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Measurement of CP violation and CKM matrix in LHCb

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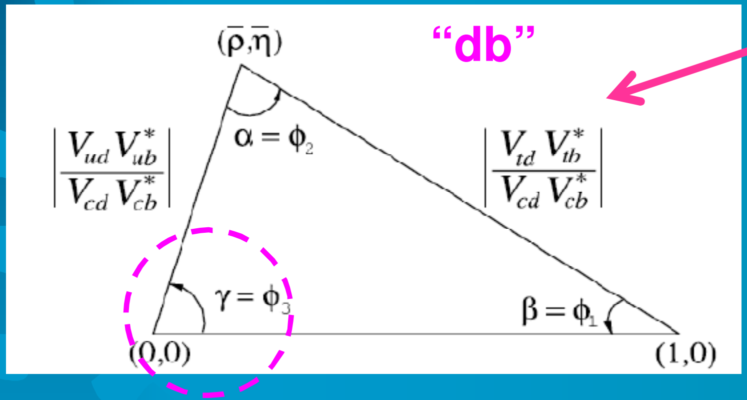
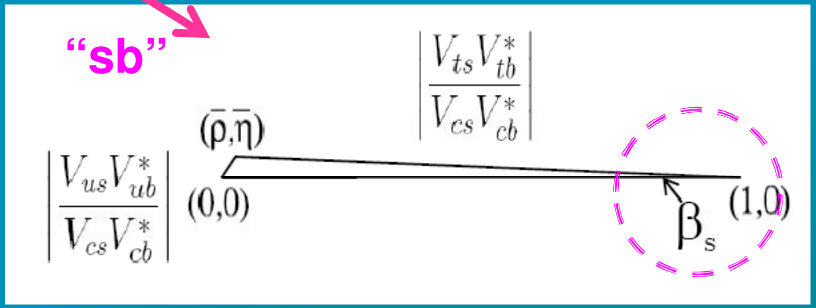
CP violation and CKM matrix

- **Current laboratory measurements of CPV are in agreement with SM predictions, encoded in the CKM matrix, but observation of universe requires much more.**

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

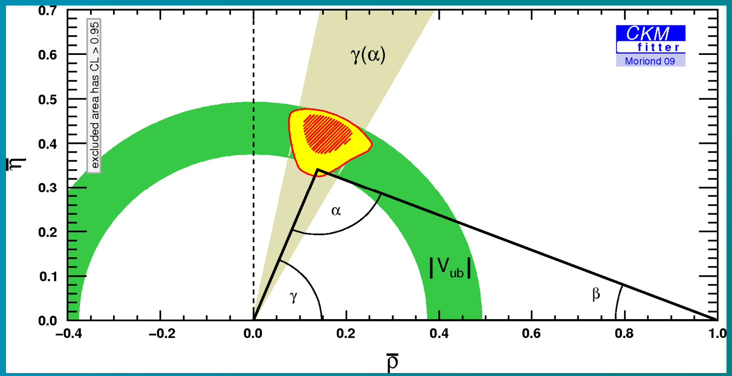
- **Unitarity relations represented by triangles.**





Still space for finding effects due to NP in less constrained elements like γ and β_s angles.

UT constraints from tree measurements only →

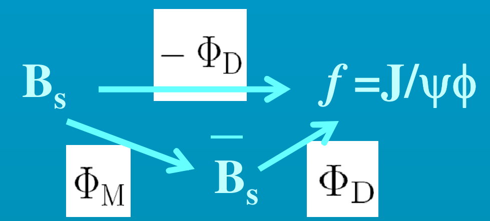


The $B^0_s \overline{B^0}_s$ mixing in $B_s^0 \to J/\psi\phi$

- **A CP violating phase arises from interference between B_s decay to $J/\psi\phi$ directly or via mixing**

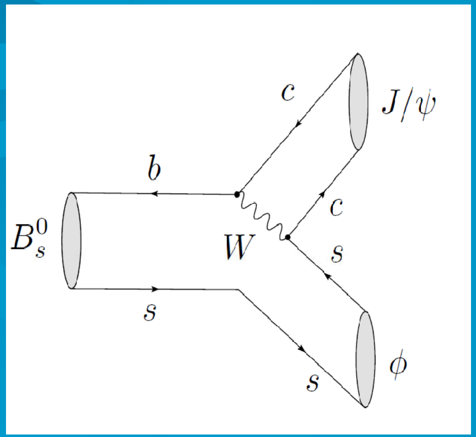
$$\Phi_{J/\psi\phi} \equiv \Phi \equiv -\arg(\eta_f \lambda_f) = \Phi_M - 2\Phi_D$$

$$\lambda_f = \frac{q}{p}\frac{\bar{A}_f}{A_f} = \eta_f e^{-i(\Phi_M - 2\Phi_D)}$$



