Precision Flavour Physics

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

Guido Fest

(26th of September, 2022)

Overture

Happy Birthday to
Guido Martinelli (70)

Guido - Sonata Nr. 1
(Premiere, Rome, 26th September 2022)

1st Movement	:	Italian Competitors and Collaborators
2nd Movement	:	SM Predictions for Rare K and B Decays without New Physics Infection
3rd Movement	:	Last Speaker at Andrzej´s Fest (2016) in Action
4th Movement	:	Visions for Coming Years

1st Movement

Italian Competitors and Collaborators

ε'/ε Competition (1989-1993)

Rome Team

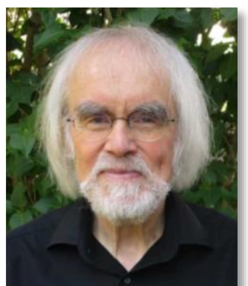

M. Ciuchini


E. Franco


G. Martinelli


L. Reina

Munich Team


AJB


M. Jamin


M. Lautenbacher


P. Weisz

Seminal dinner with Guido at Ringberg Castle (1988)
AJB: 1102.5650

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

NLO BSM Non-Leptonic

Rome Team

(1997)

M. Ciuchini

E. Franco

V. Lubicz

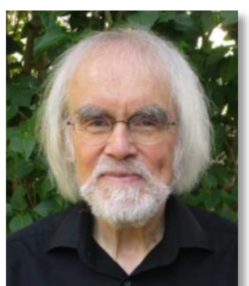
G. Martinelli

L. Silvestrini

I. Scimemi

Munich Team

(2000)



AJB

M. Misiak

J. Urban

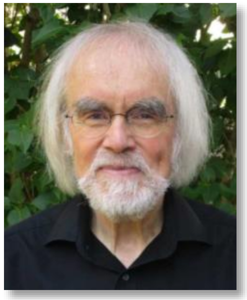
Italian Experimental Collaborators

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

Achille Stocchi

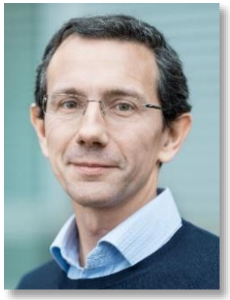
Fabrizio Parodi

FSI in ε'/ε : Critical Look (2000)


AJB


M. Ciuchini


E. Franco

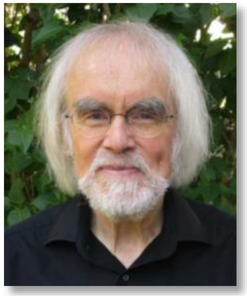

G. Isidori


G. Martinelli

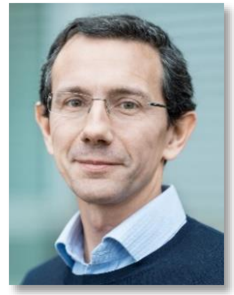

L. Silvestrini

U(1) $\otimes$ SU(5) Collaboration

AJB + Italians Papers


AJB

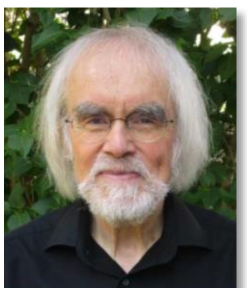

G. Colangelo


G. Isidori


A. Romanino


L. Silvestrini

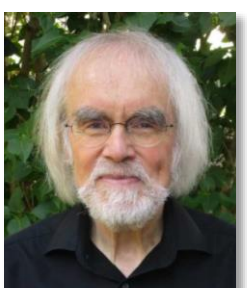
(1999)


AJB


A. Romanino


L. Silvestrini

(1997)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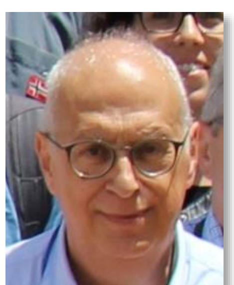

P. Colangelo


F. de Fazio


C. Manzari

(2021)

Most Recent Collaborators

F. de Fazio

(2016)

F. de Fazio

J.Girrbach-Noe

(2012-2015)

E. Venturini

(2021, 2022)

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

Ranking in Number of Papers (Journal)

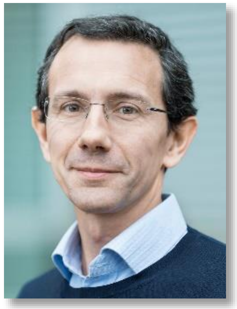
(AJB +)

L. Silvestrini

(11)

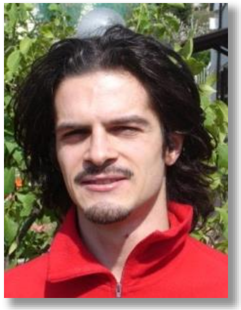
F. de Fazio

(10)



G. Isidori

(10)



D. Guadagnoli

(8)

C.Tarantino

(7)

2nd Movement

SM Predictions for Rare K and B Decays without New Physics Infection

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. (Destroy 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. (Destroy precision and should be 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

Set ΔM_d, ΔM_s, ε_K and $S_{\psi K_S}$ to experimental values

⟹ **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.

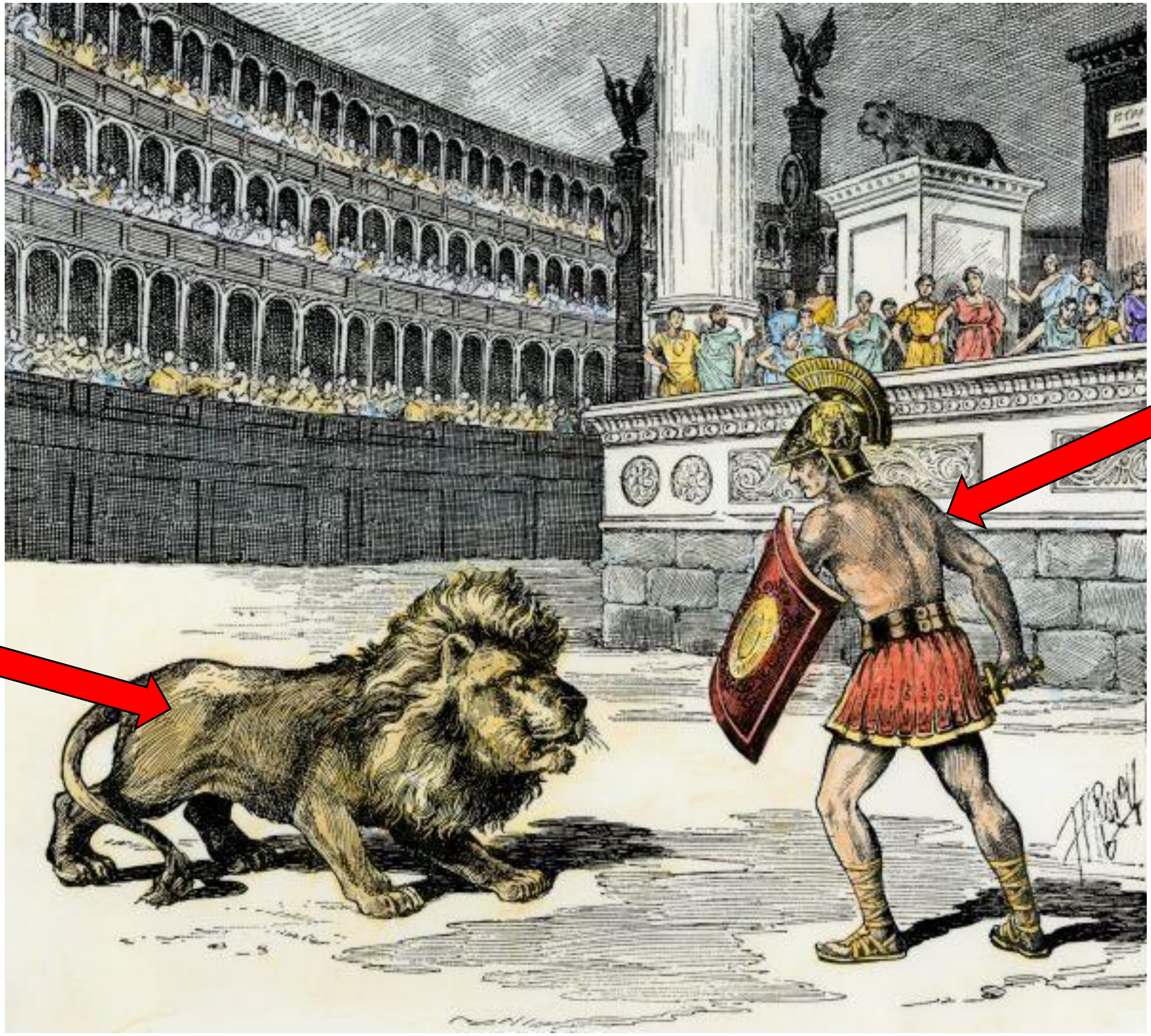
B. The remaining observables outside the "$\Delta F = 2$ archipelago" that could be infected by NP can be predicted within the SM and the pulls can be better estimated.

