# Searching for New Physics through the decay $B^0 \rightarrow K^{*0}\mu^+\mu^-$ at LHCb

## IoP HEPP & APP Annual Conference 2022

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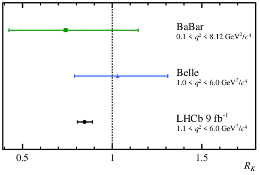
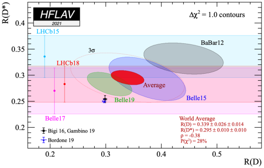
# Flavour anomalies

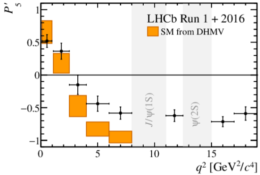
- In recent years experiments have measured quantities with discrepancies with respect to the Standard Model (SM).
- These include ratios of branching fractions (e.g. $R_K \equiv \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+e^+e^-)}$), angular coefficients, and branching fractions.



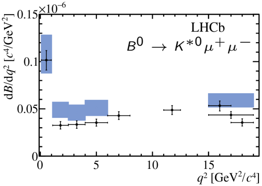

[Nat. Phys. 18, 277–282 (2022)]



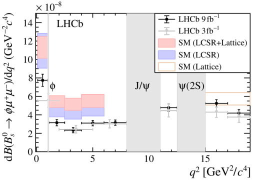

[HFLAV]



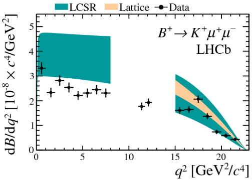

[PRL 125.011802 (2020)]




[JHEP 04 (2017) 142]




[PRL 127.151801 (2021)]



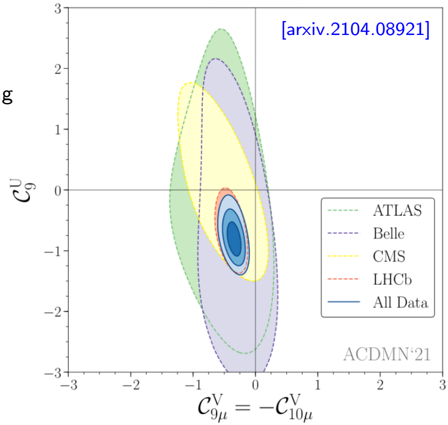

[JHEP 06 (2014) 133]

# Flavour anomalies

- **These anomalies point to potential contributions from New Physics.**
- Parameterise the weak effective Hamiltonian with Wilson Coefficients $C_i$, which describe couplings.
- Global fits e.g. [arxiv.2104.08921] claim the tension to be $> 5\sigma$.

$C_7$ = electromagnetic coupling
$C_9$ = vector coupling
$C_{10}$ = axial-vector coupling

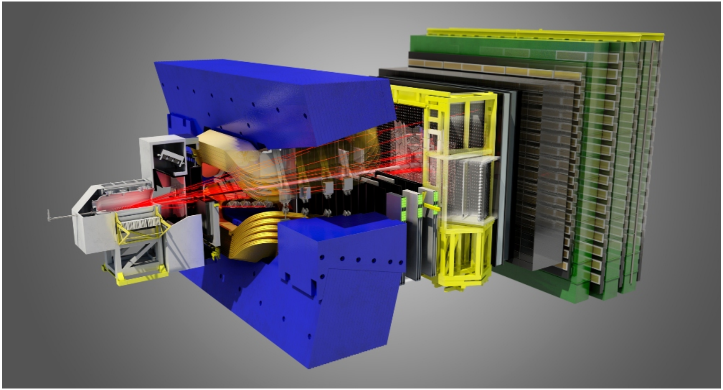
The superscripts $^V$ and $^U$ denote lepton-flavour violating and universal couplings respectively.



# The LHCb experiment

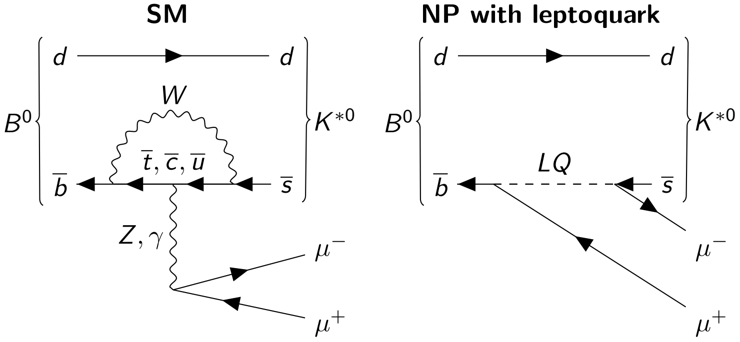
- LHCb (Large Hadron Collider beauty) is designed to measure decays and take precision measurements involving beauty and charm hadrons.

