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LHCb time-dependent results

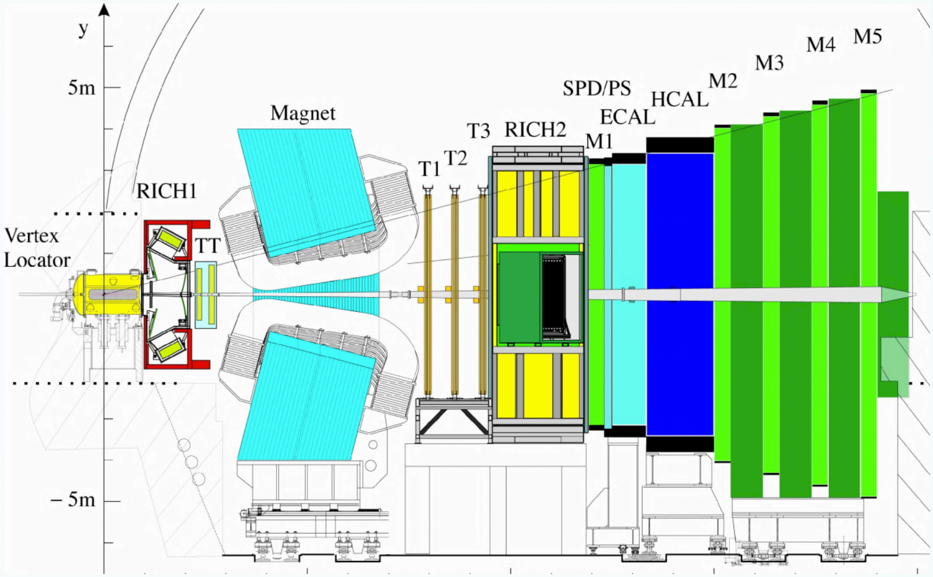
Marta Calvi
(University of Milano Bicocca and INFN)

On behalf of the LHCb Collaboration

Outline

- Introduction
- Analysis of $B \rightarrow J/\psi X$ modes: first results on the CPV phase ϕ_s at LHC and related measurements.
- Flavour oscillations in $B_s \rightarrow D_s \pi$ and Δm_s measurement.
- $B_s \rightarrow K^+K^-$ lifetime measurement.

LHCb



Single arm forward detector: $2<\eta<5$
High $b\bar{b}$ production in the forward region in pp collisions at $\sqrt{s}=7$ TeV:
$\sigma_{b\bar{b}} \approx 290\ \mu b$, but $\sigma_{inel} \approx 60$ mb .

LHCb detector performance:

- Efficient trigger for leptonic and hadronic decays (ε^{trig}~94%-60%)
- Excellent resolution for tracking and vertexing ($\sigma_{IP}^{x} \approx 15\ \mu m$)
- Good particle identification: π/K/p(RICHs), π/e/γ(ECAL), μ(MUON)

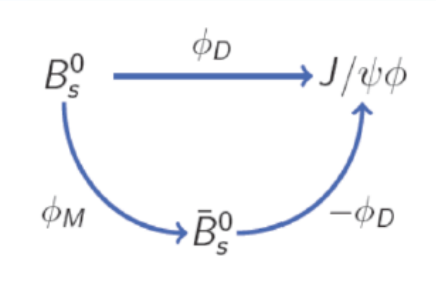
⇒ Good proper time resolution and flavour tagging power

In this talk preliminary results from analysis of ~ 36 pb^{-1} 2010 data

Expectation for 2011 ~1 fb^{-1} of data

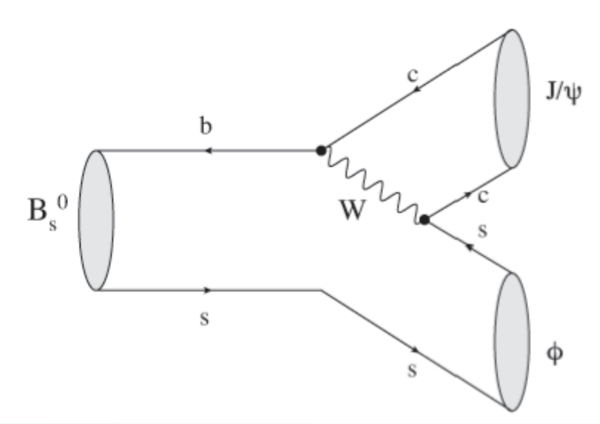
B_s mixing and CP violation

A CP violating phase can arise in the B_s system, from interference between decay with and without mixing.



$B_s \rightarrow J/\psi(\mu\mu)\,\phi(KK)$ is the golden mode.

$\phi_s = \Phi_M - 2\Phi_D$



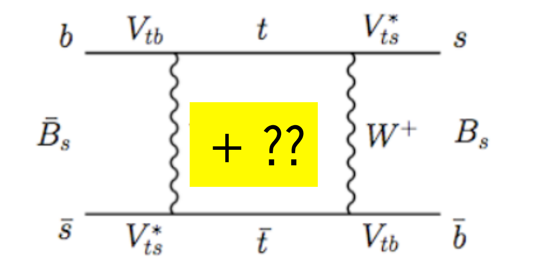
In the Standard Model ϕ_s is dominated by a single weak phase: $\phi_s^{SM} \cong -2\beta_s$

$$\beta_s = \arg\left(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right)$$

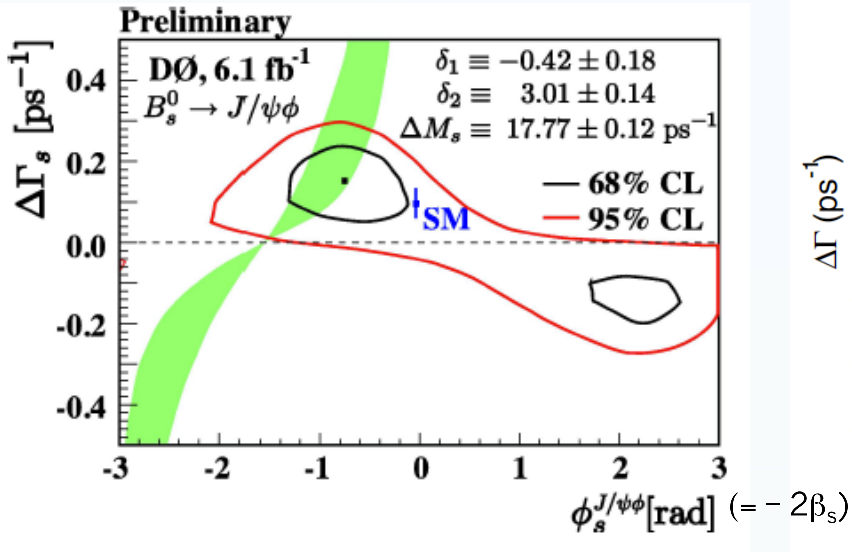
Well predicted:
$2\beta_s = 0.0363 \pm 0.0017$ rad
Additional penguin contribution ~10^{-4}-10^{-3}

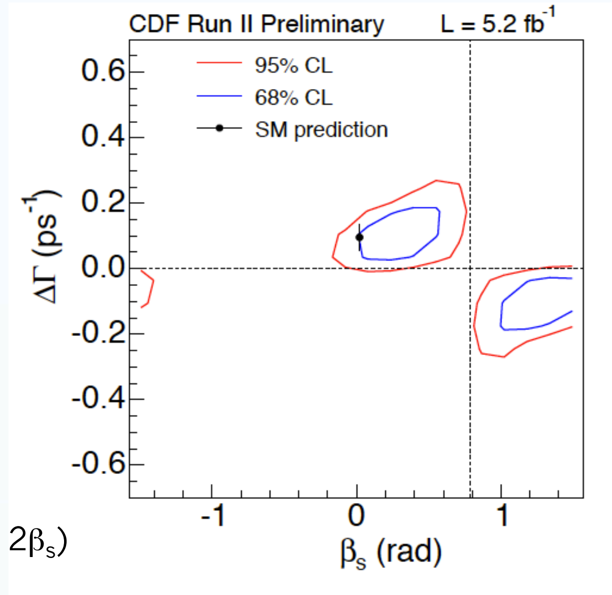
New Physics in mixing can enhance the measured ϕ_s :

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



ϕ_s from $B_s \rightarrow J/\psi(\mu\mu)\phi(KK)$





Still much space for NP to appear

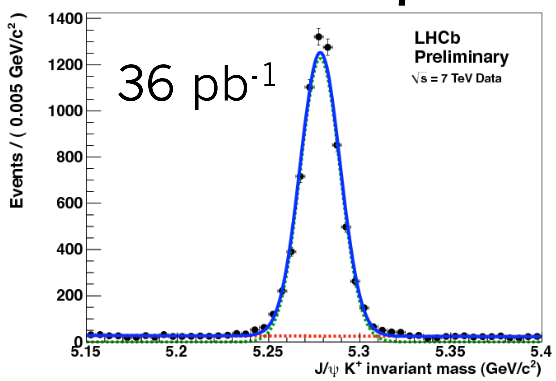
- The roadmap for a new ϕ_s measurement at LHCb requires several intermediate steps, and to demonstrate good control on:
  - Signal and control channels selection
  - Proper-time measurement
  - Angular distributions
  - Flavour tagging

LHCb-CONF-2011-001, 002,003,004,005,006,010

B→J/ψ X event samples

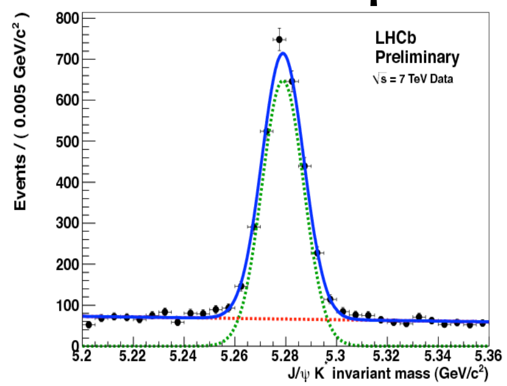
Similar selection for all $H_b \rightarrow J/\psi(\mu\mu)X$ channels, use "decay time unbiased" di-muon trigger

