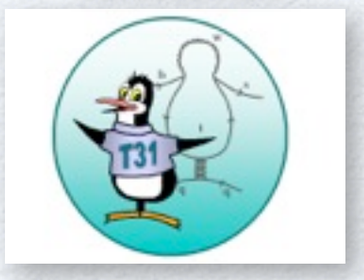
PARTICLE PHYSICS SCHOOL MUNICH COLLOQUIUM

MAX-PLANCK-INSTITUT FÜR PHYSIK - DECEMBER 14, 2012

THEORY AND PHENOMENOLOGY OF 331 MODELS



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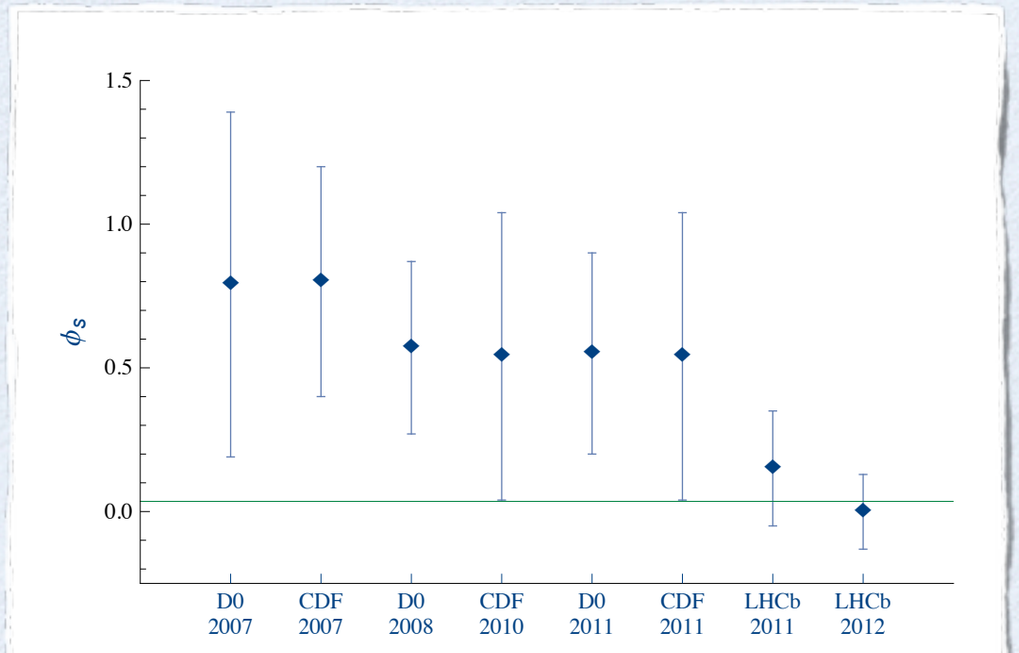
Outline

- Introduction
  - New data and old tensions in the flavour sector
  - Motivations for the 331 models
- Theory of the 331 models
  - General 331 model
  - A specific realization
- Phenomenology of the 331 models
  - Constraining the parameter space
  - Key observables
- Conclusions and Outlook

Introduction

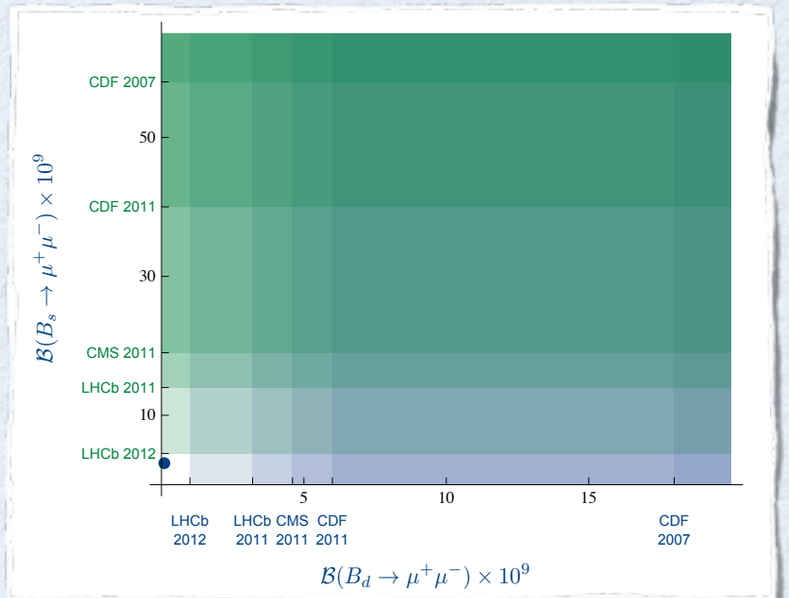
Vanishing Hopes...

$S_{\psi\phi}$: mixing-induced CP asymmetry in the B_s system

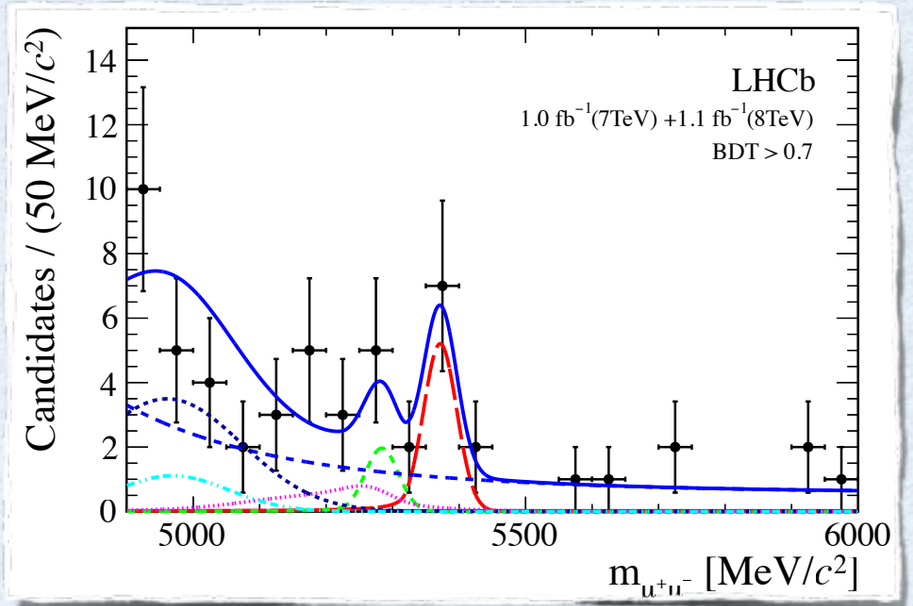


LHCb Collab., PRL **108** (2012)
LHCb Collab., LHCb-CONF-2012-002

$B_{d,s} \rightarrow \mu^+\mu^-$: doubly suppressed and very sensitive to new (pseudo)scalar particles



