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

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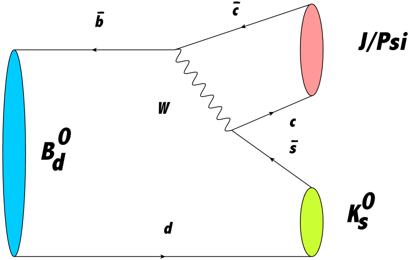
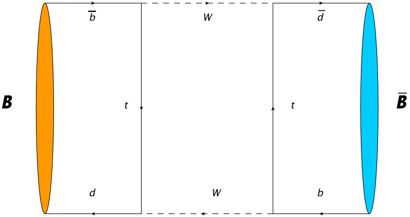
Decay $B_d^0 \longrightarrow J/\Psi K_s^0$ and $B_d^0 - \bar{B}_d^0$-Mixing





Measurement of $\mathcal{CP}$-Asymmetry $\mathcal{A}_{\mathcal{CP}}$ due to interference between direct decay and decay after mixing

Time-dependent asymmetry

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

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

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 of our work

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

- data collected 2011
- $\sqrt{s} = 7\mathrm{TeV}$
- $1.025\mathrm{fb}^{-1}$
- 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
- $\sqrt{s} = 8\mathrm{TeV}$
- $\approx 2\mathrm{fb}^{-1}$
- separation into long (Johannes) and downstream (Patrick) tracks

Cuts

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

Comparison 2011 $\leftrightarrow$ 2012

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

Fit strategy

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

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

- neglect decay time acceptance, examination of systematic effect later

Mean decay time resolution

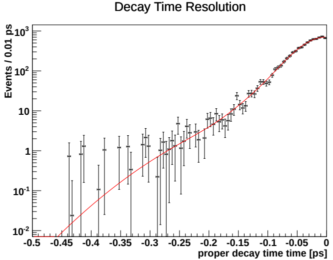
- hardly any effect on $S_{J/\Psi K_s^0}$ expected
- Resolution model

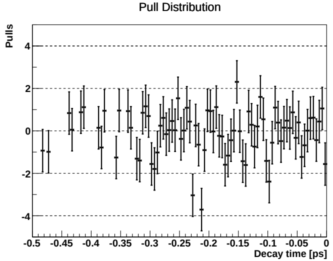
$$\mathcal{R}(t) = \sum_{i=1}^{3} \frac{f_i}{2\pi\sigma_i} e^{-\frac{t^2}{2\sigma^2}} \tag{4}$$

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

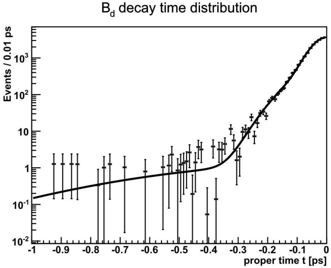
Mean decay time resolution

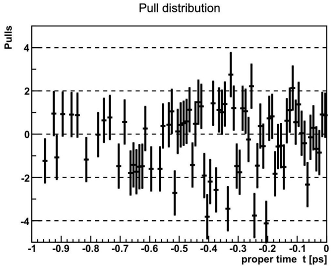
Long Tracks





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	0.0932±0.0034
σ_3	(ps)	0.037±0.003	0.04396±0.00094
f_1		0.054±0.032	0.00329±0.00099
f_2		0.294±0.138	0.257±0.027
σ_{eff}	(ps)	±	0.00665±0.0047

Mass fit

Parameterisation

Signal

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

Background

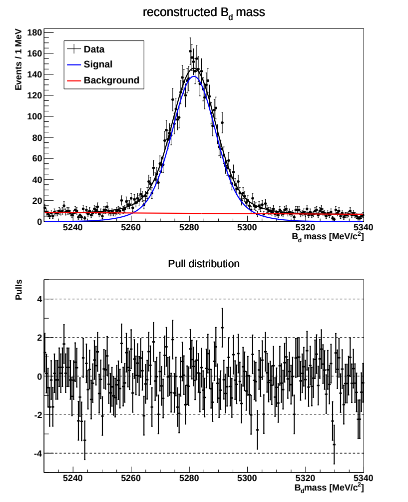
$$\mathcal{P}_{m;B}(m;\vec{\lambda}_{m;B}) = e^{-\alpha_m m}/\mathcal{N}_{m;B} \tag{6}$$

Total mass p.d.f.

