Analysis of the decay $B_s \to J/\psi\phi$ at LHCb

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Overview

1. Motivation for the analysis of $B_s \to J/\psi\phi$
2. Reconstructing the decay $B_s \to J/\psi\phi$ using LHCb
3. Important ingredients for the extraction of ϕ_s
4. Prospects and Summary

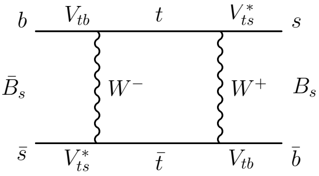
B_s-Mixing

- Time dev. governed by Schrödinger E.:

$$i\frac{d}{dt}\begin{pmatrix} B_s \\ \bar{B}_s \end{pmatrix} = \left(\mathrm{M} - \frac{i}{2}\Gamma \right) \begin{pmatrix} B_s \\ \bar{B}_s \end{pmatrix}$$

$$\Longrightarrow \quad i\frac{d}{dt}B_L = (M_L - \tfrac{i}{2}\Gamma_L)B_L \quad \text{light}$$

$$\text{Diag.} \quad i\frac{d}{dt}B_H = (M_H - \tfrac{i}{2}\Gamma_H)B_H \quad \text{heavy}$$



- Mixing Parameters

Mixing frequency: $\Delta m = M_H - M_L = 2|M_{12}| = (17.8 \pm 0.1)\,\mathrm{ps}^{-1}$ [CDF]

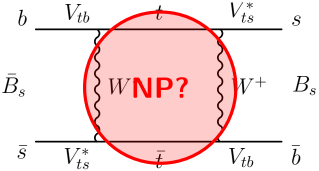
Decay width diff.: $\Delta\Gamma = \Gamma_L - \Gamma_H \approx 0.1\,\mathrm{ps}^{-1}$

Mixing phase: $\phi_M = 2\arg V_{ts}V_{tb}^*$

- Beyond the SM

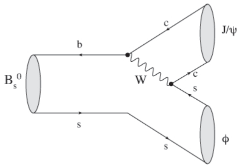
New virtual particles in box diagrams

$$\phi_M \to \phi_M^{SM} + \Delta\phi^{NP}$$

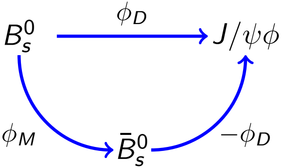


CP-violating Phase ϕ_s

- $B_s \to J/\psi\phi$ dominated by $\bar{b} \to \bar{c}c\bar{s}$ tree level transition
  - Small penguin pollution
  - Dominated by single phase $\phi_D = \arg V_{cs} V_{cb}^*$



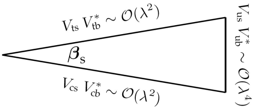
- Interference between decay and mixing and decay gives rise to CP-violating phase ϕ_s
  $\phi_s = \phi_M - 2\phi_D$



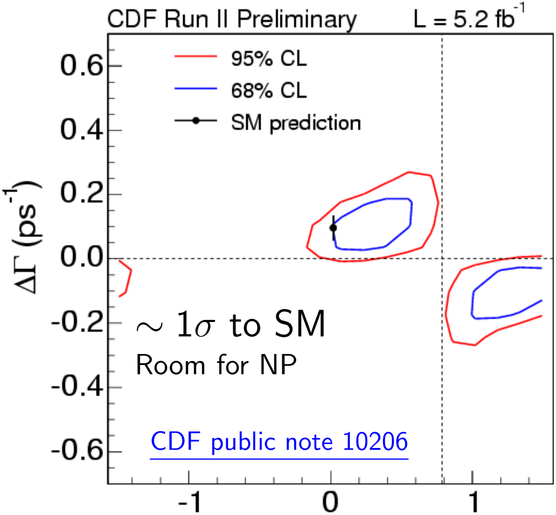
- Precise Standard Model prediction

$$\begin{aligned} \phi_s &= 2 \arg V_{ts} V_{tb}^* - 2 \arg V_{cs} V_{cb}^* \\ &= -2\beta_s = -0.0360^{+0.0016}_{-0.0020} \,\mathrm{rad} \end{aligned}$$

