

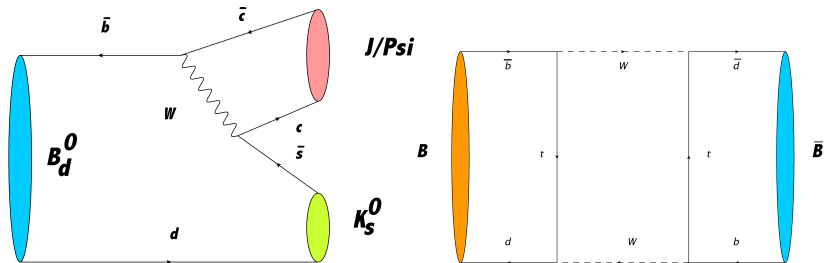
Measurement of $\sin(2\beta)$ in the decay $B_d^0 \rightarrow J/\psi K_s^0$

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Decay $B_d^0 \rightarrow J/\psi K_s^0$ and $B_d^0 - \bar{B}_d^0$ -Mixing



Time-dependent asymmetry

$$\mathcal{A}_{J/\psi K_s^0}(t) = \frac{\Gamma(\bar{B}_d^0 \rightarrow J/\psi K_s^0) - \Gamma(B_d^0 \rightarrow J/\psi K_s^0)}{\Gamma(\bar{B}_d^0 \rightarrow J/\psi K_s^0) + \Gamma(B_d^0 \rightarrow J/\psi K_s^0)} \quad (1)$$

$$= S_{J/\psi K_s^0} \sin(\Delta m_d t) - C_{J/\psi K_s^0} \cos(\Delta m_d t) \quad (2)$$

sine - term

- interference between direct decay and decay after mixing
- $S_{J/\psi K_s^0} = \sin(2\beta)$

cosine - term

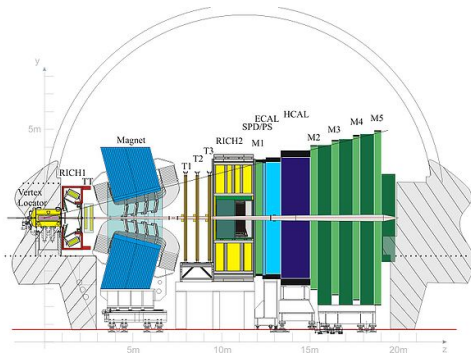
- interference between decay amplitudes or CPV in mixing
- here: $C_{J/\psi K_s^0} \approx 0$

Basis: 2011 LHCb analysis (LHCb-ANA-2012-016)

- data collected 2011
- $\sqrt{s} = 7\text{TeV}$
- 1.025fb^{-1}
- result: $S_{J/\psi K_s^0} = 0.72 \pm 0.06(\text{stat.}) \pm 0.04(\text{syst.})$
- world average: $S_{J/\psi K_s^0} = 0.679 \pm 0.020$

Our data:

- only 2012 data
- $\sqrt{s} = 8\text{TeV}$
- $\approx 2\text{fb}^{-1}$
- separation into long and downstream tracks



Tracks

- Long Tracks: VELO + T Stations (Johannes)
- Downstream Tracks: TT + T Stations (Patrick)

- in general took from 2011 analysis
- analysis on detached and biased trigger line
- New in 2012: Ghost probability. We choose ghost prob < 0.5 for π and μ tracks.

- Unbinned Maximum Likelihood Fit
- sFit: Maximise modified likelihood function

$$\mathcal{L}_W(\vec{\lambda}) = \prod_{i=1}^N \mathcal{P}(\vec{x}_e; \vec{\lambda})^{W_s(y_e)} \quad (3)$$

- sWeights $W_s(y_e)$ calculated with sPlot-technique
- total decay time p.d.f.

$$\mathcal{P}_{meas} = \underbrace{\epsilon(t)}_{=1, \text{ later more}} \mathcal{P}_{sig}(t') \otimes \mathcal{R}(t - t') \quad (4)$$

