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Result-based reinterpretation of the Belle II $B^+ \to K^+ \nu\bar{\nu}$ analysis

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Motivation

- Particle physics data is very valuable!
- Analyses are a lot of work!
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[arXiv:2109.04981 [hep-ph]]

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- Publishing full statistical models together with the corresponding data enables **combinations, reinterpretations, and the generation of pseudo data**.
- The reinterpretation of such measurements falls into two categories:
  - **No / trivial dependence** on underlying experimental or theoretical quantities: Direct reinterpretation possible.
  - **Strong dependence** on underlying quantities: For a consistent analysis, the full underlying dependence needs to be **parameterized**.

[arXiv:2109.04981 [hep-ph]]

Analysis

Where is the model dependence?

The Belle II $B^+ \to K^+ \nu\bar{\nu}$ analysis

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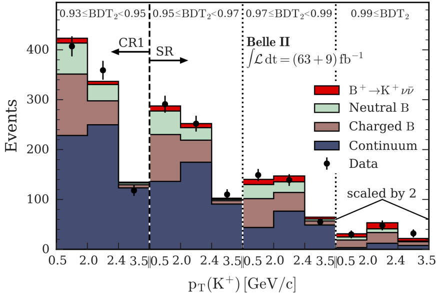
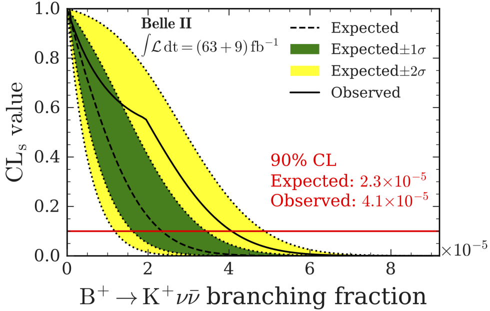
- Signal MC data is SM weighted (**model dependence**)
- Two consecutive BDTs separate signal from background
- Fitting in bins of $p_T(K) \times BDT_2$



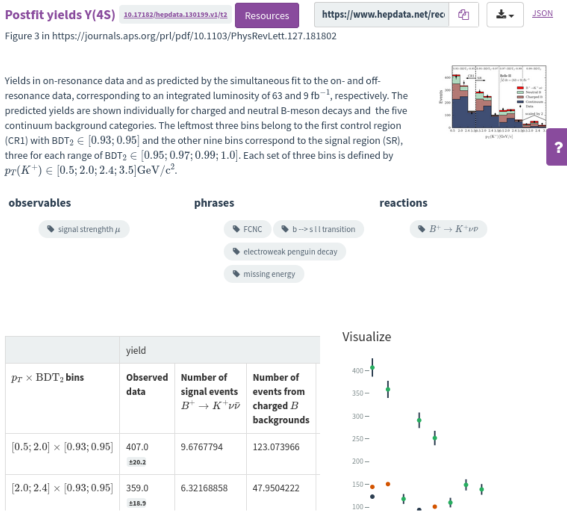


$\mathcal{B}_{B^+ \to K^+ \nu \bar{\nu}} < 4.1 \times 10^{-5} @ 90\% CL$

[Phys.Rev.Lett.127.181802]

HEPData

Unique open-access repository for high-level data from about 9000 **HEP** (`hep-ex` or `nucl-ex`) papers.



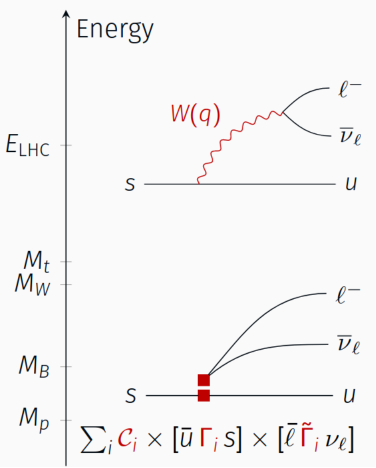
Theory

How can we parametrize our model dependence?