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


AJB

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

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

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

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

(2003)

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

(q=d,s)

Numerical Constant

Known with NLO QCD

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

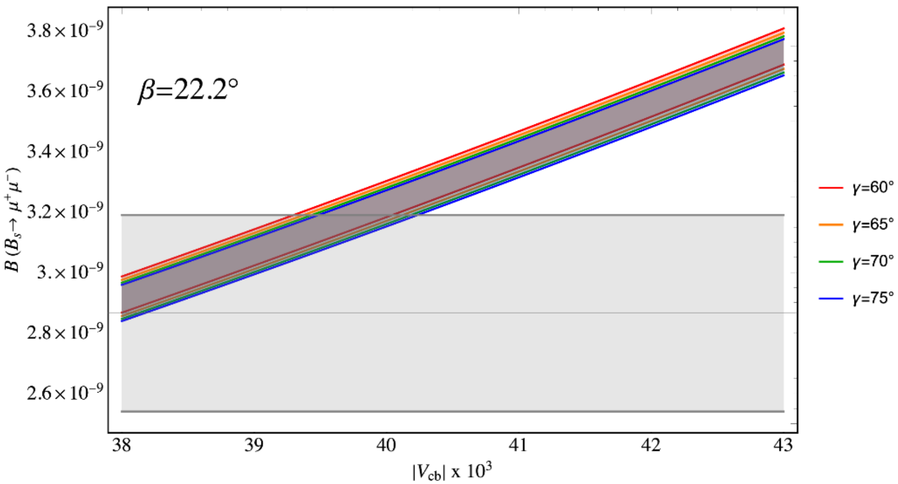
$$\left[R_{s\mu}\right]_{exp} = \left(1.61\,^{+0.19}_{-0.17}\right)\cdot 10^{-10}\,\mathrm{ps}$$

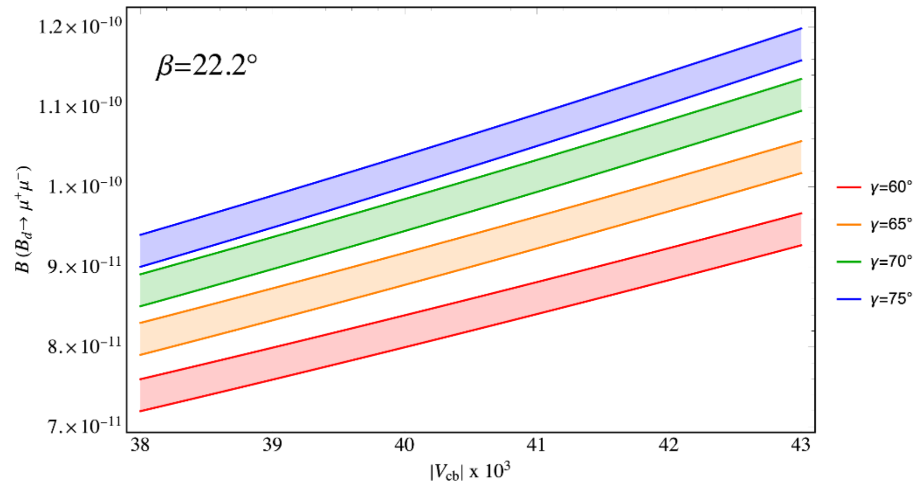
(2.7 σ tension)
(Independent of CKM parameters!!)

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

AJB + E. Venturini (2109.11032)

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





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

LHCb
CMS
ATLAS

Averages from: 2103.12738, 2103.13370, 2104.10058

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

CKM Independent !

(2.7 σ Anomaly)

Basic Strategy for Rare B and K Decays

AJB + E. Venturini (2109.11032)

E. Venturini

1. Use as basic parameters

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

2. Construct $|V_{cb}|$ independent Ratios $R_i\,(\beta,\gamma)$

3. 16 Ratios involving

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

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

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

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

Once γ will be precisely measured very good test of SM

"Critical Exponents" of Flavour Physics

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

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

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

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

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

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

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

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

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

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

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

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

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

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

AJB + E. Venturini

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

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

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

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

Important V_{cb} – Independent Formulae

AJB + E. Venturini (2109.11032)

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

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

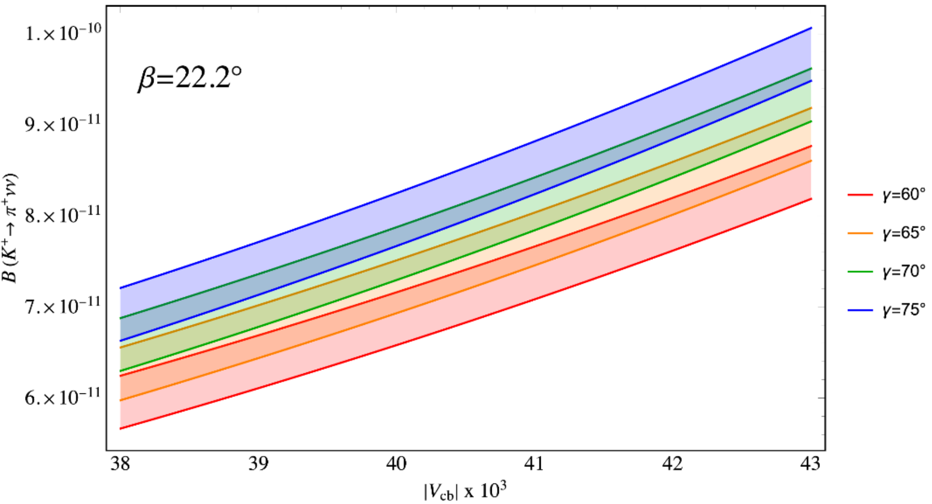
Note: practically γ-independent

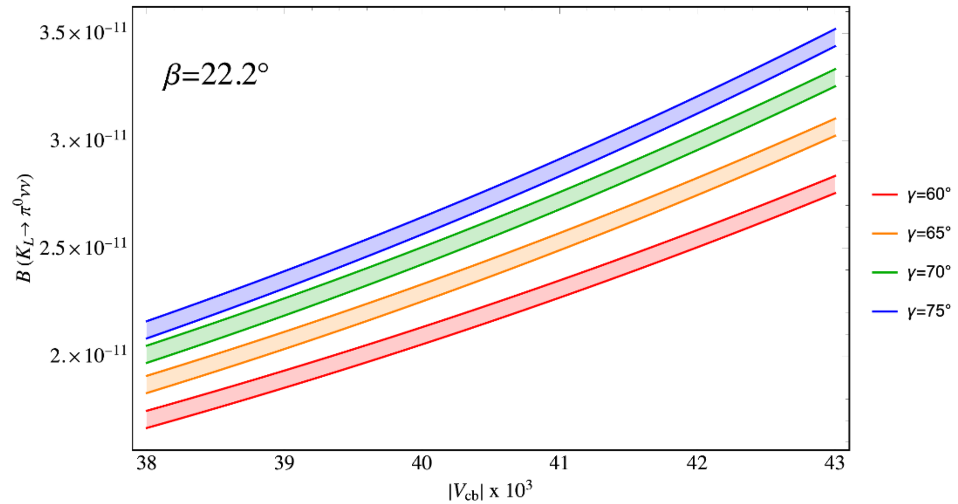
$$\left\{|\varepsilon_K|_{exp}, S_{\psi K_s}^{exp} = \sin 2\beta\right\} \Rightarrow \left\{\text{Most accurate Predictions to date}\right\}$$

