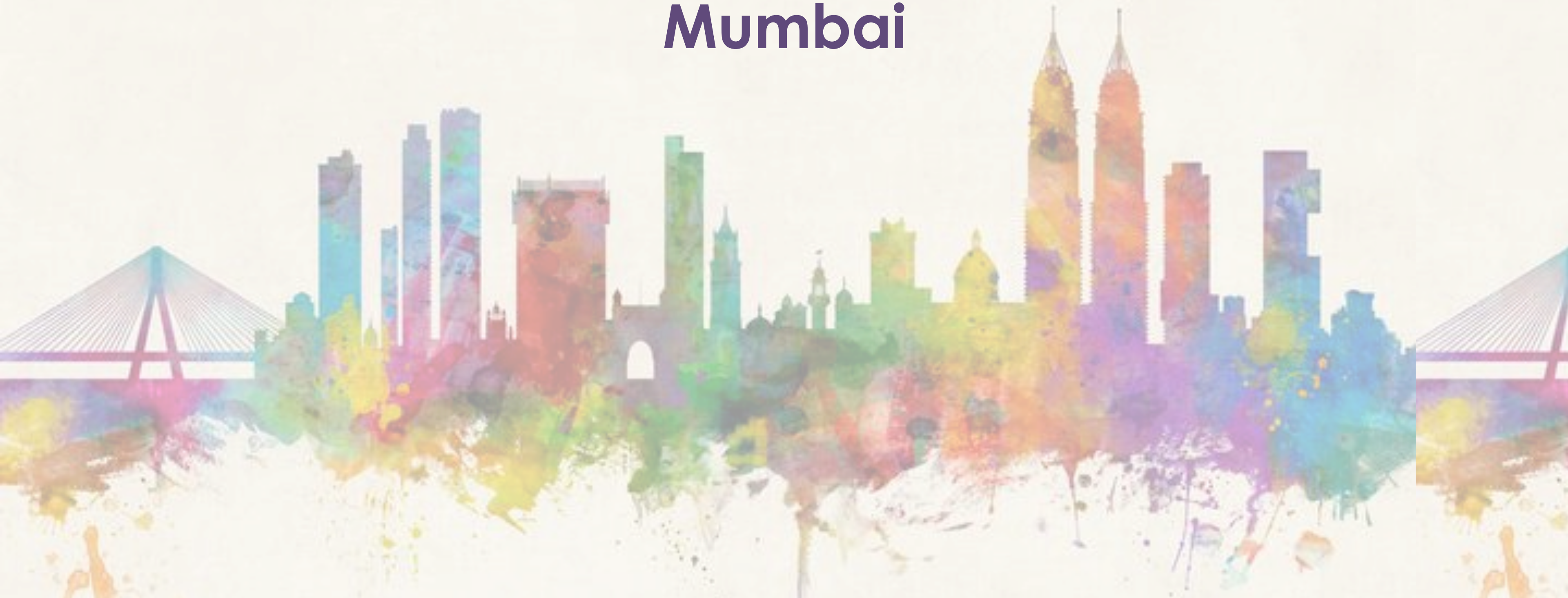
CKM 2016
Mumbai



Recent results from LHCb in charmless quasi two-body B-meson decays

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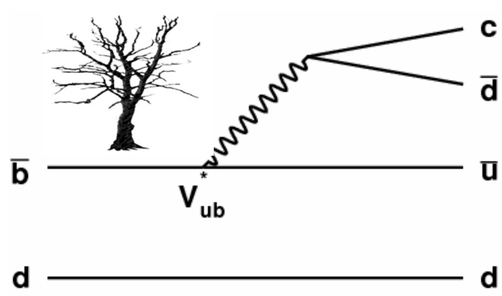
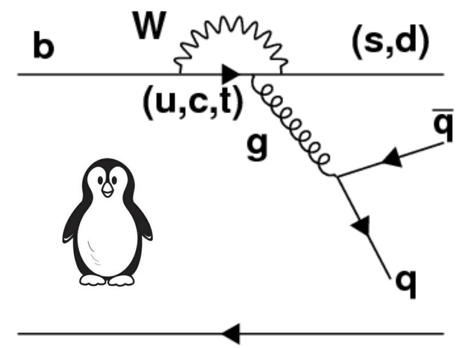
(on behalf of the LHCb collaboration)

Charmless decays

- Mediated by b → u (tree) and b → d, s (penguin) transitions.
- Both amplitudes comparably small
  ⇒ sensitive to CP asymmetries.





- New physics search: extra amplitudes from new particles could modify observables (***BR***, CP asymmetries…).
- Neutral B decays: time-dependent measurements, allow determination of mixing-induced CP asymmetries.

Outline

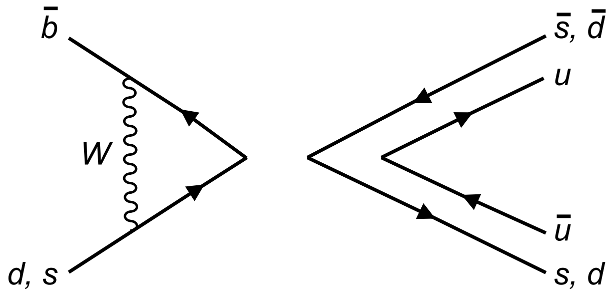
- Observation of $B^0 \to K^+K^-$
  -Submitted to Phys. Rev. Lett.,**arXiv:1610.08288**
- Observation of the decay $B_s \to \phi\, \pi^+ \pi^-$
  -To appear in Phys. Rev. D, **arXiv: 1610.05187**
- Search for $B_s \to \eta' \phi$
  -**LHCb-PAPER–2016-060 in preparation** (***NEW!***)

$B^0 \rightarrow K^+K^-$ and $B_s \rightarrow \pi^+\pi^-$

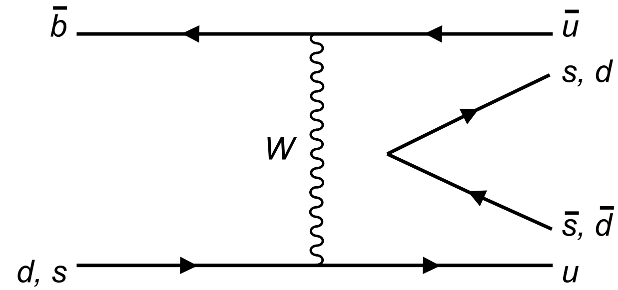
Motivations

arXiv:1610.08288

- $B^0_{(s)} \to K^+K^-(\pi^+\pi^-)$ proceed via weak annihilation transitions (all final state quarks differ from those in the initial state).