Deviations $\phi_s \to \phi_s^{SM} + \Delta\phi^{NP}$ from SM can be attributed to NP



Current Experimental Status



$\sim 1\sigma$ to SM

Room for NP

CDF public note 10206

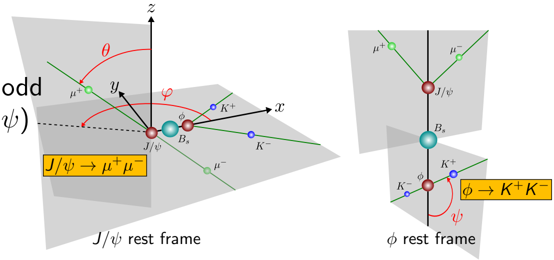
$-\phi_s/2[\mathrm{rad}]$

Measuring ϕ_s using $B_s \to J/\psi\phi$ via Angular Analysis

- $P \to VV$: final state $J/\psi\phi$ is admixture of
  CP-even ($\ell = 0, 2$): A_0, $A_\parallel$
  CP-odd ($\ell = 1$): $A_\perp$

$\mathrm{CP}|J/\psi\phi\rangle = (-1)^\ell |J/\psi\phi\rangle$

- Separate CP-even and CP-odd via angular analysis (θ, φ, ψ)



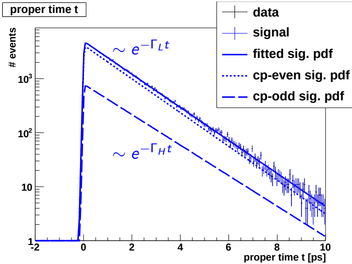
- Using Unbinned max. Likelihood fit to statistically disentangle final state
  - Observables: $\theta, \varphi, \psi, \mathrm{t}, m_{B_s}$, initial B_s flavour
  - Physics parameters: $\phi_s, \Gamma_s, \Delta\Gamma_s, \Delta m_s, |A_0|^2, |A_\perp|^2, \delta_\parallel, \delta_\perp$
  - Detector parameters: time and mass resolution, bkg. description etc.

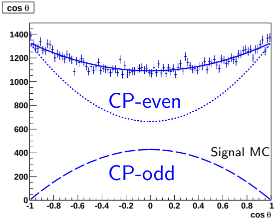
Differential Decay Rate for $B_s \to J/\psi\phi$

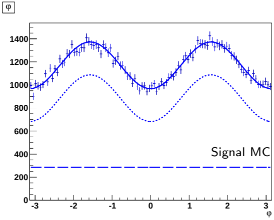
Time and parameter dependent Amplitudes

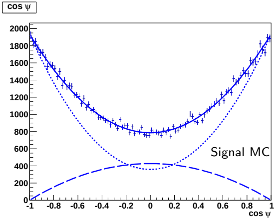
$$\frac{d^4\Gamma(B_s \to J/\psi\phi)}{d\cos\theta\, d\varphi\, d\cos\psi\, dt} = \sum_{i=1}^{6} \overbrace{A_i(t|\phi_s, \Delta\Gamma_s, \ldots)}\, \underbrace{f_i(\cos\theta, \varphi, \cos\psi)}$$

