CP Violation on B_s mixing: measuring ϕ_s

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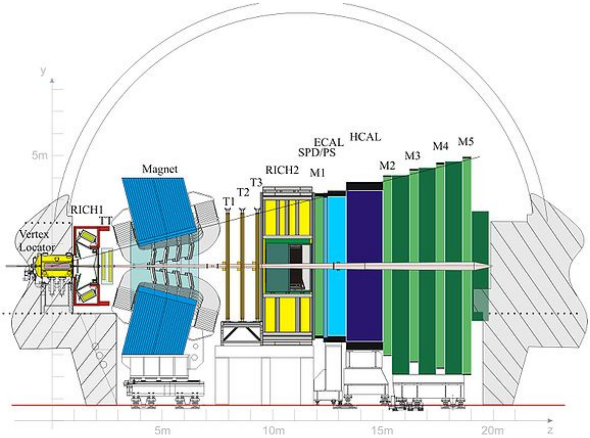
on behalf of LHCb Collaboration

IoP Joint HEPP & APP Meeting 2012

Introduction

- Background Theory
- $B_s \to J/\psi\ \phi$ Analysis
- Fitting to the data
- Results

LHCb



LHCb is a forward spectrometer designed for c and b physics.

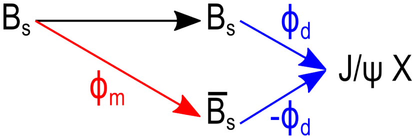
Accessible region of $2 < \eta < 5$

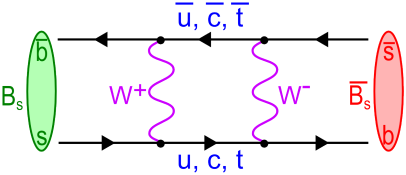
Good particle ID and vertex resolution.

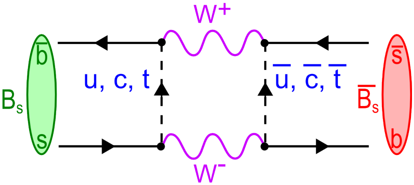
Background Theory

ϕ_s defined as difference introduced between mixing and direct decay:

$$\phi_s = \phi_m - 2\phi_d$$







New Physics may contribute virtually to loop/box diagram and modify the standard model prediction.

Technically I'm talking about $\phi_s^{J/\psi\ \phi}$ but I use ϕ_s in this talk.

Background Theory cont.

$B_s \to J/\psi(\mu^+\mu^-)\ \phi(K^+K^-)$ is a good channel to observe ϕ_s .

From the Standard Model: $\phi_d \approx 0 \Rightarrow \phi_s \approx \phi_m \approx -2\beta_s$

SM prediction:

$$\phi_{s(SM)} = -0.036 \pm 0.002 \quad , \quad \Delta\Gamma_s = 0.087 \pm 0.021$$

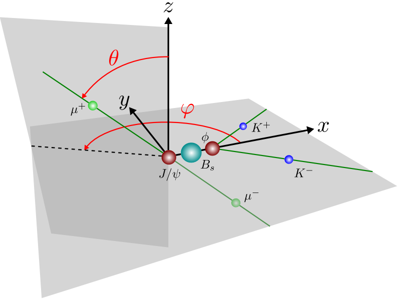
In the presence of **New Physics**: $\phi_s = \phi_{s(SM)} + \phi_{s(NP)}$

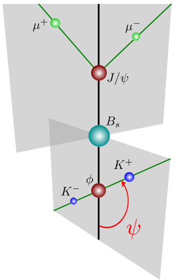
$B_s \rightarrow J/\psi\ \phi$ Analysis

Decay products are CP Even/Odd.

(pseudo-scalar to vector vector)

Need to perform a full tagged time dependent angular analysis.





Complex PDF:

10 terms including interference

13 free fit parameters

(see backups)

J/ψ rest frame

ϕ rest frame

$B_s \to J/\psi\ \phi$ Analysis Cont.

Important terms for measuring ϕ_s in the PDF are of the form:

$$\underbrace{\sin(\phi_s) \times D_{\text{mistag}} \times D_t}_{\text{Amplitude}} \times \underbrace{\sin(\Delta m_s t)}_{\text{Sinusoid}}$$

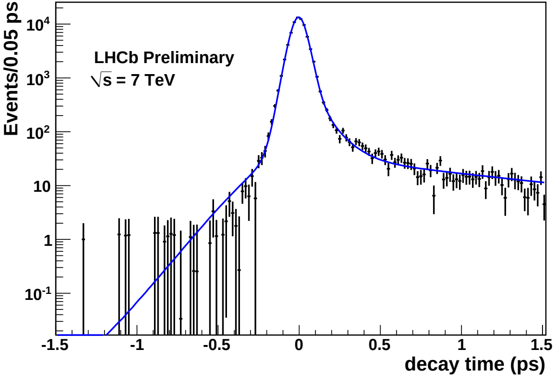
With dilutions from mistag and finite time resolution are taken into account.

