Direct CP violation measurements with an amplitude analysis: $B^0 \to (\pi^+\pi^-)(K^+\pi^-)$ results

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Future Challenges in Non-Leptonic B Decays

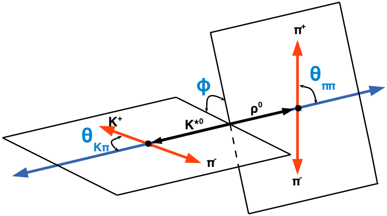
Mainz, January 14-18$^{\text{th}}$, 2019

Observables in an amplitude analysis of $B \to VV$ decays

$B \to (p_a p_b)_1 (p_c p_d)_2$ decays

Can be **fully described** in terms of:

- **Three helicity angles**: θ_1, θ_2, ϕ
- **Two invariant masses**: m_1, m_2



A **$B \to VV$ proceeds via three amplitudes** $\to$ three **spin configurations**:
P-odd $S_{VV} = 1$ and P-even $S_{VV} = 0, 2$ usually rotated into the transversity basis $\lambda = L, ||, \perp$.

Observables: number of events per amplitude (**polarisation fractions**), f^λ, and their **phase differences**: $(\delta^{\lambda_i} - \delta^{\lambda_j})$

$\to$ **Sensitivity to CPV by comparing B and $\overline{B}$ parameters**

$$f^\lambda = \frac{|A^\lambda|^2}{|A^L|^2+|A^{||}|^2+|A^{\perp}|^2}, \qquad \tilde{f}^\lambda = \frac{1}{2}(f^\lambda + \overline{f}^\lambda), \qquad \mathcal{A}^\lambda = \frac{\overline{f}^\lambda - f^\lambda}{\overline{f}^\lambda + f^\lambda}$$

T-odd quantities can be obtained from $\mathcal{A}_T = f_\perp f_{(L,||)} \sin(\delta_\perp - \delta_{(L,||)})$, to build **Triple Product asymmetries**:

$$\mathcal{A}_{T-true} = \frac{\mathcal{A}_T - \overline{\mathcal{A}}_T}{2}, \qquad \mathcal{A}_{T-fake} = \frac{\mathcal{A}_T + \overline{\mathcal{A}}_T}{2}$$

Observables in an amplitude analysis of 4-body decays

In general, a ***VV*** final state **can not be isolated** and other possible decay channels must be accounted for:
Partial waves:

VV: $\rho K^*, \omega K^*$, **VS**: $\rho(K\pi), \omega(K\pi)$,

SV: $[f_0(500), f_0(980), f_0(1370)]K^*$,

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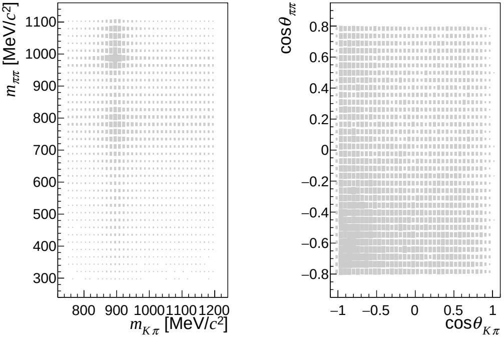
Illustrative toys

(no interferences generated, $(a+b)^2 \neq a^2 + b^2$)



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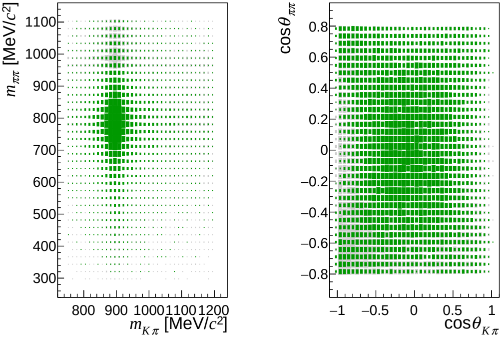

