

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

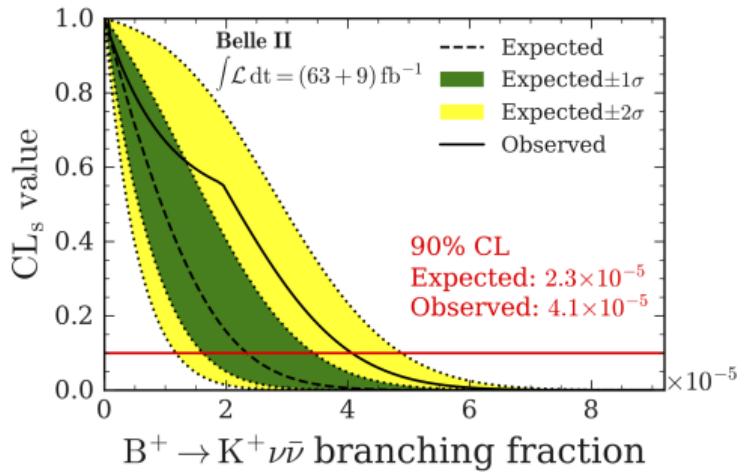
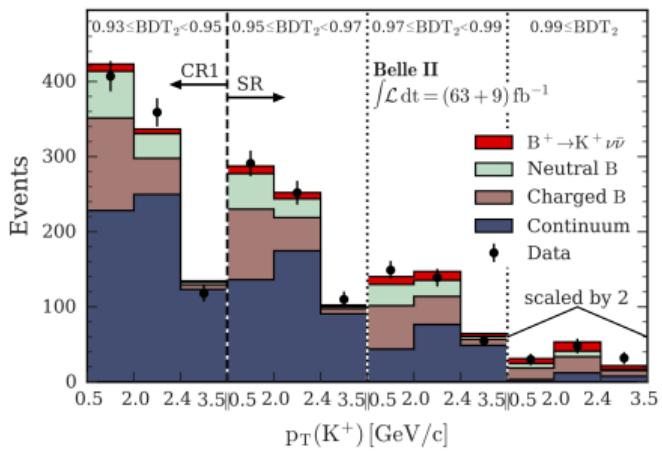
$B^+ \rightarrow K^+ \nu \bar{\nu}$ is suppressed, making it very new physics sensitive.



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



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

[Phys. Rev. Lett. 127. 181802]

HEPData



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



Postfit yields Y(4S)

[10.17182/hepdata.130159.v1/t2](https://doi.org/10.17182/hepdata.130159.v1/t2)

Resources

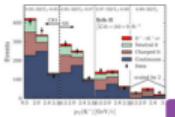
<https://www.hepdata.net/rec>



JSON

Figure 3 in <https://journals.aps.org/prl/pdf/10.1103/PhysRevLett.127.181802>

Yields in on-resonance data and as predicted by the simultaneous fit to the on- and off-resonance data, corresponding to an integrated luminosity of 63 and 9 fb^{-1} , respectively. The predicted yields are shown individually for charged and neutral B-meson decays and the five continuum background categories. The leftmost three bins belong to the first control region (CR1) with $\text{BDT}_2 \in [0.93; 0.95]$ and the other nine bins correspond to the signal region (SR), three for each range of $\text{BDT}_2 \in [0.95; 0.97; 0.99; 1.0]$. Each set of three bins is defined by $p_T(K^+) \in [0.5; 2.0; 2.4; 3.5] \text{ GeV}/c^2$.



