Beauty 2011, Amsterdam 4th-8th April

First measurement of sin2β at LHCb with $B^0 \rightarrow J/\psi K_s$

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LHCb

CP Violation

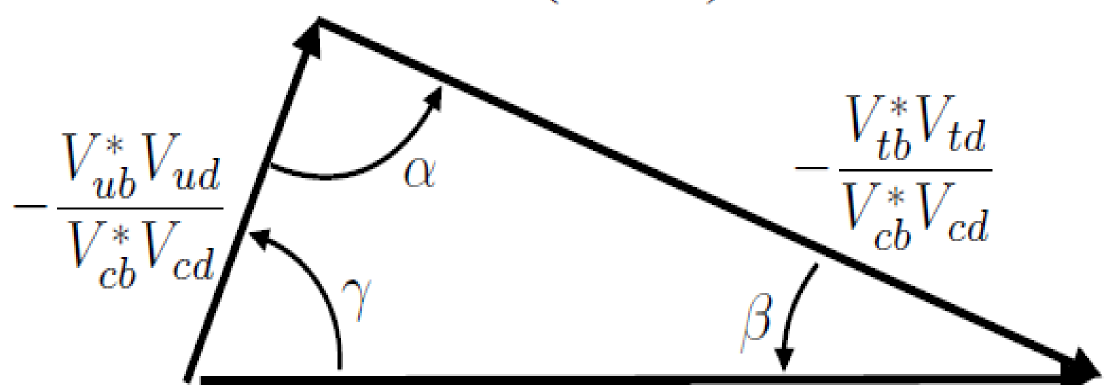
In the standard model one complex phase is enough to explain all CPV effects

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \approx \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

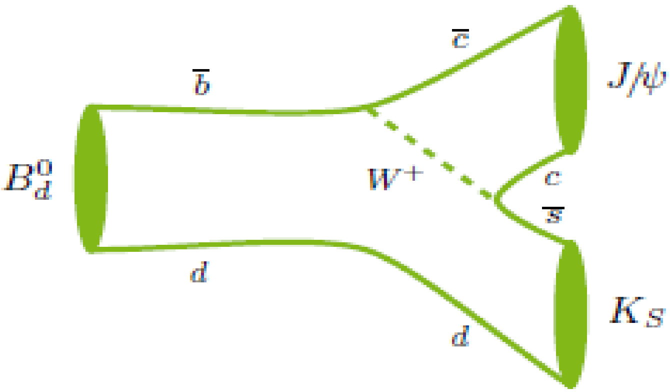
Unitarity conditions of the mixing matrix can be written as 6 Unitary Triangles

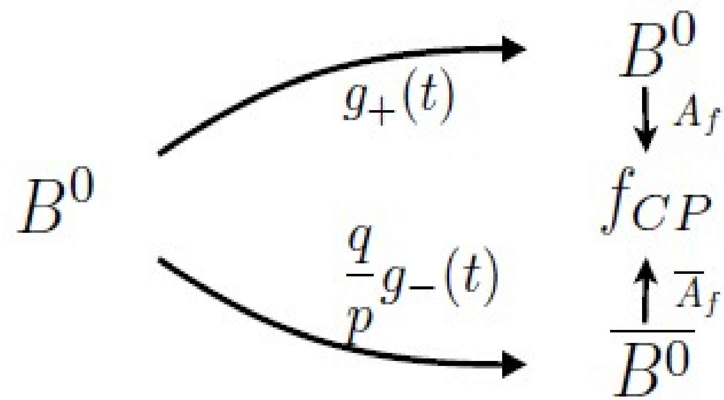
$$V_{ub}^* V_{ud} + V_{cb}^* V_{cd} + V_{tb}^* V_{td} = 0$$

$$\overline{\rho} + i\overline{\eta} \equiv (\rho + i\eta)\left(1 - \frac{\lambda^2}{2}\right)$$



sin2β in $B^0 \to J/\psi\, K_s$





$$\lambda_{f_{CP}} = \frac{q}{p}\frac{\bar{A}_{f_{CP}}}{A_{f_{CP}}}$$

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

Interference between mixing & decay

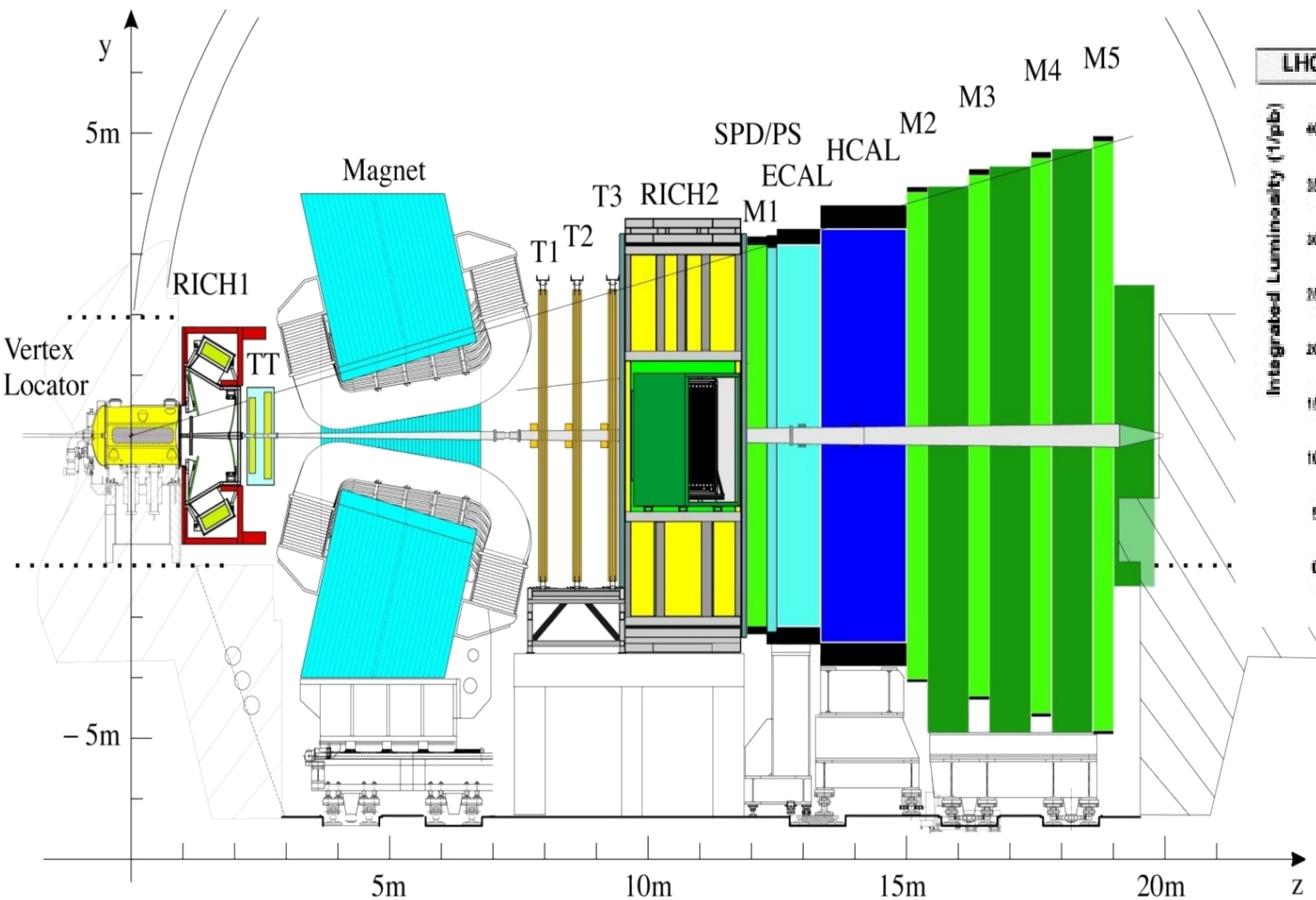
mixing & decay CP violation (negligible in SM)

