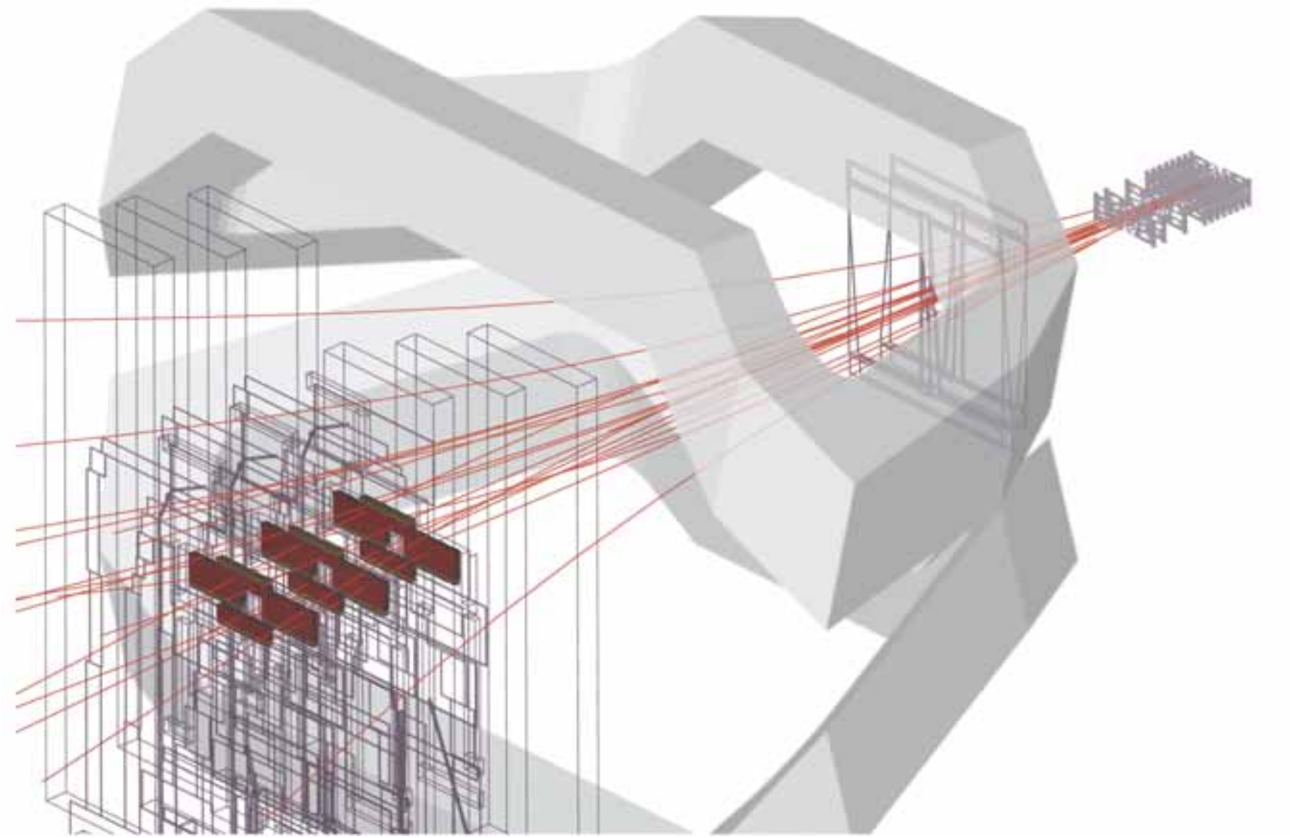
Results on CP Violation in B_s Mixing
[measurements of ϕ_s and $\Delta\Gamma_s$]

Presentation on behalf of LHCb Collaboration

Rencontres de Moriond, La Thuile, 3-10 March 2012



This talk presents new LHCb results since 2011 summer conferences

- Using the full $1fb^{-1}$ of data from 2011 (was $0.37fb^{-1}$)

- CPV phase ϕ_s ,$\Delta\Gamma_s$ and other quantities from $B_s \rightarrow J/\psi\Phi$
  - LHCb-CONF-2012-002
  - arXiv:1112.3183v2 to be published in PRL

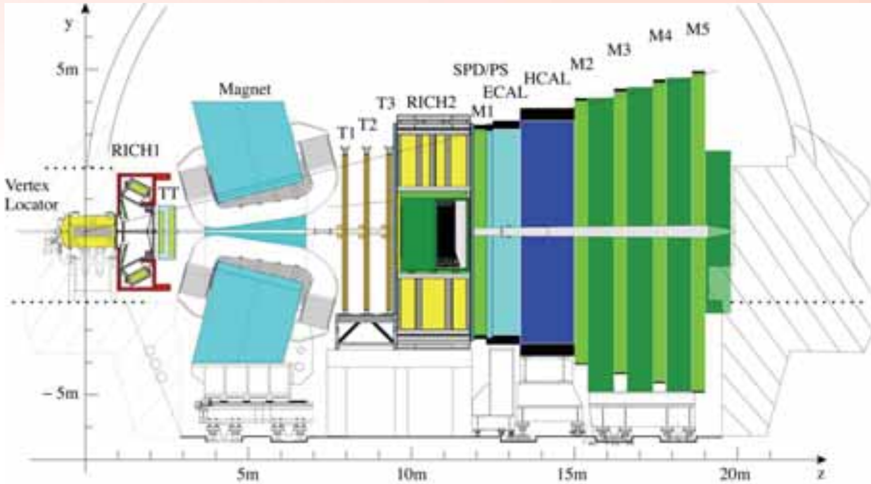
- ϕ_s from $B_s \rightarrow J/\psi\ \pi\pi$
  - LHCb-PAPER-2012-006 to be submitted to PLB

- Resolution of the "two fold ambiguity" for ϕ_s & $\Delta\Gamma_s$
  - arXiv:1202.4717v2 submitted to PRL

These new results are due to

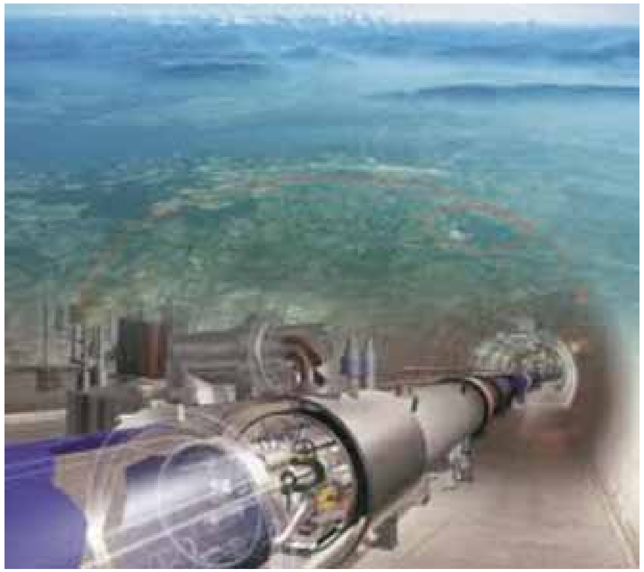
- Excellent running of detector
- Excellent running of LHC
- Efforts of all the people

The detector

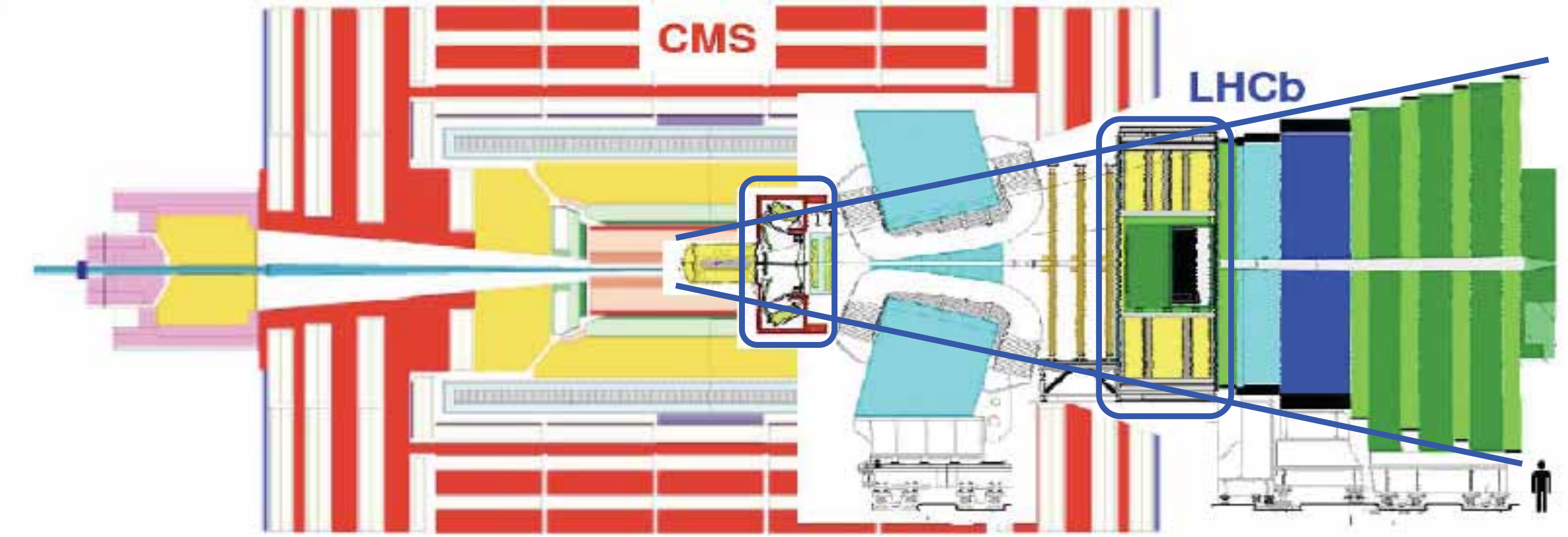


The people

The LHC



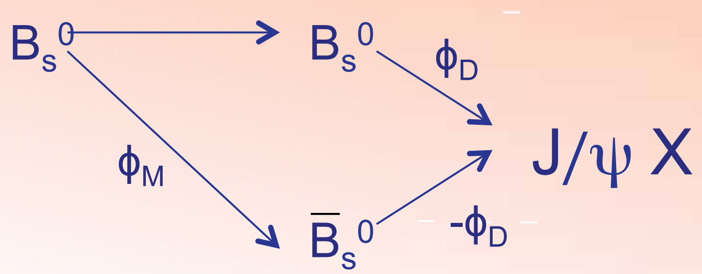
LHCb in context



- LHCb is a forward spectrometer
- $2 < \eta < 5$
- Optimised for *b* and *c* physics
- Precise tracking and decay vertex finder
- Good particle ID

