Analysis
Search for $B_s^0 \to \phi\eta'$ decays in Run 1 + Run 2 dataset at LHCb

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Review

- Flavor-Changing Neutral Current(FCNC) decays of B_s^0
- $s\bar{s}$ as Vector(V) $\phi(1020)$ or Pseudoscalar(P) $\eta'(958)$
- PP/VV/PV(VP) final states

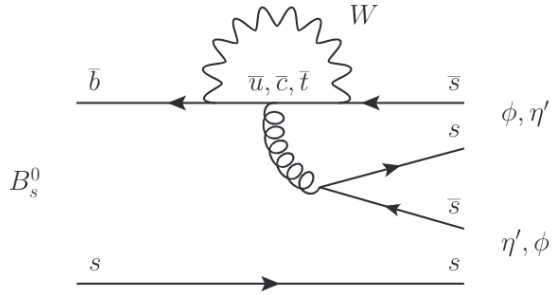


Figure: Lowest-order diagrams for the $B_s^0 \to \eta'\phi$ decay

Review

- $\mathcal{B}(B_s^0 \to \phi\phi)(VV) = (1.84 \pm 0.14) \times 10^{-5} \to$ JHEP 2015(10):53
- $\mathcal{B}(B_s^0 \to \eta'\eta')(PP) = (3.3 \pm 0.7) \times 10^{-5} \to$ PRL 115.051801
- $B_s^0 \to \phi\eta'$
  - Supressed PV/VP
  - No signal in Run 1 $\to$ JHEP 2017(05):158
    - $\mathcal{B} < 0.82(1.01) \times 10^{-6}$

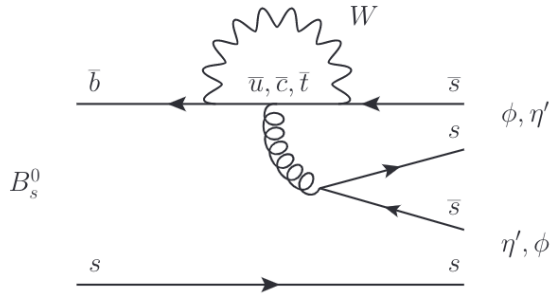


Figure: Lowest-order diagrams for the $B_s^0 \to \eta'\phi$ decay

Review

Approach	$\mathcal{B}(10^{-6})$
QCD factorisation	$0.05^{+1.18}_{-0.19}$
Pertubative QCD	$0.19^{+0.20}_{-0.13}$
QCD factorisation	$2.2^{+9.4}_{-3.1}$
SCET	$4.3^{+5.2}_{-3.6}$
SU(3) flavour symmetry	5.5 ± 1.8
FAT	13.0 ± 1.6
Pertubative QCD	$20.0^{+16.3}_{-9.1}$
Measurement Run 1	< 0.82 (90% CL)

Table: Prediction of $B_s^0 \to \phi\eta'$ Branching Fraction in different theoritical approach, and measurement with run 1 data of LHCb

This Analysis

Decay Modes:

- Signal: $B_s^0 \to \phi(K^+K^-)\eta'(\pi^+\pi^-\gamma)$
- Normalisation(Control): $B_s^0 \to \phi\phi \to 4K$
  - Golden channel for charmless B_s^0 meson decays

Dataset:

- Full Run 1+2 Data & MC Signal & Control Modes
- 2016 MC/Rapidsim for additional Background modes

Twiki page here

Strategy

- Signal: $B_s^0 \to \phi(K^+K^-)\eta'(\pi^+\pi^-\gamma)$
- Normalisation(Control): $B_s^0 \to \phi\phi \to 4K$

$$\mathcal{B}(B_s^0 \to \phi\eta') = \mathcal{B}(B_s^0 \to \phi\phi) \times \frac{\mathcal{B}(\phi \to KK)}{\mathcal{B}(\eta' \to \pi\pi\gamma)} \times \frac{N(B_s^0 \to \phi\eta')}{N(B_s^0 \to \phi\phi)} \times \frac{\epsilon(B_s^0 \to \phi\phi)}{\epsilon(B_s^0 \to \phi\eta')} \quad (1)$$

Event selections:

For Normalisation:

- Stripping and Trigger lines
- Offline cuts

For Signal:

- Same Stripping and Trigger lines
- Tighter Offline cuts
- Vetos for specific backgrounds
- MVA

