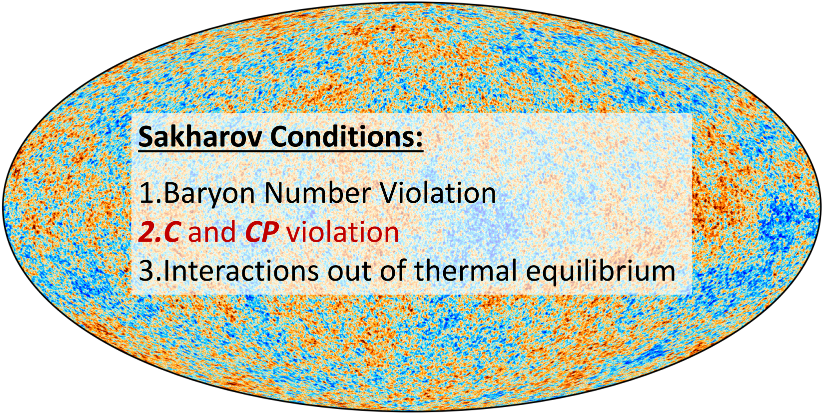
First measurement of *CP*-violation using $B_s^0 \to K^{*0}\overline{K}^{*0}$ decays

Matthew Kenzie
University of Cambridge
On behalf of the LHCb collaboration

- Precision measurement of *CP*-violation in $B_s^0 \to J/\psi K^+K^-$ decays - PRL 114 041801 (2015)
- Measurement of *CP*-violation in $B_s^0 \to \phi\phi$ decays - PRD 90 052011 (2014)
- First measurement of the *CP*-violating phase $\phi_s^{d\bar{d}}$ in $B_s^0 \to (K^+\pi^-)(K^-\pi^+)$ decays NEW
  LHCb-PAPER-2017-048

CERN LHC seminar
21st November 2017

Why is the universe matter dominated?



Sakharov Conditions:

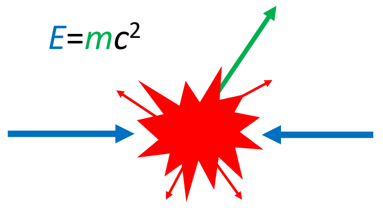
1. Baryon Number Violation
2. ***C*** and ***CP*** violation
3. Interactions out of thermal equilibrium

- We live in a matter (and photon) dominated universe: $n_b/n_\gamma \sim 10^{-10}$
- *CP*-violation is a crucial ingredient to this problem
- But *CP*-violation in the SM only accounts for $\sim 10^{-20}$
- There must be **new physics** and **new sources of *CP*-violation**

How to find New Physics at the LHC?

High energy frontier

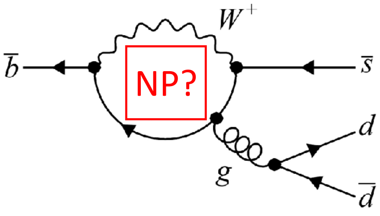
Direct observation



Require $E > MC^2$ for direct production

Precision frontier

Indirect effects

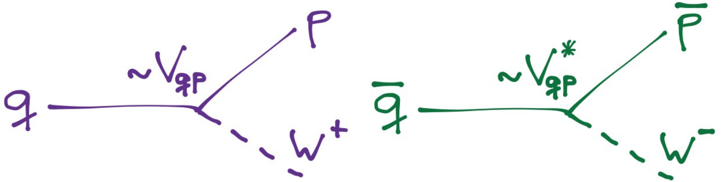


New particles effect loop processes

- Most HEP direct discoveries have been preceeded by **indirect evidence first!**
- If we don't see New Physics directly at the LHC can indirect evidence guide us where to look (or what to build) next?

CKM matrix

- In the SM quarks can change flavour by emission of a $W^{\pm}$ boson
  - So must also change charge (i.e. from up-type to down-type or vice-versa)



- The probability for such a transition is governed by the elements of the 3 × 3 **unitary** CKM matrix

CKM matrix

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

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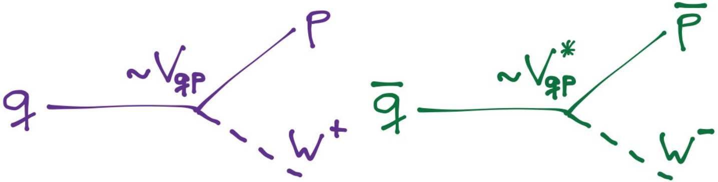

- The probability for such a transition is governed by the elements of the 3 × 3 **unitary** CKM matrix
  - It exhibits a clear hierarchy

CKM hierarchy

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \sim \begin{pmatrix} 1 & 0.2 & 0.004 \\ 0.2 & 1 & 0.04 \\ 0.008 & 0.04 & 1 \end{pmatrix}$$

CKM matrix

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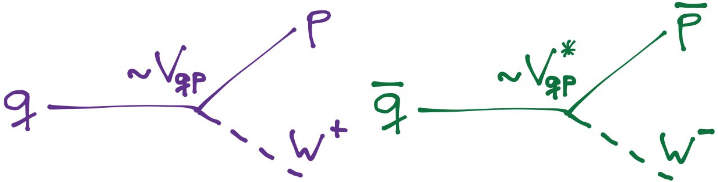
    - So must also change charge (i.e. from up-type to down-type or vice-versa)



- The probability for such a transition is governed by the elements of the 3×3 **unitary** CKM matrix
    - It exhibits a clear hierarchy
    - Contains the only source of $C\!P$-violation in the SM (i.e. if $\Lambda_{\rm QCD} = m_\nu = 0$)

Wolfenstein parametrisation

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

CKM matrix

- Unitarity imposes several conditions which give rise to “unitarity” triangles

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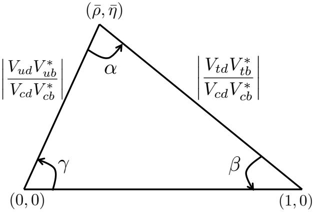
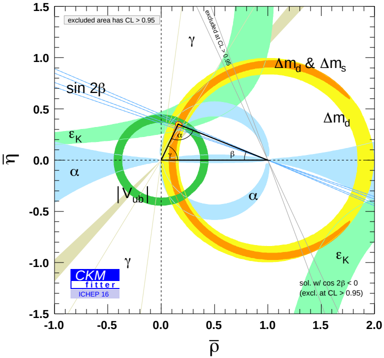
“B^0 unitarity triangle”

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





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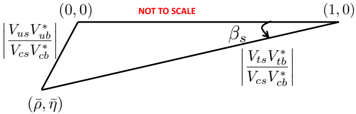
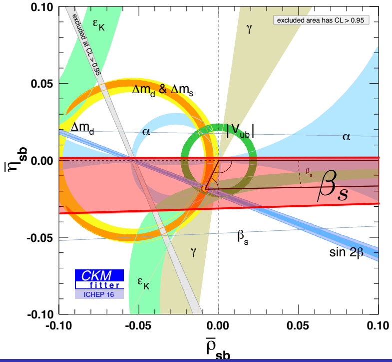
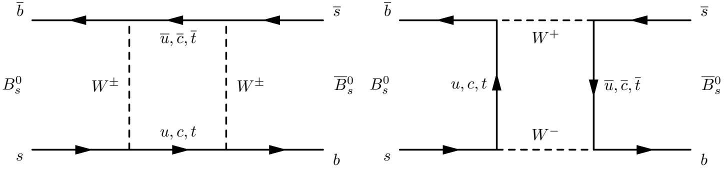
“B^0_s unitarity triangle”

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





Neutral meson mixing



- The physical mass eigenstates are admixtures of the weak eigenstates

$$|B^0_{\mathrm{s}}{}_{L,H}\rangle = p|B^0_{\mathrm{s}}\rangle \mp q|\overline{B}^0_{\mathrm{s}}\rangle$$

with mass difference, Δm, and width difference, $\Delta\Gamma$.