PENGUIN-ANNIHILATION



W-EXCHANGE

- Highly suppressed. Possible enhancement due to rescattering effects.
- $B_s \to \pi^+\pi^-$ already observed. $B^0 \to K^+K^-$ escaped detection so far.

Decay mode	BaBar	Belle	CLEO	CDF	LHCb	Average
$B^0 \to K^+K^-$	< 0.5	$0.10 \pm 0.08 \pm 0.04$	< 0.8	$0.23 \pm 0.10 \pm 0.10^\dagger$	$0.12^{+0.08}_{-0.07} \pm 0.01^\dagger$	$0.13^{+0.06}_{-0.05}$
$B^0_s \to \pi^+\pi^-$	–	< 12	–	$0.60 \pm 0.17 \pm 0.04^\dagger$	$0.98^{+0.23}_{-0.19} \pm 0.07^\dagger$	0.76 ± 0.13

$\times 10^{-6}$ (HFAG)

† : Relative BR converted to absolute BR.

- Precise BR measurements for the two mode: input to improve knowledge of QCD dynamics in B→hh.

Analysis strategy

arXiv:1610.08288

- Datasets: **full LHCb Run1** ($1fb^{-1}$ at $\sqrt{s}$ = 7TeV and $2fb^{-1}$ at $\sqrt{s}$ = 8TeV).
- **Blind analysis**.
- **Event selection:**

  -Two separate selections (K^+K^- and $\pi^+\pi^-$ samples).

  -Trigger selection: mainly using track and vertex fit qualities, kinematic information and decay topology.

  -Selection refined using multivariate classifier (**BDT**) and particle identification (**PID**) variables.

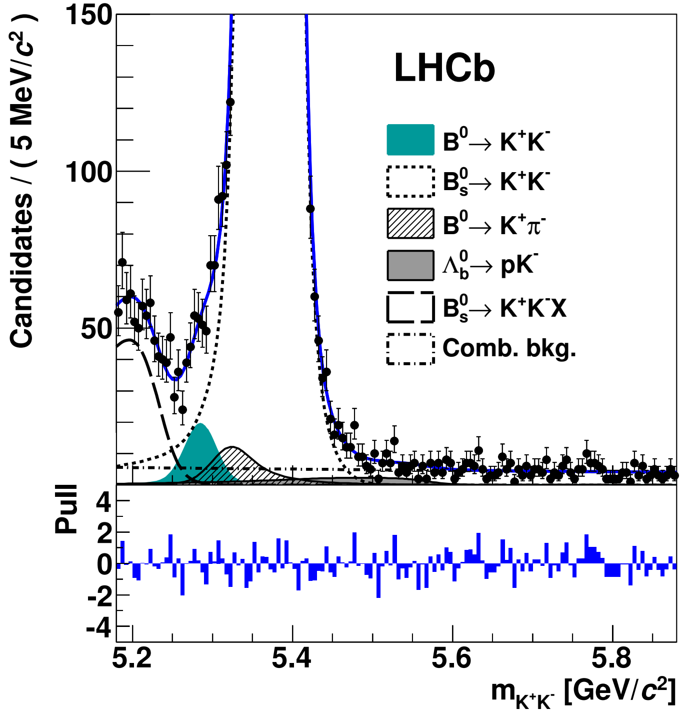
  -**PID efficiencies** determined using **data driven** method (D^{*+}, Λ and Λ_c^+ decays).

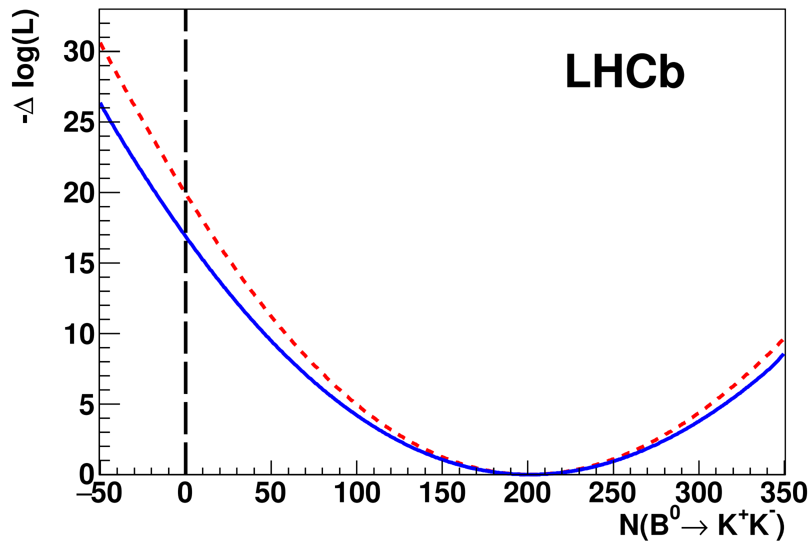
- Simultaneous optimization performed for PID and BDT selections (separately for the two channels).
- Signal extraction from a **simultaneous 2-body invariant mass fit** to several mutually exclusive subsamples (PID criteria): $K^+\pi^-$, p^+K^-, $p^+\pi^-$, $\pi^+\pi^-$ and K^+K^-.
- **BR($B^0 \rightarrow K^+\pi^-$)** used as **normalization** for the BR measurements.

Results: $B^0 \to K^+K^-$ observation

arXiv:1610.08288

KK candidates





Log-likelihood as a function of the $B^0 \to K^+K^-$ signal yield.

