Investigating the polarisation puzzle with $B^0_{(s)} \to K^{*0}\overline{K}^{*0}$ decays at LHCb

Imperial particle physics seminar

Matthew Monk

University of Cambridge

Phys. Rev. D **113** (2026), 092002

May 15, 2026

Introduction

- SM — when it works, it works! When it doesn't, it doesn't...
  - Gravity, dark matter, neutrino mass/oscillations, not enough *CP* violation *etc.*
- Can look for New Physics (NP) in precision measurements of processes involving loops

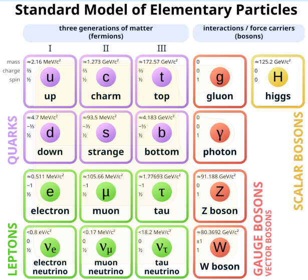
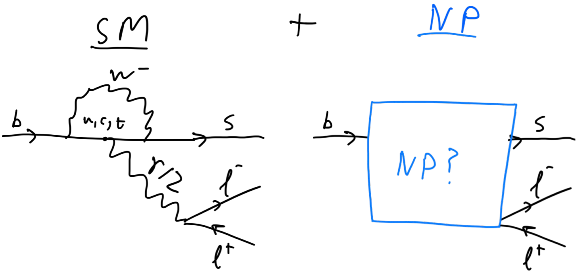
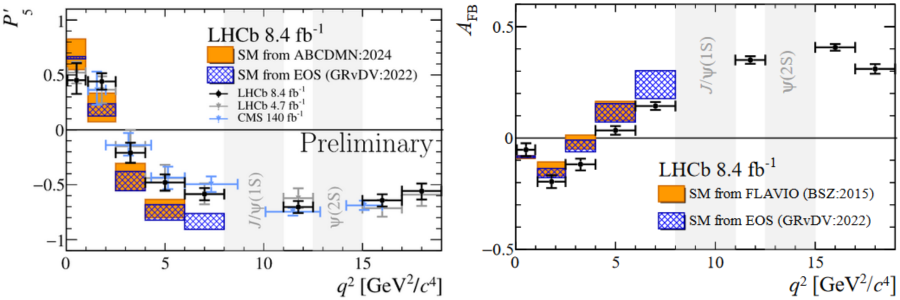


Figure: Bullet cluster – Baryonic matter (hot gas) and matter distribution (gravitational lensing)



$b \to s\ell^+\ell^-$

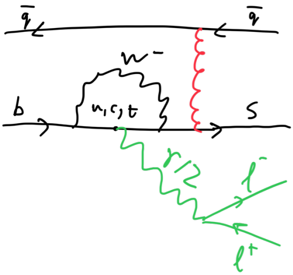
- Many measurements of $b \to s\ell^+\ell^-$ processes
- In some cases, persistent deviations between theory and experiment *e.g.* $B^0 \to K^{*0}\mu^+\mu^-$ angular observables, arXiv:2512.18053

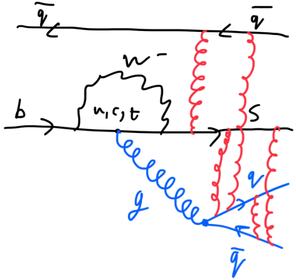


- Seen in both CMS and LHCb
- Global fits give $\sim 4\sigma$ tension with SM

Hadronic $b \to s$ decays

- If we see deviations in $b \to s\ell^+\ell^-$ processes, do we also see them in hadronic $b \to sq\overline{q}$ transitions?
- Answer: Kinda!
- Theory predictions become very challenging
- Some persistent tensions ($\gtrsim 20$ years) at about 3σ level (and some claims of $> 4\sigma$)





Charmless $B \to VV$ decays

- An interesting place to look is in charmless $B \to VV$ decays
- Charmless often means loops in the diagrams (*i.e.* $b \to s$ or $b \to d$ decays rather than $b \to c$ decays)
- $B \to VV$ = decay of a pseudo-scalar (spin 0) B meson to two vector (spin 1) particles
- Usual suspects are $V \in \{\rho^0, \rho^+, \omega, K^{*0}, K^{*+}, \phi\}$ and $B \in \{B^0, B^+, B_s^0\} \Rightarrow$ a lot of choice of decays!
- This seminar focuses on $B_{(s)}^0 \to K^{*0}\overline{K}^{*0}$ decays at LHCb
  - Paper published just last week!
  - Phys. Rev. D **113** (2026), 092002

$B \to VV$ decays

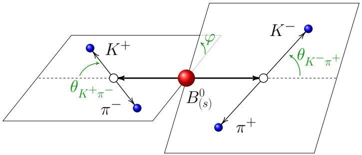
- Spin 0 particle decaying to two spin 1 particles $\Rightarrow$ 3 independent polarisation states
- Usually most interested in f_{L}, theoretically cleaner than the transverse polarisations

$$f_{\mathrm{L}} = \frac{|A_0|^2}{|A_0|^2 + |A_\perp|^2 + |A_\parallel|^2},$$

Helicity: A_0, A_+, A_-

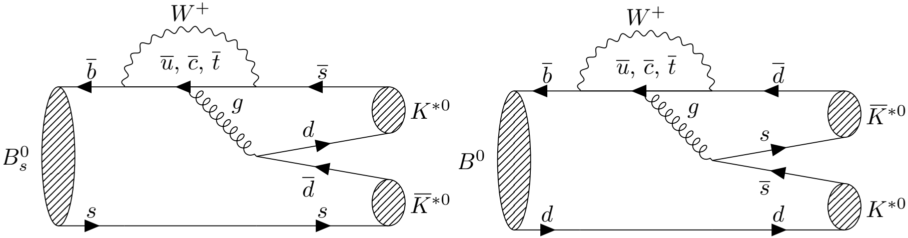
$$A_\parallel = \frac{A_+ + A_-}{\sqrt{2}} \qquad \longleftrightarrow \qquad A_\perp = \frac{A_+ - A_-}{\sqrt{2}}$$

Transversity: A_0, $A_\parallel$, $A_\perp$



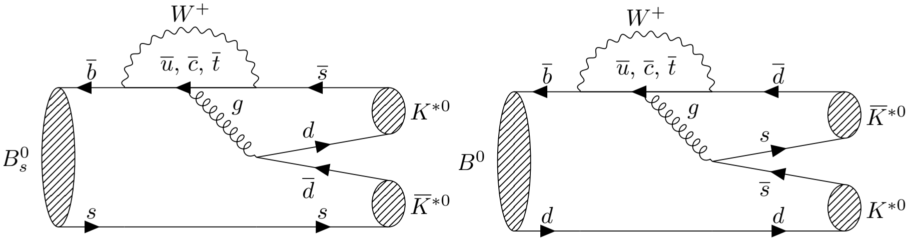
$B \to VV$ decays

- Expectation from factorised QCD is that
  - $|A_0|^2 \gg |A_+|^2 \gg |A_-|^2$
- as $A_\pm$ both need a quark spin flip, A_- is additionally chirality suppressed
- Expect a large value for f_L in charmless $B \to VV$ decays



Why $B^0_{(s)} \to K^{*0}\overline{K}^{*0}$?