- If CP is conserved in mixing then $\left|\frac{p}{q}\right| = 1$
- **States evolve** with time according to Schrödinger's equation,

$$i\frac{\partial}{\partial t}\begin{pmatrix} |B^0_{\mathrm{s}}(t)\rangle \\ |\overline{B}^0_{\mathrm{s}}(t)\rangle \end{pmatrix} = \left(\mathbf{M} - \frac{i}{2}\mathbf{\Gamma}\right)\begin{pmatrix} |B^0_{\mathrm{s}}(t)\rangle \\ |\overline{B}^0_{\mathrm{s}}(t)\rangle \end{pmatrix}$$

- **SM prediction and experimental value for** CP **violation in** B^0_{s} **mixing is** ~ 0 - [arXiv:1205.1444], [arXiv:1612.07233]

How does *CP*-violation manifest itself?

- Must have **two** interfering amplitudes with **different** strong (δ) and weak (ϕ) phases
- For a B_s^0 decay to a *CP*-eigenstate, f, *CP*-violation effects depend on $\lambda = \frac{q}{p}\frac{\bar{\mathcal{A}}_f}{\mathcal{A}_f}$

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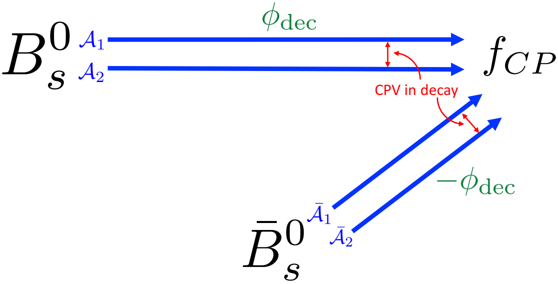
CPV in decay:

- $P(B^0_s \to f) \neq P(\bar{B}^0_s \to f)$
- $|\bar{\mathcal{A}}_f/\mathcal{A}_f| \neq 1$



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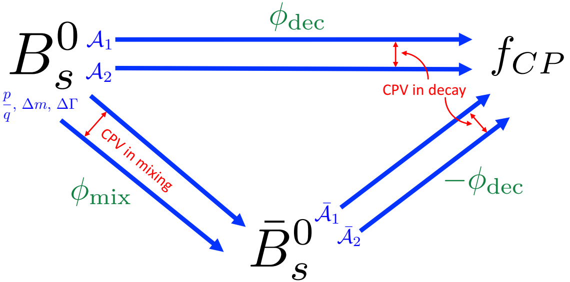

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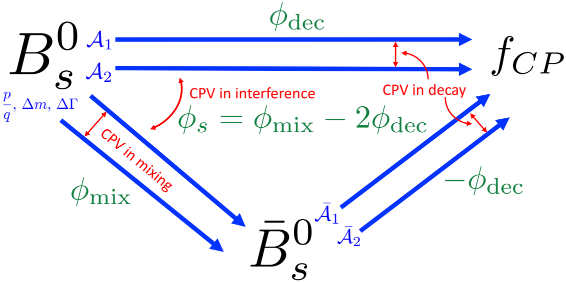


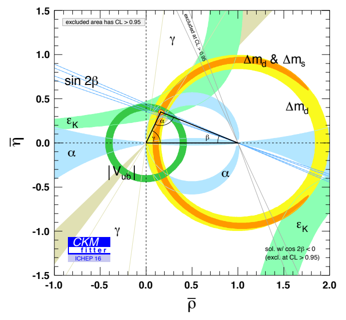
CPV in the interference between decay and mixing:

- $P(B_s^0 \to f) \neq P(B_s^0 \to \bar{B}_s^0 \to f)$
- $\arg(\lambda) \neq 0$

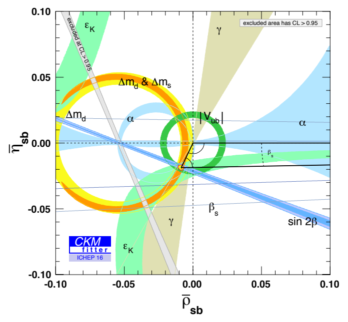
How does *CP*-violation manifest itself?

- Must have **two** interfering amplitudes with **different** strong (δ) and weak (ϕ) phases
- For $B_s^0 \to f$ decay, *CP*-violation effects depend on $\lambda = \dfrac{q}{p}\dfrac{\bar{\mathcal{A}}_{\bar{f}}}{\mathcal{A}_f}$

In B^0 system this phase is 2β



In B_s^0 system this phase is $-2\beta_s$



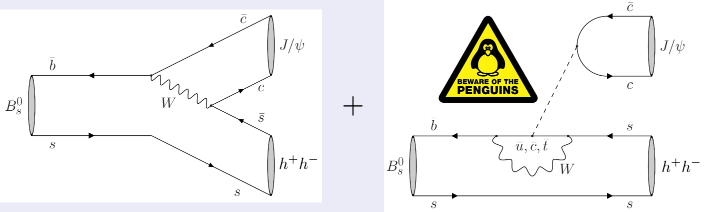
CPV in the interference between decay and mixing:

Sensitivity to ϕ_s

- SM predicts: $\phi_s = (-0.0370 \pm 0.0006)\,\mathrm{rad}$ [arXiv:1612.07233]
    - **Small** but **non-zero**

Golden mode: $B_s^0 \to J/\psi\, K^+ K^-$ - [Phys. Rev. Lett. 114 (2015) 041801]

$$\phi_s = \underbrace{\phi_{\mathrm{SM}}}_{-2\beta_s} + \Delta\phi_{\mathrm{peng}} + \Delta\phi_{\mathrm{NP}}$$

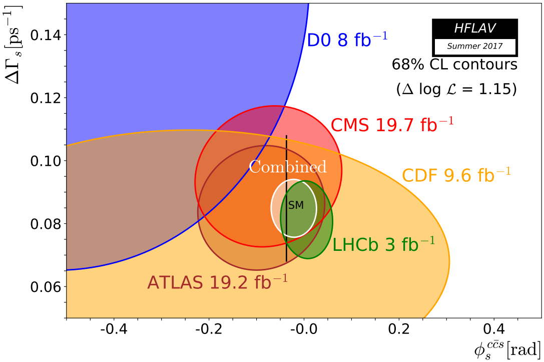


- Only for $b \to c\bar{c}s$ transitions ($\phi_s^{c\bar{c}}$)
- Estimate $\Delta\phi_{\mathrm{peng}} \approx 0.003$ [JHEP 11 (2015) 082] ($B^0 \to J/\psi\,\rho$, $B_s^0 \to J/\psi\, K^{*0}$)

Current status

- World average for these modes currently dominated by LHCb
- Consistent with both the SM and zero - [arXiv:1612.07233]

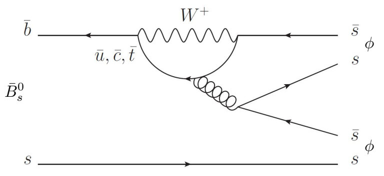
$$\phi_s^{c\bar{c}}(\mathrm{SM}) = (-0.0370 \pm 0.0006)\,\mathrm{rad}$$
$$\phi_s^{c\bar{c}}(\mathrm{WA}) = (-0.021 \pm 0.031)\,\mathrm{rad}$$



