Angular analysis of the $B_s \to \phi e^+ e^-$ decay in the very-low q^2 bin to access photon polarization in LHCb

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Flavor day - IJCLab
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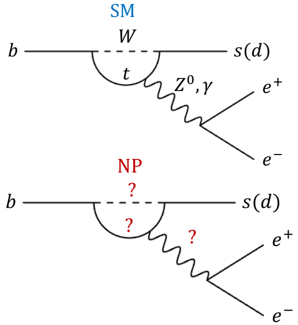
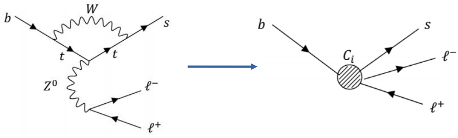


b → sll transitions in the SM mediated by loop.

- Highly suppressed
- NP contributions can be large.



Different q^2 $(m^2_{l^+l^-})$ regions probe different processes.

$$\mathcal{H}_{\text{eff}} = \frac{-4G_F}{\sqrt{2}} \cdot \frac{e^2}{16\pi^2} V_{tb} V_{ts}^* \sum_i C_i O_i + \text{h.c.}$$

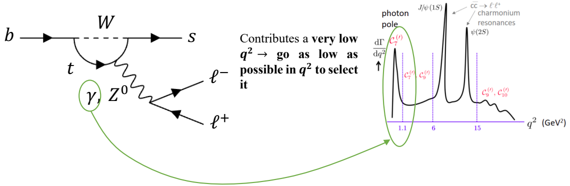
NP enters here $C_i = C_i^{SM} + C_i^{NP}$

Operator encoding Lorentz structure

i = 1,2	Tree
i = 3-6,8	Gluon penguin
i = 7	Photon penguin
i = 9,10	Electroweak penguin
i = S,P	Scalar/Pseudoscalar penguin

Photon Penguin can be:

- with a real photon (radiative decay)
- with a virtual photon in $b \to sll$ processes



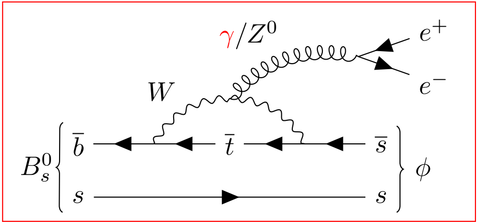
> Muons need at least $\sqrt{q^2} = 2m_\mu$
> $\to$ With electrons you can go lower in q^2 and isolate the photon pole

$$H_{\text{eff}} \sim (C_7 O_7 + C_7' O_7')$$

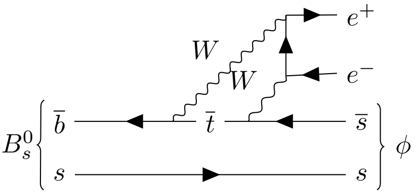
- $O_7^{(\prime)}$: left(right)-handed EM dipole operator
- $C_7^{(\prime)}$: corresponding Wilson coefficient

$$\gamma \text{ mostly left-handed in the SM} \to \frac{C_7'}{C_7} \approx 0.02$$

The Analysis - $B_s^0 \to \phi(\to K^+K^-)e^+e^-$



Dominant at low-q^2



Specific aspects compared to $B^0 \to K^{*0}(\to K^+\pi^-)e^+e^-$:

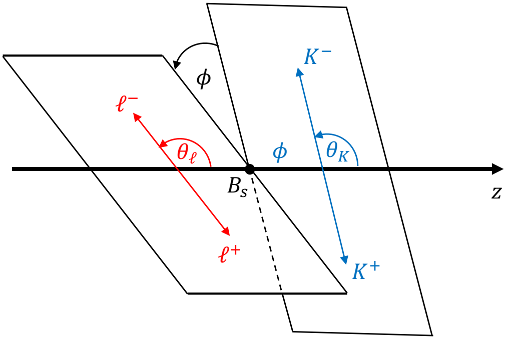
- $B_s^0 \to \phi(\to K^+K^-)e^+e^-$ mode has lower statistics:
    - f_s/f_d =1/4 suppressed
    - $B(\phi \to K^+K^-) = 50\%$ compared to $B(K^* \to K\pi) = 2/3$
- Narrow ϕ resonance $\to$ lower background level.
- Lower Partially Reconstructed Backgrounds.