observables

signal strength μ

phrases

FNC

$b \rightarrow s \ell \ell$ transition

$B^+ \rightarrow K^+ \nu \bar{\nu}$

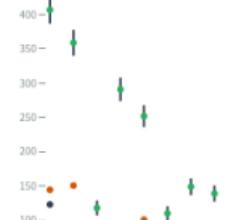
electroweak penguin decay

missing energy

reactions

$p_T \times \text{BDT}_2$ bins	yield		
	Observed data	Number of signal events $B^+ \rightarrow K^+ \nu \bar{\nu}$	Number of events from charged B backgrounds
[0.5; 2.0] \times [0.93; 0.95]	407.0 ±26.2	9.6767794	123.073966
[2.0; 2.4] \times [0.93; 0.95]	359.0 ±18.9	6.32168858	47.9504222

Visualize



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Theory

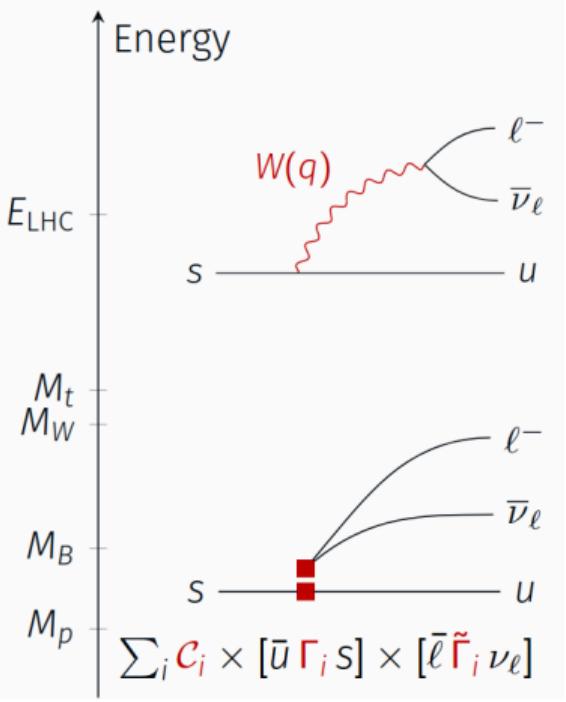
How can we parametrize our model dependence?



