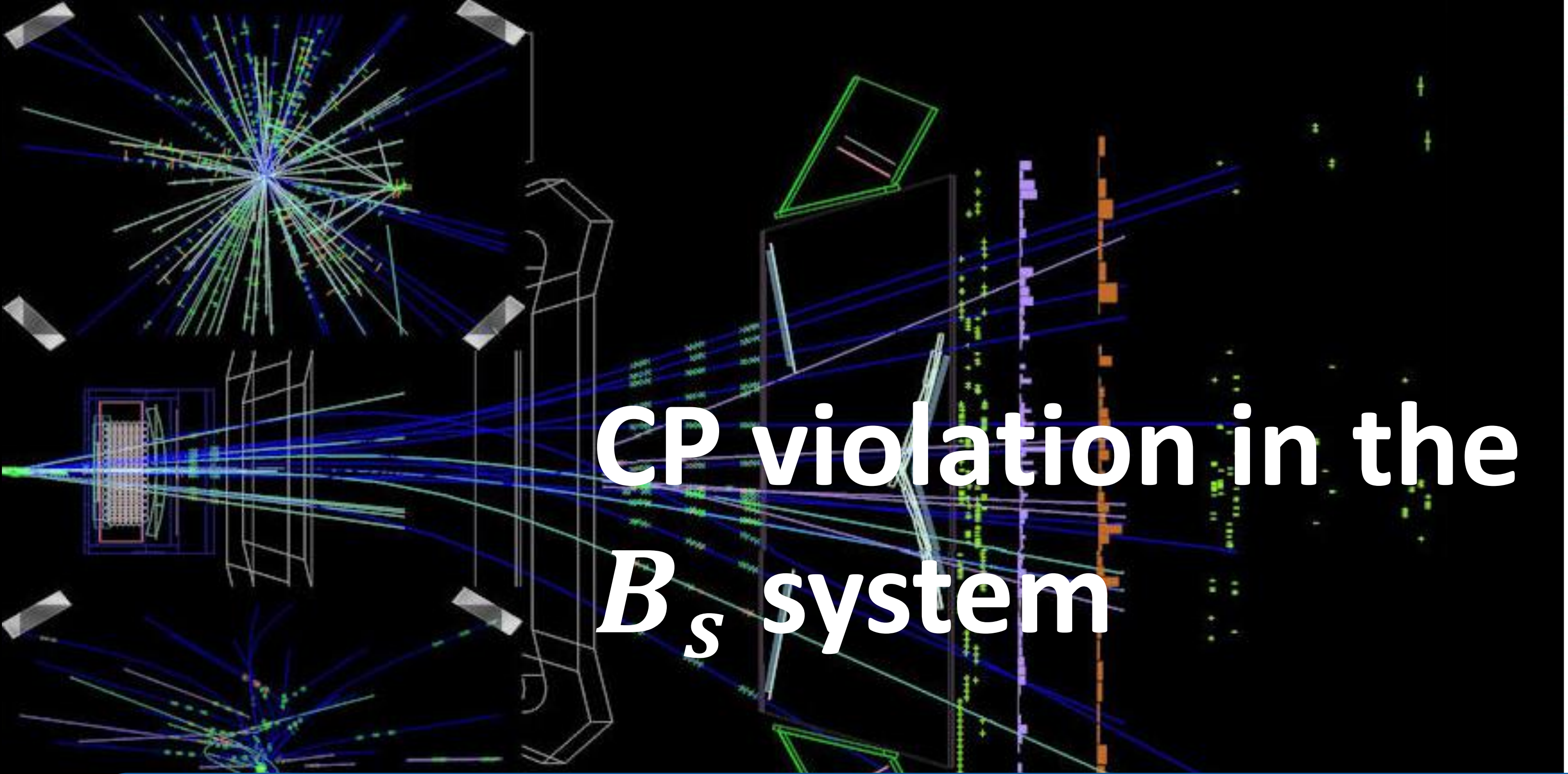

CP violation in the B_s system

Recontres de Blois - 19-23rd May 2014

Matthew M Reid
University of Warwick
On behalf of the LHCb collaboration

Overview

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- There are many ways in which one can measure CP violation in the B-system.

- This talk will discuss decays methods involving $\bar{b} \rightarrow \bar{c}c\bar{s}$ transitions and measurement of the phase $\phi_s = -2\beta_s$.

- I will present **two** analyses;
  - $\boldsymbol{B_s^0 \rightarrow J/\psi\ (\phi \rightarrow K^+K^-)}$ and
  - $\boldsymbol{B_s^0 \rightarrow J/\psi\pi\pi}$ (new, hot off the press!).

- Mention new recently **observed decay mode** that could aid ϕ_s measurements in future.
  - $\boldsymbol{B_s^0 \rightarrow J/\psi K_s K^\pm \pi^\mp}$ (new, hot off the press!).

- Summary.

Phenomenology

CPV phenomenology

CPV in decay amplitudes (only way for charged particles ☹). Asymmetry in decay amplitudes for conjugate decay.

$$\Gamma(X \to f) \neq \Gamma(\bar{X} \to \bar{f})$$

$$\text{when} \quad \left|\frac{\bar{A}_{\bar{f}}}{A_f}\right| \neq 1$$

$$\text{Example } A_{CP}(B^{\pm} \to \pi^{\pm}\pi^{\mp}\pi^{\pm})$$

(arXiv:1310.4740)

CPV in mixing. Difference between mixing probabilities

$$(X_H, X_L) \neq (X_s^0, \bar{X}_s^0)$$

mass eigenstate ≠ flavour eigenstate

"almost CP-Even" $|X_L\rangle = p|X_q^0\rangle + q|\bar{X}_q^0\rangle$

"almost CP-Odd" $|X_H\rangle = p|X_q^0\rangle - q|\bar{X}_q^0\rangle$

CP violation if $|q/p| \neq 1$

Interference between $X_q^0 \to f_{CP}$ and $X_q^0 \to \bar{X}_q^0 \to f_{CP}$ to CP eigenstates.

CPV can occur even if $|\bar{A}_f/A_f| = 1$ and $|q/p| = 1$,

$$\Im m\left(\left|\frac{q}{p}\frac{\bar{A}_f}{A_f}\right|\right) \neq 0$$

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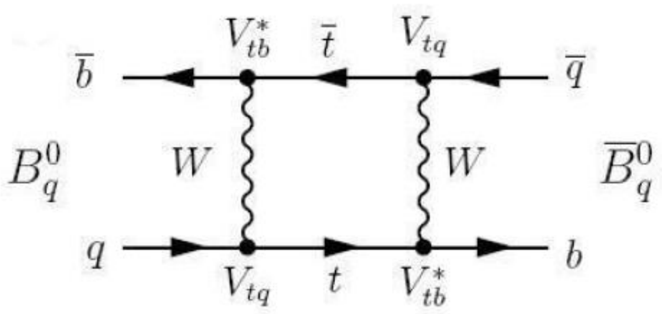
B_s mixing parameters

- Mixing in neutral decay described by a 2x2 mixing matrix. $H_{ij} = M_{ij} - i\Gamma_{ij}$. CPT implies that mass and lifetime of particle and anti-particle are the same ($M_{11} = M_{22}$ and $\Gamma_{11} = \Gamma_{22}$). This leads to **3 mixing observables**.



Virtual off-shell decay M_{12}.

Mass difference (mixing frequency) constrains magnitude of NP contribution to oscillations (off-shell component, $\bar{b} \to \bar{t}W^-$)

$$\mathbf{\Delta m = m_H - m_L \approx 2|M_{12}|}$$

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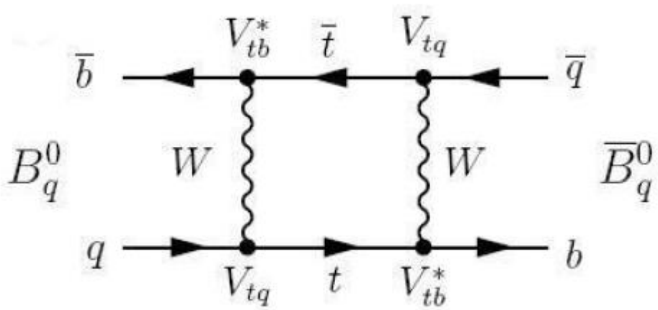

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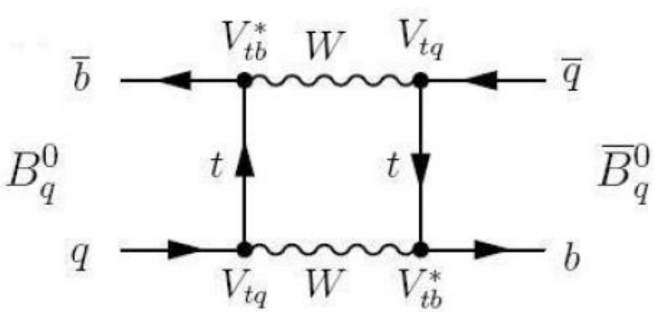

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Lifetime difference. (on-shell component)

$$\Delta\Gamma_s = \Gamma_L - \Gamma_H \approx 2|\Gamma_{12}|\cos\phi_q^{mix}$$

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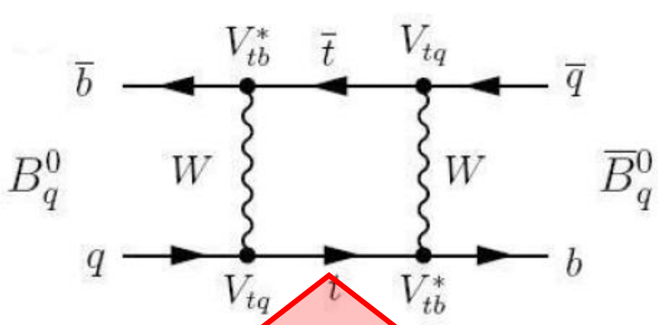