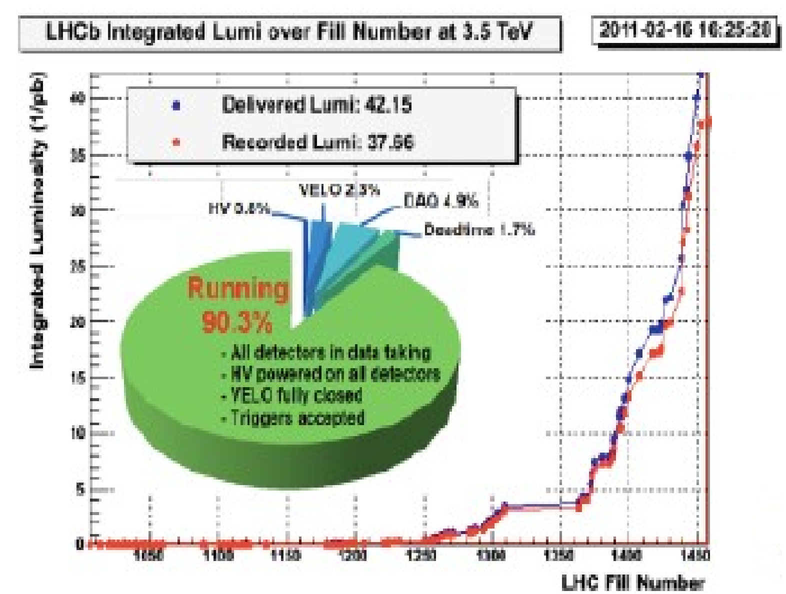
$$S_{J/\psi K^0_S} = \sin 2\beta$$

The LHCb experiment

LHCb is dedicated to study CP violation and rare decays in the beauty sector.

Forward spectrometer ($2 < \eta < 5$) characterized by excellent tracking, vertexing, and particle identification system





~$37 pb^{-1}$ collected at 7TeV in 2010 run

Analysis sin2β with $B^0 \to J/\psi K_s$

- Selection of signal and trigger
- Flavour Tagging

  Calibration of flavour tagging

- Fit

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

- Systematic uncertainties
- Results

World average

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

Show first results at LHCb of CP violation in

$B^0 \to J/\psi K_s$

Trigger and selection

- 35 pb^{-1} at $\sqrt{s}$ = 7 TeV in 2010
- Trigger

  Contains components which biases the proper time distribution of the selected events (impact parameter cut)

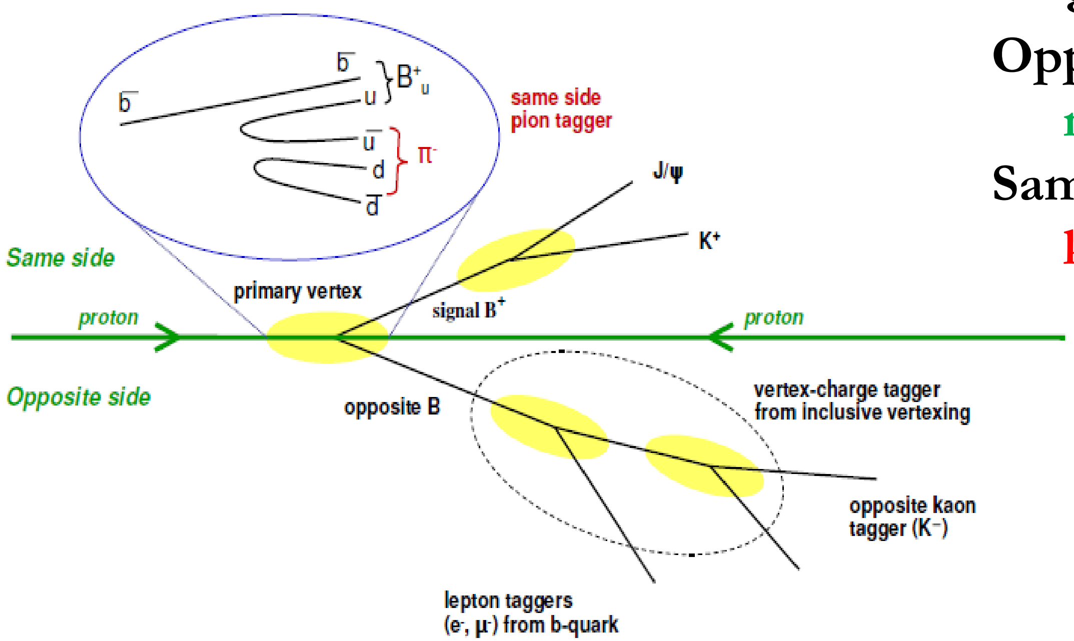
  To increase statistics time biased trigger lines (~20%) are also used

  Added acceptance for biased events $$\epsilon_S(t) = \frac{(a_a t)^{c_a}}{1 + (a_a t)^{c_a}}$$

- Common selection for $b \rightarrow J/\psi\, X$
- Only tagged events are sensitive to $\sin 2\beta$
- Selection of ~ 280 tagged events for $B^0 \rightarrow J/\psi\, K_s$

Flavour Tagging

- Flavour Tagging is the procedure to determine the flavour of the reconstructed B meson at production time



Taggers

Opposite Side:

muons, electrons, kaons, vertex charge

Same Side:

kaons (B_s) or pions ($B_{d,u}$)

$$\varepsilon_{tag} = \frac{N_R + N_W}{N_R + N_W + N_U} \qquad \omega = \frac{N_W}{N_R + N_W}$$

$$\varepsilon_{eff} = \varepsilon_{tag}(1 - 2\omega)^2$$

- When measuring sin2β it is crucial to know the initial flavour of the decaying B.

The measurement is influenced directly by the tagging dilution.

