Mixing Induced CP violation in B_s

Marina Artuso

On behalf of LHCb, including results from other collaborations

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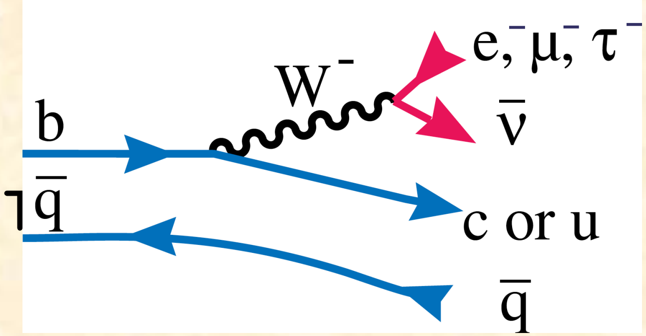
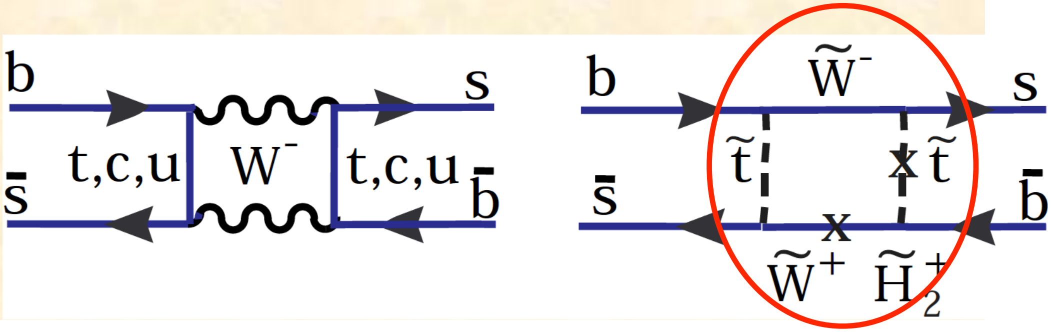
Outline

- Theoretical motivation
- Experimental method
- The semileptonic asymmetry a_{sl}^{s}
- The angle Φ_s
- Conclusions and outlook

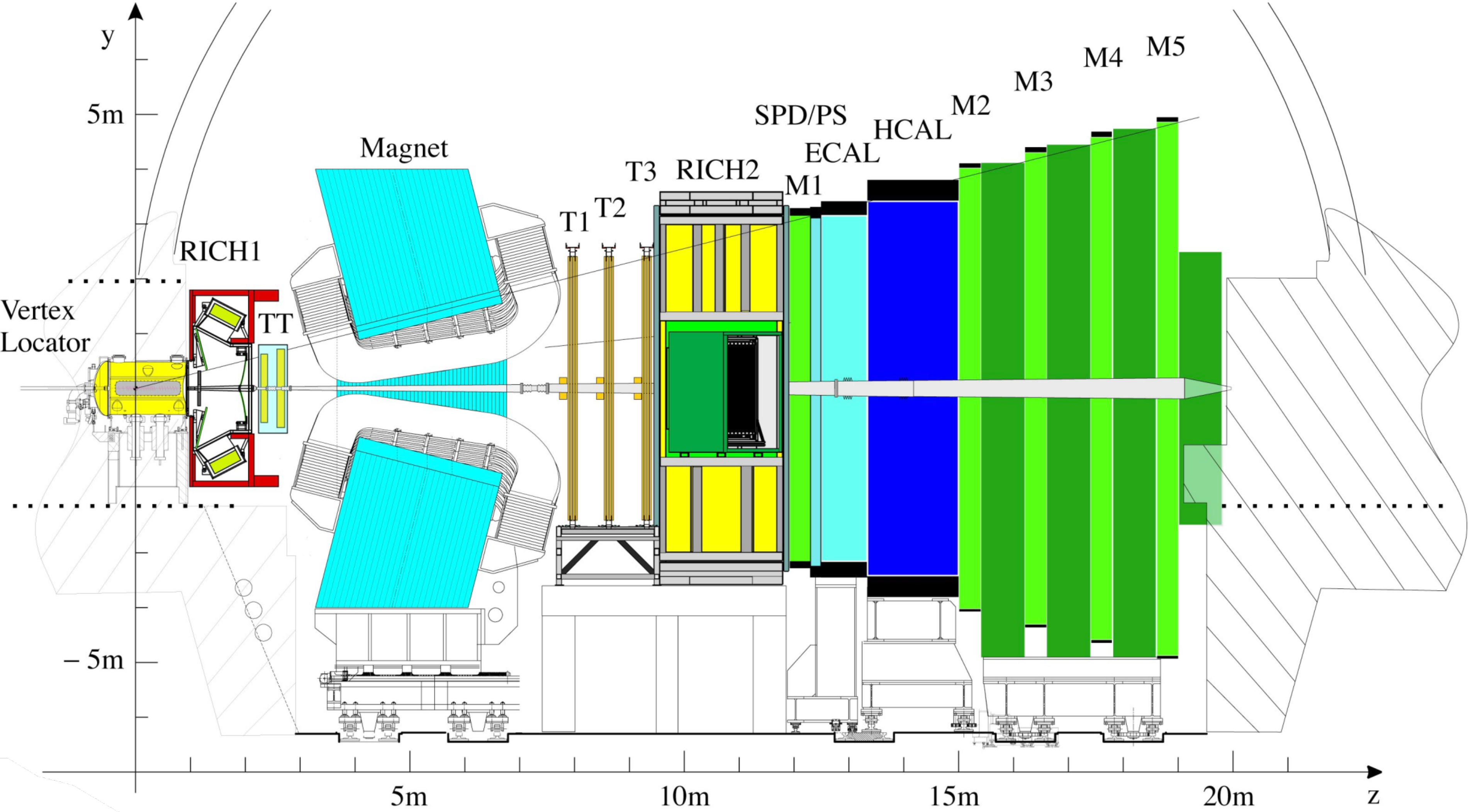
B_s mixing and new physics

- How can new physics manifest itself in beauty decays?
- One hypothesis: assume that tree level diagrams are dominated by Standard Model contributions and loop diagrams can include measurable contributions mediated by new particles





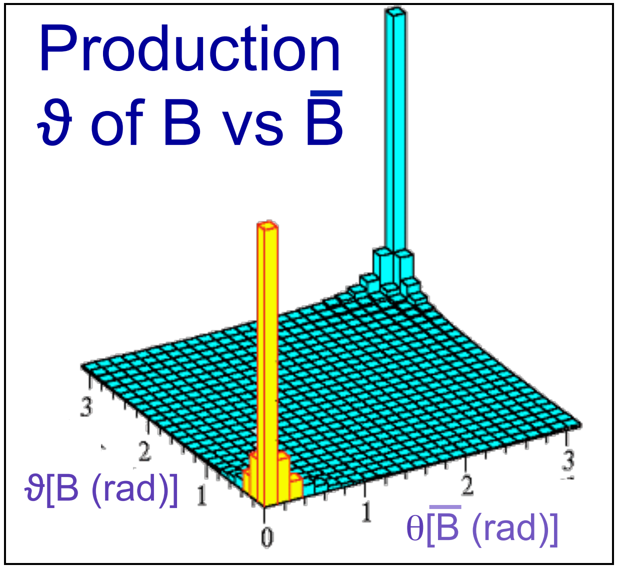
The LHCb detector



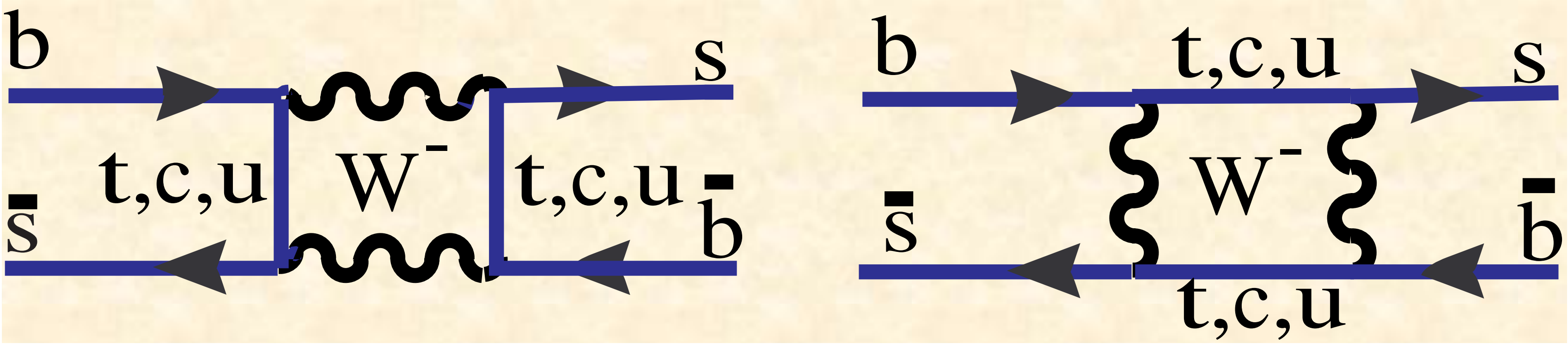
The Forward Direction at the LHC

- In the forward region at LHC the $b\bar{b}$ production σ is large
- The hadrons containing the b & $\bar{b}$ quarks are both likely to be in the acceptance. Essential for "flavor tagging"
- LHCb uses the forward direction where the B's are moving with considerable momentum ~100 GeV, thus minimizing multiple scattering
- At $\mathcal{L}=4\times10^{32}/\text{cm}^2/\text{s}$, we get $\sim10^{12}$ B hadrons in 10^7 sec in the LHCb acceptance.