The direction of the four outgoing particles can be described by three angles.

θ_l: angle between e^- and B_s^0 in the dielectron rest frame.

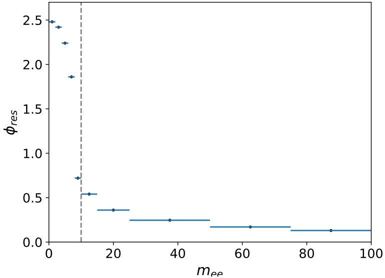
θ_K: angle between K^- and B_s^0 in the K^-K^+ rest frame.

ϕ: angle between the two leptons plane and the 2 kaons plane in the B_s^0 rest frame.



Lower Boundary In principle, can go to the threshold $m_{(ee)} = 2m_e \sim 1\text{MeV}/c^2$

→ Angle between leptons gets very small
  → Bad resolution on ϕ
  → Worse measurement of observables of interest



→ Cut at 10 MeV helps removing converted γ

Upper Boundary

→ Isolate $C_7^{(\prime)}$
→ Avoid background coming from higher mass.

$$\boxed{\mathrm{m}_{ee} \in [10, 500]\ \text{MeV}}$$

The Analysis - 4 Angular Parameters

$$\frac{1}{\frac{d(\Gamma+\bar{\Gamma})}{dq^2}} \frac{d^3(\Gamma+\bar{\Gamma})}{d\cos\theta_l d\cos\theta_k d\phi}$$
$$= \frac{9}{32\pi} \left\{ \frac{3}{4}(1-F_L)\sin^2\theta_k + F_L\cos^2\theta_k \right.$$
$$+ \left[\frac{1}{4}(1-F_L)\sin^2\theta_k - F_L\cos^2\theta_k\right]\cos 2\theta_l$$
$$+ \frac{1}{2}(1-F_L)A_T^{(2)}\sin^2\theta_k\sin^2\theta_l\cos 2\phi$$
$$+ (1-F_L)A_T^{ReCP}\sin^2\theta_k\cos\theta_l$$
$$\left. + \frac{1}{2}(1-F_L)A_T^{ImCP}\sin^2\theta_k\sin^2\theta_l\sin 2\phi \right\}$$

⋆ F_L is the longitudinal polarisation

⋆ A_T^{ReCP} related to the forward-backward asymmetry

⋆ $A_T^{(2)}$, A_T^{ImCP} are sensitive to the photon polarization

- $A_T^{(2)}(q^2 \to 0) = \frac{2Re(C_7 C_7^{'*})}{|C_7|^2+|C_7'|^2} + m_1$[1]
- $A_T^{ImCP}(q^2 \to 0) = \frac{2Im(C_7 C_7^{'*})}{|C_7|^2+|C_7'|^2} + m_2$

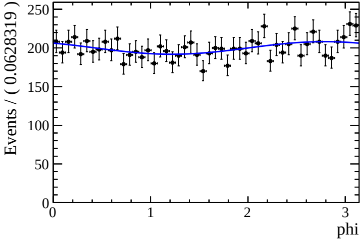
https://arxiv.org/pdf/2210.11995.pdf

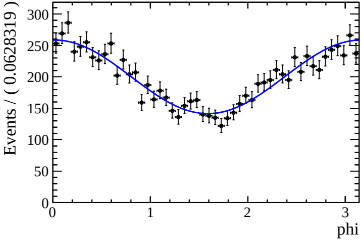
[1] where m_i are contributions induced by $B_s - \bar{B}_s$ mixing

Key Observables

A_T^{ImCP} and $A_T^{(2)}$ are our key observables:

- Sensitive to the photon polarization.
- Predicted to be small in the Standard Model.
- Can be large in the presence of New Physics contributions.





ϕ from Signal only toys, SM predictions on the left ($A_T^{(2)} = 0.094$) and a different value of $A_T^{(2)}$ (=0.500) on the right.

