Angular Analysis of $B^0 \to K^{*0} e^+ e^-$ at low q^2 with the LHCb detector

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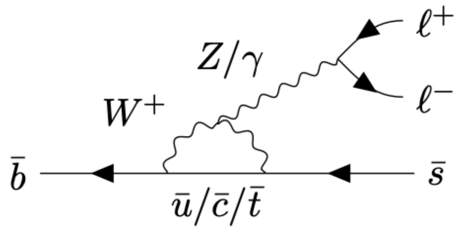
Marie Hartmann, Marie-Hélène Schune

Motivations

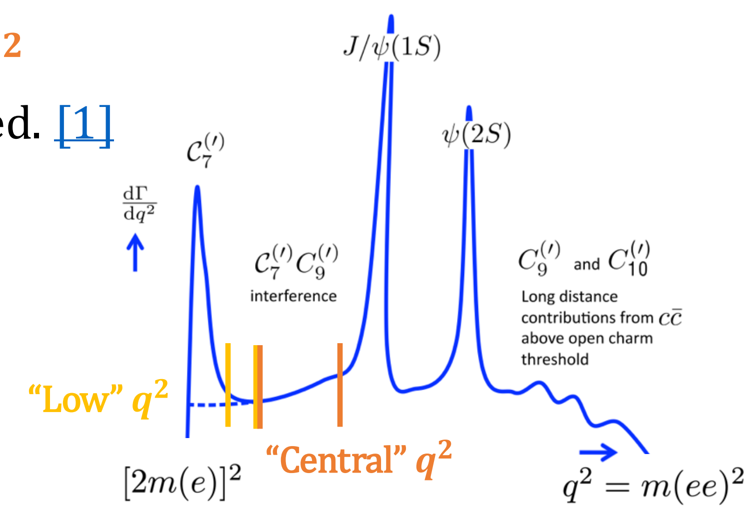
- $b \to s\ell^+\ell^-$ transitions:
  - Flavour Changing Neutral Current → only occur at loop level in the SM.
  - Sensitive to possible New Physics mediators.
  - Discrepancies have been observed.



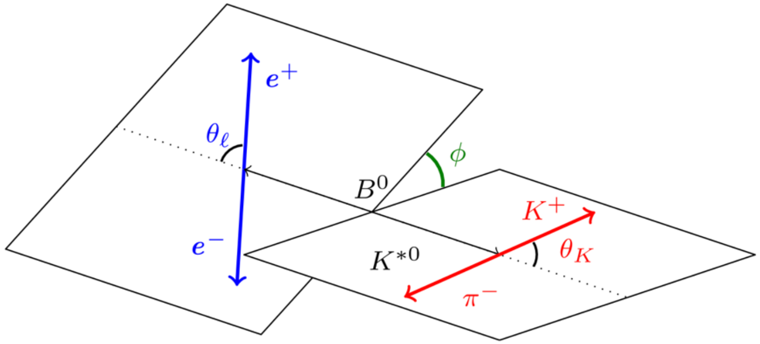
- $b \to se^+e^-$ transitions:
  - More experimentally challenging due to electrons.
  - But, provide complementary information → Test of Lepton Flavour Universality (LFU).

- Angular analysis of $B^0 \to K^{*0}e^+e^-$ at **central q^2**
  $q^2 \in [1.1, 6.0]$ GeV^2 at LHCb, soon to be published. [1]

- Angular analysis of $B^0 \to K^{*0}e^+e^-$ at **low q^2**:
  - $q^2 \in [0.1, 1.1]$ GeV^2.
  - First one at LHCb.
  - Test of LFU for the C_9 observable.



Objectives



- Decay fully described by the three angles:
  $\cos(\boldsymbol{\theta_l})$, $\cos(\boldsymbol{\theta_k})$, $\boldsymbol{\phi}$

- Differential signal decay-rate (S-wave neglected):

$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^4(\Gamma+\bar{\Gamma})}{\mathrm{d}q^2\mathrm{d}\Omega}\Big|_{\mathrm{P}} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K$$
$$+\frac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_\ell$$
$$-F_L\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi$$
$$+S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi + S_5\sin 2\theta_K\sin\theta_\ell\cos\phi$$
$$+\frac{4}{3}A_{\mathrm{FB}}\sin^2\theta_K\cos\theta_\ell + S_7\sin 2\theta_K\sin\theta_\ell\sin\phi$$
$$+S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big]$$

$$S_i = \frac{I_i+\bar{I}_i}{\mathrm{d}\Gamma/\mathrm{d}q^2},$$

$$F_L = S_1^c = -S_2^c,\quad 1-F_L = \frac{4}{3}S_1^s = 4S_2^s,$$

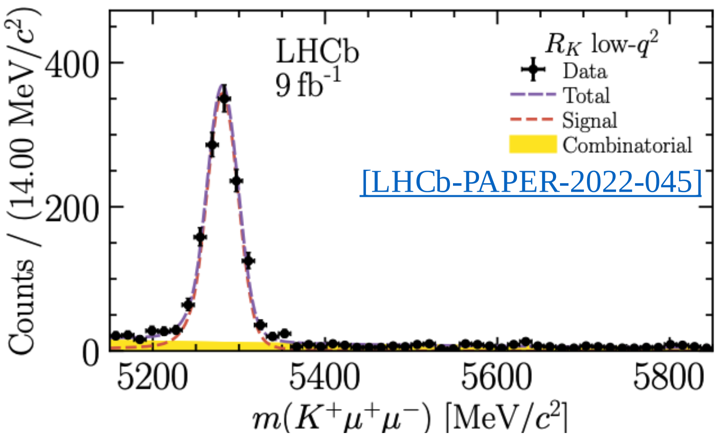
$$A_{FB} = \frac{3}{4}S_6$$

- Using Run1 (2011-2012) and Run2 (2015-2018) LHCb data:

Fit the $\cos(\boldsymbol{\theta_l})$, $\cos(\boldsymbol{\theta_k})$, $\boldsymbol{\phi}$ distributions to extract the angular observables F_L, S_3, S_4, S_5, A_{FB}, S_6, S_7, S_8, S_9.

Electrons at LHCb

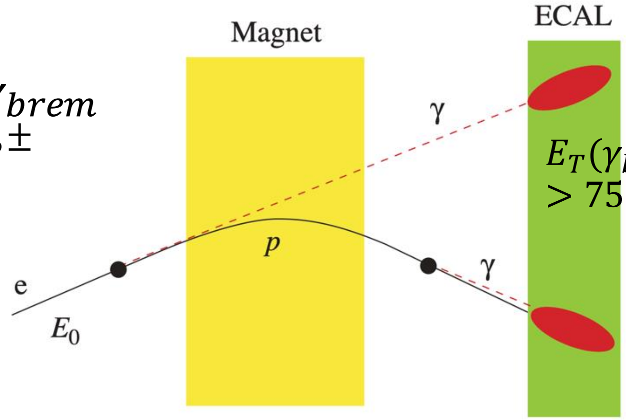
- Electrons are more experimentally challenging because of bremsstrahlung. Bremsstrahlung photons (γ_{brem}) can deteriorate the electron momentum measurement.



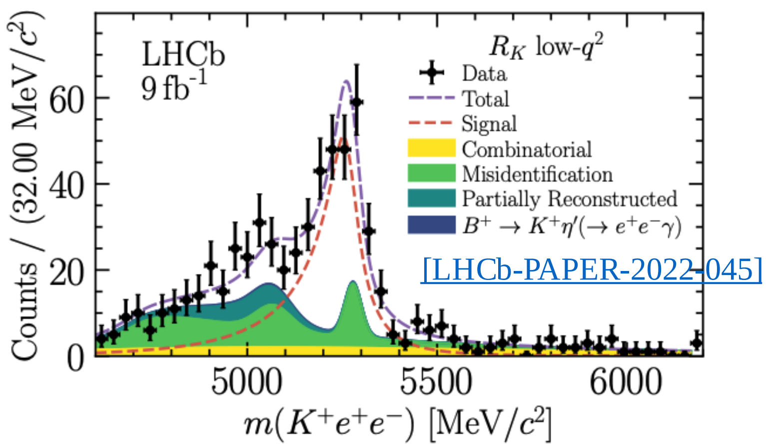
- A dedicated algorithm is used at LHCb to recover γ_{brem} energy deposits in the ECAL. Nevertheless, bremsstrahlung effects remain significant.

----- γ_{brem}

____ $e^{\pm}$

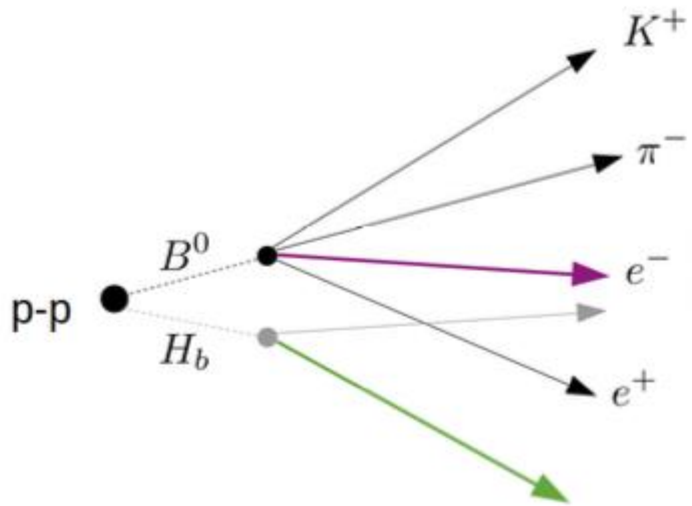


$E_T(\gamma_{brem}) > 75\ MeV$



Trigger categories

- $B^0 \to K^{*0}e^+e^-$ candidates are in the two following trigger categories:
  - **L0E**: At least one of the $e^\pm$ of the decay fired the electron trigger.
  - **L0I**: A particle which is not part of the $B^0 \to K^{*0}e^+e^-$ fired the trigger.



If an event is both L0I and L0E, it is put in the L0I trigger category.

