Measurements of the CP-violating phase ϕ_s at LHCb

Konrad Klimaszewski

UJ, Kraków
NCBJ, Warszawa

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Kraków

Outline

Introduction

LHCb experiment

B_s^0 measurements

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

$B_s^0 \to J/\psi\pi^+\pi^-$

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Why should we study flavour?

Currently the main focus of particle physics is on searches for physics beyond the Standard Model

There are two ways to discover New Physics:

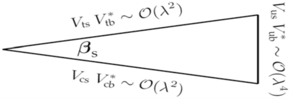
- Direct searches for production of new particles (Atlas and CMS)
- Indirect searches (LHCb contributes)
  - Tests of the SM by precision measurements of well known processes
  - Observation of a disagreement is an indirect indication for the existence of new objects
  - In particular we are interested in CPV in B and D
    - CPV in SM is too small to explain matter domination over antimatter
    - It is a good tool in searches for New Physics

CP violation

- Particles and anti-particles behave differently
- Within the Standard Model (SM) only weak interactions violate CP
- Flavour changing weak interactions characterised by CKM matrix

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \cdot \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \approx \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$



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

Time development of the mixing described by phenomenological Schroedinger equation:

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

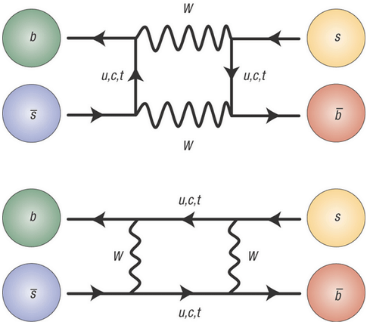
$$M = \begin{pmatrix} M_{11} & M_{12} \\ M_{12}^* & M_{22} \end{pmatrix}; \Gamma = \begin{pmatrix} \Gamma_{11} & \Gamma_{12} \\ \Gamma_{12}^* & \Gamma_{22} \end{pmatrix}$$

Diagonalizing it in terms of mass eigenstates:

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

Mass eigenstates $\neq$ flavour eigenstates:

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



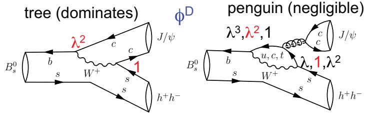
Phenomenological mixing parameters:

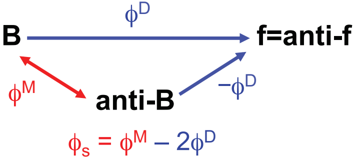
- **Lifetime difference**: $\Delta\Gamma_s = \Gamma_L - \Gamma_H$
- **Mass difference**: $\Delta m_s = m_H - m_L$
- **Mixing phase**: $\phi_M = \arg(-M_{12}/\Gamma_{12})$

B_s^0 CP violating phase ϕ_s

Three ways of CPV

- In mixing (indirect) $\Gamma(B^0 \to \overline{B}^0) \neq \Gamma(\overline{B}^0 \to B^0)$
- In decays (direct) $\Gamma(B^0 \to f) \neq \Gamma(\overline{B}^0 \to \overline{f})$
- In interference (indirect) between direct decays and decays with mixing $\Gamma(B^0 \to f_{CP}) \neq \Gamma(\overline{B}^0 \to f_{CP})$
  - Allows us to measure the value of ϕ_s



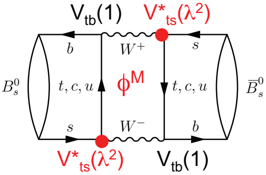


Phases

$$\phi_S = -2arg(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}) = -2\beta_s$$

$$\phi_M = 2arg(V_{ts}V_{tb}^*)$$

$$2\phi_D = arg(V_{cs}V_{cb}^*)$$



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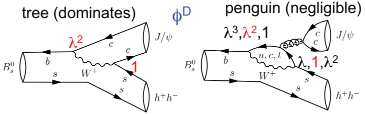
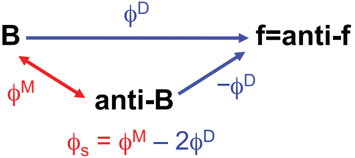
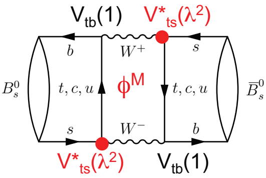




Why ϕ_s?

