B-Meson Anomalies: Effective Field Theory Meets Machine Learning

Universidad Zaragoza 1474

J. Alda Gallo[1,2,3], A. Mir Ramos[3,4], S. Peñaranda Rivas[3,4]

(1) Dipartimento di Fisica ed Astronomia "Galileo Galilei" Università degli Studi di Padova

(2) Istituto Nazionale di Fisica Nucleare (INFN)

(3) Centro de Astropartículas y Física de Altas Energías (CAPA), Universidad de Zaragoza

(4) Departamento de Física Teórica, Facultad de Ciencias, Universidad de Zaragoza

CAPA

Abstract: Discrepancies between experimental measurements and Standard Model predictions in B-meson decays, especially in lepton flavor universality ratios like $R_{D^{(*)}}$, RJ/ψ and branching ratios for processes like $B \to K^+ \nu\nu$, suggest possible new physics (NP). In this study, we use an effective field theory framework, assuming NP effects only affect a single generation in the interaction basis, leading to non-universal mixing when rotating to the mass basis. We perform a global fit to the current experimental data, exploring three scenarios characterized by different mixing patterns and constraints. Our analysis finds that the best fit involves mixing between the second and third quark generations, with no lepton sector mixing and independent coefficients for singlet and triplet four-fermion operators. To accurately capture the non-Gaussian nature of the resulting parameter distributions, we use a machine learning-based Monte Carlo algorithm, enabling the generation of representative samples that reflect the true underlying distributions. This work highlights the valuable role of machine learning in accurately modeling complex parameter distributions in particle physics analyses.

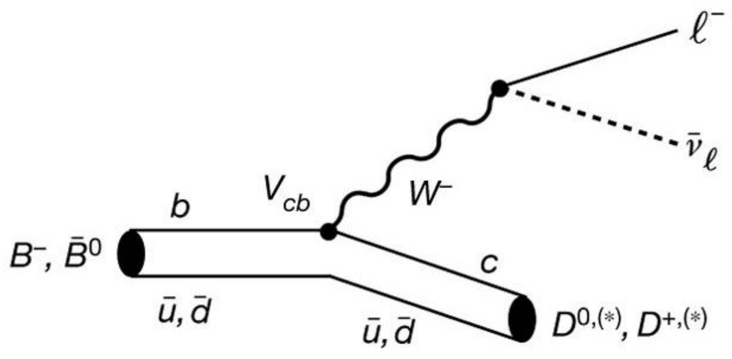
1) Introduction

Precise measurements of **B-meson decays** have revealed tensions with the Standard Model (SM) predictions, particularly in lepton flavor universality (**LFU**) observables

$b \to c\, l\, \nu$:

$$R^{l}_{D^{(*)}} = \frac{BR(B \to D^{(*)}\tau\bar{\nu}_\tau)}{[BR(B \to D^{(*)}\tau\bar{\nu}_\tau) + BR(B \to D^{(*)}\mu\,\bar{\nu}_\mu)]/2}$$

$$R_{J/\psi} = \frac{BR(Bc \to J/\psi\tau\nu_\tau)}{BR(Bc \to J/\psi\mu\nu_\mu)}$$



$b \to s\, l^+\, l^-$:

$$R_{K^{(*)}} = \frac{BR(B \to K^{(*)}\mu^+\mu^-)}{BR(B \to K^{(*)}e^+e^-)}$$

No longer present discrepancies !

	SM	EXP
R_D	0.299 ± 0.004	0.342 ± 0.026
R_{D^*}	0.257 ± 0.005	0.287 ± 0.012
$R_{J/\psi}$	0.258 ± 0.004	0.52 ± 0.20
$BR(B \to K^+ \nu\nu)$	$(0.429 \pm 0.013 \pm 0.004) \times 10^{-5}$	$(2.3 \pm 0.7) \times 10^{-5}$

Effective Field Theory (**EFT**) allows **model-independent** exploration of New Physics (NP)

Higher dimension operators (dimension 6) suppressed by the energy scale.