[Int. J. Mod. Phys. A 30, 1530022 (2015)]



# Why $B^0 \to K^{*0}\mu^+\mu^-$?

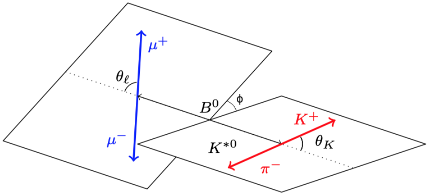
- The decay $B^0 \to K^{*0}\mu^+\mu^-$ requires a $b \to s$ Flavour Changing Neutral Current, thus it is suppressed in the SM.
- Due to the SM suppression and the coupling to 3rd generation, this decay is highly sensitive to **New Physics** (NP).
- These processes are sensitive to contributions towards $\mathcal{O}(10)$TeV, which is inaccessible by current LHC direct searches.




- Latest published binned analysis of $B^0 \to K^{*0}\mu^+\mu^-$ shows discrepancies with respect to the SM [PRL 125.011802 (2020)].

# Angular analysis

- The decay rate of $B^0 \to K^{*0}\mu^+\mu^-$ is completely described by the three angles $\theta_l$, $\theta_K$ and $\phi$ and the invariant mass of the dimuon system squared, $q^2 = m^2_{\mu^+\mu^-}$.




- Differential decay rate is given by [JHEP 01 (2009) 019]

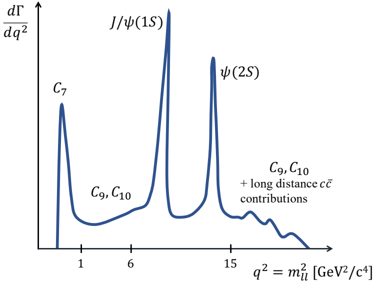
$$\frac{\mathrm{d}^4\Gamma[B^0\to K^{*0}\mu^+\mu^-]}{\mathrm{d}\cos\theta_l\,\mathrm{d}\cos\theta_K\,\mathrm{d}\phi\,\mathrm{d}q^2} = \frac{9}{32\pi}\sum_i J_i(q^2) f_i(\Omega)\varepsilon(\Omega, q^2),$$

where

- $J_i$ are $q^2$-dependent angular coefficients. These are written in terms of bilinear combinations of the complex decay amplitudes.
- $f_i$ are combinations of spherical harmonics involving $\theta_l$, $\theta_K$ and $\phi$.
- $\varepsilon$ is the acceptance function.

# $q^2$ spectrum of $b \to s\ell\ell$

- Figure below shows $\frac{\mathrm{d}\Gamma}{\mathrm{d}q^2}$ of $b \to s\ell\ell$ processes.
- $b \to s\ell\ell$ decays are sensitive to $C_7$, $C_9$, and $C_{10}$, which describe electromagnetic, vector, and axial-vector couplings respectively.




- There are disagreements between theorists with regards to the interplay between the $c\bar{c}$ resonances and the non-resonant parts.
- Since $B \to V\ell\ell$ is measured and not $b \to s\ell\ell$, predictions also suffer from hadronic uncertainties.

# Amplitude ansatz

- Only the angular coefficients have been measured before. For this analysis, we will measure the **amplitudes**.
  - The amplitudes give a complete description of $B^0 \to K^{*0}\mu^+\mu^-$.
  - Write the amplitudes as $\mathcal{A}_P^\chi$ where $\chi$ is the chirality of the dimuon system $(L, R)$, and $P$ is the polarisation of $K^{*0}$ ($\|$, $\perp$, 0, S).
- Go **unbinned** in $q^2$ in order to increase sensitivity to New Physics by exploiting the information in the $q^2$ shape of the amplitudes and the angular coefficients.
- There are many disagreements between theorists in terms of how to parameterise the Standard Model and New Physics models.
  - Consider a parameterisation of the amplitudes which is not so model dependent.
- **Solution: Use an amplitude ansatz.**
- Method is proposed by U. Egede, M. Patel, K. Petridis in JHEP 06 (2015) 084.