Measured cross section at 7 TeV in LHCb acceptance is ~90 μb


Production ϑ of B vs $\bar{B}$

CP violation in B_s mixing



Time evolution of Flavor Eigenstates

$$i\frac{d}{dt}\begin{pmatrix} B_s^0 \\ \bar{B}_s^0 \end{pmatrix} = \begin{pmatrix} M_{11}^s - i\frac{\Gamma_{11}^s}{2} & M_{12}^s - i\frac{\Gamma_{12}^s}{2} \\ M_{12}^{s*} - i\frac{\Gamma_{12}^{s*}}{2} & M_{22}^s - i\frac{\Gamma_{22}^s}{2} \end{pmatrix} \begin{pmatrix} B_s^0 \\ \bar{B}_s^0 \end{pmatrix}$$

Mass eigenstates

$$\begin{cases} \left|B_{sL}^0\right\rangle = p\left|B_s^0\right\rangle + q\left|\bar{B}_s^0\right\rangle \\ \left|B_{sH}^0\right\rangle = p\left|B_s^0\right\rangle - q\left|\bar{B}_s^0\right\rangle \end{cases}$$

The flavor specific asymmetry

$$a^s = \frac{1-\left|\frac{q}{p}\right|^4}{1+\left|\frac{q}{p}\right|^4} = \mathrm{Im}\left(\frac{\Gamma_{12}^s}{M_{12}^s}\right) + O\left(\left(\mathrm{Im}\frac{\Gamma_{12}^s}{M_{12}^s}\right)^2\right) = \left|\frac{\Gamma_{12}^s}{M_{12}^s}\right| \sin\phi_{12}^s$$

We can access a^s by measuring asymmetries in flavor specific final states, for example semileptonic decays.

$$a_{sl}^s \equiv \frac{\Gamma(\overline{B}_s^0 \to D_s^- \mu^+ \nu) - \Gamma(B_s^0 \to D_s^+ \mu^- \overline{\nu})}{\Gamma(\overline{B}_s^0 \to D_s^- \mu^+ \nu) + \Gamma(B_s^0 \to D_s^+ \mu^- \overline{\nu})} = \frac{1-(1-a_s)^2}{1+(1-a_s)^2} \sim a^s$$

Standard Model predictions

$$\begin{cases} a_{sl}^s = (1.9 \pm 0.3) \times 10^{-5} \\ a_{sl}^d = (-4.1 \pm 0.6) \times 10^{-4} \end{cases}$$

A.Lenz
arXiv:1205.1444

LHCb measurement of a_{sl}^{s}

Phys.Lett. B728 (2014)607/arXiv:1308.1048

Untagged semileptonic asymmetry

B_s^0 / $\overline{B}_s^0$

Production asymmetry

a_p effect diluted by the fast B_s (x0.2%) oscillations⇒$a_{sl}{}^{s}=2A_{meas}$

$$A_{meas} \equiv \overbrace{\frac{\Gamma[D_s^- \mu^+] - \Gamma[D_s^+ \mu^-]}{\Gamma[D_s^- \mu^+] + \Gamma[D_s^+ \mu^-]} = \frac{a_{sl}^s}{2}} + \left(\boxed{a_p} - \frac{a_{sl}^s}{2} \right) \overbrace{\frac{\int\limits_{t=0}^{\infty} e^{-\Gamma_s t} \cos(\Delta m_s t) \varepsilon(t)\, dt}{\int\limits_{t=0}^{\infty} e^{-\Gamma_s t} \cosh(\frac{\Delta \Gamma_s t}{2}) \varepsilon(t)\, dt}}$$

$$\boxed{A_{meas}^{s} = A_{\mu corr} - A^{track} - A_{bkg}}$$

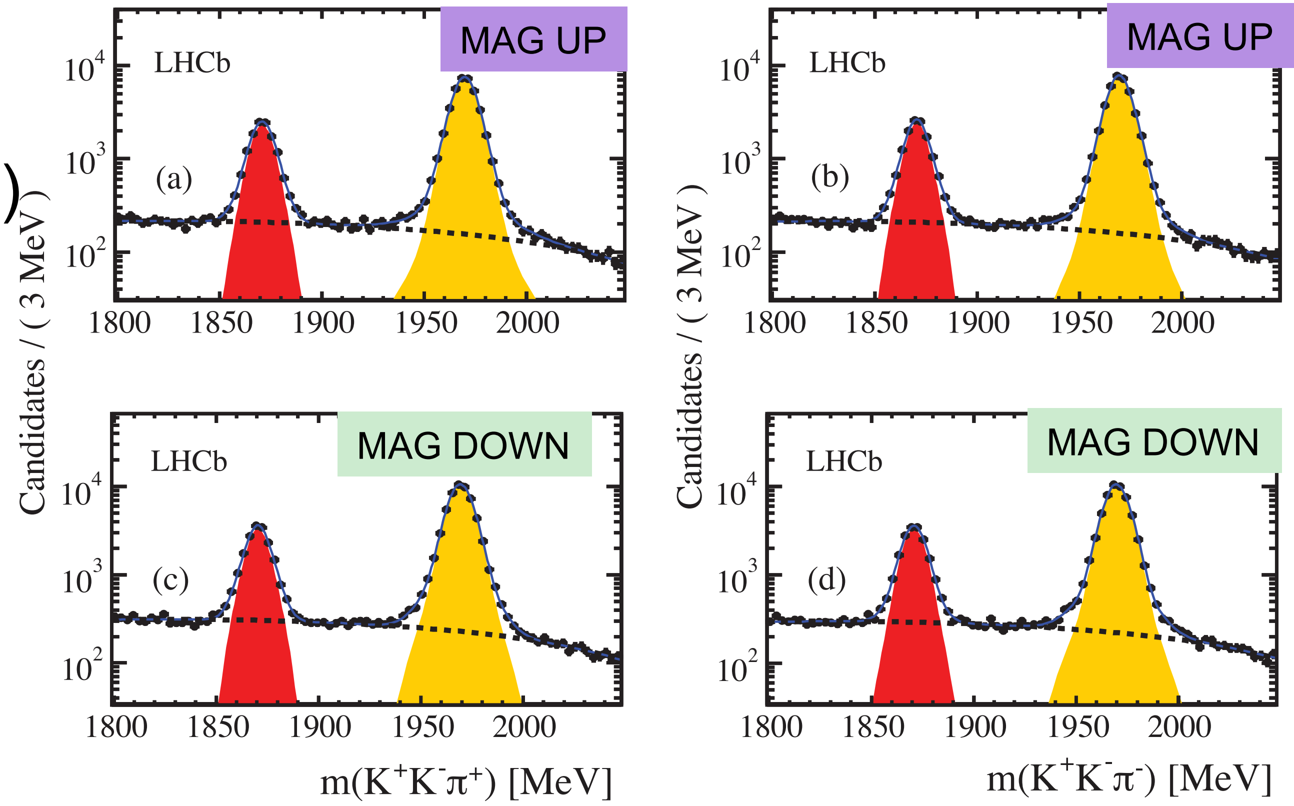
$$\boxed{A_{\mu corr} = \frac{\frac{N(D_s^- \mu^+)}{\varepsilon_{\mu^+}} - \frac{N(D_s^+ \mu^-)}{\varepsilon_{\mu^-}}}{\frac{N(D_s^- \mu^+)}{\varepsilon_{\mu^+}} + \frac{N(D_s^+ \mu^-)}{\varepsilon_{\mu^-}}}}$$

Key analysis points

Phys.Lett. B728 (2014)607
arXiv:1308.1048

447 pb^{-1} collected with magnet polarity UP and 595 pb^{-1} collected with magnet polarity DOWN (1/3 of RUN I data)

- ❑ Final states studied
  $D_s^{\pm}\mu^{\mp}, D_s^{\pm} \to \varphi\pi^{\pm}$
- ❑ Analysis in two binning schemes in μ kinematics (p, p_t, ϕ) & (p, p_x, p_y)
- ❑ Efficiencies determined with dedicated data samples
- ❑ Backgrounds estimated mostly from data