Towards the Angular Analysis

- Using Run 1 (2011 and 2012) + Run 2 (2015, 2016, 2017 and 2018) collected data corresponding to 9 fb^{-1}.
- About 100 signal candidates for $m_{ee} \in [10, 500]$ MeV

The aim of our angular analysis is to measure the four observables $F_L, A_T^{(2)}, A_T^{ReCP}$ and A_T^{ImCP}.
The total 4D fit PDF is:

$$fs \times PDF_{Signal}(m, \theta_l, \theta_K, \phi) + \sum_{BKG} f_{BKG} * PDF_{BKG}(m, \theta_l, \theta_K, \phi)$$

- The signal angular PDF is multiplied by the angular acceptance extracted from PhaseSpace MC [2]
- Background PDFs are extracted from MC fits.
- Fit procedure tested with pseudo-experiments.

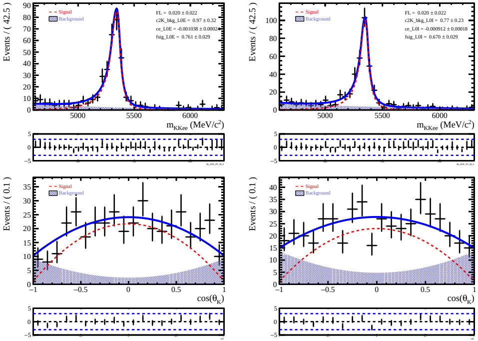
[2] Generated with flat angles

Control channel fit

$B_s^0 \to \phi\gamma$

- $m_{ee} < 10$ MeV
- 2D fit $(m_{B_s}, \cos(\theta_K))$: $\cos(\theta_L)$ and $\tilde{\phi}$ are not related to the physics of $B_s^0 \to \phi\gamma$
- Fitted F_L found to be compatible with 0 as expected (real γ)

L0E[3] - 390 Events L0I [4] - 470 Events



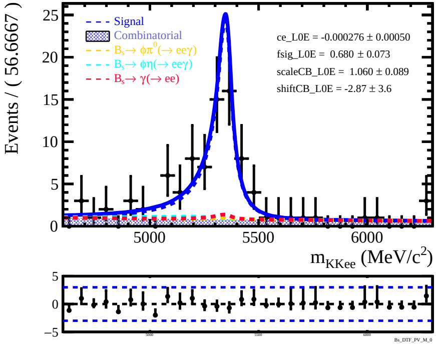
$$\boxed{F_L^{\gamma} = 0.020 \pm 0.022}$$

[3]triggered exclusively by one of the signal electrons

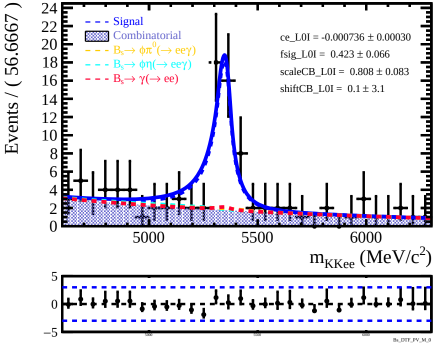
[4]triggered independent of signal

Full Mass Fit - Very-low - 1D

L0E
85 Events



L0I
95 Events



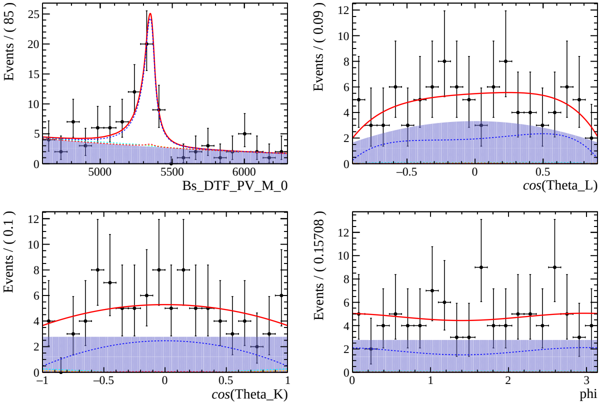
The angles are blinded.