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

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

AJB + E. Venturini (2109.11032)





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

NA62

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

KOTO

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

V_{cb} and γ independent

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

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

BV: 2109.11032
2203.11960

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

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

Only β-dependent (γ-dependence very weak)

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

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

CKM-independent

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

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

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

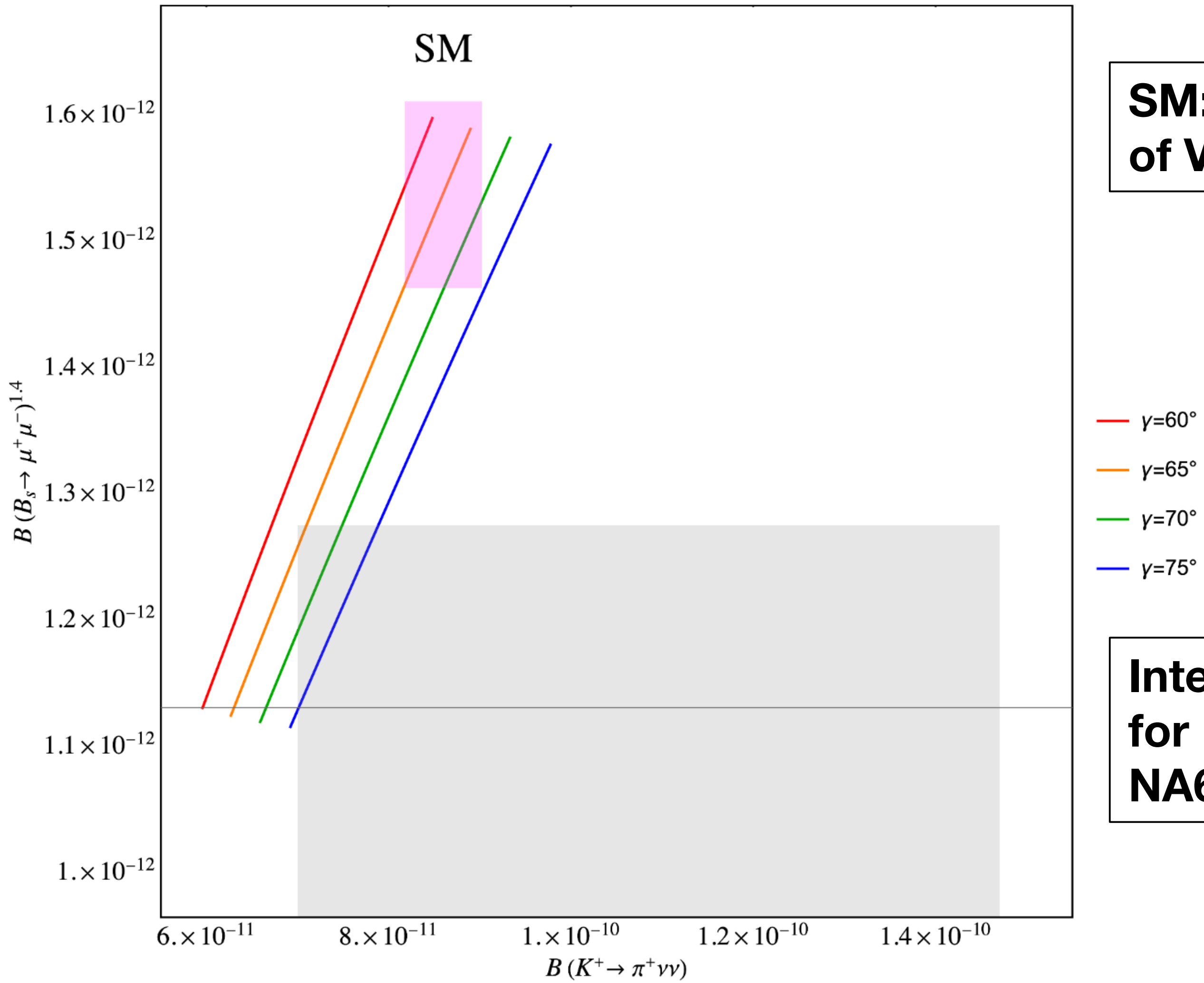
$$Br(K^+) = (8.4 \pm 1.0)\cdot 10^{-11} \qquad Br(K_L) = (3.4 \pm 0.6)\cdot 10^{-11}$$ (1503.02693)

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

(Bobeth et al.)

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

AJB + E. Venturini (2109.11032)

