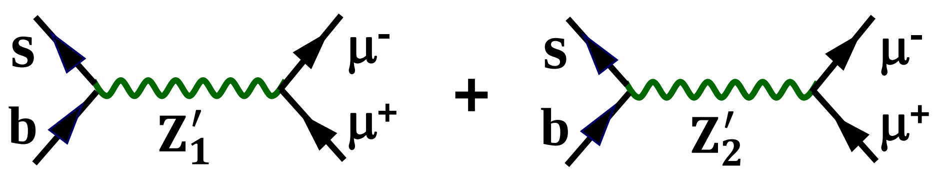
AJB 2302.01354

Two heavy neutral gauge bosons: Z'_1, Z'_2

1. **Collaborate to forbid New Physics in quark mixing (ΔM_s, ΔM_d, ε_K)**



2. **Collaborate to explain anomalies in $B \to K(K^*)\mu^+\mu^-$, $B_s \to \varphi\, \mu^+\mu^-$**



But can a UV completion with these properties be constructed ??

Another Solution: Single Z´

1. NP removed from ε_K, as in ABK

2. Fine tuning in ΔM_q q=d,s

suppression factor

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

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

$$\boxed{\mathbf{\Delta_R^{bq}(Z')\ll\Delta_L^{bq}(Z')}}$$

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

3rd Movement:
Footprints of Majorana Neutrinos in Rare K and B Decays

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

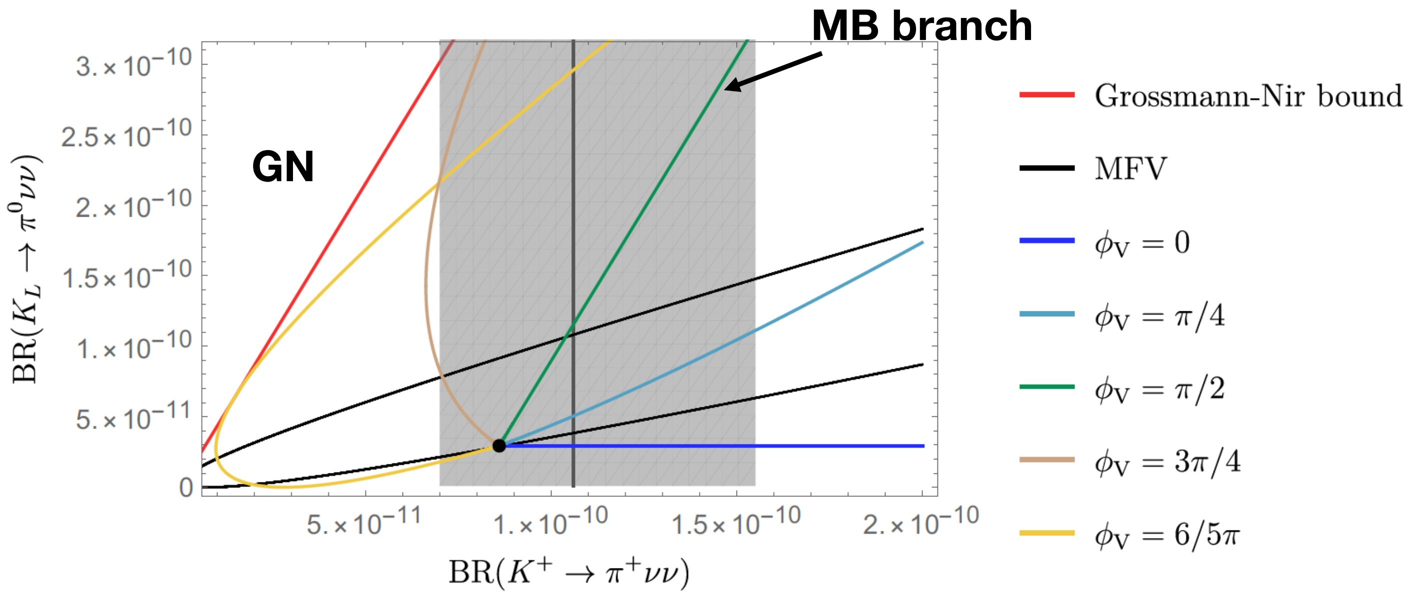
C. **Efficient strategies that would allow NA62, KOTO and Belle II to find possible footprints of Majorana neutrinos in their data.**

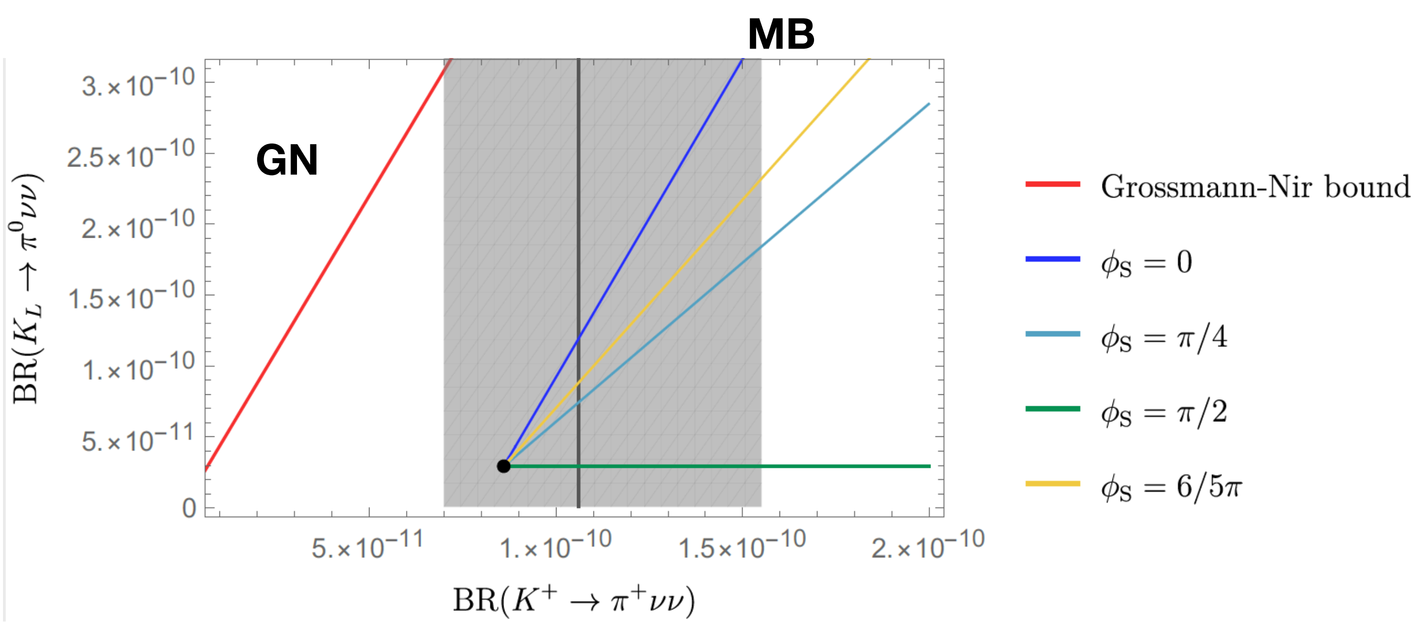
D. **Strategies valid in the presence of right-handed currents, LFUV and LFV**