- Only charmless $B \to VV$ decay that has the same final state under U-spin symmetry exchange of $s \leftrightarrow d$ quarks
- (Almost) unique that both B^0_s and B^0 decay modes have been observed
  - $\mathcal{B}(B^0_s \to K^{*0}\overline{K}^{*0}) = (1.11 \pm 0.27) \times 10^{-5}$, $\mathcal{B}(B^0 \to K^{*0}\overline{K}^{*0}) = (8.3 \pm 2.4) \times 10^{-7}$
  - Allows for more in-depth studies



Previous analyses of $B^0_{(s)} \to K^{*0}\overline{K}^{*0}$

- For $B^0 \to K^{*0}\overline{K}^{*0}$, values of $f_L^d \approx 0.7$, conforms to factorised QCD expectation
- For $B_s^0 \to K^{*0}\overline{K}^{*0}$, values of $f_L^s \approx 0.25$, weird!
- Lower than expected, *and* due to the U-spin symmetry we would expect $f_L^d \approx f_L^s$
- Lower than expected f_{L} has been seen in other charmless $B \to VV$ decays ($B_s^0 \to \phi\phi$, $B^0 \to \rho^0 K^{*0}$ and $B^0_{(s)} \to \phi K^{*0}$), whereas some ($B^0 \to \rho^+\rho^-$, $B^+ \to \rho^0\rho^+$, $B^+ \to \omega\rho^+$ and $B^+ \to \rho^0 K^{*+}$) follow QCD expectation closely
- General pattern seems to be:
    - Tree-level $b \to u$ follow expectations, large f_{L}
    - Mixture of tree- and loop-level and/or $b \to s$ *do not*
    - Dubbed the "polarisation puzzle"

Theory-optimised observable, $L_{K^{*0}\overline{K}^{*0}}$

- Theory predictions for fully hadronic final states are difficult
- arXiv:2506.12478, Biswas *et al.* proposed the following ratio observable to minimise theory uncertainties

$$L_{K^{*0}\overline{K}^{*0}} = \mathcal{G}\frac{\mathcal{B}(B_s^0 \to K^{*0}\overline{K}^{*0})}{\mathcal{B}(B^0 \to K^{*0}\overline{K}^{*0})}\frac{f_L^{B_s^0 \to K^{*0}\overline{K}^{*0}}}{f_L^{B^0 \to K^{*0}\overline{K}^{*0}}}$$

- where $\mathcal{G} \approx 1.014$ accounts for different masses and lifetimes of the B mesons
- Most recent predictions are

$$L^{\text{I}}_{K^{*0}\overline{K}^{*0}} = 18.34^{+7.47}_{-5.83}, \qquad L^{\text{II}}_{K^{*0}\overline{K}^{*0}} = 26.08^{+5.70}_{-4.72}$$

- with different predictions owing to different form-factor treatments

$B^0_{(s)} \to K^{*0}\overline{K}^{*0}$ at LHCb

- Both $B^0_{(s)} \to K^{*0}\overline{K}^{*0}$ decays have been studied before with LHCb *pp* Run 1 (2011–2012) dataset
  - Afterwards, $L_{K^{*0}\overline{K}^{*0}}$ was proposed and the experimental value was found to be $L_{K^{*0}\overline{K}^{*0}} = 4.43 \pm 0.92$, $2.3\sigma/4.4\sigma$ difference with respect to the theory predictions
- Updated measurement with full *pp* Run 1 + Run 2 (2015–2018) datasets
- Aside from roughly $\times 4$ increase in statistics, several innovations:
  - Dedicated normalisation modes to improve precision of $\mathcal{B}(B^0_{(s)} \to K^{*0}\overline{K}^{*0})$
  - Improved selection (background rejection)
  - Different amplitude analysis formalism and efficiency parameterisation
  - Better parameterisation of scalar $m(K^{\pm}\pi^{\mp})$ component

Branching fractions

- Typically measure branching fractions by comparing efficiency-corrected number of events to a "normalisation" decay, *e.g.*

$$\frac{\mathcal{B}(B_s^0 \to K^{*0}\overline{K}^{*0})}{\mathcal{B}(B_s^0 \to D_s^-\pi^+)} = \frac{N^{B_s^0 \to K^{*0}\overline{K}^{*0}}}{N^{B_s^0 \to D_s^-\pi^+}} \frac{\varepsilon^{B_s^0 \to D_s^-\pi^+}}{\varepsilon^{B_s^0 \to K^{*0}\overline{K}^{*0}}}$$

- Use dedicated normalisation modes of $B_s^0 \to D_s^-\pi^+$ for $B_s^0 \to K^{*0}\overline{K}^{*0}$ and $B^0 \to D^-\pi^+$ for $B^0 \to K^{*0}\overline{K}^{*0}$
- Reconstruct the D_s^- and D^- with $(K^+K^-\pi^-)$ – same final state as the signal modes
- Branching fractions of $B_{(s)}^0 \to D_{(s)}^-\pi^+$ measured quite precisely

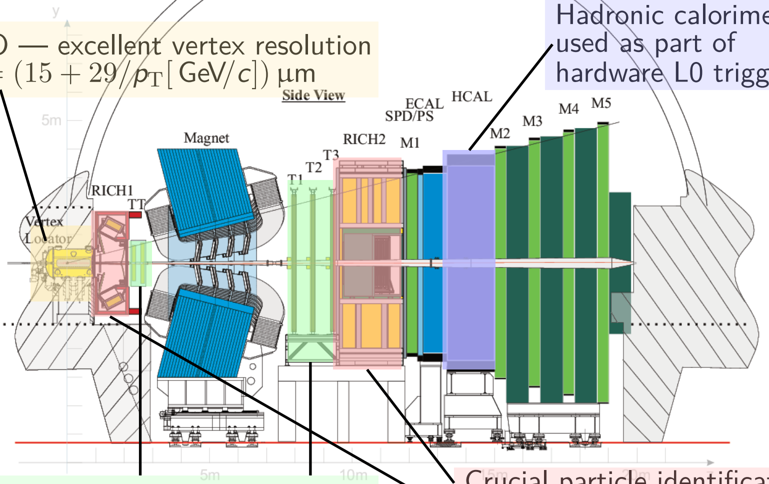
Decay	Branching fraction (PDG)
$B_s^0 \to (K^{*0} \to K^+\pi^-)(\overline{K}^{*0} \to K^-\pi^+)$	$(4.9 \pm 1.2) \times 10^{-6}$
$B^0 \to (K^{*0} \to K^+\pi^-)(\overline{K}^{*0} \to K^-\pi^+)$	$(3.7 \pm 1.1) \times 10^{-7}$
$B_s^0 \to (D_s^- \to K^+K^-\pi^-)\pi^+$	$(1.60 \pm 0.08) \times 10^{-4}$
$B^0 \to (D^- \to K^+K^-\pi^-)\pi^+$	$(2.43 \pm 0.09) \times 10^{-5}$

The LHCb detector

Single-arm forward spectrometer, $2 < \eta < 5$

VELO — excellent vertex resolution
$\sigma_{\mathrm{IP}} = (15 + 29/p_{\mathrm{T}}[\,\mathrm{GeV}/c]) \, \mu\mathrm{m}$

Hadronic calorimeter used as part of hardware L0 trigger

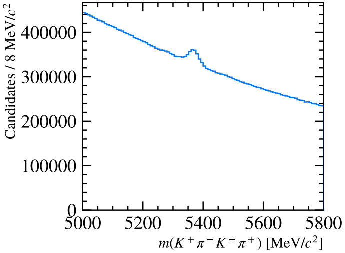


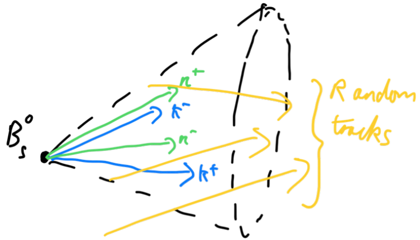
Tracking stations with momentum resolution
$\sigma_p/p \sim 0.5\,\%–1.0\,\%$ $(5–200\,\mathrm{GeV}/c)$

Crucial particle identification
$\varepsilon(K \to K) \sim 95\,\%$
$\varepsilon(\pi \to K) \sim 5\,\%$

