Search for CPV in B$\rightarrow$ $\mathrm{D}^*\mu\bar{\nu_\mu}$ at LHCb

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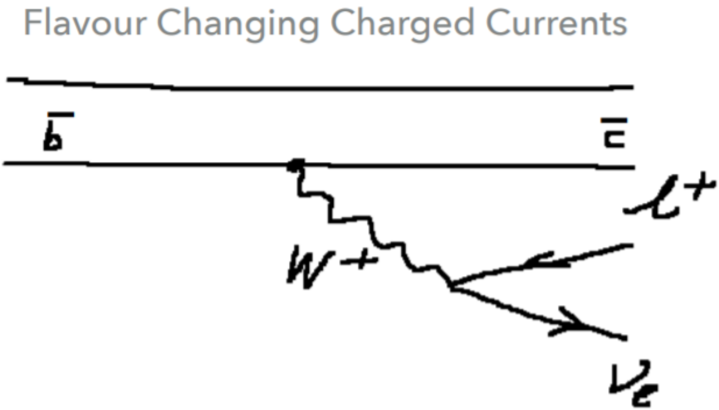
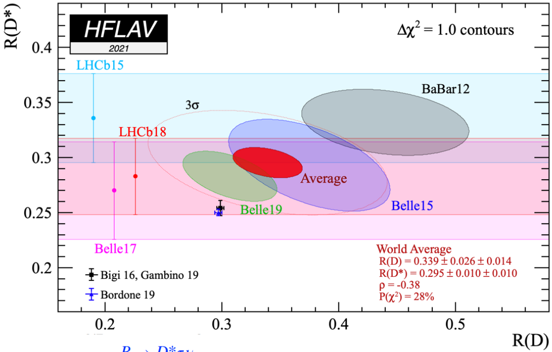
Introduction - Semileptonic B decays



- Tree level transitions: $b \to c\ell\nu$
- $\sim$ 10% of B-decays are semileptonic
- Experimental challenge: neutrinos in the final state

Introduction - Motivation

3.4σ above SM



$$R(D^*) = \frac{B \to D^* \tau \nu}{B \to D^* \mu \nu}$$

- Couplings of (e, μ, τ) should be identical in SM (LFU)
- b-anomalies (deviations from SM predictions) in <u>$b \to c\ell\nu$</u> transitions: hints of NP
- $R(D)$, $R(D^*)$ can be explained by different NP models

Introduction - CPV in $b \to c\ell\nu$ decays

- We take a different approach $\rightarrow$ sensitive to same NP as $R(D)$, $R(D^*)$, but with different set of systematic uncertainties
- This project: Search for CPV in $B \to \mathrm{D}^*\mu\nu$, first analysis of **direct CPV** in a semileptonic decay.
- No CPV in SM in SL decays $\rightarrow$ theoretically clean probe of NP.
- Sensitive to effects that could fake CP asymmetry

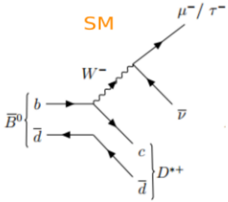
- Although NP should couple more to τ due to larger mass, same NP may affect μ. Start with μ instead of τ channel: more statistics, easier analysis (τ reconstruction is difficult).
- Can still provide meaningful constraints for NP and distinguish between NP models.