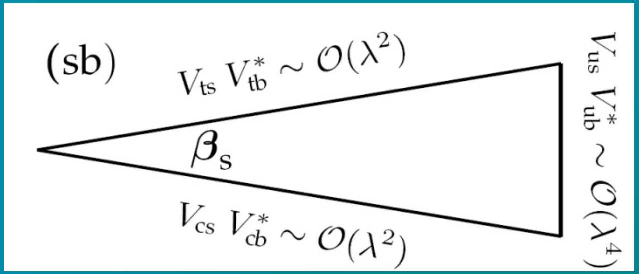
- **In the SM:**

$B_s \to J/\psi\phi$ is dominated by a single weak phase, well predicted:



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

$$\beta_s = \eta\lambda^2 + \mathcal{O}(\lambda^4)$$



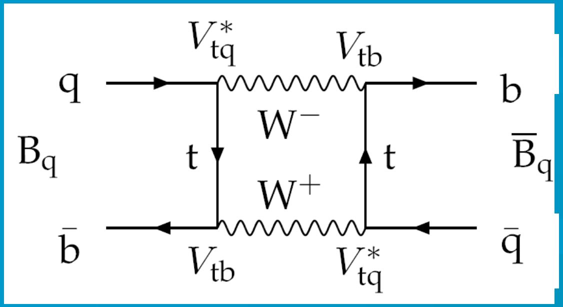
$$\Phi_{J/\psi\phi}^{SM} = -2\beta_s + \delta P$$

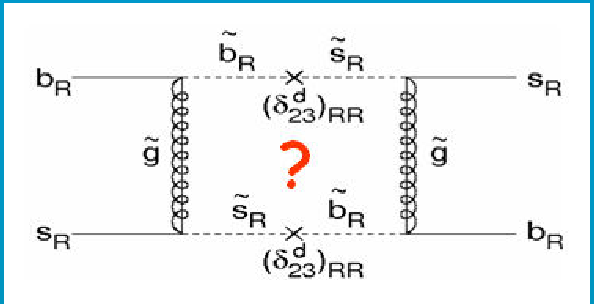
Penguin contribution estimated $\sim 10^{-4}$-10^{-3}

$$-2\beta_s = (-0.037 \pm 0.002)\ \text{rad}$$

from UT fits

$B^0_s \overline{B^0}_s$ with New Physics





- **New particles could contribute to the B_s-$\overline{B}_s$ box diagram modifying the SM prediction, adding a new phase :**

$$M_{12}^{\rm tot} = M_{12}^{\rm SM}\Delta_{\rm s} = M_{12}^{\rm SM}|\Delta_{\rm s}|e^{i\phi_{\rm s}^{\Delta}}$$

$$\Phi_{J/\psi\phi} = \Phi^{\rm SM} + \phi_{\rm s}^{\Delta}$$

- **This new phase $\phi_{\rm s}^{\Delta}$ will also modify other measurements:**

$$\Delta\Gamma_{\rm s}^{\rm meas} = 2|\Gamma_{12}^{\rm SM}|\cos(\Phi_{\rm M/\Gamma}^{\rm SM} + \phi_{\rm s}^{\Delta})$$

$$a_{\rm fs}^{\rm meas} = \frac{|\Gamma_{12}^{\rm SM}|}{|M_{12}^{\rm SM}|}\frac{\sin(\Phi_{\rm M/\Gamma}^{\rm SM} + \phi_{\rm s}^{\Delta})}{|\Delta_{\rm s}|}$$

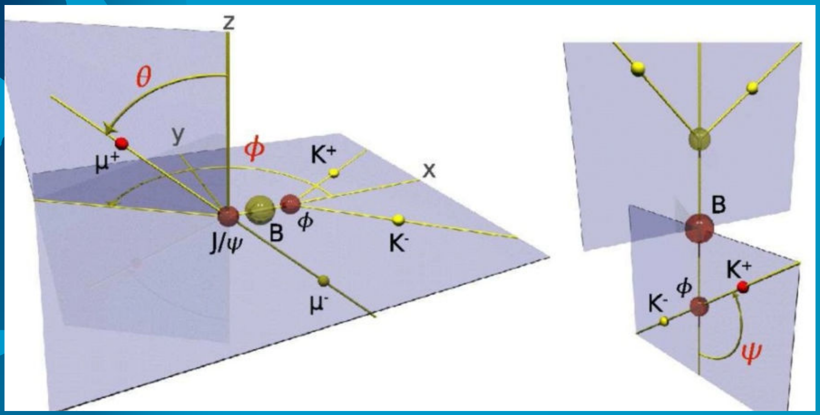
where:

$$\Phi_{\rm M/\Gamma}^{\rm SM} = \arg\left(-\frac{M_{12}}{\Gamma_{12}}\right)^{\rm SM}$$

is calculated in the SM:

$$\Phi_{\rm M/\Gamma}^{\rm SM} = (3.40^{+1.32}_{-0.77}) \times 10^{-3}$$

$B_s^0 \rightarrow J/\psi(\mu\mu)\phi(KK)$



P→VV decay : mixture of CP-even (ℓ=0,2) and CP odd (ℓ=1) final states. An angular analysis allows to separate statistically the decay amplitudes.