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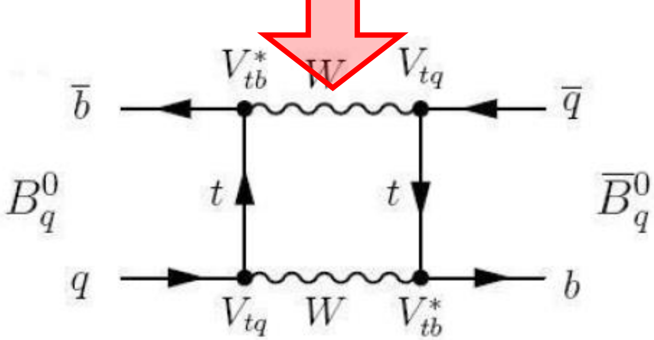

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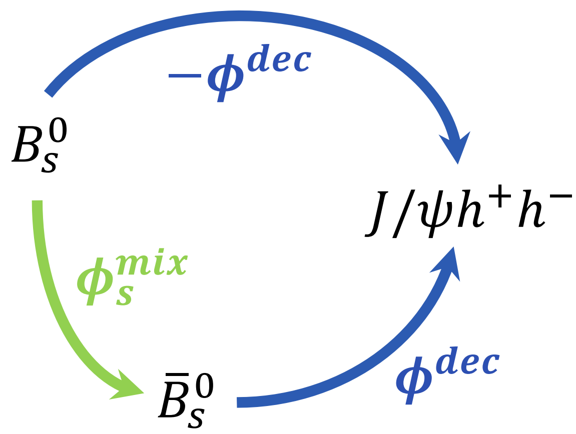
CP-violating **mixing phase**

$$\boldsymbol{\phi_q^{mix} = arg(-M_{12}/\Gamma_{12})}$$

B_s^0 interference



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- Leads to an overall weak phase

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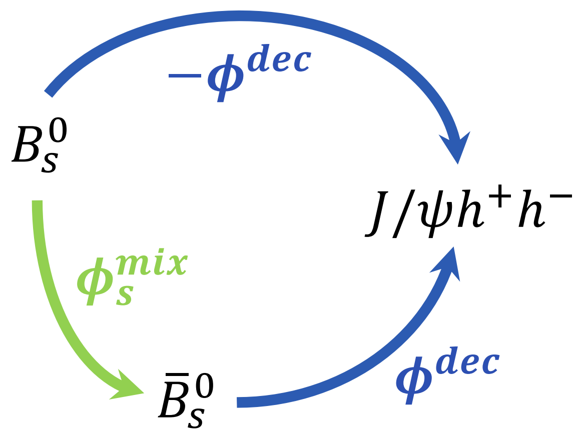

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$$A_{CP}(t) = \frac{\Gamma(\bar{B}_s^0 \to J/\psi\pi\pi)(t) - \Gamma(B_s^0 \to J/\psi\pi\pi)(t)}{\Gamma(\bar{B}_s^0 \to J/\psi\pi\pi)(t) + \Gamma(B_s^0 \to J/\psi\pi\pi)(t)} = \frac{\boldsymbol{S}\sin(\Delta m t) - \boldsymbol{C}\cos(\Delta m t)}{\cosh\left(\frac{\Delta\Gamma t}{2}\right) + \boldsymbol{A_{\Delta\Gamma}}\sinh\left(\frac{\Delta\Gamma t}{2}\right)}$$

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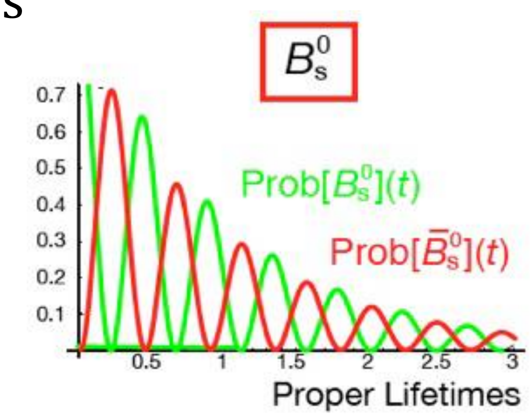

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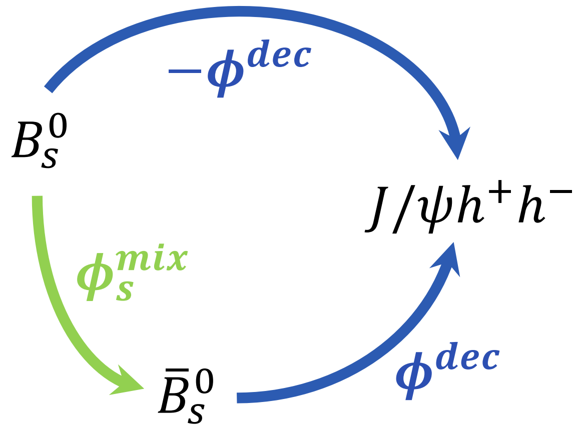

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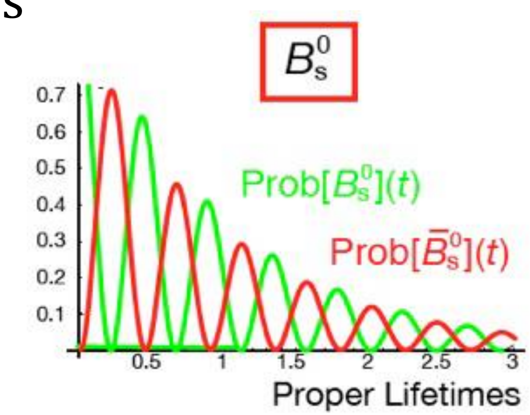

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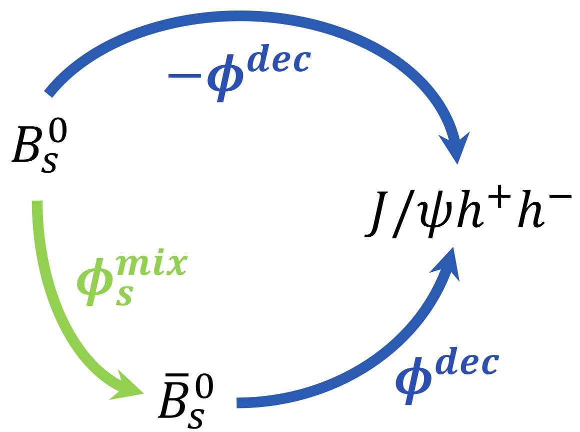

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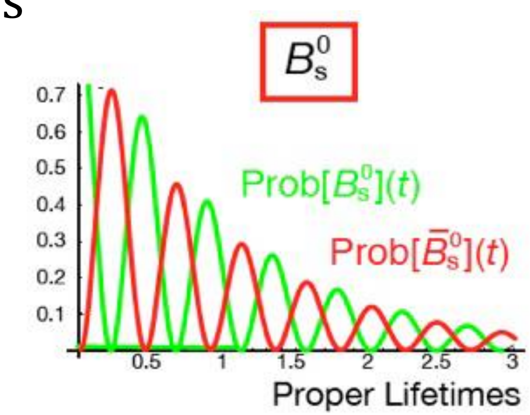

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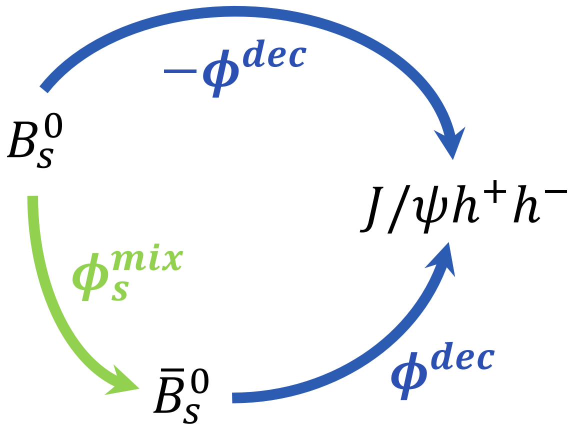

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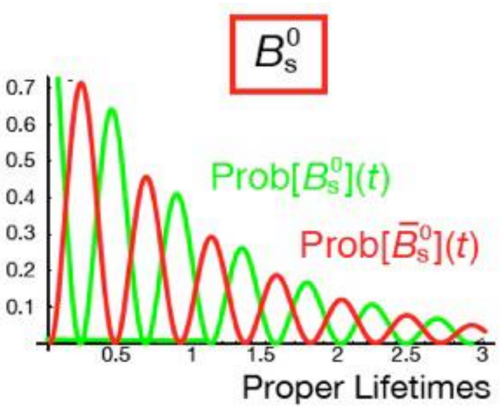
  $A_{\Delta\Gamma}$ measures admixture of B_{qL} and B_{qH} that decay to final state (hence provides effective lifetime).