$N(B^0 \to K^+K^-) = 201.1 \pm 32.7 \pm 13.5$

$N(B^0 \to K^+\pi^-) = 105010 \pm 430 \pm 990$

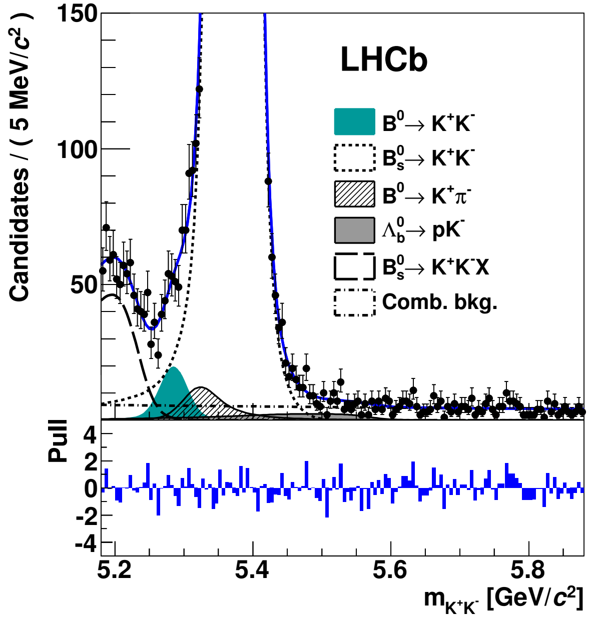
5.8 σ significance
(including systematics*)

*dominant systematic: signal mass shape

Results: BR measurements

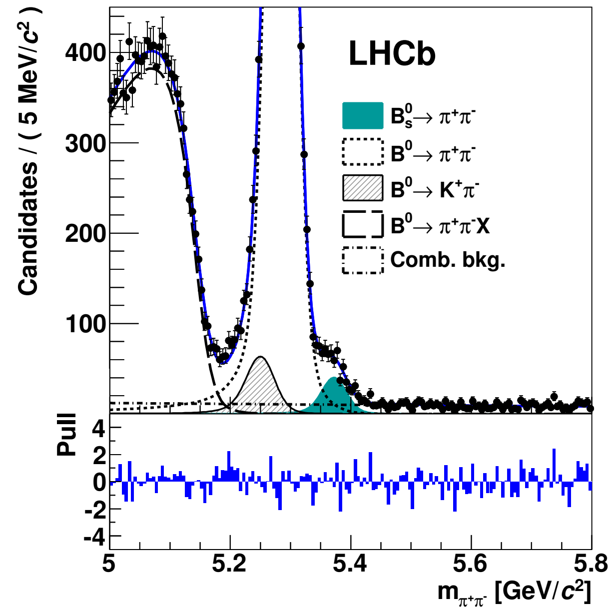
arXiv:1610.08288

KK candidates



$$BR(B^0 \to K^+K^-) = (7.80 \pm 1.27 \pm 0.81 \pm 0.21) \times 10^{-8}$$

π π candidates



$$BR(B_s^0 \to \pi^+\pi^-) = (6.91 \pm 0.54 \pm 0.63 \pm 0.19 \pm 0.40) \times 10^{-7}$$

MOST PRECISE MEASUREMENTS!!!

pQCD estimations in agreement within uncertainties (**arXiv:1111.6264v3**).
QCDF prediction agrees with BR($B^0 \to K^+K^-$) result, but BR($B_s \to \pi^+\pi^-$) significantly smaller than the measurement (**arXiv:0910.5237**).

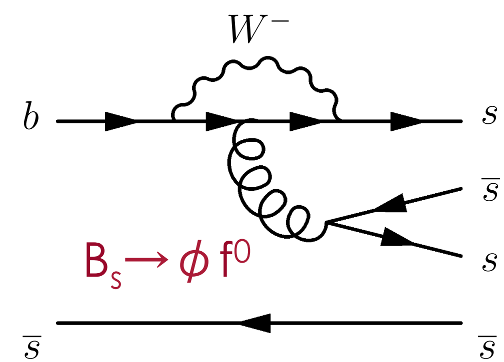
*Errors: ± stat. ± syst. ± BR($B^0 \to K^+\pi^-$) ± f_s/f_d
BR($B^0 \to K^+\pi^-$) , HFAG average

$$B^0_{(s)} \rightarrow \phi \pi^+ \pi^-$$

Motivations

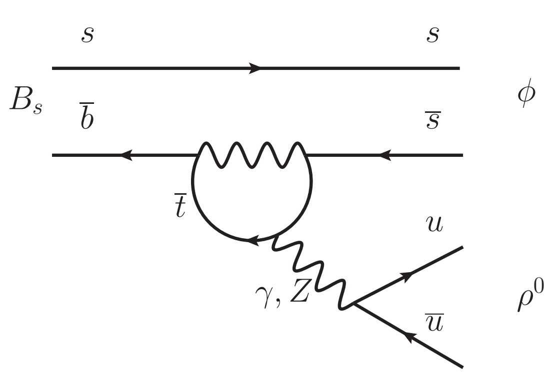
arXiv:1610.05187

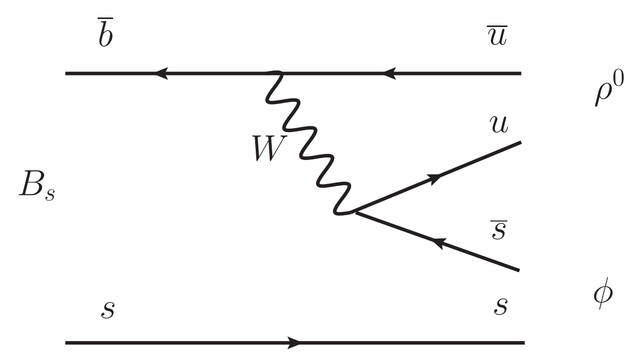
- $B^0_{(s)} \rightarrow \phi\ \pi^+ \pi^-$ decays not yet observed.
  - Upper limit on the branching fraction of the decay $B^0 \rightarrow \phi\ \rho^0$ of $3.3\ x10^{-7}$ at 90% CL (BaBar).
- Proceed via or b → d, s penguin transitions (FCNC).
  ⟶ Probe for New Physics.
- Different ratios between gluonic/EW penguins (depending on the intermediate resonance).



- Large CP asymmetries not excluded in $B_s \rightarrow \phi\ \rho^0$ decay.

$B_s \rightarrow \phi\ \rho^0$





Analysis strategy

arXiv:1610.05187

- LHCb Run1 datasets
- **Event selection:**

  -Pre-selection: set of topological and PID requirements used to drastically reduce the combinatorial background.

  -Vetoes on charmed and $B_s \to \phi K^{*0}$ physics background.

  -BDT using twelve variables related to the kinematics of the B meson candidate and its decay products, PID on the kaon, and vertex displacement from the PV.

- $B_s \to \phi\, \phi$ used as normalization mode

  -Same selection, except kaon PID for the second ϕ, $B_s \to \phi K^{*0}$ veto not applied.