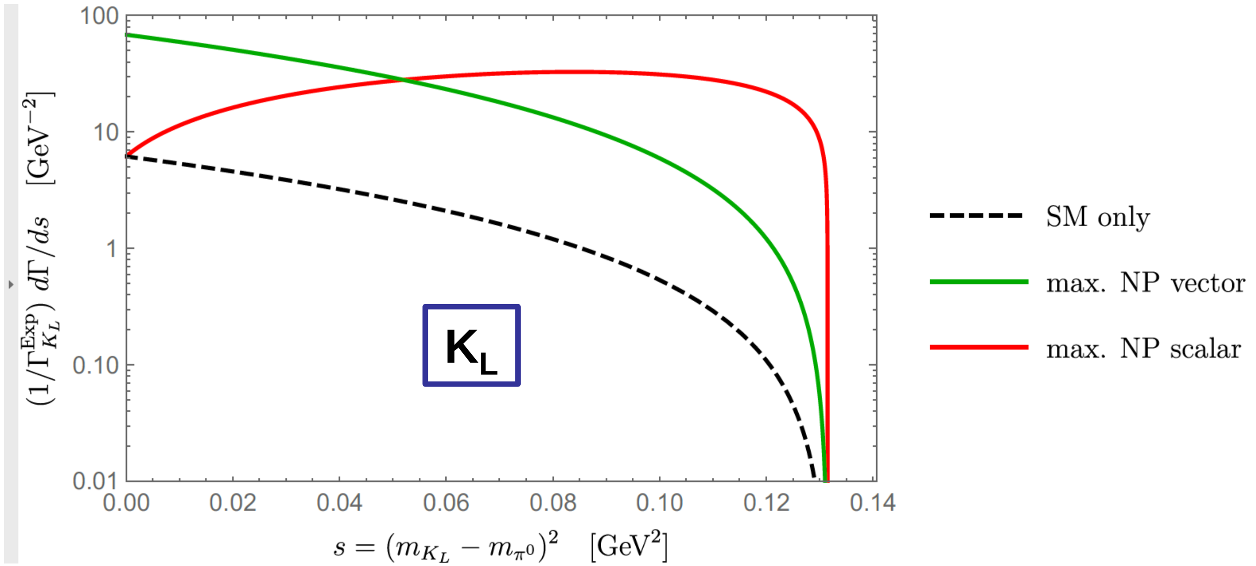
$$\Delta C_V = \left|C_V^{NP}\right| e^{i\varphi_V} \qquad C_S = |C_S| e^{i\varphi_S}$$

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

AJB + J.Harz



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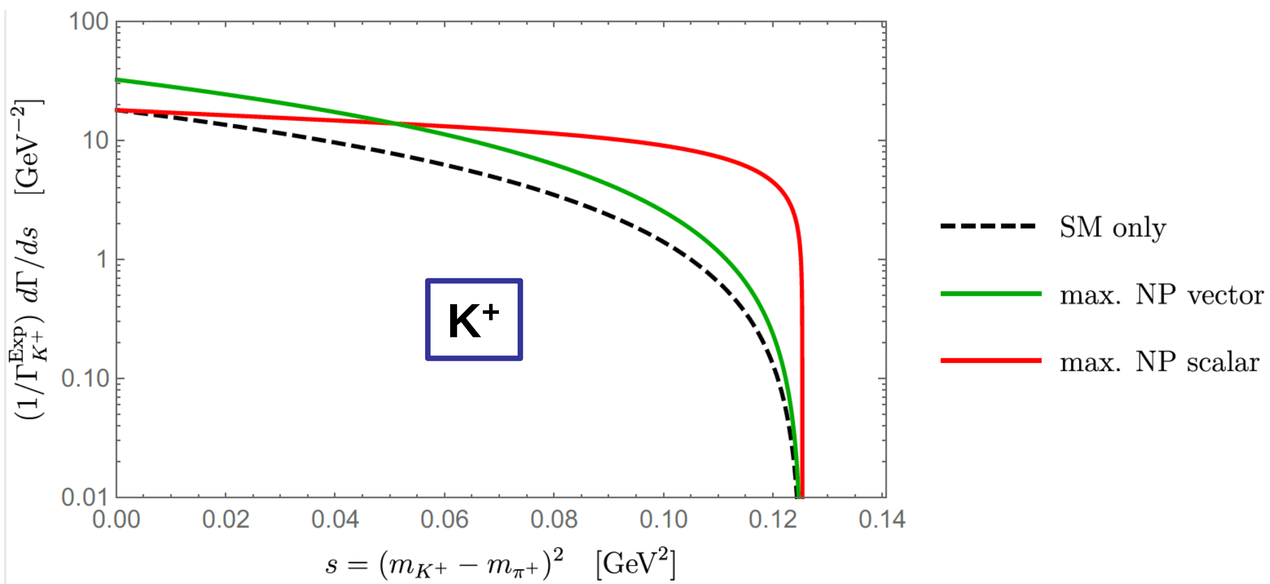
$(1/\Gamma_{K_L}^{\mathrm{Exp}})\ d\Gamma/ds\quad [\mathrm{GeV}^{-2}]$
$s = (m_{K_L} - m_{\pi^0})^2\quad [\mathrm{GeV}^2]$
$\mathrm{K_L}$
SM only
max. NP vector
max. NP scalar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$(1/\Gamma_{K^+}^{\mathrm{Exp}})\ d\Gamma/ds\quad [\mathrm{GeV}^{-2}]$
$s = (m_{K^+} - m_{\pi^+})^2\quad [\mathrm{GeV}^2]$
$\mathrm{K^+}$
SM only
max. NP vector
max. NP scalar

Searching for Majorana Footprints through LNC Sum Rules

LNC Sum Rules

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

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

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

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

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

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

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

K* longitudinal polarization fraction

4th Movement: Summary + Outlook

Main Points to take to your Homeoffice

1. Multitude of $|V_{cb}|$-independent SM ratios of flavour observables $R_i(\beta,\gamma)$ will test SM once β and γ will be precisely known.