Fit Validation with pseudo-experiments - WIP

Pseudo-expirements generated with SM values

$$F_L = 0.048,\ A_T^{(2)} = 0.094,$$
$$A_T^{Re} = 0 \text{ and } A_T^{Im} = 0$$

Example



$B_s \to \phi ee$ vs. $B_d \to K^* ee$

For $B_d \to K^* ee$:	Expected for $B_s \to \phi ee$:
450 Signal Events	98 Signal Events
$F_L = 0.044 \pm 0.026 \pm 0.014$	$F_L = XXX \pm 0.050 \pm 0.012$
$A_T^{(2)} = 0.106 \pm 0.103 \pm 0.016$	$A_T^{(2)} = XXX \pm 0.240 \pm 0.009$
$A_T^{Im} = 0.015 \pm 0.102 \pm 0.012$	$A_T^{ImCP} = XXX \pm 0.240 \pm 0.007$
$A_T^{Re} = -0.064 \pm 0.077 \pm 0.015$	$A_T^{ReCP} = XXX \pm 0.160 \pm 0.012$

Systematics are still not computed but estimated based on $B \to K^* ee$

- $B_s \to \phi ee$ angular analysis at low-q^2 is a cross check for $B_d \to K^* ee$ with a cleaner channel
- Adds precision on $C_7^{(\prime)}$
- Gives information about the $B_s - \bar{B}_s$ mixing

Stay tuned!

Backup

The full differential decay rate:

$$\frac{d^3\Gamma}{d\cos\theta_l d\cos\theta_k d\phi} = \frac{9}{32\pi}\{J_{1s}\sin^2\theta_k + J_{1c}\cos^2\theta_k + J_{2s}\sin^2\theta_k\cos 2\theta_l$$
$$+ J_{2c}\cos^2\theta_k\cos 2\theta_l + J_3\sin^2\theta_k\sin^2\theta_l\cos 2\phi + J_4\sin 2\theta_k\sin 2\theta_l\cos\phi$$
$$+ J_5\sin 2\theta_K\sin\theta_l\cos\phi + J_{6s}\sin^2\theta_K\cos\theta_l + J_{6c}\cos^2\theta_K\cos\theta_l$$
$$+ J_7\sin 2\theta_k\sin\theta_l\sin\phi + J_8\sin 2\theta_K\sin 2\theta_l\sin\phi$$
$$+J_9\sin^2\theta_k\sin^2\theta_l\sin 2\phi\}$$

where $J_i(q^2)$: combinations of amplitudes $A^{L,R}_{0,\perp,\|}$

The Analysis - $B_s^0 \to \phi(\to K^+K^-)e^+e^-$

In the case of:

- Massless lepton limit
  - $S_{1s} = 3\ S_{2s} = \frac{3}{4}(1 - F_L)$
  - $S_{1c} =$ - $S_{2c} = F_L$
- Fold $\phi \to \phi + \pi$ for $\phi < 0$

- J_i associated to B_s and $\bar{J}_i$ associated to $\bar{B}_s$
- $S_i = \frac{J_i + \bar{J}_i}{\frac{d(\Gamma+\bar{\Gamma})}{dq^2}}$ and $A_i = \frac{J_i - \bar{J}_i}{\frac{d(\Gamma+\bar{\Gamma})}{dq^2}}$

$$\frac{1}{\frac{d(\Gamma+\bar{\Gamma})}{dq^2}} \frac{d^3(\Gamma+\bar{\Gamma})}{d\cos\theta_l d\cos\theta_k d\phi} = \frac{9}{32\pi}\Big\{\frac{3}{4}(1-F_L)\sin^2\theta_k + F_L\cos^2\theta_k + \frac{1}{4}(1-F_L)\sin^2\theta_k\cos 2\theta_l$$
$$-F_L\cos^2\theta_k\cos 2\theta_l + S_3\sin^2\theta_k\sin^2\theta_l\cos 2\phi + \cancel{S_4\sin 2\theta_k\sin 2\theta_l\cos\phi}$$
$$+\cancel{A_5\sin 2\theta_K\sin\theta_l\cos\phi} + A_{6s}\sin^2\theta_K\cos\theta_l + \cancel{A_{6c}\cos^2\theta_K\cos\theta_l}$$
$$+\cancel{S_7\sin 2\theta_k\sin\theta_l\sin\phi} + \cancel{A_8\sin 2\theta_K\sin 2\theta_l\sin\phi}$$
$$+A_9\sin^2\theta_k\sin^2\theta_l\sin 2\phi\Big\}$$

