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

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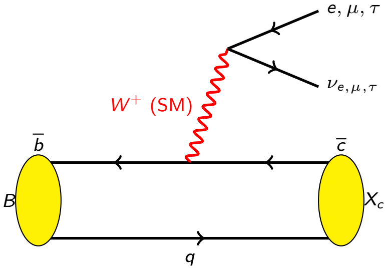
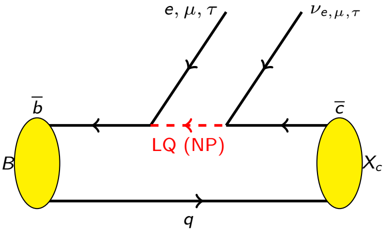
IphU days 20.01.2023

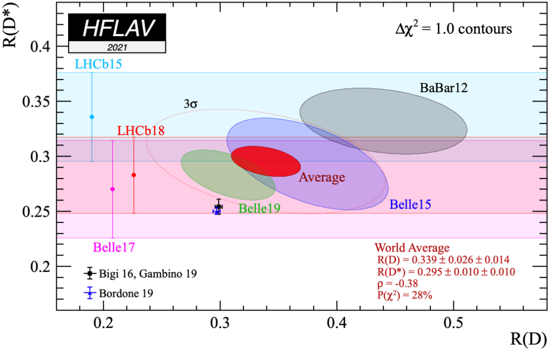
Introduction - Semileptonic B decays





- 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

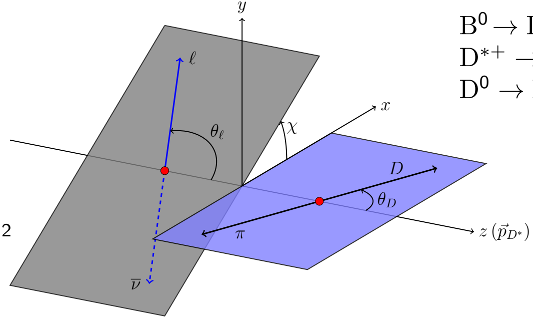


$> 3\sigma$ tension between SM and exp

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

- Couplings of (e, μ, τ) should be identical in SM (Lepton Flavor Universality)
- b-anomalies in $\underline{b \to c\ell\nu}$ transitions: hints of NP (LQ, W', H^+ etc)
- Complementary measurements needed → e.g. angular observables

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



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

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

$$d\Gamma = (P_{even} + P_{odd})dq^2 d\cos\theta_D d\cos\theta_\ell d\chi$$

- We study $d\Gamma$ with Run 2 (2016-2018) LHCb data
- 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.
- CPV $\Leftrightarrow$ two amplitudes with different weak and strong phases. SL decays have a single tree-level amplitude in SM
- *CP*-Violating terms can only appear with NP $\to$ *Null test*

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

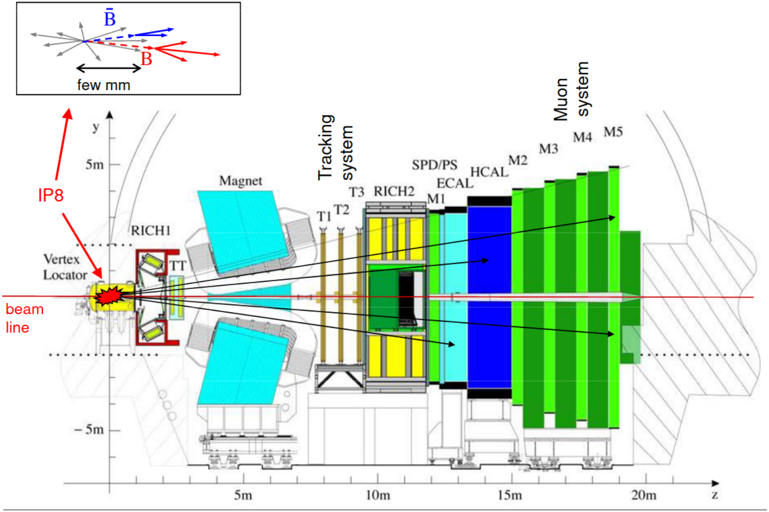
$\overline{\mathrm{B}}^0$: $\overline{a} = \frac{\overline{N}(\sin\chi>0) - \overline{N}(\sin\chi<0)}{\overline{N}(\sin\chi>0) + \overline{N}(\sin\chi<0)}$