Calibration of Flavour Tagging

- For each event an estimated probability of the tagging decision to be correct (η) is given by a neural net.

  Calibration of η is needed to obtain an ω event per event

- Use per event mistag as observable $\omega = p_0 + p_1 \cdot (\eta - \bar{\eta})$
- $B^+ \to J/\psi K^+$ used for calibration, and the kinematically similar $B^0 \to J/\psi K^*$ is used as crosscheck

  MC ω distribution/calibration totally compatible with $B^0 \to J/\psi K_s$

  Study correction function between actual mistag and calibrated mistag

Expected	Obtained
$p_0 = \bar{\eta} = 0.35$	$p_0 = 0.333 \pm 0.025$
$p_1 = 1$	$p_1 = 0.71 \pm 0.36$

Likelihood Fit

- The CP violation parameters are extracted through a simultaneous multidimensional unbinned extended maximum likelihood fit.

$$\mathcal{L}(\vec{\lambda}) = \frac{e^{-N} N^n}{n!} \prod_s \prod_{i=1}^{N^s} \mathcal{P}^s(\vec{x}_i; \vec{\lambda}_s)$$

- The fit is done simultaneous in 4 subsamples:

  triggered by lifetime **biased/unbiased** (B/U) lines, and **tagged/untagged** (t,u) events

- We consider 4 observables:

  the reconstructed **mass** of the **B** candidate, its **proper time** t, the flavour **tagging decision**, and the combined per-event mistag **ω**

- The pdf consists of three components:

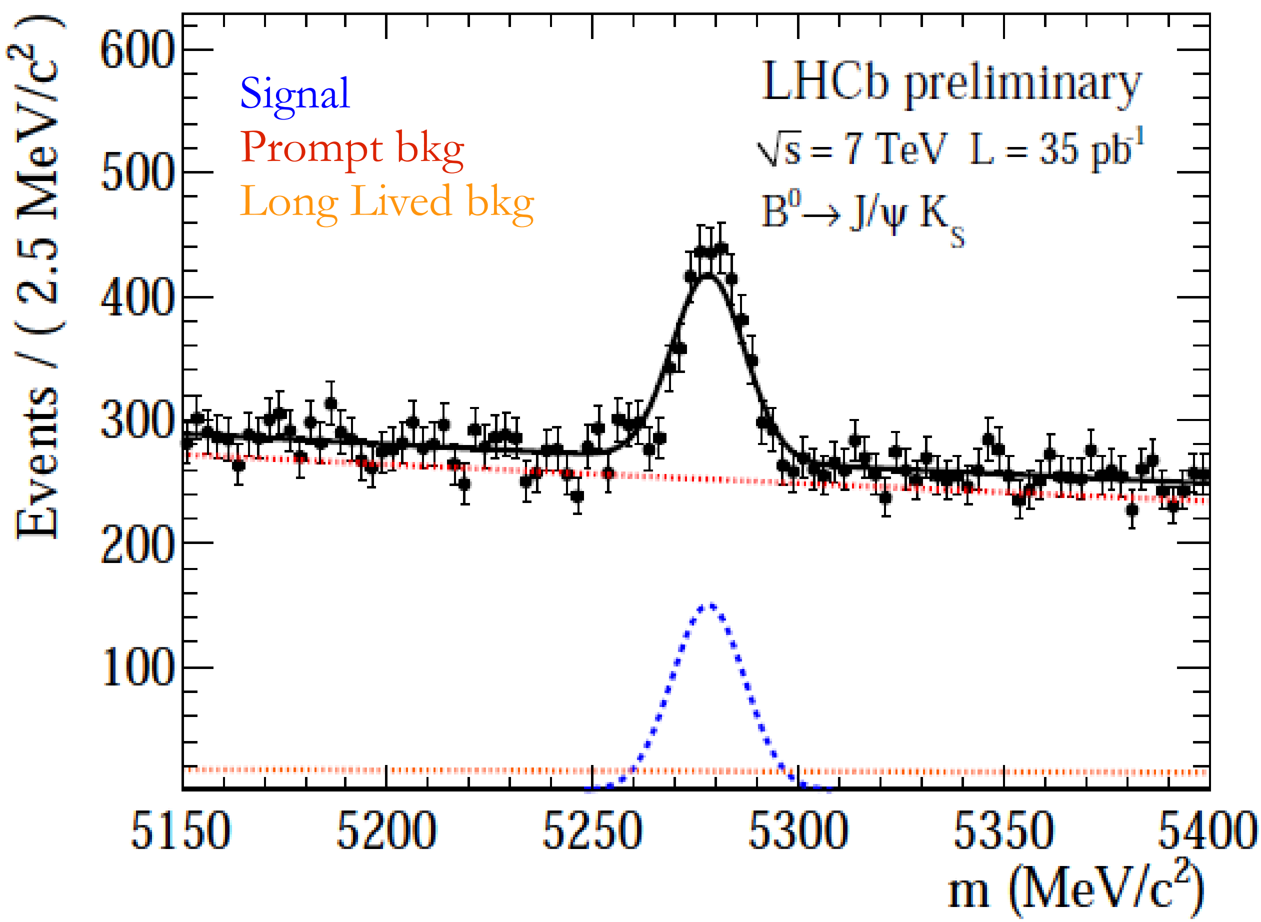
  Signal (S), **prompt bkg** (P) and **long lived bkg** (L)

Parametrization (I)

- **Mass p.d.f**

Signal: Single Gaussian (parameters shared)

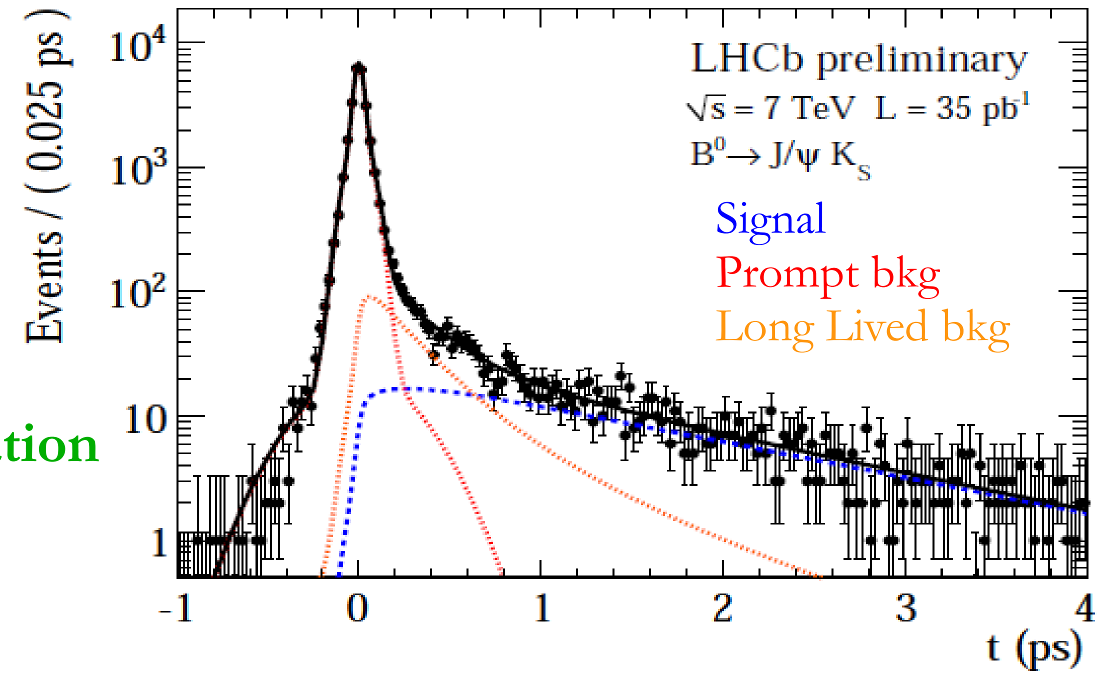
Bkg: Exponential
(P, L bkg have similar mass distribuion, use the same parametrization for both)



