Search for CP-violation in $B \to D^* \mu\nu$ at LHCb

Vlad Dedu

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

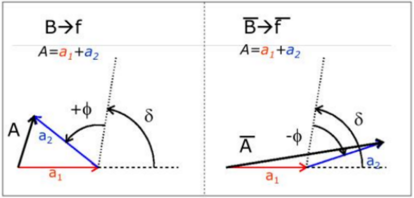
- Semileptonic decays are interesting probes of NP
- $(RD - RD^*)$ anomalies can be explained by different NP models in $b \to c\ell\nu$

- This project: Search for CPV in $B \to \mathrm{D}^*\ell\nu$, first analysis of CPV in a SL decay. Closely related to the angular analysis, but focus only on CPV terms.
- No CPV in SM in SL decays $\to$ theoretically clean probe of NP.
- Sensitive to effects that could fake CP asymmetry

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

Introduction - CP violation

- Search for Charge Parity Violation in $B \to \mathrm{D}^{*}\ell\nu$ ($b \to c\ell\nu$) analysis



- In SM $\mathrm{B}^{0} \to \mathrm{D}^{*}\ell\bar{\nu}_{\ell}$ has only 1 amplitude $\to$ **no CPV**
- NP amplitude will have different weak phase but no strong phase (QCD amplitudes are the same for SM and NP)
  $\to$ **not enough for direct CPV**

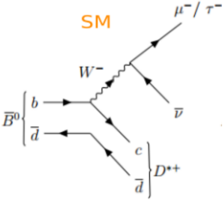
Possible ways to obtain CPV in SL decays:

- Four-(or more)-body B decays: Triple product asymmetries
- Interference of decay amplitudes with overlapping resonances, i.e. $B \to D^{**}\mu\nu$, with $D^{**} = D_0^*, D_1, D_2^*$

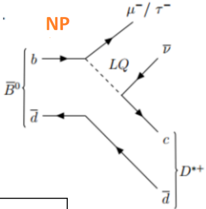
Introduction - Effective Hamiltonian

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

$$\mathcal{H}_{eff}^{NP} = \frac{G_F V_{cb}}{\sqrt{2}} \sum_i g_i \mathcal{O}_i + \text{h.c.},$$

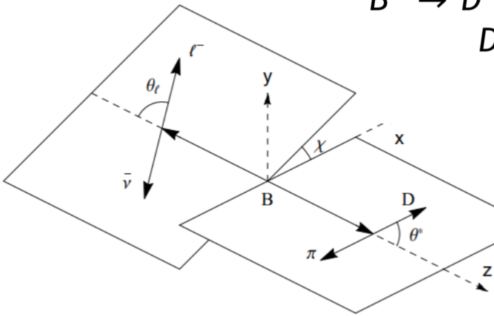


$$\mathcal{O}_S = \overline{c} b \ \ell(1-\gamma_5)\nu$$
$$\mathcal{O}_P = \overline{c}\gamma_5 b \ \ell(1-\gamma_5)\nu$$
$$\mathcal{O}_L = \overline{c}\gamma^\mu(1-\gamma_5) b \ \ell\gamma_\mu(1-\gamma_5)\nu$$
$$\mathcal{O}_R = \overline{c}\gamma^\mu(1+\gamma_5) b \ \ell\gamma_\mu(1-\gamma_5)\nu$$
$$\mathcal{O}_T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



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

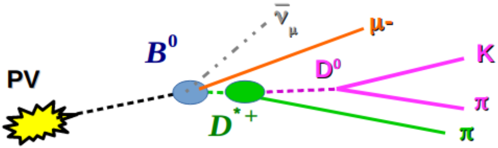
Helicity angles



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

- $\mathrm{B}^0 \rightarrow \mathrm{D}^*(\rightarrow \mathrm{D}^0\pi)\mu\bar{\nu_\mu}$ decay is described by 4 kinematic parameters: 3 helicity angles $(\theta_\ell, \theta_D, \chi)$ and q^2

Neutrino reconstruction

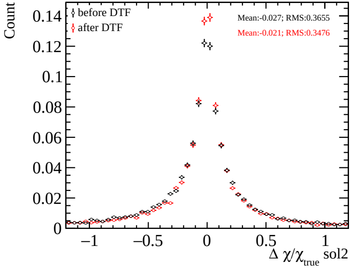


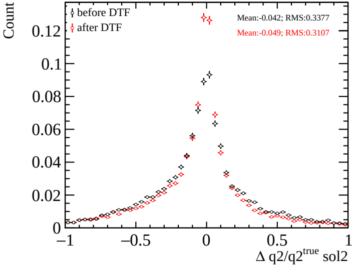
- Kinematic reco: Estimate B, ν momenta from decay topology using the B line of flight between PV and b-vertex [D. Hill et al]

