

# Measurement of $\sin(2\beta)$ in the decay

$$B_d^0 \longrightarrow J/\psi K_s^0$$

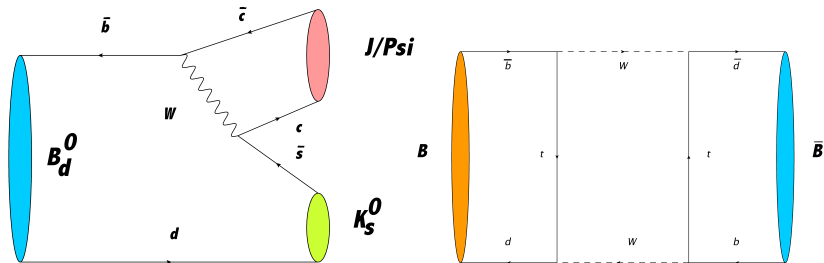
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# Decay $B_d^0 \rightarrow J/\psi K_s^0$ and $B_d^0 - \bar{B}_d^0$ -Mixing



Measurement of  $\mathcal{CP}$ -Asymmetry  $\mathcal{A}_{\mathcal{CP}}$  due to interference between direct decay and decay after 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 (Johannes) and downstream (Patrick) tracks

- in general taken from 2011 analysis
- Change in track  $\chi^2$  in stripping:  $\frac{\chi_{\text{track}}^2}{n\text{DoF}} < 3$  (2011:  $< 4$ )
- analysis on stripping line BetaSBd2JpsiKsDetachedLine and HLT2 line Hlt2DiMuonDetachedJPsiDecision
- New in 2012: Ghost probability. We choose ghost prob  $< 0.5$  for  $\pi$  and  $\mu$  tracks. But issues for Downstream  $\pi \rightarrow$  don't use ghost probability of Downstream  $\pi$ .

# Comparison 2011 $\leftrightarrow$ 2012

	2011	long	downstream
candidates	50186	21183	62184
signal	26775	17003	42907
tagged signal	8600	5116	12626
$\epsilon_{tag}$	$(32.65 \pm 0.31)\%$	$(30.09 \pm 0.57)\%$	$(29.43 \pm 0.85)\%$
$\epsilon_{eff} = \epsilon_{tag} \mathcal{D}^2$	$(2.38 \pm 0.27)\%$	$(1.78 \pm xxx)\%$	$(1.80 \pm 0.15)\%$

Used tagging: FlavourTagging v13r0 2013-06-13 (only OST)

- Unbinned Maximum Likelihood Fit
- sFit
- total decay time p.d.f.

$$\mathcal{P}_{meas} = \underbrace{\epsilon(t)}_{=1, \text{ later more}} \mathcal{P}_{sig}(t') \otimes \mathcal{R}(t - t') \quad (3)$$

- neglect decay time acceptance, examination of systematic effect later



# Mean decay time resolution

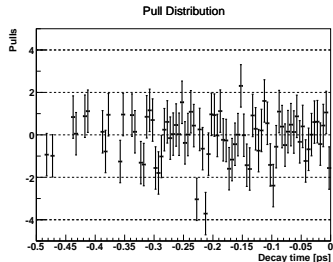
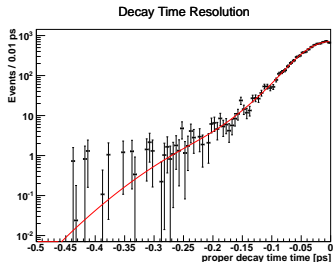
- hardly any effect on  $S_{J/\Psi K_s^0}$  expected
- Resolution model

$$\mathcal{R}(t) = \sum_{i=1}^3 \frac{f_i}{2\pi\sigma_i} e^{-\frac{t^2}{2\sigma_i^2}} \quad (4)$$

