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GEFÖRDERT VOM

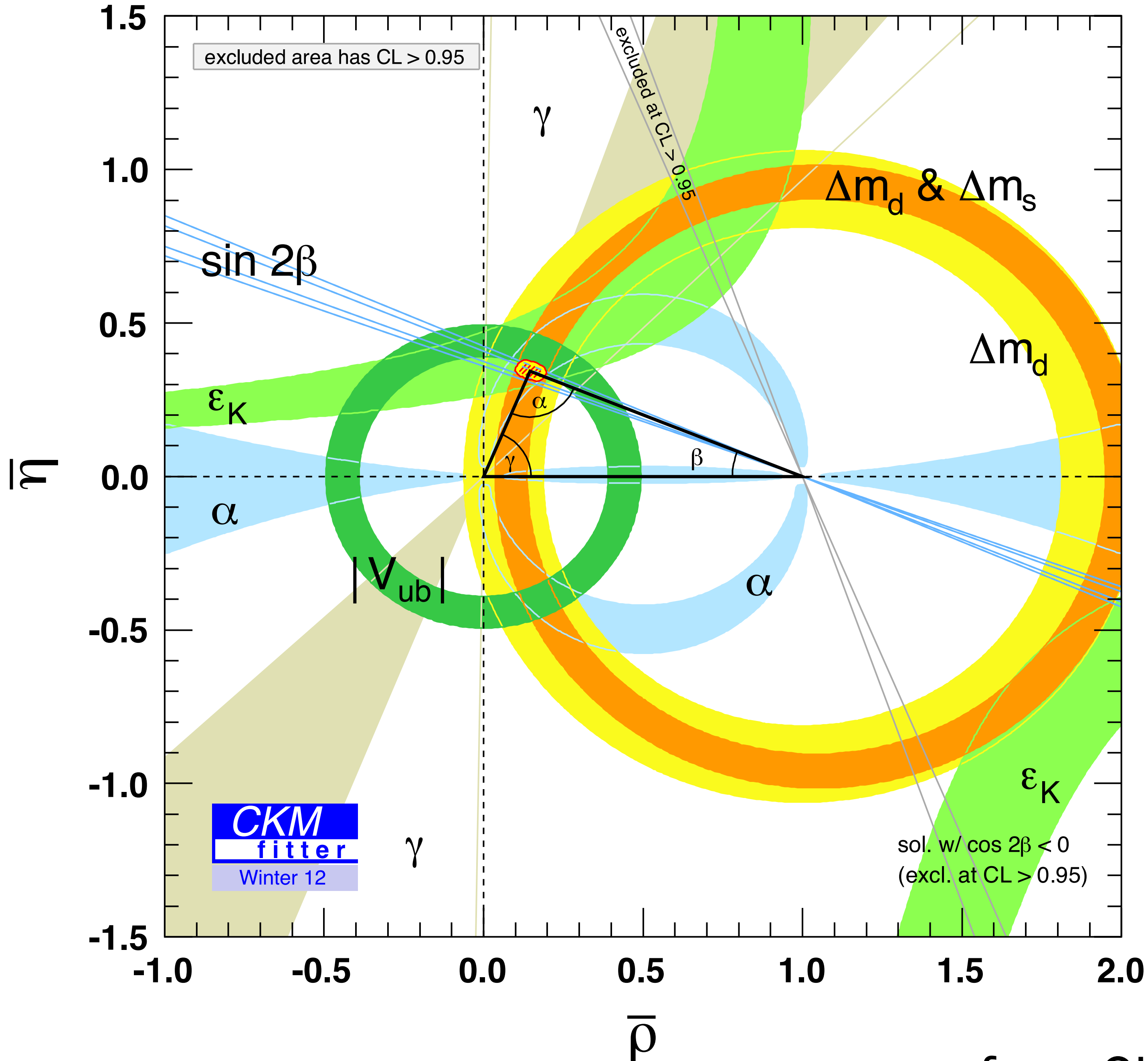
Bundesministerium
für Bildung
und Forschung

Measurement of Δm_s, Δm_d, and $\sin 2\beta$ with LHCb

Julian Wishahi – on behalf of the LHCb collaboration

7th International Workshop on the CKM Unitarity Triangle
September 29th 2012, Cincinnati, Ohio, USA