Mean decay time resolution

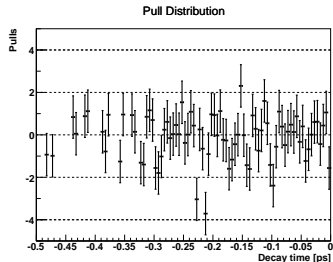
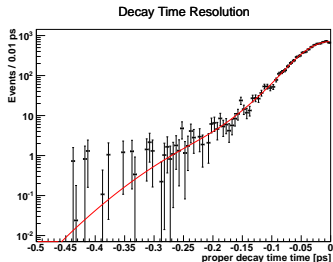
- hardly any effect on $S_{J/\psi K_s^0}$ expected
- Resolution model

$$\mathcal{R}(t) = \sum_{i=0}^3 \frac{f_i}{2\pi\sigma_i} e^{-\frac{t^2}{2\sigma^2}} \quad (5)$$

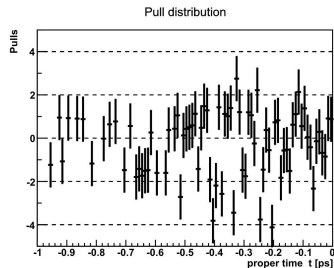
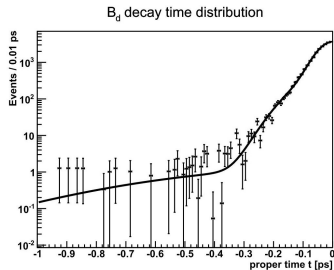
- Use prescaled trigger line
- apply all cuts except lifetime cut
- Perform sFit with reconstructed J/ψ mass as discriminating variable
- fit only negative decay times (unphysical, explainable only with resolution effects)

Mean decay time resolution

Long Tracks



Downstream Tracks



Mean decay time resolution

Fit results

Parameter		long tracks	downstream tracks
σ_1	(ps)	0.117 ± 0.016	0.480 ± 0.070
σ_2	(ps)	0.061 ± 0.037	0.04396 ± 0.00094
σ_3	(ps)	0.037 ± 0.003	0.0932 ± 0.0034
f_1		0.054 ± 0.032	0.00329 ± 0.00099
f_2		0.294 ± 0.138	0.739 ± 0.027

Mass fit

Parameterisation

Signal

$$\mathcal{P}_{m;S}(m; \vec{\lambda}_{m;S}) = f_{S,m} \mathcal{G}(m; m_{B_d^0}, \sigma_{m,1}) + (1 - f_{S,m}) \mathcal{G}(m; m_{B_d^0}, \sigma_{m,2}) \quad (6)$$

Background

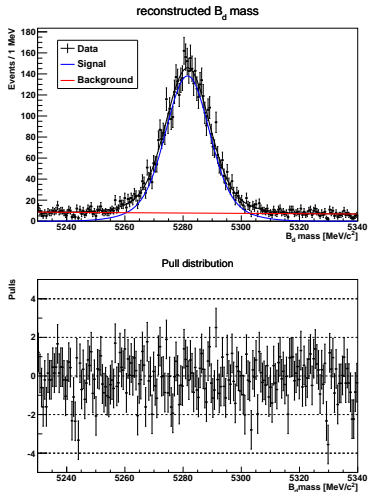
$$\mathcal{P}_{m;B}(m; \vec{\lambda}_{m;B}) = e^{-\alpha_m m} / \mathcal{N}_{m;B} \quad (7)$$

Total mass p.d.f.