Parametrization (II)

- **Proper time p.d.f**

$$\mathcal{P}_S(t,d,\omega) = \mathcal{P}_S(t,d|\omega)\cdot\mathcal{P}_S(\omega)$$
$$\mathcal{P}_B(t,d,\omega) = \mathcal{P}_B(t,d)\cdot\mathcal{P}_B(\omega)$$



Describes decay, mixing and CP violation

Acceptance effects

$$\mathcal{P}_S(t,d|\omega) = \epsilon_S(t)\cdot\left(\mathcal{P}_{S,CP}(t,d|\omega)\otimes\mathcal{R}(t)\right)$$

Resolution (triple gaussian)
Constrain due to prompt component

$$\mathcal{P}_P(t) \propto \delta(t)\otimes\mathcal{R}(t;\lambda_{\mathcal{R},t})$$

$$\mathcal{P}_L^U(t;\lambda_{L,t}^U) = \left(f_{L,t}^U\cdot\frac{1}{N_{L,1}^U}e^{-t/\tau_{L,1}^U} + (1-f_{L,t}^U)\cdot\frac{1}{N_{L,2}^U}e^{-t/\tau_{L,2}^U}\right)\otimes\mathcal{R}(t;\lambda_{\mathcal{R},t})$$

$$\mathcal{P}_{L,t}^B(t;\lambda_{L,t}^B) \propto e^{-t/\tau_L^B}\otimes\mathcal{R}(t;\lambda_{\mathcal{R},t})$$

Systematic uncertainties

- Tagging (main effect),

    Calibration: Propagate uncertainties on calibration (multiply gaussian priors to full pdf). Fit with the parameters obtained with the control channel

    Per event mistag

- Production asymmetry (asymmetry in B^0, $\overline{B}^0$ ε_{tag})
- Proper time resolution (variation to statistic accuracy)
- Acceptance

    Biased events (propagate the errors of acceptance function)

    High proper time (omited correction for high t in test fit)

- Δm_d fixed to pdg value, refit with $\pm\sigma$

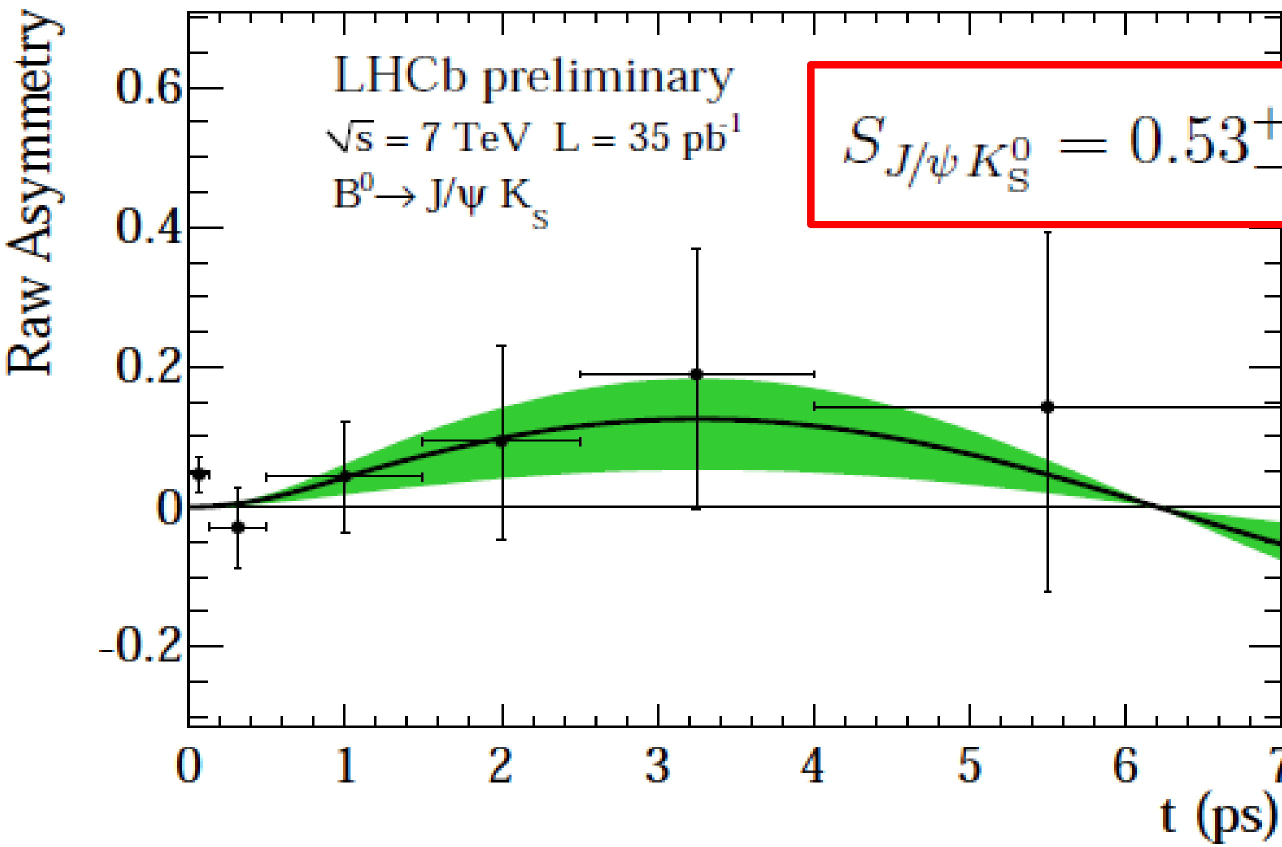
Systematic uncertainties

List of systematic uncertainties

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
production asymmetry	0.041
total (sum in squares)	0.080