CPV in $B_s \rightarrow J/\psi\ \phi$

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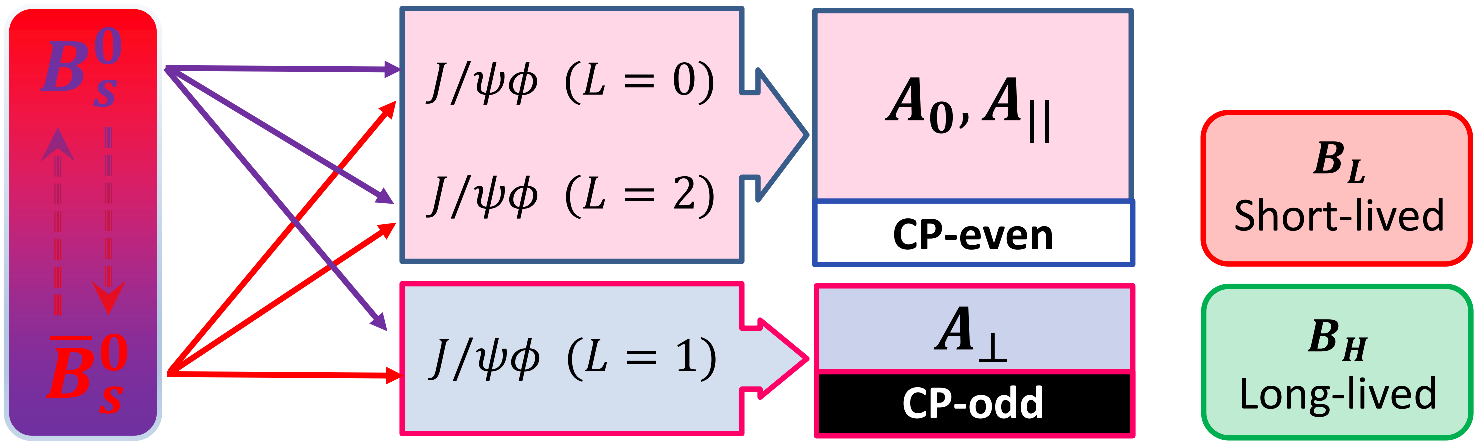

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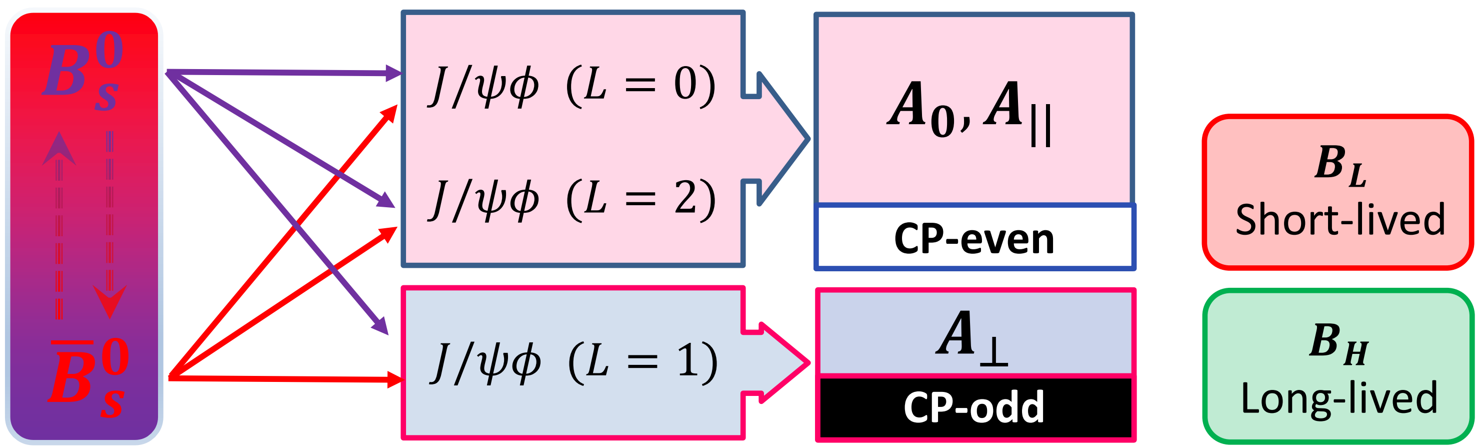

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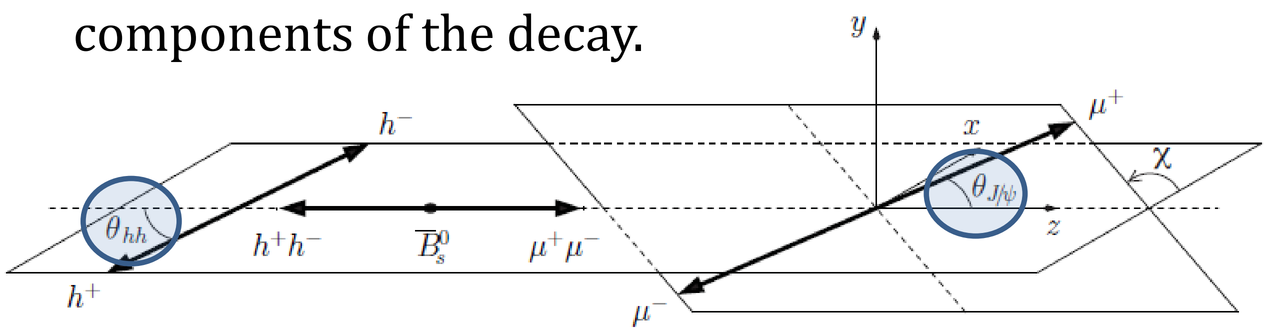

$\theta_{hh}(\theta_{J/\psi})$ angle between $h^+(\mu^+)$ momentum and direction opposite to B_s^0 momentum in the resonant $h^+h^-(J/\psi)$ COM system.

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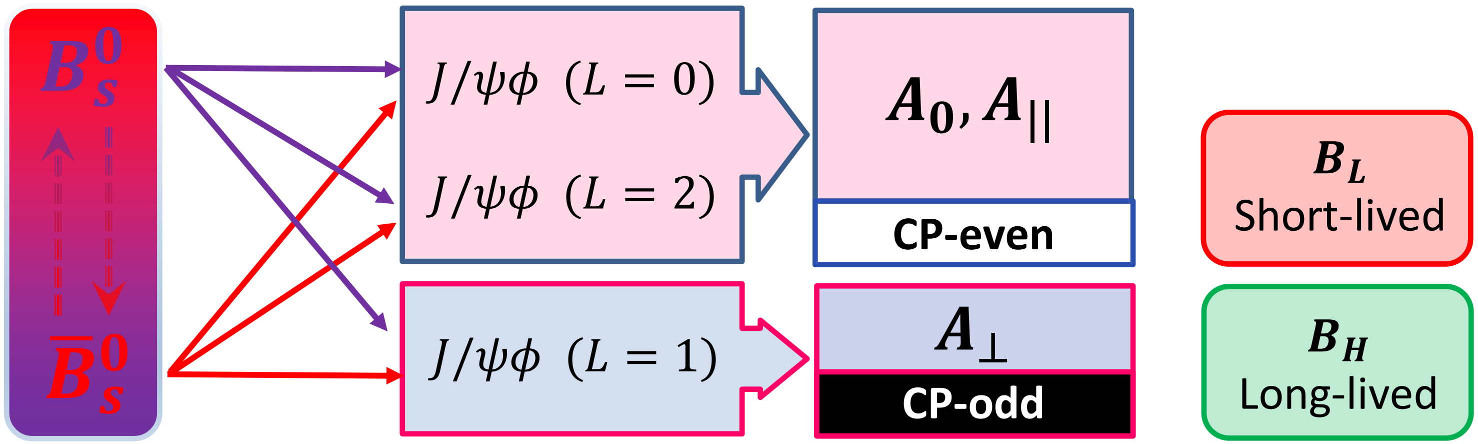

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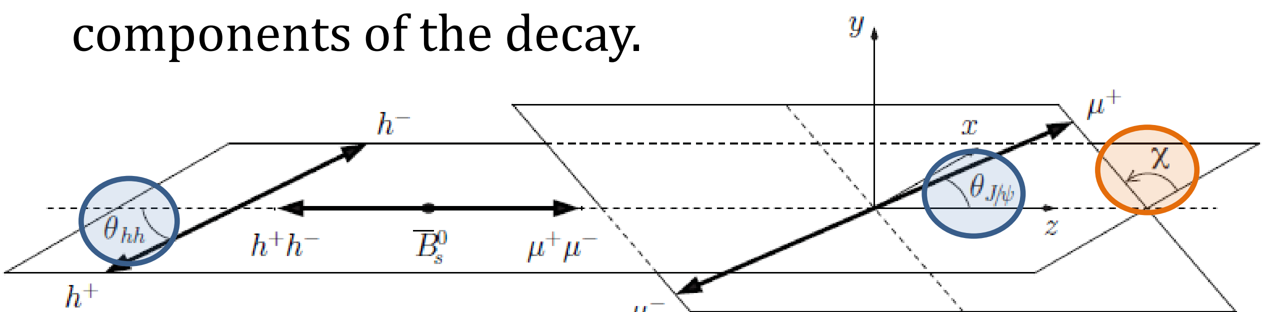