3 angles $\Omega=(\theta,\phi,\psi)$ to describe the final decay products directions.

Differential decay rate:

$$\frac{d^4\Gamma(B_s^0 \rightarrow J/\psi\phi)}{dt\; d\cos\theta\; d\varphi\; d\cos\psi} \equiv \frac{d^4\Gamma}{dt\; d\Omega} \propto \sum_{k=1}^{6} h_k(t) f_k(\Omega)$$

Bs $\quad \overline{\text{Bs}}$

k	$h_k(t)$	$\bar{h}_k(t)$	$f_k(\theta,\psi,\varphi)$
1	$\|A_0(t)\|^2$	$\|\bar{A}_0(t)\|^2$	$2\cos^2\psi(1-\sin^2\theta\cos^2\varphi)$
2	$\|A_{\|\|}(t)\|^2$	$\|\bar{A}_{\|\|}(t)\|^2$	$\sin^2\psi(1-\sin^2\theta\sin^2\varphi)$
3	$\|A_\perp(t)\|^2$	$\|\bar{A}_\perp(t)\|^2$	$\sin^2\psi\sin^2\theta$
4	$\Im\{A_{\|\|}^*(t)A_\perp(t)\}$	$\Im\{\bar{A}_{\|\|}^*(t)\bar{A}_\perp(t)\}$	$-\sin^2\psi\sin 2\theta\sin\varphi$
5	$\Re\{A_0^*(t)A_{\|\|}(t)\}$	$\Re\{\bar{A}_0^*(t)\bar{A}_{\|\|}(t)\}$	$\frac{1}{\sqrt{2}}\sin 2\psi\sin^2\theta\sin 2\varphi$
6	$\Im\{A_0^*(t)A_\perp(t)\}$	$\Im\{\bar{A}_0^*(t)\bar{A}_\perp(t)\}$	$\frac{1}{\sqrt{2}}\sin 2\psi\sin 2\theta\cos\varphi$

A_0 (0) → CP even
$A_{||}$ (0) → CP even
$A_\perp$ (0) → CP odd

Time dependent decay amplitudes

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

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

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

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

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

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

High sensitivity to small Φ values when B/$\overline{\text{B}}$ initial state is determined by Flavour tagging (Δm_s terms)

Depend on 8 physics parameters:

Φ, Γ_s, $\Delta\Gamma_s$, Δm_s, $R_\perp$, $R_\parallel$, $\delta_\perp$, $\delta_\parallel$

From Tevatrons results:
Δm_s well measured, hints of deviation from SM in Φ

$$\Phi = \Phi^{SM} + \phi_s^\Delta$$

$$R_\perp = \frac{|A_\perp(0)|^2}{|A_\perp(0)|^2 + |A_\parallel(0)|^2 + |A_0(0)|^2}$$

$$\Gamma_s = \frac{\Gamma_L + \Gamma_H}{2}$$

$$R_\parallel = \frac{|A_\parallel(0)|^2}{|A_\perp(0)|^2 + |A_\parallel(0)|^2 + |A_0(0)|^2}$$

$$\Delta\Gamma = \Gamma_L - \Gamma_H$$

$$\delta_\perp = \arg(A_\perp(0)A_0^*(0))$$

$$\Delta m_s = M_H - M_L$$

$$\delta_\parallel = \arg(A_\parallel(0)A_0^*(0))$$

LHCb @ LHC

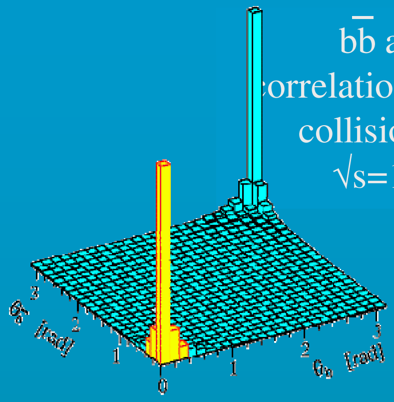
High $b\bar{b}$ production in pp collisions at $\sqrt{s}$=14TeV