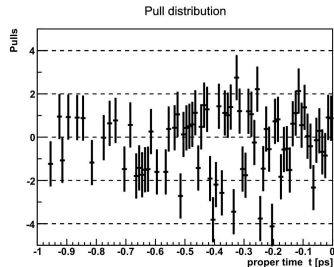
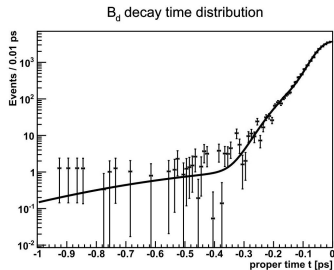
- Use prescaled trigger line
- apply all cuts except lifetime cut
- Perform sFit with reconstructed  $J/\Psi$  mass as discriminating variable
- fit only negative decay times (unphysical, explainable only with resolution effects) ( $\rightarrow$  approximation, but sufficient for our purpose)

# 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)	$0.061 \pm 0.037$	$0.0932 \pm 0.0034$
$\sigma_3$ (ps)	$0.037 \pm 0.003$	$0.04396 \pm 0.00094$
$f_1$	$0.054 \pm 0.032$	$0.00329 \pm 0.00099$
$f_2$	$0.294 \pm 0.138$	$0.257 \pm 0.027$
$\sigma_{eff}$ (ps)	$0.052 \pm 0.012$	$0.0665 \pm 0.0013$

# Mass fit

## Parameterisation

### Signal

$$\mathcal{P}_{m;S}(m; \vec{\lambda}_{m;S}) = f_{S,m} \mathcal{G}(m; m_{B_d^0}, \sigma_{m,1}) + (1 - f_{S,m}) \mathcal{G}(m; m_{B_d^0}, \sigma_{m,2}) \quad (5)$$

### Background

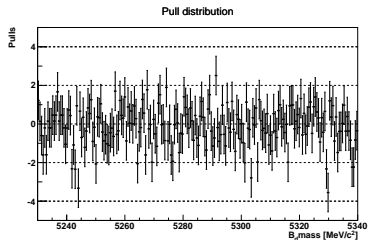
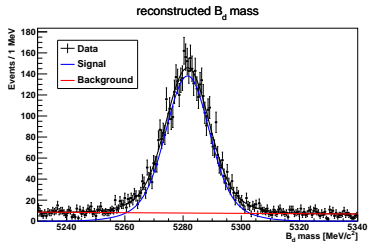
$$\mathcal{P}_{m;B}(m; \vec{\lambda}_{m;B}) = e^{-\alpha_m m} / \mathcal{N}_{m;B} \quad (6)$$

### Total mass p.d.f.

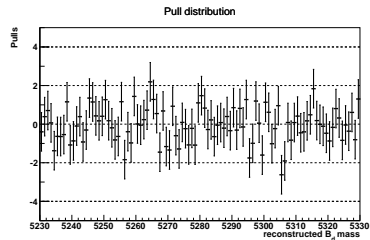
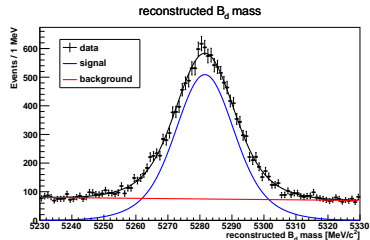
$$\mathcal{P}_m(m; \vec{\lambda}_m) = f_{sig} \mathcal{P}_{m;S}(m; \vec{\lambda}_{m;S}) + (1 - f_{sig}) \mathcal{P}_{m;B}(m; \vec{\lambda}_{m;B}) \quad (7)$$

# Mass fit

## Long Tracks



## Downstream Tracks



# Decay time fit

probability density function used in fit

$$\mathcal{P}_{\text{meas}}(t, d, \omega) \propto e^{-t/\tau} \{1 - d\mu(1 - 2\omega) - d\Delta p_0 - [d(1 - 2\omega) - \mu(1 - d\Delta p_0)] S_{J/\psi K_s^0} \sin(\Delta m_d t)\} \quad (8)$$