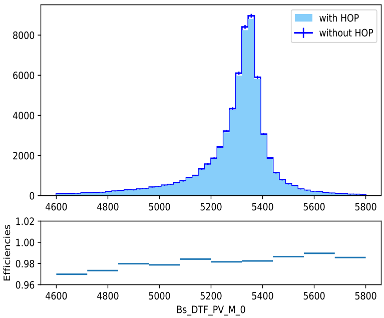
$\boxed{S_3 = \frac{1}{2}(1-F_L)A_T^{(2)}}$ $\boxed{A_{6s} = (1-F_L)A_T^{ReCP}}$ $\boxed{A_9 = \frac{1}{2}(1-F_L)A_T^{ImCP}}$

HOP

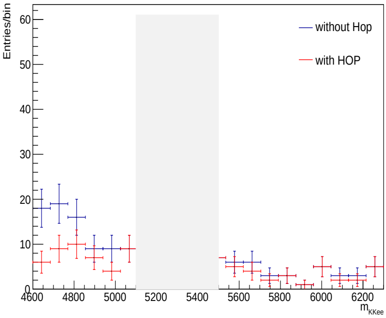
$$\alpha_{HOP} = \frac{p_T(\phi)}{p_T(e^+e^-)}$$

If $\alpha_{HOP} \neq 1 \rightarrow$ some energy is missing in the final state.

$\rightarrow p_{corr} = \alpha_{HOP} \times p_{measured} \rightarrow m_{HOP}(K^+K^-e^+e^-)$



MC Very-low



Data Very-low

Baseline

⋆ Stripping Lines: Bu2LLK_eeLine2.

- Plus some extra requirements

⋆ Two non overlapping trigger categories:

- L0I[5](as primary category): triggered independent of signal.
- L0E [6]: triggered exclusively by one of the electrons of the signal and not by L0I.

+ HLT1Track and HLT2Topo Lines are used.

⋆ The MC corrections are generated within the RX framework following the same Correction chain.

[5]L0I : L0Hadron_TIS (B_s^0) or L0Electron_TIS (B_s^0) or L0Muon_TIS (B_s^0)
[6]L0Electron(e_1, e_2) and !L0I

Framework - MC Corrections

- w_{PID} : Take ratio of data/simulation effiicencies
- w_{TRK} (only for electrons): Corrections ($\epsilon_{data}/\epsilon_{MC}$) in bins of p_T, η and ϕ.
- $w_{MultKin}$: BDT reweighter using $p(B_s), p_T(B_s), \eta(B_s), n_{Tracks}$
- w_{L0} : ratio of data/simulation computed in bins of electron E_T^{ECAL}, CaloRegion.
- w_{HLT}: computed in bins of track multiplicity
- w_{Reco}: BDT trained using $\chi^2_{IP}(B_s), \chi^2_{IP}(J/\psi)$

Framework - The stripping lines

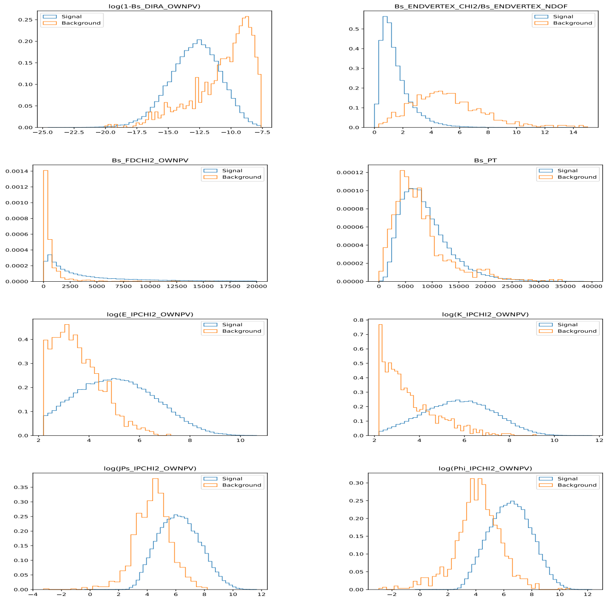
⋆ Stripping Lines: Bu2LLK_eeLine2.