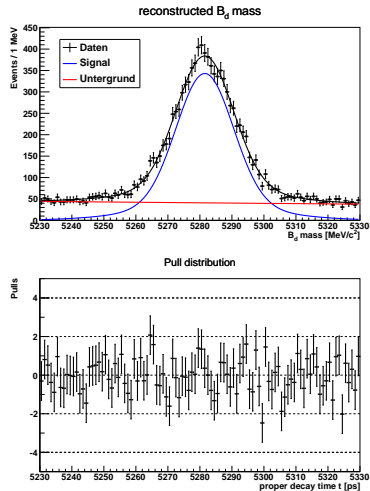
$$\mathcal{P}_m(m; \vec{\lambda}_m) = f_{sig} \mathcal{P}_{m;S}(m; \vec{\lambda}_{m;S}) + (1 - f_{sig}) \mathcal{P}_{m;B}(m; \vec{\lambda}_{m;B}) \quad (8)$$

Mass fit

Long Tracks



Downstream Tracks



Decay time fit

derivation of probability density function

$$\mathcal{P}^{true}(B_d^0 / \overline{B}_d^0) \propto \underbrace{(1 \mp \mu)}_{\text{asymmetric production}} \underbrace{e^{-t/\tau} [1 \mp S_{J/\psi K_s^0} \sin(\Delta m_d t)]}_{\text{theoretical decay time distribution}} \quad (9)$$

Imperfect tagging:

$$\mathcal{P}^{meas}(B_d^0) \propto (1 - \omega_{B_d^0}) \mathcal{P}^{true}(B_d^0) + \omega_{\overline{B}_d^0} \mathcal{P}^{true}(\overline{B}_d^0) \quad (10)$$

$$\mathcal{P}^{meas}(\overline{B}_d^0) \propto (1 - \omega_{\overline{B}_d^0}) \mathcal{P}^{true}(\overline{B}_d^0) + \omega_{B_d^0} \mathcal{P}^{true}(B_d^0) \quad (11)$$

Combination of all effects and defining

$$\Delta p_0 = \omega_{B_d^0} - \omega_{\overline{B}_d^0} \quad (12)$$

$$\omega_{B_d^0 / \overline{B}_d^0} = \omega \pm \frac{\Delta p_0}{2} \quad (13)$$

leads to...

Decay time fit

probability density function used in fit

$$\mathcal{P}_{\text{meas}}(t, d, \omega) \propto e^{-t/\tau} \{1 - d\mu(1 - 2\omega) - d\Delta p_0 - [d(1 - 2\omega) - \mu(1 - d\Delta p_0)] S_{J/\psi K_s^0} \sin(\Delta m_d t)\} \quad (14)$$

■ d : tagging decision

■ $\mu = A_P = \frac{R_{\bar{B}_d^0} - R_{B_d^0}}{R_{\bar{B}_d^0} + R_{B_d^0}}$ production asymmetry

■ ω : calibrated mistag probability

$$\omega(\eta^{OS}) = p_1(\eta^{OS} - \langle \eta^{OS} \rangle) + p_0 \quad (15)$$

p_0, p_1 : calibration parameters

η^{OS} : predicted mistag probability

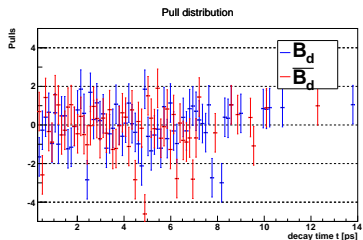
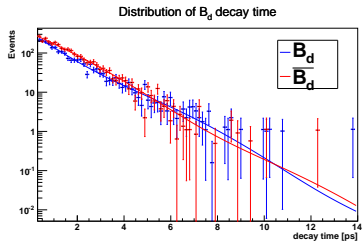
■ Δp_0 : tagging calibration asymmetry

■ Δm_d : mixing frequency

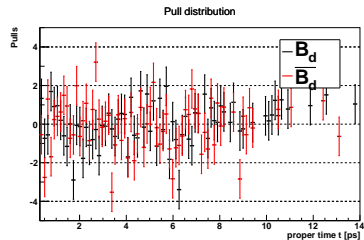
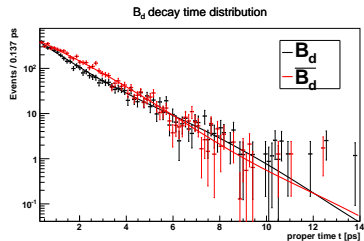
- floating parameters: $S_{J/\psi K_s^0}$, τ , Δm_d
- constrained parameters: $\mu = -0.015 \pm 0.013$,
 $p_0 = 0.382 \pm 0.003$, $p_1 = 0.981 \pm 0.024$,
 $\Delta p_0 = 0.0045 \pm 0.0053$
- fixed parameters: $\langle \eta^{OS} \rangle = 0.382$, resolution parameters
- total events: ??? (long) // 12689 (downstream)
- signal events: ??? (long) // 8585 (downstream) [2011: 8600 total]

