Measurement of CP Violation in the B_s System

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On behalf of the LHCb Collaboration

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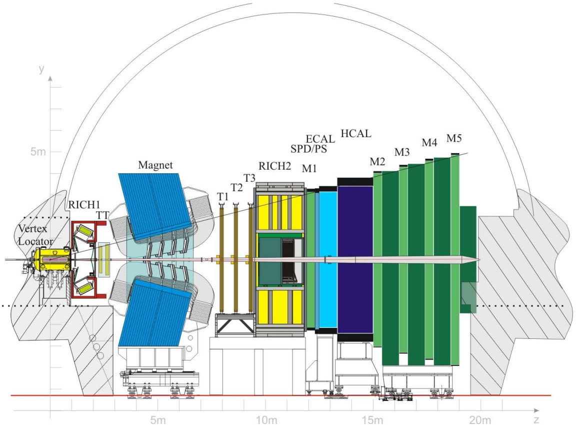
The LHCb Detector

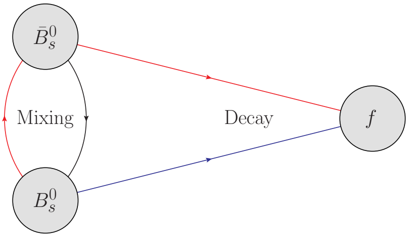


Forward arm spectrometer to study b- and c-hadron decays

- Pseudo-rapidity coverage: $2 < \eta < 5$

- Good impact parameter resolution to identify secondary vertices: 20 μm
- Decay time resolution: 40 fs ($B_s^0 \to J/\psi\pi^+\pi^-$)
- Invariant mass resolution: 8 MeV/c^2 ($B \to J/\psi X$) 22 MeV/c^2 ($B \to hh$)
- Excellent particle identification: 95 % K ID efficiency (5 % $\pi \to K$ mis-ID)
- Versatile & efficient trigger for b- and c-hadrons and forward EW signals

Measuring CP Violation: Interfering Paths



Mixing-Induced CP Violation: $\text{Prob}(B_q^0 \to f) \neq \text{Prob}(B_q^0 \to \bar{B}_q^0 \to f)$

- Interference between direct decay and decay after mixing
- Key Measurements: ϕ_s from $B_s^0 \to J/\psi h^+ h^-$; γ from $B_s^0 \to D_s^\mp K^\pm$

New Results on CP Violation in the B_s System:

- ✓ Measurement of the CP violating phase in $B_s^0 \to \phi\phi$ (3 fb^{-1} – Full Run 1)
- ✓ Update on measurement of ϕ_s from $B_s^0 \to J/\psi\pi^+\pi^-$ (3 fb^{-1} – Full Run 1)
- × Update on the measurement of γ from $B_s^0 \to D_s^\mp K^\pm$ (1 fb^{-1} – 2011 Only)
  → [See Talk by Alexis Vallier]

Measurement of the CP violating phase in $B_s^0 \to \phi\phi$

Introduction to $B_s^0 \to \phi\phi$

Excellent probe to Search for New Physics

- Originates from $\bar{b} \to \bar{s}s\bar{s}$ transition
- Forbidden at tree level
- Standard Model: Dominant contribution from gluonic penguins

- Objective: Mixing-induced CP violation
- Parametrised by

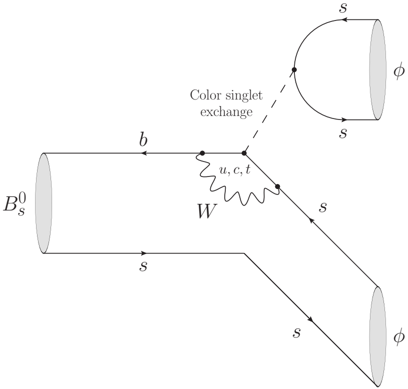
$$\lambda \equiv \frac{q}{p}\frac{A(\bar{B}_s^0 \to \phi\phi)}{A(B_s^0 \to \phi\phi)} = |\lambda|\, e^{i\,\varphi_s}$$

[Note: $\varphi_s \neq \phi_s(B_s^0 \to J/\psi h^+h^-)$]

- SM prediction:

$$\varphi_s \approx \left(S_{\phi\phi} \equiv \frac{2\,\mathrm{Im}[\lambda]}{1+|\lambda|^2}\right) \leq 0.02$$