$$\mathcal{L}_{SMEFT} = \frac{1}{\Lambda^2}\left(C^{ijkl}_{lq(1)} O^{ijkl}_{lq(1)} + C^{ijkl}_{lq(3)} O^{ijkl}_{lq(3)}\right) \qquad O^{ijkl}_{lq(1)} = (\bar{l}_i\gamma_\mu l_j)(\bar{q}_k\gamma^\mu q_l) \qquad O^{ijkl}_{lq(3)} = (\bar{l}_i\gamma_\mu\tau^I l_j)(\bar{q}_k\gamma^\mu\tau^I q_l)$$

2) Methodology

Dimension-6 Lagrangian in the "Warsaw-down" basis:

$$\mathcal{L}_{NP} = \frac{\lambda^l_{ij}\lambda^q_{kl}}{\Lambda^2}\left[C_1(\bar{l}_i\gamma_\mu l_j)(\bar{q}_k\gamma^\mu q_l) + C_3(\bar{l}_i\gamma_\mu\tau^I l_j)(\bar{q}_k\gamma^\mu\tau^I q_l)\right]$$

$$\lambda^{l,q} = \frac{1}{1 + |\alpha^{l,q}|^2 + |\beta^{l,q}|^2}\begin{pmatrix} |\alpha^{l,q}|^2 & \alpha^{l,q}\bar{\beta}^{l,q} & \alpha^{l,q} \\ \bar{\alpha}^{l,q}\beta^{l,q} & |\beta^{l,q}|^2 & \beta^{l,q} \\ \bar{\alpha}^{l,q} & \bar{\beta}^{l,q} & 1 \end{pmatrix}$$

A **global fit** is performed to extract the parameter values that best describe the experimental values of a total of 593 observables, including LFUV ratios. The fit is performed by numerical minimization of the statistic test χ^2 given by:

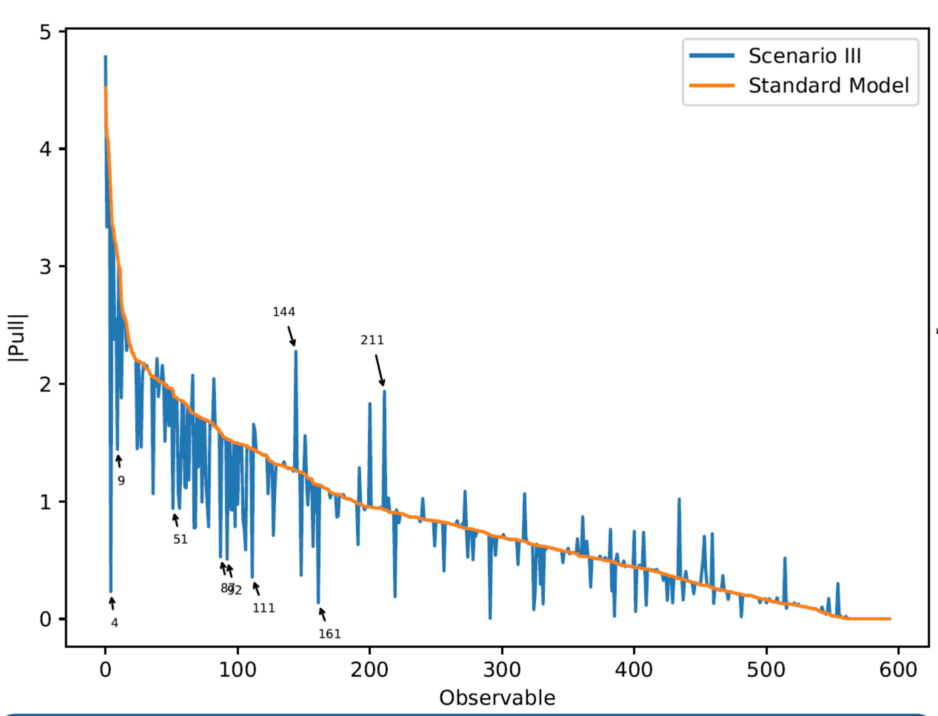
$$\chi^2_{fit} = \frac{1}{2}\sum_{i,j}\left[\mathcal{O}^{exp}_i - \mathcal{O}^{th}_i(\{C\})\right]C^{-1}_{ij}\left[\mathcal{O}^{exp}_j - \mathcal{O}^{th}_j(\{C\})\right]$$