Fit results

Long Tracks



Downstream Tracks



Note: Both results of $S_{J/\psi K_s^0}$ are blinded with the same string.

Parameter	long	downstream
$S_{J/\psi K_s^0}(\text{blinded})$	\pm	0.565 ± 0.069
τ_{eff}	\pm	1.516 ± 0.039
Δm_d	\pm	0.521 ± 0.039

- Fit Bias due to fit method sFit
- Tagging calibration
- Time acceptance
- Correlation mass \leftrightarrow decay time
- Time resolution

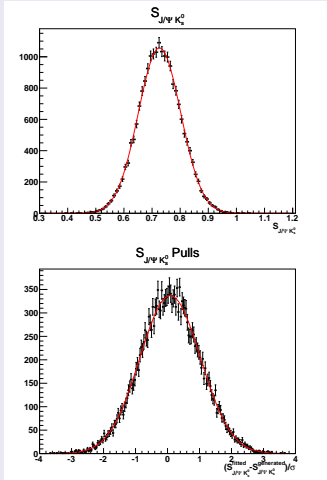
Generate Toy MC with

- ??? (long) resp. 13000 events (downstream)
- $S_{J/\psi K_s^0} = 0.72$ (long), $S_{J/\psi K_s^0} = 0.75$ (downstream)
- all other parameters derived from nominal fit
- $S_{J/\psi K_s^0}$, τ , Δm_d floating

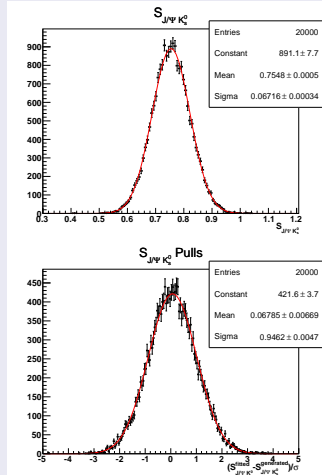
Systematic errors

Fit Bias

Long Tracks



Downstream Tracks



Systematic errors

Fit Bias

Results of the toys:

Long Tracks

$$\mu_{S_{J/\psi K_S^0}} = 0.7266 \pm 0.0005$$

$$\sigma_{S_{J/\psi K_S^0}} = 0.0754 \pm 0.0003$$

$$\mu_{\text{pull}} = 0.083 \pm 0.007$$

$$\sigma_{\text{pull}} = 0.947 \pm 0.005$$

Downstream Tracks

$$\mu_{S_{J/\psi K_S^0}} = 0.7548 \pm 0.0005$$

$$\sigma_{S_{J/\psi K_S^0}} = 0.0672 \pm 0.0003$$

$$\mu_{\text{pull}} = 0.068 \pm 0.007$$

$$\sigma_{\text{pull}} = 0.946 \pm 0.005$$

Multiply mean μ_{textpull} of pull distribution with statistical uncertainty of nominal fit.

Long Tracks

$$\delta S_{J/\psi K_S^0}^{\text{Fit}} = 0.0065$$

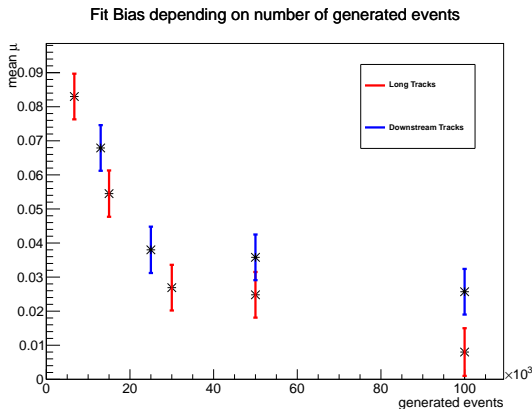
Downstream Tracks

$$\delta S_{J/\psi K_S^0}^{\text{Fit}} = 0.0047$$

Systematic errors

Fit Bias - origins

- too small pull width: background
- major contribution to bias: statistics



Systematic errors

Tagging calibration

Vary Tagging calibration parameters $p_0, p_1 \pm$ their systematic uncertainties