σ_{inel} = 80 mb

σ_{bb} = 500 μb → N ~10^{12} $b\bar{b}$ events in L_{int} = 2 fb^{-1}

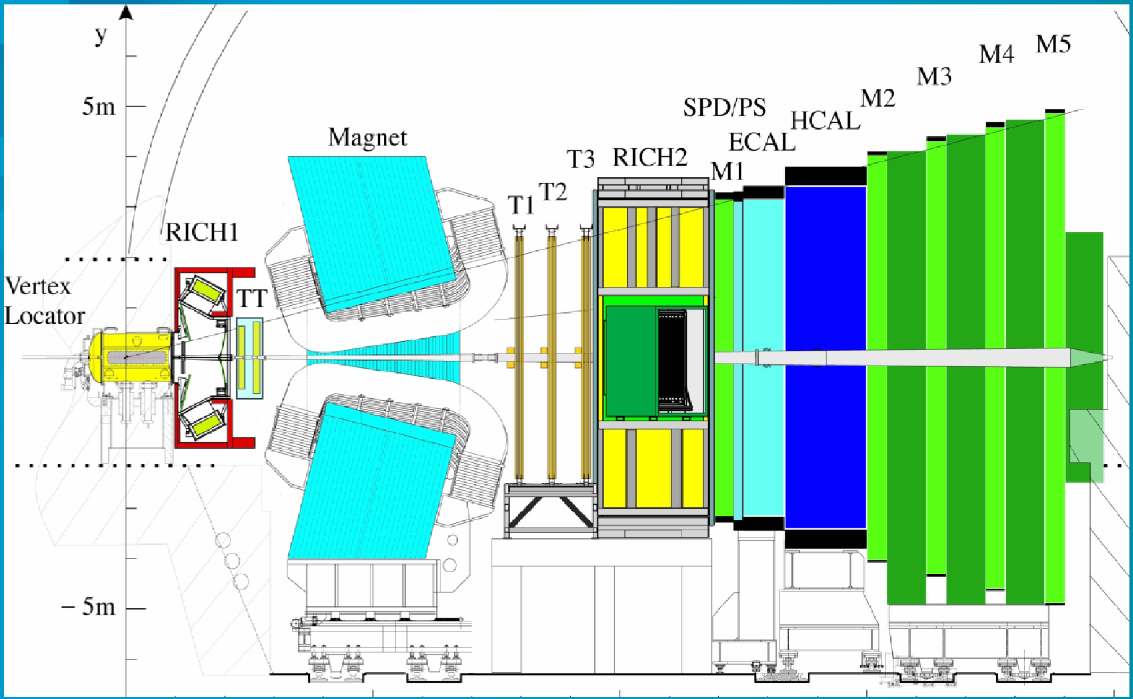
(1 nominal year 10^7 s at 2×10^{32} $cm^{-2}s^{-1}$)

~40% in the forward region

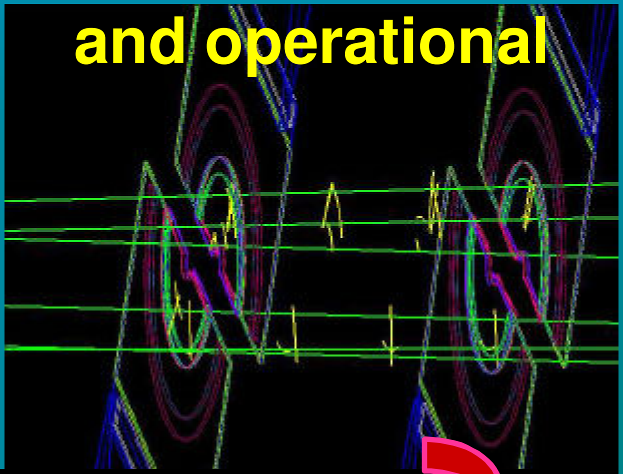


$b\bar{b}$ angular correlation in pp collisions at $\sqrt{s}$=14 TeV

LHCb single arm forward detector



Detector ready and operational



TED data June 2009

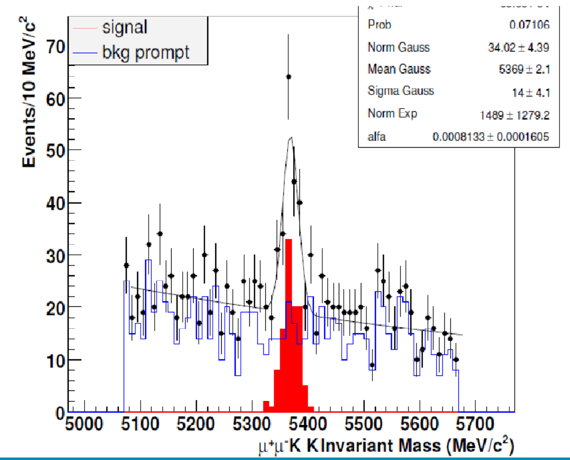
(secondary particles downstream LHC beam stopper)

$B_s^0 \rightarrow J/\psi(\mu\mu)\phi(KK)$ reconstruction

Full MC simulation all trigger levels included:

Signal yield (2 fb^{-1})	117 k
B(long-lived) /S	0.5
B(prompt J/ψ) /S	1.6

Full MC: inclusive $J/\psi(\mu\mu)$



- **High efficiency for di-muon trigger ε_{tot}~70%**
- **Baseline event selection is lifetime-unbiased:**
  - **small proper time and angular acceptance corrections needed.**
  - **High background from prompt J/ψ: harmless in β_s fit, can allow the determination of proper time resolution.**
  - **Alternative analysis under study: higher statistic sensitivity.**
- **Large use of control channels:**