LHCb Collab., Phys. Lett. B **708** (2012)
LHCb Collab., 1203.4493

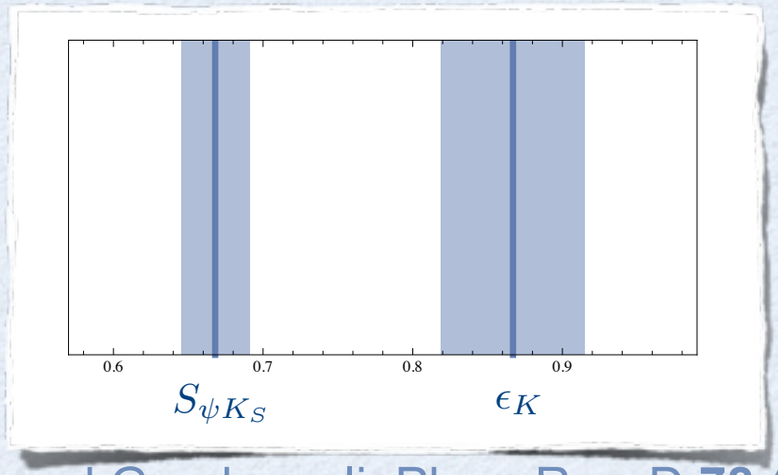


LHCb Collab. @ HCP 2012

Introduction

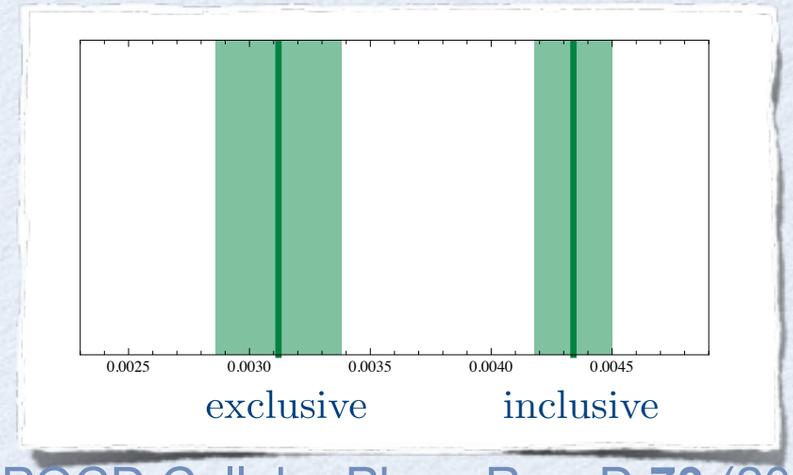
... and Old Tensions

3.2σ discrepancy
when extracting sin2β from ε_K and $S_{\psi Ks}$



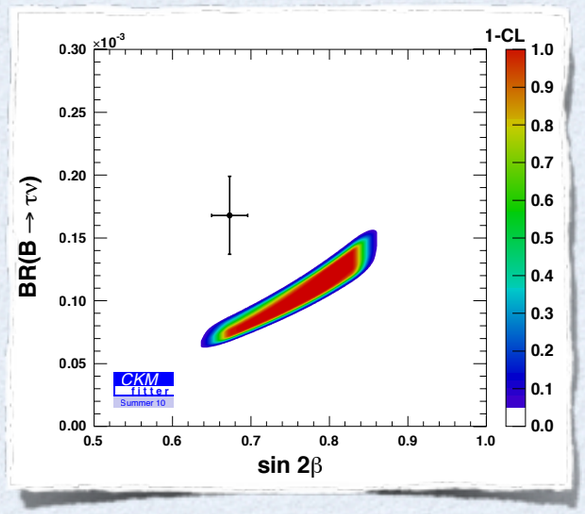
Buras and Guadagnoli, Phys. Rev. D **78** (2008)
Lunghi and Soni, Phys. Lett. B **708** (2012)

3.3σ discrepancy
between the determinations of $|V_{ub}|$



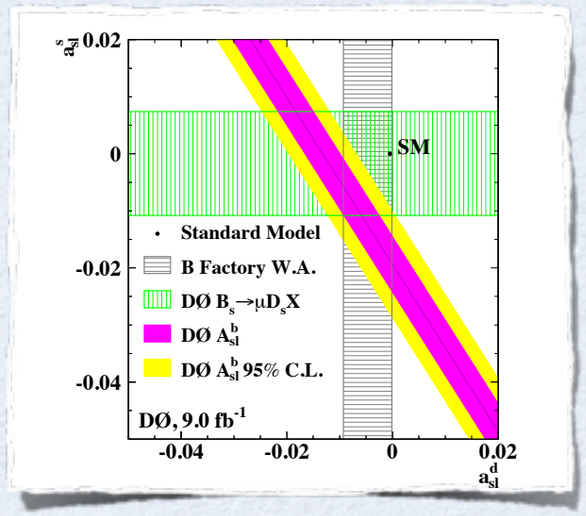
HPQCD Collab., Phys. Rev. D **73** (2006)
HFAG, 1010.1589

2.9σ discrepancy
between BR(B → τ ν) and its prediction



Lenz, Nierste and CKMfitter, 1203.0238

3.9σ deviation
of the semileptonic CP asymmetry in $B_{d,s}$



D0 Collab., Phys. Rev. D **84** (2011)

Motivations for Studying 331 Models

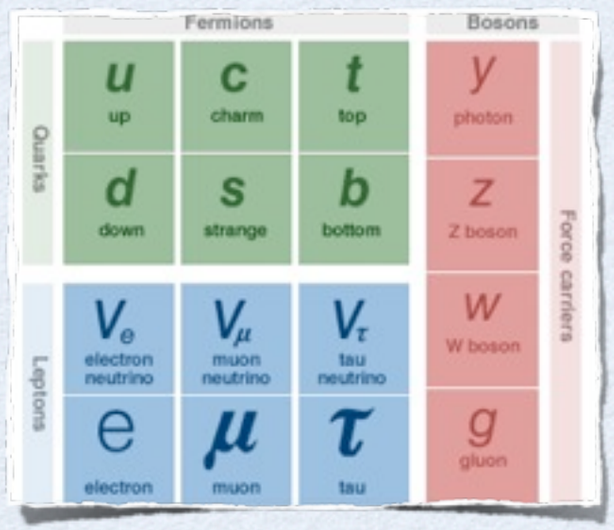
Update the phenomenological analysis of New Physics models

Are they compatible with LHC data?