- Very well predicted in the SM: $\phi_s^{SM} = -0.0368 \pm 0.0017\,\text{rad}$
- New particles can be exchanged in the box diagram and modify the value of ϕ_M



Analysis ingredients

Theoretical **CP Asymmetry** (for CP eigenstates):

$$A_{CP}(t) = \frac{\Gamma(\overline{B}_s^0(t) \to f_{CP}) - \Gamma(B_s^0(t) \to f_{CP})}{\Gamma(\overline{B}_s^0(t) \to f_{CP}) + \Gamma(B_s^0(t) \to f_{CP})} = -\eta_{CP} \cdot \sin(\phi_s) \cdot \sin(\Delta m_s t)$$

Experimental **CP Asymmetry** from a **flavour tagged time-dependent** analysis:

$$A_{CP}(t) = -\boxed{\eta_{CP}} \cdot \boxed{D_{\mathrm{tag}}(\omega_{\mathrm{mistag}})} \cdot \boxed{D_{\mathrm{t_{res}}}(\sigma_t)} \cdot \sin(\phi_s) \cdot \boxed{\sin(\Delta m_s t)}$$

Essential ingredients to measure ϕ_s:

- **CP eigenvalue of the final state**: angular analysis needed, if not unique CP eigenstate
- **Probability of getting the initial flavour**: good tagging performance and precise knowledge
- **Decay time resolution**: good performance and precise knowledge
- **Mixing frequency Δm_s**: time dependent analysis

Introduction

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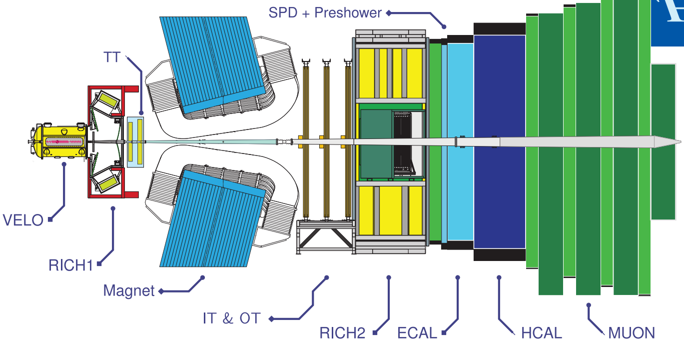
LHCb detector



- LHCb is a single-arm forward ($2 < \eta < 5$) spectrometer at the LHC
  - Precision beauty and charm physics:
    CP violation, rare decays, heavy flavour production
- High rate of $b\bar{b}$ pairs production at the LHC
  - $\sigma_{b\bar{b}} \sim 300\mu b \rightarrow$ more than 10^{13} $b\bar{b}$ pairs produced so far

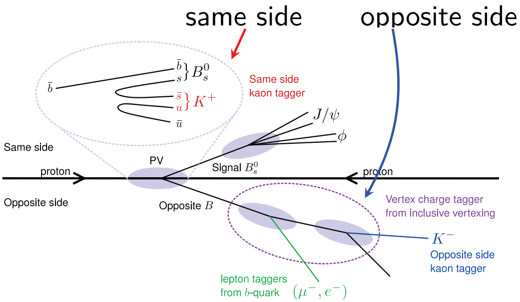
B_s^0 or $\overline{B}_s^0$ - tagging the flavour

Same side

- s quark in B_s^0 is produced with $\bar{s}$
- $\sim 50\,\%$ of $\bar{s}$ forms a charged K
- charge of the K identifies flavour of B_s^0

Opposite side

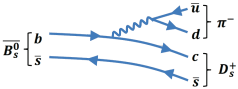
- in pp collisions b produced mostly in $b\bar{b}$ pairs
- flavour determined by the charge of decay products of opposite B:
  - leptons
  - kaons
  - global charge of secondary vertex



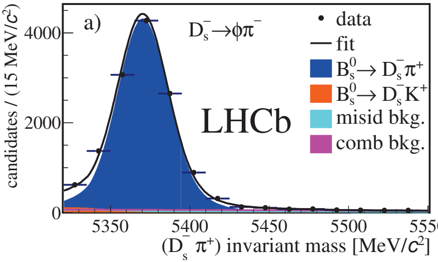
- Total effective tagging efficiency: $\epsilon(1-2\omega)^2$
- ϵ - efficiency of tagging algorithm
- ω - frequency of events with wrong tagging
- $Eff = (3.9 \pm 0.25)\%$

