Measurement of the branching ratio of $B_s^0 \to \eta_c \phi$ at LHCb

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CPPM PhD days

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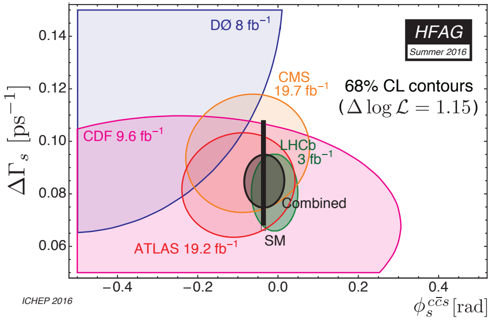
LHCb

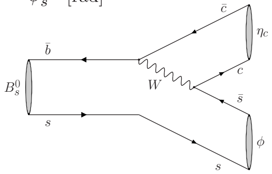
Outline

1. **Analysis strategy**
2. **Selection**
3. **Fit model/results**

Weak phase ϕ_s



- $B_s^0 \to \eta_c \phi$ sensitive to ϕ_s:
  - Never seen before
  - η_c is a pseudoscalar ($J^P = 0^-$):
    - No need for an angular analysis
    - Cannot decay into muons



$\Rightarrow$ Make the first observation of $B_s^0 \to \eta_c \phi$ with Run 1 data

Analysis of $B_s^0 \to \eta_c(\to 4h, p\bar{p})\phi(K^+K^-)$

- $\eta_c \to p\bar{p}$: Bologna team
  $\eta_c \to 4h$: CPPM team, where $4h = \{K^+K^-\pi^+\pi^-, \pi^+\pi^-\pi^+\pi^-, K^+K^-K^+K^-\}$
  $\Rightarrow$ 6 hadrons in the final state
- Measure the decay mode branching fraction with respect to reference channel with identical final state for η_c and J/ψ:

$$\mathcal{B}_{\rm meas}(B_s^0 \to \eta_c\phi) = \frac{N_{\eta_c}^{\rm fit}}{N_{J/\psi}^{\rm fit}} \times \mathcal{B}(B_s^0 \to J/\psi\,\phi) \times \frac{\mathcal{B}(J/\psi \to 4h, p\bar{p})}{\mathcal{B}(\eta_c \to 4h, p\bar{p})} \times \frac{\varepsilon_{B_s^0 \to J/\psi\,(\to 4h, p\bar{p})\phi}}{\varepsilon_{B_s^0 \to \eta_c(\to 4h, p\bar{p})\phi}}$$

  - $\frac{N_{\eta_c}^{\rm fit}}{N_{J/\psi}^{\rm fit}}$ from unbinned maximum likelihood fit to data
  - Branching fraction taken from PDG
  - Efficiency corrections estimated from MC and control samples

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  - $\frac{N_{\eta_c}^{\text{fit}}}{N_{J/\psi}^{\text{fit}}}$ from unbinned maximum likelihood fit to data
  - Branching fraction taken from PDG
  - Efficiency corrections estimated from MC and control samples
- Fitting strategy (Two-step procedure):
  1. Two-dimentional fit to the $(4h, p\bar{p})K^+K^- \times K^+K^-$ invariant mass spectra:
     - Individual 2D fits for each 4 final states
     - Compute the sWeights (optimal backgroung substraction procedure) corresponding to $B_s^0 \to (4h, p\bar{p})\phi$ event category

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     - Individual 2D fits for each 4 final states
     - Compute the sWeights (optimal backgroung substraction procedure) corresponding to $B_s^0 \to (4h, p\bar{p})\phi$ event category
  2. Simultaneous amplitude fit to the 4 weighted $(4h, p\bar{p})$ invariant mass spectra:
     - the branching fraction is direcly measured in the data, taking advantage of the correlations between η_c and J/ψ yields
     - the branching fraction is a common parameter over the 4 categories in the simultaneous fit

Selection: $4h$ final state case

- Use full Run 1 data sample $\sim 3\,\mathrm{fb}^{-1}$ (2011-2012)
- Three final states: $4h = \{KK\pi\pi, \pi\pi\pi\pi, KKKK\}$
- A lot of background because we have purelly hadronic modes
- Challenging hadronic trigger with 6 soft hadrons in the final state

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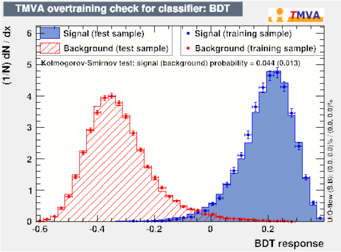
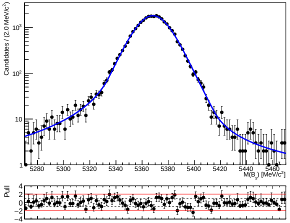
- **Offline selection**:
  1. Dedicated multivariate BDT (Boosted Decision Tree) selection for each 3 final states
  2. Particle identification selection cuts on pions and kaons



2D fit model (Monte-Carlo)

- $4hK^+K^-$ invariant mass:
  - B_s^0: Hypatia[1] with mean and resolution free (other params fixed to MC)
  - B^0: Hypatia with mean free and resolution constrained to be the same as the one B_s^0 (other params fixed to MC)
  - Combinatorial bkg: Exponential