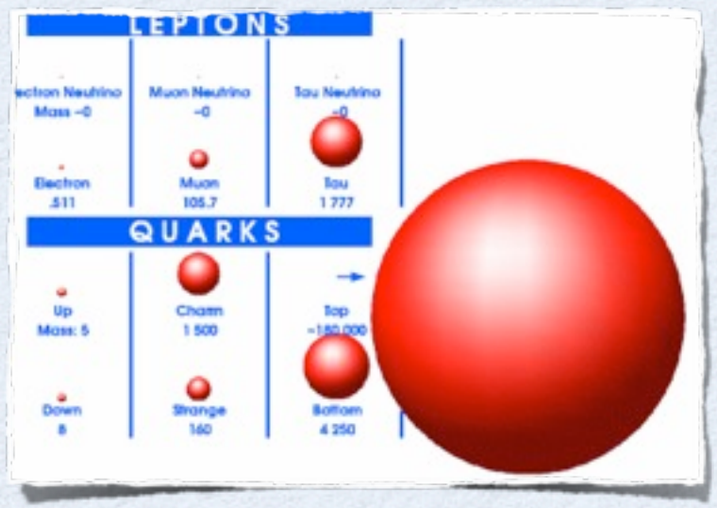
Can they solve the flavour tensions?

Features of 331 models

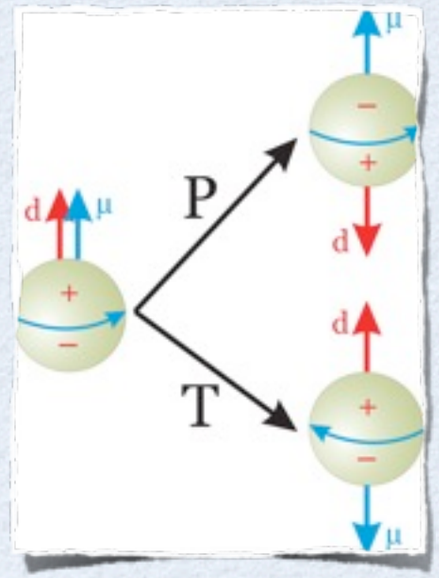
Explanation of why just 3 generations



Different treatment of the 3rd generation

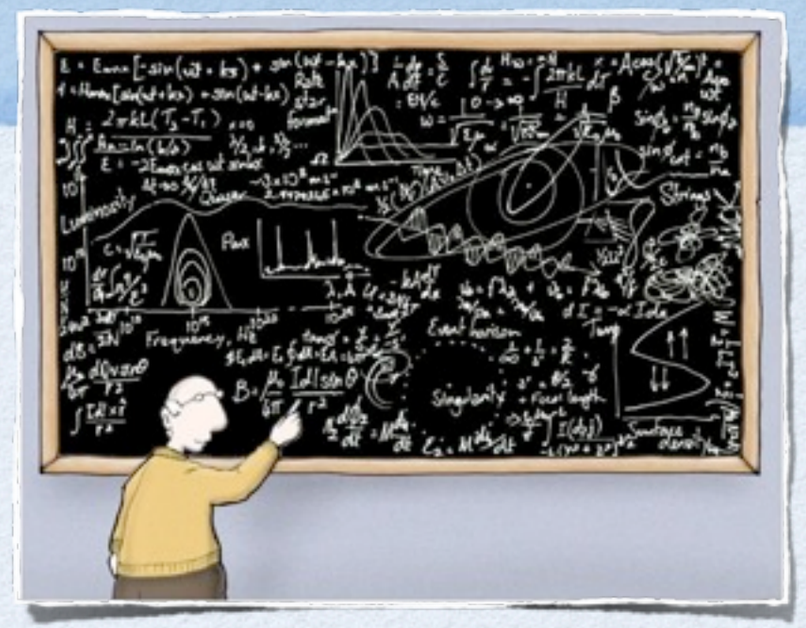


Solution to the strong CP problem



Theory of 331 Models

Definition



Gauge group $\mathcal{G} = SU(3)_C \otimes SU(3)_L \otimes U(1)_X$

Charge $\hat{Q} = \hat{T}^3 + \beta\hat{T}^8 + X\hat{I} \longrightarrow Y/2$

Gauge bosons

$$\frac{1}{2}\begin{pmatrix} W_\mu^3 + \frac{1}{\sqrt{3}}W_\mu^8 & \sqrt{2}W_\mu^+ & \sqrt{2}Y_\mu^{Q_Y} \\ \sqrt{2}W_\mu^- & -W_\mu^3 + \frac{1}{\sqrt{3}}W_\mu^8 & \sqrt{2}V_\mu^{Q_V} \\ \sqrt{2}Y_\mu^{-Q_Y} & \sqrt{2}V_\mu^{-Q_V} & -\frac{2}{\sqrt{3}}W_\mu^8 \end{pmatrix}$$

Fermions

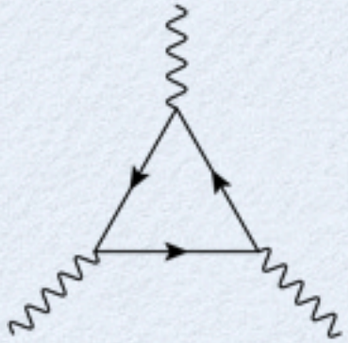
$$q_L \sim (3, 3, X_q^L) \to (3, 2, Y_q^L) \oplus (3, 1, Y_q^L)$$
$$q_R = (3, 1, Y_q^R)$$
$$\ell_L \sim (1, 3, X_\ell^L) \to (1, 2, Y_\ell^L) \oplus (1, 1, Y_\ell^L)$$
$$\ell_R = (1, 1, Y_\ell^R)$$

ANOMALY CANCELLATION

Anomaly: a symmetry of the classical action is destroyed by loop corrections.

A **gauge anomaly** leads to the inconsistency of the theory!

Using group theory we can say if a theory is anomaly free:



$$\mathcal{A}^{abc} = \mathrm{Tr}\left[t^a \left\{t^b, t^c\right\}\right]$$

Results: $N_q = N_\ell \equiv N$ $\qquad$ $t_\ell + 3t_q = \bar{t}_\ell + 3\bar{t}_q = 2N$

Asymptotic freedom: N<5 $\longrightarrow$

$$N = 3$$

$$t_q = 2\,, \quad \bar{t}_q = 1$$

Symmetry Breaking

$$SU(3)_L \otimes U(1)_X \xrightarrow{\langle \Phi_1 \rangle} SU(2)_L \otimes U(1)_Y \xrightarrow{\langle \Phi_2 \rangle} U(1)_Q$$

$$\langle \chi \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ 0 \\ u \end{pmatrix} \qquad \langle \rho \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \\ 0 \end{pmatrix} \qquad \langle \eta \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} v' \\ 0 \\ 0 \end{pmatrix} \qquad \langle S_{1\ldots4} \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & 0 & w_i \\ 0 & 0 & 0 \\ w_i & 0 & 0 \end{pmatrix}$$

Gauge bosons masses and mixing

$$u \gg v, v', w_i$$

$$\downarrow$$

$$m_Y, m_V \gg m_W$$

$$\begin{pmatrix} W_\mu^3 \\ W_\mu^8 \\ X_\mu \end{pmatrix} = U \begin{pmatrix} A_\mu \\ Z_\mu \\ Z'_\mu \end{pmatrix}$$

Fermions masses and mixing

$$\begin{pmatrix} u_L \\ c_L \\ t_L \end{pmatrix} = W_L \begin{pmatrix} u'_L \\ c'_L \\ t'_L \end{pmatrix} \qquad \begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix} = V_L \begin{pmatrix} d'_L \\ s'_L \\ b'_L \end{pmatrix}$$

$$W_L^\dagger V_L = V_{\mathrm{CKM}}$$

Different treatment of the 3rd generation

$\downarrow$

W_L and V_L are both relevant!