Latest results presented as presented at Moriond 2012 LHCb-TALK-2012-029 using 1.03fb^{-1}.

Previous results $\approx 0.41\text{fb}^{-1}$: Phys. Lett. B707 (2012) 497, arXiv:1112.3056.

Finite Time Resolution

Period of Sinusoid(Δm_s) $\approx$ 350fs. Time Resolution$\approx$ 45fs.



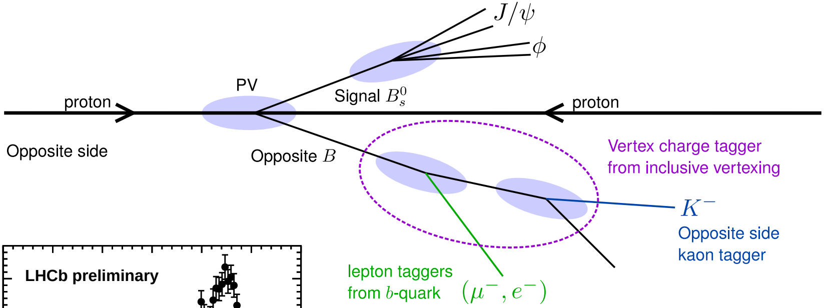
Time resolution measured from prompt J/ψ which decay at t=0.

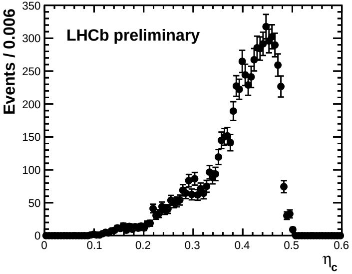
Distribution of prompt events is fitted with a dominant 45fs Gaussian.

Event by event resolution used in the full fit, this is effectivley the same as a fixed resolution of 45fs.

Tagging

Opposite Side tagger is used to tag particles at production:





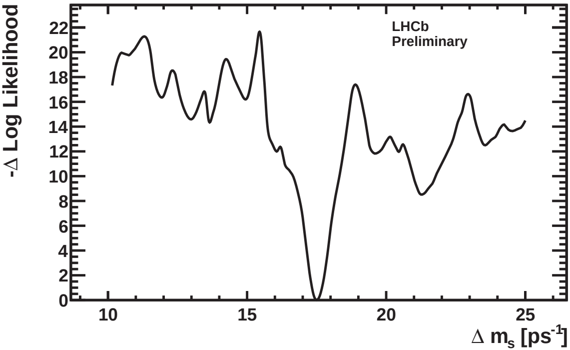
Tagging Efficiency: $\epsilon_{\text{tag}} \approx 33\%$
Effective mistag: $\omega_{\text{tag}} \approx 36\%$

Effective Tagging Power: $\epsilon_{\text{tag}} D^2 \approx 2.3\%$

Per event mistag used in fit. (Dist. on left)

$\sin(\Delta m_s t)$ (aside)

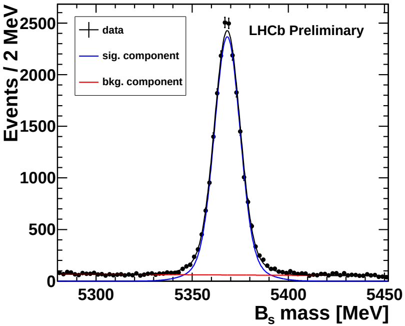
Δm_s can be fitted from $B_s \to J/\psi\phi$ using terms which don't depend on ϕ_s.

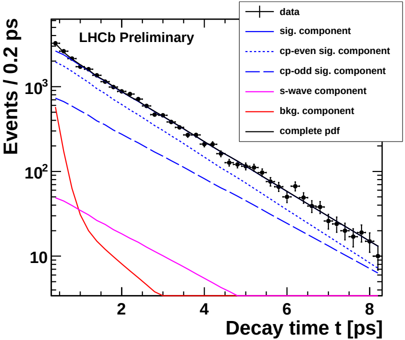


$$\Delta m_s^{J/\psi\phi} = 17.5 \pm 0.15\text{ps}^{-1} \qquad \Delta m_s^{LHCb} = 17.63 \pm 0.11 \pm 0.02\text{ps}^{-1}$$

This is an indication that we're fitting $\sin(\Delta m_s t)$ correctly.