Three scenarios:

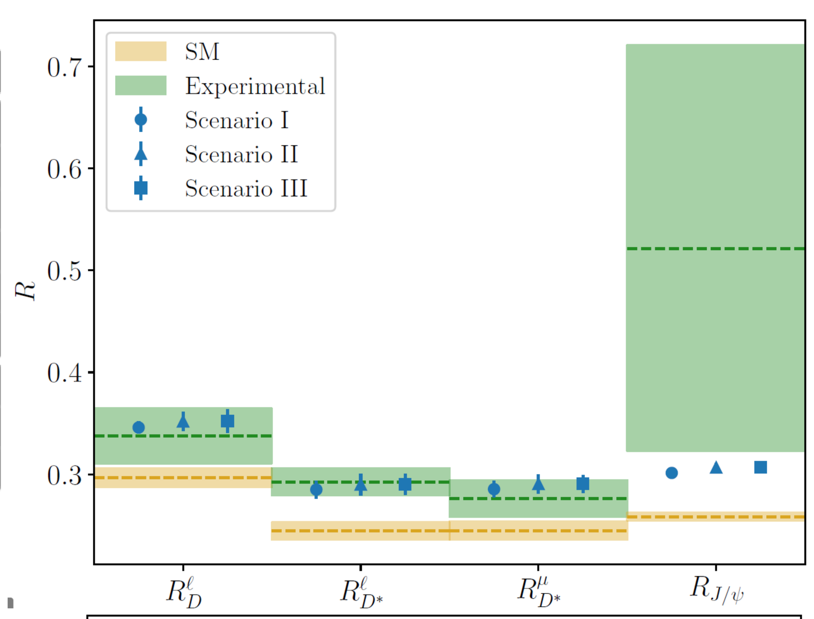
- **Scenario I:** only mixing on second and third generations ($\alpha^l = \alpha^q = 0$) and $C_1 = C_3$
- **Scenario II:** mixing on all generations and $C_1 = C_3$
- **Scenario III:** independent C1 and C3, quark mixing only ($\alpha^l = \beta^l = 0$)