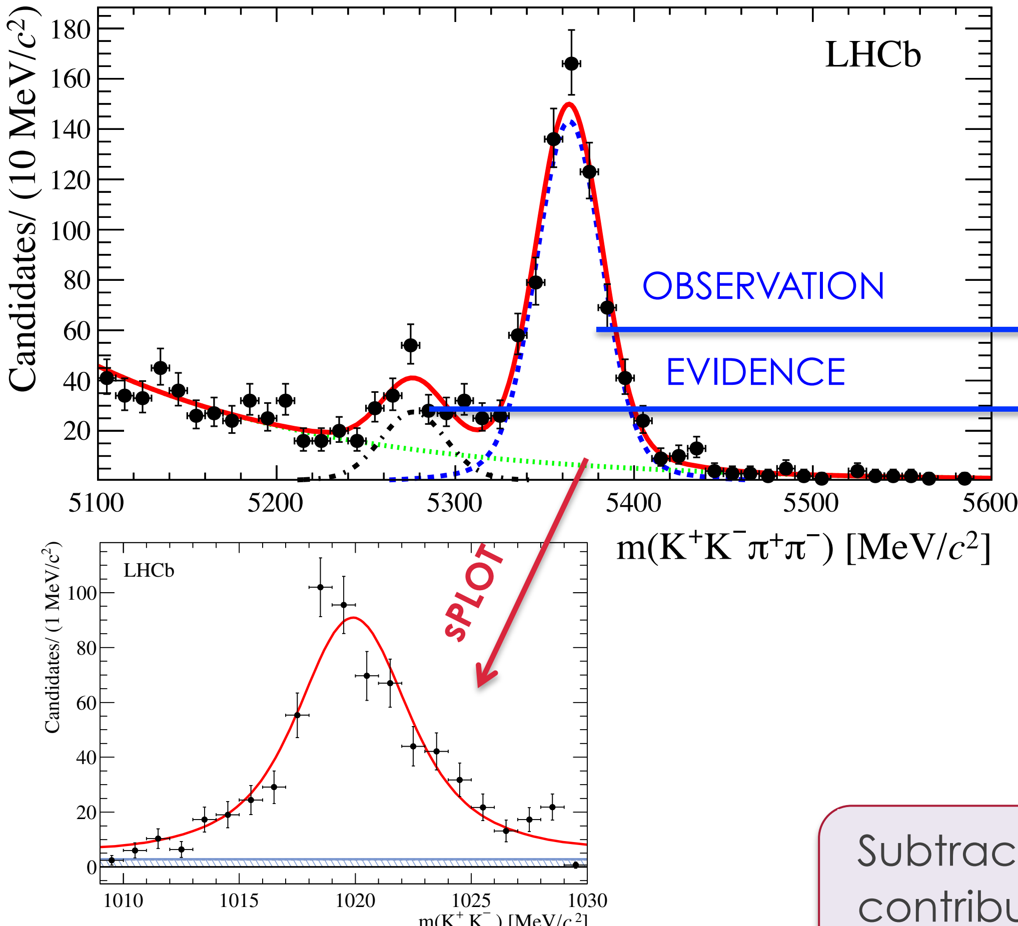
- Selection optimization: simultaneous for BDT and pion PID selections.

Results: BR measurements

arXiv:1610.05187

- Mass fit to extract signal yield and BRs.

$400 < m(\pi^+\pi^-) < 1600\,\mathrm{MeV}/c^2$



$N(B_s \to \phi\pi^+\pi^-) = 697 \pm 30$
$N(B^0 \to \phi\pi^+\pi^-) = 131 \pm 17$

$\mathcal{B}(B_s^0 \to \phi\pi^+\pi^-) = [3.48 \pm 0.23] \times 10^{-6}$

$\mathcal{B}(B^0 \to \phi\pi^+\pi^-) = [1.82 \pm 0.25] \times 10^{-7}$

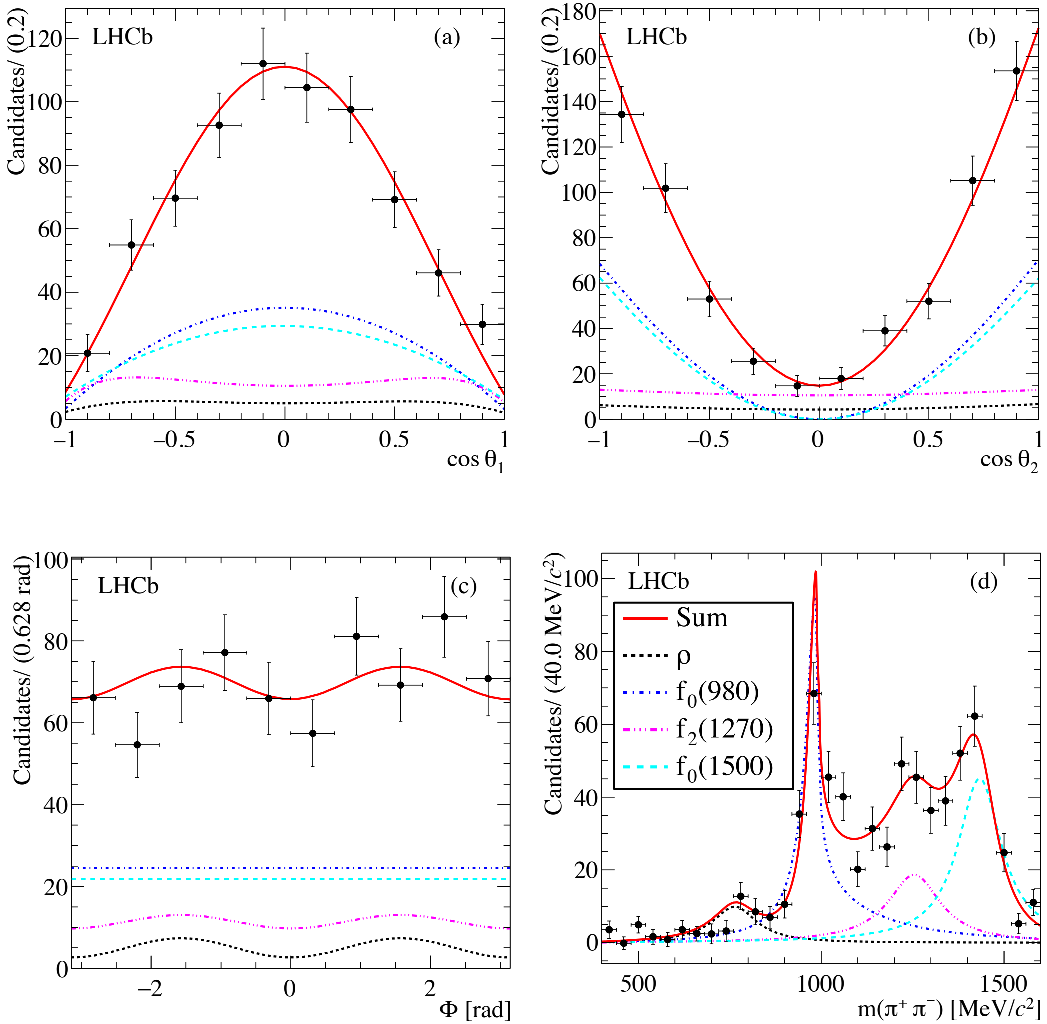
For $B^0 \to \phi\pi^+\pi^-$ the 7.7 σ statistical significance is reduced to 4.5 σ due to systematics uncertainties on the signal yield.

