CP violation in $b \to c\ell\nu_\ell$ transitions at LHCb

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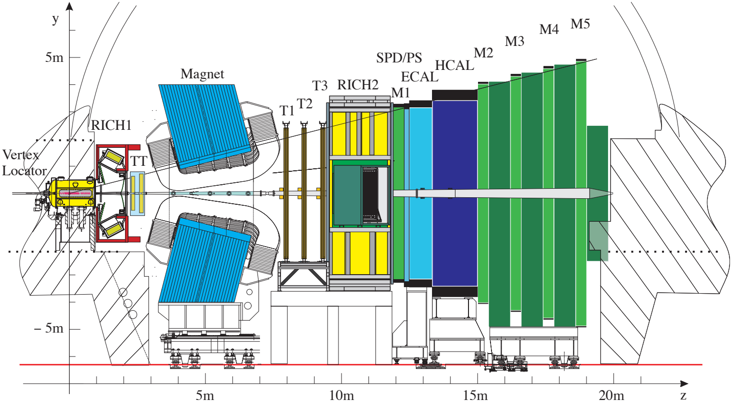
LHCb

Multi-purpose detector in the forward region (initially designed for b and c physics).



$B^0 \to D^{*-} (\to \overline{D}^0\pi^-)\ \mu^+\nu_\mu$

- $b \to c\ell\nu_\ell$ at tree-level SM W or NP
- Weak phase between SM and NP possible $\Rightarrow$ CP violation
- $B^0 \to D^{*-}\mu^+\nu_\mu$ same hadronic amplitude for SM and NP
  $\Rightarrow$ No strong phase difference possible!
- Direct CPV: often via

$$A_{\text{dir}}^{\text{CP}} = \frac{\Gamma(\overline{B}^0 \to D^{*+}\ell^-\overline{\nu}_\mu) - \Gamma(B^0 \to D^{*-}\ell^+\overline{\nu}_\mu)}{\Gamma(\overline{B}^0 \to D^{*+}\ell^-\overline{\nu}_\mu) + \Gamma(B^0 \to D^{*-}\ell^+\overline{\nu}_\mu)}$$

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- No strong phase $\Rightarrow A_{\text{dir}}^{\text{CP}} = 0$
- Where can they show up?

Angles $B^0 \to D^{*-}\ (\to \overline{D}^0 \pi^-)\ \mu^+ \nu_\mu$

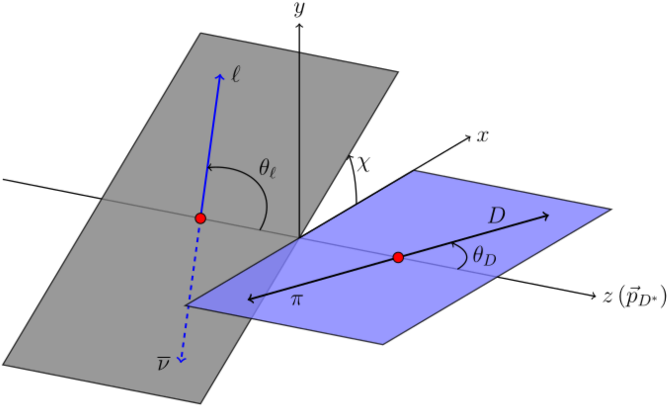

Figure: Angles characterising the $B^0 \to D^{*-} \mu^+ \nu_\mu$ from arXiv:1907.02257v2 [hep-ph]