Introduction – The CKM-triangle



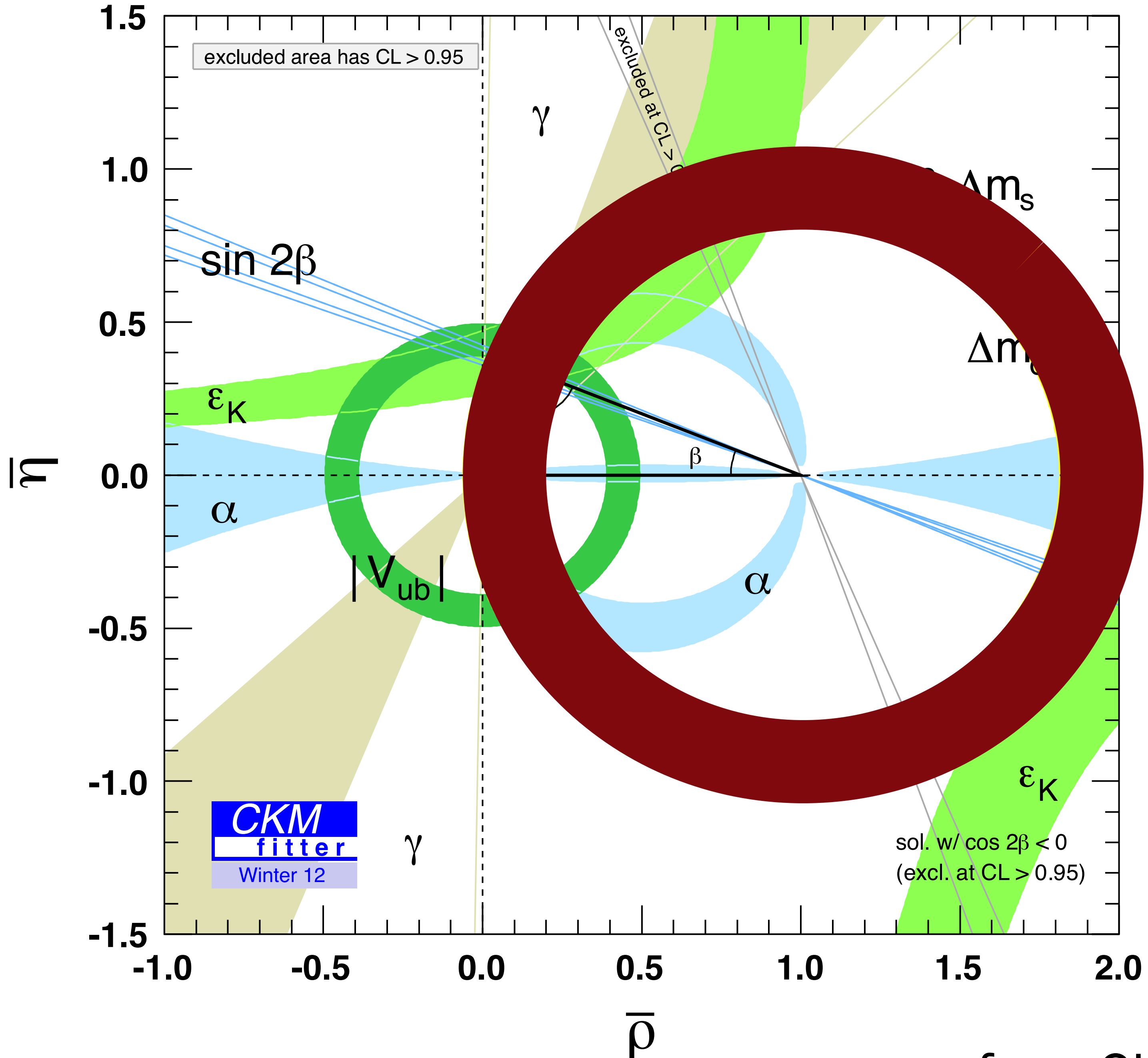
Δm_d

$\Delta m_d/\Delta m_s$

$\sin 2\beta$

from CKMfitter group

Introduction – The CKM-triangle



Δm_d

$\Delta m_d / \Delta m_s$

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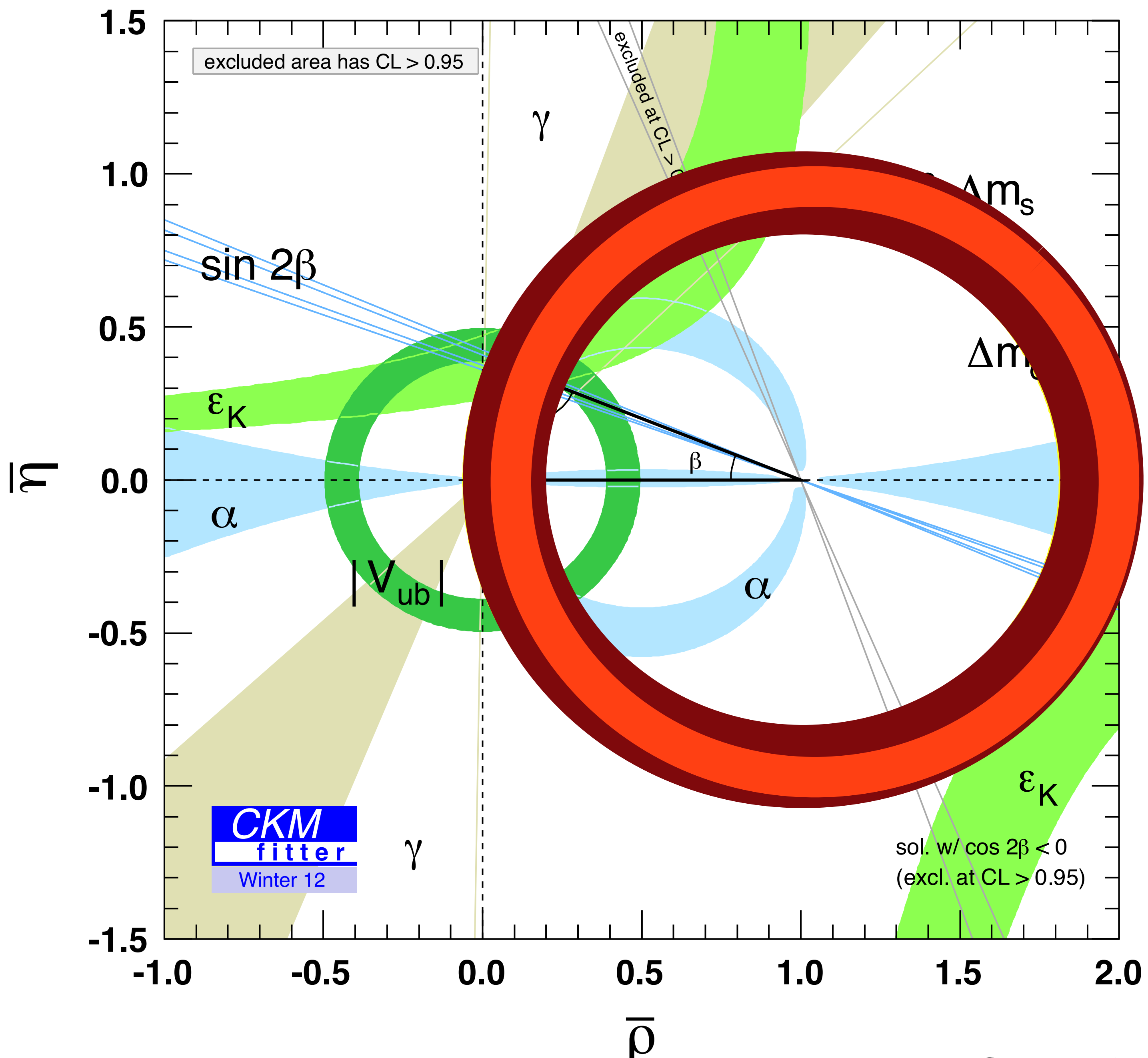
Introduction – The CKM-triangle



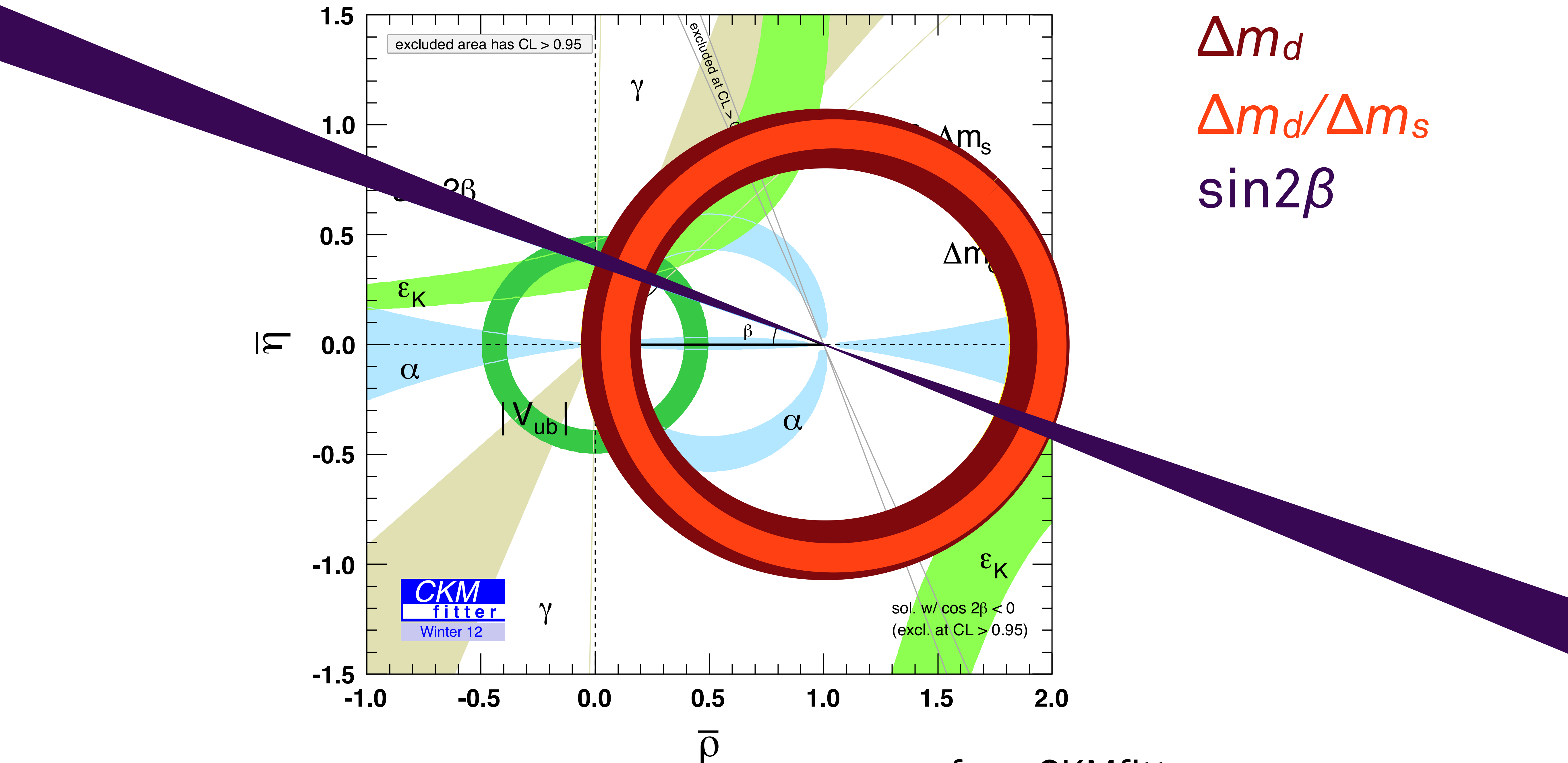
Δm_d

$\Delta m_d/\Delta m_s$

$\sin 2\beta$

from CKMfitter group

Introduction – The CKM-triangle



from CKMfitter group

Introduction

- Measurements
  - Mixing parameters
    - Δm_d in $B^0 \to J/\psi\, K^{*0}$ and $B^0 \to D^-\, \pi^+$
    - Δm_s in $B_s \to D_s\, \pi^+$

$$\mathcal{A}_q(t) = \frac{N_{\text{unmixed}}(t) - N_{\text{mixed}}(t)}{N_{\text{unmixed}}(t) + N_{\text{mixed}}(t)} = \cos \Delta m_q t$$

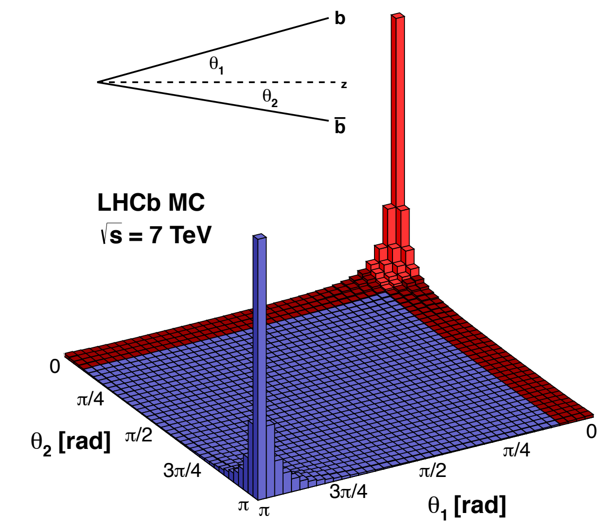
  - *CP* Violation in the interference of mixing and decay
    - sin2β in $B^0 \to J/\psi\, K_S$

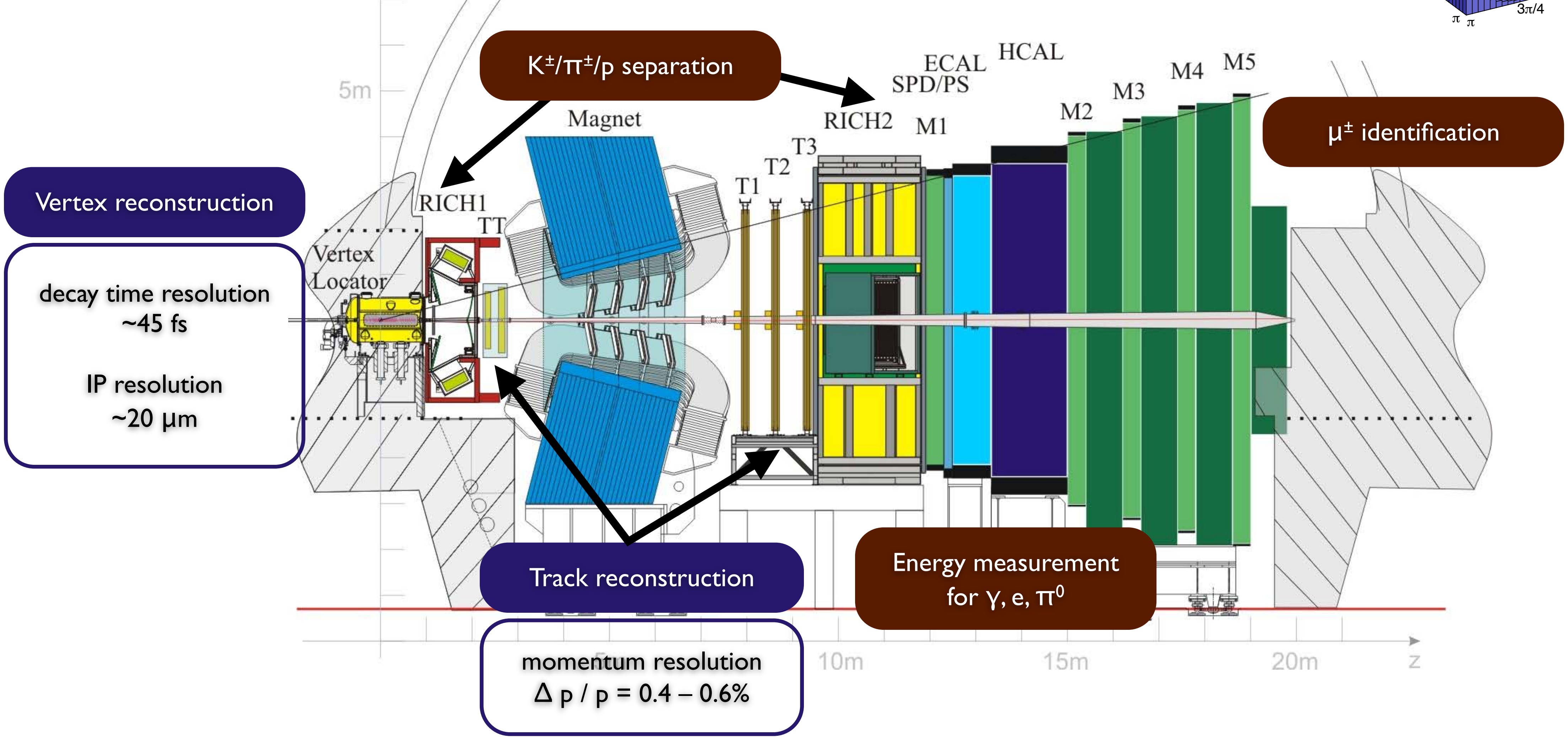
$$\mathcal{A}_{J/\psi K^0_S}(t) \equiv \frac{\Gamma(\overline{B}^0(t) \to J/\psi K^0_S) - \Gamma(B^0(t) \to J/\psi K^0_S)}{\Gamma(\overline{B}^0(t) \to J/\psi K^0_S) + \Gamma(B^0(t) \to J/\psi K^0_S)} = S_{J/\psi K^0_S} \sin(\Delta m_d t) - C_{J/\psi K^0_S} \cos(\Delta m_d t).$$