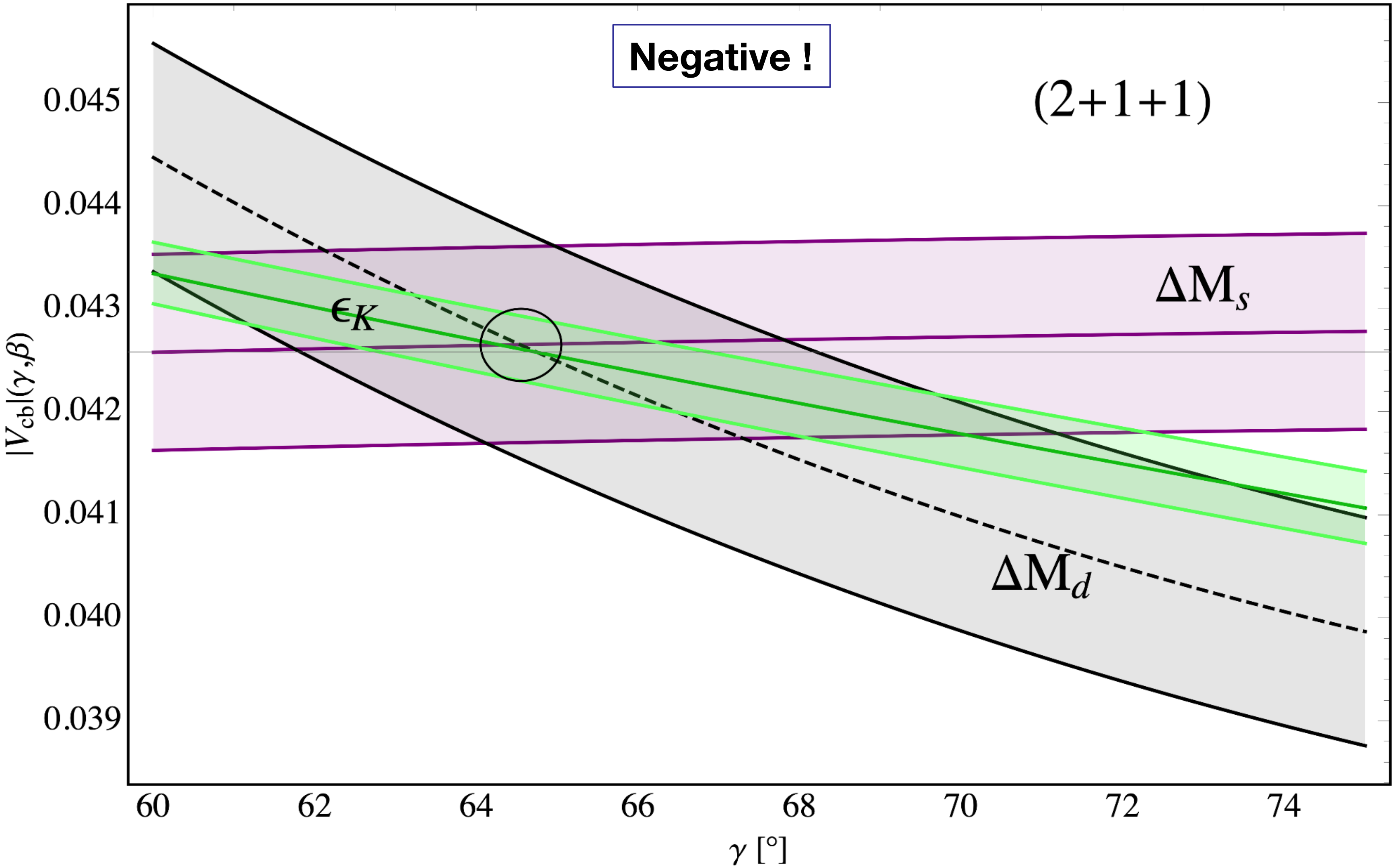


SM: independent of V_{cb} and γ

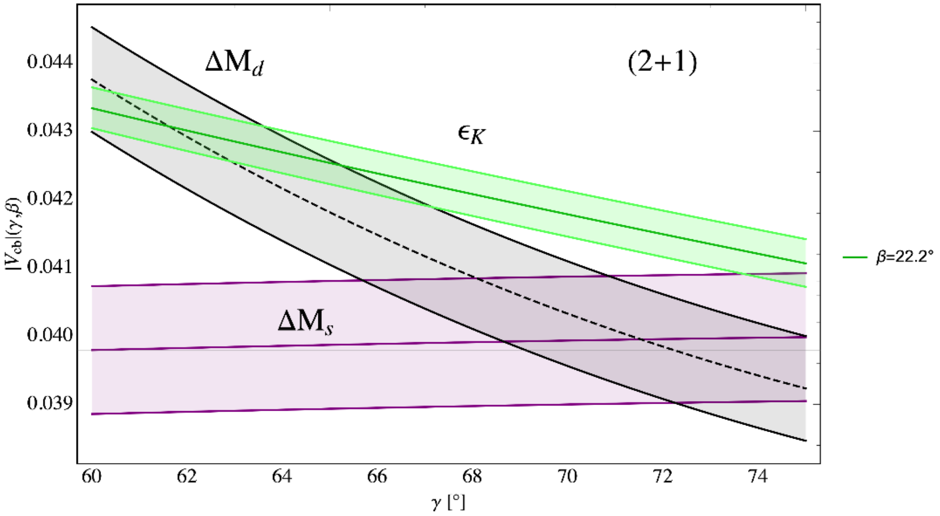
Interesting for LHCb, Belle II, NA62

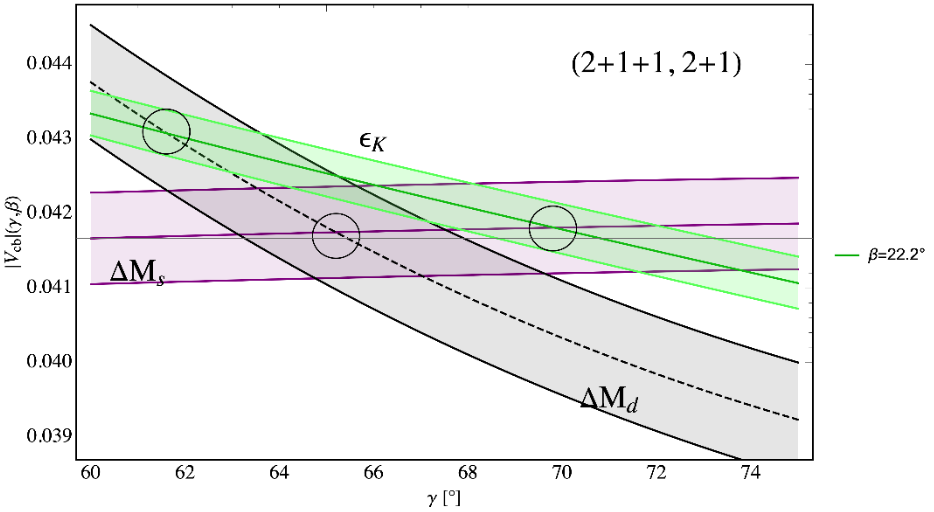
$|V_{cb}|$ - γ Plot = Rapid Test

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



Positive Tests





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

(SM)

AJB + E. Venturini (2109.11032) (2203.11960)

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

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

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

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

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

$\gamma = 65.4(40)^\circ$

LHCb

Largest Anomalies in Single Branching Ratios following from this Strategy

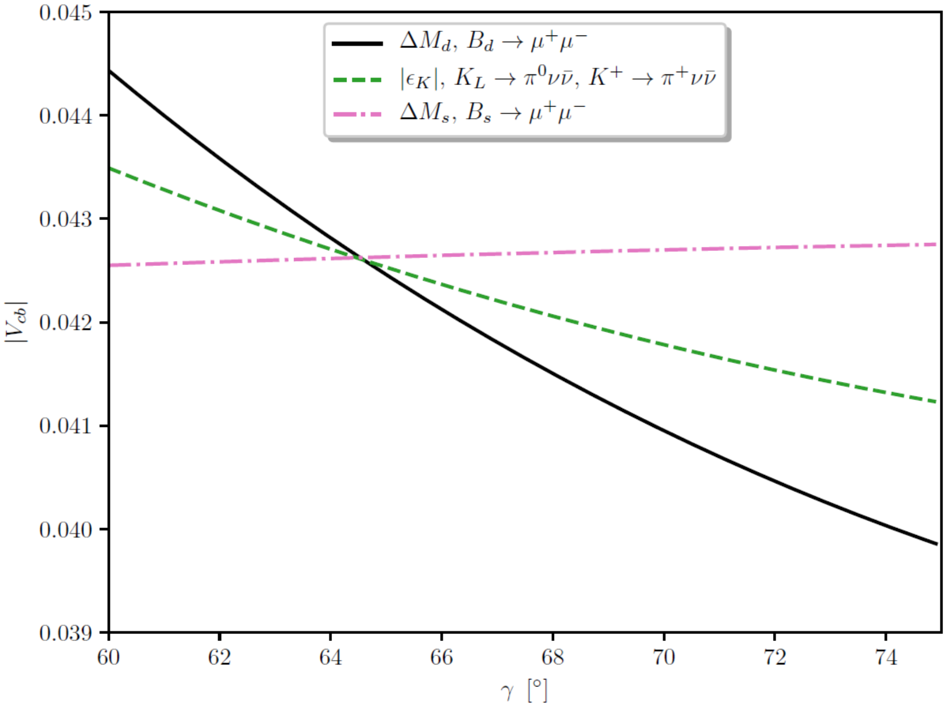
(AJB: 2209.03968)