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Hamiltonian for $B^0 \to D^{*-} (\to \overline{D}^0 \pi^-)\ \mu^+ \nu_\mu$ with arbitrary NP

$$\mathcal{H}_{eff} = \frac{G_F V_{cb}}{\sqrt{2}} \Big\{ \Big[(1 + \boxed{g_L})\, \bar{c}\gamma_\mu (1-\gamma_5) b + \boxed{g_R}\, \bar{c}\gamma_\mu (1+\gamma_5) b \Big] \bar{\ell}\gamma^\mu (1-\gamma_5)\nu_\ell$$
$$+ \Big[\boxed{g_S}\, \bar{c} b + \boxed{g_P}\, \bar{c}\gamma_5 b \Big] \bar{\ell}(1-\gamma_5)\nu_\ell + \boxed{g_T}\, \bar{c}\sigma^{\mu\nu}(1-\gamma_5) b \bar{\ell}\sigma_{\mu\nu}(1-\gamma_5)\nu_\ell$$
$$+ h.c. \Big\}$$

with complex NP couplings $\boxed{g_L}$, $\boxed{g_R}$, $\boxed{g_S}$, $\boxed{g_P}$, $\boxed{g_P}$ ($\equiv 0$ in SM) from arXiv:1903.02567v2 [hep-ph].

- characterized by $\mathcal{A}_i(q^2, \theta_D, \theta_\ell, \chi)$, for the explicit amplitudes, see arXiv:1610.02045v2 [hep-ph].

Angular terms

Terms generating CPV are the ones with $Im(A_i A_j^*), i \neq j$, those are:

Coefficient	**Coupling**	**Angular function**
$\mathrm{Im}(A_\perp A_0^*)$	$\mathrm{Im}[(1+g_L+g_R)(1+g_L-g_R)^*]$	$-\sqrt{2}\sin 2\theta_\ell \sin 2\theta_D \sin\chi$
$\mathrm{Im}(A_\parallel A_\perp^*)$	$\mathrm{Im}[(1+g_L-g_R)(1+g_L+g_R)^*]$	$2\sin^2\theta_\ell \sin^2\theta_D \sin 2\chi$
$\mathrm{Im}(A_{SP} A_{\perp,T}^*)$	$\mathrm{Im}(g_P g_T^*)$	$-8\sqrt{2}\sin\theta_\ell \sin 2\theta_D \sin\chi$

From arXiv:1903.02567v2 [hep-ph]
Angular components sensitive to NP in g_R and $g_P g_T^*$.

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From arXiv:1903.02567v2 [hep-ph]

Angular components sensitive to NP in g_R and $g_P g_T^*$.

- P: $\chi \to -\chi$ thus ang. dist. flips sign,
- C: weak phase sign flip thus ang. dist. flips sign.

CPV appears in triple-product asymmetries

Angular terms 2

- P: $\chi \to -\chi$ thus ang. dist. flips sign
- C: weak phase sign flip thus ang. dist. flips sign

Instead of true CP- (or T-) odd contribution, also *Fake T-odd asymmetry* (are *CP conserving*).

- $Im(A_i A_j^*) \neq 0$
- Different strong but same weak phase
- Not possible in SM or NP, but possible in certain backgrounds
- no CPV, (-) only from P
- Angular component of CP conjugate decay changes sign

Analysing Angular terms

Investigate P_{odd} to distinguish *true* and *fake* CPV to investigate NP couplings.

$$P(q^2, \theta_D, \theta_\ell, \chi) = P_{\text{odd}}(q^2, \theta_D, \theta_\ell, \chi) + P_{\text{even}}(q^2, \theta_D, \theta_\ell, \chi)$$

$$P_{\text{odd}}(q^2, \theta_\ell, \theta_D, \chi) = P^{(1)}_{\text{odd}}(q^2, \theta_\ell, \theta_D) \sin\chi + P^{(2)}_{\text{odd}}(q^2, \theta_\ell, \theta_D) \sin 2\chi$$

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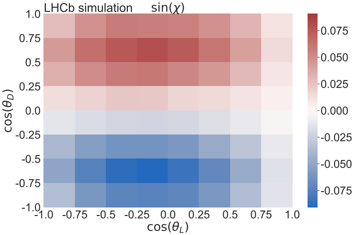
Getting $P^{(1)}_{\text{odd}}$ and $P^{(2)}_{\text{odd}}$

$$P^{(1)}_{\text{odd}}(q^2, \theta_\ell, \theta_D) = \frac{1}{\pi} \int_{-\pi}^{\pi} P(q^2, \theta_\ell, \theta_D, \chi) \sin\chi \, d\chi,$$