$B_s^0 - \overline{B}_s^0$ oscillations

Δm_s measured from 1fb^{-1} $B_s^0 \to D_s^- \pi^+$ decays



- High statistics: N $\sim$ 34000 signal candidates
- Self tagging channel
- Five different D_s^- decay modes: $(\phi\pi^-, K^*K^-, K^-K^+\pi^-, K^-\pi^+\pi^-, \pi^-\pi^+\pi^-)$
- Very low background



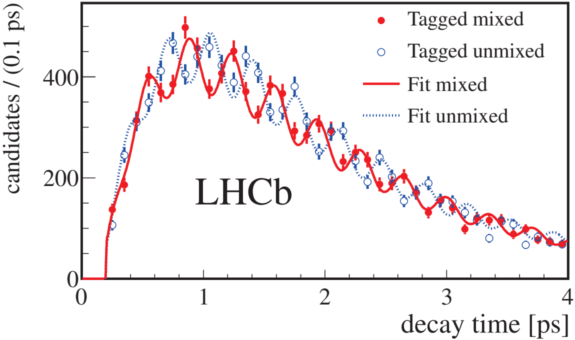
[New J. Phys. 15 (2013) 053021]

$B_s^0 - \overline{B}_s^0$ oscillations

The measured oscillation frequency:

$$\Delta m_s = 17.768 \pm 0.023(stat) \pm 0.006(syst)\,\text{ps}^{-1}$$

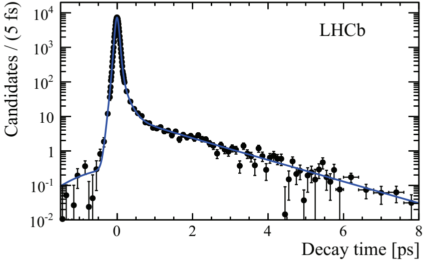
- Based on $\mathcal{L} = 1\text{fb}^{-1}$ data
- The most precise measurement to date
- Agrees with world average: $17.69 \pm 0.08\,\text{ps}^{-1}$



[New J. Phys. 15 (2013) 053021]

Decay time resolution

- B_s^0 have fast oscillations: period $2\pi/\Delta m_s \approx 350\,\text{fs}$
- Decay time resolution σ_t will dilute the measured oscillation amplitude
- The dilution factor: $D(\sigma_t) = e^{-\frac{(\sigma_t \Delta m_s)^2}{2}}$



[Phys. Rev. D 87, 112010]

- Resolution measured from data
- Combinations of $\mu^+\mu^-K^+K^-$ events
- Same selection as for B_s^0 apart for decay time cuts
- Mostly prompt events with true decay time of zero
- Effective decay time resolution $\sigma_t = 45\,\text{fs}$

$D(\sigma_t = 45\,\text{fs}) \approx 0.73$

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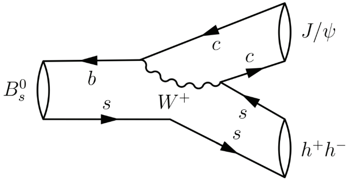
$B_s^0 \to J/\psi(\mu\mu)K^+K^-$

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

- Mostly via $B_s^0 \to J/\psi\phi$, with $\phi \to K^+K^-$(the P-wave)
- Small non-resonant component with K^+K^- in S-wave

Decay dominated by tree level diagram:



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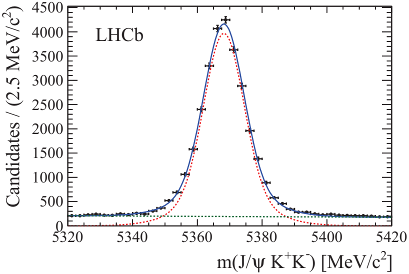


Sample

- Analysed $1\,\text{fb}^{-1}$ LHCb data
- High statistics: $N \sim 27600$ events
- Low background
  - Narrow J/ψ resonance
  - Cuts on B_s^0 decay time

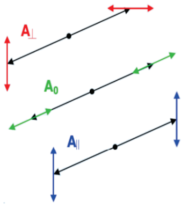
Angular analysis

[arXiv:1304.2600]

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

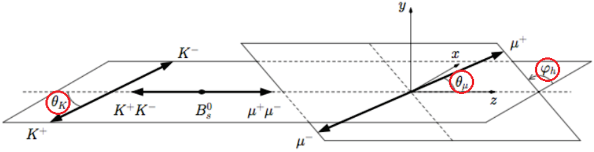
Pseudoscalar to vector mesons ($J^{PC} = 1^{--}$) decay: final states CP odd and CP even.