- Ingredients
  - tag the initial flavour of the *B*
  - measure the *B* decay time

The LHCb Experiment

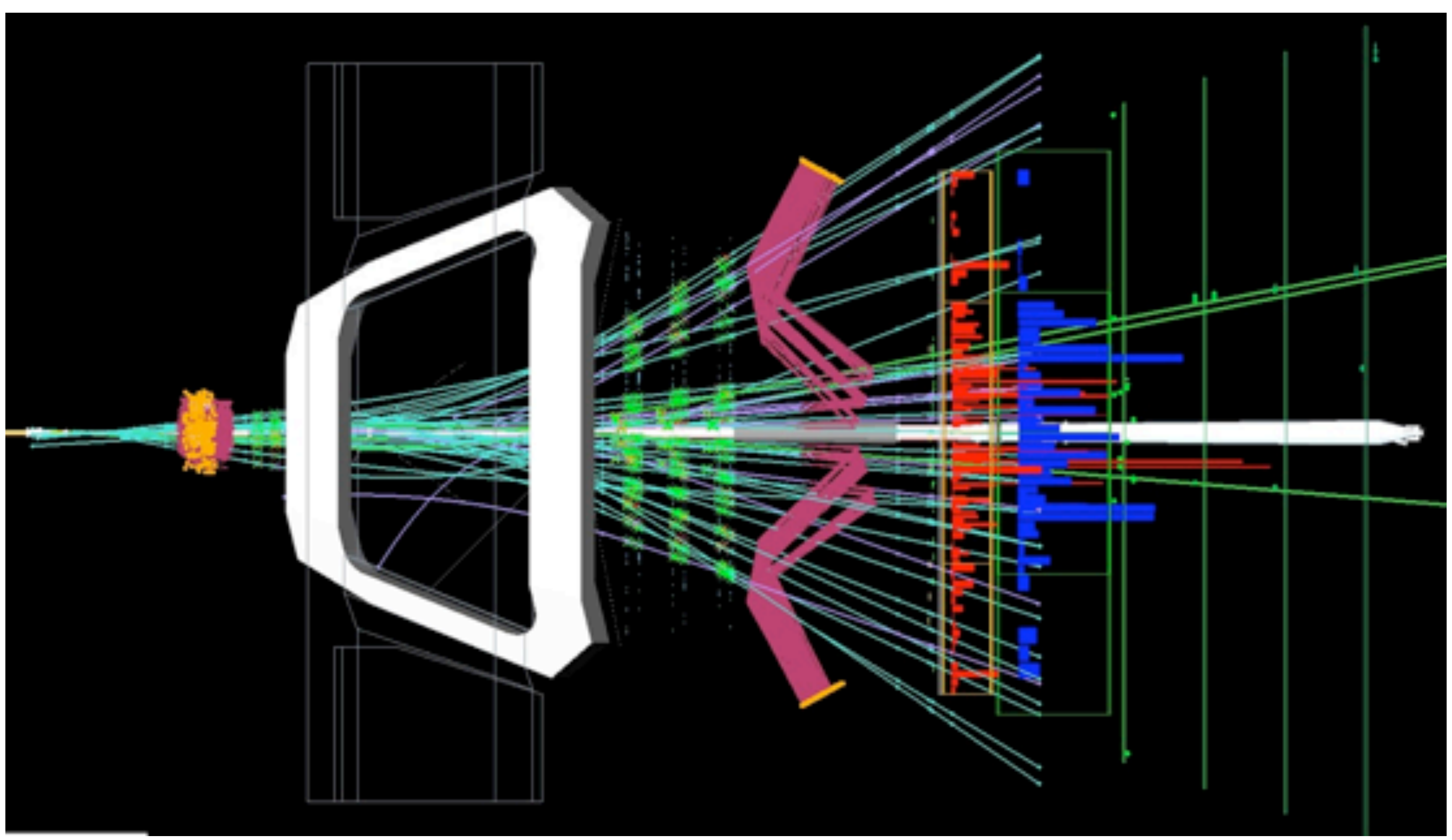
- single-arm spectrometer ($2 < \eta < 5$)
- dedicated for the study of *b* and *c* hadrons
  - rare decays
  - CP violation
- correlated (incoherent) production of *b* quark pairs in *pp*-collisions
- has to cope with harsh hadronic environment
  - efficient triggers (hardware+software stage) and selections

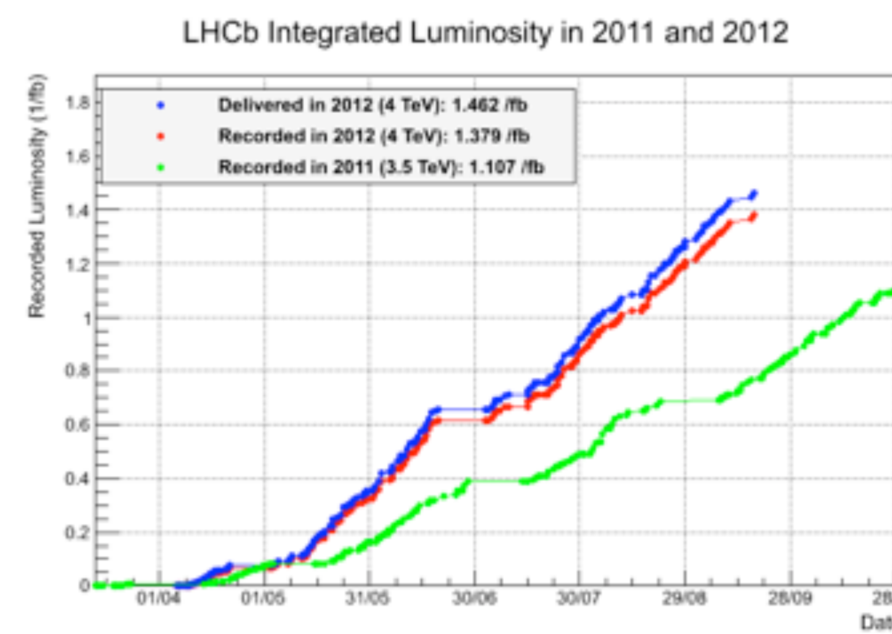




The LHCb Experiment

- Specs
  - 1 fb^{-1} at 7 TeV in 2011 (expect 2.2 fb^{-1} at 8 TeV in 2012)
  - data taking efficiency >90% (of which >99% can be used for analyses)
  - triggers reduce 20 MHz collisions to 4 kHz output
    - ~90% efficient for dimuon channels
    - ~30% efficient for multi-body hadronic final states





