

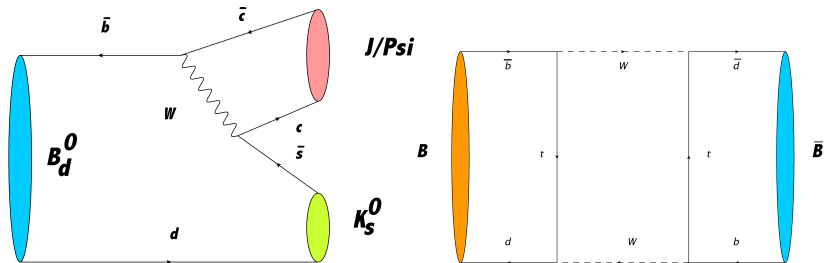
# Measurement of $\sin(2\beta)$ in the decay $B_d^0 \rightarrow J/\psi K_s^0$

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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

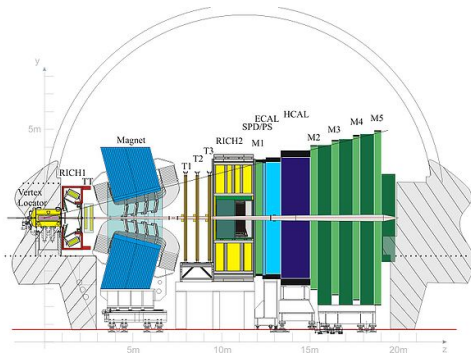
- interference between decay amplitudes or CPV in mixing
- here:  $C_{J/\psi K_s^0} \approx 0$

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

- data collected 2011
- $\sqrt{s} = 7\text{TeV}$
- $1.025\text{fb}^{-1}$
- 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  $\pi$  and  $\mu$  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

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

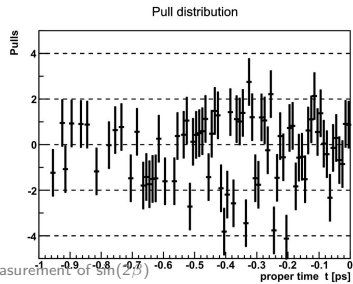
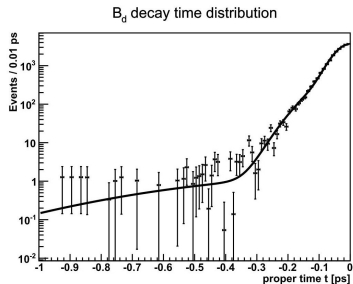
- Use prescaled trigger line
- apply all cuts except lifetime cut
- Perform sFit with reconstructed  $J/\psi$  mass as discriminating variable
- fit only negative decay times (unphysical, explainable only with resolution effects)



# Mean decay time resolution

## Long Tracks

## Downstream Tracks



# Mean decay time resolution

## Fit results

Parameter		long tracks	downstream tracks
$\sigma_1$	(ps)	$0.117 \pm 0.016$	$0.480 \pm 0.070$
$\sigma_2$	(ps)	$0.061 \pm 0.037$	$0.04396 \pm 0.00094$
$\sigma_3$	(ps)	$0.037 \pm 0.003$	$0.0932 \pm 0.0034$
$f_1$		$0.054 \pm 0.032$	$0.00329 \pm 0.00099$
$f_2$		$0.294 \pm 0.138$	$0.739 \pm 0.027$

# 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

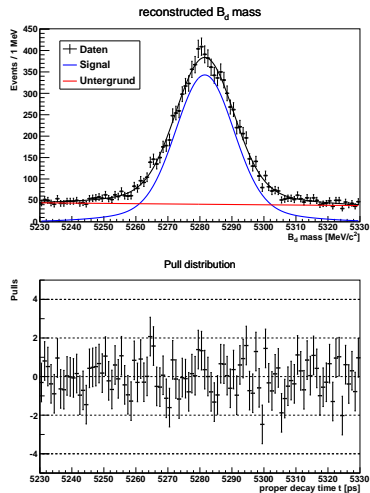
$$\mathcal{P}_{m;B}(m; \vec{\lambda}_{m;B}) = e^{-\alpha_m m} / \mathcal{N}_{m;B} \quad (7)$$

### Total mass p.d.f.

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

## 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

- $\omega$ : calibrated mistag probability

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

$p_0, p_1$ : calibration parameters

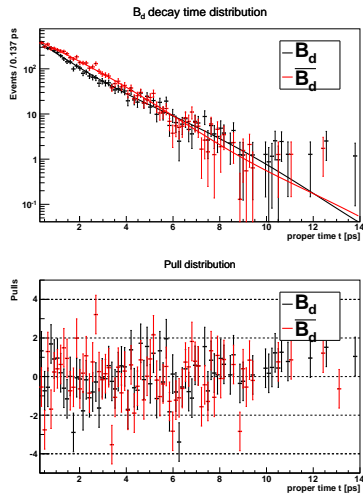
$\eta^{OS}$ : predicted mistag probability

- $\Delta p_0$ : tagging calibration asymmetry

- $\Delta m_d$ : mixing frequency

- floating parameters:  $S_{J/\psi K_s^0}$ ,  $\tau$ ,  $\Delta m_d$
- 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]