Effective field theory

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

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



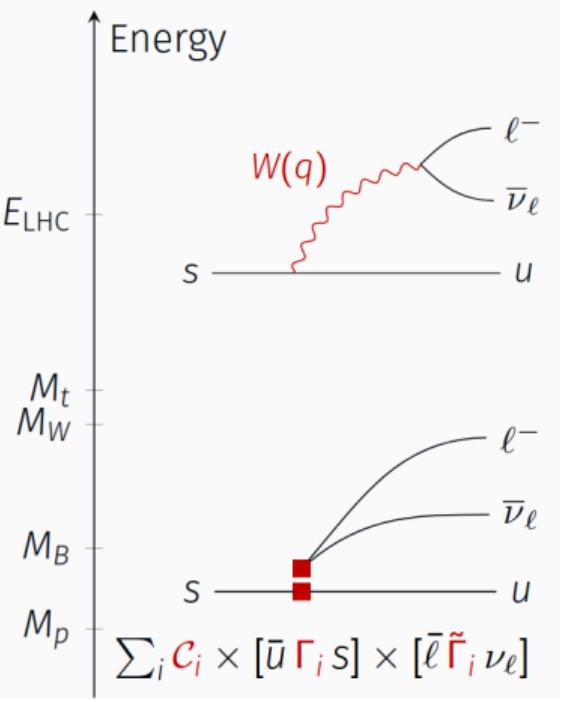


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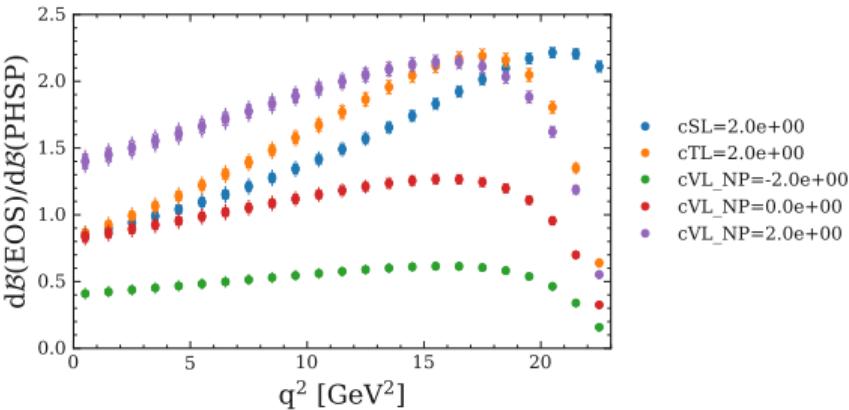
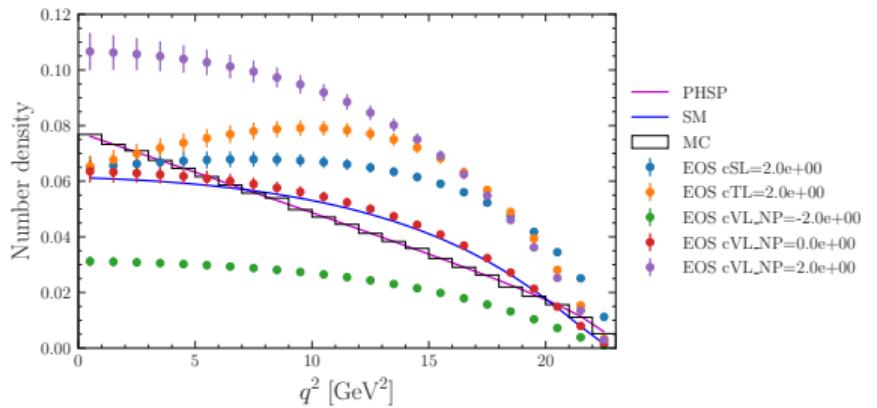
$$\mathcal{L}_{SM} \rightarrow \mathcal{L}_{EFT} = \sum C_i \mathcal{O}_i$$

- \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

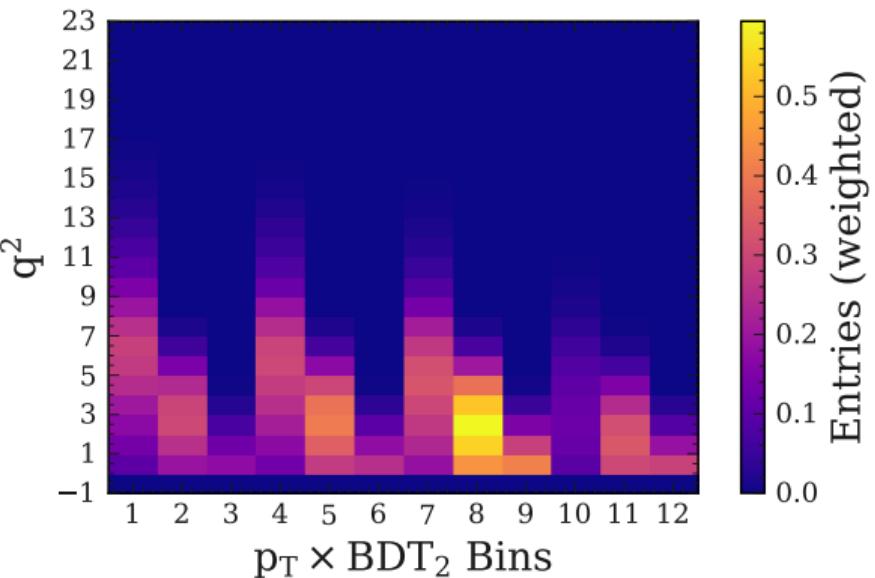
Information for reweighting needs to be supplied, in our case q^2 .