Angular dependent terms for CP-even/odd separation

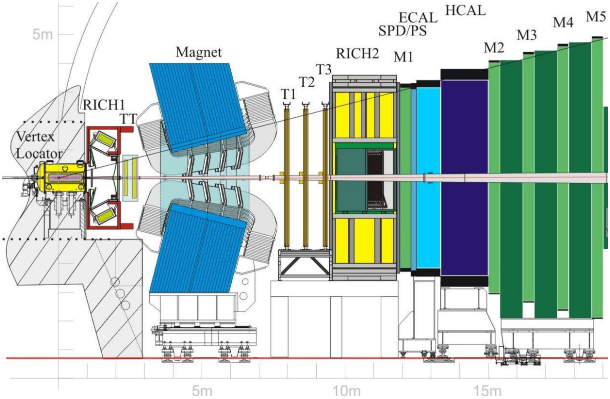


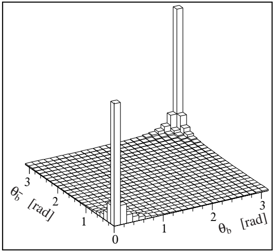






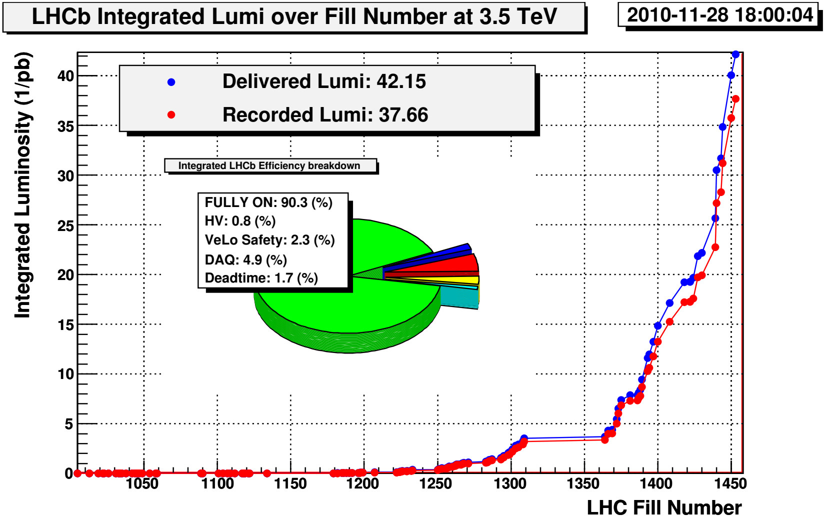
The LHCb Detector at the Large Hadron Collider





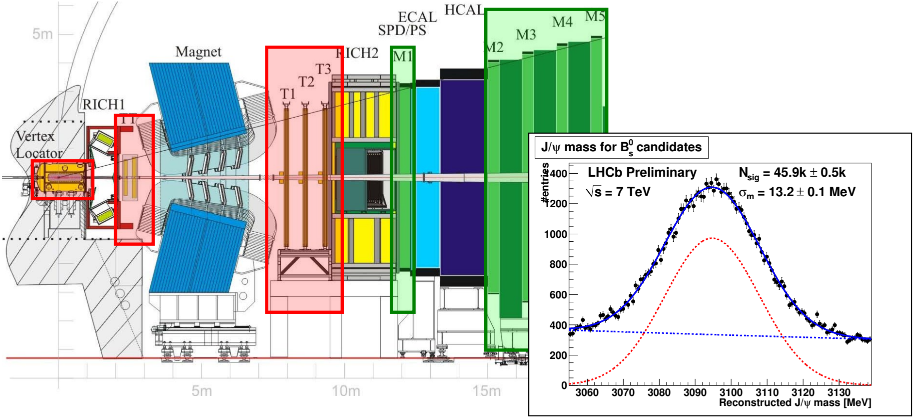
- $5 \cdot 10^{11}$ B mesons per nominal year ($2\,\mathrm{fb}^{-1}$) at $\sigma_{b\bar{b}} = 250\mu$b
- All B flavour accessible: B^0, B^+, B_s, Λ_b, etc.
- $m_B \approx 5\,\mathrm{GeV}$ production predominantly in forward direction
- Single arm forward spectrometer