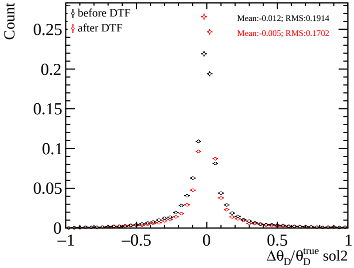
$$|\vec{p}_{B^0}| = \frac{(m_Y^2 + m_{B^0}^2)|\vec{p}_Y|\cos\theta_{B^0,Y} \pm E_Y\sqrt{(m_{B^0}^2 - m_Y^2)^2 - 4m_{B^0}^2|\vec{p}_Y|^2\sin^2\theta_{B^0,Y}}}{2(E_Y^2 - |\vec{p}_Y|^2\cos^2\theta_{B^0,Y})}$$

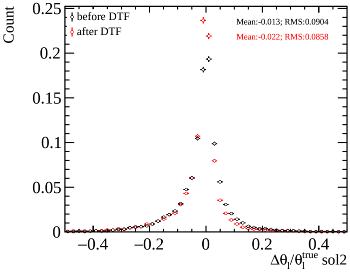
- Run full refit (DecayTreeFit) of the decay tree including all possible info: missing ν, vertex, mass constraints
- Improve precision in reconstructing quantities of interest $(\theta_L, \theta_D, \chi, q^2)$

Angle resolutions after DTF - simulation









Triple products

$$\frac{d^4\Gamma}{dq^2\, d\cos\theta_\ell\, d\cos\theta^*\, d\chi} = \frac{3}{8\pi}\frac{G_F^2|V_{cb}|^2(q^2-m_\ell^2)^2|p_{D^*}|}{2^8\pi^3 m_B^2 q^2} \times \mathcal{B}(D^*\to D\pi)\left(N_1 + \frac{m_\ell}{\sqrt{q^2}}N_2 + \frac{m_\ell^2}{q^2}N_3\right)$$

- Angular distribution derived from most general $\mathcal{H}_{eff}^{NP}$ [D.London et al]
- NP couplings → CPV terms (triple products) $\propto \sin\chi$
- Same magnitude and sign for $B0$ and $\overline{B0}$

Not suppressed	Coupling	Angular Function
$\mathrm{Im}(\mathcal{A}_\perp\mathcal{A}_0^*)$	$\mathrm{Im}[(1+g_L+g_R)(1+g_L-g_R)^*]$	$-\sqrt{2}\sin 2\theta_\ell \sin 2\theta^* \sin\chi$
$\mathrm{Im}(\mathcal{A}_\parallel\mathcal{A}_\perp^*)$	$\mathrm{Im}[(1+g_L-g_R)(1+g_L+g_R)^*]$	$2\sin^2\theta_\ell \sin^2\theta^* \sin 2\chi$
$\mathrm{Im}(\mathcal{A}_{SP}\mathcal{A}_{\perp,T}^*)$	$\mathrm{Im}(g_P g_T^*)$	$-8\sqrt{2}\sin\theta_\ell \sin 2\theta^* \sin\chi$
$\mathrm{Im}(\mathcal{A}_0\mathcal{A}_\parallel^*)$	$\mathrm{Im}[(1+g_L-g_R)(1+g_L+g_R)^*]$	$-2\sqrt{2}\sin\theta_\ell \sin 2\theta^* \sin\chi$

- Exploit orthogonality of Fourier terms and perform Fourier transformation of scattered data to obtain coefficient
- We construct a set of 50 orthogonal terms (up to 2nd order harmonics) → control terms

Sensitivity study - HAMMER

HAMMER

Helicity Amplitude Module
for Matrix Element Reweighting

[HAMMER website: paper, manual, git etc]