Background contributions

- Combinatorial background:
  → Studied with $B^0 \to K^{*0} e^{\pm} e^{\pm}$ (SS) data

- Partially-reconstructed background:
  - $B^0 \to K^{**0}(\to K^+\pi^-\pi^0)e^+e^-$, $B^+ \to K^{**+}(\to K^+\pi^-\pi^+)e^+e^-$

  → Studied with MC

- Double semi-leptonic (DSL) background:
  - $B^0 \to D^-(\to K^{*0}(\to K^+\pi^-)\ e^-\ \overline{\nu_e})e^+\nu_e$

  → Studied with MC and $B^0 \to K^{*0} e^{\pm}\mu^{\mp}$ Data

- Mis-identified (MisID) background:
  - $K^{\pm} \leftrightarrow e^{\pm}$, $\pi^{\pm} \leftrightarrow e^{\pm}$

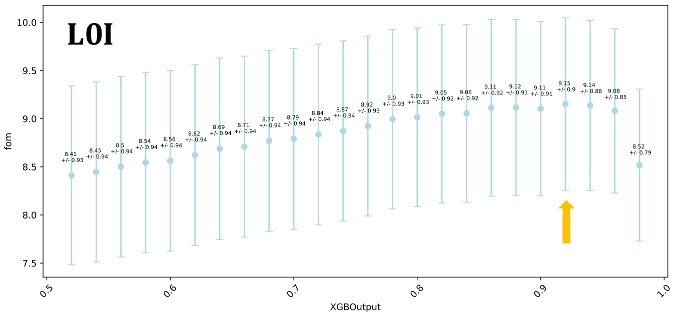
  → Studied with data computed with the Pass-and-Fail method.

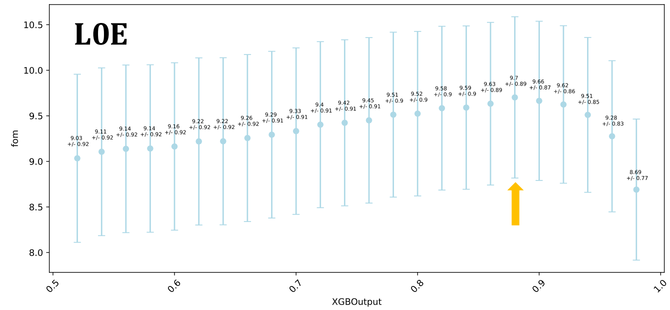
[LHCb-PAPER-2022-045]

Background contributions

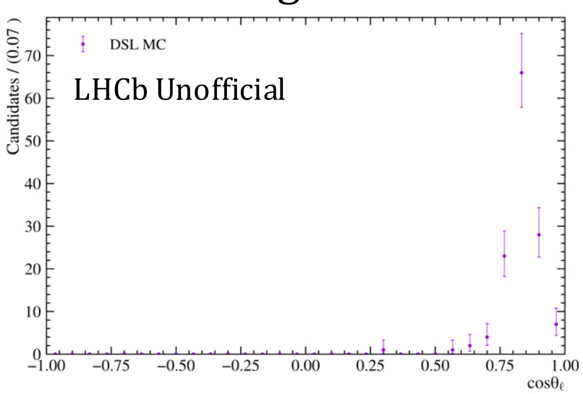
- Additional selection:
  - BDT was trained to remove both partially reconstructed and combinatorial backgrounds. Cut on the output was optimised with a figure of merit for both L0I/L0E.

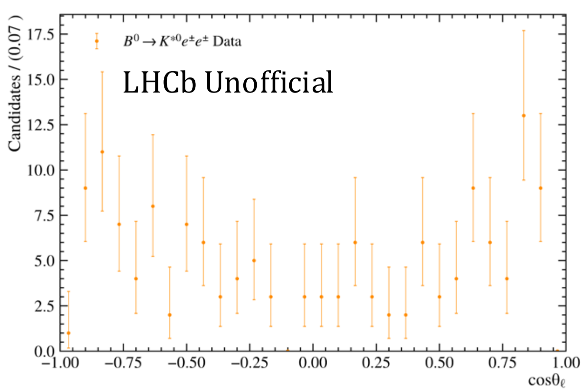
$$FOM = \frac{S}{\sqrt{S+B}}$$

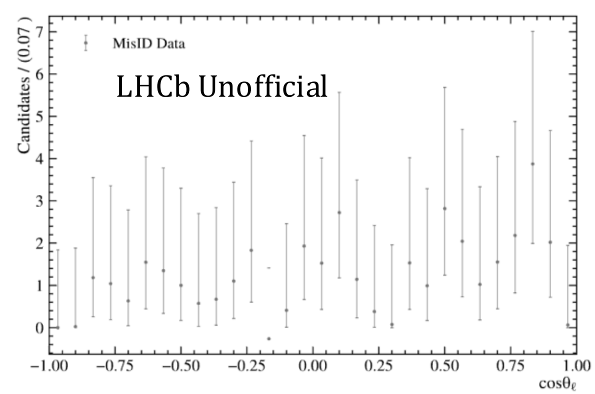




  - Cut on $|\cos(\theta_l)| < 0.8$ to remove DSL, combinatorial, and MisID background.