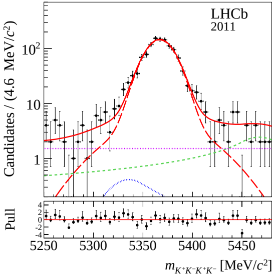
[M. Bartsch *et al.*, arxiv:0810.0249]



$B_s^0 \to \phi\phi$ at LHCb: Selection arxiv:1407.2222

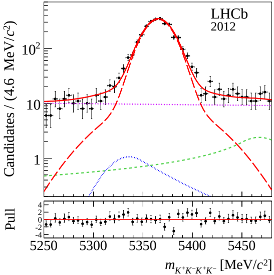
Selection:

- Reconstructed as $B_s^0 \to \phi\phi \to K^+K^-K^+K^-$
- Trigger: Topological b-decay || large p_T K's from ϕ
- Selection based on Boosted Decision Tree
  trained on Simulation (Signal) and Data (Background)
- Different trainings for 2011 and 2012 data
- Event Yield: 1185 ± 35 (2011) & 2765 ± 57 (2012)



Four Kaon Invariant Mass:

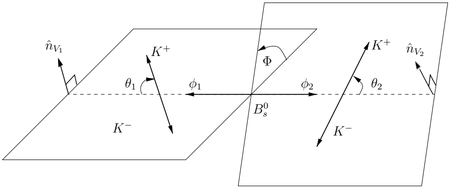
- $B_s^0 \to \phi\phi$ Signal
- $B^0 \to \phi K^{*0}$ Peaking Background (From Simulation)
- $\Lambda_b^0 \to \phi p K^-$ Peaking Background (From Data)
- Combinatoric Background



$B_s^0 \to \phi\phi$ at LHCb: Angular Analysis arxiv:1407.2222

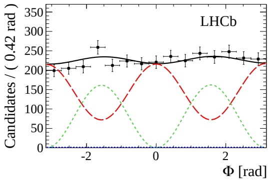
Angular Decomposition:

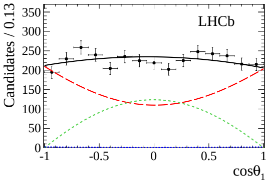
- $B_s^0 \to \phi\phi$ is a Vector-Vector final state
  $\Rightarrow$ Three components $\mathcal{A}_0$, $\mathcal{A}_{\|}$ & $\mathcal{A}_{\perp}$

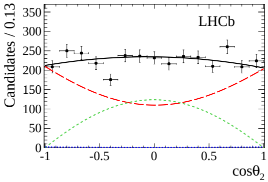


- Non-resonant $K^+K^-K^+K^-$ final states:
  S-wave $\mathcal{A}_S$ and double S-wave $\mathcal{A}_{SS}$

- Total decay amplitude: 15 contributions







CP-Even ($\mathcal{A}_0$, $\mathcal{A}_{\|}$) CP-Odd ($\mathcal{A}_{\perp}$) + S-Wave ($\mathcal{A}_S$) Double S-Wave ($\mathcal{A}_{SS}$)

$B_s^0 \to \phi\phi$ at LHCb: Perfomance arxiv:1407.2222

Time Resolution

- Using per-event resolution model
- Effective resolution:
  41.4 fs (2011) and 43.9 fs (2012)
- Difference due to independent selection

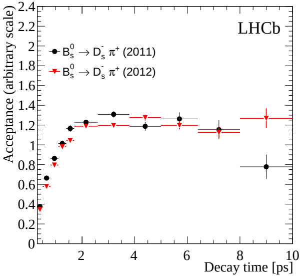
Flavour Tagging

- Including Opposite Side (OS) and Same Side Kaon (SSK) tagging

Dataset	$\epsilon\mathcal{D}^2$ (%)
2011 Total	5.33 ± 0.37
2012 Total	5.44 ± 0.30

Time Acceptance

- Determined from topologically similar $B_s^0 \to D_s^-(\to K^+K^-\pi^-)\pi^+$ decays