Experimental phenomenology of CP Violating phase ϕ_s

- Measure relative phase difference[1]
  $\phi_s = \phi_M - 2\phi_D$ between two "legs"



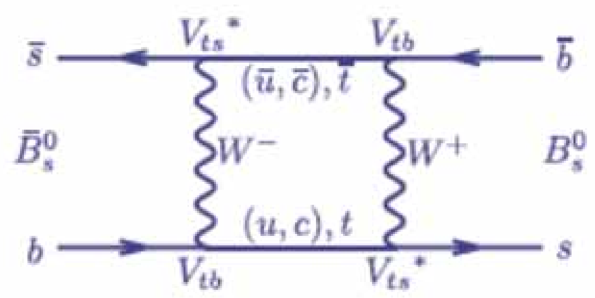
- In SM & normal conventions & ignoring penguins

  $\phi_D \sim 0$

  $\phi_s^{SM} \sim \phi_M$

  - is predominantly determined[2] by arg(V_{ts})
  - is predicted to be small ~ -0.04

    [Charles et al. Phys. Rev. D84 (2011) 033005]



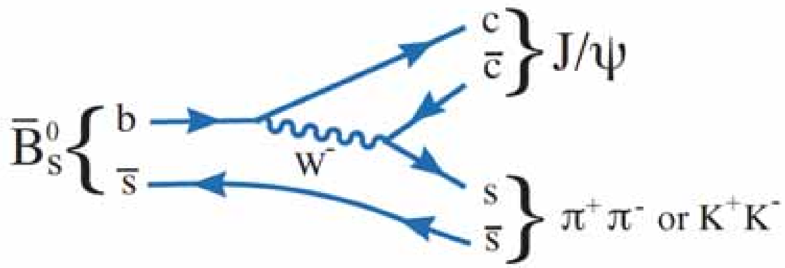
- New Physics (NP) can add large phases:

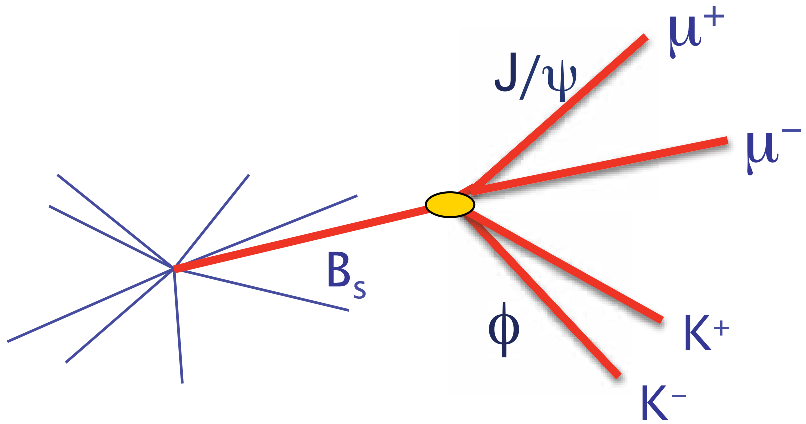
$$\phi_s = \phi_s^{SM} + \phi_s^{NP}$$

1] The term ϕ_s is overloaded. It is also used for Arg-(M_{12}/Γ_{12})
2] $\phi_s = -2 \arg(V_{ts} V_{tb}^* / V_{cs} V_{cb}^*)$

The signals

- $B_s \rightarrow J/\psi\Phi$ and $B_s \rightarrow J/\psi\pi\pi$ are very clean decays

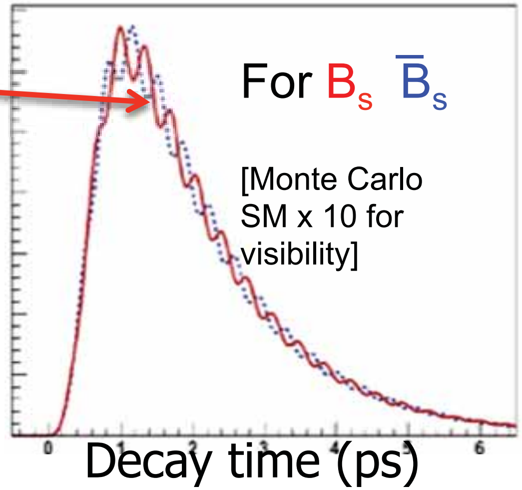




- Straightforward differential decay rates for $B_s \rightarrow J/\psi\pi\pi$:

$$\Gamma\left(B_s^0 \to J/\psi f_0\right) = \mathcal{N}_f e^{-\Gamma_s t}\left\{e^{\Delta\Gamma_s t/2}(1+\cos\phi_s) + e^{-\Delta\Gamma_s t/2}(1-\cos\phi_s) - \sin(\phi_s)\sin\left(\Delta m_s t\right)\right\},$$

$$\Gamma\left(\overline{B}_s^0 \to J/\psi f_0\right) = \mathcal{N}_f e^{-\Gamma_s t}\left\{e^{\Delta\Gamma_s t/2}(1+\cos\phi_s) + e^{-\Delta\Gamma_s t/2}(1-\cos\phi_s) + \sin(\phi_s)\sin\left(\Delta m_s t\right)\right\}.$$



- Signal is sinusoidal time distribution
  - Amplitude proportional to $\sin(\phi_s)$
  - Opposite sign for B and $\overline{B}$ → must tag
  - Diluted by wrong tagging probability ω_{tag}
  - Diluted by detector resolution σ_t

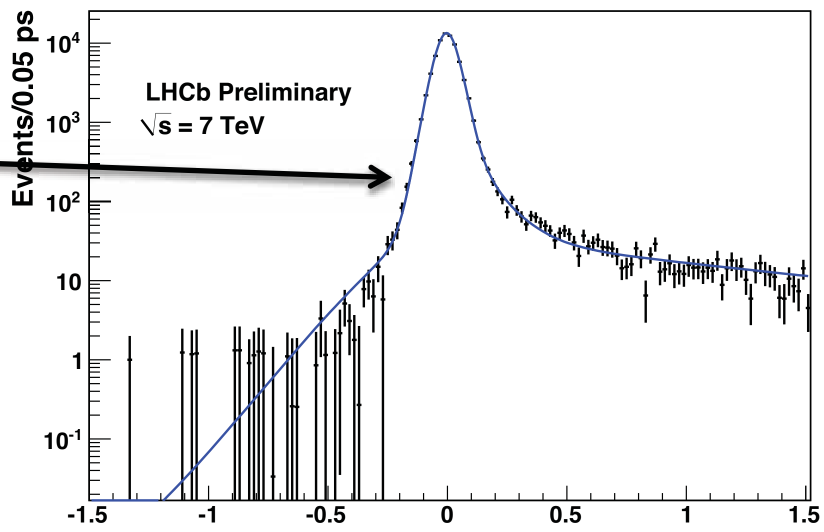
- Fundamentally we measure: $\sin(\phi_s) \times D(\sigma_t) \times (1 - 2\omega_{tag}) \times \sin(\Delta m_s t)$

Decay time resolution

$\sin(\phi_s) \times D(\sigma_t) \times (1 - 2\omega_{tag}) \times \sin(\Delta m_s t)$

Need good proper time resolution w.r.t. sinusoid period ~ 350fs

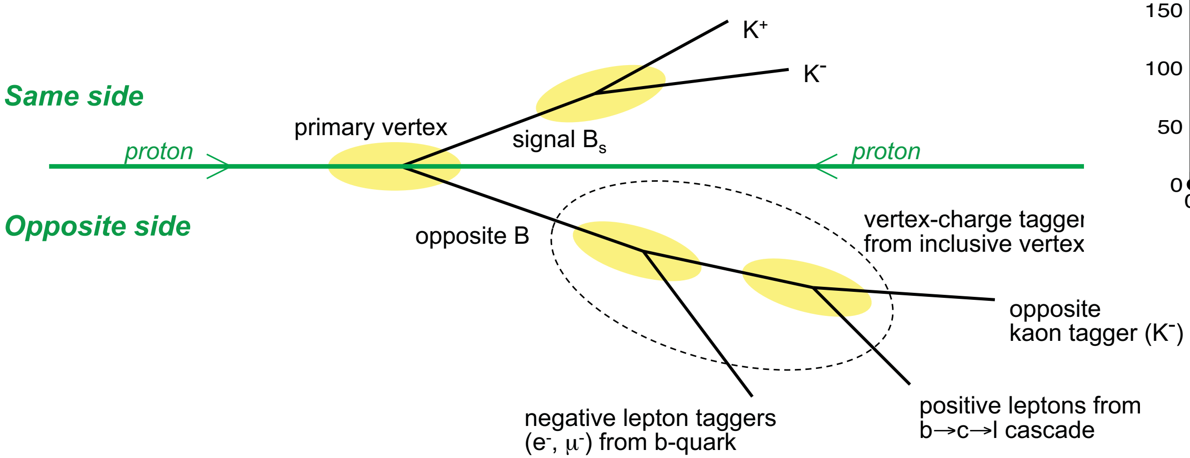
- We measure from data using prompt J/ψ which decay at t=0
- width ~ 45fs
- In analysis we actually use a resolution estimated per-event