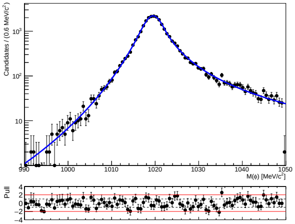
[1] Modified Gaussian with asymetric tails



B_s^0 MC events

- K^+K^- invariant mass:
  - ϕ (1020): RBW[2] $\otimes$ Gaussian with mean and resolution free (ϕ barrier radius fixed to $3.0\,\mathrm{GeV}^{-1}$)
  - Non-resonant: Exponential

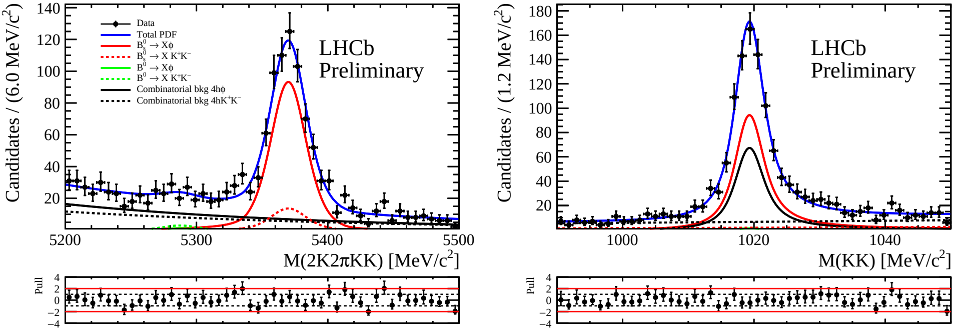
[2] Relativistic Breit-Wigner



ϕ MC events

2D fit results (real data example: $KK\pi\pi$)

- 15 free parameters:



- sWeights computed for $B_s^0 \to X\phi$ events used latter in the simultaneous amplitude fit to $2K2\pi, 4\pi, 4K, p\bar{p}$

Simultaneous amplitude fit model to the 4 η_c modes

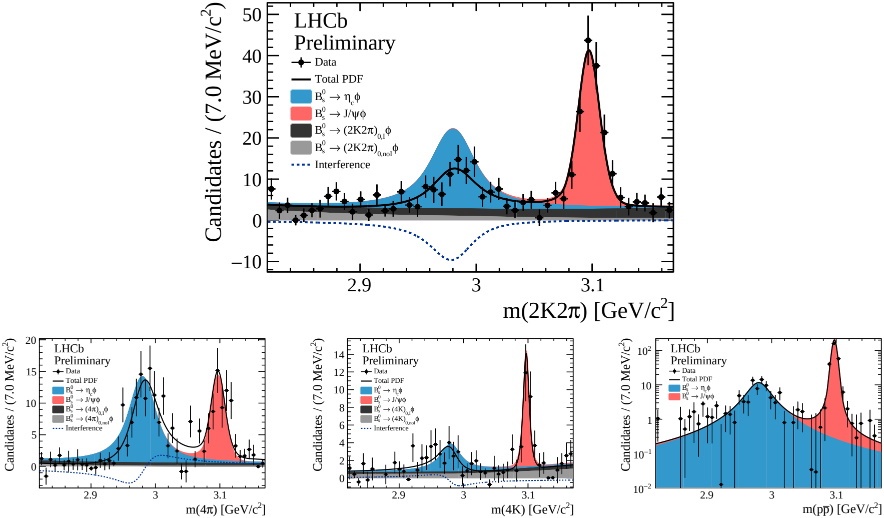
- After applying the $B_s^0 \to X\phi$ **sWeights** obtained from the 2D fit, only four (two) categories are statistically left in the $4h$ ($p\bar{p}$) invariant mass spectra:
  - $B_s^0 \to \eta_c(4h, p\bar{p})\phi$
  - $B_s^0 \to J/\psi(4h, p\bar{p})\phi$
  - $B_s^0 \to (4h)_{\mathrm{S-wave}}\phi$
  - $B_s^0 \to (4h)_{\mathrm{NR}}\phi$

- Take into account interference between η_c and S-wave:
  Total amplitude for each final state modeled as: $\left|A(m_f; c_k, \vec{x})\right|^2 = \sum_J \left|\sum_k c_k\, R_k^J(m_f; \vec{x})\right|^2$
  - see back up for details

- Fitting function taking into account detector resolution: $\mathrm{PDF}(m_f) = \left|A(m_f; c_k, \vec{x})\right|^2 \otimes \mathcal{R}(\vec{x}\,'(m_f))$
  Hypatia with mass-dependent parameters taken from MC

- The branching fraction is a common parameter over the 4 categories in the simultaneous fit

Simultaneous amplitude fit results



- Most of the information comes from $p\bar{p}$ due to (η_c-S-wave) interference in the 4h modes

Result

Systematical uncertainties	$+1\sigma$	-1σ
Fixed PDF parameters	0.10	0.10
$\phi(1020)$ range parameter	0.08	0.08
Efficiency ratios	0.02	0.02
Total systematics	0.13	0.13
External $\mathcal{B}$	0.56	0.56

