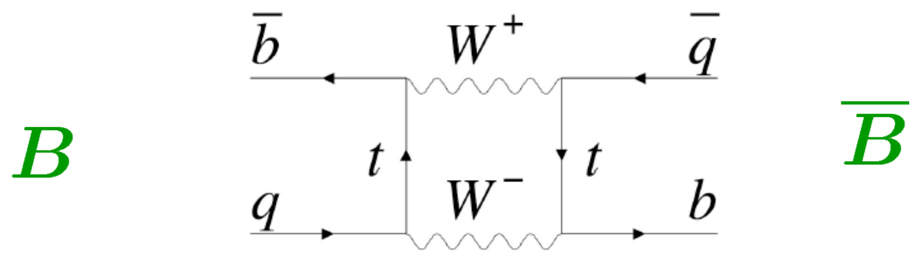
Neutral meson mixing (Beauty)

IPPP workshop on
Flavour and the 4^{th} family

Wouter Hulsbergen

Mixing formalism in a nutshell

- neutral meson mixing: matter changes spontaneously into anti-matter!
- occurs in SM via this 2nd order diagram



- mixing and decay generically described by Schrodinger-like equation

$$i\frac{\mathrm{d}}{\mathrm{d}t}\begin{pmatrix} \langle B^0|B(t)\rangle \\ \langle \bar{B}^0|B(t)\rangle \end{pmatrix} = \begin{pmatrix} M_{11}-\frac{i}{2}\Gamma_{11} & M_{12}-\frac{i}{2}\Gamma_{12} \\ M_{21}-\frac{i}{2}\Gamma_{21} & M_{22}-\frac{i}{2}\Gamma_{22} \end{pmatrix}\begin{pmatrix} \langle B^0|B(t)\rangle \\ \langle \bar{B}^0|B(t)\rangle \end{pmatrix}$$

- M and Γ are hermitian: $M_{ij} = M^*_{ji}$ $\quad \Gamma_{ij} = \Gamma^*_{ij}$
- CPT invariance: $M_{11} = M_{22}$ $\quad \Gamma_{11} = \Gamma_{22}$
- phase difference of B0 and B0-bar is arbitrary

--> 5 physical parameters: $M \quad \Gamma \quad |M_{12}| \quad |\Gamma_{12}| \quad \phi = \arg\left(-\frac{M_{12}}{\Gamma_{12}}\right)$

From parameters to observables

- time-evolution --> mass eigenstates

$$|B_L\rangle = p|B^0\rangle + q|\overline{B}^0\rangle$$
$$|B_H\rangle = p|B^0\rangle - q|\overline{B}^0\rangle$$

with eigenvalues

$$m_L + \tfrac{i}{2}\Gamma_L$$
$$m_H + \tfrac{i}{2}\Gamma_H$$

- usually characterised by observables

$$M \equiv \frac{m_H + m_L}{2} \qquad \Delta M \equiv m_H - m_L \qquad \Gamma \equiv \frac{\Gamma_H + \Gamma_L}{2} \qquad \Delta\Gamma \equiv \Gamma_L - \Gamma_H \qquad \left|\frac{q}{p}\right|$$

- that can (within reasonable approximation) be expressed as

$$\Delta M \simeq 2|M_{12}| \qquad \Delta\Gamma \simeq 2|\Gamma_{12}|\cos\phi \qquad 1 - \left|\frac{q}{p}\right|^2 \simeq \left|\frac{\Gamma_{12}}{M_{12}}\right|\sin\phi$$

mixing frequency

decay width difference

CP violation in mixing

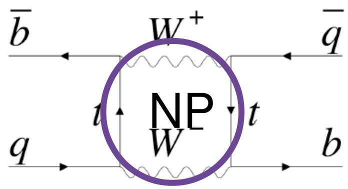
From parameters to observables

- observables sensitive to NP in mixing

$$\Delta M \simeq 2|M_{12}| \qquad \Delta\Gamma \simeq 2|\Gamma_{12}|\cos\phi \qquad 1-\left|\frac{q}{p}\right|^2 \simeq \left|\frac{\Gamma_{12}}{M_{12}}\right|\sin\phi$$

mixing frequency — decay width difference — CP violation in mixing

- in the SM, the phase ϕ is small both in Bd and in Bs
- NP models usually only consider contributions to M_{12}

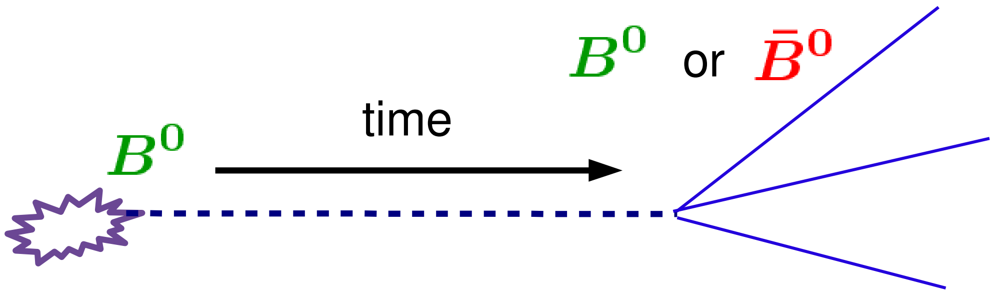


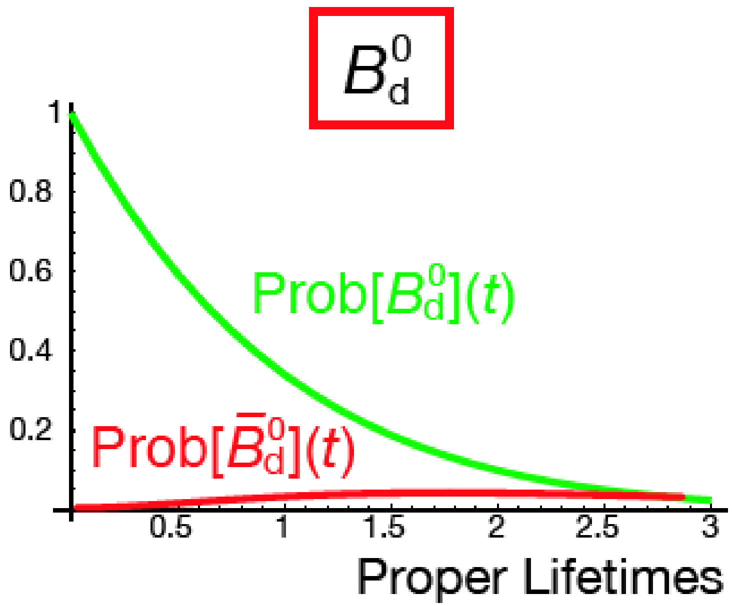
$$M_{12} = M_{12}^{\mathrm{SM}}\, r^{\mathrm{NP}} e^{i\phi^{\mathrm{NP}}} \qquad \phi = \phi^{\mathrm{SM}} + \phi^{\mathrm{NP}}$$

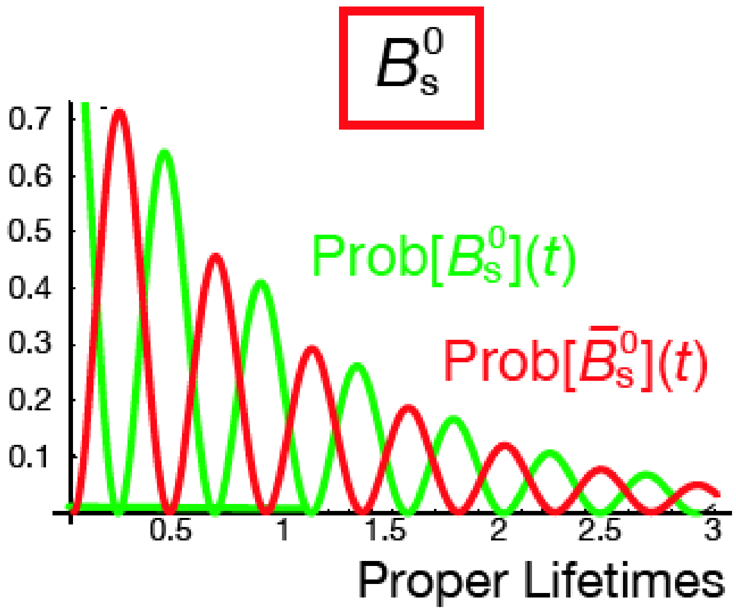
constrained by mixing frequency — constrained by CPV and $\Delta\Gamma$

Experimental observables: mixing frequency

- decay time allows to observe time-evolution

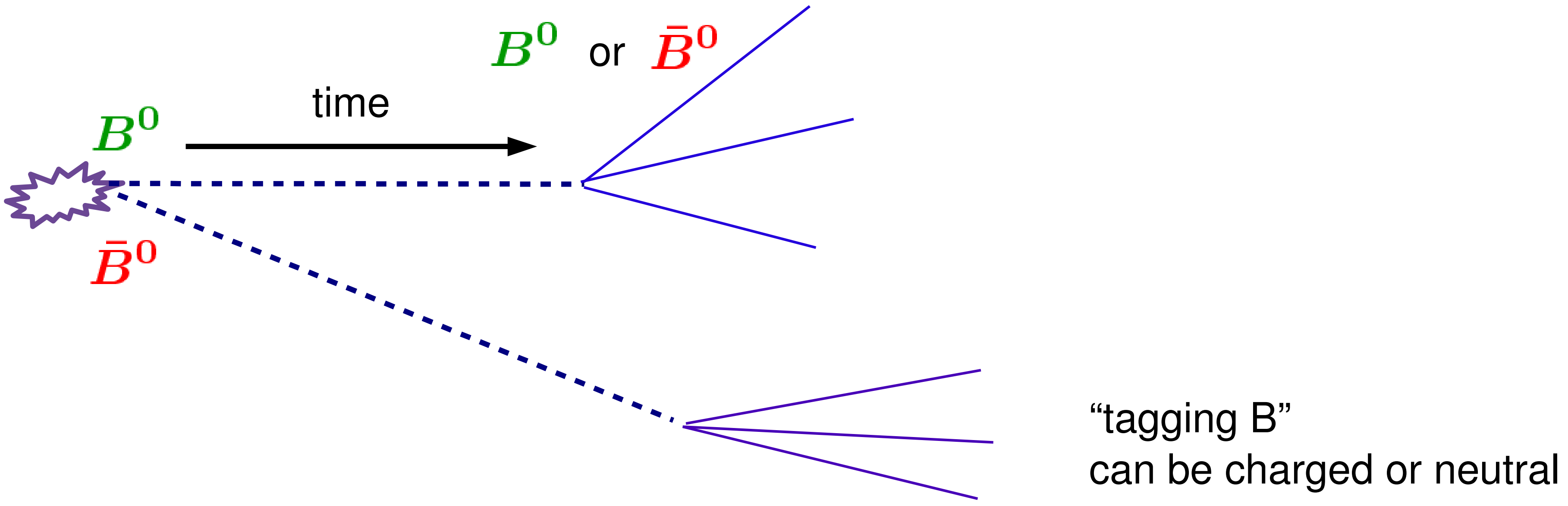




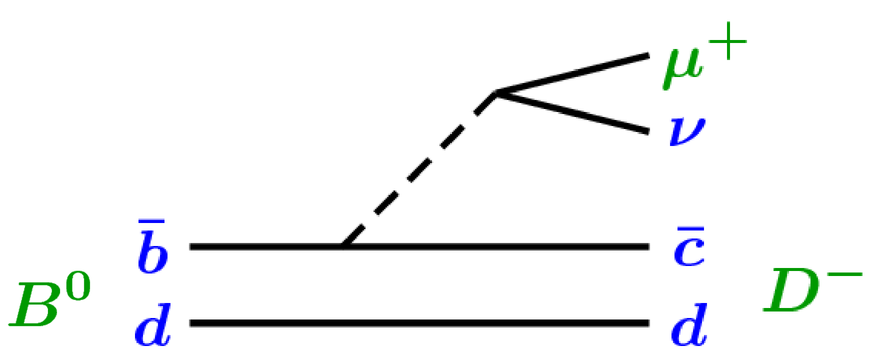


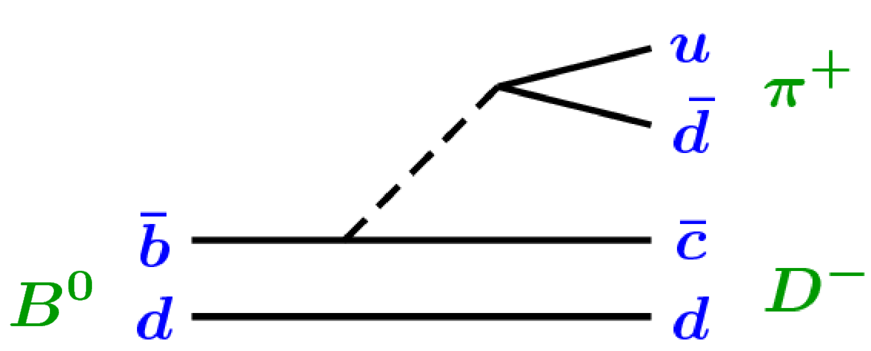
Experimental observables: mixing frequency

