# Precision measurement of CP violation in mixing at LHCb

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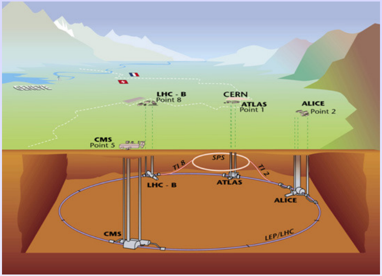
3rd IMPRS-PTFS Seminar, Heidelberg - 24$^{th}$ April 2012

INTERNATIONAL MAX PLANCK RESEARCH SCHOOL PT FS FOR PRECISION TESTS OF FUNDAMENTAL SYMMETRIES

# Outline

- The LHC and the LHCb detector
- Introduction to CP violation
- $\not{C}\not{P}$ in interference of $B_s^0$ decay and mixing
- $\phi_s$ in $B_s^0 \to J/\psi\phi$
- Challenges of precision measurement
- Conclusions

# The Large Hadron Collider (LHC)



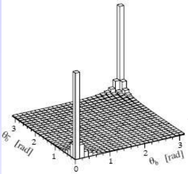

- The LHC accelerates protons in both directions until they collide at four intersection points with a central mass system energy of 8 TeV (7 TeV in 2010-2011).
- The four main experiments located at the intersection points are: ATLAS, CMS, ALICE and **LHCb**

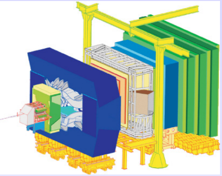
# The LHCb experiment

## LHCb

- Forward single arm spectrometer
- Acceptance: 15-300(250) mrad
- Copious source of b,c in the forward region

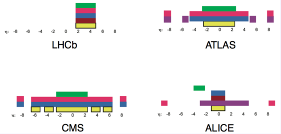
$b\bar{b}$ angular correlation





LHCb detector

Unique eta coverage




- ECAL
- HCAL
- Tracking

Muon

Hadron PID

Counters

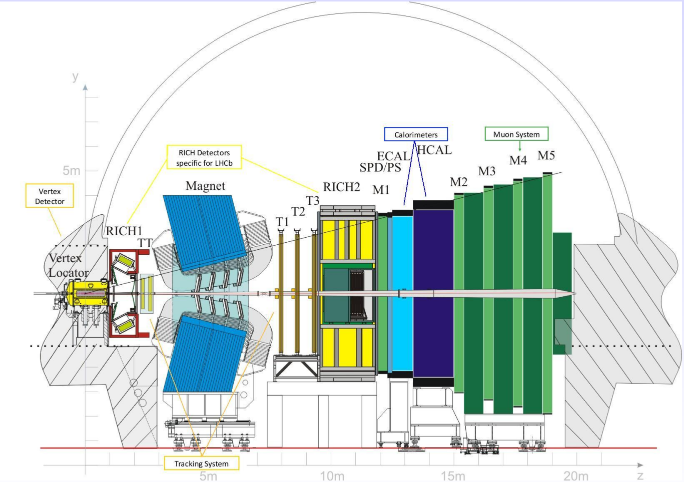
## Studies

$\not{CP}$ measurements require precision:

- Time dependent analysis need good time resolution
- Flavour tagging needs particle IDentification
- High statistics, purity and efficiency needed to reach SM predictions.

# The LHCb detector

LHCb was built precisely for this purpose!



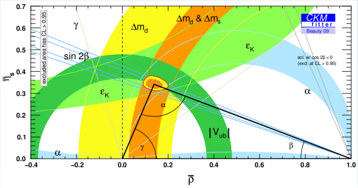
# Short introduction to $\not{CP}$

The only source of CP violation in the SM is the **Kobayshi-Maskawa mechanism**, which predicts the existence of a phase factor in the 3x3 CKM matrix:

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

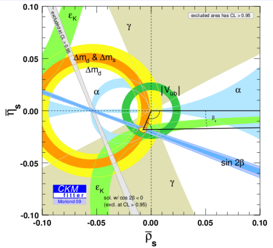
The request that the CKM matrix is unitary leads to relations between the elements:

$$V_{ub}^* V_{ud} + V_{cb}^* V_{cd} + V_{tb}^* V_{td} = 0$$




The heigth of the triangle depends on the value of the imaginary phase.

$$V_{ub}^* V_{us} + V_{cb}^* V_{cs} + V_{tb}^* V_{ts} = 0$$



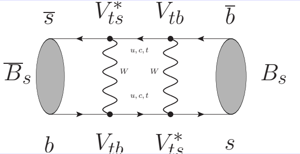

In this talk I will focus on $\not{CP}$ in interference of $B_s^0$ decay and mixing.

# $B_s^0$-$\overline{B}_s^0$ mixing and $B_s^0 \to J/\psi\phi$ decay

## $B_s^0$-$\overline{B}_s^0$ mixing

Time development of the mixing described by phenomenological Schroedinger eq:

$$i\frac{d}{dt}\begin{pmatrix} B_s \\ \bar{B}_s \end{pmatrix} = \left(M - \frac{i}{2}\Gamma\right)\begin{pmatrix} B_s \\ \bar{B}_s \end{pmatrix}$$



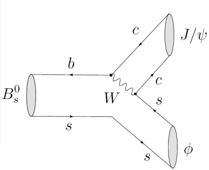

Diagonalizing it in terms of mass eigenstates:

$$i\frac{d}{dt}(B_L) = \left(M_L - \frac{i}{2}\Gamma_L\right)(B_L)$$
$$i\frac{d}{dt}(B_H) = \left(M_H - \frac{i}{2}\Gamma_H\right)(B_H)$$

Phenomenological mixing parameters:

- $\Delta\Gamma = \Gamma_L - \Gamma_H$
  $\Delta M = M_L - M_H$
- Mixing phase:
  $\phi_M = 2\,arg\,(V_{ts}V_{tb}^*)$

## $B_s^0 \to J/\psi\phi$ decay




- Decay dominated by tree level
- Decay phase: $\phi_D = arg\,(V_{cs}V_{cb}^*) \approx 0$

# $\not{CP}$ in interference of $B_s^0$ decay and mixing



- The interference between $B_s^0$ decays to $J/\psi\,\phi$ with or without $B_s^0$ -$\overline{B}_s^0$ oscillation allows the measurement of $\phi_s$, via CP violation.

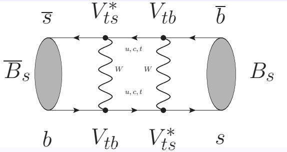
- The SM prediction is very precise:

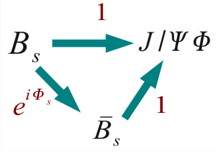
$$\phi_s^{SM} = -2\beta_s = -2\,arg\left(-V_{ts}V_{tb}^{*}/V_{cs}V_{cb}^{*}\right) = (-0.0363 \pm 0.0016)\,rad$$

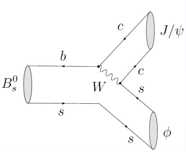
[J.Charles et al., Phys.Rev. D84, 033005 (2011)]

- $\phi_s$ sensitive to New Physics (eg. 4th generation in the box):

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



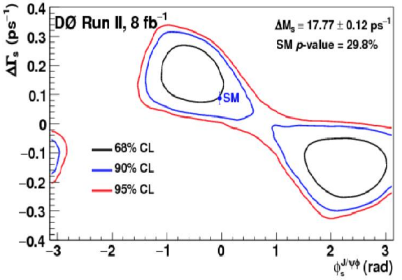



# $\phi_s$, the $\not{CP}$ phase, a bit of history

Tevatron experiments have looked to CP violation in $B_s^0 \to J/\psi\phi$, deraving confidence intervals for $\phi_s$.

Originally they found a combined $\sim 2\sigma$ deviation from $-2\beta_s$.

