Search for *CP* violation in semileptonic *B* meson decays at the LHCb experiment

Supervisors:

Anton Poluektov

Olivier Leroy

Vlad Dedu

11th October 2023

Aix Marseille Univ,
CPPM, IPhU,
Marseille, France

Jury members:

Cristinel Diaconu
Emi Kou
Matthew Charles
Lucia Grillo
Marcello Rotondo

Overview

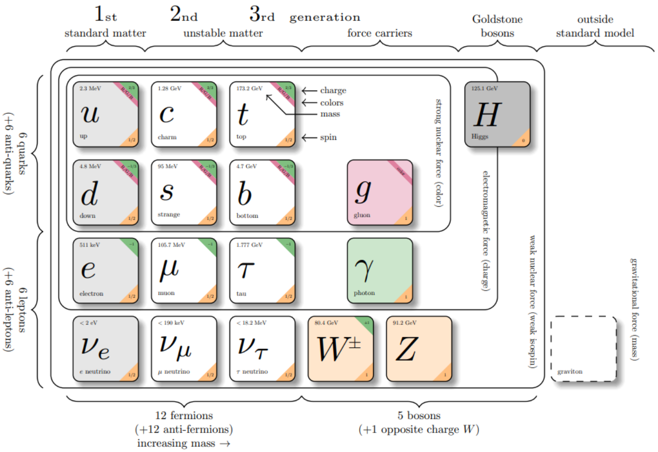
Overview

Introduction

- **What:** *CP* violation in semileptonic $B^0 \to D^{*-}\mu^+\nu_\mu$ decays
  - *CP* violation is different behaviour between matter and antimatter (B^0 and $\bar{B}^0$ decays)
- **Why:** Standard Model (SM) predicts Lepton Flavor Universality (LFU)
  Hints of LFU violation at $> 3\sigma$ in previous measurements
  New Physics (NP) models which explain these tensions may also give rise to *CP* violation
- **How:** Reconstruct $B^0 \to D^{*-}\mu^+\nu_\mu$ angular distribution using LHCb Run 2 2016-2018 data (5.4 fb^{-1})
  Novel model-independent method to measure only the *P*-odd part and cancel out *P*-even part
- **First-time measurement of *CP* violating angular terms in a semileptonic decay**
  Specific *P*-odd systematic effects
- Feasibility study with toy MC [JHEP 07 (2023) 063]
- Final result still **blind**, but analysis in advanced state
- **Started from scratch**

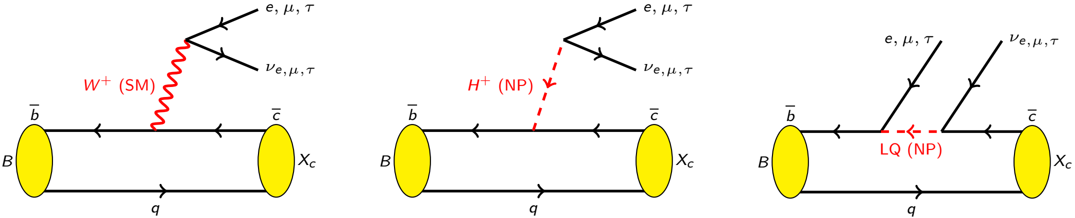
Overview

- The **Standard Model (SM)** is the theoretical framework of particle physics
- SM is a **Quantum Field Theory (QFT)** where particles are described as excitations of quantum fields
- Matter is made up from 12 **fermion** fields: 6 **quarks** and 6 **leptons**
- Four **gauge bosons** mediate 3 out of 4 fundamental interactions between particle fields.
- One **Higgs boson** responsible for the mechanism giving mass to particles.



Standard Model strengths and weaknesses

- The predictive power of the SM has been well-established:
  - Prediction of third generation quarks to accommodate *CP* violation: **top** and **bottom**
  - Prediction of **Higgs boson**
  - Prediction of unified **electroweak** interaction: **W** and **Z** bosons properties
- Ample evidence that SM is not complete:
  - **Dark matter** and **dark energy** not explained
  - **Matter-antimatter asymmetry** not explained
  - Neutrino **oscillations** and **non-zero masses** not explained
  - **Gravity** not explained
  - ...
- Searches for New Physics (NP):
  - **Direct**: Search for heavy new particles **directly** in high-energy collisions
  - **Indirect**: Search for **effects** of new particles in precise measurements of low-energy processes
    - **Flavor physics approach** (this thesis)

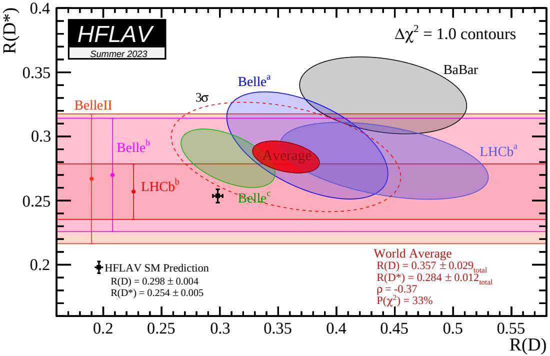


- These transitions are mediated at tree-level by the weak W boson in SM
- Three typical NP candidates that can contribute at tree-level:
  - **Heavy vector bosons e.g. W'**
  - **Charged Higgs H^+**
  - **Leptoquarks (LQ)**
- $b \to c\ell\nu_\ell$ decays are a good platform to search for physics beyond the SM

- Prediction of SM: **Lepton Flavor Universality (LFU)**: electroweak coupling is independent of lepton flavor (e, μ, τ).

- LFU can be tested by measuring ratios of branching fractions. In case of **tree-level charged current $b \to c\ell\nu_\ell$** transitions:

$$\mathcal{R}(D^{(*)}) = \frac{\mathcal{B}(B \to D^{(*)} \tau\nu_\tau)}{\mathcal{B}(B \to D^{(*)} \ell\nu_\ell)}, \ell = e, \mu$$



$> 3\sigma$ tension wrt SM

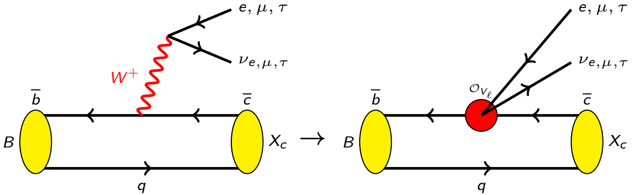
"*b*-anomalies"

- NP models can accommodate LFU violation
- **Further tests needed**: polarization, angular, ***CP*-violating observables** etc

Effective field theories

- EFT in $b \to c\ell\nu_\ell$: high-energy dof (W) are integrated out, low-energy effects described by $\mathcal{O}_{V_\ell}$
- SM can be described as low-energy approximation of heavier NP theory (NP scale $\Lambda \gg m_W$).

- $\mathcal{H}_{eff}(b \to c\ell\nu_\ell) = \frac{4G_F}{\sqrt{2}} V_{cb} \sum_i (\mathcal{O}_{SM} + g_i \mathcal{O}_i)$
  - Dominant SM. NP corrections parametrized by adding new operators and coefficients
  - **Wilson coefficients** - encode high-energy dof
  - **Wilson operators** - encode low-energy dof

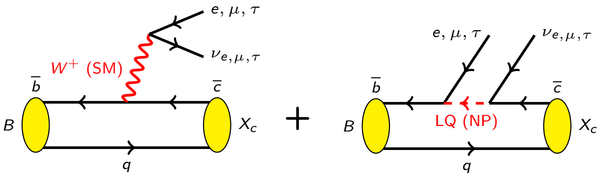


- Most general hamiltonian in $b \to c\ell\nu_\ell$ (all possible NP contributions):

$$\mathcal{H}_{eff} = \frac{4G_F}{\sqrt{2}} V_{cb} \Big\{ \Big[(1 + g_L) \bar{c}\gamma^\mu P_L b + g_R \bar{c}\gamma^\mu P_R b \Big] \bar{\ell}\gamma_\mu P_L \nu_\ell + \Big[g_S \bar{c} b + g_P \bar{c}\gamma^5 b \Big] \bar{\ell} P_L \nu_\ell + g_T \bar{c}\sigma^{\mu\nu} P_L b \bar{\ell}\sigma_{\mu\nu} P_L \nu_\ell + h.c. \Big\}$$

- g_L, g_R, g_S, g_P, g_T are **complex** NP couplings ($\equiv 0$ in SM)
- Different NP models (W', H^+, LQ, ...) $\Rightarrow$ different combinations of couplings

- CP violation $\iff$ 2 interfering amplitudes
  $\Rightarrow$ **smoking-gun signal of NP**

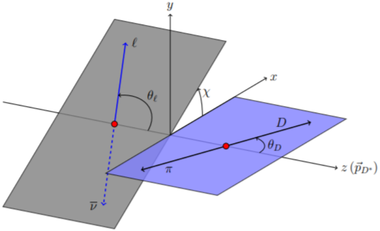


- Best known CP-violating signal is $\mathcal{A}_{dir}^{CP} \propto \Gamma(\overline{B}^0 \to D^{*+}\ell^-\overline{\nu}_\ell) - \Gamma(B^0 \to D^{*-}\ell^+\nu_\ell)$
  - **CP-odd (weak)** relative phase $\to$ from NP amplitude ✓
  - **CP-even (strong)** relative phase $\to$ hadronic transitions (gluon exchanges) ✗
    - Same hadronic $B \to D^*$ in SM or NP

  $\Rightarrow$ $\boxed{\mathcal{A}_{dir}^{CP} \approx 0}$

- Instead, CP-violating asymmetries in the angular distribution:
  - **Triple product (TP) asymmetries**
  - Arise from amplitude structure of $B \to V_1 V_2$
  - Kinematical effects, i.e. need different Lorentz structures between SM (LH) and NP (RH, S, P, T) amplitudes

$B^0 \to D^{*-}\ell^+\nu_\ell$ decay is described by 4 kinematic parameters: $q^2 = m^2(\ell\nu_\ell)$, θ_ℓ, θ_D, χ:



$$\frac{d^4\Gamma}{dq^2 d\cos\theta_D d\cos\theta_\ell d\chi} = \frac{3}{8\pi}\frac{G_F^2|V_{cb}|^2(q^2-m_\ell^2)^2|p_{D^*}|}{2^8\pi^3 m_{B^0}^2 q^2} \times \mathcal{B}(D^{*-}\to D^0\pi^-)\left(N_1 + \frac{m_\ell}{\sqrt{q^2}}N_2 + \frac{m_\ell^2}{q^2}N_3\right)$$

[B. Bhattacharya A. Datta, S. Kamalib, D. London]

Unsupressed N_1 TPs

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

- If $\exists$ only relative **strong** phase between $(\mathcal{A}_i, \mathcal{A}_j) \Rightarrow$ **Parity Violation** ($\equiv 0$ in SM or NP)
- If $\exists$ only relative **weak** phase between $(\mathcal{A}_i, \mathcal{A}_j) \Rightarrow$ ***CP* Violation** ($\equiv 0$ in SM but $\neq 0$ in NP!)
- **How to distinguish**: Angular component does (does not) change sign between B^0 and $\overline{B}^0$ for P (CP).
  - P flips sign of χ, C flips sign of weak phase

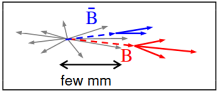
CP violation in $B^0 \to D^{*-}\ell^+\nu_\ell$ decays

- The CP-violating angular asymmetries in $B^0 \to D^{*+}\ell^-\overline{\nu}_\ell$ are equally applicable to $\ell = e, \mu, \tau$
- Typically, the explanation of the b-anomalies ($\mathcal{R}(D)$, $\mathcal{R}(D^*)$, $\mathcal{R}(J/\psi)\ldots$) is NP in $b \to c\tau\nu_\tau$
  - Angular distribution in τ mode is **difficult** to reconstruct due to additional ν in the final state

- **This thesis: Measure CP-violating angular terms in $B^0 \to D^{*-}\mu^+\nu_\mu$** Why is it important ?

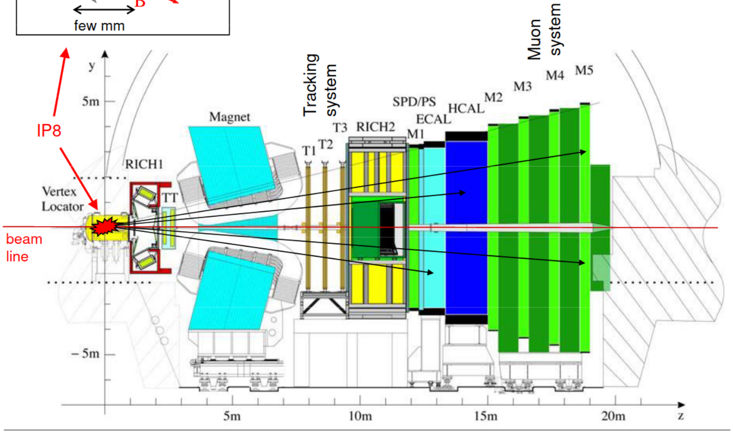
- Smoking-gun signal of NP, any CP violation implies existence of NP amplitude
- CP-violating angular terms are sensitive to $\mathrm{Im}(g_R)$ and $\mathrm{Im}(g_P g_T^*)$. If measured to be non-zero, it would place constraints on the possible NP models
  - g_R can only arise in W' models
  - g_P and g_T can only arise in LQ models
- Most NP models proposed to explain b-anomalies contribute only to g_L, i.e. predict no CP-violating effects. A non-zero measurement of CP violation would rule them out
- Measurement of CP-violating observables in $B^0 \to D^{*-}\mu^+\nu_\mu$ offers a great deal of information about the identity of NP!

Overview



b-hadrons have displaced vertices.
Fly a few mm before decaying in VELO

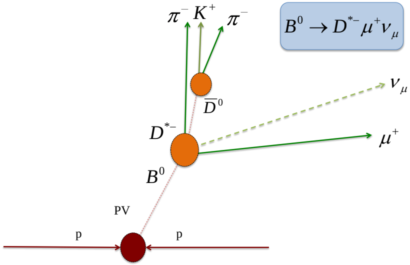
LHCb in Run 2

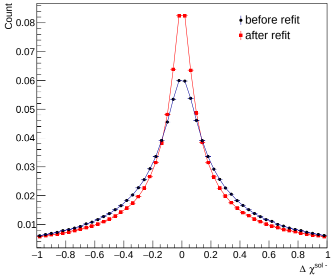


- b-hadrons produced in pairs ($b\bar{b}$) in the same direction → forward angular coverage
- **Excellent** vertex finding, momentum resolution, particle identification → precision measurements

Overview

Reconstruction of ν_μ at LHCb





- Kinematic reconstruction of ν_μ from decay topology (very precise vertexing from VELO)

$$p_B = \frac{\left(m_B^2 + m_{D^*\mu}^2\right) p_{D^*\mu}\cos\theta \pm E_{D^*\mu}\sqrt{(m_B^2 - m_{D^*\mu}^2)^2 - 4m_B^2 p_{D^*\mu}^2 \sin^2\theta}}{2(m_{D^*\mu}^2 + p_{D^*\mu}^2 \sin^2\theta)},$$

- Reconstruct kinematic variables $(q^2, \theta_D, \theta_\ell, \chi)$ with two-fold ambiguity
- Run full refit of the decay tree including all possible kinematic information (including missing ν_μ) and all possible correlations $\to$ **improve resolution**

Formalism to extract P_{odd}

- $P_{\text{tot}}(\Omega) = P_{\text{even}}(\Omega) + P_{\text{odd}}(\Omega) \rightarrow B^0 \rightarrow D^{*-}\mu^+\nu_\mu$ angular distribution $(d^4\Gamma/d\Omega)$, where $\Omega = (q^2, \theta_D, \theta_\ell, \chi)$
- $P_{\text{odd}}(\Omega) = P^{(1)}_{\text{odd}} \sin\chi + P^{(2)}_{\text{odd}} \sin 2\chi$
- Exploit symmetry properties of P_{tot} to cancel out P_{even} (and its uncertainties) and extract only P_{odd}:

$$P^{(1)}_{\text{odd}} = \frac{1}{\pi}\int_{-\pi}^{\pi} P_{\text{tot}}(\Omega)\sin\chi\, d\chi \qquad \rightarrow \qquad A^{(1)}_i = \frac{N_{\text{bins}}}{N_{\text{signal}}}\sum_{n=1}^{N_i}\sin\chi_n \simeq \mathrm{Im}(g_R)\, A^{(1)}_{RH,i} + \mathrm{Im}(g_P g_T^*)\, A^{(1)}_{PT,i}$$

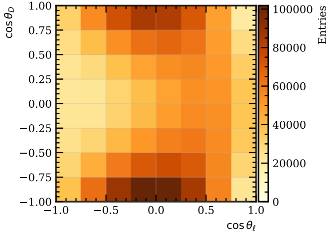
$$P^{(2)}_{\text{odd}} = \frac{1}{\pi}\int_{-\pi}^{\pi} P_{\text{tot}}(\Omega)\sin 2\chi\, d\chi \qquad \qquad A^{(2)}_i = \frac{N_{\text{bins}}}{N_{\text{signal}}}\sum_{n=1}^{N_i}\sin 2\chi_n \simeq \mathrm{Im}(g_R)\, A^{(2)}_{RH,i}$$

- Build **BINNED ASYMMETRIES** A_i from reconstructed kinematics instead of "true" P_{odd}.
- 2 sets of observables: ***CP* asymmetries** (sensitive to NP) and ***P* asymmetries** ($\equiv 0$, cross-check)
  - For P asymmetries, same definition but additional "-" sign assigned for $\bar{B}^0$ events
- Binning scheme: 8×8 bins in $(\cos\theta_\ell, \cos\theta_D)$, integrate over q^2

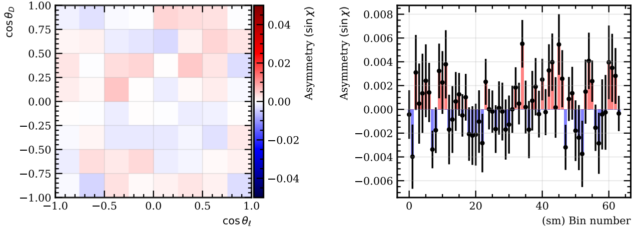
CP asymmetries: Standard Model

$B^0 \to D^{*-}\mu^+\nu_\mu$ simulation: SM

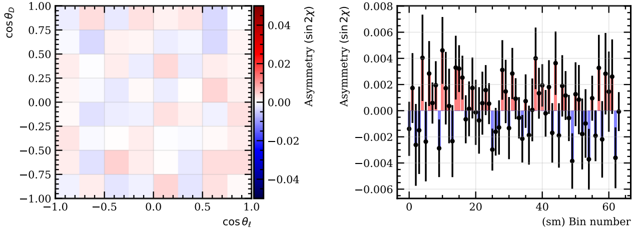
Unweighted density $\cos\theta_D, \cos\theta_\ell$



"Up-down asymmetry" $A^{(1)}$, $w \propto \sin\chi$:



"Quadratic asymmetry" $A^{(2)}$, $w \propto \sin 2\chi$:

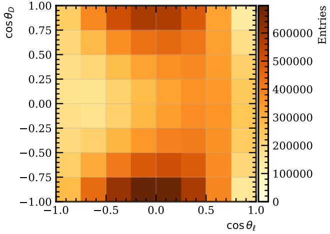


CP-asymmetry consistent with 0 as expected (no NP $\to$ no weak phases).