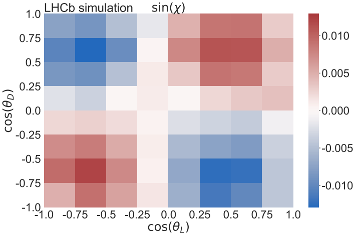
$$P^{(2)}_{\text{odd}}(q^2, \theta_\ell, \theta_D) = \frac{1}{\pi} \int_{-\pi}^{\pi} P(q^2, \theta_\ell, \theta_D, \chi) \sin 2\chi \, d\chi.$$

Control channel! Evaluate for asymmetries.

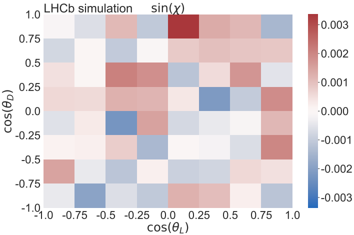
Expected Asymmetries



(a) 10 %$Im(g_P g_T^*)$

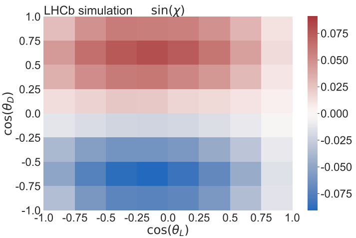


(b) 10 % $Im(g_R)$

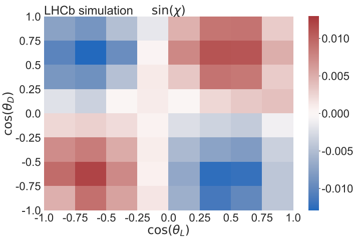


(c) SM (0 with stat. fluctuations!)

Expected Asymmetries



(a) $10\,\% Im(g_P g_T^*)$



(b) $10\,\%\ Im(g_R)$

$\Rightarrow$ Template fit to Data

State of the analysis

Expected P-odd uncertainties estimated to (for more details see Thesis V. Dedu)

$$
\begin{aligned}
Im(g_R) &: 0.5\%(\mathrm{stat.}), 1.0\%(\mathrm{syst.}), \\
Im(g_P g_T^*) &: 0.1\%(\mathrm{stat.}), 0.1\%(\mathrm{syst.}).
\end{aligned}
$$

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$$Im(g_P g_T^*) : 0.1\%(\mathrm{stat.}), 0.1\%(\mathrm{syst.}).$$

Systematic effects (excerpt):
Chiral effects can produce fake P-odd terms even in the SM-like (P-even) angular distribution:

- backgrounds from higher D^* excitations, double charmed decays, combinatorial backgrounds (data-driven)
- instrumentation effects (eg. VELO misalignment/VELO efficiency, track reconstruction efficiency)

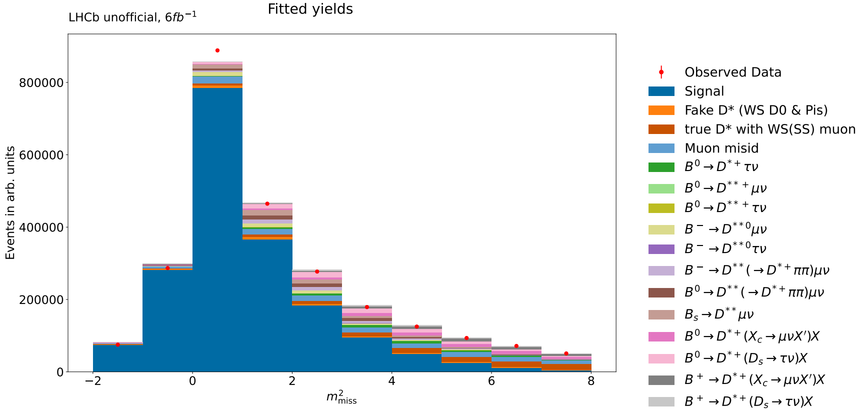
State of the analysis - Template fit

P-odd control channel: 3D Template fit for signal purity and background contributions in

- $q^2 = (p_B - p_{D^*})^2$,
- $m^2_{\text{miss}} = (p_B - p_{D^*} - p_\mu)^2$ and
- E^*_μ (in B mass frame).