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



Three polarisation amplitudes and phases:

- $|A_0|^2$, $|A_\parallel|^2$, δ_0, $\delta_\parallel$ (CP-even)
- $|A_\perp|^2$, $\delta_\perp$ (CP-odd)



Angular analysis in **helicity basis**: θ_K, θ_μ, φ_h to separate CP=$\pm$1 states and extract ϕ_s.

- s-wave component amplitude and phase included in the fit: $|A_s|^2$,δ_s (CP-odd)

Angular analysis [arXiv:1304.2600]

$$\frac{d^4\Gamma(B_s^0 \to J/\psi K^+K^-)}{dtd\Omega} \propto \sum_{k=1}^{10} h_k(t) f_k(\Omega)$$

Time-dependent part

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

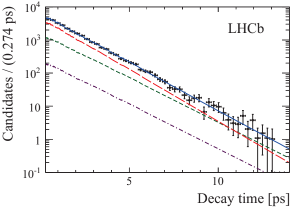
- N_k - amplitudes of the different polarisations and their interference
- a_k, b_k, c_k, d_k - coefficients expressed in terms of CP violating observables C, D, S (depending on ϕ_s)

Angular part

- $\Omega = (\theta_\mu, \theta_K, \varphi_h)$
- Various CP states differ by angular dependence

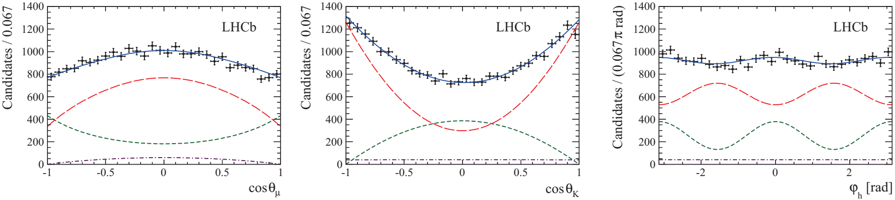
Angular analysis

[arXiv:1304.2600]



Result extracted using
unbinned maximum likelihood fit

CP-even, **CP-odd**, **S-wave**, **Total Fit**



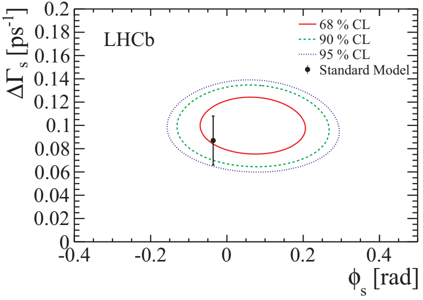
$B_s^0 \to J/\psi\phi$ results

[arXiv:1304.2600]

LHCb 2011 data corresponding to $\mathcal{L} = 1\text{fb}^{-1}$

$$\begin{aligned} \phi_s &= 0.07 \pm 0.09(stat) \pm 0.01(syst)\,\text{rad} \\ \Gamma_s &= 0.663 \pm 0.005(stat) \pm 0.006(syst)\,\text{ps}^{-1} \\ \Delta\Gamma_s &= 0.100 \pm 0.016(stat) \pm 0.003(syst)\,\text{ps}^{-1} \end{aligned}$$

- Main systematic contributions: angular and decay time acceptances



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

- My area of interest
- Same BR for $J/\psi \to ee$ as for $\mu\mu$
- Electrons are harder to trigger on and to identify
- Smaller sample expected

$B_s^0 \to J/\psi\phi$ results [arXiv:1304.2600]

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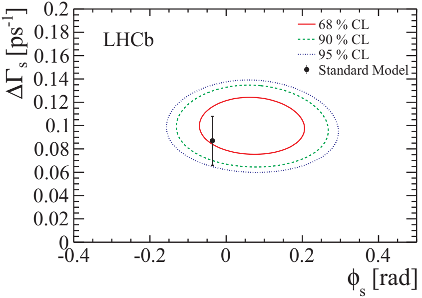