Flavour Tagging

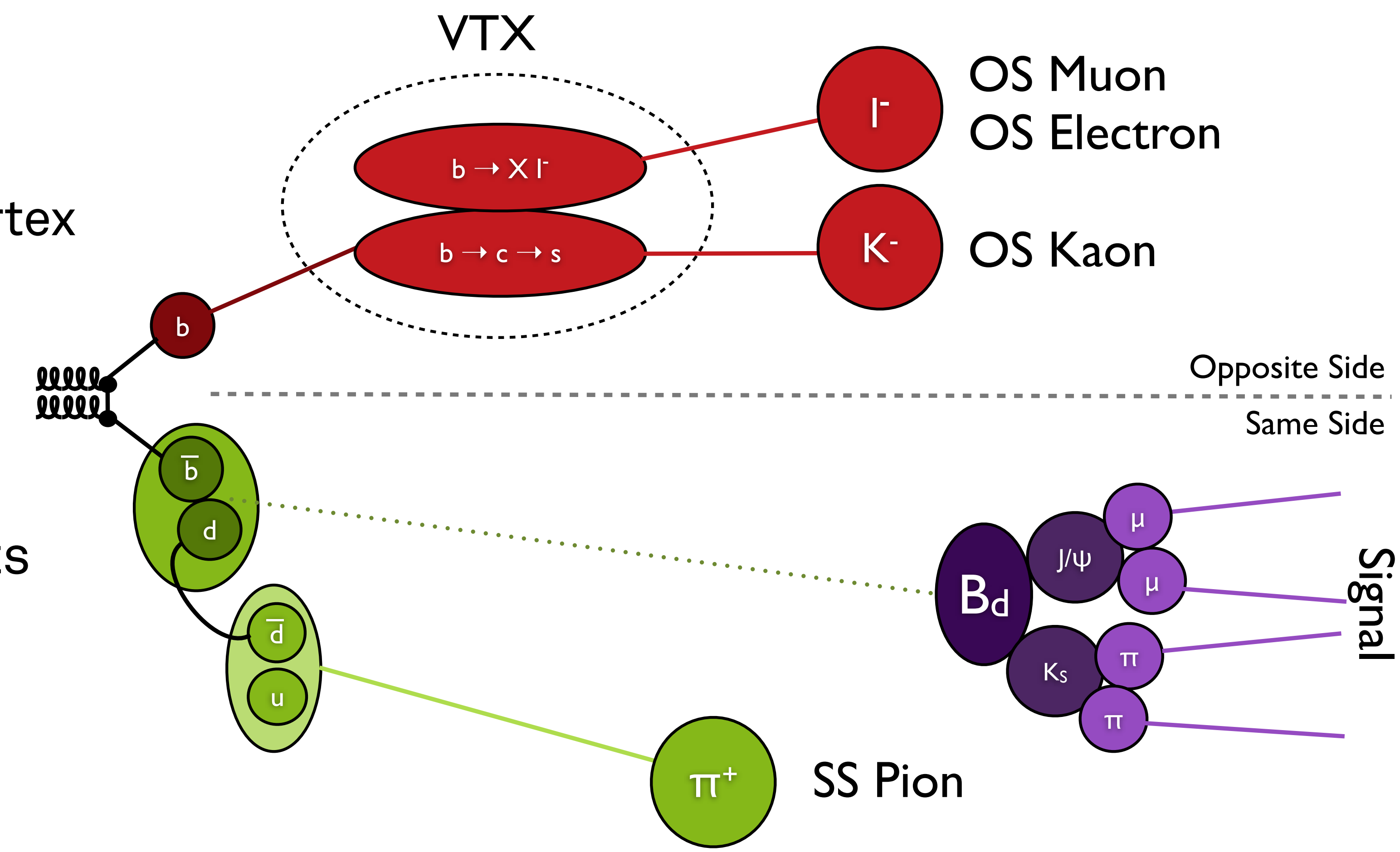
Eur. Phys. J. C 72 (2012) 2022

LHCb-CONF-2012-030

Flavour Tagging

Eur. Phys. J. C 72 (2012) 2022
LHCb-CONF-2012-026

- Tagging algorithms
  - OS tagging exploits decay of associated *b* hadron
    - lepton taggers
    - kaon tagger
    - inclusive secondary vertex reconstruction
  - SS tagging uses remnants of the signal *b* hadronization
    - SS Kaon for B_s mesons
    - SS Pion for B^0 and B^+ mesons



Flavour Tagging

Eur. Phys. J. C 72 (2012) 2022
LHCb-CONF-2012-026

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- Each tagging algorithm determines
  - tag decision d_i
  - mistag probability estimate η_i
    - from Neural Net trained on MC
  - combination of taggers gives combined d and η_c
    - can do this for OSTs only or OST+SST

- Tagging performance
  - given by
    - tagging efficiency $\varepsilon_{\text{tag}} = \frac{N_{\text{T}}}{N_{\text{T}} + N_{\text{U}}}$
    - mistag fraction $\omega = \frac{N_{\text{W}}}{N_{\text{R}} + N_{\text{W}}}$
    - tagging power $\epsilon_{\text{eff}} = \varepsilon_{\text{tag}}(1-2\omega)^2 = \varepsilon_{\text{tag}}\mathcal{D}^2$

$$\mathcal{A}_{\text{meas}} = (1-2\omega)\mathcal{A}(t)$$

  - OS taggers

Tagger	ε_{tag} %	ω %	$\varepsilon_{\text{tag}}\mathcal{D}^2$ %
μ	5.20±0.04	30.8±0.4	0.77±0.04
e	2.46±0.03	30.9±0.6	0.36±0.03
K	17.67±0.08	39.33±0.24	0.81±0.04
Q_{vtx}	18.46±0.08	40.31±0.24	0.70±0.04

  - OS combination $\varepsilon_{\text{tag}}\mathcal{D}^2 \approx 2.3\%$

$$\omega \approx 36.7\%$$

Flavour Tagging – Calibration

Eur. Phys. J. C 72 (2012) 2022
LHCb-CONF-2012-026

- Calibrate the mistag probability prediction with self-tagging channels
  - linear calibration function

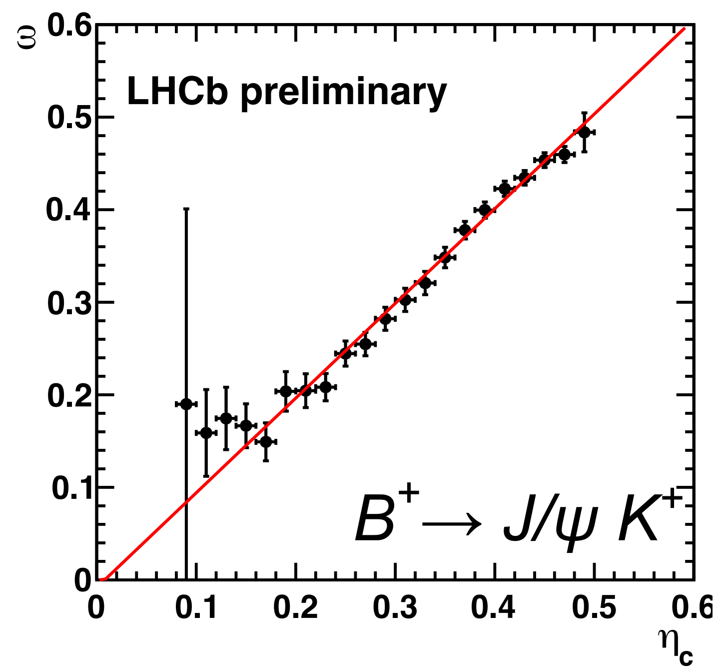
$$\omega(\eta) = p_0 + p_1(\eta_c - \langle\eta_c\rangle)$$

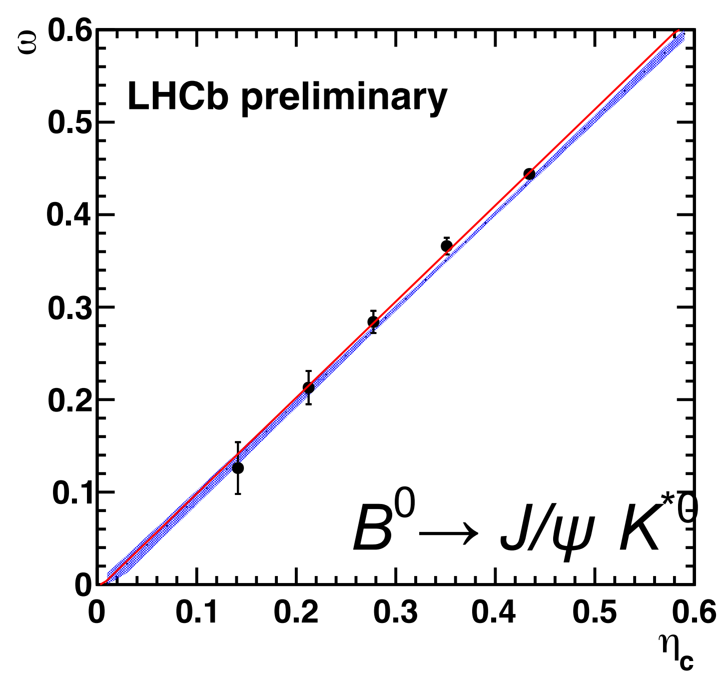
    - perfect calibration if

$$p_1 = 1$$
$$p_0 = \langle\eta_c\rangle$$

    - for OS combination on $B^+ \rightarrow J/\psi K^+$
    - validation on other control channels
  - Mistag probability asymmetry

$$\Delta\omega = p_0(B^0) - p_0(\overline{B}^0) = 0.011 \pm 0.003$$





Measurement of Δm_s

Phys. Lett. B 709 (2012)

LHCb-CONF-2011-050

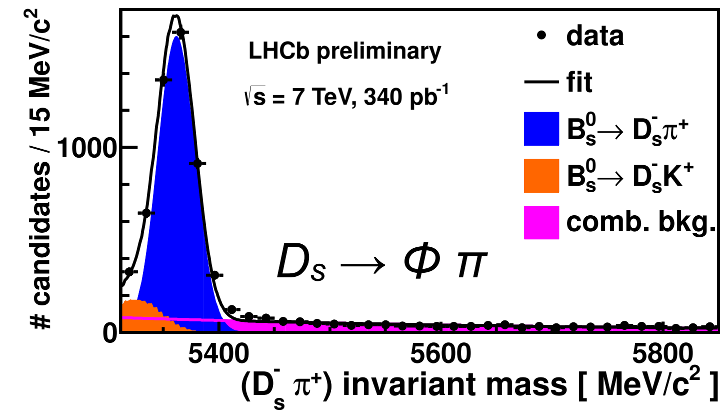
Measurement of Δm_s

Phys. Lett. B 709 (2012)
LHCb-CONF-2012-050

- Current status
  - measurement by CDF

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

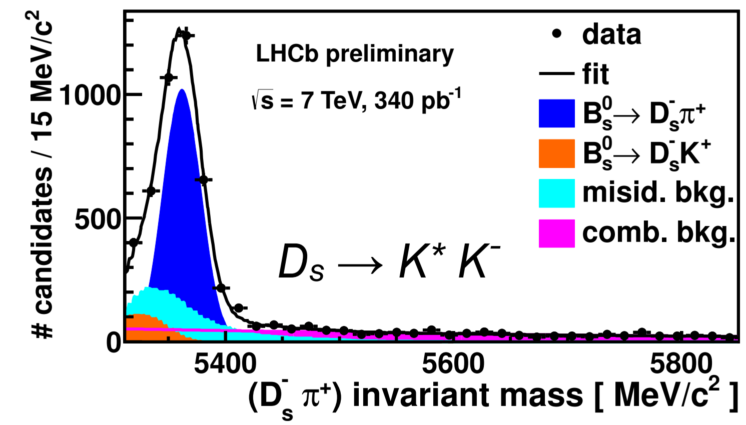
  - most precise measurement by LHCb (preliminary)