$B_s^0 \to \phi\phi$ decays

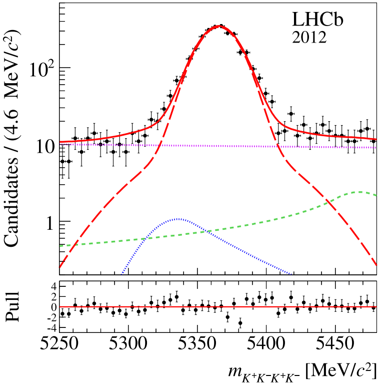
- **Pure penguin decay** - $b \to s s \bar{s}$ transition
- New Physics can be significantly enhanced
- Purely hadronic final state
- The ϕ resonance is very narrow

$B_s^0 \to \phi\phi$



$$\phi_s^{s\bar{s}} = (-0.17 \pm 0.15 \pm 0.03)\,\text{rad}$$

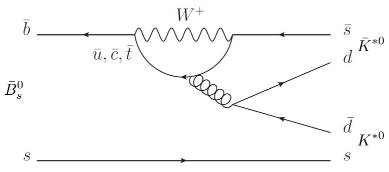
[Phys. Rev. D90 052011 (2014)]



$B_s^0 \rightarrow (K^+\pi^-)(K^-\pi^+)$ decays

- **Pure penguin decay** - $b \rightarrow sd\bar{d}$ transition
- New Physics can be significantly enhanced and entirely different from $B_s^0 \rightarrow J/\psi\,\phi$ and $B_s^0 \rightarrow \phi\phi$
- Expect similar statistical precision to $B_s^0 \rightarrow \phi\phi$
- CPV in decay is also possible

$B_s^0 \rightarrow K^{*0}\overline{K}^{*0}$



$\phi_s^{d\bar{d}} = ?$

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Experimentally challenging:

- Low branching fraction (100 times smaller than $B_s^0 \rightarrow J/\psi\,\phi$)
- Purely hadronic final state
- K^* is fairly wide (several resonant and non-resonant components)
- Several peaking backgrounds

$$\phi_s^{c\bar{c}} \neq \phi_s^{s\bar{s}} \neq \phi_s^{d\bar{d}}$$

Ingredients required for a ϕ_s analysis

- In the simplest case, and **only** if there is no *CP*-violation in decay, the time-dependent *CP*-asymmetry

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

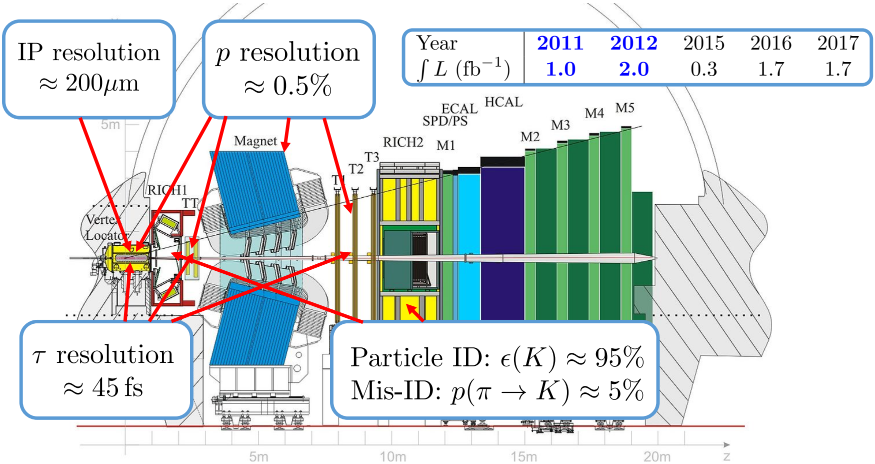
- Experimentally

$$A_{CP}(t) \approx (1-2w)e^{-\frac{1}{2}\Delta m_s^2 \sigma_t^2}\eta_f \sin(\phi_s)\sin(\Delta m_s t)$$

  - w: Probability the initial B flavour was tagged incorrectly
  - σ_t: Decay-time resolution
  - η_f: *CP*-eigenvalue $\implies$ angular analysis
- **Important requirements**
  - Good decay time resolution
  - Good flavour tagging
  - Sufficient statistics for an angular analysis
  - Good particle identification

LHCb Detector

- Copius production of B^+, B^0, B^0_s, Λ^0_b (100K $b\bar{b}$/ s)



IP resolution $\approx 200\mu\text{m}$

p resolution $\approx 0.5\%$

Year	**2011**	**2012**	2015	2016	2017
$\int L$ (fb^{-1})	**1.0**	**2.0**	0.3	1.7	1.7

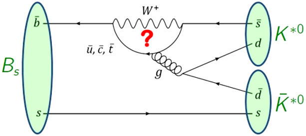
τ resolution ≈ 45 fs

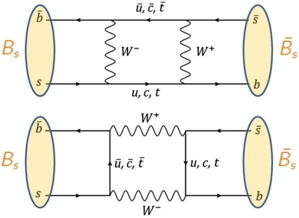
Particle ID: $\epsilon(K) \approx 95\%$
Mis-ID: $p(\pi \rightarrow K) \approx 5\%$

- **LHCb performance** - [Int. J. Mod. Phys. A30, (2015) 1530022]

The $B_s^0 \to K^{*0}\overline{K}^{*0}$ decay

- **Interference between** $B_s^0 \to K^{*0}\overline{K}^{*0}$ **and** $B_s^0 \to \overline{B}_s^0 \to K^{*0}\overline{K}^{*0}$
  - where $K^{*0} \to K^+\pi^-$ and $\overline{K}^{*0} \to K^-\pi^+$
- **Gives access to** CP**-violating phase** $\phi_s^{d\bar{d}}$
- First discovered by LHCb in [Phys. Lett. **B709** (2012) 50]
  - Update in [JHEP **07** (2015) 166]
- Discussed extensively in the literature as a promising mode for New Physics
  - Fleisher et. al. [Phys. Lett. **B660** (2008) 212]
  - Ciuchini et. al. [Phys. Rev. Lett. **100** (2008) 031802]
  - Descotes-Genon et. al. [Phys. Rev. **D85** (2012) 034010]
  - Bhattacharya et. al. [Phys. Lett. **B717** (2012) 403]



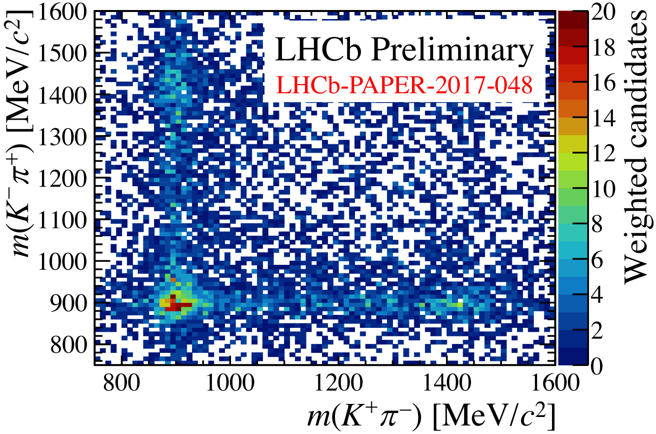


SM expectation:

- $|\lambda| = \dfrac{p}{q}\dfrac{\bar{A}_f}{A_f} \approx 1$
- $\phi_s^{d\bar{d}} = \phi_{\text{mix}} - 2\phi_{\text{decay}} \approx 0$