$B^+ \rightarrow J/\psi\ K^+$



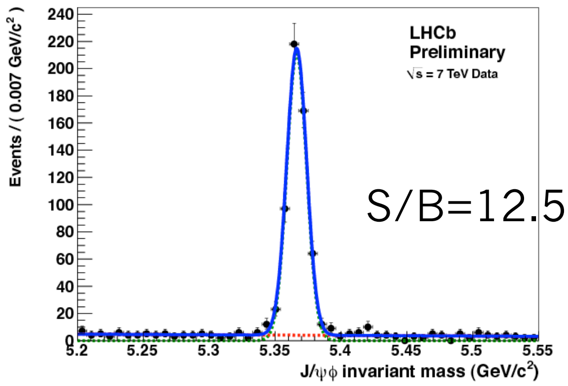
$\sigma_m = 10.7\ \mathrm{MeV}/c^2$

$B^0 \rightarrow J/\psi\ K^{0*}$



$\sigma_m = 8\ \mathrm{MeV}/c^2$

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



$\sigma_m = 7\ \mathrm{MeV}/c^2$

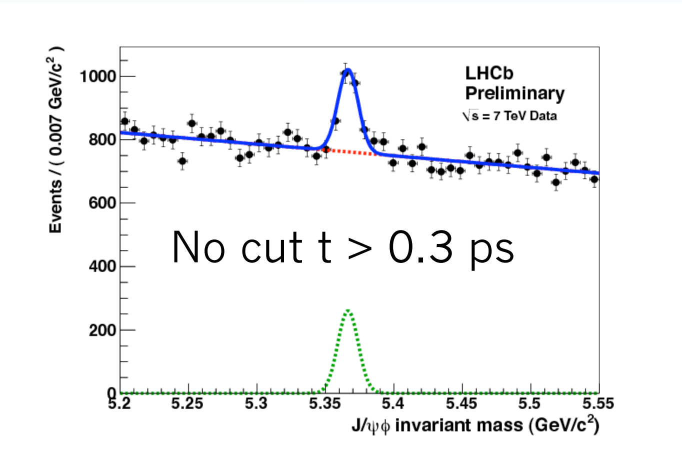
Very good mass resolution.

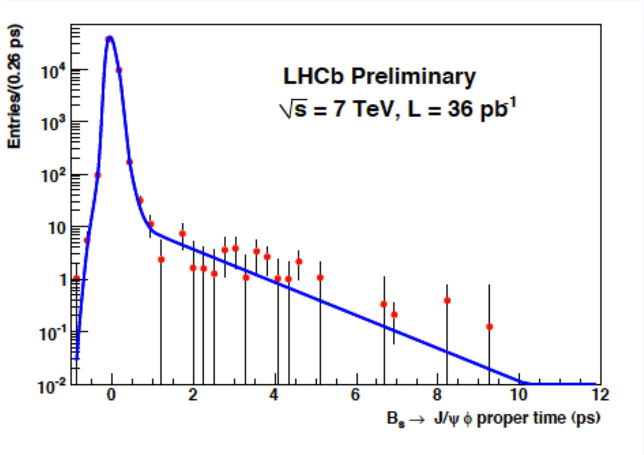
Very low background after proper-time cut t>0.3 ps removing prompt $J/\psi \rightarrow \mu\mu$.

Increase sample (~ 30%) with events from displaced track trigger "decay time biased".

Time resolution and acceptance

Proper-time resolution determined from data, using background events, mainly prompt $J/\psi \rightarrow \mu\mu$.





Triple Gaussian resolution model:

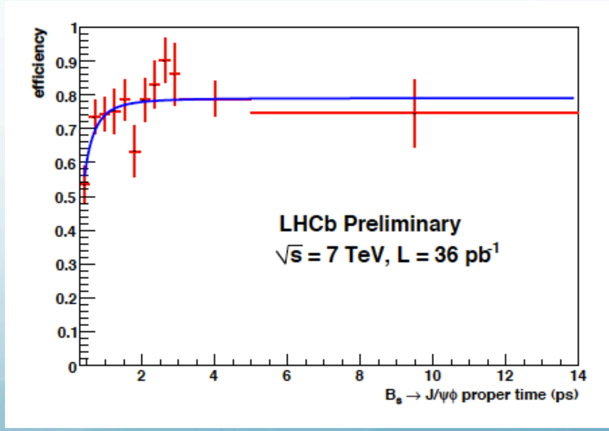
$\sigma \approx 50$ fs

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

→ Very good proper-time resolution.

Proper-time acceptance of the "decay time biased" sample from data:

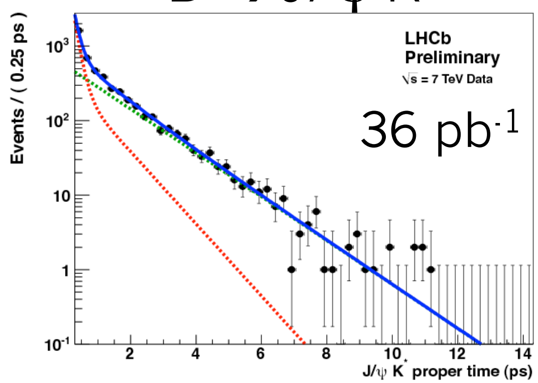
$$\varepsilon = \frac{N_{unbiased\&biased}}{N_{unbiased}}$$



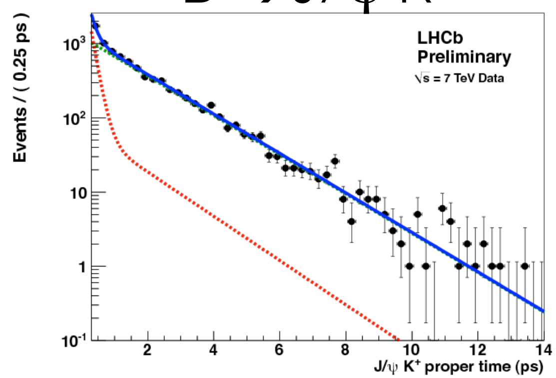
Measurement of lifetimes

Use “decay time unbiased” sample.

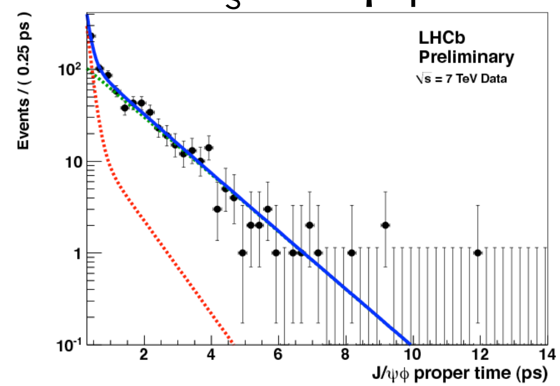
$B^+ \rightarrow J/\psi\, K^+$



$B^0 \rightarrow J/\psi\, K^{0*}$



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



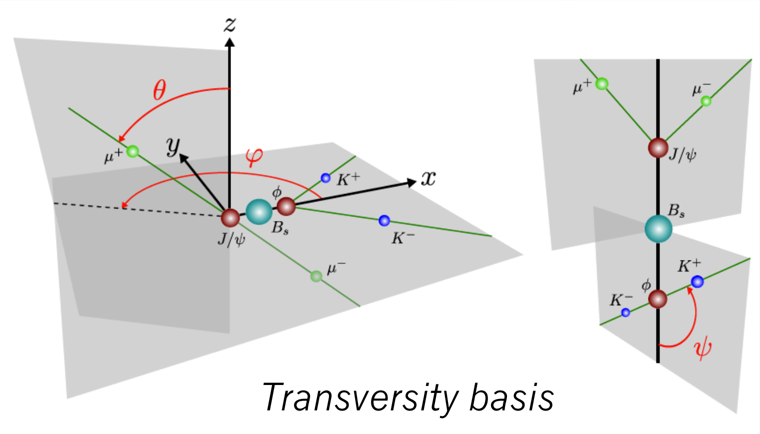
Yields for t>0.3 ps

Decay channel	Yield	LHCb result τ[ps] (*)(preliminary)	PDG τ[ps]
$B^+ \rightarrow J/\psi K^+$	6741 ± 85	$1.689 \pm 0.022_{stat.} \pm 0.047_{syst.}$	1.638 ± 0.011
$B^0 \rightarrow J/\psi K^{*0}$	2668 ± 58	$1.512 \pm 0.032_{stat.} \pm 0.042_{syst.}$	1.5252 ± 0.009
$B^0 \rightarrow J/\psi K^0_S$	838 ± 31	$1.558 \pm 0.056_{stat.} \pm 0.022_{syst.}$	1.525 ± 0.009
$B^0_s \rightarrow J/\psi \phi$ (*)	570 ± 24	$1.447 \pm 0.064_{stat.} \pm 0.056_{syst.}$	1.477 ± 0.046
$\Lambda_b \rightarrow J/\psi \Lambda$	187 ± 16	$1.353 \pm 0.108_{stat.} \pm 0.035_{syst.}$	$1.391^{+0.038}_{-0.037}$

Will become competitive with 2011 data sample. Current systematic dominated by time dependence of reconstruction efficiency, conservative estimate.