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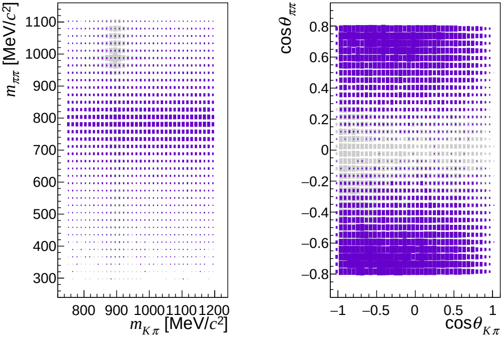

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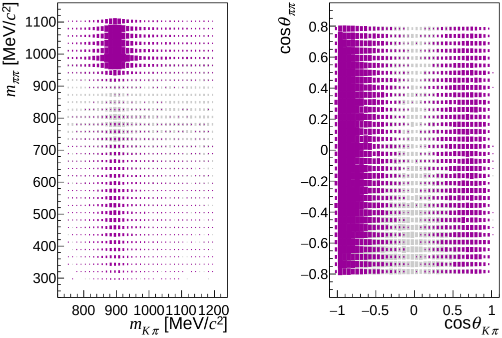

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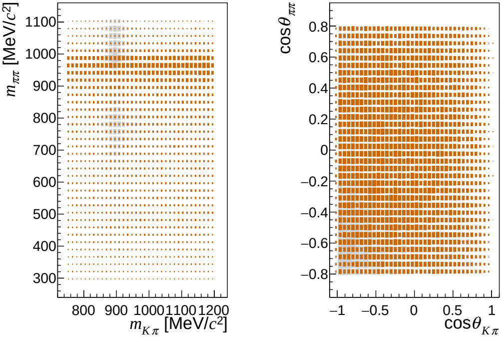

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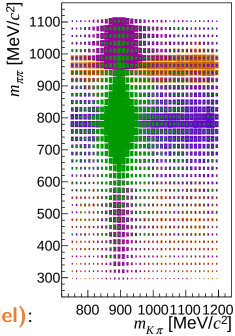
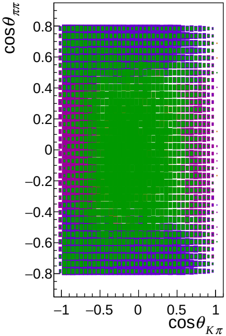




Generalise to N amplitudes (isobar model):

$$d^5\Gamma \propto \Phi_4 \left|\sum_{i=1}^{N} A_i \cdot g_i(\cos\theta_1, \cos\theta_2, \phi) \cdot M_i(m_1, m_2)\right|^2$$

More observables: $+1$ amplitude, $+1$ phase difference per new contribution

An amplitude analysis disentangles the final state!

$A_i \rightarrow$ **physical parameters**

$g_i(\theta_1, \theta_2, \phi) \rightarrow$ **spherical harm.**

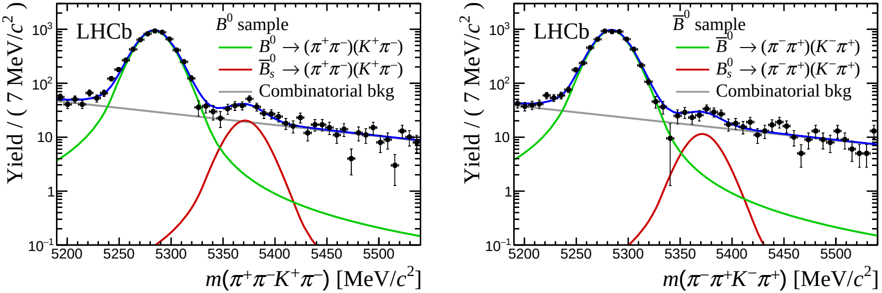
$M_i(m_1, m_2) \rightarrow$ **mass prop.**

Analysis strategy

LHCb-PAPER-2018-042

Main analysis steps:

1. Event selection:
   Trigger on final state hadrons + Particle Identification + Invariant mass windows + Multivariate Analysis
2. Four-body mass spectrum:
   Inject simulated events to cancel $B_s^0 \to (K^+\pi^-)(K^-\pi^+)$ background, then use the *s*Fit to obtain signal weights→ **background-subtracted data sample**



$\sim 11k$ signal events in $B^0 + \overline{B}^0$

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3. Build 5D model (2-body invariant masses + helicity angles):
   Describes a total of **14 amplitudes** contributing to the $B^0 \to (\pi^+\pi^-)(K^+\pi^-)$ process in the quasi-two-body approach using the Isobar model.