Preliminary:

$$\mathcal{B}(B_s^0 \to \eta_c \phi) = (4.95 \pm 0.53\,(\mathrm{stat}) \pm 0.13\,(\mathrm{syst}) \pm 0.56\,(\mathcal{B})) \times 10^{-4}$$

First observation of this decay mode

Conclusions and prospects

- **Conclusions**:
  - $B_s^0 \to \eta_c \phi$
    - **First observation of this decay mode**
    - Branching ratio slighty lower naive expectation
    - Systematic uncertainties dominated by input branching ratio

$$\mathcal{B}(B_s^0 \to \eta_c \phi) = (4.95 \pm 0.53\,(\mathrm{stat}) \pm 0.13\,(\mathrm{syst}) \pm 0.56\,(\mathcal{B})) \times 10^{-4}$$

- **Prospects**:
  - Finalizing systematics: validation of the fit model using toy MC
  - Analysis under LHCb internal review

Backup

Naive expectation branching ratio

- Using $d = s$ hypothesis, i.e. assuming

$$\frac{\mathcal{B}(B_s^0 \to \eta_c \phi)}{\mathcal{B}(B_s^0 \to J/\psi\, \phi)} = \frac{\mathcal{B}(B^0 \to \eta_c K^0)}{\mathcal{B}(B^0 \to J/\psi\, K^0)}$$

- We can predict the expected $\mathcal{B}_{\text{predict.}}(B_s^0 \to \eta_c \phi) = (9.7 \pm 1.7) \times 10^{-4}$

- We measured: $\mathcal{B}(B_s^0 \to \eta_c \phi) = (4.95 \pm 0.53\,(\text{stat}) \pm 0.13\,(\text{syst}) \pm 0.56\,(\mathcal{B})) \times 10^{-4}$

Efficiency corrections

$$\mathcal{B}_{\rm meas}(B_s^0 \to \eta_c\phi) = \frac{N^{\rm fit}_{\eta_c}}{N^{\rm fit}_{J/\psi}} \times \mathcal{B}(B_s^0 \to J/\psi\,\phi) \times \frac{\mathcal{B}(J/\psi \to 4h, p\bar{p})}{\mathcal{B}(\eta_c \to 4h, p\bar{p})} \times \frac{\varepsilon_{J/\psi}}{\varepsilon_{\eta_c}}$$

- The overall efficiencies can be factorized for each considered mode such as:

$$\frac{\varepsilon^{\rm tot}_{J/\psi}}{\varepsilon^{\rm tot}_{\eta_c}} = \frac{\varepsilon^{\rm geo}_{J/\psi}}{\varepsilon^{\rm geo}_{\eta_c}} \times \frac{\varepsilon^{\rm reco+sel}_{J/\psi}}{\varepsilon^{\rm reco+sel}_{\eta_c}} \times \frac{\varepsilon^{\rm PID}_{J/\psi}}{\varepsilon^{\rm PID}_{\eta_c}} \times \frac{F^{\rm lifetime}_{{\rm corr}\ J/\psi}}{F^{\rm lifetime}_{{\rm corr}\ \eta_c}}$$

$\varepsilon^{\rm geo}$: geometric efficiency tables
$\varepsilon^{\rm reco+sel} = \varepsilon^{\rm reco} \times \varepsilon^{\rm trigger} \times \varepsilon^{\rm stripping} \times \varepsilon^{\rm BDT}$
$\varepsilon^{\rm PID}$: calculated using PIDCalib
$F^{\rm lifetime}_{\rm corr,\ mode}$: factor correcting MC lifetimes

- Using exclusive signal MC samples: (without $F^{\rm lifetime}_{\rm corr}$)

$$\left(\frac{\varepsilon_{J/\psi}}{\varepsilon_{\eta_c}}\right)^{2K2\pi}_{\rm tot\ w/o\ F_{corr}} = 1.015 \pm 0.011 \qquad \left(\frac{F^{\rm lifetime}_{\rm corr\ J/\psi}}{F^{\rm lifetime}_{\rm corr\ \eta_c}}\right)^{2K2\pi} = 1.032$$

$$\left(\frac{\varepsilon_{J/\psi}}{\varepsilon_{\eta_c}}\right)^{4\pi}_{\rm tot\ w/o\ F_{corr}} = 1.035 \pm 0.015 \qquad \left(\frac{F^{\rm lifetime}_{\rm corr\ J/\psi}}{F^{\rm lifetime}_{\rm corr\ \eta_c}}\right)^{4\pi} = 1.032$$

$$\left(\frac{\varepsilon_{J/\psi}}{\varepsilon_{\eta_c}}\right)^{4K}_{\rm tot\ w/o\ F_{corr}} = 0.931 \pm 0.027 \qquad \left(\frac{F^{\rm lifetime}_{\rm corr\ J/\psi}}{F^{\rm lifetime}_{\rm corr\ \eta_c}}\right)^{4K} = 1.033$$

$$\left(\frac{\varepsilon_{J/\psi}}{\varepsilon_{\eta_c}}\right)^{p\bar{p}}_{\rm tot\ w/o\ F_{corr}} = 1.002 \pm 0.009 \qquad \left(\frac{F^{\rm lifetime}_{\rm corr\ J/\psi}}{F^{\rm lifetime}_{\rm corr\ \eta_c}}\right)^{p\bar{p}} = x.xxx$$