CP asymmetries: right-handed current

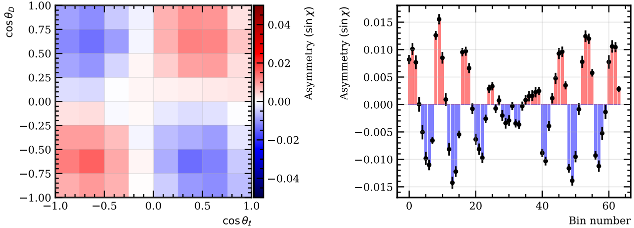
$B^0 \to D^{*-}\mu^+\nu_\mu$ simulation: $g_R = 0.1i$

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

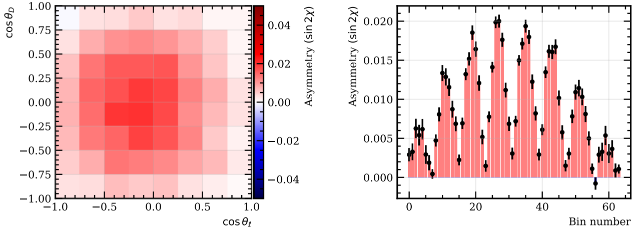


Specific pattern in both up-down and quadratic asymmetry terms.

"Up-down asymmetry" $A^{(1)}$, $w \propto \sin\chi$:

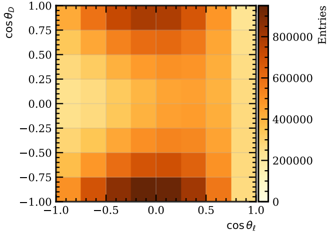


"Quadratic asymmetry" $A^{(2)}$, $w \propto \sin 2\chi$:

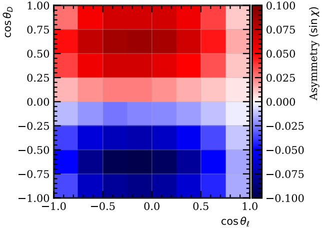


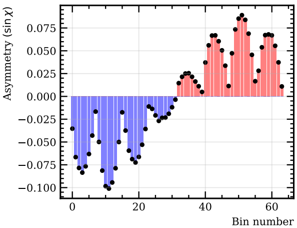
$B^0 \to D^{*-}\mu^+\nu_\mu$ simulation: $g_P g_T^* = 0.1i$

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

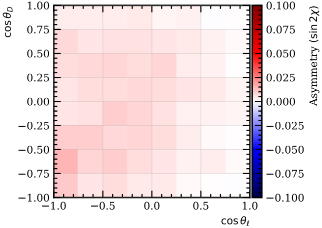


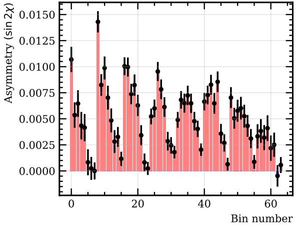
"Up-down asymmetry" $A^{(1)}$, $w \propto \sin\chi$:





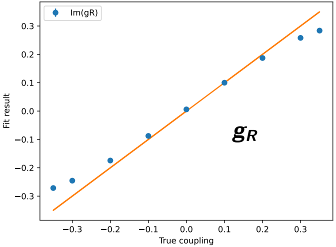
"Quadratic asymmetry" $A^{(2)}$, $w \propto \sin 2\chi$:

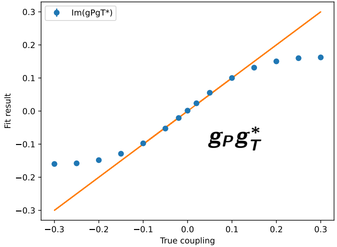




Binned asymmetry template fit

- Minimize χ^2 function. Account for correlation between $\sin\chi$ and $\sin 2\chi$.
- $\chi^2_{\mathrm{corr}} = \sum_i \sum_{a,b=1,2} \Delta A_i^{(a)} \left(\Sigma_i^{-1}\right)^{(ab)} \Delta A_i^{(b)}$, Σ_i covariance matrix
- $\Delta A_i^{(a,b)} = \underbrace{\frac{\mathrm{Im}(g_R)_{\mathrm{fit}}}{\mathrm{Im}(g_R)_0} A_{RH,i}^{(a,b)} + \frac{\mathrm{Im}(g_P g_T^*)_{\mathrm{fit}}}{\mathrm{Im}(g_P g_T^*)_0} A_{PT,i}^{(a,b)}}_{model} - \underbrace{A_i^{(a,b)}}_{data}$





Statistical uncertainty with Run 2 dataset (5.4 fb^{-1})

$\boldsymbol{\sigma_{g_R}^{\mathrm{stat}} \sim 5 \times 10^{-3}\ (0.5\%)}$

$\boldsymbol{\sigma_{g_P g_T^*}^{\mathrm{stat}} \sim 1 \times 10^{-3}\ (0.1\%)}$

- Fit works if we use templates with $g_R, g_P g_T^* \ll 1 \rightarrow$ linear regime $\boxed{\boldsymbol{g_R = 0.1\mathrm{i}, g_P g_T^* = 0.1\mathrm{i}}}$

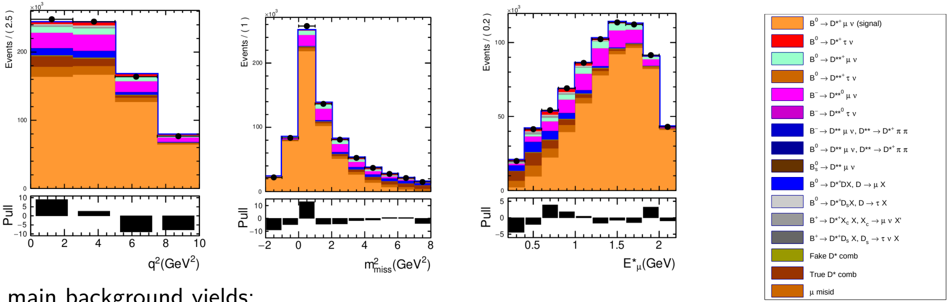
Overview

Data sample: signal fit

- Data collected by LHCb in Run 2: 2016, 2017, 2018. 5.4 fb^{-1}.
- After all selection (trigger, stripping, offline) $\sim$ 2.7M events
- Signal and background yields determined from 3D maximum likelihood binned fit to data
  - $q^2 = (p_B - p_{D^*})^2$ (4 bins)
  - $m^2_{miss} = (p_B - p_{D^*} - p_\mu)^2$ (10 bins)
  - E^*_μ muon energy in B rest frame (10 bins)
- 16 templates, 13 from MC, 3 from data
- **Tracker-Only MC samples**.
  - Trigger, PID need to be emulated offline.

Sample
$B^0 \to D^{*-}\mu^+\nu_\mu$ (**signal**)
$B^0 \to D^{*-}\tau^+\nu_\tau$
$B^0 \to (D^{**-} \to D^{*-}\pi^0)\mu^+\nu_\mu$
$B^0 \to (D^{**-} \to D^{*-}\pi^0)\tau^+\nu_\tau$
$B^+ \to (D^{**0} \to D^{*-}\pi^+)\mu^+\nu_\mu$
$B^+ \to (D^{**0} \to D^{*-}\pi^+)\tau^+\nu_\tau$
$B^+ \to D^{**0}[\to D^{*+}\pi^0\pi^+]\mu^+\nu_\mu$
$B^0 \to D^{**-}[\to D^{*-}\pi^+\pi^-]\mu^+\nu_\mu$
$B^0_s \to D^{**-}_s\mu^+\nu_\mu$
$B^0 \to D^{*-}D^+_{(s)}X, D^+_{(s)} \to X\mu^+\nu_\mu$
$B^0 \to D^{*-}D^+_{(s)}X, D^+_{(s)} \to X\tau^+\nu_\tau$
$B^+ \to D^{*-}D^+_{(s)}X, D^+_{(s)} \to X\mu^+\nu_\mu$
$B^+ \to D^{*-}D^+_{(s)}X, D^+_{(s)} \to X\tau^+\nu_\tau$
Fake-D^* combinatorial
True-D^* combinatorial
Muon Mis-ID

Data sample: signal fit results



- Signal and main background yields:
  - Signal $B^0 \to D^{*-}\mu^+\nu_\mu \sim$ 63% $\to$ high signal purity
  - Semileptonic background: $B \to D^{**}\mu\nu$ modes $\sim$ 17%
  - Double charm background: $B \to D^*DX, D \to \mu X \sim$ 5%
  - Data-driven background: Combinatorial (Fake-D^* $\sim$ 1%, True-D^* $\sim$ 5%), μ-MisID $\sim$ 6%
- We need signal and "dangerous" background fractions to assign systematics
- **Percent level precision** is sufficient. $\chi^2/\mathrm{ndf} = 4.79$ for 2016 fit ...

Overview

Systematic uncertainties can be split in two categories:

- **Parity-even** : Only affect interpretation of visible asymmetry in terms of NP couplings, i.e. enter relative to the magnitude of the measured $\mathrm{Im}(g_{\mathrm{NP}})$
- For instance: uncertainties in FFs, signal purity, reconstruction, magnitudes of sel/reco efficiency etc. **Do not** produce fake parity-odd terms if the angular distribution is SM-like

- **Parity-odd** : Can produce fake parity-odd terms even if the angular distribution is SM-like:
  - 1. *CP* and *P* asymmetries in backgrounds:
    - Semileptonic: $B \to D^{**} \mu\nu$
    - Doublecharm: $B \to D^* D_s^*$
    - Data-driven: combinatorials, misid
  - 2. Instrumentation effects:
    - Vertex Locator misalignment
    - Non-uniform reconstruction efficiencies

Overview

Systematic effects in backgrounds

- **Semileptonic background**: $B \to D^{**}\mu\nu$, $D^{**} \to D^*\pi$. **17% of data sample**
- Strong phases can appear in interference of various D^{**} states [Aloni et al]
  - **Parity violation**. CP violation in SL only with NP.
- Inject varying δ_D in $B \to D^{**}\mu\nu$ simulation and fit P asymmetry to extract bias $\to$ assign systematics

- **Main double charm background**: $B \to D^* D_s^*$, $D^* \to D^0\pi$, $D_s^* \to D_s\gamma$, $D_s \to \mu\nu X$. **5% of data sample**.
- $B \to V_1 V_2$, 4 final state particles
  - **Parity violation**. CP violation possible in SM but suppressed by $|\frac{V_{ub}}{V_{cb}}| \sim 0.1$
- Inject maximal PV in $B \to D^* D_s^*$ simulation and fit P asymmetry to extract bias $\to$ assign systematics
- Other double charm backgrounds:
  - $B \to D^* D_s$ does not exhibit parity or CP violation (three spin-0 final state particles).
  - $B \to D^* D_s^* \pi$, $B \to D^* D^{(*)} K$ contribute at **level of 1% or less**

- **Data-driven backgrounds**: Combinatorial (Fake-D^* $\sim 1\%$, True-D^* $\sim 5\%$), μ-MisID $\sim 6\%$
  - Unphysical backgrounds. Could bias both P and CP asymmetries.
  - Perform asymmetry fits to these samples to extract bias $\to$ assign systematics

Overview of background biases

Bias in parity asymmetry

Bias source	$\Delta\ \mathrm{Im}(g_R)^{\mathrm{fake}}$	$\Delta\ \mathrm{Im}(g_P g_T^*)^{\mathrm{fake}}$
Misid	$(-0.68 \pm 0.30) \times 10^{-3}$	$(0.46 \pm 0.72) \times 10^{-4}$
Fake D^* comb	$(-0.01 \pm 0.17) \times 10^{-3}$	$(0.41 \pm 0.42) \times 10^{-4}$
True D^* comb	$(1.05 \pm 0.55) \times 10^{-3}$	$(-1.27 \pm 1.50) \times 10^{-4}$
$B^- \to D^{**+}\mu^-\bar{\nu}_\mu$	**$(8.68 \pm 0.31) \times 10^{-3}$**	**$(2.55 \pm 0.87) \times 10^{-4}$**
$\overline{B}^0 \to D^{*+} D_s^{*-}$	$(0.05 \pm 0.27) \times 10^{-3}$	$(0.79 \pm 0.79) \times 10^{-4}$

Bias in *CP* asymmetry

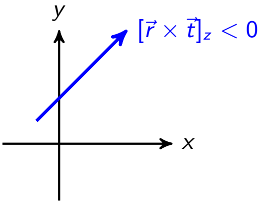
Bias source	$\Delta\ \mathrm{Im}(g_R)$	$\Delta\ \mathrm{Im}(g_P g_T^*)$
Misid	$(-0.46 \pm 0.30) \times 10^{-3}$	$(1.44 \pm 0.78) \times 10^{-4}$
Fake D^* comb	$(0.17 \pm 0.18) \times 10^{-3}$	$(0.16 \pm 0.41) \times 10^{-4}$
True D^* comb	$(0.74 \pm 0.55) \times 10^{-3}$	$(0.03 \pm 1.51) \times 10^{-4}$

Values are given as (bias from fit) $\times$ (fraction in data sample) !

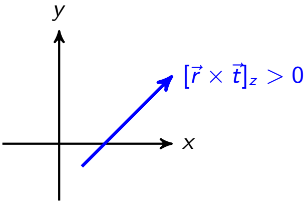
Overview

Origin of instrumentation bias

- In general, any **chiral** (asymmetric in mirror) distortion in the reconstruction procedure can introduce fake parity-odd terms to the distribution.
- If reconstruction affects "left handed" and "right-handed" tracks differently $\rightarrow$ bias parity-odd terms
- $[\vec{r} \times \vec{t}]_z = x_0 t_y - y_0 t_x$, track position at origin $\vec{r} = (x_0, y_0, z_0)$, track direction (slope) $\vec{t} = (t_x, t_y, t_z)$



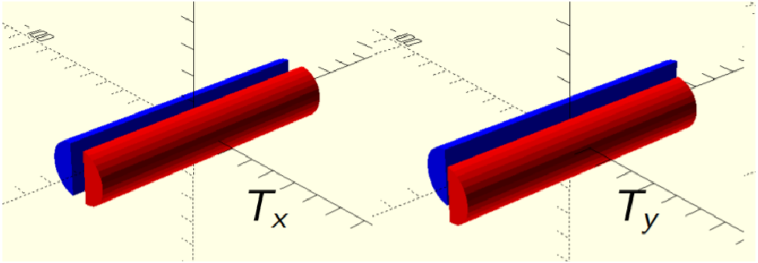
"Left-handed" track



"Right-handed" track

- 1. Misalignments of detector elements $\rightarrow$ Vertex Locator
- 2. Non-uniform (parity-odd) reconstruction efficiencies

Vertex Locator misalignment

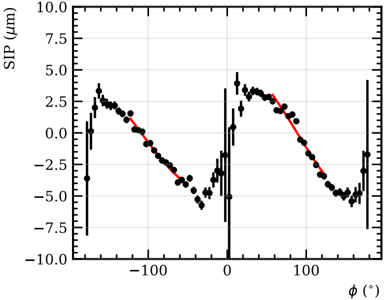


- VELO consists of two movable halves that are retracted and closed during each LHC fill
- Kinematics reconstructed from topology of vertices (PV, BV) measured by VELO
- Misalignments of the two halves $\rightarrow$ bias in vertex position $\rightarrow$ bias kinematic parameters ($\sin\chi$)
- T_y misalignment is parity-odd, can bias measurement of parity-odd terms

- Study parity-odd effects in VELO with fully reconstructed $B^+ \to J/\psi K^+$ control sample
- **Signed impact parameter** (in x-y plane) of the B is a parity-odd quantity. **Expect $< SIP >= 0$**.

$$SIP = [\vec{r} \times \vec{n}]_z = (x_{BV} - x_{PV})\frac{p_y}{p_T} - (y_{BV} - y_{PV})\frac{p_x}{p_T}$$

- Fit SIP as a function of ϕ (azimuthal angle in x-y plane) to extract shifts along x, y



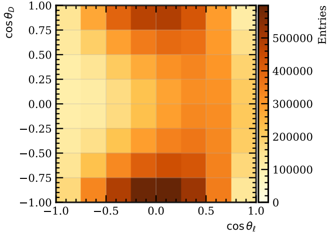
T_x misalignment $\sim 6\,\mu m$

T_y misalignment $\sim 2\,\mu m$

VELO T_y misalignment: CP asymmetries fit

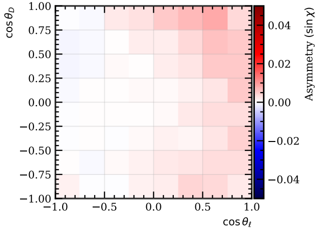
Displace tracks in $B^0 \to D^{*-}\mu^+\nu_\mu$ SM simulation along y by 2μm as if VELO halves are misaligned

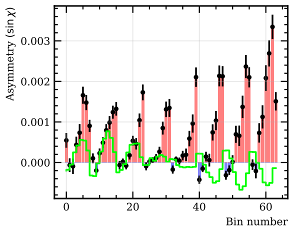
Unweighted density $\cos\theta_D, \cos\theta_\ell$



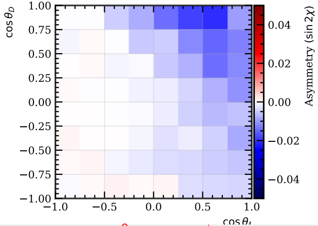
$$\Delta\mathrm{Im}(g_R) = (-3.74 \pm 0.84) \times 10^{-3}$$
$$\Delta\mathrm{Im}(g_P g_T^*) = (-0.31 \pm 0.24) \times 10^{-3}$$

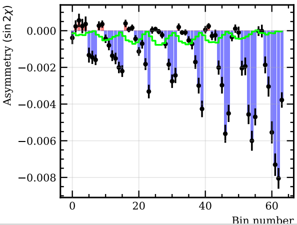
"Up-down asymmetry", $w \propto \sin\chi$:





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





P-odd efficiency at LHCb: possible effects

Parity-odd effects in the reconstruction efficiency at LHCb can bias measurement of parity-odd terms in the angular distribution

$$\sin\chi = \sum_{i\neq j} S_{ij} \sin(\phi_i - \phi_j)\ ;\ \ i,j = \{B, \mu, K_D, \pi_D, \pi_s\}$$

Two possible P-odd terms in efficiency:

- **Single-track** term:
  - $\epsilon^{1track}_{LHCb} \sim [\vec{r} \times \vec{t}]_z \sim \sin(\phi_B - \phi_i)$, with i a final state
  - Only possible parity-odd effect if efficiency depends on $\vec{r}$ and $\vec{t}$, but not on particle species
  - Can only come from VELO
- **Two-track** term:
  - $\epsilon^{2track}_{LHCb} \sim [\vec{t_i} \times \vec{t_j}]_z \sim \sin(\phi_i - \phi_j)$, with i, j two final states
  - If track efficiency still depends on $\vec{t}$ (but not on $\vec{r}$) and this dependence is different for different particle species
  - Can come from e.g. PID detector elements

P-odd efficiency at LHCb: $B^0 \to D^- \mu^+ \nu_\mu$ control sample

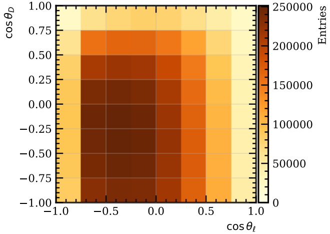
Need to use suitable **control DATA sample** with properties similar to the **signal sample** in order to estimate parity-odd effects in the track reconstruction efficiency that may arise in data

- **Signal sample**: $\overline{B}^0 \to [D^{*+} \to (D^0 \to K^- \pi^+)\pi_s^+]\mu^- \overline{\nu}_\mu$
- **Control sample**: $\overline{B}^0 \to D^+(\to K^- \pi^+ \pi^+)\mu^- \overline{\nu}_\mu$

- Control and signal have same $K^- \pi^+ \pi^+ \mu^-$ final state
- Control decay proceeds as two three-body decays and D^+ is spin-0:
  - **Inherently P-even $\to$ no parity or CP violation even with NP**
- Any parity-odd effect in control $\overline{B}^0 \to D^+ \mu^- \overline{\nu}_\mu$ should be due to parity-odd efficiency
- Perform asymmetry fits in control sample $\to$ extract bias on NP couplings and assign systematics

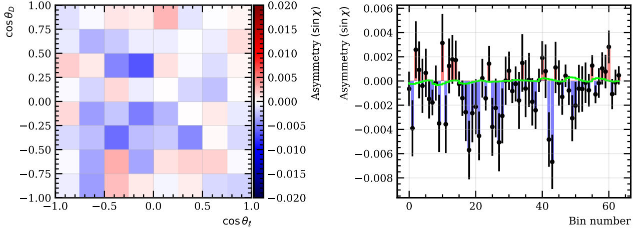
P-odd efficiency at LHCb: control sample P asymmetries fit

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

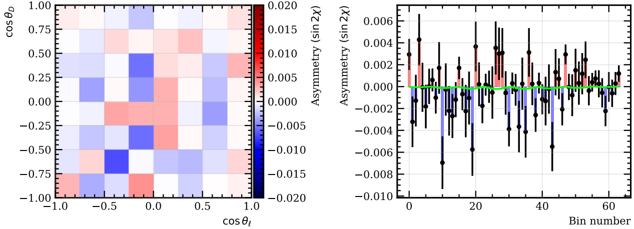


$$\Delta \mathrm{Im}(g_R)^{\text{fake}} = -0.0011 \pm 0.0017$$
$$\Delta \mathrm{Im}(g_P g_T^*)^{\text{fake}} = 0.0002 \pm 0.0004$$

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

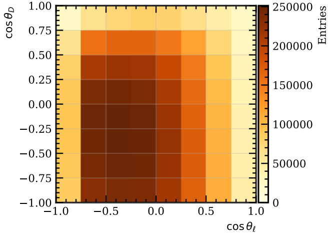


"Quadratic asymmetry", $w \propto \sin 2\chi$:



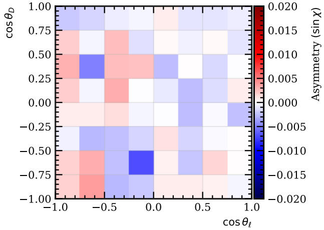
P-odd efficiency at LHCb: control sample *CP* asymmetries fit

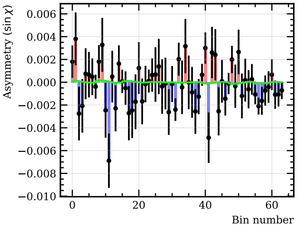
Unweighted density $\cos\theta_D, \cos\theta_\ell$



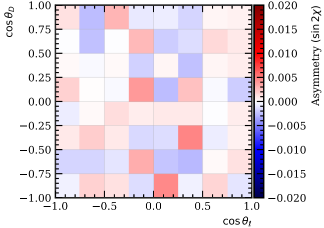
$$\Delta \mathrm{Im}(g_R) = 0.0006 \pm 0.0017$$
$$\Delta \mathrm{Im}(g_P g_T^*) = 0.0001 \pm 0.0004$$

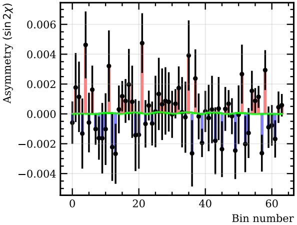
"Up-down asymmetry", $w \propto \sin\chi$:





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





Overview of background and instrumentation biases

Bias in parity asymmetry

Bias source	$\Delta\ \mathrm{Im}(g_R)^{\mathrm{fake}}$	$\Delta\ \mathrm{Im}(g_P g_T^*)^{\mathrm{fake}}$
Misid	$(-0.68 \pm 0.30) \times 10^{-3}$	$(0.46 \pm 0.72) \times 10^{-4}$
Fake D^* comb	$(-0.01 \pm 0.17) \times 10^{-3}$	$(0.41 \pm 0.42) \times 10^{-4}$
True D^* comb	$(1.05 \pm 0.55) \times 10^{-3}$	$(-1.27 \pm 1.50) \times 10^{-4}$
$B^- \to D^{**+}\mu^-\bar{\nu}_\mu$	**$(8.68 \pm 0.31) \times 10^{-3}$**	**$(2.55 \pm 0.87) \times 10^{-4}$**
$\overline{B}^0 \to D^{*+}D_s^{*-}$	$(0.05 \pm 0.27) \times 10^{-3}$	$(0.79 \pm 0.79) \times 10^{-4}$
T_y 2μm misalignment	$(-0.37 \pm 0.85) \times 10^{-3}$	$(0.20 \pm 2.39) \times 10^{-4}$
Control sample	$(-1.10 \pm 1.70) \times 10^{-3}$	$(2.00 \pm 4.00) \times 10^{-4}$

Bias in *CP* asymmetry

Bias source	$\Delta\ \mathrm{Im}(g_R)$	$\Delta\ \mathrm{Im}(g_P g_T^*)$
Misid	$(-0.46 \pm 0.30) \times 10^{-3}$	$(1.44 \pm 0.78) \times 10^{-4}$
Fake D^* comb	$(0.17 \pm 0.18) \times 10^{-3}$	$(0.16 \pm 0.41) \times 10^{-4}$
True D^* comb	$(0.74 \pm 0.55) \times 10^{-3}$	$(0.03 \pm 1.51) \times 10^{-4}$
$T_y 2\ \mu$m misalignment	**$(-3.74 \pm 0.84) \times 10^{-3}$**	**$(3.10 \pm 2.39) \times 10^{-4}$**
Control sample	$(0.60 \pm 1.70) \times 10^{-3}$	$(1.00 \pm 4.00) \times 10^{-4}$

Assign systematics using: $\sigma_{\mathrm{syst}} = |\mu_{\mathrm{bias}}| + 1.28\sigma_{\mathrm{bias}}$

Overview of background and instrumentation systematics

Parity asymmetries

Assigned systematic	$\Delta\ \mathrm{Im}(g_R)^{fake}$	$\Delta\ \mathrm{Im}(g_P g_T^*)^{fake}$
Misid	1.07×10^{-3}	1.38×10^{-4}
Fake D^* comb	0.23×10^{-3}	0.96×10^{-4}
True D^* comb	1.76×10^{-3}	3.20×10^{-4}
$B^- \to D^{**+}\mu^-\bar{\nu}_\mu$	9.64×10^{-3}	3.67×10^{-4}
$\overline{B}^0 \to D^{*+}D_s^{*-}$	0.41×10^{-3}	1.81×10^{-4}
T_y 2μm misalignment	1.44×10^{-3}	3.27×10^{-4}
Control sample	3.27×10^{-3}	7.12×10^{-4}
Total	$\mathbf{10.50 \times 10^{-3}}$	$\mathbf{0.96 \times 10^{-3}}$

CP asymmetries

Assigned systematic	$\Delta\ \mathrm{Im}(g_R)$	$\Delta\ \mathrm{Im}(g_P g_T^*)$
Misid	0.85×10^{-3}	2.45×10^{-4}
Fake D^* comb	0.40×10^{-3}	0.70×10^{-4}
True D^* comb	1.45×10^{-3}	1.98×10^{-4}
$T_y 2\,\mu$m misalignment	4.16×10^{-3}	4.33×10^{-4}
Control sample	2.78×10^{-3}	6.12×10^{-4}
Total	$\mathbf{5.82 \times 10^{-3}}$	$\mathbf{0.92 \times 10^{-3}}$

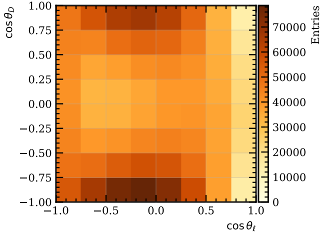
$\sigma_{g_R}^{stat} \sim 5 \times 10^{-3}$

$\sigma_{g_P g_T^*}^{stat} \sim 1 \times 10^{-3}$

Signal data: parity asymmetries fit. Cross-check and statistical uncertainty

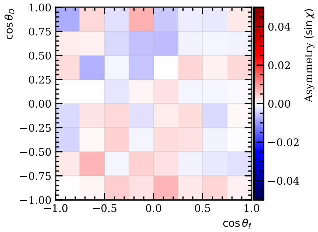
Parity asymmetry should be zero in both SM and NP

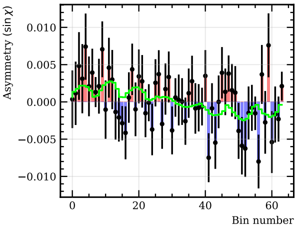
Unweighted density $\cos\theta_D, \cos\theta_\ell$



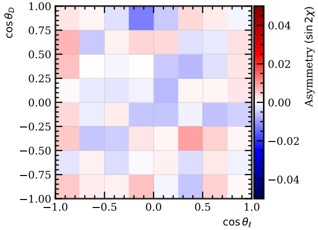
$$\Delta\mathrm{Im}(g_R)^{\mathrm{fake}} = -0.0057 \pm 0.0051$$
$$\Delta\mathrm{Im}(g_P g_T^*)^{\mathrm{fake}} = -0.0041 \pm 0.0013$$

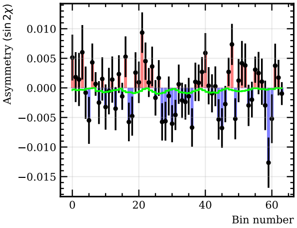
"Up-down asymmetry", $w \propto \sin\chi$:





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





Final results

- The final results for the parity and the (blinded) *CP* asymmetry measurements including the statistical and estimated systematic uncertainties are given below:

Parity asymmetries:

$$\mathrm{Im}(g_R)^{\mathrm{fake}} = (-0.57 \pm 0.51\ (\mathrm{stat.}) \pm 1.05\ (\mathrm{syst.}))\%,$$
$$\mathrm{Im}(g_P g_T^*)^{\mathrm{fake}} = (-0.41 \pm 0.13\ (\mathrm{stat.}) \pm 0.10\ (\mathrm{syst.}))\%.$$

***CP* asymmetries:**

$$\mathrm{Im}(g_R) = (\mathrm{X.XX} \pm 0.51\ (\mathrm{stat.}) \pm 0.58\ (\mathrm{syst.}))\%,$$
$$\mathrm{Im}(g_P g_T^*) = (\mathrm{X.XX} \pm 0.13\ (\mathrm{stat.}) \pm 0.09\ (\mathrm{syst.}))\%.$$

- 2.5σ deviation from expected zero result in $\mathrm{Im}(g_P g_T^*)^{\mathrm{fake}}$ in parity asymmetry fit
- Possible unaccounted for parity-violating effect (background?), mis-estimation of systematics ... ?

Overview

Conclusions

- Measurement of *CP*-violating angular observables in $B^0 \to D^{*-}\mu^+\nu_\mu$ is performed.
  - Precision measurement of complex NP couplings $\mathrm{Im}(g_R)$ and $\mathrm{Im}(g_P g_T^*)$
- Approximation techniques used to reconstruct ν_μ. **Full refit** of decay tree implemented to **improve resolution** in kinematic variables $(q^2, \theta_D, \theta_\ell, \chi)$
- **Novel model-independent method** to extract only the P-odd part in the angular distribution and cancel out the P-even terms (and their uncertainties) was demonstrated [JHEP 07 (2023) 063]
- Statistical uncertainty using method and data sample $\sim 0.5\%$ for $\mathrm{Im}(g_R)$ and $\sim 0.1\%$ for $\mathrm{Im}(g_P g_T^*)$
- Specific P-odd systematic effects considered and estimated to be at the level of stat. error
  - P-odd effects in backgrounds ($B \to D^{**}\mu\nu_\mu$, $B \to D^* D_s^*$)
  - P-odd effects in instrumentation (VELO misalignment, non-uniform reconstruction efficiencies)
  - **Data-driven methods developed to control the instrumentation systematics**
    - Calibration, control data samples: $B^+ \to J/\psi K^+$, $B^0 \to D^-\mu^+\nu_\mu$
- **Parity asymmetry fit** was performed as cross-check of the method in signal data sample.
  - Consistent with expectation in $\mathrm{Im}(g_R)$, bias in $\mathrm{Im}(g_P g_T^*)$
- ***CP* asymmetry fit** in the signal sample is still **blinded**

Prospects

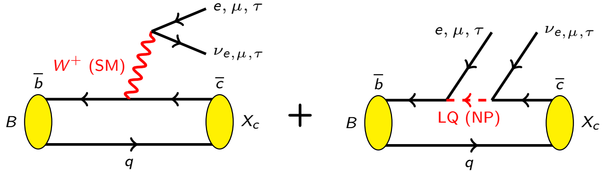
Measurement is subject to systematic uncertainties at the level of statistical precision

- Largest systematic in the **parity asymmetry** fit assigned in a conservative way by taking the maximal parity-violating strong phase in $B \to D^{**} \mu \nu_\mu$ decays.
  - A future measurement of the amplitude structure and strong phase (if any) will allow a more precise estimation of this effect
- Largest systematics in the ***CP*** **asymmetry** fit come from instrumentation effects and are estimated via data-driven methods
  - These methods will improve with more data, i.e. Run 3, Run 4
- The proposed method is currently used in $b \to c\mu\nu_\mu$, but could be extended to $b \to ce\nu_e$ and $b \to c\tau\nu_\tau$ to help constrain more NP scenarios.
- Other possibilities for CP violation in $b \to c\ell\nu_\ell$ such as interference of excited charm states in $B \to D^{**}\ell\nu_\ell$ decays. Sensitive to other NP couplings, e.g. g_S, g_P, g_T rather than g_R and $g_P g_T^*$

BACK-UP SLIDES

CP violation in $\overline{B}^0 \to D^{*+}\ell^-\overline{\nu}_\ell$ decays

- *CP* violation $\iff$ 2 interfering amplitudes
  $\Rightarrow$ **smoking-gun signal of NP**



- Best known CPV signal is $\mathcal{A}_{dir} \propto \Gamma(\overline{B}^0 \to D^{*+}\ell^-\overline{\nu}_\ell) - \Gamma(B^0 \to D^{*-}\ell^+\nu_\ell)$
  - **CP-odd (weak)** relative phase $\to$ from NP amplitude
  - **CP-even (strong)** relative phase $\to$ same hadronic $B \to D^*$ in SM or NP $\Rightarrow$ no relative strong phase $\Rightarrow$ $\boxed{\mathcal{A}_{dir} \approx 0}$
- Instead, CPV asymmetries in the angular distribution $\to$ **TRIPLE PRODUCT ASYMMETRIES**
  - Arise from amplitude structure of $B \to V_1 V_2$
  - Kinematical effects, i.e. need different Lorentz structures between SM (LH) and NP (RH, S, P, T) amplitudes
- $\overline{B}^0 \to D^{*+}(\to D^0\pi^+)W^{*-}(\to \ell\overline{\nu}_\ell)$
  - In SM $\exists$ 4 helicity amplitudes: $\mathcal{A}_\perp, \mathcal{A}_\parallel, \mathcal{A}_0, \mathcal{A}_{0t}$ $\to$ Form Factors
  - In NP $\exists$ **8** helicity amplitudes: SM, $\mathcal{A}_{SP}, \mathcal{A}_{\perp,T}, \mathcal{A}_{\parallel,T}, \mathcal{A}_{0,T}$ $\to$ Form Factors $\times\, g_{\text{NP}}$
- Compute $|\mathcal{M}|^2 \to \underbrace{|\mathcal{A}_i|^2, \mathrm{Re}(\mathcal{A}_i\mathcal{A}_j^*)}_{\text{CP-conserving}}$, $\boxed{\mathrm{Im}(\mathcal{A}_i\mathcal{A}_j^*)}$ $\to$ CP-violating triple products

- Coefficients of CP-violating terms given by $\mathrm{Im}(\mathcal{A}_i\mathcal{A}_j)$
- In general amplitudes contain both weak and strong phases, i.e. $\mathcal{A}_{i,j} = |\mathcal{A}|e^{i\phi_{i,j}}e^{i\delta_{i,j}}$