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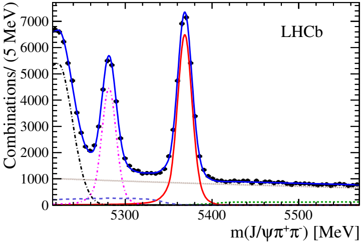
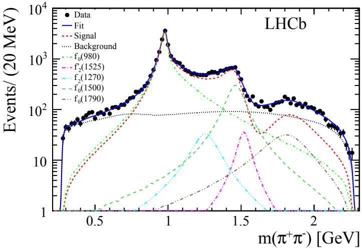
[arXiv:1405.4140]

- Predominantly via $B_s^0 \to J/\psi X$, with $X = f_0(980), f_2(1270), f_0(1370)$
- Decay mode determined to be $> 97.7\%$ CP-Odd [Phys. Rev. D 86, 052006]
- No need for angular analysis



Sample

- Analysed $3\text{fb}^{-1}$of data from LHCb
- Signal events: $N \sim 27100$
- Γ_s and $\Delta\Gamma_s$ constrained to the values from $B_s^0 \to J/\psi\phi$

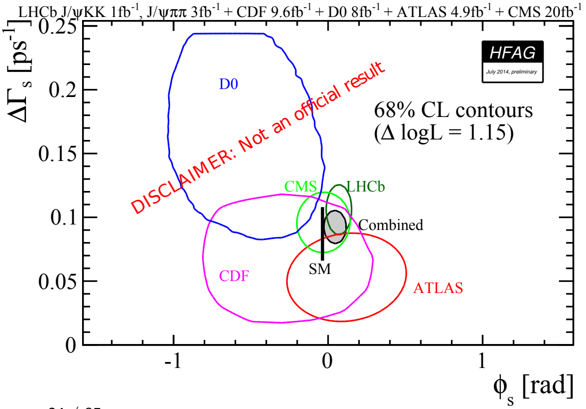


$B_s^0 \to J/\psi\pi^+\pi^-$ results

[arXiv:1405.4140]

$$\phi_s = 0.070 \pm 0.068(stat) \pm 0.008(syst)\ \text{rad}$$
$$|\lambda| = 0.89 \pm 0.05(stat) \pm 0.01(syst)$$

[PLB **736** 186 (2014)]



LHCb measurement:

- most precise
- in agreement with other experiments
- in agreement with SM

Summary

Results of LHCb ϕ_s measurements:

- $B_s^0 \to J/\psi K^+ K^-$ ($\mathcal{L} = 1\text{fb}^{-1}$) and $B_s^0 \to J/\psi \pi^+ \pi^-$ ($\mathcal{L} = 3\text{fb}^{-1}$)
  - Most precise measurement to date
  - So far compatible with SM

$$\phi_s = 0.070 \pm 0.068 \pm 0.008\,\text{rad}$$
$$\Gamma_s = 0.663 \pm 0.005 \pm 0.006\,\text{ps}^{-1}$$
$$\Delta\Gamma_s = 0.100 \pm 0.016 \pm 0.003\,\text{ps}^{-1}$$

LHCb plans for the future:

- An update for $B_s^0 \to J/\psi K^+ K^-$ channel with a factor 2 more statistics in progress (expected $\delta\phi_s \approx 0.05\,\text{rad}$)
- Work is underway for inclusion of additional channels
- More data after LHCb upgrade (expected $\delta\phi_s \approx 0.008\,\text{rad}$)

Backup

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

$$\begin{aligned}
\Delta M &= M_{\mathrm{H}} - M_{\mathrm{L}} = 2|M_{12}| \left(1 - \frac{1}{8}\frac{|\Gamma_{12}|^2}{|M_{12}|^2}\sin^2\phi_{12} + \ldots.\right), \\
\Delta\Gamma &= \Gamma_{\mathrm{L}} - \Gamma_{\mathrm{H}} = 2|\Gamma_{12}|\cos\phi_{12} \left(1 + \frac{1}{8}\frac{|\Gamma_{12}|^2}{|M_{12}|^2}\sin^2\phi_{12} + \ldots.\right), \\
a_{\mathrm{sl}} &= \frac{\Gamma\left(\overline{B}(t) \to f\right) - \Gamma\left(B(t) \to \overline{f}\right)}{\Gamma\left(\overline{B}(t) \to f\right) + \Gamma\left(B(t) \to \overline{f}\right)} = \frac{\Delta\Gamma}{\Delta M}\tan\phi_{12},
\end{aligned}$$