Increasing the statistics available

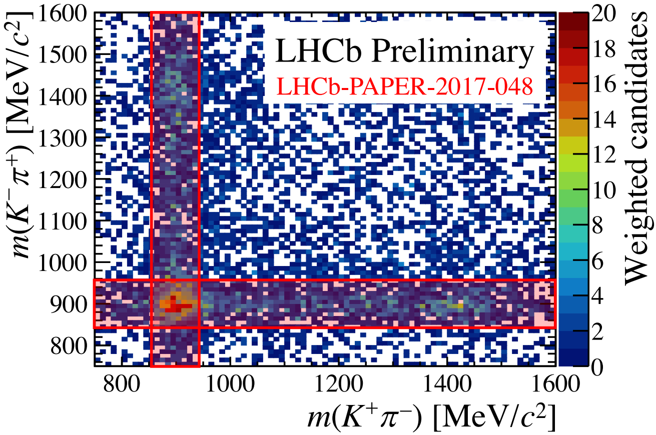
Use a wide $m(K\pi)$ mass range: $750 - 1600\,\mathrm{MeV}/c^2$



Increasing the statistics available

Use a wide $m(K\pi)$ mass range: $750 - 1600\,\mathrm{MeV}/c^2$

Vector: $K^*(892)^0$

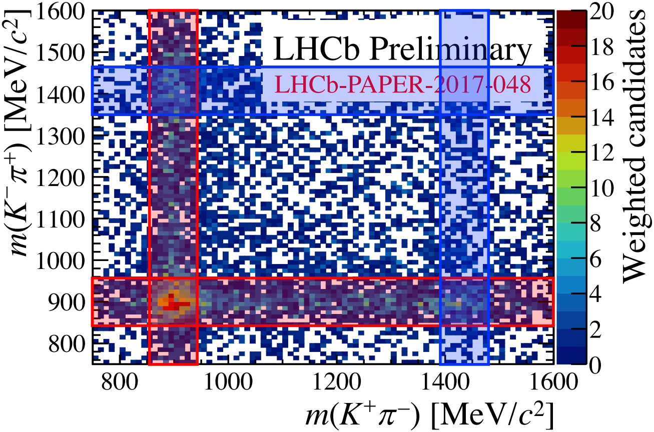


Increasing the statistics available

Use a wide $m(K\pi)$ mass range: $750 - 1600\,\mathrm{MeV}/c^2$

Vector: $K^*(892)^0$

Tensor: $K_2^*(1430)^0$



Increasing the statistics available

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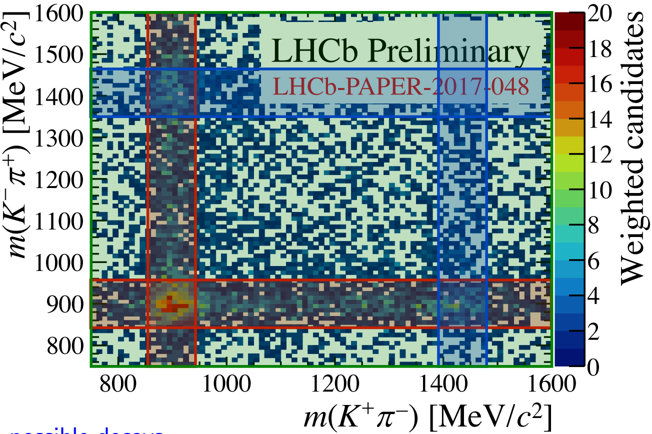
Scalar: $(K^{\pm}\pi^{\mp})^*_0$

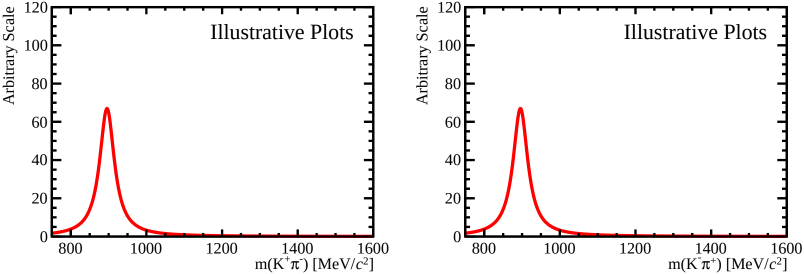
Vector: $K^*(892)^0$

Tensor: $K_2^*(1430)^0$



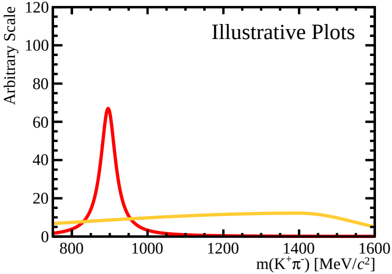
- This gives $3 \times 3 = 9$ possible decays
- **A single phase, $\phi_s^{d\bar{d}}$, is used for all**
- Scalar description from Pelaez et. al. [Phys. Rev. D **93** (2016) 074025]

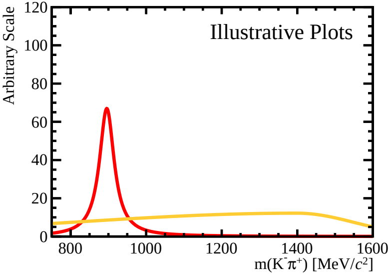
Building the decay model



Decay	Polarization Amplitudes
$B_s^0 \to K^*(892)^0\overline{K}^*(892)^0$	VV0, VV$\parallel$, VV$\perp$

Building the decay model





Decay	**Polarization Amplitudes**
$B_s^0 \to (K^+\pi^-)_0^*(K^-\pi^+)_0^*$	SS
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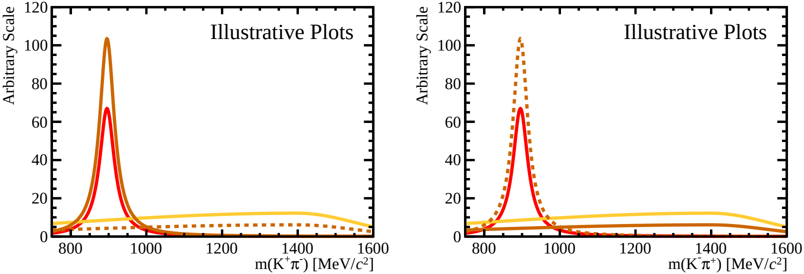

Decay	Polarization Amplitudes
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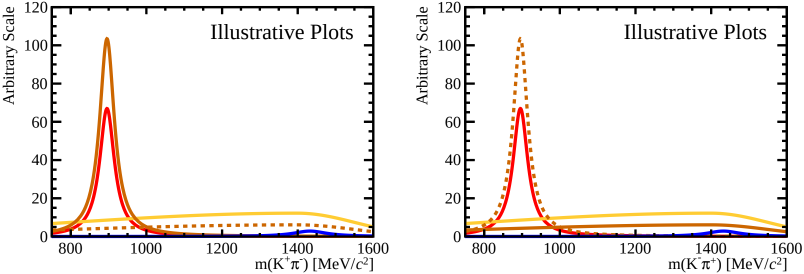
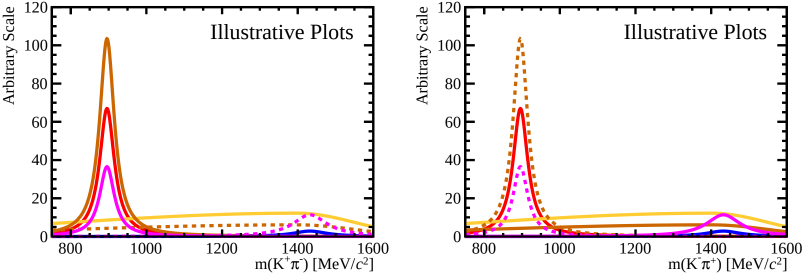
$B_s^0 \to (K^+\pi^-)_0^*\overline{K}^*(892)^0$	SV
$B_s^0 \to K^*(892)^0(K^-\pi^+)_0^*$	VS
$B_s^0 \to K^*(892)^0\overline{K}^*(892)^0$	VV0, VV$\parallel$, VV$\perp$