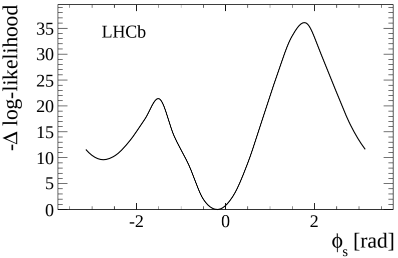


CP Violation in $B_s^0 \to \phi\phi$: Time Dependent Results arxiv:1407.2222

CP Violating Phase

$$\varphi_s = -0.17 \pm 0.15\,(\text{stat}) \pm 0.03\,(\text{syst})\ \text{rad}$$
$$|\lambda| = 1.04 \pm 0.07\,(\text{stat}) \pm 0.03\,(\text{syst})$$

- Compatible with SM prediction
- No indication for direct CP violation



Angular Analysis

$$|A_0|^2 = 0.364 \pm 0.012\,(\text{stat}) \pm 0.009\,(\text{syst})$$
$$|A_\perp|^2 = 0.305 \pm 0.013\,(\text{stat}) \pm 0.005\,(\text{syst})$$
$$\delta_1 \equiv \delta_\perp - \delta_\parallel = 0.13 \pm 0.23\,(\text{stat}) \pm 0.05\,(\text{syst})\ \text{rad}$$
$$\delta_2 \equiv \delta_\perp - \delta_0 = 2.67 \pm 0.23\,(\text{stat}) \pm 0.07\,(\text{syst})\ \text{rad}$$

CP Violation in $B_s^0 \to \phi\phi$: Time Independent Results arxiv:1407.2222

Triple Product Asymmetries: Alternative Tests of CP violation

- Quantity odd under Time reversal
- Time integrated quantity $\Rightarrow$ Reduce problem to counting experiment
- SM expectation: $\mathcal{A}_{U,V} \approx 0$

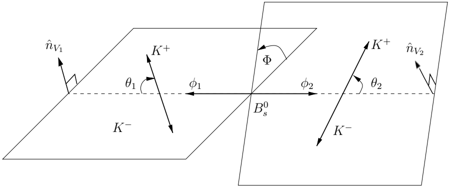
Definition:

$$\mathcal{A}_U \equiv \frac{\Gamma(U>0)-\Gamma(U<0)}{\Gamma(U>0)+\Gamma(U<0)} = -0.003 \pm 0.017\,(\text{stat}) \pm 0.006\,(\text{syst})$$

$$\mathcal{A}_V \equiv \frac{\Gamma(V>0)-\Gamma(V<0)}{\Gamma(V>0)+\Gamma(V<0)} = -0.017 \pm 0.017\,(\text{stat}) \pm 0.006\,(\text{syst})$$

where

$$U \equiv \sin(\Phi)\cos(\Phi)\,, \qquad V \equiv \sin(\pm\Phi)$$



Update on measurement of ϕ_s from $B_s^0 \to J/\psi\pi^+\pi^-$

Introduction to $B_s^0 \to J/\psi\pi^+\pi^-$

B_s^0–$\bar{B}_s^0$ mixing ϕ_s

- One of the CKM angles ⇒ Important test of the Standard Model
- Precise SM prediction: J. Charles *et al.*, Phys.Rev.D84:033005, 2011, [arxiv:1106.4041]

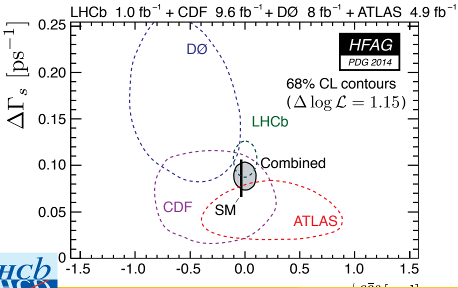
$$\phi_s^{\mathrm{SM}} = -0.0364 \pm 0.0016 \text{ rad}$$

- Small magnitude offers excellent probe to search for New Physics

$$\phi_s = \phi_s^{\mathrm{SM}} + \phi_s^{\mathrm{NP}}$$

- Experimentally accessible through CPV in $B_s^0 \to J/\psi\phi$ and $B_s^0 \to J/\psi f_0(980)$

→ Extended scope: $B_s^0 \to J/\psi K^+K^-$ and $B_s^0 \to J/\psi\pi^+\pi^-$



Current Status:

- LHCb 1 fb^{-1} result: [arxiv:1304.2600]

$$\phi_s = 0.01 \pm 0.07 \text{ (stat)} \pm 0.01 \text{ (syst) rad}$$
$$\Gamma_s = 0.661 \pm 0.004 \text{ (stat)} \pm 0.006 \text{ (syst) ps}^{-1}$$
$$\Delta\Gamma_s = 0.106 \pm 0.011 \text{ (stat)} \pm 0.007 \text{ (syst) ps}^{-1}$$

- World Average: [HFAG – PDG 2014]

$$\phi_s = 0.00 \pm 0.07$$

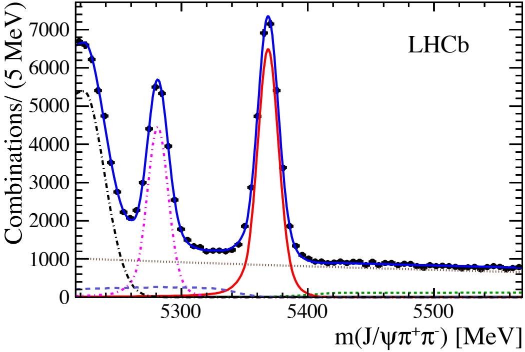
$B_s^0 \to J/\psi\pi^+\pi^-$ at LHCb: Selection arxiv:1405.4140

Selection:

- Reconstructed as $B_s^0 \to J/\psi\pi^+\pi^- \to \mu^+\mu^-\pi^+\pi^-$
- Trigger: Muons from $J/\psi \to \mu^+\mu^-$
- Selection based on Boosted Decision Tree
  trained on Simulation (Signal) and Data (Background)
- Event Yield: 27 100 $\pm$ 200 Signal candidates
- Signal purity in $\pm$20 MeV mass window around B_s^0 peak: 79.6%

Invariant Mass:

- $B_s^0 \to J/\psi\pi^+\pi^-$ Signal
- $B_d^0 \to J/\psi\pi^+\pi^-$ Signal
- $B^- \to J/\psi K^-$
  (From Simulation)
- $B_d^0 \to J/\psi K^\mp\pi^\pm$ Reflection
  (From Simulation)
- Other misreconstructed decays (From Simulation)
- Combinatoric Background
  (From Like-Sign)

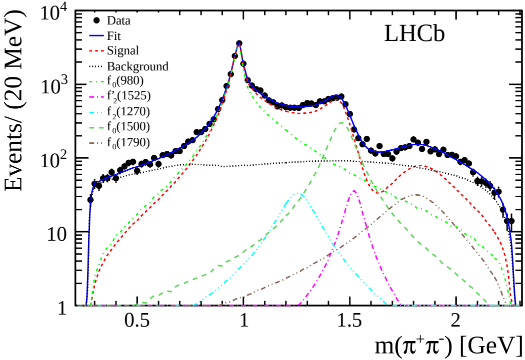


$B_s^0 \to J/\psi\pi^+\pi^-$ at LHCb: Dalitz Analysis arxiv:1402.6248

CP Content and Decomposition of $J/\psi\pi^+\pi^-$ Final State:

- Focus on ± 20 MeV mass window around B_s^0 peak
- Included Modes: $f_0(980)$ (Dominant), $f_0(1500)$, $f_0(1790)$, $f_2(1270)$, $f_2{}'(1525)$
- CP-even contributions $< 2.3\,\%$ at 95% C.L.

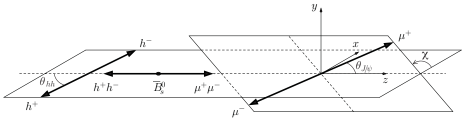
Part I: Fitting of the Dalitz Plane

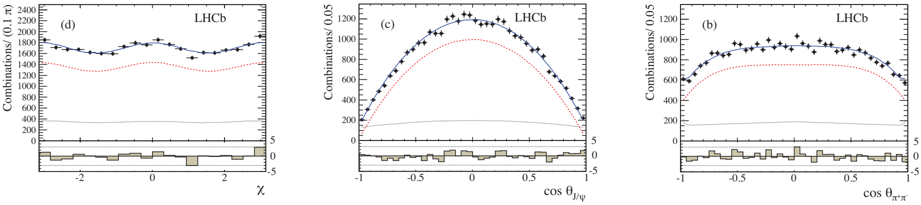


$B_s^0 \to J/\psi\pi^+\pi^-$ at LHCb: Angular Analysis arxiv:1402.6248

Part II: Angular Decomposition:

- Disentangle CP-even and CP-odd contributions





Signal Background Total

$B_s^0 \to J/\psi\pi^+\pi^-$ at LHCb: Perfomance arxiv:1405.4140

Time Resolution

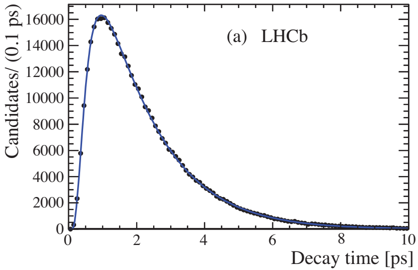
- Using per-event resolution model
- Effective resolution: 40.3 fs

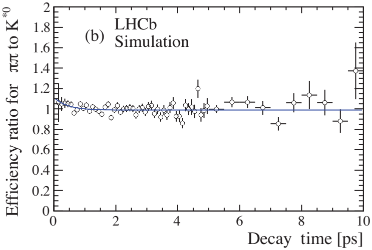
Flavour Tagging

- Including Opposite Side (OS) and Same Side Kaon (SSK) tagging
- Tagging power $\epsilon_{\text{tag}}\mathcal{D}^2 = (3.89 \pm 0.25)\,\%$

Time Acceptance

- Determined from $B_d^0 \to J/\psi K^{*0}(\to K^+\pi^-)$ decays
- Difference with $B_s^0 \to J/\psi\pi^+\pi^-$ corrected using Simulation





ϕ_s from $B_s^0 \to J/\psi\pi^+\pi^-$: Results arxiv:1405.4140

Fit Assumptions

LHCb, Phys.Rev.D87:112010, 2013, [arxiv:1304.2600]

- 1 fb^{-1} result from $B_s^0 \to J/\psi K^+K^-$ at LHCb

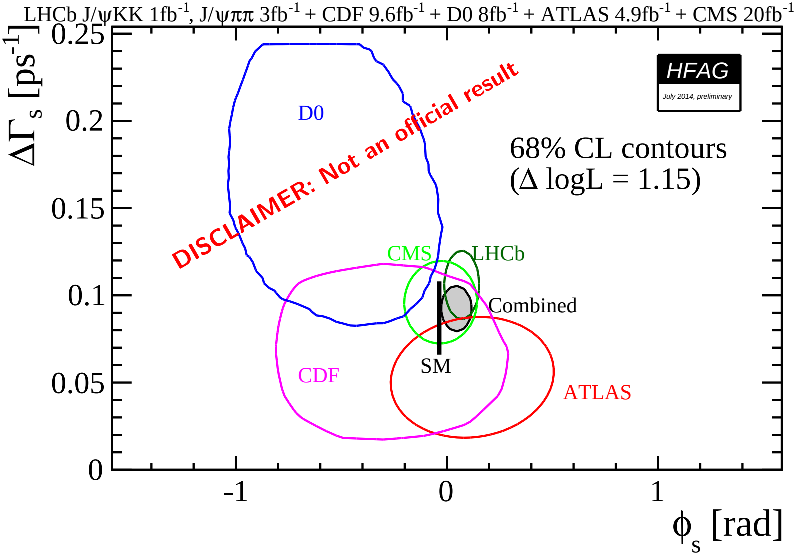
$$\Gamma_s = 0.663 \pm 0.005\,(\text{stat}) \pm 0.006\,(\text{syst})\ \text{ps}^{-1}$$
$$\Delta\Gamma_s = 0.100 \pm 0.016\,(\text{stat}) \pm 0.003\,(\text{syst})\ \text{ps}^{-1}$$

Results

$$\phi_s = 0.070 \pm 0.068\,(\text{stat}) \pm 0.008\,(\text{syst})\ \text{rad}$$
$$|\lambda| = 0.89 \pm 0.05\,(\text{stat}) \pm 0.01\,(\text{syst})$$

- Compatible with the SM

Preliminary Update on $\Delta\Gamma_s$–ϕ_s from $B_s^0 \to J/\psi h^+ h^-$



Conclusion

- LHCb has produced many first and world's best CP asymmetry measurements, in many different B decay modes.
- Discussed recent updates in $B_s^0 \to \phi\phi$ and $B_s^0 \to J/\psi\pi^+\pi^-$

$$\begin{aligned}\varphi_s^{\phi\phi} &= -0.17 \pm 0.15 \text{ (stat)} \pm 0.03 \text{ (syst) rad} \\ \phi_s^{J/\psi\pi^+\pi^-} &= 0.070 \pm 0.068 \text{ (stat)} \pm 0.008 \text{ (syst) rad}\end{aligned}$$