Particle	Requirement
B_s^0	$\lvert m_{\phi ee} - m_{B_s}\rvert < 1000 MeV/c^2$ End vertex χ^2 /ndf < 9 $\chi^2_{IP} < 25$ DIRA > 0.9995 Flight Distance $\chi^2 > 100$
Dilepton	$m_{ee} < 5500 MeV/c^2$ End vertex χ^2 /ndf < 9 Flight distance $\chi^2 > 16$
e	$p_T > 300 MeV/c$ $\chi^2_{IP} > 9$ PIDe > 0
ϕ	$m_{KK} < 1100 MeV/c^2$ $p_T > 400 MeV/c$ Origin vertex $\chi^2/ndf < 25$
K	$\chi^2_{IP} > 9$ $p_T > 400 MeV/c$

HLT Lines

	HLT1	HLT2
Run 1	Hlt1TrackAllL0	Hlt2Topo[2,3]BodyBBDT Hlt2TopoE[2,3]BodyBBDT
2015	Hlt1TrackMVA	Hlt2Topo[2,3]Body
2016 - 2017 2018	Hlt1TrackMVA	Hlt2Topo[2,3]Body Hlt2TopoE[2,3]Body Hlt2TopoEE[2,3]Body

BDT input variables



Towards the Angular Analysis - Angles Acceptance

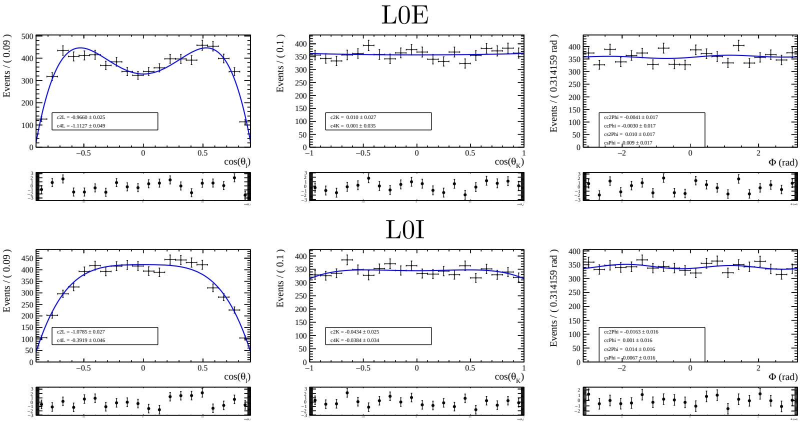
The reconstruction and selection of signal candidates induces a distortion in the angular distributions.
So If generator level events are flat in angles , events after reconstruction and selection point to the detector acceptance.

- Get the Angular Acceptance from the phase space (PHSP) MC : modelized with Legendre Polynome of order 4 for $\cos(\theta_L)$and $\cos(\theta_K)$) and by $1 + c_{c2}\cos(2\phi) + c_{s2}\sin(2\phi) + c_c\cos(\phi) + c_s\sin(\phi)$ for ϕ[7]
- Multiply the signal angular PDF by this acceptance

$$PDF_{Signal}(m, \theta_l, \theta_K, \phi) \rightarrow PDF_{Signal}(m, \theta_l, \theta_K, \phi) \times \epsilon(\theta_l, \theta_K, \phi)$$

and ϵ can be factorized: $\epsilon(\theta_l, \theta_K, \phi) = \epsilon(\theta_l) \times \epsilon(\theta_K) \times \epsilon(\phi)$

[7] ϕ is expected to be flat.



Considering $\cos(\theta_K)$ and $\tilde{\phi}$ flat.