Building the decay model



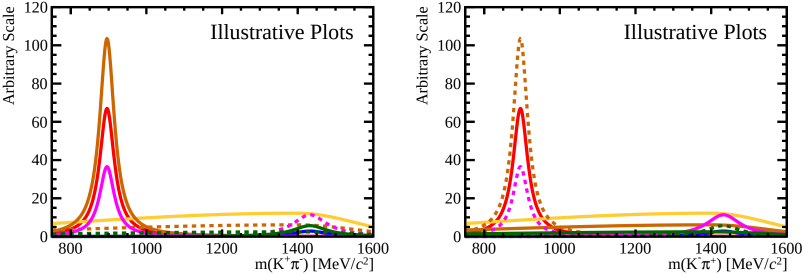
Decay	**Polarization Amplitudes**
$B_s^0 \to (K^+\pi^-)_0^*(K^-\pi^+)_0^*$	SS
$B_s^0 \to (K^+\pi^-)_0^*\overline{K}^*(892)^0$	SV
$B_s^0 \to K^*(892)^0(K^-\pi^+)_0^*$	VS
$B_s^0 \to K^*(892)^0\overline{K}^*(892)^0$	VV0, VV$\parallel$, VV$\perp$
$B_s^0 \to K_2^*(1430)^0\overline{K}_2^*(1430)^0$	TT0, TT$\parallel_1$, TT$\perp_1$, TT$\parallel_2$, TT$\perp_2$

Building the decay model



Decay	Polarization Amplitudes
$B_s^0 \to (K^+\pi^-)_0^*(K^-\pi^+)_0^*$	SS
$B_s^0 \to (K^+\pi^-)_0^*\overline{K}^*(892)^0$	SV
$B_s^0 \to K^*(892)^0(K^-\pi^+)_0^*$	VS
$B_s^0 \to K^*(892)^0\overline{K}^*(892)^0$	VV0, VV$\parallel$, VV$\perp$
$B_s^0 \to K^*(892)^0\overline{K}_2^*(1430)^0$	VT0, VT$\parallel$, VT$\perp$
$B_s^0 \to K_2^*(1430)^0\overline{K}^*(892)^0$	TV0, TV$\parallel$, TV$\perp$
$B_s^0 \to K_2^*(1430)^0\overline{K}_2^*(1430)^0$	TT0, TT$\parallel_1$, TT$\perp_1$, TT$\parallel_2$, TT$\perp_2$

Building the decay model



Decay	**Polarization Amplitudes**
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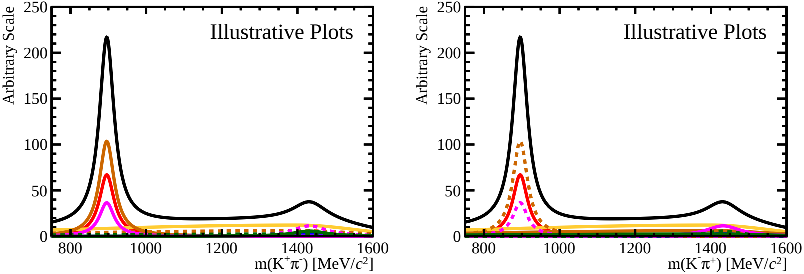
$B_s^0 \to (K^+\pi^-)_0^*\overline{K}^*(892)^0$	SV
$B_s^0 \to K^*(892)^0(K^-\pi^+)_0^*$	VS
$B_s^0 \to (K^+\pi^-)_0^*\overline{K}_2^*(1430)^0$	ST
$B_s^0 \to K_2^*(1430)^0(K^-\pi^+)_0^*$	TS
$B_s^0 \to K^*(892)^0\overline{K}^*(892)^0$	VV0, VV$\parallel$, VV$\perp$
$B_s^0 \to K^*(892)^0\overline{K}_2^*(1430)^0$	VT0, VT$\parallel$, VT$\perp$
$B_s^0 \to K_2^*(1430)^0\overline{K}^*(892)^0$	TV0, TV$\parallel$, TV$\perp$
$B_s^0 \to K_2^*(1430)^0\overline{K}_2^*(1430)^0$	TT0, TT$\parallel_1$, TT$\perp_1$, TT$\parallel_2$, TT$\perp_2$

Building the decay model



Decay	**Polarization Amplitudes**
$B_s^0 \to (K^+\pi^-)_0^*(K^-\pi^+)_0^*$	SS
$B_s^0 \to (K^+\pi^-)_0^*\overline{K}^*(892)^0$	SV
$B_s^0 \to K^*(892)^0(K^-\pi^+)_0^*$	VS
$B_s^0 \to (K^+\pi^-)_0^*\overline{K}_2^*(1430)^0$	ST
$B_s^0 \to K_2^*(1430)^0(K^-\pi^+)_0^*$	TS
$B_s^0 \to K^*(892)^0\overline{K}^*(892)^0$	VV0, VV$\parallel$, VV$\perp$
$B_s^0 \to K^*(892)^0\overline{K}_2^*(1430)^0$	VT0, VT$\parallel$, VT$\perp$
$B_s^0 \to K_2^*(1430)^0\overline{K}^*(892)^0$	TV0, TV$\parallel$, TV$\perp$
$B_s^0 \to K_2^*(1430)^0\overline{K}_2^*(1430)^0$	TT0, TT$\parallel_1$, TT$\perp_1$, TT$\parallel_2$, TT$\perp_2$

Building the decay model II

Factorise the time-dependent probability

$$p(t,\Omega) \propto \sum_{ij} \underbrace{K_{ij}(t)}_{\text{time dep}} \cdot \underbrace{F_{ij}(\Omega)}_{\text{ang/mass dep}}$$

Building the decay model II

Factorise the time-dependent probability

$$p(t,\Omega) \propto \sum_{ij} \underbrace{K_{ij}(t)}_{\text{time dep}} \cdot \underbrace{F_{ij}(\Omega)}_{\text{ang/mass dep}}$$

Time-dependent terms

$$K_{ij}(t) = \underbrace{R(t,\delta) \otimes e^{-\Gamma_s t}}_{\substack{\text{decay time}\\ +\text{ resolution}}} \left[\xi_+ \underbrace{\underbrace{\left(a_{ij}\cosh(\tfrac{1}{2}\Delta\Gamma_s t) + b_{ij}\sinh(\tfrac{1}{2}\Delta\Gamma_s t)\right)}_{\substack{\text{flavour}\\ \text{tagging}}} + \xi_-\left(c_{ij}\cos(\Delta m_s t) + d_{ij}\sin(\Delta m_s t)\right)}_{\substack{\text{mixing}\\ +\text{ decay}}}\right]$$

Coefficients contain dependence on physical parameters

$$a_{ij} = \frac{2}{1+|\lambda|^2}\left(A_i A_j^* + \eta_i\eta_j|\lambda|^2 A_{\bar{i}} A_{\bar{j}}^*\right), \quad b_{ij} = \frac{-2|\lambda|}{1+|\lambda|^2}\left(\eta_j e^{i\phi_s} A_i A_{\bar{j}}^* + \eta_i e^{-i\phi_s} A_{\bar{i}} A_j^*\right),$$

$$c_{ij} = \frac{2}{1+|\lambda|^2}\left(A_i A_j^* - \eta_i\eta_j|\lambda|^2 A_{\bar{i}} A_{\bar{j}}^*\right), \quad d_{ij} = \frac{-2|\lambda| i}{1+|\lambda|^2}\left(\eta_j e^{i\phi_s} A_i A_{\bar{j}}^* - \eta_i e^{-i\phi_s} A_{\bar{i}} A_j^*\right)$$