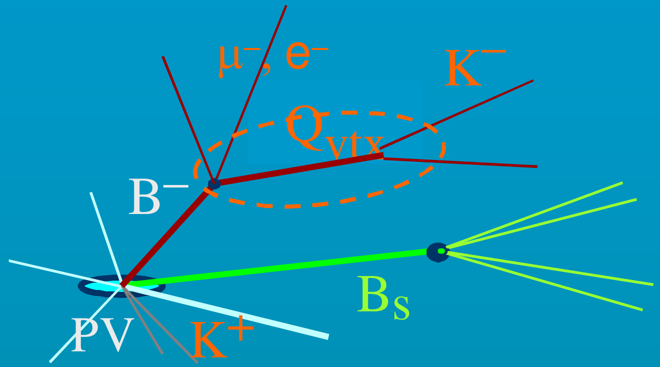
Measure resolution and acceptance for proper time and angular distributions. Flavour tagging

Channel	Yield (2 fb^{-1})	B/S total
$B_d \rightarrow J/\psi K^*$	490 k	6.7
$B_u \rightarrow J/\psi K+$	940 k	1.9
$B_s \rightarrow D_s\pi$	~70k	0.4

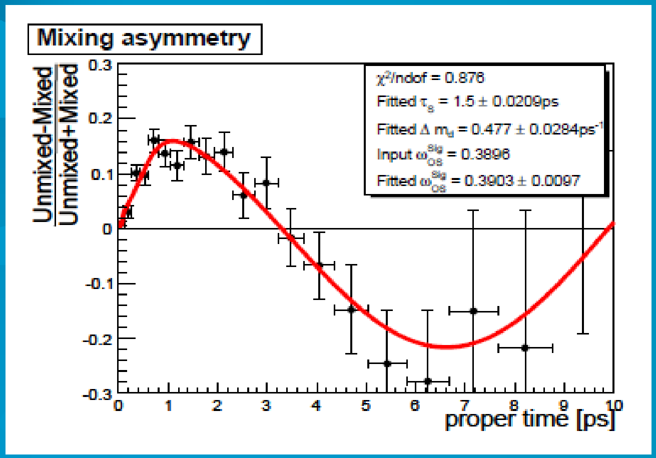
Flavour Tagging

From combination of several methods (electron, muon, kaon, inclusive vertex, same side kaon)

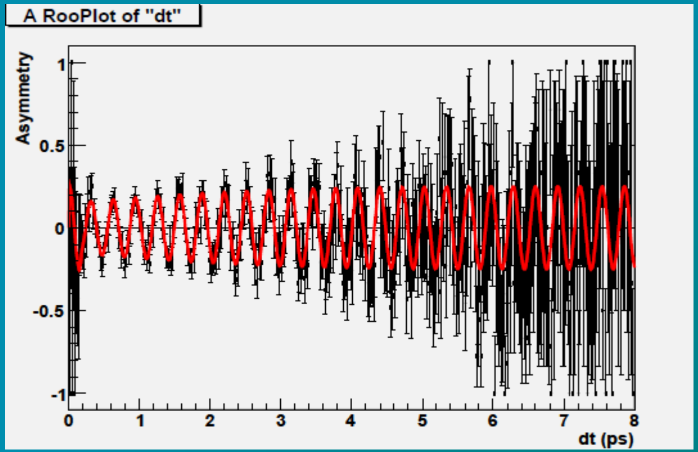
Tagger	Tag eff.	mistag	$\varepsilon(1-2\omega)^2$
Opposite side	45%	36.5%	3.3%
+ same side	56%	33.3%	6.2%