- decay time allows to observe time-evolution



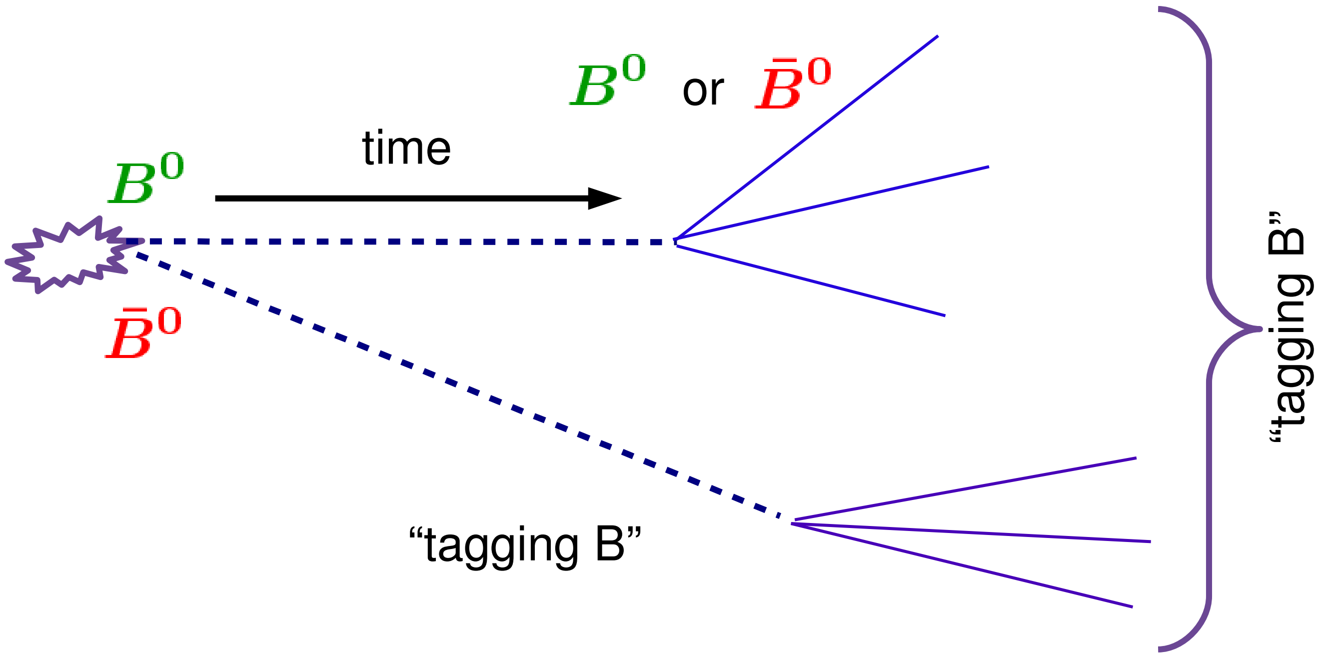
- look at "flavour specific" decays, e.g.





Experimental observables: mixing frequency

- decay time allows to observe time-evolution



	B^0	$\overline{B}^0$
B^0	mixed	unmixed
$\overline{B}^0$	unmixed	mixed

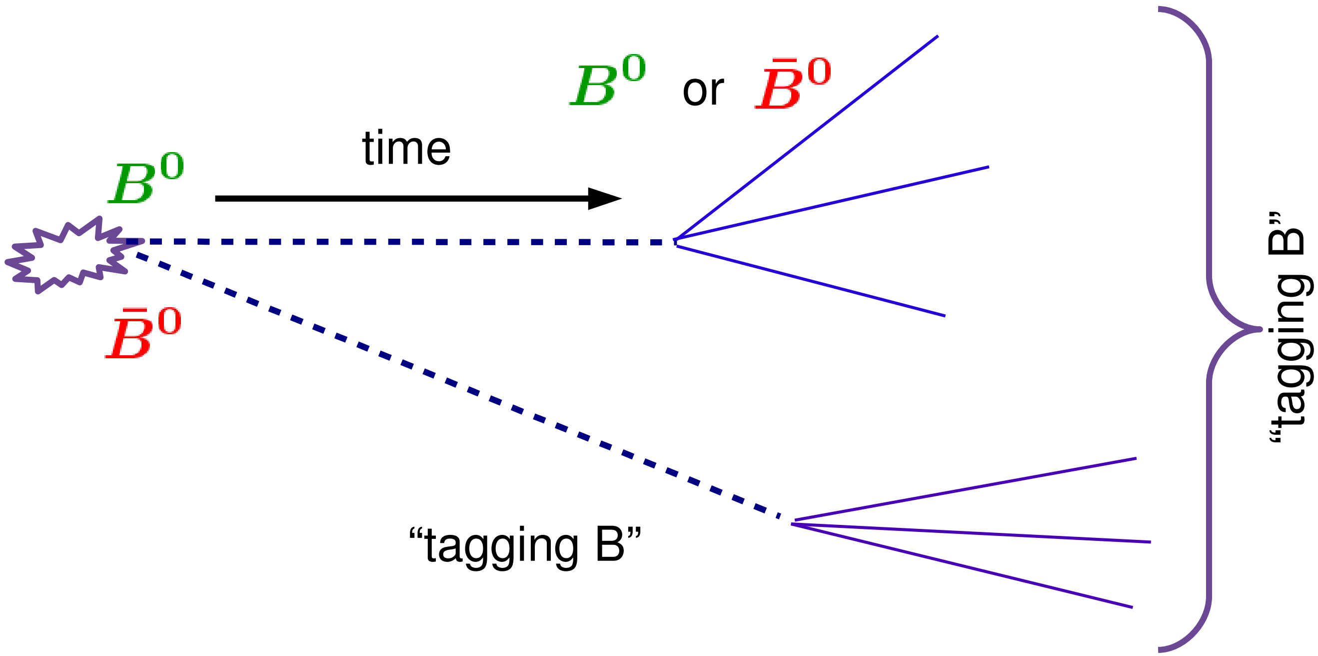
- mixing frequency: count 'mixed' versus 'unmixed'

$$A^{\mathrm{mix}}(t) = \frac{N^{\mathrm{unmixed}} - N^{\mathrm{mixed}}}{N^{\mathrm{unmixed}} + N^{\mathrm{mixed}}} = \cos \Delta M t$$

- measurement requires flavour tagging and decay time measurement

Experimental observables: A_{SL}

- decay time allows to observe time-evolution



"signal B"

	μ^+	μ^-
μ^+	mixed	unmixed
μ^-	unmixed	mixed

- from same observables, create CP asymmetry

$$a_{fs} \equiv \frac{N^{++} - N^{-}}{N^{++} + N^{-}} = \frac{1 - |q/p|^4}{1 + |q/p|^4}$$

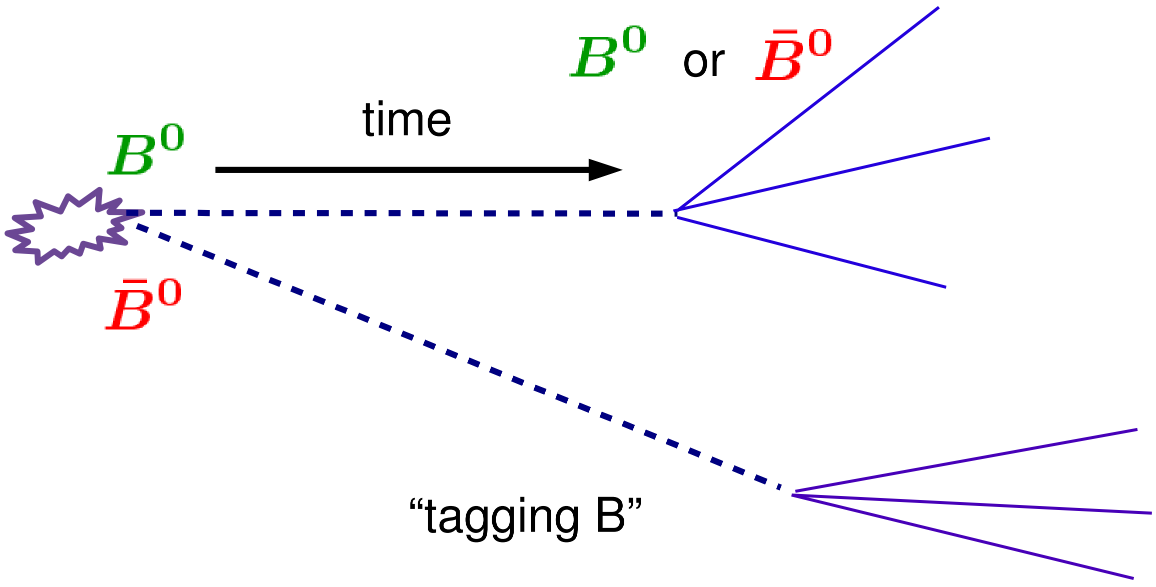
decay time independent

  - to probe CPV in mixing, use final state with zero predicted CPV in decay
  - sometimes also called "semi-leptonic" asymmetry

- measurement requires very precise knowledge of detection asymmetries

Experimental observables: TD CPV

- now consider “non-flavour specific decays”



$$B^0 \to f$$

$$\overline{B}^0 \to f$$

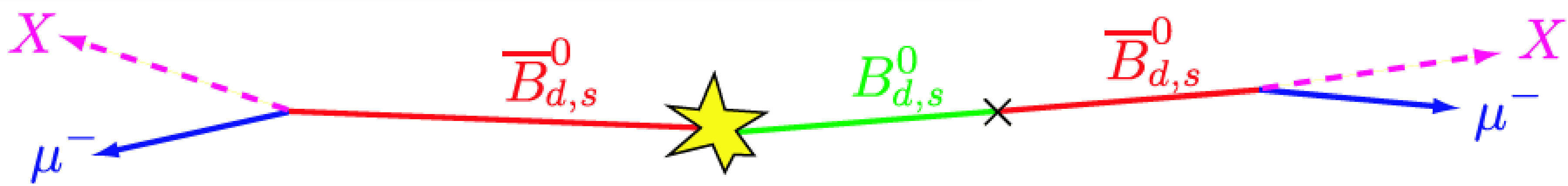
- interference between mixing and decay: “time-dependent CP violation”

$$A_{CP}(t) \equiv \frac{N(\overline{B} \to f) - N(B \to f)}{N(\overline{B} \to f) + N(B \to f)} = S \sin(\Delta m_q t)$$

- gives access to phase of mixing diagram
- measurement requires not only tagging and decay time, but also knowledge of their respective *dilutions*

Di-muon charge asymmetry

- mixing leads to 'wrong charge' combinations in B->X mu



- measure CPV in mixing via wrong charge asymmetry

$$A^b_{\rm fs} \equiv \frac{N_b(\mu^+\mu^+) - N_b(\mu^-\mu^-)}{N_b(\mu^+\mu^+) + N_b(\mu^-\mu^-)}$$

- at hadron collider: method does not distinguish between Bd and Bs

 --> measure linear combination

$$A^b_{\rm fs} = C\, a^d_{\rm fs} + (1-C)\, a^s_{\rm fs}$$

function of fragmentation fractions, mixing parameters, lifetimes and decay time acceptance

with physics in

$$a^q_{\rm fs} = \frac{\Delta\Gamma_q}{\Delta M_q} \tan\phi_q$$

CPV parameter

- with value of C at Tevatron: $A^b_{sl}(SM) = (-0.023^{+0.005}_{-0.006})\%$

Di-muon charge asymmetry at D0

- experimentally very challenging
  - asymmetries in muon detection efficiency
  - asymmetries in backgrounds (e.g. muons from Kaon decay)

} need to be controlled to better than 0.001!