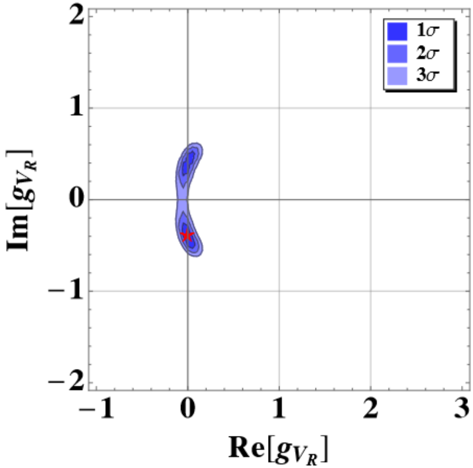
$$\mathrm{Im}(\mathcal{A}_i\mathcal{A}_j^*) = |\mathcal{A}_i||\mathcal{A}_j| \left(\underbrace{\sin(\phi_i - \phi_j)\cos(\delta_i - \delta_j)}_{CP\text{ violation}} + \underbrace{\cos(\phi_i - \phi_j)\sin(\delta_i - \delta_j)}_{\text{parity violation}} \right) . \quad (2)$$

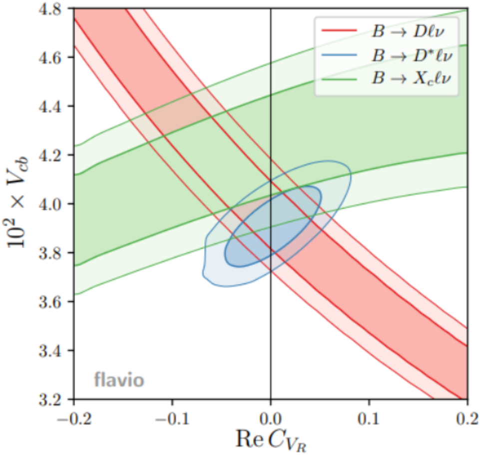
- In $b \to c\ell\nu_\ell$ decays $\Delta\delta \simeq 0$, but $\Delta\phi \neq 0$ due to NP

Binned asymmetry template fit. Statistical uncertainties

- We obtain: $\boldsymbol{\sigma^{\text{stat}}_{g_R} \sim 5 \times 10^{-3}}$ **(0.5%)**, $\boldsymbol{\sigma^{\text{stat}}_{g_P g_T^*} \sim 1 \times 10^{-3}}$ **(0.1%)**
- The precision in g_R and $g_P g_T^*$ depends on the magnitudes of the amplitudes that multiply those couplings
- Ratios of amplitude integrals:
- LH vector : RH vector : Pseudoscalar : Tensor = 1 : 1 : 0.05 : 75
- $\mathrm{Im}(g_R)$ given by LH*RH interference
- $\mathrm{Im}(g_P g_T^*)$ given by P*T interference
- The integral of the tensor amplitude (with g_T=1 and g_L=0) is 75 times larger in the full kinematic phase space than the SM amplitude (g_L=1 and other g_X=0). The integral of the pseudoscalar amplitude is smaller, but still the magnitude of the P*T interference term is $\sim \sqrt{(0.05 * 75)} \sim 2$ times larger than the LH*RH interference term which gives $\mathrm{Im}(g_R)$
- One also has to look at the differential distributions of these interference terms, and possibly P*T interference contributes somewhere in the phase space where vector amplitudes are small, which would give another factor of enhancement.

Constraints on NP couplings



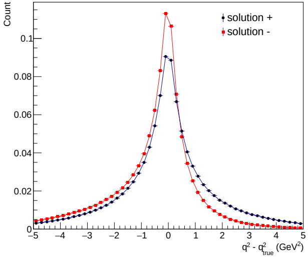


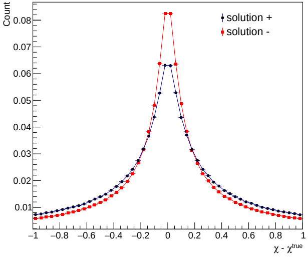
[D. Becirevic, M. Fedele, I. Nisandzic, A. Taygadunov]

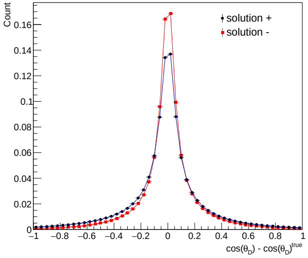
[M. Jung, D. Straub]

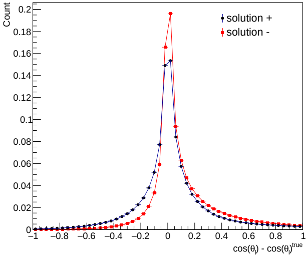
- **Parity-even** : Only affect interpretation of visible asymmetry in terms of NP couplings, i.e. enter relative to the magnitude of the measured $\mathrm{Im}(\mathrm{g_{NP}})$
- For instance: uncertainties in FFs, signal purity, reconstruction, magnitudes of sel/reco efficiency etc. **Do not** produce fake parity-odd terms if the angular distribution is SM-like
- Example: $P_{\mathrm{odd}} \sim \mathrm{Im}(g_{NP}) \times FF$. Assume $FF = 1.0 \pm 0.1$
- Case 1: we measure $\mathrm{Im}(\mathrm{g_{NP}}) = 0.01 \pm 0.01(\mathrm{stat}) \Rightarrow 0.001(syst)$
- Case 2: we measure $\mathrm{Im}(\mathrm{g_{NP}}) = 0.10 \pm 0.01(\mathrm{stat}) \Rightarrow 0.01(syst)$
- Parity-even systematic effects only become relevant if we measure non-zero $\mathrm{Im}(g_{NP})$

Reconstruction of ν_μ at LHCb. Resolution of solution "+" and "-"

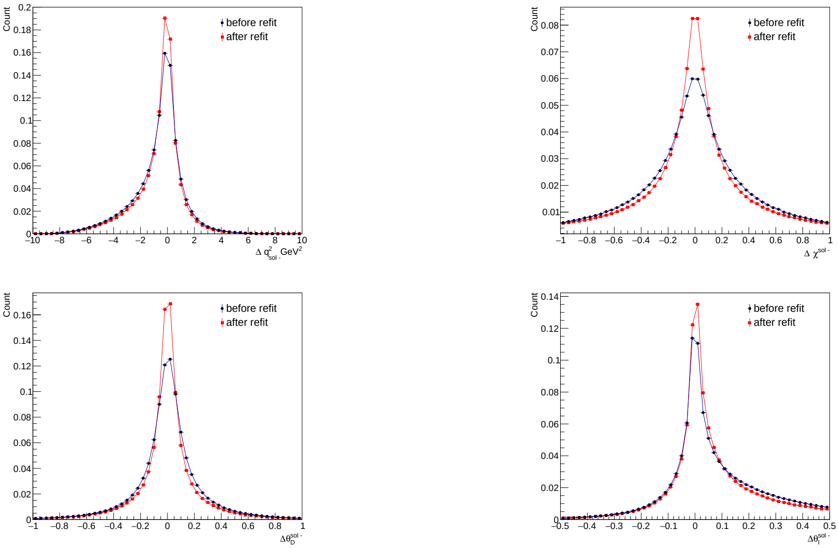




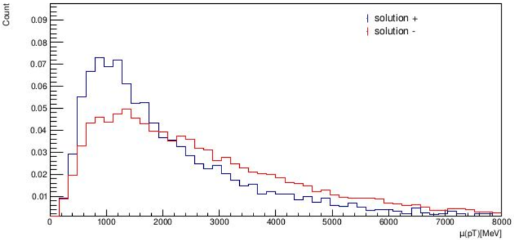


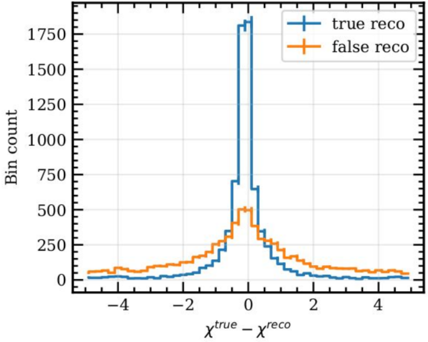


Reconstruction of ν_μ at LHCb. Angle resolutions before and after refit for solution “-”



Reconstruction of ν_μ at LHCb. Solution "+" and "-"

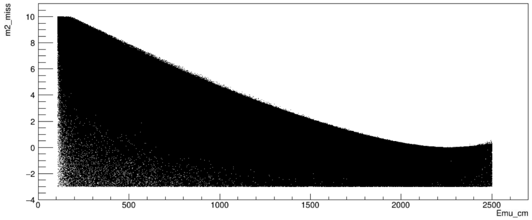


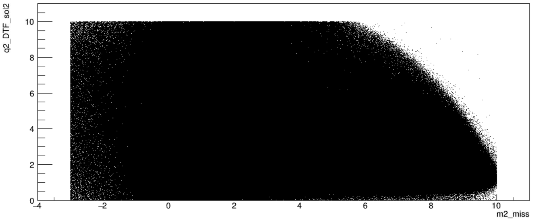


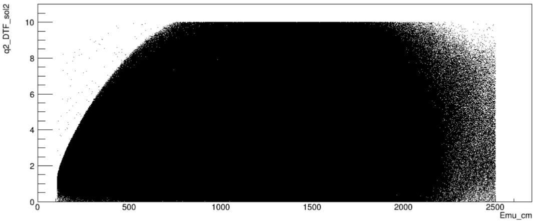
- Resolution for solutions "+" and "-" are a mixture of the "true" and "fake" resolution functions
- The ratio of this mixture depends on the efficiency of "+" and "-"
- But the efficiency for the two solutions (when they are the true one) is different due to different kinematics
- So the resolutions of the two solutions are different and it appears to be better for the "-" solution

Data sample: signal fit. Fit variables correlations.

Correlations of background fit variables q^2, E_μ^*, m^2_{miss}





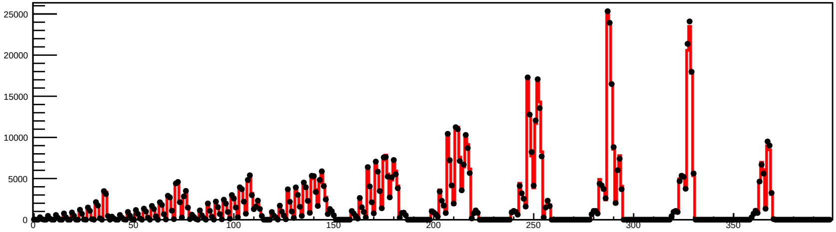


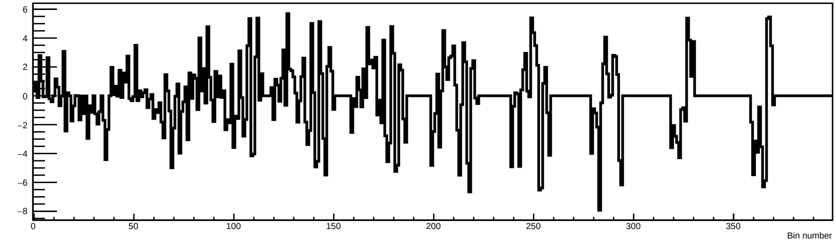
Data sample: signal fit results. 2016+2017+2018.

Component	Yield	Signal fraction
$B^0 \to D^{*-}\mu^+\nu_\mu$	1777896 ± 3232	1
$B^0 \to D^{*-}\tau^+\nu_\tau$	36424 ± 2197	$2.04\% \pm 0.12\%$
$B^0 \to [D^{**-} \to D^{*-}\pi^0]\mu^+\nu_\mu$	80508 ± 15900	$4.52\% \pm 0.89\%$
$B^+ \to [D^{**0} \to D^{*-}\pi^+]\mu^+\nu_\mu$	223117 ± 16075	$12.54\% \pm 0.90\%$
$B^0 \to D^{**-}\tau^+\nu_\tau$	1690 ± 156	$0.09\% \pm 0.01\%$
$B^+ \to D^{**0}\tau^+\nu_\tau$	9326 ± 244	$0.52\% \pm 0.01\%$
$B^+ \to [D^{**0} \to D^{*+}\pi^0\pi^-]\mu^+\nu_\mu$	1 ± 662.59	$0.00\% \pm 0.03\%$
$B^0 \to [D^{**-} \to D^{*-}\pi^+\pi^-]\mu^+\nu_\mu$	1 ± 529	$0.00\% \pm 0.03\%$
$B_s^0 \to D_s^{**-}\mu^+\nu_\mu$	1 ± 265	$0.00\% \pm 0.01\%$

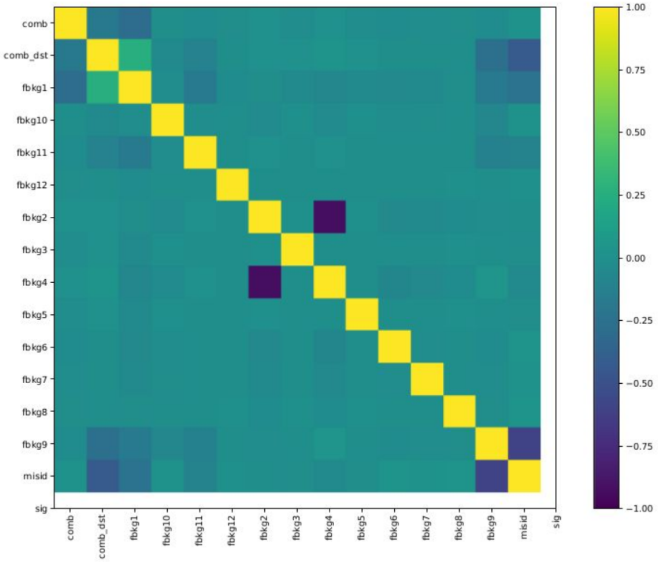
$B^0 \to D^{*-}D_{(s)}^+X, D_{(s)}^+ \to X\mu^+\nu_\mu$	82888 ± 3188	$4.66\% \pm 0.18\%$
$B^+ \to D^{*-}D_{(s)}^+X, D_{(s)}^+ \to X\mu^+\nu_\mu$	19397 ± 1289	$1.09\% \pm 0.07\%$
$B^0 \to D^{*-}D_{(s)}^+X, D_{(s)}^+ \to X\tau^+\nu_\tau$	16691 ± 798	$0.93\% \pm 0.04\%$
$B^+ \to D^{*-}D_{(s)}^+X, D_{(s)}^+ \to X\tau^+\nu_\tau$	1641 ± 124	$0.09\% \pm 0.01\%$
Fake D^* combinatorial	15124 ± 2592	$0.85\% \pm 0.14\%$
True D^* combinatorial	98871 ± 2084	$5.56\% \pm 0.11\%$
μ misid	116751 ± 4899	$6.56\% \pm 0.27\%$

Data sample: signal fit. Flattened 3D pulls. 2016





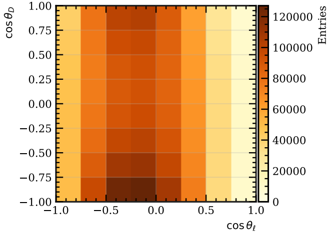
Data sample: signal fit results. Correlation matrix. 2016.



- **Semileptonic background**: $B \to D^{**}\mu\nu$, $D^{**} \to D^*\pi$. **17% of data sample**
  - Main resonances contributing in $D^*\pi$: $D_1(2420), D_1'(2430), D_2^*(2460)$
- Strong phases can appear due to interference of these excited resonances [Aloni et al] $\to$ **Parity violation**
- Inject strong phase difference (δ_D) in interference between $D_1(2420)$ and $D_2^*(2460)$ narrow states.
  - Amplitudes follow formalism in [Bernlocher et al]
  - Vary δ_D from 0^o to 315^o in steps of 45^o $\to$ generate weights.
    Same approach as Hammer ($weight = \frac{d\Gamma^{new}/dPS}{d\Gamma^{old}/dPS}$).
- Perform fits to reweighted $B \to D^{**}\mu\nu$ samples to extract bias on NP couplings.
- **This effect only concerns parity violation**. Semileptonic decays exhibit CP-violation only with NP!

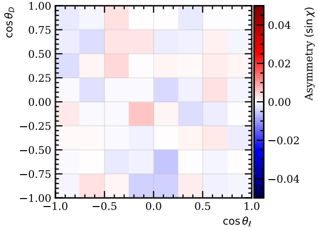
$(B^- \to D^{**0}\mu^-\nu)$ - no δ_D - P asymmetries fit

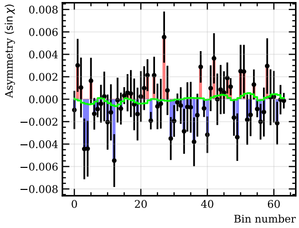
Unweighted density $\cos\theta_D, \cos\theta_\ell$



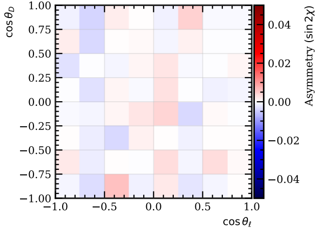
| $\Delta\mathrm{Im}(g_R) = 0.0023 \pm 0.0019$ |
| $\Delta\mathrm{Im}(g_P g_T^*) = 0.0004 \pm 0.0005$ |

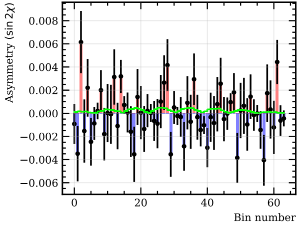
"Up-down asymmetry", $w \propto \sin\chi$:



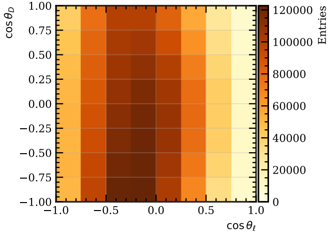


"Quadratic asymmetry", $w \propto \sin 2\chi$:

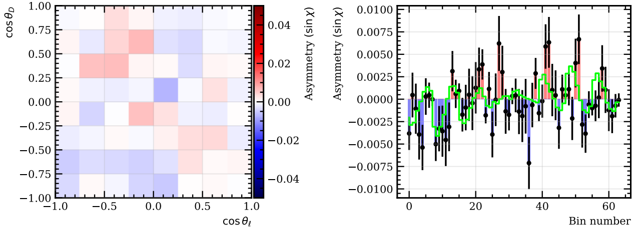




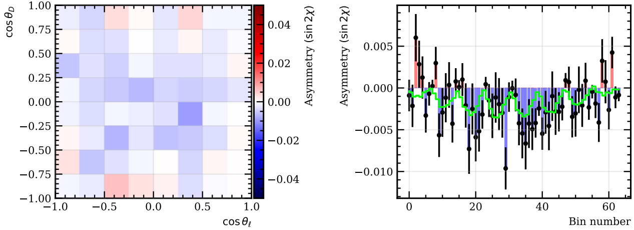
Unweighted density $\cos\theta_D, \cos\theta_\ell$



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



“Quadratic asymmetry”, $w \propto \sin 2\chi$:



$$\Delta\mathrm{Im}(g_R) = 0.0182 \pm 0.0023$$
$$\Delta\mathrm{Im}(g_P g_T^*) = 0.0015 \pm 0.0005$$

