Combined angular analysis of $B \to D^* e \nu_e$ and $B \to D^* \mu \nu_\mu$ at the LHCb detector

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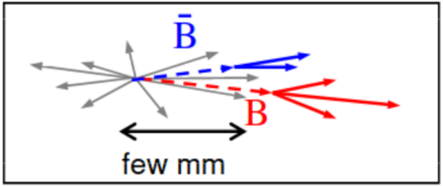
Content

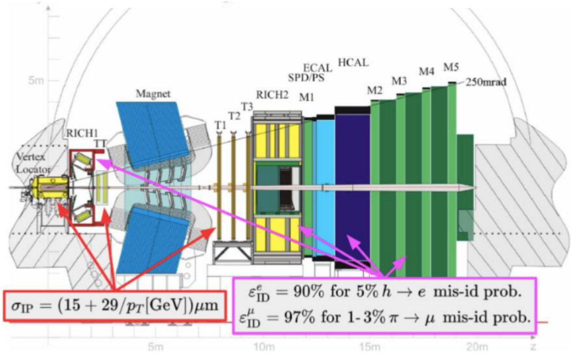
LHCb detector

Single-arm forward spectrometer:

- Forward angular coverage → b-hadrons produced in pairs ($b\bar{b}$) in the same direction
- Excellent performance of tracking, powerful particle identification allows to perform high precision measurement of semileptonic B decays



B mesons have displaced vertices. Fly a few mm before decaying in inner tracking detector - Vertex Locator

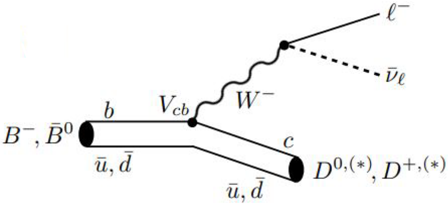


Introduction - LFU

- Semileptonic b-hadron decays provide powerful probes for testing the

  Lepton Flavor Universality,

  which states that the interactions of the electroweak bosons with the leptons are independent of the lepton flavor



- LFU can be tested with ratios of branching fractions to final states with different lepton flavors:

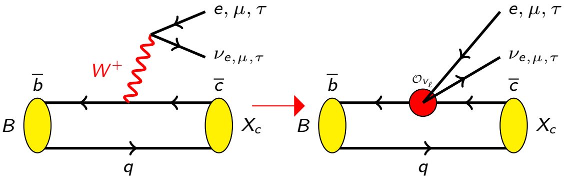
$$R(D^*)_{e/\mu} = \frac{Br(B^0 \to D^* e\nu_e)}{Br(B^0 \to D^* \mu\nu_\mu)}$$

- New Physics (NP) can be detected in angular coefficients even if $R(D^*)_{e/\mu}$ is compatible with SM. Furthermore NP can be characterized in the angular analysis

Effective field theory

- The low-energy effective theory based on the assumption of three light lefthanded neutrino flavours below the electroweak scale for $B^0 \to D^* \ell \nu_\ell$ at dimension six can be written as

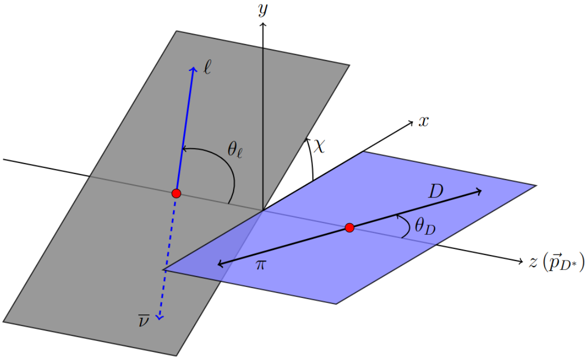
- $\mathcal{H}_{eff}(b \to c\ell) = \frac{4G_F}{\sqrt{2}} V_{cb} \sum_i (\mathcal{O}_{SM} + C_i \mathcal{O}_i)$
  - Dominant SM. NP corrections parametrized by adding new operators and coefficients
  - **Wilson coefficients**
  - **Wilson operators**



$$\mathcal{H}_{eff} = \frac{4G_F}{\sqrt{2}} V_{cb} \{ \left[(\boxed{1} + \boxed{C_{V_L}}) P_L + \boxed{C_{V_R}} P_R \right] \gamma_\mu P_L + \left[\boxed{C_S} + \boxed{C_P} \gamma^5 \right] P_L + \boxed{C_T} \sigma^{\mu\nu} P_L \sigma_{\mu\nu} P_L + h.c. \}$$

- C_L, C_R, C_S, C_P, C_T are complex NP couplings ($\equiv 0$ in SM)
- Different NP models (W', H^+, LQ, ...) $\Rightarrow$ different combinations of couplings

