LHCb measurements of ϕ_s, semileptonic asymmetries and B lifetimes

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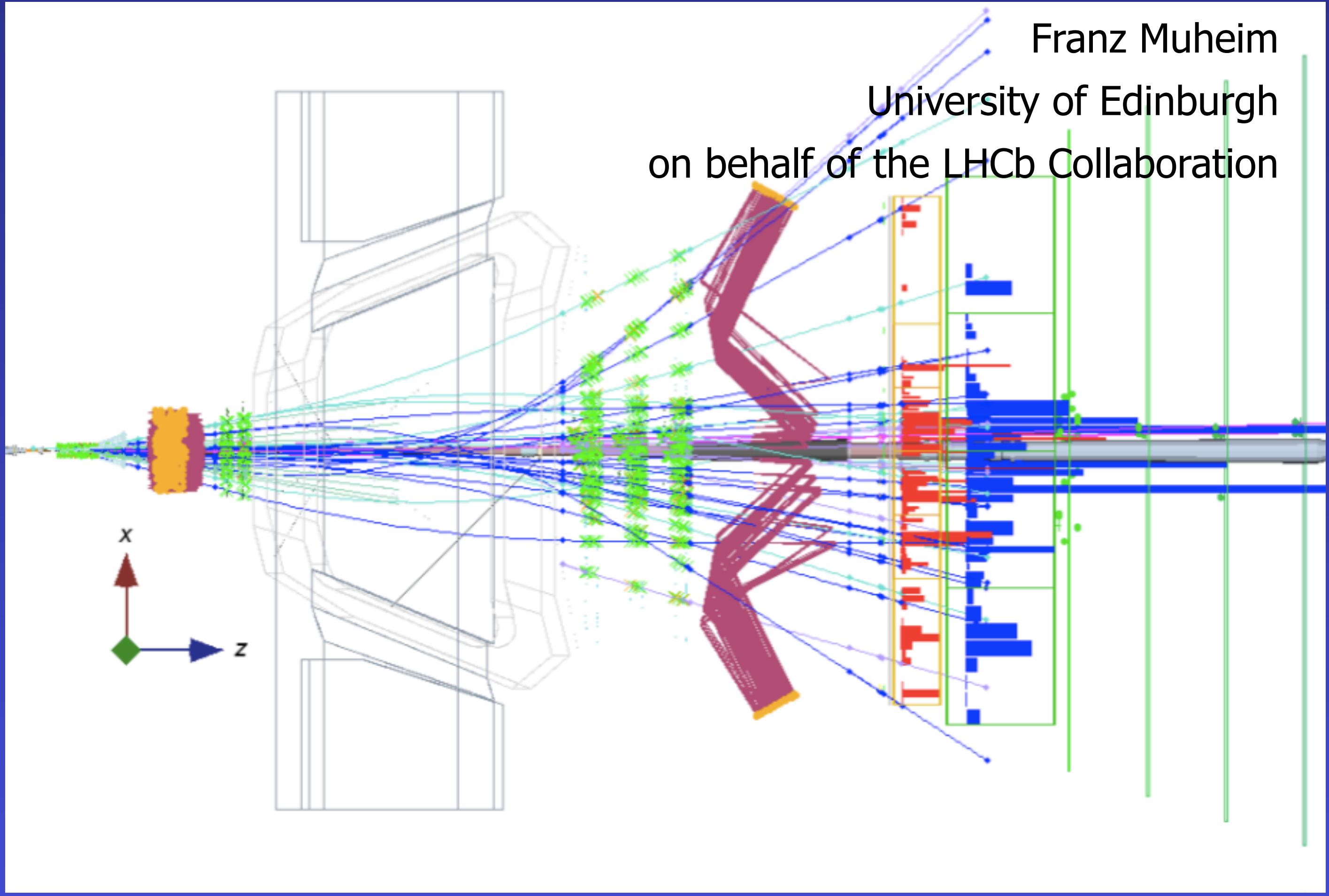
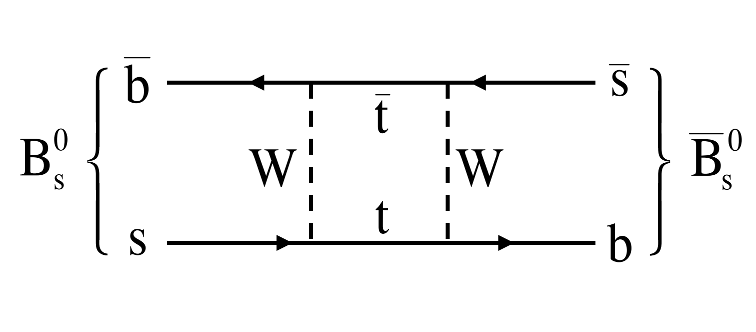


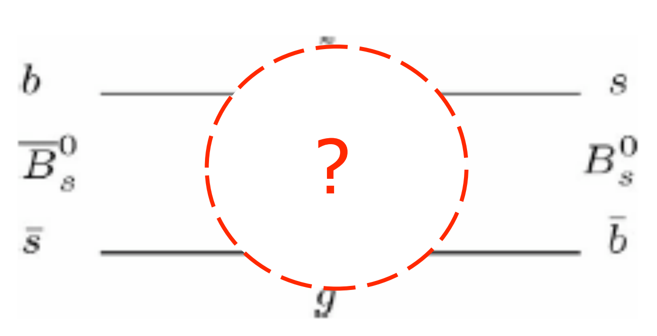
Exploring New Physics at LHCb

- **Flavour Changing Neutral Currents**
  - New Physics appears as virtual particles in loop processes
  - leading to observable deviations from SM expectations in flavour physics and CP violation (~~CP~~)

Standard Model



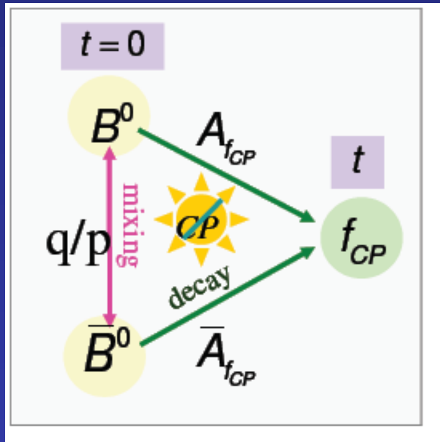
New Physics ?



B_s-$\overline{B}_s$ oscillations

CP Violation in B_s decays

- **CP Violation**
  - $\not{CP}$ in interference between mixing and decays to CP eigenstates
  - $\sin\phi_s = \Im m \lambda_f$ where $\lambda_f = \frac{q}{p}\frac{\bar{A}_f}{A_f}$ $\quad \left|\frac{q}{p}\right| = 1 = \left|\frac{\bar{A}_f}{A_f}\right|$



- **CP violating phase ϕ_s**
  - measured in $B_s \to J/\psi\phi$ decays
  - in Standard Model (SM) ϕ_s prediction is small and precise
  - ϕ_s sensitive to new physics

$$\phi_s^{SM} \cong -2\beta_s \equiv -2\arg\left(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right) = -0.036 \pm 0.002$$

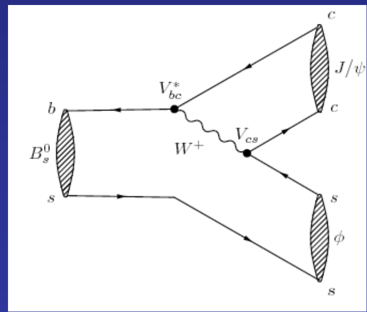
$$\phi_s = \phi_s^{SM} + \phi_s^{NP}$$

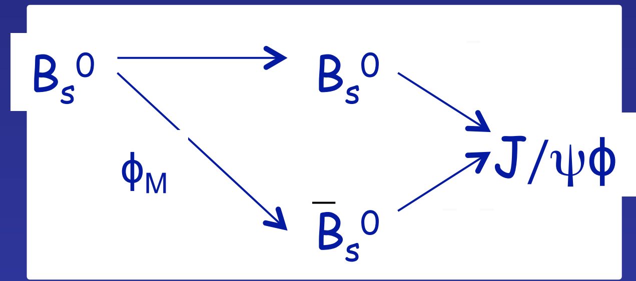
J. Charles et al., Phys. Rev. D 84, 033005 (2011).