2. Assuming negligible NP contributions to $\boxed{\Delta M_s,\ \Delta M_d,\ \varepsilon_K,\ S_{\psi K_s},\ S_{\psi\varphi}}$ results in most accurate to date SM predictions for 26 branching ratios for rare semi-leptonic K and B decays with $\mu^+\mu^-$, $\nu\bar{\nu}$ in the final state. (2203.11960, 2209.03968)

3. $|V_{cb}|$-γ plots: Rapid tests of NP infection.

4. Interesting implications for correlations between observables and anomalies in $B \to K^+(K^*)\mu^+\mu^-$, $B_s \to \varphi\mu^+\mu^-$ (2209.03968)

5. Z´ alone or in (Z_1', Z_2') tandem could be behind them.

6. Waiting for Majorana Footprints in $K \to \pi\nu\bar{\nu}$ and $B \to K(K^*)\nu\bar{\nu}$

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)

$$\left(\begin{array}{ll} K^+ \rightarrow \pi^+ \nu\bar{\nu} \left(10^{-10}\right) & \text{(CERN)} \\ K_L \rightarrow \pi^o \nu\tilde{\nu} (3 \cdot 10^{-11}) & \text{J-PARC (Japan)} \end{array} \right)$$

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

$\Delta I = \frac{1}{2}$ Rule, ΔM_K

2015-2046 : Expedition
Attouniverse → Zeptouniverse
10^{-18}m → 10^{-21}m

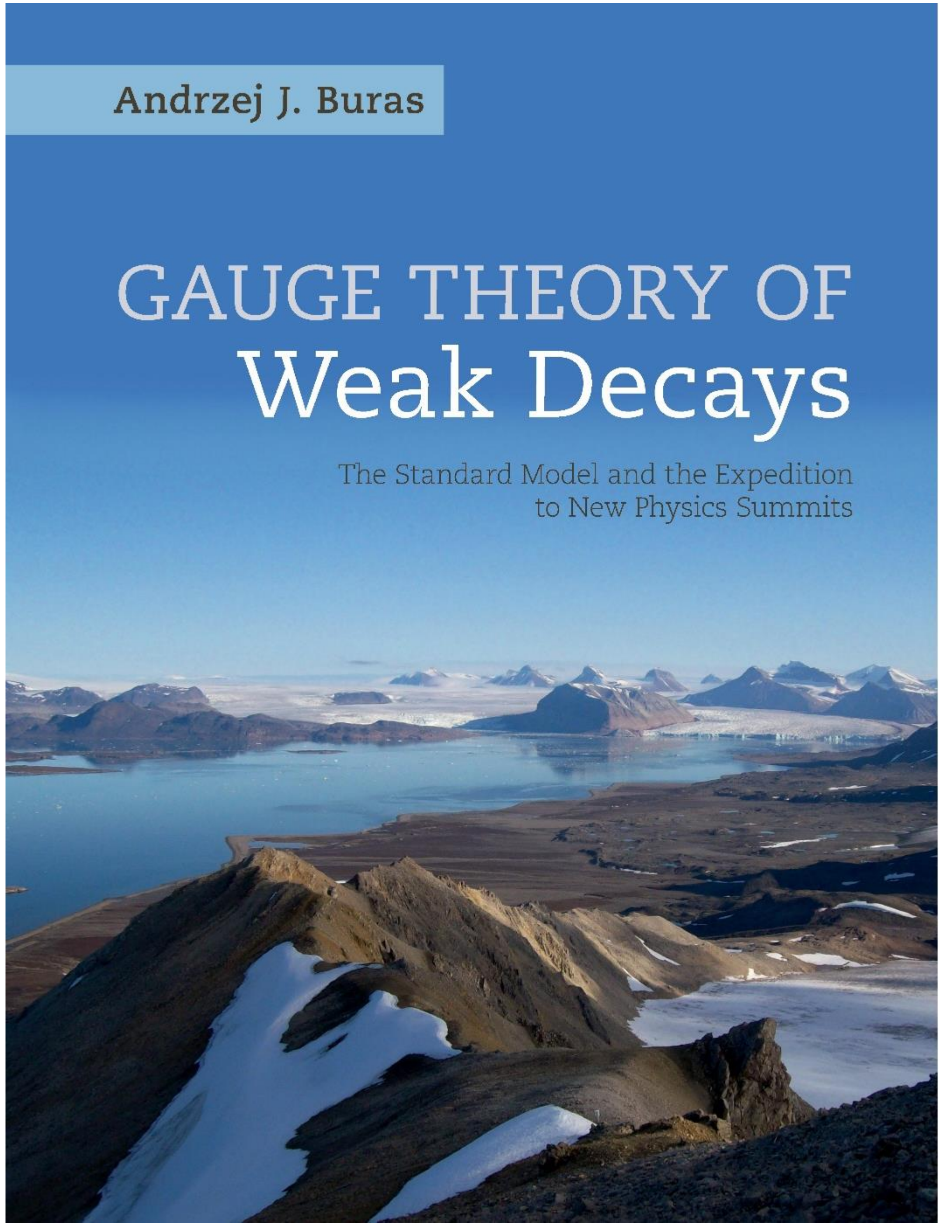
Hopefully meeting Z'_1 and Z'_2 !