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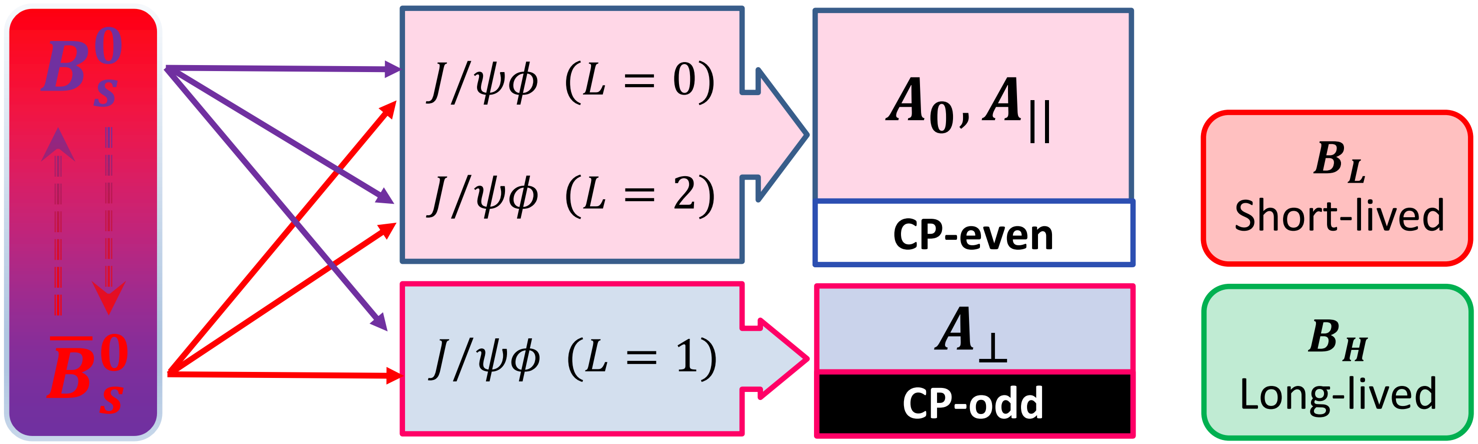

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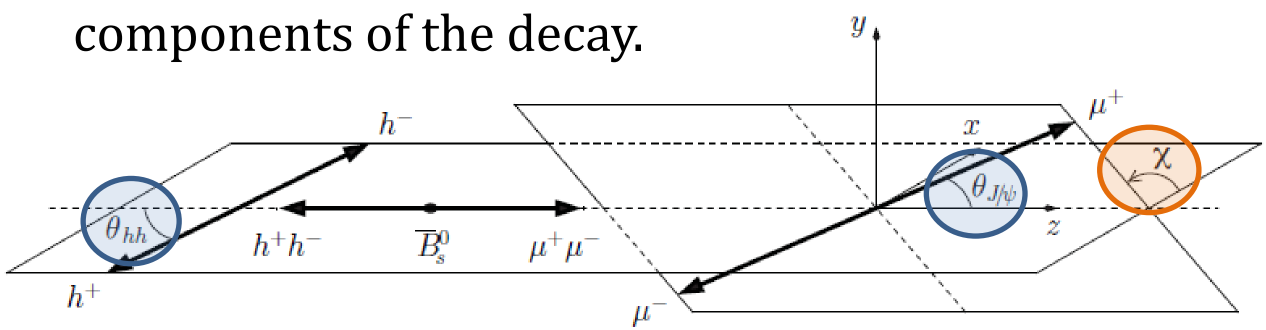

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- Predominantly $B_s \to J/\psi K^+K^-$ via P-wave, observed small S-wave.

CPV in $B_s \to J/\psi\,\phi$

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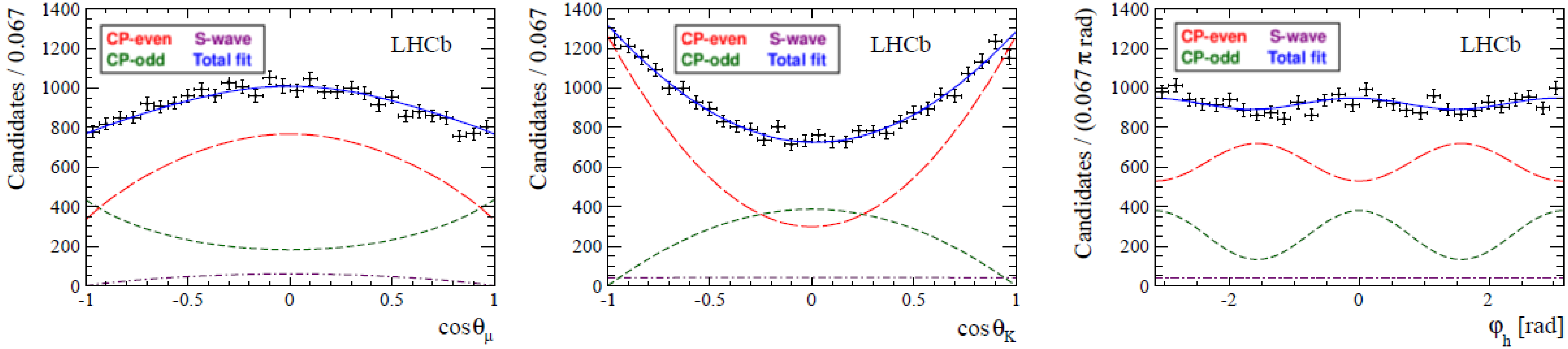
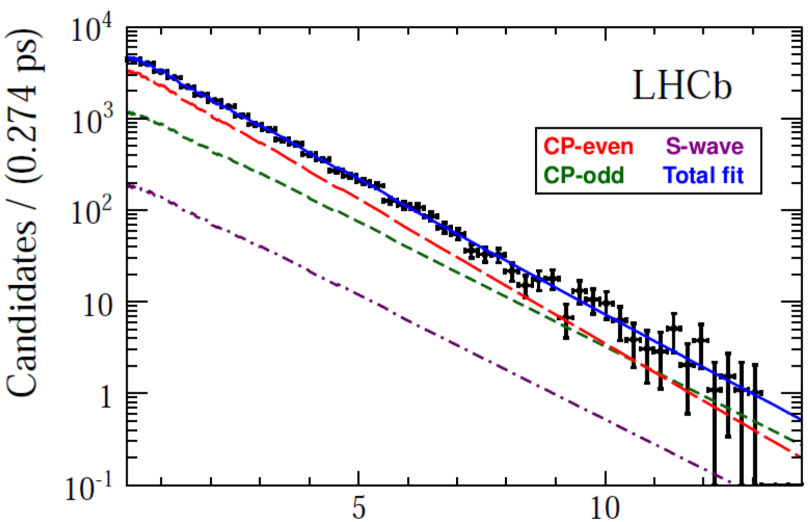
[Phys. Rev. D 87, 112010]

- An unbinned maximum likelihood fit is performed on $1fb^{-1}$ (~26k evts).



- Distinct separation between CP-odd and CP-even.



Γ_L and Γ_H visible, thus $\Delta\Gamma_s$ can be obtained.

The results using $B_s^0 \to J/\psi\ \phi$ data corresponding to $\mathcal{L} = 1\ \text{fb}^{-1}$ are:

$$\phi_s = 0.07 \pm 0.09\ (\text{stat}) \pm 0.01\ (\text{syst})\ \text{rad}$$
$$\Gamma_s = 0.663 \pm 0.005\ (\text{stat}) \pm 0.006\ (\text{syst})\ \text{ps}^{-1}$$
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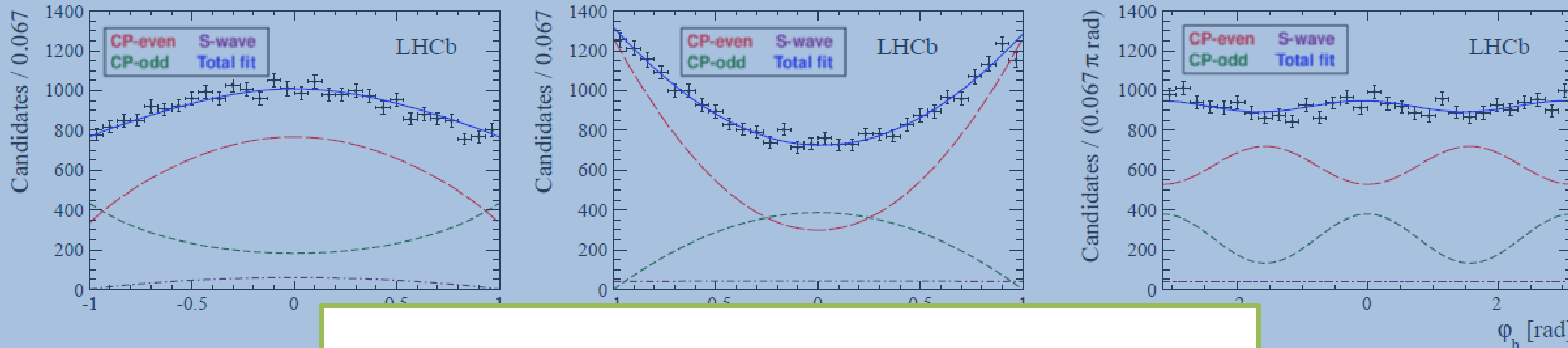
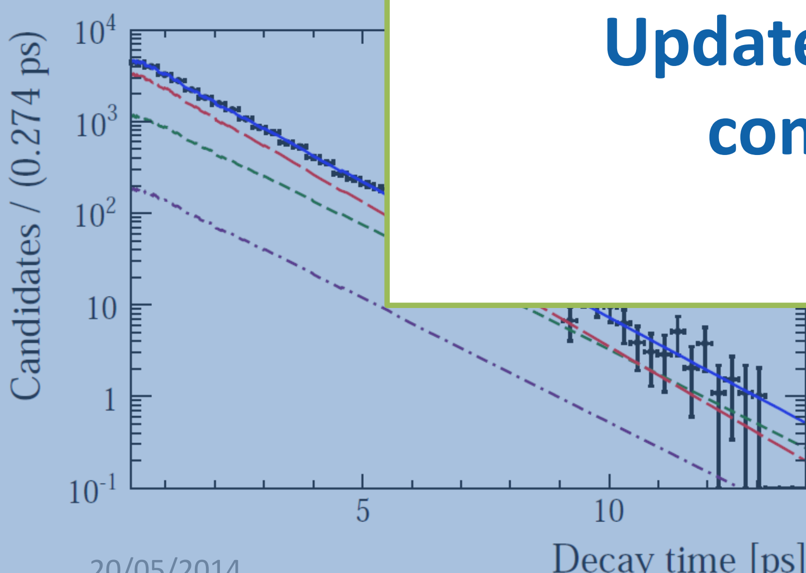


- Distinct sep … an be obtained.