(*) Fit to a single exponential

Time dependent angular analysis



Transversity basis

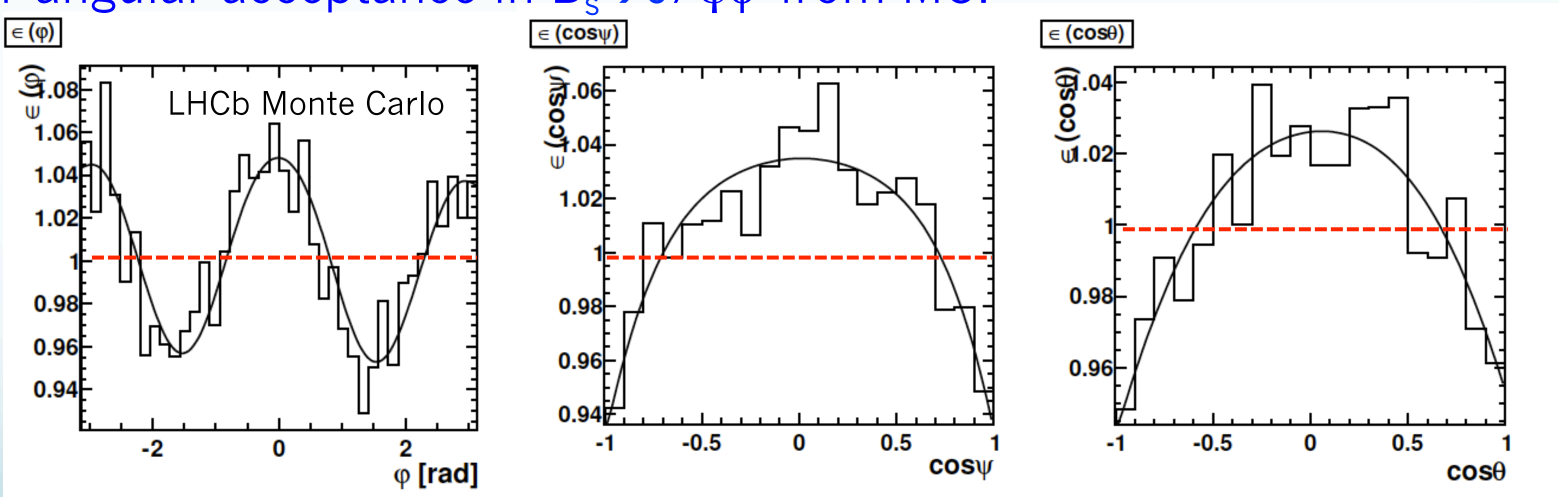
$B_s \rightarrow J/\psi\phi$ decay (P→VV) requires full angular analysis to statistically separate CP-even (ℓ=0,2) and CP odd (ℓ=1) final states.

Use θ,φ,ψ angles in the transversity basis.

Corrections for angular acceptance in $B_s \rightarrow J/\psi\phi$ from MC:

Normalized 1D projections of the 3D distributions

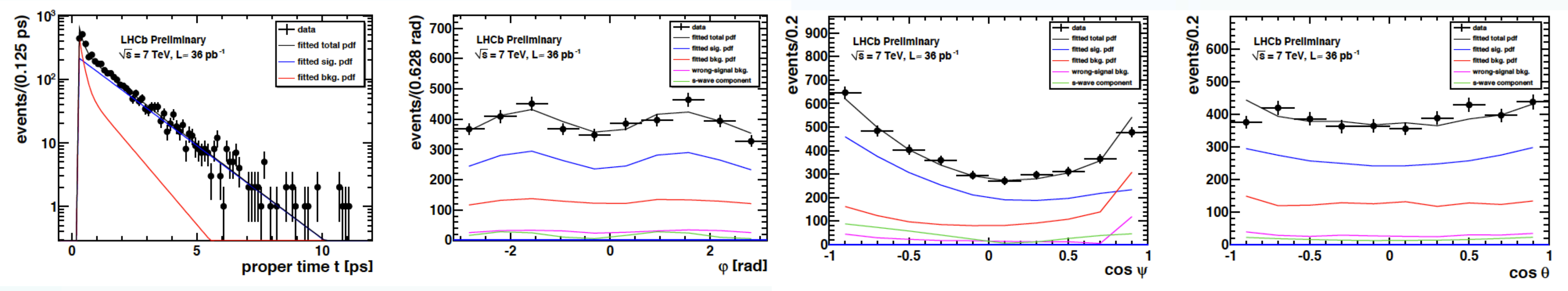
zero suppressed→



Angular acceptance effects induced by LHCb geometry, within ±5%

Polarization amplitudes for $B^0 \to J/\psi K^{0*}$

Same P→VV structure in $B^0 \to J/\psi(\mu\mu)\, K^{0*}(K\pi)$ decay.
Analysis used as a cross-check of the full 5D fit $(m, t, \phi, \psi, \theta)$.



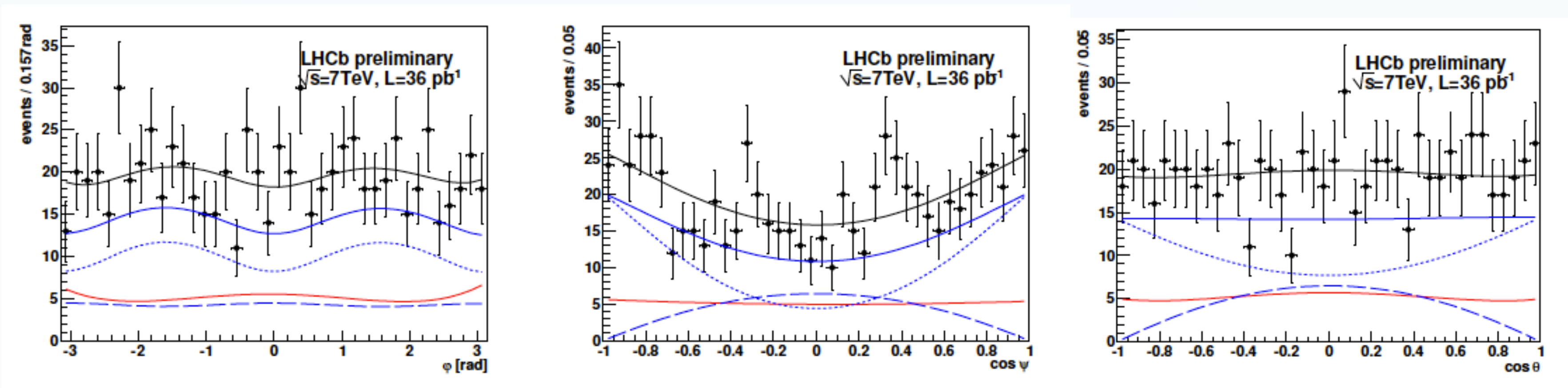
Background shape from sidebands. Non resonant S-wave Kπ contribution 5±2 %.

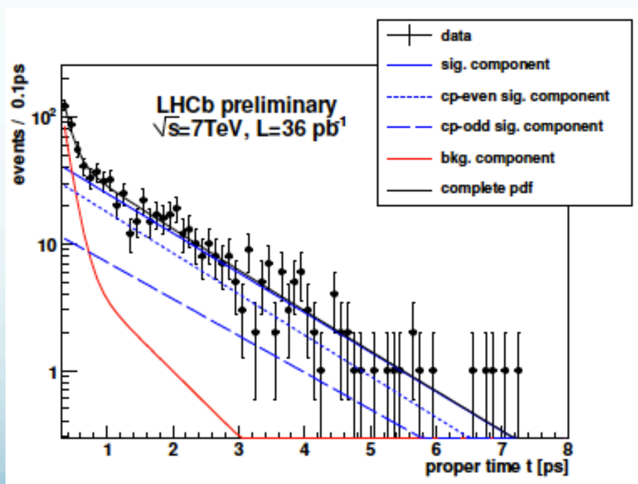
Parameter	LHCb result (preliminary)	BaBar PRD 76, 031002
$\lvert A_\parallel\rvert^2$	$0.252 \pm 0.020 \pm 0.016$	$0.211 \pm 0.010 \pm 0.006$
$\lvert A_\perp\rvert^2$	$0.178 \pm 0.022 \pm 0.017$	$0.233 \pm 0.010 \pm 0.005$
$\delta_\parallel$ [rad]	$-2.87 \pm 0.11 \pm 0.10$	$-2.93 \pm 0.08 \pm 0.04$
$\delta_\perp$ [rad]	$3.02 \pm 0.10 \pm 0.07$	$2.91 \pm 0.05 \pm 0.03$

Good agreement with previous measurements, but not yet competitive.

$B_s \rightarrow J/\psi\phi$ untagged analysis

5D fit (m,t,ψ,θ,ϕ) assuming no CPV ($\phi_s = 0$) .