- **CP Violation in mixing**
  - $\not{CP}$ in B_s mixing - A_{sl} - measured in semileptonic asymmetry

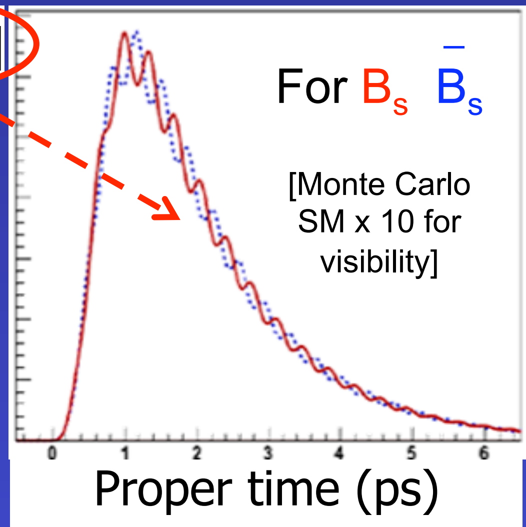
CP Violation in $B_s \to J/\psi\phi$

- $B_s \to J/\psi\phi$
  - tree decay
  - sensitive to NP in mixing





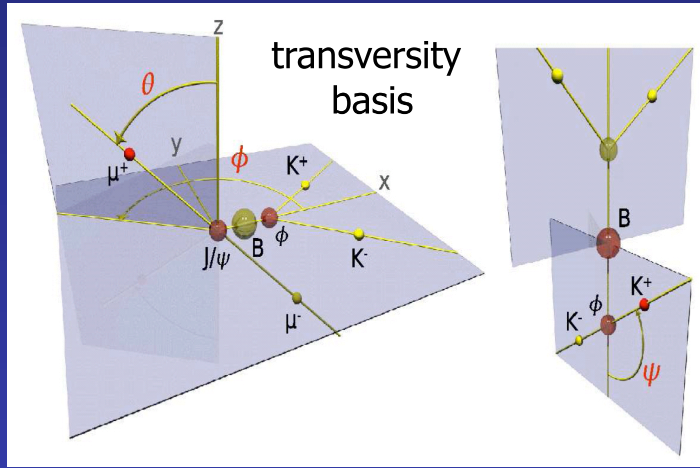
- **Decay rate terms**
  - e.g. $h_1(\overset{(-)}{B_s^0} \to J/\psi\phi)(t) = N\exp(-\Gamma_s t)\left[\cosh\left(\tfrac{1}{2}\Delta\Gamma_s t\right) - \cos\phi_s \sinh\left(\tfrac{1}{2}\Delta\Gamma_s t\right) \pm \sin\phi_s \sin\Delta m_s t\right]$
- **Signal for ~~CP~~**
  - sinusoidal term in proper time distribution
  - amplitude proportional to $\sin\phi_s$
  - opposite sign for B_s/anti-B_s → tagging required
  - diluted by wrong-tag fraction and time resolution



- **Analysis method**
  - basically we look for $\sin(\phi_s) \times (1 - 2\omega_{tag}) \times \sin(\Delta m_s t)$

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

- **Full differential decay rate**
  - B → VV decay
  - angular analysis required to disentangle CP-even and CP-odd components



$$\frac{\mathrm{d}^4\Gamma(B_s^0 \rightarrow J/\psi\,\phi)}{\mathrm{d}t\;\mathrm{d}\Omega} \propto \sum_{k=1}^{10} h_k(t)\; f_k(\Omega)$$

$$h_k(t) = N_k e^{-\Gamma_s t}\,\left[c_k \cos(\Delta m_s t) + d_k \sin(\Delta m_s t)\right. \\ \left. + a_k \cosh\left(\tfrac{1}{2}\Delta\Gamma_s t\right) + b_k \sinh\left(\tfrac{1}{2}\Delta\Gamma_s t\right)\right]$$

Angular functions $f_k(\theta,\psi,\phi)$ and coefficients a_k b_k c_k and d_k in backup slides
for B_s c_k and d_k multiplied by −1

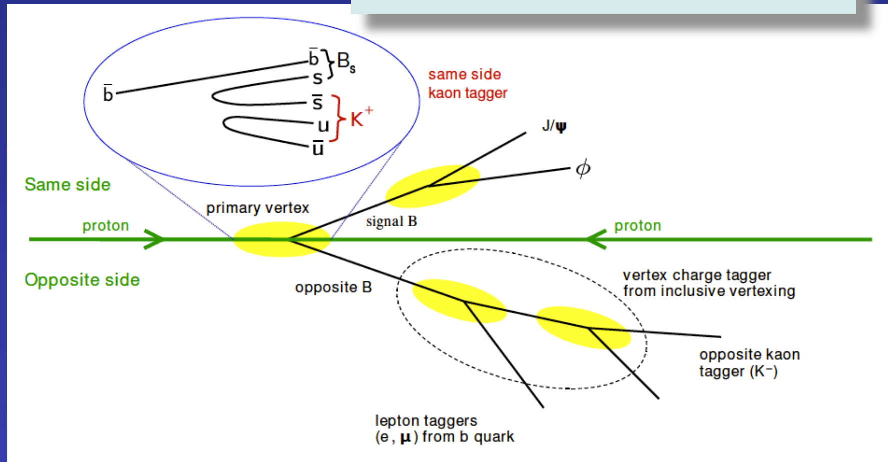
  - Include S-wave in KK final state under ϕ peak → 4 additional terms

- **Physics parameters**
  - ϕ_s, Γ_s, $\Delta\Gamma_s$, Δm_s
  - 3 polarisation amplitudes, 3 strong phase differences, set $\delta_0 = 0$

Flavour Tagging

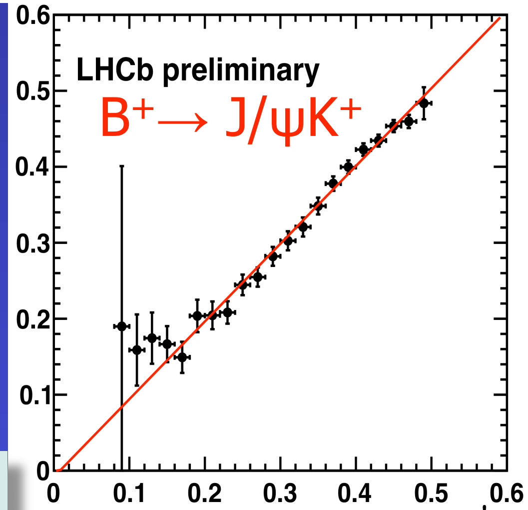
LHCb-PAPER-2011-027
arXiv:1202.4979
submitted to EPJC

- **Tagging method**
  - Tag initial B_s flavour with opposite b-decay: charge of muon, electron, kaon or vertex charge (OST)
  - tag initial B_s flavour with charge of same side kaon (SST)
  - calibrate with flavour specific decays of similar topology
- **Tagging power for $B_s \to J/\psi\phi$**
  - OST only, calibration with $B^+ \to J/\psi K^+$ and $B^0 \to J/\psi K^{*0}$



Mistag probability ω	(36.81 ± 0.18 ± 0.74) %
Tagging efficiency ε_{tag}	(32.99 ± 0.33) %
Tagging power $\varepsilon_{tag}(1-2\omega)^2$	(2.29 ± 0.07 ± 0.26) %

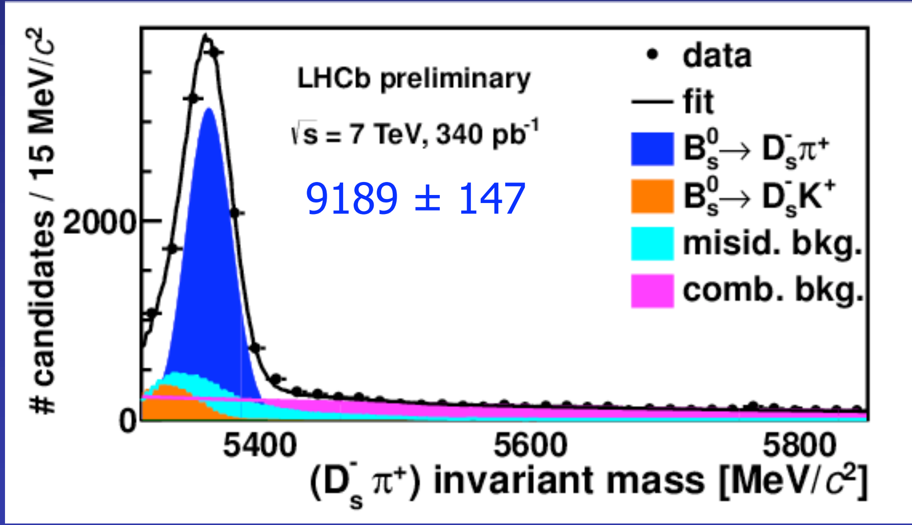
1 fb^{-1}, LHCb-CONF-2012-002



per-event mistag

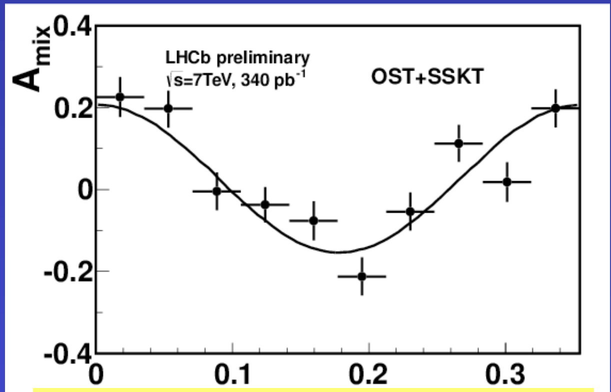
Δm_s & SST Flavour Tagging

- $B_s \rightarrow D_s^-(K^-K^+\pi^-)\pi^+$
  - SST global calibration
  - $\varepsilon D^2 = (1.2 \pm 0.4)\%$