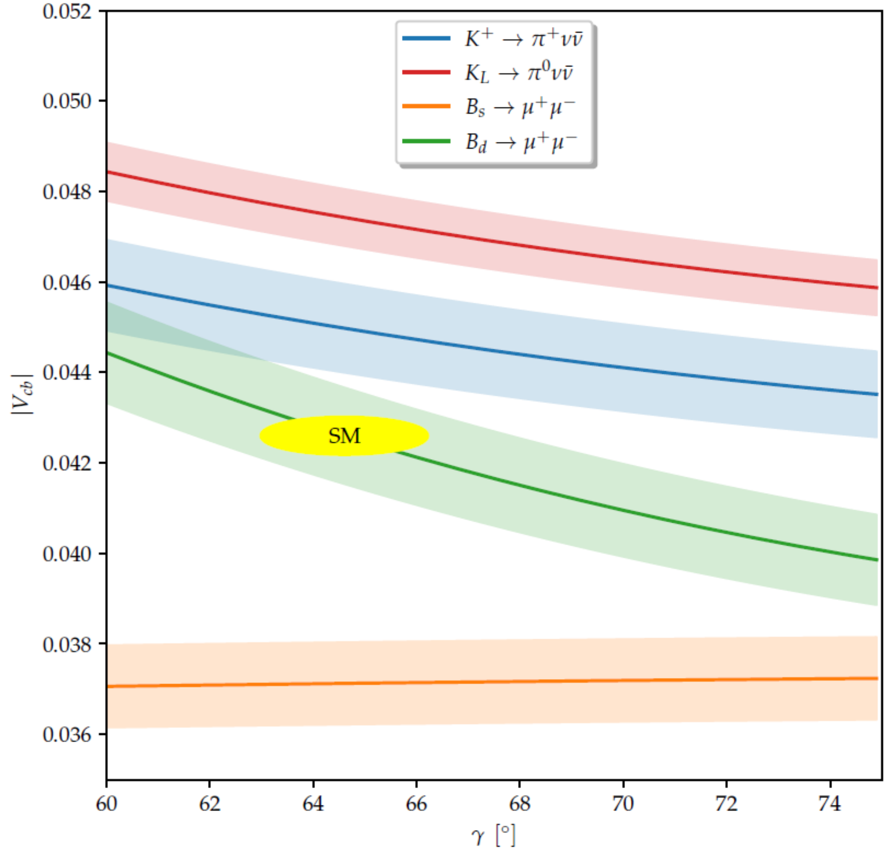
	$[q^2_{min}, q^2_{max}]$	
$B^+ \to K^+\mu^+\mu^-$	[1.1, 6]	-5.1σ ★
$B^+ \to K^+\mu^+\mu^-$	[15, 22]	-3.6σ
$B_s \to \varphi\, \mu^+\mu^-$	[1.1, 6]	-4.8σ ★
$B_s \to \mu^+\mu^-$	full	-2.7σ

New Formfactors from HPQCD (2207.13371, 2207.12468)

SM without uncertainties

Impact of New Physics



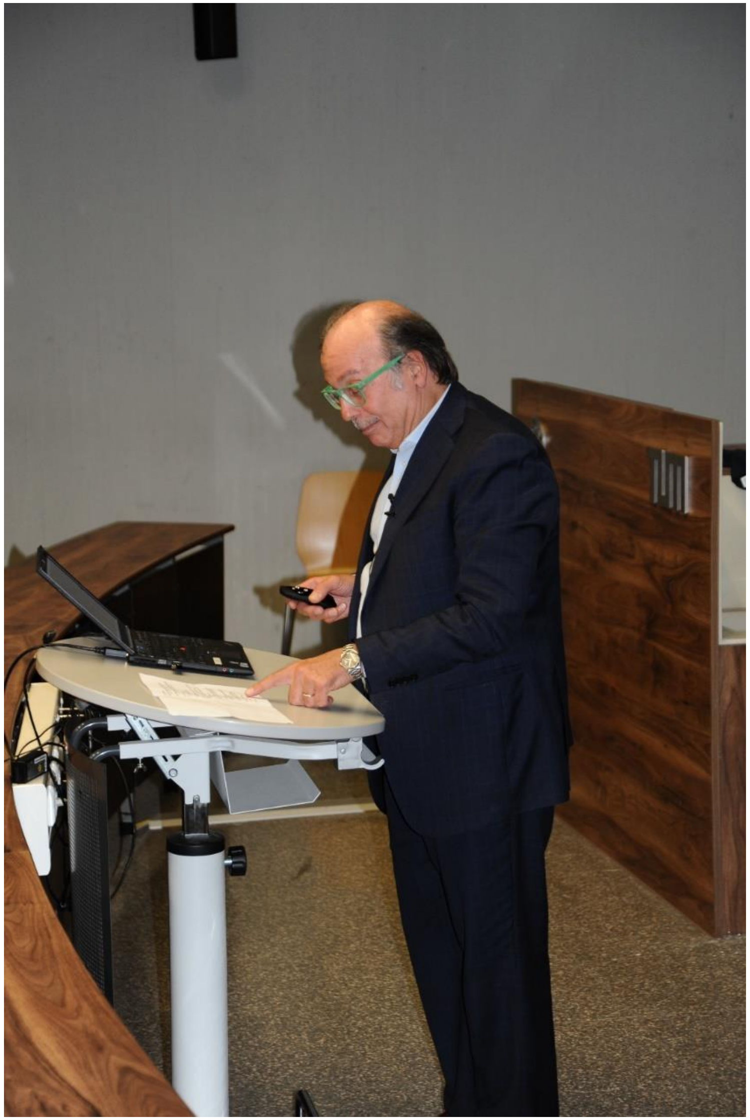


Superior over UT-triangle plots: $|V_{cb}|$ seen, γ better exposed
AJB 2204.10337

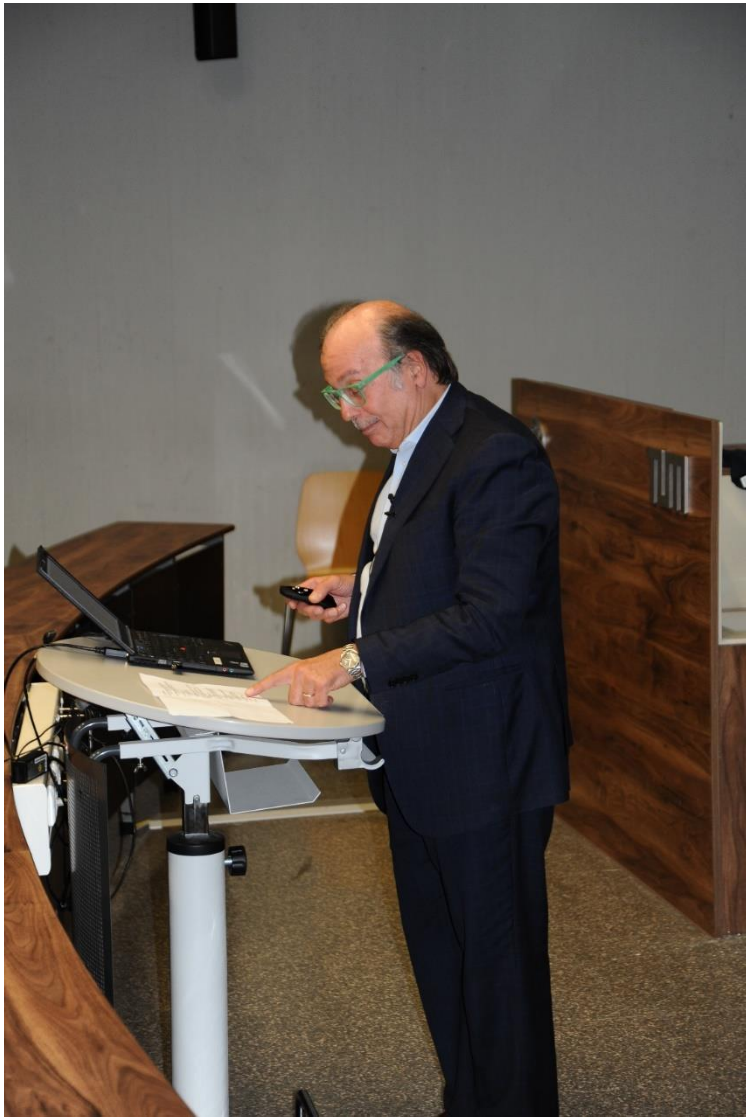
3rd Movement

Last Speaker at Andrzej´s Fest (2016) in Action

Andrzej´s Fest (2016)



Andrzej´s Fest (2016)



What´s his name again?

Several Good Jokes !

Several Good Jokes !

ΔI = ½ Rule

ΔI = ½ Rule

ΔI = ½ Rule

ε´/ε

ε´/ε

Everybody is Happy

Guido´s Lecture continues

The Happiest Participant

4th Movement

Visions for Coming Years

Main Message

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

Attouniverse → Zeptouniverse

Also Lepton Flavour Violation and EDMs

Exciting Times are just ahead of us !!!