# Amplitude ansatz

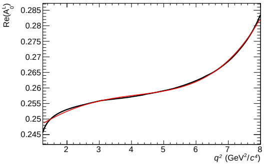
- Apply the ansatz

$$\mathcal{A} = \Sigma_i \alpha_i L_i(q^2)$$

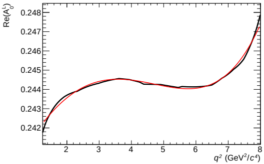
  to the amplitudes, where $L_i$ are Legendre polynomials of order $i$.

- Determine the amplitude coefficients using an unbinned extended maximum likelihood fit.

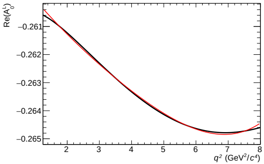
- Shown below are **theoretical predictions** obtained via EOS and fits to these predictions with **5-parameter Legendre ansatzes** for $Re(\mathcal{A}_0^L)$.




**SM**, $J/\psi$ and $\phi$ phases $= 0$



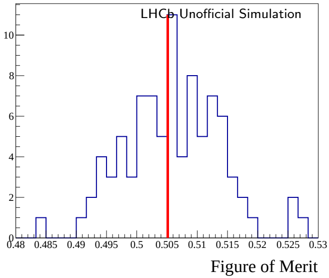

**SM**, phases $= \frac{\pi}{2}$



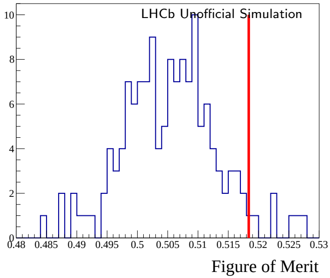

**NP** with $\Delta C_9 = -1$

# How to choose the correct ansatz?

- Example with a pseudoexperiment generated from a SM model.
  - Blue: expected distribution from statistical fluctuations.
  - Red: comparison of pseudoexperiment/fit.




Fit with 5-parameter ansatz
p-value = 55%



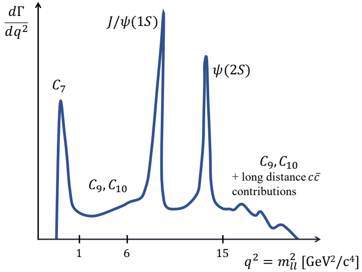

Fit with 4-parameter ansatz
p-value = 4%

- Preparing for performing the goodness-of-fit test to blinded data.

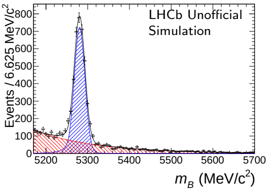
# Fit details

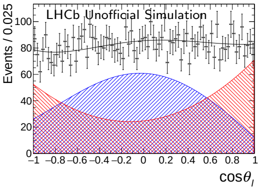
- The $q^2$ regions of interest are
  - $1.25 < q^2 < 8$ GeV$^2$/c$^4$, where the $B^0$ and $\overline{B^0}$ amplitudes are fitted separately.
  - $11 < q^2 < 12.5$ GeV$^2$/c$^4$ (region between the $J/\psi$ and the $\psi(2S)$). This region offers crucial input to the resonance contributions. Here we fit the $B^0$ and $\overline{B^0}$ amplitudes combined.
  - $9.223 < q^2 < 9.966$ GeV$^2$/c$^4$, where the $J/\psi$ is located (control mode region).

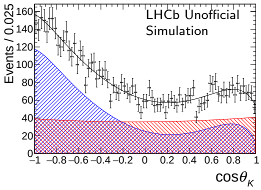
- Fit the combined Run 1 + Run 2 datasets (9 fb$^{-1}$).

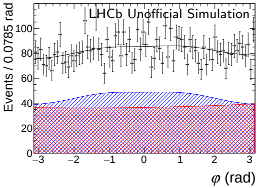


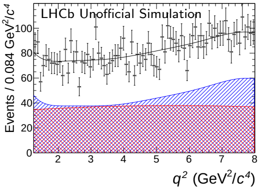
Example projections from a fit to a pseudoexperiment.