Introduction - Kinematics of $B \to D^*(\to D\pi)\ell\nu_\ell$



Taken from arXiv:1907.02257

$$B \to D^*\ell\nu_\ell$$
$$D^* \to D\pi$$
$$D \to K\pi$$

Kinematic variables : $\cos\theta_\ell, \cos\theta_D, \chi, q^2 = (p_\nu + p_\ell)^2$

$$\ell = \mu, e$$

Introduction - Analysis Idea

- The experimental fit of the full differential rate of $B \to D^* \ell \nu_\ell$ is rather complicated:
  - The analysis suffers from biases in the angular distributions caused by various reconstruction and acceptance effects at LHCb
  - Binned multidimensional template histograms must be used to resolve these biases
- For the simplification purposes, template histograms can be one dimensional if the analyses concentrate on single-differential distribution. In such case, 5(4 in CP averaged measurment) angular coefficients can be obtained

$$\frac{1}{\hat{\Gamma}^{(\ell)}}\frac{d\hat{\Gamma}^{(\ell)}}{d\cos\theta_\ell} = \frac{1}{2} + \langle A_{FB}^{(\ell)}\rangle \cos\theta_\ell + \frac{1}{4}(1 - 3\langle \tilde{F}_L^{(\ell)}\rangle)\frac{3\cos^2\theta_\ell - 1}{2}$$

$$\frac{1}{\hat{\Gamma}^{(\ell)}}\frac{d\hat{\Gamma}^{(\ell)}}{d\cos\theta_D} = \frac{3}{4}(1 - \langle F_L^{(\ell)}\rangle) sin^2\theta_D + \frac{3}{2}\langle F_L^{(\ell)}\rangle \cos^2\theta_D$$

$$\frac{1}{\hat{\Gamma}^{(\ell)}}\frac{d\hat{\Gamma}^{(\ell)}}{d\chi} = \frac{1}{2\pi} + \frac{2}{3\pi}\langle S_3^{(\ell)}\rangle \cos 2\chi + \frac{2}{3\pi}\langle S_9^{(\ell)}\rangle sin2\chi$$

Introduction - Analysis Idea

- There were hints of LFU violation in untagged measurements of data from Belle detector arXiv:2104.02094. Forward-backward assymetry of muon $\langle A^{\mu}_{FB} \rangle$ and electron $\langle A^{e}_{FB} \rangle$ are different within "4σ".
- In the latest article from 31 October 2023 arXiv:2310.20286, no significant difference is observed in $\langle A^{\mu}_{FB} \rangle - \langle A^{e}_{FB} \rangle$. However due to hadronic tag-side reconstruction statistical uncertainties increased by an order of magnitude compared to previous measurments
- Idea : Make the one dimensional model independent template fit of single-differential distributions and measure 4 angular coefficients per lepton for $B \to D^* e \nu_e$ and $B \to D^* \mu \nu_{\mu}$ based on LHCb 2016-2018 Data

Problems:

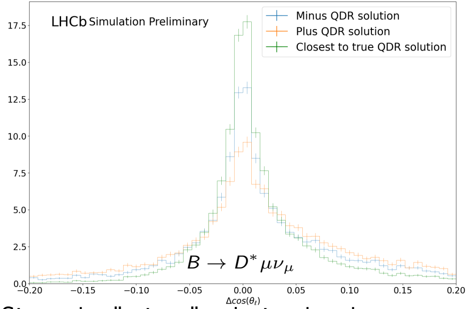
- Charged particles, especially electrons, emit Bremsstrahlung photons when passing through the detector material degrading their momentum resolution and reconstruction efficiency
- The total and missing 4-momentum is unknown, so neutrinos cannot be reconstructed... Or they still can?

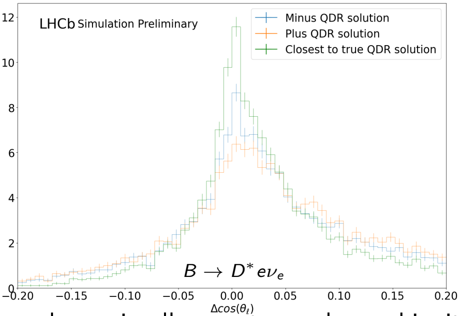
Reconstruction procedure

Solution of quadratic equation (QDR)

As the B^0 mass is well known, its momentum can be estimated up to a two-fold ambiguity from its line of flight between the reconstructed primary and B^0 vertices:

$$|\vec{p}_{B^0}| = \frac{(m_Y^2 + m_{B^0}^2)|\vec{p}_Y|\cos\theta_{B^0,Y} \pm E_Y\sqrt{(m_{B^0}^2 - m_Y^2)^2 - 4m_{B^0}^2|\vec{p}_Y|^2\sin^2\theta_{B^0,Y}}}{2(E_Y^2 - |\vec{p}_Y|^2\cos^2\theta_{B^0,Y})}$$