- 1 in the nominal fit
- 2 in the generation of Toy MC, but fit with original values

Note: Systematic studies on used tagging calibration hasn't finished yet \rightarrow no official value. We use largest differences in channels so far:

$$\delta p_0^{stat.} = 0.019, \quad \delta p_1^{stat.} = 0.07$$

Systematic errors

Tagging calibration

Choose highest difference from nominal fit / toy as estimate for the systematic uncertainty

- Long tracks:
- Downstream tracks: $\delta S_{J/\psi K_s^0}^{\text{TagCalib}} = 0.095$

Note: Estimates very large due to large $\delta p_0^{\text{stat.}}$, $\delta p_1^{\text{stat.}}$ compared to other calibrations (systematic studies of calibration need to be finished)

Note: just a cross-check, no in-depth analysis

Determination of an acceptance function

- no separation between B_d^0 and \overline{B}_d^0
⇒ simple exponential decay
- neglect lifetime cut ($t > 0.3\text{ps}$)
- contributions to acceptance:
 - turn-on-effect
 - decreasing acceptance for higher lifetimes due to VELO geometry

Systematic errors

Time acceptance

Fit p.d.f

$$\mathcal{P}_{acc}(t) \propto \underbrace{e^{-t/\tau}}_{\text{exp. decay}} \cdot \underbrace{\frac{2}{\pi} \arctan[t \cdot \exp(at + b)]}_{\text{turn-on-effect}} \cdot \underbrace{(1 + \beta t)}_{\substack{\text{higher lifetimes} \\ (\beta < 0)}}$$

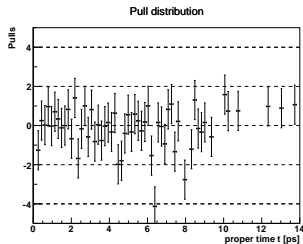
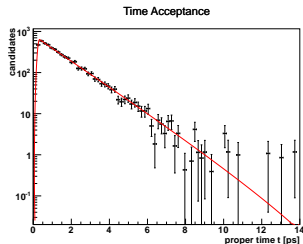
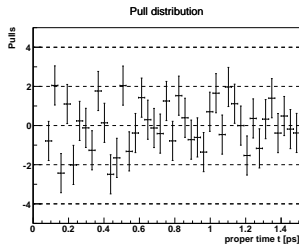
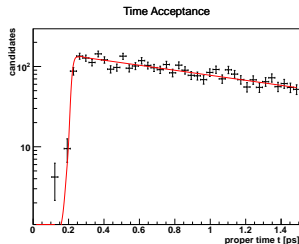
Note: τ will be constrained to the PDG value

$$\tau = 1,519 \pm 0,007 \text{ps.}$$

Systematic errors

Time acceptance

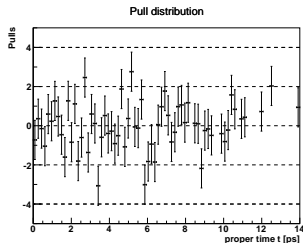
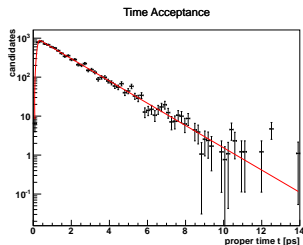
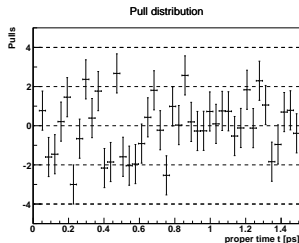
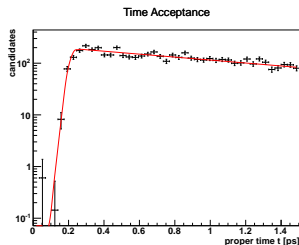
Long Tracks



