Measurement of the Mixing Phase ϕ_s in $B_s \to J/\psi\phi$

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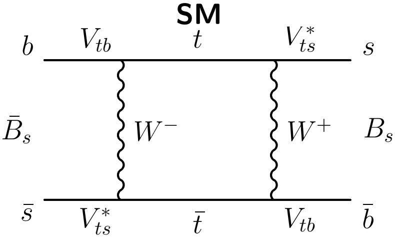
1 Introduction

2 Determination of ϕ_s

3 Prospects @ LHCb

4 Conclusions

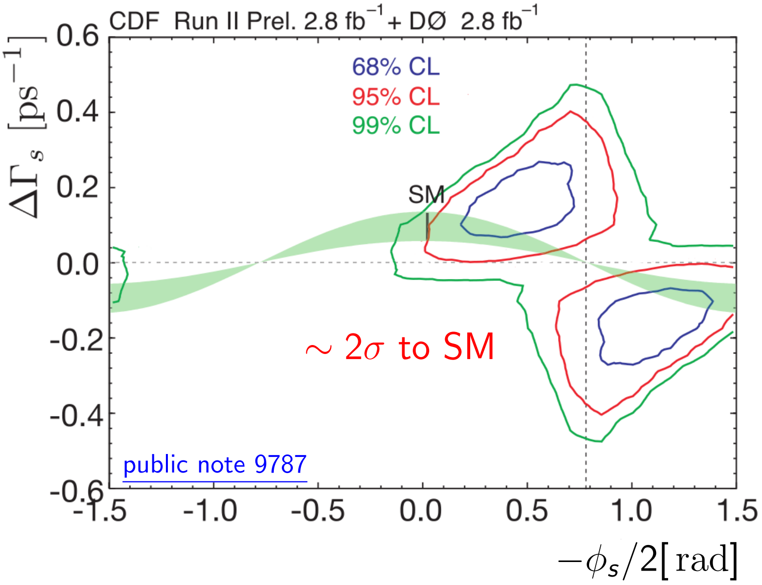
B_s-Mixing



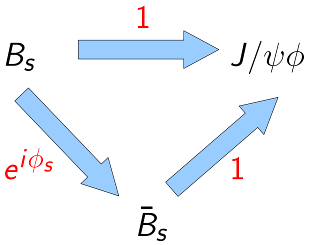
B_s mixing is defined by three quantities

- Mixing frequency $\Delta m = M_H - M_L$
  $\Delta m = (17.77 \pm 0.12)\,\mathrm{ps}^{-1}$ (CDF, hep-ex/0609040)
- Decay width difference $\Delta\Gamma = \Gamma_L - \Gamma_H$
  $\Delta\Gamma_{SM} \sim 0.1\,\mathrm{ps}^{-1}$
- Mixing phase $\phi_s = \phi_s^{SM} + \phi_s^{NP}$
  $\phi_s^{SM} = -2\beta_s = -0.04$

Current Experimental Status



$B_s \longrightarrow J/\psi\phi$



- CPV in interference between decay and mixing and decay
- Time dependent CP-Asymmetry (for CP eigenstates):

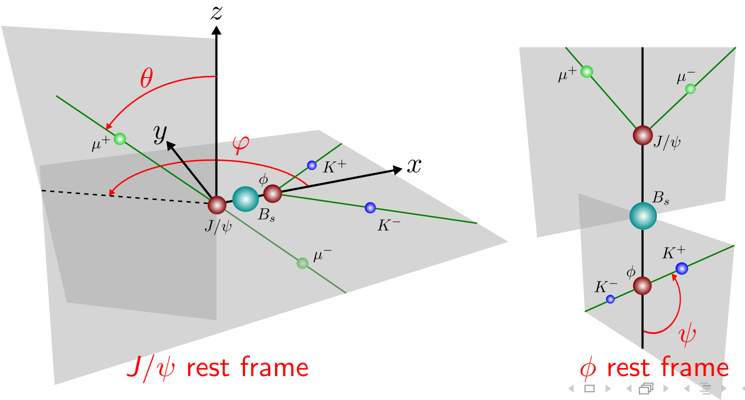
$$A_{CP}(t) = \frac{\Gamma\left(\bar{B}_s(t) \to f_{CP}\right) - \Gamma(B_s(t) \to f_{CP})}{\Gamma\left(\bar{B}_s(t) \to f_{CP}\right) + \Gamma(B_s(t) \to f_{CP})} = -\eta_f \sin\phi_s \sin(\Delta m t)$$