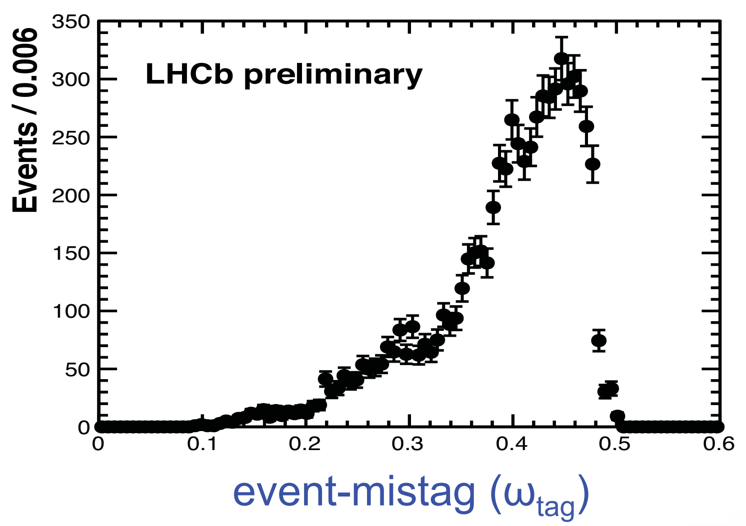


Measured decay time of prompt events [ps]

Need to tag B or $\bar{B}$ at production

$\sin(\phi_s) \times D(\sigma_t) \times (1 - 2\omega_{tag}) \times \sin(\Delta m_s t)$





tagging efficiency ε_{tag} ~ 33%

effective mistag ω_{tag} ~ 36.8%

effective tagging power $\varepsilon_{tag}(1 - 2\omega_{tag})^2$ ~ 2.3%

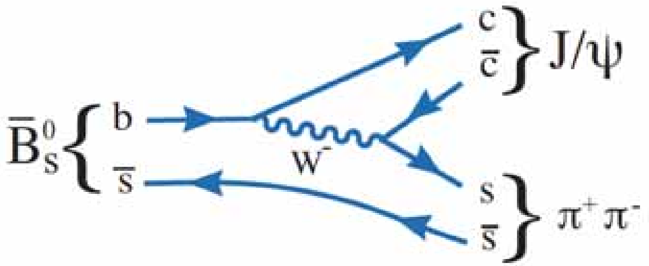
Measurements of ϕ_s using $B_s \rightarrow J/\psi\pi\pi$

$\sim 1.0\ fb^{-1}$

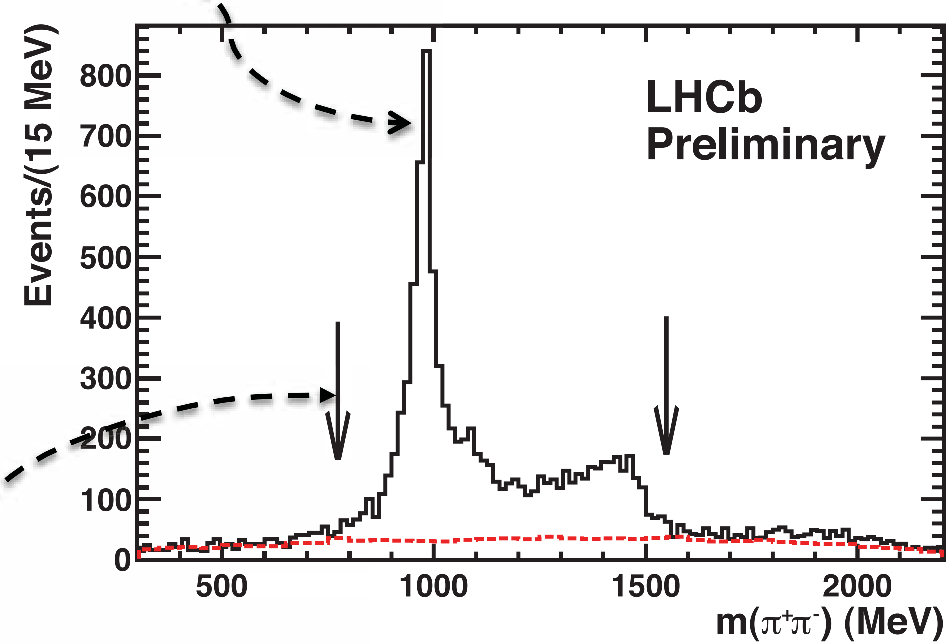
$\sim 0.41\ fb^{-1}$ published result: Phys. Lett. B707 (2012) 497, arXiv:1112.3056.

This update : LHCb-PAPER-2012-006

$B_s \rightarrow J/\psi\ \pi\pi$



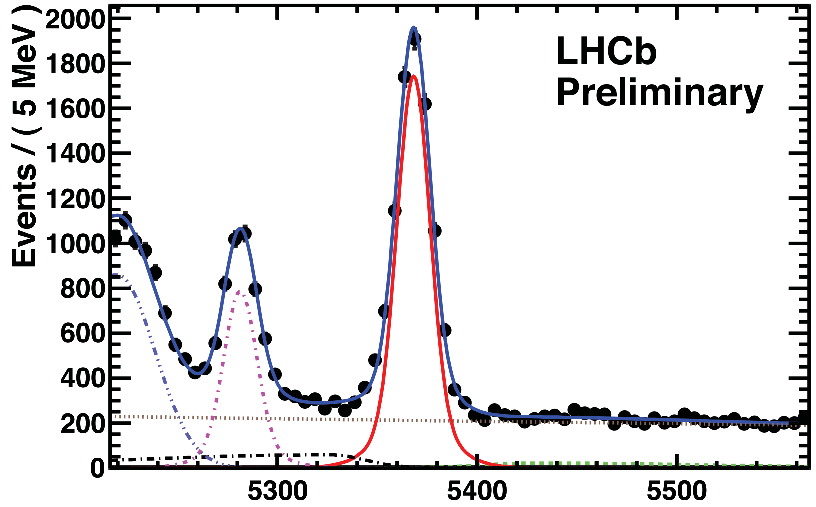
- Previous analysis was $B_s \rightarrow J/\psi f_0(980)$



- All m(ππ) range found to be CP-odd
  (97.7% @ 95% C.L)
  [LHCb-PAPER-2012-005]

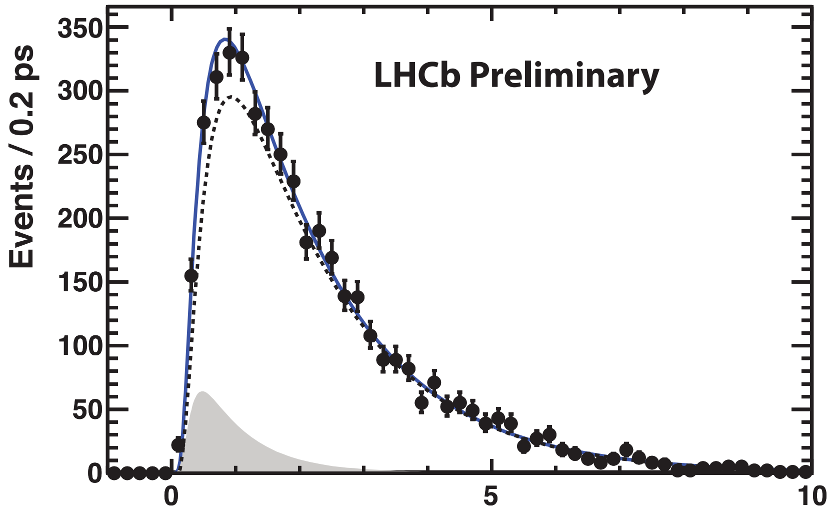
- Now use wider M(ππ) range hence: $B_s \rightarrow J/\psi\ \pi\pi$

$B_s \rightarrow J/\psi\ \pi\pi$ signal

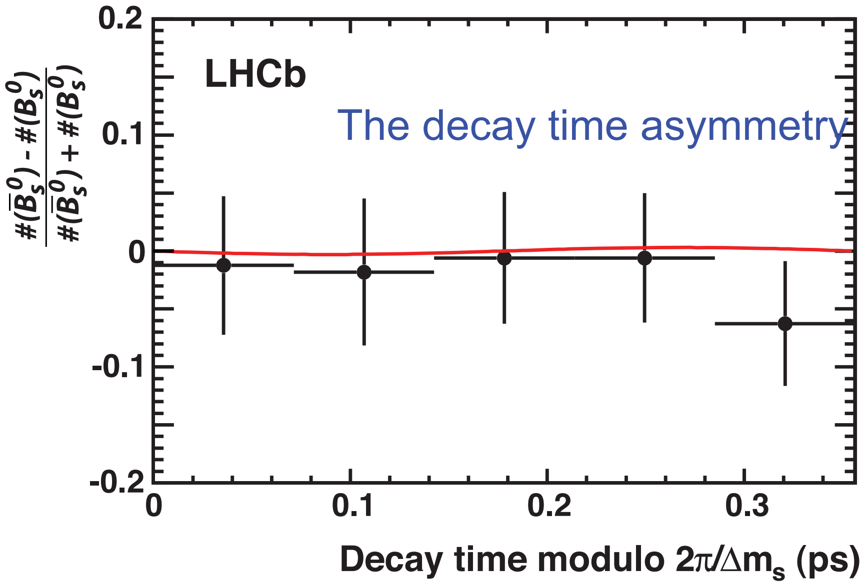


B_s Invariant mass distribution [MeV]

- Boosted Decision Tree selection
- Maximum likelihood fit to time and mass
- Uses Γ_s and $\Delta\Gamma_s$ from the $B_s \rightarrow J/\psi\Phi$ analysis (+correlation)
- Approx. 7400 signal events



B_s decay time distribution [ps]



$B_s \rightarrow J/\psi\pi\pi$ final result

ϕ_s = -0.02 ± 0.17(stat.) ± 0.02(syst.) rad.