Calibration and validations on control channels

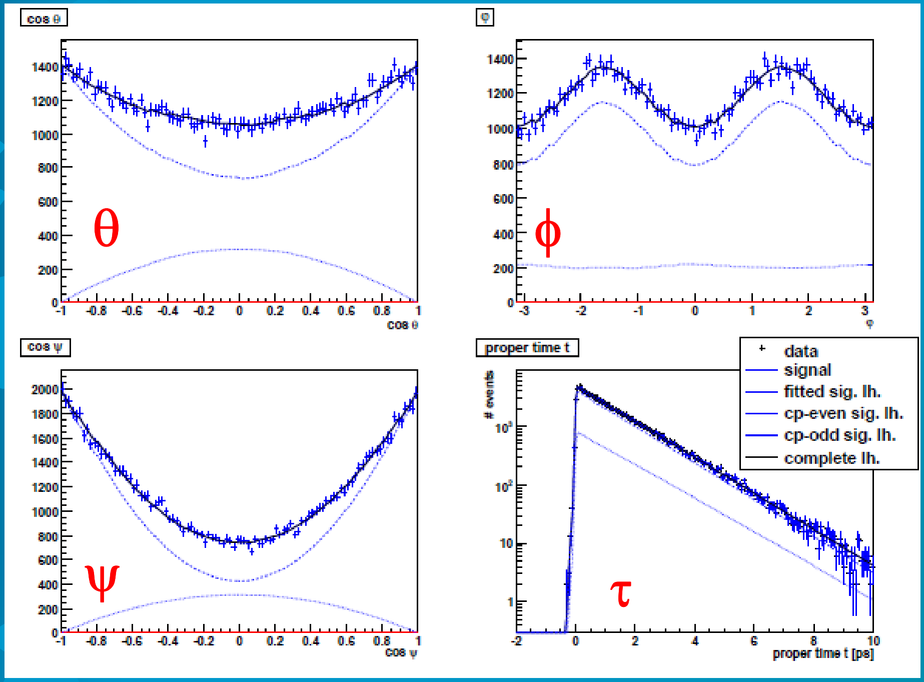


$B^0 \rightarrow J/\psi(\mu\mu)K^*(K\pi)$ oscillations for opposite side taggers



$B_s \rightarrow D_s\,(KK\pi)\,\pi$ oscillations for same side tagger

$B_s^0 \rightarrow J/\psi\phi$: fits results



Parameter	Result	Units
m_{B_s}	5368.01 ± 0.05	MeV/c^2
$f^s_{m,1}$	0.47 ± 0.13	
$\sigma^s_{m,1}$	12.0 ± 0.7	MeV/c^2
$\sigma^s_{m,2}$	19.0 ± 1.3	MeV/c^2
$\|A_0(0)\|^2$	0.599 ± 0.002	
$\|A_\perp(0)\|^2$	0.162 ± 0.004	
$\delta_\parallel$	2.49 ± 0.02	rad
$\delta_\perp$	-0.28 ± 0.10	rad
$-2\beta_s$	-0.0399 ± 0.0272	rad
Γ_s	0.686 ± 0.004	ps^{-1}
$\Delta\Gamma_s$	0.061 ± 0.010	ps^{-1}
$f^s_{t,1}$	0.96 ± 0.01	
$\sigma^s_{t,1}$	0.032 ± 0.001	ps
$\sigma^s_{t,2}$	0.12 ± 0.01	ps
Δm_s	19.96 ± 0.04	ps

- **Sensitivity studies with 2fb^{-1} (one nominal year) : $\sigma(2\beta_s)$ ~0.03**

  Good convergence for all physics parameters, all "detector parameters" can also be fitted.

- **Systematics:**
  - **Angular distortions (± 5%)** 7%
  - **Proper time resolution (40 ± 4 fs)** 5%
  - **Mistag rate (0.34 ± 0.01)** 7%

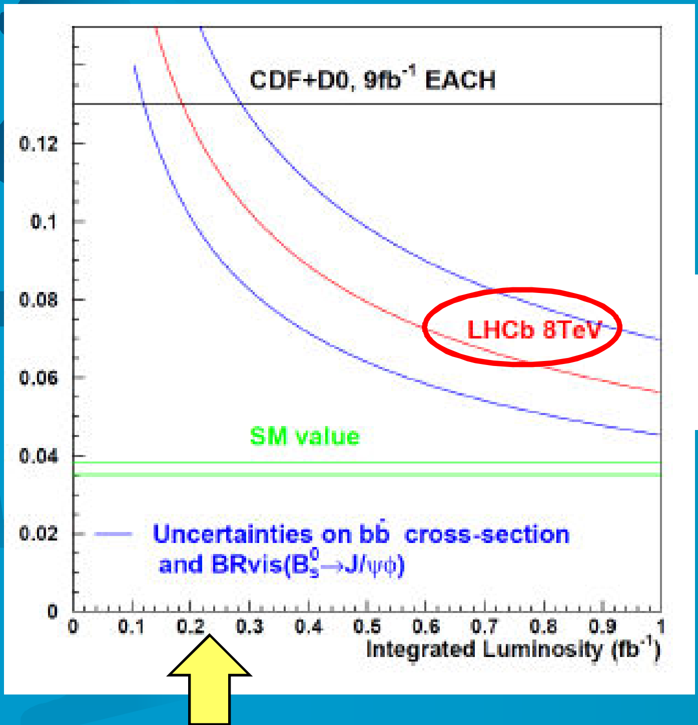
  } $\Delta\beta_s/\beta_s$

  Ignoring a possible 5-10% S-wave contamination will introduce a ~15% bias on β_s.