- Due to linear relation between efficiency ratio and $\mathcal{B}_{\rm meas}(B_s^0 \to \eta_c\phi)$ we expect $\sim +3\%$ variation on the branching ratio result

Simultaneous amplitude fit model to the 4 η_c modes

- After applying the $B_s^0 \to X\phi$ **sWeights** obtained from the 2D fit, only four (two) categories are statistically left in the $4h$ ($p\bar{p}$) invariant mass spectra:
  - $B_s^0 \to \eta_c(4h, p\bar{p})\phi$
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  - $B_s^0 \to (4h)_{\mathrm{S-wave}}\phi$
  - $B_s^0 \to (4h)_{\mathrm{NR}}\phi$
- Total amplitude for each final state modeled as:
  $\left|A(m_f; c_k, \vec{x})\right|^2 = \sum_J \left|\sum_k c_k\, R_k^J(m_f; \vec{x})\right|^2$
  - $R_k^J(m_f; \vec{x})$: line shape
  - $c_k = \alpha_k e^{i\phi_k}$
    α_k: magnitude
    ϕ_k: phase
    k: componante with spin J
- Fitting function taking into account detector resolution: $\mathrm{PDF}(m_f) = \left|A(m_f; c_k, \vec{x})\right|^2 \otimes \mathcal{R}(\vec{x}\,'(m_f))$
  Hypatia with mass-dependent parameters taken from MC
- Line shape:
  - η_c: Relativistic Breit-Wigner with mass-independant width
  - $B_s^0 \to (4h)_{\mathrm{S-wave}}\phi$: Exponential (allowed to interfere with η_c)
  - Interference term: $2\Re[c_{\eta_c} R_{\eta_c}(m_f; \vec{x}) c_{\mathrm{S}}^* R_{\mathrm{S}}^*(m_f; \vec{x})]$
  - $B_s^0 \to (4h, p\bar{p})_{\mathrm{NR}}\phi$: Exponential (not allowed to interfere with η_c)
    sum of remaining backgrounds with a flat distribution in m_{4h}
  - J/ψ: Relativistic Breit-Wigner with mass-independant width
- Fixed parameters: Γ_{η_c}(PDG), $\alpha_{J/\psi} = 1$, all resolution parameters (MC), input branching fractions (PDG) and efficiency ratio (MC)
- Free parameters (individualy different for each mode): κ_S, κ_{NR}, $\Delta\phi$, NR and S-wave fractions
- Free common parameters: $\mathcal{B}(B_s^0 \to \eta_c\phi)$, m_{η_c} and $m_{J/\psi}$

Interference term

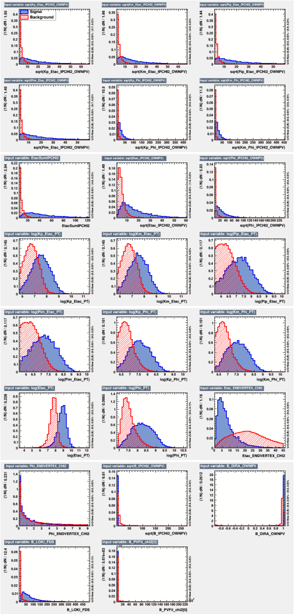
$$
\begin{aligned}
I(m_f; c_{\eta_c}, c_{\mathrm{S}}, \vec{x}) &= 2\Re[c_{\eta_c} R_{\eta_c}(m_f; \vec{x}) c_{\mathrm{S}}^* R_{\mathrm{S}}^*(m_f; \vec{x})] \\
&= 2\alpha_{\eta_c}\alpha_{\mathrm{S}} \Re[R_{\eta_c}(m_f; \vec{x}) R_{\mathrm{S}}^*(m_f; \vec{x}) e^{i(\phi_{\eta_c} - \phi_{\mathrm{S}})}] \\
&= 2\alpha_{\eta_c}\alpha_{\mathrm{S}} R_{\mathrm{S}} \big(\cos(\Delta\phi) \Re[R_{\eta_c}(m_f; \vec{x})] \\
&\qquad - \sin(\Delta\phi) \Im[R_{\eta_c}(m_f; \vec{x})] \big) ,
\end{aligned}
$$

$B_s^0 \to \eta_c(\to 4h)\phi(\to)$: Stripping BDT inputs

A total of 23 variables are used to optimize the BDT selection:

- The B_s^0 meson flight distance (FDS)
- The B_s^0 meson angle between reconstructed momentum and flight distance direction (DIRA)
- The B_s^0, η_c and ϕ mesons vertex χ^2
- The transverse momentum of the η_c and ϕ mesons and all K and π particles ($\log(p_T)$).
- The track impact parameter χ^2 of the B_s^0, η_c and ϕ mesons and all K and π particles ($\sqrt{IP\ \chi^2}$).
- The sum of track impact parameter χ^2 of hadrons from η_c ($\sum IP\ \chi^2$).