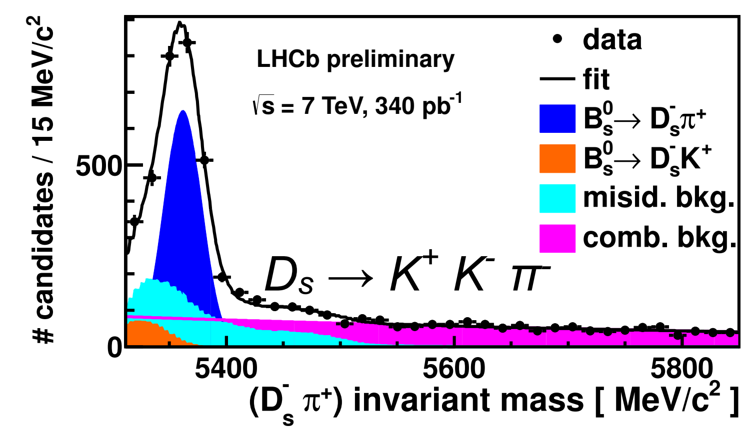
- Mixing asymmetry

$$\mathcal{A}(t) = \frac{N^{\text{sig}}_{\text{unmixed}}(t) - N^{\text{sig}}_{\text{mixed}}(t)}{N^{\text{sig}}_{\text{unmixed}}(t) + N^{\text{sig}}_{\text{mixed}}(t)} = \cos \Delta m_s t$$

  - compare flavour tag with decay flavour
    - same flavour = unmixed
    - different flavour = mixed



- Dataset 340 pb^{-1} (2011)
  - using 9189 $B_s \to D_s\,\pi^+$ decays
    - $D_s \to \Phi\,\pi$, $D_s \to K^* K^-$, $D_s \to K^+ K^- \pi$ (non-resonant)
  - OST (per-event mistag prob.) and SSK tagging

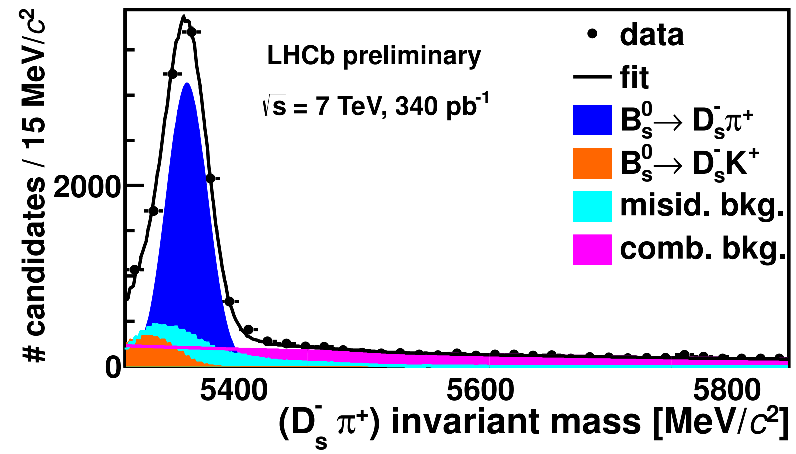


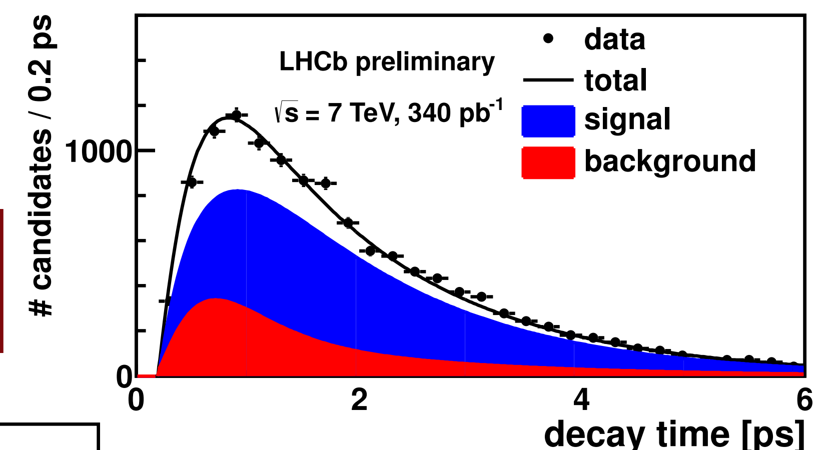
Measurement of Δm_s

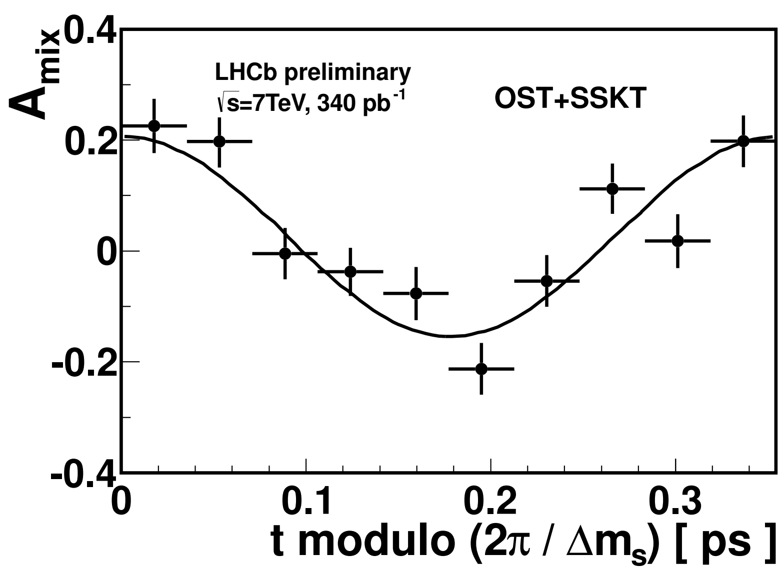
Phys. Lett. B 709 (2012)
LHCb-CONF-2012-050

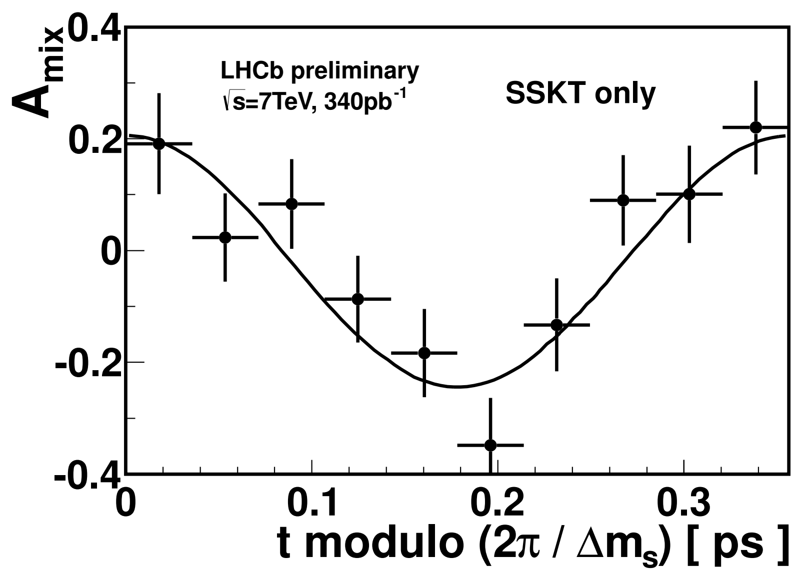
- Features
  - Decay time resolution of 45 fs
  - SSK alone: $\varepsilon\mathcal{D}^2 = (1.3 \pm 0.4)\,\%$
- Largest systematic uncertainty from length-scale
- Result

$$\Delta m_s = 17.725 \pm 0.041\ (\text{stat.}) \pm 0.026\ (\text{syst.})\ \text{ps}^{-1}$$









Measurement of Δm_d

LHCb-PAPER-2012-032 (to be published soon)

Measurement of Δm_d

LHCb-PAPER-2012-032

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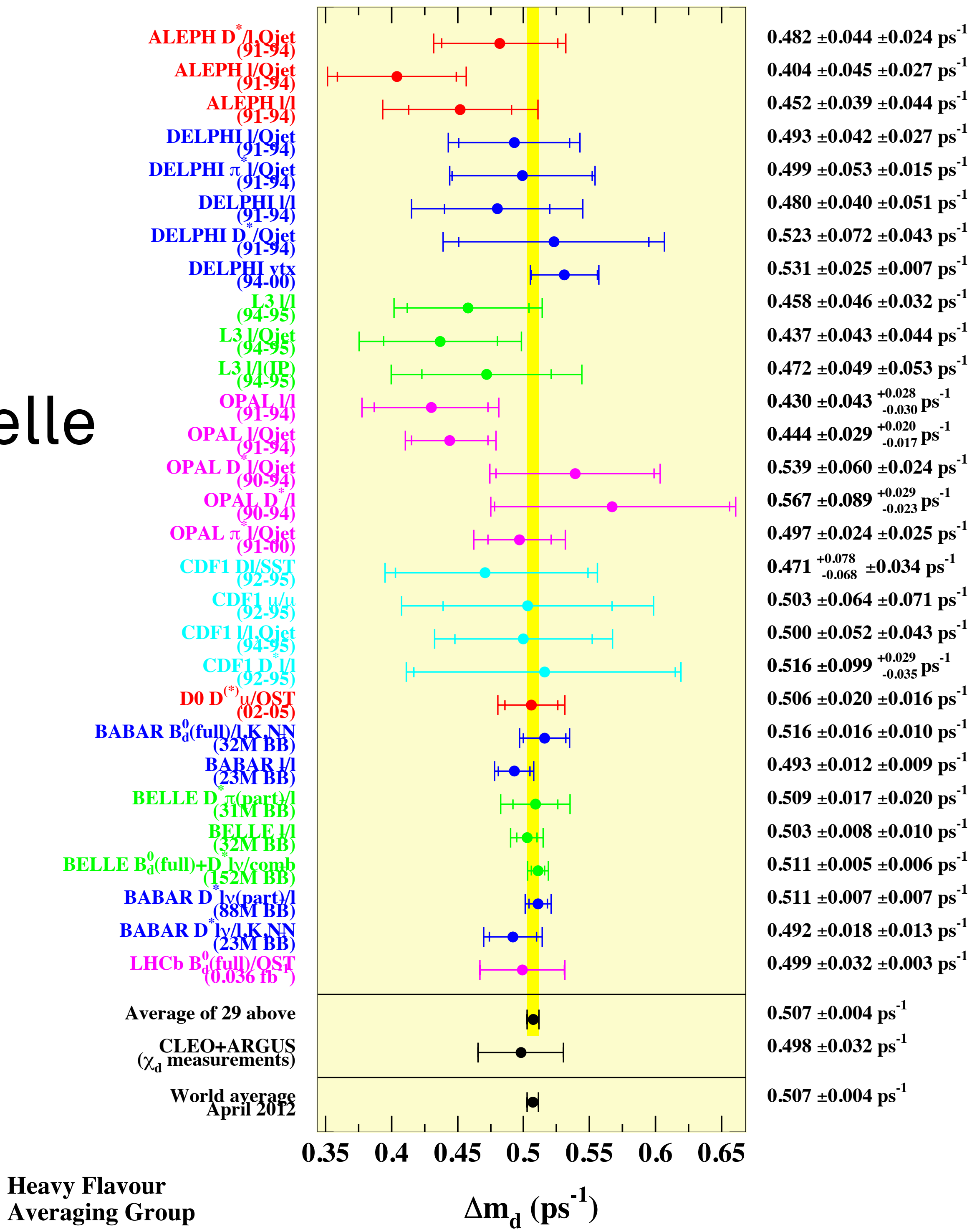
- Current status
  - world average (HFAG)