- main player: **D0** at Tevatron
  - low detection asymmetry due frequent field polarity changes
  - control of background asymmetries using single muon asymmetry

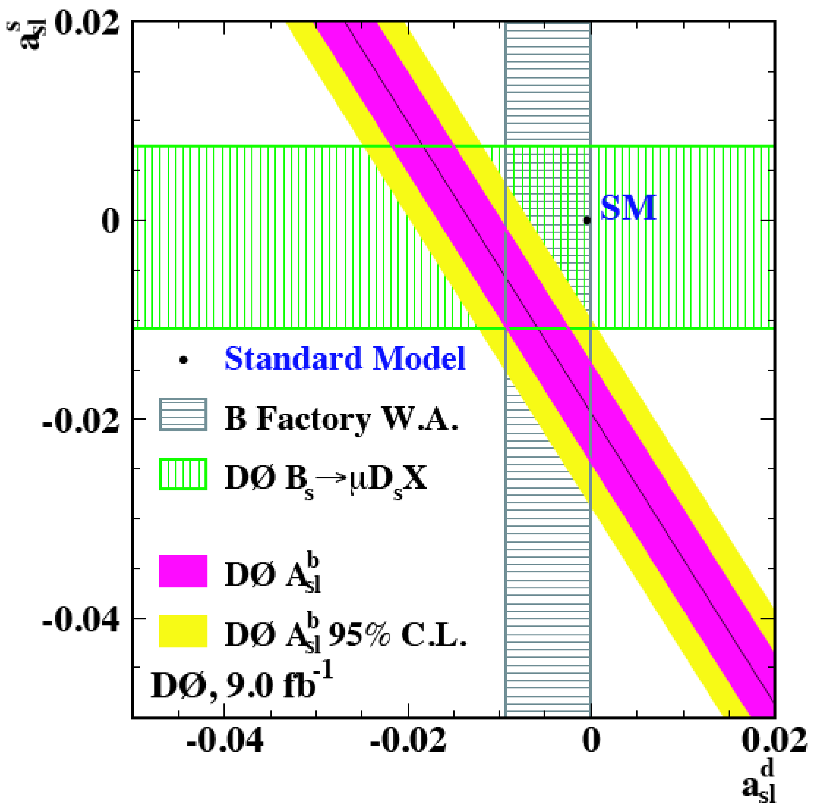
- recent D0 update, arXiv:1106.6308, subm. to PRD:

$$A^b_{sl} = (-0.787 \pm 0.172 \pm 0.093)\%$$

3.9σ deviation from SM

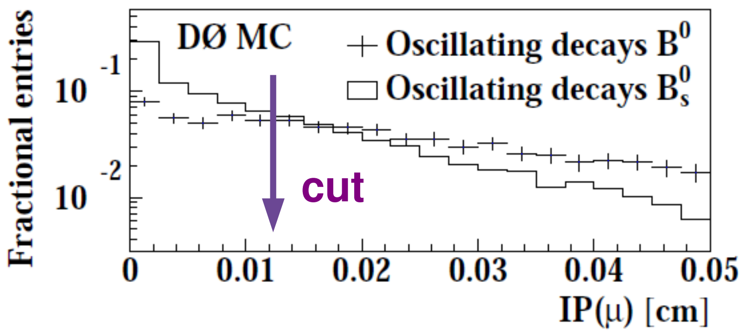
- consistent with other measurements ... but single one of its kind

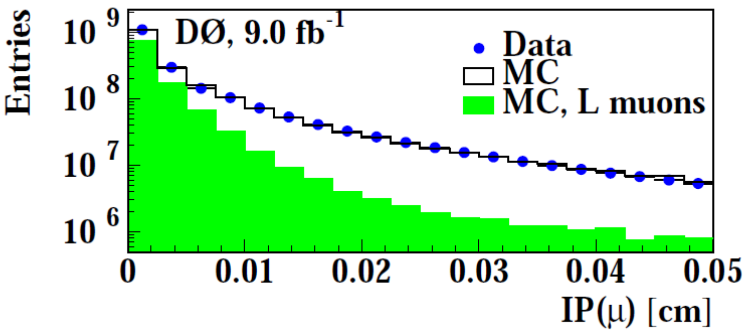
- burning question: is it B_d or B_s?



Di-muon charge asymmetry at D0

- to probe origin, split sample by IP cut to change fraction of Bd

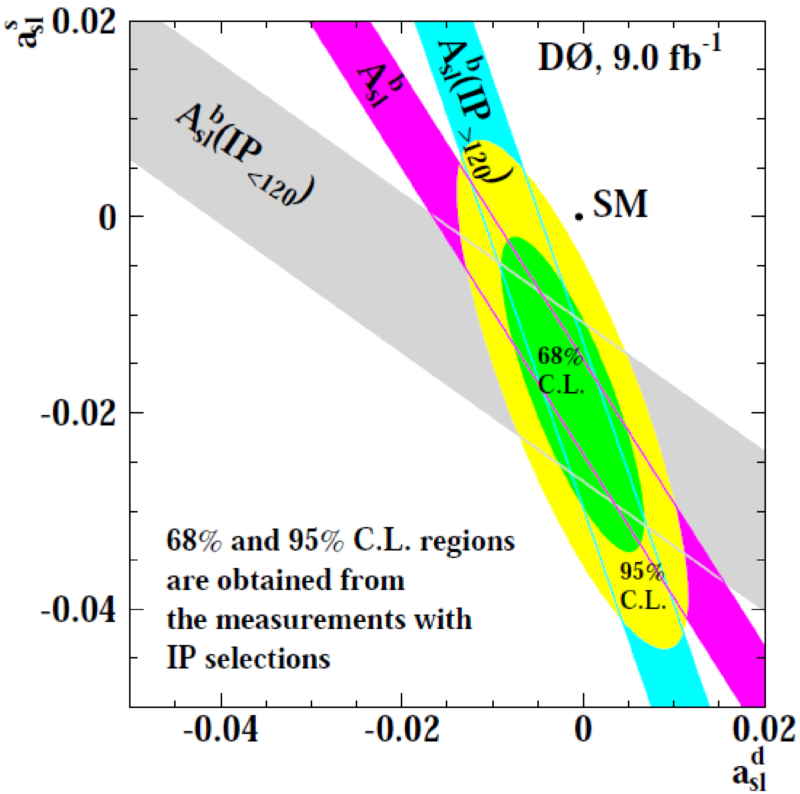




- IP>120 (both muons)
  - less background
  - higher Bd fraction
- result consistent with main result
- extract

$$a^d_{sl} = (-0.12 \pm 0.52)\%$$
$$a^s_{sl} = (-1.81 \pm 1.06)\%$$

with large correlation $\rho_{ds} = -0.799$



- uncertainties too large to be conclusive ...

LHCb plans for a_{fs}

- additional experimental challenge: production asymmetry (no problem for Bs)
- studies concentrate on B -> D l nu, with fully reconstructed D
  - less background than inclusive muons
  - can distinguish Bs from Bd
  - reasonable decay time resolution --> can do time-dependent measurement
- but ... exclusive reconstruction has a price
  - to regain statistics, perform untagged measurements
  - untagged rate related to flavour-specific asymmetry by

$$a_{\mathrm{fs,unt}}(t) = \frac{a_{\mathrm{fs}}}{2}\left(1 - \frac{\cos(\Delta M\, t)}{\cosh(\Delta\Gamma\, t/2)}\right)$$

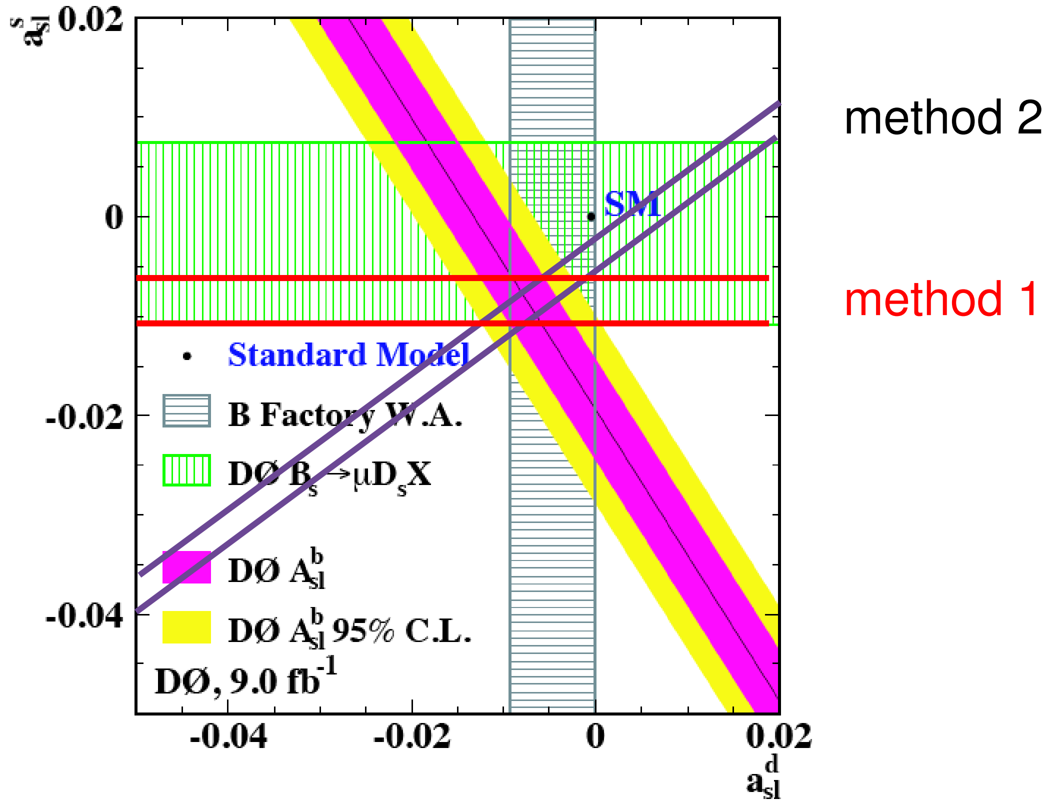
note: in contrast to a_{fs}, not constant in time

LHCb plans for a_{fs}

- two strategies to tackle production/detection asymmetries
  - **1.** take only Bs, measure detection asymmetry in control samples
  - **2.** measure the (time-dependent) difference

$$\Delta A = A(B_s \to D_s(KK\pi)\mu X) - A(B_d \to D(KK\pi)\mu^- X)$$

- a <u>sketch</u> of what this means



- actual attainable uncertainties still very unclear

Oscillations in the Bs system

- oscillation frequency places strong constraints on new physics
  - SM prediction: $\Delta m_s^{\mathrm{SM}} = 16.8^{+2.6}_{-1.5}\ \mathrm{ps}^{-1}$ PRD.83, 036004 (211)

- method: time-dependence of mixing asymmetry for a flavour-specific final state

$$A^{\mathrm{mix}} = \frac{N^{\mathrm{unmixed}}(t) - N^{\mathrm{mixed}}(t)}{N^{\mathrm{unmixed}}(t) + N^{\mathrm{mixed}}(t)} = \cos(\Delta m t)$$

ignoring $\Delta\Gamma$

- experimental requirements
  - flavour tag at 'production'
  - reconstruction of decay time

$$A^{\mathrm{mix}} = (1-2w) \times e^{-\Delta m^2 \sigma_t^2/2} \times \cos(\Delta m t)$$

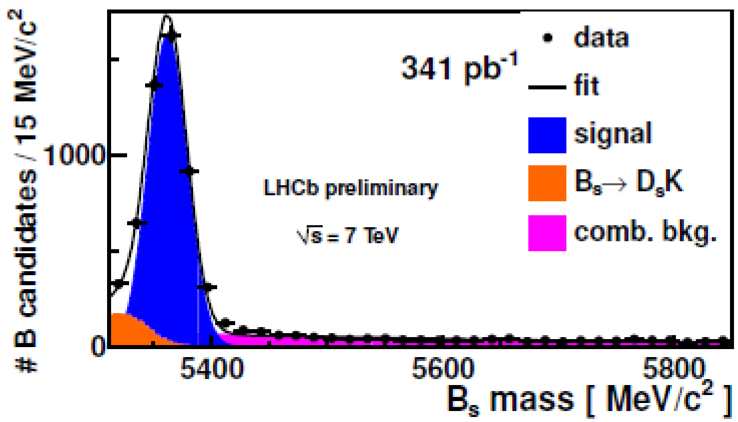
finite decay time resolution

probability for wrong flavor tag

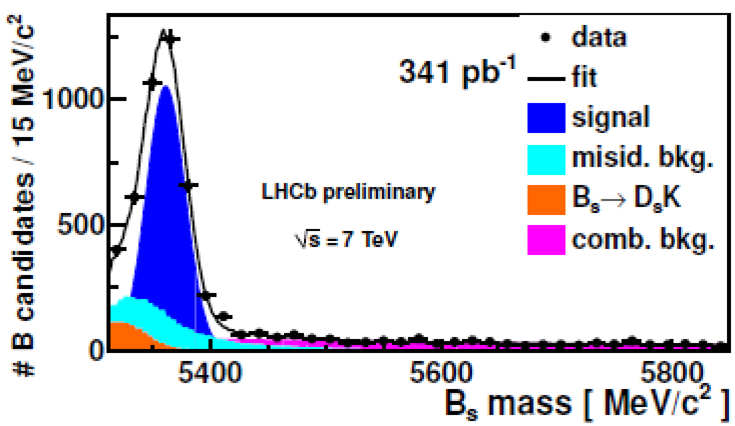
- optimal time resolution requires fully reconstructed final state
  - most easily accessible: $B_s \rightarrow D_s^- \pi^+$

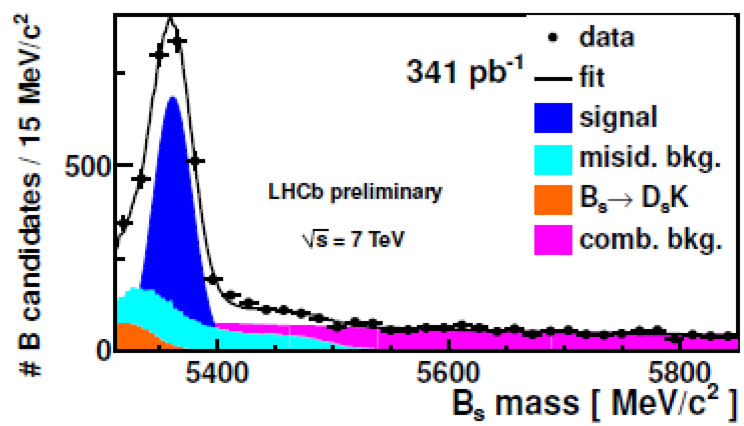
Bs mixing: latest measurement

- LHCb update in 341/pb, presented at Lepton-Photon 2011



decay mode	# signal candidates
$B_s^0 \to D_s^-(\phi\pi^-)\pi^+$	4371 ± 91
$B_s^0 \to D_s^-(K^*K^-)\pi^+$	2910 ± 89
$B_s^0 \to D_s^-\pi^+$ non-resonant	1908 ± 74