Deviation has decreased with more data, but $\sigma(\phi_s^{exp})$ still much larger than $\phi_s^{SM}$.




[*D0 Prelim, S.Burdin*]

Note the **2-fold ambiguity**

Decay rates invariant under transform:

$$\phi_s \Longleftrightarrow \pi - \phi_s \quad \Delta\Gamma_s \Longleftrightarrow -\Delta\Gamma_s$$

$$\delta_\parallel \Longleftrightarrow 2\pi - \delta_\parallel \quad \delta_\perp \Longleftrightarrow -\delta_\perp$$

# Analysis strategy

**CP Asymmetry** :

$$A_{CP} = \frac{\Gamma(\overline{B}_s(t)\rightarrow(J/\psi phi)_{CP} - \Gamma B_s(t)\rightarrow(J/\psi phi)_{CP}}{\Gamma(\overline{B}_s(t)\rightarrow(J/\psi phi)_{CP} + \Gamma B_s(t)\rightarrow(J/\psi phi)_{CP}}$$

What we measure is:

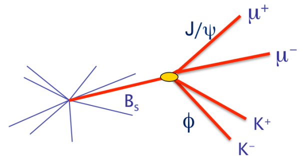
$$A_{CP} = -\eta_{CP} \cdot sin(\phi_s) \cdot sin(\Delta m_s t)$$

**Decay time**: fast $B_s^0$ oscillation needs to be resolved ($\Delta m_s = 17.63 ps^{-1}$);

**Flavour tagging**: to separate $B_s^0$ from $\overline{B}_s^0$

**Mass**: to separate signal from background;

!!! $B_s^0 \rightarrow J/\psi\phi$ is not a CP eigenstate.

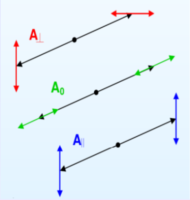


# Separation of CP eigenstates

$$B_s^0 \to J/\psi(\to \mu^+\mu^-)\phi(\to K^+K^-)$$

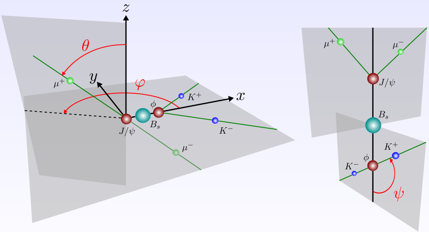
Pseudoscalar to vector mesons ($J^{PC} = 1^{--}$) decay: final states *CP* odd and *CP* even.

L = 0, 2   CP = $(-1)^L$ = +1
L = 1   CP = $(-1)^L$ = -1




Three polarisation amplitudes and phases:

- $|A_0|^2$, $|A_\parallel|^2$, $\delta_0$, $\delta_\parallel$ (*CP*-even)
- $|A_\perp|^2$, $\delta_\perp$ (*CP*-odd)

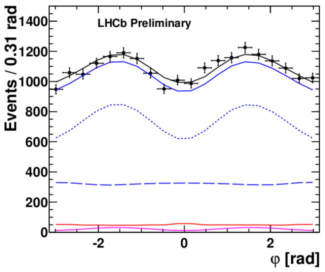


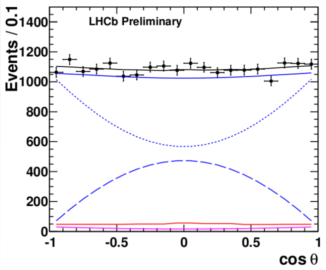

Angular analysis in $\theta$, $\phi$, $\psi$ to separate $CP$=$\pm$1 states and extract $\phi_s$.

