Measurement of ϕ_s

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Rencontres de Physique de la Vallée d'Aoste

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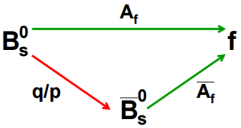
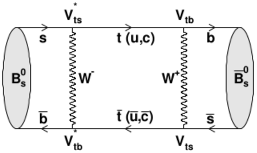
- 3 types of $\mathcal{CP}$ violation:
  - Direct $\mathcal{CP}$ violation ($\mathcal{A}_f \neq \bar{\mathcal{A}}_f$)
  - $\mathcal{CP}$ violation in mixing (arg $\left|\frac{q}{p}\right| \neq 0$)
  - $\mathcal{CP}$ violation in the interference between mixing an decay (ϕ_s)



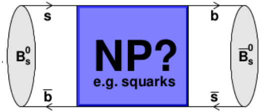
$$\phi_s = -arg(\lambda_f), \lambda_f = \eta_f \frac{q}{p}\frac{\bar{\mathcal{A}}_f}{\mathcal{A}_f}$$

η_f = 1 for CP−even states, -1 for CP−odd states



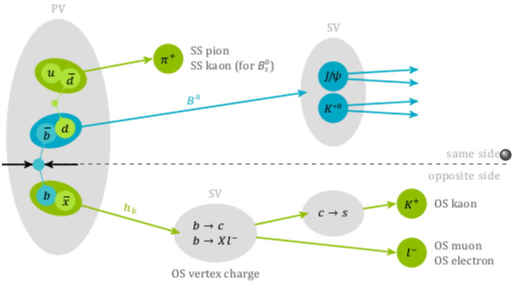
Today's menu from LHCb:

- $B_s^0 \to J/\psi K^+K^-$ (Run 1) [PRL 114, 041801 (2015)]
- $B_s^0 \to (K^+\pi^-)(K^-\pi^+)$ (Run 1) [arXiv:1712.08683]
- $B_s^0 \to \phi\phi$ (Run 1) [JHEP 10 (2015) 053]
- $\sqrt{s} = 7, 8\mathrm{TeV}$, integrated luminosity of 3.1 fb^{-1}



Flavour-Changing Neutral Currents ⇒ loop diagrams

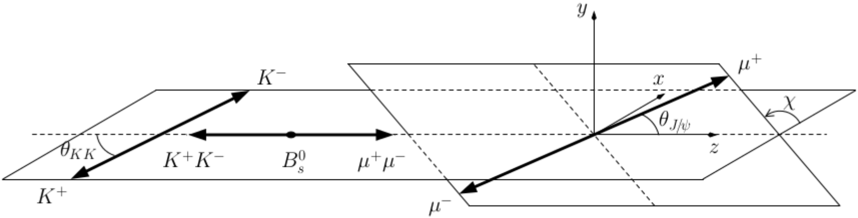
Flavour tagging: identify the initial flavour of the meson



- **Opposite-side tagging:** flavour from $b(\bar{b})$ quark produced in association with the signal $\bar{b}(b)$ quark originating from primary vertex
- **Same-side tagging:** flavour from charge of kaon, muon or electron originating from a secondary vertex

- Effective tagging power: $\epsilon\mathcal{D}^2$
  $\mathcal{D}$: dilution factor, $\mathcal{D} = (1 - 2\omega)$, ω: per event mistag probability
- Fits done in several trigger categories

Helicity angles



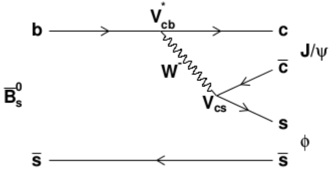
b $\to$ **c$\bar{\text{c}}$s** transition

- Very precise SM prediction : $\phi_s^{SM} = -2\beta_s$, where $\beta_s = \arg\left[\frac{-V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right]$ [1]

Golden mode

$$\phi_s^{SM} = -0.0364 \pm 0.0016\,\mathrm{rad} \text{ [PRD 84 (2011) 033005]}$$