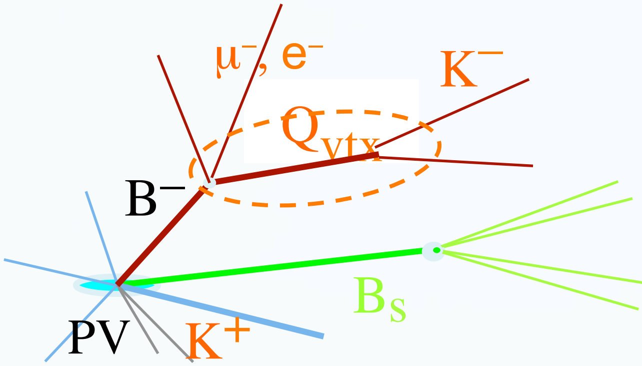


LHCb preliminary

Parameter		Result ± stat. ± syst.
Γ_s	$=$	$0.680 \pm 0.034 \pm 0.027\,\mathrm{ps}^{-1}$
$\Delta\Gamma_s$	$=$	$0.084 \pm 0.112 \pm 0.021\,\mathrm{ps}^{-1}$
$\vert A_0(0)\vert^2$	$=$	$0.532 \pm 0.040 \pm 0.028$
$\vert A_\perp(0)\vert^2$	$=$	$0.279 \pm 0.057 \pm 0.014$
$\cos\delta_\parallel$	$=$	$-1.24 \pm 0.27 \pm 0.09$

CDF 5.2 fb^{-1}: $\Delta\Gamma = 0.075 \pm 0.035(\mathrm{stat}) \pm 0.01(\mathrm{syst})\ \mathrm{ps}^{-1}$

Flavour tagging



B flavour at production determined by several algorithms

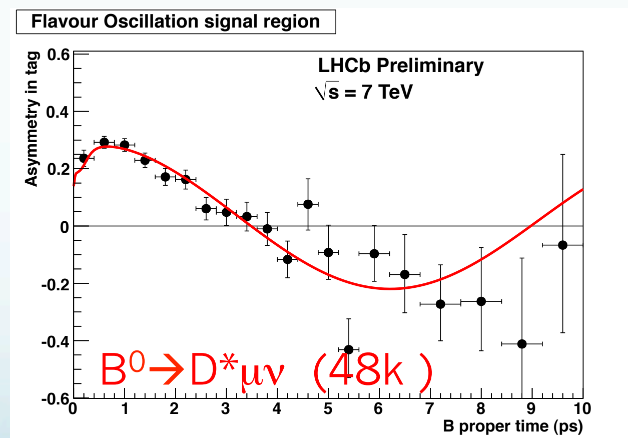
- Opposite Side (tag all b hadrons): μ, e, K, charge of inclusive secondary vertex
- Same Side: K (for B_s), π (for B_d,B_u)

Algorithms optimized on data for maximum tagging power: $\varepsilon_{tag}(1-2\omega)^2$ (*) using control channels.

OS and SSπ:

- $B^0 \to D^{*-}\mu^+\nu$, $B^+ \to J/\psi K^+$, $B^0 \to J/\psi K^{0*}$

$\varepsilon_{tag}(1-2\omega)^2 \approx 2\%$ OS
$\approx 2.8\%$ OS+SSπ



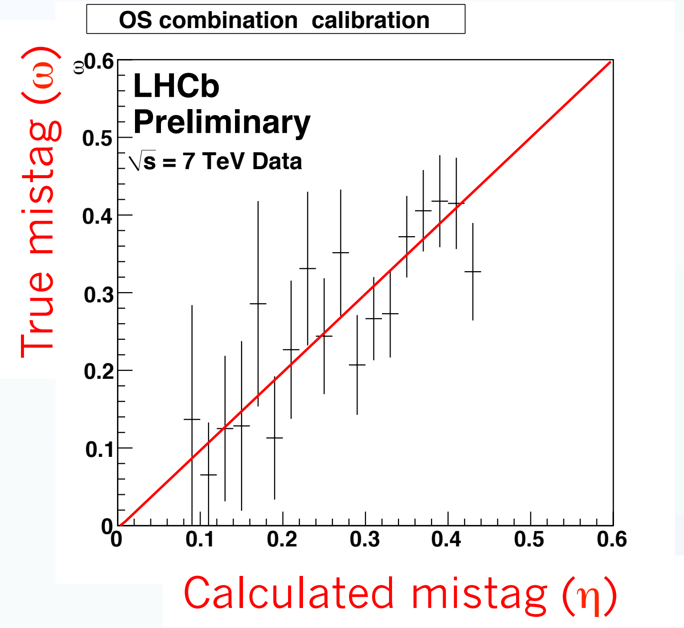
SSK: $B_s \to D_s^- \pi$ (≈1.3k) too small data sample to calibrate on data

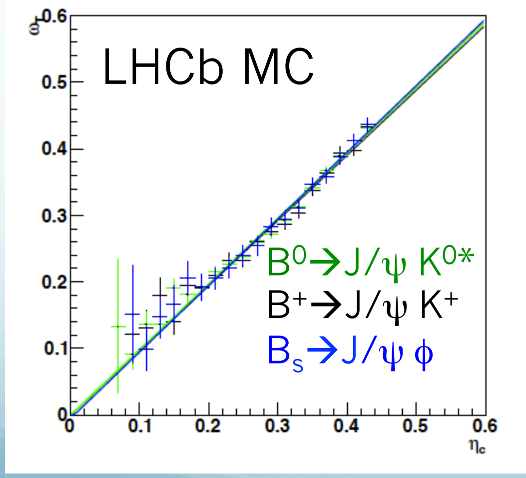
(*) ω=mistag rate

Flavour tagging calibration

- Tagging power enhanced using per-event mistag probability calculated from taggers and event properties.
- Calibrated on data with $B^+ \rightarrow J/\psi\ K^+$ events
  Validated on $B^0 \rightarrow J/\psi\ K^{0*}$.

- Uncertainty dominated by sample size:
  ± 0.012(stat) ± 0.004 (syst) on intercept
  ± 0.12 (stat) ± 0.01 (syst) on slope.





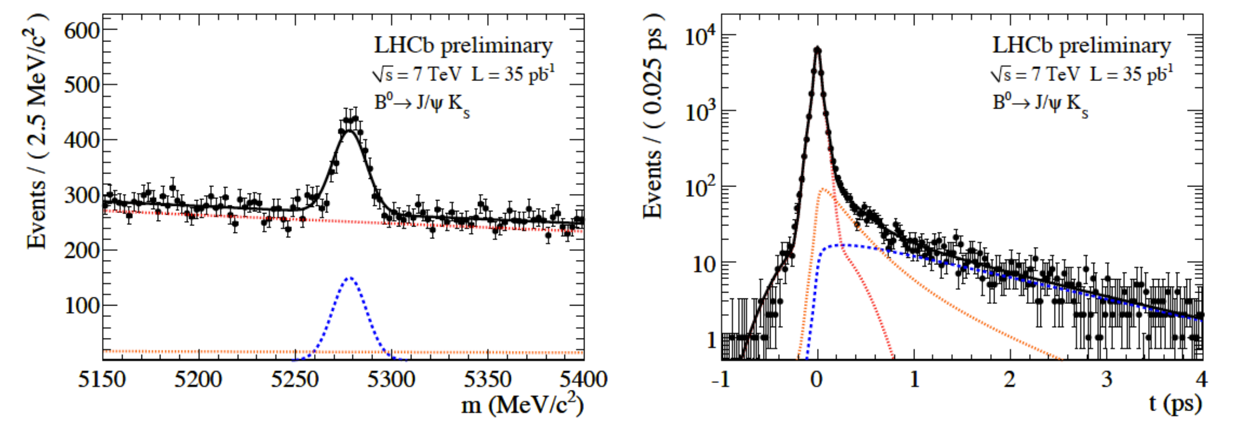
Performance on $B_s \rightarrow J/\psi\phi$ (OS only)

ε_{tag} = 17.6 ± 1.4 %

ω = 32 ± 2 %

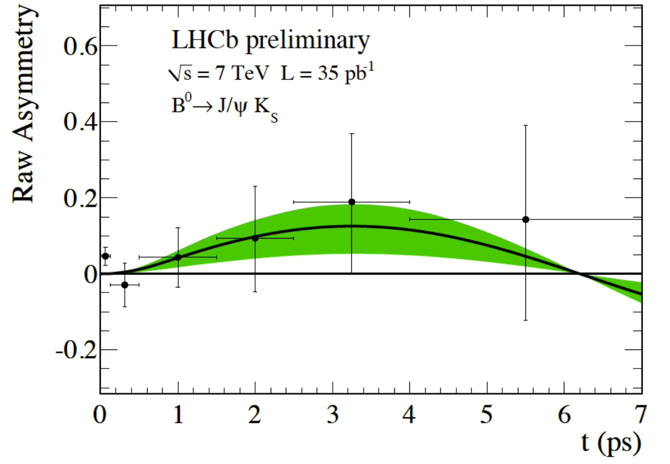
$\varepsilon_{tag}(1-2\omega)^2$ = 2.2 ± 0.5 %

sin2β from $B^0 \to J/\psi K^0_S$



1330 events in 35 pb^{-1}
Unbiased+biased trigger.
Use OS and SSπ tag.

Too small data sample for a measurement competitive with B-factories, but valid demonstration of LHCb capability in time dependent CPV analysis.



$$\mathcal{A}_{J/\psi K^0_S}(t) \equiv \frac{\Gamma(\overline{B}^0(t) \to J/\psi K^0_S) - \Gamma(B^0(t) \to J/\psi K^0_S)}{\Gamma(\overline{B}^0(t) \to J/\psi K^0_S) + \Gamma(B^0(t) \to J/\psi K^0_S)}$$
$$= S_{J/\psi K^0_S}\cos(\Delta m_d t) - C_{J/\psi K^0_S}\sin(\Delta m_d t)$$

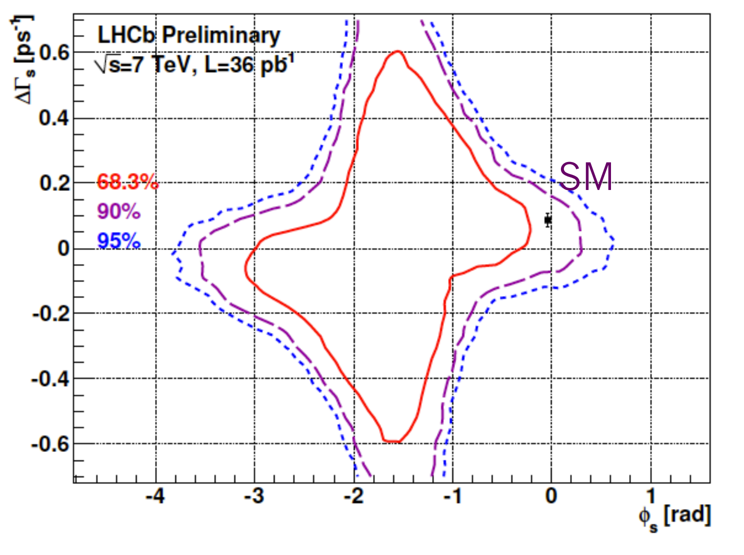
LHCb preliminary

$$S_{J/\psi K^0_S} = 0.53^{+0.28}_{-0.29}(\text{stat}) \pm 0.07(\text{syst})$$

Main systematic from tagging calibration.