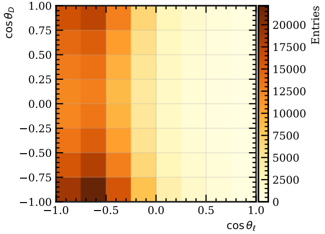
Doublecharm background $B \to D^* D_s^*$

- **Double charm background**: $B \to D^* D_s^*$, $D^* \to D^0 \pi$, $D_s^* \to D_s \gamma$, $D_s \to \mu\nu X$. **5% of data sample**.
- $B \to V_1 V_2$, 4 final state particles, can exhibit parity violation
- Amplitude structure measured by [LHCb]:

$$
\begin{aligned}
|H_0| &= \ \ 0.760 \pm 0.007 \pm 0.007, \\
|H_-| &= \ \ 0.195 \pm 0.022 \pm 0.032, \\
|H_+| &= \ \ 0.620 \pm 0.011 \pm 0.013, \\
\phi_- &= -0.046 \pm 0.102 \pm 0.020 \text{ rad}, \\
\phi_+ &= \ \ 0.108 \pm 0.170 \pm 0.051 \text{ rad}.
\end{aligned}
$$

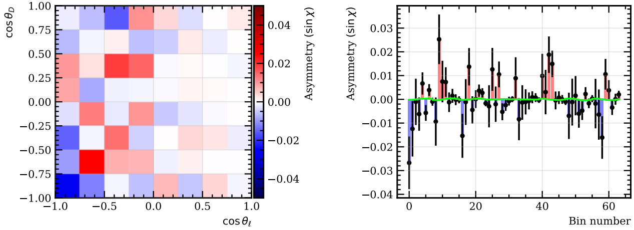
- Degree of parity violation determined by $\phi_\pm$. **Consistent with 0** .
- Inject maximal PV $\phi_\pm = \pm\frac{\pi}{2}$. Obtain *weight* $= \frac{d\Gamma^{\text{new}}/dPS}{d\Gamma^{\text{old}}/dPS}$. Fit reweighted $B \to D^* D_s^*$ sample.
- **This effect concerns only parity violation**. *CP*-violation is possible in SM but suppressed by $|\frac{V_{ub}}{V_{cb}}| \sim 0.1$
- Other double charm backgrounds:
  - $B \to D^* D_s$ does not exhibit parity or *CP* violation (three spin-0 final state particles).
  - $B \to D^* D_s^* \pi$, $B \to D^* D^{(*)} K$ contribute at **level of 1% or less**

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

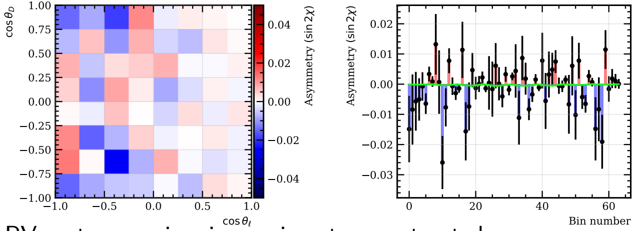


$$\Delta \mathrm{Im}(g_R) = 0.0011 \pm 0.0060$$
$$\Delta \mathrm{Im}(g_P g_T^*) = 0.0017 \pm 0.0017$$

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



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



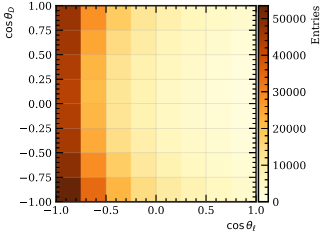
No visible P-odd effect even with maximal PV: not a surprise since γ is not reconstructed

Data driven backgrounds

- 1. Fake D^* combinatorial: Combinations of D^0 with random pions (primarily coming from PV). Modelled from data using wrong sign $D^0\pi^-\mu^+/\overline{D}^0\pi^+\mu^-$ sample.
  - **$\sim$ 1% of data sample**
- 2. True D^* combinatorial: Combinations of true D^* with μ coming from other decay chains. Modelled from data using same sign $D^{*+}\mu^+/D^{*-}\mu^-$ sample.
  - **$\sim$ 5% of data sample**
- 3. Muon misID background: Modelled from special data sample which requires muon candidates to fail μ PID, but be in acceptance of muon chambers (hadrons misid-ed as muons).
  - **$\sim$ 6% of data sample**

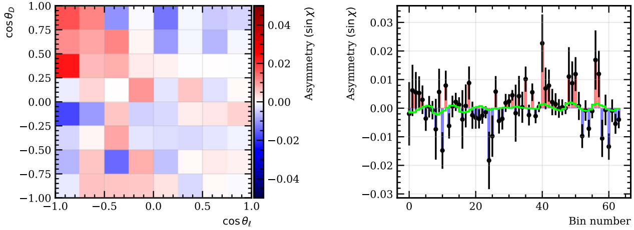
- They can bias both P and CP asymmetries $\rightarrow$ fits to extract biases on NP couplings

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

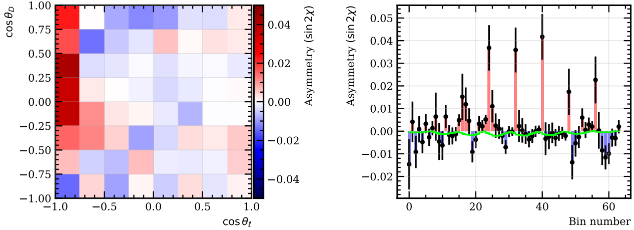


$$\Delta \mathrm{Im}(g_R) = -0.0105 \pm 0.0046$$
$$\Delta \mathrm{Im}(g_P g_T^*) = 0.0007 \pm 0.0011$$

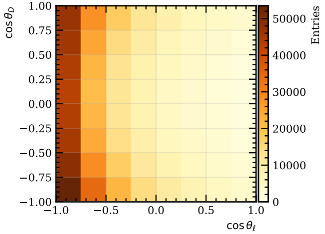
"Up-down asymmetry", $w \propto \sin\chi$:



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

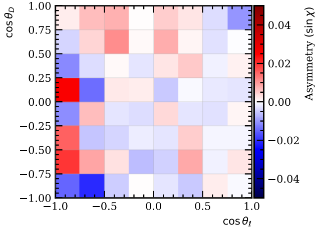


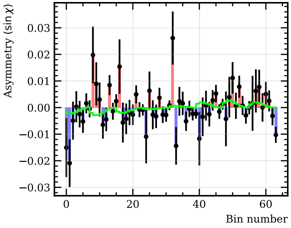
Unweighted density $\cos\theta_D, \cos\theta_\ell$



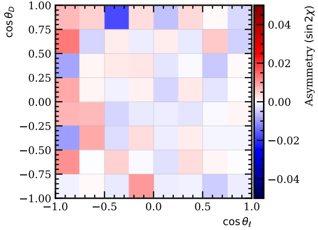
$$\Delta\mathrm{Im}(g_R) = -0.0070 \pm 0.0046$$
$$\Delta\mathrm{Im}(g_P g_T^*) = 0.0022 \pm 0.0012$$

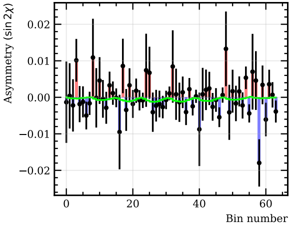
"Up-down asymmetry", $w \propto \sin\chi$:



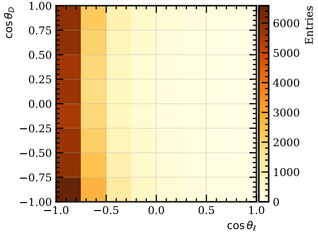


"Quadratic asymmetry", $w \propto \sin 2\chi$:



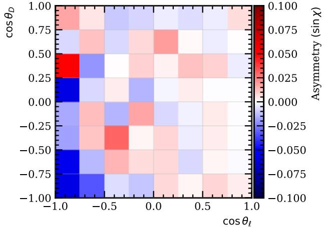


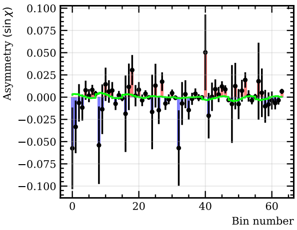
Unweighted density $\cos\theta_D, \cos\theta_\ell$



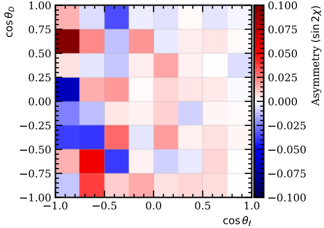
$$\Delta \mathrm{Im}(g_R) = 0.0190 \pm 0.0099$$
$$\Delta \mathrm{Im}(g_P g_T^*) = -0.0023 \pm 0.0027$$

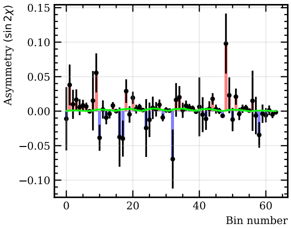
"Up-down asymmetry", $w \propto \sin\chi$:



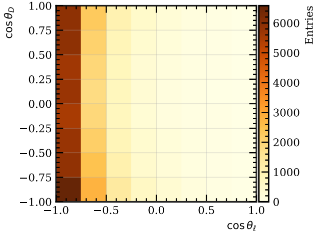


"Quadratic asymmetry", $w \propto \sin 2\chi$:



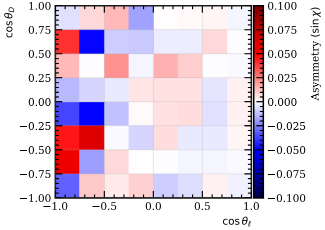


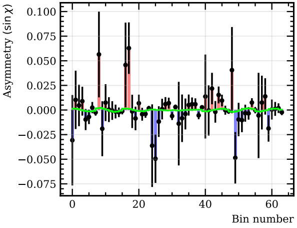
Unweighted density $\cos\theta_D, \cos\theta_\ell$



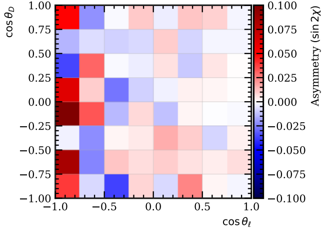
$\Delta\mathrm{Im}(g_R) = 0.0134 \pm 0.0099$
$\Delta\mathrm{Im}(g_P g_T^*) = 0.000006 \pm 0.002730$

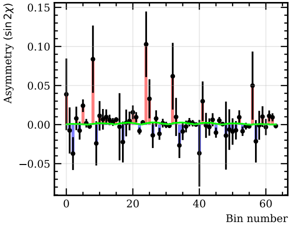
"Up-down asymmetry", $w \propto \sin\chi$:



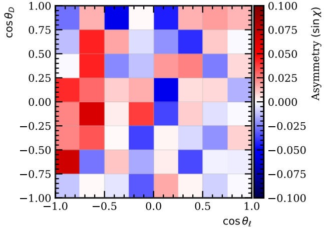


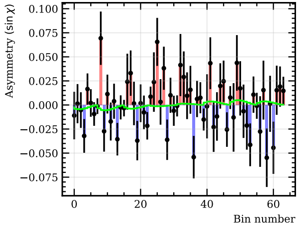
"Quadratic asymmetry", $w \propto \sin 2\chi$:



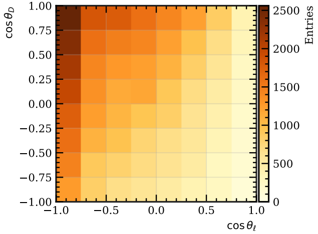


"Up-down asymmetry", $w \propto \sin\chi$:

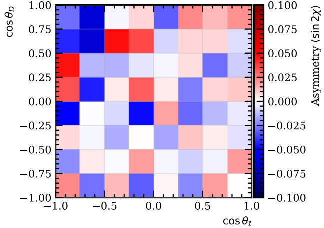


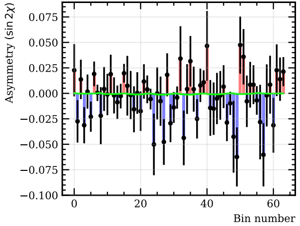


Unweighted density $\cos\theta_D, \cos\theta_\ell$



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

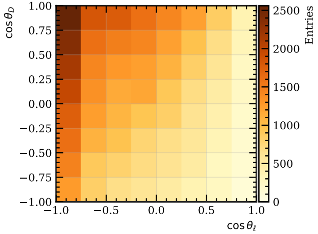




$$\Delta \mathrm{Im}(g_R) = -0.0008 \pm 0.0208$$
$$\Delta \mathrm{Im}(g_P g_T^*) = 0.0049 \pm 0.0049$$

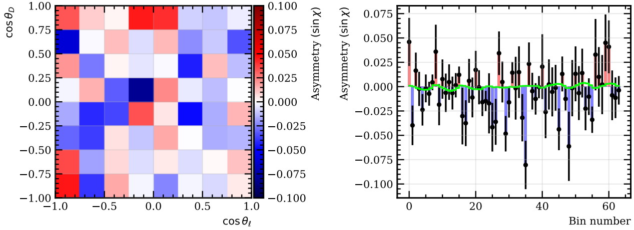
Combinatorial Fake-D^* - CP asymmetries

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

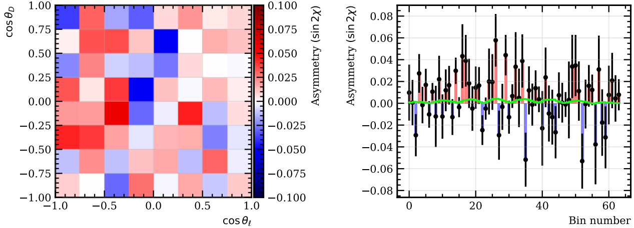


$$\Delta\mathrm{Im}(g_R) = -0.0008 \pm 0.0208$$
$$\Delta\mathrm{Im}(g_P g_T^*) = 0.0049 \pm 0.0049$$

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

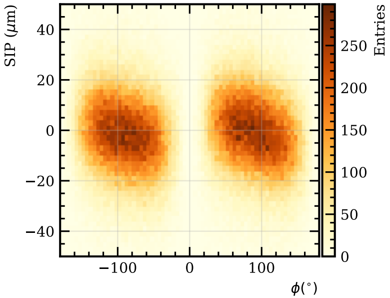


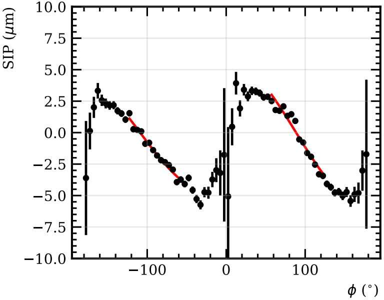
"Quadratic asymmetry", $w \propto \sin 2\chi$:



VELO misalignment calibration: $B^+ \to J/\psi K^+$ control sample (2)

Take candidates where all tracks are $p_x > 0$ or $p_x < 0$, i.e. reconstructed purely in **left** or **right** VELO halves.





Fit SIP vs ϕ dependence with simple χ^2 function to obtain Δx, Δy shifts of VELO halves:

$$SIP(\phi; \Delta x, \Delta y) = \sqrt{\Delta x^2 + \Delta y^2} \cos(\phi - \text{atan2}(\Delta y, -\Delta x)),$$

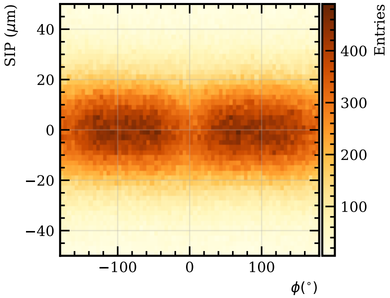
`MagDown` 2016: $\Delta x_+ = -5.82 \pm 0.14\ \mu m$, $\boldsymbol{\Delta y_+ = -0.15 \pm 0.05\ \mu m}$
$\Delta x_- = +4.53 \pm 0.14\ \mu\text{m}$, $\boldsymbol{\Delta y_- = +1.56 \pm 0.05\ \mu m}$

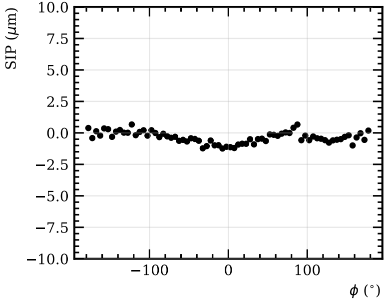
VELO halves misalignment
along $y \sim 2\mu$m

VELO misalignment calibration: $B^+ \to J/\psi K^+$ control sample (3)

Shift track states by Δx, Δy and refit B vertex using DTF

Do not refit PV (assume shifts of two VELO halves average out for a large number of PV tracks)

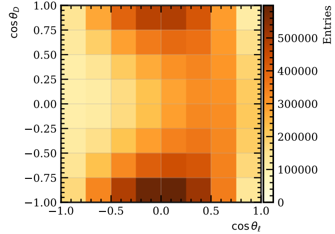




Bias mostly fixed, remaining systematics $< 1\mu$m.

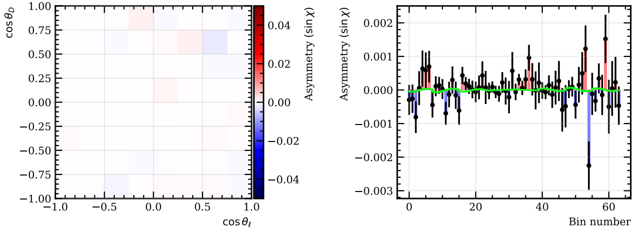
Displace tracks in $B^0 \to D^{*-}\mu^+\nu_\mu$ simulation along y by 2μm as if VELO halves are misaligned

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

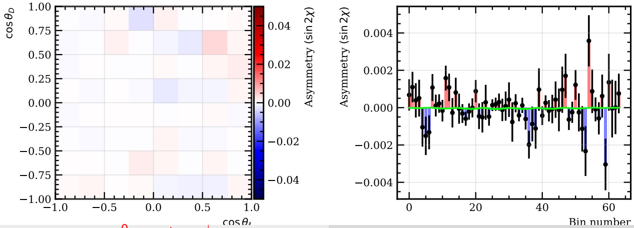


$$\Delta \mathrm{Im}(g_R) = (-0.37 \pm 0.84) \times 10^{-3}$$
$$\Delta \mathrm{Im}(g_P g_T^*) = (0.02 \pm 0.24) \times 10^{-3}$$

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



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



P-odd efficiency at LHCb: control vs signal samples

Obtain kinematic parameters in control data sample. Build the $\sin\chi$ and $\sin 2\chi$ asymmetries and apply following parity-odd effects as arbitrarily large **$\mathcal{O}(1)$ weights**:

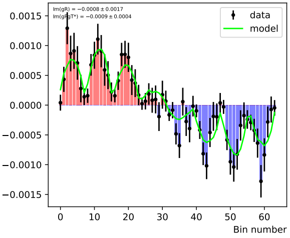
- **"Left-right" asymmetry in track efficiency (single track)**: Efficiency weight $\varepsilon = \mathrm{sign}[\vec{r} \times \vec{t}]_z$.
- $[\vec{r} \times \vec{t}]$ **term in track efficiency (single track)**: Efficiency weight $\varepsilon = [\vec{r} \times \vec{t}]_z / 1\,\mathrm{mm}$.
- ϕ **dependence of track efficiency (two-track)**: Efficiency weight $\varepsilon = \sin\phi_i \cos\phi_j$.
- $\Delta\phi$ **dependence of track pair efficiency (two-track)**: Efficiency weight $\varepsilon = \sin(\phi_i - \phi_j)$.