Zeptouniverse
Guide

Published
July 2020

7

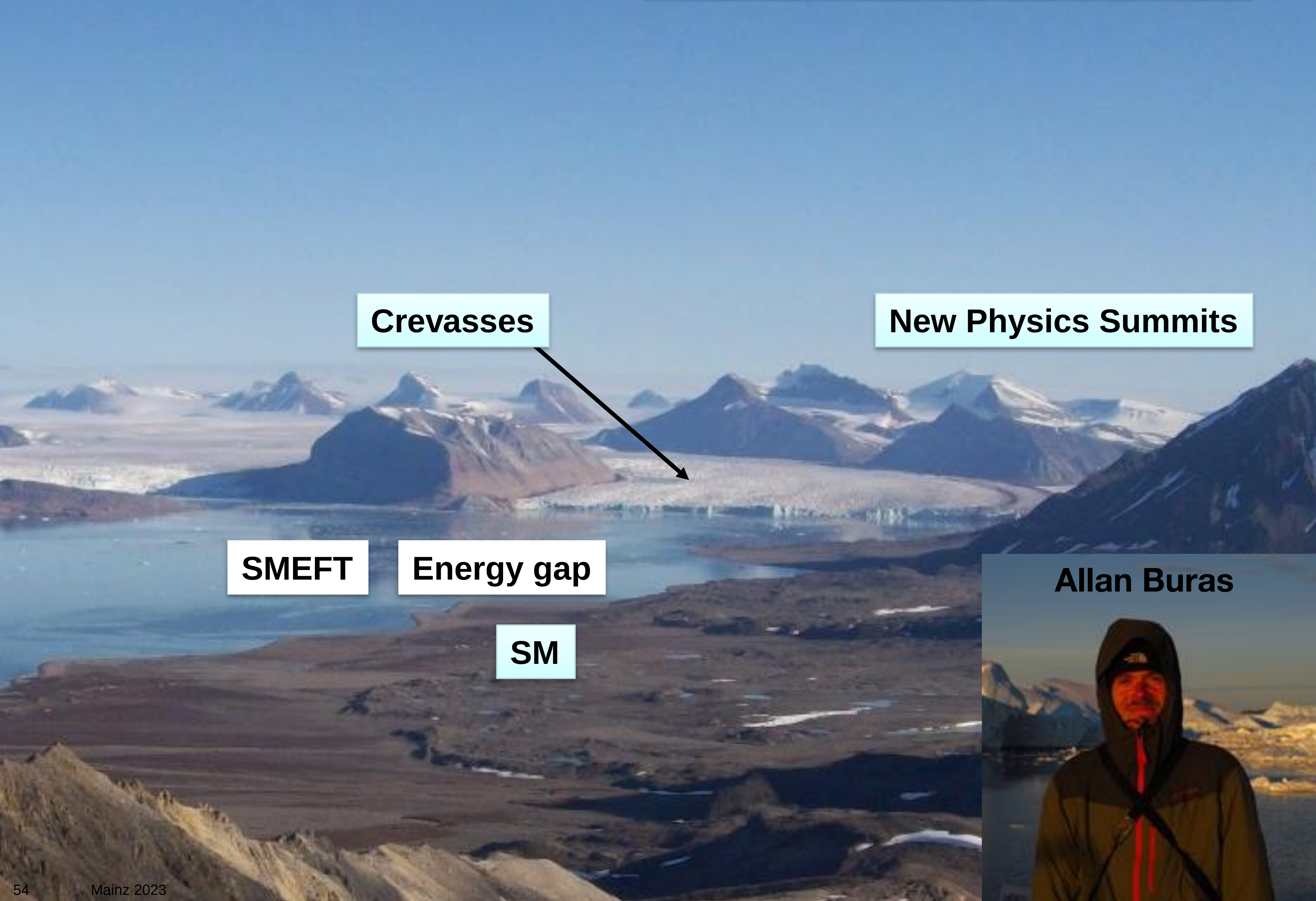
Exciting
Years !

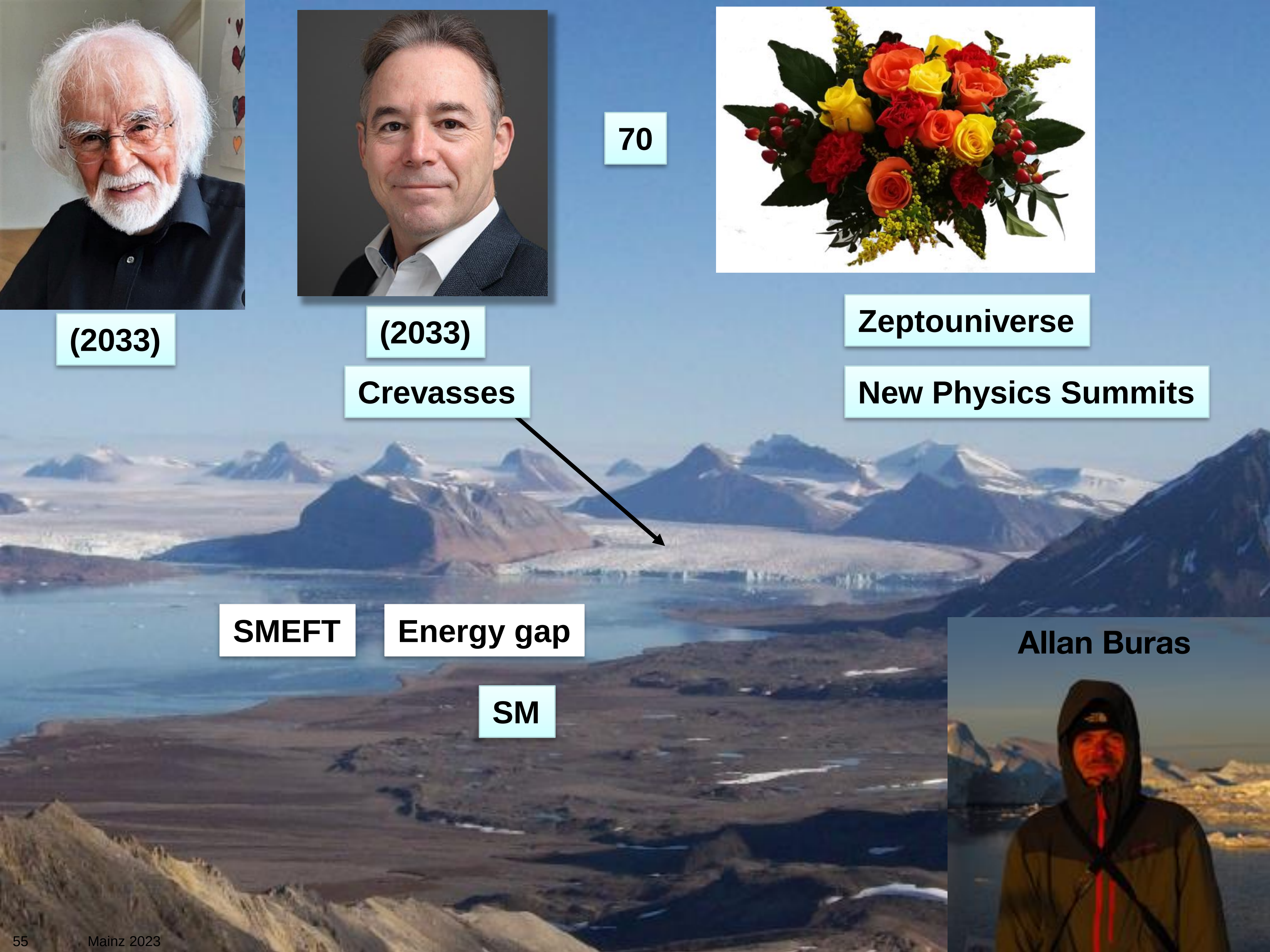


739 pages
1350 references

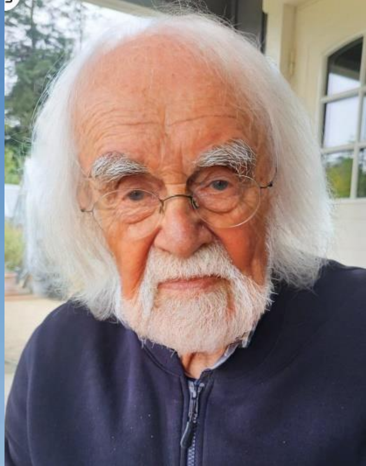
Cambridge
University
Press

Flavour Physics (2023-)





