Measurement of *CP*-violating observables in $B^0 \to D^{*+}\mu^-\overline{\nu}_\mu$ decays at the LHCb experiment

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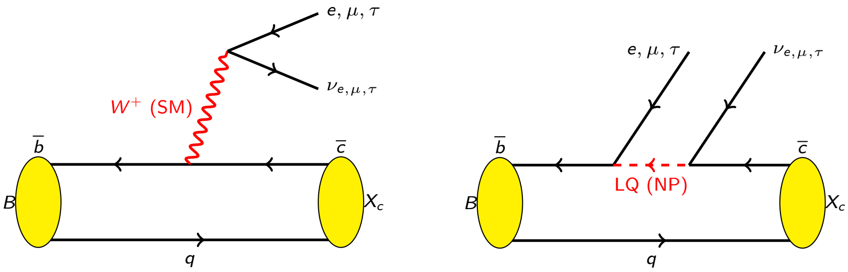
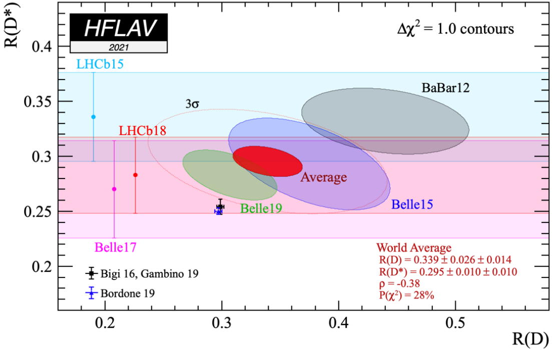
Introduction - Semileptonic B decays



- SL B-decays are interesting → possible NP contributions
- $>$ 20% of B-decays are semileptonic → good statistics!
- Experimental challenge: neutrinos in the final state

Introduction - Motivation



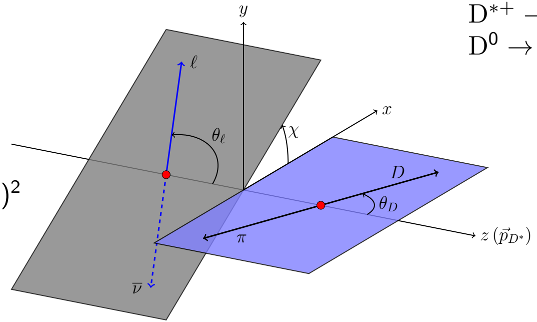
$$R(X_c) = \frac{\mathcal{B}(B^0 \to X_c \tau^+ \nu_\tau)}{\mathcal{B}(B^0 \to X_c \mu^+ \nu_\mu)}, \; X_c = D^* \text{ or } D^0$$

- Couplings of (e, μ, τ) should be identical in SM (Lepton Flavor Universality)
- b-anomalies in $b \to c\ell\nu$ transitions: hints of NP (LQ, W', H^+ etc)
- Need more measurements to shed light on these anomalies

Introduction - Angular distribution of $B^0 \to D^{*+}\mu^-\overline{\nu}_\mu$

$B^0 \to D^{*+}\mu^-\overline{\nu}_\mu$
$D^{*+} \to D^0\pi^+$
$D^0 \to K^+\pi^-$

$q^2 = (p_B - p_{D^*})^2$



- We study the angular distribution of $B^0 \to D^{*+}\mu^-\overline{\nu}_\mu$ decays with Run 2 LHCb data → fully described by 3 angles (θ_D,θ_ℓ,χ) and q^2.
- Angular distribution can contain parity-odd terms $\propto \sin\chi$ (i.e. $\sin 2\theta_\ell \sin 2\theta_D \sin\chi$) that are *P*- or *CP*-violating. *CP*-Violating terms can only appear with NP (are 0 in SM). We look for them!

Parity- and CP-violation

Angular terms $\propto \sin\chi$ are parity-odd $\rightarrow$ asymmetric w.r.t. reflection in the mirror.