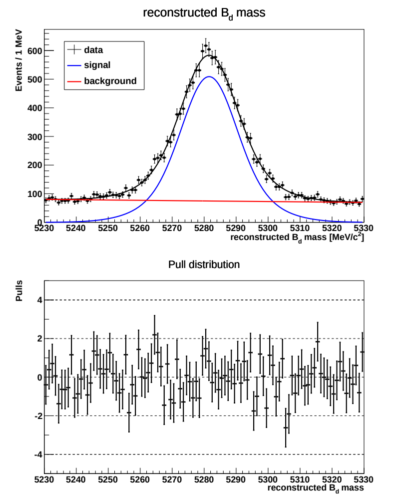
$$\mathcal{P}_m(m;\vec{\lambda}_m) = f_{sig}\mathcal{P}_{m;S}(m;\vec{\lambda}_{m;S}) + (1-f_{sig})\mathcal{P}_{m;B}(m;\vec{\lambda}_{m;B}) \tag{7}$$

Mass fit

Long Tracks



Downstream Tracks



Decay time fit

probability density function used in fit

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

- 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
- ω: calibrated mistag probability

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

p_0, p_1: calibration parameters
η^{OS}: predicted mistag probability

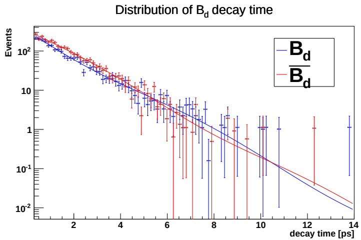
- Δp_0: tagging calibration asymmetry
- Δm_d: mixing frequency

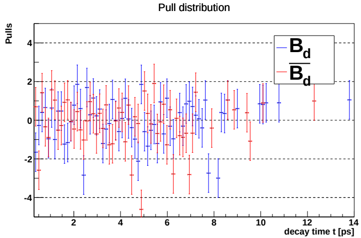
Fit results

- 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: $\left\langle \eta^{OS} \right\rangle = 0.382$, resolution parameters

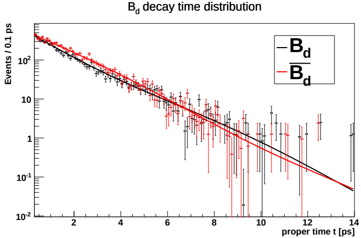
Fit results

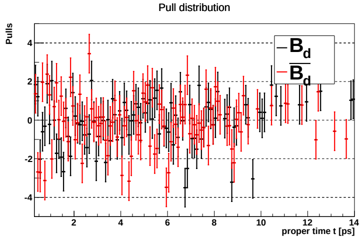
Long Tracks





Downstream Tracks





fit results

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

Parameter	long	downstream
$S_{J/\Psi K_s^0}$(blinded)	0.610±0.078	0.535±0.063
$S_{J/\Psi K_s^0}$(2011)	*xxx*±0.11	*xxx*±0.08
τ_{eff}	1.355±0.021	1.498±0.017
Δm_d	0.60±0.05	0.47±0.03
Δm_d(2011)	0.58±0.15	0.50±0.04

Note: τ_{eff} not compatible to PDG values due to neglect of acceptance and biased trigger lines Question: Why is Δm_d that much higher in the long track sample?

Systematic errors

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

Systematic errors

Fit Bias

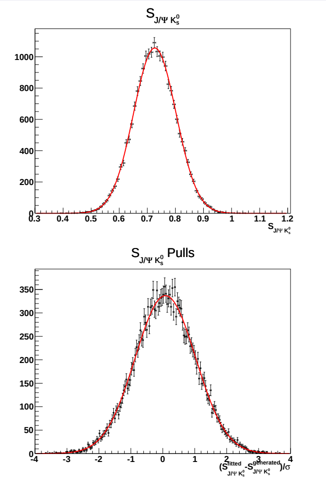
Generate Toy MC with

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

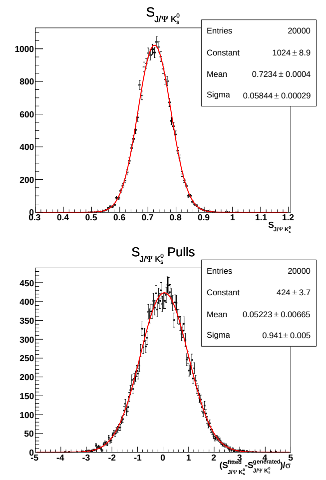
Systematic errors

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

$$\mu_{S_{J/\Psi K_s^0}} = 0.7234 \pm 0.0004$$
$$\sigma_{S_{J/\Psi K_s^0}} = 0.0584 \pm 0.0003$$
$$\mu_{\text{pull}} = 0.052 \pm 0.007$$
$$\sigma_{\text{pull}} = 0.941 \pm 0.005$$