70
(2033)
(2033)
Crevasses
Zeptouniverse
New Physics Summits
SMEFT
Energy gap
SM
Allan Buras



(2043)

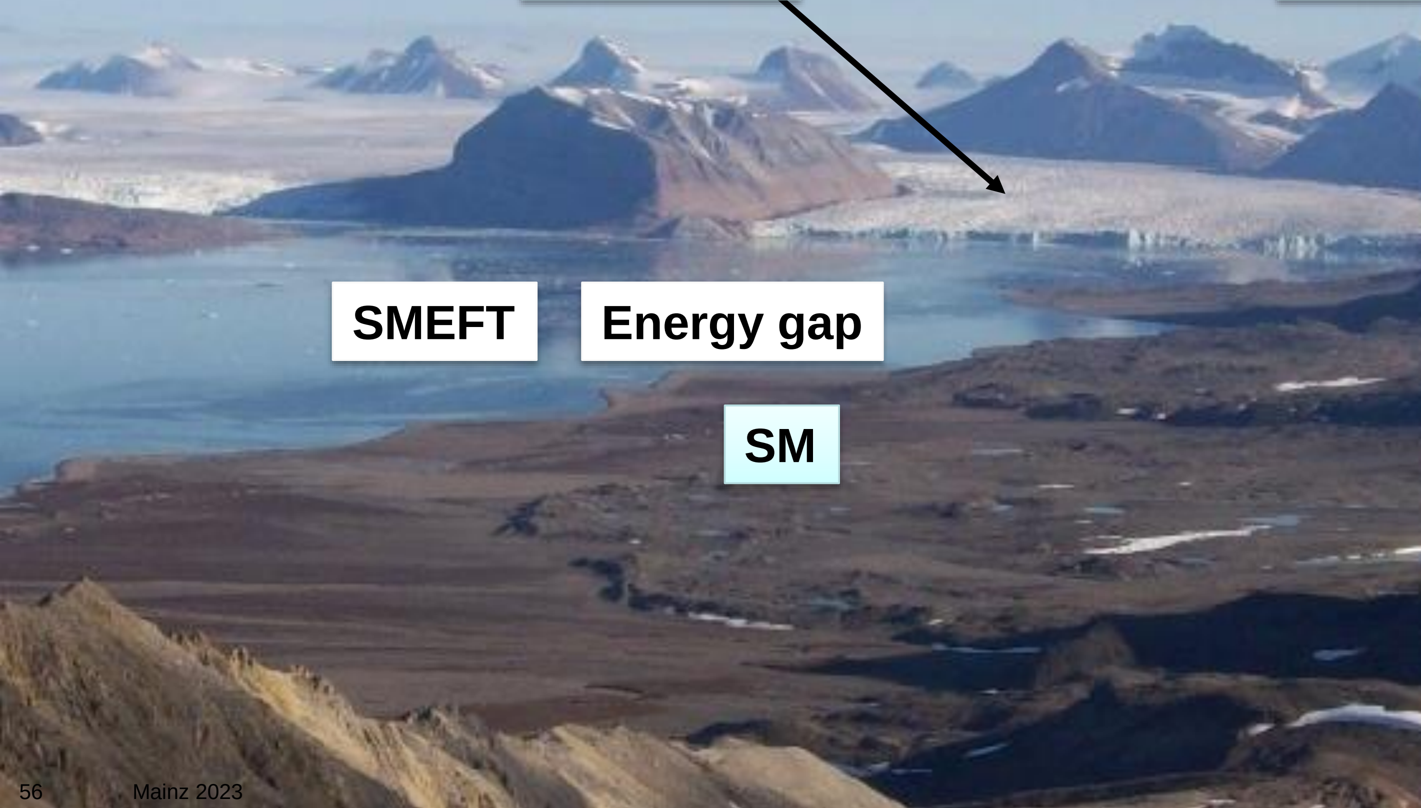
(2043)

Crevasses

80

Zeptouniverse

New Physics Summits

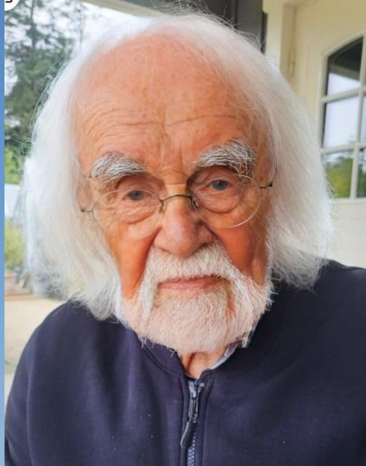


SMEFT

Energy gap

SM

Allan Buras



(2043)

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Crevasses

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Zeptouniverse

New Physics Summits

SMEFT

Energy gap

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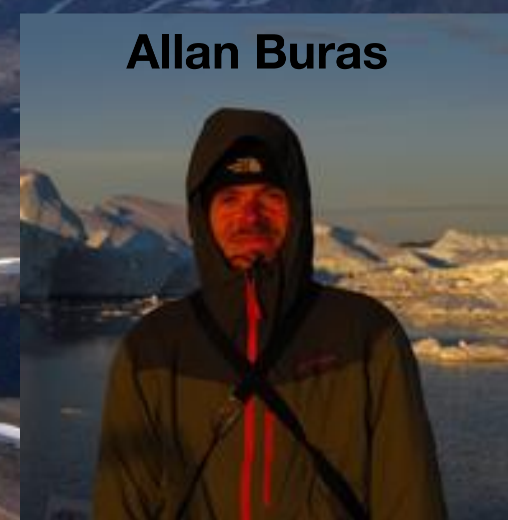


Thank You !

Backup

Cabibbo Anomaly ⇒ Violation of the CKM Unitarity?