- $d$ : 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

$$\omega(\eta^{OS}) = p_1(\eta^{OS} - \langle \eta^{OS} \rangle) + p_0 \quad (9)$$

$p_0, p_1$ : calibration parameters

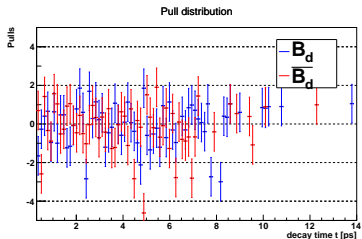
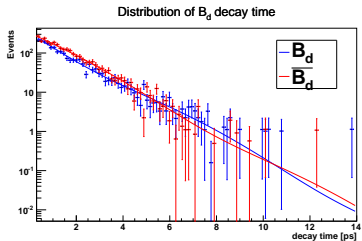
$\eta^{OS}$ : predicted mistag probability

- $\Delta p_0$ : tagging calibration asymmetry
- $\Delta m_d$ : mixing frequency

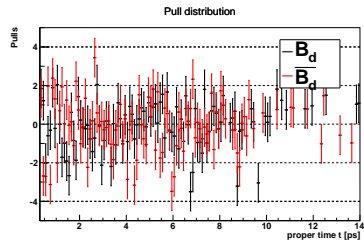
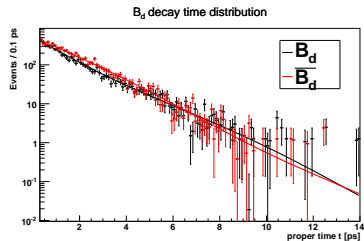
- floating parameters:  $S_{J/\psi K_s^0}$ ,  $\tau$ ,  $\Delta m_d$
- constrained parameters:  $\mu = -0.015 \pm 0.013$ ,  
 $p_0 = 0.382 \pm 0.003$ ,  $p_1 = 0.981 \pm 0.024$ ,  
 $\Delta p_0 = 0.0045 \pm 0.0053$
- fixed parameters:  $\langle \eta^{OS} \rangle = 0.382$ , resolution parameters

# 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
$S_{J/\psi K_s^0}(\text{blinded})$	$0.610 \pm 0.078$	$0.535 \pm 0.063$
$S_{J/\psi K_s^0}(2011)$	$\text{xxx} \pm 0.11$	$\text{xxx} \pm 0.08$
$\tau_{\text{eff}}$	$1.355 \pm 0.021$	$1.498 \pm 0.017$
$\Delta m_d$	$0.60 \pm 0.05$	$0.47 \pm 0.03$
$\Delta m_d(2011)$	$0.58 \pm 0.15$	$0.50 \pm 0.04$

**Note:**  $\tau_{\text{eff}}$  not compatible to PDG value due to neglect of time acceptance in fit (systematic study later)

**Question:** Why is  $\Delta m_d$  that much higher in the long track sample?

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

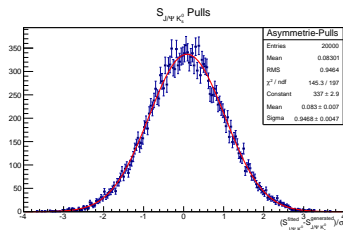
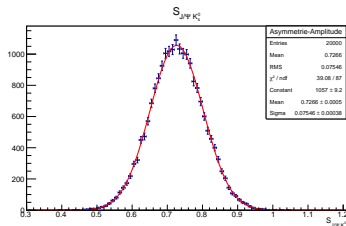
Generate Toy MC with

- 6700 (long) resp. 20000 events (downstream)
- $S_{J/\psi K_s^0} = 0.72$
- all other parameters derived from data fit
- $S_{J/\psi K_s^0}$ ,  $\tau$ ,  $\Delta m_d$  floating