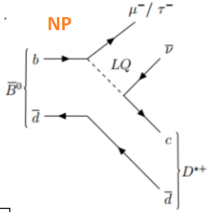
Introduction - NP Effective Hamiltonian

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

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

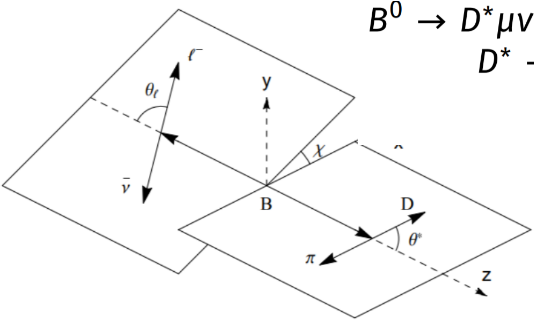
$$\mathcal{O}_S = \overline{c}b\ \ell(1-\gamma_5)\nu$$
$$\mathcal{O}_P = \overline{c}\gamma_5 b\ \ell(1-\gamma_5)\nu$$
$$\mathcal{O}_L = \overline{c}\gamma^\mu(1-\gamma_5)b\ \ell\gamma_\mu(1-\gamma_5)\nu$$
$$\mathcal{O}_R = \overline{c}\gamma^\mu(1+\gamma_5)b\ \ell\gamma_\mu(1-\gamma_5)\nu$$
$$\mathcal{O}_T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





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

Helicity angles



$B^0 \rightarrow D^*\mu\nu$
$D^* \rightarrow D^0\pi_s$
$D^0 \rightarrow K\pi$

- $\mathrm{B}^0 \rightarrow \mathrm{D}^*(\rightarrow \mathrm{D}^0\pi)\mu\bar{\nu_\mu}$ differential decay rate is function of 4 kinematic parameters: 3 helicity angles $(\theta_\ell, \theta_D, \chi)$ and q^2
- χ is angle between the two decay planes

Parity- and CP-violation

Angular distribution of $B \to \mathrm{D}^* \mu\nu$ can contain terms $\propto \sin\chi$.

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

Simplified view $\to$ 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 $\overline{\mathrm{B}}^0$

Both *P* and *CP* asymmetries can be nonzero

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

Binned CPV fit

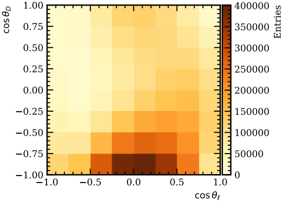
- We reconstruct all angles, how do we measure CPV ?
- Deal with $\cos\theta_\ell$ and $\cos\theta_D$ as 2D binned histograms and weigh them by $\sin\chi$ and $\sin 2\chi$ to measure asymmetry
- 2 sets of observables: *P*-asymmetries and *CP*-asymmetries

- Simulation generated with SM $\rightarrow$ inject NP
- Estimate asymmetry effect in SM and NP

- Plan to perform 2D binned template fit of these asymmetries in data, with NP templates from NP reweighted simulation.

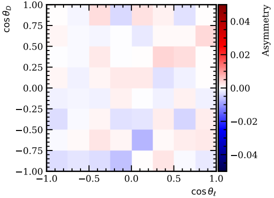
CP asymmetries (SM MC)

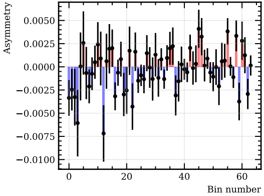
MC sample size $\sim$ 2x the expected dataset of Run 2.



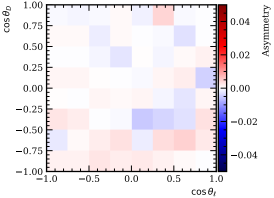
Unweighted density
$\cos\theta_D, \cos\theta_\ell$

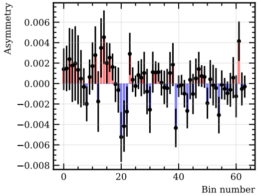
"Up-down asymmetry", $w \propto \sin\chi$:





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

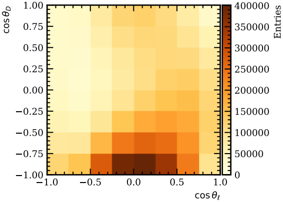




No CPV as expected (no NP $\rightarrow$ no weak phases).

P asymmetries (SM MC)

MC sample size $\sim$ 2x the expected dataset of Run 2.