Data taken in 2010



Reconstructing $J/\psi \to \mu^+\mu^-$

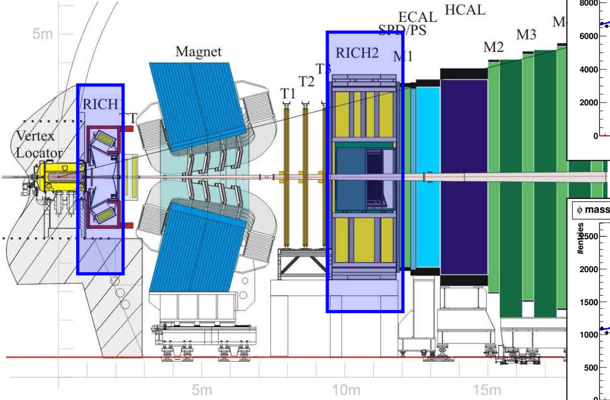
Tracking system **Muon chambers**

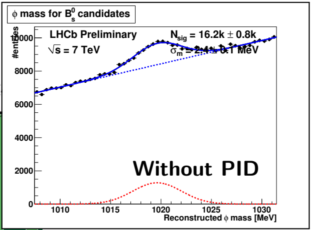


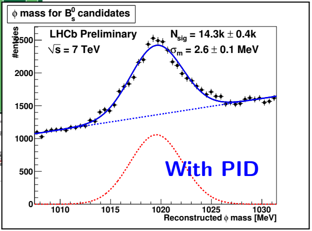
- Muon trigger with low $p_T(\mu) > 1.3\,\mathrm{GeV}$
- Momentum resolution $\Delta p/p \sim 0.5\%$ from the Tracking system

Reconstructing $\phi \to K^+K^-$

Particle Identification

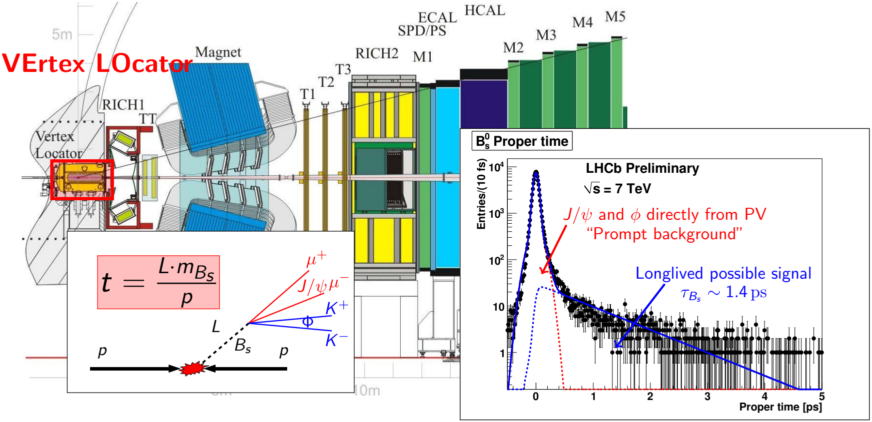






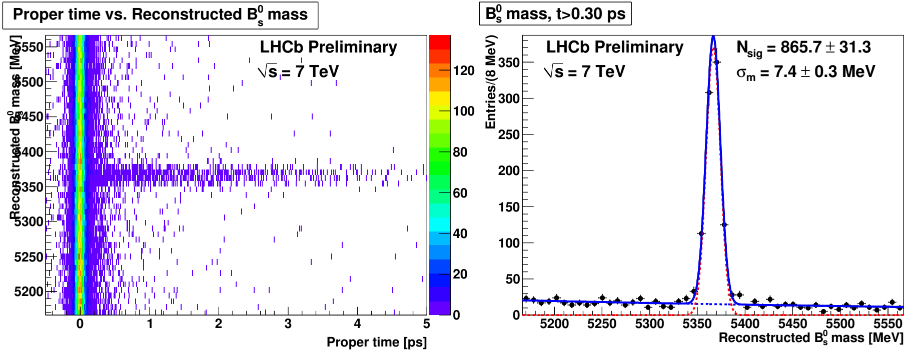
- K/π separation via RICH detectors $\cos\theta_C = \frac{1}{n\beta}$
- RICH1/2 have different n $\to$ Cover momentum range $1 - 100\,\mathrm{GeV}$

B_s Decay Time t



- Useful for signal/background separation
- Good σ_t needed to resolve fast B_s oscillation $\Delta m_s = 17.8\,\mathrm{ps}^{-1}$
- σ_t can be calibrated from prompt peak
- Current resolution $\sigma_t \sim 60\,\mathrm{fs}$