$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9985\ (5)$

$|V_{ud}|^2 + |V_{cd}|^2 + |V_{td}|^2 = 0.9970\ (18)$

Review A. Crivellin (2207.02507)

1. **In the absence of new quarks CKM Unitarity cannot be violated! The violation is only apparent due to possible contributions of bosons to decays used to determine $|V_{ud}|$, $|V_{us}|$, due to hadronic uncertainties or wrong measurements (otherwise GIM mechanism would fail and at one-loop gauge dependence would be present)**

2. **In the presence of vector-like quarks CKM Unitarity can be violated with CKM matrix being submatrix of a unitary matrix involving SM quarks + vector quarks.**

CKM Uncertainties

AJB, Buttazzo, Girrbach-Noe, Knegjens 1503.02693

$$Br(K^+ \to \pi^+ \nu\bar{\nu}) = (8.39 \pm 0.30) \cdot 10^{-11} \left[\frac{|V_{cb}|}{0.0407}\right]^{2.8} \left[\frac{\gamma}{73.2^\circ}\right]^{0.74}$$

$$Br(K_L \to \pi^0 \nu\bar{\nu}) = (3.36 \pm 0.05) \cdot 10^{-11} \left[\frac{|V_{ub}|}{3.88 \cdot 10^{-3}}\right]^{2} \left[\frac{|V_{cb}|}{0.0407}\right]^{2} \left[\frac{\sin\gamma}{\sin(73.2)}\right]^{2}$$

$$Br(K^+ \to \pi^+ \nu\bar{\nu}) = (8.39 \pm 0.58) \cdot 10^{-11} \left[\frac{\gamma}{73.2^\circ}\right]^{0.81} \left[\frac{\overline{Br}(B_s \to \mu^+\mu^-)}{3.4 \cdot 10^{-9}}\right]^{1.42} \left[\frac{227.7}{F_{B_s}}\right]^{2.84}$$

$$Br(K^+ \to \pi^+ \nu\bar{\nu}) = (8.39 \pm 1.11) \cdot 10^{-11} \left[\frac{|\varepsilon_K|}{2.23 \cdot 10^{-3}}\right]^{1.07} \left[\frac{\gamma}{73.2^\circ}\right]^{-0.11} \left[\frac{V_{ub}}{3.88 \cdot 10^{-3}}\right]^{-0.95}$$

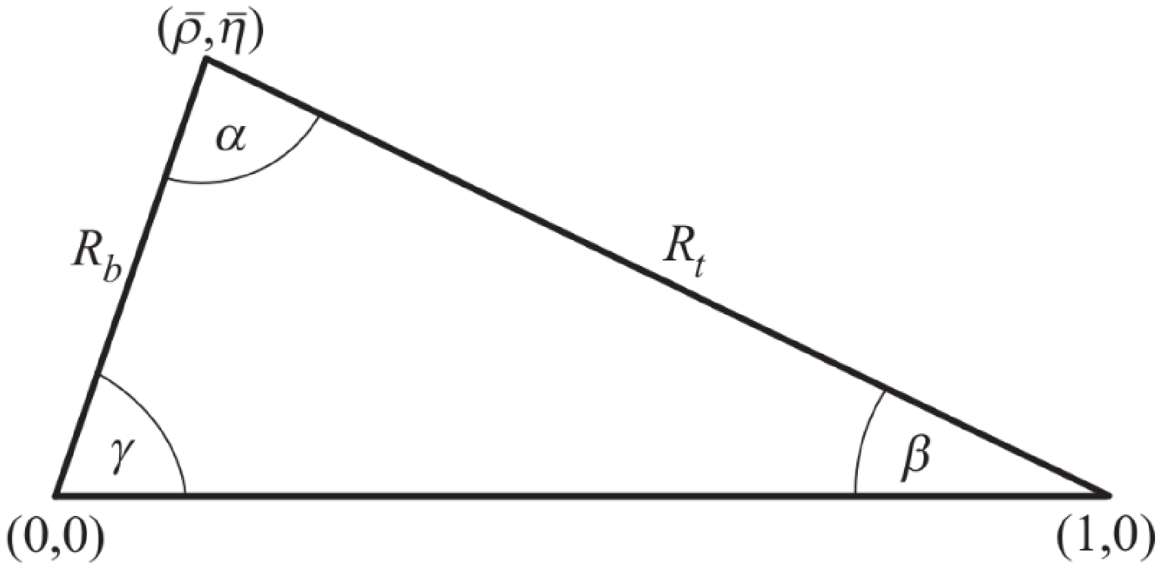
$$Br(K^+ \to \pi^+ \nu\bar{\nu}) = (8.4 \pm 1.0) \cdot 10^{-11}$$

$$Br(K_L \to \pi^0 \nu\bar{\nu}) = (3.4 \pm 0.6) \cdot 10^{-11}$$

CKM Matrix

50th Anniversary in 2023

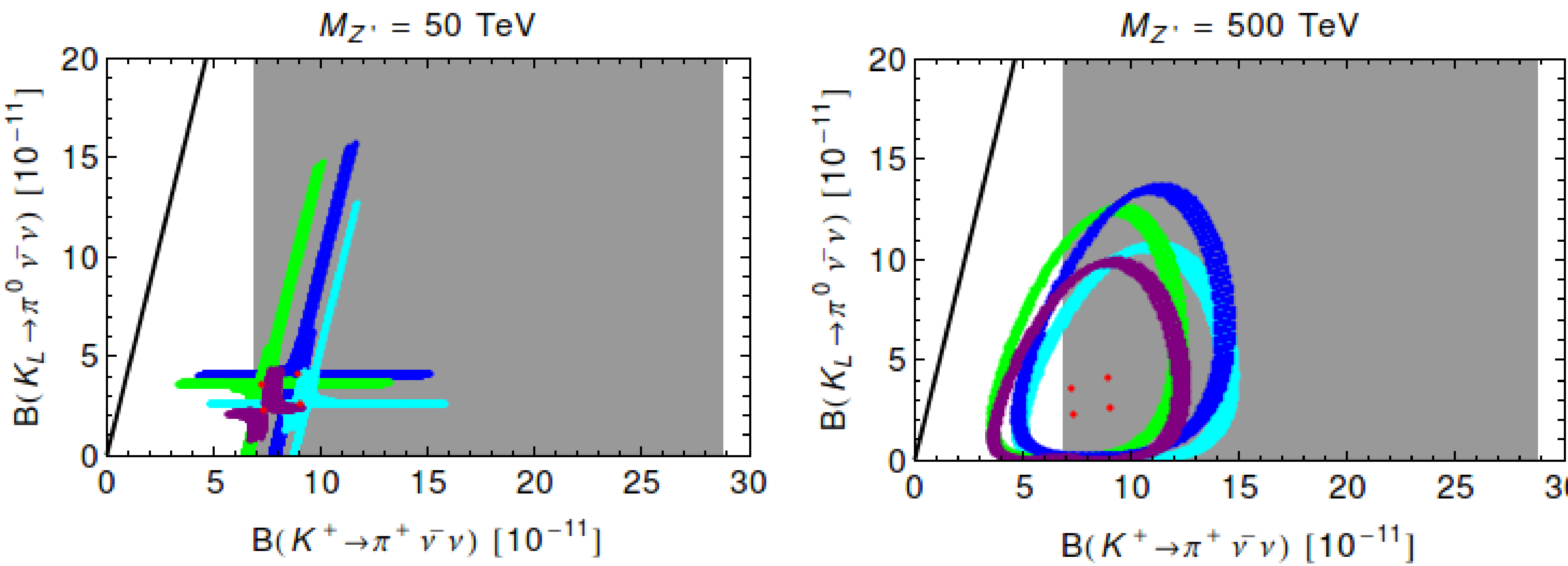
V_{us}, V_{cb}, β, γ



V_{cb} is not seen in this plot. Cancelled out in construction.