$B_s \to J/\psi\phi$ tagged analysis

757±28 events (t>0.3ps) from unbiased+biased trigger. 7D fit (m,t,tag,ω, ϕ,ψ,θ)
No point-estimate, CL contours (Feldman-Cousins) in $\Delta\Gamma_s$- ϕ_s plane.



SM p-value 22% (1.2 σ)

Projection on ϕ_s:

LHCb preliminary

$$\phi_s \in [-2.7, -0.5]\ \mathrm{rad\ at}\ 68\%\ \mathrm{CL}$$

Include statistical uncertainty and systematic from tagging and Δm_s floated in the fit.
All other syst. uncertainties give negligible effect on the contours.

	LHCb 36 pb^{-1}	CDF 5.2 fb^{-1}
$B_s \to J/\psi\,\phi$	836	6500
Proper time resolution	50 fs	100 fs
OS tagging power	$2.2 \pm 0.5\%$	$1.2 \pm 0.2\%$
SS tagging power	work ongoing	$3.5 \pm 1.4\%$

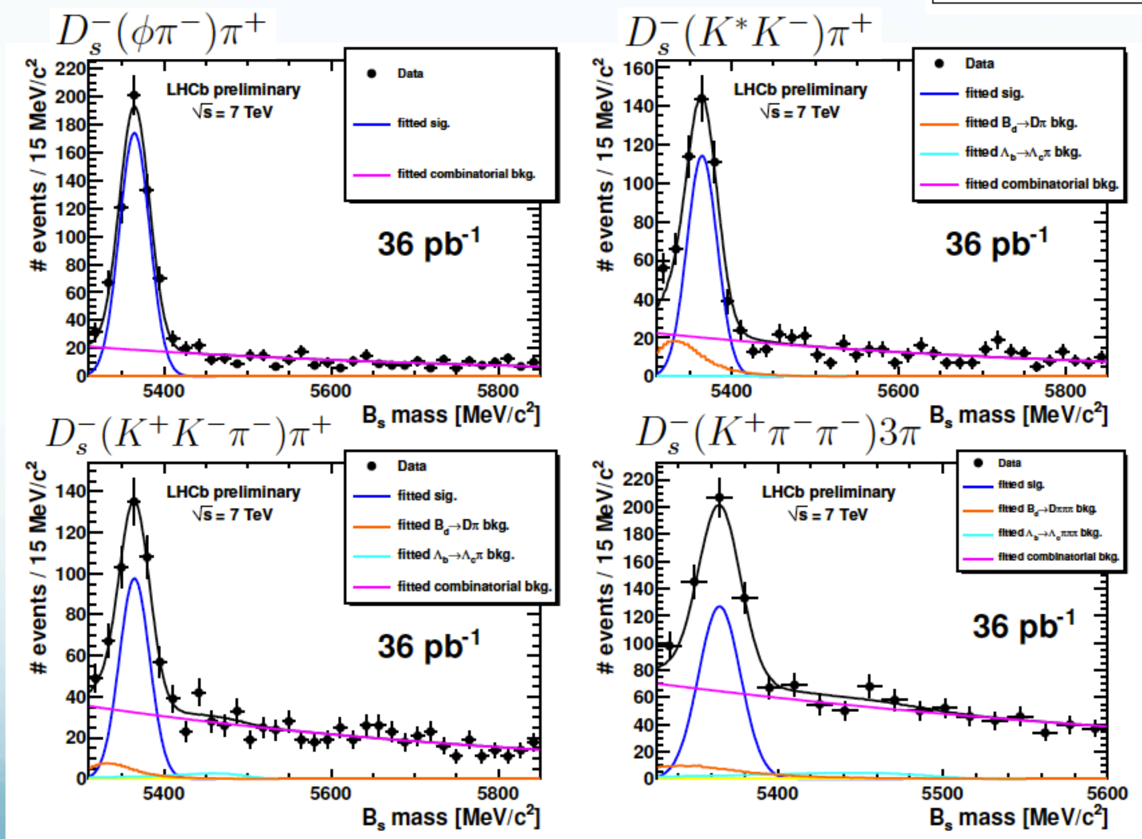
Improvements expected with 2011 data: x30 larger data sample and addition of SSK tag.

Preparing for world best measurement!

B_s mixing in $B_s \rightarrow D_s^-(3)\ \pi^+$

Combine four decay modes for a total of ~1300 signal events:

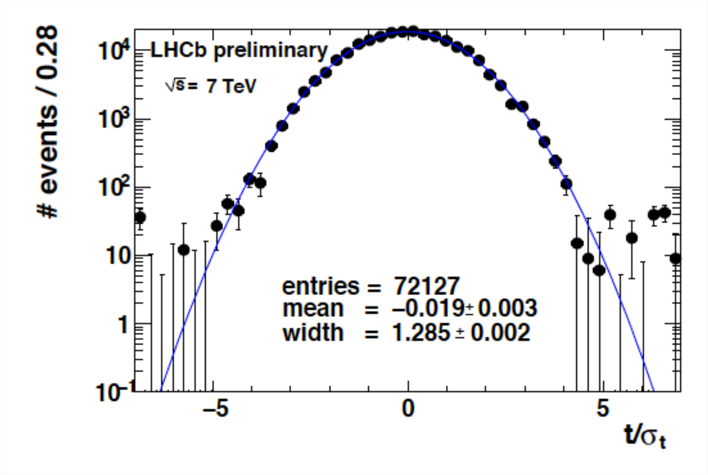
decay mode	# signal candidates
$B_s \to D_s^-(\phi\pi^-)\pi^+$	515 ± 25
$B_s \to D_s^-(K^*K)\pi^+$	338 ± 27
$B_s \to D_s^-(K^+K^-\pi^-)\pi^+$	283 ± 27
$B_s \to D_s^-(K^+K^-\pi^-)3\pi$	245 ± 46



σ_m=18 MeV/c^2 ($D_s\pi$)

σ_m=12.7 MeV/c^2 ($D_s3\pi$)

B_s mixing in $B_s \to D_s^-(3)\pi^+$



Per-event proper-time resolution calibrated on data with prompt D_s and random π^+ :

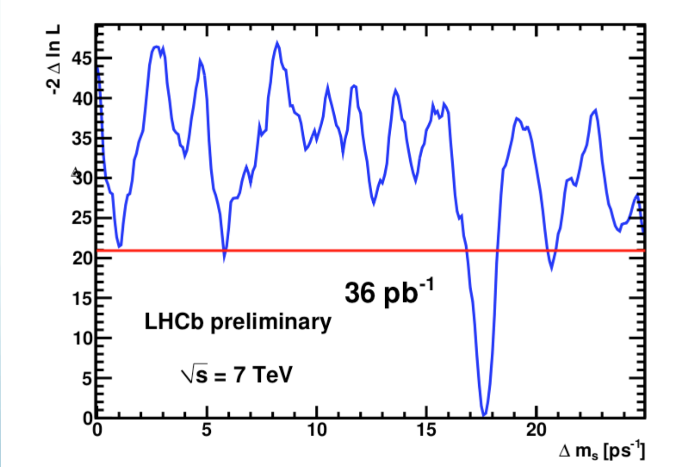
$\langle\sigma_t\rangle$ = 44 fs ($D_s\pi$), 36 fs ($D_s 3\pi$)

Propertime acceptance from MC.

Per-event mistag probability as re-calibrated in the $B^0 \to D^-\pi^+$ channel:

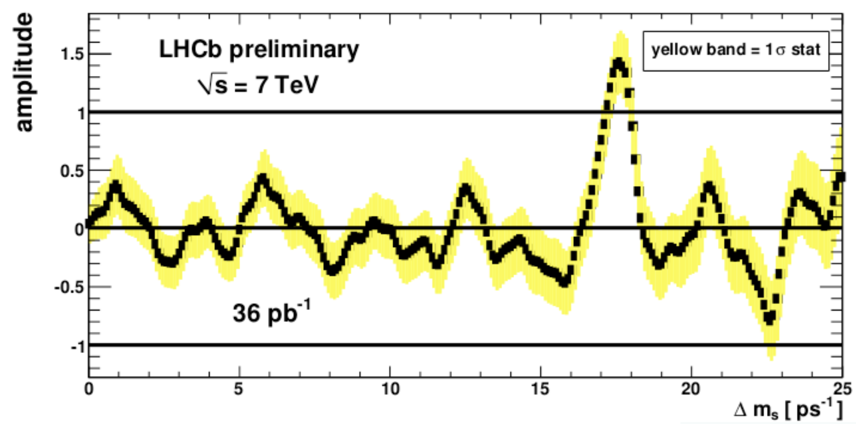
$\varepsilon D^2 = 3.8 \pm 2.1$ % (OS tag)

Minimum in the likelihood at $\Delta m_s \sim 17.6\ ps^{-1}$ with 4.6 σ statistical significance