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4. Data fit:
   Unbinned maximum likelihood fit **simultaneous in year and trigger categories** for B^0 and $\overline{B^0}$ (8 subsamples) using MultiNest. →Multinest project
   LHCb acceptance effect accounted for using simulated events.
5. Systematic uncertainties study: **Dominant systs.**: for **VV** channels, $\boldsymbol{B^0 \to a_1(1260)^- K^+}$ pollution; for **S-waves**, parameters in the **mass propagators** and experimental **resolution**.

Fit results (I): projections on the helicity angles

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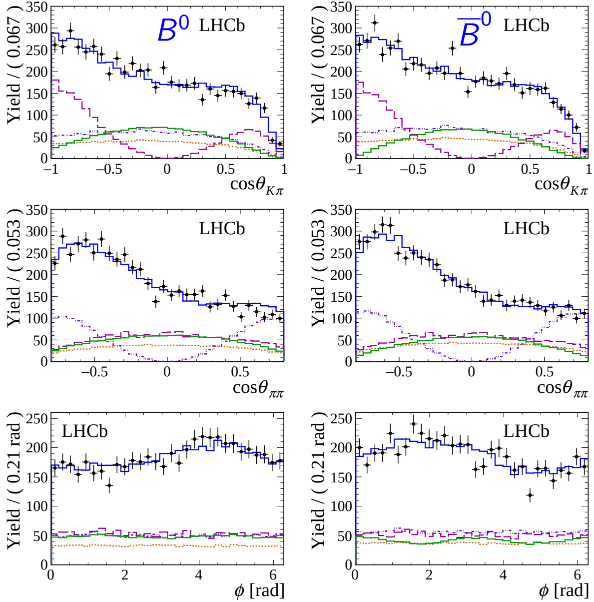

$\leftarrow \cos\theta_{\pi\pi}$

$\leftarrow \cos\theta_{K\pi}$

$\leftarrow \phi$

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Fit results (II): projections on the invariant masses

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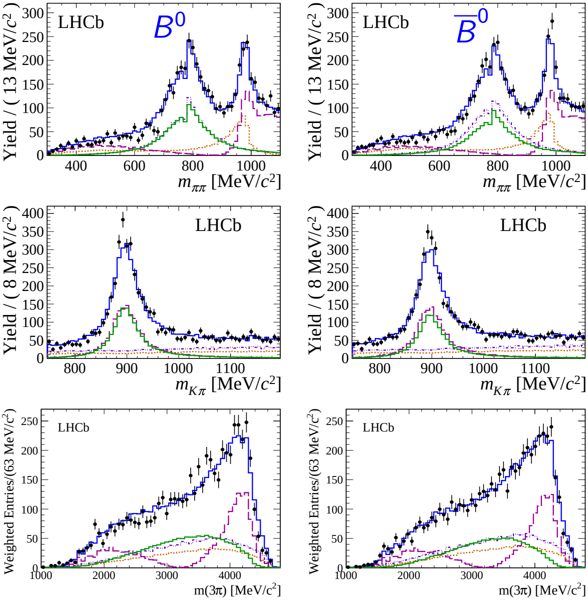

$\leftarrow m(\pi\pi)$

$\leftarrow m(K\pi)$

$\leftarrow m(\pi\pi\pi)$ (Not fitted)

VV: $\rho K^*, \omega K^*$

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Full set of numerical results