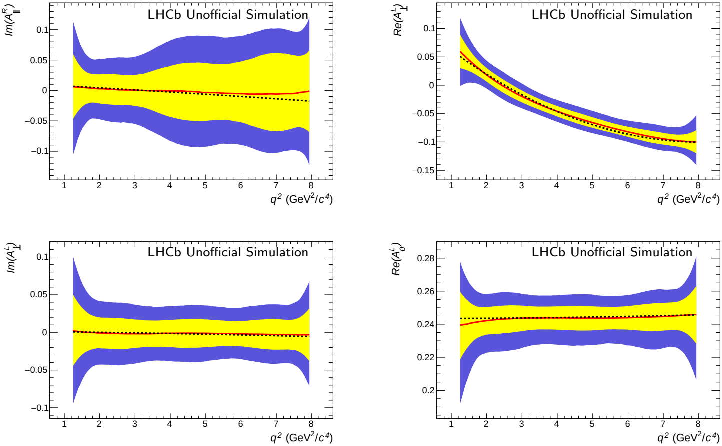



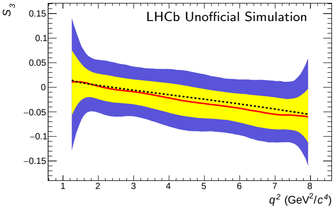
# Amplitude band plots from pseudoexperiments

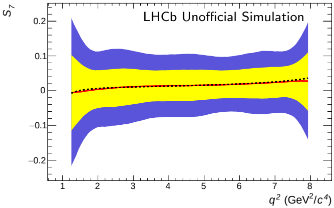
- Shown are error band plots for $Im(\mathcal{A}_{\parallel}^{R})$, $Re(\mathcal{A}_{\perp}^{L})$, $Im(\mathcal{A}_{\perp}^{L})$, and $Re(\mathcal{A}_{0}^{L})$ in the region $1.25 < q^2 < 8\ \text{GeV}^2/c^4$, where the amplitudes are parameterised with Legendre polynomials up to 5 orders.
- Black = true value, red = median, yellow and blue = $1\sigma$ and $2\sigma$ bands.

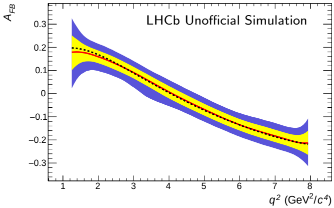


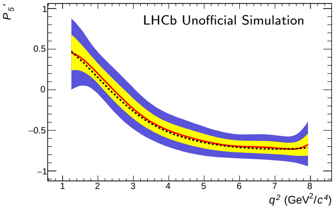
# Angular coefficients band plots from pseudoexperiments

- As mentioned, the amplitudes give a complete description of the decay.
- One can construct angular coefficients from the amplitudes such as $S_3$, $S_7$, $A_{FB}$, and $P_5'$. These are shown below.



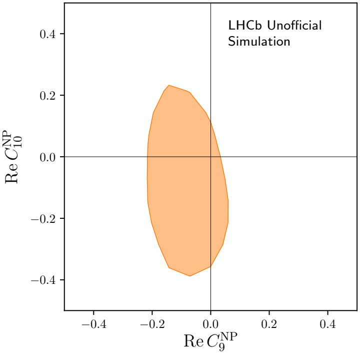



# Applications of our results

- Aim to present amplitude components with uncertainties and correlations.
  - **Parameterise LHCb data in a way which can be used by theorists.**
- This would allow one to generate pseudoexperiments and fit with any choice of model.
- Can also fit the Wilson coefficients e.g. by using flavio. Below is the $1\sigma$ $Re(C_9^{NP})/Re(C_{10}^{NP})$ contour when fitting a pseudoexperiment.



# Summary

- This analysis will provide the amplitude components and correlations for the decay $B^0 \to K^{*0}\mu^+\mu^-$ in the regions $1.25 < q^2 < 8\ \mathrm{GeV}^2/c^4$ and $11 < q^2 < 12.5\ \mathrm{GeV}^2/c^4$.

- Developed a model-independent method to ascertain the required ampliutde ansatz polynomial orders.

- LHCb data would thus be parameterised in a model-independent way which includes statistical and systematic uncertainties.

- This would allow one to generate pseudoexperiments from these results and fit with any choice of model.

- Very exciting times ahead!