Perform fits and compare **signal** and **control** sample bias on $\mathrm{Im}(g_R)$ and $\mathrm{Im}(g_P g_T^*)$.

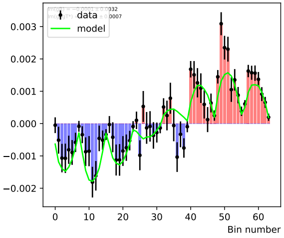
- Four categories: `MagUp`, `MagDown`, B^0, $\overline{B}^0$.
- Efficiency may depend on the track curvature and consequently the dependence on ϕ may differ across the four categories $\Rightarrow$ check for consistency, i.e that bias does not cancel out when looking at the full sample.

Fits to P-odd efficiency reweighted samples (sin χ only)

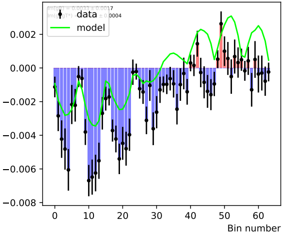
$\mu(\vec{r} \times \vec{t})_Z$ signal



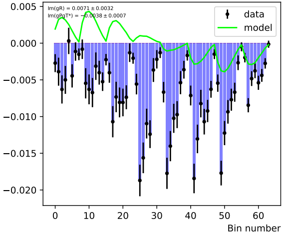
$\mu(\vec{r} \times \vec{t})_Z$ control



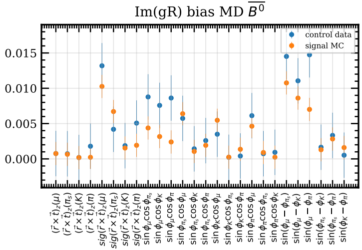
$\sin\phi_\mu \cos\phi_{\pi_s}$ signal

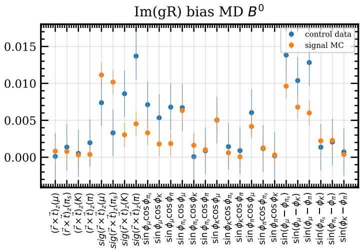


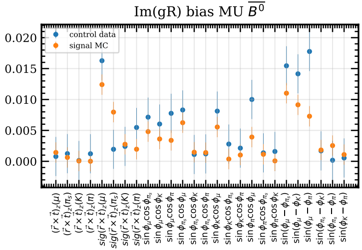
$\sin\phi_\mu \cos\phi_{\pi_s}$ control

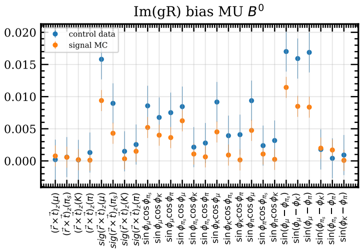


P-odd efficiency at LHCb: control vs signal samples. Bias in $\mathrm{Im}(g_R)$



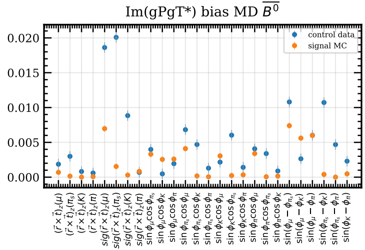


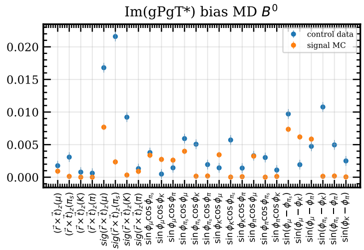


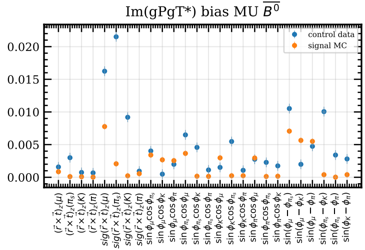


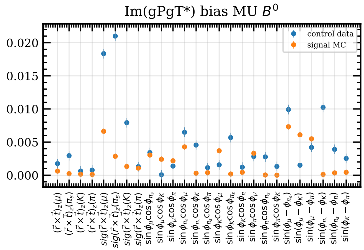
Consistent behavior of the two samples under the P-odd effects across the four categories. Control bias (almost) always larger than signal. **No P-odd effect which affects signal but not control**.

P-odd efficiency at LHCb: control vs signal samples. Bias in $\mathrm{Im}(g_P g_T^*)$







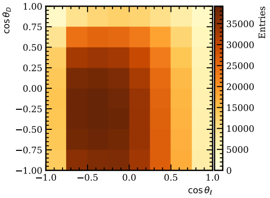


Consistent behavior of the two samples under the P-odd effects across the four categories. Control bias (almost) always larger than signal. **No P-odd effect which affects signal but not control**.

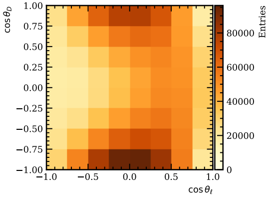
P-odd efficiency at LHCb: control vs signal samples kinematics

- Ideally, estimate syst due to P-odd efficiency terms in signal by fitting the control sample, extract bias on NP couplings and directly translate this information to the signal sample. But kinematics are different:

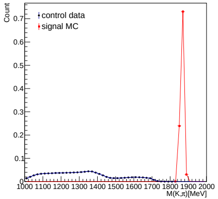
control



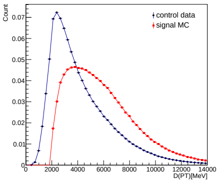
signal



$m(K^-\pi^+)$



D^0 proxy p_{T}

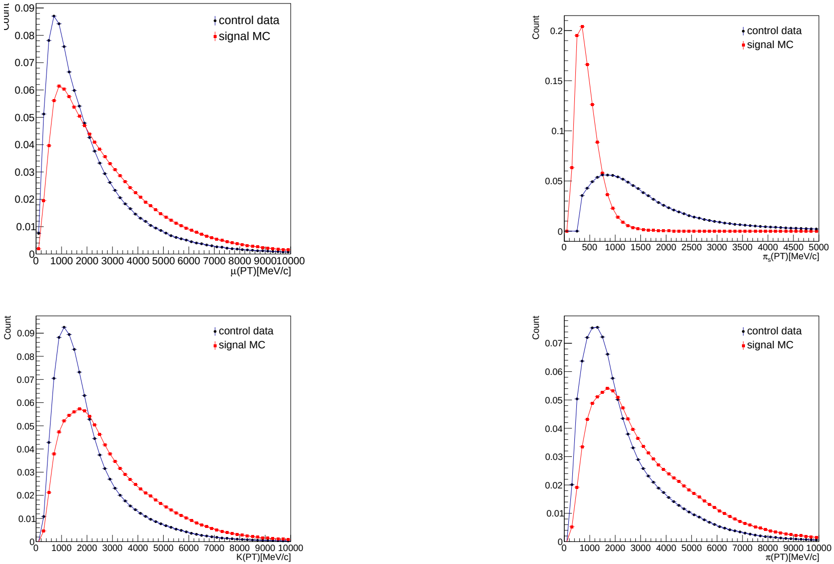


- Need to check whether bias depends on kinematics. Perform fits in bins of kinematic variables.

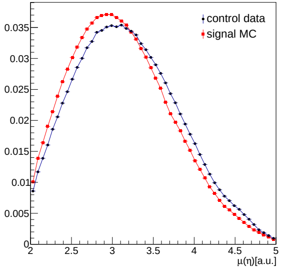
The logic for assigning systematics due to P-odd effects in reconstruction efficiency using control sample:

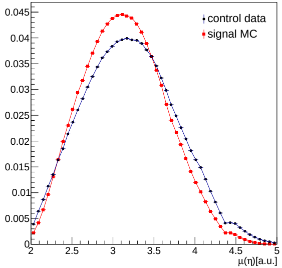
- 1. Apply P-odd effects as weights in both signal and control sample. Fit NP couplings and obtain bias.
- 2. Show that, if those effects exist in data, they produce effects in both signal and control at similar level. In addition, bias in control sample is larger than in signal in almost all cases. No case where bias in control is zero but nonzero in signal. Good!
- 3. Fit the NP couplings in the control sample itself (without any efficiency weights). If there are any P-odd efficiency effects in real data, there will be a bias in the control sample fit.
- 4. Kinematics are different between signal and control. Check if the bias depends on those kinematics.
  - If it depends, then extrapolate the bias from control to signal as a function of those variables.
  - If it does not depend, we can still use the bias in control sample to assign upper-limit systematics in signal.
- 5. We see no trends of the bias in terms of kinematics. Fit control sample (consistent with zero) and use the numbers from fit to assign systematic uncertainty in signal.

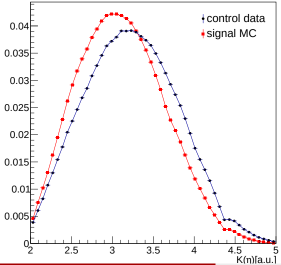
Kinematic variables comparison final states p_{T}

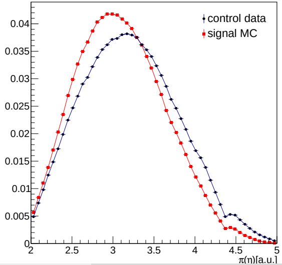


Kinematic variables comparison final states η

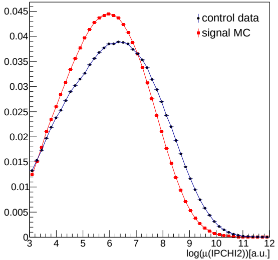


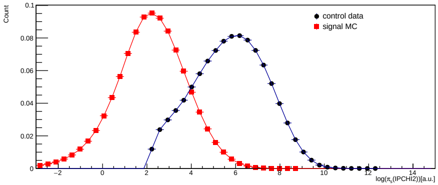


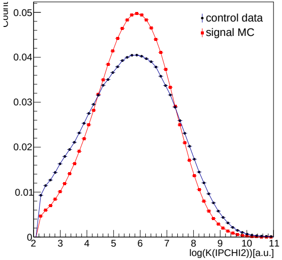


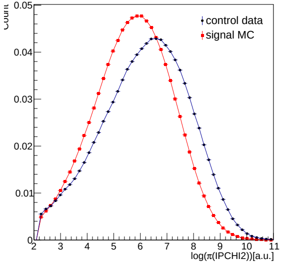


Kinematic variables comparison final states χ^2_{IP}

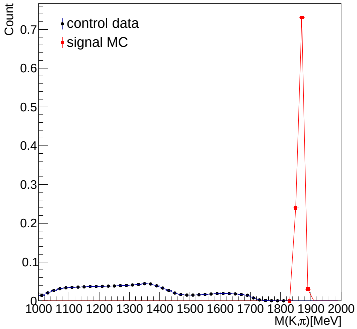


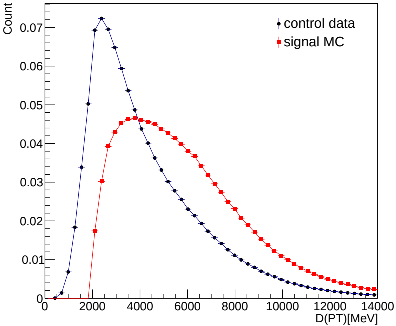




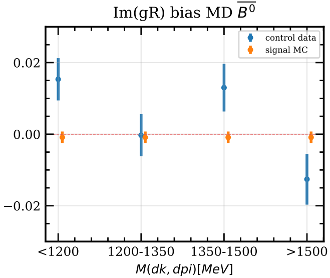


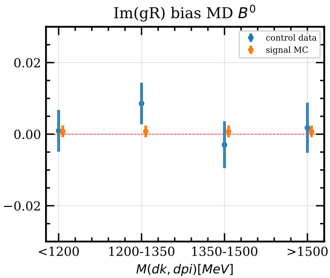
Kinematic variables comparison - Proxy D^0

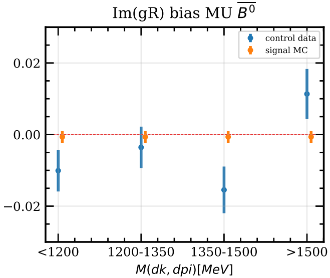


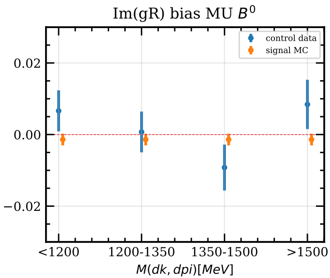


P-odd efficiency at LHCb: control vs signal bias in bins of $m(K^-\pi^+)$ for $\mathrm{Im}(g_R)$

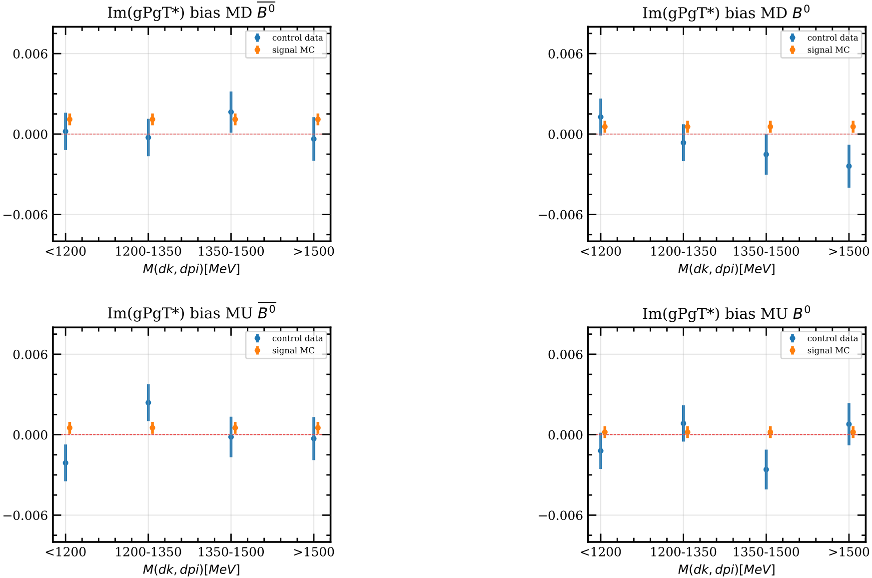




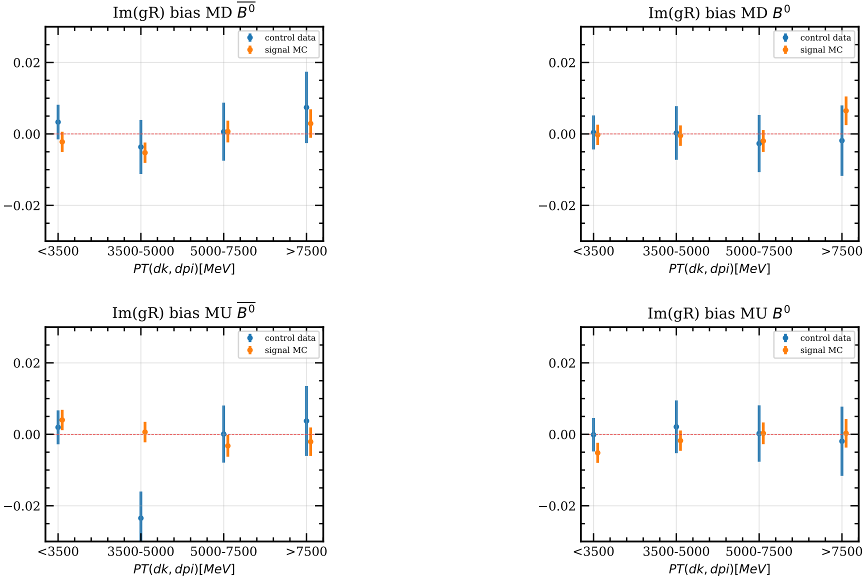




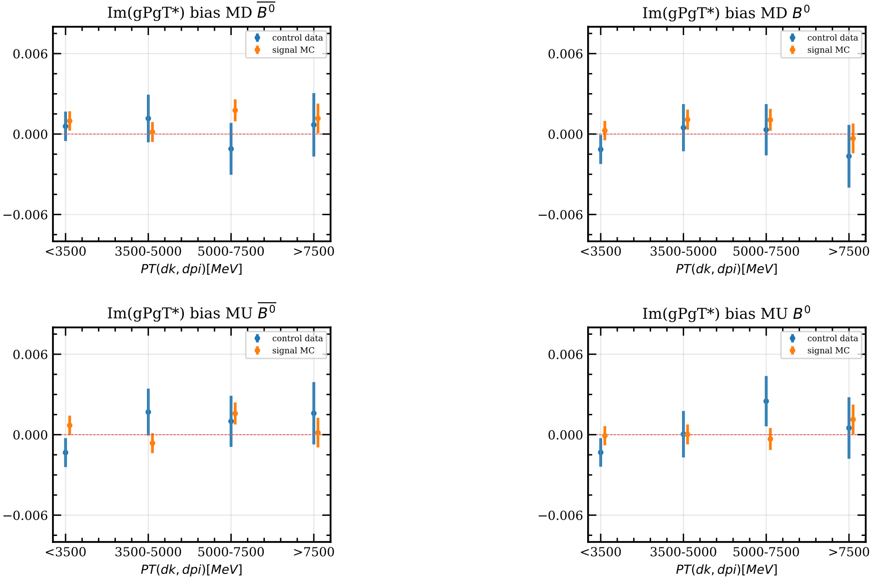
P-odd efficiency at LHCb: control vs signal bias in bins of $m(K^-\pi^+)$ for $\mathrm{Im}(g_P g_T^*)$