Asymmetries in nr of evts with $\sin\chi > 0$ ($\chi \in [-\pi, 0]$) and $\sin\chi < 0$ ($\chi \in [0, \pi]$)

Simplified view $\rightarrow$ counting events:

B^0: $a = \frac{N(\sin\chi>0) - N(\sin\chi<0)}{N(\sin\chi>0) + N(\sin\chi<0)}$

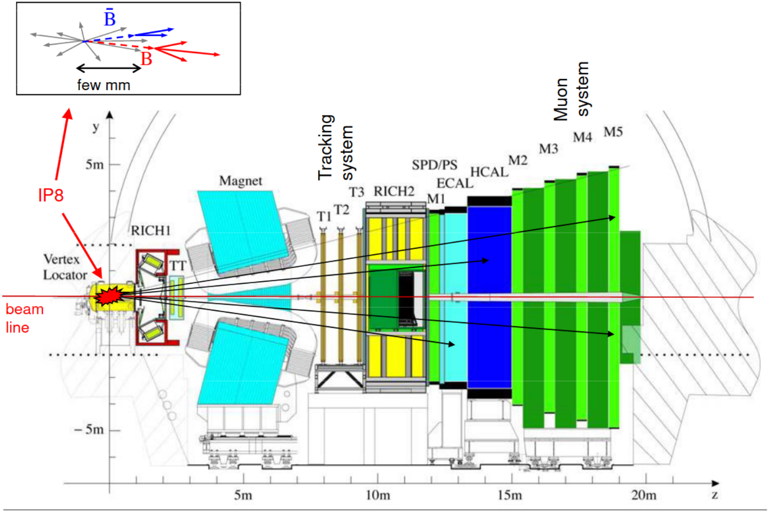
$\overline{\mathrm{B}}^0$: $\overline{a} = \frac{\overline{N}(\sin\chi>0) - \overline{N}(\sin\chi<0)}{\overline{N}(\sin\chi>0) + \overline{N}(\sin\chi<0)}$

$$a_P = \frac{1}{2}(a - \overline{a})$$

$$a_{CP} = \frac{1}{2}(a + \overline{a})$$

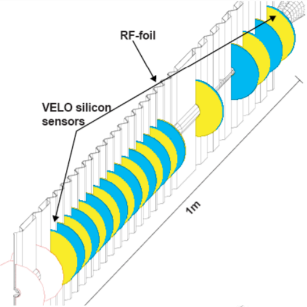
- Distinguish between P- and CP-violation by looking at both B^0 and $\overline{\mathrm{B}}^0$
- P asymmetry can be nonzero in the SM
- CP asymmetry can be nonzero only if NP coupling is present. Either Right-Handed (RH) vector or interference between Pseudoscalar (P) and Tensor (T).

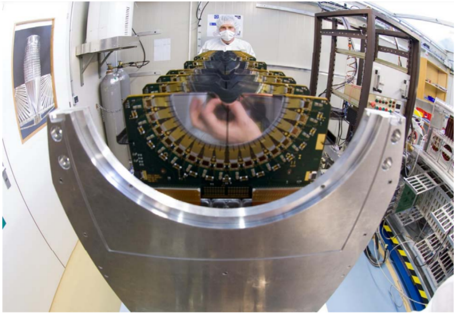
LHCb detector

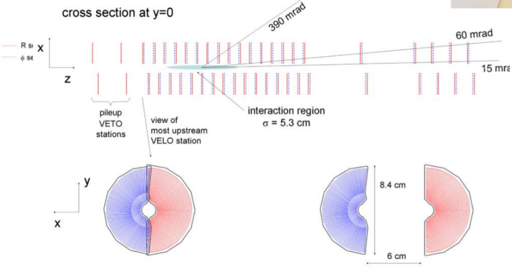


- b-hadrons produced in pairs ($b\bar{b}$) in the same forward direction
- Excellent vertex finding, momentum resolution, particle identification

LHCb detector - VErtex LOcator (VELO)