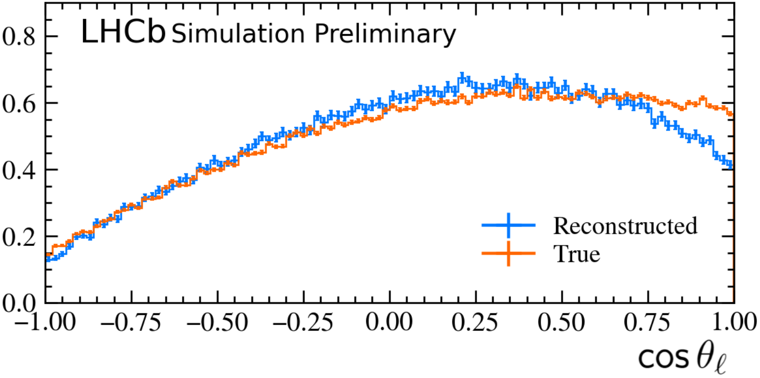


Since the "minus" solution has better resolution, it was chosen in all cases to resolve ambiguity

Methodology

The following effects significantly change kinematic distributions:

- Non-linear detector efficiencies, such as the reconstruction resolution dependence on the transverse momentum of the lepton
- Neutrino reconstruction procedure



Template fit procedure

- To resolve these discrepancies between reconstructed and true angles the angular fit procedure described in JHEP 11, (2019) 133 can be used

$$\frac{1}{\hat{\Gamma}^{(\ell)}}\frac{d\hat{\Gamma}^{(\ell)}}{d\cos\theta_\ell} = \frac{1}{2}\cdot \boxed{1} + \langle A_{FB}^{(\ell)}\rangle \boxed{\cos\theta_\ell} + \frac{1}{4}(1-3\langle\tilde{F}_L^{(\ell)}\rangle)\frac{3\boxed{\cos^2\theta_\ell}-1}{2}$$

$$\frac{1}{\hat{\Gamma}^{(\ell)}}\frac{d\hat{\Gamma}^{(\ell)}}{d\cos\theta_D} = \frac{3}{4}(1-\langle F_L^{(\ell)}\rangle)\boxed{sin^2\theta_D} + \frac{3}{2}\langle F_L^{(\ell)}\rangle\boxed{\cos^2\theta_D}$$

$$\frac{1}{\hat{\Gamma}^{(\ell)}}\frac{d\hat{\Gamma}^{(\ell)}}{d\chi} = \frac{1}{2\pi}\cdot \boxed{1} + \frac{2}{3\pi}\langle S_3^{(\ell)}\rangle\boxed{\cos 2\chi} + \frac{2}{3\pi}\langle S_9^{(\ell)}\rangle\boxed{sin2\chi}$$

$$\downarrow$$

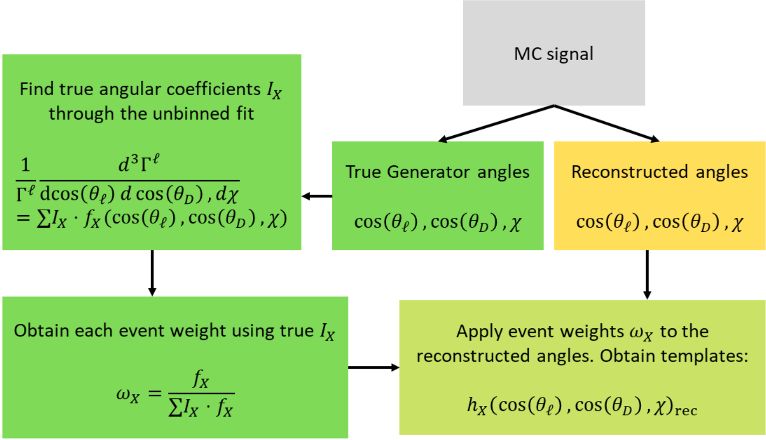
$$\frac{1}{\hat{\Gamma}^{(\ell)}}\frac{d\hat{\Gamma}^{(\ell)}}{d\cos\theta_\ell} = (\frac{1}{2}-\frac{1}{8}(1-3)\langle\tilde{F}_L^{(\ell)}\rangle)\boxed{h_{const,\theta_\ell}} + \langle A_{FB}^{(\ell)}\rangle\boxed{h_{\cos\theta_\ell}} + \frac{3}{8}(1-3\langle\tilde{F}_L^{(\ell)}\rangle)\boxed{h_{\cos^2\theta_\ell}}$$

$$\frac{1}{\hat{\Gamma}^{(\ell)}}\frac{d\hat{\Gamma}^{(\ell)}}{d\cos\theta_D} = \frac{3}{4}((1-\langle F_L^{(\ell)}\rangle)\boxed{h_{const,\theta_D}} + (3\langle F_L^{(\ell)}\rangle - 1)\boxed{h_{\cos^2\theta_D}}$$

$$\frac{1}{\hat{\Gamma}^{(\ell)}}\frac{d\hat{\Gamma}^{(\ell)}}{d\chi} = (\frac{1}{2\pi}-\frac{2}{3\pi}\langle S_3^{(\ell)}\rangle)\boxed{h_{const,\chi}} + \frac{2}{3\pi}\langle S_3^{(\ell)}\rangle\boxed{h_{(1+\cos 2\chi)}}$$