Update with $3\ fb^{-1}$ coming soon!

[Phys. Rev. D 87, 112010]



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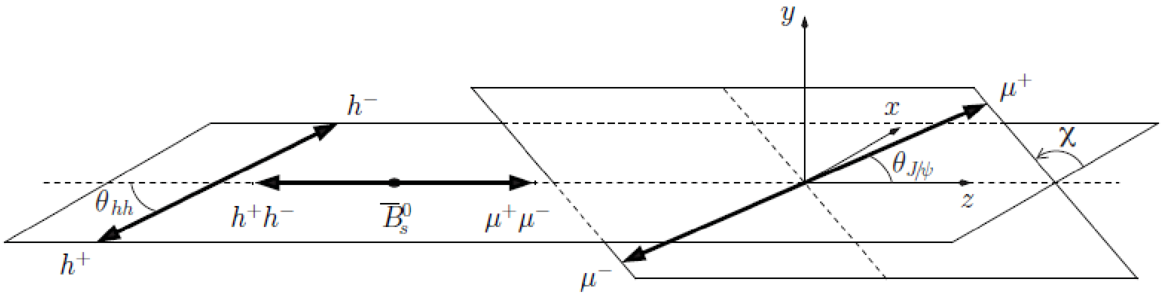

$$CP|J/\psi\ X\rangle = \eta_{J/\psi X}|J/\psi\ X\rangle$$

$B_s^0\ :\ J^P = 0^-$

$J/\psi\ :\ J^{PC} = 1^{--}$

X: $J^{PC} = 0^{++}(f_0), 2^{++}(f_2)$

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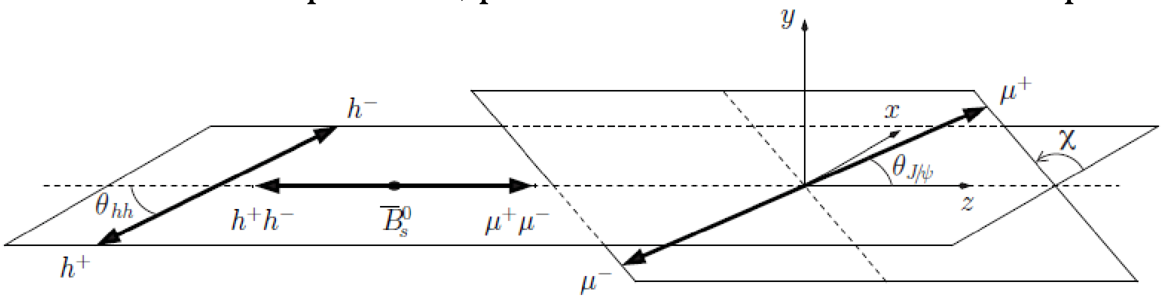
  - **Angular**: when the resonance is non scalar we need to account for the relative orbital angular momentum between mesons (same as $B_s^0 \to J/\psi\phi$).
  - **Amplitude**: $B_s^0 \to J/\psi\ X$ where $X \to \pi\pi$ so a dedicated amplitude analysis required to fit the spectrum, provides fractions of the CP components.



$$CP|J/\psi\ X\rangle = \eta_{J/\psi X}|J/\psi\ X\rangle$$

$$B_s^0\ :\ J^P = 0^-$$

$$J/\psi\ :\ J^{PC} = 1^{--}$$

$$X:\ J^{PC} = 0^{++}(f_0), 2^{++}(f_2)$$

1) CPV in $B_s \to J/\psi\, \pi\pi$

- Result from $L = 1\, fb^{-1}$ corresponding to ≈ 7500 events.
- Since assumed CP-odd no angular analysis was required.
- Input Γ_s, $\Delta\Gamma_s$ and Δm_s are fixed from data available.

$-$ when B_s^0

$$\Gamma(\bar{B}_s^0 \to f_{odd}) = N e^{-\Gamma_s t}\left\{\frac{e^{\Delta\Gamma_s t/2}}{2}(1+cos\phi_s) + \frac{e^{\Delta\Gamma_s t/2}}{2}(1-cos\phi_s) + sin\phi_s \sin(\Delta m_s t)\right\},$$

- Need to measure the time dependent CP asymmetry.

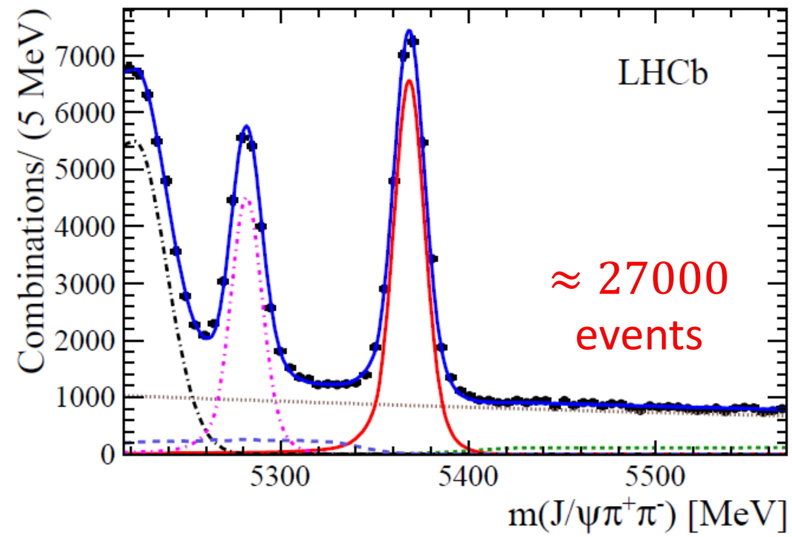
$$A(t) = \frac{\Gamma(\bar{B}_s^0 \to J/\psi\pi\pi)(t) - \Gamma(B_s^0 \to J/\psi\pi\pi)(t)}{\Gamma(\bar{B}_s^0 \to J/\psi\pi\pi)(t) + \Gamma(B_s^0 \to J/\psi\pi\pi)(t)}$$

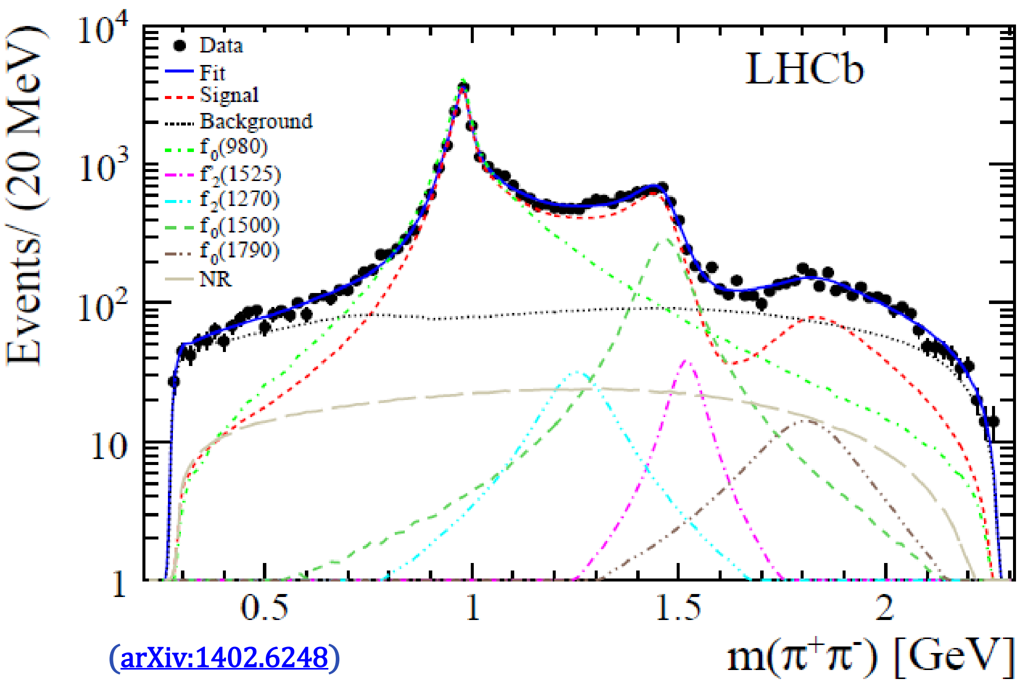
- Leads to a measured value of $\phi_s = -19.0^{+173+4}_{-174-3}\ mrad$. Consistent with SM expectation, large statistical uncertainty.

(arXiv.1204.5675)

2) Amplitude $B_s \to J/\psi\, \pi\pi$

- Recent amplitude analysis has been performed using $L = 3\ fb^{-1}$.
- First precise study of CP content.
- Five resonances required; $f_0(980)$, $f_2(1525)$, $f_2(1270)$, $f_0(1500)$, $f_0(1790)$.





(arXiv:1402.6248)

- CP-odd > 97.7% @ 95% CL.
- Analysis of mixing angle between $f_0(550)$ and $f_0(980)$ states gives,
  - $|\phi_m| < 7.7^{\circ}$ @ 90% CL.