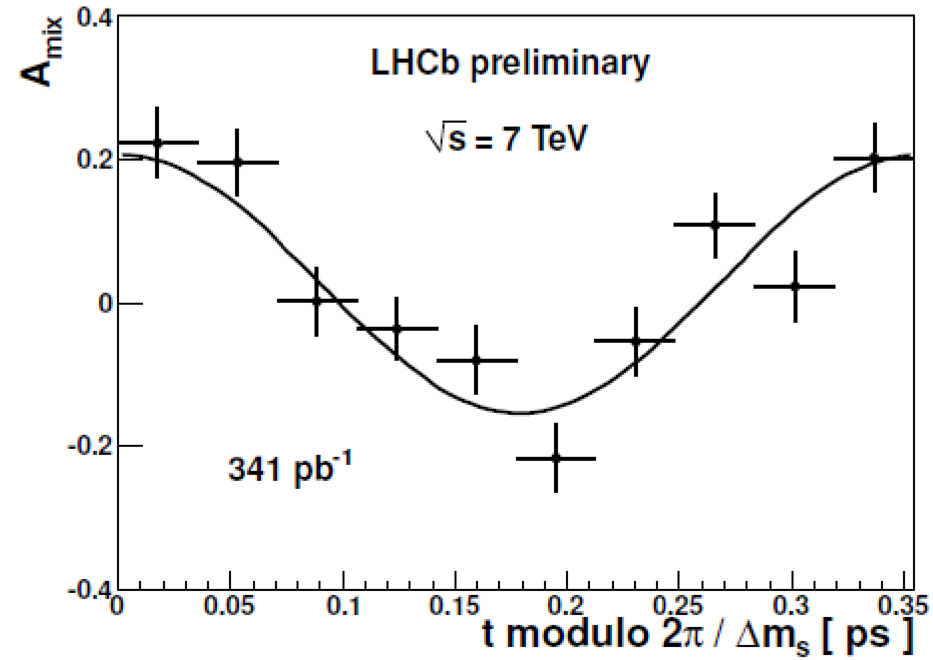
- average time resolution: ~44 fs
- flavour tagger performance:
  - OST: $\epsilon(1-2w)^2 = (3.2 \pm 0.8)\ \%$
  - SST: $\epsilon(1-2w)^2 = (1.3 \pm 0.4)\ \%$

} reduction in signal efficiency due to loss/dilution from tagging

Bs mixing: latest measurement

- LHCb, preliminary result, 341/pb (LHCb-CONF-2011-050)

$$\Delta m_s = 17.725 \pm 0.041 \pm 0.026 \ \mathrm{ps}^{-1}$$



- dominant systematics
  - z-scale and momentum scale
  - no 'easy' improvements expected

- compare older results

CDF (2006)	$\Delta m_s = 17.77 \pm 0.10 \pm 0.07 \ \mathrm{ps}^{-1}$	(PRL97,242003 (2006)))
LHCb, 37/pb:	$\Delta m_s = 17.63 \pm 0.11 \pm 0.03 \ \mathrm{ps}^{-1}$	(LHCb-CONF-2011-005)

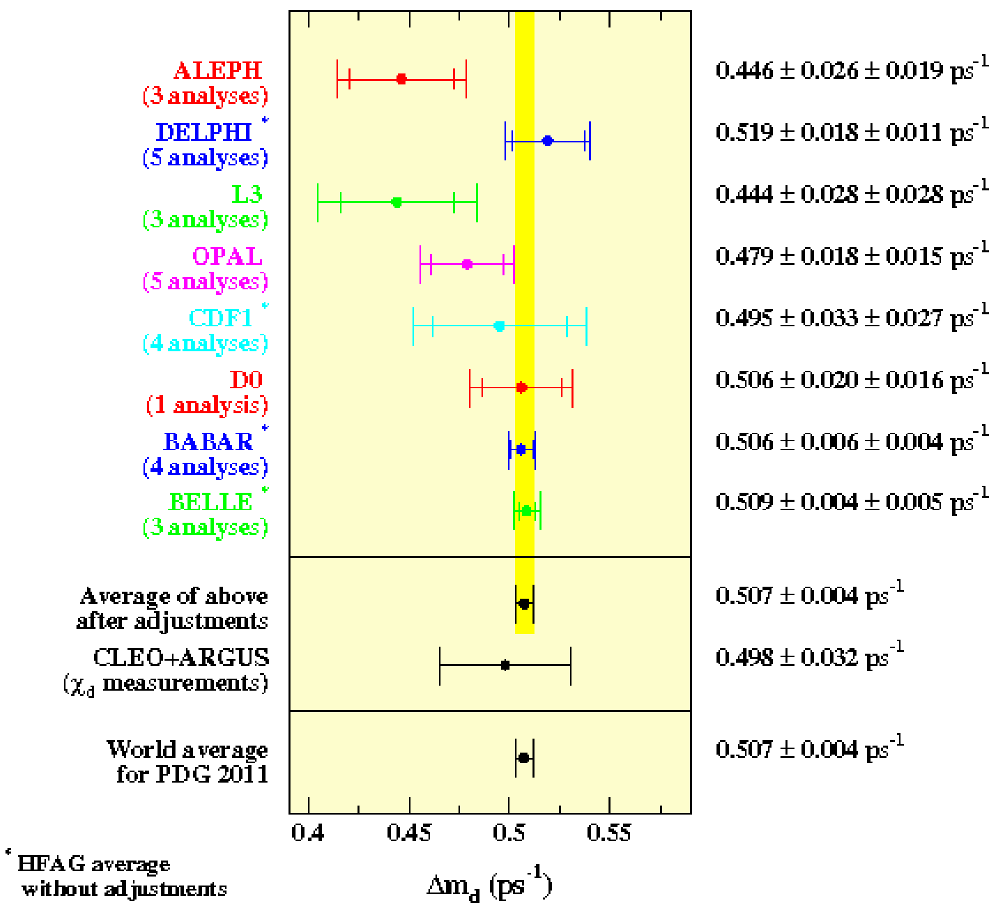
- new WA: $\Delta m_s^{\mathrm{WA}} = 17.731 \pm 0.045 \ \mathrm{ps}^{-1}$

⇒ $$\left|\frac{V_{td}}{V_{ts}}\right| = 0.2090 \pm 0.0009 \pm 0.0046$$
exper. lattice

(R. van Kooten, LP2011)

Oscillations in the Bd system

- experimental precision is currently about 0.1%
- LHCb: unlike in B-s system, measurement is sensitive to decay time acceptance



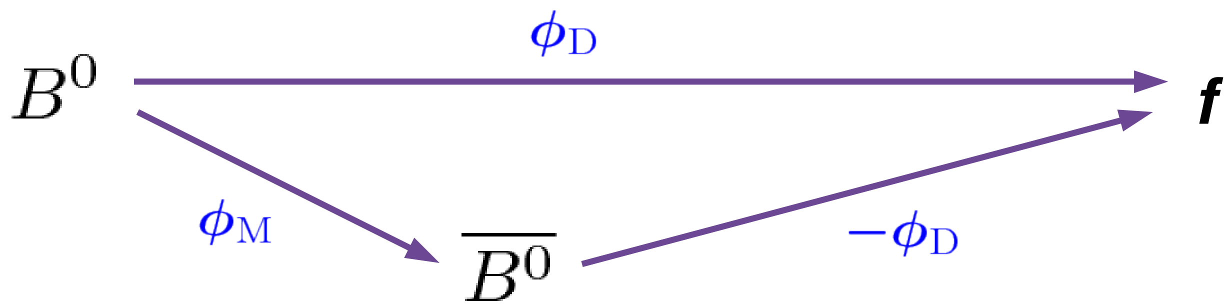
- LHCb preliminary result, using Bd->Dpi in 37/pb

$$\Delta M_d = 0.499 \pm 0.032 \pm 0.003$$ (LHCb-CONF-2011-010, prelim.)

  - first priority is to get much more stats; systematics can probably be reduced too
  - Bd->D*μν gives much higher yields, but systematics not clear yet

CPV in mixing via time-dependent CPV

- mixing induced CPV due to interference in decays to common final state



- if ***f*** is *CP eigenstate*, time dependent CP violation with pattern

$$A_{CP}(t) \equiv \frac{N(\overline{B} \to f) - N(B \to f)}{N(\overline{B} \to f) + N(B \to f)} = S \,\sin(\Delta m_q t)$$

flavor at production

$$S = \sin(\phi_M - 2\phi_D)$$

- b->ccs transitions: decay dominated by TREE amplitude

  ==> expect no NP in ϕ_D ==> CPV probes mixing phase ϕ_M

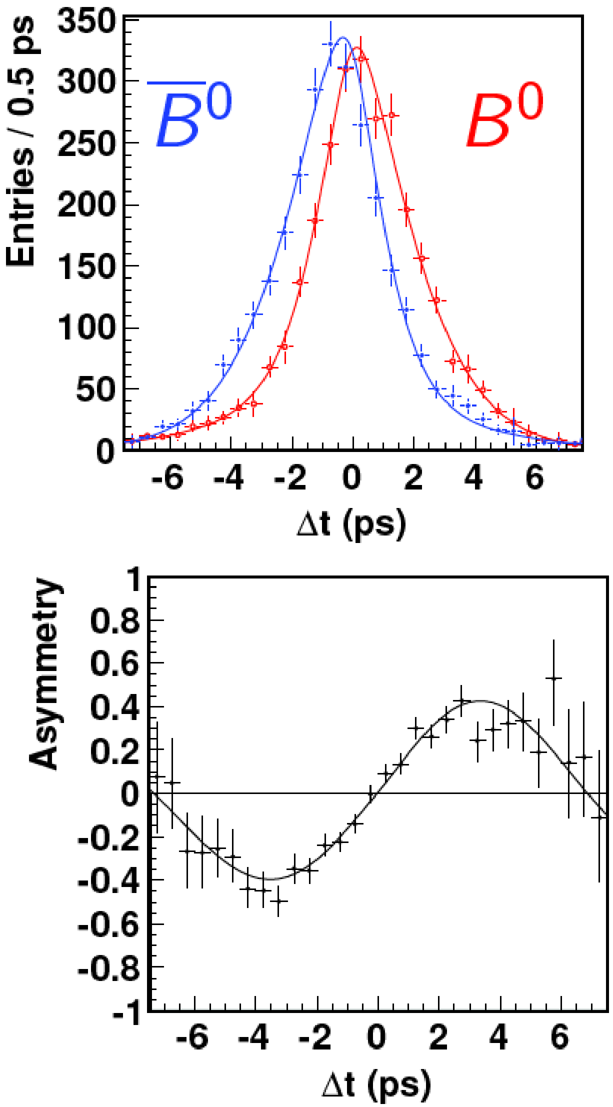
- 'golden' modes:

$$B_d \to \psi K_s : \quad S = \sin 2\beta$$
$$B_s \to \psi\phi : \quad S = \sin 2\beta_s$$

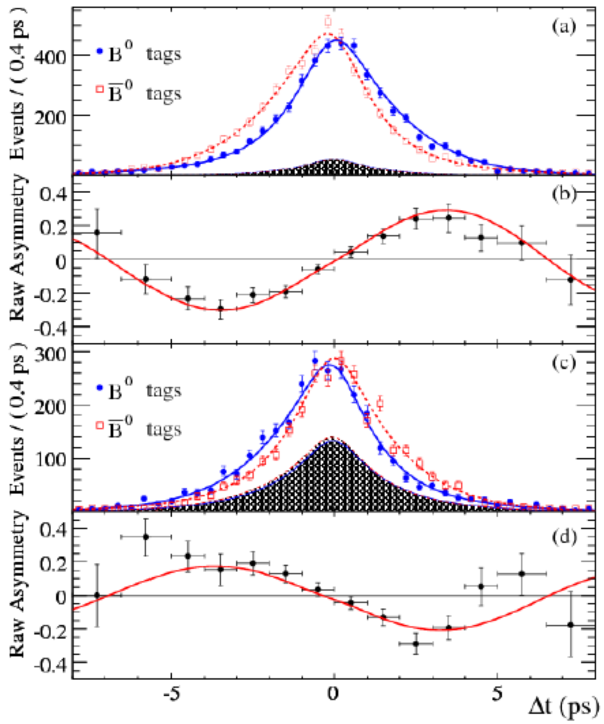
sin2β from J/ΨK$_s$, J/ΨK$_L$ (etc)