Quantity (Q)	$\pm\Delta$Q	+Change in ϕ_s (rad)	$-$Change in ϕ_s (rad)
β	4.4×10^{-3}	0.0008	-0.0007
τ_{bkg_1} (ps)	0.046	-0.0006	0.0014
τ_{bkg_2} (ps)	0.8	-0.0014	0.0014
f_2	0.02	-0.0006	0.0012
N_{bkg}	38	0.0009	-0.0001
$N_{\eta'}$	9	0.0006	0.0001
N_{sig}	105	0.0021	0.0006
m_0 (MeV)	0.12	0.0012	-0.0004
σ_1^m (MeV)	0.1	-0.0002	0.0008
α	1.1×10^{-4}	0.0003	0.0003
T function	5%	0.0005	0.0005
CP-even	increase mistag by 2.3%	-0.0160	0
Direct CP	free in fit	-0.0020	0
Total systematic error on ϕ_s $^{-0.017}_{+0.004}$			

Systematic errors

Measurements of ϕ_s using $B_s \rightarrow J/\psi\Phi$

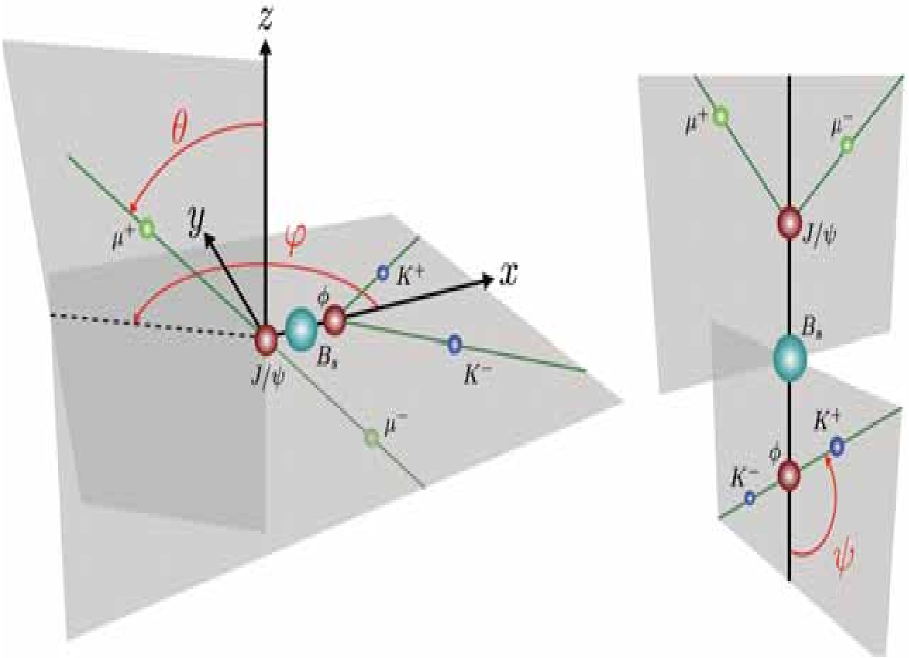
~ 1.0 fb^{-1}

0.37 fb^{-1} published result: arXiv:1112.3183 [LHCB-PAPER-2011-021]

This update: LHCb-CONF-2012-002

$B_s \rightarrow J/\psi\Phi$ analysis

- Decay to CP-odd and CP-even final states,
  ➔ need analysis of decay angle distribution



J/ψ rest frame Φ rest frame

- Much larger branching fraction

$J/\psi\Phi \;/\; J/\psi\pi\pi \sim 5$

- Differential cross section is "very rich"
- 3 "P-wave" amplitudes of KK system
- 1 "S"-wave amplitude
- 10 terms with all interferences

- ..but fundamentally for ϕ_s we still measure:

$\sin(\phi_s) \times D(\sigma_t) \times (1 - 2\omega_{tag}) \times \sin(\Delta m_s t)$

- ..and because we separate the terms, we measure the lifetimes of Heavy and Light eigenstates separately:

$\Gamma_L \;\&\; \Gamma_H \;\Leftrightarrow\; \Gamma_s \;\&\; \Delta\Gamma_s$

- There is a two fold ambiguity in the solutions

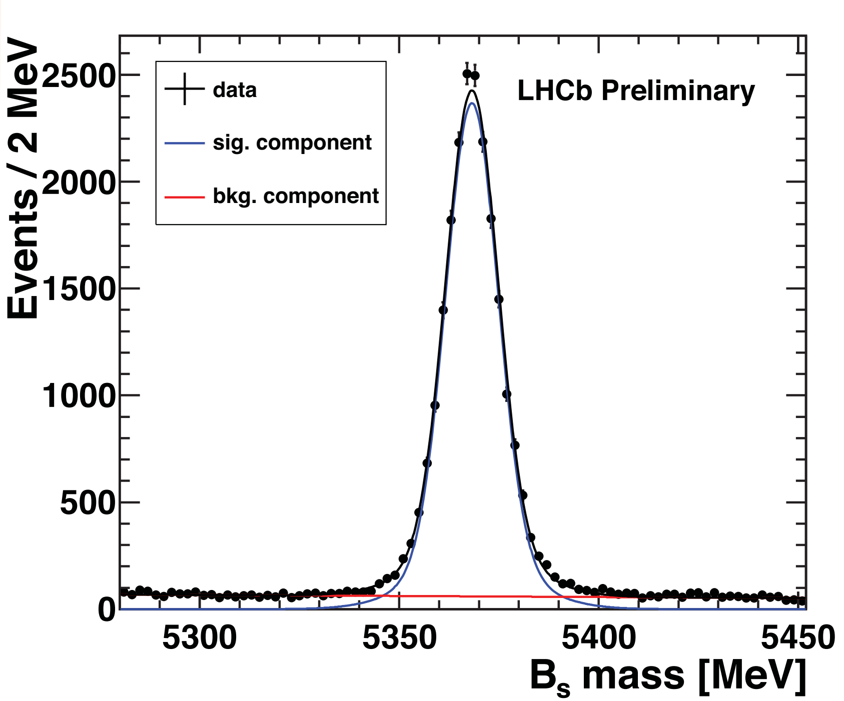
$\phi_s \Leftrightarrow \pi - \phi_s$

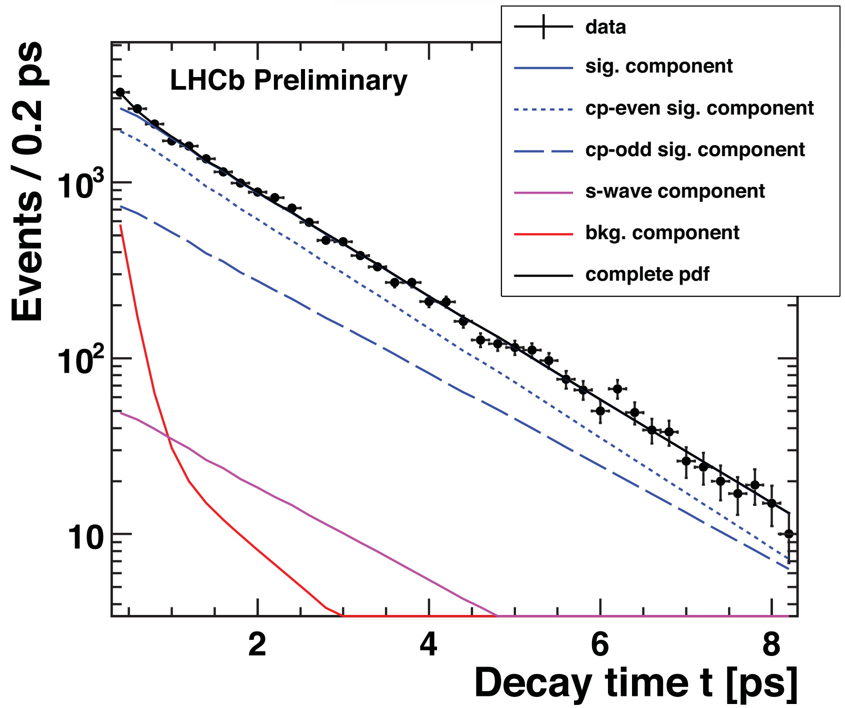
$\Delta\Gamma_s \Leftrightarrow -\Delta\Gamma_s$

\+ strong phase changes

$$
\begin{aligned}
A_1 &= |A_0|^2 e^{-\Gamma_s t}[\cosh\left(\frac{\Delta\Gamma}{2}t\right) - \cos\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right) + \sin\phi_s \sin(\Delta m t)] \\
A_2 &= |A_\parallel|^2 e^{-\Gamma_s t}[\cosh\left(\frac{\Delta\Gamma}{2}t\right) - \cos\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right) + \sin\phi_s \sin(\Delta m t)] \\
A_3 &= |A_\perp|^2 e^{-\Gamma_s t}[\cosh\left(\frac{\Delta\Gamma}{2}t\right) + \cos\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right) - \sin\phi_s \sin(\Delta m t)] \\
A_4 &= |A_\parallel||A_\perp| e^{-\Gamma_s t}[-\cos(\delta_\perp - \delta_\parallel)\sin\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right) - \cos(\delta_\perp - \delta_\parallel)\cos\phi_s \sin(\Delta m t) \\
&\quad + \sin(\delta_\perp - \delta_\parallel)\cos(\Delta m t)] \\
A_5 &= |A_0||A_\parallel| e^{-\Gamma_s t}\cos(\delta_\parallel - \delta_0)[\cosh\left(\frac{\Delta\Gamma}{2}t\right) - \cos\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right) + \sin\phi_s \sin(\Delta m t)] \\
A_6 &= |A_0||A_\perp| e^{-\Gamma_s t}[-\cos(\delta_\perp - \delta_0)\sin\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right) - \cos(\delta_\perp - \delta_0)\cos\phi_s \sin(\Delta m t) \\
&\quad + \sin(\delta_\perp - \delta_0)\cos(\Delta m t)] \\
A_7 &= |A_s|^2 e^{-\Gamma_s t}[\cosh\left(\frac{\Delta\Gamma}{2}t\right) + \cos\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right) - \sin\phi_s \sin(\Delta m t] \\
A_8 &= |A_s||A_\parallel| e^{-\Gamma_s t}[-\sin(\delta_\parallel - \delta_S)\sin\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right) - \sin(\delta_\parallel - \delta_S)\cos\phi_s \sin(\Delta m t) \\
&\quad + \cos(\delta_\parallel - \delta_S)\cos(\Delta m t)] \\
A_9 &= |A_s||A_\perp| e^{-\Gamma_s t}\sin(\delta_\perp - \delta_S)[\cosh\left(\frac{\Delta\Gamma}{2}t\right) + \cos\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right) - \sin\phi_s \sin(\Delta m t)] \\
A_{10} &= |A_s||A_0| e^{-\Gamma_s t}[-\sin(\delta_0 - \delta_S)\sin\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right) - \sin(\delta_0 - \delta_S)\cos\phi_s \sin(\Delta m t) \\
&\quad + \cos(\delta_0 - \delta_S)\cos(\Delta m t)]
\end{aligned}
$$