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

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

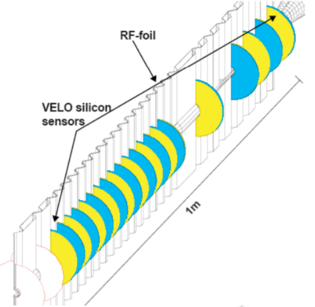
- Distinguish between *P*- and *CP*-violation by looking at both B^0 and $\overline{\mathrm{B}}^0$
- *P* asymmetry can be nonzero in the SM
- *CP* asymmetry can be nonzero only if NP coupling is present.
- In $\mathrm{B}^0 \rightarrow \mathrm{D}^{*+}\mu^-\overline{\nu}_\mu$ either Right-Handed (RH) vector or interference between Pseudoscalar (P) and Tensor (T) [D.London et al]

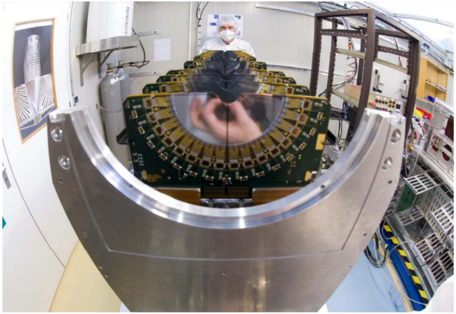
LHCb detector



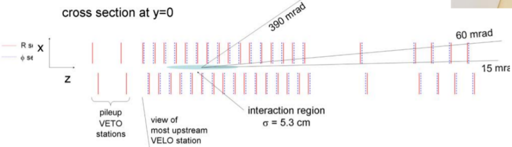
- b-hadrons produced in pairs ($b\bar{b}$) in the same forward direction
- Excellent vertex finding, momentum resolution, particle identification

LHCb detector - VErtex LOcator (VELO)



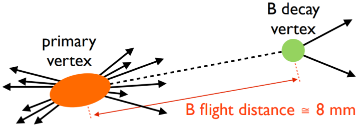


cross section at y=0

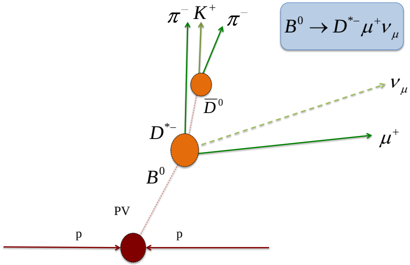


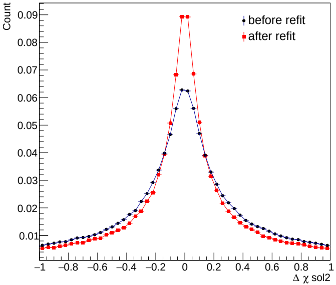
VELO fully closed (stable beam)

VELO fully open



Neutrino reconstruction



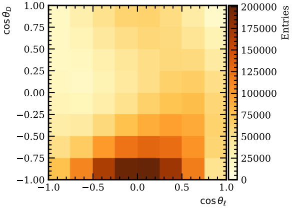


- ν is not visible in the detector
- Kinematic reconstruction of B (ν) from decay topology (very precise vertexing from VELO)
- Run full refit of the decay tree including all possible kinematic information (including missing ν) and all possible correlations
- Improve precision in reconstructing quantities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

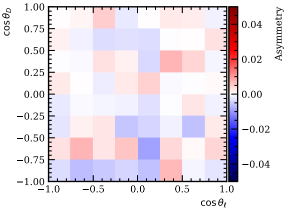
CP asymmetries (SM MC)

- 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 $\sim 0.1\%$)

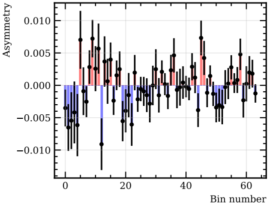
unweighted 2D density $\cos\theta_D, \cos\theta_\ell$