Combinatorial background

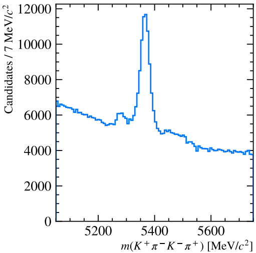
- Large background from random combinations of tracks/hits
- Roughly follows an exponential distribution in the B-mass, $m(K^+\pi^-K^-\pi^+)$
- Reject it using a Boosted Decision Tree (BDT)
- 19 input variables, uses kinematics, decay topology and isolation information
- Isolation information not included in previous analysis, found $\sim 5\%$ improvement in background rejection by including them

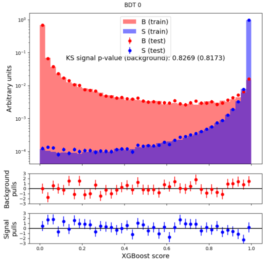


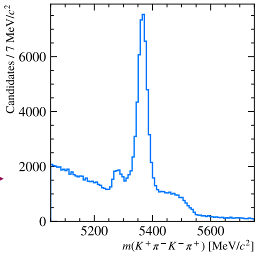


Combinatorial BDT

- Use BDT from XGBoost, with $k = 5$ cross-fold validation
- Simulation used for signal sample, upper-mass sideband in data used for background sample
- Cut on BDT distribution optimised later

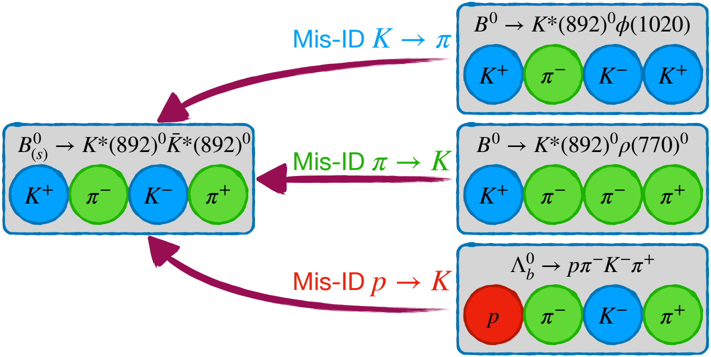






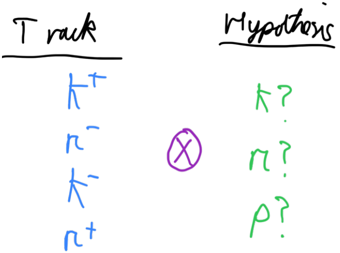
Mis-identified backgrounds

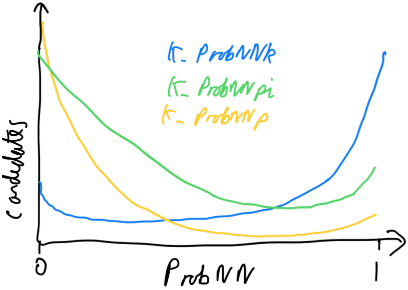
- We assign mass hypotheses (*e.g.* K, π) to charged tracks using particle identification (PID) information
- Hypothesis can be *wrong i.e.* we mis-identify a particle
- Main mis-identified backgrounds are from $B^0 \to \rho^0 K^{*0}$, $B^0 \to \phi K^{*0}$ and $\Lambda_b^0 \to p K^- \pi^+ \pi^-$



Mis-identified backgrounds

- We have loose requirements on PID information already
- Optimise a tighter selection to further reduce the backgrounds
- Based on `ProbNN` distributions
- Combine `ProbNNs` into three variables, each representing one of the mis-identified backgrounds
- Correlated with BDT output $\Rightarrow$ 4D simultaneous optimisation of BDT and three PID variables





Optimising cuts

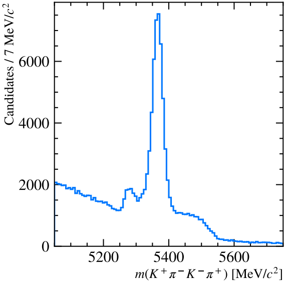
- Need to pick a metric to optimise! Ideally this would be the uncertainty on $L_{K^{*0}\overline{K}^{*0}}$ but this is difficult, choose significance of $B^0 \to K^{*0}\overline{K}^{*0}$ as a proxy

$$\mathrm{FOM} = \frac{S}{\sqrt{S+B}}$$

- where S is expected number of $B^0 \to K^{*0}\overline{K}^{*0}$ signal decays, B is expected number of background decays
- Determine initial yields of signal and background from mass fit with loose BDT cut
- Optimisation performed with Basin-Hopping algorithm from `SciPy`
- Constrain optimisation to reject at least 90% of $B^0 \to \rho^0 K^{*0}$ background

Mass fits

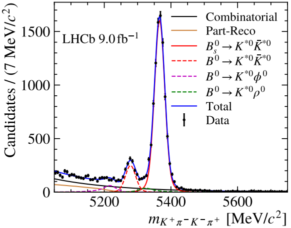
- Perform a fit to the B-mass with all of our selection applied
  - Provides the yield, N, that we need to calculate the branching fractions
  - Determines the size of the regions to use in the amplitude analysis (separate amplitude analysis for B^0 and B_s^0)
  - Used to extract *sWeights* for amplitude analysis (projects out signal component)
- Procedure:
  - Fit to simulation samples to determine shape parameters
  - Fit to data, with yields floating and a global shift and scaling for the peak position



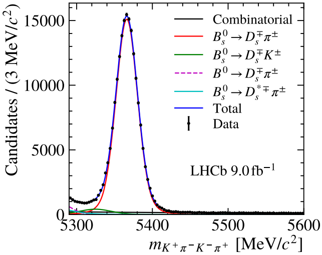
- How much signal $B^0_{(s)} \to K^{*0}\overline{K}^{*0}$?
- How much background (combinatorial, misID)?
- Width and position of peaks?

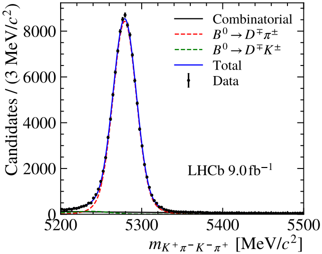
Mass fit results

- Fit results for Run 1 and Run 2 combined (top left), including the normalisation modes $B_s^0 \to D_s^- \pi^+$ (bottom left) and $B^0 \to D^- \pi^+$ (bottom right)

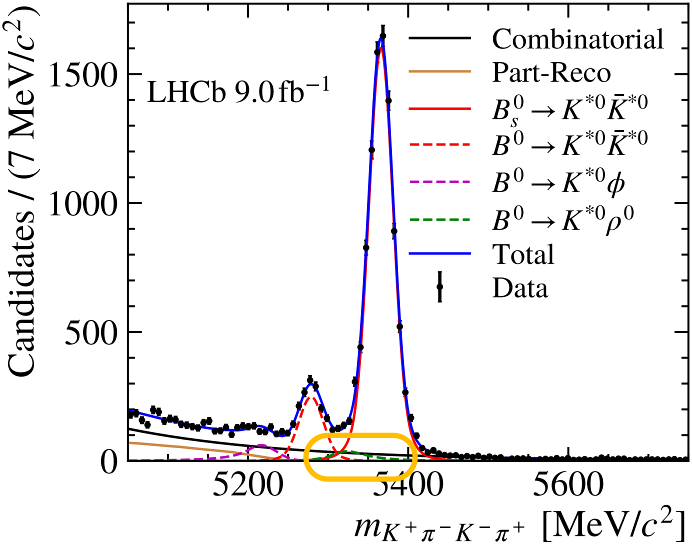


$$N^{B_s^0 \to K^{*0}\bar{K}^{*0}} = 9190 \pm 114,$$
$$N^{B^0 \to K^{*0}\bar{K}^{*0}} = 1424 \pm 59,$$
$$N^{B_s^0 \to D_s^- \pi^+} = 180\ 807 \pm 483,$$
$$N^{B^0 \to D^- \pi^+} = 105\ 666 \pm 348$$