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

Long Tracks

$$\delta S^{\text{Fit}}_{J/\Psi K_s^0} = 0.0066$$

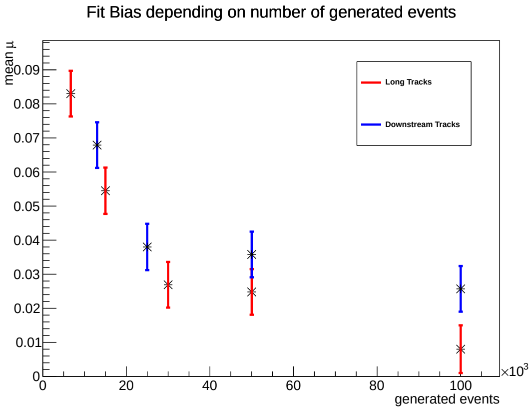
Downstream Tracks

$$\delta S^{\text{Fit}}_{J/\Psi K_s^0} = 0.0033$$

Systematic errors

Fit Bias - origins

- too small pull width due to background ($\rightarrow$ overestimation of fit error)
- major contribution to bias: too little statistics
- σ_{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
2. in the generation of Toy MC, but fit with original values

Note: Systematic studies on used tagging calibration hasn't finished yet $\longrightarrow$ no official value. Use systematic errors of 2011:

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

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

- Long tracks: $\delta S_{J/\Psi K_s^0}^{\mathrm{TagCalib}} = 0.0320$
- Downstream tracks: $\delta S_{J/\Psi K_s^0}^{\mathrm{TagCalib}} = 0.0331$

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

Determination of an acceptance function

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

Systematic errors

Time acceptance

Fit p.d.f

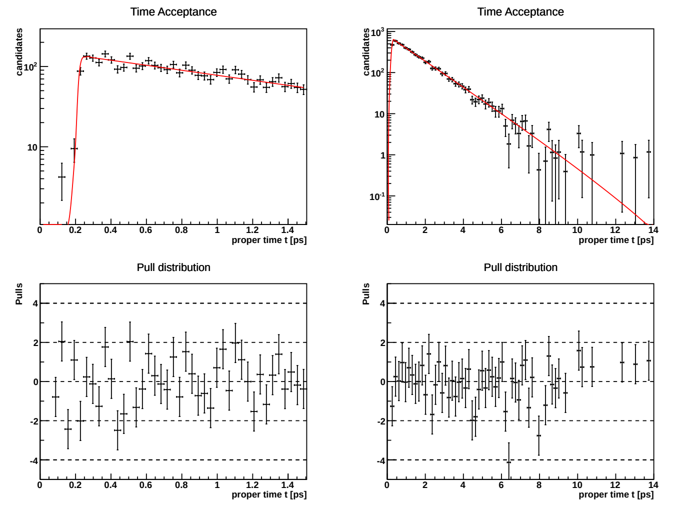
$$\mathcal{P}_{acc}(t) \propto \underbrace{e^{-t/\tau}}_{\text{exp. decay}} \cdot \underbrace{\frac{2}{\pi}\arctan[t \cdot \exp(at+b)]}_{\text{turn-on-effect}} \cdot \underbrace{(1+\beta t)}_{\substack{\text{higher lifetimes} \\ (\beta<0)}}$$

Note: τ will be constrained to the PDG value
$\tau = 1.519 \pm 0.007\mathrm{ps}.$

Systematic errors

Time acceptance

Long Tracks



Downstream Tracks

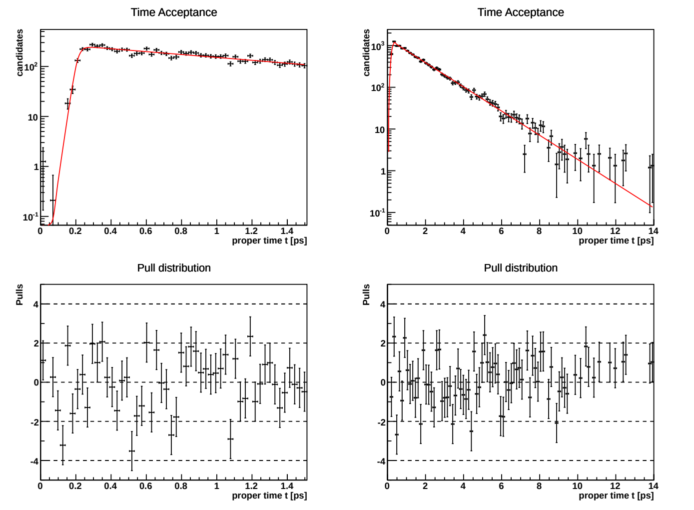


Table : Fit results for exponential decay fit with acceptance function. τ was constrained to the PDG value $\tau = 1.519 \pm 0.007\mathrm{ps}$

parameter	long	downstream
τ	1.518±0.007	1.519±0.007
a	153±36	47.9±5.6
b	-31.44±7.7	-8.4±1.1
β	-0.057±0.007	-0.0090±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 cooresponding mean of fit bias toy