Control mode $B_s^0 \to \phi\phi \to 4K$

- Stripping/Trigger
- Offline cuts: kinematics of B_s^0 and products

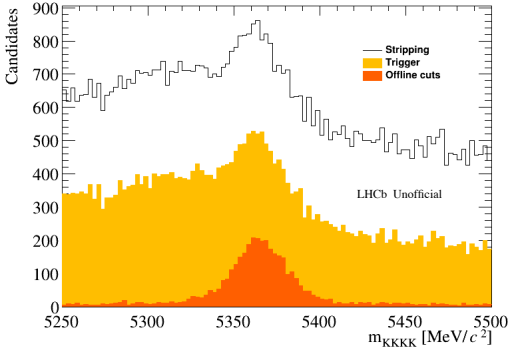


Figure: Run 1 data from Stripping

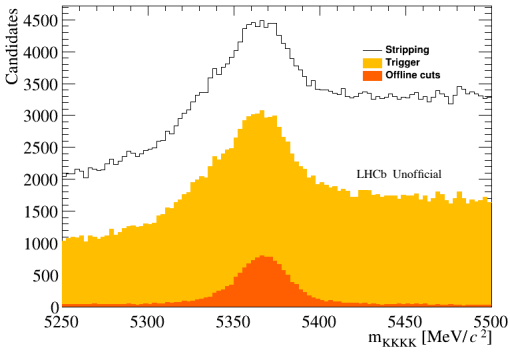


Figure: Run 2 data from Stripping

- 72.9(73.8)% ϵ_{sig} in Run 1(2) from MC

Fit for $B_s^0 \to \phi\phi \to 4K$ Data

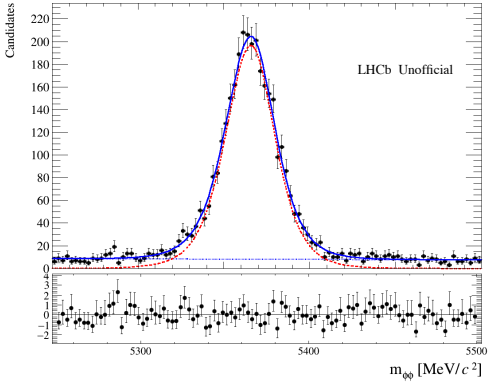


Figure: Run 1 data selected

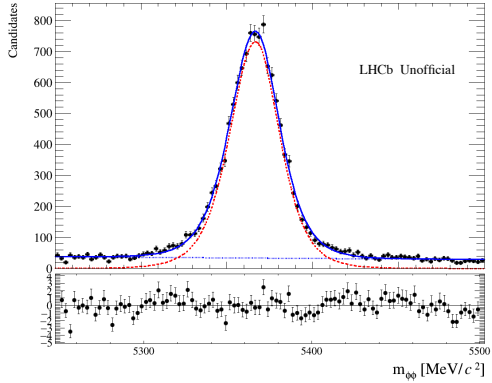


Figure: Run 2 data selected

- Shape from MC: Double sided crystal ball function
- Combinatorials: Exponential
- Run 1 Yield: 3053.5 ± 62.2
- Run 2 Yield: 11439.9 ± 122.4

Offline Cuts for Signal $B_s^0 \to \phi(K^+K^-)\eta'(\pi^+\pi^-\gamma)$

Same cuts as the control mode

- Same Stripping/Trigger
- Tighter Offline cuts
  - B_s^0 kinematics
  - γ kinematics

Veto of specific background modes:

With misidentified Kaons

- $K^* \to K^{\pm}\pi^{\mp}$
- $\Lambda_b \to pK\eta'$

PartReco

- $\phi \to \pi^+\pi^-(\pi^0 \to \gamma\gamma)$

With random γ

- $B^0_{d,s} \to (\phi \to KK)\pi\pi$

Additional cuts

- Reconstructed $m_{\phi K\pi}$ and $m_{\phi\pi\pi}$
- Mass windows of ϕ, η' and $(\rho \to \pi\pi)$
- PID cuts
- Performance validated with MC