- final Belle/Babar datasets

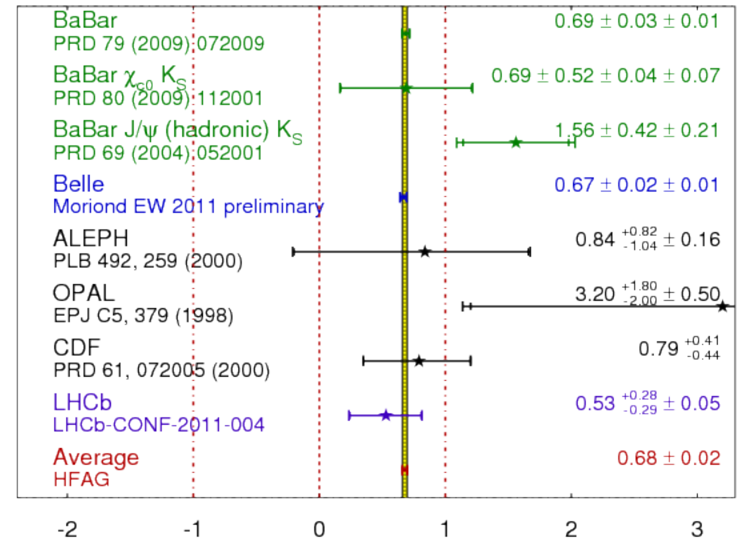
Belle, Moriond 2011



Babar, PRD 79 (2009) 072009



$\sin(2\beta) \equiv \sin(2\phi_1)$ HFAG Beauty 2011 PRELIMINARY



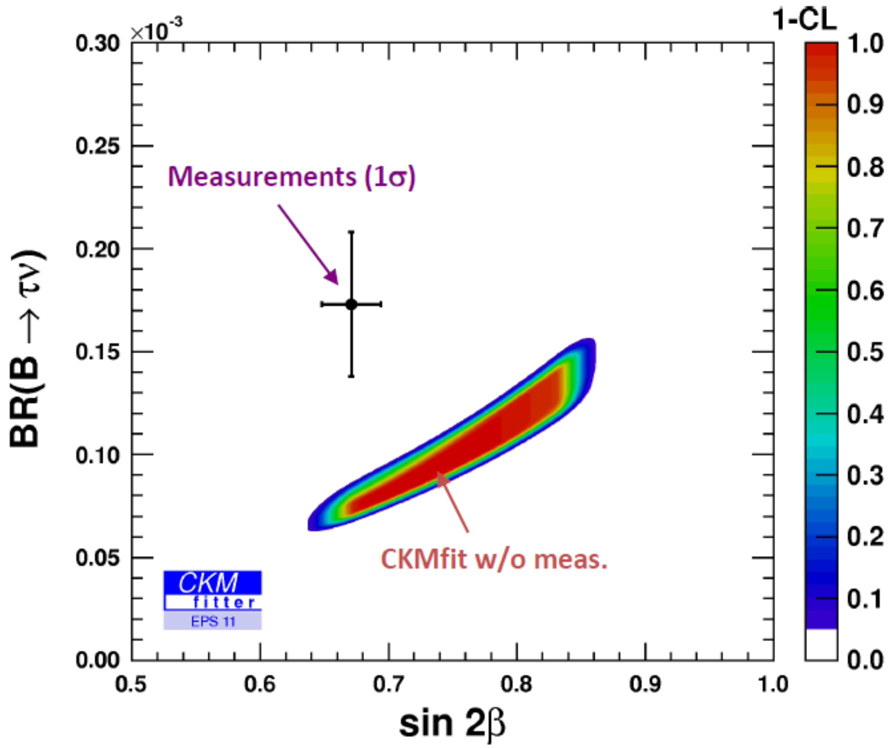
HFAG average: $\Phi_{\psi K}^{\mathrm{HFAG}} = (42.8 \pm 1.5)^\circ$

has some tension with results from global SM fits

$2\beta^{\mathrm{SM,UTFit}} = (50.4 \pm 3.2)^\circ$ (summer 2010)

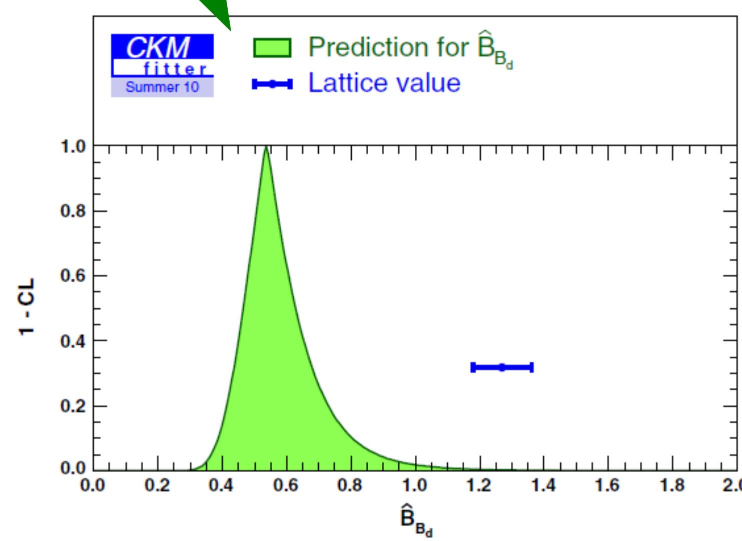
$2\beta^{\mathrm{SM,CKMFitter}} = (56.3^{+1.4}_{-3.3})^\circ$ (PRD83,036004)

- one part of the problem: correlation with the measurement of B->tau nu in the fits



Lenz, Nierste, CKMFitter
PRD83, 036004 (2011))

$$\frac{\mathcal{B}(B \to \tau\nu)}{\Delta m_d} = \frac{3\pi}{4} \frac{m_\tau^2}{m_W^2 S(x_t)} \left(1 - \frac{m_\tau^2}{m_{B^+}^2}\right)^2 \tau_{B^+} \times \frac{1}{\hat{B}_{B_d} \eta_B} \frac{1}{|V_{ud}|^2} \left(\frac{\sin\beta}{\sin\gamma}\right)^2.$$



- suppressed contributions may 'pollute' expected CPV

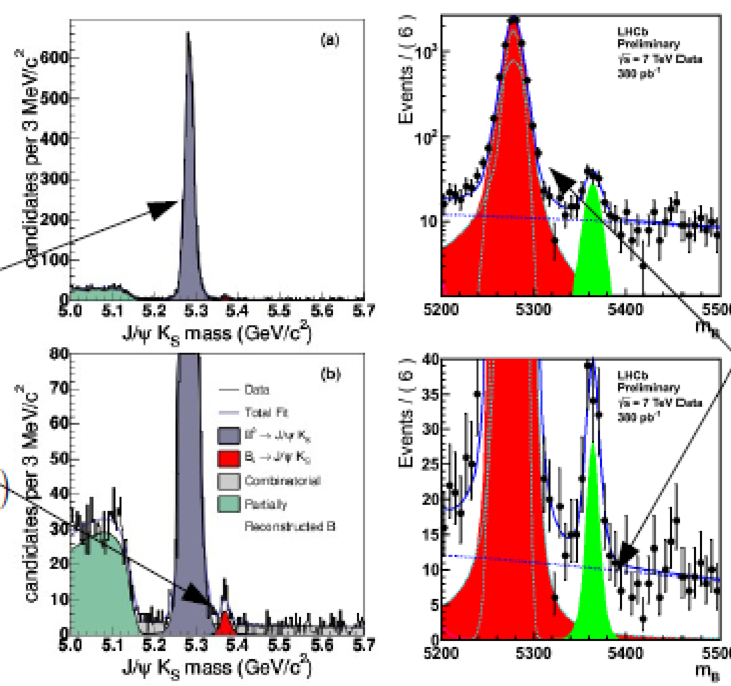
$$S_{\Psi K} = \sin(2\beta + \delta^{\text{SM penguins}} + \phi_d^{\text{NP}})$$

[need picture plus result of U-spin symmetry]

- can estimate contributions with BF of suppressed modes related by symmetry
  - Bd --> J/psi pi0 and Bs --> J/psi Ks (PRD79 (2009) 014030)

CDF experiment
PRD 83 (2011) 052012

$$\frac{B(B_s^0 \to J/\psi K_S)}{B(B^0 \to J/\psi K_S)} = 0.041 \pm 0.007(stat) \pm 0.004(syst) \pm 0.005(f_s/f_d)$$



LHCb experiment
LHCb-CONF-2011-048

NEW

$$\frac{B(B_s^0 \to J/\psi K_S)}{B(B^0 \to J/\psi K_S)} = 0.0378 \pm 0.0058(stat) \pm 0.0020(syst) \pm 0.0030(f_s/f_d)$$

Tim Gershon
CKM Matrix Overview

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(question: based on this, what are estimates of 'penguin' polution?)

CPT and $\Delta\Gamma_d/\Gamma_d$

- introduce complex parameter for CPT violation (see e.g. PRD70(2004)012007)

$$\mathsf{z} = \frac{\delta m - \frac{i}{2}\delta\Gamma}{\Delta m - \frac{i}{2}\Delta\Gamma} \longrightarrow \begin{aligned} |B_L\rangle &= p\sqrt{1-\mathsf{z}}|B^0\rangle + q\sqrt{1+\mathsf{z}}|\overline{B}^0\rangle \\ |B_H\rangle &= p\sqrt{1+\mathsf{z}}|B^0\rangle - q\sqrt{1-\mathsf{z}}|\overline{B}^0\rangle \end{aligned}$$

- extract from simultaneous analysis of CP and flavour specific states
- new result, Belle EPS2011 (prelim.):

$$\mathrm{Re}(z) = (+1.9 \pm 3.7 \pm 3.2) \times 10^{-2}$$
$$\mathrm{Im}(z) = (-5.7 \pm 3.3 \pm 6.0) \times 10^{-3}$$
$$\Delta\Gamma_d/\Gamma_d = (-1.7 \pm 1.8 \pm 1.1) \times 10^{-2}$$

535 x 10^6 $B\bar{B}$ pairs

compatible with Babar
analysis on 88M/232M BBbar pairs

bonus: strongest single-experiment constraint on $\Delta\Gamma/\Gamma$
compare SM:

$$\frac{\Delta\Gamma_d}{\Gamma_d}^{\mathrm{SM}} = (5.8^{+1.1}_{-2.1}) \cdot 10^{-3}$$

(my comp. using $\Delta\Gamma$ from
SM fit in PRD83,036004 (2011)
and PDG lifetime)

time-dependent CPV in the B_s-system

- time-dependent CPV in $B_s \rightarrow J/\psi\phi$ allows to NP in mixing in Bs system

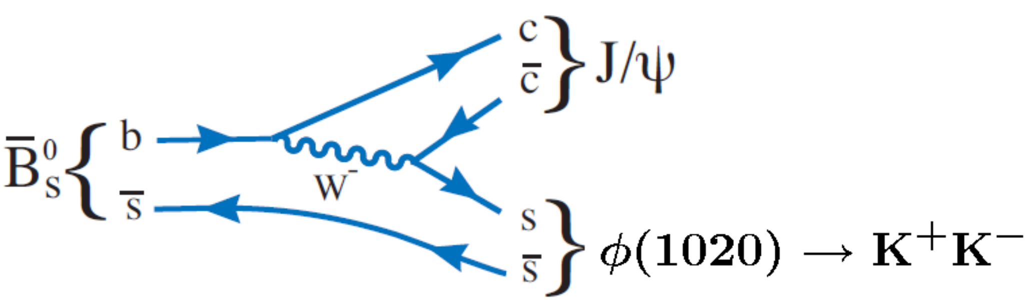
$$S_{\Psi\phi} \equiv \text{"} \sin\phi_s \text{"} = \sin(-2\beta_s^{\mathrm{SM}} + \phi_s^{\mathrm{NP}})$$

- in contrast to β, CKM-angle β_s is very small

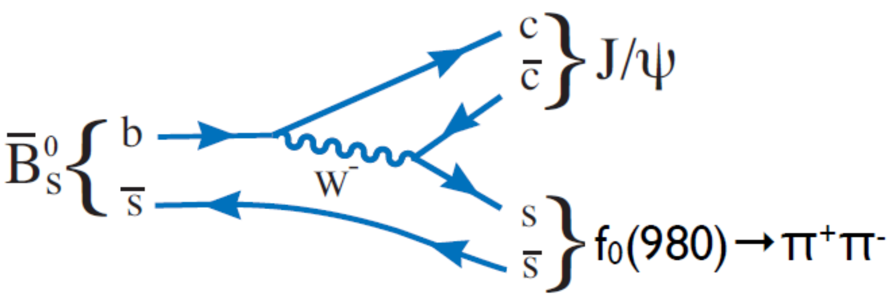
$$-2\beta_s^{\mathrm{SM}} = (-2.08 \pm 0.10)^\circ$$

(PRD83, 036004 (2011))

- two most interesting modes



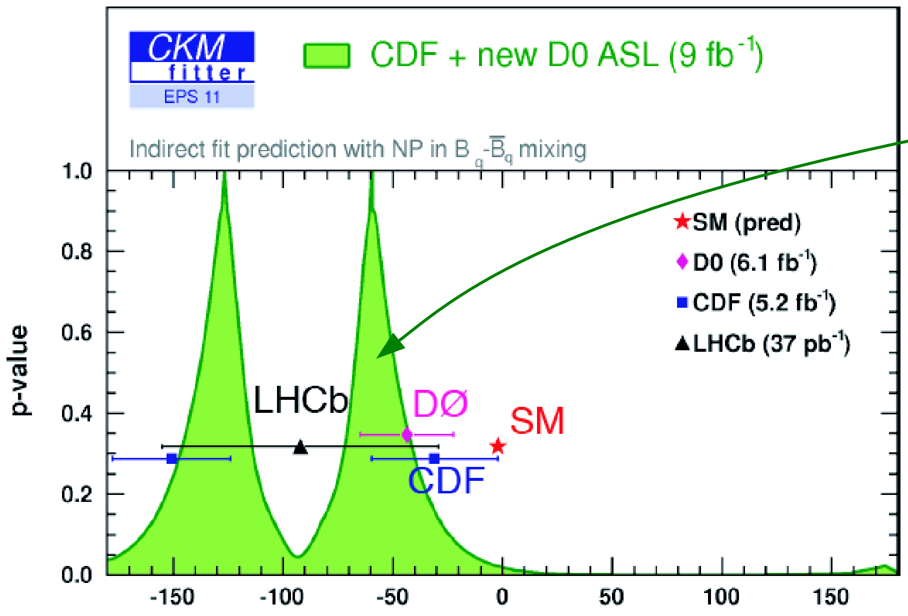
  - narrow resonance --> clean
  - vector-vector final state ("P-wave")
    - requires time-dependent angular analysis
    - measure also $\Delta\Gamma_s$ w/o external input



  - bit lower branching fraction
  - vector-pseudoscaler final state ("S-wave")
    - no angular analysis needed

β_s with $B_s \rightarrow J/\Psi\varphi$

- status quo, before LP2011
  - CDF 5.2/fb, about 6500 events, $\sigma(\varphi_s) \sim 0.5$ rad
  - D0 9/fb, about 5000 events, $\sigma(\varphi_s) \sim 0.35$ rad
  - LHCb 37/pb, about 800 events, , $\sigma(\varphi_s) \sim 0.7$ rad



CKMFitter <u>prediction</u> from fit with NP phase, using A_{sl}, but <u>not</u> φ_s

another hint of NP in Bs mixing?