Results: sin2β

LHCb measurement of CP violation in sin2β



$$S_{J/\psi K^0_S} = 0.53^{+0.28}_{-0.29}(\text{stat}) \pm 0.08(\text{syst})$$

Statistically compatible with world average $\sin 2\beta = 0.673 \pm 0.023$

Floating $C_{J/\Psi Ks}$

- Refit without assuming null direct CP violation in SM
- When floating $C_{J/\psi\, Ks}$ a correlation appears

  $\rho(S_{J/\psi Ks} C_{J/\psi Ks}) = 0.53$

  will not decrease with more statistics (sensitivity comes from proper time)
- Results are compatible with world average meaurements

$$C_{J/\psi\, K^0_S} = 0.28^{+0.32}_{-0.32}$$

$$S_{J/\psi\, K^0_S} = 0.38^{+0.34}_{-0.35}$$

Conclusion

- Performed time dependent tagged CP analysis
- Flavour tagging is already performing in LHCb
- First measurement of sin2β in LHCb

  Measurement of sin2β $S_{J/\psi K^0_S} = 0.53^{+0.28}_{-0.29}(\text{stat}) \pm 0.08(\text{syst})$

  Results consistent with world average

- Waiting for more data

LHCb coll. "Measurement of CP violation in the time-dependent analysis of $B^0 \to J/\psi\ K_s$ decays with the 2010 data", LHCb-CONF-2011-004