State of the analysis - Template fit

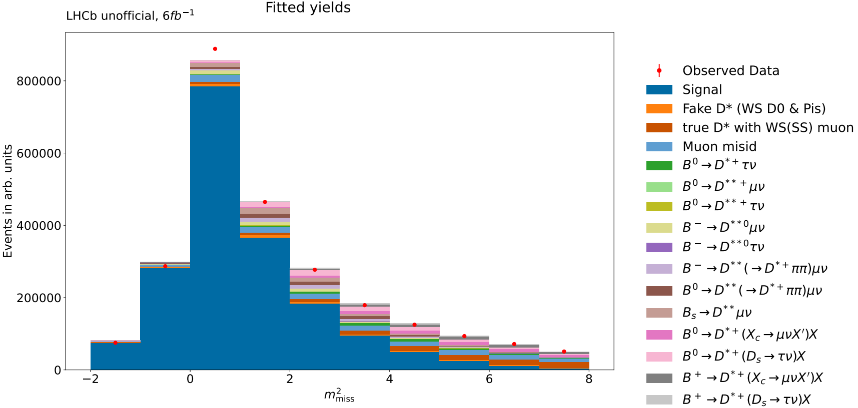
1D projection of 3D fit



(Projections for q^2 and E^*_μ in Backup)

State of the analysis - Template fit

1D projection of 3D fit



(Projections for q^2 and E^*_μ in Backup)
$\Rightarrow$ Ang. analysis of T-odd $\cos\theta_D$, $\cos\theta_\ell$ asymmetry for g_R and $g_P g_T$,
True asymmetry blinded.

More effects in P_{odd}

In control channel asymmetry must be 0, but previously: 2.5σ from 0
Where from?

More effects in P_{odd}

In control channel asymmetry must be 0, but previously: 2.5σ from 0
Where from?

- In data, not only $B^0 \to D^{*-}(\to \overline{D}^0\pi^-)\mu^+\nu_\mu$ present, also $B^0 \to \overline{D}^0\pi^-\mu^+\nu_\mu$ *s*-wave
- $\mathcal{A} = \mathcal{A}_{\text{vector}} + a\mathcal{A}_{\text{scalar}}$
- Interference with *s*-wave possible: P-odd possible
- Interference may affect fake T-odd asymmetry
- Not background that can be reduced by selections, contributes to amplitude
- Need to estimate contribution!

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Amplitudes, normalised

- With available statistics: sensitive to % CPV effects
- $D\ \pi$ S-wave admixture small: $\ll 1\,\%$

Amplitudes, normalised

- With available statistics: sensitive to % CPV effects
- $D\ \pi\ S$-wave admixture small: $\ll 1\,\%$

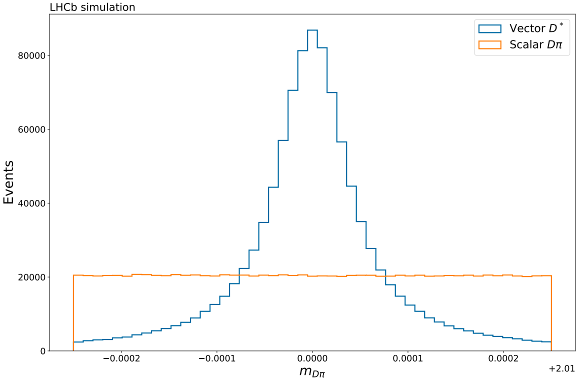
$$P = \sum_{\mu\text{pol}} |\mathcal{A}_{\text{vector}} + a\mathcal{A}_{\text{scalar}}|^2$$
$$= \sum_{\mu\text{pol}} |\mathcal{A}_V|^2 + a^2|\mathcal{A}_S|^2 + \text{interference.}$$