### Downstream Tracks





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

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

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

# Systematic errors

## Fit Bias

Generate Toy MC with

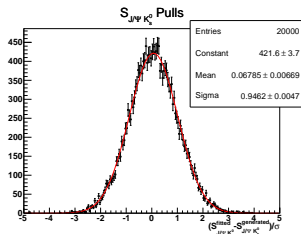
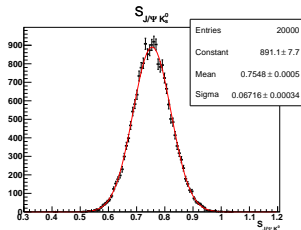
- ??? (long) resp. 13000 events (downstream)
- $S_{J/\psi K_s^0} = 0.75$
- all other parameters derived from nominal fit
- $S_{J/\psi K_s^0}$ ,  $\tau$ ,  $\Delta m_d$  floating

# Systematic errors

## Fit Bias

## Long Tracks

## Downstream Tracks



# Systematic errors

## Fit Bias

Results of the toys:

### Long Tracks

### 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  $\mu$  of pull distribution with statistical uncertainty of nominal fit.

### Long Tracks

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

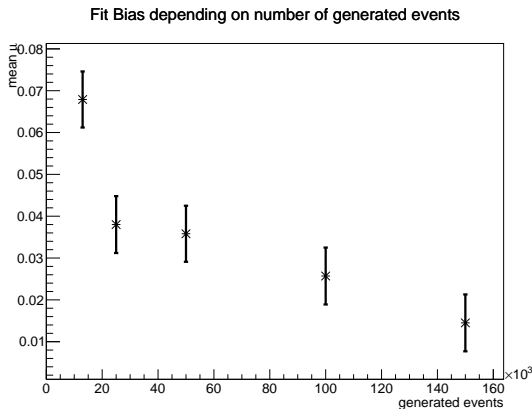
### Downstream Tracks

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

# 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:**  $\tau$  will be constrained to the PDG value

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

# Systematic errors

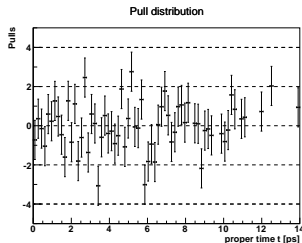
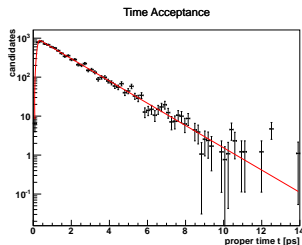
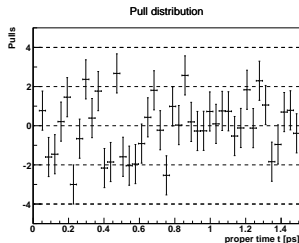
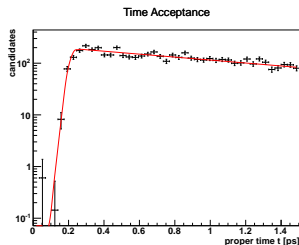
Time acceptance

Long Tracks

# Systematic errors

## Time acceptance

### Downstream Tracks



# Systematic errors

## Time acceptance

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

parameter	long	long
$\tau$	$\pm$	$1.519 \pm 0.007$
$a$	$\pm$	$52.8 \pm 8.6$
$b$	$\pm$	$-9.2 \pm 1.6$
$\beta$	$\pm$	$-0.0053 \pm 0.0089$

# 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. Subsequently, fix mass values to the values obtained in the 4 bins and fit the whole sample. Choose highest difference of  $S_{J/\psi K_s^0}$  as estimate.

Bin	time range of mass fit	long	down
1	$t \in [0.3, 0.7]\text{ps}$	$\pm$	$0.559 \pm 0.069$
2	$t \in [0.7, 1.5]\text{ps}$	$\pm$	$0.567 \pm 0.068$
3	$t \in [1.5, 3]\text{ps}$	$\pm$	$0.566 \pm 0.069$
4	$t \in [3, 14]\text{ps}$	$\pm$	$0.566 \pm 0.069$
weighted average		$\pm$	$0.565 \pm 0.034$
nominal fit		$\pm$	$0.565 \pm 0.069$
$\delta S_{J/\psi K_s^0}^{\text{mass}/t}$		xxx	???

# Systematic errors

## Resolution

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

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



# Systematic errors

## Summary

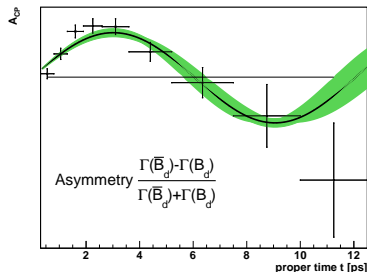
effect	long	downstream
fit method		0.0047
tagging calibration		0.0952
time acceptance		0.0013
mass $\leftrightarrow$ decay time		???
resolution		0.001
total		xxx

# Conclusion

## Long Tracks

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

## Downstream Tracks



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

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)	$0.565 \pm 0.069$
2011 analysis	$0.72 \pm 0.06$
world average	$0.679 \pm 0.020$
BaBar (most precise)	$0.687 \pm 0.028$