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Parameter	CP average, $\tilde{f}$	CP asymmetry, $\mathcal{A}$
$\lvert A^0_{\rho K^*}\rvert^2$	$0.32 \pm 0.04 \pm 0.07$	$-0.75 \pm 0.07 \pm 0.17$
$\lvert A^{\parallel}_{\rho K^*}\rvert^2$	$0.70 \pm 0.04 \pm 0.08$	$-0.049 \pm 0.053 \pm 0.019$
$\lvert A^{\perp}_{\rho K^*}\rvert^2$	$0.67 \pm 0.04 \pm 0.07$	$-0.187 \pm 0.051 \pm 0.026$
$\lvert A^0_{\omega K^*}\rvert^2$	$0.019 \pm 0.010 \pm 0.012$	$-0.6 \pm 0.4 \pm 0.4$
$\lvert A^{\parallel}_{\omega K^*}\rvert^2$	$0.0050 \pm 0.0029 \pm 0.0031$	$-0.30 \pm 0.54 \pm 0.28$
$\lvert A^{\perp}_{\omega K^*}\rvert^2$	$0.0020 \pm 0.0019 \pm 0.0015$	$-0.2 \pm 0.9 \pm 0.4$
$\lvert A_{\omega(K\pi)}\rvert^2$	$0.026 \pm 0.011 \pm 0.025$	$-0.47 \pm 0.33 \pm 0.45$
$\lvert A_{f_0(500)K^*}\rvert^2$	$0.53 \pm 0.05 \pm 0.10$	$-0.06 \pm 0.09 \pm 0.04$
$\lvert A_{f_0(980)K^*}\rvert^2$	$2.42 \pm 0.13 \pm 0.25$	$-0.022 \pm 0.052 \pm 0.023$
$\lvert A_{f_0(1370)K^*}\rvert^2$	$1.29 \pm 0.09 \pm 0.20$	$-0.09 \pm 0.07 \pm 0.04$
$\lvert A_{f_0(500)(K\pi)}\rvert^2$	$0.174 \pm 0.021 \pm 0.039$	$0.30 \pm 0.12 \pm 0.09$
$\lvert A_{f_0(980)(K\pi)}\rvert^2$	$1.18 \pm 0.08 \pm 0.07$	$-0.083 \pm 0.066 \pm 0.023$
$\lvert A_{f_0(1370)(K\pi)}\rvert^2$	$0.139 \pm 0.028 \pm 0.039$	$-0.48 \pm 0.17 \pm 0.15$
$f^0_{\rho K^*}$	$0.164 \pm 0.015 \pm 0.022$	$-0.62 \pm 0.09 \pm 0.09$
$f^{\parallel}_{\rho K^*}$	$0.435 \pm 0.016 \pm 0.042$	$0.188 \pm 0.037 \pm 0.022$
$f^{\perp}_{\rho K^*}$	$0.401 \pm 0.016 \pm 0.037$	$0.050 \pm 0.039 \pm 0.015$
$f^0_{\omega K^*}$	$0.68 \pm 0.17 \pm 0.16$	$-0.13 \pm 0.27 \pm 0.13$
$f^{\parallel}_{\omega K^*}$	$0.22 \pm 0.14 \pm 0.15$	$0.26 \pm 0.55 \pm 0.22$
$f^{\perp}_{\omega K^*}$	$0.10 \pm 0.09 \pm 0.09$	$0.3 \pm 0.8 \pm 0.4$