- BUT interference is prop. to the sqrt
  $\Rightarrow$ contributions at % level, might still be affected
  $\Rightarrow$ Simulation using formulas from arXiv:1610.02045v2 [hep-ph] for vector (only lh ν) and from arXiv:1711.03110v2 [hep-ph] for scalar.

Amplitudes and interference

$$P = \sum_{\mu\text{pol}} |\mathcal{A}_V|^2 + a^2|\mathcal{A}_S|^2 + \text{interference}$$

- Estimation needs simulation of interference of amplitudes (impossible with existing tools eg. HAMMER.)



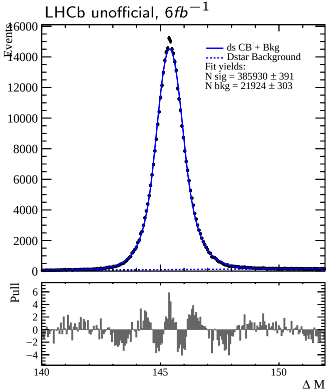
Tuning to data - Conservative upper limit

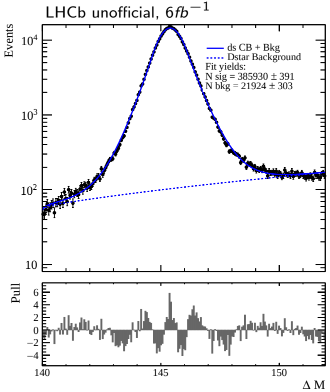
$$\frac{N_{\text{bkg}}}{N_{\text{sig}}} \stackrel{!}{=} a^2 \frac{\int |A_S|^2 \, dm}{\int |A_V|^2 \, dm}$$

$$\Delta M = m_{D^*} - m_D$$

for $\Delta M \in [140, 152]$MeV

- $N_{\text{Sig}} = 385930 \pm 391$
- $N_{\text{Bkg}} = 21924 \pm 303$
- $a \approx 0.0031$

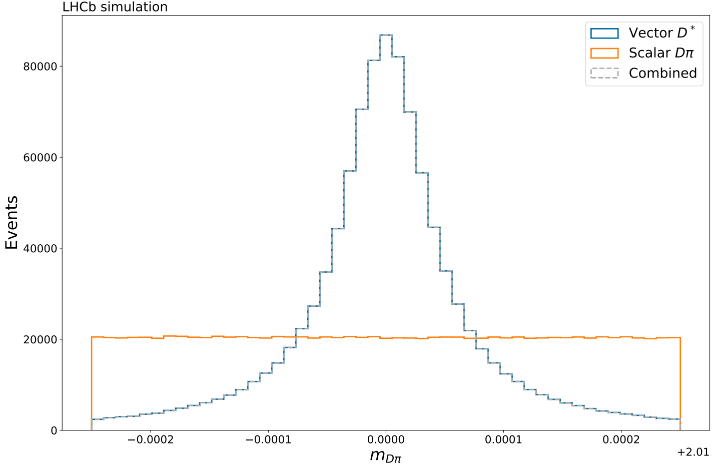




Compare interference

Amplitudes not to scale!