$B_s^0 \to \eta_c(\to 4h)\phi(\to)$: Stripping BDT inputs



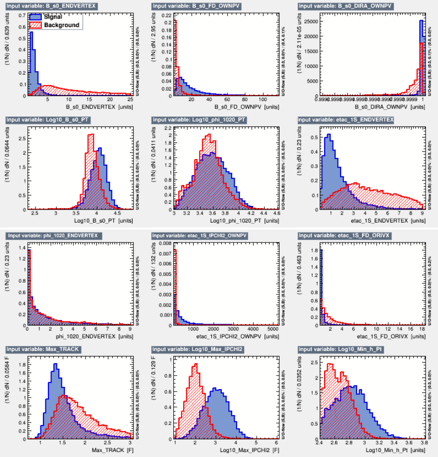
Rank	Variable	Importance $\times 10^{-2}$
1	B_s^0: DIRA	8.549
2	B_s^0: $\sqrt{IP\ \chi^2}$	8.206
3	η_c: $\log(p_T)$	7.773
4	ϕ: $\log(p_T)$	6.085
5	B_s^0: FDS	5.679
6	η_c: vertex χ^2	5.429
7	η_c: $\sum IP\ \chi^2$	4.604
8	K^-: η_c $\log(p_T)$	4.441
9	ϕ: $\sqrt{IP\ \chi^2}$	4.369
10	K^+: ϕ $\log(p_T)$	4.343
11	ϕ: vertex χ^2	4.256
12	π^-: η_c $\log(p_T)$	4.208
13	K^+: η_c $\log(p_T)$	4.150
14	K^-: ϕ $\log(p_T)$	4.060
15	π^+: η_c $\log(p_T)$	3.722
16	π^+: η_c $\sqrt{IP\ \chi^2}$	3.354
17	π^-: η_c $\sqrt{IP\ \chi^2}$	3.332
18	K^+: ϕ $\sqrt{IP\ \chi^2}$	3.070
19	η_c: $\sqrt{IP\ \chi^2}$	2.942
20	K^-: ϕ $\sqrt{IP\ \chi^2}$	2.634
21	K^+: η_c $\sqrt{IP\ \chi^2}$	2.541
22	K^-: η_c $\sqrt{IP\ \chi^2}$	1.419
23	B_s^0: vertex χ^2	0.833

$B_s^0 \to \eta_c(\to 4h)\phi(\to)$: Offline BDT inputs

A total of 12 variables are used to optimize the MVA selection:

- The B_s^0, η_c and ϕ mesons vertex χ^2
- The maximum logarithm value of impact parameter χ^2 and track quality in all hadrons (Log_Max_IP χ^2 and Max_TRACK_χ^2).
- The minimum logarithm value of transverse momentum in all hadrons (Log_Min_p_T).
- The B_s^0 and η_c meson flight distance (FD)
- The B_s^0 meson angle between reconstructed momentum and flight distance direction (DIRA)
- The track impact parameter χ^2 of the η_c (*IP* χ^2).
- The transverse momentum of the B_s^0 and ϕ mesons ($\log(p_T)$).

$B_s^0 \to \eta_c(\to 4h)\phi(\to)$: Offline BDT inputs



$2K2\pi$ – 2012

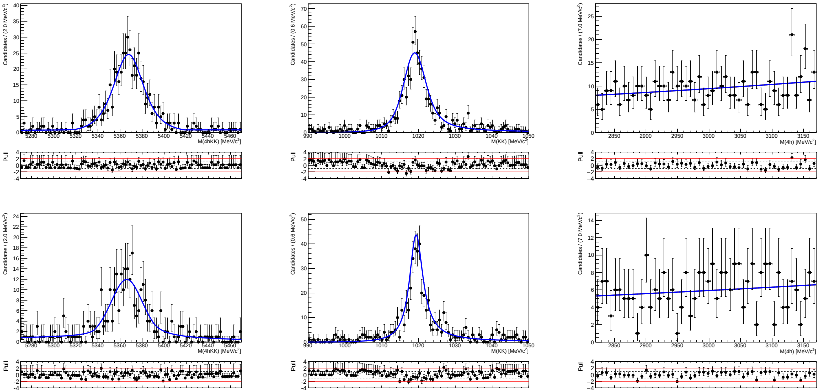
Rank	Variable	Importance (%)
1	B_s^0:ENDVERTEX(χ^2/ndf)	10.61
2	Log_Max_IP χ^2	10.37
3	Log_Min_p_T	9.899
4	η_c:ENDVERTEX(χ^2/ndf)	9.657
5	Max_TRACK_χ^2/ndf	9.643
6	ϕ:Log_p_T	9.521
7	B_s^0:Log_p_T	9.229
8	ϕ:ENDVERTEX(χ^2/ndf)	8.527
9	B_s^0:FD_OWNPV	6.474
10	η_c:FD_ORIVX	6.190
11	B_s^0:DIRA_OWNPV	4.976
12	η_c:IP χ^2_OWNPV	4.899