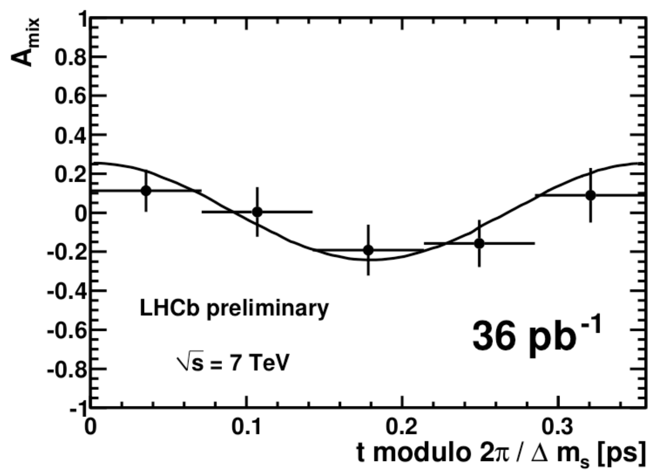


B_s mixing in $B_s \to D_s^-(3)\pi^+$

- Amplitude scan: A=1.41 ± 0.26 (stat) for Δm_s =17.6 ps^{-1}



Systematic uncertainties on Δm_s source	$\Delta_{\Delta m_s}[ps^{-1}]$
proper time resolution $\mathcal{S}_{\sigma_t} = [1.2 - 1.4]$	0.006
proper time resolution model	0.001
proper time acceptance function	0.000
fixed parameters floating	0.003
diff. background shape in mass fit	0.010
phys. bkg mass templates	0.002
variation of η and σ_t PDFs	0.026
z-scale (0.1%)	0.018
momentum scale (0.1%)	0.018
$\Delta\Gamma_s = [0 - 0.2] \times \Gamma_s$	0.002
total systematic uncertainties	**0.038**



LHCb preliminary

$$\Delta m_s = 17.63 \pm 0.11\ (\text{stat.}) \pm 0.04\ (\text{syst.})\ \text{ps}^{-1}$$

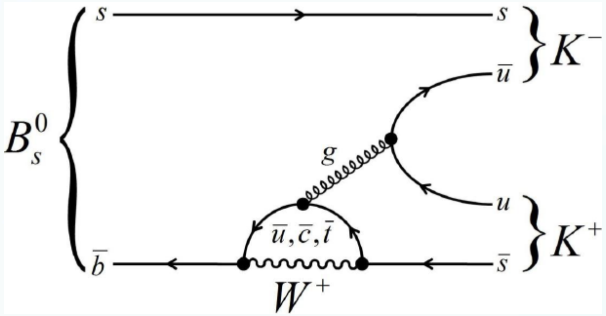
Competitive with world best (CDF, 1 fb^{-1}):

$$\Delta m_s = 17.77 \pm 0.10\ (\text{stat.})\ \pm 0.07\ (\text{syst.})\ \text{ps}^{-1}$$

$B_s \rightarrow K^-K^+$ lifetime

Several test of SM and NP searches are possible with $B_{d,s} \rightarrow \pi K, \pi\pi, KK, pp$ decays, as CP asymmetries and γ angle masurements.

$B_s \rightarrow K^- K^+$ decay dominated by penguin diagram.
Can receive important NP contributions affecting lifetime difference: $\Delta\Gamma_s = \Gamma_L - \Gamma_H \cong \Delta\Gamma_s^{SM} \cos(\phi^{NP})$



Fitting the decay rate with a single exponential an effective lifetime is measured:

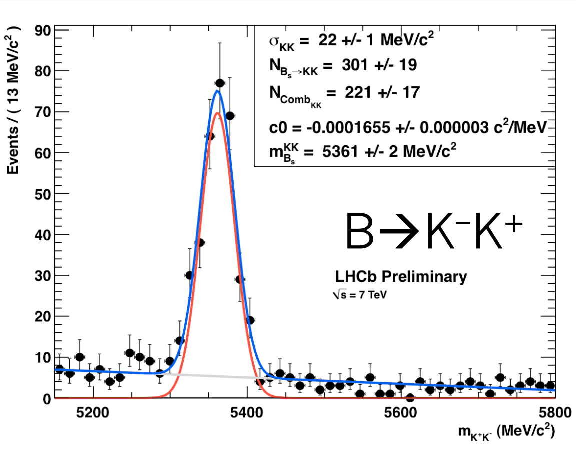
$$\tau^{-1}{}_{KK} = \frac{R_L/\Gamma_L + R_H/\Gamma_H}{R_L/\Gamma_L^2 + R_H/\Gamma_H^2}$$

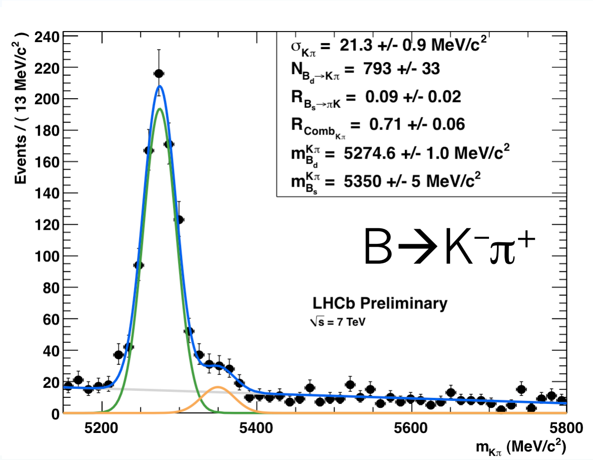
R_L, R_H: fraction of L,H states in the $B_s \rightarrow K^- K^+$ decay, mainly light.

Compared with a lifetime in a flavour specific final state: $\tau_{Bs}^{-1} = (\Gamma_L + \Gamma_H)/2$ can constrain $\Delta\Gamma_s/\Gamma_s$ and the NP B_s mixing phase ϕ^{NP}

$B_s \rightarrow K^-K^+$ lifetime measurement

$B \rightarrow hh'$ states well separated using π/K identification from RICHs.





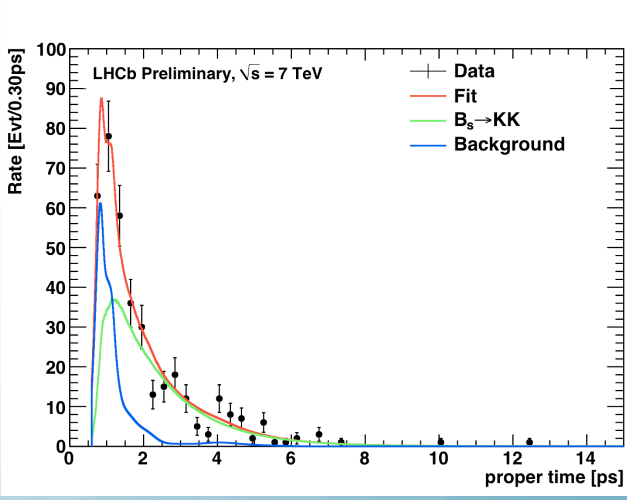
Two τ measurements:

- **Relative lifetime:** proper-time acceptance cancelled by using the ratio to the kinematically similar decay $B_d \rightarrow K\pi$, and B_d lifetime.
- **Absolute lifetime:** proper-time acceptance determined from data on event-by event basis

LHCb preliminary

$$\tau_{B_s^0} = 1.440 \pm 0.096\ (\mathrm{stat}) \pm\ 0.010\ (\mathrm{syst})\ \mathrm{ps}$$

CDF: τ = 1.53±0.18±0.02 ps



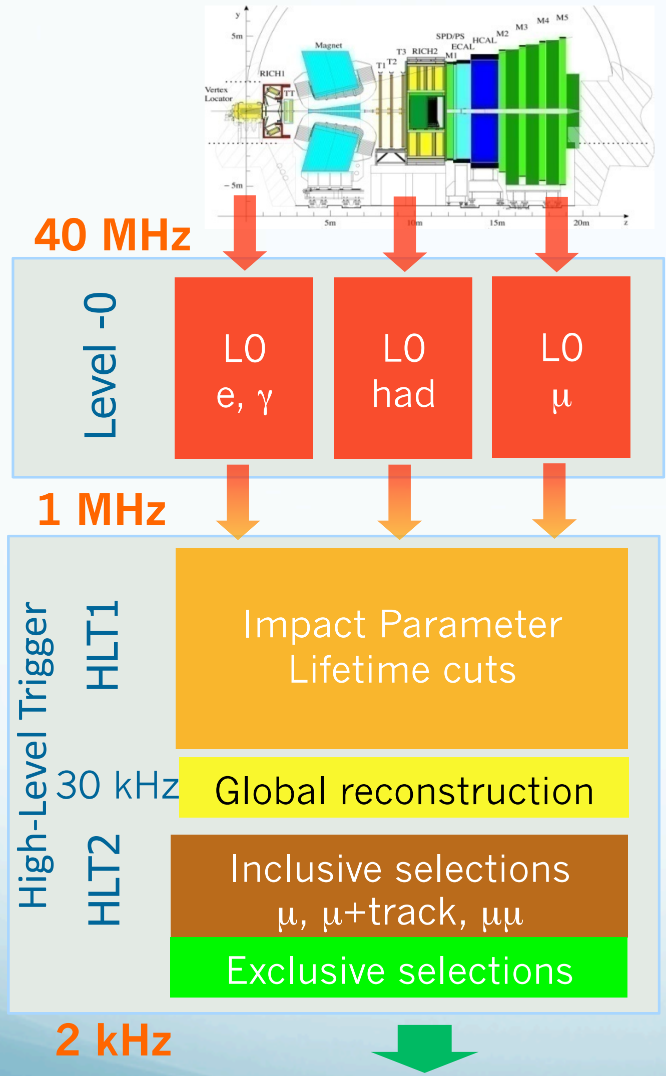
Interesting NP constraints will come with 2011 data

Conclusions & Prospects

- Excellent performance of LHCb in time dependent measurements proved on 2010 data.
- Preliminary result on Δm_s in $B_s \rightarrow D_s\pi$ oscillations at LHCb with 36 pb^{-1} competitive with world best.
- Successfully completed all steps towards a ϕ_s measurement in $B_s \rightarrow J/\psi\phi$. Will allow world best result to be reached with 2011 data.
- Many other decays modes under study: $B_s \rightarrow J/\psi f_0$, $J/\psi\eta'$, $D_s^- D_s^+$ ... and also $B_s \rightarrow K^{0*}\overline{K}^{0*}$, $B_s \rightarrow \phi\phi$ ... will provide CPV measurements and constraints on penguin contributions.
- With 2011 data tagged time dependent analysis of hadronic charmed ($B_s \rightarrow D_s K$) and charmless ($B_{d,s} \rightarrow hh'$) modes will also allow new measurements on γ angle.

backup

LHCb trigger



- L0 Hardware Trigger 40 MHz → 1 MHz
  - Search for high p_T , μ, e, γ, hadron candidates
- High Level Software Trigger Farm
  - HLT1: Add Impact parameter cuts
  - HLT2: Global event reconstruction
    - Physics output rate 2 kHz – 3. kHz
    - Fully operational.