Offline Cuts for Signal Mode

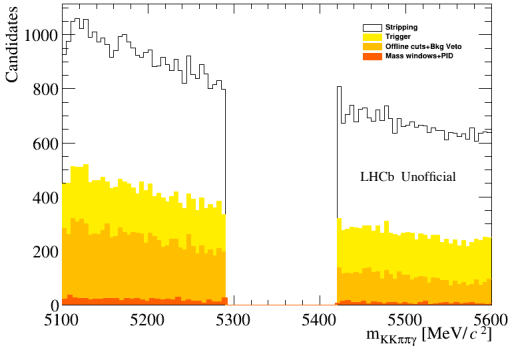


Figure: Run 1 data from Stripping

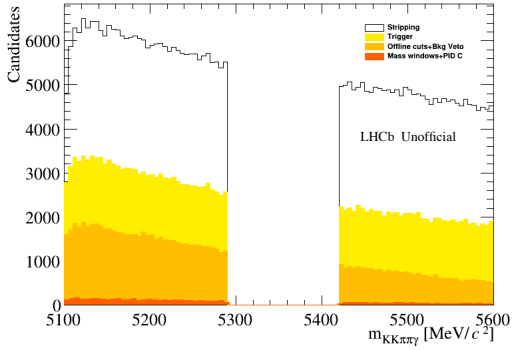


Figure: Run 2 data from Stripping

- 3σ within signal region blinded
- 43.1(44.3)% ϵ_{sig} in Run 1(2) from MC

MVA

Classifier for combinatorials

- Boosted Decision Trees(BDT)
- with XGBoost
- 18 input variables
- Calibrated MC signal
- Sideband background data
- $m_{\phi\eta'} > 5600\text{MeV}/c^2$

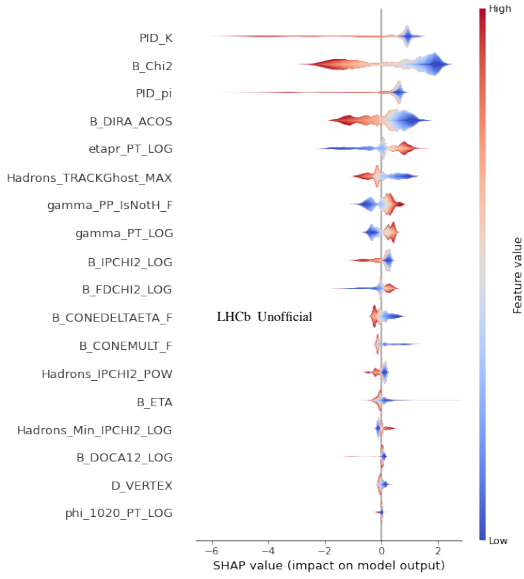


Figure: SHAP plot of input variables

MVA

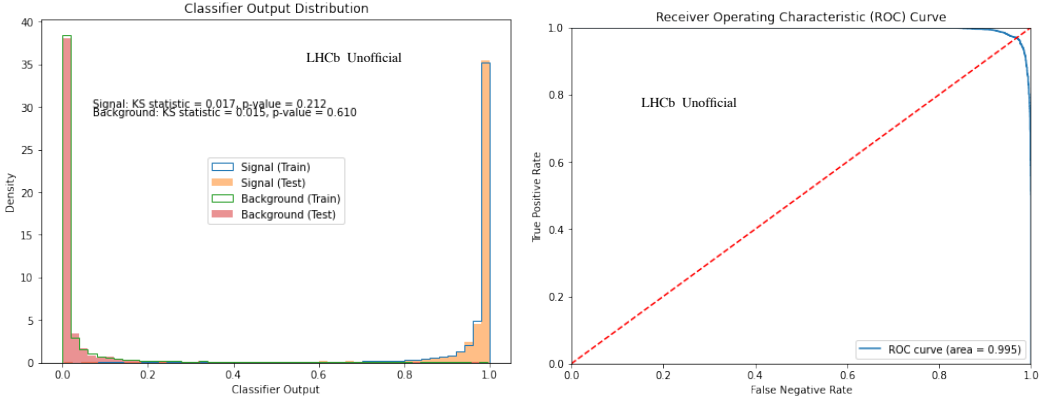


Figure: Performance of the XGBoost BDT classifier

- Well discriminated output
- No indication of over/underfit

MVA Cut

MVA cut based on maximised Punzi Figure of Merit(FoM)

$$FoM(t) = \frac{\epsilon_s(t)}{a/2 + \sqrt{N_B(t)}} \qquad (2)$$

- $\epsilon_s(t)$: Signal efficiency from MC with cut t
- $N_B(t)$ Number of background events left with cut t
- $a = 5$