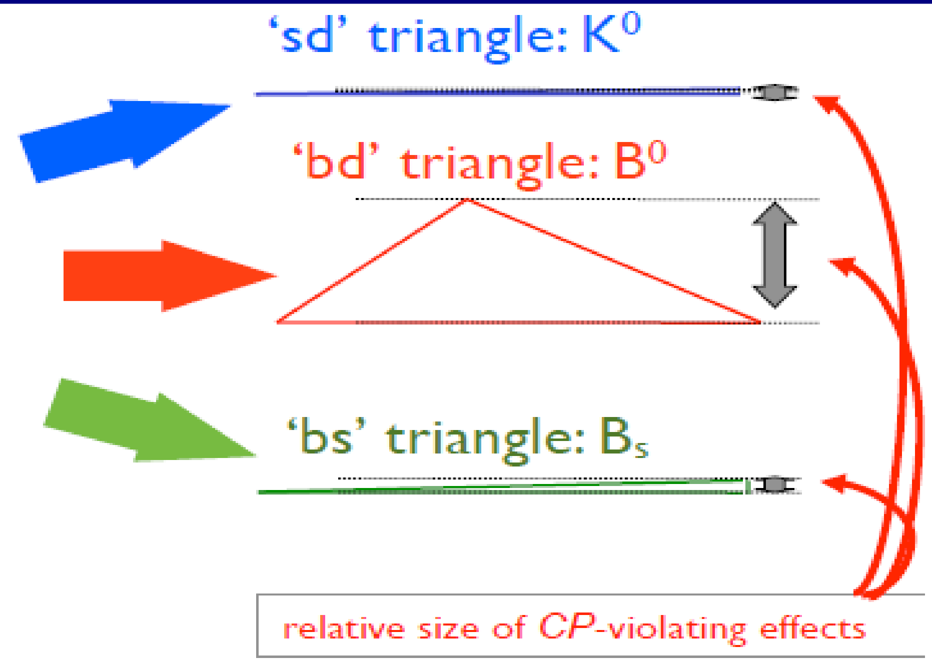
Back-Up

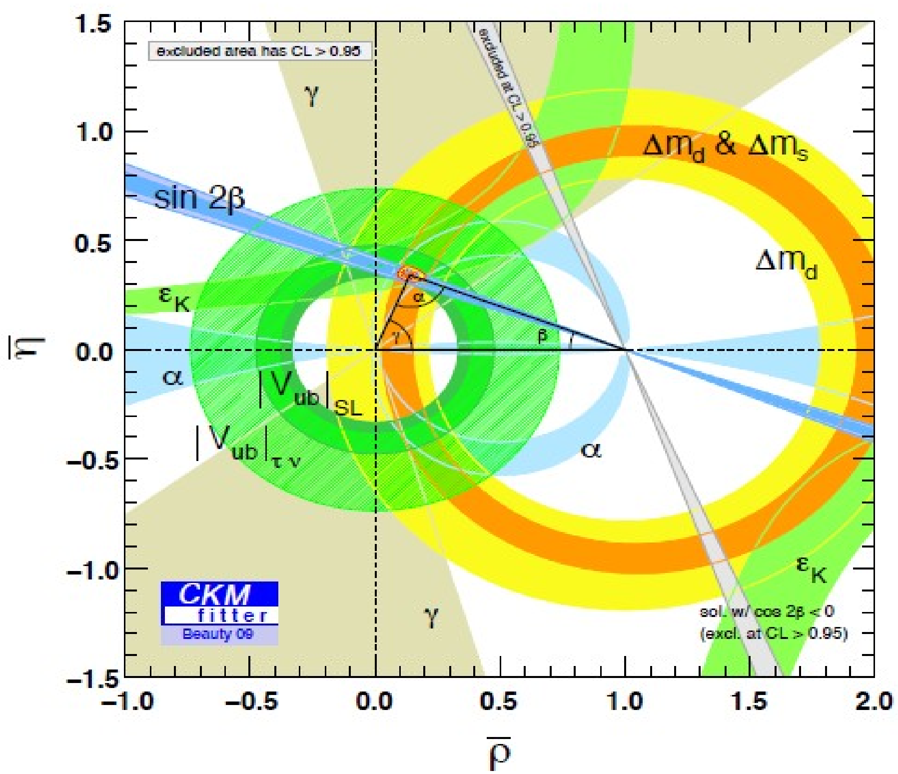
More on CP violation

$$V_{us}^* V_{ud} + V_{cs}^* V_{cd} + V_{ts}^* V_{td} = 0$$

$$V_{ub}^* V_{ud} + V_{cb}^* V_{cd} + V_{tb}^* V_{td} = 0$$

$$V_{ub}^* V_{us} + V_{cb}^* V_{cs} + V_{tb}^* V_{ts} = 0$$



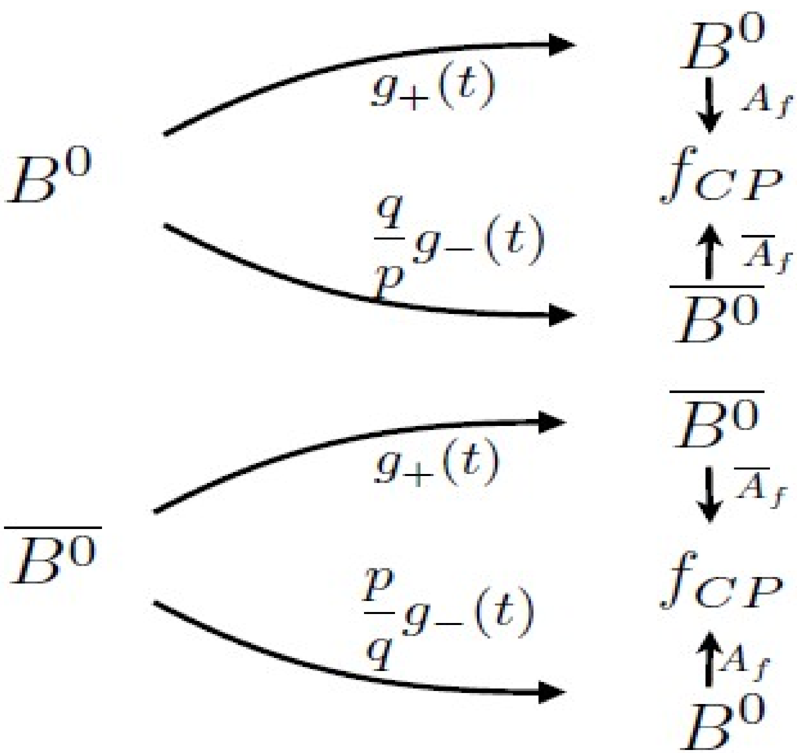


$$\alpha = \arg\left(-\frac{V_{tb}^* V_{td}}{V_{ub}^* V_{ud}}\right)$$

$$\gamma = \arg\left(-\frac{V_{ub}^* V_{ud}}{V_{cb}^* V_{cd}}\right)$$

$$\beta = \arg\left(-\frac{V_{cb}^* V_{cd}}{V_{tb}^* V_{td}}\right)$$

CP violation in B mesons



Amplitude

$$A_{f_{CP}} e^{-imt} e^{-\Gamma t/2} \left(\cos \frac{\Delta m t}{2} + \lambda_{f_{CP}} i \sin \frac{\Delta m t}{2} \right)$$

$$g_+(t) = e^{-imt} e^{-\Gamma t/2} \cos \frac{\Delta m t}{2}$$

$$g_-(t) = e^{-imt} e^{-\Gamma t/2} i \sin \frac{\Delta m t}{2}$$

$$\lambda_{f_{CP}} = \frac{q}{p} \frac{\overline{A}_{f_{CP}}}{A_{f_{CP}}}$$

$$\overline{A}_{f_{CP}} e^{-imt} e^{-\Gamma t/2} \left(\cos \frac{\Delta m t}{2} + \frac{1}{\lambda_{f_{CP}}} i \sin \frac{\Delta m t}{2} \right)$$

Rate

$B^0 \rightarrow f_{CP}$

$$\frac{1}{2} e^{-\Gamma t} \left[1 + \left(\frac{1 - |\lambda|^2}{1 + |\lambda|^2} \right) \cos(\Delta m t) - \left(\frac{2\mathcal{I}(\lambda)}{1 + |\lambda|^2} \right) \sin(\Delta m t) \right]$$

$\overline{B^0} \rightarrow f_{CP}$

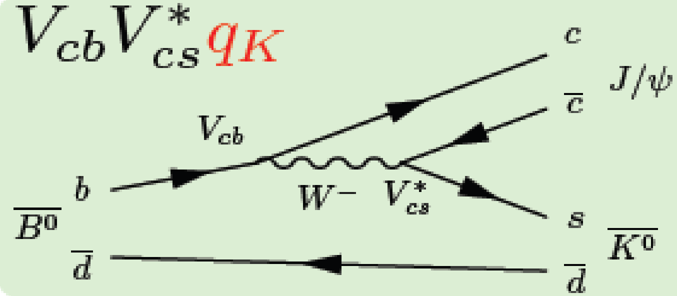
$$\frac{1}{2} e^{-\Gamma t} \left[1 - \left(\frac{1 - |\lambda|^2}{1 + |\lambda|^2} \right) \cos(\Delta m t) + \left(\frac{2\mathcal{I}(\lambda)}{1 + |\lambda|^2} \right) \sin(\Delta m t) \right]$$

CP violation in $B^0 \to J/\Psi\ K_s$

$$\lambda_{J/\psi K_S} \equiv \frac{q}{p}\frac{\overline{A}_{J/\psi K_S}}{A_{J/\psi K_S}}$$

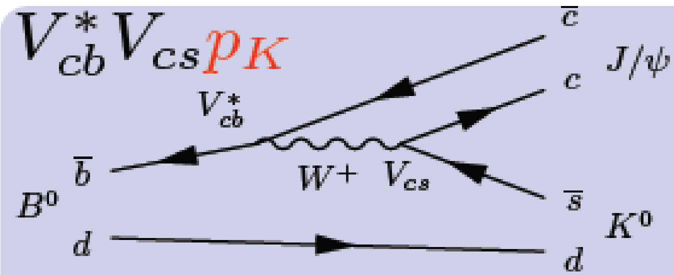
$$= -\frac{q}{p}\frac{\overline{A}_{J/\psi \overline{K^0}, \overline{K^0}\to K_S}}{A_{J/\psi K^0, K^0 \to K_S}}$$

$$V_{cb}V_{cs}^{*}q_K$$



$$\times \left\langle K_s \middle| \overline{K^0} \right\rangle$$

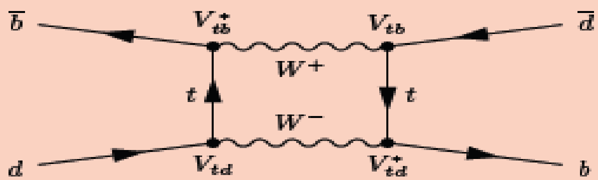
$$V_{cb}^{*}V_{cs}p_K$$



$$\times \left\langle K_s \middle| K^0 \right\rangle$$

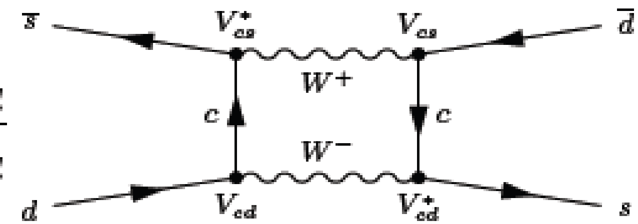
$$\left|K_s\right\rangle = p_K \left|K^0\right\rangle + q_K \left|\overline{K^0}\right\rangle$$

$$\frac{V_{tb}^{*}V_{td}}{V_{tb}V_{td}^{*}}$$



$$\lambda_{J/\psi K_S} = -e^{-2i\beta}$$

$$\frac{q_K}{p_K} \approx \frac{V_{cs}^{*}V_{cd}}{V_{cs}V_{cd}^{*}}$$

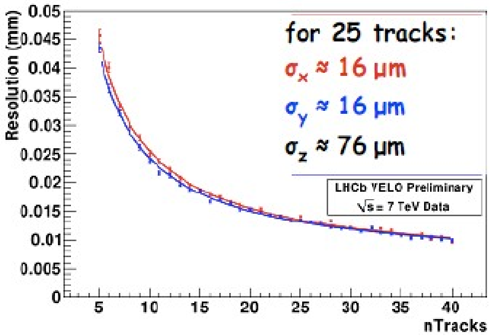


$$\mathcal{A}_{CP} = \frac{\Gamma(\overline{B^0} \to J/\psi K_S) - \Gamma(B^0 \to J/\psi K_S)}{\Gamma(\overline{B^0} \to J/\psi K_S) + \Gamma(B^0 \to J/\psi K_S)} = \sin(2\beta)\sin(\Delta m t)$$