Signal and Lifetime Fit Results

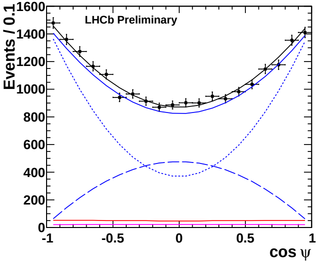


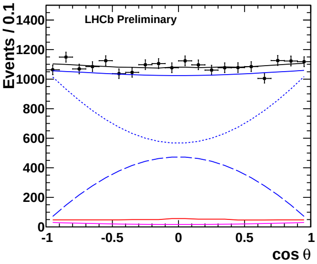


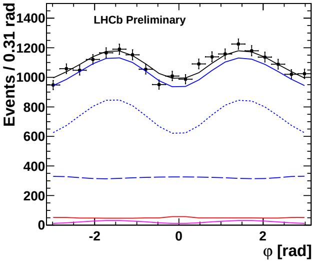
Very clean channel with $\approx 21,000$ signal events.

Most background removed by decay time cut: $t > 0.3\text{ps}^{-1}$

Angular Fit Results





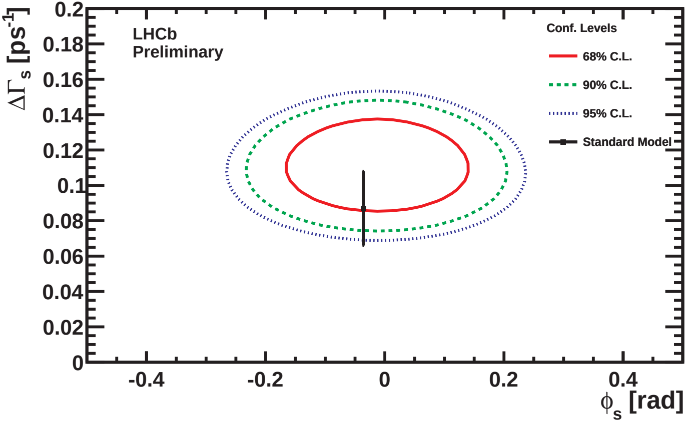


Clear separation of CP Even/Odd component in all angular distributions.

(fine blue dashes CP-Even, corse blue dashes CP-Odd)

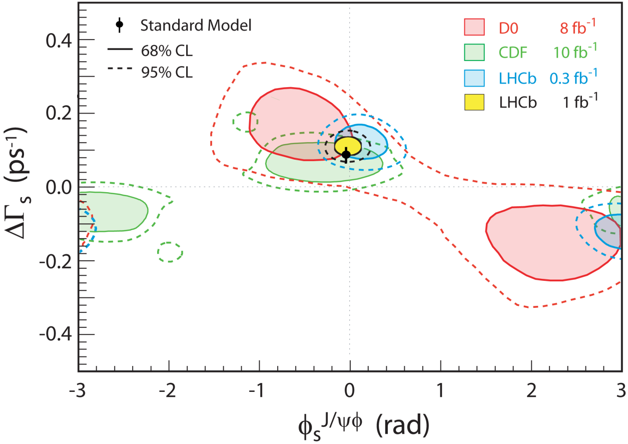
Fit Result

$\phi_{s(SM)} = -0.036 \pm 0.002$ $\phi_{s(Data)} = -0.001 \pm 0.101 \pm 0.027$



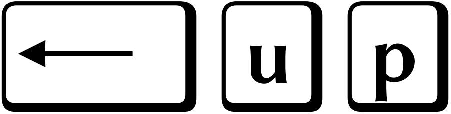
$$\phi_s = -0.001 \pm 0.101(\text{stat}) \pm 0.027(\text{syst})\ \text{rad}$$
$$\Delta\Gamma_s = 0.116 \pm 0.018(\text{stat}) \pm 0.006(\text{syst})\ \text{ps}^{-1}$$
$$\Gamma_s = 0.580 \pm 0.0054(\text{stat}) \pm 0.0066(\text{syst})\ \text{ps}^{-1}$$

Final Results



World's most precise measurement of ϕ_s .

First Direct observation of non-zero $\Delta\Gamma_s$.