Building the decay model II

Factorise the time-dependent probability

$$p(t,\Omega) \propto \sum_{ij} \underbrace{K_{ij}(t)}_{\text{time dep}} \cdot \underbrace{F_{ij}(\Omega)}_{\text{ang/mass dep}}$$

Angular and mass dependence $\Omega = (\cos\theta_1, \cos\theta_2, \varphi, m_1, m_2)$

$$F_{ij}(\Omega) = \underbrace{\Theta_{j_1,j_2,h}(\cos\theta_1,\cos\theta_2,\varphi)\;\; \Theta^*_{j'_1,j'_2,h'}(\cos\theta_1,\cos\theta_2,\varphi)}_{\text{angular terms}}$$

$$\times \qquad \underbrace{\mathcal{M}_{j_1}(m_1)\mathcal{M}_{j_2}(m_2)\;\; \mathcal{M}^*_{j'_1}(m_1)\mathcal{M}^*_{j'_2}(m_2)}_{\text{mass terms}}$$

$$\times \qquad \underbrace{\mathcal{F}_{j_1,j_2,h}(m_1,m_2)\mathcal{F}^*_{j'_1,j'_2,h'}(m_1,m_2)}_{\text{ang. mom. factors}}$$

Building the decay model II

Factorise the time-dependent probability

$$p(t,\Omega) \propto \sum_{ij} \underbrace{K_{ij}(t)}_{\text{time dep}} \cdot \underbrace{F_{ij}(\Omega)}_{\text{ang/mass dep}}$$

Angular and mass dependence $\Omega = (\cos\theta_1, \cos\theta_2, \varphi, m_1, m_2)$

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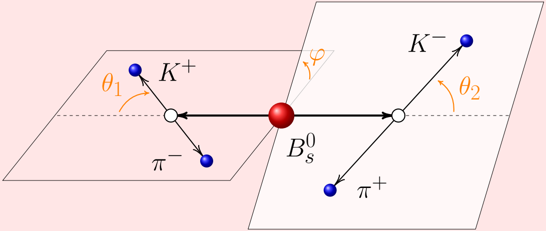
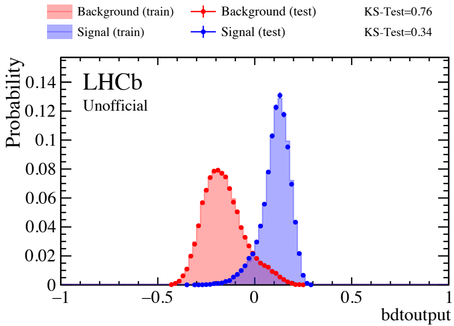
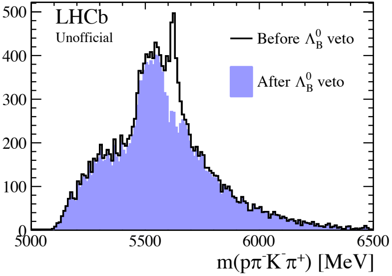


Selecting the signal

Remove unwanted backgrounds:

- Use particle identification requirements from Cherenkov detectors
- Boosted Decision Tree to reject combinatorial background
- Mass vetoes for unwanted contributions

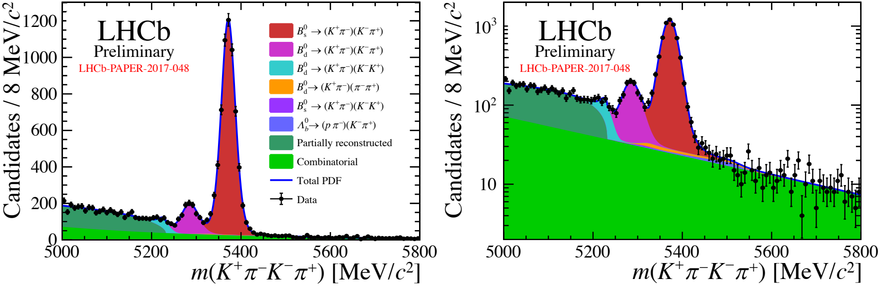




Selecting the signal

Remove unwanted backgrounds:

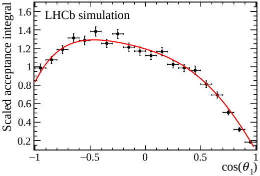
- Use particle identification requirements from Cherenkov detectors
- Boosted Decision Tree to reject combinatorial background
- Mass vetoes for unwanted contributions
- Use ${}_s\mathcal{P}lot$ procedure to subtract background

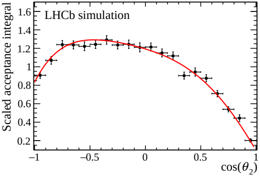


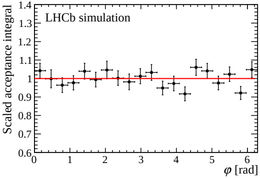
$N_S = 6080 \pm 84$ events

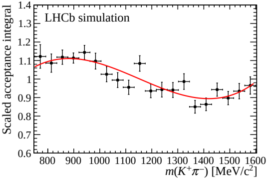
Kinematic acceptance

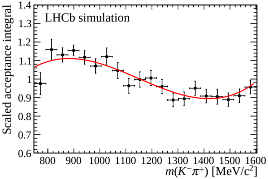
- Detector geometry and selection criteria introduce non-uniform acceptance
- Introduce event weights in the normalisation term of the model
- Create a 5D efficiency map for angular terms, $F_{ij}(\Omega)$





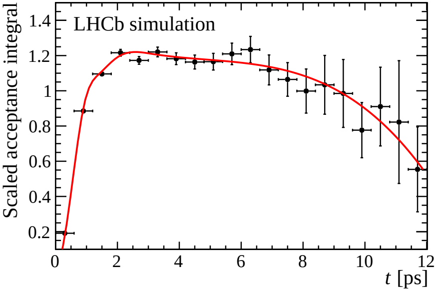






Kinematic and decay-time acceptance

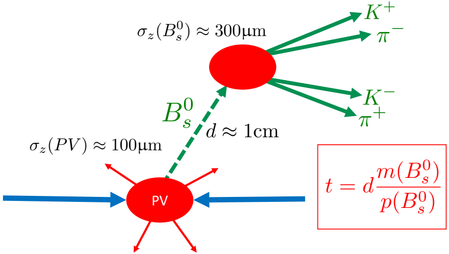
- Detector geometry and selection criteria introduce non-uniform acceptance
- Model the decay-time acceptance parametrically using cubic splines