Coming Years : Flavour Precision Era

LHC Upgrade
E = 14 TeV
(CERN)

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

★

$$\left(\begin{array}{ll} K^+ \to \pi^+ \nu\bar{\nu} & (10^{-10})\ \text{(CERN)} \\ K_L \to \pi^0 \nu\tilde{\nu} & (3 \cdot 10^{-11})\ \text{J-PARC (Japan)} \end{array} \right)$$

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

★ $(g-2)_\mu$

★ ε'/ε

$\Delta I = 1/2$ Rule, ΔM_K

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

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

Homeoffice in Ottobrunn

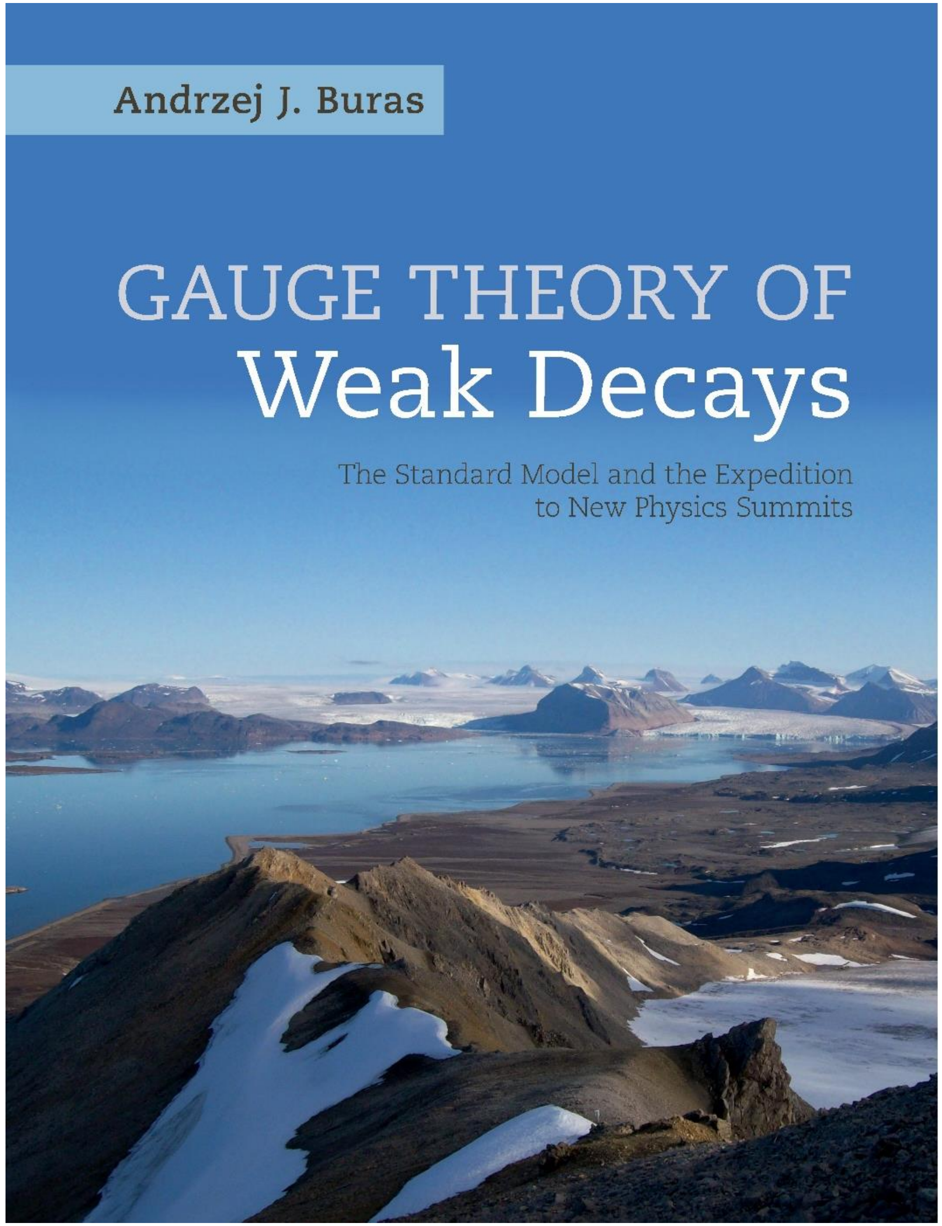
March 2020 →

Zeptouniverse Guide

Published July 2020

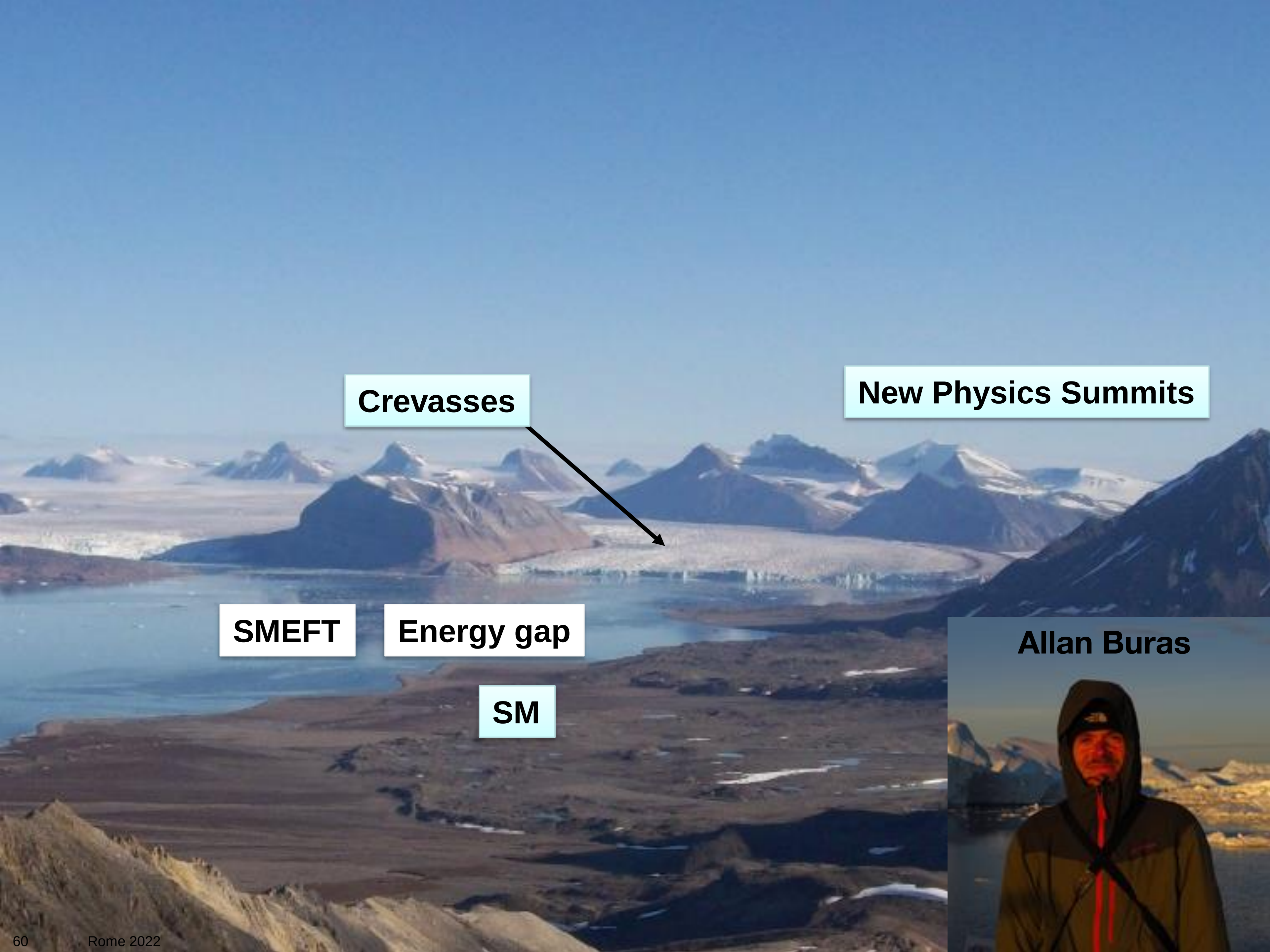
7

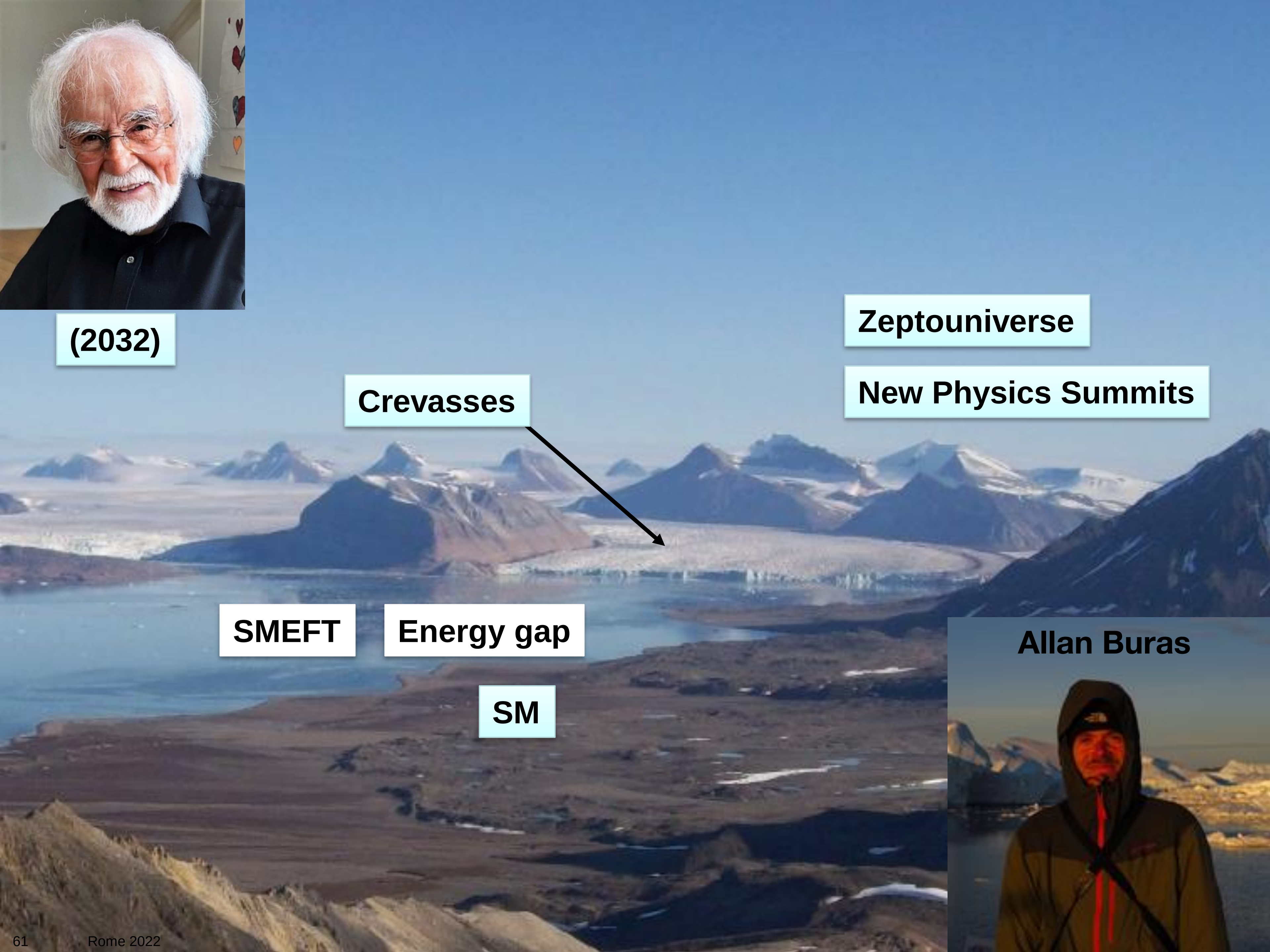
Exciting Years !



739 pages
1350 references

Cambridge University Press


Crevasses
New Physics Summits
SMEFT
Energy gap
SM
Allan Buras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Zeptouniverse
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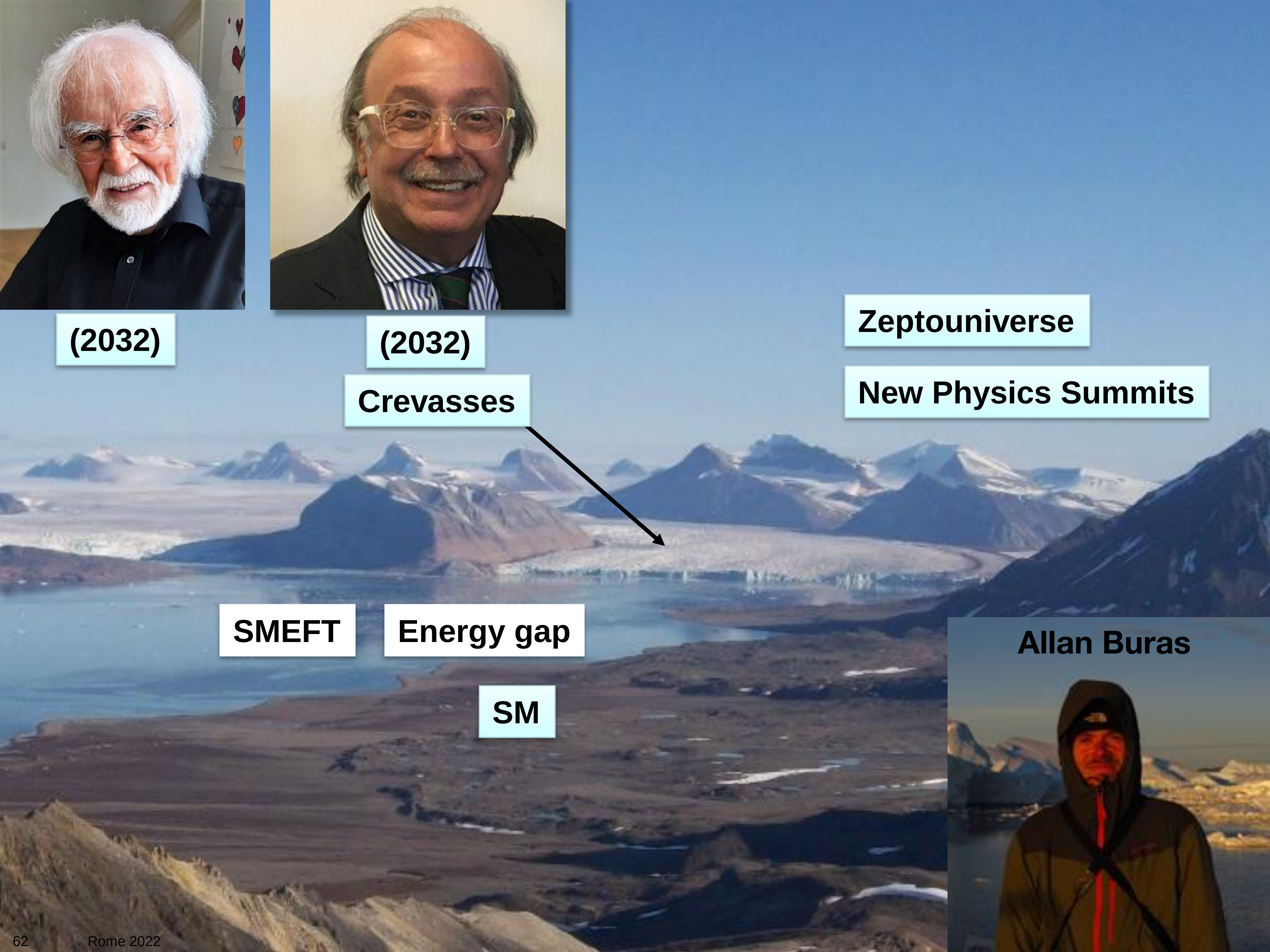
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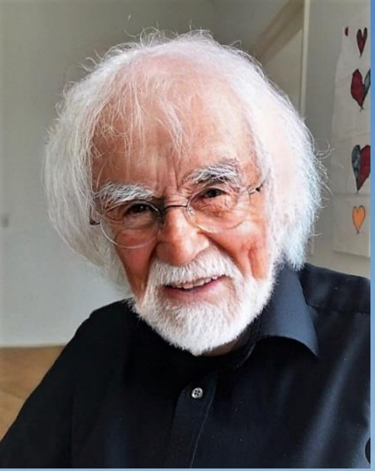