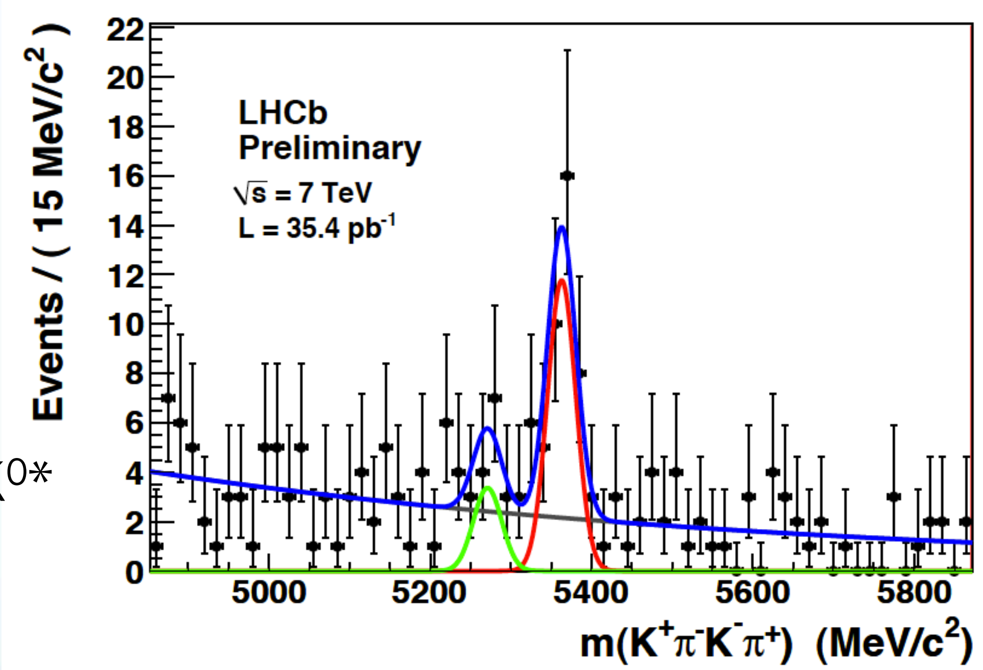
First evidence of $B_s \to K^{0*}\overline{K^{0*}}$

$B_s \to K^{0*}(K^+\pi^-)\ \overline{K^{0}}^*(K^-\pi^+)$ only from penguin decay. Future measurement of time-dependent CP asymmetries will probe new physics in $b \to s$ transitions.

First evidence at LHCb with 35 pb^{-1}:

34.5 ±7.4 events (7.3 σ)

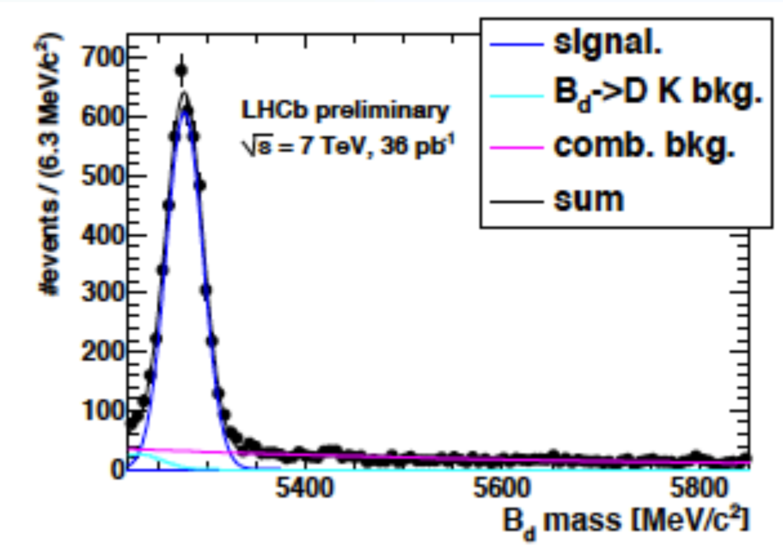
Branching fraction with $B^0 \to J/\psi\ K^{0*}$ as normalization channel.



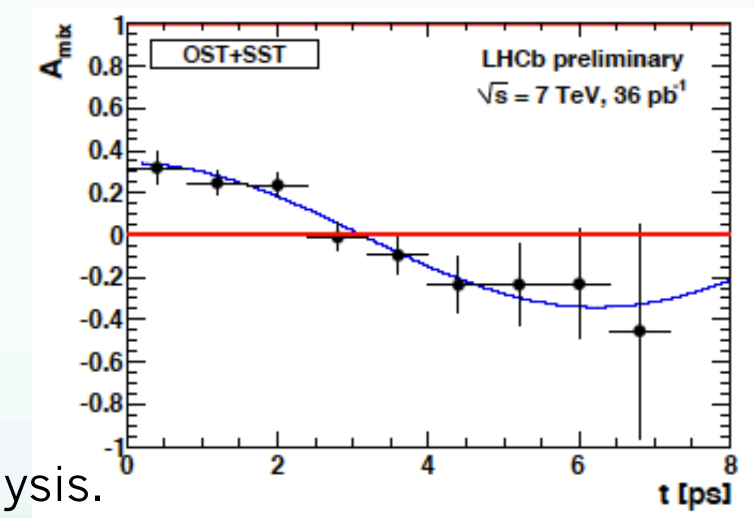
$$\mathcal{B}\left(B_s^0 \to K^{*0}\overline{K}^{*0}\right) = (1.95 \pm 0.47(stat.) \pm 0.51(syst.) \pm 0.29\,(f_d/f_s)) \times 10^{-5}$$

Predictions from QCD factorization: $(7.9^{+4.3}_{-3.9}) \times 10^{-6}$

B^0 mixing in $B^0 \rightarrow D^-(K^+\pi^-\pi^-)\pi^+$



~ 6000 signal events.
Double Gaussian proper-time resolution model from Monte Carlo (tuned to data): $\langle\sigma_t\rangle$ = 49 fs.



Per-event mistag probability with free calibration parameters (different trigger and selection with respect to $B^+ \rightarrow J/\psi K^+$).
OS tagger parameters used for the Δm_s analysis.

$$\Delta m_d = 0.499 \pm 0.032(\text{stat}) \pm 0.003(\text{sys})\ ps^{-1}$$

$(\Delta m_d = 0.507 \pm 0.005\ ps^{-1}$ world average, PDG [1])

$B^0 \rightarrow J/\psi K^{0*}$ and $B_s \rightarrow J/\psi\phi$ untagged

$B^0 \rightarrow J/\psi K^{0*}$

Systematic effect	$\lvert A_\parallel\rvert^2$	$\lvert A_\perp\rvert^2$	$\delta_\parallel$	$\delta_\perp$
proper time acceptance	-	-	-	-
data/MC differences	0.008	0.006	0.07	0.05
statistical error of acceptance	0.002	0.001	-	0.01
wrong-signal fraction	0.004	0.001	-	0.01
background treatment	0.002	0.008	0.04	0.01
statistical error of background	0.008	0.005	0.02	0.01
mass model	0.010	0.002	0.01	0.01
s-wave treatment	0.001	0.013	0.05	0.05
sum	0.016	0.017	0.10	0.07

$B_s \rightarrow J/\psi\phi$

Systematic effect	Γ_s [ps^{-1}]	$\Delta\Gamma_s$ [ps^{-1}]	$\lvert A_\perp(0)\rvert^2$	$\lvert A_\parallel(0)\rvert^2$	$\cos\delta_\parallel$
Proper time resolution	0.0001	-	-	-	-
Angular acceptance	-	-	-	0.0007	-
Acceptance parametrisation	0.0002	0.001	0.0017	0.0013	-
Proper time acceptance	0.0272	0.001	0.0003	0.0002	-
S-wave treatment	0.003	0.003	0.013	0.028	0.09
Background treatment	0.0002	0.02	0.0016	0.0012	-
Mass model	0.0004	0.004	0.0032	0.0006	-
Total (quadratic sum)	0.0274	0.0206	0.0136	0.0281	0.09

sin2β from $B^0 \to J/\psi K^0_S$

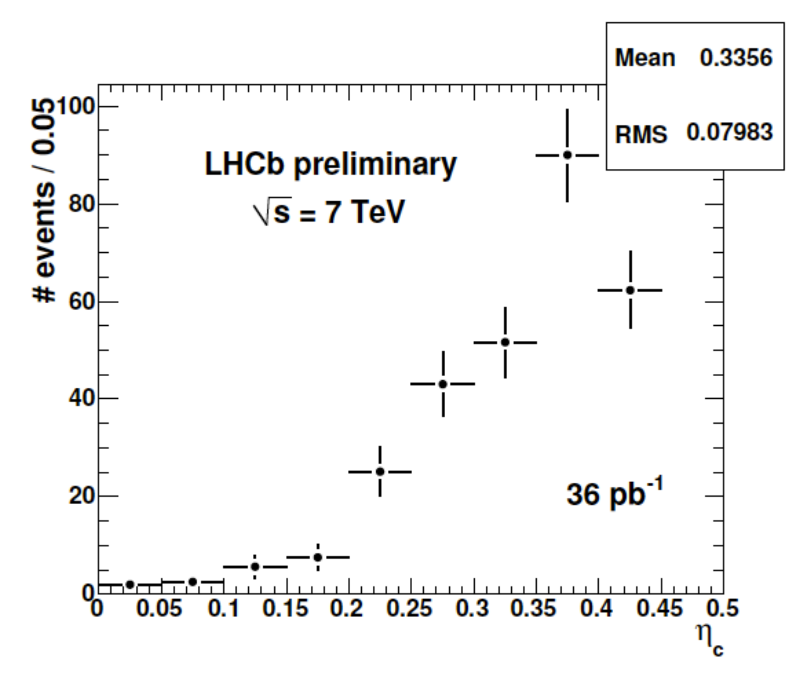
$$\mathcal{A}^{\mathrm{meas}}_{J/\psi K^0_S}(t) = (1-2\omega)\mathcal{A}_{J/\psi K^0_S}(t) \otimes \mathcal{R}(t)$$