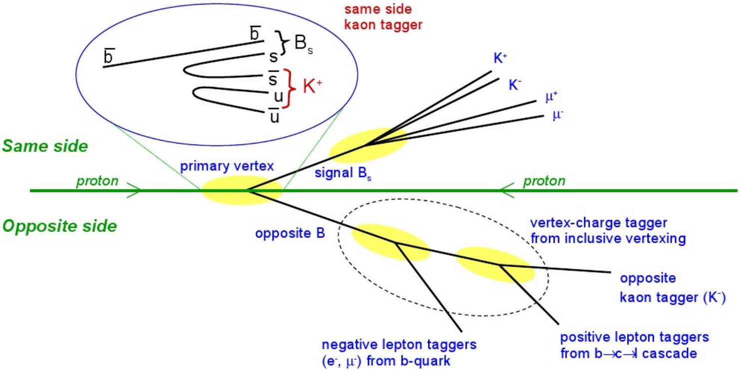
Reconstructing the B_s mass peak



- Data corresponds to ca. 34 pb^{-1}
- Clean mass peak for $t > 0.3\,\mathrm{ps}$
- We are currently very busy analyzing this ☺

Crucial ingredient: Flavour Tagging

Tagging = Determination of the B_s production flavour



Tagging not perfect, key quantities

- Tagging efficiency ϵ_{tag}
- Mistag probability ω
- Effective tagging power $\epsilon_{\text{eff}} = \epsilon_{\text{tag}}(1 - 2\omega)^2$

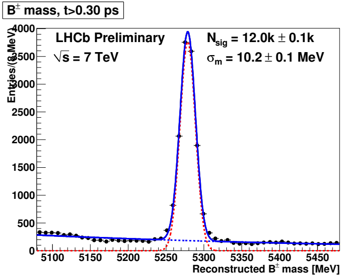
Numbers from MC			
Tagger	$\epsilon_{\text{tag}}[\%]$	$\omega[\%]$	$\epsilon_{\text{eff}}[\%]$
Same side	26.4	34.9	2.4
Opposite side	45.6	36.5	3.3
Combined	55.7	33.3	6.2

Crucial ingredient: Tagging Calibration

Do not rely on MC estimates for tagging calibration

- Calibrate OS tagger with $B^\pm \to J/\psi K^\pm$
  Reconstruct B^+, No oscillation $\Rightarrow$ Correct tagging decision known

  High statistics in $B^\pm \to J/\psi K^\pm$:

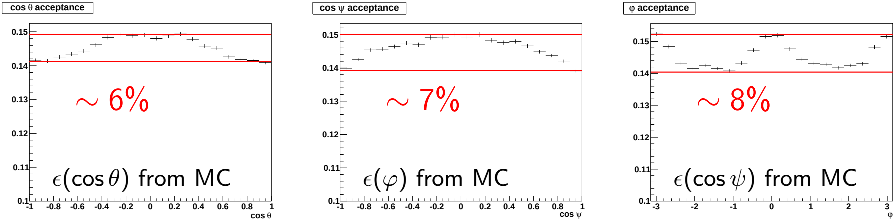


- Calibrate SS tagger with $B_s \to D_s\pi$

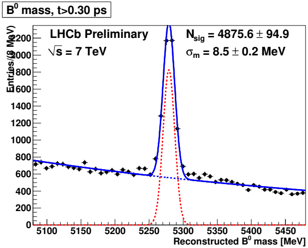
$\Rightarrow$ More in talk by Pavel Krokovny

Angular Acceptances

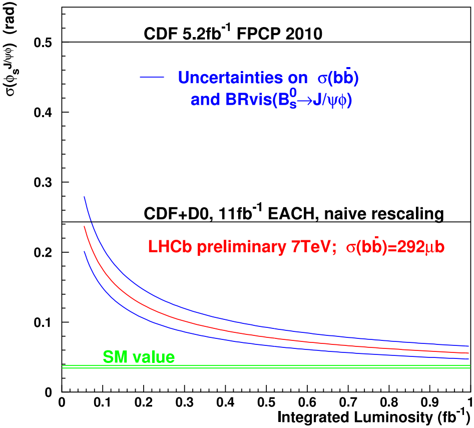
Detector geometry and signal selection distorts the angular distributions:



- Effect mainly due to detector forward geometry $30 - 300\,\mathrm{mrad}$
- Bias in $|A_0|$, $|A_\perp|$ if neglected $\Rightarrow$ Needs to be corrected for in analysis
- Control on data possible using $B^0 \to J/\psi K^*$ ($P \to VV$ process!)