- $CP|f\rangle = \eta_f|f\rangle$
- $f = J/\psi\phi$ is no CP eigenstate

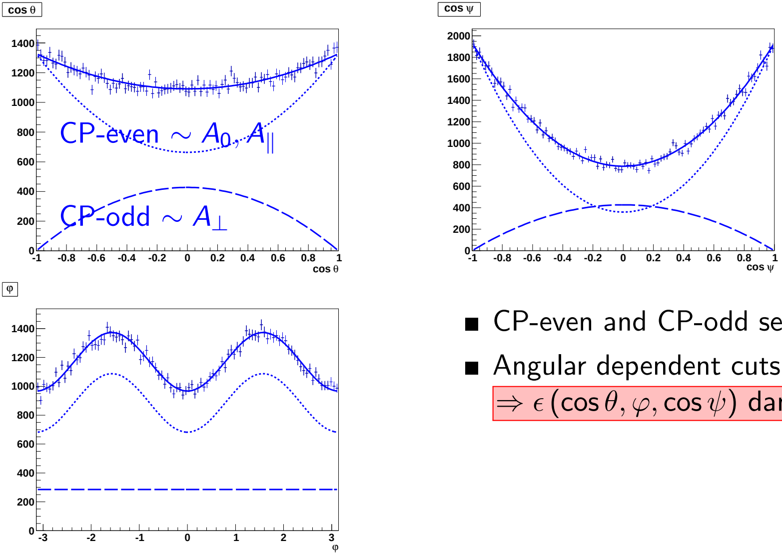
Angular Analysis of $B_s \to J/\psi\phi$

- J/ψ and ϕ are vector mesons with relative angular momentum L
- $\eta_f = CP\,(J/\psi\phi) = (-1)^L$
- Separate CP-odd and CP-even by angular analysis

η_f	L	Amplitude
+1	0	$A_0, A_\parallel$
-1	1	$A_\perp$
+1	2	$A_0, A_\parallel$



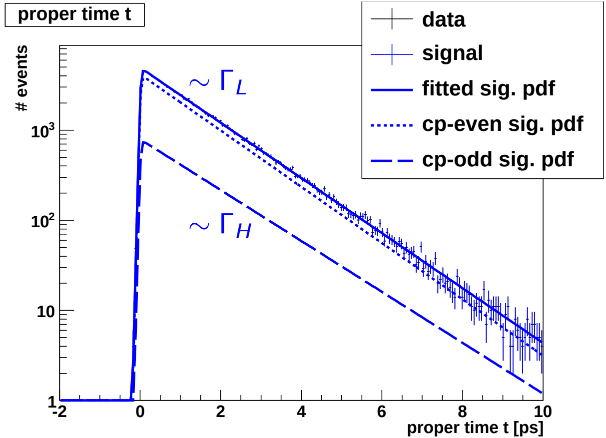
Angular separation of CP-even and CP-odd component



- CP-even and CP-odd separation
- Angular dependent cuts

  $\Rightarrow \epsilon\left(\cos\theta, \varphi, \cos\psi\right)$ dangerous

Decay time for CP-even and CP-odd component



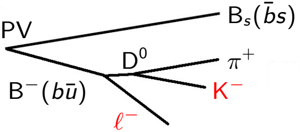
- CP-even and CP-odd slightly separated: $\Gamma_L = \Gamma + \frac{\Delta\Gamma}{2}$, $\Gamma_H = \Gamma - \frac{\Delta\Gamma}{2}$
- Time dependent cuts $\Rightarrow \epsilon(t)$ dangerous
- Correlation between t and the angles $\cos\theta, \varphi, \cos\psi$

Tagging = B_s production flavour determination

$$A_{CP}(t) = \frac{\Gamma\left(\bar{B}_s(t)\to f_{CP}\right) - \Gamma\left(B_s(t)\to f_{CP}\right)}{\Gamma\left(\bar{B}_s(t)\to f_{CP}\right) + \Gamma\left(B_s(t)\to f_{CP}\right)} = -\eta_f \sin\phi_s \sin(\Delta m t)$$

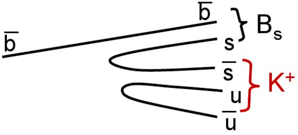
Need to determine the B_s flavour at production: Flavour Tagging

Opposite side Tagging (OST)



Opposite side ℓ/K/Vtx charge

Same side Tagging (SST)



Charge of K from fragmentation

- Tagging not perfect: mistag probability ω, tagging efficiency ϵ_{tag}
- $\Gamma\left(\bar{B}_s \to f_{CP}\right) \Rightarrow (1-\omega)\Gamma\left(\bar{B}_s \to f_{CP}\right) + \omega\Gamma\left(B_s \to f_{CP}\right)$
  $\Gamma\left(B_s \to f_{CP}\right) \Rightarrow (1-\omega)\Gamma\left(B_s \to f_{CP}\right) + \omega\Gamma\left(\bar{B}_s \to f_{CP}\right)$
  $\Rightarrow A_{CP}(t) = -\eta_f (1-2\omega) \sin\phi_s \sin(\Delta m t)$
- Knowledge of ω required $\Rightarrow$ **Tagging Calibration**