THEORY OF 331 MODELS

$\overline{331}$ MODEL: $\beta = 1/\sqrt{3}$

Fermions

$$\begin{pmatrix} u \\ d \\ D \end{pmatrix} \quad \begin{pmatrix} c \\ s \\ S \end{pmatrix} \quad \begin{pmatrix} b \\ -t \\ T \end{pmatrix}$$

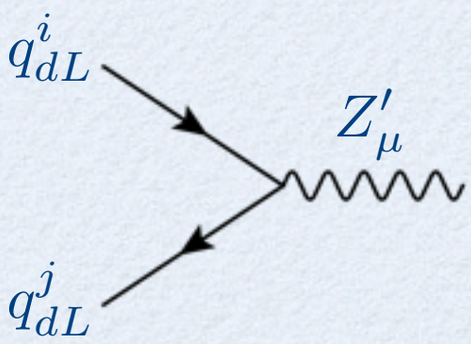
Gauge bosons

$$\frac{1}{2}\begin{pmatrix} \dots & \sqrt{2}W_\mu^+ & \sqrt{2}Y_\mu^+ \\ \sqrt{2}W_\mu^- & \dots & \sqrt{2}V_\mu^0 \\ \sqrt{2}Y_\mu^- & \sqrt{2}\bar{V}_\mu^0 & \dots \end{pmatrix} \quad \begin{pmatrix} A_\mu \\ Z_\mu \\ Z'_\mu \end{pmatrix}$$

Higgs sector

Feynman rules: what to take home

Y^+, V^0, $\bar{V}^0$ only interact with D, S, T → all phenomenologically irrelevant



$$\propto i\, g\, v^*_{3i} v_{3j}$$

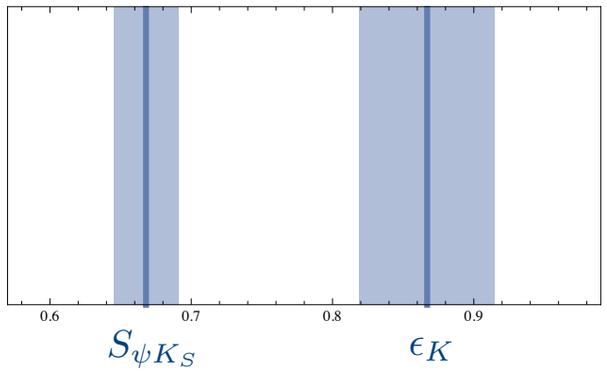
$$V_L = \begin{pmatrix} \tilde{c}_{12}\tilde{c}_{13} & \tilde{s}_{12}\tilde{c}_{23}e^{i\delta_3} - \tilde{c}_{12}\tilde{s}_{13}\tilde{s}_{23}e^{i(\delta_1-\delta_2)} & \tilde{c}_{12}\tilde{c}_{23}\tilde{s}_{13}e^{i\delta_1} + \tilde{s}_{12}\tilde{s}_{23}e^{i(\delta_2+\delta_3)} \\ -\tilde{c}_{13}\tilde{s}_{12}e^{-i\delta_3} & \tilde{c}_{12}\tilde{c}_{23} + \tilde{s}_{12}\tilde{s}_{13}\tilde{s}_{23}e^{i(\delta_1-\delta_2-\delta_3)} & -\tilde{s}_{12}\tilde{s}_{13}\tilde{c}_{23}e^{i(\delta_1-\delta_3)} - \tilde{c}_{12}\tilde{s}_{23}e^{i\delta_2} \\ -\tilde{s}_{13}e^{-i\delta_1} & -\tilde{c}_{13}\tilde{s}_{23}e^{-i\delta_2} & \tilde{c}_{13}\tilde{c}_{23} \end{pmatrix} \quad (6$$

Z' mediates FCNCs governated by 4 parameters:

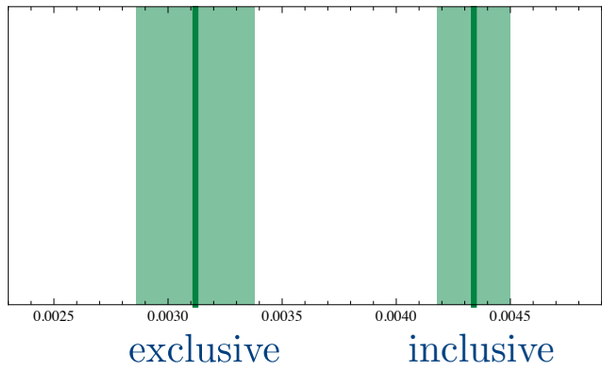
$$s_{13} \qquad s_{23} \qquad \delta_1 \qquad \delta_2$$

TENSIONS IN THE UNITARITY TRIANGLE: ε_K – $S_{\psi Ks}$ VS. V_{ub}

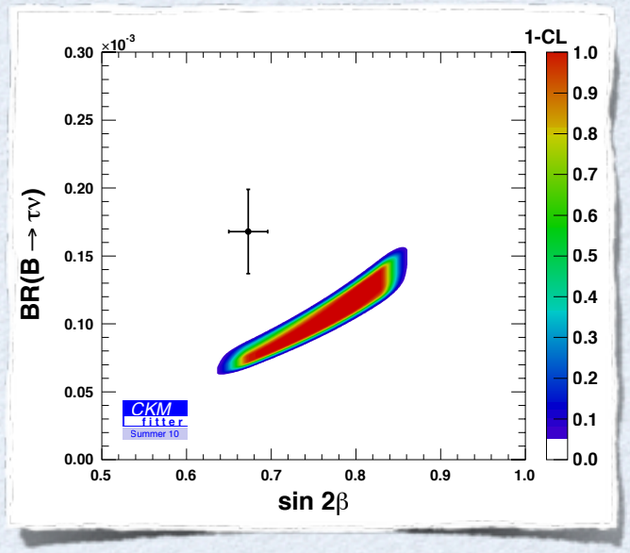
sin2β from...



Determination of $|V_{ub}|$ ...



Prediction of BR(B → τ ν)...