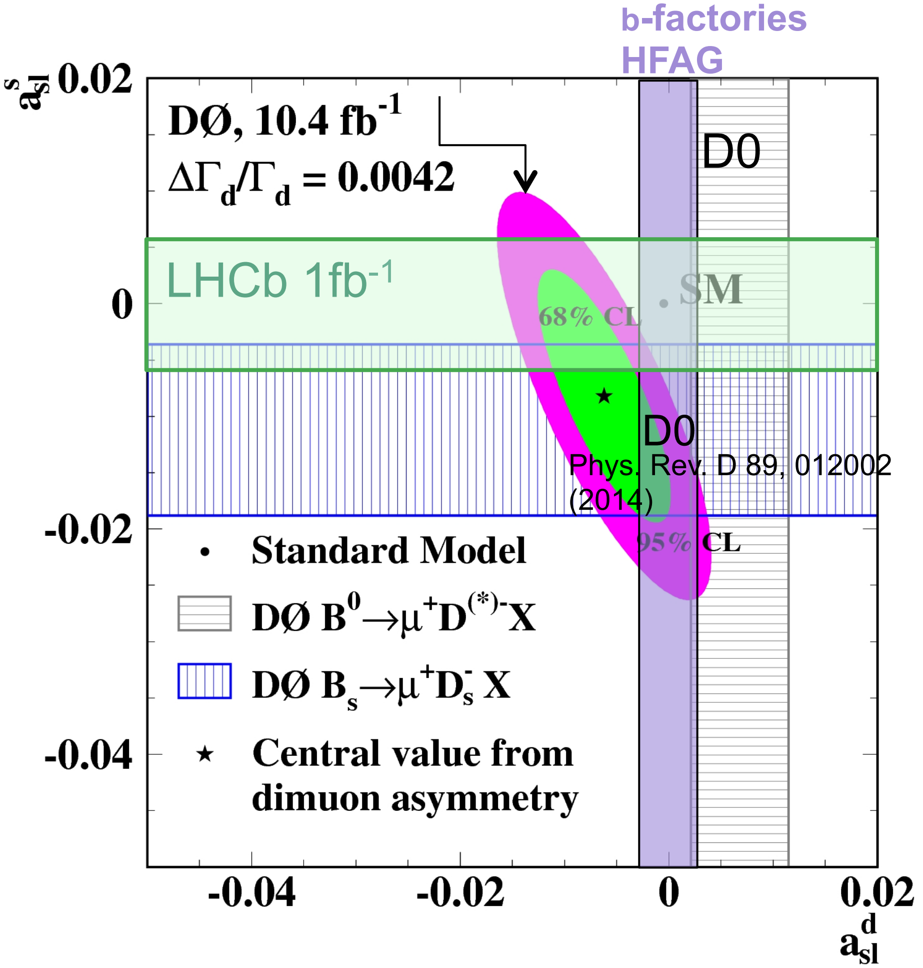
LHCb Result

Phys.Lett. B728 (2014)607/arXiv:1308.1048

$$a_{sl}^{s} = (-0.06 \pm 0.50 \pm 0.36)\%$$

Source of systematic uncertainty	$[\sigma(a_{sl}^{s})(\%)]$
Signal modeling and muon corrections	0.14
Stat. uncertainty on muon e	0.16
Background subtraction	0.10
Asymmetry in track reconstruction	0.26
Varying conditions between field up and down	0.02
Software trigger bias	0.10
total	0.36

LHCb results on 3fb^{-1} data sample will be available soon



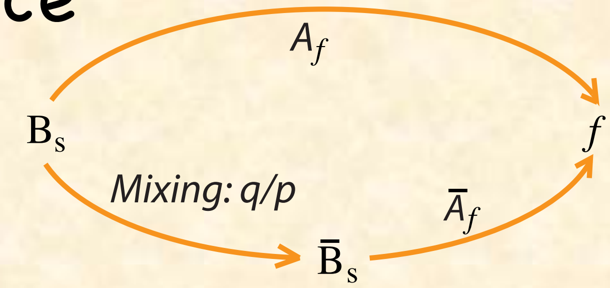
$$a_{sl}^{s} = (1.9 \pm 0.3) \times 10^{-5}$$

$$a_{sl}^{d} = (-4.1 \pm 0.6) \times 10^{-4}$$

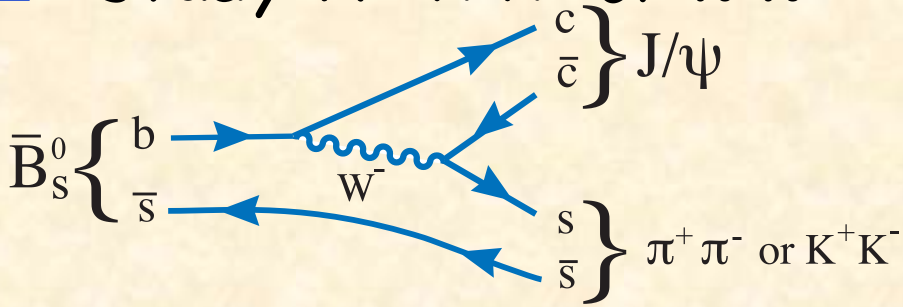
A.Lenz
arXiv:1205.1444

CPV in $B_s \to J/\psi\ X$

- CPV can occur via interference between mixing & decay



- Study X= K^+K^- or $\pi^+\pi^-$



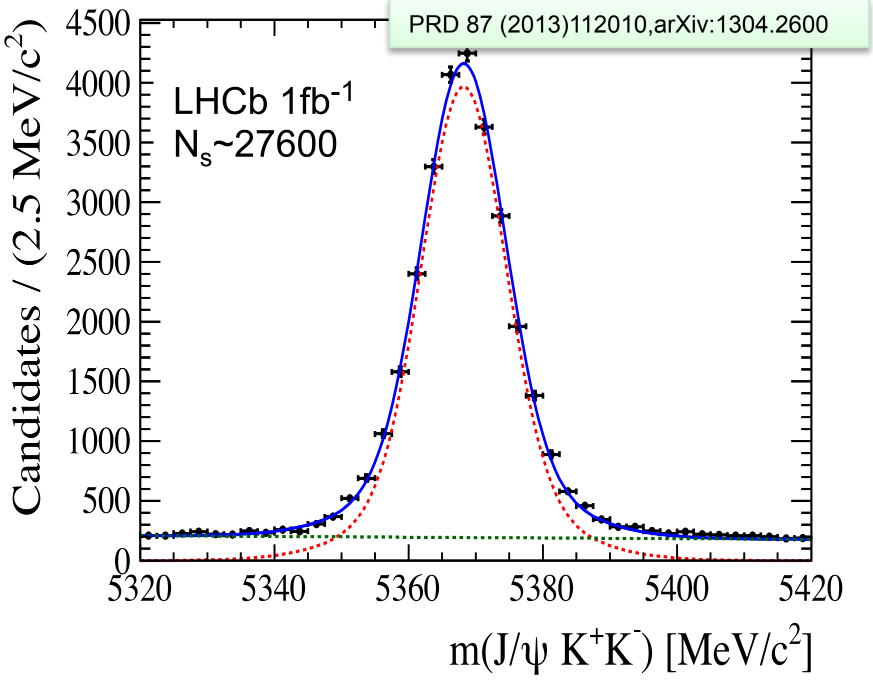
$$\varphi_s^{SM} \equiv -2\beta_s = -2\arg\left(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right) = -36.3^{+1.6}_{-1.5}\ mrad$$

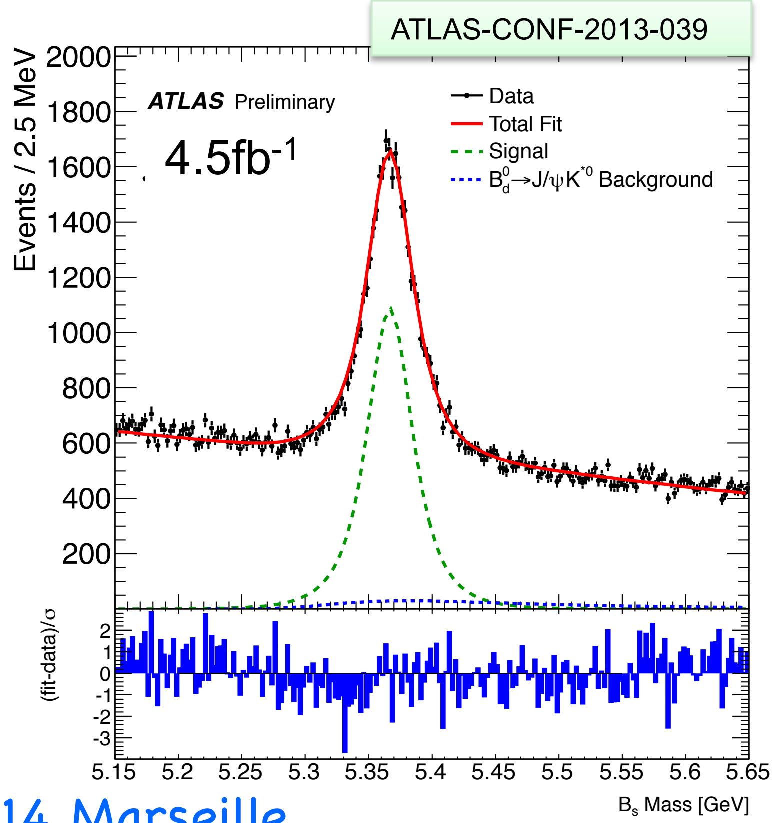
J. Charles et al., Phys.Rev.D84(2011)033005, arXiv:1106.4041