- Δm_s measurement
  - OST calibration with $B^0 \rightarrow D^-\pi^+$
  - $\varepsilon D^2 = (3.1 \pm 0.8)\%$
  - $\Delta m_s = 17.725 \pm 0.041 \pm 0.026\ \mathrm{ps}^{-1}$

LHCb-CONF-2011-050



Decay time modulo $2\pi/\Delta m_s$

- Reminder
  - 2010 result, independent data set
  - $\Delta m_s = 17.63 + 0.11 + 0.01\ \mathrm{ps}^{-1}$

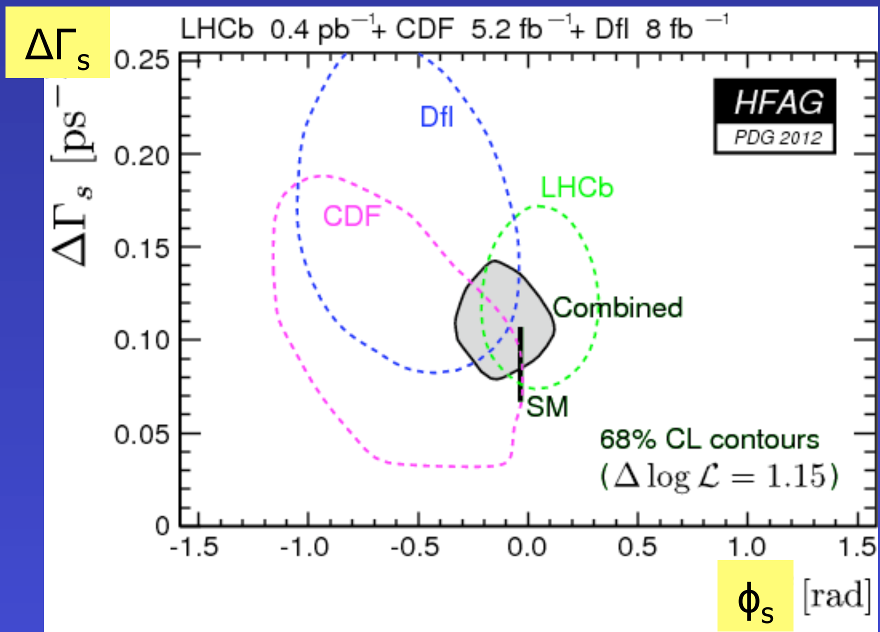
LHCb, PLB 709 (2012) 177

CP Violation in $B_s \to J/\psi\phi$

- **Published result**
  - 0.37 fb^{-1} data set

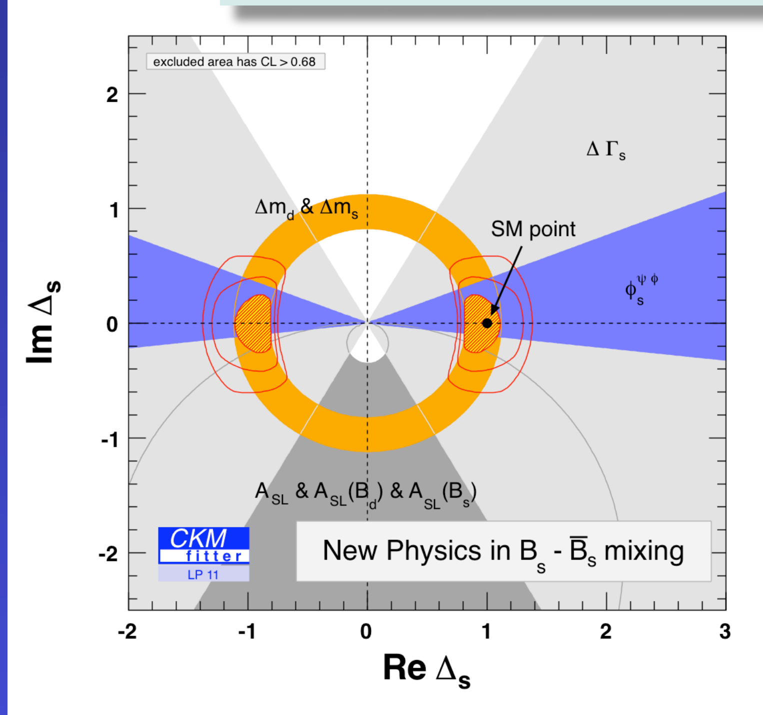
0.37 fb^{-1}, PRL 108, 101803 (2012)

$$\phi_s = 0.15 \pm 0.18(\text{stat}) \pm 0.06(\text{syst})\text{rad},$$
$$\Gamma_s = 0.657 \pm 0.009(\text{stat}) \pm 0.008(\text{syst})\ \text{ps}^{-1},$$
$$\Delta\Gamma_s = 0.123 \pm 0.029(\text{stat}) \pm 0.011(\text{syst})\ \text{ps}^{-1}$$



- **Implications**
  - limits parameter space for new physics
  - $M_{12} = M_{12}^{SM}\,\Delta_s$

A. Lenz et al., arXiv:1203.0238

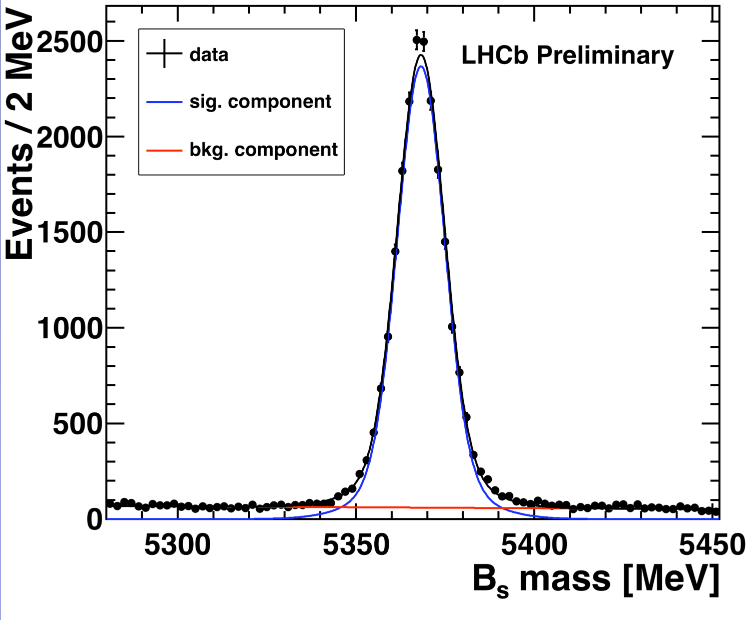


CP Violation in $B_s \to J/\psi\phi$

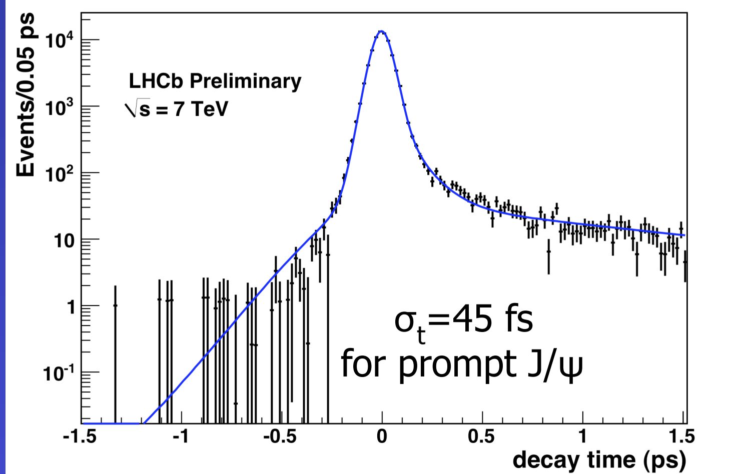
1 fb^{-1}, LHCb-CONF-2012-002

- **New preliminary measurement**
  - full 2011 data set (1 fb^{-1})
  - ~ 21200 $B_s \to J/\psi\phi$ signal candidates
- **Resolutions**
  - B_s Mass ~ 8 MeV/c^2
  - ~ 45 fs decay time resolution
  - measured with prompt J/ψ's