Scenario 1

exclusive (small) V_{ub}
ε_K below the data of 1-2σ
$S_{\psi Ks}$ in agreement with data
BR(B → τ ν) below data of 3σ

Scenario 2

inclusive (large) V_{ub}
ε_K in agreement with data
$S_{\psi Ks}$ above the data of 2-3σ
BR(B → τ ν) below data of 1σ

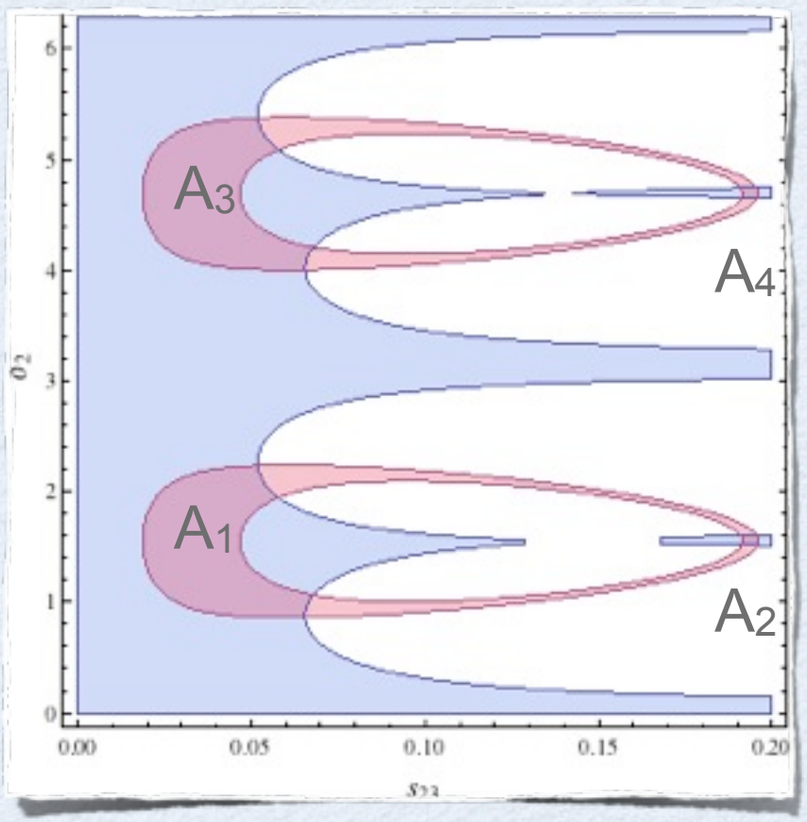
FCNCs AND THE PARAMETER SPACE

$$i\mathcal{L}_{\rm FCNC} = i\left[\Delta^{sd}\left(\bar{s}\gamma^\mu P_L d\right) + \Delta^{bd}\left(\bar{b}\gamma^\mu P_L d\right) + \Delta^{bs}\left(\bar{b}\gamma^\mu P_L s\right)\right] Z'_\mu$$

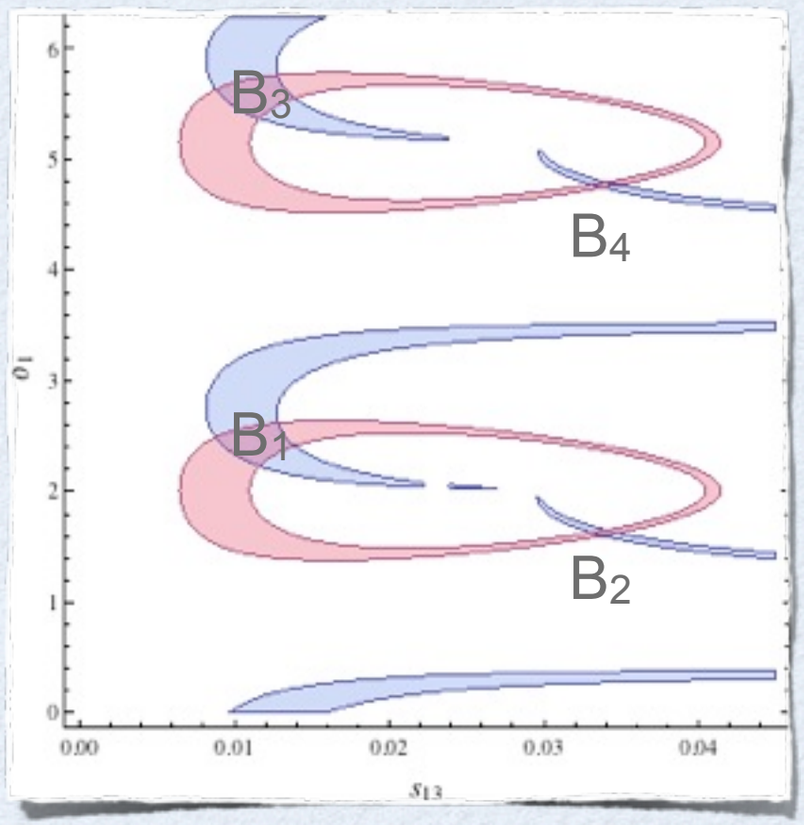
$$\Delta^{sd} = 0.61\; g\; s_{13}s_{23}\; e^{i(\delta_2-\delta_1)} \qquad \Delta^{bd} = -0.61\; g\; s_{13}\; e^{-i\delta_1} \qquad \Delta^{bs} = -0.61\; g\; s_{23}\; e^{-i\delta_2}$$

B_d observables depend only from s_{13} and δ_1, B_s observables only from s_{23} and δ_2