- Small CPV expected (note small theoretical errors!) ⟹ good place for NP to appear

CP violation in $B_s \to J/\psi K^+K^-$

- ❑ $B_s \to J/\psi K^+K^-$ predominantly $J/\psi\phi$
- ❑ small non-resonant component with KK in s-wave
- ❑ Angular analysis necessary to disentangle CP even and CP odd final states
- ❑ B_s flavor tagging needed





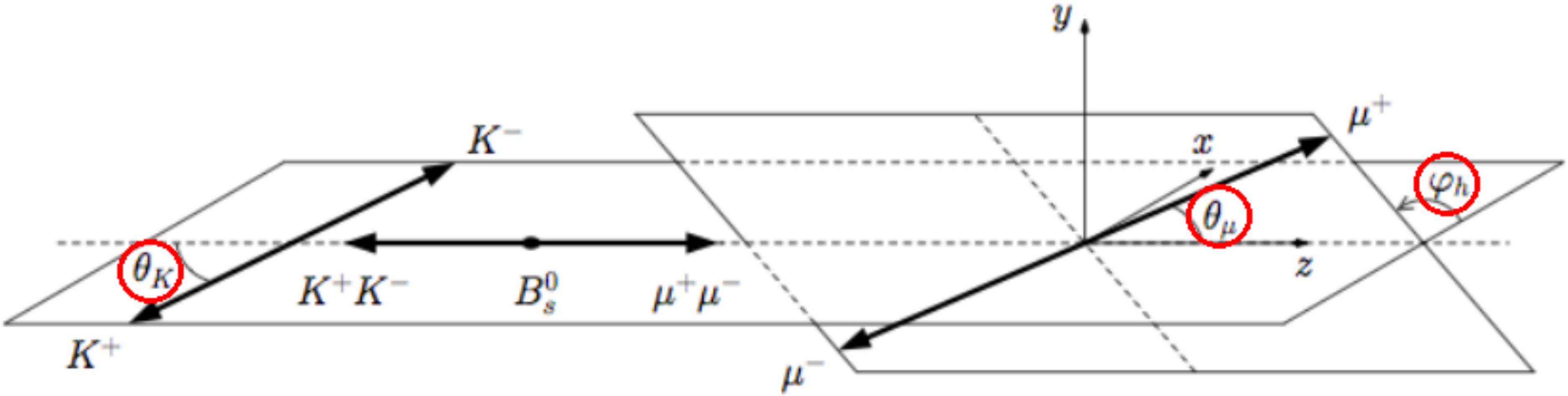
CMS studies in progress

LHCb Fitting method

PRD 87 (2013)112010,arXiv:1304.2600

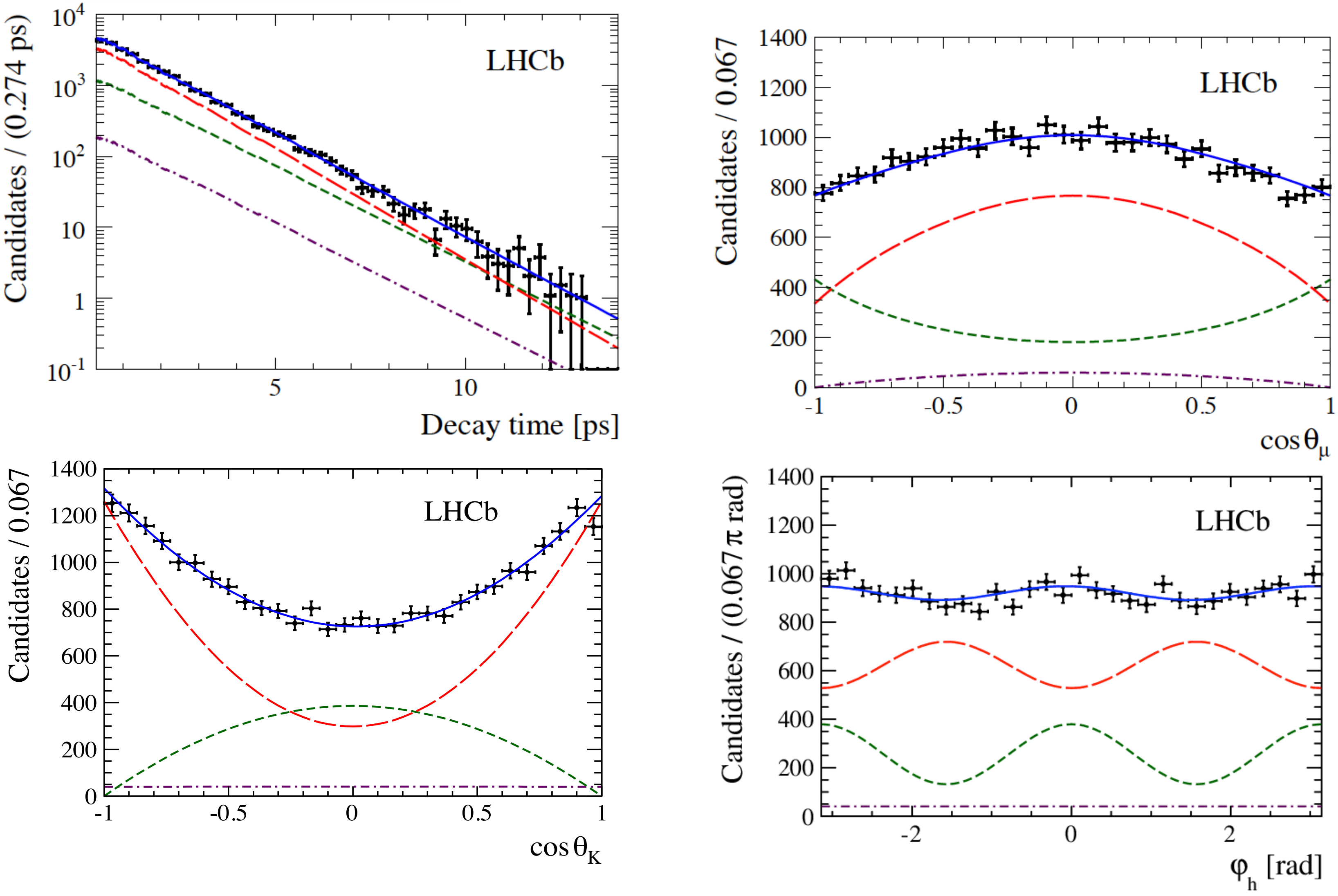
- Unbinned maximum likelihood fit in 4 dimensions: B_s proper time and 3 helicity angles θ_K,θ_μ, and ϕ_h
- Different lifetimes for CP odd and even components:

$$\Delta\Gamma_s \equiv \Gamma_L - \Gamma_H$$



$B_s \rightarrow J/\psi\phi$ angular and decay time projections

PRD 87 (2013)112010,arXiv:1304.2600



LHCb results

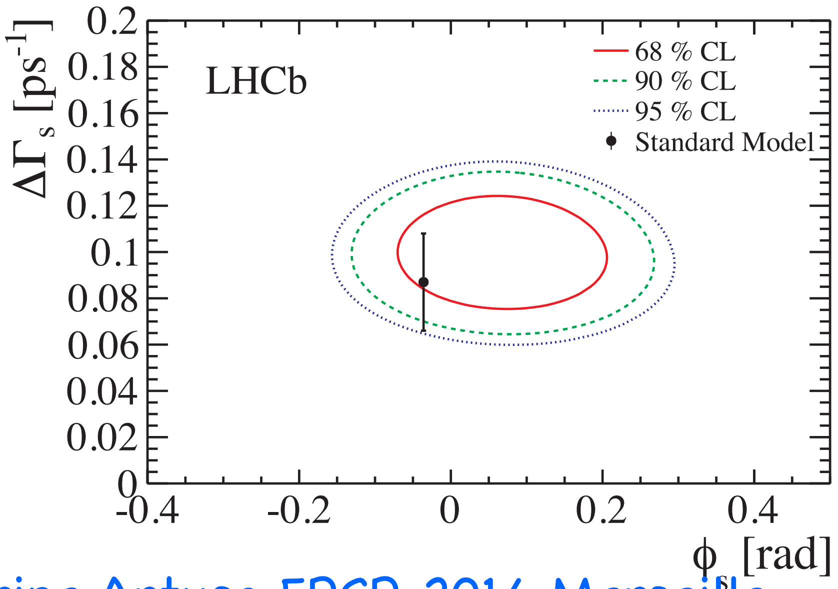
PRD 87 (2013)112010,arXiv:1304.2600

- From the 1fb^{-1} data set, LHCb obtains:

$$\Phi_s = +0.07 \pm 0.09 \pm 0.01\, rad$$

$$\Gamma_s = 0.663 \pm 0.005 \pm 0.006\ ps^{-1}$$

$$\Delta\Gamma_s = 0.100 \pm 0.016 \pm 0.003\ ps^{-1}$$



ATLAS Φ_s measurement

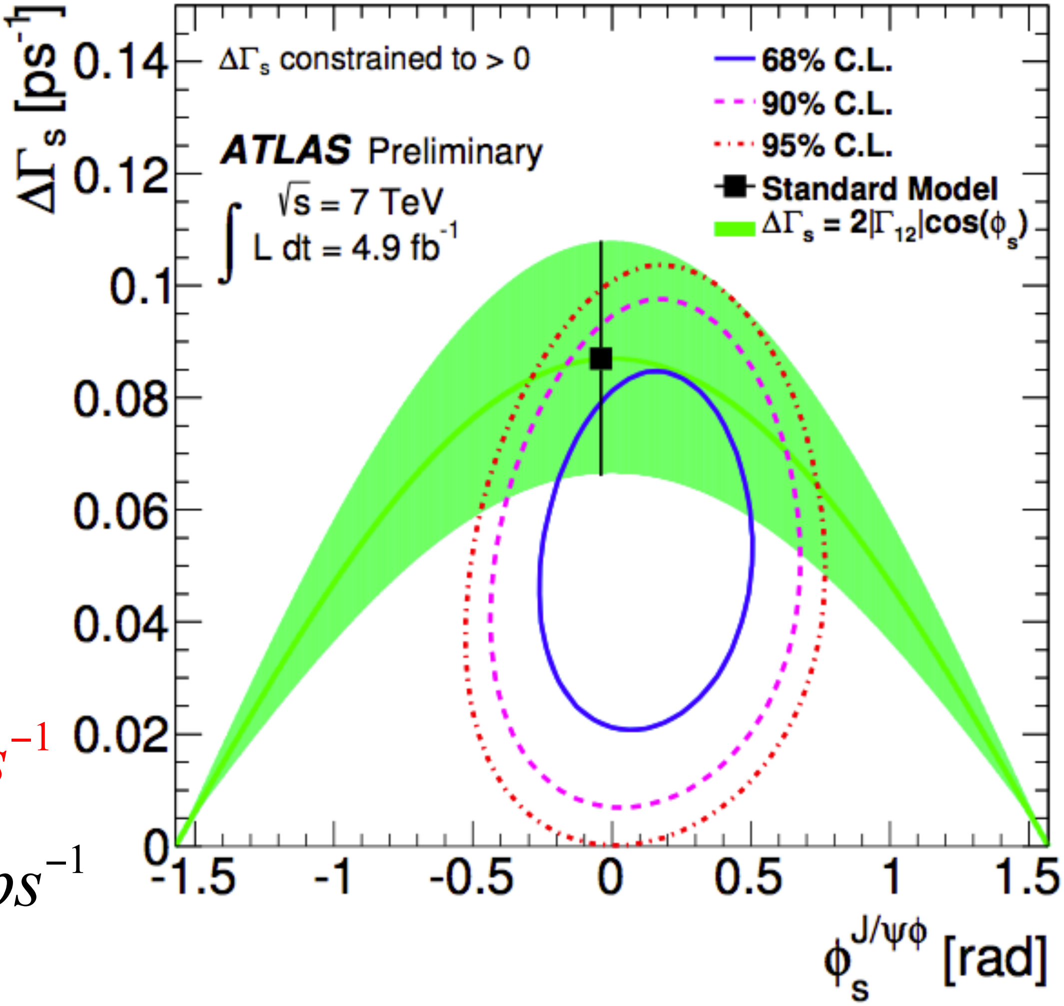
ATLAS-CONF-2013-039

- ☐ Unbinned maximum likelihood fit using reconstructed mass, measured proper time, measured mass and proper time uncertainty, the tag probability and the helicity angles of the B_s candidates gives:

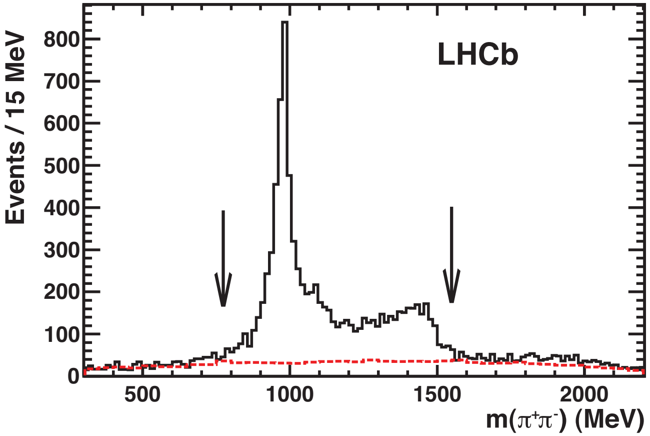
$$\Phi_s = +0.12 \pm 0.25 \pm 0.11\, rad$$

$$\Gamma_s = 0.677 \pm 0.007 \pm 0.003\ ps^{-1}$$

$$\Delta\Gamma_s = 0.053 \pm 0.021 \pm 0.009\ ps^{-1}$$



CPV in $B_s \rightarrow J/\psi\pi^+\pi^-$



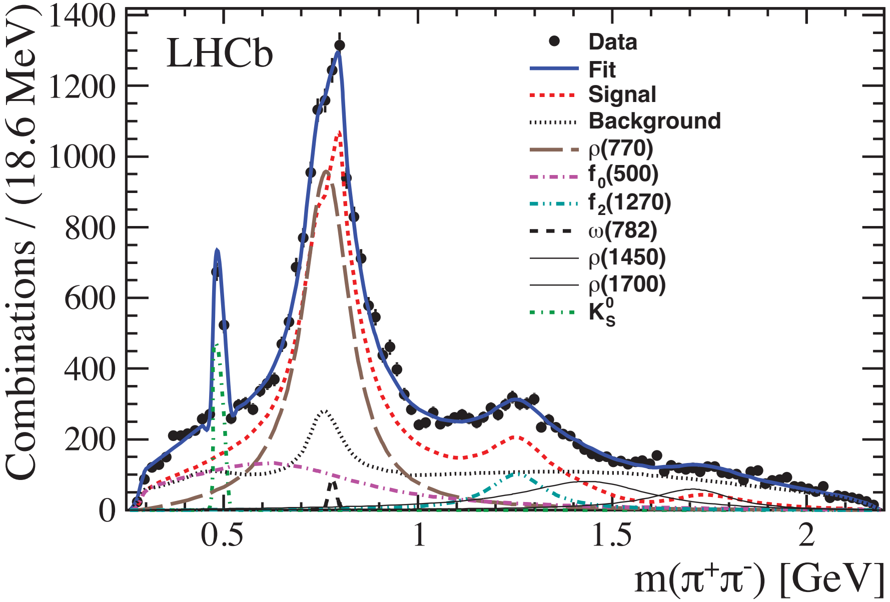
- ☐ $J/\psi f_0(980)$ suggested as being a useful state for measuring Φ_s as it is a CP-eigenstate [Stone,Zhang, PRD 79(2009)074024] ⇒ no need of angular analysis.
- ☐ Extended to CP odd S-wave $\pi^+\pi^-$ final state gives [PLB 713 (2012)]378,arXiv:1204.5675]

$$\boxed{\Phi_s = -19^{+173+4}_{-174-3}\ mrad}$$

❑ Is the f_0 a tetraquark? If so, things are not so simple! [Fleisher, Knegjens,Ricciardi,arXiv:1109.1112]

What is the true nature of the f_0? The clue from $B^0 \rightarrow J/\psi\pi\pi$

arXiv:1404.5673



More details in Darya Savrina’s talk

- Ratio between $f_0(980)$ and $f_0(500)$ elucidates nature of $f_0(980)$

Stone,Zhang, PRL 111(2013)062001,arXiv:1305.6554

- The $f_0(980)$ meson is not seen in $B^0 \rightarrow J/\psi\pi^+\pi^- \Rightarrow$ inconsistent with having a tetraquark substructure at the eight standard deviation level.
- Mixing angle with $f_0(500) < 17^\circ$ at 90% CL

Measurement of Φ_s in $B_s \to J/\psi\pi^+\pi^-$

New!

arXiv:1405.4140

- LHCb constructs a model for this decay considering a superposition of 5 final state $\pi\pi$ resonances + (possibly) non-resonant component
- CP even and CP odd components disentangled with angular analysis

For each resonant (+ non-resonant) final state:

General expression of time dependent decay rates:

$$\Gamma(t) = \mathcal{N}e^{-\Gamma_s t}\left\{\frac{|\mathcal{A}|^2+|\overline{\mathcal{A}}|^2}{2}\cosh\frac{\Delta\Gamma_s t}{2}+\frac{|\mathcal{A}|^2-|\overline{\mathcal{A}}|^2}{2}\cos(\Delta m_s t)\right.$$
$$\left.-\mathcal{R}e(\mathcal{A}^*\overline{\mathcal{A}})\sinh\frac{\Delta\Gamma_s t}{2}-\mathcal{I}m(\mathcal{A}^*\overline{\mathcal{A}})\sin(\Delta m_s t)\right\}$$

$$\overline{\Gamma}(t) = \left|\frac{p}{q}\right|^2\mathcal{N}e^{-\Gamma_s t}\left\{\frac{|\mathcal{A}|^2+|\overline{\mathcal{A}}|^2}{2}\cosh\frac{\Delta\Gamma_s t}{2}-\frac{|\mathcal{A}|^2-|\overline{\mathcal{A}}|^2}{2}\cos(\Delta m_s t)\right.$$
$$\left.-\mathcal{R}e(\mathcal{A}^*\overline{\mathcal{A}})\sinh\frac{\Delta\Gamma_s t}{2}+\mathcal{I}m(\mathcal{A}^*\overline{\mathcal{A}})\sin(\Delta m_s t)\right\}$$

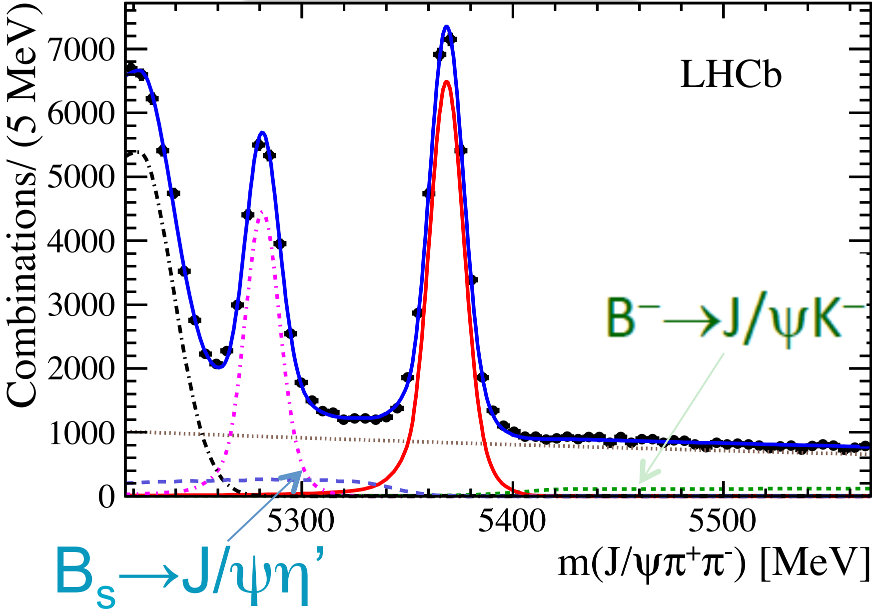
$\mathcal{A} \equiv A_f$ and $\overline{\mathcal{A}} \equiv \frac{q}{p}\overline{A}_f$

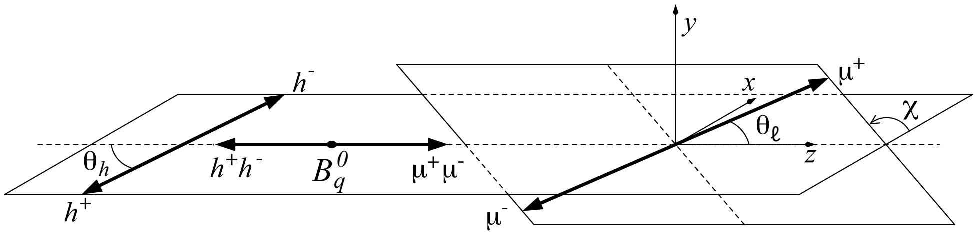
Decay amplitudes

Analysis Method

arXiv:1405.4140

- Data set: 3 fb^{-1} (total of run 1 data) (~27100 signal events)
- Only events within ±20 MeV of B_s mass peak are used in CP violation fit