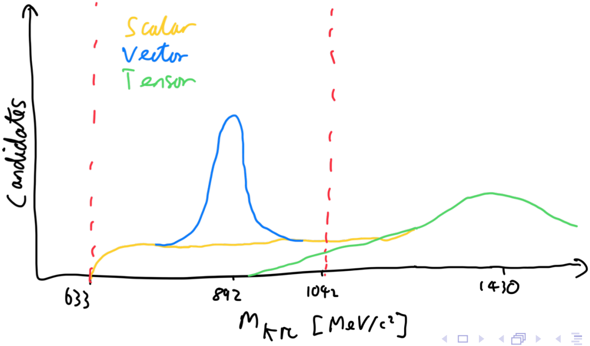


Mass fit results



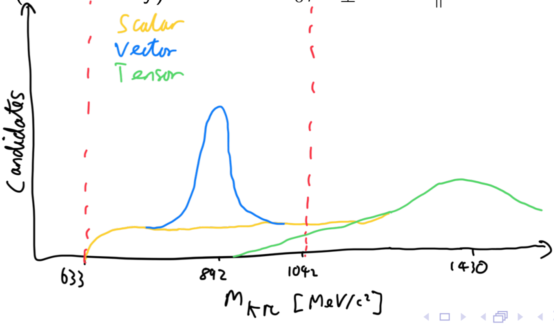
Amplitude analysis

- Interested in the vector branching fractions and polarisations
- Experimentally, we reconstruct $(K\pi)$ pairs within some $m(K\pi)$ mass window so non-vector contributions will be present
- Need amplitude analysis to tell us:
  - How much of our data is VV
  - The polarisations of the VV part
- Consider scalar (S, spin 0) and vector contributions



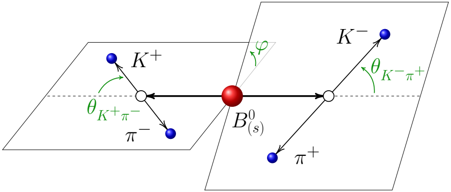
Amplitude analysis

- Consider scalar (S, spin 0) and vector contributions
  - Lowest-lying tensor (spin 2) has a mass of $\approx 1430\,\text{MeV}/c^2$, mass window used is $(633 < m(K\pi) < 1042)\,\text{MeV}/c^2$ so ignore tensor contributions in nominal fit
- Each $(K\pi)$ pair can be S or V so six amplitudes in total:
  - SS
  - VS^+ or VS^-
  - VV^S, VV^P or VV^D, correspond to the $L = 0, 1, 2$ waves respectively, which (non-trivially) relate to A_0, $A_\perp$ and $A_\parallel$



Amplitude formalism

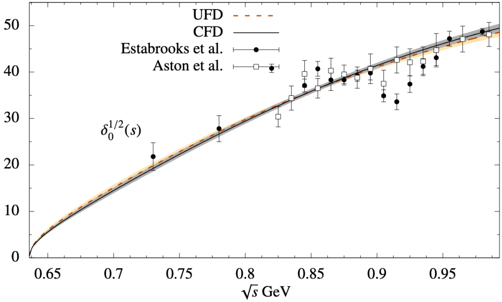
- Previous analyses used the transversity formalism, fit basis is 5D $(m_{K^+\pi^-}, m_{K^-\pi^+}, \cos\theta_{K^+\pi^-}, \cos\theta_{K^-\pi^+}, \varphi)$
- Difficult to reliably estimate some of the systematics
- We instead use the "covariant tensor" formalism
    - Has not been used for charmless $B \to VV$ analyses before, but common in Charm analyses
- Fit basis is the four-vectors of the final state particles, VV amplitudes are eigenstates of $L = 0, 1, 2$
- Project back into the transversity basis for plots (1D projections of 5D space easier than 16D space...) and transversity fractions, particularly for f_L



S-wave parameterisation

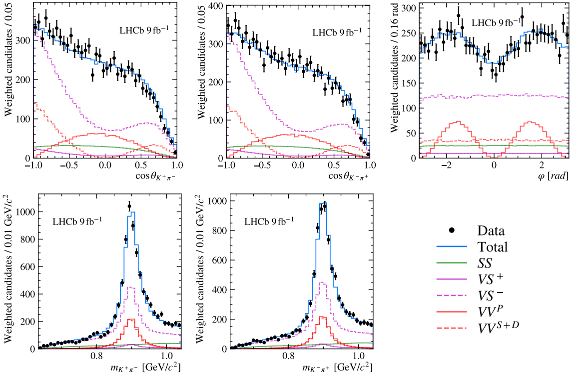
- Getting the shape of the scalar $m(K\pi)$ part right is tricky
- Often use the so-called LASS parameterisation
  - Not very physically motivated, only respects unitarity
- Difficulty in accounting for $\kappa/K_0^*(700)$
  - Does not really peak, resonance pole is deep in the complex plane
- Use parameterisation derived from $\pi\pi \to KK$ and $\pi K \to \pi K$ scattering data by Peláez and Rodas arXiv:2010.11222
  - More physical, respects unitarity, analyticity and crossing symmetry

- To account for production, scattering line shape is modified by unknown production function $\Rightarrow$ use a complex polynomial, with coefficients determined in the amplitude fit to data



B_s^0 amplitude fit

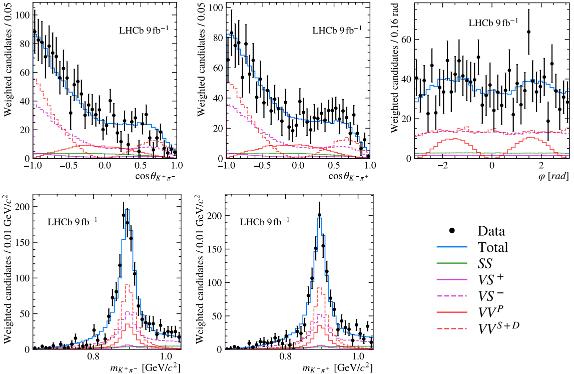
- Projection of covariant fit results into transversity basis
- Previous LHCb analysis: $f_L = (24.0 \pm 3.1\,(\text{stat}) \pm 2.5\,(\text{syst}))\,\%$



Parameter	Fit value	Parameter	Fit value	Parameter	Fit value
f_L (%)	$15.9 \pm 1.0 \pm 0.7$	$f_\parallel$ (%)	$34.2 \pm 1.3 \pm 1.0$	$f_\perp$ (%)	$50.0 \pm 1.4 \pm 0.3$
$\delta_\parallel$ (rad)	$0.73 \pm 0.08 \pm 0.12$				
f_{VV}^{S+D} (%)	$15.6 \pm 0.6 \pm 0.3$	f_{VV}^{P} (%)	$15.6 \pm 0.6 \pm 0.4$	f_{VS}^{+} (%)	$3.6 \pm 0.6 \pm 2.3$
f_{VS}^{-} (%)	$54.8 \pm 0.9 \pm 1.1$	f_{SS} (%)	$10.6 \pm 0.6 \pm 0.2$	δ_{VV}^{D} (rad)	$-0.074 \pm 0.005 \pm 0.008$
δ_{VS}^{+} (rad)	$-1.92 \pm 0.11 \pm 0.84$	δ_{VS}^{-} (rad)	$-2.98 \pm 0.04 \pm 0.12$	δ_{SS} (rad)	$0.12 \pm 0.06 \pm 0.25$