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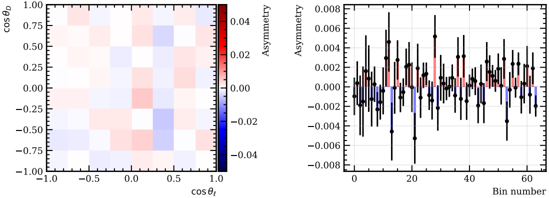

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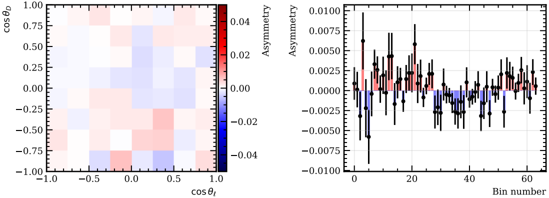
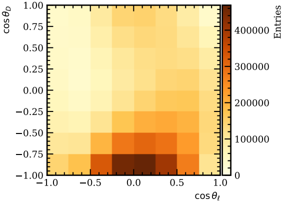


No PV either (all formfactors are real $\rightarrow$ no strong phases)

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



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

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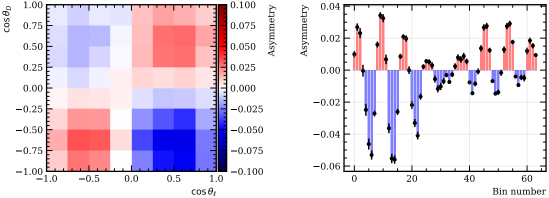

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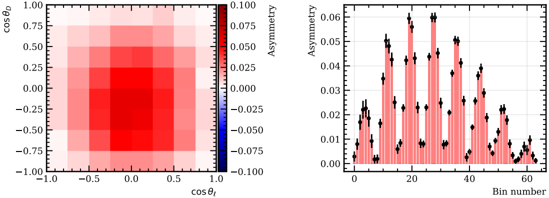
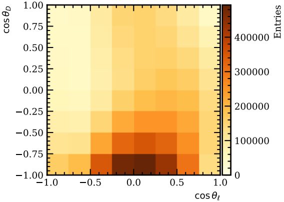


Specific pattern in both up-down and quadratic asymmetry terms.

CP asymmetries: interference of tensor and pseudoscalar

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



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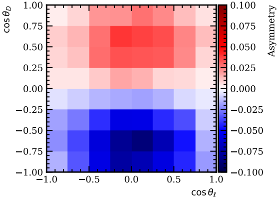

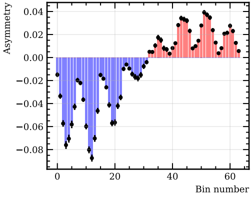

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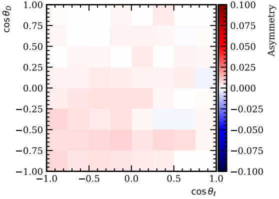
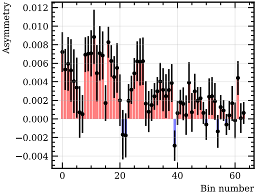
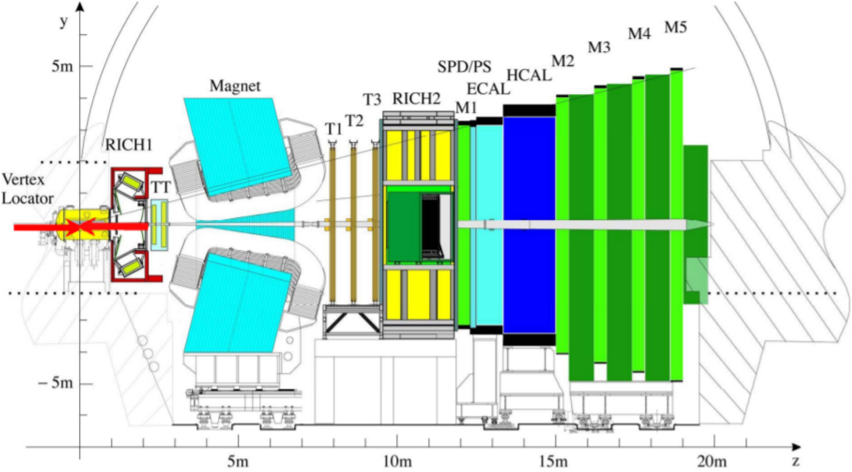