Study of background contributions: $B_s^0 \to D_s^+ X$

Mode	$\mathcal{B}$
$B_s^0 \to D_s^-(\to K^+K^-\pi^-)\pi^+\pi^-\pi^+$	$(3.4 \pm 0.6)\times 10^{-4}$
$B_s^0 \to D_s^+(\to K^+K^-\pi^+)D_s^-(\to K^+K^-\pi^-)$	$(13.1 \pm 1.6)\times 10^{-6}$
$B_s^0 \to D_s^+(\to K^+K^-\pi^+)D_s^-(\to \pi^+\pi^-\pi^-)$	$(26.1 \pm 3.3)\times 10^{-7}$
$B_s^0 \to D_s^+(\to K^+\pi^+\pi^-)D_s^-(\to K^+K^-K^-)$	$(6.3 \pm 1.0)\times 10^{-9}$
$B_s^0 \to D_s^+(\to K^+K^-K^+)D_s^-(\to K^+K^-K^-)$	$(2.1 \pm 0.4)\times 10^{-10}$
$B_s^0 \to \overline{D^0}(\to K^+K^+K^-\pi^-)K^-\pi^+$	$(2.2 \pm 0.5)\times 10^{-7}$
$B_s^0 \to D_s^-(\to K^+K^-K^-)K^+\pi^+\pi^-$	$(7.2 \pm 1.7)\times 10^{-8}$
$B_s^0 \to D_s^-(\to K^+K^-\pi^-)D^+(\to K^+K^-\pi^+)$	$(15.2 \pm 2.8)\times 10^{-8}$
$B_s^0 \to D_s^-(\to K^+K^-\pi^-)D^+(\to \pi^+\pi^-\pi^+)$	$(5.0 \pm 1.0)\times 10^{-8}$
$B_s^0 \to D^+(\to K^+K^-\pi^+)D^-(\to K^+K^-\pi^-)$	$(2.2 \pm 0.6)\times 10^{-8}$
$B_s^0 \to D^+(\to K^+K^-\pi^+)D^-(\to \pi^+\pi^-\pi^-)$	$(7.2 \pm 2.0)\times 10^{-9}$
$B_s^0 \to D^0(\to K^+K^-K^-\pi^+)\overline{D^0}(\to K^+\pi^-)$	$(1.7 \pm 0.5)\times 10^{-9}$

Study of background contributions: $B_s^0 \to D_s^+ D_s^-$

- Naively dangerous background because final state identical to our signal and due to its large branching fraction
- Studied $B_s^0 \to D_s^+(\to KK\pi)D_s^-(\to KK\pi)$ [top] and $B_s^0 \to D_s^+(\to KK\pi)D_s^-(\to \pi\pi\pi)$ [bottom] MC samples with only stripping and corresponding final state PID selections



Study of background contributions: $\Lambda_b \to \eta_c pK$

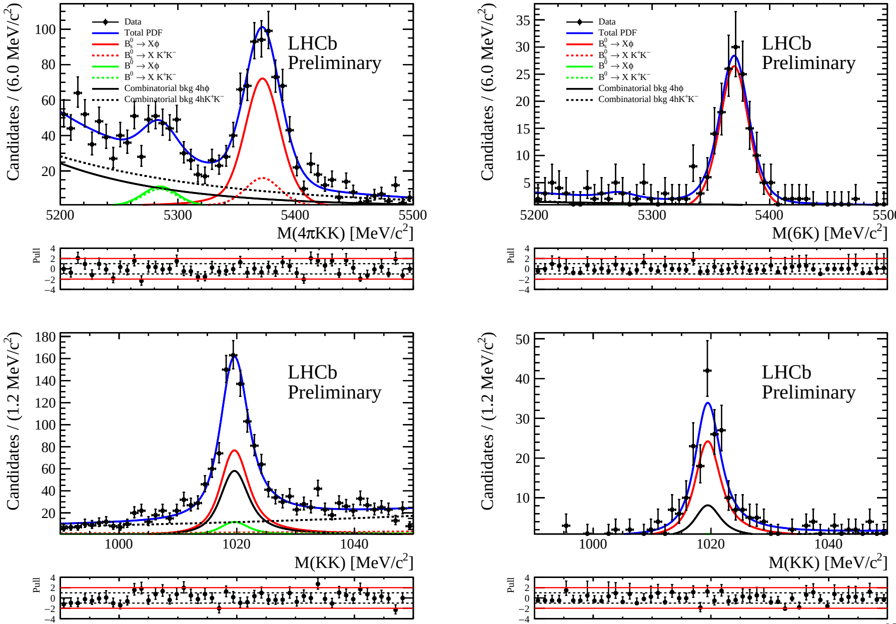
- Similar estimated branching fraction compared to our signal
- Only one proton mis-identification
- Using $\Lambda_b \to \eta_c pK$ MC sample, no events passed the full selection
- Assuming similar visible branching fractions, we could put the upper limit:
  $N_{\Lambda_b \to \eta_c pK} \leq N_{B_s^0 \to \eta_c \phi} \times 10^{-4}$