# Back up

# Angular distribution

$$\frac{\mathrm{d}^4\Gamma[B^0\to K^{*0}\mu^+\mu^-]}{\mathrm{d}\cos\theta_l\,\mathrm{d}\cos\theta_K\,\mathrm{d}\phi\,\mathrm{d}q^2} = \frac{9}{32\pi}\sum_i J_i f_i(\Omega)$$

| $i$ | $J_i$ | $f_i$ |
|---|---|---|
| $1s$ | $\frac{3}{4}\left[\lvert\mathcal{A}_{\parallel}^{\mathrm{L}}\rvert^2 + \lvert\mathcal{A}_{\perp}^{\mathrm{L}}\rvert^2 + \lvert\mathcal{A}_{\parallel}^{\mathrm{R}}\rvert^2 + \lvert\mathcal{A}_{\perp}^{\mathrm{R}}\rvert^2\right]$ | $\sin^2\theta_K$ |
| $1c$ | $\lvert\mathcal{A}_0^{\mathrm{L}}\rvert^2 + \lvert\mathcal{A}_0^{\mathrm{R}}\rvert^2$ | $\cos^2\theta_K$ |
| $2s$ | $\frac{1}{4}\left[\lvert\mathcal{A}_{\parallel}^{\mathrm{L}}\rvert^2 + \lvert\mathcal{A}_{\perp}^{\mathrm{L}}\rvert^2 + \lvert\mathcal{A}_{\parallel}^{\mathrm{R}}\rvert^2 + \lvert\mathcal{A}_{\perp}^{\mathrm{R}}\rvert^2\right]$ | $\sin^2\theta_K\cos 2\theta_l$ |
| $2c$ | $-\lvert\mathcal{A}_0^{\mathrm{L}}\rvert^2 - \lvert\mathcal{A}_0^{\mathrm{R}}\rvert^2$ | $\cos^2\theta_K\cos 2\theta_l$ |
| 3 | $\frac{1}{2}\left[\lvert\mathcal{A}_{\perp}^{\mathrm{L}}\rvert^2 - \lvert\mathcal{A}_{\parallel}^{\mathrm{L}}\rvert^2 + \lvert\mathcal{A}_{\perp}^{\mathrm{R}}\rvert^2 - \lvert\mathcal{A}_{\parallel}^{\mathrm{R}}\rvert^2\right]$ | $\sin^2\theta_K\sin^2\theta_l\cos 2\phi$ |
| 4 | $\sqrt{\frac{1}{2}}\mathrm{Re}(\mathcal{A}_0^{\mathrm{L}}\mathcal{A}_{\parallel}^{\mathrm{L}*} + \mathcal{A}_0^{\mathrm{R}}\mathcal{A}_{\parallel}^{\mathrm{R}*})$ | $\sin 2\theta_K\sin 2\theta_l\cos\phi$ |
| 5 | $\sqrt{2}\mathrm{Re}(\mathcal{A}_0^{\mathrm{L}}\mathcal{A}_{\perp}^{\mathrm{L}*} - \mathcal{A}_0^{\mathrm{R}}\mathcal{A}_{\perp}^{\mathrm{R}*})$ | $\sin 2\theta_K\sin\theta_l\cos\phi$ |
| $6s$ | $2\mathrm{Re}(\mathcal{A}_{\parallel}^{\mathrm{L}}\mathcal{A}_{\perp}^{\mathrm{L}*} - \mathcal{A}_{\parallel}^{\mathrm{R}}\mathcal{A}_{\perp}^{\mathrm{R}*})$ | $\sin^2\theta_K\cos\theta_l$ |
| 7 | $\sqrt{2}\mathrm{Im}(\mathcal{A}_0^{\mathrm{L}}\mathcal{A}_{\parallel}^{\mathrm{L}*} - \mathcal{A}_0^{\mathrm{R}}\mathcal{A}_{\parallel}^{\mathrm{R}*})$ | $\sin 2\theta_K\sin\theta_l\sin\phi$ |
| 8 | $\sqrt{\frac{1}{2}}\mathrm{Im}(\mathcal{A}_0^{\mathrm{L}}\mathcal{A}_{\perp}^{\mathrm{L}*} + \mathcal{A}_0^{\mathrm{R}}\mathcal{A}_{\perp}^{\mathrm{R}*})$ | $\sin 2\theta_K\sin 2\theta_l\sin\phi$ |