Effective field theory

- The SM treated as valid up to arbitrary energies
- **Effective field theory**: Lower energies $\rightarrow$ expansion in energy cutoff parameter

$$\mathcal{L}_{SM} \rightarrow \mathcal{L}_{EFT} = \sum C_i \mathcal{O}_i$$



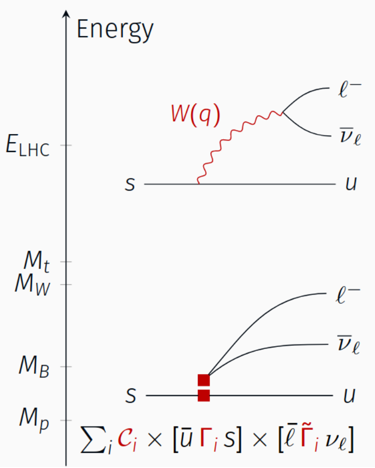
Effective field theory

- The SM treated as valid up to arbitrary energies
- **Effective field theory**: Lower energies $\rightarrow$ expansion in energy cutoff parameter

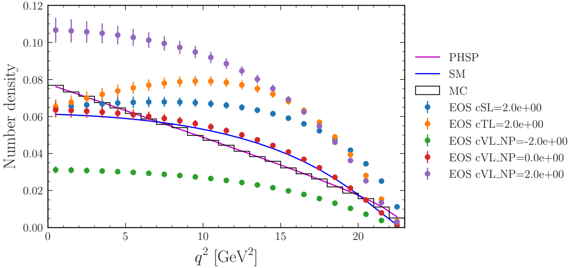
$$\mathcal{L}_{SM} \rightarrow \mathcal{L}_{EFT} = \sum C_i \mathcal{O}_i$$

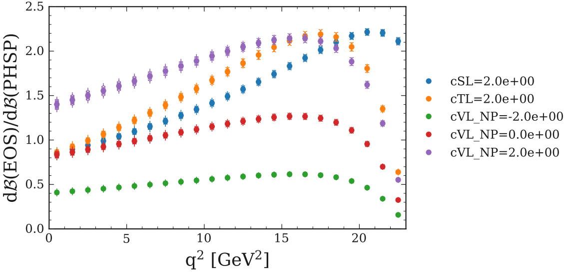
- $\mathcal{O}_i$ are completely model independent.

➜ Model independent **parametrization**, constrained only by Wilson coefficients C_i.



Theoretical models





Our weights are only dependent on the dineutrino invariant mass squared q^2.

Reinterpretation

How do we bring it all together?

Reweighting

Information for reweighting needs to be supplied, in our case q^2.

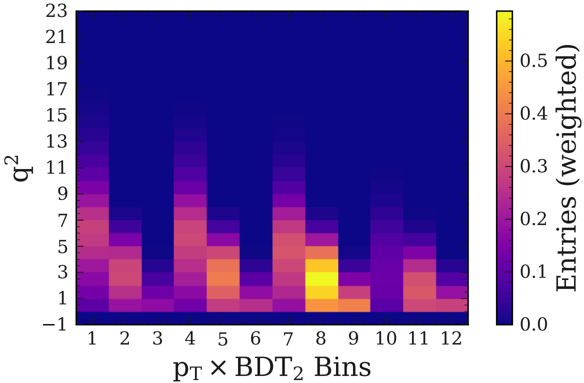
Additional dimension

- 3d binning:

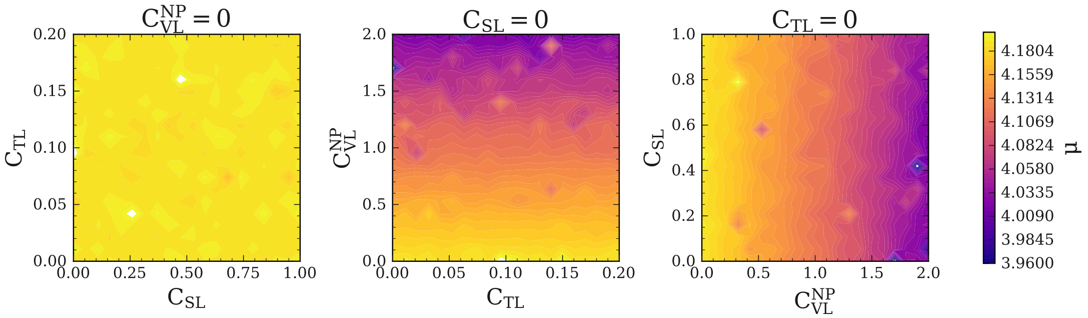
$$\underbrace{p_T \times BDT_2}_{\text{analysis binning}} \times \underbrace{q^2}_{\text{new}}$$