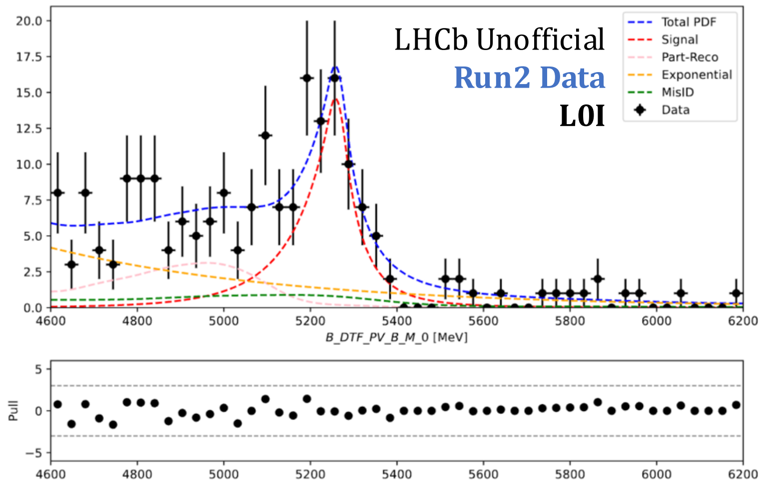






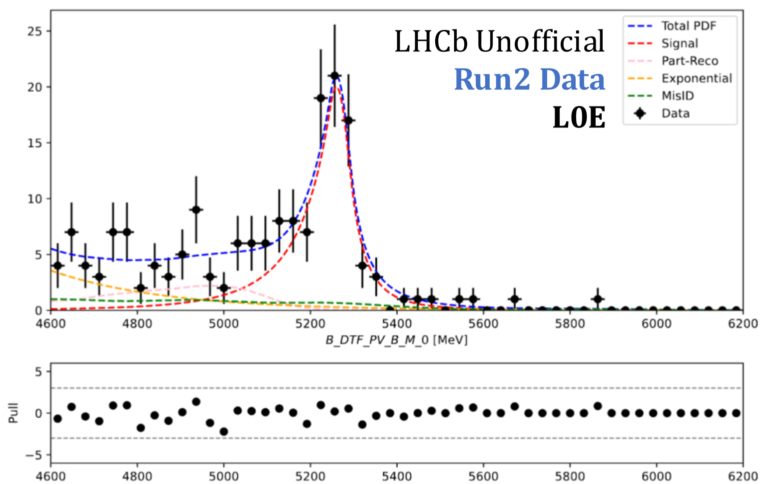
Mass fit

- Mass fit using Run2 data, in the L0I and L0E trigger categories:



L0I	
n_{sig}	76 ± 11
$n_{\text{part-reco}}$	40 ± 19
n_{comb}	66 ± 21
n_{dsl}	3 ± 1
n_{misid}	20 ± 3

DSL contribution is negligible.



L0E	
n_{sig}	94 ± 12
$n_{\text{part-reco}}$	28 ± 15
n_{comb}	26 ± 16
n_{dsl}	3 ± 1
n_{misid}	3 ± 1

sPlot technique [2]

- The mass fit is well controlled, but it is challenging to correctly model the angular distribution of the different backgrounds.

- Use the sPlot technique on the mass fit to extract the signal angular distribution.
  - sPlot works only if $m(K^+\pi^-e^+e^-)$ is uncorrelated with the three angles $\cos(\theta_l)$, $\cos(\theta_k)$, ϕ, for all the components of the mass fit. Because of bremsstrahlung, correlation could be expected between $m(K^+\pi^-e^+e^-)$ and $\cos(\theta_l)$.

  $\rightarrow$ After tests, $m(K^+\pi^-e^+e^-)$ and $\cos(\theta_l)$ are considered uncorrelated for all the components of the mass fit.

- The sWeights are computed separately for the L0I and L0E trigger categories.

Angular model

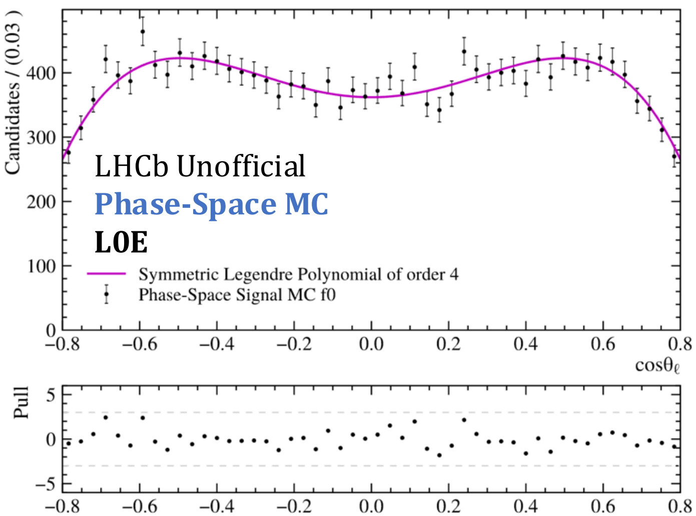
- Simultaneous L0I/L0E 3D-fit to the sWeighted distribution of $\Omega = (\cos(\theta_l), \cos(\theta_k), \phi)$:

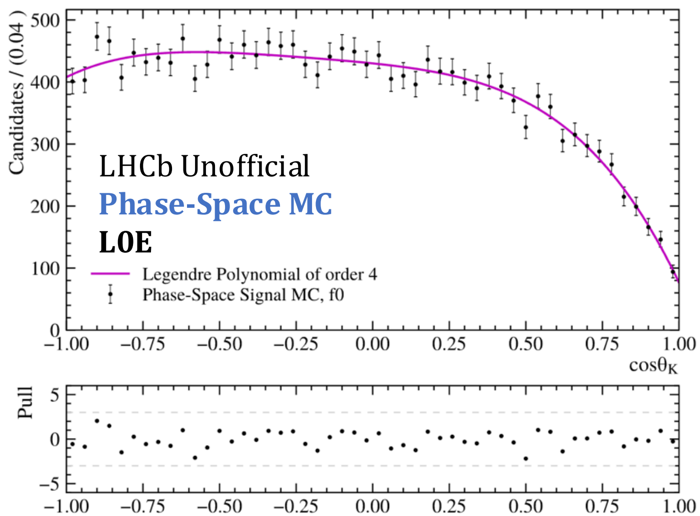
$$PDF_{L0X} = \frac{1}{d\,(\Gamma + \bar{\Gamma})/dq^2} \frac{d^4(\Gamma + \bar{\Gamma})}{dq^2 d\Omega} \times \epsilon_{L0X}(\Omega)$$

Differential decay rate with all parameters shared between L0I and L0E.

Acceptance computed for both L0I/L0E using phase-space MC:

$$\epsilon_{L0X}(\Omega) = \epsilon_{L0X}(\cos(\theta_l)) \times \epsilon_{L0X}(\cos(\theta_k)) \times \epsilon_{L0X}(\phi)$$





Tests with pseudo data-sets

- Pseudo data-sets:
  - Signal: generated with

$$\frac{1}{d\,(\Gamma+\overline{\Gamma})/dq^2}\frac{d^4(\Gamma+\overline{\Gamma})}{dq^2 d\Omega} \times \epsilon_{L0X}(\Omega)$$

  - Combinatorial: generated with

$$\mathrm{pdf}_{m(K^+\pi^-e^+e^-)} \times \mathrm{pdf}_{\cos(\theta_l)} \times \mathrm{pdf}_{\cos(\theta_k)} \times \mathrm{pdf}_{\phi},$$

  where the 1D pdfs are extracted from fits to $B^0 \to K^{*0}e^{\pm}e^{\pm}$ data

  - Partially-reconstructed: bootstraped from MC

- sPlot and angular fit tested on pseudo-data sets with expected yields:
  - $\sim$ 50% convergence rate

  $\rightarrow$ Not enough statistics to fit all 8 angular observables at the same time.

Tests with pseudo data-sets

- Instead, extract all the angular observables from 5 different angular fits with 5 different angular folding [LHCb-PAPER-2020-041]:
  - From 8 to 3/4 angular observable per fit
  - No loss in sensitivity

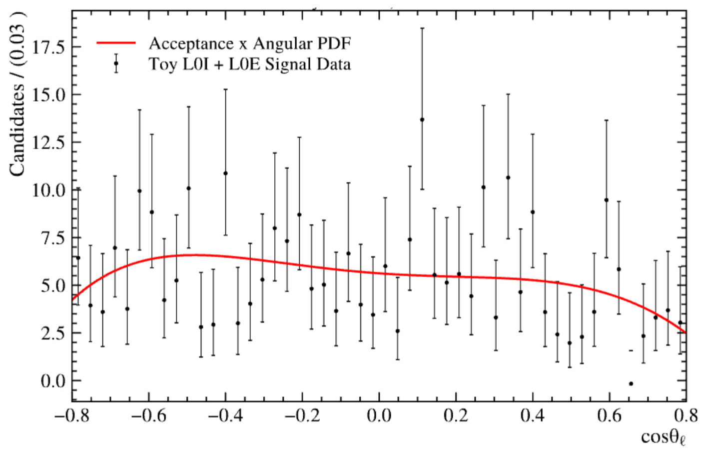
Fold Number	Angular Fold	Angular Observable
0	$\begin{cases} \phi + \pi & \text{for } \phi < 0 \end{cases}$	F_L, S_3, A_{FB}, and S_9
1	$\begin{cases} \phi \to -\phi & \text{for } \phi < 0 \\ \phi \to \pi - \phi & \text{for } \theta_\ell > \pi/2 \\ \theta_\ell \to \pi - \theta_\ell & \text{for } \theta_\ell > \pi/2 \end{cases}$	F_L, S_3, and S_4
2	$\begin{cases} \phi \to -\phi & \text{for } \phi < 0 \\ \theta_\ell \to \pi - \theta_\ell & \text{for } \theta_\ell > \pi/2, \end{cases}$	F_L, S_3, and S_5