Additional dimension

- 3d binning:

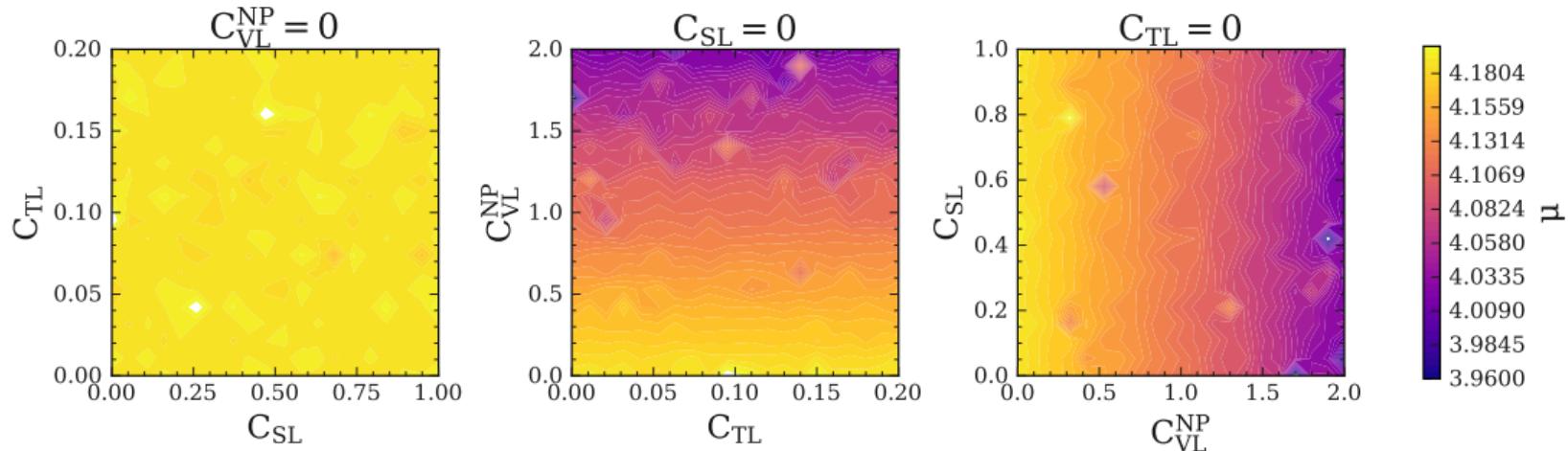
$$\underbrace{p_T \times BDT_2}_{\text{analysis binning}} \times \underbrace{q^2}_{\text{new}}$$

- 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

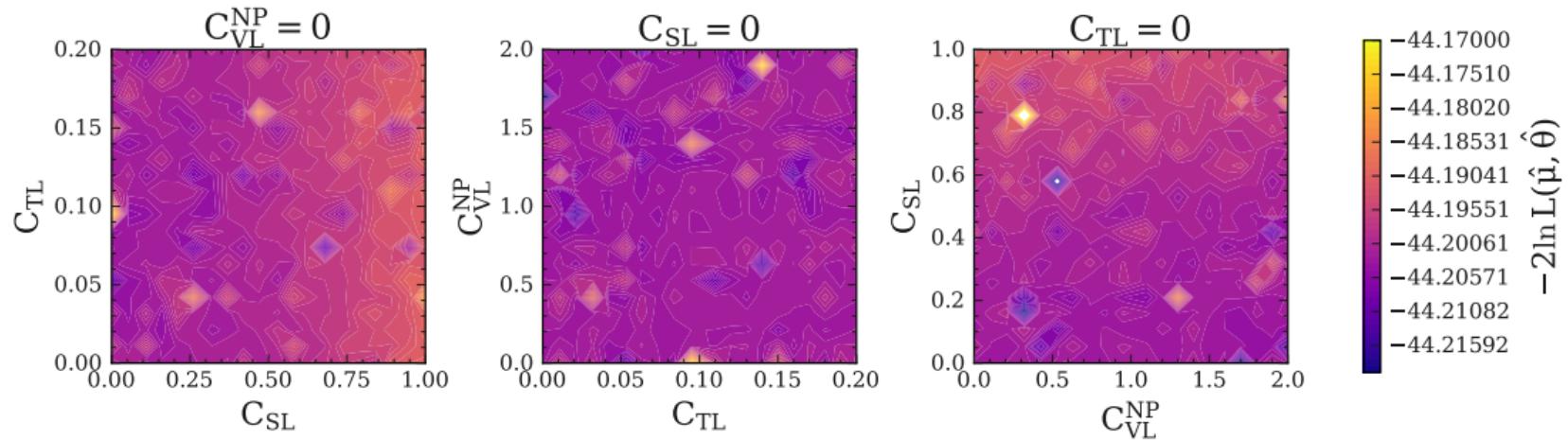
- Select theoretical models to study and analyse in detail.
 - Identify features to generalize the procedure and make it applicable to other analyses too.
 - Any ideas for improvement are welcome!
-