- LHCb at LP2011: update with 341/pb
  - about 10x more statistics
  - important improvement: account for S-wave contribution

$B_s \to J/\psi\phi$ at LHCb

- including S-wave: from 6 to 10 terms in angular/time distributions

LHCb-CONF-2011-049

k	$h_k(t)$	$f_k(\theta,\psi,\varphi)$
1	$\|A_0\|^2(t)$	$2\cos^2\psi\,(1-\sin^2\theta\cos^2\phi)$
2	$\|A_\parallel(t)\|^2$	$\sin^2\psi\,(1-\sin^2\theta\sin^2\phi)$
3	$\|A_\perp(t)\|^2$	$\sin^2\psi\sin^2\theta$
4	$\Im(A_\parallel(t)\,A_\perp(t))$	$-\sin^2\psi\sin 2\theta\sin\phi$
5	$\Re(A_0(t)\,A_\parallel(t))$	$\frac{1}{2}\sqrt{2}\,\sin 2\psi\sin^2\theta\sin 2\phi$
6	$\Im(A_0(t)\,A_\perp(t))$	$\frac{1}{2}\sqrt{2}\,\sin 2\psi\sin 2\theta\cos\phi$
7	$\|A_s(t)\|^2$	$\frac{2}{3}(1-\sin^2\theta\cos^2\phi)$
8	$\Re(A_s^*(t)A_\parallel(t))$	$\frac{1}{3}\sqrt{6}\sin\psi\sin^2\theta\sin 2\phi$
9	$\Im(A_s^*(t)A_\perp(t))$	$\frac{1}{3}\sqrt{6}\sin\psi\sin 2\theta\cos\phi$
10	$\Re(A_s^*(t)A_0(t))$	$\frac{4}{3}\sqrt{3}\cos\psi(1-\sin^2\theta\cos^2\phi)$

The terms 7–10 are related to the description of the S-wave component, which has been added to this analysis. Expressed in terms of the size $|A_i(0)|$ and phase δ_i of the transversity and S-wave amplitudes at $t=0$, the time dependent amplitudes are given by

$$|A_0|^2(t) = |A_0|^2 e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma}{2}t\right) - \cos\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right) + \sin\phi_s\sin(\Delta m t)\right], \quad (4)$$

$$|A_\parallel(t)|^2 = |A_\parallel|^2 e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma}{2}t\right) - \cos\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right) + \sin\phi_s\sin(\Delta m t)\right], \quad (5)$$

$$|A_\perp(t)|^2 = |A_\perp|^2 e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma}{2}t\right) + \cos\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right) - \sin\phi_s\sin(\Delta m t)\right], \quad (6)$$

$$\Im(A_\parallel(t)A_\perp(t)) = |A_\parallel||A_\perp|e^{-\Gamma_s t}\left[-\cos(\delta_\perp-\delta_\parallel)\sin\phi_s\sinh\left(\frac{\Delta\Gamma}{2}t\right) - \cos(\delta_\perp-\delta_\parallel)\cos\phi_s\sin(\Delta m t) + \sin(\delta_\perp-\delta_\parallel)\cos(\Delta m t)\right], \quad (7)$$

$$\Re(A_0(t)A_\parallel(t)) = |A_0||A_\parallel|e^{-\Gamma_s t}\cos(\delta_\parallel-\delta_0)\left[\cosh\left(\frac{\Delta\Gamma}{2}t\right) - \cos\phi_s\sinh\left(\frac{\Delta\Gamma}{2}t\right) + \sin\phi_s\sin(\Delta m t)\right], \quad (8)$$

$$\Im(A_0(t)A_\perp(t)) = |A_0||A_\perp|e^{-\Gamma_s t}\left[-\cos(\delta_\perp-\delta_0)\sin\phi_s\sinh\left(\frac{\Delta\Gamma}{2}t\right) - \cos(\delta_\perp-\delta_0)\cos\phi_s\sin(\Delta m t) + \sin(\delta_\perp-\delta_0)\cos(\Delta m t)\right], \quad (9)$$

$$|A_s(t)|^2 = |A_s|^2 e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma}{2}t\right) + \cos\phi_s\sinh\left(\frac{\Delta\Gamma}{2}t\right) - \sin\phi_s\sin(\Delta m t\right], \quad (10)$$

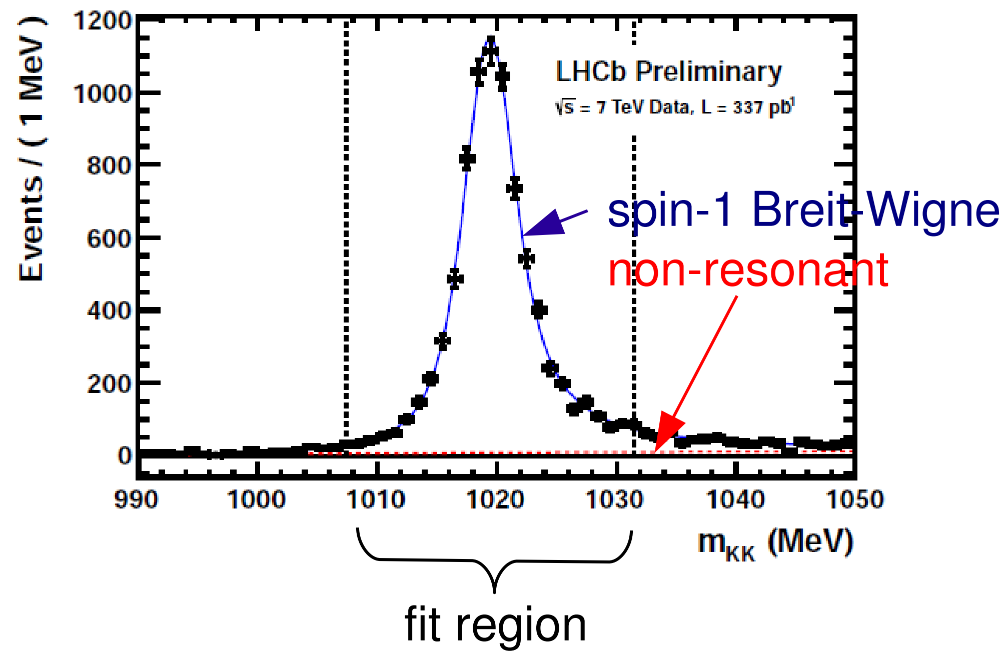
$$\Re(A_s^*(t)A_\parallel(t)) = |A_s||A_\parallel|e^{-\Gamma_s t}\left[-\sin(\delta_\parallel-\delta_s)\sin\phi_s\sinh\left(\frac{\Delta\Gamma}{2}t\right) - \sin(\delta_\parallel-\delta_s)\cos\phi_s\sin(\Delta m t) + \cos(\delta_\parallel-\delta_s)\cos(\Delta m t)\right], \quad (11)$$

$$\Im(A_s^*(t)A_\perp(t)) = |A_s||A_\perp|e^{-\Gamma_s t}\sin(\delta_\perp-\delta_s)\left[\cosh\left(\frac{\Delta\Gamma}{2}t\right) + \cos\phi_s\sinh\left(\frac{\Delta\Gamma}{2}t\right) - \sin\phi_s\sin(\Delta m t)\right], \quad (12)$$

$$\Re(A_s^*(t)A_0(t)) = |A_s||A_0|e^{-\Gamma_s t}\left[-\sin(\delta_0-\delta_s)\sin\phi_s\sinh\left(\frac{\Delta\Gamma}{2}t\right) - \sin(\delta_0-\delta_s)\cos\phi_s\sin(\Delta m t) + \cos(\delta_0-\delta_s)\cos(\Delta m t)\right]. \quad (13)$$

where we have chosen a phase convention such that $\delta_0 = 0$. The decay time dependent decay rates for an initial $\overline{B}_s^0$ decaying to $J/\psi\phi$ can be obtained from those above by inserting a factor -1 in front of the terms involving mixing ($\sin(\Delta m_s t)$ and $\cos(\Delta m_s t)$).

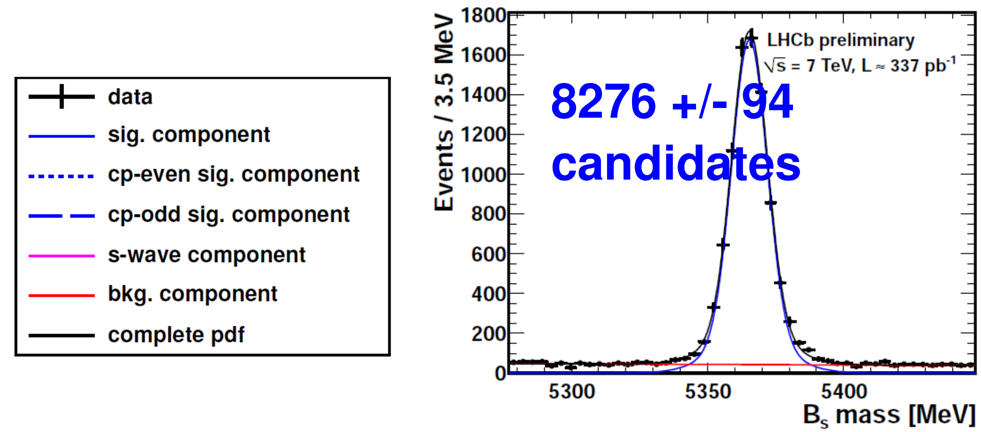
accounts for ~4% “non-resonant” KK in 12 MeV mass window around phi



note: S-wave contribution identified by angular distribution, not by KK mass

ML fit to LHCb the data

- ML fit with 10 physics parameters
  - 7 angular amplitudes and phases
  - Γ_s, $\Delta\Gamma_s$, ϕ_s

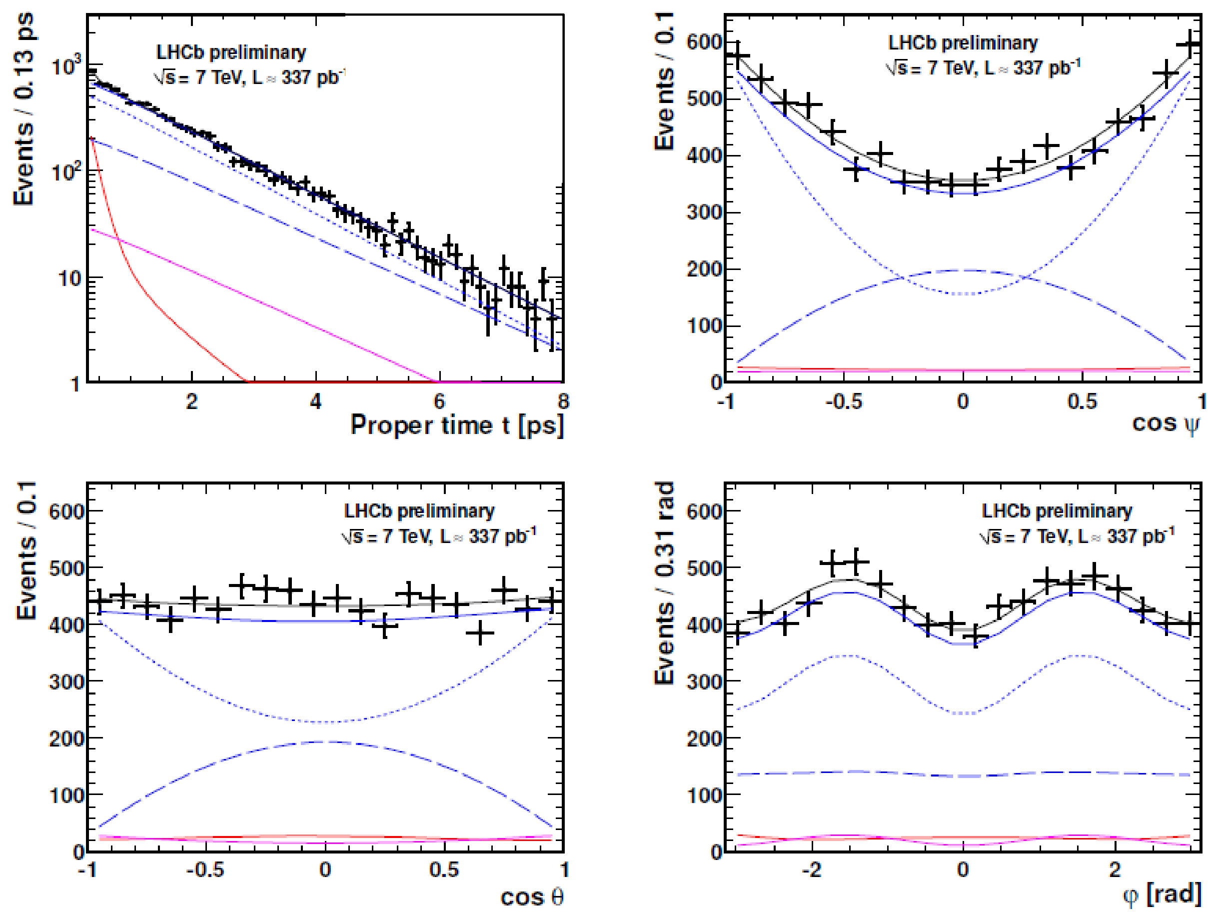


- proper-time resolution, calibrated on prompt J/psi gives $\sigma(t)$ ~ 50 ps

- only OS flavour tagging used, calibrated on J/psiK+

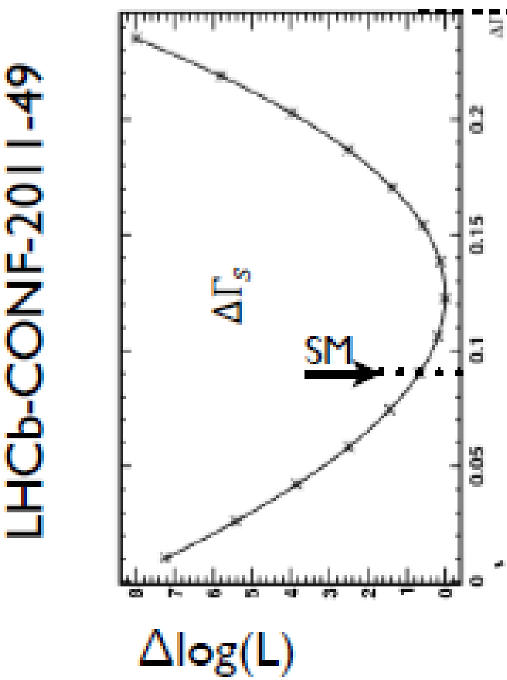
$$\varepsilon_{\rm tag}\mathcal{D}^2 = (2.08 \pm 0.41)\%$$