$B_s \rightarrow J/\psi\Phi$ signal





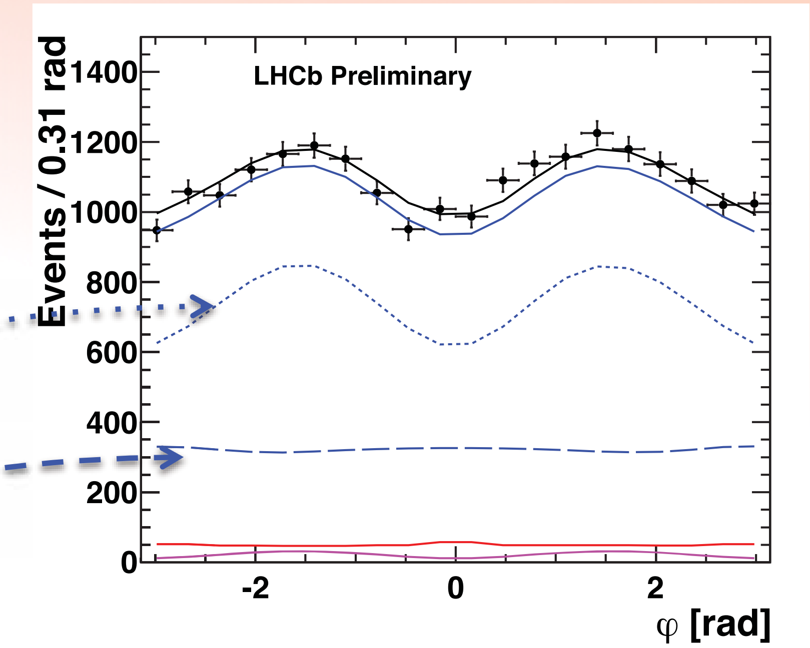
- ❑ Simple selection with kinematic cuts
- ❑ Most background removed by decay time cut t > 0.3 ps
- ❑ Very clean signal
- ❑ Approx. 21200 signal events

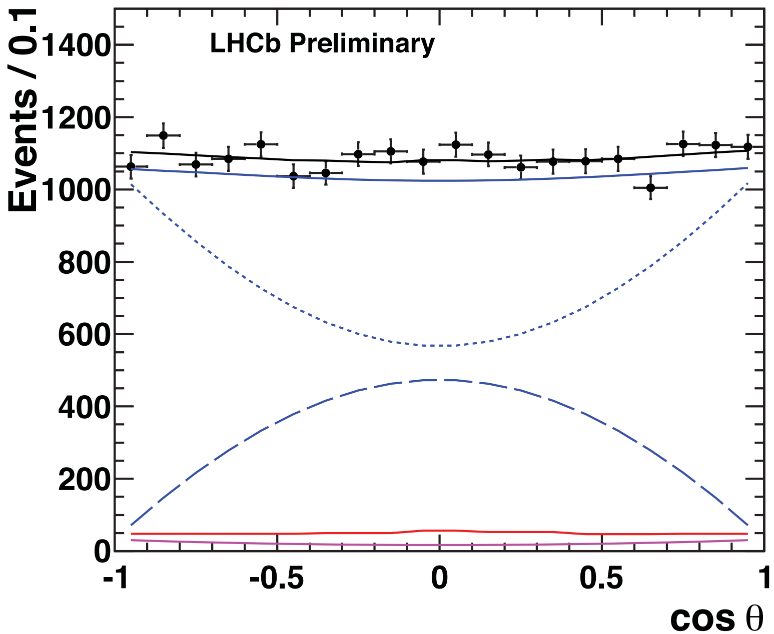
$B_s \rightarrow J/\psi\Phi$ decay angle distributions

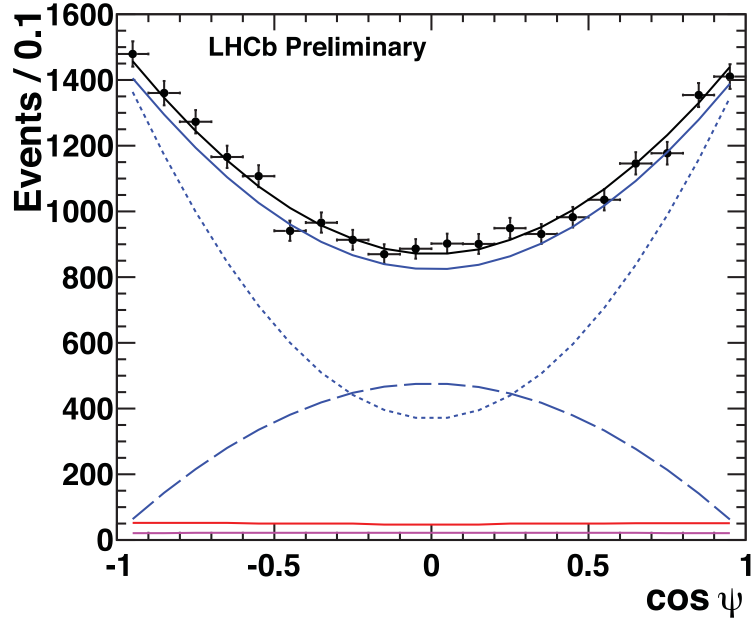
- The CP-even / CP-odd separation is very clear in all distributions.

CP-even

CP-odd

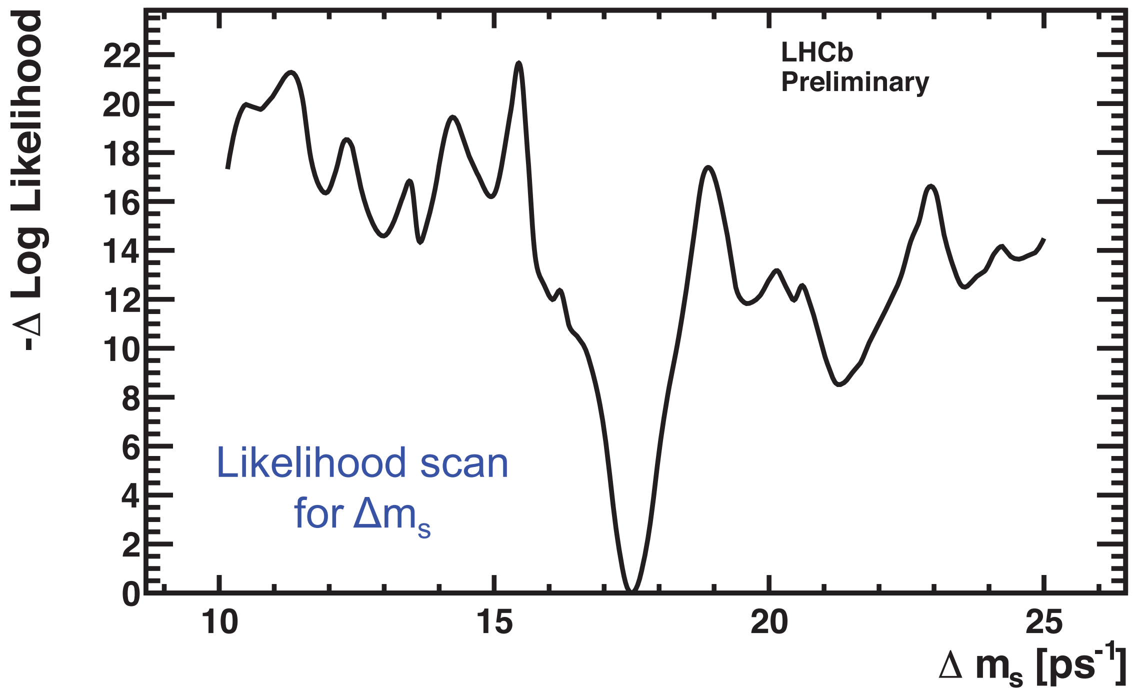






Digression: measurement of Δm_s

- The data has sinusoidal terms which measure Δm_s independently of ϕ_s



- We observe a central value Δm_s= 17.50 ± 0.15 (stat) ps^{-1}
  - Compare to LHCb published measurement 17.63 ± 0.11 ± 0.02 arXiv:1112.4311
  - This gives confidence that if there is a $\sin(\phi_s) \times \sin(\Delta m_s t)$ term we would see it.