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

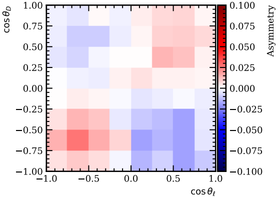


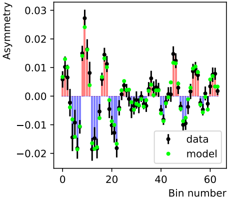
flattened to 1D asymmetry



CP asymmetries: adding NP couplings and fit

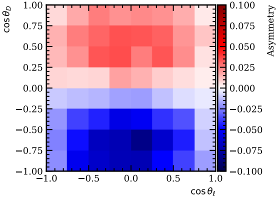
CP-asymmetry plots in case of RH NP, $g_R = 0.1i$ (asym up to 3%)

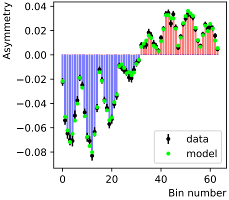




Im(g_R) Stat err from fit $\sim$ 4e-3

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

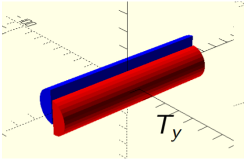
With NP, CP-asymmetry becomes nonzero. Specific pattern of asymmetry in both NP cases → use them as templates to fit for asymmetry in data.

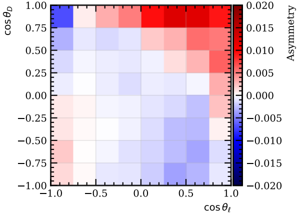
Systematic uncertainties - Vertex Locator misalignment

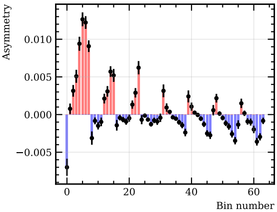
- We need to control any parity-odd effects that introduce bias in $\sin\chi$:

- Vertex Locator (VELO) misalignment
  $\rightarrow$ reco angles from PV and BV

$\pm 5\,\mu$m displacement



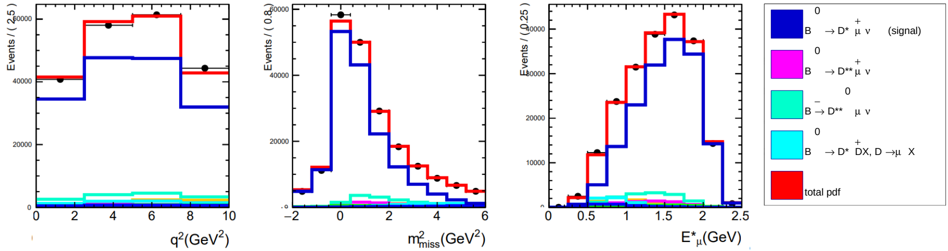




- Asymmetry due to VELO misalignment up to $\sim$1% and different pattern than "true" one, can be included in the fit. Bias on NP couplings $\sim$ 0.3%.
- Possibility to correct misalignment at $\sim 1\mu m$ level using control samples.

Systematic uncertainties - Backgrounds

3D background template fit

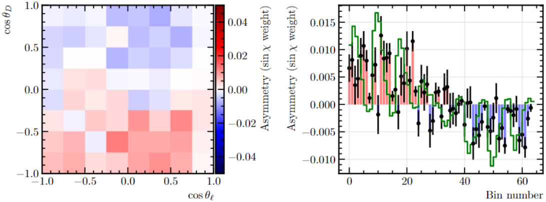


- $q^2 = (p_B - p_{D^*})^2$
- $m^2_{\text{miss}} = (p^\mu_B - p^\mu_{D^*} - p^\mu_\mu)^2$ missing mass squared
- E^*_μ muon energy in B^0 rest frame

- Signal purity in data sample about 80%
- Largest backgrounds are $B \to D^{**}\mu\nu$ modes ($\sim$20%) and double charm, i.e. $B \to D^{(*)} D^{(*)}_s$ ($\sim$5%)

Systematic uncertainties - Backgrounds

- **SL background**: $B \to D^{**}\mu\nu$, $D^{**} \to D^*\pi$ where D^{**} can be $D_1(2420), D_1'(2430), D_2^*(2460)$. Strong phases can appear due to interference of these excited resonances [Aloni et al]$\to$ P-asymmetry



- Toy study with varying strong phase values shows maximum P-asymmetry bias $\sim 1\%$. Max NP coupling bias up to 1%
- SL decays exhibit CP-asymmetry only with NP.