Angular analysis

$$\lambda_i = \frac{q}{p}\frac{\overline{A}_i}{A_i}$$

$$\phi_s = -arg(\lambda)$$

$$C = \frac{1-|\lambda|^2}{1+|\lambda|^2}$$

$$S = -\frac{2|\lambda| sin\phi_s}{1+|\lambda|^2}$$

$$D = -\frac{2|\lambda| cos\phi_s}{1+|\lambda|^2}$$

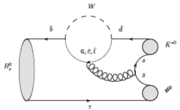
TABLE II. Definition of angular and time-dependent functions.

k	$f_k(\theta_\mu, \theta_K, \varphi_h)$	N_k	a_k	b_k	c_k	d_k
1	$2\cos^2\theta_K \sin^2\theta_\mu$	$\|A_0\|^2$	1	D	C	$-S$
2	$\sin^2\theta_K(1-\sin^2\theta_\mu\cos^2\varphi_h)$	$\|A_\parallel\|^2$	1	D	C	$-S$
3	$\sin^2\theta_K(1-\sin^2\theta_\mu\sin^2\varphi_h)$	$\|A_\perp\|^2$	1	$-D$	C	S
4	$\sin^2\theta_K \sin^2\theta_\mu \sin 2\varphi_h$	$\|A_\parallel A_\perp\|$	$C\sin(\delta_\perp-\delta_\parallel)$	$S\cos(\delta_\perp-\delta_\parallel)$	$\sin(\delta_\perp-\delta_\parallel)$	$D\cos(\delta_\perp-\delta_\parallel)$
5	$\frac{1}{2}\sqrt{2}\sin 2\theta_K \sin 2\theta_\mu \cos\varphi_h$	$\|A_0 A_\parallel\|$	$\cos(\delta_\parallel-\delta_0)$	$D\cos(\delta_\parallel-\delta_0)$	$C\cos(\delta_\parallel-\delta_0)$	$-S\cos(\delta_\parallel-\delta_0)$
6	$-\frac{1}{2}\sqrt{2}\sin 2\theta_K \sin 2\theta_\mu \sin\varphi_h$	$\|A_0 A_\perp\|$	$C\sin(\delta_\perp-\delta_0)$	$S\cos(\delta_\perp-\delta_0)$	$\sin(\delta_\perp-\delta_0)$	$D\cos(\delta_\perp-\delta_0)$
7	$\frac{2}{3}\sin^2\theta_\mu$	$\|A_S\|^2$	1	$-D$	C	S
8	$\frac{1}{3}\sqrt{6}\sin\theta_K \sin 2\theta_\mu \cos\varphi_h$	$\|A_S A_\parallel\|$	$C\cos(\delta_\parallel-\delta_S)$	$S\sin(\delta_\parallel-\delta_S)$	$\cos(\delta_\parallel-\delta_S)$	$D\sin(\delta_\parallel-\delta_S)$
9	$-\frac{1}{3}\sqrt{6}\sin\theta_K \sin 2\theta_\mu \sin\varphi_h$	$\|A_S A_\perp\|$	$\sin(\delta_\perp-\delta_S)$	$-D\sin(\delta_\perp-\delta_S)$	$C\sin(\delta_\perp-\delta_S)$	$S\sin(\delta_\perp-\delta_S)$
10	$\frac{4}{3}\sqrt{3}\cos\theta_K \sin^2\theta_\mu$	$\|A_S A_0\|$	$C\cos(\delta_0-\delta_S)$	$S\sin(\delta_0-\delta_S)$	$\cos(\delta_0-\delta_S)$	$D\sin(\delta_0-\delta_S)$

Pure penguin decays

- **Decays forbiden at tree level. New Physics (NP) can enter in decay through** **loop** **diagrams (or** **penguin** **diagrams)**

- **$B_s^0 \rightarrow \phi \overline{K}^{*0}$ and $B_s^0 \rightarrow K^{*0} \overline{K}^{*0}$ are** **pure penguin** **decays. No tree amplitude contribution**