$B_s \rightarrow J/\psi\Phi$: New Preliminary Results

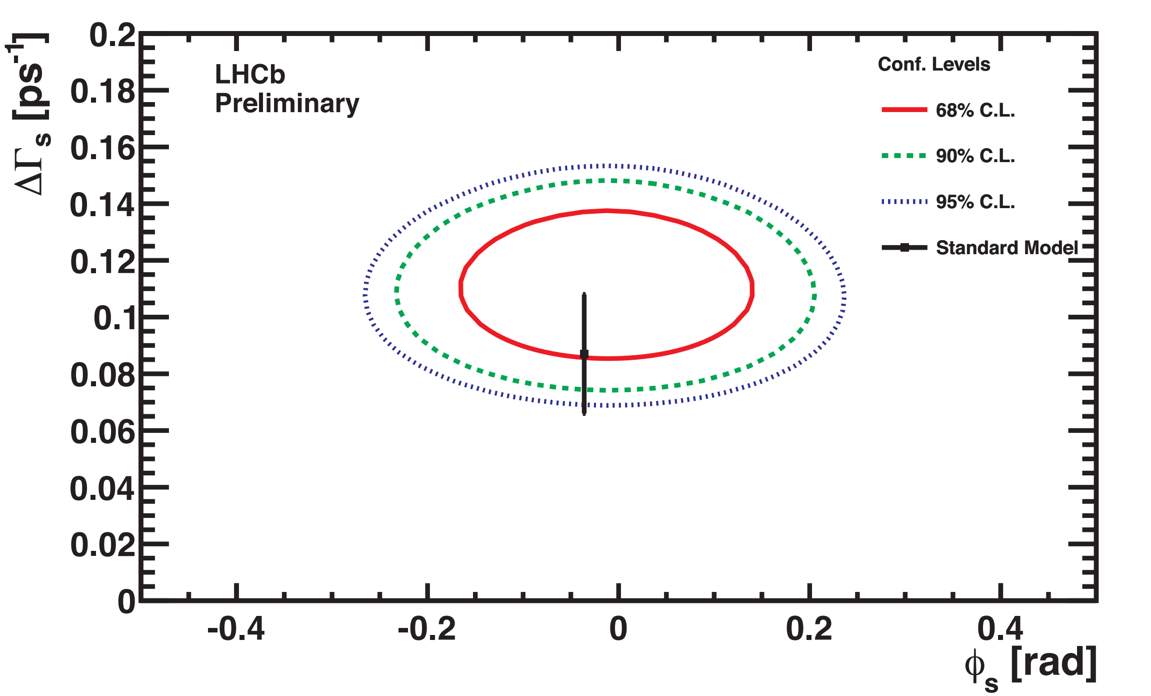
- Maximum likelihood fit to signal + background time, angle and mass distributions.
- Constrain Δm_s to 17.63 ± 0.11 ps
- "Solution-I" shown here
- ϕ_s uncorrelated with other quantities

Parameter	Value	Stat.	Syst.
Γ_s [ps^{-1}]	0.6580	0.0054	0.0066
$\Delta\Gamma_s$ [ps^{-1}]	0.116	0.018	0.006
$\|A_\perp(0)\|^2$	0.246	0.010	0.013
$\|A_0(0)\|^2$	0.523	0.007	0.024
F_S	0.022	0.012	0.007
$\delta_\perp$ [rad]	2.90	0.36	0.07
$\delta_\parallel$ [rad]	[2.81, 3.47]		0.13
δ_s [rad]	2.90	0.36	0.08
ϕ_s [rad]	-0.001	0.101	0.027

	Γ_s	$\Delta\Gamma_s$	$\|A_\perp\|^2$	$\|A_0\|^2$	ϕ_s
Γ_s	1.00	−0.38	0.39	0.20	−0.01
$\Delta\Gamma_s$		1.00	−0.67	0.63	−0.01
$\|A_\perp(0)\|^2$			1.00	−0.53	−0.01
$\|A_0(0)\|^2$				1.00	−0.02
ϕ_s					1.00

$B_s \rightarrow J/\psi\Phi$: New Preliminary Results 1.0 fb^{-1}

Contour for
ϕ_s - $\Delta\Gamma_s$



Γ_s = 0.6580 ± 0.0054(stat.) ± 0.0066(syst.) ps^{-1}

$\Delta\Gamma_s$ = 0.116 ± 0.018(stat.) ± 0.006(syst.) ps^{-1}

ϕ_s = -0.001 ± 0.101(stat.) ± 0.027(syst.) rad

Systematics

Source	Γ_s [ps^{-1}]	$\Delta\Gamma_s$ [ps^{-1}]	$A_\perp^2$	A_0^2	F_S	$\delta_\parallel$ [rad]	$\delta_\perp$ [rad]	δ_s [rad]	ϕ_s [rad]
Description of background	0.0010	0.004	-	0.002	0.005	0.04	0.04	0.06	0.011
Angular acceptances	0.0018	0.002	0.012	0.024	0.005	0.12	0.06	0.05	0.012
t acceptance model	0.0062	0.002	0.001	0.001	-	-	-	-	-
z and momentum scale	0.0009	-	-	-	-	-	-	-	-
Production asymmetry ($\pm$ 10%)	0.0002	0.002	-	-	-	-	-	-	0.008
CPV mixing & decay ($\pm$ 5%)	0.0003	0.002	-	-	-	-	-	-	0.020
Fit bias	-	0.001	0.003	-	0.001	0.02	0.02	0.01	0.005
Quadratic sum	0.0066	0.006	0.013	0.024	0.007	0.13	0.07	0.08	0.027

- Note: Tagging and resolution parameters floated in fit within uncertainties, hence not explicitly included in systematics

$B_s \to J/\psi\Phi$ and $B_s \to J/\psi\pi\pi$ combined prelim.result

- Used a simultaneous fit to both datasets, taking all common parameters and correlations into account.
- Used largest syst. error.

$$\phi_s = -0.002 \pm 0.083(\text{stat.}) \pm 0.027(\text{syst.})\ \text{rad}$$

Resolving the ambiguous solution

The sign of $\Delta\Gamma_s$

$\sim 0.37\ fb^{-1}$

LHCb-PAPER-2012-28, submitted PRL, arXiv:1202.4717v2

- There are two ambiguous solutions related by $\phi_s \Leftrightarrow \pi - \phi_s$ and $\Delta\Gamma \Leftrightarrow -\Delta\Gamma$
- We can disambiguate using the P-Wave ⇔ S-Wave interference

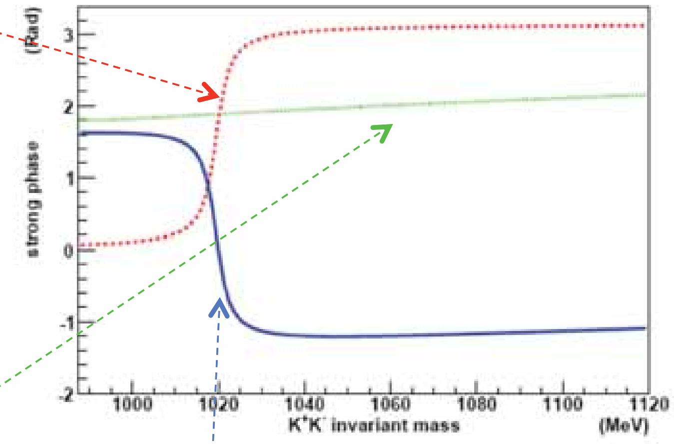
[Y. Xie et al., JHEP 0909:074, 2009]

Similar to Babar measurement of sign of cos(2β), PRD 71, 032005 (2007)

K^+K^- P-wave:

Phase of Breit-Wigner amplitude increases rapidly across $\phi(1020)$ mass region

$$BW(m_{KK}) = \frac{F_r F_D}{m_\phi^2 - m_{KK}^2 - i m_\phi \Gamma(m_{KK})}$$



K^+K^- S-wave:

Phase of Flatté amplitude for $f_0(980)$ relatively flat (similar for non-resonance)

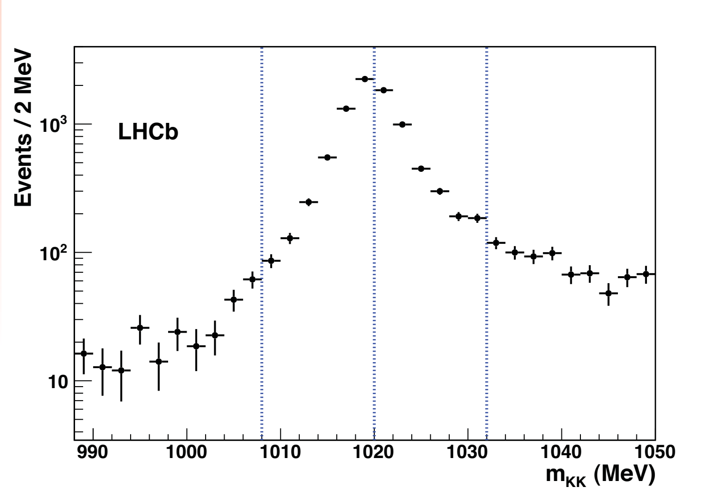
Phase difference between S- and P-wave amplitudes

Decreases rapidly across $\phi(1020)$ mass region

Resolution method: choose the solution with decreasing trend of δ_s-δ_P vs m_{KK} in the $\phi(1020)$ mass region