J/ψKK mass

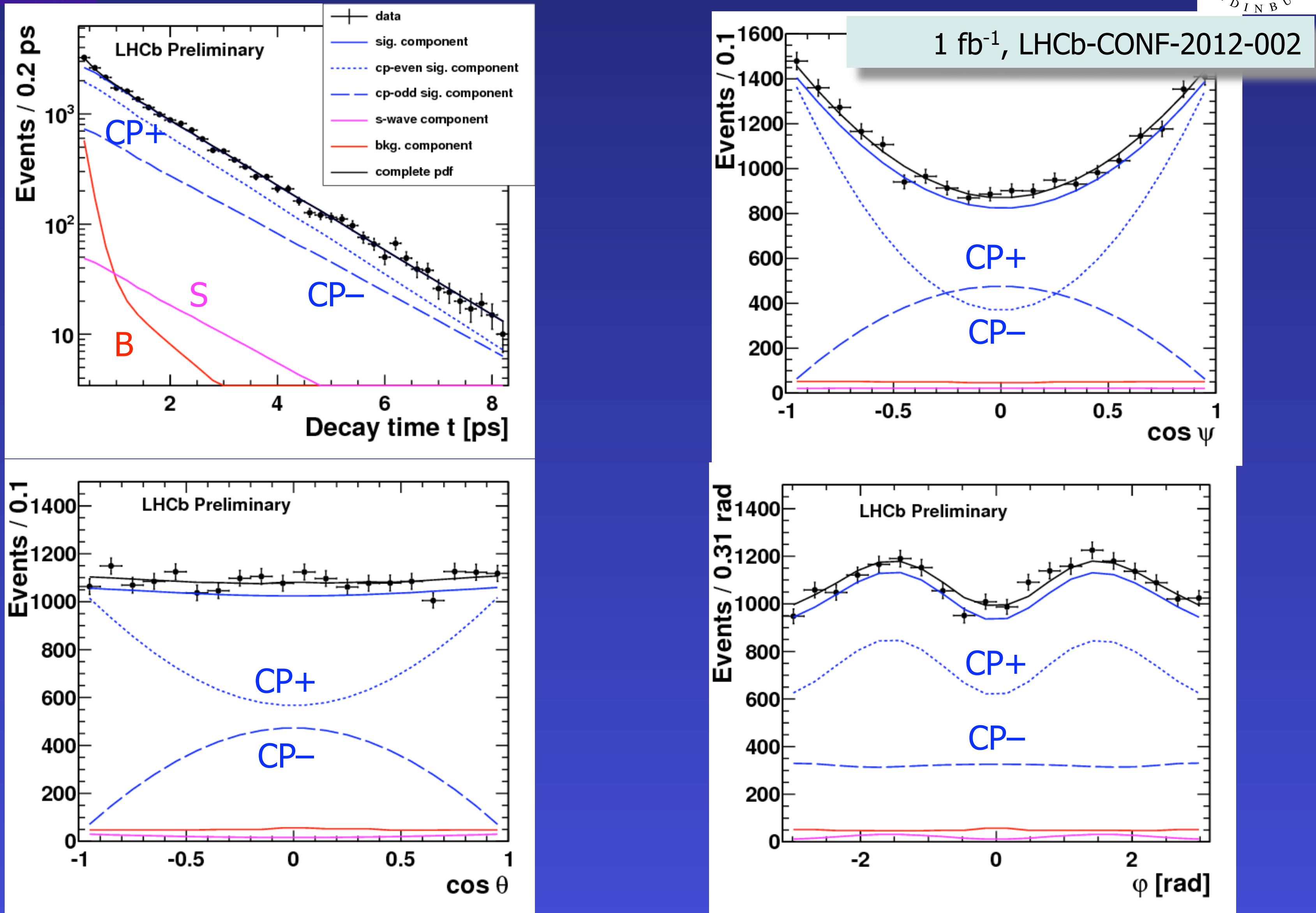


Decay time for J/ψ's



$B_s \to J/\psi\phi$ Decay time and angles

1 fb^{-1}, LHCb-CONF-2012-002



CP Violation in $B_s \to J/\psi\phi$

1 fb^{-1}, LHCb-CONF-2012-002

- **New preliminary measurement**
  - full fit to B_s mass, decay time and angular distribution
  - use opposite sign tags
- **CP violating weak phase ϕ_s and decay width difference $\Delta\Gamma_s$**
  - ϕ_s and $\Delta\Gamma_s$ compatible with SM prediction
  - first >5σ observation of non-zero $\Delta\Gamma_s$
  - two fold ambiguity → 2^{nd} solution with $\phi_s \to \pi-\phi_s$ and $\Delta\Gamma_s \to -\Delta\Gamma_s$

$\phi_s = -0.001 \pm 0.101 \pm 0.027$

$\Delta\Gamma_s = 0.116 \pm 0.018 \pm 0.006\ ps^{-1}$

$\Gamma_s = 0.6580 \pm 0.0054 \pm 0.0066\ ps^{-1}$

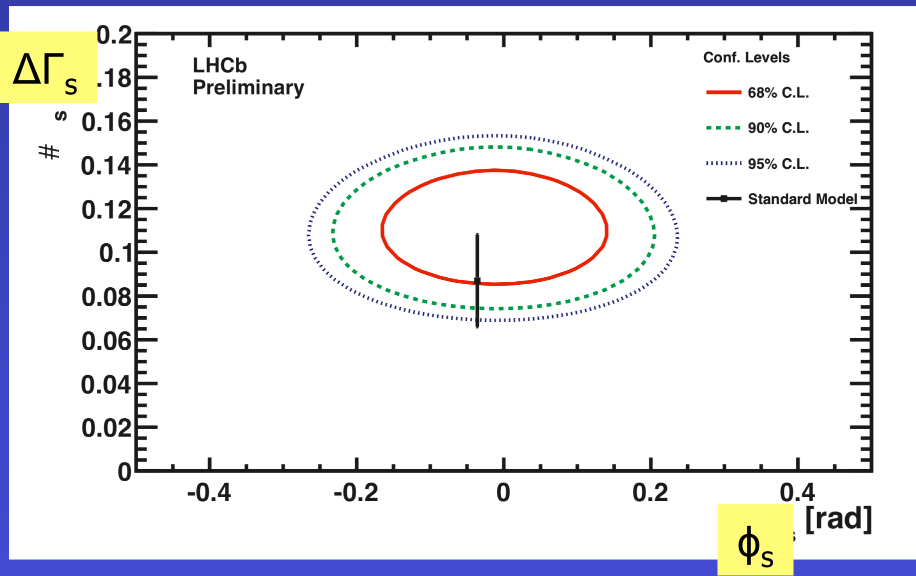
$|A_\perp|^2 = 0.246 \pm 0.010 \pm 0.013$

$|A_0|^2 = 0.523 \pm 0.007 \pm 0.024$

$F_S = 0.022 \pm 0.012 \pm 0.007$

$\delta_\perp = 2.90 \pm 0.36 \pm 0.07$

$\delta_{||} = [2.81, 3.47] \pm 0.13$



Sign of B_s Width Difference $\Delta\Gamma_s$

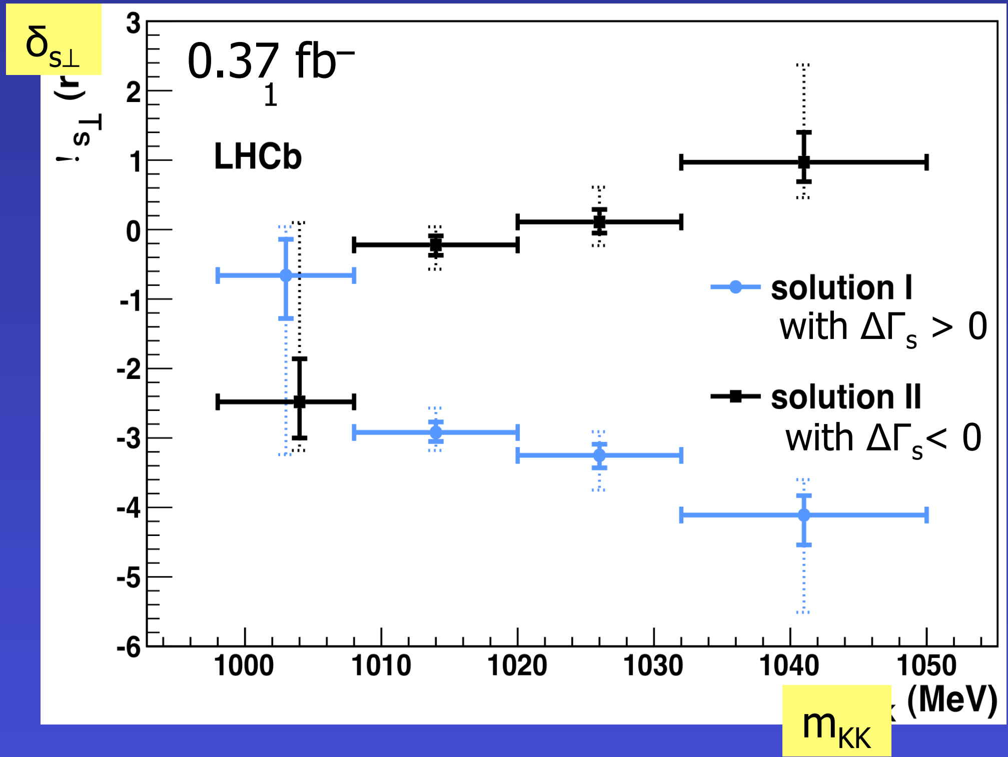
0.37 fb[-1], LHCb-PAPER-2011-028
arXiv:1202.4717, submitted to PRL

- **Intrinsic 2-fold ambiguity**

$$\left(\phi_s, \Delta\Gamma_s, \delta_{//}, \delta_\perp, \delta_S\right) \Leftrightarrow \left(\pi - \phi_s, -\Delta\Gamma_s, -\delta_{//}, \pi - \delta_\perp, -\delta_S\right)$$

$$\delta_{S\perp} \Leftrightarrow -\pi - \delta_{S\perp}$$
$$\text{where} \quad \delta_{S\perp} = \delta_S - \delta_\perp$$