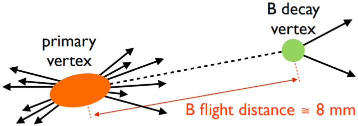




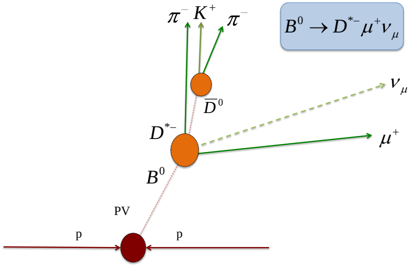


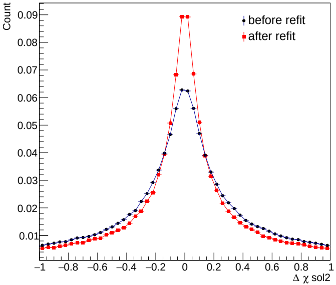
VELO fully closed (stable beam)

VELO fully open



Neutrino reconstruction





- ν is not visible in the detector
- Kinematic reconstruction of B (ν) from decay topology (very precise vertexing from VELO)
- Run full refit of the decay tree including all possible kinematic information (including missing ν) and all possible correlations
- Improve precision in reconstructing quantities of interest $(\theta_\ell, \theta_D, \chi, q^2)$

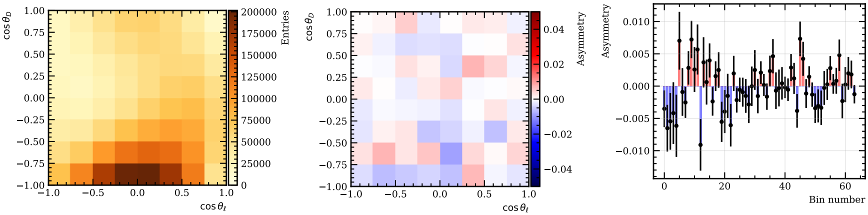
CP asymmetries (SM MC)

- We reconstruct all angles, how do we measure *CP*-asymmetry?
- 2D histogram in $\cos\theta_D, \cos\theta_\ell$ reweighed by $\sin\chi$ to get asymmetry
- First thing to look at: *CP* asymmetry in SM MC is consistent with zero (no NP).
- MC sample size $\sim$ our expected dataset of Run 2 (error bars $\sim$ 0.1%)

unweighted 2D density $\cos\theta_D, \cos\theta_\ell$

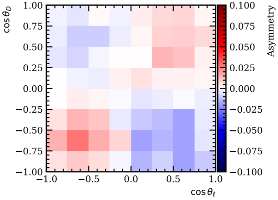
reweigh by $\sin\chi$ (2D asymmetry)

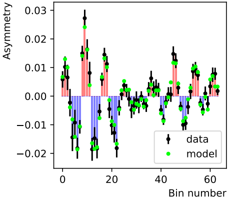
flattened to 1D asymmetry



CP asymmetries: adding NP couplings and fit

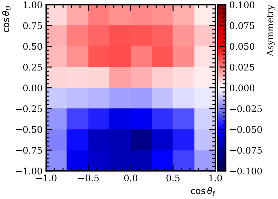
CP-asymmetry plots in case of RH NP, $g_R = 0.1i$ (asym up to 3%)

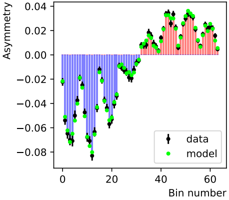




Im(g_R) Stat err from fit $\sim$ 4e-3

CP-asymmetry plots in case of P and T NP, $g_P g_T^* = 0.1i$ (asym up to 8%)



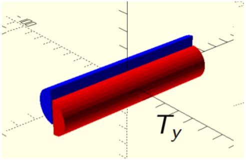


Im($g_P g_T^*$) Stat err from fit $\sim$ 1e-3

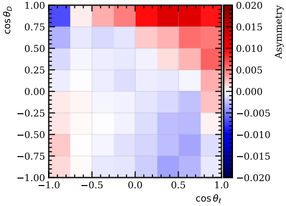
With NP, *CP*-asymmetry becomes nonzero. Specific pattern of asymmetry in both NP cases $\rightarrow$ use them as templates to fit for asymmetry in data.