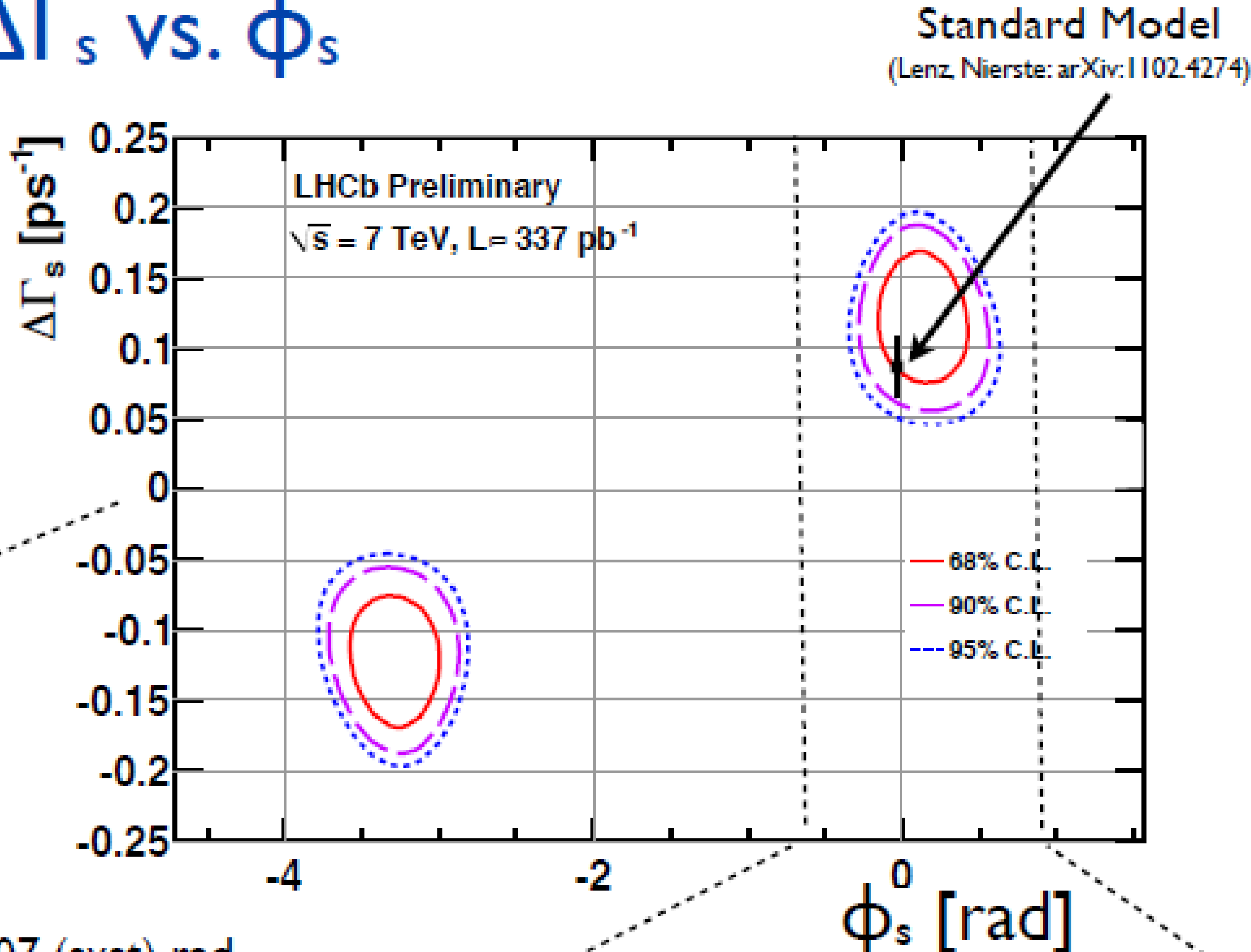
- goodness of fit, using "point-to-point dissimilarity test" (*) gives P-value of 0.44



(*) see eg. M. Williams, JINST 5 (2010) P09004 [arXiv:1006.3019 [hep-ex]]

$B_s \rightarrow J/\psi\varphi$: $\Delta\Gamma_s$ vs. ϕ_s



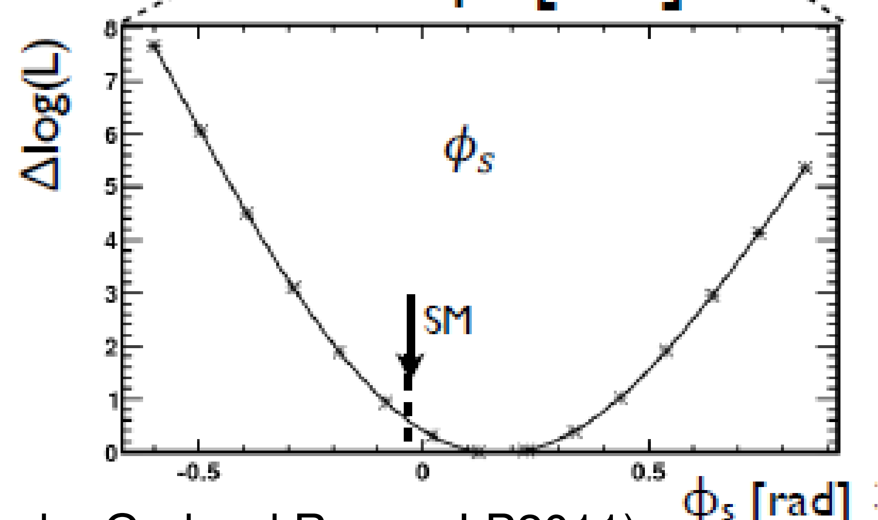


Most precise measurement of ϕ_s

- $\phi_s = 0.13 \pm 0.18$ (stat) ± 0.07 (syst) rad
- Consistent with SM

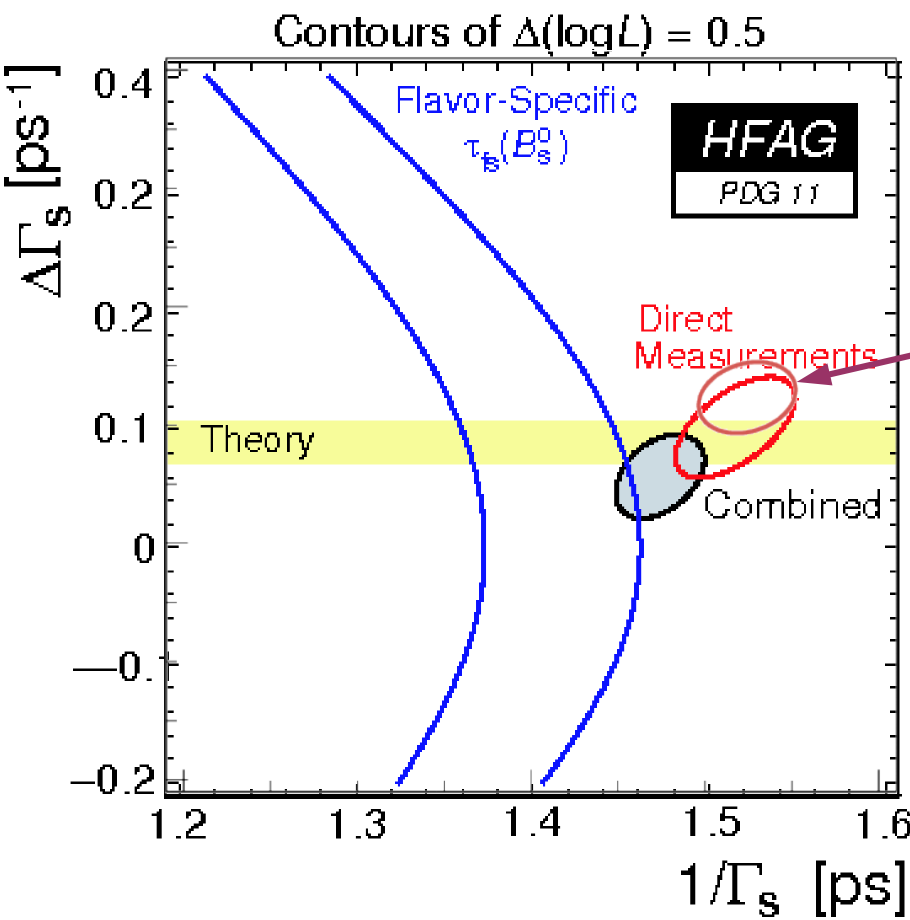
4 σ Evidence for $\Delta\Gamma_s \neq 0$:

- $\Delta\Gamma s = 0.123 \pm 0.029$ (stat) ± 0.008 (syst) ps^{-1}
- $\Gamma_s = 0.656 \pm 0.009$ (stat) ± 0.008 (syst) ps^{-1}



$\Delta\Gamma_s$

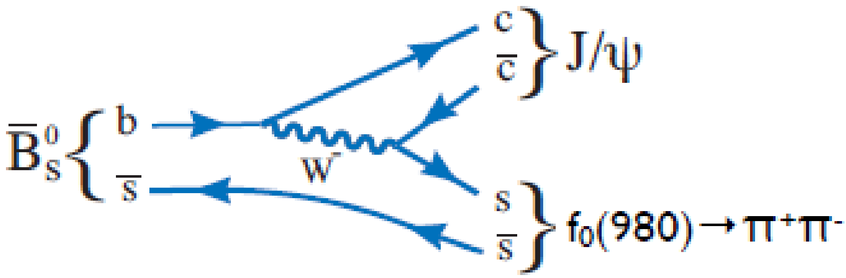
- J/psi phi analysis also gives most precise single measurement of Γ_s and $\Delta\Gamma_s$



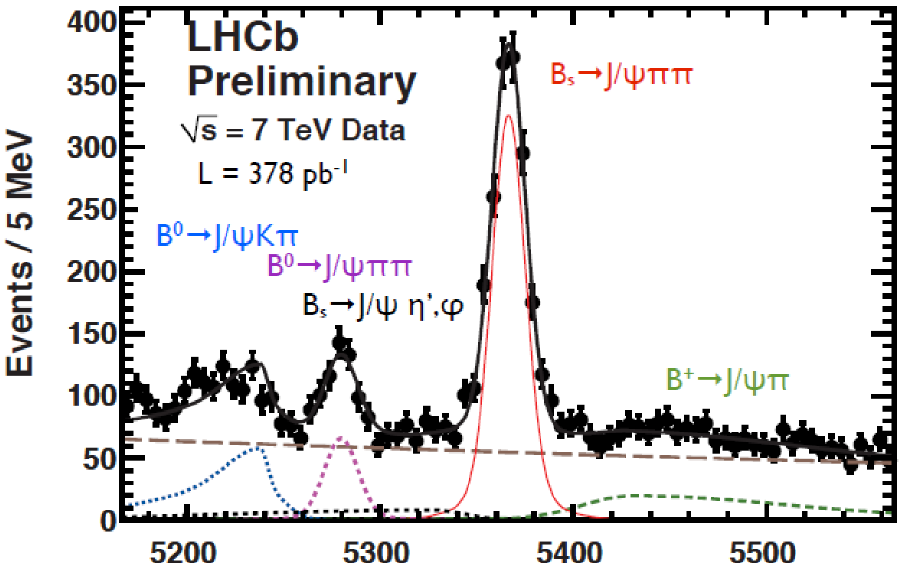
$$\tau(B_s^0)_{\rm fs} = \frac{1}{\Gamma_s}\frac{1+\left(\frac{\Delta\Gamma_s}{2\Gamma_s}\right)^2}{1-\left(\frac{\Delta\Gamma_s}{2\Gamma_s}\right)^2}$$

slight inconsistency in Γ between direct measurement and measurement with flavour specific decays?