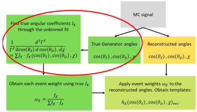
Template fit procedure

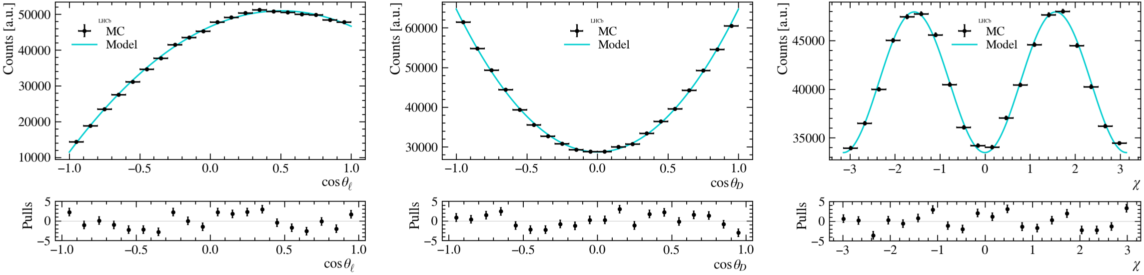
- Truth-level angular coefficients are obtained from True MC distributions with a specific description of the SM for these types of decays



True MC distributions $B \to D^* \mu \nu_\mu$, $\cos\theta_D, \cos\theta_\ell, \chi$

Generator SM:



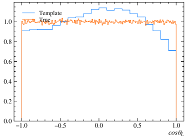


(a) $\cos\theta_\ell$ (b) $\cos\theta_D$ (c) χ

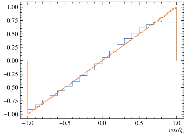
Fit of True MC distributions

Template fit cosθ_ℓ, $B \to D^* \mu \nu_\mu$

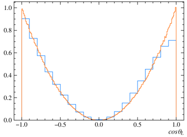
Template for a constant

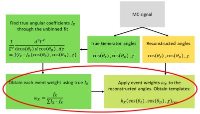


Template for a cos θ_ℓ

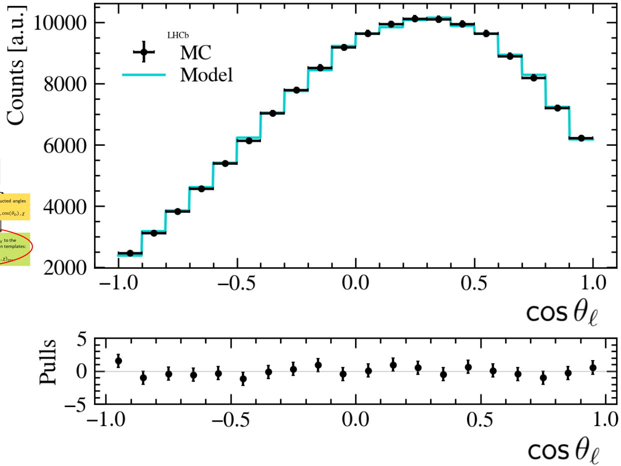


Template for a cos^2 θ_ℓ





Template fit of MC with SM formfactor parametrization



New Physics contributions

The dependence of angular observables from Wilson Coefficients

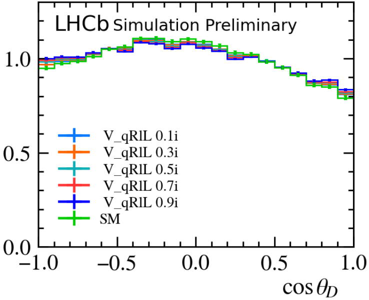
$$C_V^{\ell\ell'} = C_{V_R}^{\ell\ell'} + C_{V_L}^{\ell\ell'}, \qquad C_A^{\ell\ell'} = C_{V_R}^{\ell\ell'} - C_{V_L}^{\ell\ell'}, \qquad C_P^{\ell\ell'} = C_{S_R}^{\ell\ell'} - C_{S_L}^{\ell\ell'},$$

Observable	$\lvert C_A\rvert^2$	$\lvert C_V\rvert^2$	$\lvert C_P\rvert^2$	$\lvert C_T\rvert^2$	$\mathrm{Re}(C_A C_V^*)$	$\mathrm{Re}(C_A C_P^*)$	$\mathrm{Re}(C_A C_T^*)$	$\mathrm{Re}(C_V C_P^*)$	$\mathrm{Re}(C_V C_T^*)$	$\mathrm{Re}(C_P C_T^*)$
$d\Gamma/dq^2$	✓	✓	✓	✓	–	(m)	(m)	–	(m)	–
$\mathrm{num}(A_{\mathrm{FB}})$	(m^2)	–	–	(m^2)	✓	(m)	(m)	–	(m)	✓
$\mathrm{num}(F_L)$	✓	–	✓	✓	–	(m)	(m)	–	–	–
$\mathrm{num}(F_L\text{-}1/3)$	✓	✓	✓	✓	–	(m)	(m)	–	(m)	–
$\mathrm{num}(\widetilde{F}_L)$	✓	(m^2)	✓	✓	–	(m)	(m)	–	(m)	–
$\mathrm{num}(\widetilde{F}_L\text{-}1/3)$	✓	✓	–	✓	–	–	–	–	–	–
$\mathrm{num}(S_3)$	✓	✓	–	✓	–	–	–	–	–	–