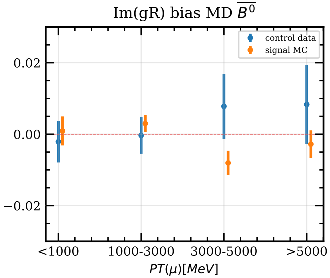
P-odd efficiency at LHCb: control vs signal bias in bins of $p_{\mathrm{T}}(K^-\pi^+)$ for $\mathrm{Im}(g_{\mathrm{R}})$

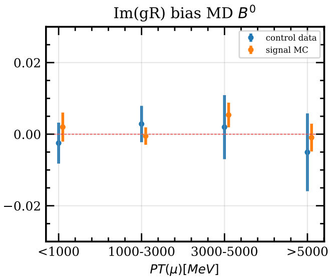


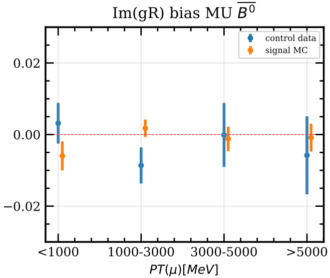
P-odd efficiency at LHCb: control vs signal bias in bins of $p_{\mathrm{T}}(K^-\pi^+)$ for $\mathrm{Im}(g_P g_T^*)$

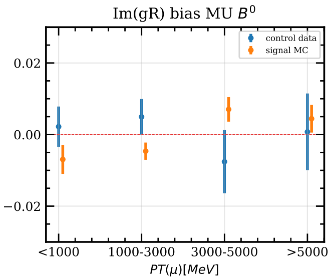


Im(gR) bias in bins of $p_{\mathrm{T}}(\mu)$

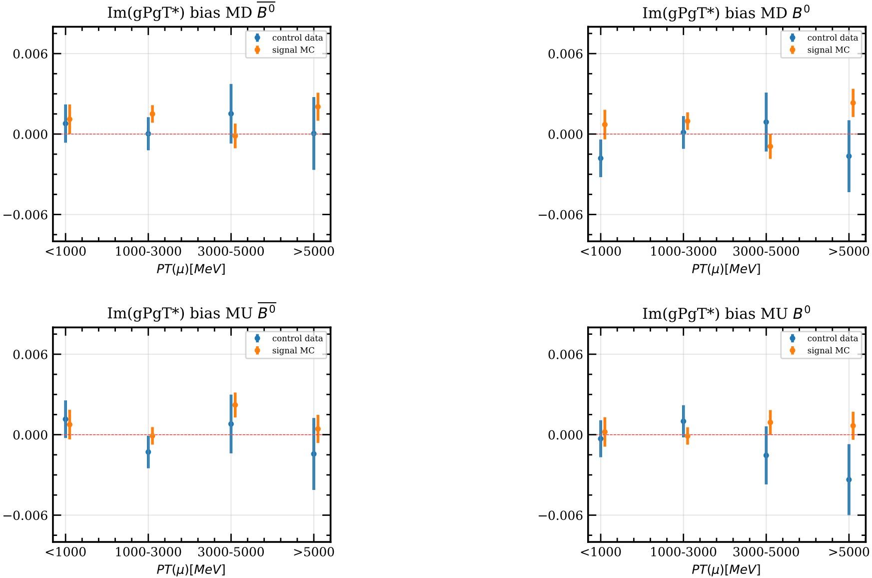




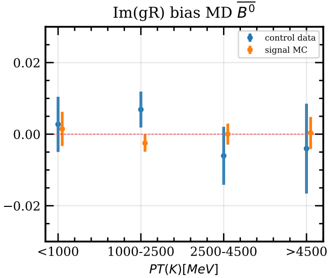


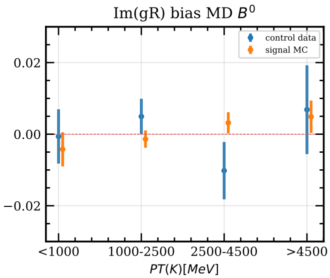


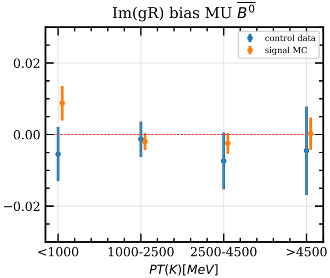
Im(gPgT*) bias in bins of $p_{\mathrm{T}}(\mu)$

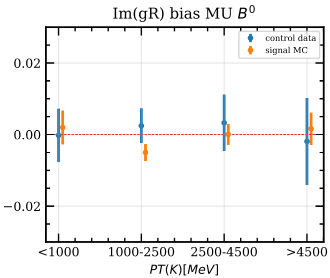


Im(gR) bias in bins of $p_{\mathrm{T}}(K)$

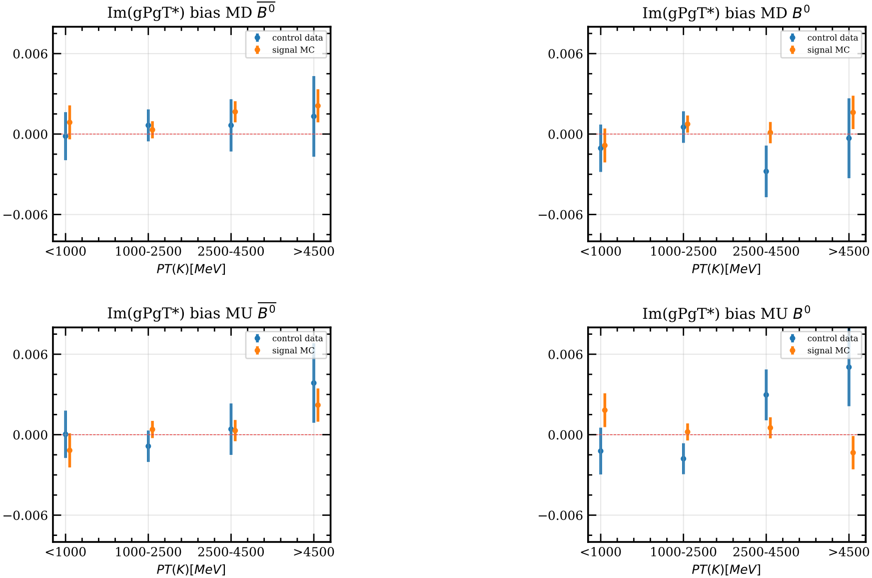




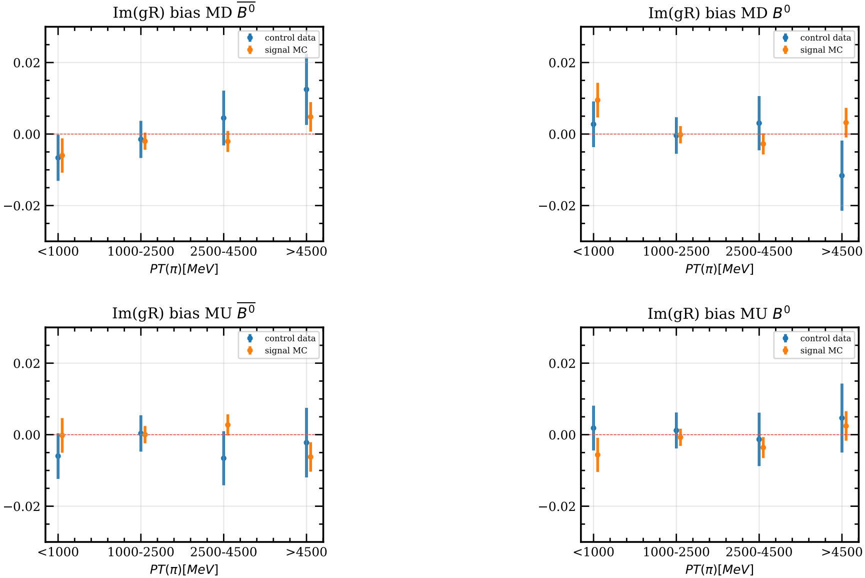




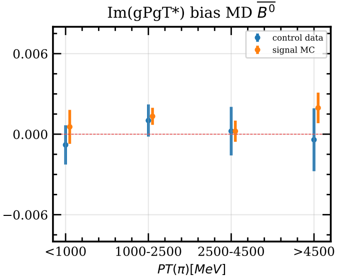
Im(gPgT*) bias in bins of $p_{\mathrm{T}}(K)$

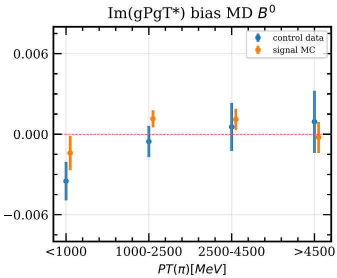


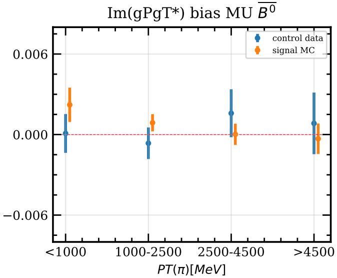
Im(gR) bias in bins of $p_{\mathrm{T}}(\pi)$

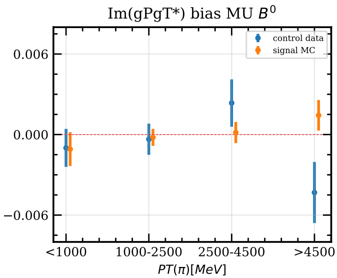


Im(gPgT*) bias in bins of $p_{\mathrm{T}}(\pi)$

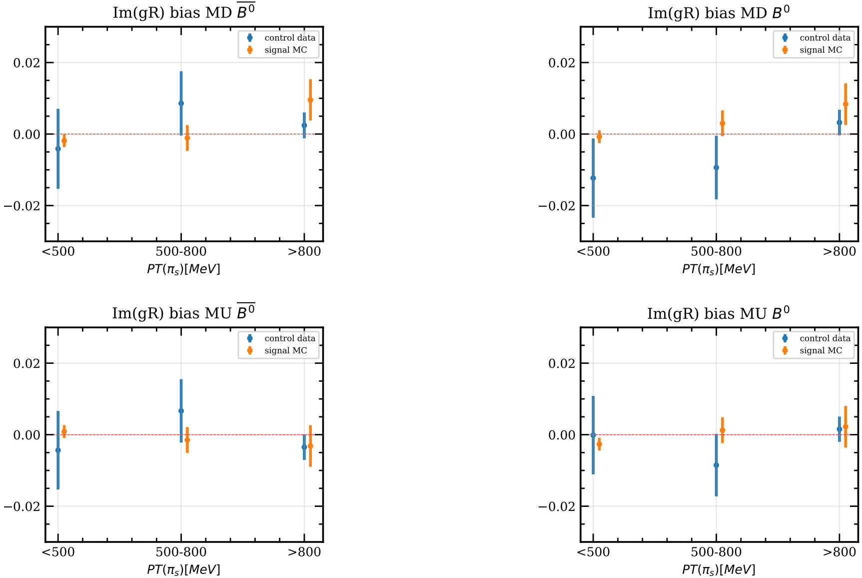




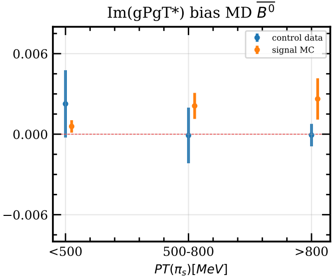


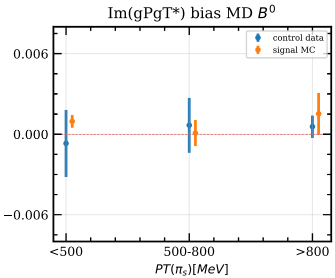


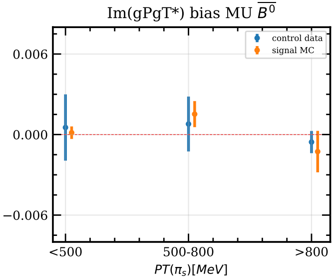
Im(gR) bias in bins of $p_\mathrm{T}(\pi_s)$