Systematic errors

Time acceptance

Downstream Tracks



Systematic errors

Time acceptance

Table : Fit results for exponential decay fit with acceptance function. τ was constrained to the PDG value $\tau = 1,519 \pm 0,007\text{ps}$

parameter	long	long
τ	1.518 ± 0.007	1.519 ± 0.007
a	153 ± 36	52.8 ± 8.6
b	-31.44 ± 7.7	-9.2 ± 1.6
β	-0.057 ± 0.007	-0.0053 ± 0.0089

Systematic errors

Time acceptance

Toy MC Study

- generate with acceptance function
- use parameters mentioned above
- fit without acceptance function
- compare mean of $S_{J/\psi K_s^0}$ distribution with cooresponding mean of fit bias toy

Assignment of systematic error due to neglect of any time acceptance:

Long Tracks

$$\delta S_{J/\psi K_s^0}^{\text{Acc}} = \text{xxx}$$

Downstream Tracks

$$\delta S_{J/\psi K_s^0}^{\text{Acc}} = 0.0013$$

Systematic errors

Correlation mass \leftrightarrow decay time

Fit reconstructed B_d^0 -mass in different time bins. Fix mass parameters to the ones obtained in 1 bin and fit $S_{J/\psi K_s^0}$ in the whole sample. Choose signal weighted rms of $S_{J/\psi K_s^0}$ differences to fit bias toy as estimate.

Bin	time range of mass fit	long	down
1	$t \in [0.3, 0.7]\text{ps}$	\pm	0.559 ± 0.069
2	$t \in [0.7, 1.5]\text{ps}$	\pm	0.567 ± 0.068
3	$t \in [1.5, 3]\text{ps}$	\pm	0.566 ± 0.069
4	$t \in [3, 14]\text{ps}$	\pm	0.566 ± 0.069
nominal fit		\pm	0.565 ± 0.069
$\delta S_{J/\psi K_s^0}^{\text{mass}/t}$		xxx	0.0031

Systematic errors

Resolution

Vary σ_i of resolution $\pm 20\%$, fit with these parameters and compare $S_{J/\psi K_s^0}$

	long	down
+20%	\pm	0.565 ± 0.069
-20%	\pm	0.564 ± 0.069
nominal fit	\pm	0.565 ± 0.069
$\delta S_{J/\psi K_s^0}^{\text{resolution}}$	xxx	0.001

Systematic errors

Summary

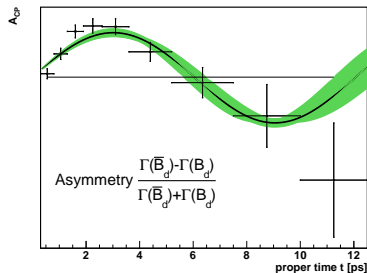
effect	long	downstream
fit method	0.0065	0.0047
tagging calibration		0.0952
time acceptance		0.0013
mass \leftrightarrow decay time		0.0031
resolution		0.001
total		0.095

Conclusion

Long Tracks

$$S_{J/\psi K_s^0} = \\ \text{xxx} \pm \text{xxx}(\text{stat.}) \pm \text{xxx}(\text{syst.})$$

Downstream Tracks



$$S_{J/\psi K_s^0} = \\ 0.565 \pm 0.069(\text{stat.}) \pm 0.095(\text{syst.})$$

Both results are blinded with the same string

Conclusion

Comparison with other results

	$S_{J/\psi K_s^0}$
long tracks (blinded)	\pm
downstream tracks (blinded)	0.565 ± 0.069
2011 analysis	0.72 ± 0.06
world average	0.679 ± 0.020
BaBar (most precise)	0.687 ± 0.028