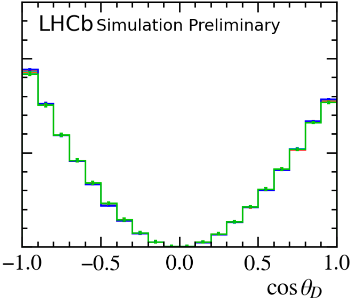
The table is taken from C. Bobeth, et al

Template fit model independence

- The simplest way to prove the model Independence of 1D template fit is to remake templates with different NP contributions, i.e. to reweigh reconstructed and generator angles. If the approach is indeed model-independent, all templates are supposed to be the same within statistical uncertainty



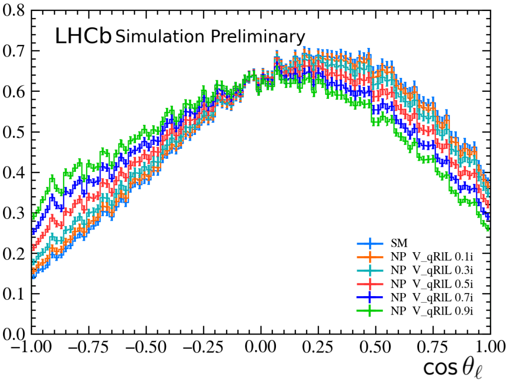
Constant template

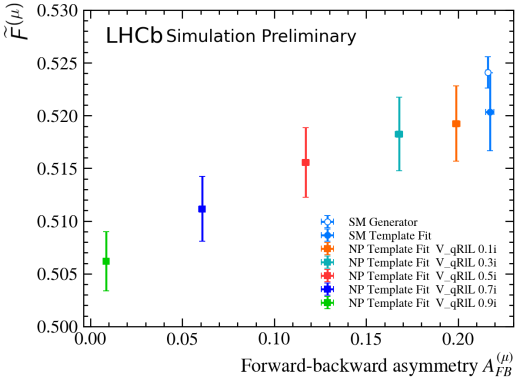


Quadratic template

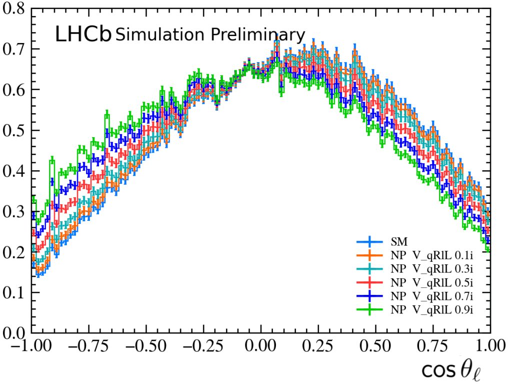
NP template fit $\cos\theta_\ell$, $B \to D^*\mu\nu_\mu$

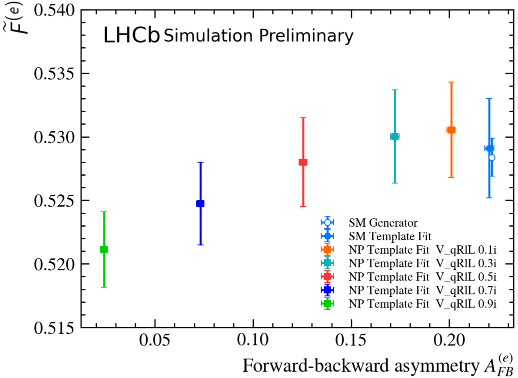
- Example of sensitivity to NP of angular observable - $\langle A^{\mu}_{FB}\rangle$ for vector contribution with right helicity of b quark V_qRlL with different amplitudes:





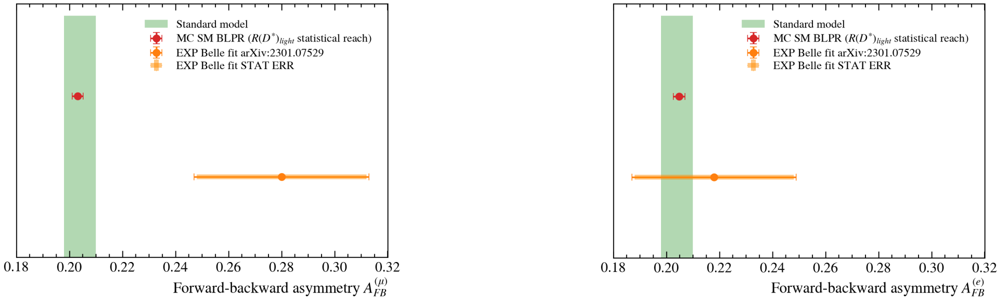
NP template fit $\cos\theta_\ell$, $B \to D^* e \nu_e$