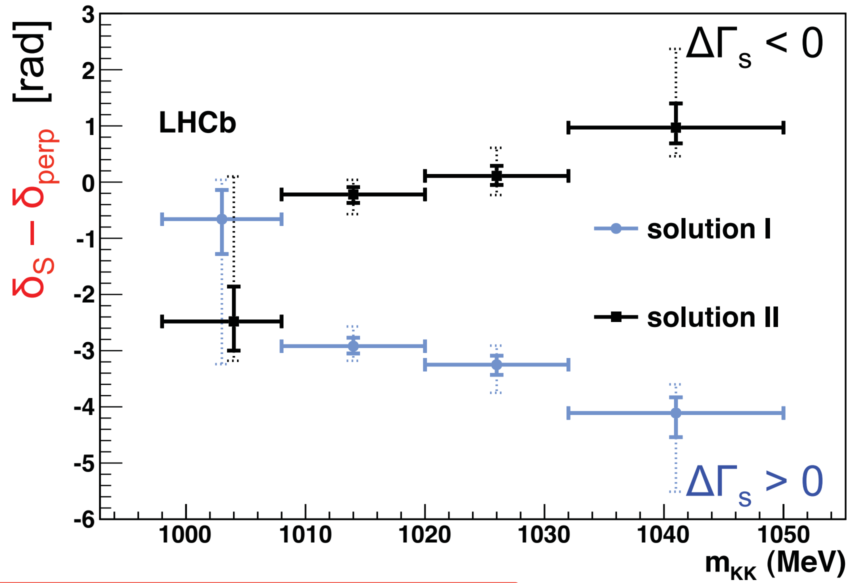
5

- Split data into 4 bins of m_{KK}



- In each bin measure
  - Fraction of S-wave
  - Measure relative strong phase difference $\delta_S - \delta_{perp}$

Parameter	Solution I	Solution II
ϕ_s (rad)	0.167 ± 0.175	2.975 ± 0.175
$\Delta\Gamma$ (ps^{-1})	0.120 ± 0.028	-0.120 ± 0.028
$F_{S;1}$	0.283 ± 0.113	0.283 ± 0.113
$F_{S;2}$	0.061 ± 0.022	0.061 ± 0.022
$F_{S;3}$	0.044 ± 0.022	0.044 ± 0.022
$F_{S;4}$	0.269 ± 0.067	0.269 ± 0.067
$\delta_{S\perp;1}$ (rad)	$-0.46\ ^{+0.35}_{-0.42}$	$-2.68\ ^{+0.42}_{-0.35}$
$\delta_{S\perp;2}$ (rad)	$-2.92\ ^{+0.15}_{-0.13}$	$-0.22\ ^{+0.13}_{-0.15}$
$\delta_{S\perp;3}$ (rad)	$-3.25\ ^{+0.16}_{-0.18}$	$0.11\ ^{+0.18}_{-0.16}$
$\delta_{S\perp;4}$ (rad)	$-4.11\ ^{+0.28}_{-0.43}$	$0.97\ ^{+0.43}_{-0.28}$

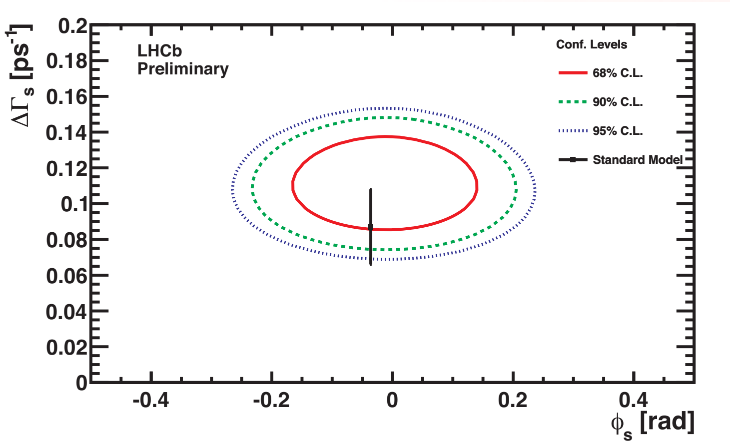


Solution-I is selected [4.7σ from being flat]

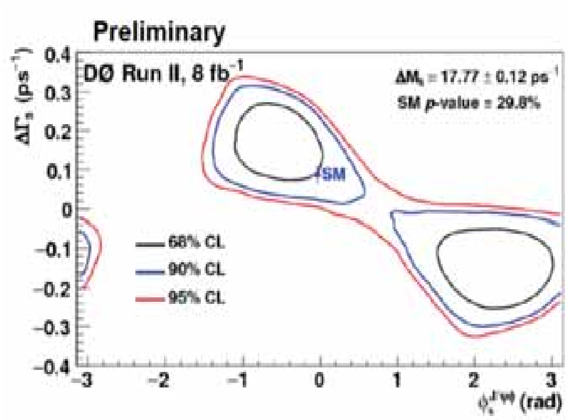
$\Delta\Gamma_s > 0$

LHC + Tevatron Results

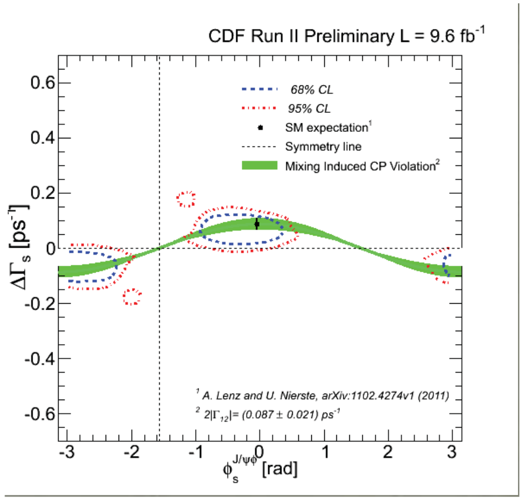
This result 1 fb^{-1}



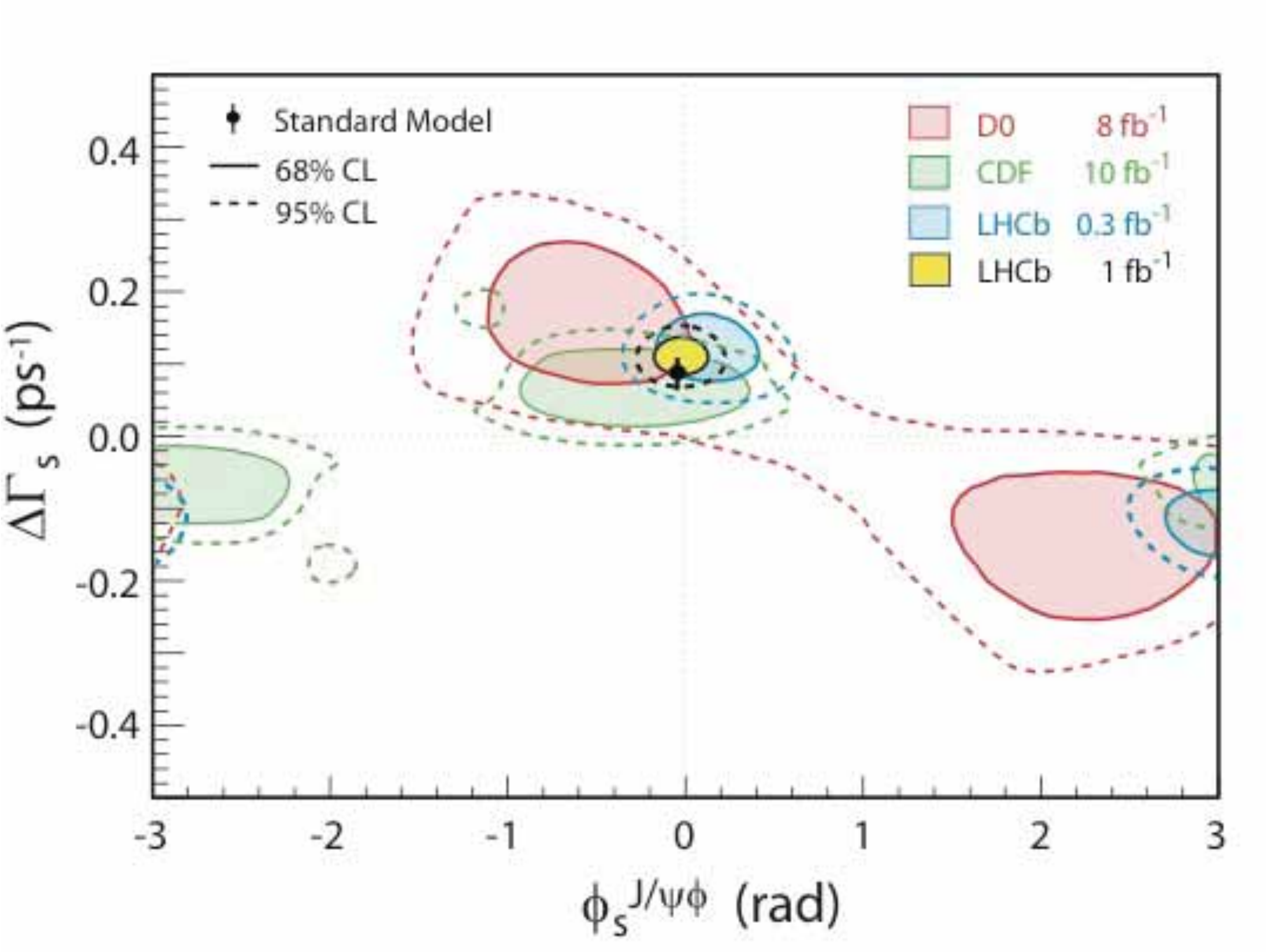
D0 8 fb^{-1} [S.Burdin, EPS 2011]



CDF 10 fb^{-1} [Sabato Leo talk, Lake Louise]



Pictorial overlay - winter 2012



Conclusion

- **LHCb has presented new preliminary results using the full 2011 data (1 fb^{-1})**
- **From an analysis of the J/ψϕ channel we find:**

$$\Gamma_s = 0.6580 \pm 0.0054(\text{stat.}) \pm 0.0066(\text{syst.})\ ps^{-1}$$

$$\Delta\Gamma_s = 0.116 \pm 0.018(\text{stat.}) \pm 0.006(\text{syst.})\ ps^{-1}$$

$$\phi_s = -0.001 \pm 0.101(\text{stat.}) \pm 0.027(\text{syst.})\ \text{rad.}$$

- **From an analysis of the J/ψππ channel we find:**

$$\phi_s = -0.02 \pm 0.17(\text{stat.}) \pm 0.02(\text{syst.})\ \text{rad}$$

- **Combining both results we find:**

$$\phi_s = -0.002 \pm 0.083(\text{stat.}) \pm 0.027(\text{syst.})\ \text{rad.}$$

- **We resolve the 2-fold ambiguity and find:** $\Delta\Gamma_s > 0$

Extra Information

1. CP-odd fraction: Table from LHCb-PAPER-2012-006

Table 1: Fit fractions of contributing resonances [16]. The final state helicity of the D-wave is denoted by Λ. Only statistical errors are quoted.