$$\Delta m_d = 0.507 \pm 0.003 \pm 0.003\,\mathrm{ps}^{-1}$$

  - single best measurement by Belle

$$\Delta m_d = 0.511 \pm 0.005 \pm 0.006\,\mathrm{ps}^{-1}$$



Measurement of Δm_d

LHCb-PAPER-2012-032

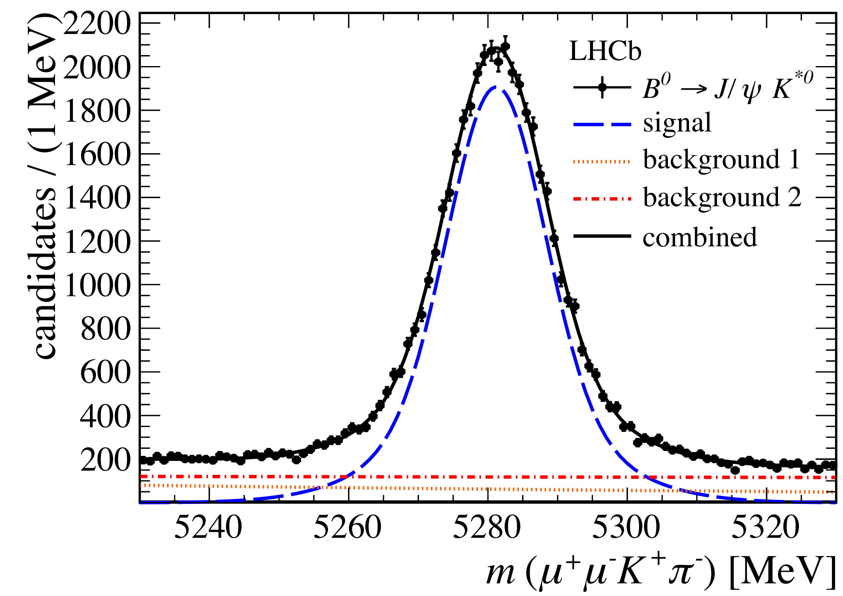
- Measure asymmetry

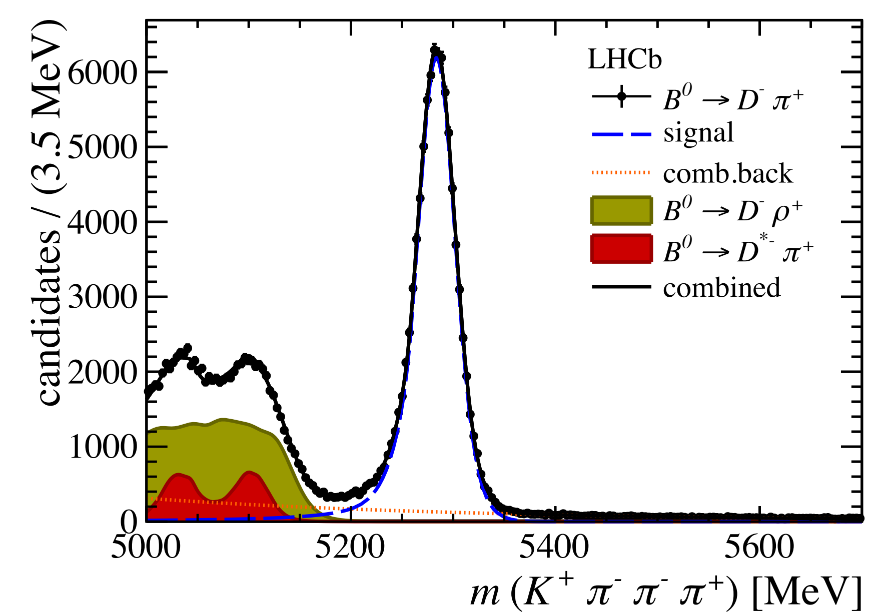
$$\mathcal{A}(t) = \frac{N^{\rm sig}_{\rm unmixed}(t) - N^{\rm sig}_{\rm mixed}(t)}{N^{\rm sig}_{\rm unmixed}(t) + N^{\rm sig}_{\rm mixed}(t)} = \cos \Delta m_d t$$

  - get mixed/unmixed information from comparing initial flavour tag with decay flavour

- Datasample 1 fb^{-1}
  - decay channels
    - ~88000 $B^0 \rightarrow D^- \pi^+$
    - ~39000 $B^0 \rightarrow J/\psi K^{*0}$

- OST+SSπ combination used
  - per-event mistag probability





Measurement of Δm_d

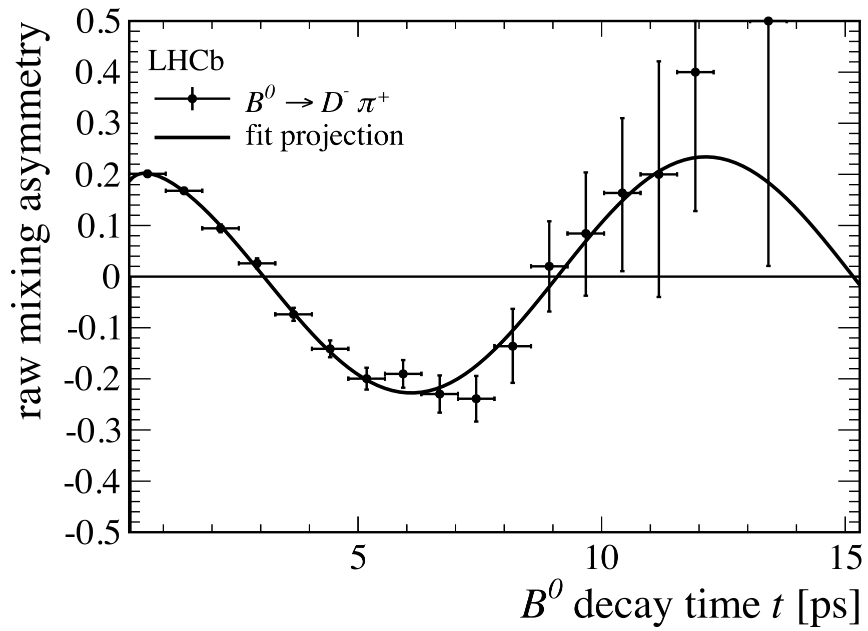
LHCb-PAPER-2012-032

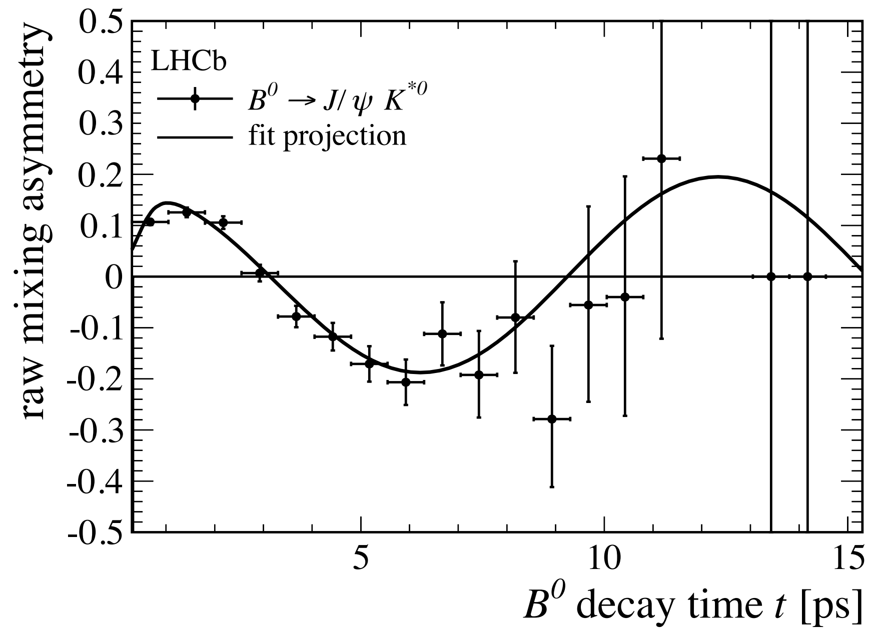
- Results

$$\Delta m_d^{B^0\to D^-\pi^+} = 0.518 \pm 0.006(\text{stat.}) \pm 0.004(\text{syst.})\ \text{ps}^{-1}$$
$$\Delta m_d^{B^0\to J/\psi K^{*0}} = 0.510 \pm 0.011(\text{stat.}) \pm 0.002(\text{syst.})\ \text{ps}^{-1}$$