# Angular distribution

$$\frac{\mathrm{d}^4\Gamma[B^0\to K^{*0}\mu^+\mu^-]}{\mathrm{d}\cos\theta_l \mathrm{d}\cos\theta_K \mathrm{d}\phi \mathrm{d}q^2} = \frac{9}{32\pi}\sum_i J_i f_i(\Omega)$$

| $i$ | $J_i$ | $f_i$ |
|---|---|---|
| 9 | $\mathrm{Im}(\mathcal{A}_\parallel^{\mathrm{L}*}\mathcal{A}_\perp^{\mathrm{L}} + \mathcal{A}_\parallel^{\mathrm{R}*}\mathcal{A}_\perp^{\mathrm{R}})$ | $\sin^2\theta_K \sin^2\theta_l \sin 2\phi$ |
| 10 | $\frac{1}{3}\left[\lvert\mathcal{A}_\mathrm{S}^\mathrm{L}\rvert^2 + \lvert\mathcal{A}_\mathrm{S}^\mathrm{R}\rvert^2\right]$ | $1$ |
| 11 | $\sqrt{\frac{4}{3}}\mathrm{Re}(\mathcal{A}_\mathrm{S}^\mathrm{L}\mathcal{A}_0^{\mathrm{L}*} + \mathcal{A}_\mathrm{S}^\mathrm{R}\mathcal{A}_0^{\mathrm{R}*})$ | $\cos\theta_K$ |
| 12 | $-\frac{1}{3}\left[\lvert\mathcal{A}_\mathrm{S}^\mathrm{L}\rvert^2 + \lvert\mathcal{A}_\mathrm{S}^\mathrm{R}\rvert^2\right]$ | $\cos 2\theta_l$ |
| 13 | $-\sqrt{\frac{4}{3}}\mathrm{Re}(\mathcal{A}_\mathrm{S}^\mathrm{L}\mathcal{A}_0^{\mathrm{L}*} + \mathcal{A}_\mathrm{S}^\mathrm{R}\mathcal{A}_0^{\mathrm{R}*})$ | $\cos\theta_K \cos 2\theta_l$ |
| 14 | $\sqrt{\frac{2}{3}}\mathrm{Re}(\mathcal{A}_\mathrm{S}^\mathrm{L}\mathcal{A}_\parallel^{\mathrm{L}*} + \mathcal{A}_\mathrm{S}^\mathrm{R}\mathcal{A}_\parallel^{\mathrm{R}*})$ | $\sin\theta_K \sin 2\theta_l \cos\phi$ |
| 15 | $\sqrt{\frac{8}{3}}\mathrm{Re}(\mathcal{A}_\mathrm{S}^\mathrm{L}\mathcal{A}_\perp^{\mathrm{L}*} - \mathcal{A}_\mathrm{S}^\mathrm{R}\mathcal{A}_\perp^{\mathrm{R}*})$ | $\sin\theta_K \sin\theta_l \cos\phi$ |
| 16 | $\sqrt{\frac{8}{3}}\mathrm{Im}(\mathcal{A}_\mathrm{S}^\mathrm{L}\mathcal{A}_\parallel^{\mathrm{L}*} - \mathcal{A}_\mathrm{S}^\mathrm{R}\mathcal{A}_\perp^{\mathrm{R}*})$ | $\sin\theta_K \sin\theta_l \sin\phi$ |
| 17 | $\sqrt{\frac{2}{3}}\mathrm{Im}(\mathcal{A}_\mathrm{S}^\mathrm{L}\mathcal{A}_\perp^{\mathrm{L}*} + \mathcal{A}_\mathrm{S}^\mathrm{R}\mathcal{A}_\perp^{\mathrm{R}*})$ | $\sin\theta_K \sin 2\theta_l \sin\phi$ |

# Acceptance

- The angular and $q^2$ distributions are distorted due to selection cuts, reconstruction and detector effects.