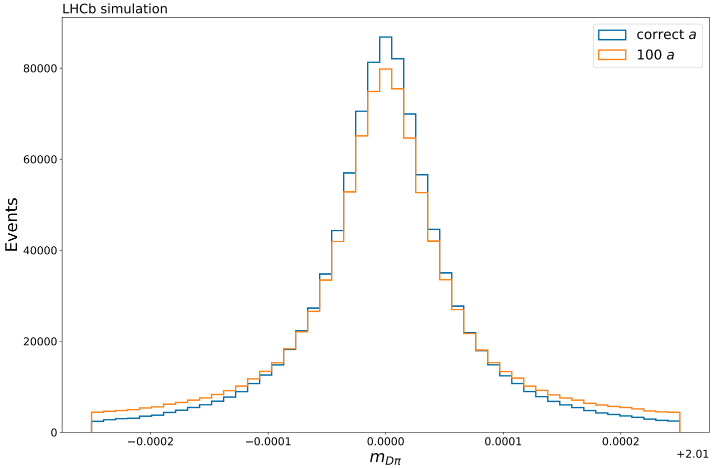
Combined amplitude clearly dominated by vector contribution



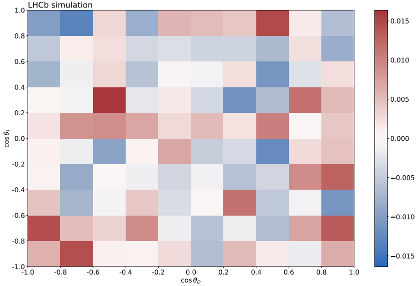
Compare interference

Amplitudes not to scale!

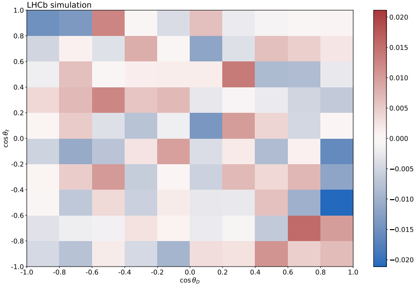
Combined flatter for stronger scalar contribution



Results



(a) Weight: $\sin\chi$

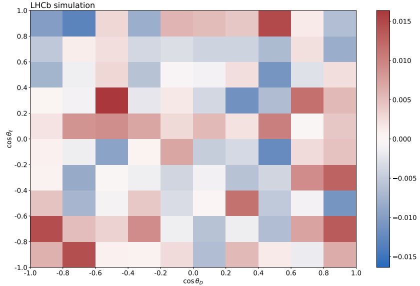


(b) Weight: $\sin 2\chi$

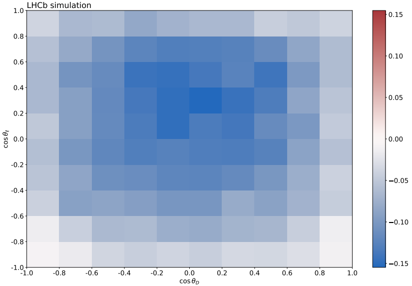
Figure: Asymmetry for the determined value of *a* estimated from data.

Within stat. fluctuations: compatible with 0!

Comparison with different values for a



(a) Correct a



(b) 100 a

$\Rightarrow \sim 1.5\,\%$ asymmetry with this S-wave estimation (conservative upper limit)

$\Rightarrow$ affected little because very different shape from expected $Im(g_R), Im(g_P g_T^*)$ asymmetries

$\Rightarrow$ tighter constrained needed, work in progress

Conclusion

- For CPV in $B^0 \to D^{*-}$ $(\to \bar{D}^0\pi^-)$ $\mu^+\nu_\mu$: triple products from angular terms
- Sensitive to $Im(g_R), Im(g_P g_T^*)$
- Fitting Run 2 LHCb data, blinded CP observables
- Control channel with P-odd observables: expected 0
- Remaining systematic effects:
- From interference with s-wave $B^0 \to \bar{D}^0\pi^-\mu^+\nu_\mu$ simulated
- Same order of magnitude as sensitivity
- Need to be taken into account
  $\Rightarrow$ Continue with angular analysis to determine NP contributions