- Apply weights in q^2 bins and resum

+ Good accuracy with sufficient q^2 bins
+ Very versatile
+ Easily publishable



Signal strength scan



WC bounds from [JHEP12(2021)118]

Outlook

- Select theoretical models to study and analyse in detail.
- Identify features to generalize the procedure and make it applicable to other analyses too.
- Any ideas for improvement are welcome!

Thank you!

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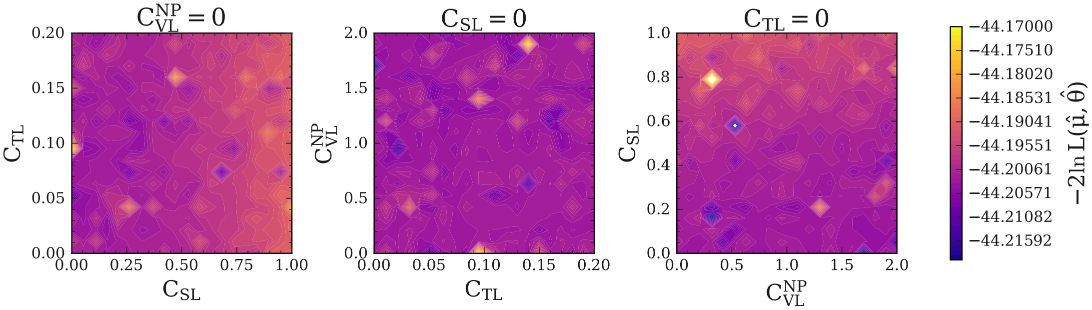
Likelihood scan



Weak Effective Theory for $B \to K\nu\bar{\nu}$

Contribution operators

The effective Lagrangian is [arXiv:2111.04327 [hep-ph]]

$$\mathcal{L} = \sum_{X=L,R} C_{\nu d}^{\mathrm{VLX}} \mathcal{O}_{\nu d}^{\mathrm{VLX}} + \left(\sum_{X=L,R} C_{\nu d}^{\mathrm{SLX}} \mathcal{O}_{\nu d}^{\mathrm{SLX}} + C_{\nu d}^{\mathrm{TLL}} \mathcal{O}_{\nu d}^{\mathrm{TLL}} + \text{ h.c. } \right)$$

The contributing operators in and beyond the SM are given by

$$\mathcal{O}_{\nu d}^{\mathrm{VLL}} = (\overline{\nu_L} \gamma_\mu \nu_L) \left(\overline{d_L} \gamma^\mu d_L \right) \qquad \mathcal{O}_{\nu d}^{\mathrm{VLR}} = (\overline{\nu_L} \gamma_\mu \nu_L) \left(\overline{d_R} \gamma^\mu d_R \right)$$

$$\mathcal{O}_{\nu d}^{\mathrm{SLL}} = \left(\overline{\nu_L^c} \nu_L \right) \left(\overline{d_R} d_L \right) \qquad \mathcal{O}_{\nu d}^{\mathrm{SLR}} = \left(\overline{\nu_L^c} \nu_L \right) \left(\overline{d_L} d_R \right)$$

$$\mathcal{O}_{\nu d}^{\mathrm{TLL}} = \left(\overline{\nu_L^c} \sigma_{\mu\nu} \nu_L \right) \left(\overline{d_R} \sigma^{\mu\nu} d_L \right)$$