Resonance	Normalized fraction (%)
$f_0(980)$	69.7 ± 2.3
$f_0(1370)$	21.2 ± 2.7
non-resonant $\pi^+\pi^-$	8.4 ± 1.5
$f_2(1270)$, $\Lambda = 0$	0.49 ± 0.16
$f_2(1270)$, $\Lambda = \|1\|$	0.21 ± 0.65

- Upper limit on ρ(770) found to be 1.5% @ 95% C.L.
- Total is quadrature sum of f2(1270) + ρ(770)

2. Profile Likelihood

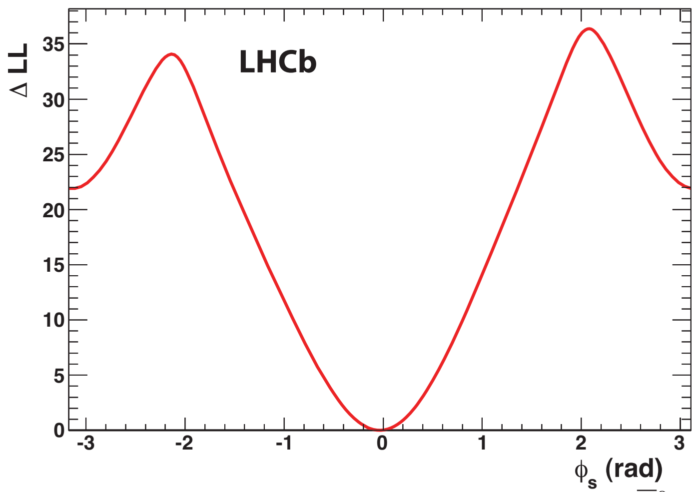
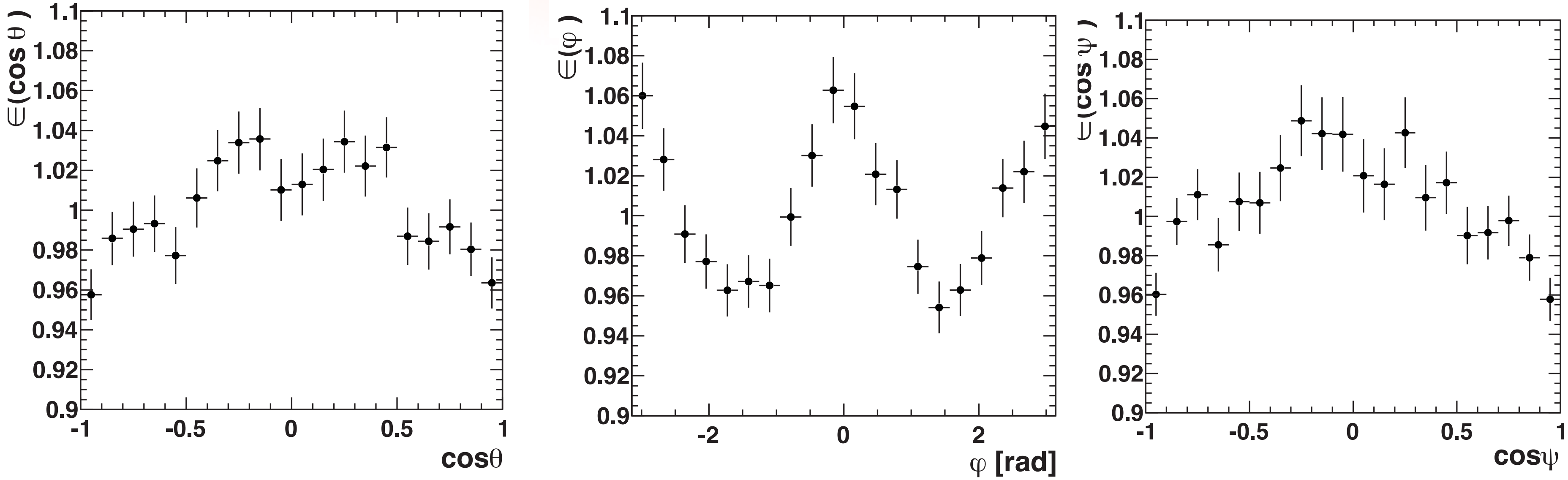


Figure 8: Log-likelihood difference as a function of ϕ_s for $\overline{B}^0_s \to J/\psi f_{\rm odd}$ events.

Decay angle acceptances

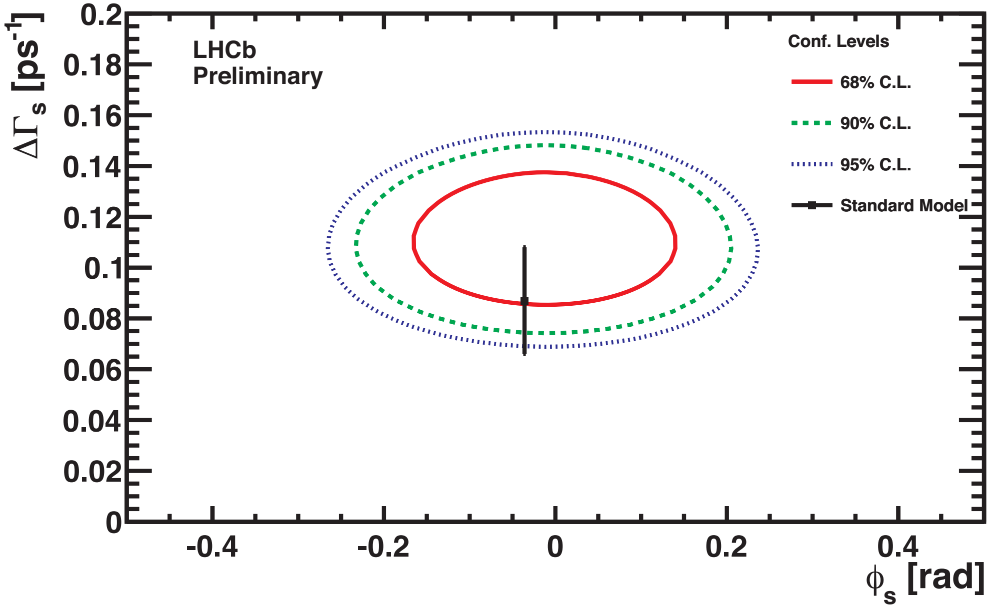


All acceptances ~ 5% effects

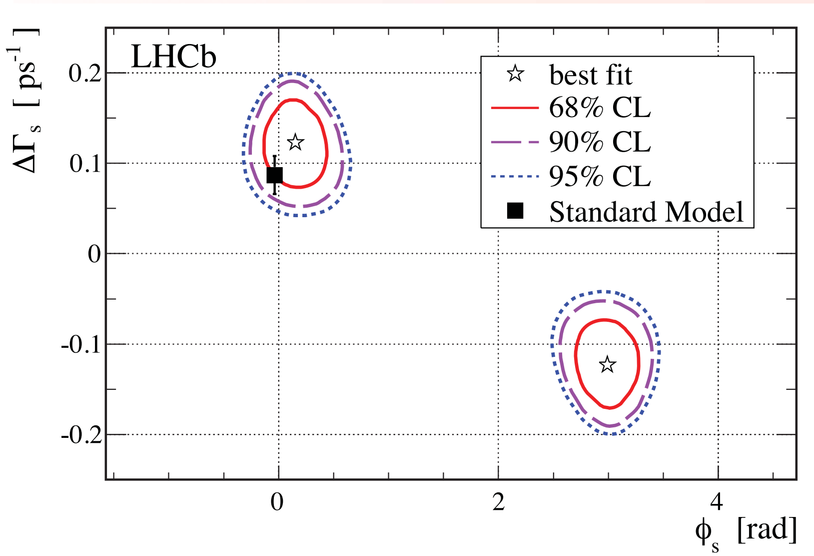
Accounted for in ML fit

$B_s \rightarrow J/\psi\Phi$: New Preliminary Results

This new preliminary result 1.0 fb^{-1}



Previous published result 0.37 fb^{-1}
arXiv:1112.3183



Γ_s = 0.6580 ± 0.0054(stat.) ± 0.0066(syst.) ps^{-1}

$\Delta\Gamma_s$ = 0.116 ± 0.018(stat.) ± 0.006(syst.) ps^{-1}

ϕ_s = -0.001 ± 0.101(stat.) ± 0.027(syst.) rad.

Γ_s = 0.657 ± 0.009(stat.) ± 0.008(syst.) ps^{-1}

$\Delta\Gamma_s$ = 0.123 ± 0.029(stat.) ± 0.011(syst.) ps^{-1}

ϕ_s = 0.151 ± 0.18(stat.) ± 0.06(syst.) rad.

Syst error due to possible direct CVP

- We vary $|\lambda|^2$ by 5%
- Motivated by a fit for $|\lambda|^2$ gives < 5%

$$R(t,q) \propto e^{-\Gamma_s t}\left\{\cosh\frac{\Delta\Gamma_s t}{2} + \frac{2|\lambda|}{1+|\lambda|^2}\cos\phi_s \sinh\frac{\Delta\Gamma_s t}{2} - \frac{2qD}{1+|\lambda|^2}\left[|\lambda|\sin\phi_s\sin(\Delta m_s t) + (1-|\lambda|^2)\cos(\Delta m_s t)\right]\right\}.$$