Parameter	CP average, $\frac{1}{2}(\delta_{\overline{B}} + \delta_B)$ [rad]	CP difference, $\frac{1}{2}(\delta_{\overline{B}} - \delta_B)$ [rad]
$\delta^0_{\rho K^*}$	$1.57 \pm 0.08 \pm 0.18$	$0.12 \pm 0.08 \pm 0.04$
$\delta^{\parallel}_{\rho K^*}$	$0.795 \pm 0.030 \pm 0.068$	$0.014 \pm 0.030 \pm 0.026$
$\delta^{\perp}_{\rho K^*}$	$-2.365 \pm 0.032 \pm 0.054$	$0.000 \pm 0.032 \pm 0.013$
$\delta^0_{\omega K^*}$	$-0.86 \pm 0.29 \pm 0.71$	$0.03 \pm 0.29 \pm 0.16$
$\delta^{\parallel}_{\omega K^*}$	$-1.83 \pm 0.29 \pm 0.32$	$0.59 \pm 0.29 \pm 0.07$
$\delta^{\perp}_{\omega K^*}$	$1.6 \pm 0.4 \pm 0.6$	$-0.25 \pm 0.43 \pm 0.16$
$\delta_{\omega(K\pi)}$	$-2.32 \pm 0.22 \pm 0.24$	$-0.20 \pm 0.22 \pm 0.14$
$\delta_{f_0(500)K^*}$	$-2.28 \pm 0.06 \pm 0.22$	$-0.00 \pm 0.06 \pm 0.05$
$\delta_{f_0(980)K^*}$	$0.39 \pm 0.04 \pm 0.07$	$0.018 \pm 0.038 \pm 0.022$
$\delta_{f_0(1370)K^*}$	$-2.76 \pm 0.05 \pm 0.09$	$0.076 \pm 0.051 \pm 0.025$
$\delta_{f_0(500)(K\pi)}$	$-2.80 \pm 0.09 \pm 0.21$	$-0.206 \pm 0.088 \pm 0.034$
$\delta_{f_0(980)(K\pi)}$	$-2.982 \pm 0.032 \pm 0.057$	$-0.027 \pm 0.032 \pm 0.013$
$\delta_{f_0(1370)(K\pi)}$	$1.76 \pm 0.10 \pm 0.11$	$-0.16 \pm 0.10 \pm 0.04$
$\delta^{\parallel-\perp}_{\rho K^*}$	$3.160 \pm 0.035 \pm 0.044$	$0.014 \pm 0.035 \pm 0.026$
$\delta^{\parallel-0}_{\rho K^*}$	$-0.77 \pm 0.09 \pm 0.06$	$-0.109 \pm 0.085 \pm 0.034$
$\delta^{\perp-0}_{\rho K^*}$	$-3.93 \pm 0.09 \pm 0.07$	$-0.123 \pm 0.085 \pm 0.035$
$\delta^{\parallel-\perp}_{\omega K^*}$	$-3.4 \pm 0.5 \pm 0.7$	$0.84 \pm 0.52 \pm 0.16$
$\delta^{\parallel-0}_{\omega K^*}$	$-1.0 \pm 0.4 \pm 0.6$	$0.57 \pm 0.41 \pm 0.17$
$\delta^{\perp-0}_{\omega K^*}$	$2.4 \pm 0.5 \pm 0.8$	$-0.28 \pm 0.51 \pm 0.24$

Amplitudes and phase differences measured for 13 waves ($\mathcal{CP}$-av. and asym.)

- ✓ **First measurements for several modes**
- ✓ **First measurements of CP-phase differences per channel**
- ✓ **First observation of CPV in angular distributions of *VV* decays**

Numerical fit results

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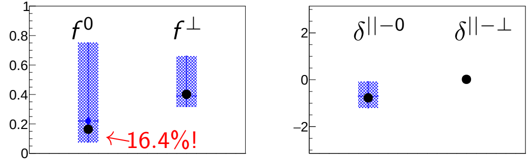
Remarks

- $B^0 \to \rho^0(K^+\pi^-)$ amplitude fixed (normalisation)
- Measurements of the relative amplitudes and phases for the remaining 13 waves

Results for the $B^0 \to \rho^0 K^{*0}$ related observables compared with QCDF predictions:

Nucl.Phys. B774 (2007) 64-101

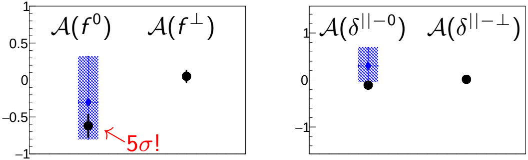
CP-averages



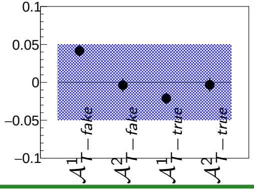
Fit results (stats. and syst. uncertainties included)