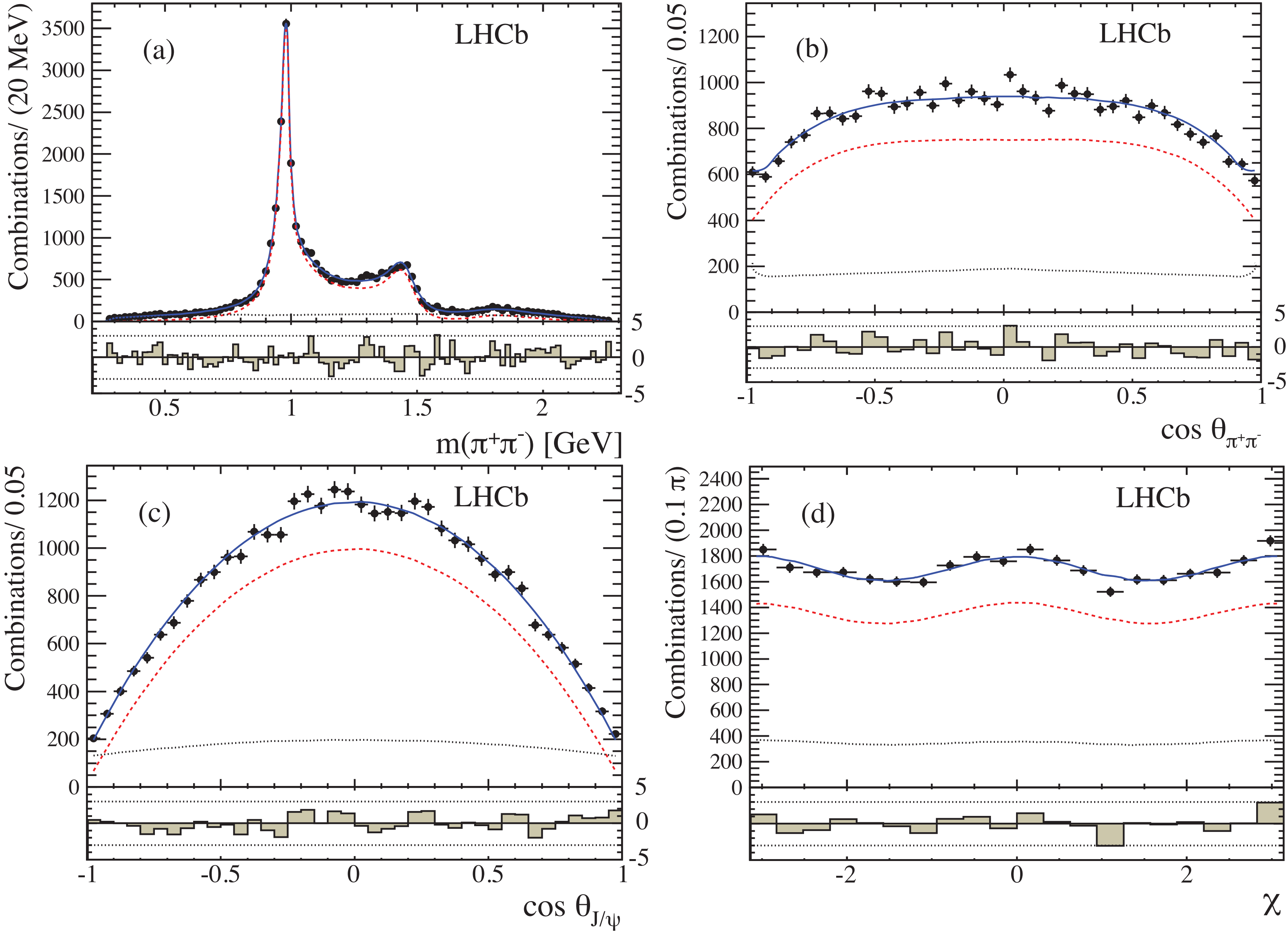




CP even and odd decay amplitudes measured simultaneously

CP violation fit

arXiv:1405.4140



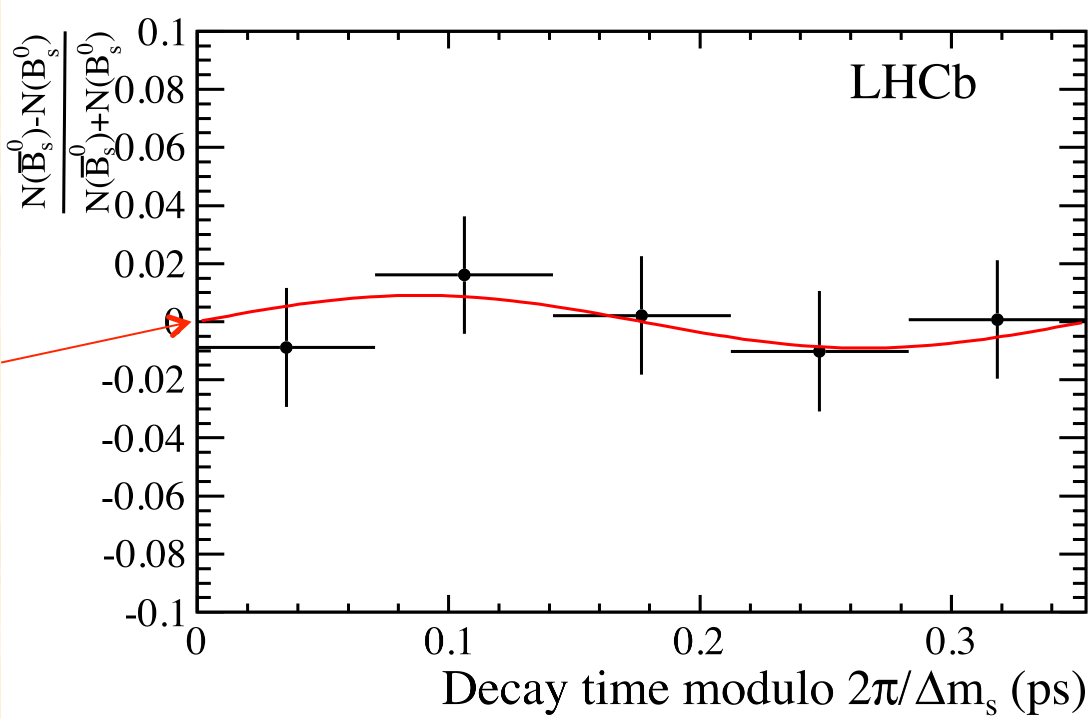
Results

arXiv:1405.4140

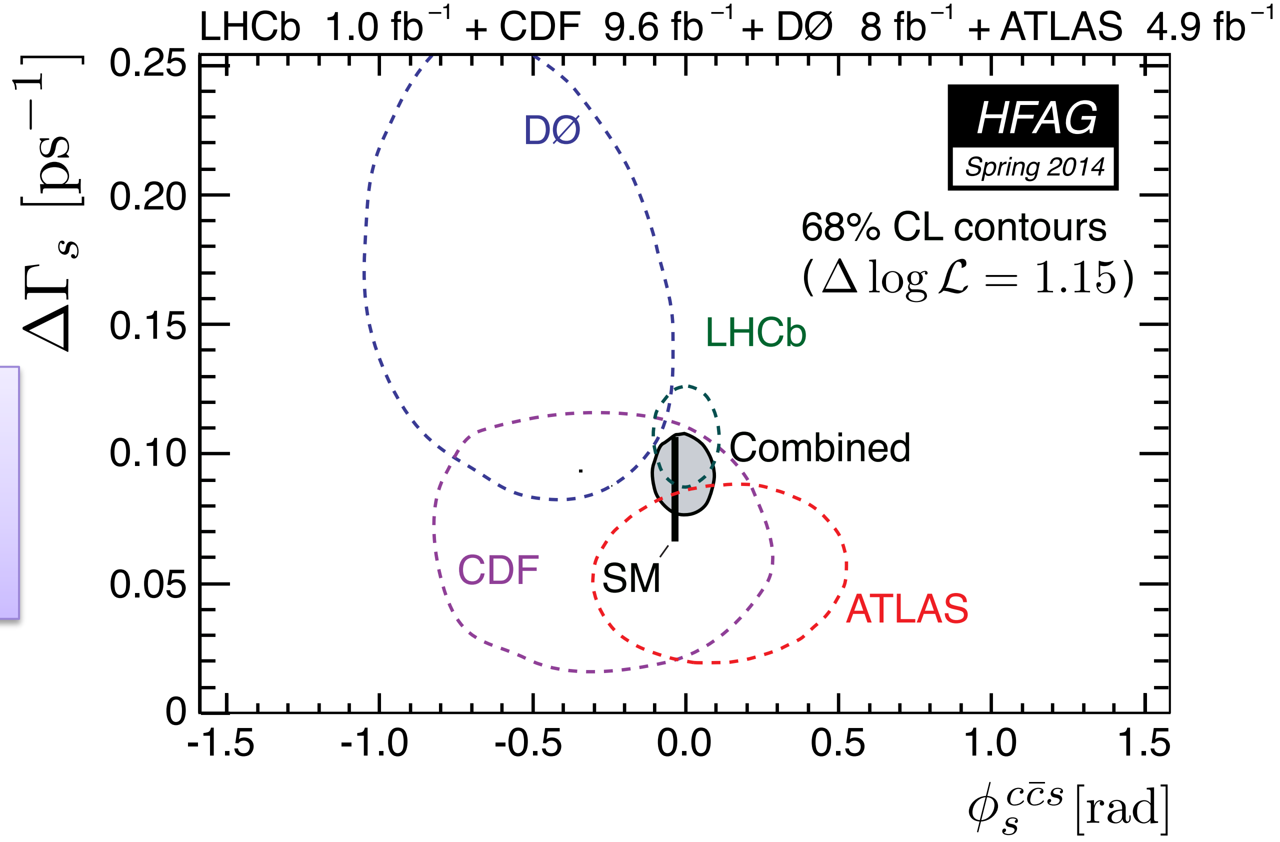
- Mixing induced CPV phase **$\Phi_s=(70\pm68\pm8)$ mrad**
- Note statistical error smaller than error from combined J/ψKK and J/ψππ fit in 1 fb^{-1} data
- Presence of $\sin(\Phi_s)$ can be discerned from background-subtracted tagged yields as a function of decay time
- Current naïve average of LHCb J/ψKK and J/ψππ data would give **UNOFFICIAL** AVERAGE

$$\boxed{\Phi_s = 70 \pm 54 \pm 8\ mrad}$$

Red curve: expectation for Φ_s = 70 mrad



Current ϕ_s measurements



More details on $\Delta\Gamma_s$ in talk by S.Stone

HFAG Spring 2014 Average $\Phi_s^{c\bar{c}s} = 0 \pm 70\ mrad$

Current Unofficial LHCb Average $\Phi_s^{c\bar{c}s} = 70 \pm 54 \pm 8\ mrad$

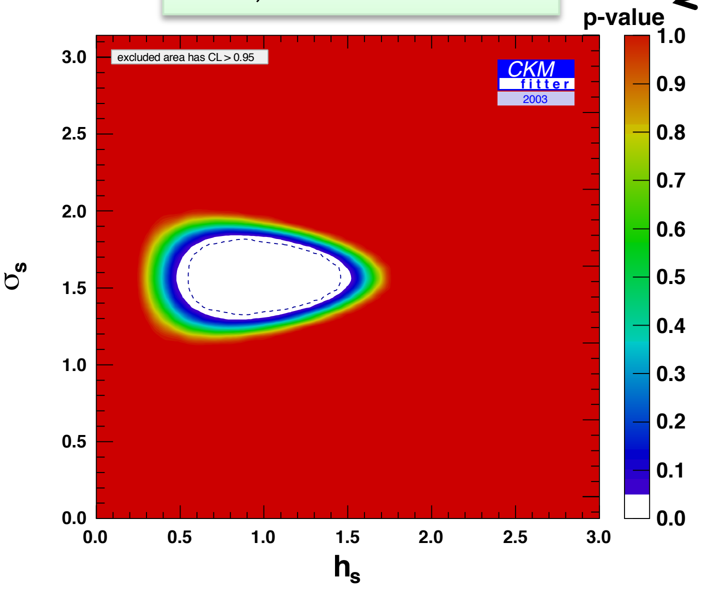
Putting it all together

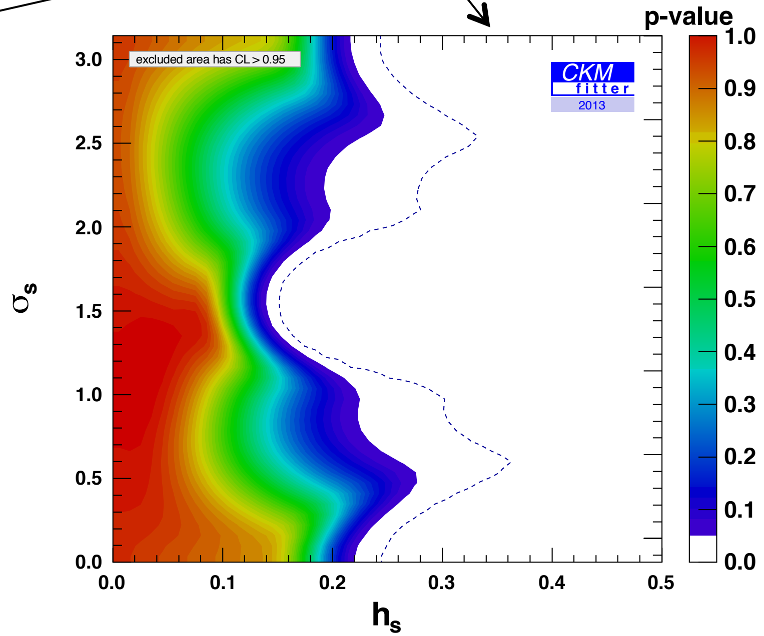
Data on a_{sl}^{s}, and Φ_s are among the inputs used in a generic parameterization of new physics in B_s mixing:

$$M_{12} = \underbrace{M_{12}^{\rm SM}\, r^2\, e^{2i\theta}}_{\text{easy to relate to data}} \equiv \underbrace{M_{12}^{\rm SM}(1 + h\, e^{2i\sigma})}_{\text{easy to relate to models}}$$