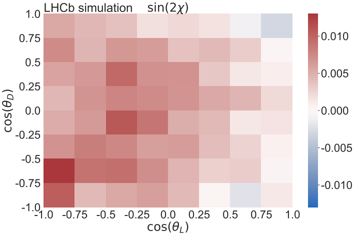
Thank you for listening

Selections

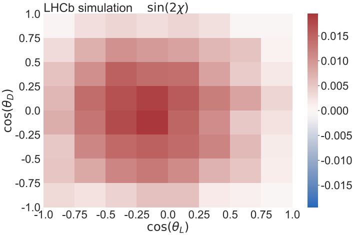
Particle	Variable	Selection
μ	p	$<$ 100 GeV
	PIDμ	$>$ 2
	$\log_{10}(1 - \vec{p}_\mu \cdot \vec{p}_i / \lvert p_\mu \rvert \lvert p_i \rvert)_{i=K,\pi,\pi_S}$	$>$ -5
D^0	p_{T}	$>$ 2 GeV
	χ^2_{IP}	$>$ 9
	lnIP	$>$ -3.5
	mass window	1842-1888 MeV
D^*	$\lvert\Delta m$-$\Delta m_{PDG}\rvert$	$<$ 2.5 MeV
	π_S GhostProb	$<$ 0.25
$D^0\mu$	DIRA	$>$ 0.999
$D^*\mu$	mass window	$<$ 5280 MeV
	DIRA	$>$ 0.999
	d_{XY} (transverse FD)	$<$ 7 mm
	χ^2_{vtx}/ndf	$<$ 6

Figure: Selections from V. Dedu Search for CP violation in semileptonic B meson decays at the LHCb experiment

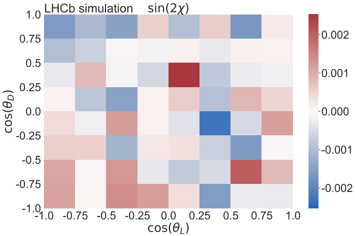
Estimating $P_{\rm odd}$ with $\sin 2\chi$



(a) Expected asymmetry 10 %$g_P g_T$



(b) Expected asymmetry 10 % g_R



(c) Expected asymmetry SM

Systematic effects

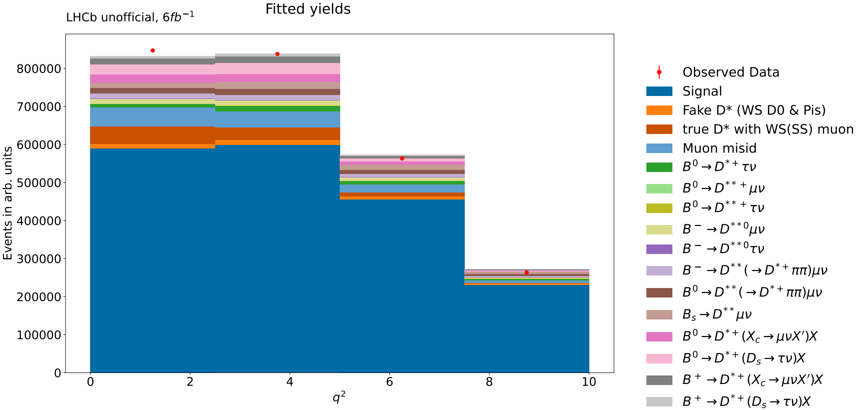
Systematic effects also contribute to *true* and *fake* P_{odd}:

- P-even effects can not produce fake P-odd terms in the angular distribution
  - from signal purity
  - from background composition
  - form factor parametrisations
  - magnitudes of efficiencies of reconstruction and selection
- Chiral effects **can** produce fake P-odd terms even in the SM-like (P-even) angular distribution:
  - backgrounds from higher D^* excitations, double charmed decays, combinatorial backgrounds (data-driven)
  - instrumentation effects (eg. VELO misalignment/VELO efficiency, track reconstruction efficiency)