Theoretical predictions (QCDF) with uncertainties

CP-asymmetries



TPAs



VV dominated angular distributions

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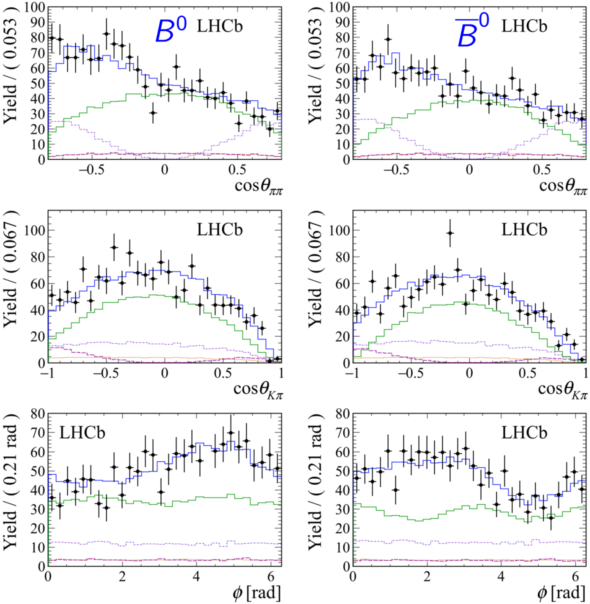


CP-violating effects can be seen in:

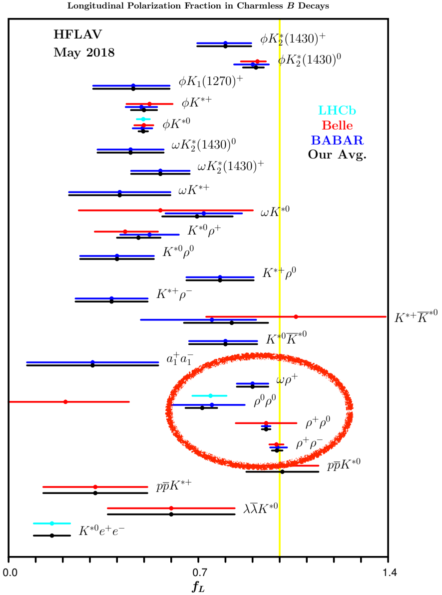
Different shapes of the inverted green parabola for the *VV*

Different oscillation in the *VV*

The landscape of longitudinal polarisations

Available results:

- Large f_L values confirmed in $b \to u$ tree dominated decays
- Penguin dominated modes span wider ranges for f_L
- The $B^0 \to K^*(892)^0 \bar{K}^*(892)^0$ seems to be an exception ($f_L > 0.7$)



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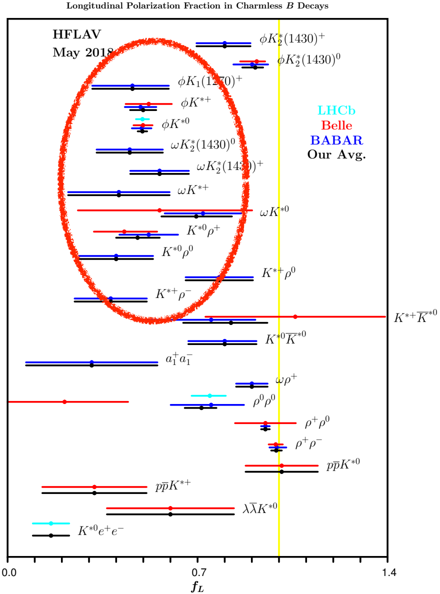