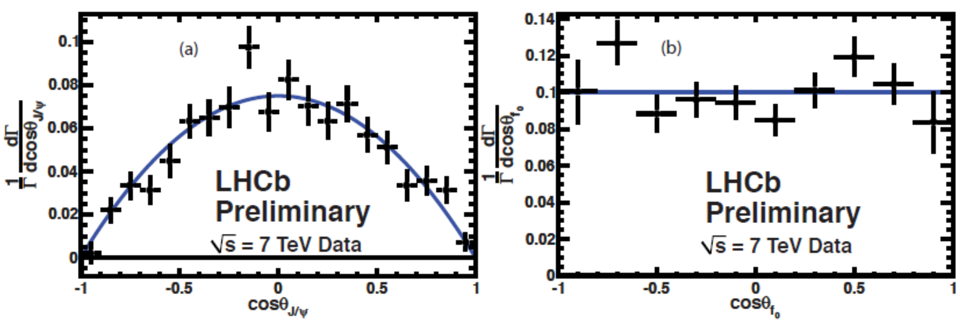
$B_s \rightarrow J/\psi f^0$ at LHCb

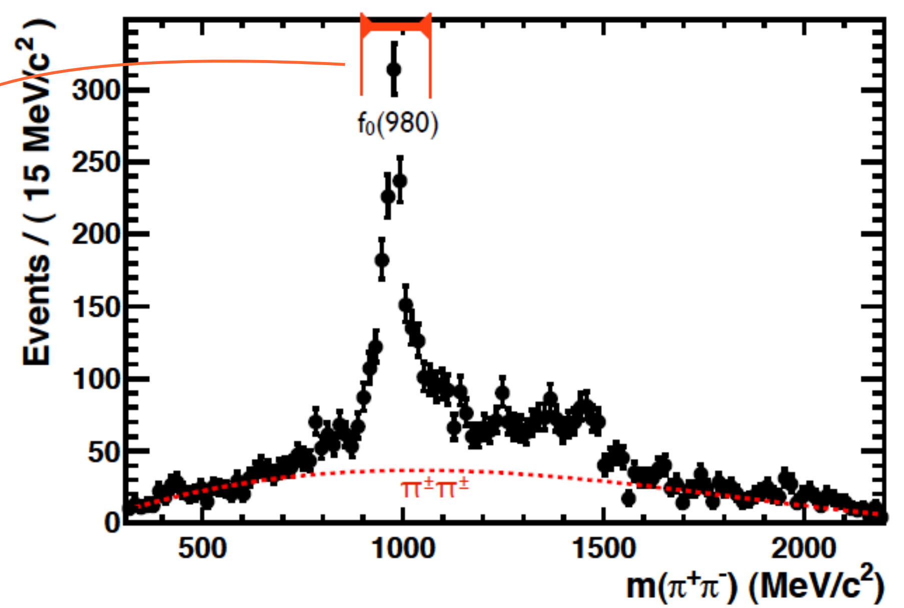


LHCB-CONF-2011-051



- some history
  - predicted by Stone, Zhang (2009)
  - first seen by LHCb (PLB689(2011)115)
  - LP2011: first measurement of CPV
- angular distribution of psi and f0 candidates

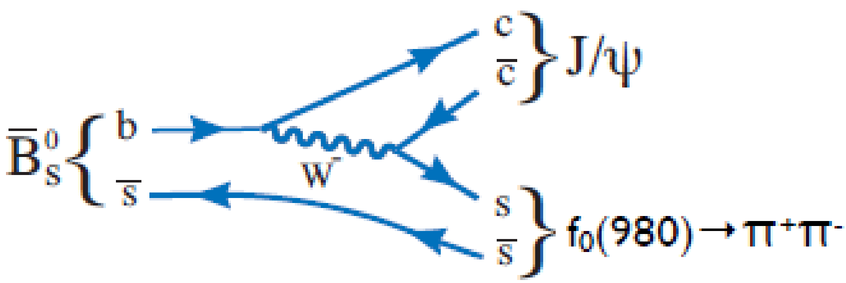


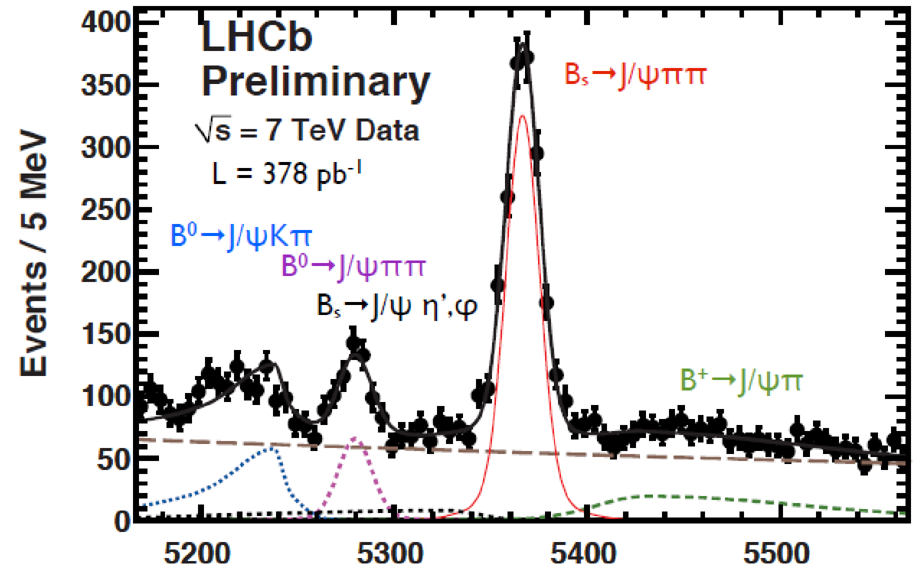


candidates in f(980) region look pure scalar
--> no angular analysis needed

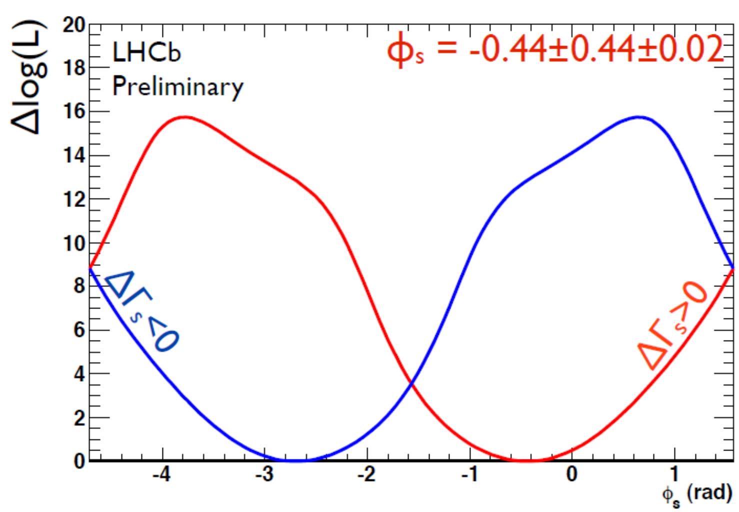
$B_s \to J/\psi f^0$ at LHCb

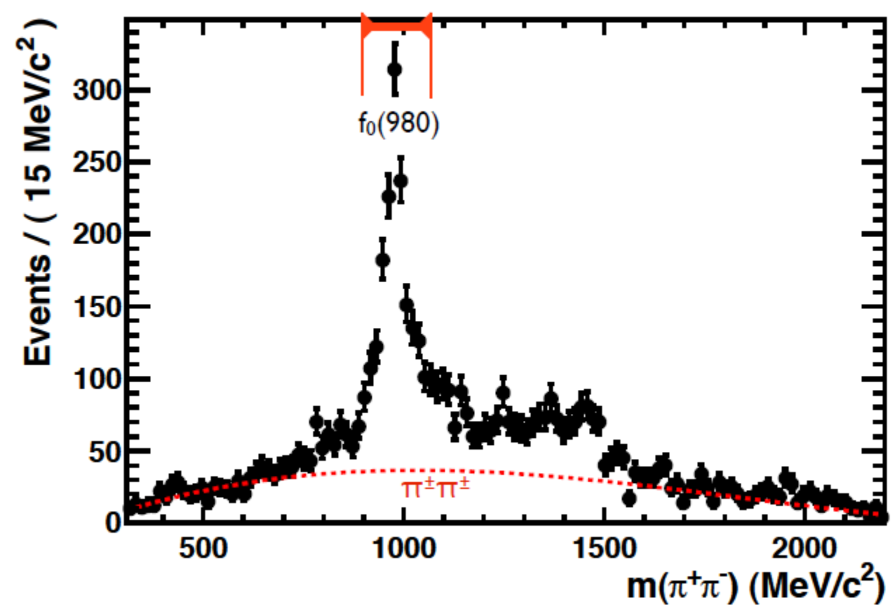
LHCB-CONF-2011-051





- some history
  - predicted by Stone, Zhang (2009)
  - first seen by LHCb (PLB689(2011)115)
  - LP2011: first measurement of CPV
- result from the LL fit





- beware: hadronic uncertainties, e.g. arXiv:1109.1112 [hep-ph]

combination of J/psiphi and J/psif0

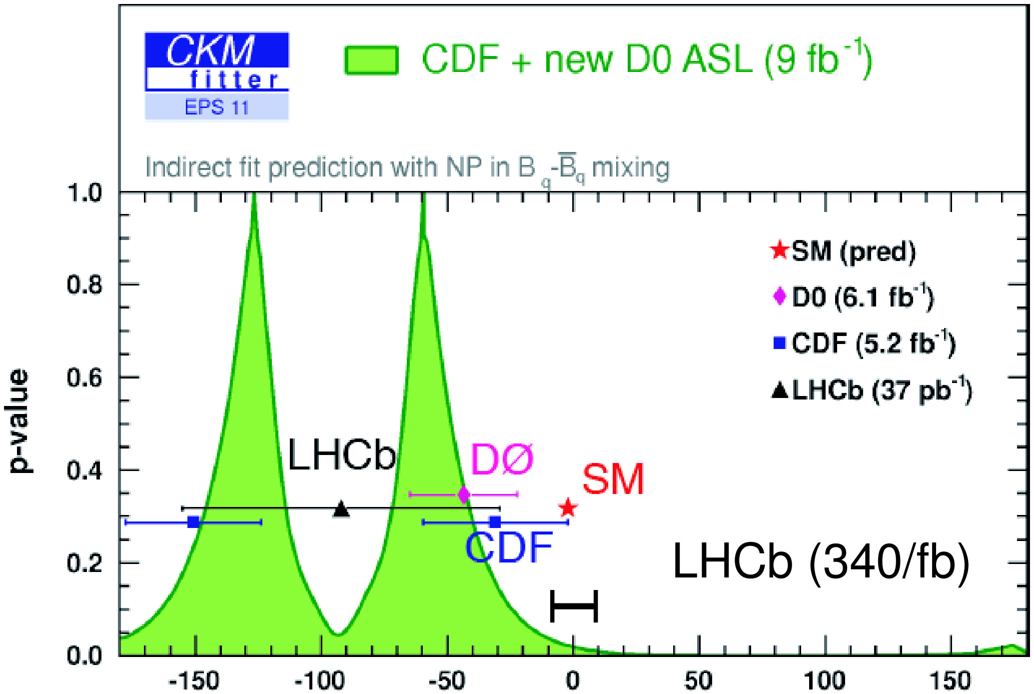
- Bs -> J/psi f0 alone cannot constraint both Γ_s, $\Delta\Gamma_s$ and ϕ_s
  - requires combination with J/psi phi

- simultaneous fit to both samples

$$\phi_s = 0.03 \pm 0.16 \pm 0.07$$

(prelim, LHCb-CONF-2011-056)

- TDCPV gives no evidence (yet) for NP in Bs mixing



- next steps
  - add more data
  - use same-side Kaon tagger
  - resolve two-fold ambiguity by relative S-wave strong phase in bins of M(KK) (Y. Xie et al., JHEP 0909:074, (2009))

conclusions/summary

- precision measurements of mixing observables:
  - mixing frequencies
  - CP asymmetries in final states with no expected CPV from decay amplitude
  - time-dependence CP asymmetries to CP eigenstates dominates by tree diagram
- one tantalizing result: D0 A_SL is 3.9s from SM prediction
- LHCb experiment is working on measurements in all these areas

backup

how about a_{fs}^{d}?

- current HFAG average

$$|q/p| = 1.0002 \pm 0.0028$$
$$A_{SL} = -0.0005 \pm 0.0056$$

- many measurements, most constraining:

Babar, 232M BBbar

$$|q/p| - 1 = (-0.8 \pm 2.7(\text{stat.}) \pm 1.9(\text{syst.})) \times 10^{-3},$$

B. Aubert *et al.* (BaBar Collab.), Phys. Rev. Lett. **96**, 251802 (2006).

$$A_{\rm sl} = (-1.1 \pm 7.9(\text{stat}) \pm 8.5(\text{sys})) \times 10^{-3},$$

$$|q/p| = 1.0005 \pm 0.0040(\text{stat}) \pm 0.0043(\text{sys}).$$

Belle, 87M BBbar

PHYSICAL REVIEW D **73**, 112002 (2006)

- B factories still have quite a bit more data ...