Opposite Side Tagger Calibration with $B^+ \to J/\psi K^+$

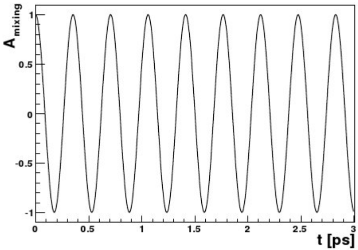
Opposite Side Tagger Calibration with $B^+ \to J/\psi K^+$

- Reconstruct $B^+ \to J/\psi K^+$
  No $B^+(u\bar{b})$ oscillation $\Rightarrow$ Know flavour of the other B (Xb)
- Combined OST: $\epsilon = 45.6\%$, $\omega = 36.5\%$

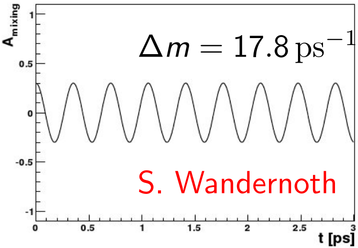
- Tagging power: $\epsilon\,(1-2\omega)^2 = \epsilon\mathcal{D}^2$
- $\sigma_{\text{stat.}}\,(\phi_s) \propto \frac{1}{\sqrt{\epsilon(1-2\omega)^2}}$
- From Opposite Side Taggers only: $\epsilon\,(1-2\omega)^2 = 3.3\%$

Same Side Tagger Calibration with $B_s^0 \to D_s^- \pi^+$

- Mixing asymmetry $A_{\text{mixing}}(t) = \frac{N_{\text{unmixed}}(t) - N_{\text{mixed}}(t)}{N_{\text{unmixed}}(t) + N_{\text{mixed}}(t)}$



(a) perfect tagging



(b) realistic tagging

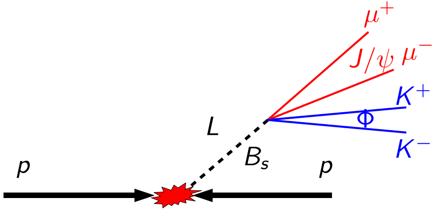
- $A_{\text{mixing}}^{\text{measured}} = (1 - 2\omega) A_{\text{mixing}}$
- Good knowledge of decay time resolution needed (M. Schiller)
- Same Side Kaon Tagger $\epsilon = 26.4\%$, $\omega = 34.9\%$

Combination of Opposite and Same Side Taggers: $\epsilon(1 - 2\omega)^2 = 6.2\%$

Decay time measurement

Need to resolve the fast ($\sim 17.8\,\mathrm{ps}^{-1}$) B_s oscillation:

$$A_{CP}(t) = \frac{\Gamma(\bar{B}_s(t)\to f_{CP}) - \Gamma(B_s(t)\to f_{CP})}{\Gamma(\bar{B}_s(t)\to f_{CP}) + \Gamma(B_s(t)\to f_{CP})} \propto -\eta_F \sin\phi_s \sin\Delta m t$$



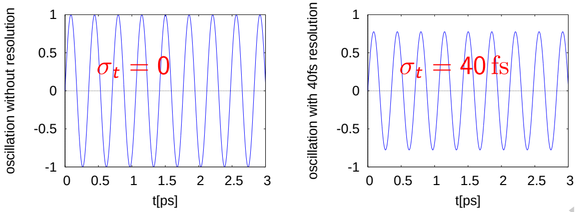
$$t = \frac{\vec{L}\cdot\vec{p}\, m_{B_s}}{|\vec{p}|^2} = \frac{L m_{B_s}}{p}$$

$$\sigma_t = \sqrt{\left(\frac{m_{B_s}}{p}\sigma_L\right)^2 + \left(\frac{L\cdot m_{B_s}}{p^2}\sigma_p\right)^2}$$

$\frac{\Delta p}{p} < 1\%$

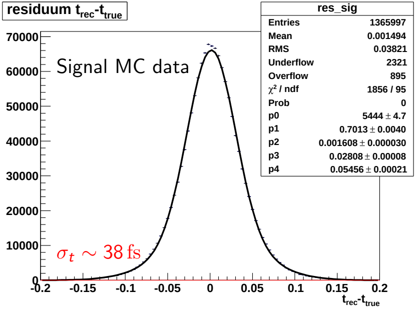
σ_t dominated by vertex resolution

Gaussian Convolution: $\sin(\Delta m t) \Rightarrow e^{-\frac{\Delta m^2 \sigma_t^2}{2}} \sin(\Delta m t)$