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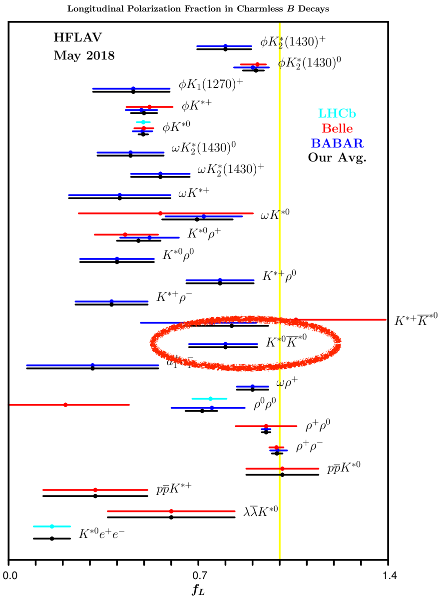

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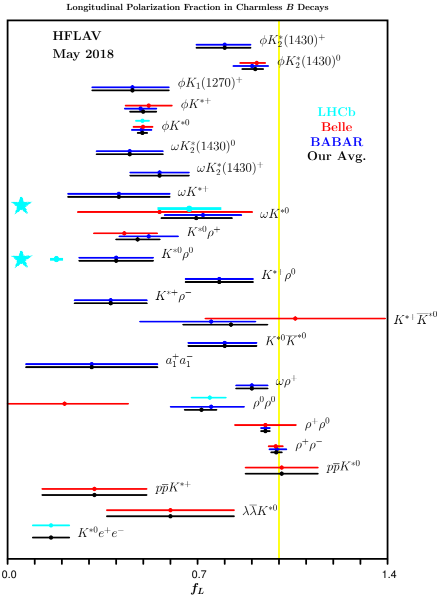
★ This work

As for the plausible explanations ...

[I am hoping for your input here]



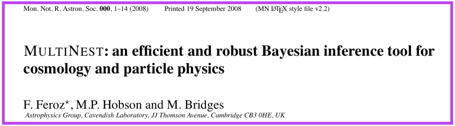
Summary

- **Amplitude analyses**
  - Give access to large sets of observables probing structures of potential new contributions
  - Exp.: high technicality, require careful treatment of correlations and very good understanding of the detector effects
  - Th.: challenging calculations still affected by very large uncertainties
- **Some comments**
  - $M_i(m_1, m_2)$: mass propagators shapes (magnitude and phase) introduce some model-dependency. Sensible choices needed.
  - Description of the S-wave is a long standing *feature*: rich dynamics, phenomenology...
  - Backgrounds: either describe or subtract with statistical methods.
  - High dimensional problems, with many parameters... could some of these be shared among contributions?

Backup slides

A glimpse into MultiNest

Uses clustered nested sampling: a **Monte Carlo** method targetted at the efficient calculation of the probability for a set of parameter values given a data sample



Mon. Not. R. Astron. Soc. **000**, 1–14 (2008) Printed 19 September 2008 (MN LaTeX style file v2.2)

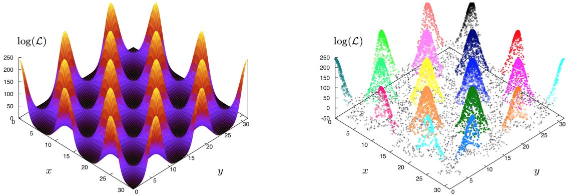
MultiNest: an efficient and robust Bayesian inference tool for cosmology and particle physics

F. Feroz*, M.P. Hobson and M. Bridges
Astrophysics Group, Cavendish Laboratory, JJ Thomson Avenue, Cambridge CB3 0HE, UK

Highlighted characteristics:

- Defines “high dimensionality” as > 50D :-)
- Nested sampling: new algorithm type ($\sim$ 2004) performing better (less evaluations needed) than MC-Markov-Chain reference
- Clustered nested sampling: very good finding several modes in the posterior distributions (induced by non smoothness of the $\log \mathcal{L}$ in our case)
- Very slow **but**: parameter estimation, uncertainties, $\log \mathcal{L}$ profiles, iso-$\log \mathcal{L}$ contours, correlations, ... **all produced at once**

Example of MultiNest performance finding peaks in a multimodal $\log \mathcal{L}$ distribution. Toy (left) vs fit (right).