ΔM_s and $S_{\psi\varphi}$



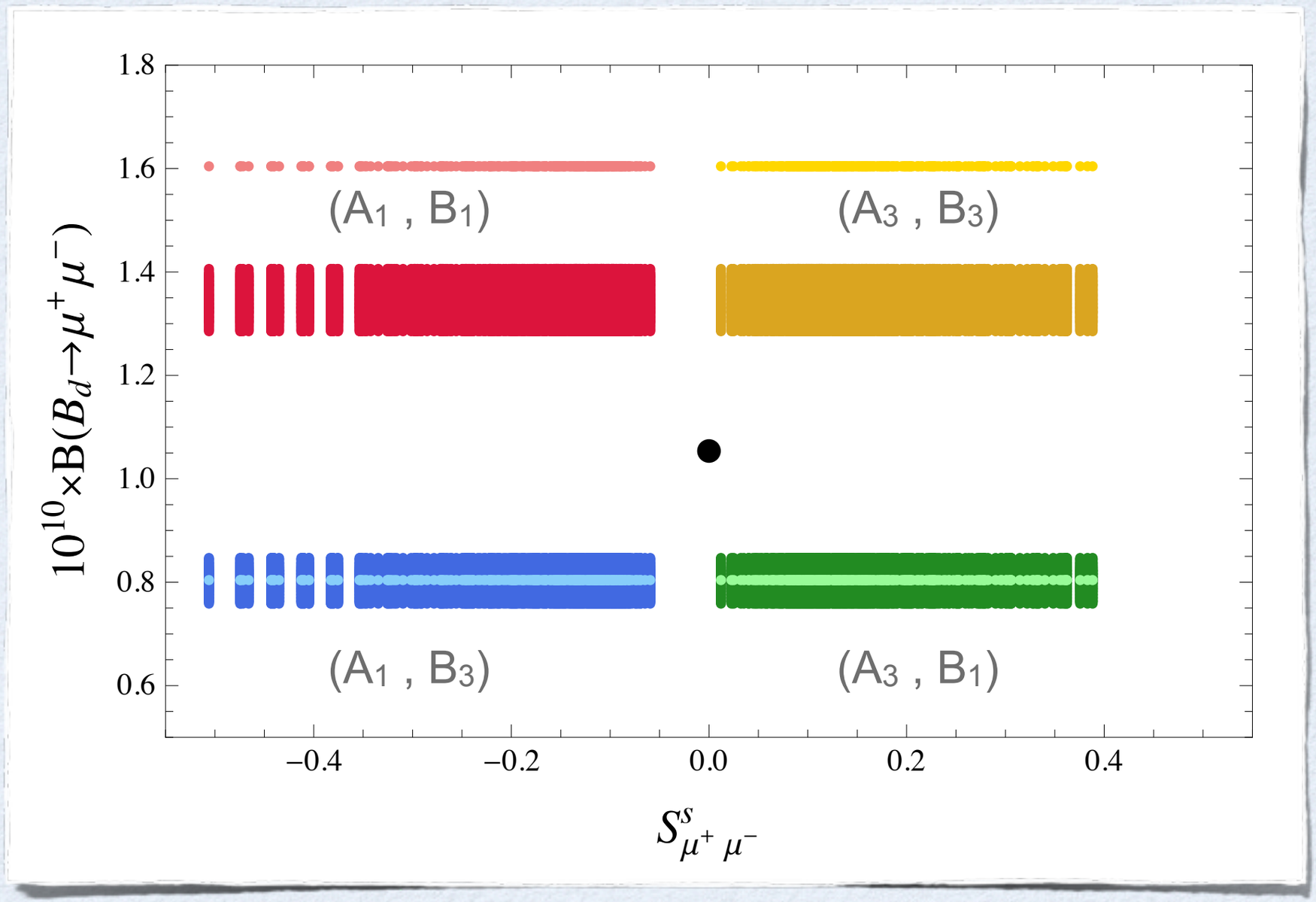
ΔM_d and $S_{\psi Ks}$



Phenomenology of 331 Models

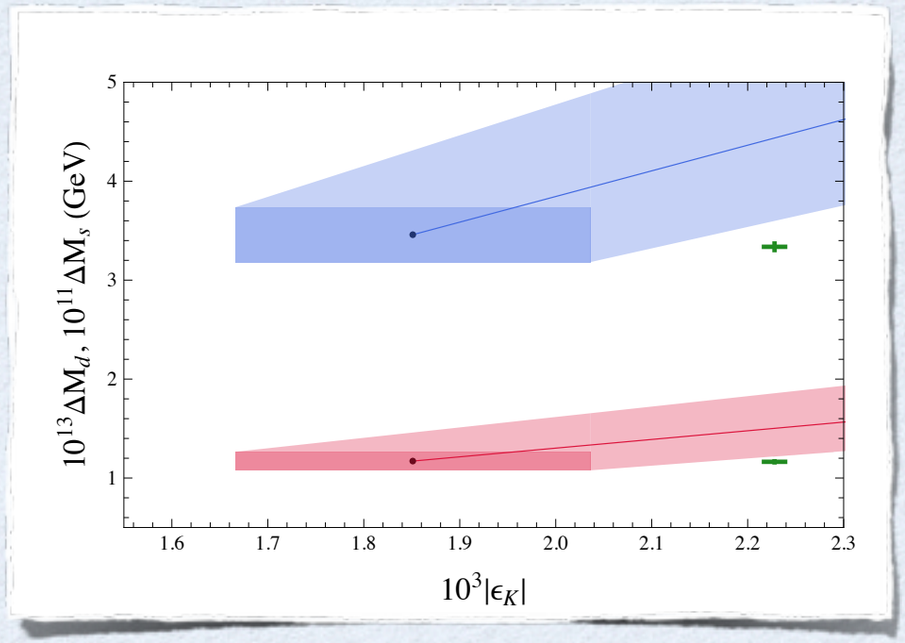
$B_{d,s} \to \mu^+\mu^-$ and the Parameter Space

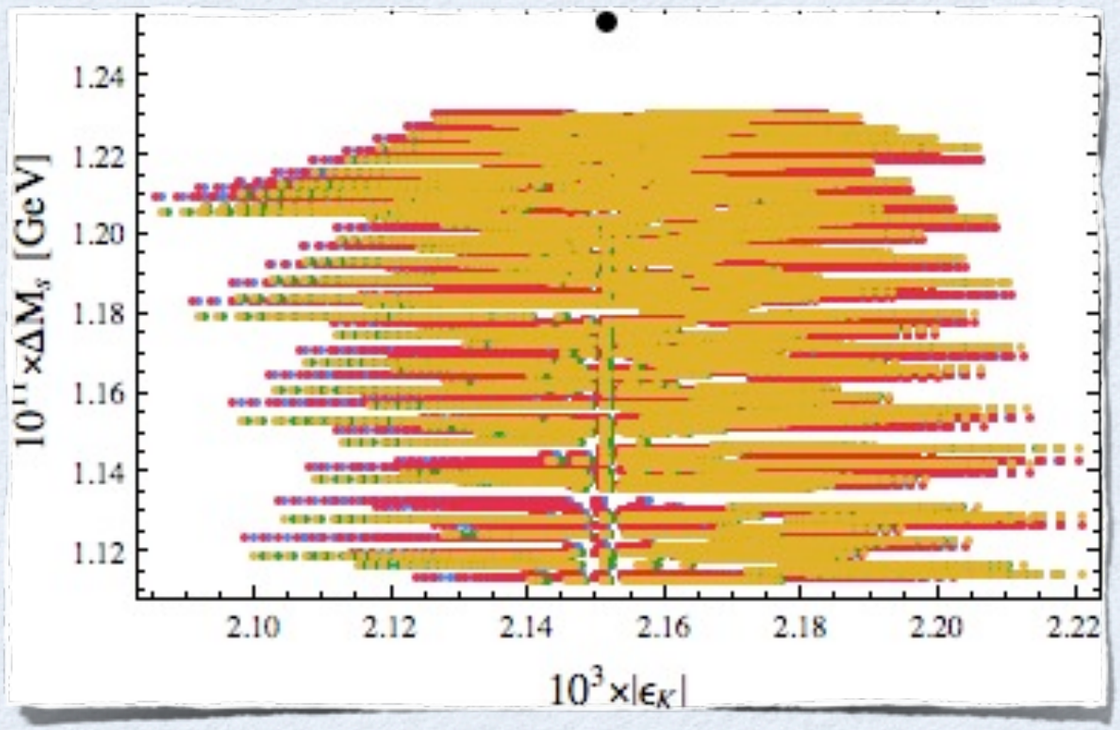
Combining B_d and B_s observables → univocal selection of the parameter space area