Background Components

Background	Contamination [8] (Very-Low)	Mass and angular modeling
Combinatorial	Given by fit	$B_s \to \phi e^+ e^-$ data: Mass $B_s \to \phi e \mu$ data: Angles
$B_s^0 \to \phi\eta(\to e^+e^-\gamma)$	L0E: 4.2 ± 0.6 % L0I: 5.1 ± 0.7 %	$\mathrm{B}_s^0 \to \phi\eta(\to e^+e^-\gamma)$ MC
$B_s^0 \to \phi\pi^0(\to e^+e^-\gamma)$	L0E: 1.1 ± 0.2 % L0I: 2.5 ± 0.5 %	$B_s^0 \to \phi\pi^0(\to e^+e^-\gamma)$ MC
$B_s^0 \to \phi\gamma(\to e^+e^-)$	L0E: 2.4 ± 0.3 % L0I: 1.9 ± 0.3 %	$B_s^0 \to \phi e^+ e^-$ γ-bin Data and MC
$B_s^0 \to \phi\phi(\to K^+K^-)$	$< 1\%$	NO
$\Lambda_b^0 \to pK^-e^+e^-$	$< 1\%$	NO
$B^+ \to \phi K^+ e^+ e^-$	$< 1\%$	NO

⋆ The same background components were checked for the γ-bin and are negligible.
⋆ $B_s^0 \to \phi\eta(\gamma\gamma)$ and $B_s^0 \to \phi\pi^0(\gamma\gamma)$ still need to be studied

[8] $C_{bkg} = \frac{\mathcal{B}(bkg)) \times \epsilon(bkg))}{\mathcal{B}(B_s^0 \to \phi e^+ e^-)_{m_{ee} \in [10,500]} \times \epsilon(B_s^0 \to \phi e^+ e^-)_{m_{ee} \in [10,500]}}$

Fit Strategy in the γ bin (1/2)

Presence of the electrons in $B_s^0 \to \phi\gamma(\to e^+e^-)$ decay only due to the interaction of the photon with the detector

$\to$ $\cos(\theta_L)$ and $\tilde{\phi}$ are not related to the physics of $B_s^0 \to \phi\gamma$.

$\to$ Angular PDF integrated over $\cos(\theta_L)$ and ϕ including the acceptance

$\to$ 2D simultaneous fit (m_{B_s}, $\cos(\theta_K)$) in 2 trigger categories on data sharing F_L^γ considering only combinatorial for the background.

$$
\begin{aligned}
PDF_\gamma(m, cos(\theta_K)) = \quad & f_{sig}^\gamma \times DSCB_m(\alpha_L, \alpha_R, n_L, n_R, s.\sigma_L, s.\sigma_R, \delta.m_{CB}) \\
& \times PDF_{(cos(\theta_K))}(F_L^\gamma) \\
& + (1 - f_{sig}^\gamma) \times Expo_m(c_{exp}) \times Poly_{(cos(\theta_K))}(c2K)
\end{aligned}
$$

- Fix DSCB's parameters from MC
- Allow data/MC difference with a shift and a scale

Fit strategy in the very-low bin

Simultaneous 4D fit (m_{B_s}, $\cos(\theta_L)$, $\cos(\theta_K)$, $\tilde{\phi}$) in 2 trigger cat.: L0E and L0I.

$$
\begin{aligned}
PDF_{tot}^{VL}(m,\Omega) = & f_{sig} & \times\ & PDF_{sig}(m) & \times\ & A_{sig}(\Omega) \\
& + (f_\gamma \times f_{sig}) & \times\ & PDF_\gamma(m) & \times\ & A_\gamma(\Omega) \\
& + (f_\eta \times f_{sig}) & \times\ & PDF_\eta(m) & \times\ & A_\eta(\Omega) \\
& + (f_{\pi^0} \times f_{sig}) & \times\ & PDF_{\pi^0}(m) & \times\ & A_{\pi^0}(\Omega) \\
& + (1 - f_{sig}(1 + f_\gamma + f_\eta + f_{\pi^0})) & \times\ & PDF_{comb}(m) & \times\ & A_{comb}(\Omega)
\end{aligned}
$$