- **Double charm background**: $B \to D^* D_s^*$, $D_s^* \to D_s\gamma$, $D_s \to \mu\nu X$ is most significant. Amplitude structure measured by [LHCb]. No bias on NP couplings from P-asymmetry
- CP-asymmetry is possible in SM in double charm but very suppressed by $\left|\frac{V_{ub}}{V_{cb}}\right|$

Systematic uncertainties - *P*-odd efficiency terms

- Other instrumentantion effects such as non-uniform reconstruction efficiencies can introduce *P*-odd effects in the decay distribution
- Single track terms if efficiency depends on track direction $\vec{t}$ and origin coordinates $\vec{r}$. Proportional to $\vec{r} \times \vec{t}$ which is a *P*-odd quantity
- Two-track terms if efficiency is $f(\vec{t})$ but different for different particle species i.e. reconstruction efficiencies of particle identification subdetectors

- These effects can be addressed by using a control sample that has no *P*-odd component even with NP and has similar final state
- Good choice would be $\mathrm{B}^0 \to \mathrm{D}^- \mu^+ \nu_\mu$ with $\mathrm{D}^- \to \mathrm{K}^+ \pi^- \pi^-$ since D^- has spin-0 (*P*-even) and same particles in the final state (μ, K, π, π)
- Control sample has $\sim 3\times$ statistics of signal sample $\to$ can control these instrumentation effects at level of stat uncertainty or lower

Conclusions and outlook

Conclusions:

- $\mathrm{B}^0 \to \mathrm{D}^{*+}\mu^-\overline{\nu}_\mu$: direct CPV from angular distribution. Complementary to $R(D, D^*)$ $\to$ sensitive to same NP but with different systematics
- Sensitivity to NP couplings $\to$ $\Delta Im(g_R)_{stat} \sim 0.4\%$ and $\Delta Im(g_p g_T^*)_{stat} \sim 0.1\%$
- Systematics - *P*-odd effect in backgrounds small and under control (bias of $\Delta Im(g_R) \sim 1\%$ in D^{**} and $\Delta Im(g_R) \sim 0$ in double charm bkg)
- Systematics - *P*-odd effect from detector misalignment $\Delta Im(g_R) \sim 0.3\%$.

Outlook:

- Systematics - *P*-odd effect from non-uniform efficiency can be controlled with large control sample at the level of stat. uncertainty.

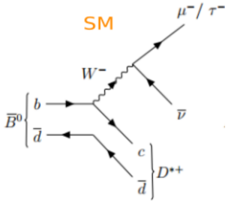
BACK-UP SLIDES

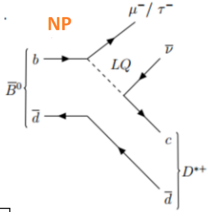
Introduction - NP Effective Hamiltonian

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

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

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





- 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

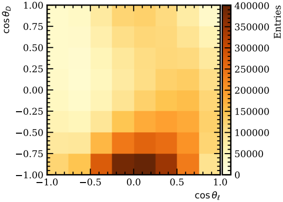
Coefficient	Coupling	Angular function
$\mathrm{Im}(\mathcal{A}_\perp \mathcal{A}_0^*)$	$\mathrm{Im}[(1+g_L+g_R)(1+g_L-g_R)^*]$	$-\sqrt{2}\sin 2\theta_\ell \sin 2\theta^* \sin\chi$
$\mathrm{Im}(\mathcal{A}_\parallel \mathcal{A}_\perp^*)$	$\mathrm{Im}[(1+g_L-g_R)(1+g_L+g_R)^*]$	$2\sin^2\theta_\ell \sin^2\theta^*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

- 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

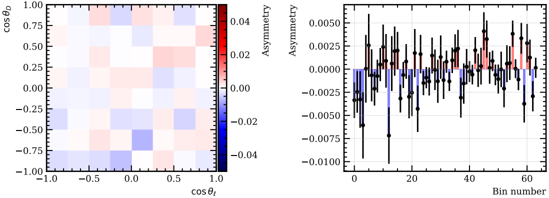
CP asymmetries (SM MC)