- Combined

$$\Delta m_d^{\text{LHCb}} = 0.516 \pm 0.005(\text{stat.}) \pm 0.003(\text{syst.})\ \text{ps}^{-1}$$





- Major syst. uncertainties from background modeling

Measurement of sin2β

LHCb-PAPER-2012-035 (to be published soon)

Measurement of sin2β

LHCb-PAPER-2012-035

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- Current status
  - one of the most precise measured CP parameters
  - world average (HFAG, all charmonium)

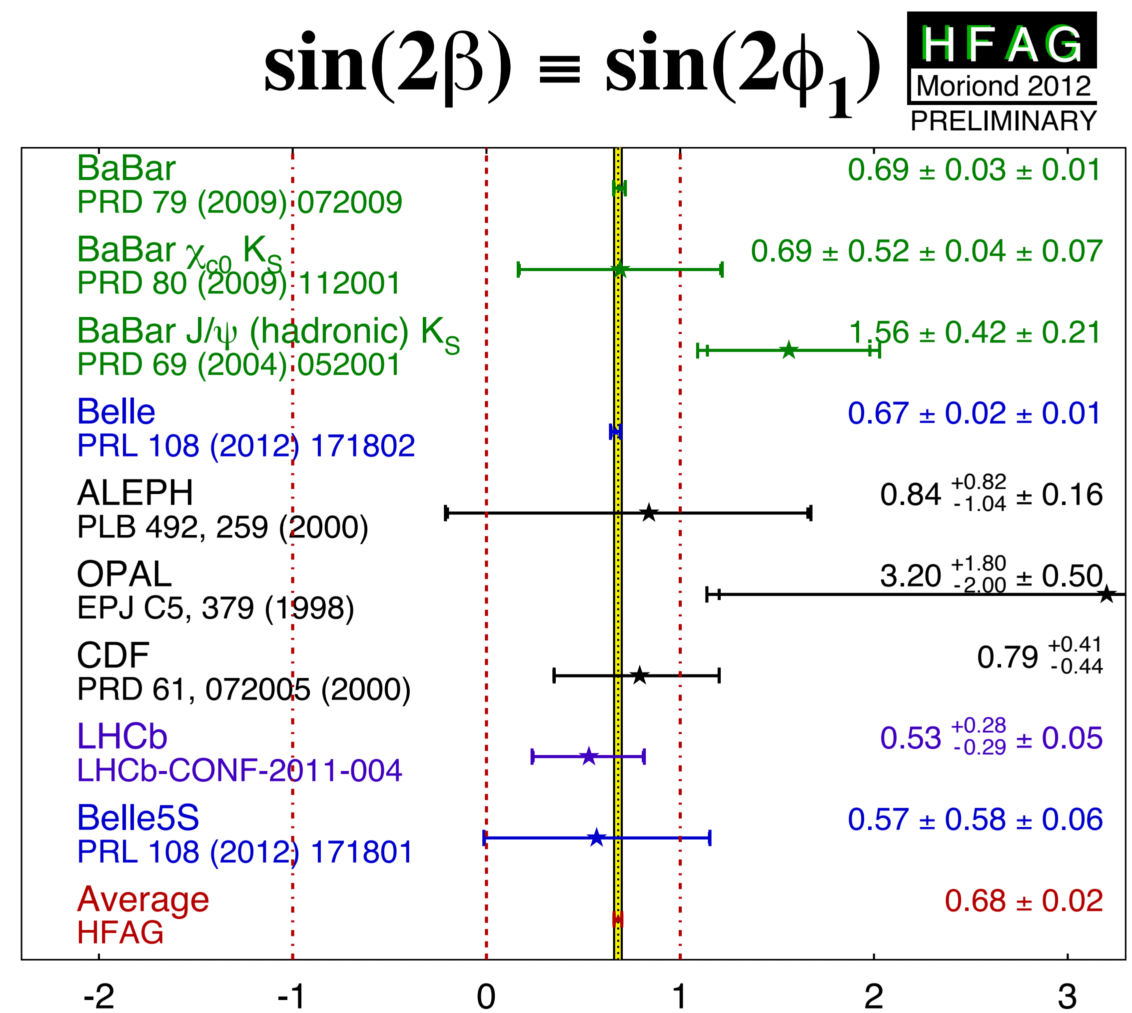
$$\sin 2\beta = 0.667 \pm 0.023 \pm 0.012$$

  - single best measurement in $B^0 \to J/\psi\, K_S$ by Belle

$$\sin 2\phi_1 = 0.670 \pm 0.029 \pm 0.013$$

  - best published measurement at hadronic colliders by CDF

$$\sin 2\beta = 0.79^{+0.41}_{-0.44}\ (\text{stat+syst})$$



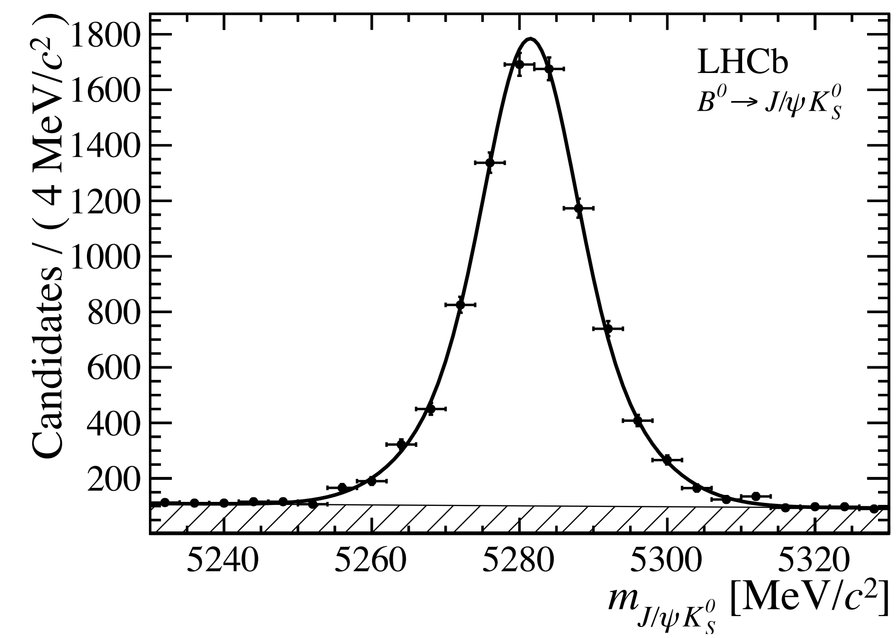
Measurement of sin2β

LHCb-PAPER-2012-035

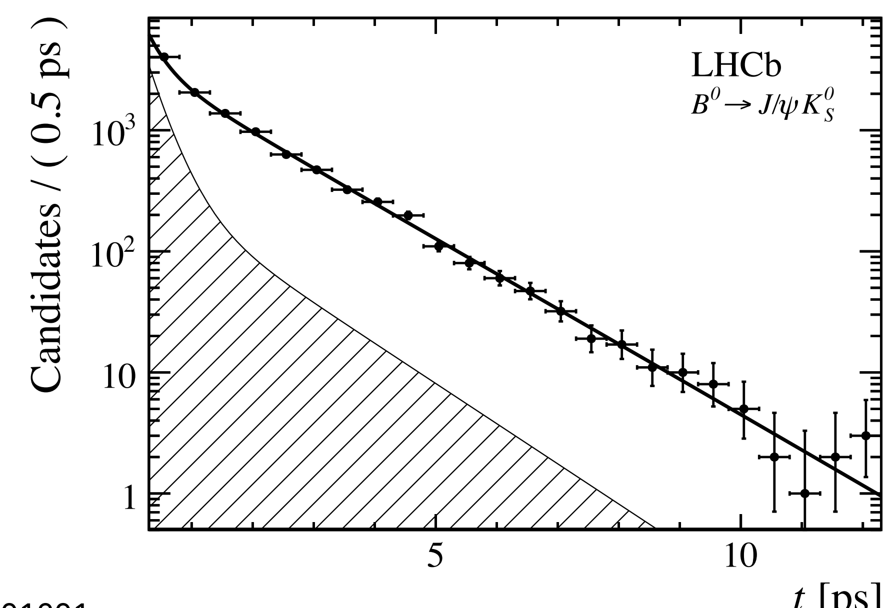
- Time-dependent CP asymmetry

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

$S = \sqrt{1 - C^2} \sin 2\beta$ $\qquad$ $C \approx 0$



- Analysis
  - ~8000 tagged $B^0 \to J/\psi K_S$ decays
    - with $J/\psi \to \mu^+\mu^-$ and $K_S \to \pi^+\pi^-$
    - K_S have non-negligible flight distance, i.e. >70% decay outside the VELO
  - use OST only
    - per-event mistag probability
    - calibration from $B^+ \to J/\psi K^+$
  - need to account for production asymmetry