Weak Effective Theory for $B \to K\nu\bar{\nu}$

Decay width

Decay width dependence on the Wilson coefficients is given by
`[arXiv:2111.04327 [hep-ph]]`

$$\frac{d\Gamma\left(B \to K\nu\bar{\nu}\right)}{dq^2} = \frac{\sqrt{\lambda_{BK}}q^2}{(4\pi)^3 m_B^3}\left[\frac{\lambda_{BK}}{24q^2}\left|f_+(q^2)\right|^2 \left|C^{\mathrm{VL}} + C^{\mathrm{VR}}\right|^2 + \frac{\left(m_B^2 - m_K^2\right)^2}{8\left(m_b - m_s\right)^2}\left|f_0(q^2)\right|^2 \left|C^{\mathrm{SL}} + C^{\mathrm{SR}}\right|^2 + \frac{2\lambda_{BK}}{3\left(m_B + m_K\right)^2}\left|f_T(q^2)\right|^2 \left|C^{\mathrm{TL}}\right|^2\right]$$

Model selection

Leptoquarks

- Coupling to leptons and quarks at tree level
- Scalar or vector particles
- Further classification according to

$$SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$$

- Contribution

$$C^{\alpha L \beta},\ \alpha \in [V, S, T],\ \beta \in [L, R],$$

depending on the model

[PhysRevD.104.053007]
[Gauge Theory of Weak Decays, A. Buras]

Heavy/Light Z'

- Additional neutral vector boson
- Mass constraint:

$$M_{Z'} > 1.5 TeV$$

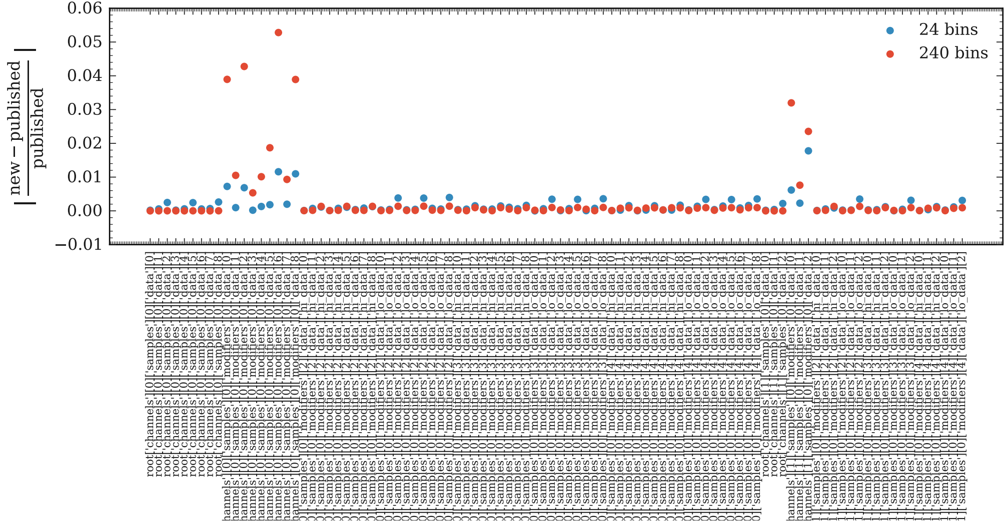
[J. High Energy Phys. 08(2019)106]

- Possible $Z - Z'$ mixing
- Contribution:

$$C^{VL\beta},\ \beta \in [L, R],$$

depending on the model

Accuracy of binned weighting



pyhf

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$$f(\boldsymbol{x} \mid \phi) = f(\boldsymbol{x} \mid \overbrace{\boldsymbol{\eta}}^{\text{free}}, \underbrace{\boldsymbol{\chi}}_{\text{constrained}}) = f(\boldsymbol{x} \mid \overbrace{\boldsymbol{\psi}}^{\text{parameters of interest}}, \underbrace{\boldsymbol{\theta}}_{\text{nuisance parameters}})$$