Results on MC

- Expected statistical uncertainty is estimated using the same selection criteria as in the ongoing analysis for $R(D^*)_{e/\mu}$, which is currently in the advanced state
- All of the results obtained on the simulation
- The same plots were obtained for all four angular coefficients



- Competitive measurement to Belle II will be possible
- But we expect to be dominated by systematic uncertainties ($B \to D^{**}\ell\nu_\ell$ decay model, MC correction)

Status and outlook

- Precision measurements of flavor physics observables provide a great test of the SM
- LHCb allows to perform these high precision measurements
- Analysis of 1D angular distributions for $B \to D^* \mu\nu_\mu$ and $B \to D^* e\nu_e$ was conducted on MC samples
- This analysis is sensitive to New Physics (NP) couplings
- Expected statistical uncertainty for angular observables is estimated
- Measurements can be competitive with Belle
- It will be the first-ever angular analysis at LHCb for $B \to D^* e\nu_\ell$

Plans:

- Finalize data fit
- Obtain blinded results for data
- Evaluate systematic uncertainties contributions

Thank you!

Introduction - Analysis Idea

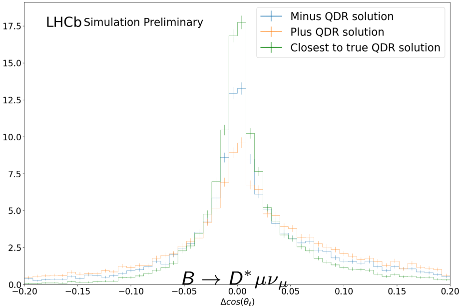
- One dimensional fit was performed based on Belle data, the discrepancy with SM was observed in lepton Forward-Backward asymmetry :
  1. Belle's 2018 untagged data (4 angular coefficients per lepton were measured) were analyzed by C. Bobeth et. al.
     $\langle A_{FB}^{\mu} \rangle = 0.2300 \pm 0.0059$ (2.4σ higher than SM)
     $\langle F_L^{\mu} \rangle = 0.5271 \pm 0.0046$
     $\langle A_{FB}^{e} \rangle = 0.1951 \pm 0.0069$ (1.6σ lower than SM)
     $\langle F_L^{e} \rangle = 0.5336 \pm 0.0045$
  2. Belle's 2022 hadronic tag-side reconstruction (2 angular coefficients per lepton was measured) analysis arXiv:2301.07529 :
     $\langle A_{FB}^{\mu} \rangle = 0.280 \pm 0.032(stat.) \pm 0.009(syst.)$ (2.3σ higher than SM)
     $\langle F_L^{\mu} \rangle = 0.503 \pm 0.023(stat.) \pm 0.007(syst.)$
     $\langle A_{FB}^{e} \rangle = 0.218 \pm 0.030(stat.) \pm 0.008(syst.)$
     $\langle F_L^{e} \rangle = 0.471 \pm 0.024(stat.) \pm 0.007(syst.)$ (2.6σ lower than SM)
- Idea : Make the one dimensional model independent template fit of single-differential distributions and measure 4 angular coefficients per lepton for $B \to D^* e \nu_e$ and $B \to D^* \mu \nu_\mu$ based on LHCb Run 2 Data

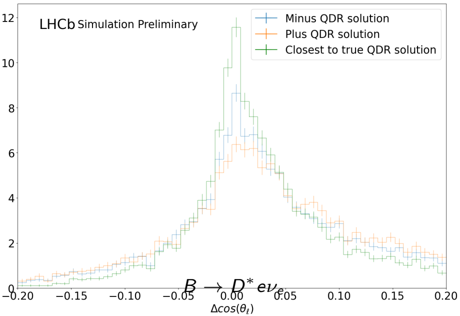
Backup Slides

Solution of quadratic equation (QDR)

As the B^0 mass is well known, its momentum can be estimated up to a two-fold ambiguity from its line of flight between the reconstructed primary and B^0 vertices:

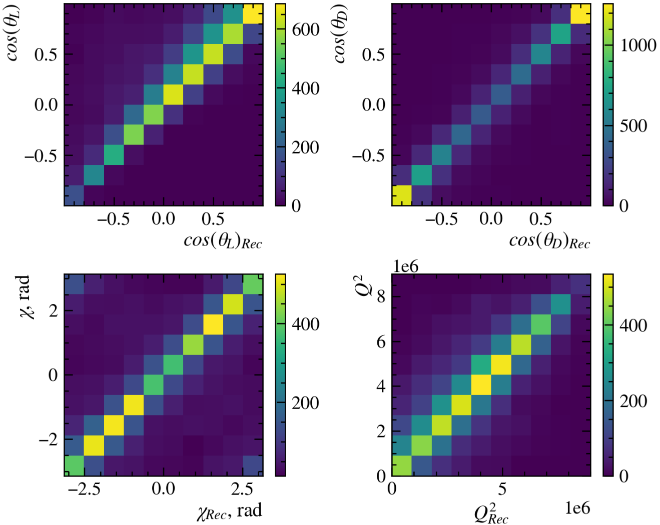
$$|\vec{p}_{B^0}| = \frac{(m_Y^2 + m_{B^0}^2)|\vec{p}_Y|\cos\theta_{B^0,Y} \pm E_Y\sqrt{(m_{B^0}^2 - m_Y^2)^2 - 4m_{B^0}^2|\vec{p}_Y|^2\sin^2\theta_{B^0,Y}}}{2(E_Y^2 - |\vec{p}_Y|^2\cos^2\theta_{B^0,Y})}$$





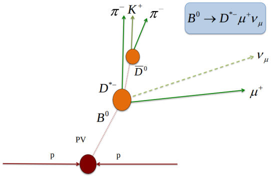
Since the "minus" solution has better resolution, it was chosen in all cases to resolve ambiguity

$B \to D^* \mu \nu_\mu$ correlations, QDR

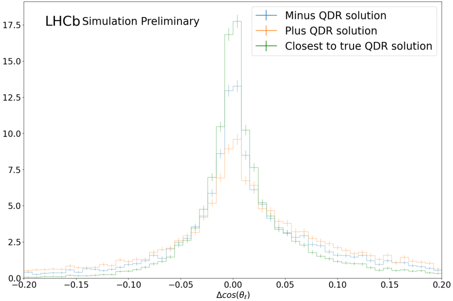


Reconstruction procedure

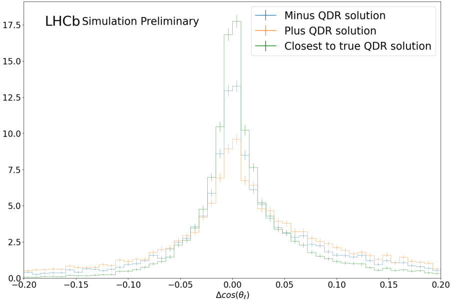
As the B^0 mass is well known, its momentum can be estimated using conservation of energy and momentum up to a two-fold ambiguity from its line of flight between the reconstructed primary and B^0 vertices by solving the quadratic equation (QDR):



$$|\vec{p}_{B^0}| = \frac{(m_Y^2 + m_{B^0}^2)|\vec{p}_Y|\cos\theta_{B^0,Y} \pm E_Y\sqrt{(m_{B^0}^2 - m_Y^2)^2 - 4m_{B^0}^2|\vec{p}_Y|^2\sin^2\theta_{B^0,Y}}}{2(E_Y^2 - |\vec{p}_Y|^2\cos^2\theta_{B^0,Y})}$$