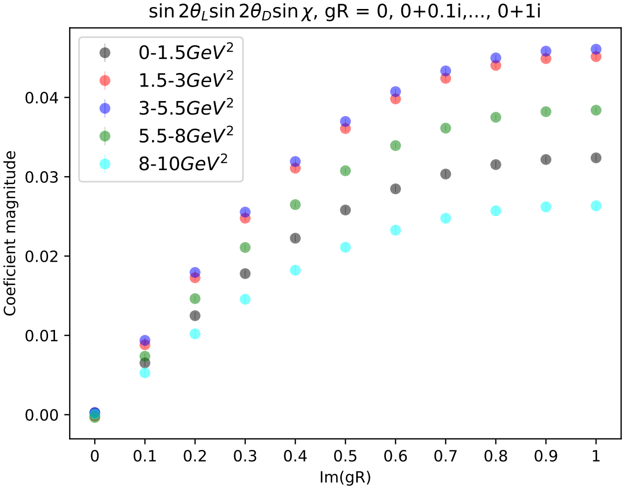
- "A fast and efficient means to reweight large MC samples to any desired NP, or to any description of the hadronic matrix elements"
- Set FF scheme (BLPR) and Wilson coefficients (complex) values

$B \to (D^* \to D\pi)\ell\nu$	$\texttt{ISGW2}^*$, $\texttt{BGL}^{*\ddagger}$, $\texttt{CLN}^{*\ddagger}$, $\texttt{BLPR}^{\ddagger}$

- Calculate weight to NP scenario for each event based on true 4-momenta and particle IDs

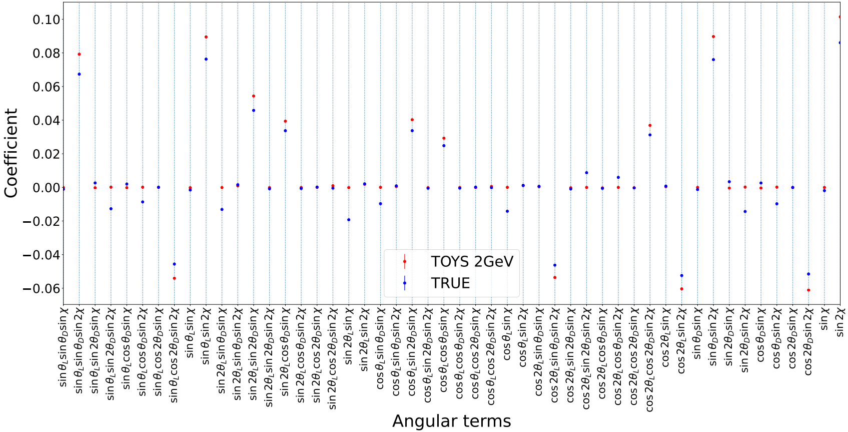
CPV terms. Sensitivity study with simulation

- Inject NP in MC with HAMMER (reweighs each event based on NP: $g_L, g_R, g_P, g_T \neq 0$)



Stat. error $\sim 0.1\%$

LHCb simulation true angles


Coefficient
0.10
0.08
0.06
0.04
0.02
0.00
−0.02
−0.04
−0.06
TOYS 2GeV
TRUE
$\sin\theta_L \sin\theta_D \sin\chi$
$\sin\theta_L \sin\theta_D \sin 2\chi$
$\sin\theta_L \sin 2\theta_D \sin\chi$
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$\cos\theta_D \sin\chi$
$\cos\theta_D \sin 2\chi$
$\cos 2\theta_D \sin\chi$
$\cos 2\theta_D \sin 2\chi$
$\sin\chi$
$\sin 2\chi$
Angular terms

Systematic uncertainties

We would need to control any systematics that could introduce "fake CP-asymmetry" at the 0.1% level

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

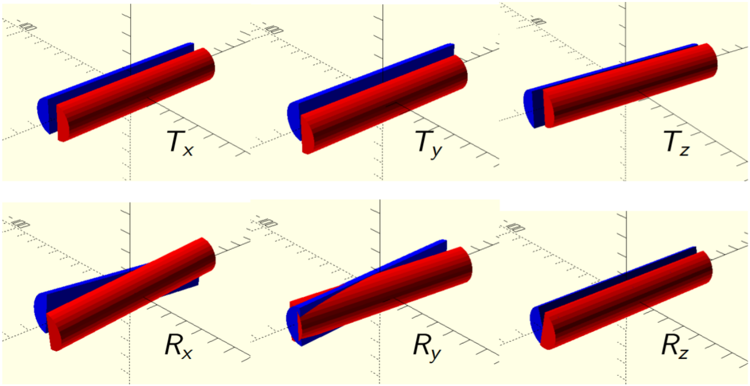
ν direction is reconstructed from topology of PV and secondary vertices.