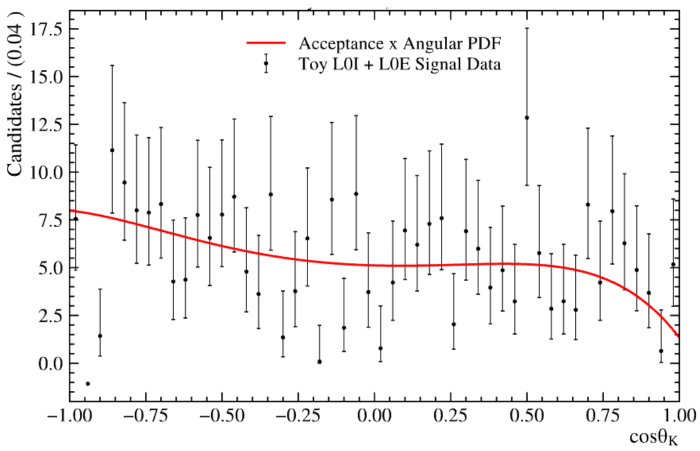
Fold Number	Angular Fold	Angular Observable
3	$\begin{cases} \phi \to \pi - \phi & \text{for } \phi > \pi/2 \\ \phi \to -\pi - \phi & \text{for } \phi < -\pi/2 \\ \theta_\ell \to \pi - \theta_\ell & \text{for } \theta_\ell > \pi/2, \end{cases}$	F_L, S_3, and S_7
4	$\begin{cases} \phi \to \pi - \phi & \text{for } \phi > \pi/2 \\ \phi \to -\pi - \phi & \text{for } \phi < -\pi/2 \\ \theta_K \to \pi - \theta_K & \text{for } \theta_\ell > \pi/2 \\ \theta_\ell \to \pi - \theta_\ell & \text{for } \theta_\ell > \pi/2. \end{cases}$	F_L, S_3, and S_8

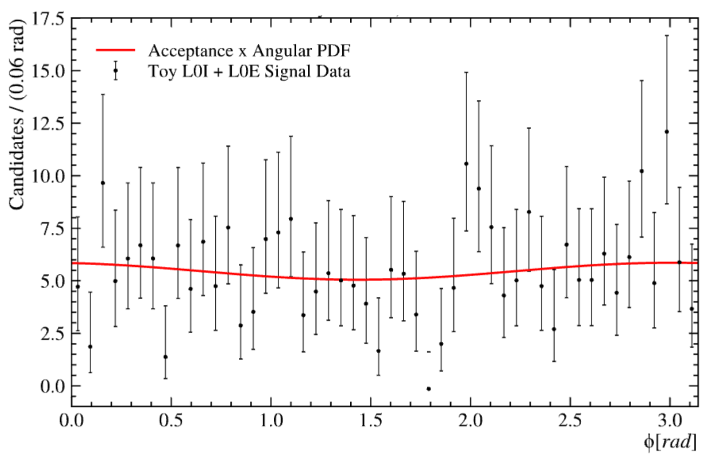
- The sPlot and angular fits are tested on pseudo-data with expected yields:
  - Average convergence rate for each fold $\sim$ 99%.
  - Pulls are well-centred at 0 and width compatible with 1.

Tests with pseudo data-sets

- Angular fit with folding n°0 on a pseudo-data experiment :







Tests with pseudo data-sets

- First estimation of the sensitivity:

Low q^2		
Angular observable	**SM value**	**Sensitivity**
F_L	0.351	0.053
S_3	0.014	0.068
S_4	0.116	0.091
S_5	0.291	0.068
A_{FB}	-0.109	0.070
S_7	-0.024	0.071
S_8	-0.003	0.091
S_9	-0.001	0.066

Central q^2 (from LHCb $B^0 \to K^{*0}e^+e^-$ Angular Analysis at Central q^2) [1]		
Angular observable	**SM value**	**Sensitivity**
F_L	0.771	0.045
S_3	-0.015	0.043
S_4	-0.157	0.067
S_5	-0.215	0.059
A_{FB}	0.028	0.047
S_7	0.0	0.058
S_8	0.0	0.070
S_9	0.0	0.044

- Correlation matrix will be computed using a bootstrapping technique. [LHCb-PAPER-2020-041]

Conclusion

- Angular analysis of $B^0 \to K^{*0}e^+e^-$ at low $q^2 \in [0.1, 1.1]$ GeV^2 with full Run1 and Run2 LHCb data with ~ 275 signal events.
- Will provide complementary information to the $b \to s\mu\mu$ angular analyses on the C_9 observable.
- Fit strategy in place and validated by pseudo data sets.

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- Correlation matrix computation and MisID implementation on-going.
- Soon to start with the systematic studies.

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Thank you for your attention!