3) CPV in $B_s \to J/\psi\,\pi\pi$

NEW!

- Using the CP amplitude analysis on last page, a time-dependent measurement of the mixing angle can be made.

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

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

$$\mathcal{A} \equiv \sum_i A_i \qquad \overline{\mathcal{A}} \equiv \sum_i (\eta_i A_i) \qquad \lambda \equiv \eta_i \frac{q}{p}\frac{A_i}{A_i}$$

- We sum over individual $\pi^+\pi^-$ resonant traversity amplitudes, which are functions of $m(\pi^+\pi^-)$ invariant mass and three helicity angles Ω.

$\phi_s = 75 \pm 67 \pm 8$ (fixed $|\lambda| = 1$ CPV in decay not allowed) ,
$\phi_s = 70 \pm 67 \pm 8$ and $|\lambda| = 0.89 \pm 0.05 \pm 0.01$,

(arXiv.1404.5673)

LHCb

NEW!

3) CPV in $B_s \to J/\psi\,\pi\pi$

THE UNIVERSITY OF WARWICK

- Using the CP amplitude analysis on last page time-dependent measurement of the mixing angle can be made.

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

$\overline{\Gamma}(t, m_{hh}, \Omega$ … $\Delta m_s t)$ … $n(\Delta m_s t)\}$

$\mathcal{A}$ … A_i … A_i

No evidence for CPV in decay is seen.

ϕ_s consistent with SM expectation

$\phi_s^{SM} = 36.3^{+1.6}_{-1.5}$ mrad

and previous LHCb measurement.

- We sum ov… es, which are functio… angles Ω.

$$\phi_s = 75 \pm 67 \pm 8 \text{ (fixed } |\lambda| = 1 \text{ CPV in decay not allowed)},$$
$$\phi_s = 70 \pm 67 \pm 8 \text{ and } |\lambda| = 0.89 \pm 0.05 \pm 0.01,$$

(arXiv.1404.5673)

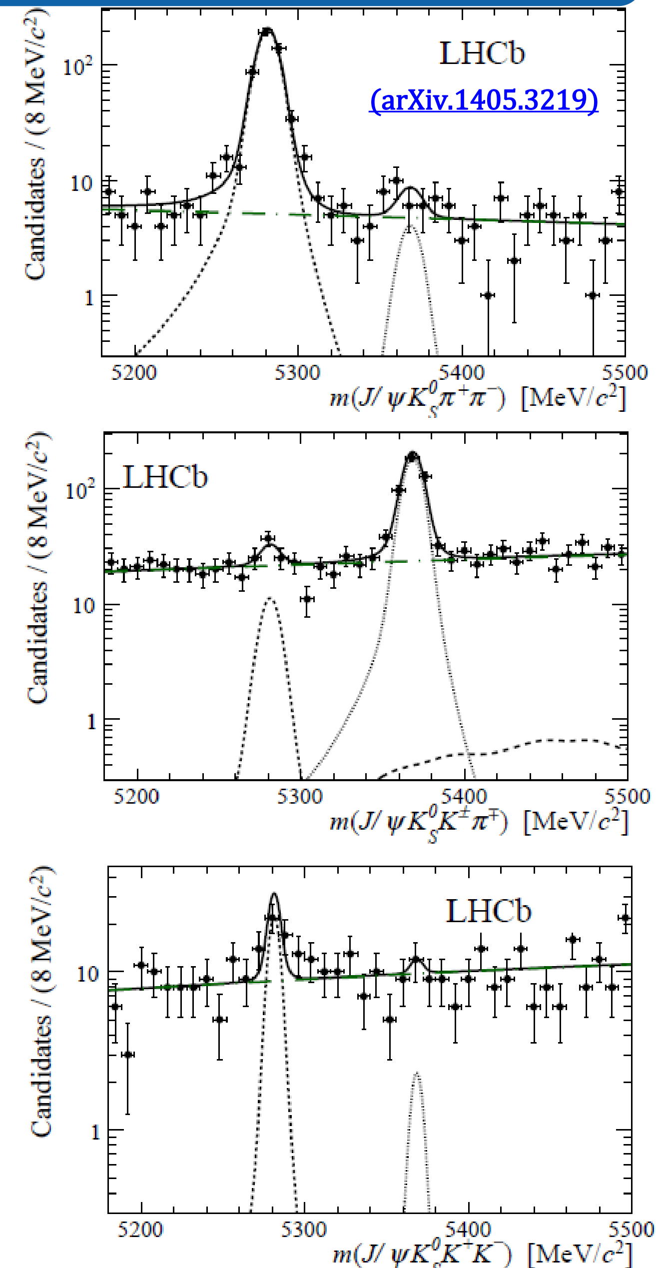
New decays

Measurement $J/\psi K_S^0 K\pi$

NEW!

- New branching fraction measurements of $B^0_{(s)} \rightarrow J/\psi K_S^0 h^{(\prime)+} h^{-}$ ($h^{(\prime)} = K, \pi$) has been performed using $L = 1\ fb^{-1}$. (arXiv.1405.3219)
- $B^0 \rightarrow J/\psi K_S^0 \pi\pi$ confirmed and first observations of $B_s^0 \rightarrow J/\psi K_S^0 K\pi$ and $B^0 \rightarrow J/\psi K_S^0 KK$ greater than 7 σ.

Mode	Total Yield	Significance
$B^0 \rightarrow J/\psi K_S^0 \pi\pi$	**717**	**>30.0**
$B^0 \rightarrow J/\psi K_S^0 K\pi$	27	2.4
$B^0 \rightarrow J/\psi K_S^0 KK$	**45**	**7.7**
$B_s^0 \rightarrow J/\psi K_S^0 \pi\pi$	14	2.7
$B_s^0 \rightarrow J/\psi K_S^0 K\pi$	**525**	**30.0**
$B_s^0 \rightarrow J/\psi K_S^0 KK$	5	0.5



Measurement $J/\psi K_S^0 K\pi$

NEW!

- We measure $B^0 \to J/\psi K_s^0 \pi\pi$ relative to $B^0 \to J/\psi K_s^0$.
- This provides a measurement that has 4x better statistical precision over current PDG average.

$$\mathcal{B}(B^0 \to J/\psi K^0 \pi^+\pi^-) = (43.0 \pm 3.0\,(\text{stat}) \pm 3.3\,(\text{syst}) \pm 1.6\,(\text{PDG})) \times 10^{-5},$$

PDG: $\boldsymbol{B(B^0 \to J/\psi\, K_S^0\pi\pi) = (100.0 \pm 40.0) \times 10^{-5}}$

- A cross check was performed measuring $B(B^0 \to \psi(2S)K^0)$ where the PDG uncertainty is much smaller, good agreement was found.

$$\mathcal{B}(B^0 \to \psi(2S)K^0) = (4.7 \pm 0.7\,(\text{stat}) \pm 0.4\,(\text{syst}) \pm 0.6\,(\text{PDG})) \times 10^{-4},$$

PDG: $\boldsymbol{B(B^0 \to \psi(2S)K^0) = (6.2 \pm 0.5) \times 10^{-4}}$

Measurement $J/\psi K_S^0 K\pi$

NEW!

- Using $B^0 \to J/\psi K_S^0 \pi\pi$ updated branching fraction we measure all other modes.

$$\mathcal{B}(B^0 \to J/\psi \overset{(-)}{K}{}^0 K^\pm \pi^\mp) = (11 \pm 5\,(\text{stat}) \pm 3\,(\text{syst}) \pm 1\,(\text{PDG})) \times 10^{-6}\,,$$
$$< 21 \times 10^{-6} \text{ at } 90\% \text{ CL}\,,$$
$$< 24 \times 10^{-6} \text{ at } 95\% \text{ CL}\,,$$
$$\mathcal{B}(B^0 \to J/\psi K^0 K^+ K^-) = (20.2 \pm 4.3\,(\text{stat}) \pm 1.7\,(\text{syst}) \pm 0.8\,(\text{PDG})) \times 10^{-6}\,,$$
$$\mathcal{B}(B_s^0 \to J/\psi \overline{K}{}^0 \pi^+ \pi^-) = (2.4 \pm 1.4\,(\text{stat}) \pm 0.8\,(\text{syst}) \pm 0.1\,(f_s/f_d) \pm 0.1\,(\text{PDG})) \times 10^{-5}\,,$$
$$< 4.4 \times 10^{-5} \text{ at } 90\% \text{ CL}\,,$$
$$< 5.0 \times 10^{-5} \text{ at } 95\% \text{ CL}\,,$$
$$\mathcal{B}(B_s^0 \to J/\psi \overset{(-)}{K}{}^0 K^\pm \pi^\mp) = (91 \pm 6\,(\text{stat}) \pm 6\,(\text{syst}) \pm 3\,(f_s/f_d) \pm 3\,(\text{PDG})) \times 10^{-5}\,,$$
$$\mathcal{B}(B_s^0 \to J/\psi \overline{K}{}^0 K^+ K^-) = (5 \pm 9\,(\text{stat}) \pm 2\,(\text{syst}) \pm 1\,(f_s/f_d)) \times 10^{-6}\,,$$
$$< 12 \times 10^{-6} \text{ at } 90\% \text{ CL}\,,$$
$$< 14 \times 10^{-6} \text{ at } 95\% \text{ CL}\,,$$

$\mathbf{1.3\sigma}$

Summary

- Still no tension with the SM regarding ϕ_s.
- Measurements still statistically limited.
- Update for $B_s^0 \rightarrow J/\psi(\phi \rightarrow K^+K^-)$ coming soon!
- We have more modes becoming available, $J/\psi K_S^0 h^{(\prime)+}h^-$ and others such as $\mathrm{B}_s^0 \rightarrow J/\psi\pi\pi\pi\pi$ (arXiv:1310.2145).
- LHC run 2 will start in 2015 ($\sim$ April):
  - COM energy 13/14 TeV so production cross section of $\sigma_{b\bar{b}}$ ~doubles.