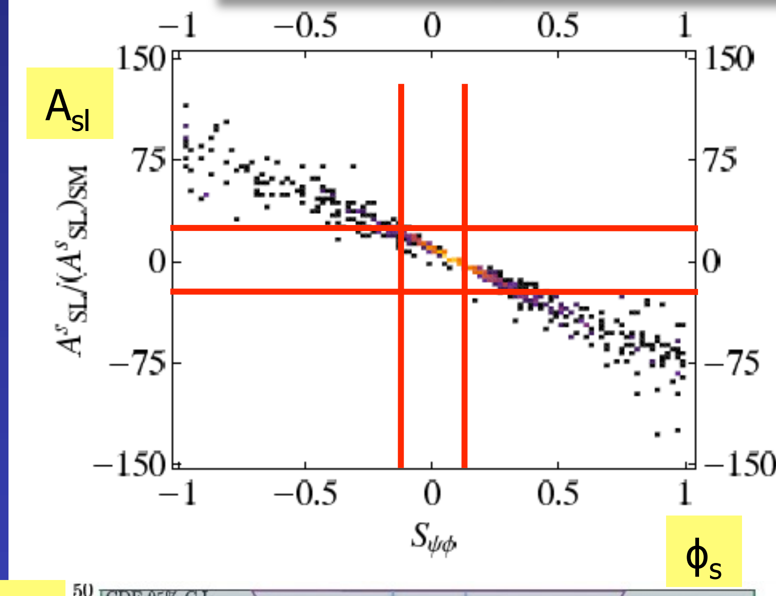
- **Interference between S and P-wave**
  - sensitive to $\cos\phi_s$ (Y. Xie et al., arXiv:1107.0266)
  - P-wave phases increase rapidly with m(KK)
  - S-wave phase varies slowly
  - physical solution for $\delta_{S\perp}$ decreases with m(KK)
- **Result**
  - using 0.37fb[-1] data set
  - analyse larger m(KK) range
  - $\delta_{S\perp}$ decreases for solution with $\Delta\Gamma_s > 0$ at 4.7σ
  - Heavy B_s meson lives longer

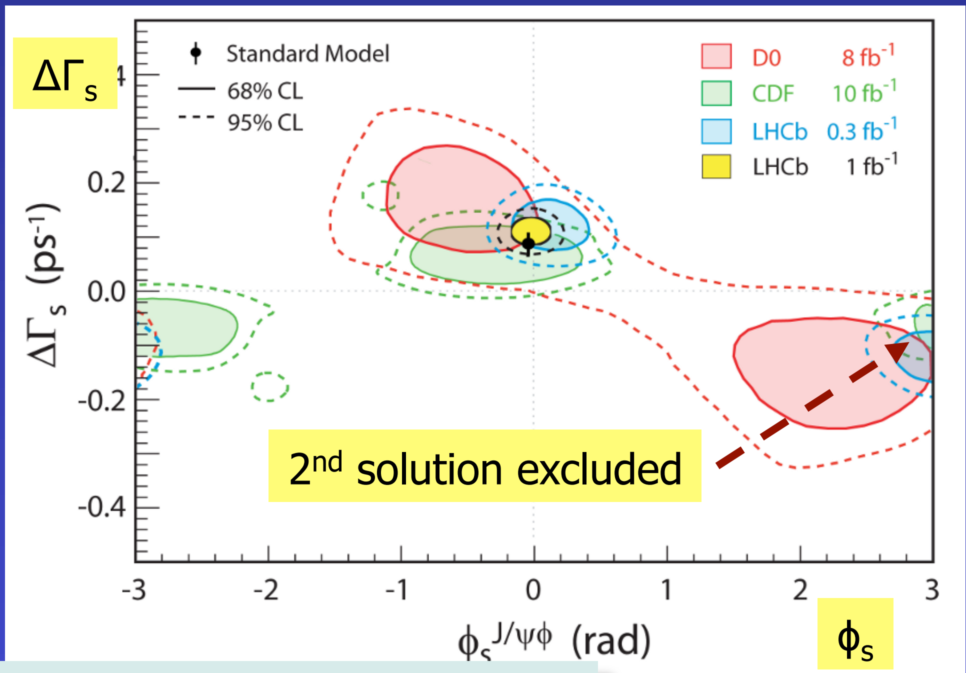


CP Violation in $B_s \to J/\psi\phi$

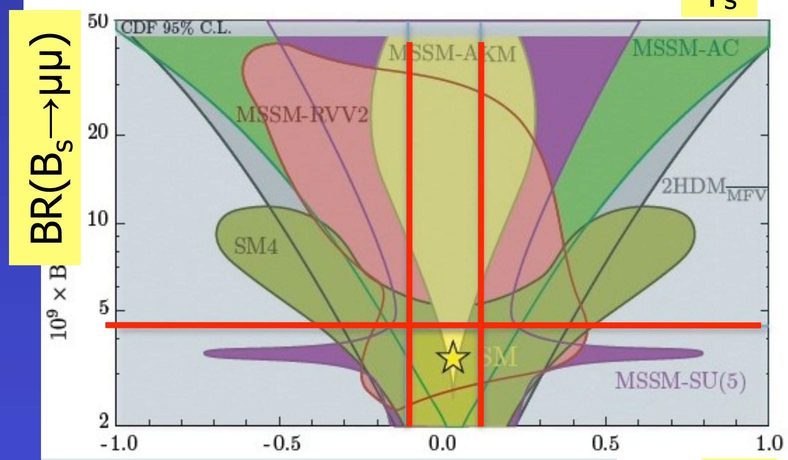
- **Implications**
  - ϕ_s limits allowed A_{sl} range
  - ϕ_s and $B_s \to \mu\mu$ severely restrict NP parameter space

M. Blanke et al., arXiv0809.1073





0.37 fb^{-1}, PRL 108, 101803 (2012)
0.37 fb^{-1}, LHCb-PAPER-2011-028
1 fb^{-1}, LHCb-CONF-2012-002



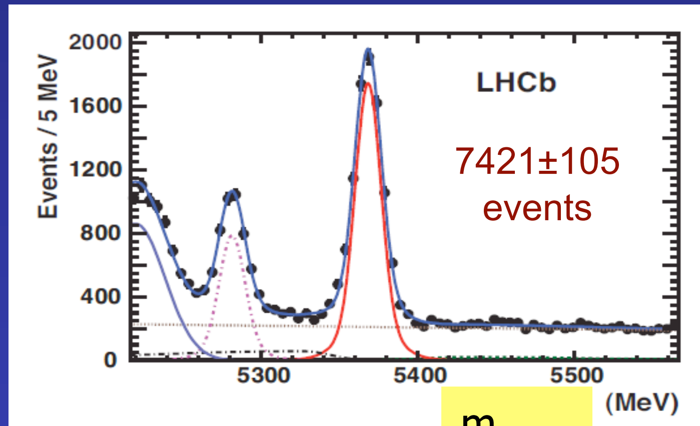
D.M. Straub, arXiv:1107.0266

CP Violation in $B_s \to J/\psi f_0$

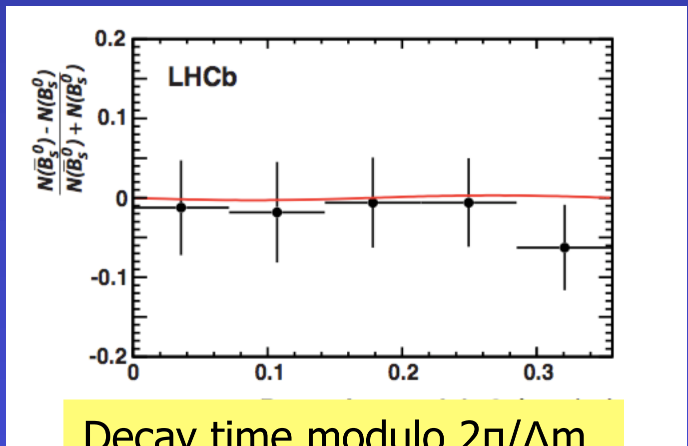
1 fb^{-1}, LHCb-PAPER-2012-006

- **CP violating weak phase ϕ_s**
  - no angular analysis required
    CP-odd fraction > 97.7%
    at 95% CL
  - $\phi_s = -0.02 \pm 0.17 \pm 0.02$
- **Combination of $B_s \to J/\psi\phi$ and $B_s \to J/\psi f_0$**
  - $\phi_s = -0.002 \pm 0.083 \pm 0.027$