B^0 amplitude fit

- Projection of covariant fit results into transversity basis
- Previous LHCb analysis: $f_L = (72 \pm 5\,(\text{stat}) \pm 2\,(\text{syst}))\,\%$



Parameter	Fit value	Parameter	Fit value	Parameter	Fit value
f_L (%)	$60 \pm 2 \pm 2$	$f_\parallel$ (%)	$17 \pm 2 \pm 2$	$f_\perp$ (%)	$24 \pm 2 \pm 2$
$\delta_\parallel$ (rad)	$0.3 \pm 0.2 \pm 0.1$				
f_{VV}^{S+D} (%)	$37 \pm 2 \pm 2$	f_{VV}^{P} (%)	$14 \pm 1 \pm 1$	f_{VS}^{+} (%)	$6 \pm 2 \pm 1$
f_{VS}^{-} (%)	$38 \pm 2 \pm 3$	f_{SS} (%)	$5 \pm 1 \pm 0.2$	δ_{VV}^{D} (rad)	$-0.10 \pm 0.04 \pm 0.02$
δ_{VS}^{+} (rad)	$2.1 \pm 0.2 \pm 0.3$	δ_{VS}^{-} (rad)	$-0.4 \pm 0.1 \pm 0.1$	δ_{SS} (rad)	$-1.7 \pm 0.2 \pm 0.3$

Systematic uncertainties

Source	$\mathcal{B}(B^0 \to K^{*0}\overline{K}^{*0})$ $\times 10^{-8}$	$\mathcal{B}(B_s^0 \to K^{*0}\overline{K}^{*0})$ $\times 10^{-7}$	$\frac{\mathcal{B}(B^0 \to K^{*0}\overline{K}^{*0})}{\mathcal{B}(B_s^0 \to K^{*0}\overline{K}^{*0})}$ $\times 10^{-3}$	$L_{K^{*0}\overline{K}^{*0}}$
Tail parameters	0.460	0.683	0.692	0.161
Signal model	0.763	0.829	1.982	0.206
Background model	3.357	0.214	4.836	0.367
Barrier factors	0.441	0.571	1.176	0.097
BDT	0.045	0.054	0.161	0.010
PID weights	0.529	0.018	0.639	0.170
Kinematic weights	1.131	0.609	2.262	0.266
Trigger correction	0.087	0.442	0.376	0.024
Total combined syst.	3.719	1.448	5.905	0.559
Amplitude syst.	2.069	1.065	4.843	0.211
Total syst.	4.255	1.797	7.000	0.474
Total stat.	2.925	2.468	3.656	0.553

- B_s^0 is statistically dominated
- B^0 is systematically dominated
- Seems counter-intuitive as $N^{B_s^0} > N^{B^0}$
  - Systematics estimated from data
  - Less data and poorer S/B for B^0 results in larger systematics

Branching fractions

- Use yields from four-body fits, efficiencies from signal MC (for $B^0_{(s)} \to K^{*0}\overline{K}^{*0}$ this is VV component only MC) and f_{VV} fractions from amplitude analysis
- Present the branching fractions with purely static amplitudes to ensure clear comparison with theory calculations, see backup for details
- $\mathcal{B}(B^0_{(s)} \to K^{*0}\overline{K}^{*0})$ calculated with ratio to $B^0_{(s)} \to D^-_{(s)}\pi^+$ decays, $\mathcal{B}(B^0 \to K^{*0}\overline{K}^{*0})/\mathcal{B}(B^0_s \to K^{*0}\overline{K}^{*0})$ just single ratio

$$\mathcal{B}(B^0_s \to K^{*0}\overline{K}^{*0}) = (0.938 \pm 0.025\,(\text{stat}) \pm 0.019\,(\text{syst}) \pm 0.036\,(\text{extn})) \times 10^{-5},$$
$$\mathcal{B}(B^0 \to K^{*0}\overline{K}^{*0}) = (4.73 \pm 0.30\,(\text{stat}) \pm 0.43\,(\text{syst}) \pm 0.16\,(\text{extn})) \times 10^{-7},$$
$$\frac{\mathcal{B}(B^0 \to K^{*0}\overline{K}^{*0})}{\mathcal{B}(B^0_s \to K^{*0}\overline{K}^{*0})} = 0.054 \pm 0.004\,(\text{stat}) \pm 0.007\,(\text{syst}) \pm 0.002\,(f_s/f_d),$$

- Compare with PDG:

$$\mathcal{B}(B^0_s \to K^{*0}\overline{K}^{*0}) = (1.11 \pm 0.27) \times 10^{-5}, \qquad \mathcal{B}(B^0 \to K^{*0}\overline{K}^{*0}) = (8.3 \pm 2.4) \times 10^{-7},$$
$$\frac{\mathcal{B}(B^0 \to K^{*0}\overline{K}^{*0})}{\mathcal{B}(B^0_s \to K^{*0}\overline{K}^{*0})} = 0.075 \pm 0.028$$

$L_{K^{*0}\overline{K}^{*0}}$

$$L_{K^{*0}\overline{K}^{*0}} = \mathcal{G}\frac{\mathcal{B}(B_s^0 \to K^{*0}\overline{K}^{*0})}{\mathcal{B}(B^0 \to K^{*0}\overline{K}^{*0})}\frac{f_L^{B_s^0 \to K^{*0}\overline{K}^{*0}}}{f_L^{B^0 \to K^{*0}\overline{K}^{*0}}}$$

- Multiply relative branching fraction by ratio of f_L values
- $\mathcal{G}$ is a phase-space factor, $\mathcal{G} = 1.014 \pm 0.004$

$$L_{K^{*0}\overline{K}^{*0}} = 4.92 \pm 0.55\,(\text{stat}) \pm 0.48\,(\text{syst}) \pm 0.02\,(\text{extn}) \pm 0.10\,(f_s/f_d)$$

- Previous value:

$$L_{K^{*0}\overline{K}^{*0}} = 4.43 \pm 0.74\,(\text{stat}) \pm 0.55\,(\text{syst})$$

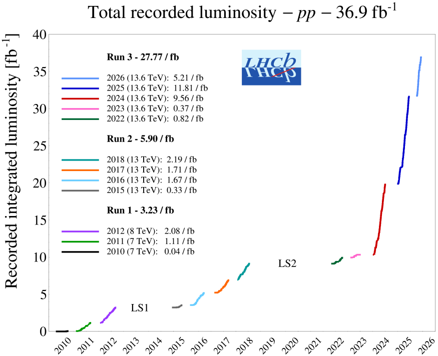
- Very good agreement with previous results, uncertainty has decreased
- Latest SM predictions: $L^{I}_{K^{*0}\overline{K}^{*0}} = 18.34^{+7.47}_{-5.83}$ and $L^{II}_{K^{*0}\overline{K}^{*0}} = 26.08^{+5.70}_{-4.72}$
- Tensions remain the same to 1 d.p., 2.3σ or 4.4σ

The future — time-dependence

- This was a flavour-untagged, decay-time-integrated analysis
- Time-dependent analysis of $B_s^0 \to K^{*0}\overline{K}^{*0}$ provides access to ϕ_s CKM angle (similar to $B_s^0 \to \phi\phi$)
- Previous Run 1 LHCb analysis, this would be an update with Runs 1 + 2 and all the new techniques mentioned
- Now have enough statistics to also attempt time-dependent analysis of $B^0 \to K^{*0}\overline{K}^{*0}$
  - Interesting as it provides sensitivity to penguin-pollution of ϕ_s determination, $\phi_s^{\mathrm{Exp}} = \phi_s^{\mathrm{SM}} + \Delta\phi_s^{\mathrm{SM}} + \delta^{\mathrm{NP}}$
  - Not been attempted before
  - Time-dependent measurements of $B_{(s)}^0 \to K^{*0}\overline{K}^{*0}$ build off this work, currently on-going

- In Run 3 LHCb has collected *triple* the Run 1 + Run 2 datasets

- Move to fully software-based trigger increases number of signal candidates per fb^{-1} for fully hadronic decays by ~ 2–3 times $\Rightarrow$ huge dataset of charmless $B \to VV$ decays to explore!