σ_t calibration

1. Take σ_t from Monte Carlo prediction



2. Fit σ_t from data (add. parameter $\rightarrow$ Larger $\sigma_{\text{stat.}}$)
3. Extract σ_t from data using prompt J/ψ (A. Weber)

Signal Selection

Goals for unified trigger and offline selection

- Maximize signal yield
- Minimize biases (Angular, Decay time acceptance)

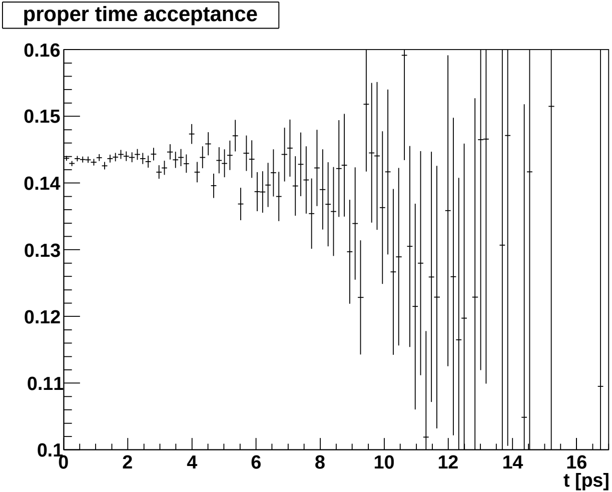
Interaction	$\Rightarrow$	L0	$\Rightarrow$	HLT	$\Rightarrow$	Offline
40 MHz		1 MHz		2 kHz		

$$\epsilon_{tot} = \underbrace{\epsilon_{rec}}_{0.045} \cdot \underbrace{\epsilon_{sel}}_{0.62} \cdot \underbrace{\epsilon_{L0}}_{0.94} \cdot \underbrace{\epsilon_{HLT}}_{0.75} = \boxed{1.96\%}$$

$$\text{Annual Yield } \mathcal{S} = \epsilon_{tot} \cdot \underbrace{\mathcal{L}_{int}}_{2\,\mathrm{fb}^{-1}} \cdot 2\, \underbrace{\sigma_{b\bar{b}}}_{500\mu b} \cdot \underbrace{f_{B_s}}_{0.11} \cdot \underbrace{\mathcal{BR}\left(B_s \to J/\psi[\mu\mu]\phi[KK]\right)}_{2.7\cdot 10^{-5}} = \boxed{117\text{k}}$$

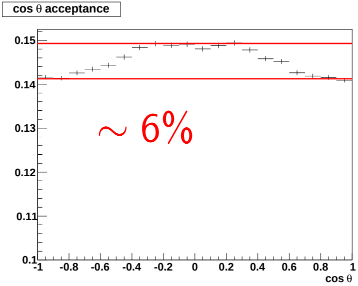
Signal Yield	Bkg. from prompt J/ψ: B/S	Bkg. from $b\bar{b}$: B/S
117k	1.6	0.5

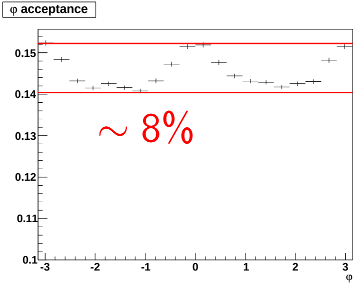
Decay Time Acceptance

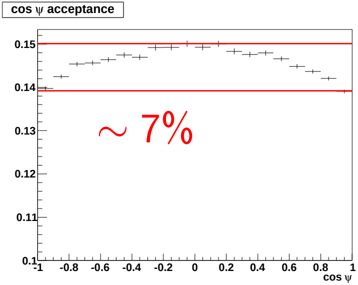


- Acceptance practically flat

Angular Acceptances due to Selection and Geometry







- Effect mainly due to detector geometry: $30 - 300\,\mathrm{mrad}$
- Bias in $|A_0|$, $|A_\perp|$ if neglected
- Control via $B^0 \to J/\psi K^{*0}$

Extraction of the Physics Parameters: Likelihood Fit

- Physics Parameter extraction using an Unbinned Maximum Likelihood Fit
- Likelihood $\mathcal{L} = \prod_i^{\text{all events}} \mathcal{P}_i\left(t_i, \cos\theta_i, \varphi_i, \cos\psi_i, m_i, q_i | \phi_s, \ldots\right)$
- The PDF $\mathcal{P}$ consist of signal $\mathcal{S}$ and background component $\mathcal{B}$

$$\mathcal{P}_i = f_{\text{sig}}\mathcal{S}_i + (1 - f_{\text{sig}})\,\mathcal{B}_i$$