Summary

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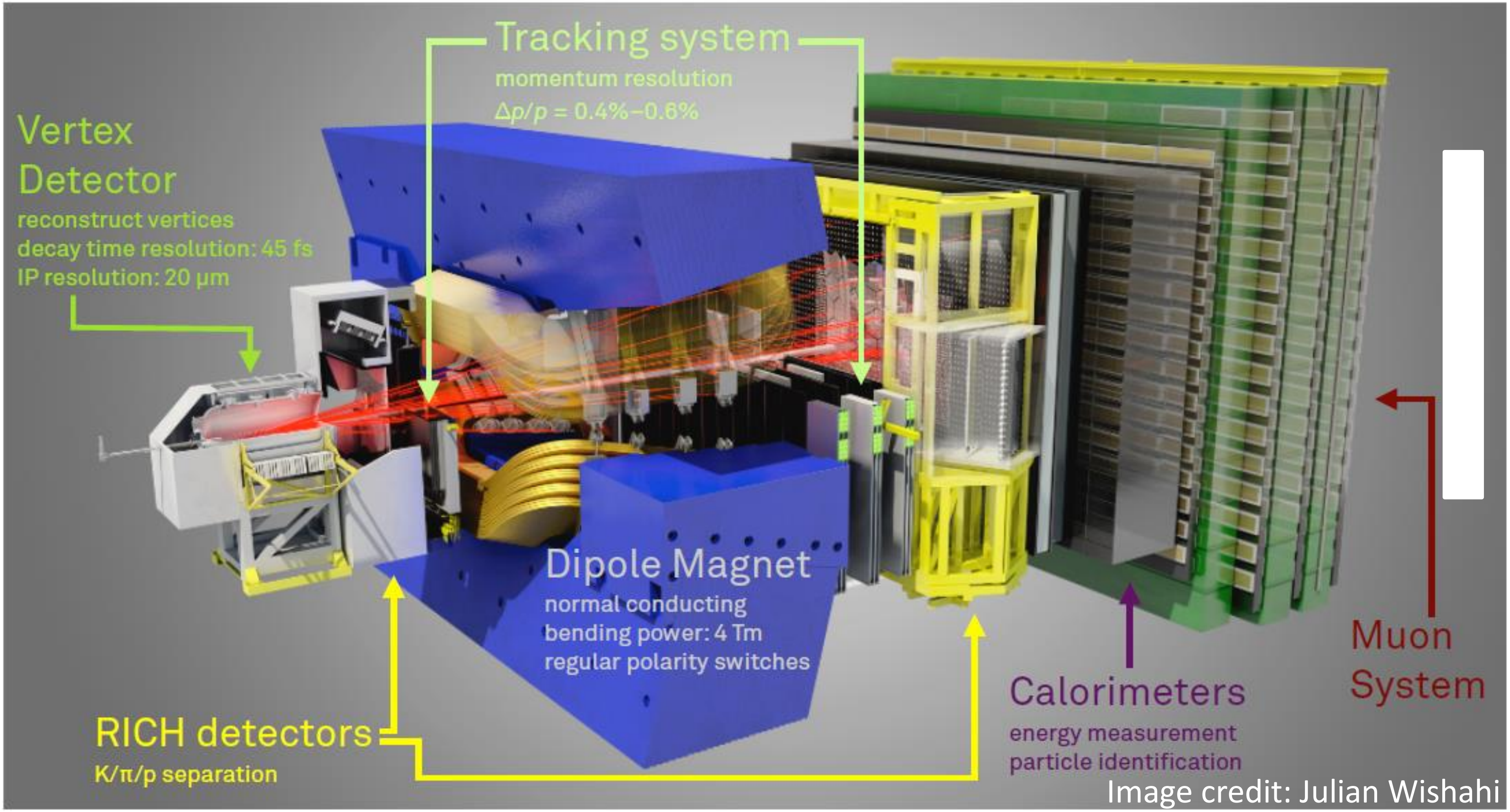
- LHC run 2 will start in 2015 ($\sim$ April):
  - COM energy 13/14 TeV so production cross section of $\sigma_{b\bar{b}}$ ~doubles.
- Next time we should begin making constraints on NP through ϕ_s. Bring it on!!!!

Backup

The LHCb detector

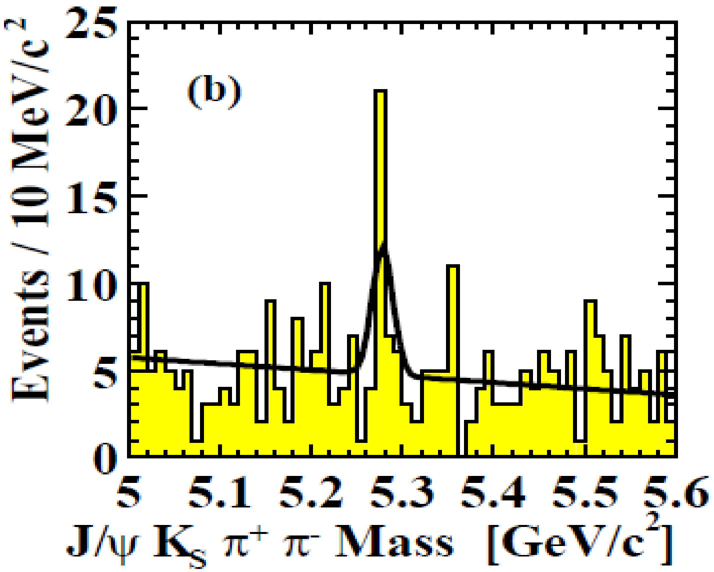
- Forward arm spectrometer in $2 < \eta < 5$ range.



Previous measurements

- CDF: $\mathrm{B}^0 \to J/\psi K_S^0 \pi\pi$

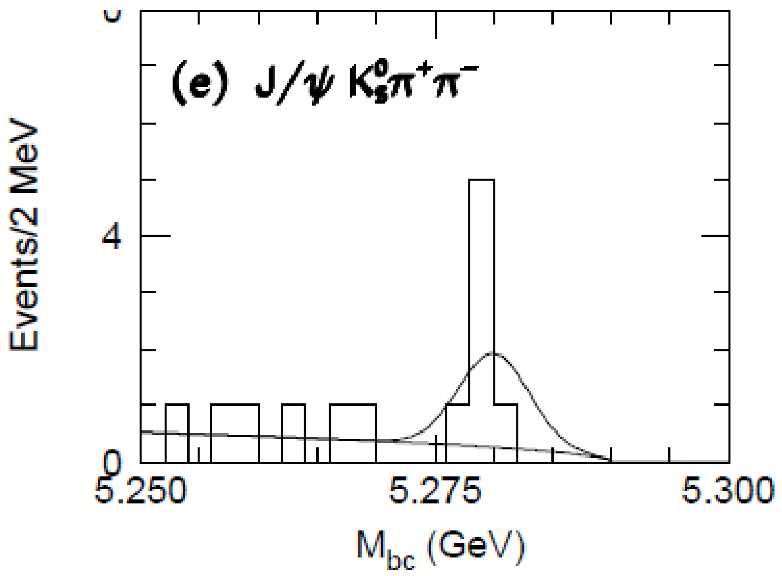
http://xxx.lanl.gov/pdf/hep-ex/0108022v1.pdf



- 3.3σ evidence observing 39 evts.

- Belle: $\mathrm{B}^0 \to J/\psi K_1(1270)^0$

http://arxiv.org/pdf/hep-ex/0105014.pdf

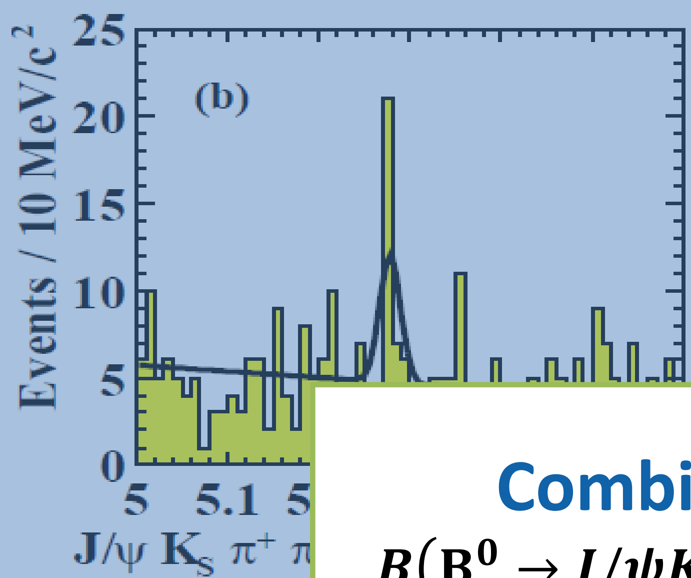


- Observed 6.2 evts to our mode $\mathrm{B}^0 \to J/\psi K_S^0 \pi\pi$.