- Work now on-going to start analysing Run 3 data

Summary

- Charmless $B \to VV$ decays offer interesting laboratory to test the SM
- Updated LHCb analysis of $B^0_{(s)} \to K^{*0}\overline{K}^{*0}$ decays
  - New most precise branching fraction measurements
  - New most precise polarisation measurements, confirms low value of f_{L} in $B^0_s \to K^{*0}\overline{K}^{*0}$ decays
  - Confirms difference between theory and experiment of $L_{K^{*0}\overline{K}^{*0}}$ value at $2.3\sigma/4.4\sigma$ depending on form factor treatment
- Work on-going to extend to time-dependent analyses and starting to look at recently collected Run 3 data

Backup slides

Amplitude analysis

- Use covariant tensor formalism rather than helicity formalism
  - Uses set of four-momentum of final state particles, Φ_4, as the fit basis (instead of angles)
  - Spin amplitudes are eigenstates of orbital angular momentum $\Rightarrow$ Blatt-Weisskopf barrier factors more meaningful
- Total amplitude constructed with isobar approach:

$$A(\Phi_4) = \sum_i a_i S_i(\Phi_4) T_i(\Phi_4) B_i(\Phi_4)$$

- a_i are complex coefficients, $S_i(\Phi_4)$ spin amplitudes (from covariant formalism), $T_i(\Phi_4)$ mass line-shapes of the resonances and $B_i(\Phi_4)$ Blatt-Weisskopf barrier factors

Amplitude analysis

$$A(\Phi_4) = \sum_i a_i S_i(\Phi_4) T_i(\Phi_4) B_i(\Phi_4)$$

- Sum over $i = 6$ amplitudes, each $\mathrm{m}(K\pi)$ can be a vector (V) or scalar (S):
  - SS (S-wave only)
  - VS and SV (P-wave only)
  - VV (S-, P- and D- wave)
- Only consider the region $(K^{\pm}\pi^{\mp})_{\text{threshold}} \leq m(K^{\pm}\pi^{\mp}) \leq 1042\,\text{MeV}/c^2$
- Upper limit set to keep us in the elastic region – S-wave parameterisation is simpler and away from $K_2^*(1430)^0$
- First time at LHCb fitting the $K^{\pm}\pi^{\mp}$ S-wave down to the threshold
- Higher-order spins (*e.g.* tensors) not included as nominal — are considered for systematics
- $V_{K\pi}$ mass modelled by a relativistic Breit-Wigner line-shape
- $S_{K\pi}$ mass modelled by Peláez-Rodas parameterisation (with LASS alternative as a systematic)

Spin amplitudes

- Final spin amplitudes are given by:

$$
\begin{aligned}
A^S_{VV}: &\quad S \propto L_\mu(p_{V_1}, q_{V_1})\, L^\mu(p_{V_2}, q_{V_2})\ , \\
A^P_{VV}: &\quad S \propto \varepsilon_{\mu\nu\alpha\beta}\, L^\beta(p_B, q_B)\, L^\alpha(p_{V_1}, q_{V_1})\, L^\nu(p_{V_2}, q_{V_2})\, p^\mu(B)\ , \\
A^D_{VV}: &\quad S \propto L_{\mu\nu}(p_B, q_B)\, L^\mu(p_{V_1}, q_{V_1})\, L^\nu(p_{V_2}, q_{V_2})\ , \\
A^+_{VS}: &\quad S \propto L_\mu(p_{V_1}, q_{V_1})\, L^\mu(p_B, q_B) + L_\nu(p_{V_2}, q_{V_2})\, L^\nu(p_B, q_B)\ , \\
A^-_{VS}: &\quad S \propto L_\mu(p_{V_1}, q_{V_1})\, L^\mu(p_B, q_B) - L_\nu(p_{V_2}, q_{V_2})\, L^\nu(p_B, q_B)\ , \\
A_{SS}: &\quad S \propto 1\ .
\end{aligned}
$$

- *CP*-conjugated amplitude is:

$$\bar{A}(\bar{\Phi}_4) = \sum_i a_i \lambda_i S_i\left(\bar{\Phi}_4\right) T_i\left(\bar{\Phi}_4\right) B_i\left(\bar{\Phi}_4\right)$$

- where $\bar{\Phi}_4$ is the *CP*-conjugated phase-space vectors *i.e.* flip 3-momentum and swap charges

S-wave parameterisation

- Peláez-Rodas parameterisation arXiv:2010.11222
- Phenomenological model which factors out the scattering component from the production amplitude

$$T^{\text{scat}}_{\pi K-\pi K}(s) = \frac{1}{\cot\delta_0^{1/2}(s) - i}\,, \quad \cot\delta_0^{1/2}(s) = \frac{\sqrt{s}}{2\,q(s)(s-s_A)}\Big(B_0 + B_1\,\omega(s)\Big)$$

- We want this for production rather than scattering $\Rightarrow$

$$T(s) = P(s)\,S^{\text{scat}}_{\pi K-\pi K}(s) = P(s)\,\left(1 + i\,T^{\text{scat}}_{\pi K-\pi K}(s)\right)\,,$$

- $P(s)$ is an unknown production function $\Rightarrow$ parameterise with complex polynomial of degree 3:

$$P(s) = \left(1 + c_1^{\text{Abs}}\,X(s) + c_2^{\text{Abs}}\,X^2(s) + \ldots\right)\,e^{i\left(c_1^{\text{Arg}}\,X(s) + c_2^{\text{Arg}}\,X^2(s) + \ldots\right)}\,,$$

- with c_i^{Abs} and c_i^{Arg} a set of parameters that must be determined from a fit to data

BDT input variables

main slide

Signal mode variables

$\log_{10}$(1-B_DIRA_OWNPV)
$\log_{10}$(B_IPCHI2_OWNPV)
$\log_{10}$(B_FDCHI2_OWNPV)
B_PT
B_IP_OWNPV
B_FD_OWNPV
B_ETA
B_ENDVERTEX_CHI2_NDOF
B_DOCA
$\log_{10}$(Kst(b)_IPCHI2_OWNPV)
Kst(b)_IP_OWNPV
MIN_PT_daughters
$\log_{10}$(Kp_pim_MIN_IPCHI2)
$\log_{10}$(Km_pip_MIN_IPCHI2)
B_ptasy_1_50
B_SmallestDeltaChi2OneTrack
B_SmallestDeltaChi2TwoTracks

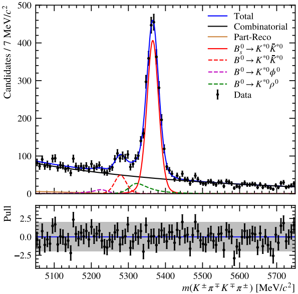
Normalisation mode variables

$\log_{10}$(1-B_DIRA_OWNPV)
$\log_{10}$(B_IPCHI2_OWNPV)
$\log_{10}$(B_FDCHI2_OWNPV)
B_ETA
B_ENDVERTEX_CHI2_NDOF
B_DOCA
$\log_{10}$(D_IPCHI2_OWNPV)
D_IP_OWNPV
$\log_{10}$(1-D_DIRA_ORIXV)
D_FD_OWNPV
D_ENDVERTEX_CHI2_NDOF
MIN_PT_D_CHILDS
$\log_{10}$(D_CHILDS_MIN_IPCHI2)
$\log_{10}$(Bpi_IPCHI2_OWNPV)
Bpi_PT
B_SmallestDeltaChi2OneTrack
B_SmallestDeltaChi2TwoTracks