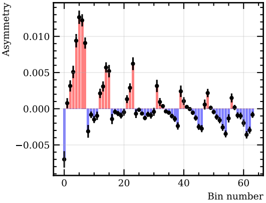
Systematic uncertainties - Vertex Locator misalignment

- We need to control any systematics that could introduce bias in $\sin\chi$:
- 1. Vertex Locator (VELO) misalignment
  $\rightarrow$ reco angles from PV and BV



$\pm 5\,\mu\mathrm{m}$ displacement

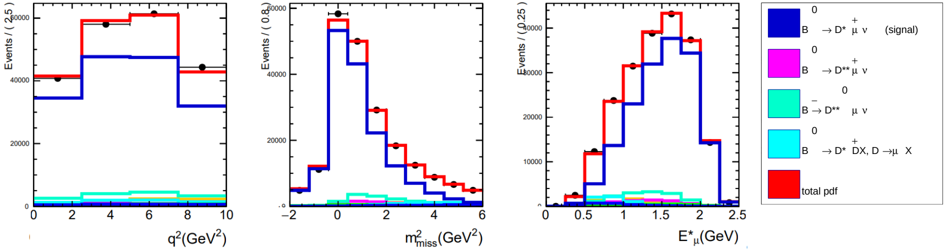




- Asymmetry due to VELO misalignment up to $\sim$1% and different pattern than "true" one, can be included in the fit.
- Possibility to correct misalignment at $\sim 1\mu m$ level using control samples.

Systematic uncertainties - *CP*-Violation in backgrounds

2. 3D background template fit



- $q^2 = (p_B - p_{D^*})^2$
- $m^2_{\mathrm{miss}} = (p^\mu_B - p^\mu_{D^*} - p^\mu_\mu)^2$ missing mass squared
- E^*_μ muon energy

- Signal purity in data sample about 80%
- Backgrounds where *CP*-Violation is possible are $B \to D^{**}\mu\nu$ modes ($\sim$10%) and double charm, i.e. $B \to D^{(*)}D_s^{(*)}$ ($\sim$5%)

Conclusions and outlook

Conclusions:

- $B^0 \to D^{*+}\mu^-\overline{\nu}_\mu$: direct CPV from angular distribution. Complementary to $R(D, D^*)$ $\to$ sensitive to same NP but with different systematics
- Missing ν $\to$ reconstruct angles from decay topology and better resolution with kinematic refit
- Sensitivity to *CP*-asymmetry $\to$ a few % with stat error $\sim$ 0.1%. Fit asymmetry with NP templates.
- Systematic uncertainties - detector misalignments, *CP*-Violation in backgrounds

Outlook:

- Estimate systematic due to *CP*-Violation in backgrounds
- Systematic effects coming from parity-odd detector efficiencies

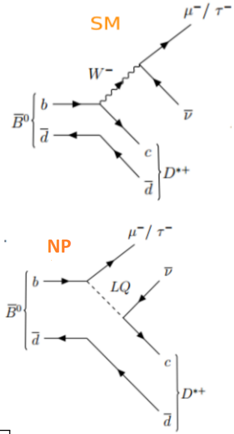
BACK-UP SLIDES

Introduction - NP Effective Hamiltonian

- Effective field theory for $b \to c\ell\overline{\nu}$ decays

$$\mathcal{H}_{eff} = \mathcal{H}_{eff}^{NP} + \mathcal{H}_{eff}^{SM} = \frac{G_F V_{cb}}{\sqrt{2}}\left(\sum_i g_i \mathcal{O}_i + \mathcal{O}_L\right)$$

$$\mathcal{O}_S = \overline{c}b\ \ell(1-\gamma_5)\nu$$
$$\mathcal{O}_P = \overline{c}\gamma_5 b\ \ell(1-\gamma_5)\nu$$
$$\mathcal{O}_L = \overline{c}\gamma^\mu(1-\gamma_5)b\ \ell\gamma_\mu(1-\gamma_5)\nu$$
$$\mathcal{O}_R = \overline{c}\gamma^\mu(1+\gamma_5)b\ \ell\gamma_\mu(1-\gamma_5)\nu$$
$$\mathcal{O}_T = \overline{c}\sigma^{\mu\nu}(1-\gamma_5)b\ \ell\sigma_{\mu\nu}(1-\gamma_5)\nu$$