Charles et al.,arXiv:1309.2293

2003, before LHCb



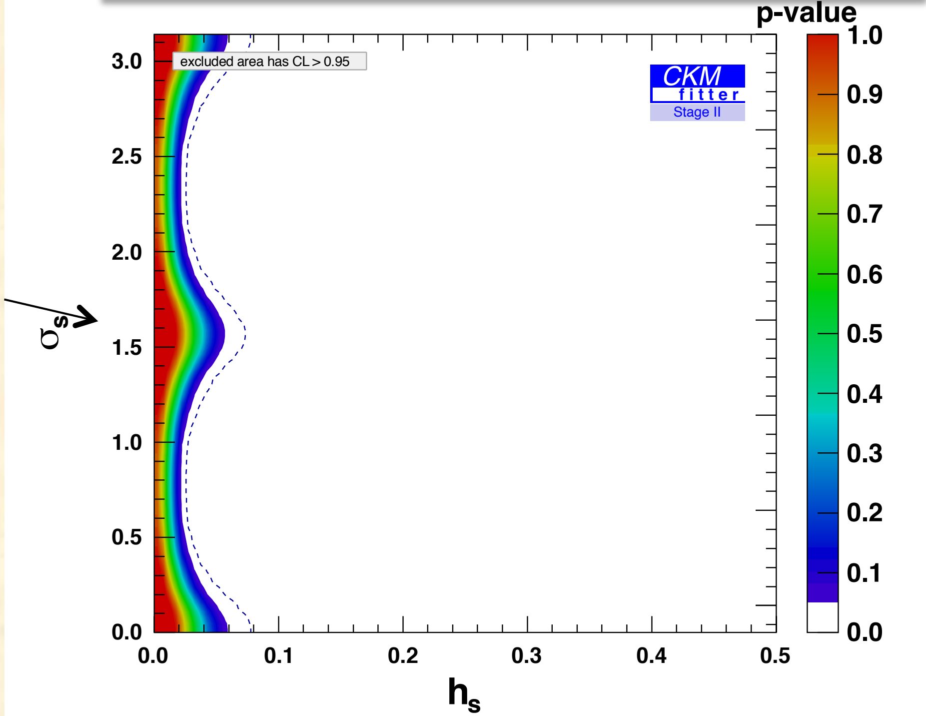


The future

- In order to develop a complete picture we need more statistics! The LHCb upgrade is clearly needed to reach a firm conclusion.
- Our knowledge of key parameters of CPV in Bs mixing has increased a lot but much more is yet to come!

Charles et al.,arXiv:1309.2293

Sensitivity 50fb^{-1} LHCb data (LHCb Upgrade)



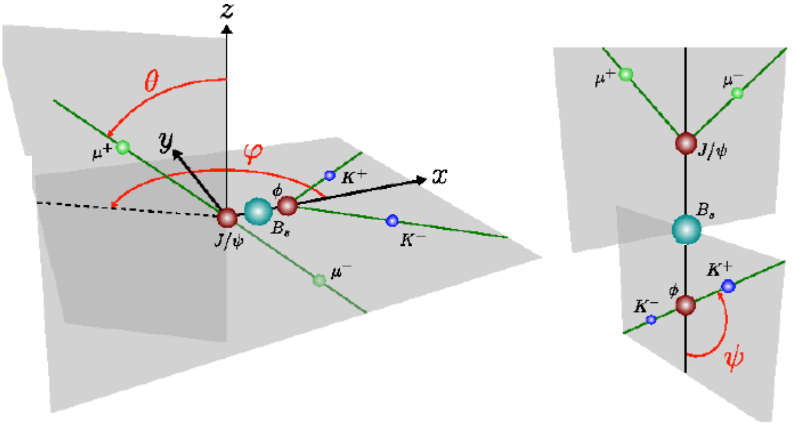
THE END

Summary of Φ_s and $\Delta\Gamma_s$ measurements

	Φ_s (mrad)	$\Delta\Gamma_s$ (ps^{-1})
LHCb (3fb^{-1} $J/\psi\ \pi^+\pi^-$)	70±68±8	
LHCb (Moriond)	70±90±10	0.100±0.016±0.003
ATLAS	120±250±110	0.053±0.021±0.009
CMS	-	0.048±0.024±0.003
CDF	-600 - 120	0.068±0.026±0.009
D0	560	0.179±0.060

Transversity

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



k	$h_k(t)$	$f_k(\theta,\psi,\varphi)$
1	$\lvert A_0\rvert^2(t)$	$2\cos^2\psi\,(1-\sin^2\theta\cos^2\phi)$
2	$\lvert A_\parallel(t)\rvert^2$	$\sin^2\psi\,(1-\sin^2\theta\sin^2\phi)$
3	$\lvert A_\perp(t)\rvert^2$	$\sin^2\psi\sin^2\theta$
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	$\lvert A_s(t)\rvert^2$	$\frac{2}{3}(1-\sin^2\theta\cos^2\phi)$
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	$\Re(A_s^*(t)A_0(t))$	$\frac{4}{3}\sqrt{3}\cos\psi(1-\sin^2\theta\cos^2\phi)$

for S-wave under ϕ predicted by Stone & Zhang PRD 79, 074024 (2009)

Transversity II

$$
\begin{aligned}
|A_0|^2(t) &= |A_0|^2 e^{-\Gamma_s t}[\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)]\,, \\
|A_\|(t)|^2 &= |A_\||^2 e^{-\Gamma_s t}[\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)]\,, \\
|A_\perp(t)|^2 &= |A_\perp|^2 e^{-\Gamma_s t}[\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)]\,, \\
\Im(A_\|^*(t)\,A_\perp(t)) &= |A_\||\,|A_\perp| e^{-\Gamma_s t}[-\cos(\delta_\perp - \delta_\|) \sin\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right) \\
&\quad - \cos(\delta_\perp - \delta\_\|) \cos\phi_s \sin(\Delta m t) + \sin(\delta_\perp - \delta_\|) \cos(\Delta m t)]\,, \\
\Re(A_0^*(t)\,A_\|(t)) &= |A_0|\,|A_\|| e^{-\Gamma_s t} \cos(\delta_\| - \delta_0)[\cosh\left(\frac{\Delta\Gamma}{2}t\right) - \cos\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right) \\
&\quad + \sin\phi_s \sin(\Delta m t)]\,, \\
\Im(A_0^*(t)\,A_\perp(t)) &= |A_0|\,|A_\perp| e^{-\Gamma_s t}[-\cos(\delta_\perp - \delta_0) \sin\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right) \\
&\quad - \cos(\delta_\perp - \delta_0) \cos\phi_s \sin(\Delta m t) + \sin(\delta_\perp - \delta_0) \cos(\Delta m t)]\,, \\
|A_s(t)|^2 &= |A_s|^2 e^{-\Gamma_s t}[\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]\,, \\
\Re(A_s^*(t) A_\|(t)) &= |A_s|\,|A_\|| e^{-\Gamma_s t}[-\sin(\delta_\| - \delta_s) \sin\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right) - \sin(\delta_\| - \delta_s)\ \cos\phi_s \sin(\Delta m t) \\
&\quad + \cos(\delta_\| - \delta_s) \cos(\Delta m t)]\,, \\
\Im(A_s^*(t) A_\perp(t)) &= |A_s|\,|A_\perp| e^{-\Gamma_s t} \sin(\delta_\perp - \delta_s)[\cosh\left(\frac{\Delta\Gamma}{2}t\right) + \cos\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right) \\
&\quad - \sin\phi_s \sin(\Delta m t)]\,, \\
\Re(A_s^*(t) A_0(t)) &= |A_s|\,|A_0| e^{-\Gamma_s t}[-\sin(\delta_0 - \delta_s) \sin\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right) \\
&\quad - \sin(\delta_0 - \delta_s) \cos\phi_s \sin(\Delta m t) + \cos(\delta_0 - \delta_s) \cos(\Delta m t)]\,.
\end{aligned}
$$

only term for $f=f_{cp}$