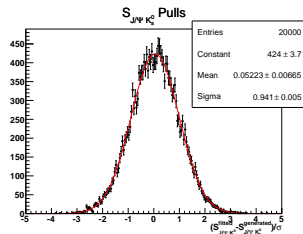
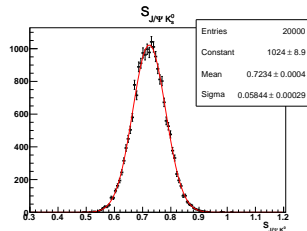
# Systematic errors

## Fit Bias

### Long Tracks



### Downstream Tracks



# Systematic errors

## Fit Bias

Results of the toys:

### Long Tracks

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

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

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

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

### Downstream Tracks

$$\mu_{S_{J/\psi K_S^0}} = 0.7234 \pm 0.0004$$

$$\sigma_{S_{J/\psi K_S^0}} = 0.0584 \pm 0.0003$$

$$\mu_{\text{pull}} = 0.052 \pm 0.007$$

$$\sigma_{\text{pull}} = 0.941 \pm 0.005$$

Multiply mean  $\mu_{\text{pull}}$  of pull distribution with statistical uncertainty of nominal fit (long:  $\sigma_{\text{data}} = 0.078$ , down:  $\sigma_{\text{data}} = 0.063$ ).

### Long Tracks

$$\delta S_{J/\psi K_S^0}^{\text{Fit}} = 0.0066 \text{ (8.5\%)}$$

### Downstream Tracks

$$\delta S_{J/\psi K_S^0}^{\text{Fit}} = 0.0033 \text{ (5.2\%)}$$

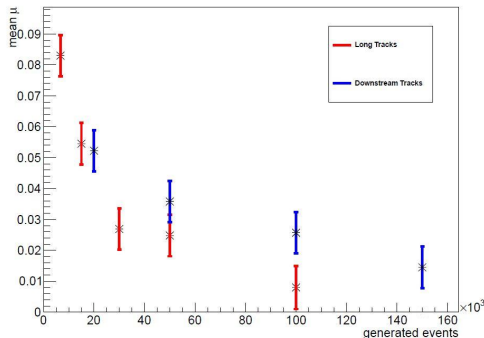
(in Brackets: systematic error relative to systematic)

# Systematic errors

## Fit Bias - origins

- major contribution to bias: too little statistics

Fit Bias depending on number of generated events



- too small pull width due to background ( $\rightarrow$  overestimation of fit error)
- $\sigma_{\text{pull}}$  doesn't change with higher statistics

# Systematic errors

## Tagging calibration

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

- 1 in the nominal fit (gives first impression of size of effect)
- 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. Use systematic errors of 2011 (to get a feeling for size of effect, need to be redone with final calibration):

$$\delta p_0^{stat.} = 0.0076, \quad \delta p_1^{stat.} = 0.0012$$

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

- Long tracks:  $\delta S_{J/\psi K_s^0}^{TagCalib} = 0.0320$  (41.0%)
- Downstream tracks:  $\delta S_{J/\psi K_s^0}^{TagCalib} = 0.0331$  (52.5%)

**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

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

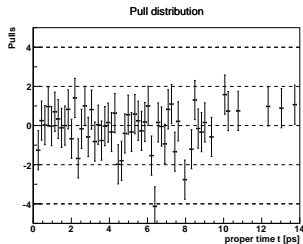
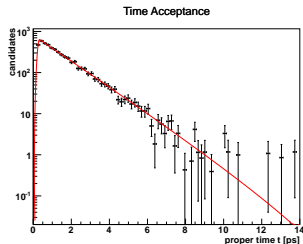
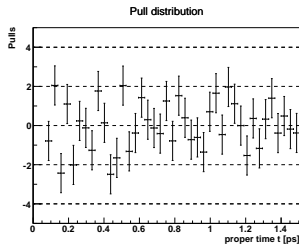
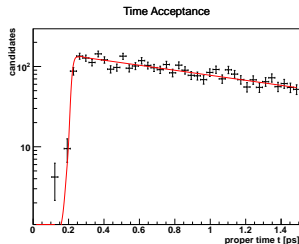
**Note:**  $\tau$  will be constrained to the PDG value

$\tau = 1.519 \pm 0.007 \text{ps}$ .