- Also measured by **CDF**,**D0**, **ATLAS** and **CMS**

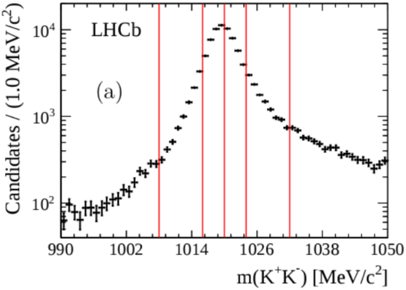


[1](assuming no penguin contributions)

- **Observables:** $|\lambda|$, Γ_s,$\Delta\Gamma_s$, $|A_\perp|^2$,$|A_0|^2$, $\delta_{||}$,$\delta_\perp$, ϕ_s, Δm_s
  - In the baseline fit : $|\lambda|$ common to all polarization states, f
  - Checks with different λ_f consistent with previous assumption
- 4 amplitudes : 3 from P-wave for the K^+K^- pair $(\mathcal{A}_0, \mathcal{A}_{||}, \mathcal{A}_\perp)$ + 1 from S-wave $(\mathcal{A}_S)$

Analysis overview

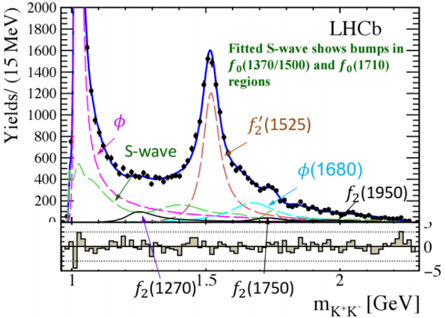
- Angular and time acceptance + time resolution effects considered
- $\epsilon\mathcal{D}^2 = 3.73 \pm 0.15\%$
- **Backgrounds** (sWeights): $B^0 \to J/\psi K^{*0}$,$\Lambda_b^0 \to J/\psi p K^-$
- **Fit** to $m(J/\psi K^+K^-)$: 2 years$\times$2 trigger categories$\times$6 bins in $m(K^+K^-)$
- 6 C_{SP} factors (coupling between P-wave and S-wave, $\in$ [0,1])



Main systematic source:
angular acceptance

$B_s^0 \to J/\psi K^+K^-$ high $m(K^+K^-)$ region [JHEP 08 (2017) 037]

- **K^+K^- mass spectrum** : P-wave $\phi(1020)$ resonance + S-wave fraction + **D-wave $f_2'(1525)$ resonance** [2]
- m_{KK} above the ϕ meson to measure ϕ_s, Γ_s,$\Delta\Gamma_s$



Analysis overview

- sWeights, ϵ_{tag} computed for :
  - $m_{KK} < 1050$ MeV
  - $m_{KK} > 1050$ MeV
- Background from:
  - $\bar{B}^0 \to J/\psi K^-\pi^+$
  - $\Lambda_b^0 \to J/\psi p K^-$

- **Main systematic source:** resonance modelling

[2] not included the unconfirmed $f_2(1640)$

Fit results (Run 1 data)

$\phi_s = -\mathbf{0.058} \pm \mathbf{0.049}(\text{stat.}) \pm \mathbf{0.006}(\text{syst.}) \leftarrow$ low m_{KK} range
$\phi_s = -\mathbf{0.010} \pm \mathbf{0.039} \leftarrow$ combination with $B_s^0 \to J/\psi\pi^+\pi^-$ [a]
$\phi_s = -\mathbf{0.119} \pm \mathbf{0.107}(\text{stat.}) \pm \mathbf{0.034}(\text{syst.}) \leftarrow$ high m_{KK} range

$B_s^0 \to J/\psi K^+K^-$ combination:
$\phi_s = -0.025 \pm 0.045(\text{stat.}) \pm 0.008(\text{syst.})$

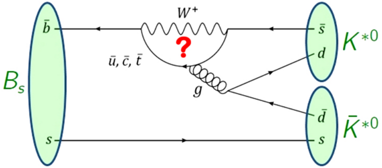
[a] [PRL 114 (2015) 041801]

Experiment	ϕ_s[rad]
CDF (9.6 fb^{-1})	[-0.60,+0.12], 68% CL [PRL 109 (2012) 171802]
D0 (8.0 fb^{-1})	$-0.55^{+0.38}_{-0.36}$ [PRD 85 (2012) 032006]
ATLAS (19.2 fb^{-1})	$-0.090 \pm 0.078 \pm 0.041$ [JHEP 08 (2016) 147]
CMS (19.7 fb^{-1})	$-0.075 \pm 0.097 \pm 0.031$ [PLB 757 (2016) 97-120]