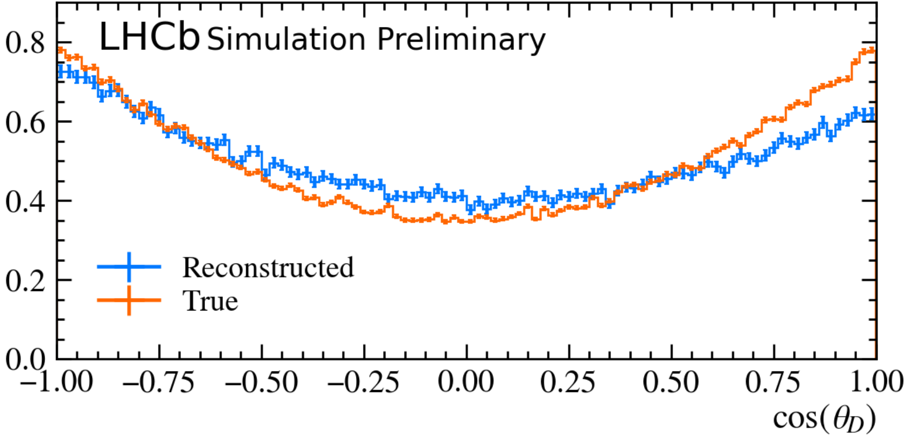


$B \to D^*\mu\nu_\mu$

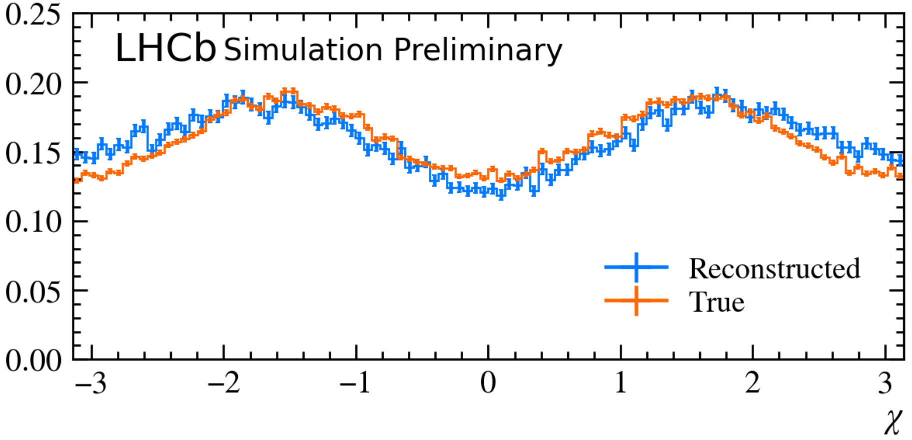


$B \to D^*e\nu_e$

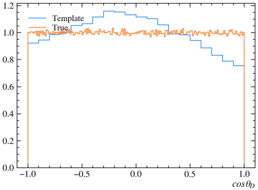
Reconstructed and True angles

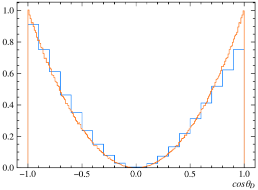


Reconstructed and True angles

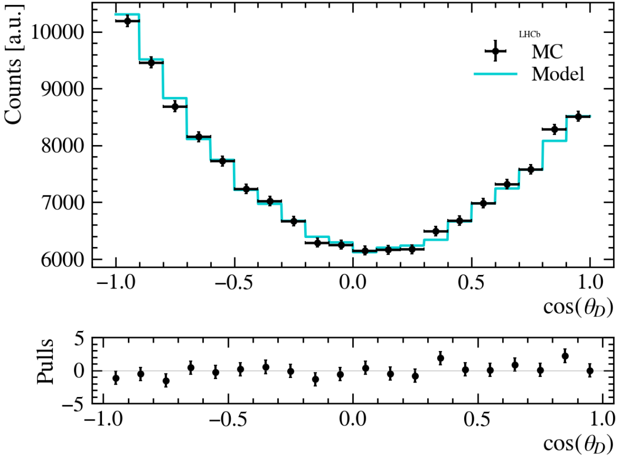


Template fit $\cos\theta_D$, $B \to D^*\mu\nu_\mu$

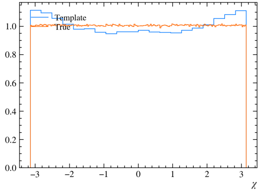


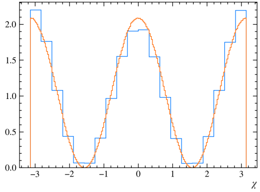


Template fit of MC with SM formfactor parametrization

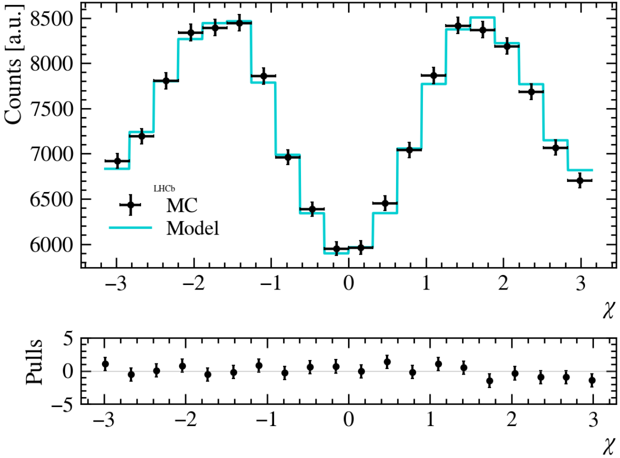


Template fit cosχ, $B \to D^{*}\mu\nu_{\mu}$

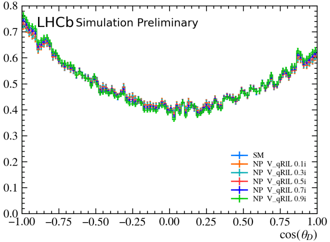


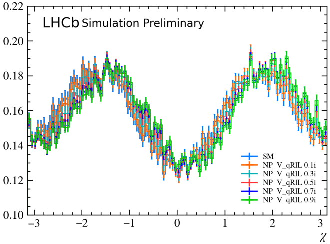


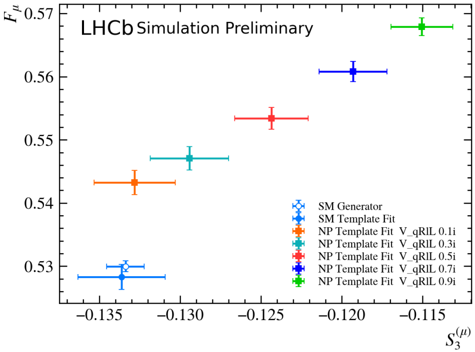
Template fit of MC with SM formfactor parametrization



New Physics template fit $\cos\theta_D$, χ, $B \to D^*\mu\nu_\mu$







NP template fit $\cos\theta_D$, χ, $B \to D^* e\nu_e$