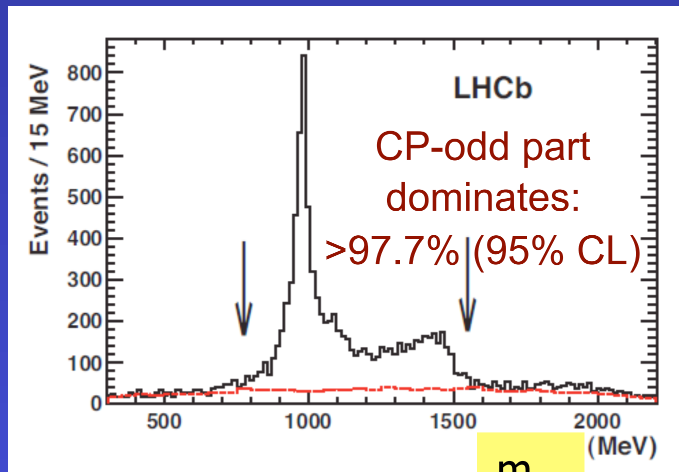
preliminary



$m_{J/\psi\pi\pi}$



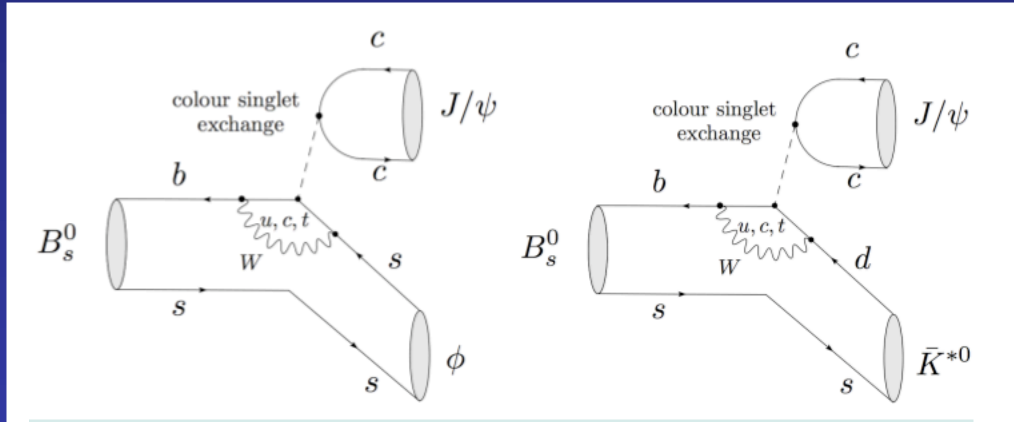
Decay time modulo $2\pi/\Delta m_s$



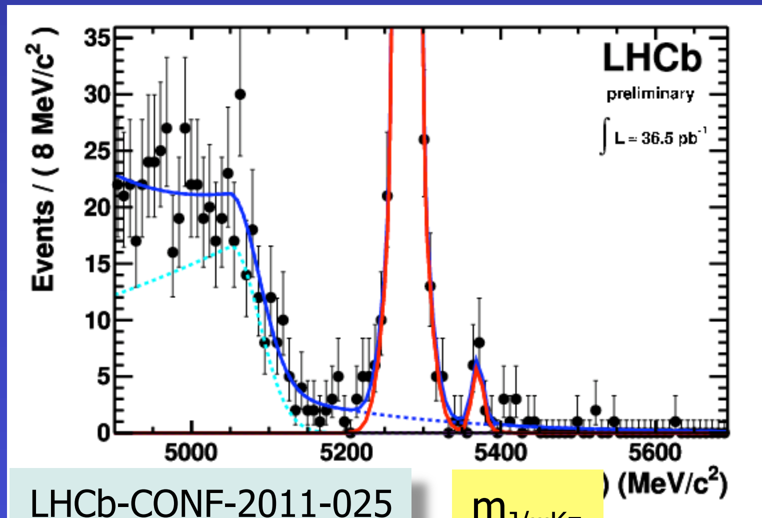
$m_{\pi\pi}$

Penguin in $B_s \to J/\psi\phi$ decay

- **Penguin diagrams**
  - can contribute to $B_s \to J/\psi\phi$
  - expected to be small
- **Question to theorists**
  - require calculation of irreducible error for ϕ_s
- **$B_s \to J/\psi K^{*0}$**
  - related to $B_s \to J/\psi\phi$ by SU(3) Flavour
  - useful for penguin control ?
  - angular time dependent analysis
  - direct CP asymmetries
- **LHCb $B_s \to J/\psi K^{*0}$ result**
  - 2010 data, observe evidence at 4.7σ



S.Faller, R. Fleischer, T. Mannel, Phys. Rev. D 79, 014005 (2009)



LHCb-CONF-2011-025

Lifetimes

- **Preliminary measurements**
  - 2010 dataset
  - B^+ and B^0 lifetime limited by systematics

36 pb^{-1}, LHCb-CONF-2011-001

$$\tau(B^+ \to J/\psi K^+) = 1.689 \pm 0.022\,(\text{stat.}) \pm 0.047\,(\text{syst.})\ \text{ps},$$
$$\tau(B^0 \to J/\psi K^{*0}) = 1.512 \pm 0.032\,(\text{stat.}) \pm 0.042\,(\text{syst.})\ \text{ps},$$
$$\tau(B^0 \to J/\psi K^0_S) = 1.558 \pm 0.056\,(\text{stat.}) \pm 0.022\,(\text{syst.})\ \text{ps},$$
$$\tau^{\text{single}}(B^0_s \to J/\psi \phi) = 1.447 \pm 0.064\,(\text{stat.}) \pm 0.056\,(\text{syst.})\ \text{ps},$$
$$\tau(\Lambda_b \to J/\psi \Lambda) = 1.353 \pm 0.108\,(\text{stat.}) \pm 0.035\,(\text{syst.})\ \text{ps},$$

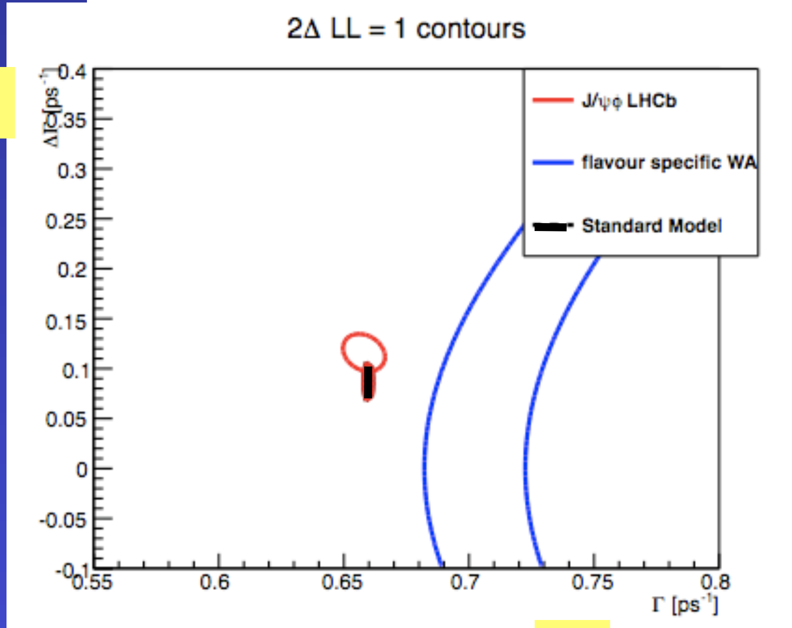
- **LHCb - Ongoing Work and Plans**
  - Λ_b lifetime with $\Lambda_b \to J/\psi\Lambda$ expected precision $\tau(\Lambda_b) \sim 0.020$ ps
  - B_s lifetime and width difference Γ_s and $\Delta\Gamma_s$
  - B^0 width difference $\Delta\Gamma_d$
  - experimentally – must determine acceptances from trigger, reconstruction and selection
  - question to theorists – is it worth pushing B^+ and B^0 lifetimes?
  - PDG 2012: $\tau(B^0) = 1.519 \pm 0.007$ ps and $\tau(B^+) = 1.641 \pm 0.008$ ps

Lifetimes - Γ_s & $\Delta\Gamma_s$ and $\Delta\Gamma_d$

- **B_s lifetime and width difference Γ_s and $\Delta\Gamma_s$**
  - measure CP-odd, CP-even, average and flavour specific lifetimes
    $B_s \to J/\psi\phi$, $J/\psi f_0$, $B_s \to J/\psi\eta(\eta')$, $B_s \to D_s^- D_s^+$
    $B_s \to D_s^-(K^-K^+\pi^-)\pi^+$ and $B_s \to K^+K^-$
  - precision measurement of $\Delta\Gamma_s$
    $\sigma(\Delta\Gamma_s) < 0.01\ ps^{-1}$
  - question to theorists -
    precision of $\tau(B_s)/\tau(B^0)$ prediction?
- **B^0 width difference $\Delta\Gamma_d$**
  - SM null test
  - measure lifetime ratio
    $\tau(B^0 \to J/\psi K_S^0)$ / $\tau(B^0 \to J/\psi K^{*0})$
  - estimated statistical sensitivity
    $\sigma(\Delta\Gamma_d/\Gamma_d)$ ~0.02 for 2011 data set