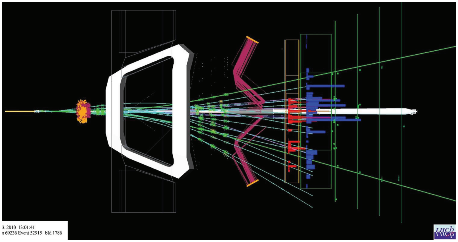
- **Very good framework to find New Physics (NP) contributions, since** **new heavy particles can enter in loops**

- **They are $B \rightarrow V_1 V_2$ (V_i vector mesons). Angular analysis is necessary**

- **$B_s^0 \rightarrow \phi \overline{K}^{*0}$ and $B_s^0 \rightarrow K^{*0} \overline{K}^{*0}$ are studied.** **First observation** **of decays and measurement of longitudinal polarization fraction was performed**

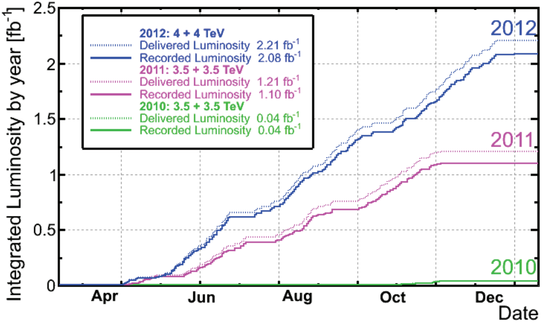
LHCb in numbers

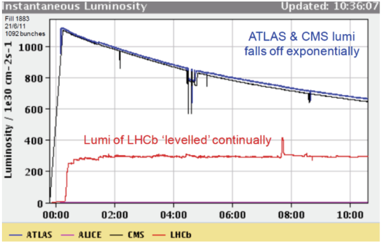
- Vertex Finder
  - IP resolution$\approx$ 20mm
  - Decay time resolution $\approx$ 45fs
- Tracking
  - $\delta p/p = 0.4\%$ at 5GeV up to 0.6% at 100GeV



- Particle ID
  - RICH:
    - $\varepsilon_{PID}(K) \approx 95\%$
    - $\text{MisID}(K \to \pi) \approx 5\%$
  - Electromagnetic Calorimeter:
    - Resolution$\approx 1\% + 10\%/\sqrt{E}$(GeV)
  - Muon ID:
    - $\varepsilon_{PID}(\mu) \approx 97\%$
    - $\text{MisID}(\mu) \approx 1 - 3\%$

LHCb running conditions





- LHCb designed to run at lower luminosity than ATLAS/CMS
  - Tracking, PID sensitive to pile-up
  - Mean number of interactions/bunch crossing ~ 2
- pp beams displaced to reduce instantaneous luminosity
- For $\mathcal{L} = 1\text{fb}^{-1}$ about $3 \cdot 10^{11}$ $b\bar{b}$ produced

LHCb upgrade

➡ *See talk by J. Panman on hot topics for run II / upgrade*

- Take quark flavour physics to the precision and very high precision regime
  - Towards experimental sensitivities matching theoretical uncertainties
- Upgrade detector *and* trigger system
  - Full readout at 40 MHz and availability of full event info from first-stage software trigger
- Installation in 2018-19
  $\Rightarrow$ ready for data taking in 2020
- Collect ~ 50 fb^{-1}
- Gain in collected yields from (1) increased luminosity and (2) trigger
  - Trigger efficiencies for hadronic decays saturate with present trigger system
  - Inst. lumi: $4\times10^{32}\ cm^{-2}\ s^{-1} \rightarrow 2\times10^{33}\ cm^{-2}\ s^{-1}$

LHC run I	LHCb 2018	LHCb upgrade
$\int L dt \approx 3\ fb^{-1}$	$\int L dt \approx 8\ fb^{-1}$	$\int L dt \approx 50\ fb^{-1}$

2010 2011 2012 2013 2014 2015 2016 2017 2018 2019 2020 2021 2022 2023 2024 2025 2026