Thank you!

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Likelihood scan





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

Contribution operators

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

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

The contributing operators in and beyond the SM are given by

$$\begin{aligned} \mathcal{O}_{\nu d}^{\text{VLL}} &= (\bar{\nu}_L \gamma_\mu \nu_L) (\bar{d}_L \gamma^\mu d_L) & \mathcal{O}_{\nu d}^{\text{VLR}} &= (\bar{\nu}_L \gamma_\mu \nu_L) (\bar{d}_R \gamma^\mu d_R) \\ \mathcal{O}_{\nu d}^{\text{SLL}} &= (\bar{\nu}_L^c \nu_L) (\bar{d}_R d_L) & \mathcal{O}_{\nu d}^{\text{SLR}} &= (\bar{\nu}_L^c \nu_L) (\bar{d}_L d_R) \\ \mathcal{O}_{\nu d}^{\text{TLL}} &= (\bar{\nu}_L^c \sigma_{\mu\nu} \nu_L) (\bar{d}_R \sigma^{\mu\nu} d_L) \end{aligned}$$



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

Decay width

Decay width dependence on the Wilson coefficients is given by

[arXiv:2111.04327 [hep-ph]]

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



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:

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

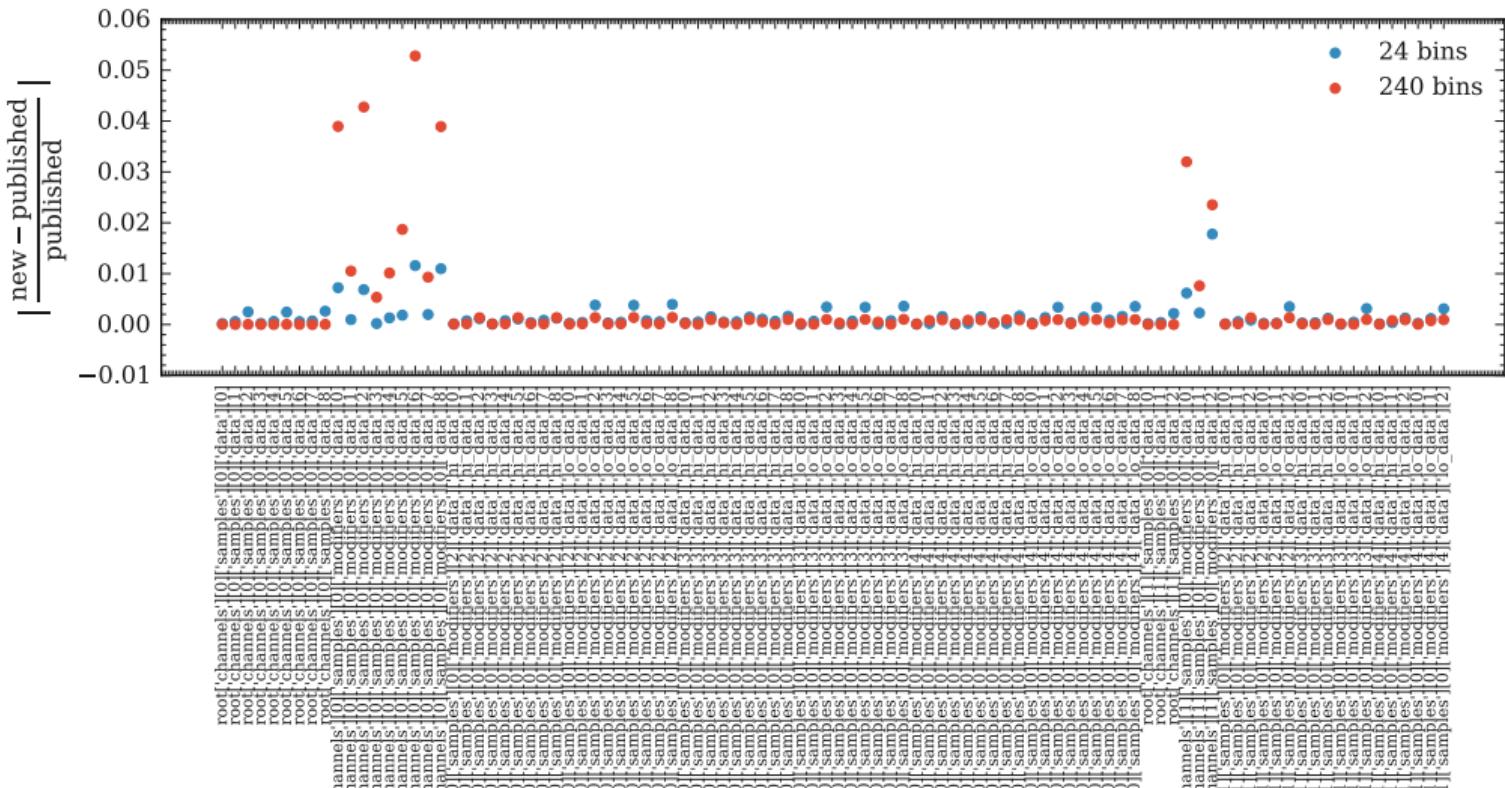
[J. High Energy Phys. 08(2019)106]