- The signal component $\mathcal{S}$:

$$\begin{aligned}\mathcal{S}_i &= \frac{1 + q_i\left(1 - 2\omega\right)}{2}\mathcal{P}_{B_s}\left(t_i, \cos\theta_i, \varphi_i, \cos\psi_i | \phi_s, \ldots\right) \\ &+ \frac{1 - q_i\left(1 - 2\omega\right)}{2}\mathcal{P}_{\bar{B}_s}\left(t_i, \cos\theta_i, \varphi_i, \cos\psi_i | \phi_s, \ldots\right)\end{aligned}$$

- Minimize neg. log. Likelihood by varying ϕ_s and other parameters

$$-\ln\mathcal{L} = -\sum_i^{\text{all events}} \ln\mathcal{P}_i$$

$\Rightarrow$ Finds the parameter values for which the data is most likely

Extraction of the Physics Parameters: Full PDF

$$\mathcal{P}_{B_s} = \sum_{i=1}^{6} A_i(t) \cdot f_i(\cos\Theta, \varphi, \cos\Psi)$$

$$\mathcal{P}_{\bar{B}_s} = \sum_{i=1}^{6} \bar{A}_i(t) \cdot f_i(\cos\Theta, \varphi, \cos\Psi)$$

i	$f_i(\cos\Theta, \varphi, \cos\Psi)$
1	$\frac{9}{32\pi} 2\cos^2\psi \left(1 - \sin^2\Theta\cos^2\varphi\right)$
2	$\frac{9}{32\pi} \sin^2\psi \left(1 - \sin^2\Theta\sin^2\varphi\right)$
3	$\frac{9}{32\pi} \sin^2\psi \sin^2\Theta$
4	$-\frac{9}{32\pi} \sin^2\psi \sin 2\Theta \sin\varphi$
5	$\frac{9}{32\pi\sqrt{2}} \sin 2\psi \sin^2\Theta \sin 2\varphi$
6	$\frac{9}{32\pi\sqrt{2}} \sin 2\psi \sin 2\Theta \cos\varphi$

$$|A_0(t)|^2 = |A_0|^2 e^{-\Gamma t}\left[\cosh\left(\frac{\Delta\Gamma t}{2}\right) - \cos\phi_s \sinh\left(\frac{\Delta\Gamma t}{2}\right) \pm \sin\phi_s \sin(\Delta m t)\right]$$

$$\left|A_{\parallel}(t)\right|^2 = \left|A_{\parallel}\right|^2 e^{-\Gamma t}\left[\cosh\left(\frac{\Delta\Gamma t}{2}\right) - \cos\phi_s \sinh\left(\frac{\Delta\Gamma t}{2}\right) \pm \sin\phi_s \sin(\Delta m t)\right]$$

$$|A_{\perp}(t)|^2 = |A_{\perp}|^2 e^{-\Gamma t}\left[\cosh\left(\frac{\Delta\Gamma t}{2}\right) + \cos\phi_s \sinh\left(\frac{\Delta\Gamma t}{2}\right) \mp \sin\phi_s \sin(\Delta m t)\right]$$

$$\Im\left(A_{\parallel}^*(t)A_{\perp}(t)\right) = \left|A_{\parallel}\right| |A_{\perp}| e^{-\Gamma t}\left[-\cos\left(\delta_{\perp} - \delta_{\parallel}\right)\sin\phi_s \sinh\left(\frac{\Delta\Gamma t}{2}\right) \pm \sin\left(\delta_{\perp} - \delta_{\parallel}\right)\cos(\Delta m t) \mp \cos\left(\delta_{\perp} - \delta_{\parallel}\right)\cos\phi_s \sin(\Delta m t)\right]$$

$$\Re\left(A_0^*(t)A_{\parallel}(t)\right) = |A_0| \left|A_{\parallel}\right| e^{-\Gamma t}\cos\delta_{\parallel}\left[\cosh\left(\frac{\Delta\Gamma t}{2}\right) - \cos\phi_s \sinh\left(\frac{\Delta\Gamma t}{2}\right) \pm \sin\phi_s \sin(\Delta m t)\right]$$

$$\Im\left(A_0^*(t)A_{\perp}(t)\right) = |A_0| |A_{\perp}| e^{-\Gamma t}\left[-\cos\delta_{\perp}\sin\phi_s \sinh\left(\frac{\Delta\Gamma t}{2}\right) \pm \sin\delta_{\perp}\cos(\Delta m t) \mp \cos\delta_{\perp}\cos\phi_s \sin(\Delta m t)\right]$$