Unofficial - preliminary LHCb $B_s \to J/\psi\phi$
vs HFAG 2011 flavour specific

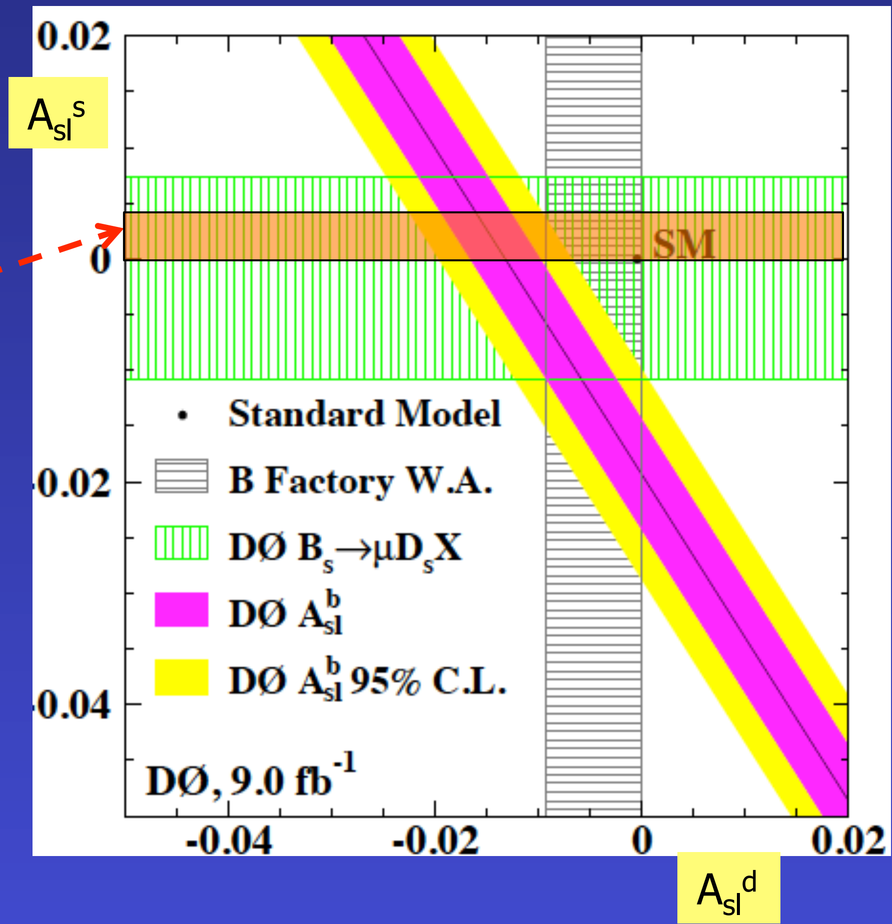
$\Delta\Gamma_s$



Γ_s

Semileptonic Asymmetry A_{sl}

- **D0 evidence**
  - A_{sl} >> SM prediction
- **What can LHCb do?**
  - Time-integrated measurement of $B_s \rightarrow D_s^- \mu^+ \nu$
  - 0.25% projected statistical uncertainty with 1 fb^{-1}
  - Result expected soon
  - (Time-dependent) measurement of $A_{sl}^s - A_{sl}^d$ with $B_s \rightarrow D_s^- \mu^+ \nu$ and $B^0 \rightarrow D^- \mu^+ \nu$



Outlook / Conclusion

- **LHCb updated ϕ_s and $\Delta\Gamma_s$ measurements**
  - ϕ_s = -0.001 ± 0.101 ± 0.027 from $B_s \to J/\psi\phi$
  - $\Delta\Gamma_s$ = 0.116 ± 0.018 ± 0.006 ps^{-1} from $B_s \to J/\psi\phi$
  - ϕ_s = –0.02 ± 0.17 ± 0.02 from $B_s \to J/\psi f_0$
  - puts severe restrictions on new physics parameter space
- **Outlook on ϕ_s**
  - add Same-Side Tag
  - improve selections
  - add new modes $B_s \to J/\psi\eta(\eta')$, $B_s \to \psi(2S)\phi$
- **Semileptonic Asymmetry**
  - expect A_{sl}^s result with time-integrated measurement with $B_s \to D_s\mu\nu$
- **B lifetimes**
  - Λ_b lifetime
  - B_s lifetime and width difference Γ_s and $\Delta\Gamma_s$
- **Collect ~1.5 fb^{-1} in 2012 – Stay tuned**

Backup Slides

$B_s \to J/\psi\phi$ decay rates

- **Full differential decay rate**

$$\frac{d^4\Gamma(B_s^0 \to J/\psi\,\phi)}{dt\;d\Omega} \propto \sum_{k=1}^{10} h_k(t)\; f_k(\Omega)$$

$$\begin{aligned} h_k(t) \;=\; & N_k e^{-\Gamma_s t}\left[c_k\cos(\Delta m_s t) + d_k \sin(\Delta m_s t)\right. \\ & \left. + a_k \cosh\left(\tfrac{1}{2}\Delta\Gamma_s t\right) + b_k \sinh\left(\tfrac{1}{2}\Delta\Gamma_s t\right)\right] \end{aligned}$$

Coefficients a_k b_k c_k and d_k
for $\overline{B}_s$ c_k and d_k multiplied by –1

  - S-wave KK final state under ϕ peak $\rightarrow$ 4 additional terms

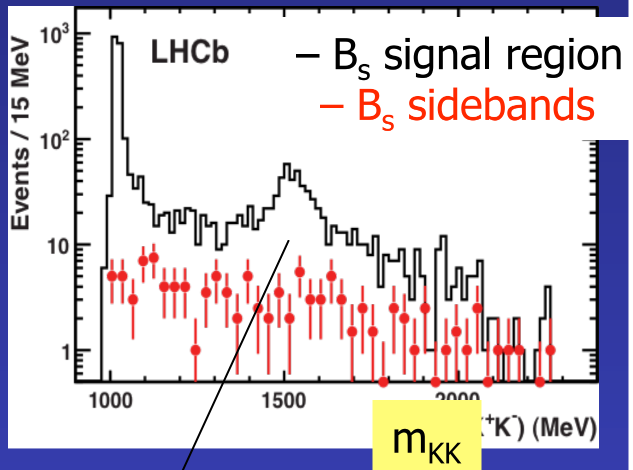
- **Physics parameters**

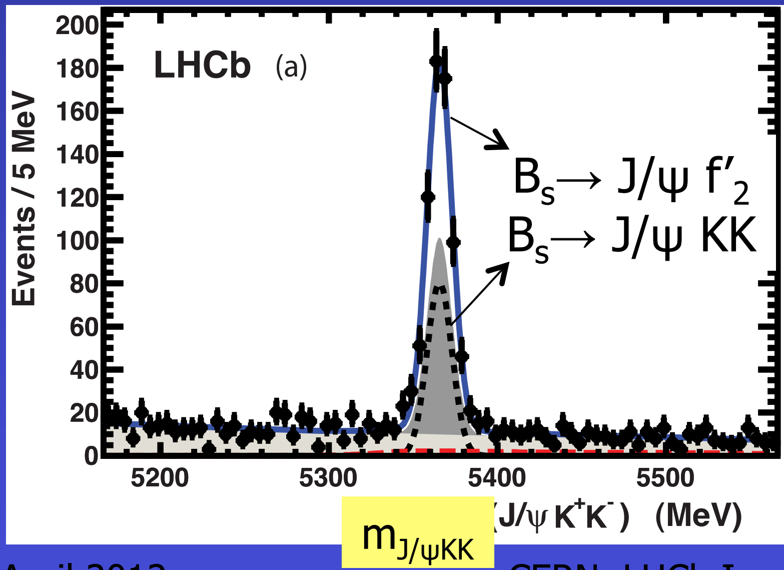
k	$f_k(\theta,\psi,\varphi)$	N_k	a_k	b_k	c_k	d_k
1	$2\cos^2\psi\left(1-\sin^2\theta\cos^2\phi\right)$	$\lvert A_0(0)\rvert^2$	1	$-\cos\phi_s$	0	$\sin\phi_s$
2	$\sin^2\psi\left(1-\sin^2\theta\sin^2\phi\right)$	$\lvert A_\|(0)\rvert^2$	1	$-\cos\phi_s$	0	$\sin\phi_s$
3	$\sin^2\psi\sin^2\theta$	$\lvert A_\perp(0)\rvert^2$	1	$\cos\phi_s$	0	$-\sin\phi_s$
4	$-\sin^2\psi\sin 2\theta\sin\phi$	$\lvert A_\|(0)A_\perp(0)\rvert$	0	$-\cos(\delta_\perp-\delta_\|)\sin\phi_s$	$\sin(\delta_\perp-\delta_\|)$	$-\cos(\delta_\perp-\delta_\|)\cos\phi_s$
5	$\frac{1}{2}\sqrt{2}\sin 2\psi\sin^2\theta\sin 2\phi$	$\lvert A_0(0)A_\|(0)\rvert$	$\cos(\delta_\|-\delta_0)$	$-\cos(\delta_\|-\delta_0)\cos\phi_s$	0	$\cos(\delta_\|-\delta_0)\sin\phi_s$
6	$\frac{1}{2}\sqrt{2}\sin 2\psi\sin 2\theta\cos\phi$	$\lvert A_0(0)A_\perp(0)\rvert$	0	$-\cos(\delta_\perp-\delta_0)\sin\phi_s$	$\sin(\delta_\perp-\delta_0)$	$-\cos(\delta_\perp-\delta_0)\cos\phi_s$
7	$\frac{2}{3}\left(1-\sin^2\theta\cos^2\phi\right)$	$\lvert A_s(0)\rvert^2$	1	$\cos\phi_s$	0	$-\sin\phi_s$
8	$\frac{1}{3}\sqrt{6}\sin\psi\sin^2\theta\sin 2\phi$	$\lvert A_s(0)A_\|(0)\rvert$	0	$-\sin(\delta_\|-\delta_S)\sin\phi_s$	$\cos(\delta_\|-\delta_S)$	$-\sin(\delta_\|-\delta_S)\cos\phi_s$
9	$\frac{1}{3}\sqrt{6}\sin\psi\sin 2\theta\cos\phi$	$\lvert A_s(0)A_\perp(0)\rvert$	$\sin(\delta_\perp-\delta_S)$	$\sin(\delta_\perp-\delta_S)\cos\phi_s$	0	$-\sin(\delta_\perp-\delta_S)\sin\phi_s$
10	$\frac{4}{3}\sqrt{3}\cos\psi\left(1-\sin^2\theta\cos^2\phi\right)$	$\lvert A_s(0)A_0(0)\rvert$	0	$-\sin(\delta_0-\delta_S)\sin\phi_s$	$\cos(\delta_0-\delta_S)$	$-\sin(\delta_0-\delta_S)\cos\phi_s$