# Systematic errors

## Time acceptance

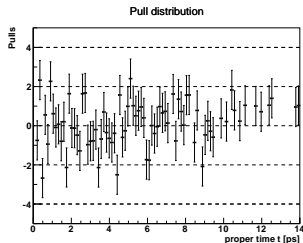
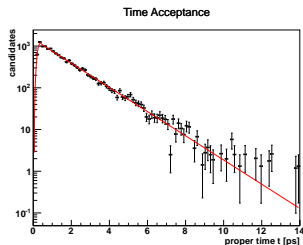
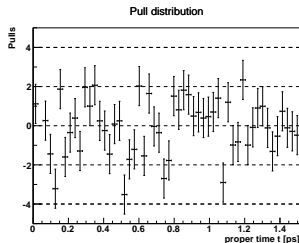
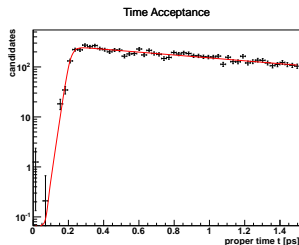
### Long Tracks



# 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	downstream
$\tau$	$1.518 \pm 0.007$	$1.519 \pm 0.007$
$a$	$153 \pm 36$	$47.9 \pm 5.6$
$b$	$-31.44 \pm 7.7$	$-8.4 \pm 1.1$
$\beta$	$-0.057 \pm 0.007$	$-0.0090 \pm 0.0076$

# 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 corresponding mean of fit bias toy

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

#### Long Tracks

$$\delta S_{J/\psi K_s^0}^{\text{Acc}} = 0.0003 \text{ (0.4\%)}$$

#### Downstream Tracks

$$\delta S_{J/\psi K_s^0}^{\text{Acc}} = 0.0008 \text{ (1.3\%)}$$

# 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.

Bin	time range of mass fit	long	down
1	$t \in [0.3, 0.7]\text{ps}$	$0.614 \pm 0.078$	$0.532 \pm 0.063$
2	$t \in [0.7, 1.5]\text{ps}$	$0.608 \pm 0.078$	$0.536 \pm 0.063$
3	$t \in [1.5, 3]\text{ps}$	$0.609 \pm 0.079$	$0.536 \pm 0.063$
4	$t \in [3, 14]\text{ps}$	$0.609 \pm 0.078$	$0.535 \pm 0.062$
nominal fit		$0.610 \pm 0.078$	$0.534 \pm 0.063$
$\delta S_{J/\psi K_s^0}^{\text{mass}/t}$		0.0020 (2.6%)	0.0018 (2.9%)

# 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%	$0.6100 \pm 0.0782$	$0.5351 \pm 0.0626$
-20%	$0.6095 \pm 0.0782$	$0.5345 \pm 0.0625$
nominal fit	$0.6098 \pm 0.0782$	$0.5347 \pm 0.0626$
$\delta S_{J/\psi K_s^0}^{\text{resolution}}$	0.0003 (0.4%)	0.0004 (0.6%)

# Systematic errors

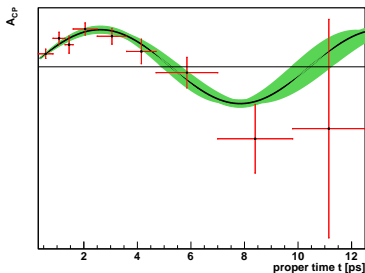
## Summary

effect	long		downstream	
fit method	0.0066	(8.5%)	0.0033	(5.2%)
tagging calibration	0.0320	(42.0%)	0.0331	(52.5%)
time acceptance	0.0003	(0.4%)	0.0008	(1.3%)
mass $\leftrightarrow$ decay time	0.0020	(2.6%)	0.0018	(2.9%)
resolution	0.0003	(0.4%)	0.0004	(0.6%)
total	0.0328	(42.1%)	0.0333	(52.9%)
statistic uncertainty	0.0782		0.0626	