Sources of systematic uncertainties

$$\texttt{PDF term} \sim \frac{\mathcal{A}_i \cdot g_i(\theta_1, \theta_2, \phi) \cdot \mathcal{M}_i(m_1, m_2) \times (\ldots)^*_j}{\sum_{i,j} \mathcal{A}_i \mathcal{A}^*_j nw_{ij}}$$

Normalisation: $\sum_{i,j} \mathcal{A}_i \mathcal{A}^*_j nw_{ij}$

- $\mathcal{A}_i \mathcal{A}^*_j \rightarrow$ polarisation affects acceptance.
- nw_{ij} obtained from MC sample, limited statistics

Experimental resolution $(\theta_1, \theta_2, \phi, m_1, m_2)$ and **Orbital angular momentum barriers** $(m_1 \times m_2)$

- Neglected in the nominal model

Mass propagators: $\mathcal{M}(m_1, m_2)$

- Vary the parameters in the propagators: $BW(m, L, m_0, \Gamma_0, r_0) \rightarrow x_0 \rightarrow Gauss(x_0, \sigma_{x_0})$

Neglected contributions in the model: $\mathcal{A}_i \mathcal{A}^*_j$

- Identical π exchange, $B^0 \rightarrow (\pi^+\pi^-)(K^+\pi^-)$, and $B^0 \rightarrow a_1(1240)^- K^+$ pollution

Pull distributions: to estimate possible model-induced biases

Data-Simulation corrections: nw_{ij}

- `PIDCalib` 2D maps plus iterative reweight to correct for p_T^B and `Ntracks`

Data sample:

- Negative weights cancelling the $B^0_s \rightarrow K^*(892)^0 \bar{K}^*(892)^0$ contribution (yield and shapes)
- Signal weights from the *s*Fit

Systematic uncertainties

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- The $B^0 \to a_1(1260)^- K^+$, being sensitive to polarisations too, **dominates the systematics for the *VV* parameters**. *S*-waves are mostly affected by the parameters used in the mass propagators and the experimental resolution.

	Systematic uncertainty	$f^0_{\rho K^*}$	$f^{\|\|}_{\rho K^*}$	$f^{\perp}_{\rho K^*}$	$\delta^{\|\|-\perp}_{\rho K^*}$	$\delta^{\|\|-0}_{\rho K^*}$	$\delta^{\perp-0}_{\rho K^*}$
CP averages	Centrifugal barrier factors	0.001	0.001	0.002	0.001	–	–
	Hypatia parameters	0.001	0.001	0.001	0.001	–	–
	$B^0_s \to K^{*0}\overline{K}^{*0}$ bkg.	0.005	0.003	0.005	0.018	0.02	0.02
	Simulation sample size	0.004	0.004	0.004	0.009	0.02	0.02
	Data-Simulation corrections	–	–	–	0.001	–	–
CP asym.	Centrifugal barrier factors	–	0.001	0.002	0.004	0.007	0.004
	Hypatia parameters	–	0.003	0.002	0.001	0.002	0.002
	$B^0_s \to K^{*0}\overline{K}^{*0}$ bkg.	0.03	0.007	0.011	0.024	0.020	0.026
	Simulation sample size	0.02	0.010	0.009	0.011	0.027	0.023
	Data-Simulation corrections	–	0.001	0.001	–	0.002	0.002
Common (B^0,$\overline{B}^0$)	Mass propagators parameters	0.011	0.005	0.006	0.004	0.028	0.024
	Masses and angles resolution	0.010	0.016	0.018	0.031	0.029	0.040
	Fit method	0.003	0.001	0.002	0.003	0.005	0.004
	$a_1(1260)$ pollution	0.015	0.040	0.031	0.024	0.035	0.032
	Symmetrised $(\pi\pi)$ PDF	0.004	–	0.004	0.005	0.001	0.001

LO and NLO systematic uncertainties.

The LHCb detector

LHCb Detector Performance