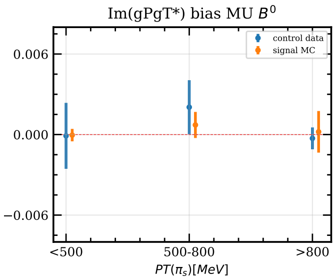


Im(gPgT*) bias in bins of $p_{\mathrm{T}}(\pi_s)$

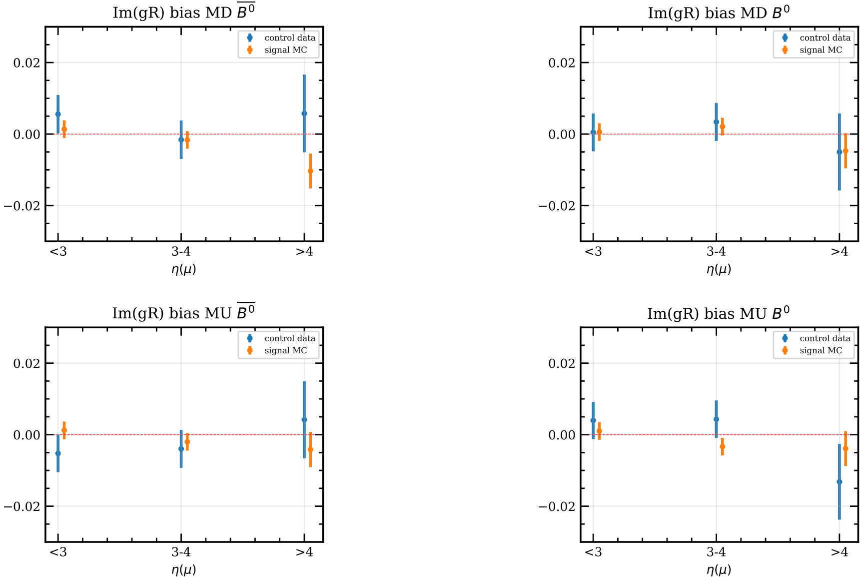




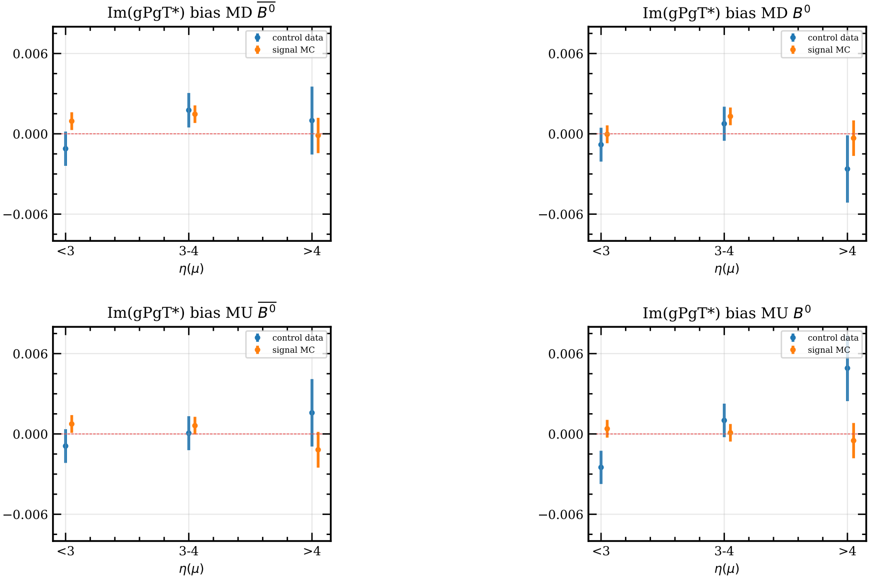




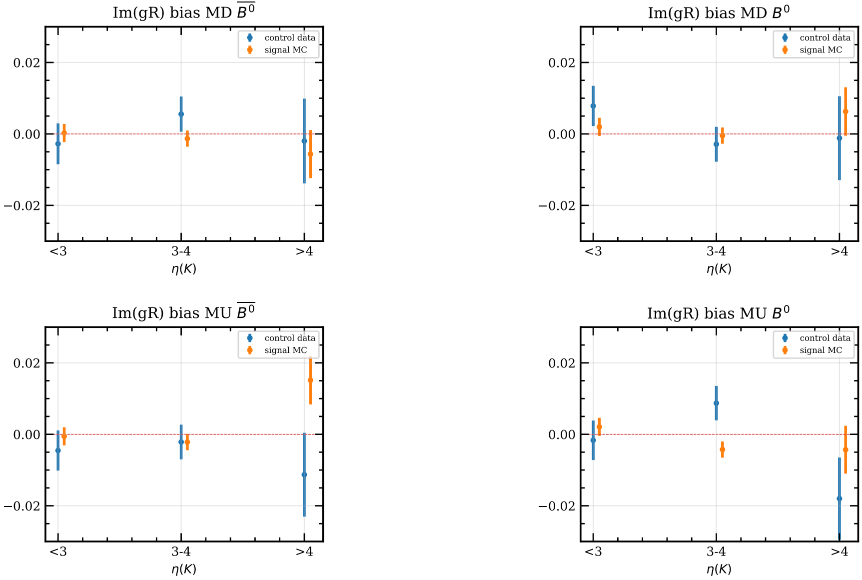
Im(gR) bias in bins of $\eta(\mu)$



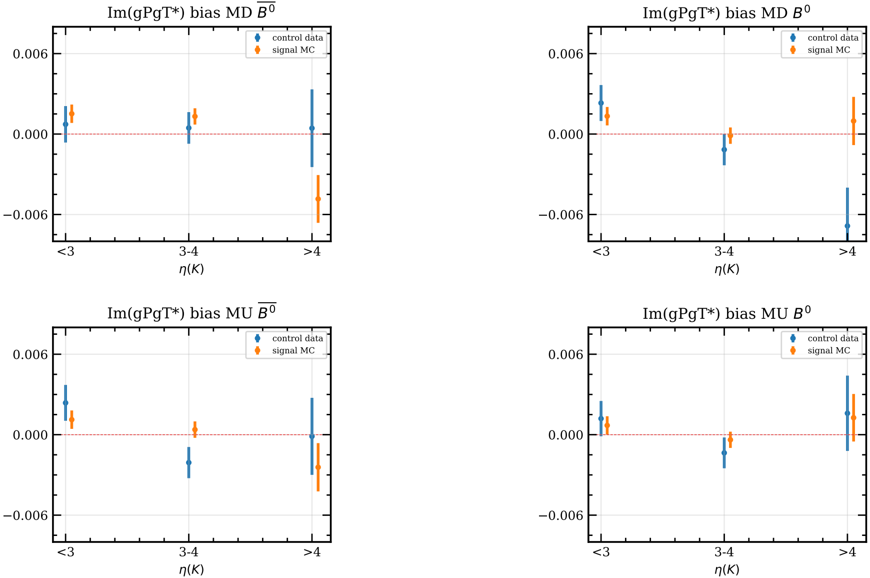
Im(gPgT*) bias in bins of $\eta(\mu)$



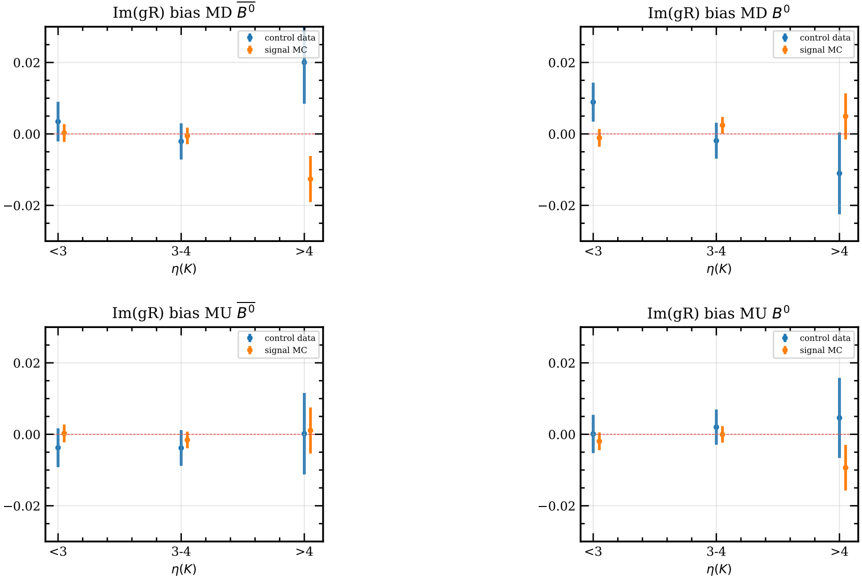
Im(gR) bias in bins of $\eta(K)$



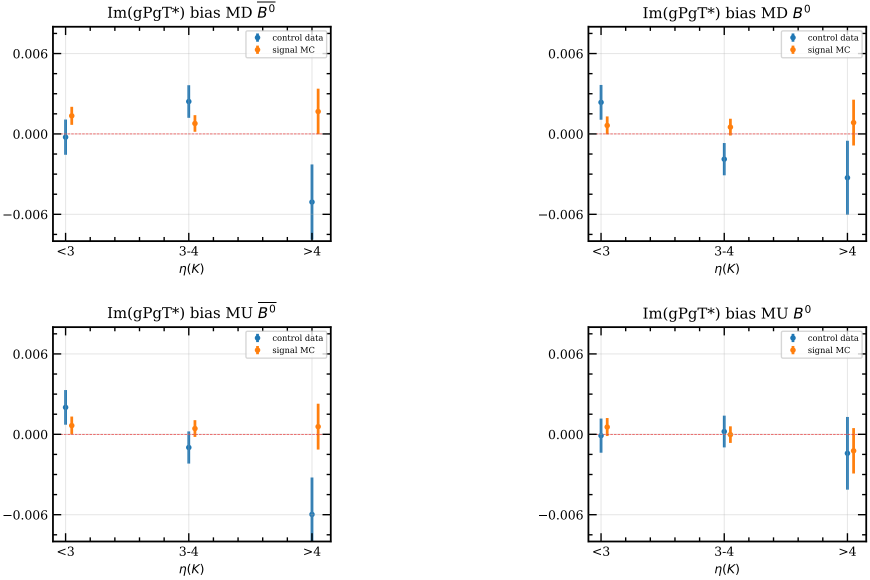
Im(gPgT*) bias in bins of $\eta(K)$



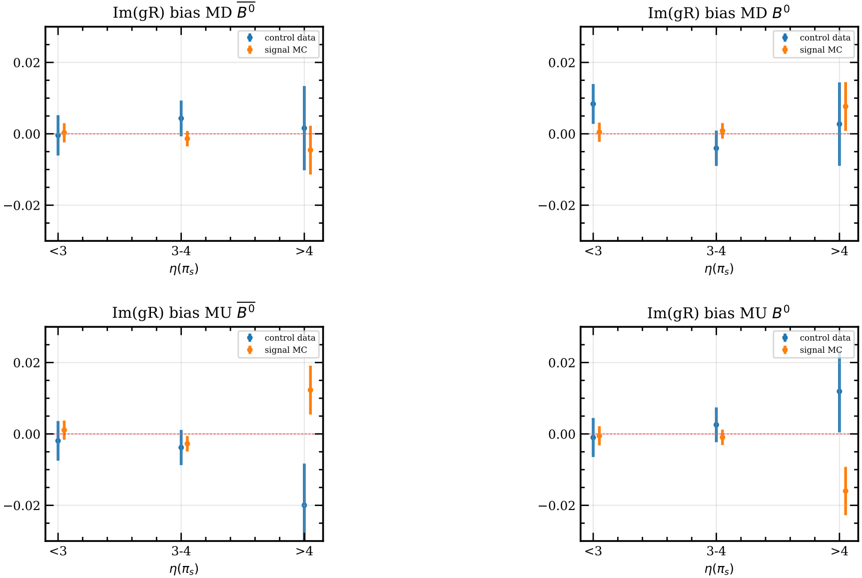
Im(gR) bias in bins of $\eta(\pi)$



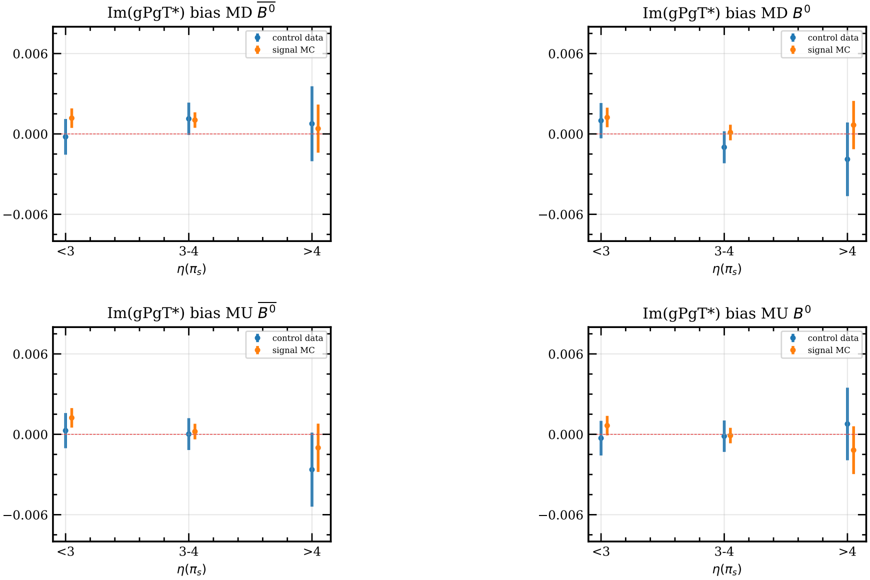
Im(gPgT*) bias in bins of $\eta(\pi)$



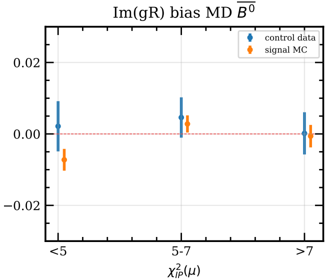
Im(gR) bias in bins of $\eta(\pi_s)$

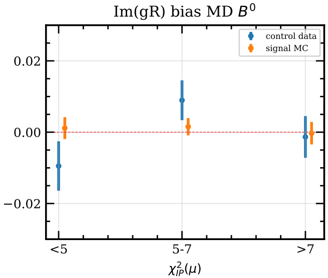


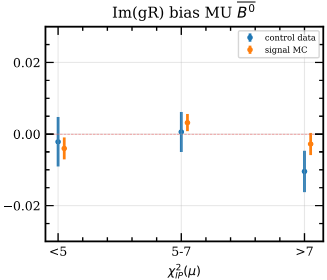
Im(gPgT*) bias in bins of $\eta(\pi_s)$

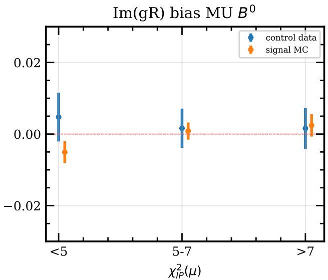


Im(gR) bias in bins of $\chi^2_{\text{IP}}(\mu)$

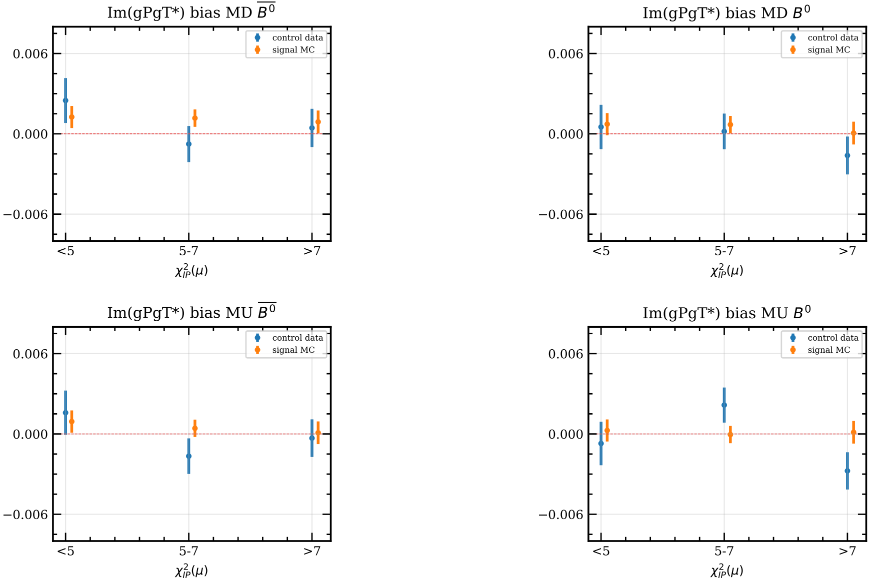




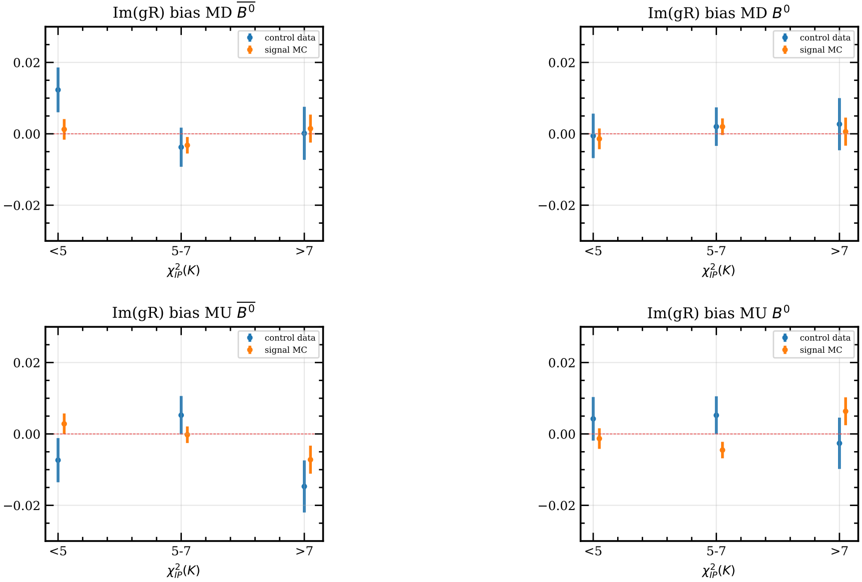




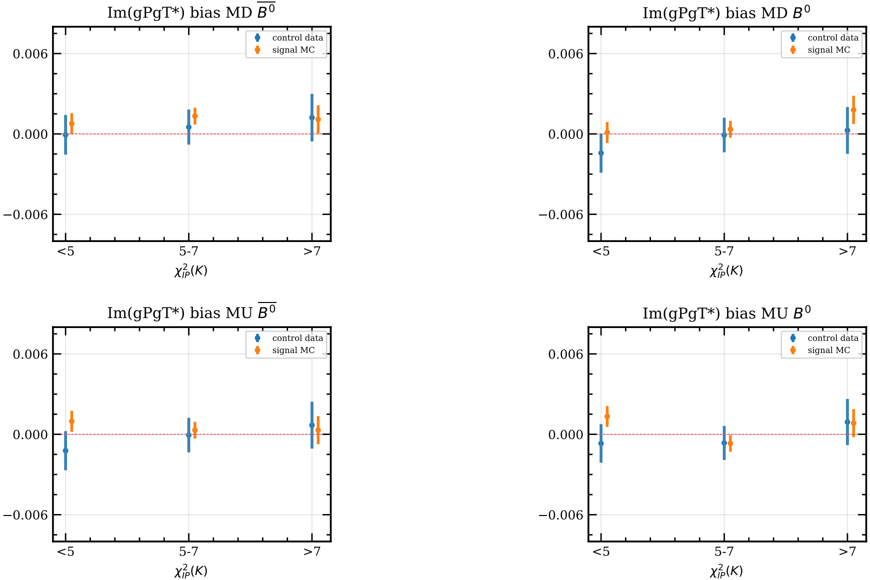
Im(gPgT*) bias in bins of $\chi^2_{\text{IP}}(\mu)$



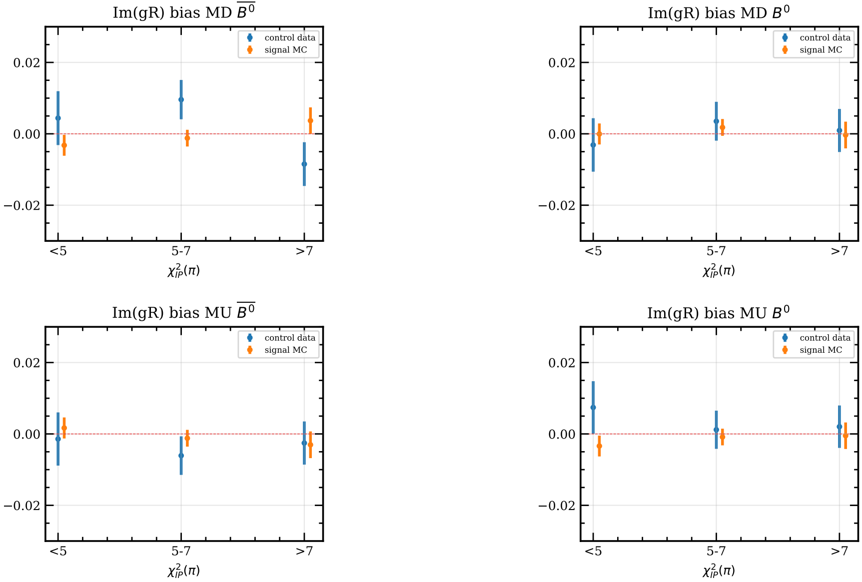
Im(gR) bias in bins of $\chi^2_{\text{IP}}(K)$



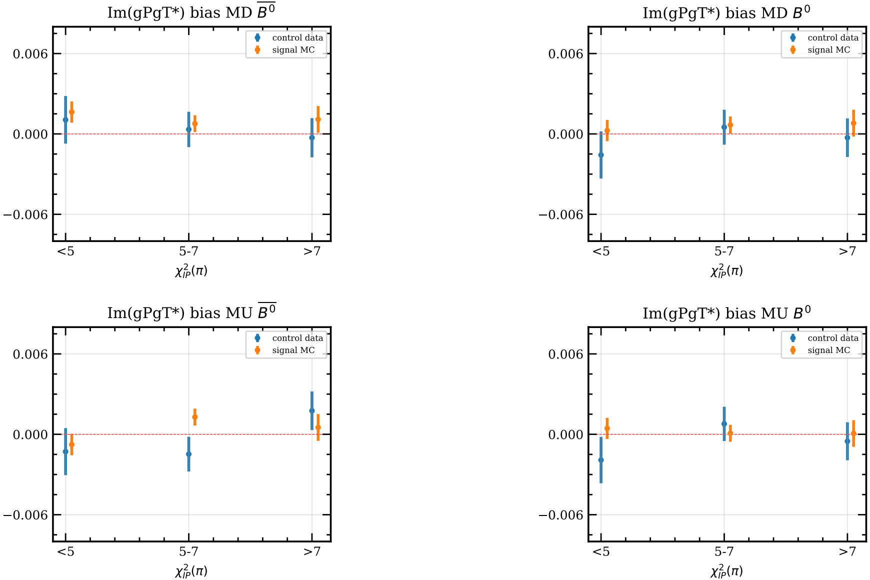
Im(gPgT*) bias in bins of $\chi^2_{\text{IP}}(K)$



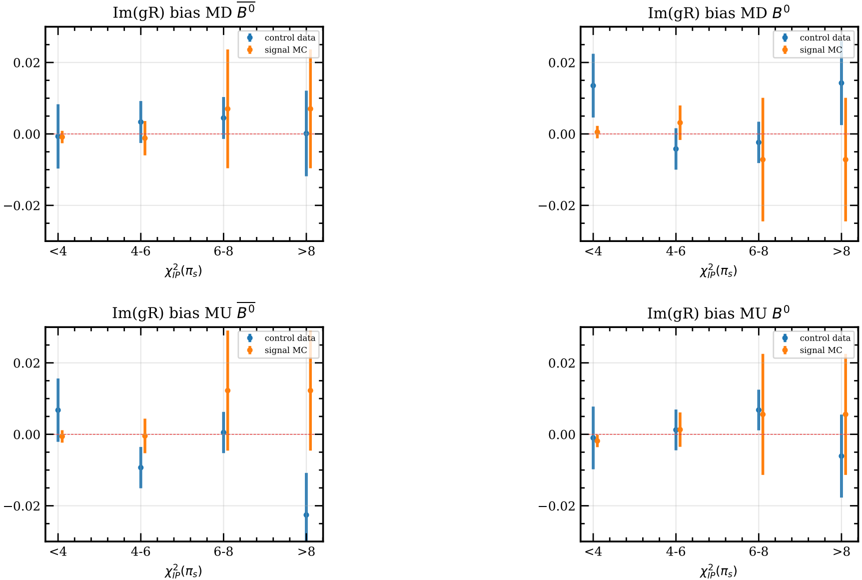
Im(gR) bias in bins of $\chi^2_{\mathrm{IP}}(\pi)$



Im(gPgT*) bias in bins of $\chi^2_{\text{IP}}(\pi)$



Im(gR) bias in bins of $\chi^2_{\text{IP}}(\pi_s)$



Im(gPgT*) bias in bins of $\chi^2_{\mathrm{IP}}(\pi_s)$