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

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

depending on the model

Accuracy of binned weighting





pyhf

- $f(\mathbf{x} | \phi) = f(\mathbf{x} | \overbrace{\eta}^{\text{free}}, \underbrace{\chi}_{\text{constrained}}) = f(\mathbf{x} | \overbrace{\psi}^{\text{parameters of interest}}, \underbrace{\theta}_{\text{nuisance parameters}})$
- $$f(\mathbf{n}, \mathbf{a} | \boldsymbol{\eta}, \chi) = \underbrace{\prod_{c \in \text{channels}} \prod_{b \in \text{bins}} \text{Pois}(n_{cb} | \nu_{cb}(\boldsymbol{\eta}, \chi))}_{\text{Simultaneous measurement of multiple channels}} \underbrace{\prod_{x \in \chi} c_x(a_x | \chi)}_{\text{constraint terms for "auxiliary measurements"}}$$
- $$\nu_{cb}(\phi) = \sum_{s \in \text{samples}} \nu_{scb}(\boldsymbol{\eta}, \chi) = \sum_{s \in \text{samples}} \underbrace{\left(\prod_{\kappa \in \kappa} \kappa_{scb}(\boldsymbol{\eta}, \chi) \right)}_{\text{multiplicative modifiers}} (\nu_{scb}^0(\boldsymbol{\eta}, \chi) + \underbrace{\sum_{\Delta \in \Delta} \Delta_{scb}(\boldsymbol{\eta}, \chi)}_{\text{additive modifiers}}).$$

Modifiers and constraints



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



Fitting

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