- $SM: g_S = g_P = g_L = g_R = g_T = 0;\ \mathcal{H}_{eff}^{SM} \propto \mathcal{O}_L$
- Couplings g_L, g_R, g_S, g_P, g_T can be complex.

Triple products

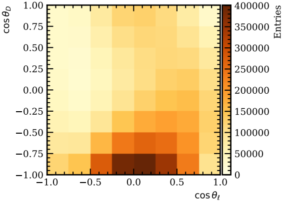
Coefficient	Coupling	Angular function
$\mathrm{Im}(\mathcal{A}_\perp \mathcal{A}_0^*)$	$\mathrm{Im}[(1+g_L+g_R)(1+g_L-g_R)^*]$	$-\sqrt{2}\sin 2\theta_\ell \sin 2\theta^* \sin\chi$
$\mathrm{Im}(\mathcal{A}_\parallel \mathcal{A}_\perp^*)$	$\mathrm{Im}[(1+g_L-g_R)(1+g_L+g_R)^*]$	$2\sin^2\theta_\ell \sin^2\theta^* \sin 2\chi$
$\mathrm{Im}(\mathcal{A}_{SP} \mathcal{A}_{\perp,T}^*)$	$\mathrm{Im}(g_P g_T^*)$	$-8\sqrt{2}\sin\theta_\ell \sin 2\theta^* \sin\chi$
$\mathrm{Im}(\mathcal{A}_0 \mathcal{A}_\parallel^*)$	$\mathrm{Im}[(1+g_L-g_R)(1+g_L+g_R)^*]$	$-2\sqrt{2}\sin\theta_\ell \sin 2\theta^* \sin\chi$

- Parity Violation $\rightarrow$ if amplitudes (A_i, A_j) have different strong but same weak phase (can appear in SM).
- CP-violation $\rightarrow$ if amplitudes (A_i, A_j) have different weak but same strong phase **(can appear only in NP)**.

Plan to measure these terms in data $\rightarrow$ constrain g_R, g_T, g_P NP couplings

CP asymmetries (SM MC)

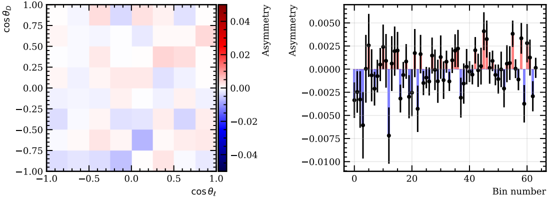
MC sample size $\sim$ 2x the expected dataset of Run 2. Error bars $\sim$ 0.1%



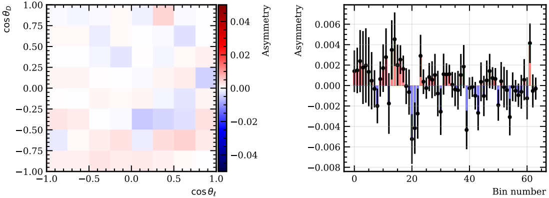
Unweighted density

$\cos\theta_D, \cos\theta_\ell$

"Up-down asymmetry", $w \propto \sin\chi$:



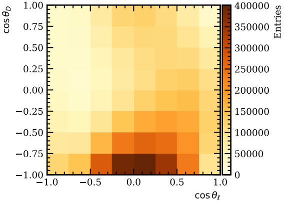
"Quadratic asymmetry", $w \propto \sin 2\chi$:



No CPV as expected (no NP $\rightarrow$ no weak phases).