Negligible contribution compared to our signal

2D fit results

Parameter	Mode			
	$2K2\pi$	4π	$4K$	$p\bar{p}$
$N_{B_s^0\phi}$	586 ± 34	502 ± 33	148 ± 14	448 ± 25
$\mu_{B_s^0}$	5370.0 ± 0.7	5371.9 ± 1.6	5369.8 ± 1.3	5370.3 ± 0.8
μ_{B^0}	5287 ± 16	5284.7 ± 2.8	5272 ± 12	5271 ± 13
μ_{ϕ}	1019.38 ± 0.12	1019.65 ± 0.13	1019.53 ± 0.24	1019.99 ± 0.15
$\sigma_{B_s^0}$	16.4 ± 1.0	17.4 ± 1.0	15.5 ± 1.5	15.8 ± 0.8
σ_{ϕ}	0.99 ± 0.22	1.20 ± 0.26	0.9 ± 0.5	0.6 ± 0.4
$\kappa(4h, p\bar{p})_{\mathrm{comb.},\phi}$	-0.0033 ± 0.0030	-0.0102 ± 0.0015	-0.0027 ± 0.0023	0.0033 ± 0.0030
$\kappa(4h, p\bar{p})_{\mathrm{comb.},KK}$	0.0043 ± 0.0010	0.0069 ± 0.0007	0.0071 ± 0.0033	-0.0004 ± 0.0013
$\kappa(KK)_{B,KK}$	0.012 ± 0.011	0.012 ± 0.007	-0.08 ± 0.11	-0.028 ± 0.050
$\kappa(KK)_{\mathrm{comb.},KK}$	0.006 ± 0.004	0.0132 ± 0.0030	0.025 ± 0.012	0.0052 ± 0.0077
N_{B^0KK}	18 ± 16	67 ± 24	0.0 ± 0.7	-4 ± 4
$N_{B^0\phi}$	7 ± 17	77 ± 23	6 ± 5	11 ± 7
$N_{B_s^0KK}$	86 ± 21	112 ± 25	3 ± 3	10 ± 11
$N_{\mathrm{comb.}KK}$	329 ± 33	599 ± 43	34 ± 9	109 ± 18
$N_{\mathrm{comb.}\phi}$	418 ± 39	380 ± 43	50 ± 13	43 ± 17
$N_{\text{mis-ID}\,p\bar{p}K\pi}$	n/a	n/a	n/a	11 ± 13
$\kappa(KK)_{\text{mis-ID},K\pi}$	n/a	n/a	n/a	-0.0325 ± 0.0002

2D fit results



Hypatia model

- D. Martinez Santos and F. Dupertuis, Mass distributions marginalized over per-event errors, Nucl. Instrum. Meth. A764 (2014) 150, arXiv:1312.5000
- Resolution function:
  - asymetric radiation
  - mass resolution with mass-dependence

$$I(m,\mu,\sigma,\lambda,\zeta,\beta,a_1,a_2,n_1,n_2) \propto \begin{cases} \frac{A}{(B+m-\mu)^{n_1}}, \text{ if } m-\mu < -a_1\sigma\,, \\ \frac{C}{(D+m-\mu)^{n_2}}, \text{ if } m-\mu > a_2\sigma\,, \\ \left((m-\mu)^2+\delta^2\right)^{\frac{1}{2}\lambda-\frac{1}{4}} e^{\beta(m-\mu)} K_{\lambda-\frac{1}{2}}\left(\alpha\sqrt{(m-\mu)^2+\delta^2}\right), \text{otherwise,} \end{cases} \quad (1)$$

where $K_\nu(z)$ is the modified Bessel function of the second kind, $\delta \equiv \sigma\sqrt{\frac{\zeta K_\lambda(\zeta)}{K_{\lambda+1}(\zeta)}}$, $\alpha \equiv \frac{1}{\sigma}\sqrt{\frac{\zeta K_{\lambda+1}(\zeta)}{K_\lambda(\zeta)}}$, and A, B, C, D are obtained by imposing continuity and differentiability.

Systematics: RBW with mass-dependant width

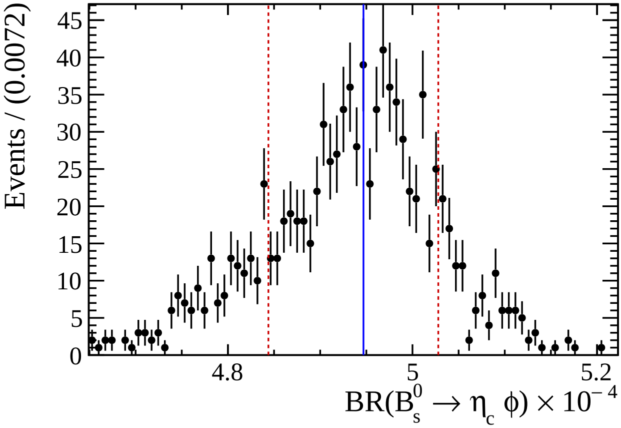
- The RBW parametrization used to describe the $\phi(1020)$ resonance in the 2D fit model is defined as:
  - $R_j(m) = \frac{1}{(m_0^2 - m^2) - i m_0 \Gamma(m)}$
  - m_0 is the nominal mass of the resonance
  - $\Gamma(m)$ is the mass-dependent width
- $\Gamma(m) = \Gamma_0 \left(\frac{|\mathbf{q}|}{|\mathbf{q}|_0}\right)^{2J+1} \left(\frac{m_0}{m}\right) \frac{X_J^2(|\mathbf{q}|r)}{X_J^2(|\mathbf{q}|_0 r)}$
  - The $X_J(|\mathbf{q}|r)$ function describes the Blatt-Weisskopf barrier factor with a barrier radius of r
  - For the K^* and the ρ resonances, literature reports values between $[2-4]\,\mathrm{GeV}^{-1}$
  - No good external inputs for the ϕ radius...
  - Variation the ϕ radius value in the range $[1.5-5.0]\,\mathrm{GeV}^{-1}$
  - Take the difference between the maximum and the minimum branching fractions as systematics