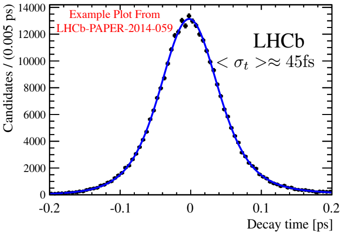
Decay-time resolution

Time-dependent decay rate of B_s^0

$$\frac{d\Gamma}{dt} \propto \sum_{ij} R(t,\delta t) \otimes e^{-\Gamma_s t}\left[a_{ij}\cosh\left(\frac{1}{2}\Delta\Gamma_s t\right) + b_{ij}\sinh\left(\frac{1}{2}\Delta\Gamma_s t\right) + c_{ij}\cos(\Delta m_s t) + d_{ij}\sin(\Delta m_s t)\right]$$



$$t = d\frac{m(B_s^0)}{p(B_s^0)}$$

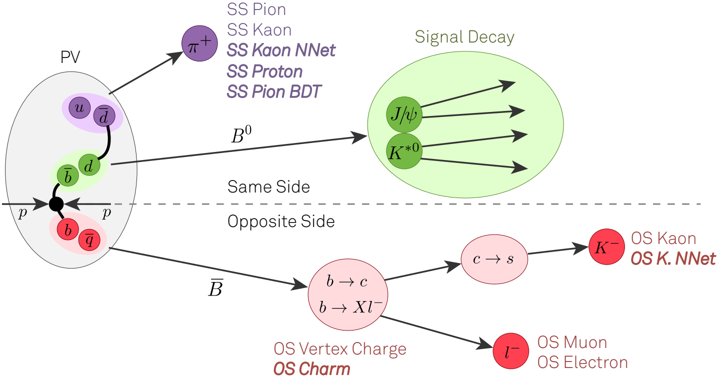


Decay-time resolution

- Modelled as a Gaussian
- True decay-time resolution, σ_t, as a function of the estimated decay-time resolution, δ_t, obtained from simulation using a linear calibration

Flavour tagging

Use both same side (SS) and opposite side (OS) taggers calibrated on real data



Effective tagging power
Fraction with tagging decision
Calibrated mis-tag probability

$$\epsilon_{\text{eff}} = \epsilon_{\text{tag}}(1-2\omega)^2$$

Combined Tagging Performance: $\epsilon_{\text{tag}} = (75.6 \pm 0.6)\%$ and $\epsilon_{\text{eff}} = (5.15 \pm 0.14)\%$

Systematics

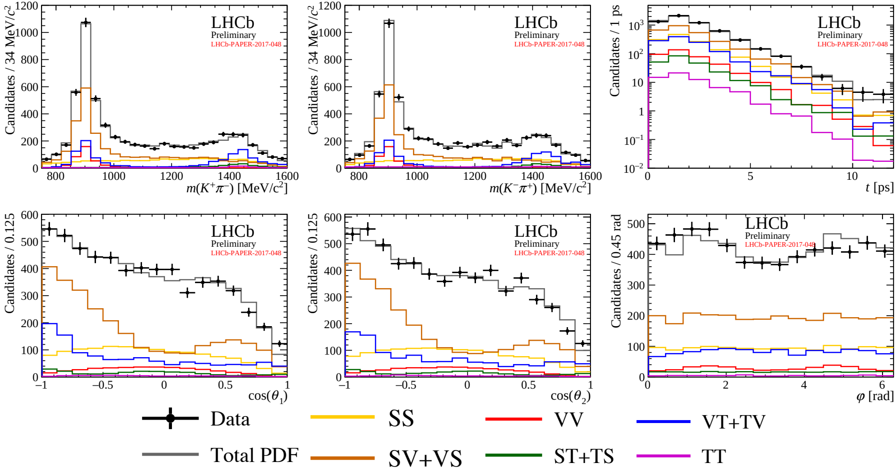
Table of systematic uncertainties

Parameter	$\phi_s^{d\bar{d}}$ [rad]	$\lvert\lambda\rvert$
Yield and shape of mass model	0.012	0.001
Signal weights of mass model	0.012	0.007
TD fit procedure	0.006	0.002
TD fit parametrisation	0.049	0.013
Acceptance weights (simulated sample size)	0.106	0.078
Other acceptance and resolution effects	0.063	0.008
Production asymmetry	0.002	0.002
Total	**0.141**	**0.089**

- Only shown for the *CP* observables, $\phi_s^{d\bar{d}}$ and λ
- There are 39 physical observables in total

Fit Projections

- Nominal fit took too long on a conventional CPU
- Novel implementation in GPUs with `Ipanema` ([arXiv:1706.01420]) - ∼ 60× faster
- Δm_s, $\Delta\Gamma_s$, Γ_s are constrained to their known values



Numerical Results

Parameter	Value
Common parameters	
ϕ_s^{dd} [rad]	$-0.10 \pm 0.13 \pm 0.14$
$\lvert\lambda\rvert$	$1.035 \pm 0.034 \pm 0.089$
$B_s^0 \to K^*(892)^0 \bar{K}^*(892)^0$ (VV)	
f^{VV}	$0.067 \pm 0.004 \pm 0.024$
f_{L}^{VV}	$0.208 \pm 0.032 \pm 0.046$
$f_{\parallel}^{VV}$	$0.297 \pm 0.029 \pm 0.042$
$\delta_{\parallel}^{VV}$ [rad]	$2.40 \pm 0.11 \pm 0.33$
$\delta_{\perp}^{VV}$ [rad]	$2.62 \pm 0.26 \pm 0.64$
Single S-wave (SV and VS)	
f^{SV}	$0.329 \pm 0.015 \pm 0.071$
f^{VS}	$0.133 \pm 0.013 \pm 0.065$
δ^{SV} [rad]	$-1.31 \pm 0.10 \pm 0.35$
δ^{VS} [rad]	$1.86 \pm 0.11 \pm 0.41$
Double SS-wave (SS)	
f^{SS}	$0.225 \pm 0.010 \pm 0.069$
δ^{SS} [rad]	$1.07 \pm 0.10 \pm 0.40$
Single P-wave decays (ST and TS)	
f^{ST}	$0.014 \pm 0.006 \pm 0.031$
f^{TS}	$0.025 \pm 0.007 \pm 0.033$
δ^{ST} [rad]	$-2.3 \pm 0.4 \pm 1.69$
δ^{TS} [rad]	$-0.10 \pm 0.26 \pm 0.82$

Parameter	Value
Single D-wave (VT and TV)	
f^{VT}	$0.160 \pm 0.016 \pm 0.049$
f_{L}^{VT}	$0.911 \pm 0.020 \pm 0.165$
$f_{\parallel}^{VT}$	$0.012 \pm 0.008 \pm 0.053$
f^{TV}	$0.036 \pm 0.014 \pm 0.048$
f_{L}^{TV}	$0.62 \pm 0.16 \pm 0.25$
$f_{\parallel}^{TV}$	$0.24 \pm 0.10 \pm 0.143$
δ_0^{VT} [rad]	$-2.06 \pm 0.19 \pm 1.17$
$\delta_{\parallel}^{VT}$ [rad]	$-1.8 \pm 0.4 \pm 1.16$
$\delta_{\perp}^{VT}$ [rad]	$-3.08 \pm 0.29 \pm 0.97$
δ_0^{TV} [rad]	$1.91 \pm 0.30 \pm 0.80$
$\delta_{\parallel}^{TV}$ [rad]	$1.09 \pm 0.19 \pm 0.55$
$\delta_{\perp}^{TV}$ [rad]	$0.2 \pm 0.4 \pm 1.1$
Double DD-wave (TT)	
f_{TT}	$0.011 \pm 0.003 \pm 0.007$
f_{L}^{TT}	$0.25 \pm 0.14 \pm 0.18$
$f_{\parallel_1}^{TT}$	$0.17 \pm 0.11 \pm 0.14$
$f_{\perp_1}^{TT}$	$0.30 \pm 0.18 \pm 0.21$
$f_{\parallel_2}^{TT}$	$0.015 \pm 0.033 \pm 0.107$
δ_0^{TT} [rad]	$1.3 \pm 0.5 \pm 1.8$
$\delta_{\parallel_1}^{TT}$ [rad]	$3.00 \pm 0.29 \pm 0.57$
$\delta_{\perp_1}^{TT}$ [rad]	$2.6 \pm 0.4 \pm 1.5$
$\delta_{\parallel_2}^{TT}$ [rad]	$2.3 \pm 0.8 \pm 1.7$
$\delta_{\perp_2}^{TT}$ [rad]	$0.7 \pm 0.6 \pm 1.3$