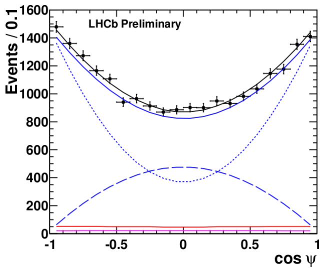
# $B_s^0 \to J/\psi\phi$ angular and proper time distributions



- clear separation of CP even and CP odd states
- different shapes in angular distributions



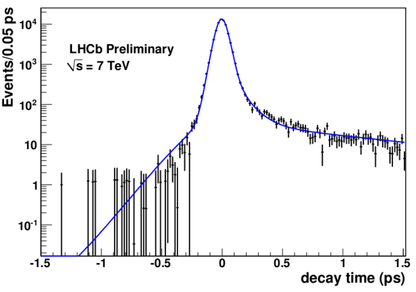



# Decay time resolution

Fast $B_s^0$ oscillation need to be resolved! Time resolution affect the observed $A_{CP}$:

$$A_{CP} \approx -\eta_{CP} \cdot sin(\phi_s) \cdot D_{\sigma_{ct}} \cdot sin(\Delta m_s t) \qquad D_{\sigma_{ct}} \approx exp[-(\Delta m_s \, \sigma_{ct})^2/2]$$

We need good proper time resolution $\sigma_{ct}$ w.r.t. sinusoid period of oscillation $\approx 350 fs$, and excellent knowledge of $\sigma_{ct}$ in data.



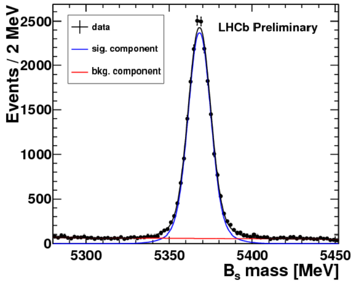

[LHCB-CONF-2012-002]

How to determine $\sigma_{ct}$ in data?
!! IDEA

- Reconstructing fake $B_s^0$ with zero lifetime;
- Using prompt $J/\psi$ bkg plus 2 random tracks: $\tau = 0 \pm \sigma_{ct}$
- Decay time resolution $\sigma_{ct} \approx 45\ fs$

# $B_s^0 \to J/\psi\phi$ in LHCb



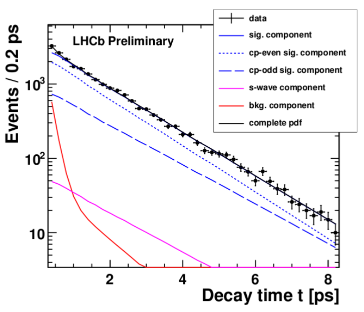



[LHCB-CONF-2012-002]

- $\mathcal{L} = 1 fb^{-1}$
- Very pure sample:
  - $\approx$ 21200 signal candidates.
  - background $\mathcal{O}(\%)$
- World's largest $B_s^0 \to J/\psi\phi$ dataset!

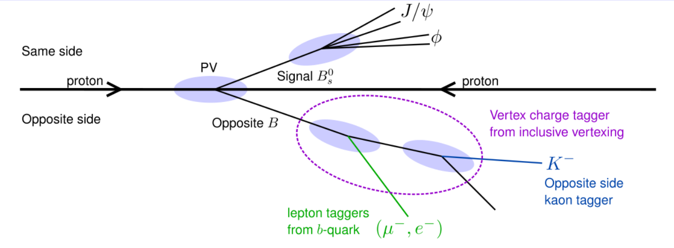
- Different lifetimes for CP odd and CP even components

$$\Delta\Gamma_s = \Gamma_L - \Gamma_H \approx \Gamma_{CP\,odd} - \Gamma_{CP\,even}$$



# Flavour tagging - $B_s^0$ or $\overline{B}_s^0$ ?

**Tagging**: determine flavour of decaying $B_s^0$ -meson.




- tagging efficiency $\epsilon_{tag} = (32.99 \pm 0.33)\%$
- wrong tag probability $\omega_{tag} = (36.81 \pm 0.18 \pm 0.74)\%$
- effective tagging power $\epsilon_{tag}(1 - 2\omega_{tag})^2 = (2.29 \pm 0.07 \pm 0.26)\%$

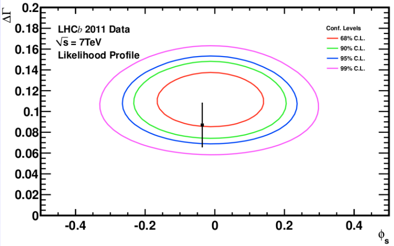
$$A_{CP} \approx -\eta_{CP} \cdot (1 - 2\omega_{tag}) \cdot sin(\phi_s) \cdot D_{\sigma_{ct}} \cdot sin(\Delta m_s t)$$

# Other ingredients

There are still other ingredients needed:

- Proper time acceptance.
- Angular acceptances.
- Mass distribution modelling.
- Background composition and acceptances.
- S-wave modelling.
- ...