P asymmetries (SM MC)

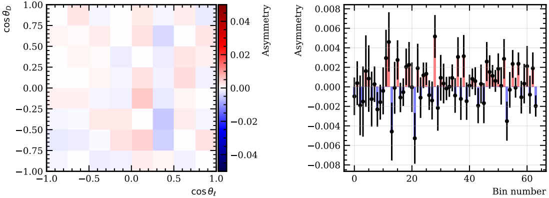
MC sample size $\sim$ 2x the expected dataset of Run 2. Error bars $\sim$ 0.1%



Unweighted density

$\cos\theta_D, \cos\theta_\ell$

"Up-down asymmetry", $w \propto \sin\chi$:



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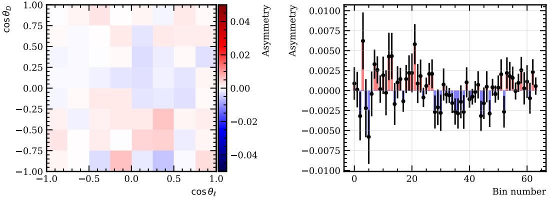
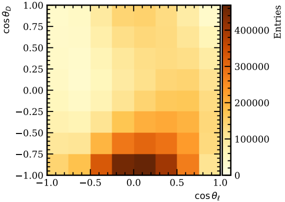


No PV either (all formfactors are real $\rightarrow$ no strong phases)

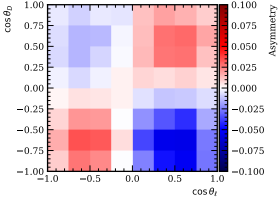
CP asymmetries: adding right-handed current

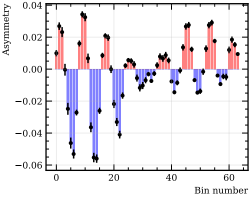
The same MC reweighted with RH current NP, $g_R = 0.3i$



Unweighted density
$\cos\theta_D, \cos\theta_\ell$

"Up-down asymmetry", $w \propto \sin\chi$:





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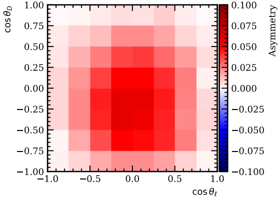
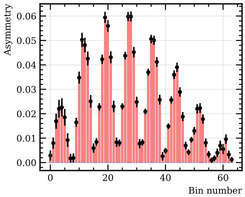
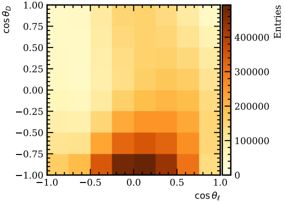




Specific pattern in both up-down and quadratic asymmetry terms.

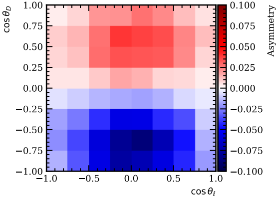
CP asymmetries: interference of tensor and pseudoscalar

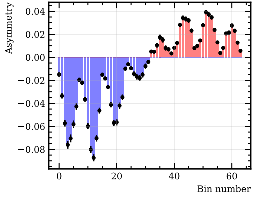
SM MC reweighted with combination of P and T NP, $g_P g_T^* = 0.1i$



Unweighted density
$\cos\theta_D, \cos\theta_\ell$

"Up-down asymmetry", $w \propto \sin\chi$:





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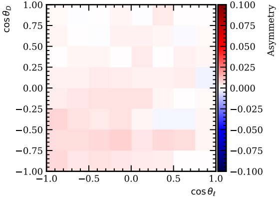

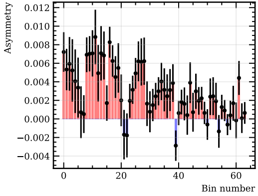

Large up-down asymmetry, small contribution to quadratic ("leakage" due to asymmetric efficiency in $\cos\chi$?)