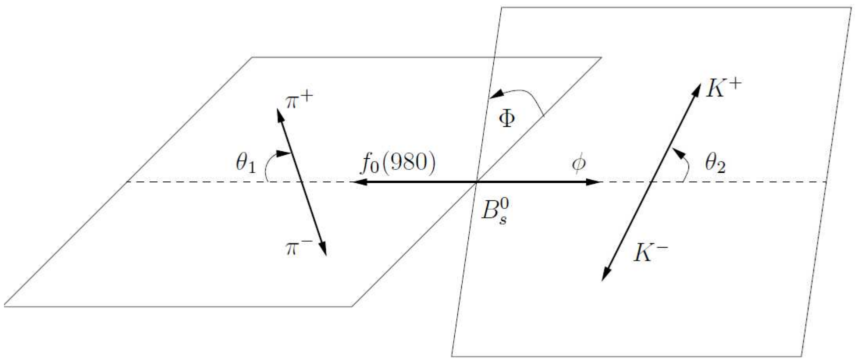
Subtract combinatorial and B^0 contributions using sPlot method, in order to study $B_s \to \phi\pi^+\pi^-$ resonance structure.

Results: amplitude analysis

arXiv:1610.05187

$B_s \to \phi\, \pi^+\pi^-$ signal distribution angular and $\pi^+\pi^-$ invariant mass distributions.





$$BR(B_s^0 \to \phi f_0(980)) = (1.12 \pm 0.16)\times 10^{-6} \quad > 5\sigma$$

$$BR(B_s^0 \to \phi f_2(1270)) = (0.61 \pm 0.13)\times 10^{-6} \quad > 5\sigma$$

$$BR(B_s^0 \to \phi \rho^0) = (2.7 \pm 0.6)\times 10^{-7} \quad 4\sigma$$

$BR(B_s \to \phi\, \rho^0)$: lower but still consistent with SM prediction.

$B^0_s \to \eta' \phi$

Motivations

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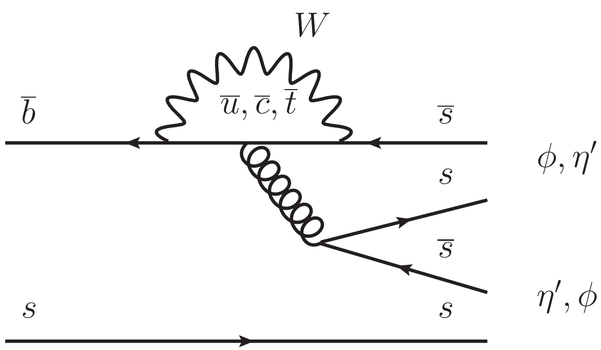
- Never observed decay proceeding via $b \to s\bar{s}s$ penguin transition.



$B_s \to \varphi\varphi$
"Golden mode": large yield, but needs angular analysis
$\varphi_s = -0.17 \pm 0.15 \pm 0.03$
[PRD 90 (2014) 052011]

$B_s \to \eta'\eta'$
Pure CP eigenstate, large BF, but modest yield
$N_{B_s \to \eta'\eta'}$ (Run1) = $36.4 \pm 7.8 \pm 1.6$
$\mathcal{B}(B_s \to \eta'\eta') = (33.1 \pm 6.4 \pm 2.8 \pm 1.2) \times 10^{-6}$
[PRL 115 (2015) 051801]

$B_s \to \eta'\varphi$
As for η′η′: no need for angular analysis, but higher reconstruction efficiency and cleaner

- Wide range of predictions.
- BR prediction small due to strong cancellation of PV and VP final states.
- $B \to \phi$ form factor: variation can enhance the BR by more than one order of magnitude.
- $B_s \to \phi\, \eta^{(\prime)}$ hierarchy: penguin loops size can affect relative BR.

Theory approach	$\mathcal{B}$ (10^{-6})
QCD factorisation	$0.05^{+1.18}_{-0.19}$
QCD factorisation	$2.2^{+9.4}_{-3.1}$
Perturbative QCD	$0.19^{+0.20}_{-0.13}$
Perturbative QCD	$20.0^{+16.3}_{-9.1}$
SCET	$4.3^{+5.2}_{-3.6}$
SU(3) flavour symmetry	5.5 ± 1.8
FAT	13.0 ± 1.6

References:
arXiv:hep-ph/0308039
arXiv:hep-ph/0701146
arXiv:hep-ph/0703162
arXiv:0910.5237
arXiv:0801.3123.
arXiv:1409.5026
arXiv:1608.02819

Analysis strategy

LHCb-PAPER–2016-060

- Blind analysis performed using full Run 1 data.
- $B^+ \to \eta' K^+$ used as normalization channel.
  - High yield and precisely known branching fraction $(70.6 \pm 2.5) \times 10^{-6}$.
- Reconstruct η' candidates as $\eta' \to \pi^+ \pi^- \gamma$ (BR = 0.291±0.001).
- Optimise similar selections for signal and normalization channels.
- Event selection:
  - Loose pre-selection on topological and kinematical variables.
  - Multivariate classifier (BDT) using as nine input variables: B vertex quality and isolation, daughter kinematics.
  - No ϕ information used in the BDT to minimize systematics.
- 2D ($m_{\eta' KK (K)}$, $m_{\pi\pi\gamma}$) simultaneous fit for $B^+ \to \eta' K^+$ and $B^0_s \to \eta' \phi$ to extract yields.
- Analysis sensitivity: more than 5 sigma (40 events) expected for $BR(B^0_s \to \eta' \phi)=4 \times 10^{-6}$.