$\phi_s - \Delta\Gamma_s$ profile Likelihood contour plot




[LHCb-CONF-2012-002]

$$\Gamma_s = 0.6580 \pm 0.0054\,(stat.) \pm 0.0066\,(syst.)\; ps^{-1}$$

$$\Delta\Gamma_s = 0.116 \pm 0.018\,(stat.) \pm 0.006\,(syst.)\; ps^{-1}$$

$$\phi_s = -0.001 \pm 0.101\,(stat.) \pm 0.027\,(syst.)\; rad$$

Two-fold ambiguity resolved in a different measurement!
Solution with positive $\Delta\Gamma_s$ is preferred at $4.7\sigma$.

[LHCb-PAPER-2011-028, arXiv:1202.4717[hep-ex]]

# Systematic Uncertanties

| Source | $\Gamma_s$ [ps$^{-1}$] | $\Delta\Gamma_s$ [ps$^{-1}$] | $A_\perp^2$ | $A_0^2$ | $F_S$ | $\delta_\parallel$ | $\delta_\perp$ | $\delta_s$ | $\phi_s$ |
|---|---|---|---|---|---|---|---|---|---|
| Description of background | 0.0010 | 0.004 | - | 0.002 | 0.005 | 0.04 | 0.04 | 0.06 | 0.011 |
| Angular acceptances | 0.0018 | 0.002 | 0.012 | 0.024 | 0.005 | 0.12 | 0.06 | 0.05 | 0.012 |
| $t$ acceptance model | 0.0062 | 0.002 | 0.001 | 0.001 | - | - | - | - | - |
| $z$ and momentum scale | 0.0009 | - | - | - | - | - | - | - | - |
| Production asymmetry ($\pm$ 10%) | 0.0002 | 0.002 | - | - | - | - | - | - | 0.008 |
| CPV mixing & decay ($\pm$ 5%) | 0.0003 | 0.002 | - | - | - | - | - | - | 0.020 |
| Fit bias | - | 0.001 | 0.003 | - | 0.001 | 0.02 | 0.02 | 0.01 | 0.005 |
| Quadratic sum | 0.0066 | 0.006 | 0.013 | 0.024 | 0.007 | 0.13 | 0.07 | 0.08 | 0.027 |

- The dominant contribution for $\Gamma_s$ from the proper time acceptance.
- The dominant contribution for $\phi_s$ from the $\not{CP}$ in mixing and decay.
- In view of more data, with the goal of separating the observed $\phi_s$ from the SM prediction to see if New Physics is playing a role, the measurement must be very precise.
- Systematic uncertainty need to be reduced!

# Nuisance « CP » asymmetries

There are several effects that may affect the the CP asymmetry:

- $B_s^0$-$\overline{B}_s^0$ production. A difference in the production rate of $B$ and $\overline{B}$ introduces a **production asymmetry**
- Tagging efficiency. A different probability to tag $B$ and $\overline{B}$ may cause a **tagging efficiency asymmetry**.
- Wrong-tag probability. A different probability for a wrong tag for $B$ and $\overline{B}$ can be parametrized by **wron tag asymmetry**.
- Additional CP violation in mixing and/or decay. Can be parametrized by a parameter $\lambda$.