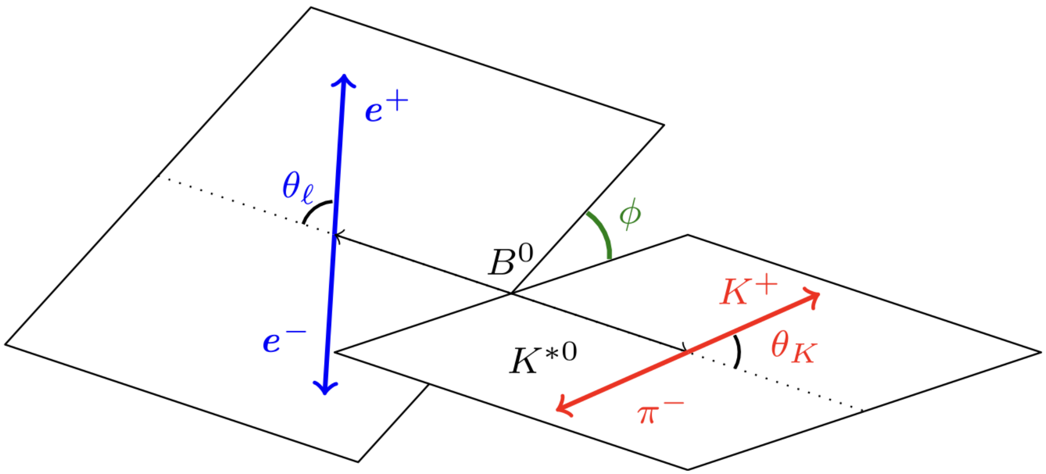
Bibliography

- [1] First angular analysis of $B^0 \to K^{*0}e^+e^-$ decay at the central q^2, ICHEP 2024, Rafael Silva Coutinho.
- [LHCb-PAPER-2022-045]: Measurement of lepton universality parameters in $B^+ \to K^+\ell^+\ell^-$ and $B^0 \to K^{*0}\ell^+\ell^-$ decays, LHCb Collaboration.
- [2] sPlot: a statistical tool to unfold data distributions, M. Pivk, and F.R. Le Diberder.
- [LHCb-PAPER-2020-041]: Angular Analysis of the $B^+ \to K^{*+}\mu^+\mu^-$, LHCb Collaboration.

Back-up slides

Angular Distribution

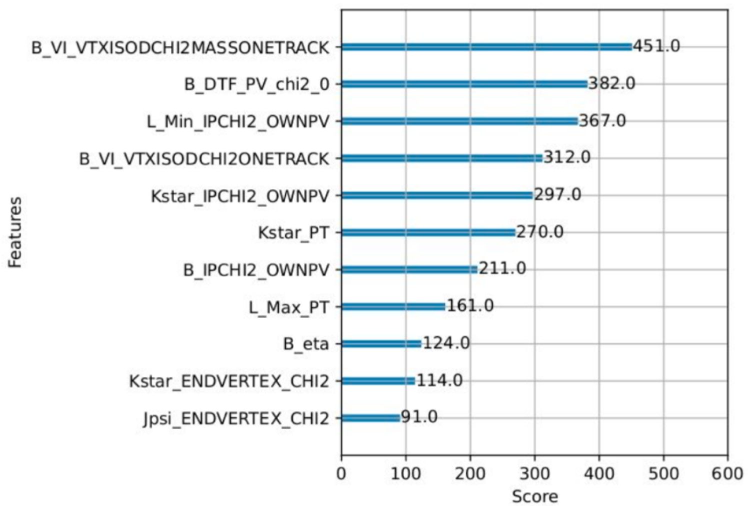
- Angle definition
  - θ_l: angle between the direction of the e^+ in the dielectron rest frame and the direction of the dielectron of the B^0 rest frame.
  - θ_k: angle between the direction of K^+ in the K^{*0} rest frame and the direction of the K^{*0} in the B^0 rest frame.
  - ϕ: angle between the planes containing $e^+ e^-$ and the plane containing $K^+ \pi^-$

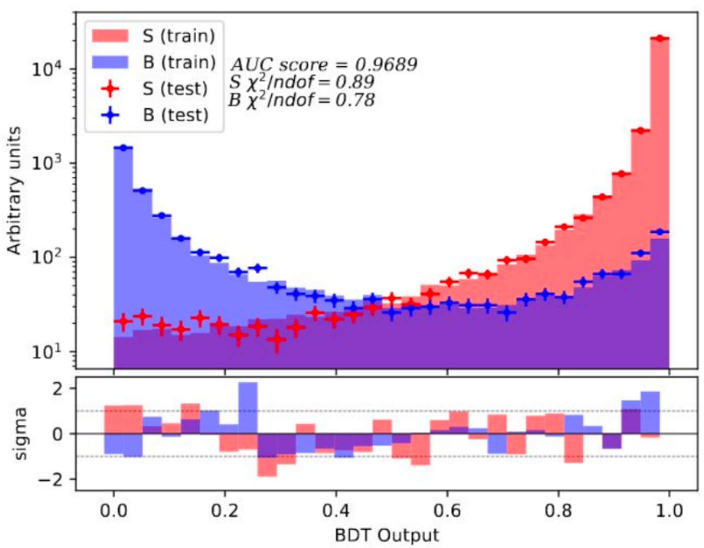


BDT

- Variables to train the BDT:
  - Standard kinematic variables, topology variables, and isolation variables

11 Features, AUC = 0.97





FOM details

- FOM computed in a tight mass window (5000-5400 MeV):

$$FOM^i = \frac{S^i}{\sqrt{S^i + B^i}}$$

- Signal yield:

$$S^i = N^i_{data\ J/\psi} \times \frac{BF(B^0 \to K^{*0}e^+e^-)_{low/central} \times \epsilon^i_{MC\ low/central\ q2}}{BF(B^0 \to K^{*0}J/\psi(\to e^+e^-)) \times \epsilon^i_{MC\ J/\psi}}$$

$N^i_{data\ J/\psi}$ = number of events in data with B_DTF_PVandJpsi_B_M_0 $\in$ [5200; 5360] MeV (tight window)

- Background yield: Extracted from low/central mass fit. Mass fit includes one Comb+DSL component (exponential), and a part-reco component (RooKeysPdf).