- sharing the angular observables (F_L, $A_T^{(2)}$, A_T^{ImCP}, A_T^{ReCP})
- f_γ, f_η and f_{π^0} fixed from MC
- Blinding the angles but not the mass

Fit strategy in the very-low bin: Mass fits

- Fix mass shapes from MC
  - $B_s^0 \to \phi e^+e^-$: Double Sided Crystal Ball
  - $B_s^0 \to \phi\gamma(\to e^+e^-)$: Double Sided Crystal Ball
  - $B_s^0 \to \phi\eta(\to \gamma e^+e^-)$: RooKeyPDF
  - $B_s^0 \to \phi\pi^0(\to \gamma e^+e^-)$: RooKeyPDF

- Combinatorial: Exponential function

- Allow small data/MC differences in Signal's CB shift and mean (gaussian constraint to the resutls obtained on the data fit performed in the γ bin)

Fit strategy in the very-low bin: Angular fits

- Get Angular acceptance from PhaseSpace MC
- Signal PDF is the PDF($F_L, A_T^{(2)}, A_T^{ImCP}, A_T^{ReCP}$) $\times$ Acceptance
- Fix Angular shapes from MC for
  - $B_s^0 \to \phi\gamma(\to e^+e^-)$:
    - $\cos(\theta_K)$: Signal Angular PDF integrated over $\cos(\theta_L)$ and ϕ with $F_L^\gamma = 0$ including the acceptance
    - $\cos(\theta_L)$: Symmetric Legendre Polynomials of order 4
    - $\tilde{\phi}$: $1 + c_{c2}\cos(2\phi) + c_{s2}\sin(2\phi)$
  - $B_s^0 \to \phi\eta(\to \gamma e^+e^-)$ and $B_s^0 \to \phi\pi^0(\to \gamma e^+e^-)$:
    - $\cos(\theta_K)$: Symmetric Chebychev Polynomial of order 4 with $c2 = 1 + c4$
    - $\cos(\theta_L)$: Symmetric Legendre Polynomials of order 4
    - $\tilde{\phi}$: $1 + c_{c2}\cos(2\phi) + c_{s2}\sin(2\phi)$
- Gaussian constrain the Combinatorial's angular shape with the values of $B_s \to \phi e\mu$ data:
  - $\cos(\theta_K)$ and $\cos(\theta_L)$: Symmetric Legendre Polynomial of order 2
  - $\tilde{\phi}$: $1 + c_{c2}\cos(2\phi) + c_{s2}\sin(2\phi)$

Expected Sensitivity

$F_L = XXX \pm 0.050 \pm 0.012$

$A_T^{(2)} = XXX \pm 0.240 \pm 0.009$

$A_T^{ImCP} = XXX \pm 0.240 \pm 0.007$

$A_T^{ReCP} = XXX \pm 0.160 \pm 0.012$

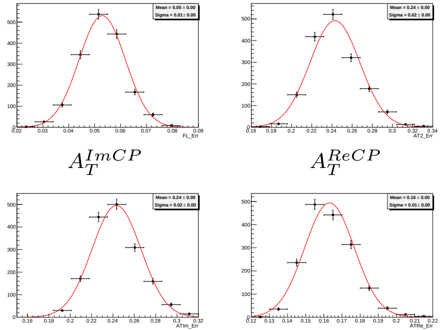
Systematics estimated based on $\underline{B \to K^* ee}$.

Not computed yet

Toys with nominal stat

F_L $A_T^{(2)}$

A_T^{ImCP} A_T^{ReCP}



	$A_T^{(2)}$	A_T^{ImCP}	A_T^{ReCP}	F_L
Acceptance function modeling	0.004	0.001	0.008	0.001
Comb/SL Modeling	0.007	0.007	0.007	0.003
η or π angular modeling	0.0004	0.0001	0.002	0.010
Corrections to simulations	0.003	0.001	0.003	0.007
Signal mass shape	0.002	0.002	0.004	0.001
Total systematic uncertainty	0.009	0.007	0.012	0.012