Heavy Z´ at Work

AJB, Buttazzo, Girrbach-Noe, Knegjens, 1408.0728



ε_K constraint

General discussion:
Blanke 0904.2528

No ε_K constraint

Colours: different CKM input

● SM

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

AJB: 2209.03968

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

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

HPQCD

$$\boxed{R_{\mathrm{exp}} = (8.26 \pm 0.06)\cdot 10^{-5}} \qquad \boxed{K = 1.00 \pm 0.07}$$

$\Delta I = 1/2$ 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

2020

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

RBC-UKQCD
Lattice Collaboration

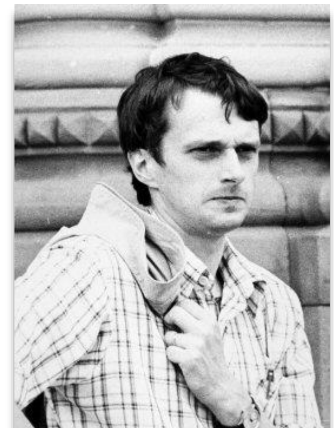
QCD dynamics dominate this rule
but New Physics could still contribute

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

Dual QCD Approach for Weak Decays

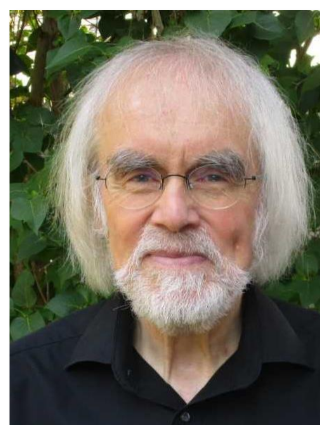
Successful low energy approximation of QCD
for $K \to \pi\pi$ K^0-K^0 mixing

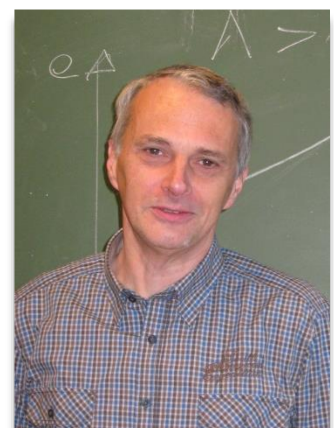
1986



W. Bardeen **AJB** **J.-M. Gérard**

2022





Good News on ε´/ε

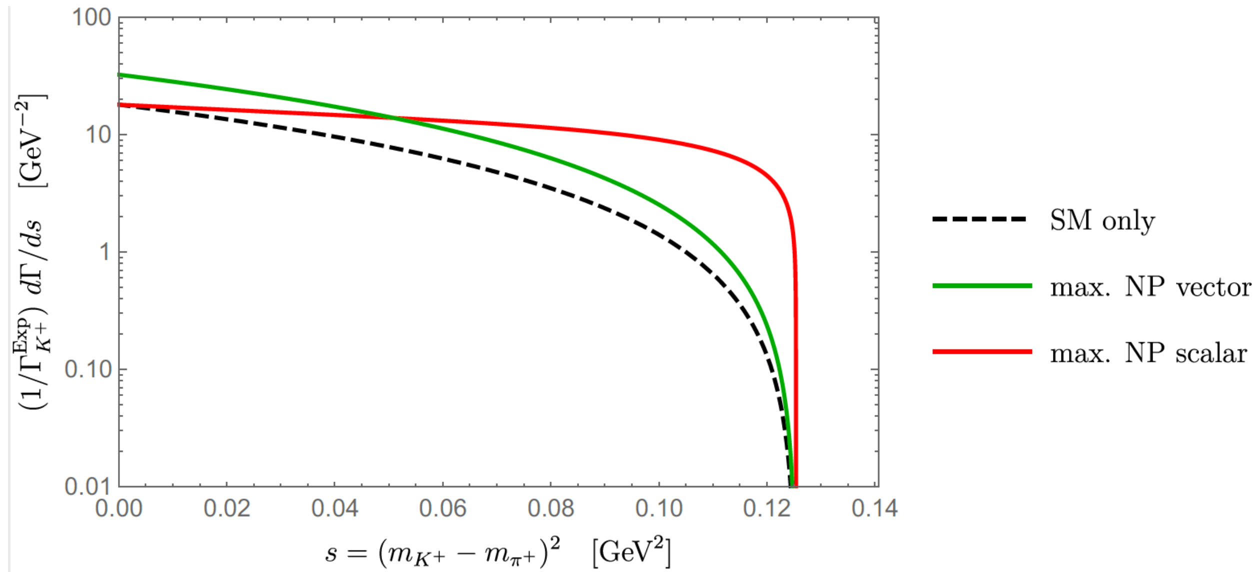
ε´/ε = QCD Penguins – Electroweak Penguin

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

Perfect Agreement!

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

Disagreements on QCD Penguin contribution.