Previous measurements

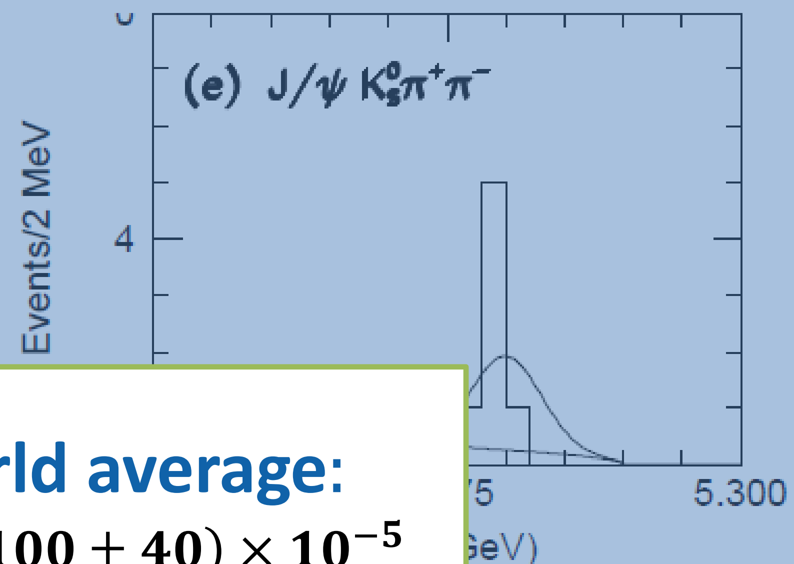
- **CDF: $\mathrm{B}^0 \rightarrow J/\psi K^0_S \pi\pi$**

http://xxx.lanl.gov/pdf/hep-ex/0108022v1.pdf



- **Belle: $\mathrm{B}^0 \rightarrow J/\psi K_1(1270)^0$**

http://arxiv.org/pdf/hep-ex/0105014.pdf



- 3.3σ evidenc … to our mode
evts.

Combined world average:

$$B\left(\mathrm{B}^0 \rightarrow J/\psi K^0 \pi\pi\right) = (100 \pm 40) \times 10^{-5}$$

40% uncertainty, dominated by statistical precision.

Amplitude $B_s \to J/\psi\, \pi\pi$

- CP-even fraction < 2.3% @ 95% CL.
- Table shows the relevant resonant components and their CP contribution.

Component	Solution I	Solution II
$f_0(980)$	$70.3 \pm 1.5^{+0.4}_{-5.1}$	$92.4 \pm 2.0^{+0.8}_{-16.0}$
$f_0(1500)$	$10.1 \pm 0.8^{+1.1}_{-0.3}$	$9.1 \pm 0.9 \pm 0.3$
$f_0(1790)$	$2.4 \pm 0.4^{+5.0}_{-0.2}$	$0.9 \pm 0.3^{+2.5}_{-0.1}$
$f_2(1270)_0$	$0.36 \pm 0.07 \pm 0.03$	$0.42 \pm 0.07 \pm 0.04$
$f_2(1270)_\parallel$	$0.52 \pm 0.15^{+0.05}_{-0.02}$	$0.42 \pm 0.13^{+0.11}_{-0.02}$
$f_2(1270)_\perp$	$0.63 \pm 0.34^{+0.16}_{-0.08}$	$0.60 \pm 0.36^{+0.12}_{-0.09}$
$f_2'(1525)_0$	$0.51 \pm 0.09^{+0.05}_{-0.04}$	$0.52 \pm 0.09^{+0.05}_{-0.04}$
$f_2'(1525)_\parallel$	$0.06^{+0.13}_{-0.04} \pm 0.01$	$0.11^{+0.16+0.03}_{-0.07-0.04}$
$f_2'(1525)_\perp$	$0.26 \pm 0.18^{+0.06}_{-0.04}$	$0.26 \pm 0.22^{+0.06}_{-0.05}$
NR	-	$5.9 \pm 1.4^{+0.7}_{-4.6}$
Sum	85.2	110.6
$-\ln\mathcal{L}$	-93738	-93739
χ^2/ndf	2005/1822	2008/1820

Table 2: Possible resonance candidates in the $\overline{B}{}^0_s \to J/\psi\pi^+\pi^-$ decay mode and their parameters used in the fit.

Resonance	Spin	Helicity	Resonance formalism	Mass (MeV)	Width (MeV)	Source
$f_0(500)$	0	0	BW	471 ± 21	534 ± 53	LHCb [19]
$f_0(980)$	0	0	Flatté	see text		
$f_2(1270)$	2	$0, \pm1$	BW	1275.1 ± 1.2	$185.1^{+2.9}_{-2.4}$	PDG [6]
$f_0(1500)$	0	0	BW	see text		
$f_2'(1525)$	2	$0, \pm1$	BW	1522^{+6}_{-3}	84^{+12}_{-8}	LHCb [28]
$f_0(1710)$	0	0	BW	1720 ± 6	135 ± 8	PDG [6]
$f_0(1790)$	0	0	BW	1790^{+40}_{-30}	270^{+60}_{-30}	BES [27]
$\rho(770)$	1	$0, \pm1$	BW	775.49 ± 0.34	149.1 ± 0.8	PDG [6]

- Resonant contribution and the models used to describe poles.

$f_0(980) - f_0(550)$ angle

arXiv.1305.6554

When the σ and f_0 are considered as $q\bar{q}$ states there is the possibility of their being mixtures of light and strange quarks that is characterized by a 2×2 rotation matrix with a single parameter, the angle ϕ, so that their wave-functions are

$$\begin{aligned} |f_0\rangle &= \cos\phi|s\bar{s}\rangle + \sin\phi|n\bar{n}\rangle \\ |\sigma\rangle &= -\sin\phi|s\bar{s}\rangle + \cos\phi|n\bar{n}\rangle, \\ \text{where } |n\bar{n}\rangle &\equiv \frac{1}{\sqrt{2}}\left(|u\bar{u}\rangle + |d\bar{d}\rangle\right). \end{aligned} \quad (1)$$

While there have been several attempts to measure the mixing angle ϕ, the model dependent results give a wide range of values. We describe here only a few examples. $D^{\pm}$ and $D_s^{\pm}$ decays into $f_0(980)\pi^{\pm}$ and $f_0(980)K^{\pm}$ give values of $31^{\circ} \pm 5^{\circ}$ or $42^{\circ} \pm 7^{\circ}$ [10]. $D_s^{+} \to \pi^{+}\pi^{+}\pi^{-}$ transitions give a range $35^{\circ} < |\phi| < 55^{\circ}$ [11]. In light meson radiative decays two solutions are found either $4^{\circ} \pm 3^{\circ}$ or $136^{\circ} \pm 6^{\circ}$ [12]. Resonance decays from both $\phi \to \gamma\pi^0\pi^0$ and $J/\psi \to \omega\pi\pi$ give a value of $\simeq 20^{\circ}$. On the basis of SU(3), a value of $19^{\circ} \pm 5^{\circ}$ is provided [13]. Finally, Ochs [14], averaging over several processes, finds $30^{\circ} \pm 3^{\circ}$

When these states are viewed as $q\bar{q}q\bar{q}$ states the wave functions becomes

$$|f_0\rangle = \frac{1}{\sqrt{2}}\left([su][\bar{s}\bar{u}] + [sd][\bar{s}\bar{d}]\right), \quad |\sigma\rangle = [ud][\bar{u}\bar{d}]. \quad (2)$$

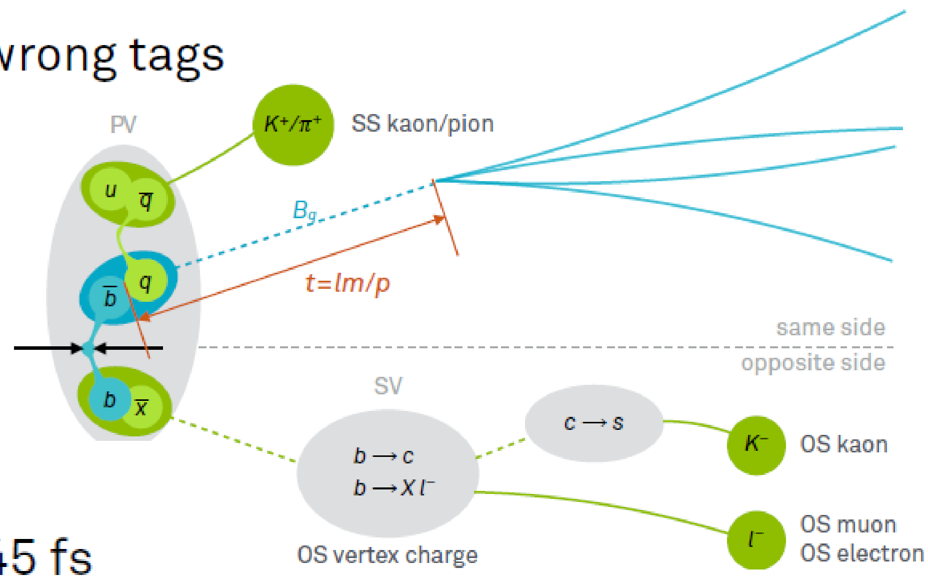
In this Letter we assume the tetraquark states are unmixed, for which there is some justification [2,10,15], with a mixing angle estimate of $< 5^{\circ}$ [9].

CPV mixing and decay

- ingredients to measure asymmetry

$$A_{CP}(t) = \frac{\Gamma(\overline{B}(t) \to f) - \Gamma(B(t) \to f)}{\Gamma(\overline{B}(t) \to f) + \Gamma(B(t) \to f)}$$

- flavour tagging
  - determine initial flavour of *B* meson at t=0
  - need to control the rate of wrong tags
- decay time reconstruction
  - resolution
  - acceptance



- fast B_s oscillation Δm_s
- LHCb decay time resolution ≈45 fs
- flavour tagging required