LHC Run I	LS1	LHC Run II	LS 2	LHC Run III	LS3	LHC Run IV
pp runs with - 50ns bunch spacing - E_{CM} 7TeV and 8 TeV LHCb $\mathcal{L}$~4x10³²/cm²/s LHCb $\int\mathcal{L}$ ~3/fb	LHC splice consoli-dation	pp runs with - 25ns bunch spacing, - E_{CM} 13 TeV LHCb $\mathcal{L}$>4x10³²/cm²/s LHCb $\int\mathcal{L}$ >5/fb	LHC injector upgrade LHCb upgrade	pp runs with - 25ns b.spacing - E_{CM} 14 TeV $\mathcal{L}$ > 1x10³³/cm²/s LHCb $\int\mathcal{L}$ > 15/fb	HL-LHC prep GPD phase 2 upgrades	$\mathcal{L}$=2x10³³/cm²/s $\int\mathcal{L}$ > 23/fb

* Integrated luminosity always include lumi. from previous runs

Eduardo Rodrigues CKM 2014, Vienna, Austria, 11 Sep. 2014 3/22

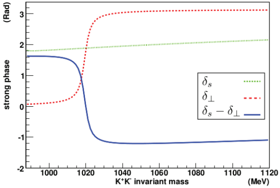
Observable	LHC run I	LHC run II	LHC run III
$\phi_s(B_s^0 \to J/\psi\phi)$ [rad]	0.050	0.025	0.009
$\phi_s(B_s^0 \to J/\psi f_0)$ [rad]	0.068	0.035	0.012

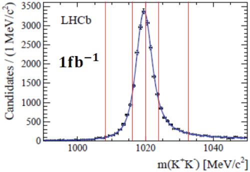
$\Delta\Gamma_s$ sign ambiguity

There are two possible fit solutions: $\Delta\Gamma_s, \phi_s$ and $-\Delta\Gamma_s, \pi - \phi_s$

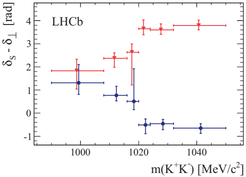
- For physical solution:
  - P-wave phase $(\delta_\perp)$ increases rapidly across $\phi(1020)$ mass resonance
  - S-wave phase (δ_s) varies slowly
- Measuring $\delta_s - \delta_\perp$ in bins of $M(K^+K^-)$ resolves the ambiguity
- LHCb results using $\mathcal{L} = 1\text{fb}^{-1}$ in 6 bins of $M(K^+K^-)$

[Phys. Rev. D 87, 112010]





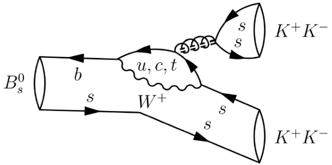
The **physical solution** has to decrease in bins of $M(K^+K^-)$



$B_s^0 \to \phi\phi$

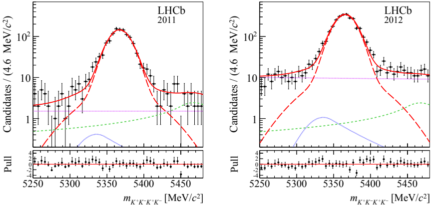
- Similar CKM phases as for $B_s^0 \to J/\psi K^+ K^-$
- Mixture of CP eigenstates, 2 CP-even and 3 CP-odd
- Angular analysis needed

Decay dominated by penguin diagram:



Sample

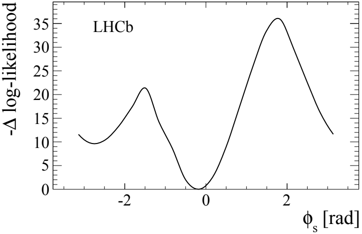
- Analysed $3\,\text{fb}^{-1}$ LHCb data
- Clean signal in purely hadronic channel: $N \sim 4000$ events
- Selection based on Boosted Decision Tree
- Similar resolution and effective tagging power



[to appear in Phys. Rev. D, arXiv:1407.2222]

$B_s^0 \to \phi\phi$ angular analysis

[arXiv:1407.2222]



Result extracted using
unbinned maximum likelihood fit

CP-even, **CP-odd**, **S-wave**, **Total Fit**

$$\phi_s = -0.17 \pm 0.15(stat) \pm 0.03(syst)\ \text{rad}$$

$$|\lambda| = 1.04 \pm 0.07(stat) \pm 0.03(syst)$$

Compatible with SM prediction