# Systematic uncertainties

In the past this systematic uncertainties due to nuisance “CP ”asymmetries were:

- **production asymmetry ($\nu_p$)** $\longrightarrow$ performing a toy study, which includes a $\nu_p = 10\%$ and fitting a decay model without the nuisance asymmetry. The bias in the parameter of interested is the resulting systematic uncertainty;
- **additional CP violation in mixing and/or decay** $\longrightarrow$ fitting for it in data to get a feeling of the magnitude and then using the same procedure as before with $|\lambda|^2 = 1 \pm 5\%$;
- **tagging/wrong tag asymmetries** $\longrightarrow$ already covered by the uncertainties on the tagging calibration parameters.

The systematic uncertainties quoted are :

| | $\Gamma_s$ | $\Delta\Gamma_s$ | $\phi_s$ |
|---|---|---|---|
| Additional $\not{CP}$ in mix and/or decay | 0.0003 | 0.002 | **0.020** |
| Production asymmetry | 0.0002 | 0.002 | 0.008 |
| Total | 0.0066 | 0.006 | 0.027 |

# $\not\!CP$ in mixing and/or decay

Can we fit directly in data for the additional $\not\!CP$ in mixing and/or decay?
Defining

$$\lambda = \frac{q}{p}\frac{\overline{A}_f}{A_f}$$

- q,p complex numbers that define $B_s^0$ mass eigenstates in terms of flavour eigenstates $| B_{H,L} >= p | B_s^0 > \mp q | \overline{B}_s^0 >$
- $\overline{A}_f$ and $A_f$ the decay amplitudes.

Both the CP violation in $B_s^0$ mixing $| q/p | \neq 1$ or the CP violation in the decay (direct $\not\!CP$) $| \overline{A}_f / A_f | \neq 1$ result in $| \lambda | \neq 1$.

Parametrizing $\lambda$ as:

$$\lambda = | \lambda | e^{-i\phi_s}$$

and allowing for $| \lambda | \neq 1$ is it possible to fit for the $\not\!CP$ in mixing and/or decay.

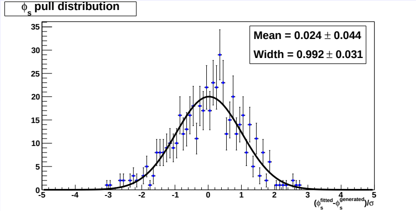
# Fitting for the $\not{CP}$ in mixing and/or decay

Allowing for $|\lambda| \neq 1$ is it possible to fit for the $\not{CP}$ in mixing and/or decay.

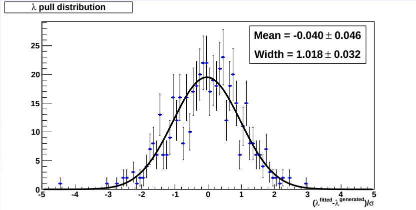
- Making toy studies to check if there are bias introduced fitting for $|\lambda|$;
- I generated the same statistics as in data and run over 500 toys.
- looking to the pull distribution for the parameter $\vartheta$:

$$\frac{\vartheta_{fitted} - \vartheta_{generated}}{\sigma(\vartheta_{fitted})}$$

**$\phi_s$ pull distribution**




**$\lambda$ pull distribution**




We can fit for the $\not{CP}$ in mixing and/or decay without any bias!

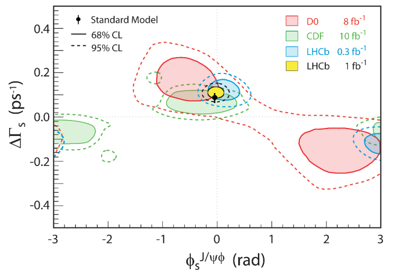
# What about the other asymmetries?

- Included performing a toy study
- Adding a tagging efficiency, a wrong tag probability and a production asymmetry in generation
- fitting using a decay model without any asymmetry.