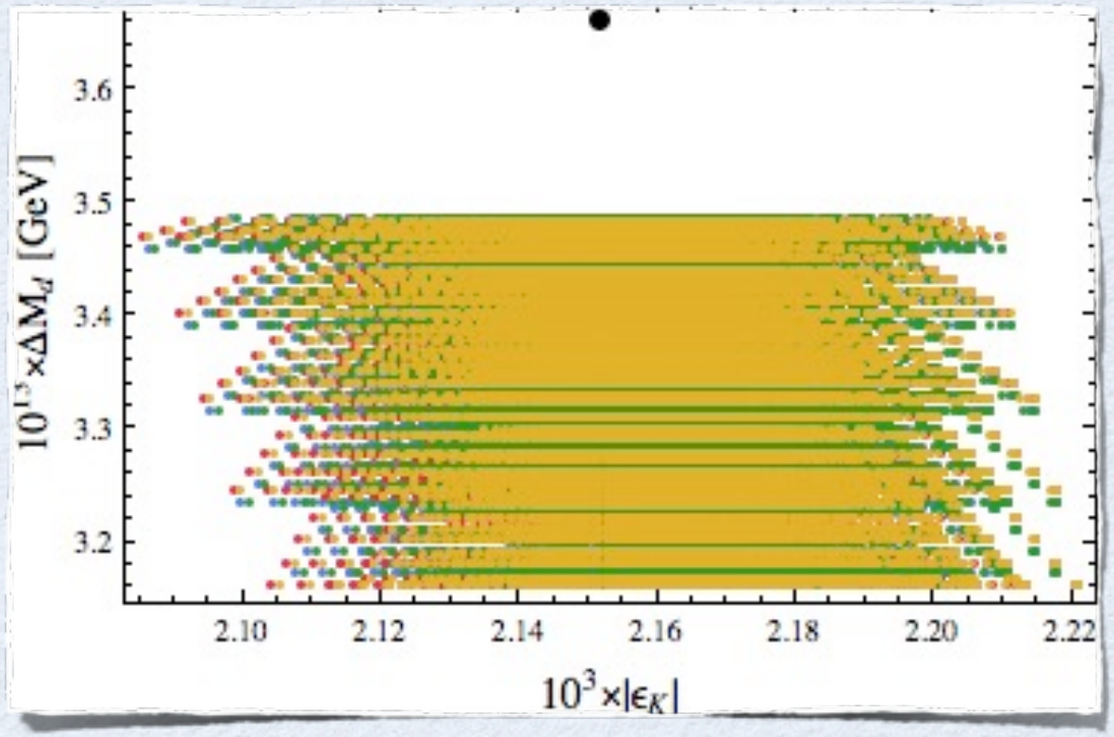


MOVING TO THE K SECTOR: ε_K VS $\Delta M_{d,s}$

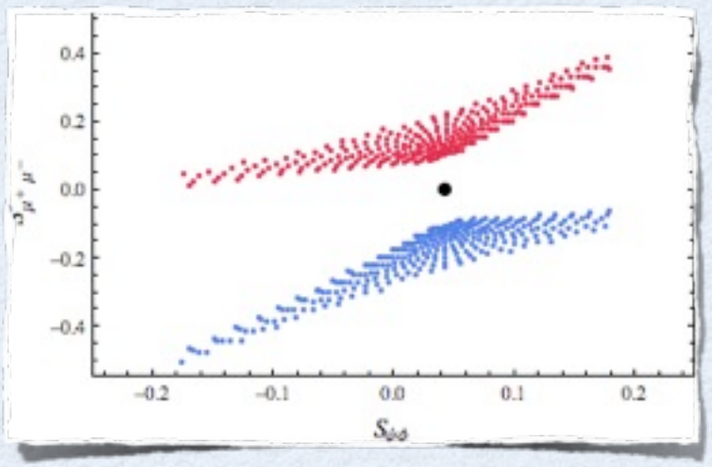
SM
&
Constrained MFV

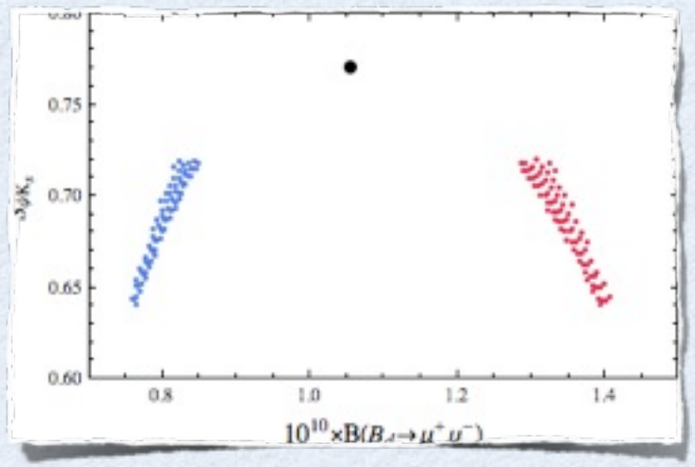


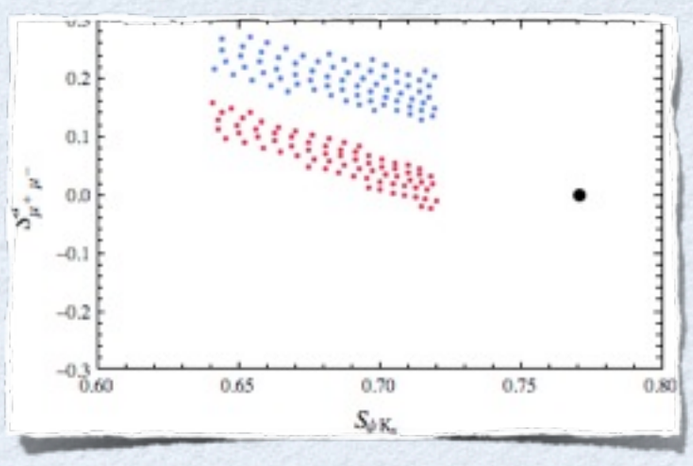


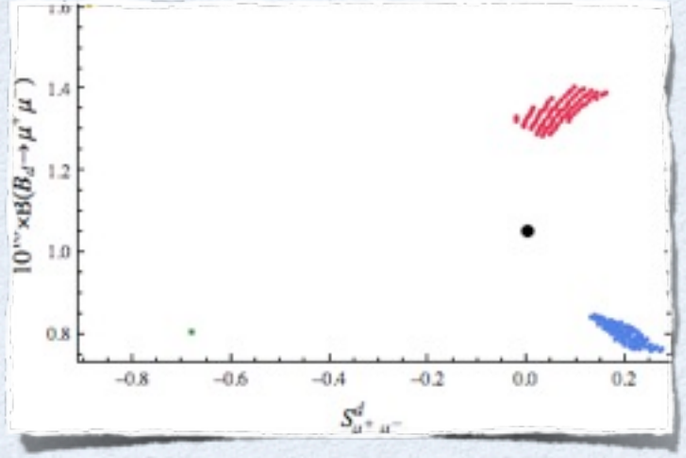


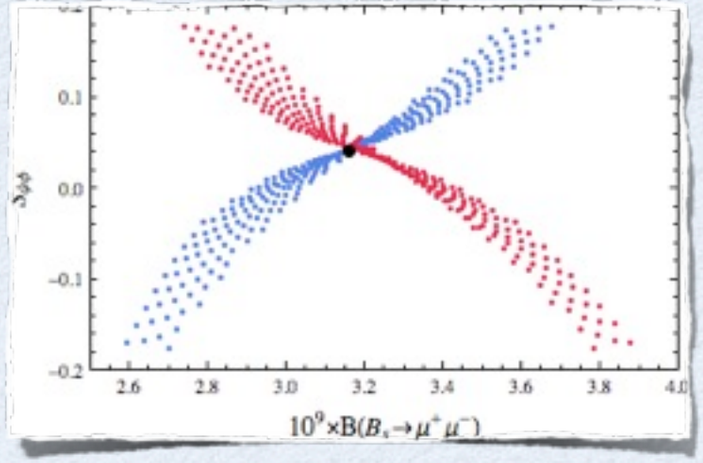
MORE OBSERVABLES AND CORRELATIONS

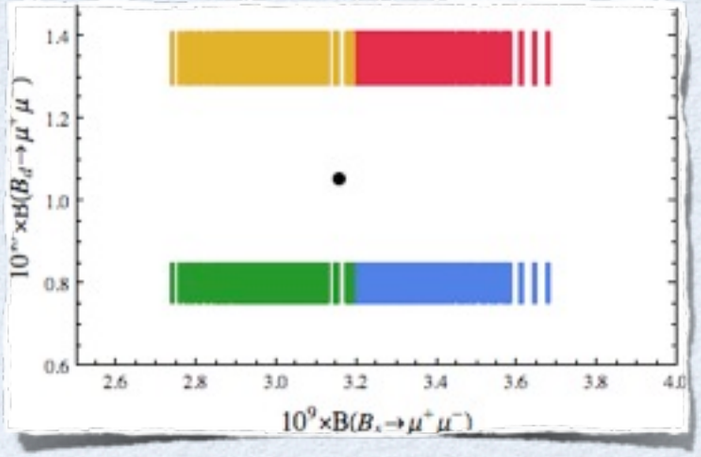


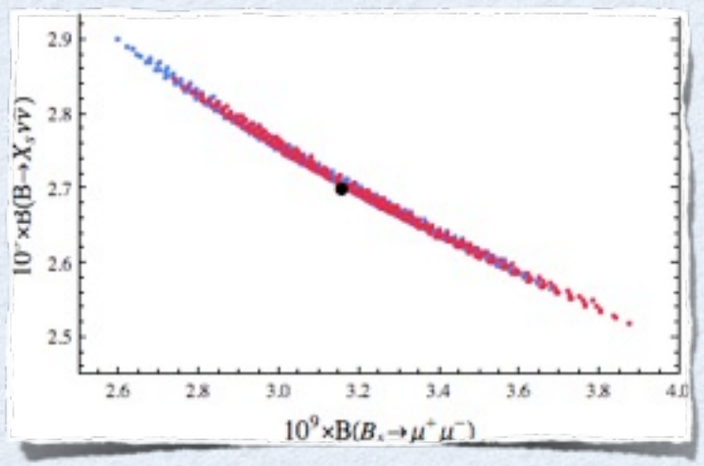


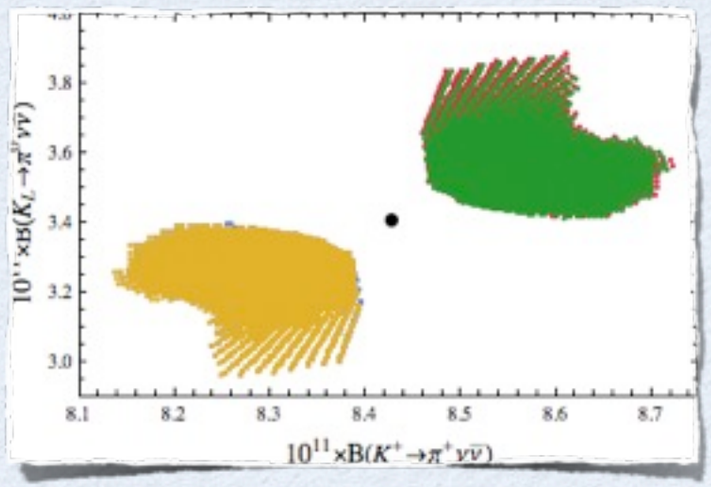


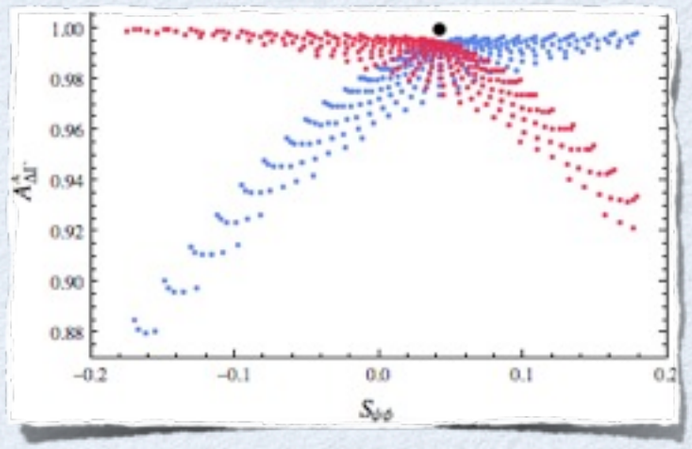












Conclusions

- Last data from LHCb indicates that the SM has passed also to the tests of $S_{\psi\phi}$ and $B_{d,s} \to \mu^+\mu^-$; nevertheless, 1-3σ tensions in flavour observabes continue to seriously afflict the SM.

- The 331 models are worth of study since they explain why there are just 3 generations of fermions. They feature a *Z'* which mediate tree-level FCNCs with few new parameters.

- The parameter space will be strongly constrained in the next future: the model can survive and relax many flavour tensions, or can be ruled out.

Buras, De Fazio, Girrbach and MVC, 1211.1237
MVC, 1210.5421; MVC, 1210.0719; MVC, 1209.5230

Thanks!