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

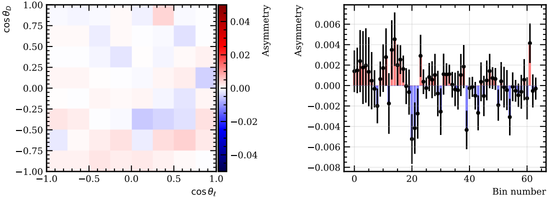


Unweighted density
$\cos\theta_D, \cos\theta_\ell$

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



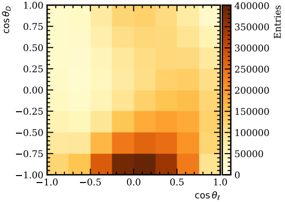
"Quadratic asymmetry", $w \propto \sin 2\chi$:



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

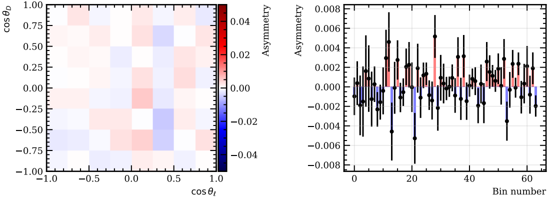
P asymmetries (SM MC)

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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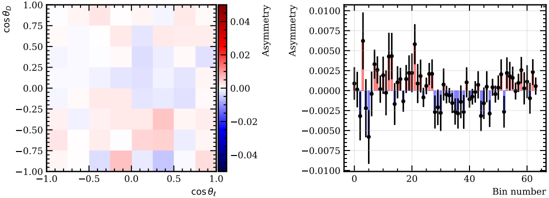
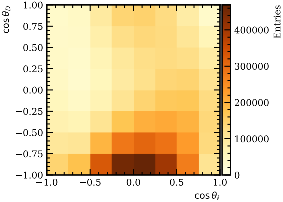


No PV either (all formfactors are real $\rightarrow$ no strong phases)

CP asymmetries: adding right-handed current

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



Unweighted density
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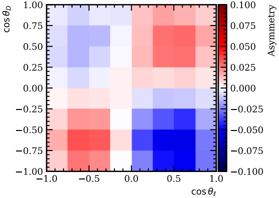
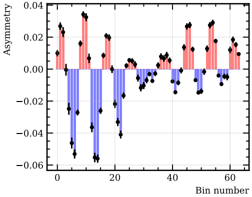
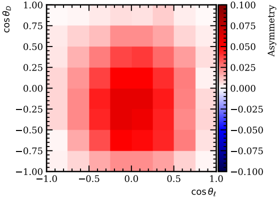
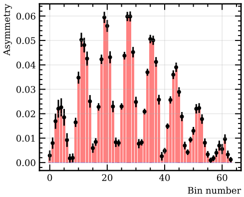




"Quadratic asymmetry", $w \propto \sin 2\chi$:

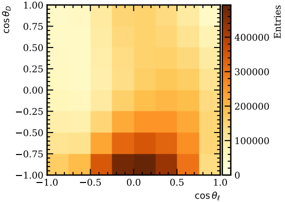




Specific pattern in both up-down and quadratic asymmetry terms.

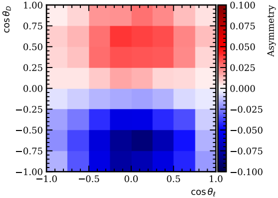
CP asymmetries: interference of tensor and pseudoscalar

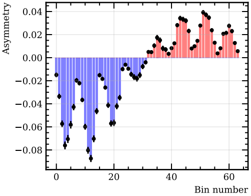
SM MC reweighted with combination of P and T NP, $g_P g_T^* = 0.1i$



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

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





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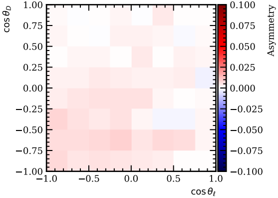

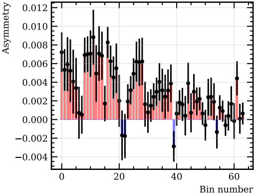

Large up-down asymmetry, small contribution to quadratic ("leakage" due to asymmetric efficiency in $\cos\chi$?)