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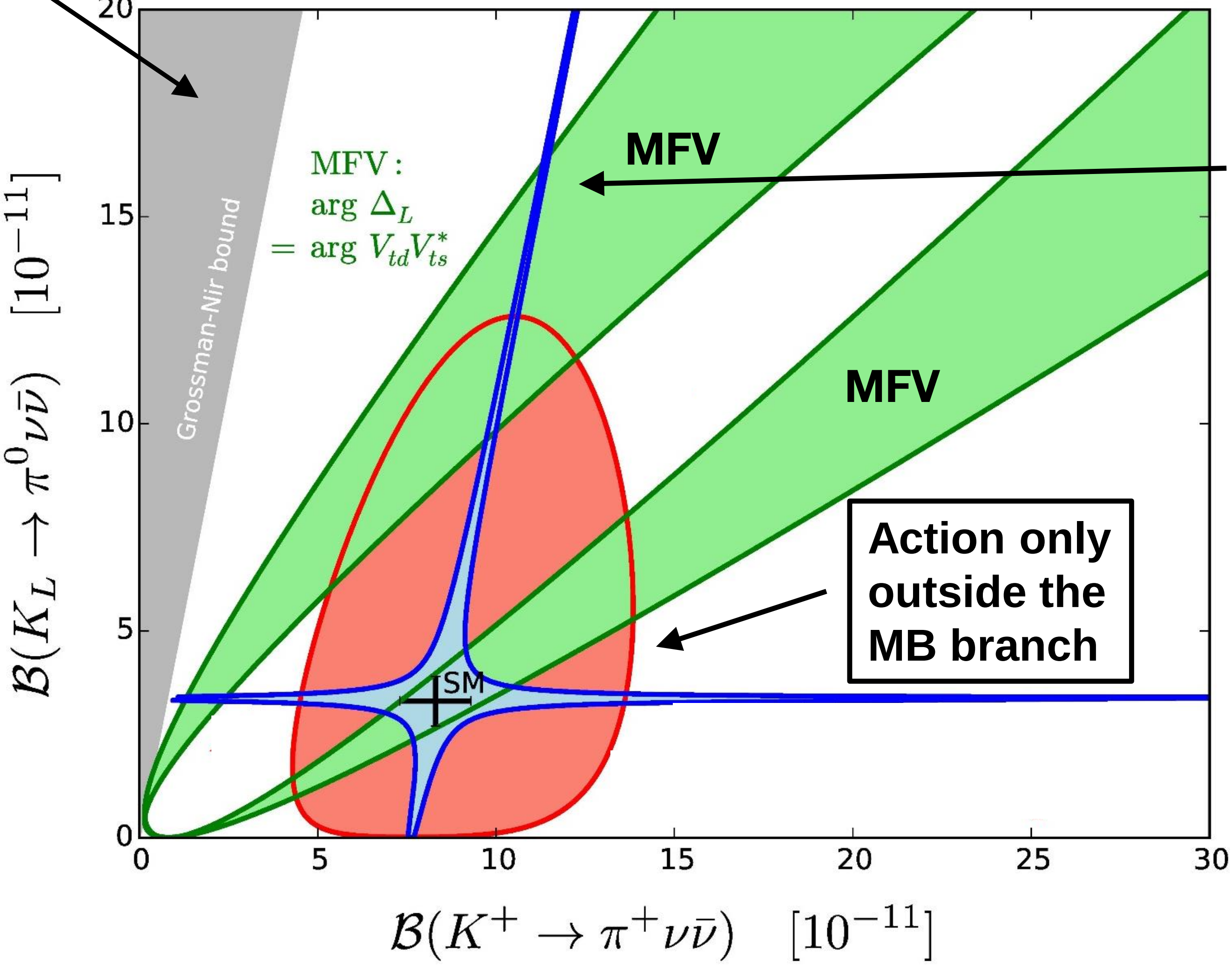
$(1/\Gamma_{K^+}^{\rm Exp})\ d\Gamma/ds\quad [{\rm GeV}^{-2}]$
$s = (m_{K^+} - m_{\pi^+})^2\quad [{\rm GeV}^2]$
SM only
max. NP vector
max. NP scalar

Z´- Tandem at Work

GN bound

AJB 2302.01354



MB branch

Action only outside the MB branch

Z´- Tandem Framework

$$\Delta_{ij}(Z_2') = \Delta_{ij}(Z_1')\,\frac{M_2}{M_1}\,e^{i90^\circ} \quad (i \neq j)$$

AJB 2302.01354

1. Determine CKM Parameters from Quark Mixing only and predict SM Branching Ratios (without NP infection)

(Z_1', Z_2') collaborate to remove NP from quark mixing

2. Determine Parameters $\Delta_{ij}(Z_1')$ and $\Delta_{ij}(Z_2')$ from B, D, K decays
Only tree level NP contribution relevant

(Z_1', Z_2') collaborate to explain anomalies

However: Other solutions with a single Z´ exist with some tuning of parameters

AJB, De Fazio, Girrbach-Noe, 1404.3824
AJB, Buttazzo, Girrbach-Noe, Knegjens, 1408.0728

$|V_{cb}|$ from ε_K, ΔM_s, ΔM_d, $S_{\psi K}$

(SM)

AJB + E. Venturini (2109.11032) (2203.11960)

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

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

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

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

Most Precise V_{cb} – Independent Estimates (SM)

BV: 2109.11032
2203.11960

$$\mathrm{Br}\left(K^+ \to \pi^+ \nu\bar{\nu}\right) = \left(8.60 \pm 0.42\right)\cdot 10^{-11}$$

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

Only β-dependent (γ-dependence very weak)

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

$$\overline{\mathrm{Br}}\left(B_d \to \mu^+\mu^-\right) = \left(1.02 \pm 0.04\right)\cdot 10^{-10}$$

CKM-independent

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

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

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

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

$$\overline{\mathrm{Br}}\left(B_s\right) = \left(3.66 \pm 0.12\right)\cdot 10^{-9} \qquad \overline{\mathrm{Br}}\left(B_s\right) = \left(1.03 \pm 0.05\right)\cdot 10^{-10}$$

(Bobeth et al.)

Solution: Z´-Tandem

AJB 2302.01354

★

$\mathbf{Z_2'}$ plays the role of charm in GIM

$\mathbf{Z_1'}$ and $\mathbf{Z_2'}$ collaborate to get $\mathbf{M_{12}^{NP} = 0}$

Conditions

$$\frac{\left|\Delta_L^{\bar{b}s}(Z_1')\right|}{M_1} = \frac{\left|\Delta_L^{\bar{b}s}(Z_2')\right|}{M_2}, \qquad \varphi_2 = \varphi_1 + 90^\circ$$

New CPV Phase

⇒ No tree-level contributions to ΔM_s

But sizeable contributions to $B^+ \to K^+\mu^+\mu^-, B_s \to \varphi\mu^+\mu^-$ and interesting implications for $K \to \pi\nu\bar{\nu}$ if applied to K-system

But can a UV completion with these properties be constructed ??

$\Delta M_s, B^+ \to K^+\mu^+\mu^-, B_s \to \varphi\mu^+\mu^-$

AJB 2302.01354

$$\Delta M_s = 2\left|M_{12}^{SM} + M_{12}^{NP}\right|$$ ⟹

Choosing
$\mathrm{Re}\left(\Delta_L^{\bar{b}s}(Z')\right) = 0$
does not help!

One has to eliminate
M_{12}^{NP} **keeping** $\Delta_L^{bs}(Z') \neq 0$
and this is not possible!!

But GIM solved similar problem by adding to (u, d, s) charm quark !
Let us add second Z´