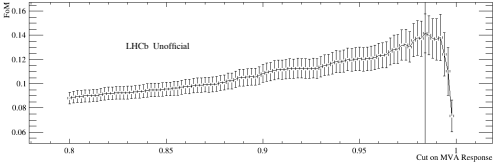


Figure: Punzi FoM at different MVA cut value

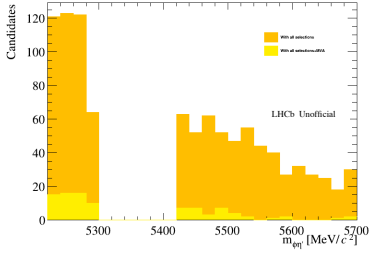


Figure: Performance of MVA cut

- 31.0(34.8)% ϵ_{sig} in Run 1(2) from MC

$B_s^0 \to \phi\eta'$ background Mass fit

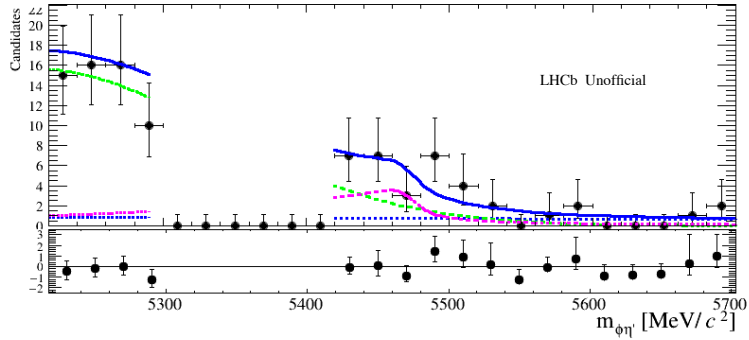


Figure: Fitting of Run 1+2 data with 3σ around the B_s^0 signal region blinded.

- Combinational (Blue dash)
- $B_s \to (\phi \to 2K)(\phi \to 3\pi)$ (Green) Yield: 116.44 ± 32.47
- $\Lambda_b \to \eta'(\Lambda(1520) \to pK)$ (Magenta) Yield: 30.77 ± 22.25

Expect yields

$$\mathcal{N}(B_s^0 \to \phi\eta') = \mathcal{N}(B_s^0 \to \phi\phi) \times \frac{\mathcal{B}(B_s^0 \to \phi\eta')}{\mathcal{B}(B_s^0 \to \phi\phi)} \times \frac{\mathcal{B}(\eta' \to \pi\pi\gamma)}{\mathcal{B}(\phi \to KK)} \times \frac{\epsilon(B_s^0 \to \phi\eta')}{\epsilon(B_s^0 \to \phi\phi)} \quad (3)$$

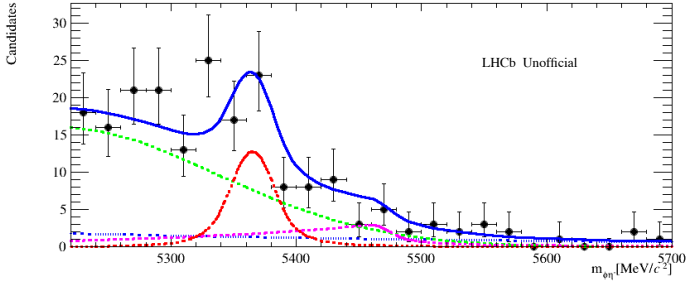


Figure: $B_s^0 \to \phi\eta'$ Toy data with signal yield from Run 1 limit, signal shape from MC

If $\mathcal{B}(B_s^0 \to \phi\eta')$ as Run 1 limit at 95(90)% CL we expect:

- 4.72(5.82) events in Run 1
- 39.09(48.15) events in Run 2

CLs test

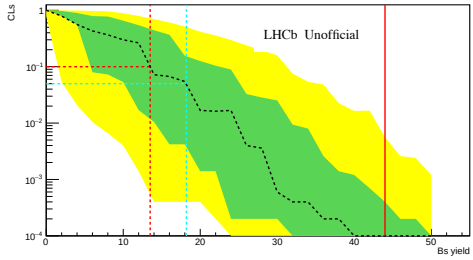


Figure: CLs for background Model, calculated from toy data

Event number from Run 1 limit(solid lines):

- $\mathcal{B}(B_s^0 \to \phi\eta') < 0.82(1.01) \times 10^{-6}$
- 44(53) events at 90(95)% CL

This analysis(dashed lines):

- 13.5(18.2) events
- $\mathcal{B} < 0.251(0.340) \times 10^{-6}$

Next Stage

Going to unblind
Look at the signal region if:

- 3σ Signal observed $\rightarrow$ First measurement
- No signal/ lower than 3σ $\rightarrow$ New upper limit