Sign flip for $\bar{B}_s$

Extraction of the Physics Parameters: Full PDF

$$\mathcal{P}_{B_s} = \sum_{i=1}^{6} A_i(t) \cdot f_i(\cos\Theta, \varphi, \cos\Psi)$$

$$\mathcal{P}_{\bar{B}_s} = \sum_{i=1}^{6} \bar{A}_i(t) \cdot f_i(\cos\Theta, \varphi, \cos\Psi)$$

i	$f_i(\cos\Theta, \varphi, \cos\Psi)$
1	$\frac{9}{32\pi} 2\cos^2\psi \left(1 - \sin^2\Theta\cos^2\varphi\right)$
2	$\frac{9}{32\pi} \sin^2\psi \left(1 - \sin^2\Theta\sin^2\varphi\right)$
3	$\frac{9}{32\pi} \sin^2\psi \sin^2\Theta$
4	$-\frac{9}{32\pi} \sin^2\psi \sin 2\Theta \sin\varphi$
5	$\frac{9}{32\sqrt{}} \sin 2\psi \sin^2\Theta \sin 2\varphi$
	φ

Simplified

- Measure $t, \cos\theta, \varphi, \cos\psi, m_{B_s}, q$ for all events
- Extract $\phi_s, \Delta\Gamma,$ $\Gamma, \Delta m, |A_0|^2, |A_\perp|^2, \delta_\parallel, \delta_\perp$ using the Maximum Likelihood technique

$$|A_0(t)|^2 = |A_0 \ldots$$

$$|A_\parallel(t)|^2 = |A_\parallel \ldots$$

$$|A_\perp(t)|^2 = |A_\perp \ldots$$

$$\Im\left(A_\parallel^*(t)A_\perp(t)\right) = |A_\parallel||A_\perp| e^{-\Gamma t}\left[-\cos\left(\delta_\perp - \delta_\parallel\right)\sin\phi_s \sinh\left(\frac{\Delta\Gamma t}{2}\right) \pm \sin\left(\delta_\perp - \delta_\parallel\right)\cos(\Delta m t) \mp \cos\left(\delta_\perp - \delta_\parallel\right)\cos\phi_s \sin(\Delta m t)\right]$$

$$\Re\left(A_0^*(t)A_\parallel(t)\right) = |A_0||A_\parallel| e^{-\Gamma t}\cos\delta_\parallel\left[\cosh\left(\frac{\Delta\Gamma t}{2}\right) - \cos\phi_s \sinh\left(\frac{\Delta\Gamma t}{2}\right) \pm \sin\phi_s \sin(\Delta m t)\right]$$

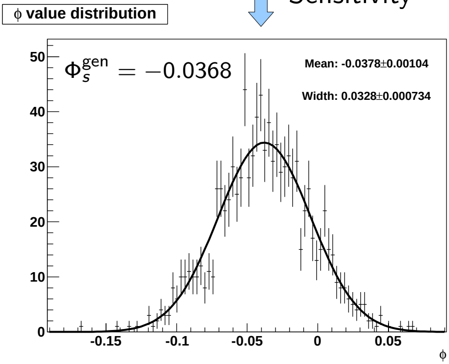
$$\Im\left(A_0^*(t)A_\perp(t)\right) = |A_0||A_\perp| e^{-\Gamma t}\left[-\cos\delta_\perp \sin\phi_s \sinh\left(\frac{\Delta\Gamma t}{2}\right) \pm \sin\delta_\perp \cos(\Delta m t) \mp \cos\delta_\perp \cos\phi_s \sin(\Delta m t)\right]$$

Sign flip for $\bar{B}_s$

LHCb Sensitivity for One Nominal Year ($2\,\mathrm{fb}^{-1}$)

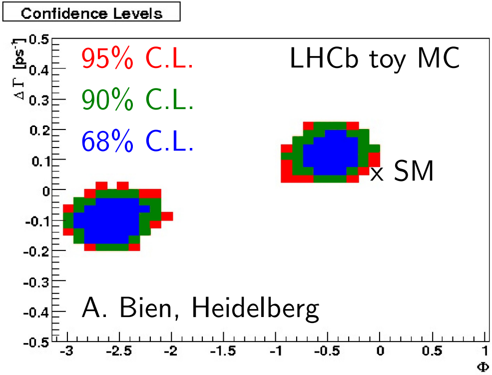
Generate and fit 1000 data sets of toy MC corresponding to $2\,\mathrm{fb}^{-1}$

Sensitivity $= \sigma\,(\phi_s$ distribution)



parameter	sensitivity ($2\,\mathrm{fb}^{-1}$)	unit
ϕ_s	0.033 ± 0.001	rad
$\Delta\Gamma_s$	0.009 ± 0.000	ps^{-1}
$\lvert A_0\rvert^2$	0.003 ± 0.000	
$\lvert A_\perp\rvert^2$	0.004 ± 0.000	
$\delta_\parallel$	0.097 ± 0.002	rad
$\delta_\perp$	0.118 ± 0.003	rad
Γ_s	0.003 ± 0.000	ps^{-1}
Δm_s	0.048 ± 0.001	ps^{-1}