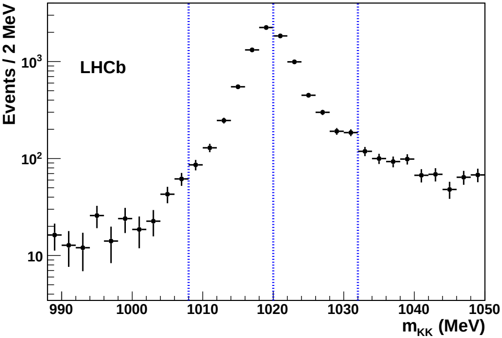


(backup...)

Sign of $\Delta\Gamma_s$

The sign on $\Delta\Gamma_s$ can be resolved by examining interference between the P-Wave and S-Wave contributions.

This involves seperating the fit into 4 bins in the ϕ mass and plotting the variation of $\delta_s - \delta_\perp$ over the full mass range.

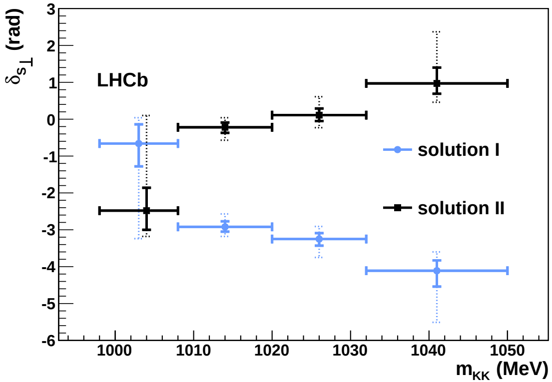


Sign of $\Delta\Gamma_s$

$(\delta_{s_\perp} = \delta_s - \delta_\perp)$

solution I:
$\Delta\Gamma_s > 0$

solution II:
$\Delta\Gamma_s < 0$.



Physical solution has a negative gradient in $\delta_{s_\perp}$, therefore $\Delta\Gamma_s > 0$ is most likely.

What is ϕ_s in terms of the CKM matrix?

$$\phi_s \approx -2\beta_s$$

$$\mathbf{V_{CKM}} = \begin{bmatrix} \mathbf{V_{ud}} & \mathbf{V_{us}} & \mathbf{V_{ub}} \\ \mathbf{V_{cd}} & \mathbf{V_{cs}} & \mathbf{V_{cb}} \\ \mathbf{V_{td}} & \mathbf{V_{ts}} & \mathbf{V_{tb}} \end{bmatrix} \approx \begin{bmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|\, e^{-i\gamma} \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}|\, e^{i\beta} & -|V_{ts}|\, \mathbf{e^{i\beta_s}} & |V_{tb}| \end{bmatrix}$$

P-Wave (tag==1)

$$|A_0(t)|^2 = |A_0(0)|^2 e^{-\Gamma_s t} \begin{bmatrix} + \cosh\left(\frac{\Delta\Gamma_s t}{2}\right) \\ -\cos\phi_s \sinh\left(\frac{\Delta\Gamma_s t}{2}\right) \\ + \sin\phi_s \sin(\Delta m_s t) \end{bmatrix}$$

$$\left|A_\parallel(t)\right|^2 = \left|A_\parallel(0)\right|^2 e^{-\Gamma_s t} \begin{bmatrix} + \cosh\left(\frac{\Delta\Gamma_s t}{2}\right) \\ -\cos\phi_s \sinh\left(\frac{\Delta\Gamma_s t}{2}\right) \\ + \sin\phi_s \sin(\Delta m_s t) \end{bmatrix}$$

$$|A_\perp(t)|^2 = |A_\perp(0)|^2 e^{-\Gamma_s t} \begin{bmatrix} + \cosh\left(\frac{\Delta\Gamma_s t}{2}\right) \\ +\cos\phi_s \sinh\left(\frac{\Delta\Gamma_s t}{2}\right) \\ - \sin\phi_s \sin(\Delta m_s t) \end{bmatrix}$$

$$\mathfrak{Im}\{A_\parallel(t)^* A_\perp(t)\} = \left|A_\parallel(0)\right| |A_\perp(0)| e^{-\Gamma_s t} \begin{bmatrix} -\cos\left(\delta_\perp - \delta_\parallel\right) \sin\phi_s \sinh\left(\frac{\Delta\Gamma_s t}{2}\right) \\ + \sin\left(\delta_\perp - \delta_\parallel\right) \cos(\Delta m_s t) \\ -\cos\left(\delta_\perp - \delta_\parallel\right) \cos\phi_s \sin(\Delta m_s t) \end{bmatrix}$$