Numerical Results

Parameter	Value
Common parameters	
ϕ_s^{dd} [rad]	$-0.10 \pm 0.13 \pm 0.14$
f	$0.014 \pm 0.006 \pm 0.031$
f^{TS}	$0.025 \pm 0.007 \pm 0.033$
δ^{ST} [rad]	$-2.3 \pm 0.4 \pm 1.69$
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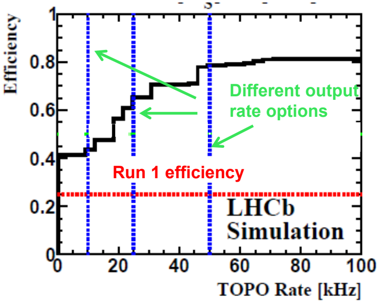
Single D-wave (VT and TV)	
f^{VT}	$0.160 \pm 0.016 \pm 0.049$
f_{L}^{VT}	$0.911 \pm 0.020 \pm 0.165$
$\delta_{\parallel_1}^{TT}$ [rad]	$3.00 \pm 0.29 \pm 0.57$
$\delta_{\perp_1}^{TT}$ [rad]	$2.6 \pm 0.4 \pm 1.5$
$\delta_{\parallel_2}^{TT}$ [rad]	$2.3 \pm 0.8 \pm 1.7$
$\delta_{\perp_2}^{TT}$ [rad]	$0.7 \pm 0.6 \pm 1.3$

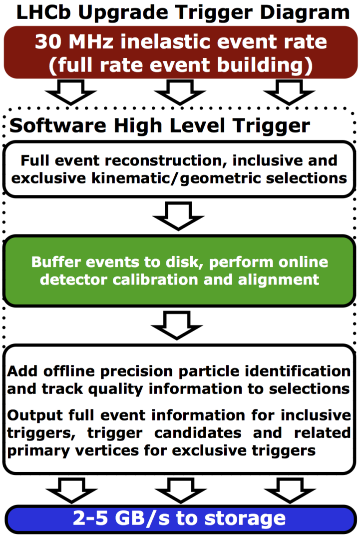
Summary

- Measure *CP*-averaged fractions, f, and strong phase differences, δ, for **19 different amplitudes**
- In particular:
  - $\mathbf{f_L^{VV}} = \mathbf{0.208 \pm 0.032 \pm 0.046}$ - small value (as in previous - [JHEP 07 (2015) 166])
  - $\mathbf{f^{SS}} = \mathbf{0.225 \pm 0.010 \pm 0.069}$ - large value
  - $\mathbf{f^{VV}} = \mathbf{0.067 \pm 0.040 \pm 0.024}$ - small value
- Measure CP-violation parameters
  - $\phi_s^{d\bar{d}} = (-\mathbf{0.10} \pm \mathbf{0.13} \pm \mathbf{0.14})\,\mathrm{rad}$
  - $|\lambda| = (\mathbf{1.035} \pm \mathbf{0.034} \pm \mathbf{0.089})$
- **SM wins again!**

Future prospects

- LHCb Upgrade will be installed in LS2
- Ready for operation in Run 3
- Completely redesigned tracking systems
- Redesigned readout for all subsystems





LHCb Upgrade Trigger Diagram

30 MHz inelastic event rate (full rate event building)

Software High Level Trigger

Full event reconstruction, inclusive and exclusive kinematic/geometric selections

Buffer events to disk, perform online detector calibration and alignment

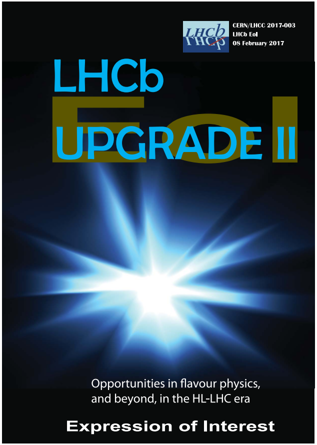
Add offline precision particle identification and track quality information to selections

Output full event information for inclusive triggers, trigger candidates and related primary vertices for exclusive triggers

2-5 GB/s to storage

Beyond Run 4?

- Expression of interest submitted for Phase-II upgrade

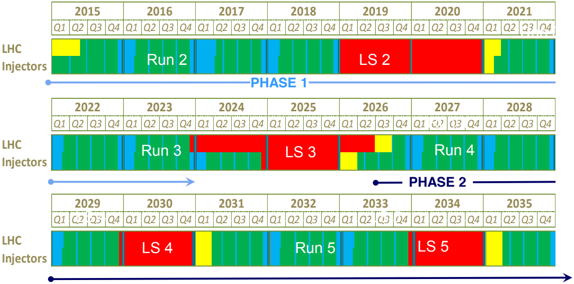


CERN/LHCC 2017-003
LHCb EoI
08 February 2017

LHCb
UPGRADE II

Opportunities in flavour physics,
and beyond, in the HL-LHC era

Expression of Interest



Expected luminosities

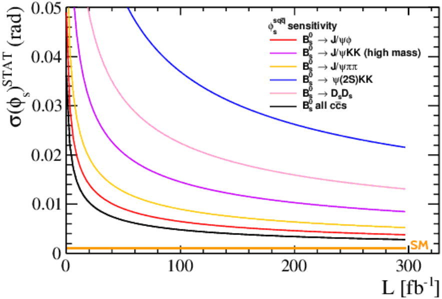
Run 1 + Run 2	$\int L \approx 8.5\ \text{fb}^{-1}$
Run 3 + Run 4	$\int L \approx 50\ \text{fb}^{-1}$
Run 5 +	$\int L \approx 300\ \text{fb}^{-1}$

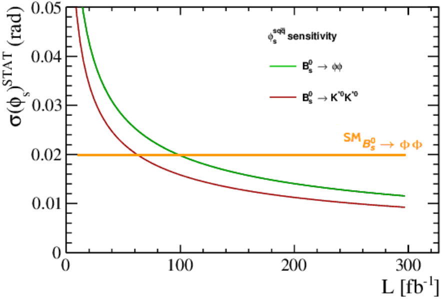
Current developments in $B_s^0 \to J/\psi K^+ K^-$

Run 2 analysis of $B_s^0 \to J/\psi K^+ K^-$ is underway

- More than double the statistics of Run 1 (with just 2015 and 2016)
- $\sigma_{\rm stat} \approx 0.042\,\rm rad$ (Run 1: $0.049\,\rm rad$)

Run 2 analysis of $B_s^0 \to \phi\phi$ also underway



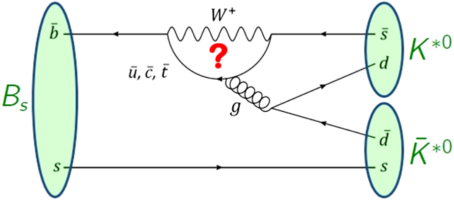


Watch this space....

Summary and Outlook

First ever measurement of $\phi_s^{d\bar{d}} = (-0.10 \pm 0.13 \pm 0.14)\,\mathrm{rad}$

- Statistical precision similar to $B_s^0 \to \phi\phi$ with a large systematic contribution
- Statistical precision $\sim 2.5\times$ worse than $B_s^0 \to J/\psi\,\phi$
- Dominant systematics arise from limited MC statistics so are reducible



- At present no evidence of *CP*-violation in interference between B_s^0 decay and mixing
- Currently all *CP*-measurements are consistent with the SM
- **Let's hope we can break it in Run 2 and beyond!**

THANK YOU!