Thank You

Backup Sildes

Stripping

`B2CharmlessInclusive4piAllX0SelectionLine`

- Desighed for $B_s^0 \to \rho\rho$ with $\rho \to \pi^+\pi^-$ or $\rho \to \pi^+\pi^-\gamma$
- Substitute to $\phi \to K^+K^-$ and $\eta' \to \pi^+\pi^-\gamma$

Year	Stripping
2011	21r1p2
2012	21r0p2
2015	24r2
2016	28r2
2017	29r2p1
2018	34r0p1

Table: Version of Stripping Lines used each year

Trigger

	Line
All	L0_Global_TIS
	L0_HadronDecision_TOS
Run 1	Hlt1TrackAllL0Decision
Run 2	Hlt1TrackMVADecision
	Hlt1TwoTrackMVADecision
Run 1	Hlt2Topo(2‖3‖4)BodyBBDTDecision
	Hlt2IncPhiDecision
Run 2	Hlt2Topo(2‖3‖4)BodyDecision
	Hlt2IncPhiDecision
	Hlt2PhiIncPhiDecision

Table: Triggers for events, the events are required to pass at least one of the lines in L0, and pass at least one of line in HLT1 and HLT2 as TOS

Offline Cuts for Normalisation mode

Particle	Quantity	Cut values
B_s^0	Mass [MeV/c^2]	> 5000
	ACos(DIRA)	< 0.02
	χ^2_{FD}	$> 50.$
	$Log(\chi^2_{IP})$	$> -6.$
	χ^2_{VTX}/ndf	< 6.0
$\phi(1020)$	Mass [MeV/c^2]	$1000 - 1040$
Track	Multiple_tracks	$== 0$
	Type I$\|\|$Type II Clones	$== 0$

Table: Offline selections for the $B_s^0 \to \phi\phi$ candidates

Offline Cuts for Signal mode

Particle	Quantity	Cut value
B_s^0	Mass [MeV/c^2]	> 5000
	ACos(DIRA)	< 0.02
	χ^2_{FD}	$> 50.$
	Log(χ^2_{IP})	$> -6.$
	χ^2_{VTX}/ndf	< 6.0
γ	P_T [MeVc]	> 500
$\phi(1020)$	Mass [MeV/c^2]	$1000 - 1040$
η'	Mass [MeV/c^2]	$880 - 1040$
$\rho(\pi^+\pi^-)$	Mass [MeVc^2]	$620 - 920$
K	(1-ProbNNp)*ProbNNK	> 0.1
	Momentum [MeV/c]	< 10000
Track	Multiple_tracks	$== 0$
	Type I‖Type II Clones	$== 0$

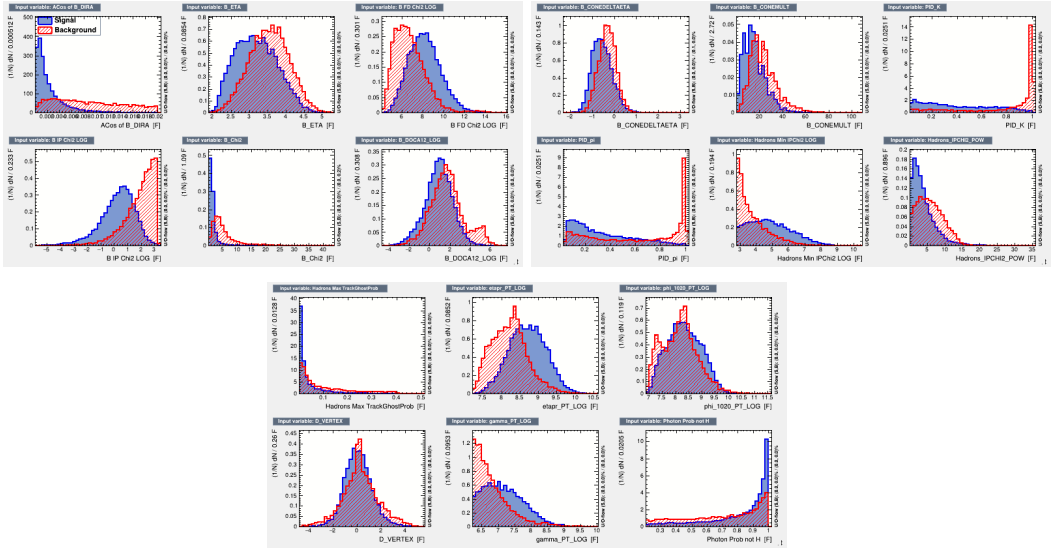
Table: Cuts for the $B_s^0 \to \phi\eta'$ candidates, the first part is applied on dataset before the MVA training and secon part after.