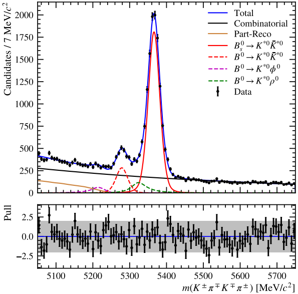
PID selection

- Use ProbNN cuts to reduce misID backgrounds from $B^0 \to \rho^0 K^{*0}$, $B^0 \to \phi K^{*0}$ and $\Lambda_b^0 \to p K^- \pi^+ \pi^-$
- $B^0 \to \rho^0 K^{*0}$ most difficult misID – peaks in-between $B_s^0 \to K^{*0} \overline{K}^{*0}$ and $B^0 \to K^{*0} \overline{K}^{*0}$
- $\Lambda_b^0 \to p K^- \pi^+ \pi^-$ easy to remove with loose cuts: $K^\pm$ ProbNNk > 0.1 and $K^\pm$ ProbNNp < 0.9
- Perform “preliminary” B-mass fit with loose BDT cut and Λ_b^0 cut to estimate amount of misID background

Run 1



Run 2



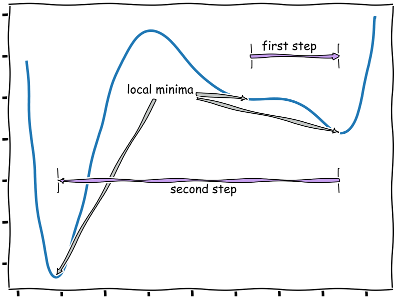
PID selection

- Combine some ProbNN variables together to target specific misIDs:
  - min_k_ProbNN = min(K1_ProbNNk×(1-K1_ProbNNpi), K2_ProbNNk×(1-K2_ProbNNpi)),
  - min_pi_ProbNN = min(pi1_ProbNNpi×(1-pi1_ProbNNk), pi2_ProbNNpi×(1-pi2_ProbNNk)),
  - max_p_ProbNN = max(h_ProbNNp)
- min_k_ProbNN targets $B^0 \to \rho^0 K^{*0}$, min_pi_ProbNN targets $B^0 \to \phi K^{*0}$ and max_p_ProbNN any remaining Λ_b^0
- 4D optimisation of min_k_ProbNN, min_pi_ProbNN, max_p_ProbNN and BDT
- Optimise the significance of the $B^0 \to K^{*0}\overline{K}^{*0}$ *i.e.* $\frac{S}{\sqrt{S+B}}$ in the B^0 peak region
- S and B estimated using preliminary fits to data

Variable	Optimal Run 1	Optimal Run 2
BDT	> 0.989	> 0.960
min_k_ProbNN	> 0.454	> 0.600
min_pi_ProbNN	> 0.273	> 0.047
max_p_ProbNN	< 0.563	< 0.949
B^0 significance	12.6	33.4

Basin-Hopping

- Cool function from `SciPy` for function minimisation
- Originates from determining energy levels in atomic physics
- Effectively:
  - Runs *some* minimisation function
  - Perturbs values in parameter space, rerun to look for a new/better minimum
  - Repeat!



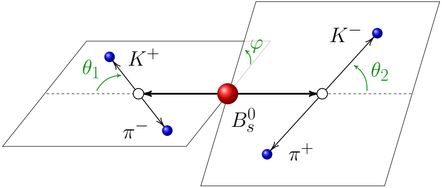
- Results in global minimisation, to avoid falling in local minima
- Not so bad in 4D, have also successfully used it in an 18D minimisation problem

sWeights

- *sPlot* or *sWeights* technique commonly used in LHCb, not so much outside it
- Idea is:
  - We know what our signal and background look like in *some* variables
  - We want to extract our signal distribution in some other variables, without wanting to know what the background looks like in the other variables
  - By fitting in the variables we know, we can determine a weight function which projects the signal distribution in *any** set of variables
- *Only if signal *and* background distributions in known variable set are independent from distributions in other variable set!
- In this case, known variable is the B-mass, other variable set is the fit basis for amplitude fit (*e.g.* angles and resonance masses)
- Amplitude fit is signal-only fit to *sWeighted* data (per-event weights)

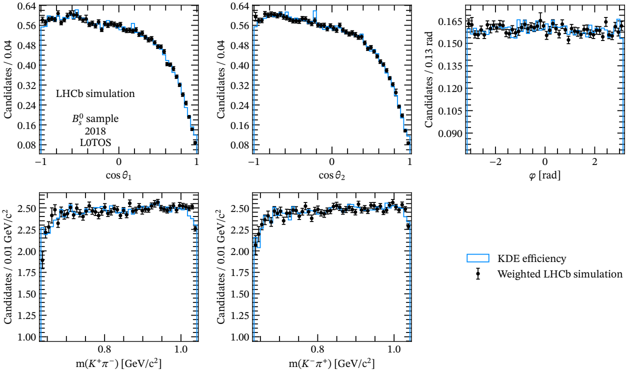
Efficiency map

- Use a 5D KDE (custom GPU implementation of `kalepy` package) on LHCb MC samples generated flat in the $m(K^{\pm}\pi^{\mp})$ phase-space for B_s^0 and B^0
- Separate for B_s^0, B^0, per year and separate trigger categories
- Additional data-MC corrections for:
  - Trigger efficiency of `L0HadronTOS`
  - Tracking efficiency `TrackCalib`
  - PID efficiency (`PIDCalib2`)



Efficiency map

- Use a 5D KDE (custom GPU implementation of `kalepy` package) on LHCb MC samples generated flat in the $m(K^{\pm}\pi^{\mp})$ phase-space for B_s^0 and B^0
- Separate for B_s^0 and B^0 and per year and separate trigger categories



Barrier factors systematic

$$B_0(q) = 1,$$
$$B_1(q) = \frac{1}{\sqrt{1+(qr)^2}},$$
$$B_2(q) = \frac{1}{\sqrt{9+3(qr)^2+(qr)^4}},$$

- Blatt-Weisskopf barrier factors depend on the radius of the meson, r
- Not very well measured, we use a fixed value of $4\,\text{GeV}^{-1} \approx 0.8\,\text{fm}$
- Vary *production* and *decay* barrier factors independently between 3–$5\,\text{GeV}^{-1}$ as a systematic
- Changing these radii changes the scale of the amplitude parameters — cannot directly compare to other amplitude systematics ⇒ throw transversity toys to assess impact on f_L
- This has been a very large systematic in previous analyses — now under much better control with covariant formalism!