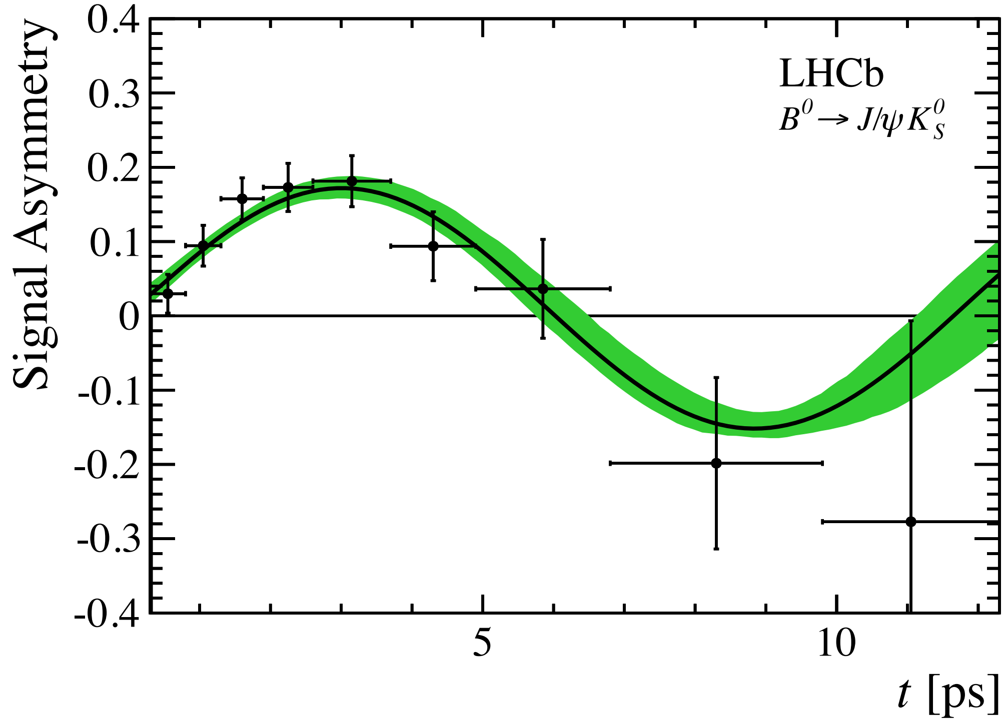
$$\mu = \frac{R_{\overline{B}^0} - R_{B^0}}{R_{\overline{B}^0} + R_{B^0}} = (-1.5 \pm 1.3)\%$$

Phys. Rev. Lett. 108 (2012) 201601
LHCb-CONF-2012-007

Measurement of sin2β

LHCb-PAPER-2012-035

- Result
  - $$S_{J/\psi K^0_S} = 0.73 \pm 0.07\,(\text{stat}) \pm 0.04\,(\text{syst}),$$
    $$C_{J/\psi K^0_S} = 0.030 \pm {}^{0.089}_{0.091}\,(\text{stat}) \pm 0.012\,(\text{syst}),$$
    $$\rho(S_{J/\psi K^0_S}, C_{J/\psi K^0_S}) = 0.416$$



  - best measurement at hadronic colliders
  - in good agreement with former measurements at the B factories
- largest syst. uncertainty from tagging calibration

Conclusion

Conclusion

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- LHCb features
  - clean signals
  - excellent decay time resolution
  - flavour tagging understood and under control

Eur. Phys. J. C 72 (2012) 2022
LHCb-CONF-2012-026

- Best measurements of oscillation parameters

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

Phys. Lett. B 709 (2012)
LHCb-CONF-2012-050

$$\Delta m_d^{\text{LHCb}} = 0.516 \pm 0.005(\text{stat.}) \pm 0.003(\text{syst.})\ \text{ps}^{-1}$$

LHCb-PAPER-2012-032

- first precision measurement of time-dependent CPV in $B^0 \to J/\psi\, K_S$ at hadronic colliders

$$S_{J/\psi K^0_S} = 0.73 \pm 0.07\,(\text{stat}) \pm 0.04\,(\text{syst}),$$

$$C_{J/\psi K^0_S} = 0.030 \pm {}^{0.089}_{0.091}\,(\text{stat}) \pm 0.012\,(\text{syst}),$$

LHCb-PAPER-2012-035

- More time-dependent precision measurements on their way...
  - Gerhard Raven "Measurement of mixing and the CPV phase ϕ_s in the B_s system at LHCb"
  - Zhou Xing "Measurement of semileptonic asymmetries at LHCb"
  - Stefano Perazzini "Measurement of time-dependent CPV in two-body decays at LHCb"
  - Steve Blusk "Measurement of γ in $B_s \to D_s K$ at LHCb"
  - Francesca Dordei "Lifetime measurements at LHCb"
  - Frederic Dupertuis "Prospect for time-dependent asymmetries at LHCb"

Backup

FT – OST performance

Tagger	$\varepsilon_{\rm tag}$ %	ω %	$\varepsilon_{\rm tag}\mathcal{D}^2$ %
μ	5.20±0.04	30.8±0.4	0.77±0.04
e	2.46±0.03	30.9±0.6	0.36±0.03
K	17.67±0.08	39.33±0.24	0.81±0.04
$Q_{\rm vtx}$	18.46±0.08	40.31±0.24	0.70±0.04
OS sum of categories	33.2±0.09	36.8±0.2	2.31±0.07
OS event-by-event	33.2±0.09	36.7±0.2	2.35±0.06

Table 1: Tagging efficiency, mistag probability and tagging power of the individual OS taggers and for their combination measured in the $B^+ \to J/\psi K^+$ control channel. The quoted uncertainties are statistical only. In the case of the single taggers the quoted results are average values. In the case of the OS combination, to better exploit the tagging information, the results are determined on independent samples obtained by splitting the data sample in bins of predicted mistag (sum of categories) or by using the predicted mistag event-by-event.

FT – OST calibration

p_0	p_1	$\langle \eta_c \rangle$	$\rho(p_0, p_1)$
0.392±0.002±0.009	1.035±0.021±0.012	0.391	0.13

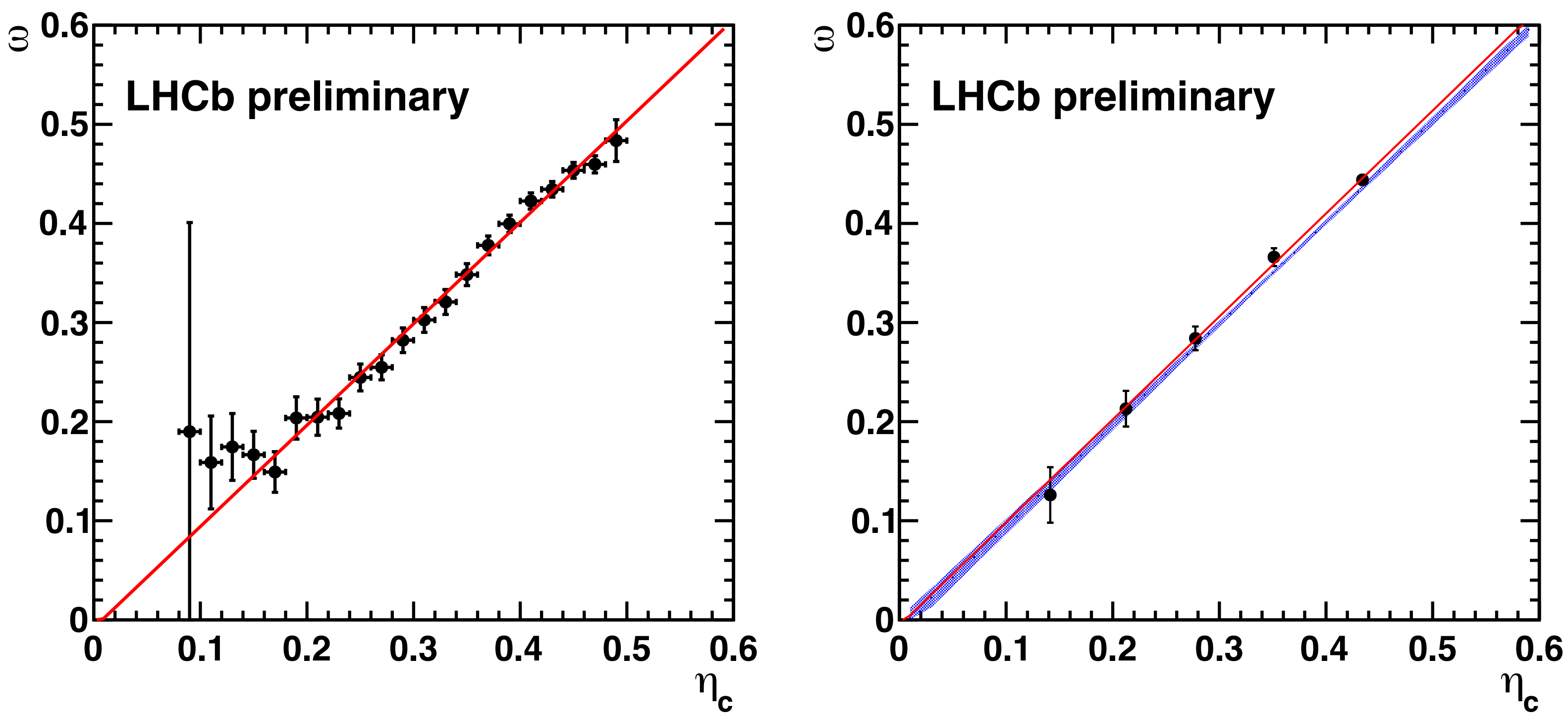

Figure 2: Measured mistag fraction (ω) versus predicted mistag probability (η_c) for background subtracted $B^+ \to J/\psi K^+$ candidates (left) and $B^0_d \to J/\psi K^{*0}$ candidates (Figure2, right). In each case, the solid (red) line represents the result of a linear fit to the presented data set. In the right plot the calibration obtained from $B^+ \to J/\psi K^+$ sample is superimposed as the shaded (blue) area, corresponding to $\pm 1\sigma$ variation of this calibration. The parameters of the fit to the $B^+ \to J/\psi K^+$ data are given in Table 2.

FT – comparison with other exp.

	experiment	$\varepsilon_{tag}\mathcal{D}^2$ %	notes
OS	LHCb	2.1±0.1	$B \to J/\psi X$ channels
		2.5±0.1	$B^0 \to D^{*-}\mu^+\nu_\mu$
		3.4±0.9	$B_{(s)} \to D_{(s)}\pi$ channels
	CDF	1.54±0.05	$B \to D\mu X$
		1.2±0.2	$B^+ \to J/\psi K^+$
	D0	2.48±0.21	$B \to D\mu X$
	B-factories	∼30	coherent $B - \bar{B}$ production
SSK	LHCb	1.3±0.4	preliminary optimization using prompt D_s
	CDF	3.5±1.4	$B_s^0 \to D_s(3)\pi$
OS&SSK	D0	4.68±0.54	for $B_s^0 \to J/\psi\phi$