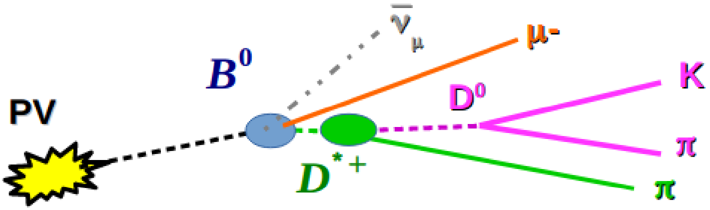
Large up-down asymmetry, small contribution to quadratic ("leakage" due to asymmetric efficiency in $\cos\chi$?)

LHCb detector



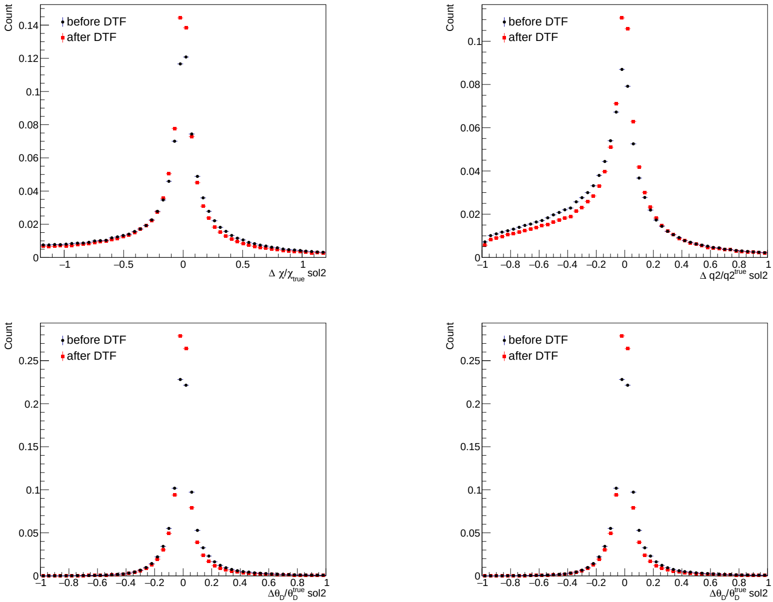
- b-hadrons produced in pairs ($b\bar{b}$) in the same forward cone
- Excellent vertex finding, momentum resolution, PID

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 $(\theta_\ell, \theta_D, \chi, q^2)$

Angle resolutions before and after refit



Systematic uncertainties

We would need to control any systematics that could introduce non-zero $\sin\chi$ terms

Non-zero $\sin\chi$ terms: what does it practically mean?

- $\sin\chi = +1$: ν flies "up" wrt. observable $D^0\pi^+\mu^-$ plane ($\uparrow$).
- $\sin\chi = -1$: ν flies "down" ($\downarrow$)
- Term $\propto \sin\chi$: up-down asymmetry $(N_\uparrow - N_\downarrow)/N_{\rm tot}$.

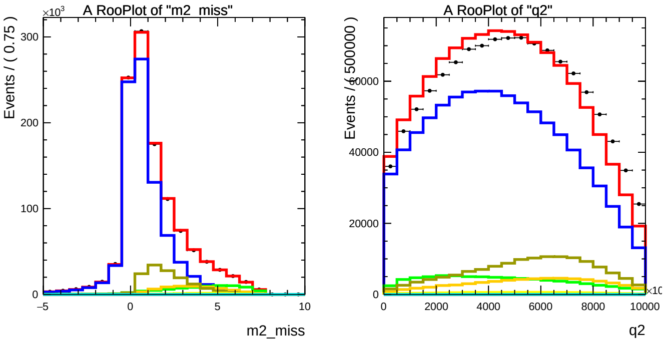
ν direction is reconstructed from topology of PV and secondary vertices.