The LHCb experiment

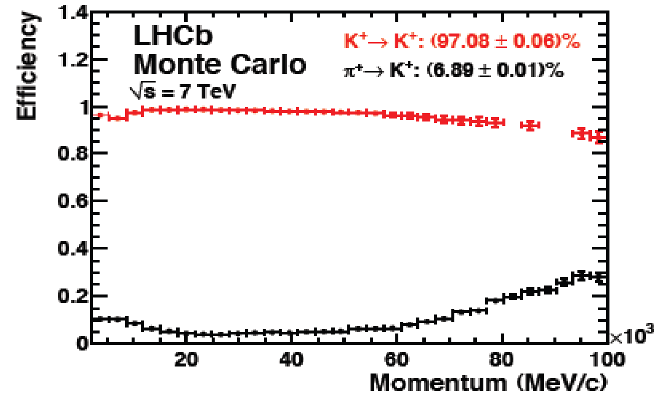
PV resolution:

Data: 16 μm for ***X*** *&* ***Y*** *and 76 μm for Z*
MC: 11 μm for X & Y and 60 μm for Z



IP resolution:

~15 μm for highest pt bins



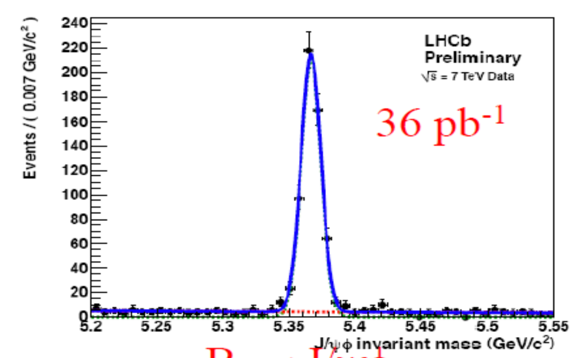
PID: RICH

Enables clean reconstruction of various hadronic decay channels of D(s) and B(s) mesons

Tracking:

Excellent mass resolution

$\sigma_m = 7$ MeV



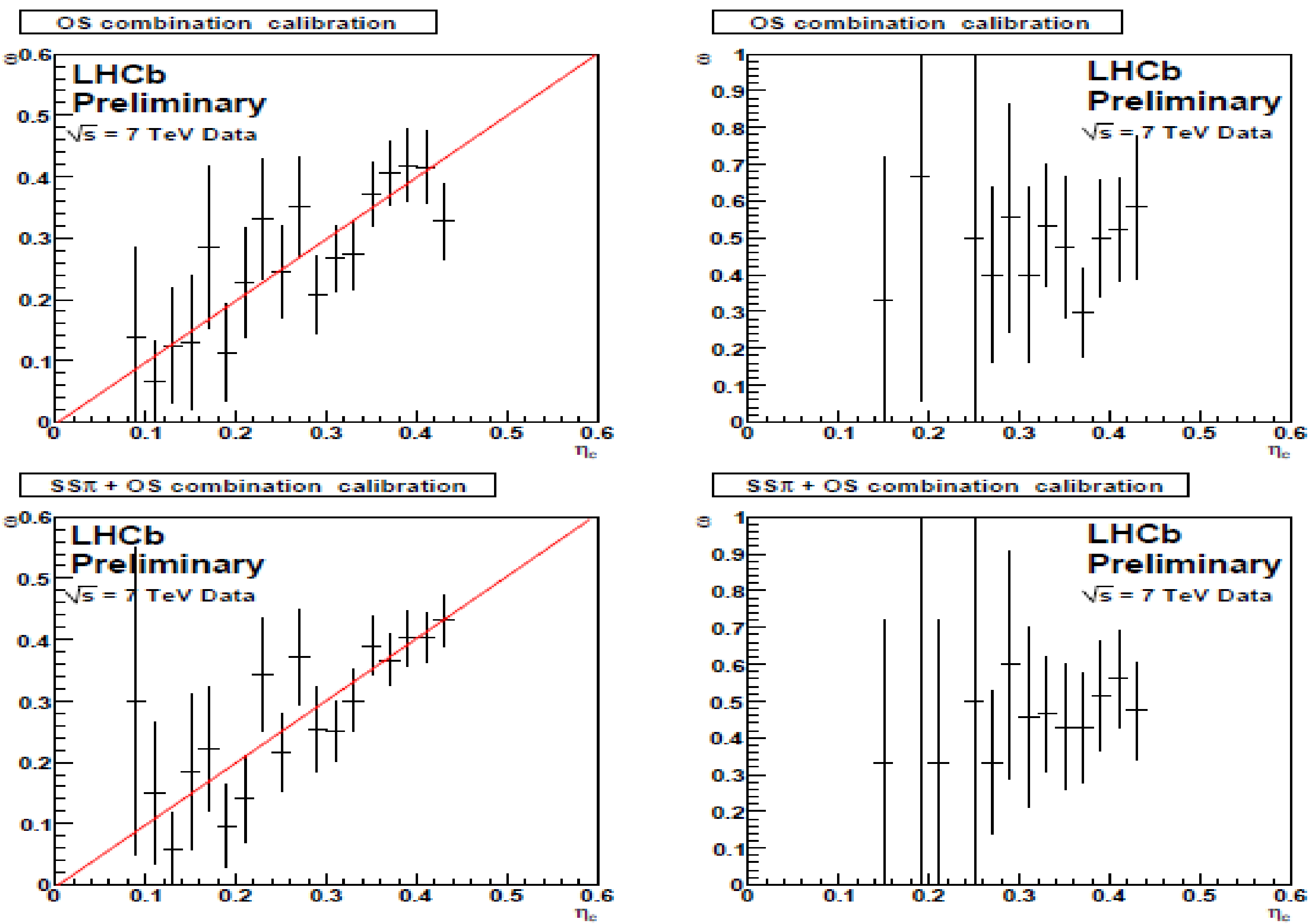
$B_s \rightarrow J/\psi\phi$

Calibration of Flavour Tagging

- Calibration of $B^+ \to J/\psi\, K^+$

Signal

Bkg

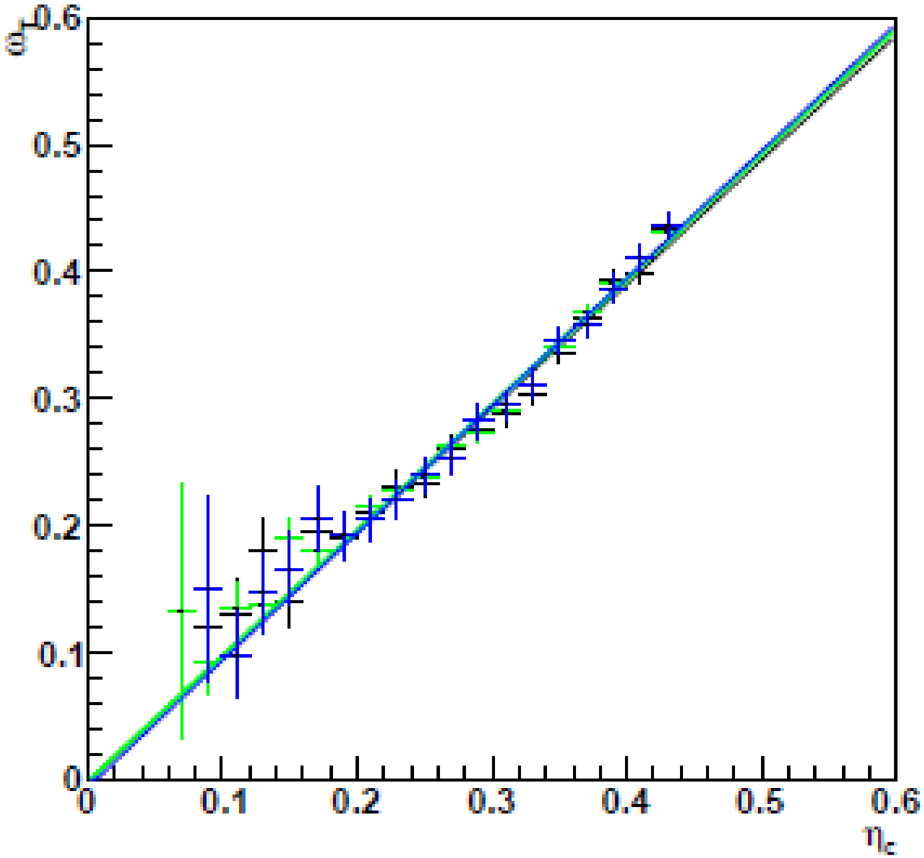


OS combination

OS + SS combination

Calibration of Flavour Tagging

- MC validation of tagging with other channels



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

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

$B^0 \rightarrow J/\psi \phi$

LHCb coll. "Optimization and calibration of the LHCb flavour tagging performance using 2010 data", LHCb-CONF-2011-003

Lifetime

- The fited value is:

$$\tau(B^0 \to J/\psi K^0_\mathrm{S}) \quad = \quad 1.558 \pm 0.056\,(\mathrm{stat.}) \pm 0.022\,(\mathrm{syst.})\ \mathrm{ps}$$

$$\text{PDG evaluation (ps)} \qquad 1.525 \pm 0.009$$

- The proper time has a high precision in the fit
- We include acceptance correction in agreement with:

LHCb coll. "b-hadron lifetime measurements with exclusive b → J/ψ X decays reconstructed in the 2010 data", LHCb-CONF-2011-001

Parametrization (III)

- The efficiency function describes acceptance effects observed in the biased sample at low proper times..

$$\epsilon_{\mathrm{S}}(t) = \frac{(a_a t)^{c_a}}{1 + (a_a t)^{c_a}}$$

- CP p.d.f

Correction for acceptance
at high lifetimes

$$\mathcal{P}^{\mathrm{t}}_{\mathrm{S},CP}(t, d|\omega) \propto e^{-t/\tau'} (1 - d(1-2\omega)\, S_{J/\psi K^0_{\mathrm{S}}} \sin \Delta m_d t + d(1-2\omega)\, C_{J/\psi K^0_{\mathrm{S}}} \cos \Delta m_d t)$$

$$\mathcal{P}^{\mathrm{u}}_{\mathrm{S},CP}(t) \propto e^{-t/\tau'}$$

Describes decay, mixing and CP violation in the B^0 system.

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Parametrization (IV)

- Per event mistag probability (included in full pdf)

  Use sPlot technique to extract histo pdf for sig/bkg η_c distribution

- The B^0 lifetime is shared in all four sample
- Δm_d, $S_{J/\psi K}$, $C_{J/\psi K}$ shared between the tagged sample

Fit details

- Fit results and fitted event yields on the full $B^0 \to J/\psi\, K_s$

Parameter	Unit	Fitted Value
$S_{J/\psi K^0_S}$		$0.53^{+0.28}_{-0.29}$
m_S	MeV/c^2	$5278.13^{+0.29}_{-0.29}$
$\sigma_{S,m}$	MeV/c^2	$8.82^{+0.24}_{-0.24}$
τ	ps	$1.517^{+0.046}_{-0.045}$
α_m^B	$(MeV/c^2)^{-1}$	$-8.71^{+3.8}_{-3.8} \cdot 10^{-4}$
α_m^U	$(MeV/c^2)^{-1}$	$-5.864^{+0.87}_{-0.87} \cdot 10^{-4}$
$f^U_{L,t}$		$0.836^{+0.049}_{-0.054}$
$\tau^U_{L,1}$	ps	$0.221^{+0.036}_{-0.032}$
$\tau^U_{L,2}$	ps	$1.04^{+0.24}_{-0.16}$
τ^B_L	ps	$0.482^{+0.029}_{-0.027}$
$f_{\mathcal{R},1}$		$0.500^{+0.019}_{-0.019}$
$f_{\mathcal{R},2}$		$0.477^{+0.017}_{-0.017}$
$\sigma_{\mathcal{R},1}$	ps	$0.02522^{+0.00066}_{-0.00066}$
$\sigma_{\mathcal{R},2}$	ps	$0.0685^{+0.0016}_{-0.0015}$
$\sigma_{\mathcal{R},3}$	ps	$0.293^{+0.019}_{-0.017}$

Sample	Parameter	Fitted Value
U,t	$N_S^{U,t}$	221^{+17}_{-17}
	$N_P^{U,t}$	3218^{+62}_{-62}
	$N_L^{U,t}$	309^{+33}_{-30}
B,t	$N_S^{B,t}$	$59.8^{+8.7}_{-8.0}$
	$N_P^{B,t}$	164^{+14}_{-14}
	$N_L^{B,t}$	102^{+12}_{-12}
U,u	$N_S^{U,u}$	767^{+32}_{-31}
	$N_P^{U,u}$	21134^{+161}_{-161}
	$N_L^{U,u}$	807^{+79}_{-74}
B,u	$N_S^{B,u}$	279^{+18}_{-18}
	$N_P^{B,u}$	747^{+30}_{-29}
	$N_L^{B,u}$	339^{+23}_{-22}