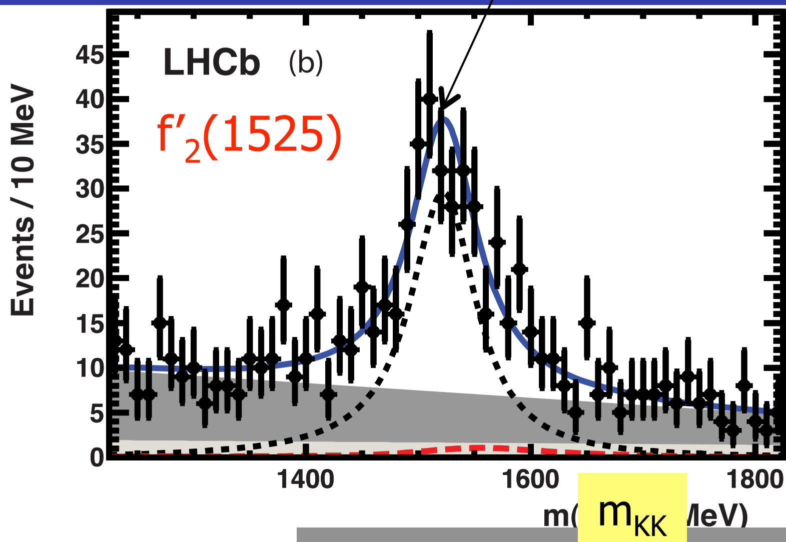
$B_s \rightarrow J/\psi f_J$

LHCb, arXiv:1112.4695,
Phys. Rev. Lett. 108, 151801 (2012)

- **First observation of $B_s \rightarrow J/\psi f'_2(1525)$**
  - observe $f'_2(1525) \rightarrow K^+K^-$ mass peak
  - dominant $\phi(1020)$ peak
  - non-resonant K^+K^- component
- **$B_s \rightarrow J/\psi f_0(980)$, $f_0(980) \rightarrow \pi^+\pi^-$**
  - pure CP-odd mode
  - no angular analysis required



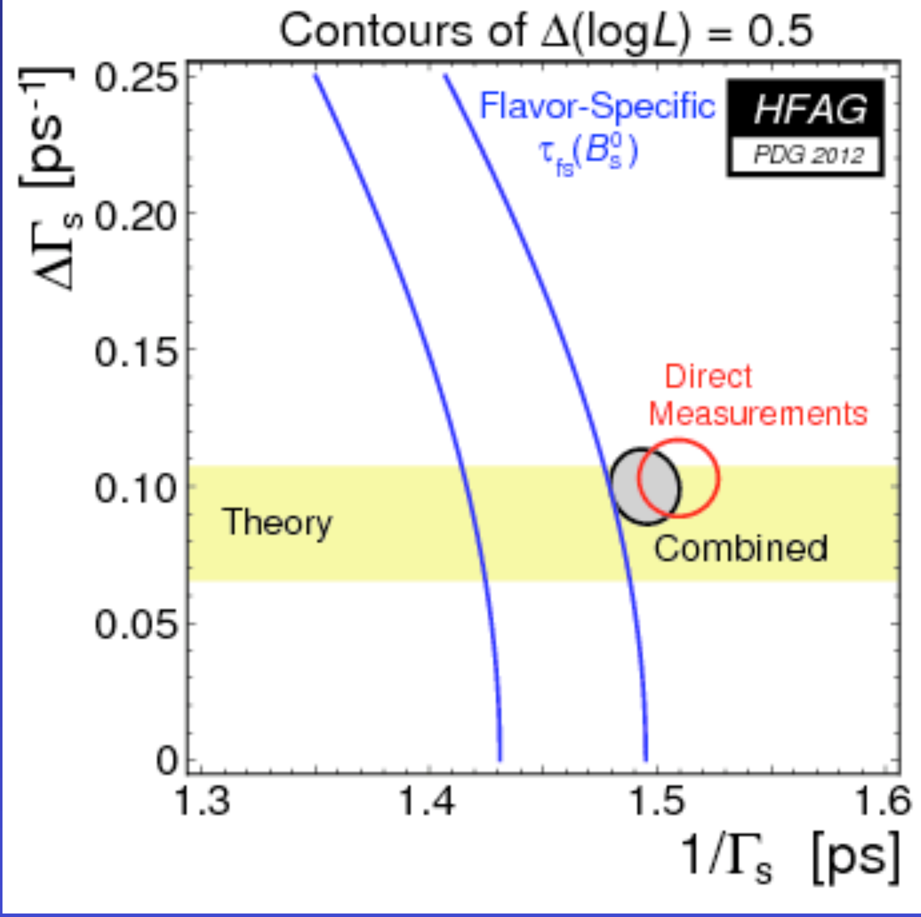


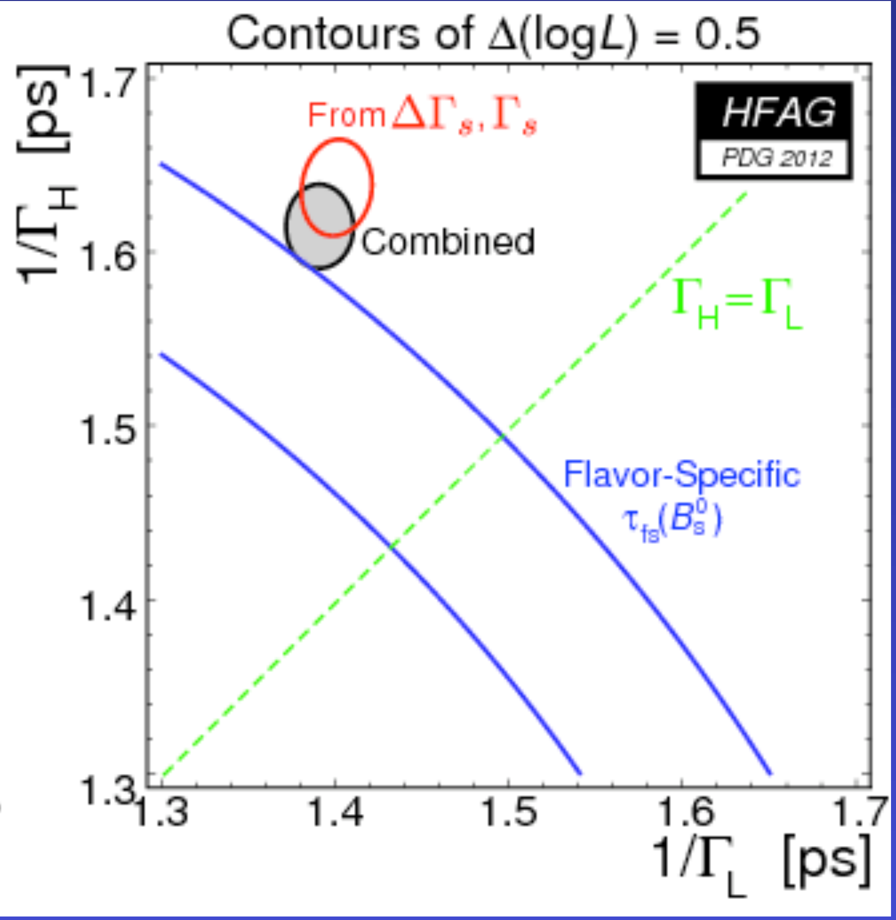


LHCb, PLB 707 (2012) 497

Lifetimes - Γ_s & $\Delta\Gamma_s$

- HFAG 2012





The End