Prospects for ϕ_s from LHCb



- Competitive with the Tevatron with 2011 data
- $2\,\mathrm{fb}^{-1}$ at $14\,\mathrm{TeV}$: $\sigma(\phi_s) \sim |\phi_s^{SM}| = 0.036$

Summary

- $B_s \to J/\psi\phi$ the golden channel for ϕ_s
- Provides an interesting indirect probe for new physics
- Challenging measurement:
  - Time and angular analysis
  - Acceptances
  - Tagging
  - Background
- LHCb already delivered quality data in 2010:
  $\sim$ 850 signal candidates
- Analysis is on the way
- News on ϕ_s from LHCb soon!

Backup: Angular distributions

i	$A_i(\mathrm{t})$	$\bar{A}_i(\mathrm{t})$	$f_i(\cos\theta, \varphi, \cos\psi)$
1	$\lvert A_0(\mathrm{t})\rvert^2$	$\lvert \bar{A}_0(\mathrm{t})\rvert^2$	$\frac{9}{32\pi} 2\cos^2\psi\left(1-\sin^2\theta\cos^2\varphi\right)$
2	$\lvert A_\parallel(\mathrm{t})\rvert^2$	$\lvert \bar{A}_\parallel(\mathrm{t})\rvert^2$	$\frac{9}{32\pi}\sin^2\psi\left(1-\sin^2\theta\sin^2\varphi\right)$
3	$\lvert A_\perp(\mathrm{t})\rvert^2$	$\lvert \bar{A}_\perp(\mathrm{t})\rvert^2$	$\frac{9}{32\pi}\sin^2\psi\sin^2\theta$
4	$\Im\left(A_\parallel^*(\mathrm{t})A_\perp(\mathrm{t})\right)$	$\Im\left(\bar{A}_\parallel^*(\mathrm{t})\bar{A}_\perp(\mathrm{t})\right)$	$-\frac{9}{32\pi}\sin^2\psi\sin 2\theta\sin\varphi$
5	$\Re\left(A_0^*(\mathrm{t})A_\parallel(\mathrm{t})\right)$	$\Re\left(\bar{A}_0^*(\mathrm{t})\bar{A}_\parallel(\mathrm{t})\right)$	$\frac{9}{32\pi\sqrt{2}}\sin 2\psi\sin^2\theta\sin 2\varphi$
6	$\Im\left(A_0^*(\mathrm{t})A_\perp(\mathrm{t})\right)$	$\Im\left(\bar{A}_0^*(\mathrm{t})\bar{A}_\perp(\mathrm{t})\right)$	$\frac{9}{32\pi\sqrt{2}}\sin 2\psi\sin 2\theta\cos\varphi$

Backup: Amplitudes for B_s

$$|A_0(t)|^2 = |A_0(0)|^2 e^{-\Gamma t}\left[\cosh\left(\frac{\Delta\Gamma}{2}t\right) - \cos\phi \sinh\left(\frac{\Delta\Gamma}{2}t\right) + \sin\phi\sin(\Delta m t)\right]$$

$$|A_\parallel(t)|^2 = |A_\parallel(0)|^2 e^{-\Gamma t}\left[\cosh\left(\frac{\Delta\Gamma}{2}t\right) - \cos\phi \sinh\left(\frac{\Delta\Gamma}{2}t\right) + \sin\phi\sin(\Delta m t)\right]$$

$$|A_\perp(t)|^2 = |A_\perp(0)|^2 e^{-\Gamma t}\left[\cosh\left(\frac{\Delta\Gamma}{2}t\right) + \cos\phi \sinh\left(\frac{\Delta\Gamma}{2}t\right) - \sin\phi\sin(\Delta m t)\right]$$

$$\Im\left(A_\parallel^*(t)A_\perp(t)\right) = |A_\parallel(0)|\,|A_\perp(0)|\,e^{-\Gamma t}\Big[-\cos(\delta_\perp-\delta_\parallel)\sin\phi\sinh\left(\frac{\Delta\Gamma}{2}t\right) + \sin(\delta_\perp-\delta_\parallel)\cos(\Delta m t) - \cos(\delta_\perp-\delta_\parallel)\cos\phi\sin(\Delta m t)\Big]$$