For Low Statistics: Feldman-Cousins method



- $N_{\text{signal}} = 2925\ (50\,\mathrm{pb}^{-1})$
- $\phi_s = -0.736$
- Tagging:
  $\omega = 0.33,\ \epsilon = 56\%$
- t Resolution: $\sigma_t = 40\,\mathrm{fs}$

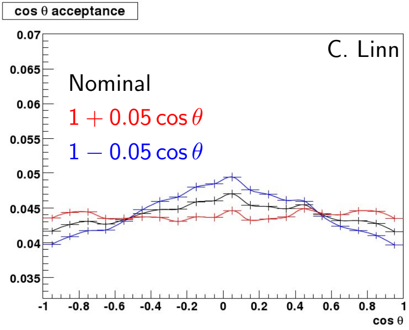
⇒ Promising for early data

Summary and Conclusion

- Determination of ϕ_s is one of the key measurements at LHCb
- Precise determination of ϕ_s requires detailed knowledge of
  - Tagging
  - Resolutions
  - Acceptances
  - Background
- Sensitivity $2\,\mathrm{fb}^{-1}$: $\sigma(\phi_s) = 0.03\,\mathrm{rad}$
- Already with $50\,\mathrm{pb}^{-1}$ we are competitive with the current Tevatron limit

Control of the Angular Acceptances with $B^0 \to J/\psi K^{*0}$

- Angular distribution of $B^0 \to J/\psi[\mu\mu]K^{*0}[K^+\pi^-]$ well known
- Distortion study:



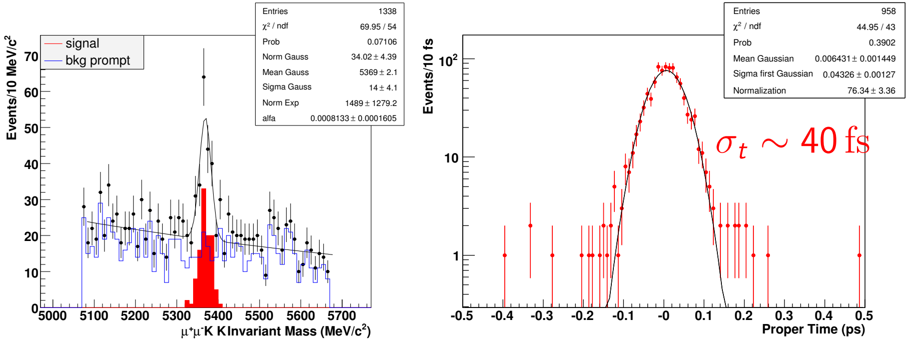
parameter	deviation [%]
$\lvert A_{\parallel}\rvert^2$	6.74 ± 0.13
$\lvert A_{\perp}\rvert^2$	-13.29 ± 0.13

parameter	deviation [%]
$\lvert A_{\parallel}\rvert^2$	-6.49 ± 0.13
$\lvert A_{\perp}\rvert^2$	13.20 ± 0.19

Babar measurement	
parameter	rel. prec. [%]
$\lvert A_{\parallel}\rvert^2$	5.5
$\lvert A_{\perp}\rvert^2$	4.8

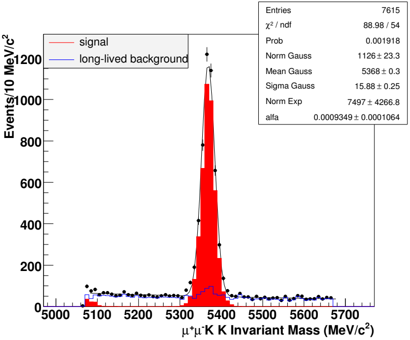
- We will probably not see acceptance deviations $< 5\%$
  $\Rightarrow$ Sufficient for ϕ_s measurement

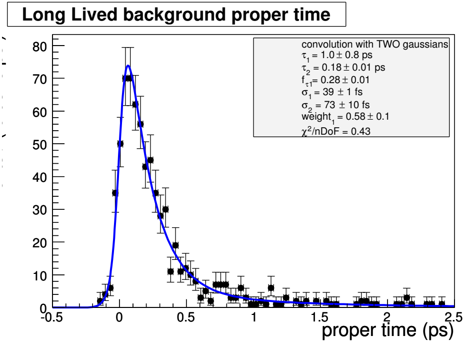
Background from prompt J/ψ



- Combinatorics from PV (prompt J/ψ)
- Main background
- Easy to separate from signal in Likelihood fit: $t \sim 0$
- Can be used to estimate time resolution: $\sigma_t \sim 40\,\text{fs}$