Mass fit

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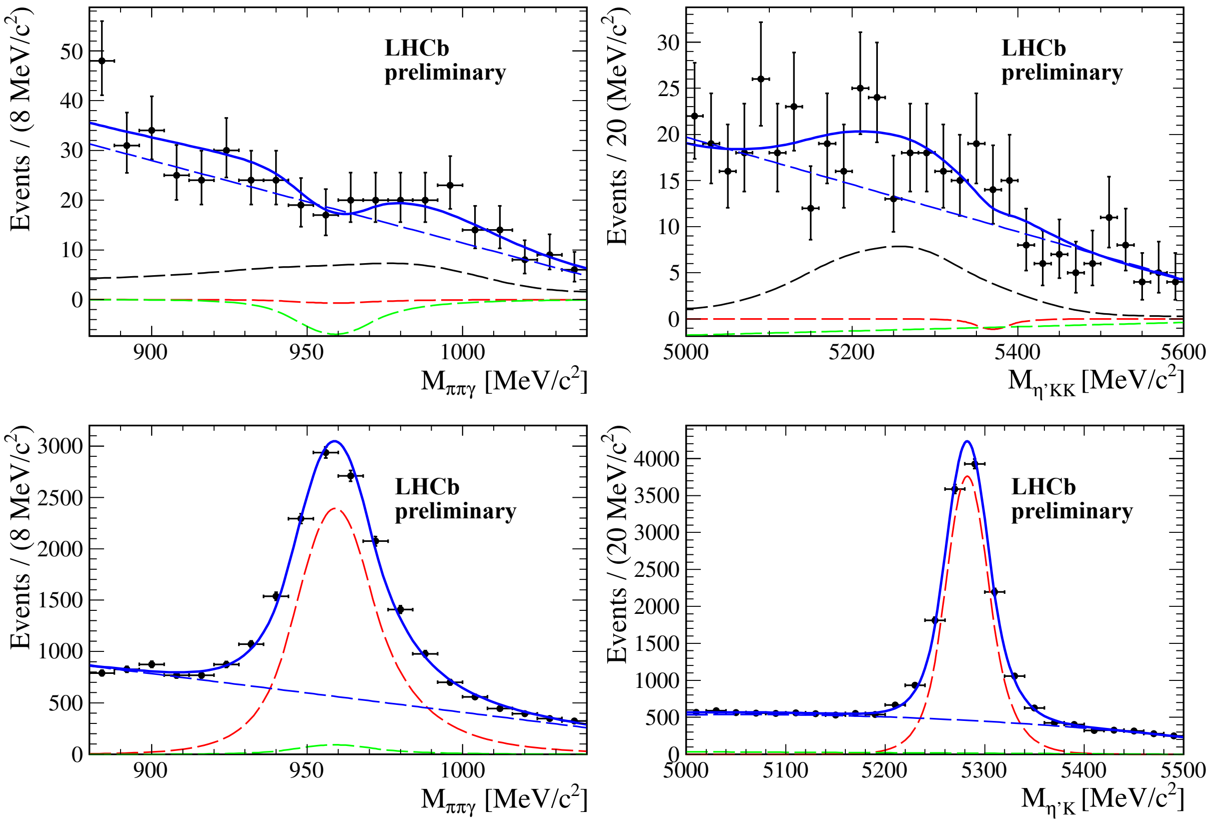


Irreducible $B_s \to \phi\,\phi\,(\pi^+\pi^-\pi^0)$ physics background included in the fit (expected 104±34).

Fit components:
- signal
- $B_s \to \phi\,\phi$
- combinatorial
- comb. with real η'

$$N(B_s^0 \to \eta'\varphi) = -3.2^{+5.0}_{-3.8}$$

$$N(B^+ \to \eta' K^+) = 11081 \pm 127$$

$$N(B_s^0 \to \varphi\varphi) = 105 \pm 29$$

$$\frac{N(B_s^0 \to \eta'\varphi)}{N(B^+ \to \eta' K^+)} = (-2.90^{+4.54}_{-3.45}) \times 10^{-4}$$

→ **No indication for the signal .**

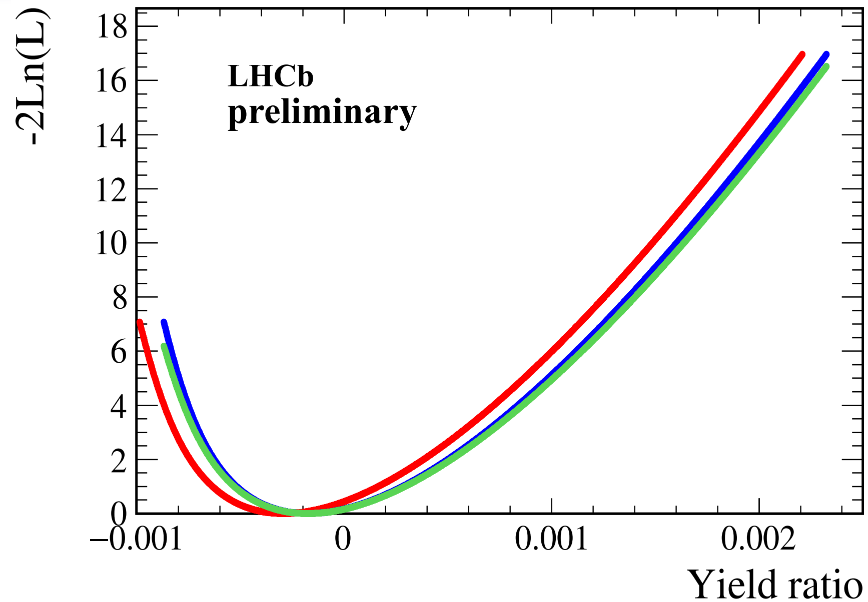
Results

LHCb-PAPER–2016-060

- Fit results corrected for small bias due to $B_s \to \phi\,\phi\,(\pi^+\pi^-\pi^0)$ component (1.3 ± 0.7 events):

$$N(B_s^0 \to \eta'\varphi) = -1.9^{+5.0}_{-3.8}(stat) \pm 1.1(syst)$$

$$\frac{N(B_s^0 \to \eta'\varphi)}{N(B^+ \to \eta' K^+)} = (-1.73^{+4.54}_{-3.45}(stat) \pm 0.99(syst)) \times 10^{-4}$$



-2lnL as a function of **yield ratio** (red), **corrected yield ratio** (blue) and **accounting for the systematic** uncertainty.