Systematics: Fit model

- Fixed parameters to the MC in the fit procedure
- Natural width of the η_c and the natural width of the ϕ have been fixed to the average value reported in the PDG
- Generated 1000 values from the covariance matrix for each fixed parameter in the fit procedure
- For the natural width of the η_c and the natural width of the ϕ generated as a Gaussian with mean and error taken from the PDG
- For each new set of values, we performed the 2D fit of the $p\bar{p}KK$ and KK invariant masses extracting the corresponding sWeights
- For each new set of sWeight, we performed the $p\bar{p}$ fit varying simultaneously the fixed parameters of the J/ψ and of the η_c
- The uncertainty is taken as the difference between the nominal value and the value at $1\sigma(-1\sigma)$ of the branching fractions distribution

Systematics: Fit model

- Distribution of $\mathcal{B}(B_s^0 \to \eta_c\phi)$ obtained after varying the fixed PDF parameters in both the two-dimensional and simultaneous amplitude fit models. The vertical blue line corresponds to the nominal value of $\mathcal{B}(B_s^0 \to \eta_c\phi)$ and the dashed red lines correspond to the plus- and minus-one sigma values



Systematics: BDT

Variable	Mode/Year					
	$2K2\pi$		4π		$4K$	
	2011	2012	2011	2012	2011	2012
B_s0_ENDVERTEX_CHI2	1.004 ± 0.039	1.005 ± 0.025	1.001 ± 0.041	0.998 ± 0.026	0.993 ± 0.134	0.949 ± 0.087
B_s0_FD_OWNPV	0.998 ± 0.038	0.999 ± 0.024	0.996 ± 0.039	0.999 ± 0.025	0.920 ± 0.126	0.997 ± 0.089
B_s0_DIRA_OWNPV	0.999 ± 0.037	0.999 ± 0.024	0.997 ± 0.039	0.995 ± 0.025	0.998 ± 0.132	0.991 ± 0.088
log10(B_s0_PT)	0.999 ± 0.037	0.999 ± 0.024	0.999 ± 0.039	0.999 ± 0.025	0.992 ± 0.132	0.961 ± 0.086
log10(phi_1020_PT)	0.996 ± 0.037	0.998 ± 0.024	0.993 ± 0.039	0.998 ± 0.025	0.901 ± 0.125	0.983 ± 0.087
phi_1020_ENDVERTEX_CHI2	0.996 ± 0.038	0.999 ± 0.024	0.995 ± 0.039	0.996 ± 0.025	0.960 ± 0.131	0.996 ± 0.090
etac_1S_ENDVERTEX_CHI2	0.994 ± 0.038	0.994 ± 0.024	0.988 ± 0.040	0.998 ± 0.025	0.996 ± 0.133	0.991 ± 0.090
etac_1S_IPCHI2_OWNPV	0.989 ± 0.038	0.988 ± 0.024	0.981 ± 0.039	0.979 ± 0.025	0.885 ± 0.126	0.965 ± 0.087
log10(etac_1S_FD_ORIVX)	1.016 ± 0.039	1.008 ± 0.025	1.000 ± 0.040	1.001 ± 0.025	1.000 ± 0.135	1.006 ± 0.091
Max_TRACK	1.001 ± 0.038	1.003 ± 0.024	0.983 ± 0.039	1.002 ± 0.025	1.003 ± 0.134	0.983 ± 0.088
log10(Max_IPCHI2)	0.998 ± 0.038	0.995 ± 0.024	0.994 ± 0.039	0.991 ± 0.025	0.980 ± 0.131	0.986 ± 0.087
log10(Min_h_Pt)	0.997 ± 0.037	0.995 ± 0.024	0.977 ± 0.039	0.978 ± 0.024	0.971 ± 0.129	0.980 ± 0.088

sWeight

- Using the likelihood information from each fit, an event-per-event set of weights, w_i, are computed based on the sPlot procedure [arXiv:physics/0402083].
- These weights are further corrected based on the procedure given in [arXiv:0905.0724], such as:
  $\mathrm{w}_i^{\mathrm{corr}} = \mathrm{w}_i(\sum_j \mathrm{w}_j / \sum_j \mathrm{w}_j^2)$
  and are used to statistically subtract the backgrounds not corresponding to decays of the type $B_s^0 \to (4h, p\bar{p})\phi$