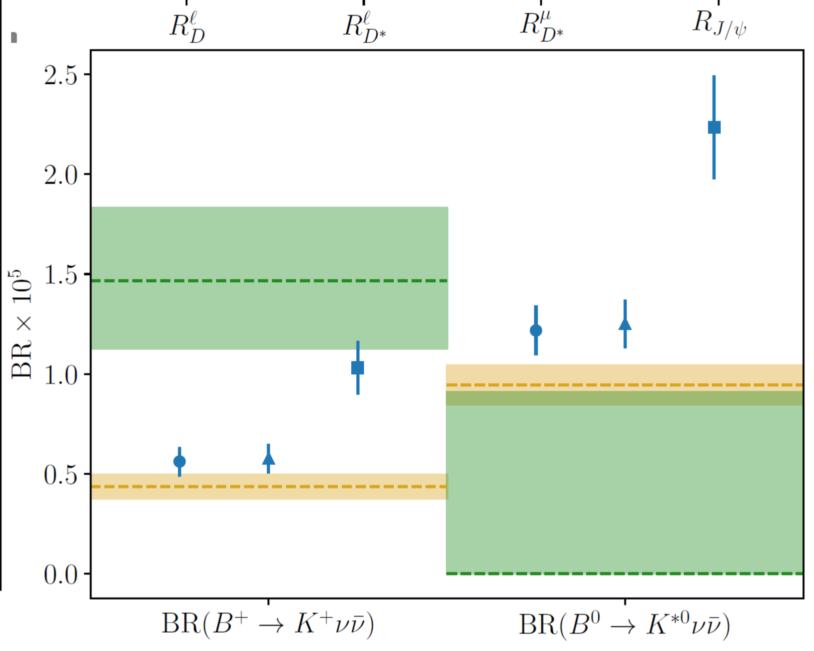
3) Results

	Scenario I	Scenario II	Scenario III
C_1	$-0.11^{+0.03}_{-0.04}$	-0.12 ± 0.03	-0.205 ± 0.015
C_3	$-0.11^{+0.03}_{-0.04}$	-0.12 ± 0.03	$-0.12^{+0.02}_{-0.01}$
α^ℓ	–	0.0 ± 0.07	–
β^ℓ	0.00 ± 0.02	0.000 ± 0.014	–
α^q	–	-0.076	–
β^q	$0.78^{+1.22}_{-0.36}$	$0.85^{+1.05}_{-0.6}$	$0.64^{+1.36}_{-0.24}$
Pull	$5.71\,\sigma$	$5.51\,\sigma$	$6.25\,\sigma$
$\Delta\chi^2_{SM}$	39.8	43.12	46.66
p-value	1.2×10^{-8}	3.5×10^{-8}	4.1×10^{-10}



Pull of the observables considered for the global fit in the SM (orange line) and Scenario III