LHCb dominates world average

$B_s^0 \to (K^+\pi^-)(K^-\pi^+)$ [arXiv:1712.08683]

- $\bar{b} \to \bar{s}d\bar{d}$ flavour-changing neutral current transition dominated by a penguin diagram
  - Loop also in the decay $\Rightarrow$ more places where to find New Physics contributions
  - New heavy particles could enter the loop, affecting the measurement



- **First** measurement of the weak phase $\phi_s^{d\bar{d}}$ in $B_s^0 \to (K^+\pi^-)(K^-\pi^+)+$ polarization fractions and strong phases
- Decay first observed in 2011 by LHCb [PLB 709 (2012) 50], updated in 2012 [JHEP 07 (2015) 166]

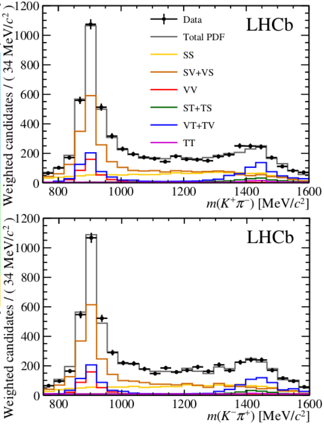
$B_s^0 \to (K^+\pi^-)(K^-\pi^+)$ [arXiv:1712.08683]

Full time-dependent and angular analysis in the $K\pi$ mass window [750,1600] $\mathrm{MeV/c^2}$

- **9** decay channels + **19 polarization amplitudes**

Decay channel	Polarization amplitudes
$B_s^0 \to (K^+\pi^-)_0^*(K^-\pi^+)_0^*$	A^{SS}
$B_s^0 \to (K^+\pi^-)_0^*\bar{K}^*(892)^0$	A^{SV}
$B_s^0 \to K^*(892)^0(K^-\pi^+)_0^*$	A^{VS}
$B_s^0 \to (K^+\pi^-)_0^*\bar{K}_2^*(1430)^0$	A^{ST}
$B_s^0 \to K_2^*(1430)^0(K^-\pi^+)_0^*$	A^{TS}
$B_s^0 \to K^*(892)^0\bar{K}^*(892)^0$	$A_0^{VV}, A_\parallel^{VV}, A_\perp^{VV}$
$B_s^0 \to K^*(892)^0\bar{K}_2^*(1430)^0$	$A_0^{VT}, A_\parallel^{VT}, A_\perp^{VT}$
$B_s^0 \to K_2^*(1430)^0\bar{K}^*(892)^0$	$A_0^{TV}, A_\parallel^{TV}, A_\perp^{TV}$
$B_s^0 \to K_2^*(1430)^0\bar{K}_2^*(1430)^0$	$A_0^{Tt}, A_{\parallel,1}^{TT}, A_{\perp,1}^{TT}., A_{\parallel,2}^{TT}, A_{\perp,2}^{TT}$

S = scalar (j=0), V = vector (j=1)
T = tensor (j=2)



$B_s^0 \to (K^+\pi^-)(K^-\pi^+)$ [arXiv:1712.08683]

Differential decay rate in a nutshell (B_s^0): ($\bar{B}_s^0$: $c_{ij} \to -c_{ij}, d_{ij} \to -d_{ij}$)

$$\propto \sum e^{-\Gamma_s t}\left[a_{ij}\cosh\left(\tfrac{1}{2}\Delta\Gamma_s t\right) + b_{ij}\sinh\left(\tfrac{1}{2}\Delta\Gamma_s t\right) + c_{ij}\cos\left(\Delta m_s t\right) + d_{ij}\sin\left(\Delta m_s t\right)\right]$$

Where $a_{ij}, b_{ij}, c_{ij}, d_{ij}$ depend on $\eta_{i,j}$, the mixing angle and $\mathcal{A}_{i,j}$:

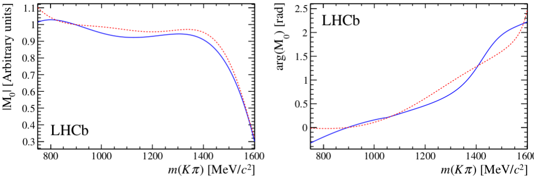
- **Angular dependence:** spherical harmonics
- **Mass dependence:** mass propagators + barrier factors (Blatt-Weisskopf functions) + phase space factor

Mass propagators

- spin 0: phase from scattering studies + modulus from data [a]
- spin 1,2: relativistic Breit Wigner ($K^*(892)^0$,$K^*(1430)^2$)

[a] [PRD 93 (2016) 074025]

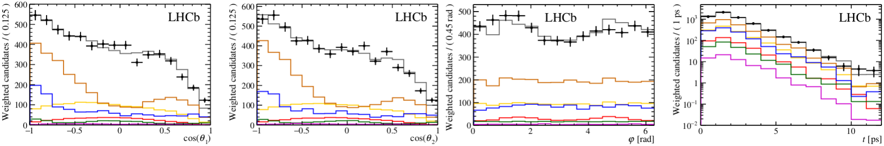
Scalar Kπ mass-dependent amplitude



$B_s^0 \to (K^+\pi^-)(K^-\pi^+)$ [arXiv:1712.08683]

Analysis workflow:

- **Event selection**
  - Multivariate selection (BDT) for combinatorial background + mass vetoes + cuts on Particle Identification variables
  - **Peaking backgrounds** ($B^0 \to (K^+\pi^-)(K^-\pi^+)$, $B^0_{(s)} \to \phi(K^+\pi^-)$, $B^0 \to \rho(K^+\pi^-)$, Λ_b decays) + **partially reconstructed decays** and **combinatorial background** subtracted using **sWeights** in $m(K^+\pi^-K^-\pi^+)$
- **Acceptance**: angular and invariant mass acc. + cubic splines (decay time acc.)
- **Decay time resolution**: analytical convolution; gaussian model, width and per event decay time error linearly related.
- **Flavour tagging**: $\epsilon\mathcal{D}^2 = 5.165 \pm 0.173\%$



$B_s^0 \to (K^+\pi^-)(K^-\pi^+)$ [arXiv:1712.08683]

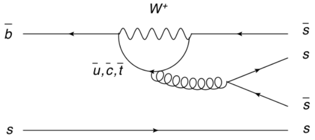
Flavour-tagged time-dependent amplitude fit

- Separate datasets for 2011 and 2012 + 2 trigger categories
- High complexity of fit ⇒ implemented within **Ipanema** package [arXiv:1706.01420], uses GPU (high speed gain)

Fit results

- **19 polarisation amplitudes** measured with highest (first) precision
- $\mathbf{f_L^{VV} = 0.208 \pm 0.032(stat.) \pm 0.046(syst.)}$ (relatively low value, interesting for penguin dynamics)
- $\phi_s^{d\bar{d}} = -0.10 \pm 0.13(\text{stat.}) \pm 0.14(\text{syst.})$, consistent with **SM** prediction and $B_s^0 \to \phi\phi$ measurement [JHEP 10 (2015) 053]
- Main systematic source : multi-dimensional acceptance. Expected to decrease increasing the size of simulation sample.

- **FCNC decay**, proceeds via $b \to \bar{s}s\bar{s}$ process $\Rightarrow$ close to 0 in the SM
- **First observed** in 2005, updated in 2010 **[CDF]** [PRL 95 (2005) 031801], [CDF Note 10064 (2010)]



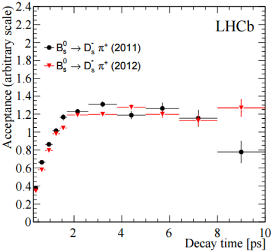
- **Decay time-dependent measurement** to measure $\phi^{ss\bar{s}}$ and **time-integrated study** to determine the triple product asymmetries

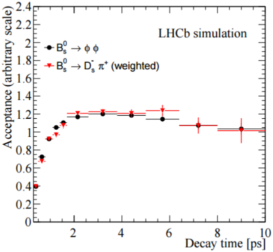
Amplitude of the decay:

- ϕ close to $f_0(890)$ (S-wave) $\Rightarrow$ VV + VS ($B_s^0 \to \phi f_0$) + SS ($B_s^0 \to f_0 f_0$)
- Angular distribution used to determine the S-wave fraction
- **C_{SP} factors** to account for the coupling between the P-wave (Breit-Wigner) and S-wave (flat model) line shapes

Analysis workflow:

- **Simulation** : P-wave simulated (small S-wave fraction)
- **Peaking backgrounds:**
  - $B^+ \to \phi K^+$, $B^0_{(s)} \to \phi\pi^+\pi^-$: negligible contributions
  - Expected 101 ± 35 events from $\Lambda_b^0 \to \phi K^- p$, 25 ± 1 from $B^0 \to \phi K^*(892)^0$ and ~ 1 from $B_s^0 \to \phi K^*(892)^0$
- **Flavour tagging**: $\epsilon\mathcal{D}^2_{2011} = 3.17 \pm 0.26\%$, $\epsilon\mathcal{D}^2_{2012} = 3.04 \pm 0.24\%$
- **Angular acceptance**: as for $B_s^0 \to (K^+\pi^-)(K^-\pi^+)$
- **Time acceptance**: data-driven, $B_s^0 \to D_s^+(\to K^+K^-\pi^+)\pi^-$ as control mode ($\tau(D_s^+) < 1\text{ps}$):



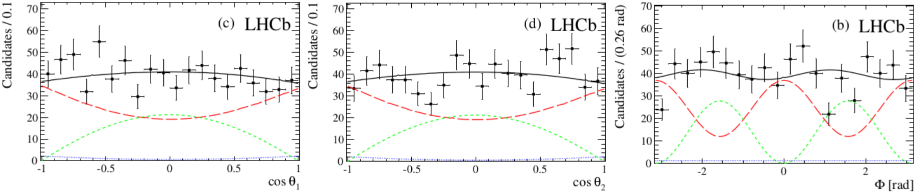


$B_s^0 \to \phi\phi$ [JHEP 10 (2015) 053]

- 3 polarisation amplitudes + strong phases + direct CP-violation parameter
- 4 trigger categories + 3 mass regions of $m^1_{K^+K^-}$ vs $m^2_{K^+K^-}$
- Decay width (Γ_s) and decay width difference ($\Delta\Gamma_s$) taken from $B_s^0 \to J/\Psi K^+K^-$, $B_s^0 \to J/\Psi \pi^+\pi^-$ as Gaussian constraints

Fit results (Run 1 data)

- $\phi_s^{s\bar{s}s} = -\mathbf{0.17} \pm \mathbf{0.15(stat.)} \pm \mathbf{0.03(syst.)}$, consistent with **SM** [PRL 89 (2002) 231803]
- Largest systematic source : decay time and angular acceptances.



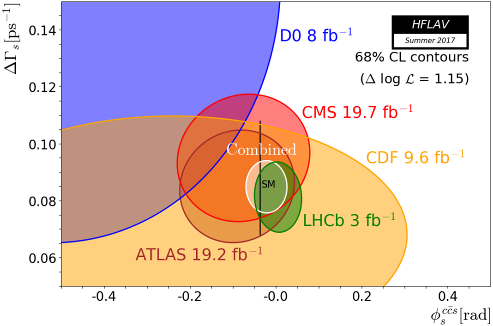
P-wave; CP-odd P-wave; S-wave

Conclusions

$\phi_s^{s\bar{s}s\bar{s}} = -\mathbf{0.17} \pm \mathbf{0.15}(\mathbf{stat.}) \pm \mathbf{0.03}(\mathbf{syst.})$ [3] ← world's best measurement

$\phi_s^{d\bar{d}} = -\mathbf{0.10} \pm \mathbf{0.13}(\mathbf{stat.}) \pm \mathbf{0.14}(\mathbf{syst.})$ [4]

$\phi_s^{c\bar{c}s} = -\mathbf{0.025} \pm \mathbf{0.045}(\mathbf{stat.}) \pm \mathbf{0.008}(\mathbf{syst.})$ [5] ← dominates world average



Measurements consistent with SM, but still a lot of room for NP!

[3] [PRL 114, 041801 (2015)]

[4] [arXiv:1712.08683, **submitted to JHEP**]

[5] [JHEP 10 (2015) 053]

Thanks for your attention!