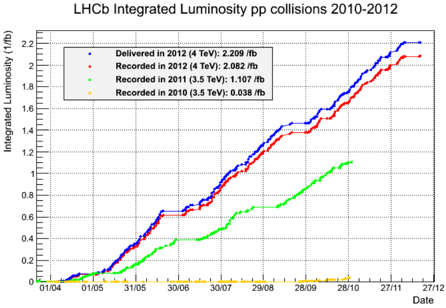
- Most of the LHCb results are limited by their statistical uncertainty.

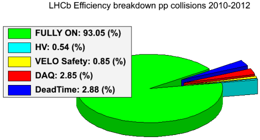
Expect many more updates soon!

Back-up

Performance of the LHCb Detector

Data Taking





- Data taking efficiency: 93.05%
- Percentage of working detector channels: $\approx$ 99%

Efficiencies

- Trigger efficiency:
  Dimuon channels: $\approx$ 90%
  Multibody hadronic channels: $\approx$ 30%
- Track reconstruction efficiency: $>$ 96%

Resolution

- Momentum resolution:
  $\Delta p/p = 0.4\%$ at 5 GeV/c
  $\Delta p/p = 0.6\%$ at 100 GeV/c
- ECAL resolution: $1\% \pm 10\%$

Further Details on $B_s^0 \to \phi\phi$ arxiv:1407.2222

Flavour Tagging

Dataset	$\epsilon_{\rm tag}$ (%)	$\mathcal{D}$ (%)	$\epsilon\mathcal{D}^2$ (%)
2011 OS	12.3 ± 1.0	31.6 ± 0.2	1.23 ± 0.10
2012 OS	14.5 ± 0.7	32.7 ± 0.3	1.55 ± 0.08
2011 SSK	40.2 ± 1.4	15.2 ± 2.0	0.93 ± 0.25
2012 SSK	33.1 ± 0.9	16.0 ± 1.6	0.85 ± 0.17
2011 Both	26.0 ± 1.3	34.9 ± 1.1	3.17 ± 0.26
2012 Both	27.5 ± 0.9	33.2 ± 1.2	3.04 ± 0.24
2011 Total			5.33 ± 0.37
2012 Total			5.44 ± 0.30

Further Details on $B_s^0 \to \phi\phi$ arxiv:1407.2222

Systematic Uncertainties

Parameter	$\lvert A_0\rvert^2$	$\lvert A_\perp\rvert^2$	δ_1 (rad)	δ_2 (rad)	φ_s (rad)	$\lvert\lambda\rvert$
Mass model	–	–	0.03	0.04	–	0.02
AA (statistical)	0.003	0.004	0.02	0.02	0.02	0.02
AA (tagging)	0.006	0.002	–	0.01	–	0.01
Fit bias	–	–	0.02	–	–	–
Time acceptance	0.005	0.003	0.02	0.05	0.02	–
Peaking background	–	–	0.01	0.01	–	0.01
Total	0.009	0.005	0.05	0.07	0.03	0.03

AA = Angular Acceptance

Source	$\mathcal{A}_U$	$\mathcal{A}_V$	Uncertainty
Angular acceptance	0.001	0.003	0.003
Time acceptance	0.005	0.003	0.005
Mass model	0.002	0.002	0.002
Peaking background	–	0.001	0.001
Total	0.006	0.005	0.006

Further Details on ϕ_s from $B_s^0 \to J/\psi\pi^+\pi^-$ arxiv:1405.4140

Systematic Uncertainties

Sources	ϕ_s(mrad)	λ
Decay time acceptance	± 0.6	± 0.0008
Mass acceptance	± 0.3	± 0.0003
Background time PDF	± 0.2	± 0.0011
Background mass distribution PDF	± 0.6	± 0.0016
Resonance model	± 6.0	± 0.0100
Resonance parameters	± 0.7	± 0.0007
Other fixed parameters	± 0.4	± 0.0009
Production asymmetry	± 5.8	± 0.0017
Total	± 8.4	± 0.010