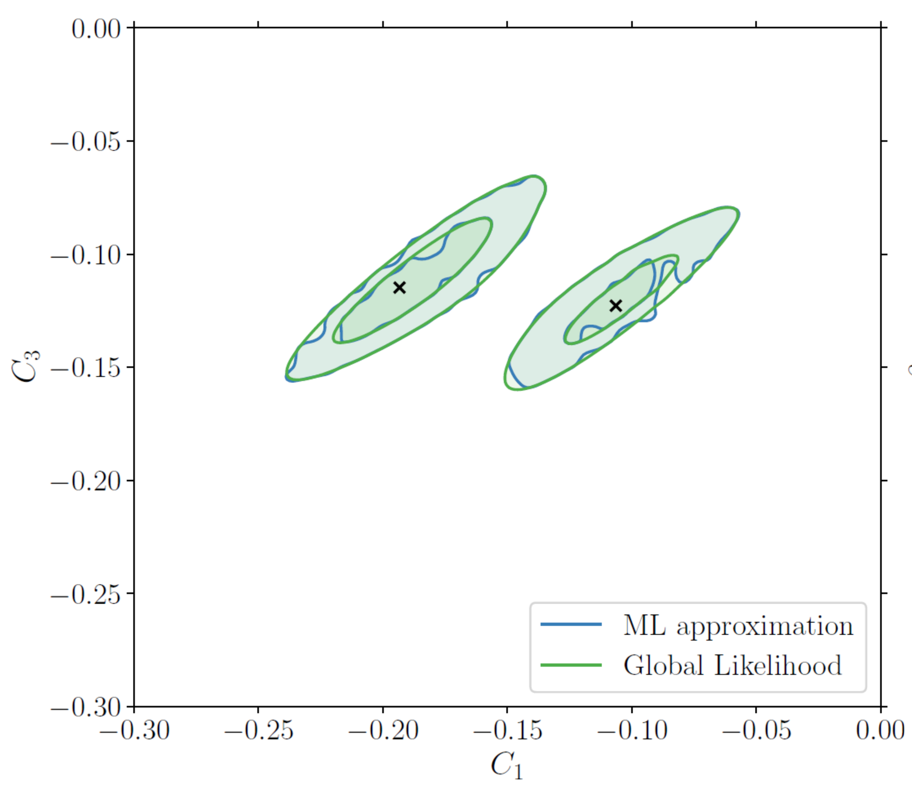


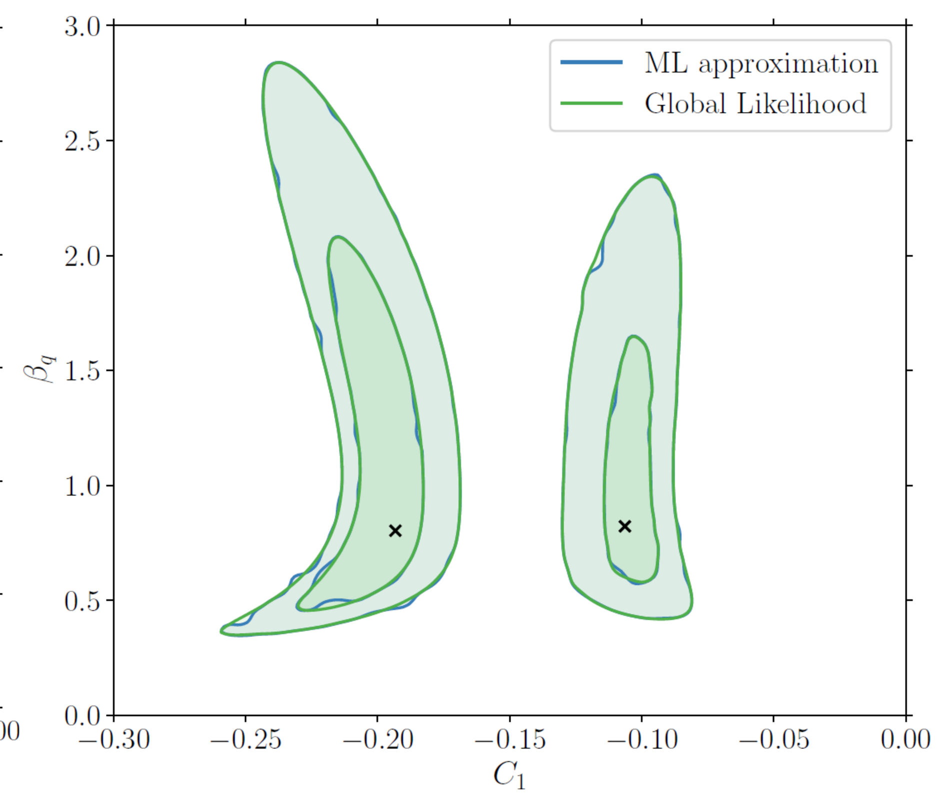


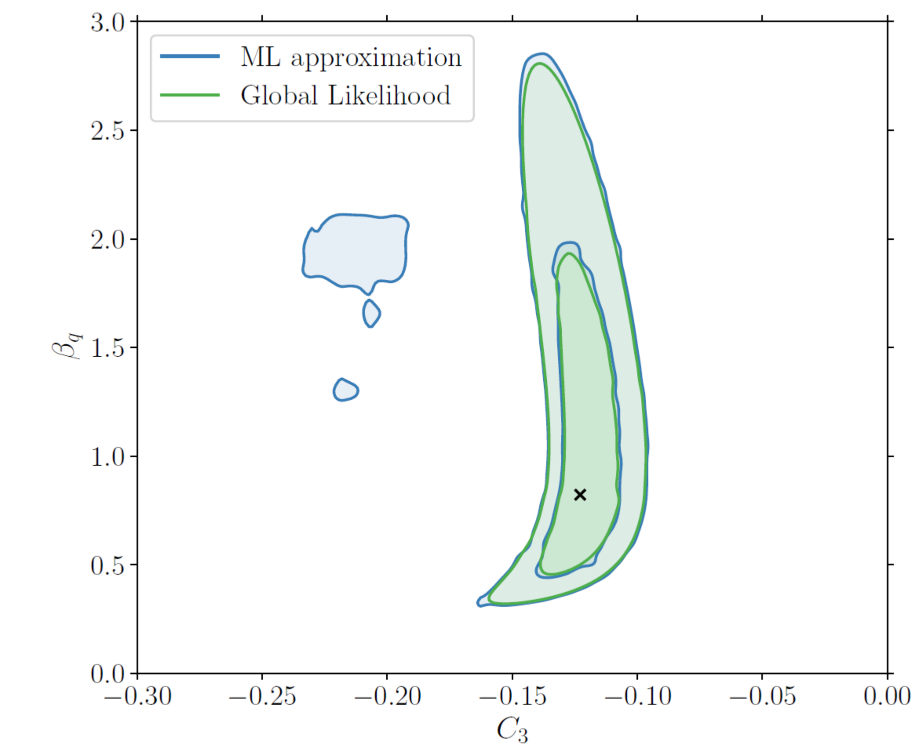
Predictions for selected (a) b → cℓν LFU ratios and (b) b → sνν branching ratios

4) Machine Learning

- We train an **XGBoost regression model** on the log-likelihood landscape, accurately capturing **non-Gaussian parameter distributions** in EFT.
- This ML approach enables efficient sampling, robust confidence intervals, and insights into parameter correlations.