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

Long Tracks

$$\delta S^{\mathrm{Acc}}_{J/\Psi K_s^0} = 0.0003$$

Downstream Tracks

$$\delta S^{\mathrm{Acc}}_{J/\Psi K_s^0} = 0.0008$$

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	$t \in [0.3, 0.7]\mathrm{ps}$	0.614±0.078	0.532±0.063
2	$t \in [0.7, 1.5]\mathrm{ps}$	0.608±0.078	0.536±0.063
3	$t \in [1.5, 3]\mathrm{ps}$	0.609±0.079	0.536±0.063
4	$t \in [3, 14]\mathrm{ps}$	0.609±0.078	0.535±0.062
nominal fit		0.610±0.078	0.534±0.063
$\delta S_{J/\Psi K_s^0}^{\mathrm{mass/t}}$		0.0020	0.0018

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

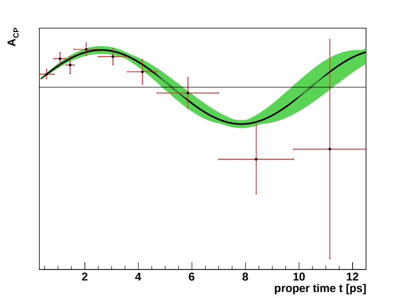
	long	down
$+20\%$	0.6100±0.0782	0.5351±0.0626
-20%	0.6095±0.0782	0.5345±0.0625
nominal fit	0.6098±0.0782	0.5347±0.0626
$\delta S_{J/\Psi K_s^0}^{\text{resolution}}$	0.0003	0.0004

Systematic errors
Summary

effect	long	downstream
fit method	0.0066	0.0033
tagging calibration	0.0320	0.0331
time acceptance	0.0003	0.0008
mass $\leftrightarrow$ decay time	0.0020	0.0018
resolution	0.0003	0.0004
total	0.0328	0.0333

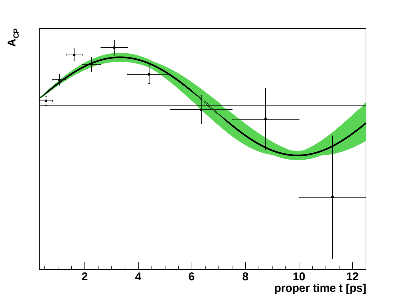
Conclusion

Long Tracks



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

Downstream Tracks



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

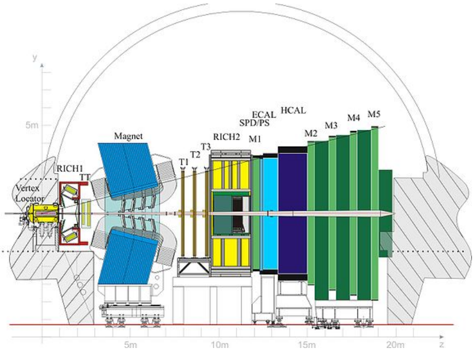
Both results are blinded with the same string

Conclusion
Comparison with other results

	$S_{J/\Psi K_s^0}$
long tracks (blinded)	0.610±0.0740.033± 0.033
downstream tracks (blinded)	0.565±0.059± 0.033
combined	xxx±0.046± 0.023
2011 analysis	0.72± 0.06 ±0.04
world average	0.679±0.020
BaBar (most precise)	0.687±0.028±0.012

BACKUP

LHCb-detector



Tracks

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

Decay time fit

derivation of probability density function

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

Imperfect tagging:

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

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

Combination of all effects and defining

$$\Delta p_0 = \omega_{B_d^0} - \omega_{\overline{B_d^0}} \tag{13}$$

$$\omega_{B_d^0/\overline{B_d^0}} = \omega \pm \frac{\Delta p_0}{2} \tag{14}$$

leads to...

Decay time fit

probability density function used in fit

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

- 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
- ω: calibrated mistag probability

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

  p_0, p_1: calibration parameters
  η^{OS}: predicted mistag probability
- Δp_0: tagging calibration asymmetry
- Δm_d: mixing frequency