- Term $\propto \sin\chi$: up-down asymmetry $(N_{\uparrow} - N_{\downarrow})/N_{\mathrm{tot}}$.
- ν "up" $\Leftrightarrow$ PV "below" $\mathrm{D}^0\pi^+\mu^-$ plane
- ν "down" $\Leftrightarrow$ PV "above" $\mathrm{D}^0\pi^+\mu^-$ plane

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

- CPV in backgrounds
- VELO misalignment
- Asymmetry of tracking efficiency

Systematic uncertainties - VELO misalignment



- Misalignments of VELO as a whole should not introduce bias in angles, but displacements of the two halves wrt each other can
- Expect T_y and R_x to show largest source of bias

Misalignment in VELO

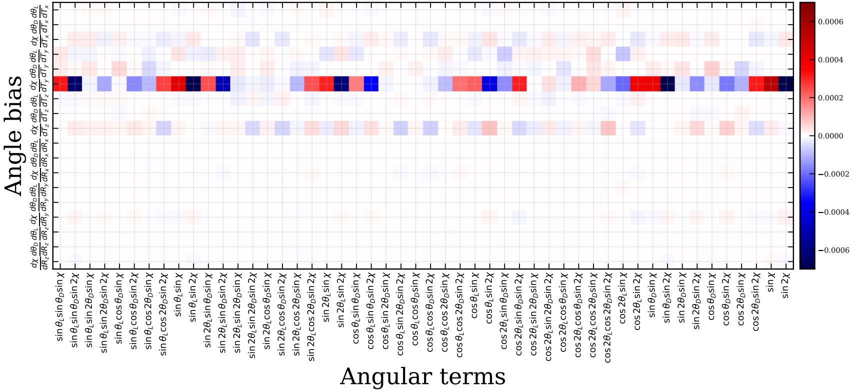
- VELO misalignment can affect the angles and introduce bias in CP asymmetry
- $\vec{\Theta} = \Theta_i \equiv (\theta_D, \theta_\ell, \chi, q^2)$, $P(\vec{\Theta})$ is an angular term

$$\boxed{A_{CP} = \frac{1}{N}\sum_{\alpha=1}^{N} P(\vec{\Theta}_\alpha) = \langle P(\vec{\Theta})\rangle}$$

$$\delta A_{CP} = \sum_k \rho_k \left\langle \frac{\partial P}{\partial \Theta_i}(\vec{\Theta}) \frac{\partial \Theta_i}{\partial \rho_k}(\vec{\Theta}) \right\rangle$$

- Calculate partial derivative for each event (α) by introducing small displacement in tracks i.e.:

$$\theta^{'}_{D,\alpha} = \theta_{D,\alpha} + \frac{\partial \theta_{D,\alpha}}{\partial \Delta x}\Delta x$$



- Typical VELO alignment precision: 1 μm for $T_{x,y}$, 3 μm for T_z, 3μrad in $R_{x,y}$, 10 μrad in R_z
- Largest source of bias is T_y, up to 0.05%
- Can use control terms to control misalignment systematics in a data-driven way

Conclusions and outlook

Conclusions:

- $B \to \mathrm{D}^*\mu\nu$: indirect CPV from angular distribution.
- MC study for sensitivity to CPV $\to$ a few % with stat error $\sim 0.1\%$
- Helicity angle resolution studies (10-20 % improvement with DTF)
- Systematic uncertainties - detector misalignments

Outlook:

- Estimate all systematics: CPV in backgrounds and non-uniform detector efficiencies (similar approach as for misalignment)
- Look in data
- τ channel

BACK-UP SLIDES

Fourier transform method

- $P(\theta_\ell, \theta_D, \chi) = \sum_n C_n F_n(\theta_\ell, \theta_D, \chi)$, F_n are all orthogonal
- $C_k = \int P(\theta_\ell, \theta_D, \chi) F_k(\theta_\ell, \theta_D, \chi) d\theta_\ell d\theta_D d\chi$
- $P(\theta_\ell, \theta_D, \chi) = \frac{1}{n} \sum_{i=1}^{n} \delta(\theta_\ell - \theta_\ell^{(i)}) \delta(\theta_D - \theta_D^{(i)}) \delta(\chi - \chi^{(i)})$
- $\boxed{C_k = \frac{1}{n} \sum_{i=1}^{n} F_k(\theta_\ell^{(i)}, \theta_D^{(i)}, \chi^{(i)})}$
- Example:
- $F_k(\theta_\ell, \theta_D, \chi) = \sin 2\theta_\ell \sin 2\theta_D \sin \chi$
- $C_k = \frac{1}{n} \sum_{i=1}^{n} (\sin 2\theta_\ell^{(i)} \sin 2\theta_D^{(i)} \sin \chi^{(i)})$