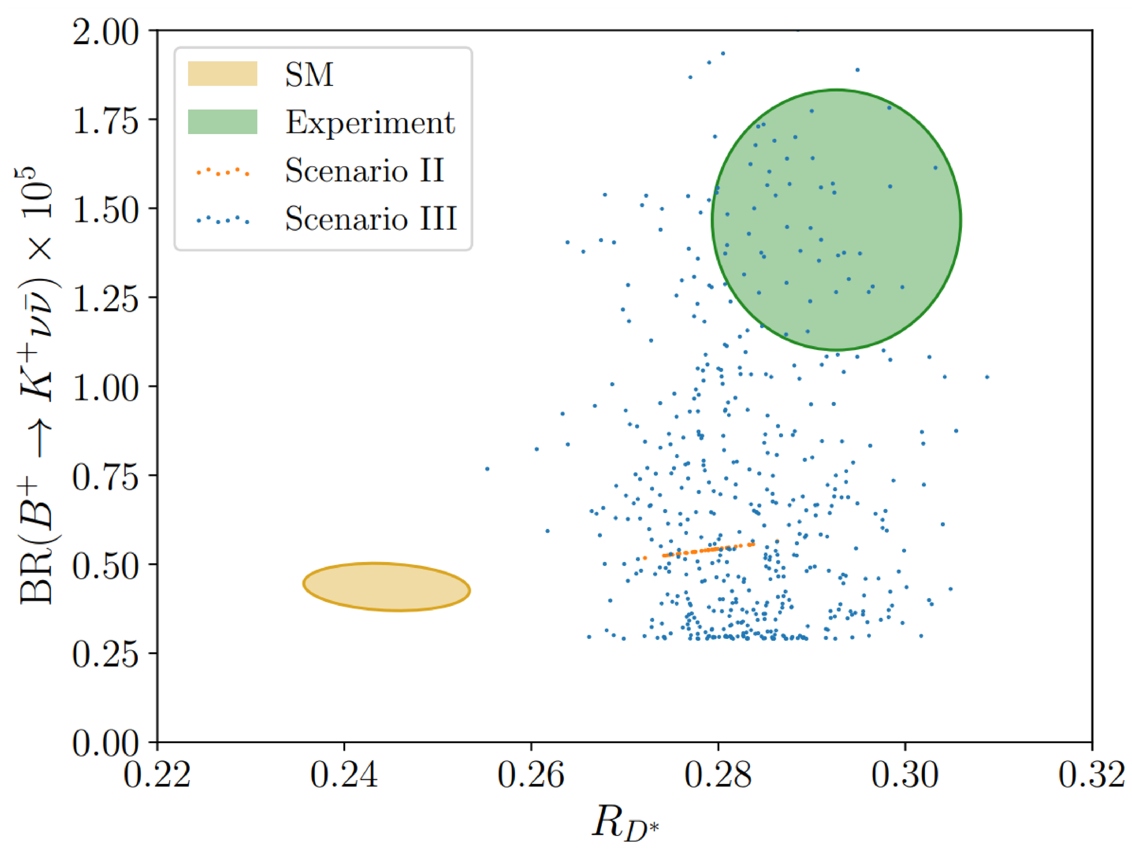




Comparison between the 1 σ and 2 σ likelihood contours obtained using the ML approximation(blue) and the actual contours (green)

Strong agreement between ML-approximated and true likelihood contours

Values of the observables R_{D^*} and $BR(B \to K^+\nu\nu)$ in the ML-generated samples for scenario II (orange points) and scenario III (blue points), compared to the SM prediction (yellow region) and experimental measurement (green region)



The correlation between both observables dissappear !!!

This approach shows the power of **ML techniques in modern particle physics**, especially for global fits involving many observables and scenarios.

5) Conclusions

- **Scenario III** provides the **best global fit** with independent Wilson coefficients C1, C3, and no lepton mixing.
- **ML** techniques enable **realistic modeling of the EFT parameter space**, capturing complex features beyond traditional methods.
- Future measurements of $R_{J/\psi}$ and τ observables such as BR(**B→K$^{(*)}$τ$^+$τ$^-$**) will be critical to further test this NP hypothesis.
- This study showcases the **synergy between EFT and ML** in exploring New Physics in flavor anomalies.

6) Acknowledgements

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