$$\mathfrak{Re}\{A_0(t)^* A_\parallel(t)\} = |A_0(0)| \left|A_\parallel(0)\right| e^{-\Gamma_s t} \cos\left(\delta_\parallel - \delta_0\right) \begin{bmatrix} + \cosh\left(\frac{\Delta\Gamma_s t}{2}\right) \\ +\cos\phi_s \sinh\left(\frac{\Delta\Gamma_s t}{2}\right) \\ - \sin\phi_s \sin(\Delta m_s t) \end{bmatrix}$$

$$\mathfrak{Im}\{A_0(t)^* A_\perp(t)\} = |A_0(0)| |A_\perp(0)| e^{-\Gamma_s t} \begin{bmatrix} -\cos(\delta_\perp - \delta_0) \sin\phi_s \sinh\left(\frac{\Delta\Gamma_s t}{2}\right) \\ + \sin(\delta_\perp - \delta_0) \cos(\Delta m_s t) \\ -\cos(\delta_\perp - \delta_0) \cos\phi_s \sin(\Delta m_s t) \end{bmatrix}$$

$$+ \quad h.c.$$

S-Wave (tag==1)

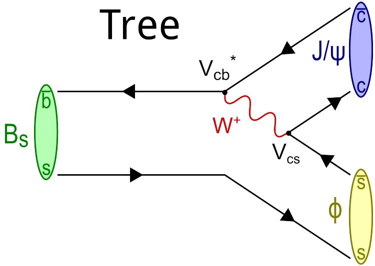
$$|A_s(t)|^2 = |A_s(0)|^2 e^{-\Gamma_s t} \begin{bmatrix} + & \cosh\left(\frac{\Delta\Gamma_s t}{2}\right) \\ + \cos\phi_s & \sinh\left(\frac{\Delta\Gamma_s t}{2}\right) \\ - \sin\phi_s & \sin(\Delta m_s t) \end{bmatrix}$$

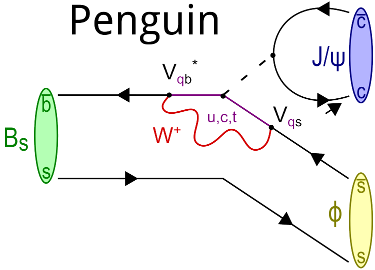
$$\mathfrak{Im}\{A_\parallel(t)^* A_s(t)\} = \left|A_\parallel(0)\right| |A_s(0)| e^{-\Gamma_s t} \begin{bmatrix} -\sin\left(\delta_\parallel - \delta_s\right)\sin\phi_s\sinh\left(\frac{\Delta\Gamma_s t}{2}\right) \\ +\cos\left(\delta_\parallel - \delta_s\right) \quad \cos(\Delta m_s t) \\ -\sin\left(\delta_\parallel - \delta_s\right)\cos\phi_s \quad \sin(\Delta m_s t) \end{bmatrix}$$

$$\mathfrak{Re}\{A_s(t)^* A_\perp(t)\} = |A_s(0)| |A_\perp(0)| e^{-\Gamma_s t} \sin(\delta_\perp - \delta_s) \begin{bmatrix} + & \cosh\left(\frac{\Delta\Gamma t}{2}\right) \\ -\cos\phi_s & \sinh\left(\frac{\Delta\Gamma_s t}{2}\right) \\ + \sin\phi_s & \sin(\Delta m_s t) \end{bmatrix}$$

$$\mathfrak{Im}\{A_0(t)^* A_s(t)\} = |A_0(0)| |A_s(0)| e^{-\Gamma_s t} \begin{bmatrix} -\sin(\delta_0 - \delta_s)\sin\phi_s\sinh\left(\frac{\Delta\Gamma_s t}{2}\right) \\ +\cos(\delta_0 - \delta_s) \quad \cos(\Delta m_s t) \\ -\sin(\delta_0 - \delta_s)\cos\phi_s \quad \sin(\Delta m_s t) \end{bmatrix}$$

$$+ \quad h.c.$$


Tree
V_{cb}^*
W^+
V_{cs}
B_s
$\bar{b}$
s
$\bar{c}$
c
J/ψ
$\bar{s}$
s
ϕ


Penguin
V_{qb}^*
u,c,t
W^+
V_{qs}
B_s
$\bar{b}$
s
$\bar{c}$
c
J/ψ
$\bar{s}$
s
ϕ