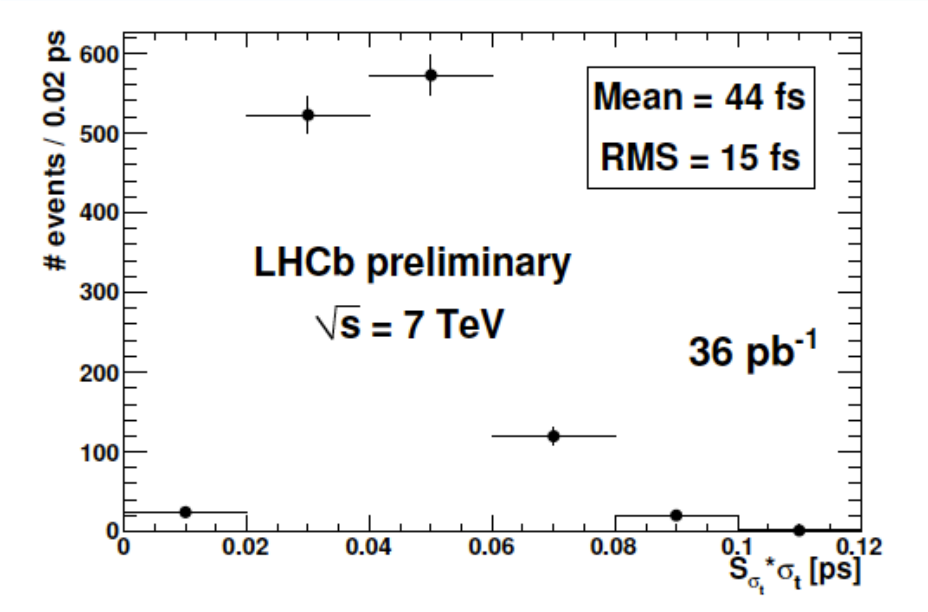
Table 3: Systematic uncertainties to $S_{J/\psi K^0_S}$ in absolute terms.

Source	uncertainty
tagger calibration	0.067
per-event mistags p.d.f.	0.012
Δm_d uncertainty, z scale	0.0017
proper time resolution	0.0085
high propertime acceptance	0.00065
biased events acceptance	0.0042
biased TIS events acceptance	0.0063
production asymmetry	0.024
total (sum in squares)	0.073

WA: $\sin 2\beta = 0.673 \pm 0.023$

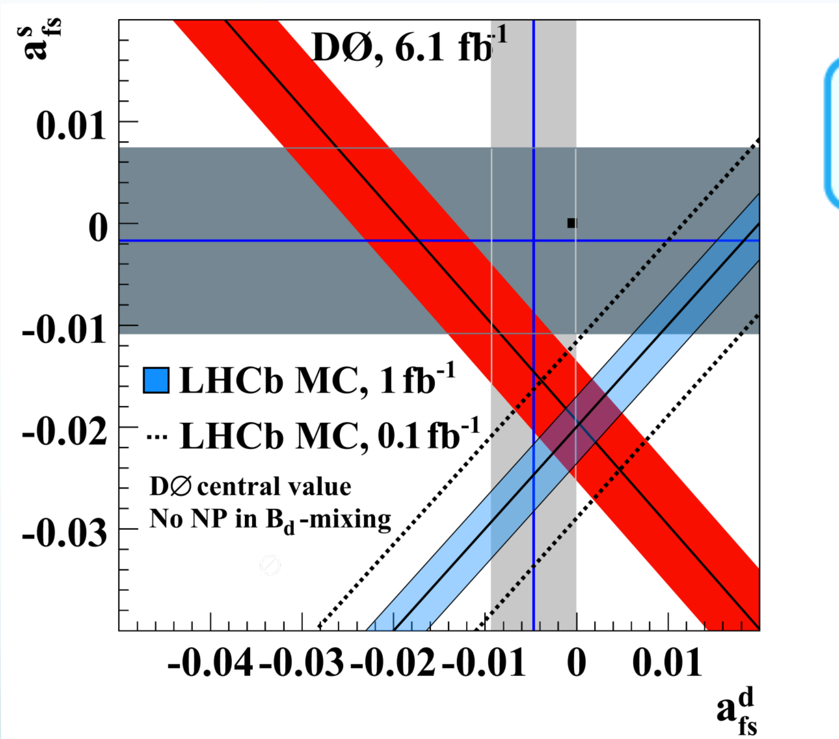
$B_s \to D_s\pi$ signal mistag distribution & time resolution





A_{sl}

Di-muon charge asymmetry measured by D0, giving hints of anomalous CPV in the mixing of neutral B mesons.

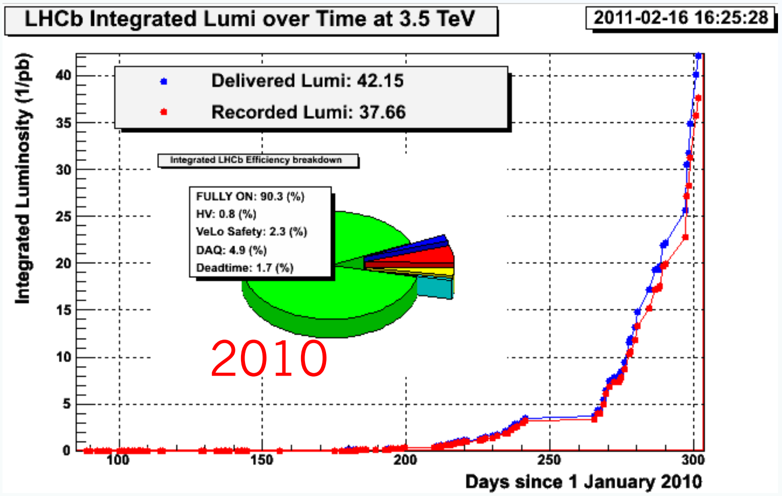


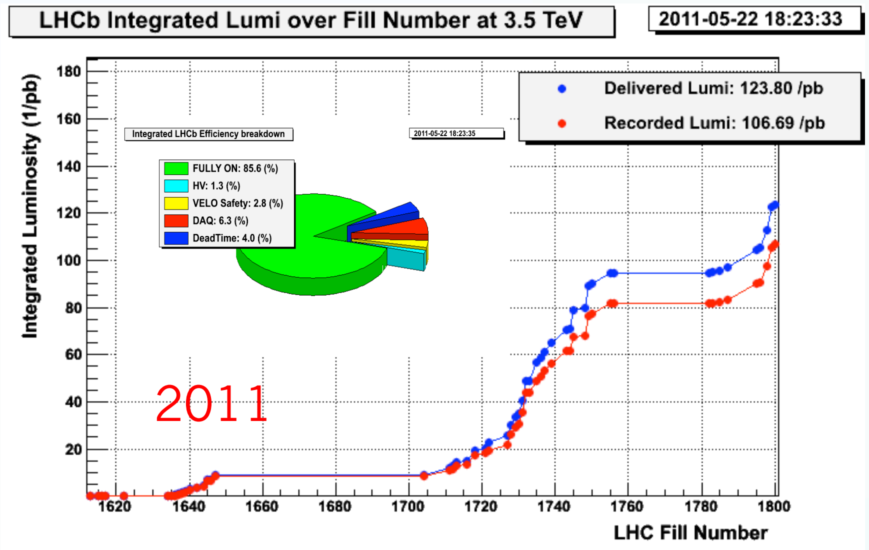
$$\Delta A_{fs} = \frac{a^s_{fs} - a^d_{fs}}{2} \rightarrow (2.1 \pm 0.3) \times 10^{-4} [S.M.]$$

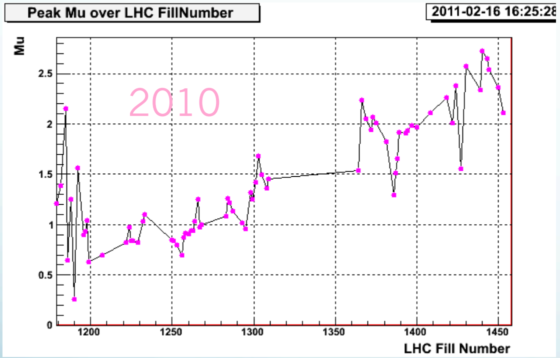
- LHCb will measure $a^s_{sl} - a^d_{sl}$ from difference in asymmetry in $B_s \rightarrow D_s(KK\pi)\mu\nu$, $B^0 \rightarrow D^+(KK\pi)\mu\nu$.
- Orthogonal constraint to D0.

If there is NP in B_s mixing it will be seen by LHCb also in the ϕ_s measurement

Data taking @ √s=7TeV







Running conditions with up to ~2 collisions/event more demanding than originally planned.
Trigger and offline analysis well coping with it.

2011 use *luminosity levelling* to keep L<3.10^{32} cm^{-2}s^{-1}
Expect to collect ~1 fb^{-1} by the end of the year.