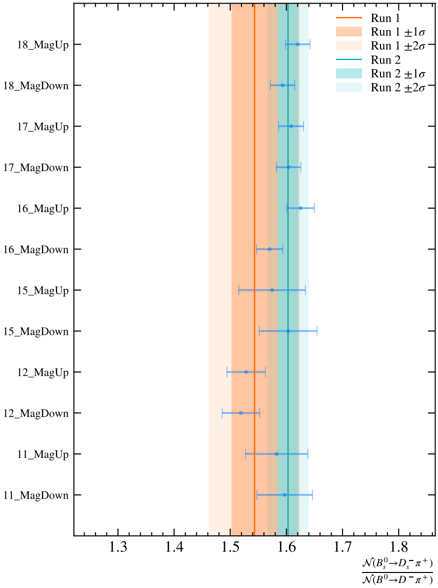
Amplitude systematic uncertainties

	Parameter	KDE bandwidth	KDE kernel	Fit bias	Lineshape	S-wave	*sWeights*	Tensor resonance	Tracking	Decay-time	Total syst	Total stat
B_s^0	f_{VV}^{S+D}	0.071	0.036	0.047	0.001	0.143	0.050	0.184	<0.001	0.031	0.26	0.63
	f_{VV}^{P}	0.062	0.080	0.222	<0.001	0.147	0.192	0.082	<0.001	0.134	0.38	0.56
	f_{VS}^{+}	0.048	0.144	0.185	<0.001	0.607	0.174	**2.191**	<0.001	0.030	2.29	0.59
	f_{VS}^{-}	0.108	0.039	0.503	<0.001	0.807	0.477	0.257	0.001	0.111	1.11	0.89
	f_{SS}	0.022	0.011	0.048	<0.001	0.090	0.061	0.192	<0.001	0.021	0.23	0.56
	δ_{VV}^{D}	<0.001	0.001	<0.001	<0.001	0.008	<0.001	0.002	<0.001	<0.001	0.01	<0.01
	δ_{VS}^{+}	0.008	0.029	0.013	0.007	0.088	0.019	0.838	<0.001	<0.001	0.84	0.11
	δ_{VS}^{-}	<0.001	0.003	0.009	0.007	0.121	0.014	0.009	<0.001	<0.001	0.12	0.04
	δ_{SS}	0.008	0.016	0.016	0.014	0.253	0.019	0.005	<0.001	<0.001	0.25	0.06
B^0	f_{VV}^{S+D}	0.789	**2.064**	0.263	0.027	0.143	0.050	0.715	<0.001	0.080	2.34	2.04
	f_{VV}^{P}	0.375	0.452	0.236	0.003	0.147	0.192	0.276	<0.001	0.122	0.74	1.35
	f_{VS}^{+}	0.394	0.758	0.267	0.018	0.607	0.174	0.110	0.002	0.049	1.10	2.17
	f_{VS}^{-}	0.925	**2.467**	0.110	0.007	0.807	0.477	0.721	0.002	0.080	2.89	2.27
	f_{SS}	0.116	0.097	0.122	0.017	0.090	0.061	0.097	<0.001	0.011	0.24	1.00
	δ_{VV}^{D}	0.012	0.003	0.006	<0.001	0.008	<0.001	<0.001	<0.001	<0.001	0.02	0.04
	δ_{VS}^{+}	0.106	0.208	0.020	0.007	0.088	0.019	<0.001	<0.001	<0.001	0.25	0.22
	δ_{VS}^{-}	0.032	0.033	0.009	0.007	0.121	0.014	<0.001	<0.001	<0.001	0.13	0.11
	δ_{SS}	0.070	0.097	0.014	0.013	0.253	0.019	<0.001	<0.001	<0.001	0.28	0.15

Branching fraction closure test

- Can calculate the branching fraction ratio of the normalisation modes to each other, $\mathcal{B}(B_s^0 \to D^-\pi^+)/\mathcal{B}(B^0 \to D_s^-\pi^+)$
- Compare to Run 1 LHCb paper measuring BF of $B_s^0 \to D_s^-\pi^+$: LHCb-PAPER-2011-022 and Run 2 f_s/f_d paper: LHCb-PAPER-2020-046
- The values of $\frac{\mathcal{B}(B_s^0 \to D_s^-\pi^+)}{\mathcal{B}(B^0 \to D^-\pi^+)}$ are calculated to be:
  - 1.15 ± 0.05 in Run 1.
  - 1.10 ± 0.05 in Run 2.
- Compared to 1.10 ± 0.10 for Run 1 and 1.17 ± 0.04 for Run 2 from previous LHCb results
- We also compute this per-year and per-polarity (but not correcting for the D-decay branching fractions) and find good consistency between the sub-samples (see next slide)

$\frac{\mathcal{B}(B_s^0 \to D_s^- \pi^+)}{\mathcal{B}(B^0 \to D^- \pi^+)}$ per year and polarity



Branching fractions main slide

- Branching fractions are measured using efficiency-corrected yields and fit fractions from amplitude fit
- Must be clear about how the yields, efficiencies and fit fractions are defined so that it is clear what branching fraction we are reporting
- E.g. previous theory papers using Run 1 LHCb $B^0_{(s)} \to K^{*0}\overline{K}^{*0}$ results have added a 7% "uncertainty" on our reported values because of this
- Theory-calculated decay rates are in terms of static decay rates $\Rightarrow$ report our branching fractions in the same way
- Have to watch out for:
  - Efficiency of amplitude model we fit for *vs.* model used in the MC
  - Whether our yields/efficiencies include B^0_s-$\overline{B}^0_s$ mixing or not
  - Mixing correction is small in this case, 99.5%

Phase-space factor, $\mathcal{G}$ main slide

$$\mathcal{G} = \frac{g_{b\to d}}{g_{b\to s}},$$

with

$$g_{b\to q} = \omega\sqrt{\left[M_{B_q}^2 - \Sigma_{V_1 V_2}\right]\left[M_{B_q}^2 - \Delta_{V_1 V_2}\right]},$$

where $\omega = \tau_{B_q}/(16\pi M_{B_q}^3)$, $\Sigma_{ab} = (m_a + m_b)^2$ and $\Delta_{ab} = (m_a - m_b)^2$. In this case, $m_a = m_b = m_{K^{*0}}$ and so $\Delta_{ab} = 0$ and writing the full expression for $\mathcal{G}$ we find:

$$\mathcal{G} = \frac{\tau_{B^0}}{\tau_{B_s^0}}\left(\frac{m_{B_s^0}}{m_{B^0}}\right)^2\sqrt{\frac{m_{B^0}^2 - 4m_{K^{*0}}^2}{m_{B_s^0}^2 - 4m_{K^{*0}}^2}}$$

$$\mathcal{G} = 1.014 \pm 0.004,$$

using $\tau_{B^0} = (1.519 \pm 0.004)$ ps, $\tau_{B_s^0} = (1.520 \pm 0.005)$ ps, $m_{B^0} = (5279.72 \pm 0.08)$ MeV/c^2, $m_{B_s^0} = (5366.93 \pm 0.1)$ MeV/c^2 and $m_{K^{*0}} = (895.55 \pm 0.2)$ MeV/c^2 from PDG.

Time-dependence

- $B^0_{(s)} \to K^{*0}\overline{K}^{*0}$ decays proceed as loop diagrams at leading order
- Three contributions in the loop from u, c and t quarks
- Can rewrite away one term with CKM unitarity

$$A(B^0 \to K^{*0}\overline{K}^{*0}) = |V^*_{ub}V_{ud}|e^{i\gamma}(P_u - P_c) + |V^*_{tb}V_{td}|e^{-i\beta}(P_t - P_c),$$
$$A(B^0_s \to K^{*0}\overline{K}^{*0}) = |V^*_{ub}V_{us}|e^{i\gamma}(P'_u - P'_c) + |V^*_{tb}V_{ts}|e^{i\beta_s}(P'_t - P'_c),$$

- Assuming U-spin symmetry, $P_q = P'_q$
- For B^0_s, terms are proportional to $\mathcal{O}(\lambda^4)$ and $\mathcal{O}(\lambda^2)$
- For B^0, terms are *both* proportional to $\mathcal{O}(\lambda^3)$
- Can use B^0 to disentangle sub-leading contribution for B^0_s!
- Note, $\beta_s = \arg\left(-\frac{V_{ts}V^*_{tb}}{V_{cs}V^*_{cb}}\right)$
- We measure experimentally $\phi_s = -2\beta_s + \delta\phi_s$