The bias in the parameter of interested is the resulting systematic uncertainty on the parameter:

| | $\Gamma_s$ | $\Delta\Gamma_s$ | $\phi_s$ |
|---|---|---|---|
| Tagging efficiency asym | 0.0002 | 0.003 | 0.007 |
| Wrong tag asym | 0.0003 | 0.002 | 0.006 |
| Production asym | 0.0001 | 0.001 | 0.005 |
| **All asimmetries** | 0.0003 | 0.002 | 0.007 |
| $\not{CP}$ mix and/or decay | 0.0003 | 0.002 | 0.020 |
| Production asym | 0.0002 | 0.002 | 0.008 |

# Conclusions




[LHCb-CONF-2012-002]

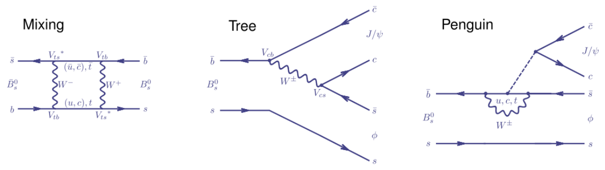
- First direct observation of a non-zero value for $\Delta\Gamma_s$
- World's most precise measurement of CP violation in $B_s^0 \rightarrow J/\psi\phi$
- The measurement of $\phi_s$ is*:

$$\phi_s = -0.002 \pm 0.083\,(stat) \pm 0.027\,(syst)\;rad$$

* In combination with $\phi_s$ from $B_s^0 \rightarrow J/\psi\pi^+\pi^-$

Backup slides

# More theory




- Mixing phase: $\phi_{mix} = \arg(V_{ts}V_{tb}^*)^2$
- $B_s^0 \to J/\psi\phi$ is a $b \to c\bar{c}s$ transition, Tree (T) and Penguin ($P_q$) terms:

$$\begin{aligned} A_{c\bar{c}s} &= V_{cs}V_{cb}^*(T + P_c) + V_{us}V_{ub}^*P_u + V_{ts}V_{tb}^*P_t \\ &= V_{cs}V_{cb}^*(T + P_c - P_t) + V_{us}V_{ub}^*(P_u - P_t) \end{aligned}$$

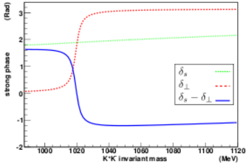
- $V_{us}V_{ub}^*$ suppressed by $O(\lambda^2)$ WRT $V_{cs}V_{cb}^*$ so $(P_u - P_t)$ penguin pollution $(\delta P)$ small
- This leaves $\phi_{decay} = \arg(V_{cs}V_{cb}^*)$

$$\begin{aligned} \phi_s &= \phi_{mix} - 2\phi_{decay} = \arg(V_{ts}V_{tb}^*)^2 - 2\arg(V_{cs}V_{cb}^*) + \delta P \\ &= 2\arg\left[\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right] = -2\beta_s = -2\eta\lambda^2 - \eta\lambda^4 - O(\lambda^6) \end{aligned}$$

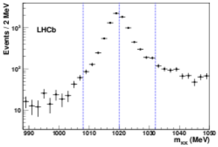
# Ambiguity

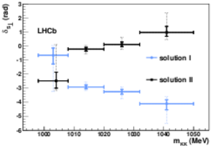
- Two solutions to decay rates in $B_s^0 \to J/\psi\,\phi$:

| Solution I | | Solution II |
|---|---|---|
| $\delta_\parallel - \delta_0$ | | $\delta_0 - \delta_\perp$ |
| $\delta_\perp - \delta_0$ | | $\pi + \delta_0 - \delta_\perp$ |
| $\delta_s - \delta_0$ | $\Leftrightarrow$ | $\delta_0 - \delta_s$ |
| $\phi_s$ | | $\pi - \phi_s$ |
| $\Delta\Gamma_s$ | | $-\Delta\Gamma_s$ |




- P-wave phase ($\delta_\perp$) increases rapidly across $\phi(1020)$ mass resonance, S-wave phase ($\delta_s$) varies slowly
- Measuring $\delta_s - \delta_\perp$ in bins of $M(K^+K^-)$ resolves the ambiguity arXiv:0908.3627 [hep-ph]
- LHCb results, 0.37 fb$^{-1}$ in 4 bins of $M(K^+K^-)$:



# More about the pdf

Signs in blue are tag dependent and change for $\bar{B}_s^0$

$$
\begin{aligned}
A_1 &= |A_0|^2 e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_s}{2}t\right) - \cos\phi_s \sinh\left(\frac{\Delta\Gamma_s}{2}t\right) \boxed{+} \sin\phi_s \sin(\Delta m_s t)\right] \\
A_2 &= |A_\parallel|^2 e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_s}{2}t\right) - \cos\phi_s \sinh\left(\frac{\Delta\Gamma_s}{2}t\right) \boxed{+} \sin\phi_s \sin(\Delta m_s t)\right] \\
A_3 &= |A_\perp|^2 e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_s}{2}t\right) + \cos\phi_s \sinh\left(\frac{\Delta\Gamma_s}{2}t\right) \boxed{-} \sin\phi_s \sin(\Delta m_s t)\right] \\
A_4 &= |A_\parallel||A_\perp| e^{-\Gamma_s t}\left[-\cos(\delta_\perp - \delta_\parallel)\sin\phi_s \sinh\left(\frac{\Delta\Gamma_s}{2}t\right)\right. \\
&\quad \left.\boxed{-}\cos(\delta_\perp - \delta_\parallel)\cos\phi_s \sin(\Delta m_s t) \boxed{+} \sin(\delta_\perp - \delta_\parallel)\cos(\Delta m_s t)\right] \\
A_5 &= |A_0||A_\parallel| e^{-\Gamma_s t}\cos(\delta_\parallel - \delta_0)\left[\cosh\left(\frac{\Delta\Gamma_s}{2}t\right) - \cos\phi_s \sinh\left(\frac{\Delta\Gamma_s}{2}t\right)\right. \\
&\quad \left.\boxed{+}\sin\phi_s \sin(\Delta m_s t)\right] \\
A_6 &= |A_0||A_\perp| e^{-\Gamma_s t}\left[-\cos(\delta_\perp - \delta_0)\sin\phi_s \sinh\left(\frac{\Delta\Gamma_s}{2}t\right)\right. \\
&\quad \left.\boxed{-}\cos(\delta_\perp - \delta_0)\cos\phi_s \sin(\Delta m_s t) \boxed{+} \sin(\delta_\perp - \delta_0)\cos(\Delta m_s t)\right] \\
A_7 &= |A_s|^2 e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_s}{2}t\right) + \cos\phi_s \sinh\left(\frac{\Delta\Gamma_s}{2}t\right) \boxed{-} \sin\phi_s \sin(\Delta m_s t)\right] \\
A_8 &= |A_s||A_\parallel| e^{-\Gamma_s t}\left[-\sin(\delta_\parallel - \delta_s)\sin\phi_s \sinh\left(\frac{\Delta\Gamma_s}{2}t\right)\right. \\
&\quad \left.\boxed{-}\sin(\delta_\parallel - \delta_s)\cos\phi_s \sin(\Delta m_s t) \boxed{+} \cos(\delta_\parallel - \delta_s)\cos(\Delta m_s t)\right] \\
A_9 &= |A_s||A_\perp| e^{-\Gamma_s t}\sin(\delta_\perp - \delta_s)\left[\cosh\left(\frac{\Delta\Gamma_s}{2}t\right) + \cos\phi_s \sinh\left(\frac{\Delta\Gamma_s}{2}t\right)\right. \\
&\quad \left.\boxed{-}\sin\phi_s \sin(\Delta m_s t)\right] \\
A_{10} &= |A_s||A_0| e^{-\Gamma_s t}\left[-\sin(\delta_0 - \delta_s)\sin\phi_s \sinh\left(\frac{\Delta\Gamma_s}{2}t\right)\right. \\
&\quad \left.\boxed{-}\sin(\delta_0 - \delta_s)\cos\phi_s \sin(\Delta m_s t) \boxed{+} \cos(\delta_0 - \delta_s)\cos(\Delta m_s t)\right]
\end{aligned}
$$