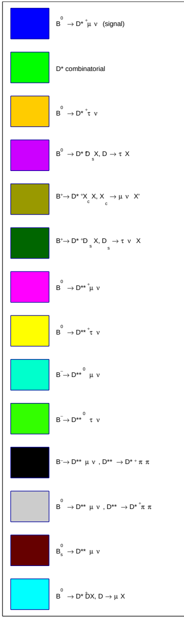
- ν "up" $\Leftrightarrow$ PV "below" $D^0\pi^+\mu^-$ plane
- ν "down" $\Leftrightarrow$ PV "above" $D^0\pi^+\mu^-$ plane

What experimental effects can introduce non-zero "PV below-above" asymmetry?

- CPV in backgrounds
- Vertex Locator misalignment
- Asymmetry of tracking efficiency

Preliminary 2D fit - background estimation

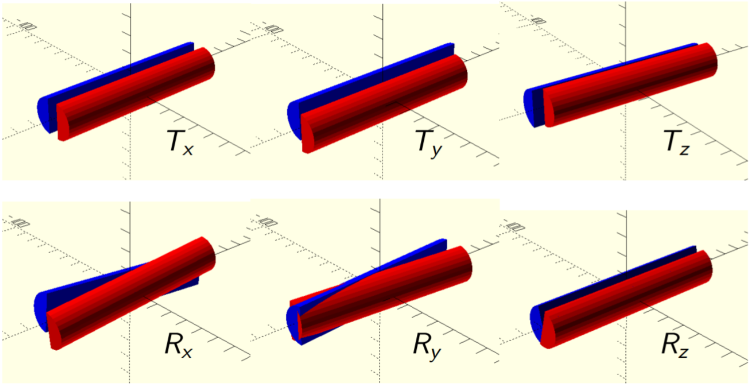




- Squared missing invariant mass due to ν
- q^2 - invariant mass of the (μ, ν) combination

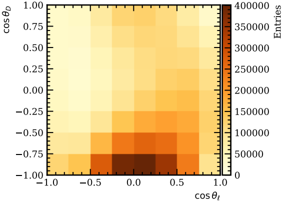
- **MC needs corrections (PID, trigger, kinematics) + external bkg constraints in the fit to adjust templates**
- Sample purity about 80%
- Background yields needed to assign systematics for CPV in bkgs

Vertex Locator misalignment



- Displacements of the two halves wrt each other can introduce bias in χ
- Expect T_y and R_x to show largest source of bias
- We are looking for ‘twists’ in the decay rate, ‘twisted’ detector can give fake CPV

SM MC, track parameters ($\pm 5\,\mu$m displacement, $\times 5$ larger than alignment precision) $\rightarrow$ displace tracks by hand as if Vertex Locator is misaligned



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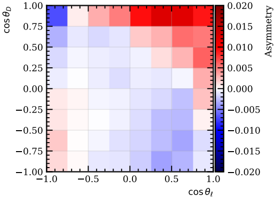

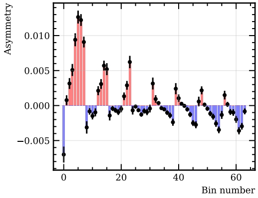

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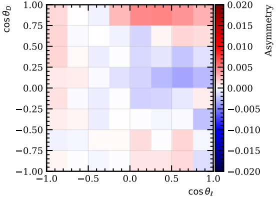

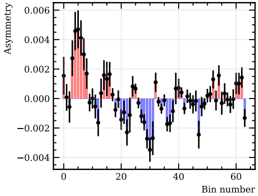

Different pattern from "true" CPV, can be included in the fit.

Conclusions and outlook

Conclusions:

- $B \to \mathrm{D}^*\mu\nu$: direct CPV from angular distribution.
- Sensitivity to *CPV* $\to$ a few % with stat error $\sim$ 0.1%
- Angle reconstruction from decay topology and 10-20% improvement with kinematic refit
- Systematic uncertainties - CPV in backgrounds, detector misalignments

Outlook:

- Perform 2D binned template fit for *P*- and *CP*-asymmetries
- Estimate all systematics: CPV in backgrounds and non-uniform detector efficiencies