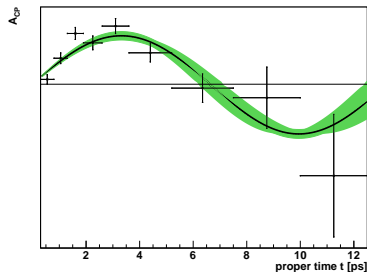
# Conclusion

## Long Tracks



$$S_{J/\psi K_s^0} = 0.610 \pm 0.074(\text{stat.}) \pm 0.033(\text{syst.})$$

## Downstream Tracks



$$S_{J/\psi K_s^0} = 0.535 \pm 0.059(\text{stat.}) \pm 0.033(\text{syst.})$$

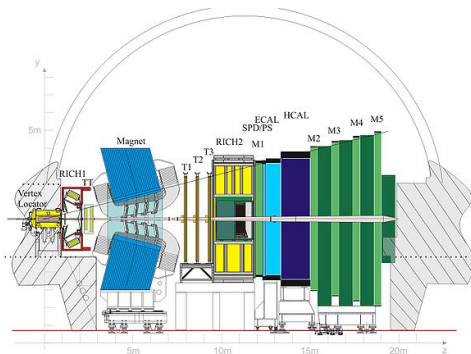
Both results are blinded with the same string. Statistical errors are corrected with  $\sigma_{\text{pull}}$  of fit bias toy.

# Conclusion

## Comparison with other results

	$S_{J/\psi K_s^0}$
long tracks (blinded)	$0.610 \pm 0.074 \pm 0.033$
downstream tracks (blinded)	$0.565 \pm 0.059 \pm 0.033$
combined	$xxx \pm 0.046 \pm 0.033$
2011 analysis	$0.72 \pm 0.06 \pm 0.04$
world average	$0.679 \pm 0.020$
BaBar (most precise)	$0.687 \pm 0.028 \pm 0.012$

BACKUP



## Tracks

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

# Decay time fit

derivation of probability density function

$$\mathcal{P}^{true}(B_d^0 / \overline{B}_d^0) \propto \underbrace{(1 \mp \mu)}_{\text{asymmetric production}} \underbrace{e^{-t/\tau} [1 \mp S_{J/\psi K_s^0} \sin(\Delta m_d t)]}_{\text{theoretical decay time distribution}} \quad (10)$$

Imperfect tagging:

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

$$\mathcal{P}^{meas}(\overline{B}_d^0) \propto (1 - \omega_{\overline{B}_d^0}) \mathcal{P}^{true}(\overline{B}_d^0) + \omega_{B_d^0} \mathcal{P}^{true}(B_d^0) \quad (12)$$

Combination of all effects and defining

$$\Delta p_0 = \omega_{B_d^0} - \omega_{\overline{B}_d^0} \quad (13)$$

$$\omega_{B_d^0 / \overline{B}_d^0} = \omega \pm \frac{\Delta p_0}{2} \quad (14)$$

leads to...

# Decay time fit

probability density function used in fit

$$\mathcal{P}_{\text{meas}}(t, d, \omega) \propto e^{-t/\tau} \{1 - d\mu(1 - 2\omega) - d\Delta p_0 - [d(1 - 2\omega) - \mu(1 - d\Delta p_0)] S_{J/\psi K_s^0} \sin(\Delta m_d t)\} \quad (15)$$

■  $d$ : 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

$$\omega(\eta^{OS}) = p_1(\eta^{OS} - \langle \eta^{OS} \rangle) + p_0 \quad (16)$$

$p_0, p_1$ : calibration parameters

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

■  $\Delta p_0$ : tagging calibration asymmetry

■  $\Delta m_d$ : mixing frequency