- Upper limit (including systematics uncertainty) calculated from the integral of the likelihood in the positive region:

$N(B_s \to \eta'\phi) < 8.9$ (10.9) at 90% (95%) CL

$BR(B_s \to \eta'\phi) < 0.82$ (1.01) x 10^{-6} at 90% (95%) CL

- Most central values of theoretical predictions significantly larger.

Summary

- Recent LHCb results in charmless quasi 2-body B decays presented.

- $B^0 \to KK$, $B_s \to \pi\ \pi$:
  - -First observation of the rarest fully hadronic decay ever seen.
  - -$B^0 \to KK$ important input in understanding of the QCD effects involving penguin annihilation diagrams.
  - -Most precise measurement of BR($B^0_s \to \pi^+\pi^-$).

- Observation of the decay $B^0_s \to \phi\ \pi^+\pi^-$ and evidence for $B^0 \to \phi\ \pi^+\pi^-$:
  - -Observations of $B^0_s \to \phi f_0(980)$ and of $B^0_s \to \phi f_2$ (1270).

- Search for $B_s \to \eta' \phi$:
  - - Set of a stringent upper limit.
  - - Most centrals values of theoretical predictions significanlty larger.

- Run 2 data in the pipeline.

Thanks !!!

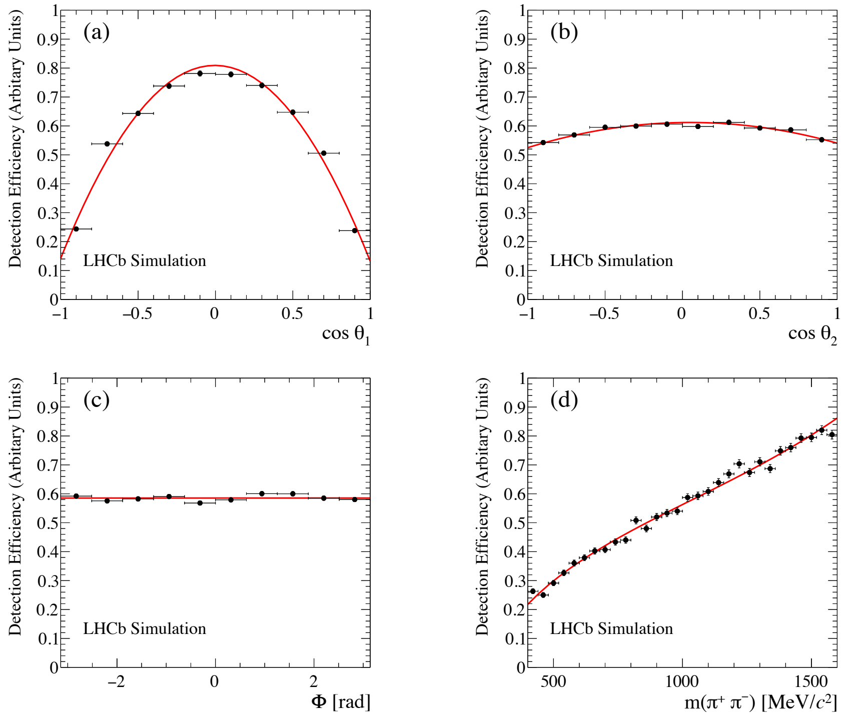
Backup

$B^0_{(s)} \to K^+K^-$ ($\pi^+\pi^-$) : systematic uncertainties

Systematic uncertainty	$N(B^0 \to K^+K^-)$	$N(B^0_s \to \pi^+\pi^-)$
Signal mass shape	11.8	6.3
Combinatorial mass shape	5.5	2.6
Partially reco. mass shape	1.3	23.1
PID efficiencies	3.4	2.5
Sum in quadrature	13.5	24.2

- The results of the nominal fit used to generate pseudo-experiments which are then fitted with alternative models.
- Alternative model considered for: signal, combinatorial background, background from partially reconstructed b-hadron decays and cross-feed background.
- Systematic due to PID efficiencies: pseudo-experiments are generated varying randomly the PID efficiencies in each pseudo-experiment according to their estimated uncertainties.
- The standard deviation of the distribution of the yields determined in each set of pseudo-experiments is taken as a systematic uncertainty.

$B^0_{(s)} \to \phi\, \pi^+ \pi^-$: efficiency and systematics



- Detection efficiency not flat on angular variables and $m_{\pi\,\pi}$ due to LHCb detector geometry and the kinematic selections on the final state particles.
- Studied performed using simulated signal events.
- Parameterised by a 4D function using Legendre polynomials (accounting for variables correlations).

Efficiencies and models systematics:

Systematic	$B_s^0 \to \phi\rho$	$B_s^0 \to \phi f_0(980)$	$B_s^0 \to \phi f_2(1270)$	$B_s^0(B^0) \to \phi\pi^+\pi^-$
Trigger	0.5	0.5	0.5	0.5
Hadronic interactions	0.5	0.5	0.5	0.5
Offline selection	2.3	2.3	2.3	2.3
Particle identification	0.3	0.3	0.3	0.3
Angular acceptance	3.8	–	3.8	3.8 (10.7)
Decay time acceptance	1.1	1.1	1.1	1.1 (–)
$m(K^+K^-\pi^+\pi^-)$ fit	1.2	1.2	1.2	1.2 (19.5)
Amplitude analysis	2.5	$+4.7/-0.4$	$+17.6/-2.7$	–
S-wave K^+K^-	6.0	6.0	6.0	–
Total	7.0	$+8.2/-6.7$	$+19.2/-8.1$	4.8 (22.4)

$B_s \to \phi\, \pi^+ \pi^-$: amplitude analysis:

T_i: squares of the amplitudes A_i or interference terms between them.

f_i : decay angle distributions.

M_i : resonant $m_{\pi\pi}$ distributions.