Background Modes

Decay Modes	MC Type	BF($\times 10^{-6}$)	Visible BF ($\times 10^{-6}$)
$B_d \to (K^* \to K\pi)\eta'$	RapidSim	2.8 ± 0.6	0.551 ± 0.118
$\Lambda_b \to \eta' pK$	15104212	8.48 ± 1.31	2.50 ± 0.38
$\Lambda_b \to \eta'(\Lambda(1520) \to pK)$	RapidSim	3.14 ± 0.48	0.417 ± 0.065
$B_d \to K^*(\phi \to 3\pi)$	RapidSim	10.0 ± 0.5	1.03 ± 0.06
$B_s \to (\phi \to 2K)(\phi \to 3\pi)$	13104401	18.4 ± 1.4	2.78 ± 0.22
$\Lambda_b \to pK(\phi \to 3\pi)$	RapidSim	N/A	N/A
$B_s \to (\phi \to 2K)\pi\pi$	RapidSim	3.5 ± 0.5	1.72 ± 0.24
$B_d \to (\phi \to 2K)\pi\pi$	RapidSim	0.18 ± 0.05	0.088 ± 0.003
$B_s \to \phi\phi(\to 4K)$	13104013	18.4 ± 1.4	4.43 ± 0.34
$B_d \to K^*(\phi \to KK)$	11104020	10.0 ± 0.05	3.27 ± 0.16
$\Lambda_b \to (\phi \to KK)pK$	RapidSim	N/A	N/A
$B_s^0 \to (\phi \to KK)\eta'$	13104231	< 0.82	< 0.119

Table: Decay modes accounted for in this analysis with Branching fraction, and visible Branching Fraction calculated from the BF times the BF of each product to their specific final states. Red modes are expected peaking in the background

MVA Variables



MVA inputs Pt.1

Variables	Description
B_DIRA_OWNPV	Angle between primary and end vertex
B_ETA	B pseudorapidity η
B_FDCHI2_OWNPV	B flight distance
B_IPCHI2_OWNPV	B impact parameter
B_ENDVERTEX_CHI2	B decay end vertex χ^2
B_DOCA12	Distance between the ϕ and η' vertex
B_CONEDELTAETA	Difference in the direction of the tracks in the cone
B_CONEMULT	Number of tracks in the cone
PID_K	Probability of K as K not π or proton
PID_pi	Probability of π as π not K or proton

Table: MVA input variables Part 1

MVA inputs Pt.2

Variables	Description
Hadrons_PT	Transverse momentum of all hadrons
Hadrons_IPCHI2_OWNPV	Impact parameter of all hadrons
Hadrons_TRACK_GhostProb	Probability of a hadron as ghost
etapr_PT	η' transverse momentum
D_VERTEX	Position difference of ϕ and η' end vertex
gamma_PT	Photon transverse momentum
gamma_ProbNN_H	Photon probability as is hadron

Table: MVA input variables Part 2

Efficiencies and expect yields

$$\mathcal{N}(B_s^0 \to \phi\eta') = \mathcal{N}(B_s^0 \to \phi\phi) \times \frac{\mathcal{B}(B_s^0 \to \phi\eta')}{\mathcal{B}(B_s^0 \to \phi\phi)} \times \frac{\mathcal{B}(\eta' \to \pi\pi\gamma)}{\mathcal{B}(\phi \to KK)} \times \frac{\epsilon(B_s^0 \to \phi\eta')}{\epsilon(B_s^0 \to \phi\phi)} \quad (4)$$

$$\epsilon_{total} = \epsilon_{gen} \times \epsilon_{reco} \times \epsilon_{sel} \quad (5)$$

	$\epsilon_{\phi\phi}^{run1}$	$\epsilon_{\phi\phi}^{run2}$	$\epsilon_{\phi\eta'}^{run1}$	$\epsilon_{\phi\eta'}^{run2}$
Generation(%)	16.6	17.6	17.7	18.7
Reconstruction(%)	2.738	3.391	0.257	0.652
Selection(%)	72.98	77.89	31.03	34.82
Total($\times 10^{-3}$)	3.317	4.648	0.141	0.424

If $\mathcal{B}(B_s^0 \to \phi\eta')$ as Run 1 limit at 95(90)% CL we expect:

- $3.17 \pm 0.06(3.91 \pm 0.08)$ events in Run 1
- $25.28 \pm 0.27(31.14 \pm 0.33)$ events in Run 2