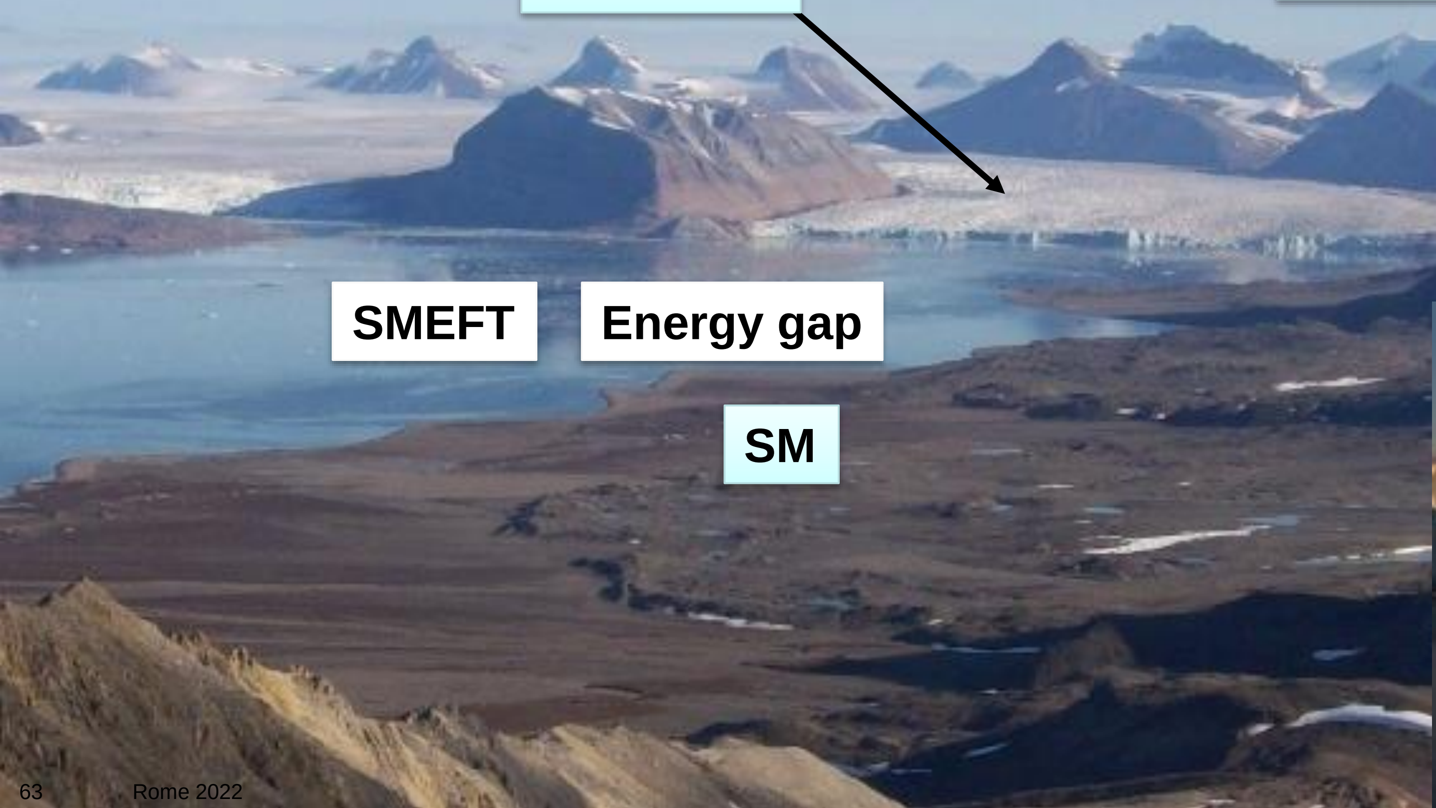
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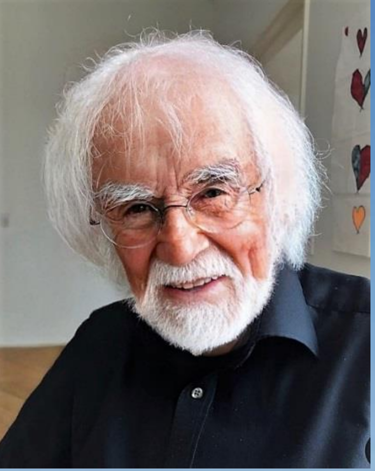

(2032)

(2032)

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Zeptouniverse

New Physics Summits

Crevasses

SMEFT

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Thank You !

Backup

$\Delta I = 1/2$ Rule

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

Puzzle since
1954 (Gell-Mann + Pais)

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

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

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

QCD dynamics dominate this rule
but New Physics could still contribute

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

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

Hep-arxiv: 2101.00020

ε'/ε Controversy

2015-2022

CP Violation in $K_L \to \pi\pi$

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

(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.

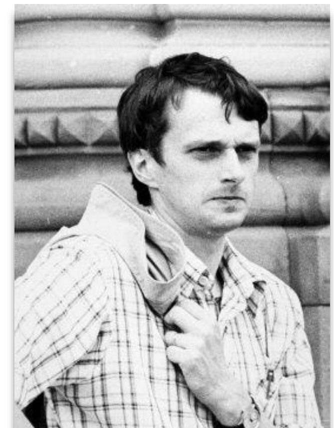
Dual QCD Approach for Weak Decays

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

1986

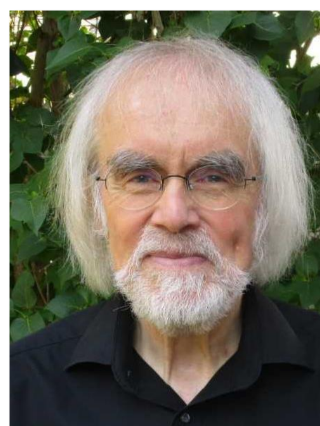
W. Bardeen

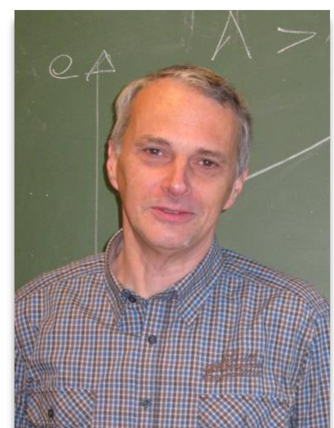
AJB



J.-M. Gérard

2020





Lattice QCD	Dual QCD	Chiral Perturbation Theory	
New Physics	New Physics	New Physics	
Short Distance RG Evolution	Short Distance RG Evolution	Short Distance RG Evolution	↓
			0(1GeV)
Numerical sophisticated and demanding calculations lasting many years. (from first principles)	Meson Evolution: The only analytic approach allowing matching with short distance	Problems with matching with short distance, L_i (No meson evolution)	
		Based on global symmetries of QCD	$0(m_K)$

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

(2021) **Age Sum Rule**

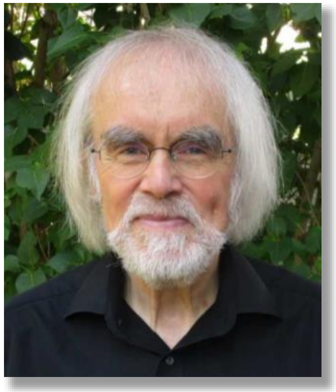
Accurate to 1‰ !

N. Christ

+

C. Sachrajda

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



AJB

A. Pich

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