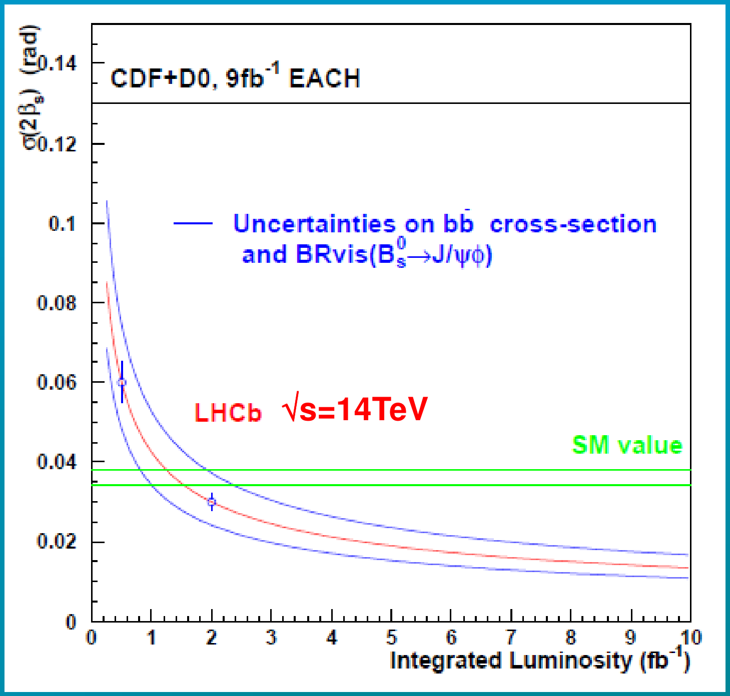
  Included in the fit will reduce the resolution ~20% but allows $\cos 2\beta_s$ measurement

Sensitivity versus integrated Luminosity

First important results can come already from 2010 running.



Reduced LHC collision energy

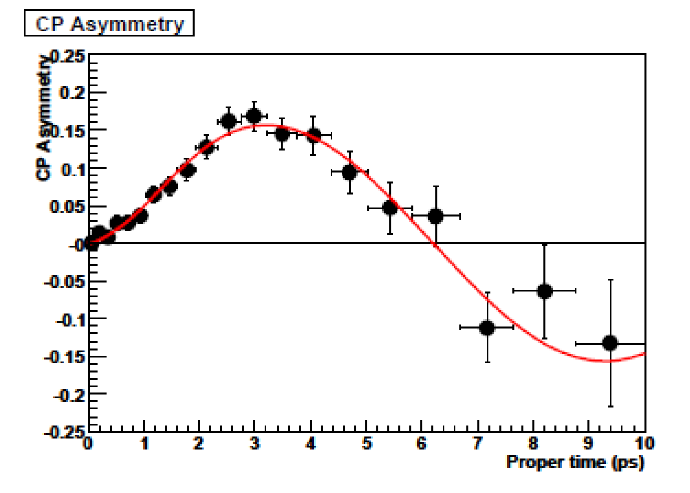


If true β_s value is the current Tevatron measurement (NP-like) we should measure it from $B_s \to J/\psi(\mu\mu)\phi$ with 200 pb^{-1} !

With 10 fb^{-1} $> 3\sigma$ evidence of non-zero β_s even if only SM.

Other channels also under study: $B_s \to J/\psi(ee)\phi$, $B_s \to J/\psi\eta$, $B_s \to D_s^+ D_s^-$ …

$\sin(2\beta)$ with $B^0 \rightarrow J/\psi(\mu\mu)K_S(\pi\pi)$



Will be the first time dependent CP asymmetry measurement at LHCb: with 200 pb^{-1} expect $\sigma(\sin 2\beta)\sim 0.06$

Channel	Signal yield ($2\ fb^{-1}$)	B/S
$B_d \rightarrow J/\psi\ K_S$	94 k	0.6

$\sigma(\sin 2\beta)\sim 0.020$ in $2\ fb^{-1}$

With additional luminosity will give insight into possible NP contributions to $b \rightarrow c\bar{c}s$. Will also constrain direct CP asymmetry.

NP from $b \rightarrow s\bar{s}s$ penguin decays

Good perspective at LHCb for $B_s \rightarrow \phi\phi$.

Channel	Yield ($2\ fb^{-1}$)	B/S (90% CL)
$B_s \rightarrow \phi\ \phi$	3100	< 0.8
$B_d \rightarrow \phi\ K_S$	920	< 1.1

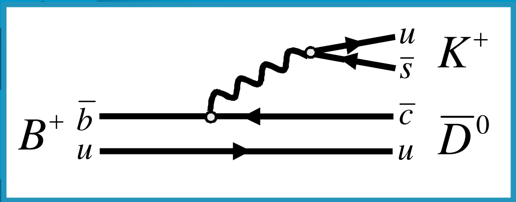
Time dependent analysis of angular distribution of flavour tagged events:

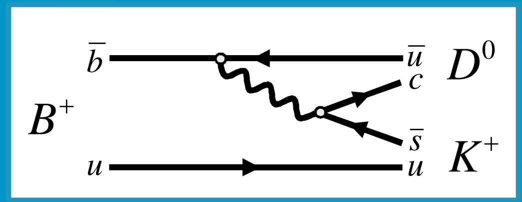
$\sigma_{stat}(\phi_{Bs \rightarrow \phi\phi}^{NP}) = 0.11$ in $2\ fb^{-1}$

From $B_d \rightarrow \phi K_S$ expect $\sigma(\sin 2\beta_{eff}) \approx 0.23$

γ measurements

- **Many approaches to γ angle measurements. Most powerful through 'B→DK' strategies (charged and neutral B modes). D final state is common to D^0 and $\overline{D}^0$.**





Many possibilities for D final states: $K\pi$, KK, $\pi\pi$, $K\pi\pi\pi$, $K_S\pi\pi$ ...