DIFFERENZIAL DECAY RATE:

$$\frac{d^4\Gamma}{d\cos\theta_1 d\cos\theta_2 d\Phi dm_{\pi\pi}} = \frac{9}{8\pi} \sum_i T_i\ f_i(\theta_1, \theta_2, \Phi)\ \mathcal{M}_i(m_{\pi\pi}) d\Omega_4(KK\pi\pi)$$

i	T_i	$f_i\ (\theta_1, \theta_2, \Phi)$	$\mathcal{M}_i(m_{\pi\pi})$
1	$\lvert A_0\rvert^2$	$\cos^2\theta_1 \cos^2\theta_2$	$\lvert M_1(m_{\pi\pi})\rvert^2$
2	$\lvert A_\parallel\rvert^2$	$\frac{1}{4}\sin^2\theta_1 \sin^2\theta_2(1+\cos 2\Phi)$	$\lvert M_1(m_{\pi\pi})\rvert^2$
3	$\lvert A_\perp\rvert^2$	$\frac{1}{4}\sin^2\theta_1 \sin^2\theta_2(1-\cos 2\Phi)$	$\lvert M_1(m_{\pi\pi})\rvert^2$
4	$\lvert A_\parallel A_0^*\rvert$	$\sqrt{2}\cos\theta_1 \sin\theta_1 \cos\theta_2 \sin\theta_2 \cos\Phi$	$\lvert M_1(m_{\pi\pi})\rvert^2 \cos(\delta_\parallel - \delta_0)$
5	$\lvert A_S\rvert^2$	$\frac{1}{3}\cos^2\theta_2$	$\lvert M_0(m_{\pi\pi})\rvert^2$
6	$\lvert A_\perp A_S^*\rvert$	$\frac{\sqrt{6}}{3}\sin\theta_1 \cos\theta_2 \sin\theta_2 \sin\Phi$	$\mathcal{R}e[M_1(m_{\pi\pi})M_0^*(m_{\pi\pi})e^{i\delta_\perp}]$
7	$\lvert A_0^{1270}\rvert^2$	$\frac{5}{12}(3\cos^2\theta_1 - 1)^2 \cos^2\theta_2$	$\lvert M_2(m_{\pi\pi})\rvert^2$
8	$\lvert A_\parallel^{1270}\rvert^2$	$\frac{5}{2}\sin^2\theta_1 \sin^2\theta_2 \cos^2\theta_1 \cos^2\Phi$	$\lvert M_2(m_{\pi\pi})\rvert^2$
9	$\lvert A_\perp^{1270}\rvert^2$	$\frac{5}{2}\sin^2\theta_1 \sin^2\theta_2 cos^2\theta_1 \sin^2\Phi$	$\lvert M_2(m_{\pi\pi})\rvert^2$
10	$\lvert A_\parallel^{1270} A_0^{1270*}\rvert$	$\frac{5}{4\sqrt{6}}(3\cos^2\theta_1 - 1)\sin 2\theta_1 \sin 2\theta_2 \cos\Phi$	$\lvert M_2(m_{\pi\pi})\rvert^2 \cos(\delta_\parallel^{1270} - \delta_0^{1270})$
11	$\lvert A_\parallel^{1270} A_S^*\rvert$	$\frac{\sqrt{10}}{3}\sin\theta_1 \cos\theta_1 \sin\theta_2 \cos\theta_2 \cos\Phi$	$\mathcal{R}e[M_2(m_{\pi\pi})M_0^*(m_{\pi\pi})e^{i\delta_\parallel^{1270}}]$
12	$\lvert A_0^{1270} A_S^*\rvert$	$\frac{\sqrt{5}}{3}(3\cos^2\theta_1 - 1)\cos^2\theta_2$	$\mathcal{R}e[M_2(m_{\pi\pi})M_0^*(m_{\pi\pi})e^{-i\delta_0^{1270}}]$

Amplitude	Fit value	Phase	Fit value (rad)
A_0	0.212 ± 0.035		
$A_\parallel$	0.049 ± 0.031		
$A_\perp$	0.168 ± 0.026	$\delta_\perp$	$+1.90 \pm 0.28$
A_S	0.603 ± 0.036		
A_0^{1270}	0.295 ± 0.058	δ_0^{1270}	-0.62 ± 0.18
$A_\parallel^{1270}$	0.203 ± 0.042	$\delta_\parallel^{1270}$	$+1.26 \pm 0.25$
$A_\perp^{1270}$	0.261 ± 0.037		
A_S^{1500}	0.604 ± 0.031	δ_S^{1500}	$+3.14 \pm 0.30$

1. Scalar resonances: one complex term (A_S)
2. Vector and tensor resonances: three complex terms (A0, A_+, $A_{||}$).
3. Interference term for CP-odd, CP-even amplitudes (No CP violation as indicated by $B_s \to \phi\, \phi$ measuremnts.
4. Interference terms P-wave/D-wave and P-wave only small: neglected in the final fit.

$B_s \to \eta'\phi$: systematic uncertainties

Efficiency ratio systematics:

Source	Relative uncertainty [%]
BDT efficiency calibration	2.5
Pion/kaon identification	1.1
Trigger efficiency calibration	2.3
SPD multiplicity (mis-modelling)	0.9
Tracking reconstruction	0.4
Hadronic interactions	1.4
Photon reconstruction	0.1
Simulation statistics	1.6
Quadratic sum	4.3

- The difference between the efficiencies in data and simulation of the BDT requirement for the normalisation channel used as a measure of the systematic uncertainty on the BDT efficiency.
- The correlation evaluated in simulation between the BDT variables for signal and normalisation channel is then used to determine the systematic uncertainty on the ratio of the BDT efficiencies.

Yield (N) and yield ratio (R) systematics:

Source	σ_N (events)	σ_R (10^{-4})
Fit bias	0.7	0.7
Combinatorial background modelling	0.6	0.6
$B_s^0 \to \phi\phi$ background modelling	0.4	0.3
Fixed parameters in the fit	0.3	0.3
Quadratic sum	1.1	1.0

- **Comb. background modelling:** mass fi repeated replacing background models.
  Quadratic sum of the differences between the values obtained in alternative fits and the nominal result assigned as a systematic uncertainty.
- **Limited size** of the simulated $\mathbf{B_s \to \phi\phi}$ sample leads to an uncertainty on the determination of the PDF, which is propagated as a systematic.
- Pseudo-experiments performed with **fixed parameters** sampled randomly according to their uncertainties determined in simulated data. RMS of the result distribution assigned as systematic.