$$\Re\left(A_0^*(t)A_\parallel(t)\right) = |A_0(0)|\,|A_\parallel(0)|\,e^{-\Gamma t}\cos\delta_\parallel\Big[\cosh\left(\frac{\Delta\Gamma}{2}t\right) - \cos\phi\sinh\left(\frac{\Delta\Gamma}{2}t\right) + \sin\phi\sin(\Delta m t)\Big]$$

$$\Im\left(A_0^*(t)A_\perp(t)\right) = |A_0(0)|\,|A_\perp(0)|\,e^{-\Gamma t}\Big[-\cos\delta_\perp\sin\phi\sinh\left(\frac{\Delta\Gamma}{2}t\right) + \sin\delta_\perp\cos(\Delta m t) - \cos\delta_\perp\cos\phi\sin(\Delta m t)\Big]$$

Backup: Amplitudes for $\bar{B}_s$

$$|\bar{A}_0(t)|^2 = |A_0(0)|^2 e^{-\Gamma t}\left[\cosh\left(\frac{\Delta\Gamma}{2}t\right) - \cos\phi\sinh\left(\frac{\Delta\Gamma}{2}t\right) - \sin\phi\sin\left(\Delta m t\right)\right]$$

$$|\bar{A}_\parallel(t)|^2 = |A_\parallel(0)|^2 e^{-\Gamma t}\left[\cosh\left(\frac{\Delta\Gamma}{2}t\right) - \cos\phi\sinh\left(\frac{\Delta\Gamma}{2}t\right) - \sin\phi\sin\left(\Delta m t\right)\right]$$

$$|\bar{A}_\perp(t)|^2 = |A_\perp(0)|^2 e^{-\Gamma t}\left[\cosh\left(\frac{\Delta\Gamma}{2}t\right) + \cos\phi\sinh\left(\frac{\Delta\Gamma}{2}t\right) + \sin\phi\sin\left(\Delta m t\right)\right]$$

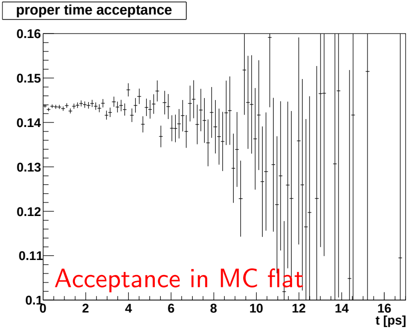
$$\Im\left(\bar{A}_\parallel^*(t)\bar{A}_\perp(t)\right) = |A_\parallel(0)|\,|A_\perp(0)|\,e^{-\Gamma t}\Big[-\cos\left(\delta_\perp-\delta_\parallel\right)\sin\phi\sinh\left(\frac{\Delta\Gamma}{2}t\right) - \sin\left(\delta_\perp-\delta_\parallel\right)\cos\left(\Delta m t\right) + \cos\left(\delta_\perp-\delta_\parallel\right)\cos\phi\sin\left(\Delta m t\right)\Big]$$

$$\Re\left(\bar{A}_0^*(t)\bar{A}_\parallel(t)\right) = |A_0(0)|\,|A_\parallel(0)|\,e^{-\Gamma t}\cos\delta_\parallel\Big[\cosh\left(\frac{\Delta\Gamma}{2}t\right) - \cos\phi\sinh\left(\frac{\Delta\Gamma}{2}t\right) - \sin\phi\sin\left(\Delta m t\right)\Big]$$

$$\Im\left(\bar{A}_0^*(t)\bar{A}_\perp(t)\right) = |A_0(0)|\,|A_\perp(0)|\,e^{-\Gamma t}\Big[-\cos\delta_\perp\sin\phi\sinh\left(\frac{\Delta\Gamma}{2}t\right) - \sin\delta_\perp\cos\left(\Delta m t\right) + \cos\delta_\perp\cos\phi\sin\left(\Delta m t\right)\Big]$$

Backup: B_s Lifetime Acceptance

- Lifetime unbiased trigger+selection: Large effort not to bias lifetime distr.



- Biased trigger gives higher yield
  - Fit needs to correct for this
  - Control on data possible using the high statistics channels $B^{\pm} \to J/\psi K^{\pm}$ and $B^0 \to J/\psi K^*$