- **Opportunity for LHCb to make a contribution already with 200 pb^{-1} : expect ~10k events B→D(hh)K .**

- **Dalitz plot analysis giving currently the single best γ results: LHCb will reconstruct in B→D($K_S\pi\pi$)K ~6.800 events /2 fb^{-1} with B/S<1.5 90%CL.**

- **$B_s \to D_s K$ time dependent CP asymmetry is unique to LHCb: exploit good PID for separation from $B_s \to D_s \pi$ and excellent proper time resolution.**

Global fit to all measurements of γ from tree decays only :

$\sigma(\gamma)$ ~ 4º with 2 fb^{-1}

More details in poster session: M. Gersabeck

Conclusions

- LHCb detector is on place and operational, ready for data taking at LHC start-up.

- $2\beta_s$ value could bring good news for NP: first LHCb results could come already from 2010 running. Expected sensitivity ~0.03/ 2 fb^{-1}

- Extensive LHCb program includes studies on many hadronic channels for measurements on all CKM matrix parameters, as well as searches for rare decays.

- First year data will also provide a lot of inclusive measurements and studies on control channels.

- In the coming years LHCb results will finally provide a strong improvement to flavour physics, in particular to the knowledge of the B_s sector.

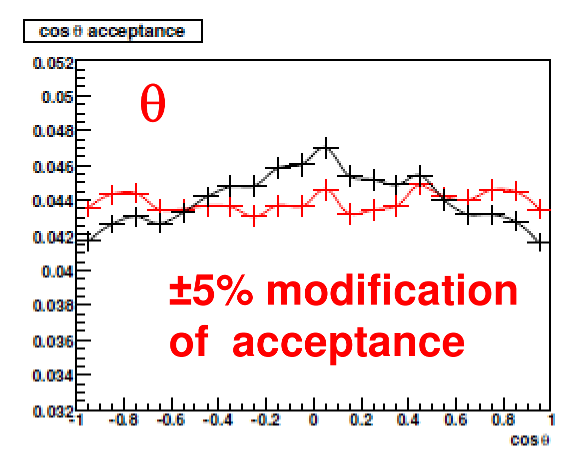
BACKUP

Angular acceptance checks with $B^0 \rightarrow J/\psi K^*$

- Measurement of polarization amplitudes and phases in the $B^0 \rightarrow J/\psi K^*$ decay from fit to time dependent angular distributions.

- Comparison with existing results from B Factories and Tevatron will validate the use of simulated acceptance functions and allow estimation of systematic uncertainties to $2\beta_s$ related to angular acceptance.

Parameters	Expected uncertainty $2\,fb^{-1}$ @ LHCb	CDF result (2007)
$\|A_\parallel\|^2$	0.001	$0.211 \pm 0.012 \pm 0.006$
$\|A_0\|^2$	0.001	$0.569 \pm 0.009 \pm 0.009$
$\|A_\perp\|$	0.001	-
$\delta_\parallel$ [rad]	0.007	$-2.96 \pm 0.08 \pm 0.03$
$\delta_\perp$ [rad]	0.006	$2.97 \pm 0.06 \pm 0.01$
Γ_d [ps^{-1}]	0.0009	-



- Strong constrain already for a ± 5% modified angular acceptance .

Parameters	Nominal	Correct ϵ	Random $\pm 1\sigma$	All angles
$\|A_\parallel\|^2$	0.240	0.239 ± 0.001 (-0.3σ)	0.236 ± 0.001 (-2.6σ)	0.223 ± 0.001 (-13.3σ)
$\|A_\perp\|^2$	0.160	0.159 ± 0.001 (-0.5σ)	0.159 ± 0.001 (-1.2σ)	0.178 ± 0.001 ($+14.6\sigma$)
$\delta_\parallel$	2.501	2.509 ± 0.007 ($+1.3\sigma$)	2.519 ± 0.007 ($+2.7\sigma$)	2.838 ± 0.007 ($+5.3\sigma$)
$\delta_\perp$	-0.170	-0.166 ± 0.006 ($+0.8\sigma$)	-0.148 ± 0.006 ($+3.8\sigma$)	-0.145 ± 0.006 ($+3.6\sigma$)