DSL Yield

- $C_{dsl} = \frac{B\left(B^0 \to D^-\left(\to K^{*0} e^- \nu_e\right) e^+ \nu_e\right) \times \epsilon\left(B^0 \to D^-\left(\to K^{*0} e^- \nu_e\right) e^+ \nu_e\right)}{\int_{q^2_{true\ min}}^{q^2_{true\ max}} \frac{dB(B^0 \to K^{*0} e^+ e^-)}{dq^2} dq^2 \times \epsilon(B^0 \to K^{*0} e^+ e^-)(q^2_{true\ min}, q^2_{true\ max})}$

- $n_{dsl} = n_{sig}^{fit} \times C_{dsl}$, $n_{comb} = n_{comb+dsl}^{fit} - n_{dsl}$

Angular folds and pdfs

Folding 0: The following angular fold is performed to be sensitive to the observables F_L, S_3, A_{FB}, and S_9:

$$F_0 : \begin{cases} \phi + \pi & \text{for } \phi < 0 \end{cases} \tag{1}$$

This leads to the following differential decay rate:

$$\begin{aligned} \frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2} \frac{\mathrm{d}^4(\Gamma+\bar{\Gamma})}{\mathrm{d}q^2\mathrm{d}\Omega}\Big|_{F_0} = \frac{9}{16\pi}\Big[&\frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K \\ &+\frac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_\ell \\ &-F_L\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi \\ &+\frac{4}{3}A_{\mathrm{FB}}\sin^2\theta_K\cos\theta_\ell + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big] \end{aligned} \tag{2}$$

Folding 1: The following angular fold is performed to be sensitive to the observables F_L, S_3, and S_4:

$$F_1 : \begin{cases} \phi \to -\phi & \text{for } \phi < 0 \\ \phi \to \pi - \phi & \text{for } \theta_\ell > \pi/2 \\ \theta_\ell \to \pi - \theta_\ell & \text{for } \theta_\ell > \pi/2 \end{cases} \tag{3}$$

This leads to the following differential decay rate:

$$\begin{aligned} \frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2} \frac{\mathrm{d}^4(\Gamma+\bar{\Gamma})}{\mathrm{d}q^2\mathrm{d}\Omega}\Big|_{F_1} = \frac{9}{8\pi}\Big[&\frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K \\ &+\frac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_\ell \\ &-F_L\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi \\ &+S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi\Big] \end{aligned} \tag{4}$$

Angular folds and pdfs

Folding 2: The following angular fold is performed to be sensitive to the observables F_L, S_3, and S_5:

$$F_2 : \begin{cases} \phi \to -\phi & \text{for } \phi < 0 \\ \theta_\ell \to \pi - \theta_\ell & \text{for } \theta_\ell > \pi/2, \end{cases} \tag{5}$$

This leads to the following differential decay rate:

$$\begin{aligned} \frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2} \frac{\mathrm{d}^4(\Gamma+\bar{\Gamma})}{\mathrm{d}q^2\mathrm{d}\Omega}\Big|_{F_2} = \frac{9}{8\pi}\Big[& \frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K \\ & + \frac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_\ell \\ & - F_L\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi \\ & + S_5\sin 2\theta_K\sin\theta_\ell\cos\phi\Big] \end{aligned} \tag{6}$$

Folding 3: The following angular fold is performed to be sensitive to the observables F_L, S_3, and S_7:

$$F_3 : \begin{cases} \phi \to \pi - \phi & \text{for } \phi > \pi/2 \\ \phi \to -\pi - \phi & \text{for } \phi < -\pi/2 \\ \theta_\ell \to \pi - \theta_\ell & \text{for } \theta_\ell > \pi/2, \end{cases} \tag{7}$$

This leads to the following differential decay rate:

$$\begin{aligned} \frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2} \frac{\mathrm{d}^4(\Gamma+\bar{\Gamma})}{\mathrm{d}q^2\mathrm{d}\Omega}\Big|_{F_3} = \frac{9}{8\pi}\Big[& \frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K \\ & + \frac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_\ell \\ & - F_L\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi \\ & + S_7\sin 2\theta_K\sin\theta_\ell\sin\phi\Big] \end{aligned} \tag{8}$$

Angular folds and pdfs

Folding 4: The following angular fold is performed to be sensitive to the observables F_L, S_3, and S_8:

$$F_4 : \begin{cases} \phi \to \pi - \phi & \text{for } \phi > \pi/2 \\ \phi \to -\pi - \phi & \text{for } \phi < -\pi/2 \\ \theta_K \to \pi - \theta_K & \text{for } \theta_\ell > \pi/2 \\ \theta_\ell \to \pi - \theta_\ell & \text{for } \theta_\ell > \pi/2. \end{cases} \tag{9}$$

This leads to the following differential decay rate:

$$\begin{aligned} \frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2} \frac{\mathrm{d}^4(\Gamma+\bar{\Gamma})}{\mathrm{d}q^2\mathrm{d}\Omega}\bigg|_{F_4} = \frac{9}{8\pi}\bigg[& \frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K \\ & + \frac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_\ell \\ & - F_L\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi \\ & + S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi\bigg] \end{aligned} \tag{10}$$