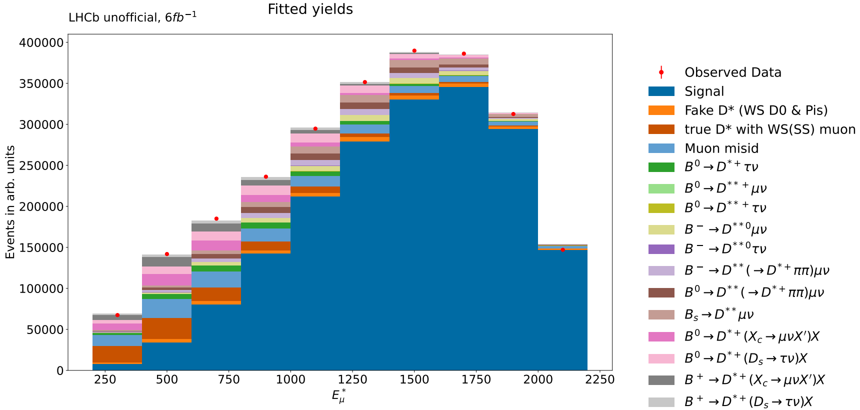
Backgrounds for template fit

- Higher excitations: $B^0 \to D^{*+}\tau\nu$, $B^0 \to D^{**+}\mu\nu$, $B^0 \to D^{**+}\tau\nu$, $B^- \to D^{**0}\mu\nu$, $B^- \to D^{**0}\tau\nu$, $B^- \to D^{**}(\to D^{*+}\pi\pi)\mu\nu$, $B^0 \to D^{**}(\to D^{*+}\pi\pi)\mu\nu$, $B_s \to D^{**}\mu\nu$,
- Double Charmed: $B^0 \to D^{*+}(X_c \to \mu\nu X')X$, $B^0 \to D^{*+}(D_s \to \tau\nu)X$, $B^+ \to D^{*+}(X_c \to \mu\nu X')X$, $B^+ \to D^{*+}(D_s \to \tau\nu)X$,
- Data driven combinatorical: Fake (wrong sign D^0 and π), True with wrong (same) sign μ, Misidentified muons. (data driven)

State of the analysis - q^2 Template fit



State of the analysis - E_μ^* Template fit



Tuning to data

$$P = \sum_{\mu \mathrm{pol}} |\mathcal{A}_V|^2 + a^2 |\mathcal{A}_S|^2 + \text{interference.}$$

$$r := \frac{N_{\mathrm{bkg}}}{N_{\mathrm{sig}}} \stackrel{!}{=} a^2 \frac{\int |A_S|^2\, dm}{\int |A_V|^2\, dm}$$

$$\int P dm = N_{\mathrm{Sig}} + N_{\mathrm{Bkg}}$$

$$\Rightarrow \frac{\int |A_S|^2 dm}{\int |A_V|^2 dm} = 9.510^{-6}$$

Tuning to data - Fit

$$\frac{N_{\text{bkg}}}{N_{\text{sig}}} \stackrel{!}{=} a^2 \frac{\int |A_S|^2 \, dm}{\int |A_V|^2 \, dm}$$

- Obtain from fit to Data
- Extended ML fit
- $\Delta M = m_{D^0\pi} - m_{D^0}$
- Double-sided Crystall Ball for Signal
- Background specific shape (`RooDstD0BG`)

Full fit params

Table: Fit parameters for the full fit.

Parameter	**Value ± Error**	Fixed
mean	145.4580 ± 0.0011	
σ_{L}	0.5700 ± 0.0007	
σ_{R}	0.5889 ± 0.0006	
α_{L}	1.2714 ± 0.0044	
α_{R}	17.61 ± 0.58	
n_{L}	1.1881 ± 0.0023	
n_{R}	15.8985 ± 0.4067	
A	10 ± 20	
B	7 ± 11	
C	0.1875 ± 0.0006	
N_{sig}	385930 ± 391	
N_{bkg}	21924 ± 303	