- Take this into account by computing an acceptance function, modelled as the sum

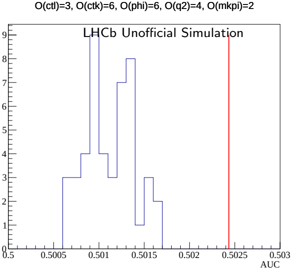
$$\varepsilon(\cos\theta_l, \cos\theta_K, \phi, q^2) = \sum_{ijmn} c_{ijmn} L_i(\cos\theta_l) L_j(\cos\theta_K) L_m(\phi) L_n(q^2),$$

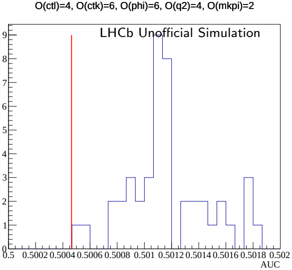
  where $L_a$ are Legendre polynomials of order $a$ and $c_{ijmn}$ are coefficients obtained via method of moments.

- Use BDTs to determine the goodness-of-fit of the acceptance function.

# Acceptance goodness-of-fit

- Example goodness of fit plots shown below.
  - Blue: expected distribution from statistical fluctuations
  - Red: comparison of MC/fit
  - Left: bad fit (p-value = 0%); right: good fit (p-value = 100%)




- Previous generations had a systematic uncertainty in the required polynomial orders. With this goodness-of-fit test, one can determine most suitable orders and remove the systematic.

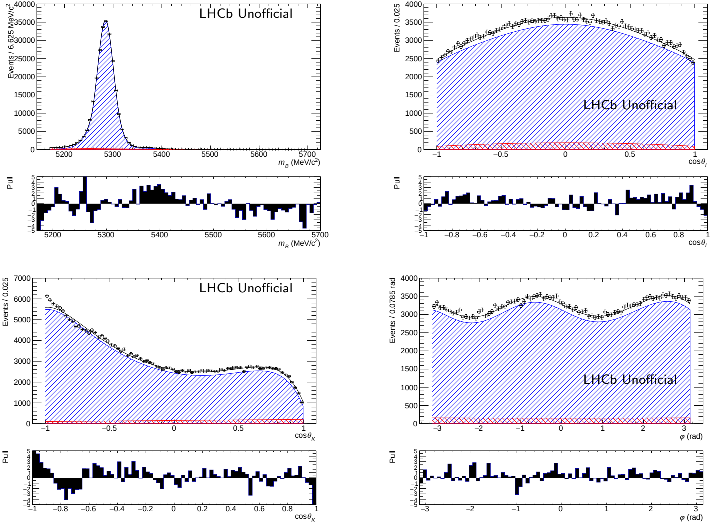
# Symmetries of the 4D angular distribution

- The 4D angular distribution obeys the symmetry $n_i \to n_i' = U n_i$, where
  - $n_i = n_{\|}, n_{\perp}, n_0, n_{00}$ are complex amplitude vectors, e.g. $n_0 = \begin{pmatrix} \mathcal{A}_0^L \\ \mathcal{A}_0^{R*} \end{pmatrix}$
  - $U = \begin{pmatrix} e^{i\phi_L} & 0 \\ 0 & e^{-i\phi_R} \end{pmatrix} \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \cosh i\eta & -\sinh i\eta \\ -\sinh i\eta & \cosh i\eta \end{pmatrix}$
- Thus the number of amplitudes (16) is greater then the number of degrees of freedom $(16 - 4 = 12)$.
- Thus apply a basis-fixing condition where $Im(\mathcal{A}_\perp^R) = Im(\mathcal{A}_0^L) = Re(\mathcal{A}_0^R) = Im(\mathcal{A}_0^R) = 0$.
  - Obtain the angles which satisfies the transformation from the **SM basis** to the **new basis**.
  - Find the new basis by transforming all amplitude vectors according to the angles obtained.

# Mass fit and background

- Parameterise the B mass lineshape as a double-sided Crystal Ball function, $P_B = f_{core} P_{CB}(\mu, \sigma_1, \alpha_1, n_1) + (1 - f_{core}) P_{CB}(\mu, \sigma_2, \alpha_2, n_2)$
- Add in a second signal component due to the $B_s^0$ with a fixed shift of the mean $\mu$ and fixed relative yield.
- Describe the background in the B mass by an exponential distribution.
- The background in the angles and $q^2$ are described by Chebyshev polynomials with maximum order $= 2$.

# Control mode fits - $B^0 \to K^{*0} J/\psi$ (Run 1)




- Note: large pulls at low $\cos\theta_K$ are due to $J/\psi\pi$ exotic states.

# Example projections in the interresonance region

Example projections from a fit to a pseudoexperiment.