-

$$f(\boldsymbol{n}, \boldsymbol{a} \mid \boldsymbol{\eta}, \chi) = \underbrace{\prod_{c \in \text{ channels}} \prod_{b \in \text{ bins}} \text{Pois}\left(n_{cb} \mid \nu_{cb}(\boldsymbol{\eta}, \boldsymbol{\chi})\right)}_{\substack{\text{Simultaneous measurement} \\ \text{of multiple channels}}} \quad \underbrace{\prod_{\chi \in \chi} c_{\chi}\left(a_{\chi} \mid \chi\right)}_{\substack{\text{constraint terms} \\ \text{for "auxiliary measurements"}}}$$

-

$$\nu_{cb}(\boldsymbol{\phi}) = \sum_{s \in \text{ samples}} \nu_{scb}(\boldsymbol{\eta}, \boldsymbol{\chi}) = \sum_{s \in \text{ samples}} \underbrace{\left(\prod_{\kappa \in \kappa} \kappa_{scb}(\boldsymbol{\eta}, \boldsymbol{\chi})\right)}_{\text{multiplicative modifiers}} (\nu^{0}_{scb}(\boldsymbol{\eta}, \boldsymbol{\chi}) + \underbrace{\sum_{\Delta \in \Delta} \Delta_{scb}(\boldsymbol{\eta}, \boldsymbol{\chi})}_{\text{additive modifiers}}).$$

Modifiers and constraints

Description	Modification	Constraint Term c_χ	Input
Uncorrelated Shape	$\kappa_{scb}(\gamma_b) = \gamma_b$	$\prod_b \mathrm{Pois}\left(r_b = \sigma_b^{-2} \middle| \rho_b = \sigma_b^{-2}\gamma_b\right)$	σ_b
Correlated Shape	$\Delta_{scb}(\alpha) = f_p\left(\alpha \middle| \Delta_{scb,\alpha=-1}, \Delta_{scb,\alpha=1}\right)$	$\mathrm{Gaus}\left(a = 0 \middle| \alpha, \sigma = 1\right)$	$\Delta_{scb,\alpha=\pm1}$
Normalisation Unc.	$\kappa_{scb}(\alpha) = g_p\left(\alpha \middle| \kappa_{scb,\alpha=-1}, \kappa_{scb,\alpha=1}\right)$	$\mathrm{Gaus}\left(a = 0 \middle| \alpha, \sigma = 1\right)$	$\kappa_{scb,\alpha=\pm1}$
MC Stat. Uncertainty	$\kappa_{scb}(\gamma_b) = \gamma_b$	$\prod_b \mathrm{Gaus}\left(a_{\gamma_b} = 1 \middle| \gamma_b, \delta_b\right)$	$\delta_b^2 = \sum_s \delta_{sb}^2$
Luminosity	$\kappa_{scb}(\lambda) = \lambda$	$\mathrm{Gaus}\left(l = \lambda_0 \middle| \lambda, \sigma_\lambda\right)$	$\lambda_0, \sigma_\lambda$
Normalisation	$\kappa_{scb}(\mu_b) = \mu_b$		
Data-driven Shape	$\kappa_{scb}(\gamma_b) = \gamma_b$		

Fitting

Channel	Definition	Samples	Errors
Signal Region	$\mathrm{2D}:$ Kaon $p_T \in [0.5, 2.0, 2.4, 3.5]\mathrm{x}$ $\mathrm{BDT}_2 \in [0.95, 0.97, 0.99, 1.0]$	signal $+$ all bkgs	statistical $+$ systematics
Control Region 1	$\mathrm{2D}:$ Kaon $p_T \in [0.5, 2.0, 2.4, 3.5]$ $\mathrm{BDT}_2 \in [0.93, 0.95]$	signal $+$ all bkgs	statistical systematics
Control Region 2	$\mathrm{2D}:$ Kaon $p_T \in [0.5, 2.0, 2.4, 3.5]$ BDT $_2 \in [0.95, 0.97, 0.99, 1.0]$	off-resonance (continuum bkgs)	statistical $+$ systematics
Control Region 3	2D: Kaon $p_T \in [0.5, 2.0, 2.4, 3.5]$ $\mathrm{BDT}_2 \in [0.93, 0.95]$	off-resonance (continuum bkgs)	statistical + systematics