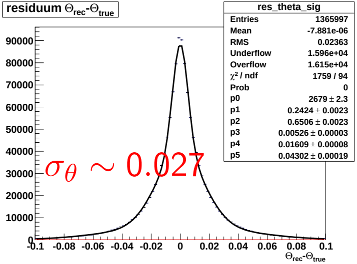
$b\bar{b}$ Background

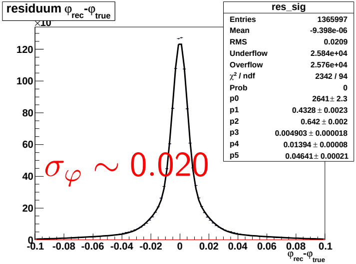


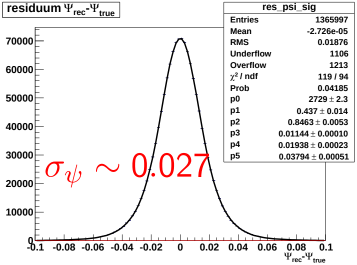


- Combinatorics from B-decays
- Significant livetime $\tau \sim 0.18\,\mathrm{ps}$ (signal $\tau \sim 1.5\,\mathrm{ps}$)

Angular Resolutions





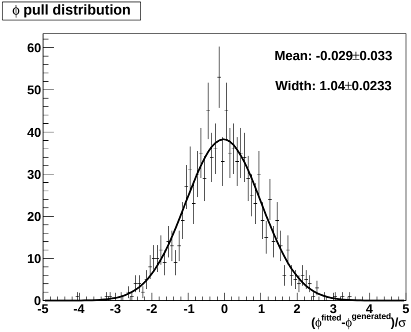


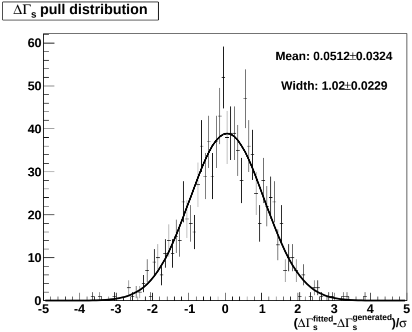
- No effect seen for nominal resolution
- For 3σ: Bias in $|A_0|$

Check fitting procedure: Pull distributions

Repeatedly generate and fit toydata $\Rightarrow$ $\text{pull} = \frac{\phi_s^{\text{generated}} - \phi_s^{\text{fitted}}}{\sigma_{\phi_s}^{\text{fitted}}}$

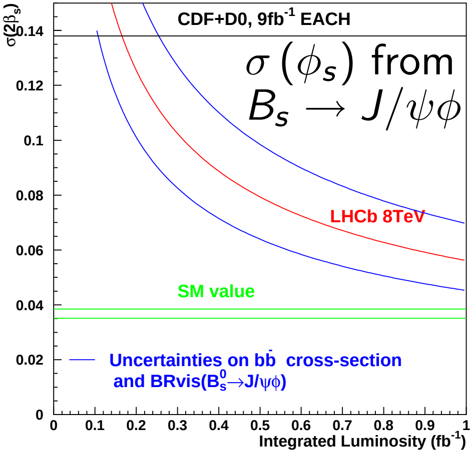
Fitting method works correctly if $\bar{p} \sim 0$, $\sigma_p \sim 1$



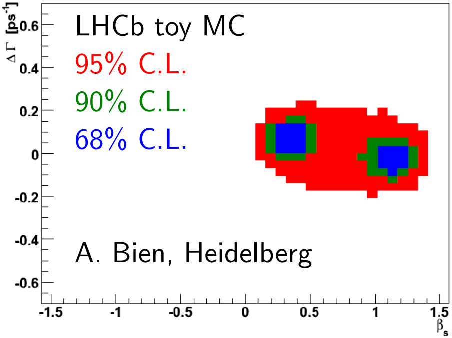


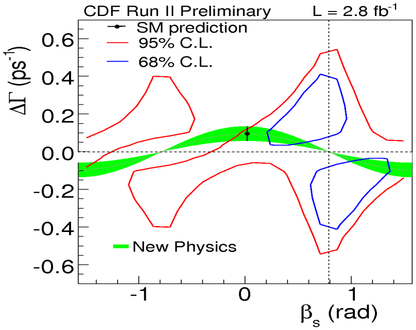
$\Rightarrow$ No bias, correct error estimation

ϕ_s Sensitivity for 0.2 to 1 fb^{-1}



Feldman-Cousins method: LHCb and CDF





3200 signal events

$\sigma_t = 40\,\mathrm{fs}$

3200 signal events

$\sigma_t = 100\,\mathrm{fs}$