Angular analysis of $B^0 \to K^+\pi^-\mu^+\mu^-$ decay using method of moments

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Doctoral seminar

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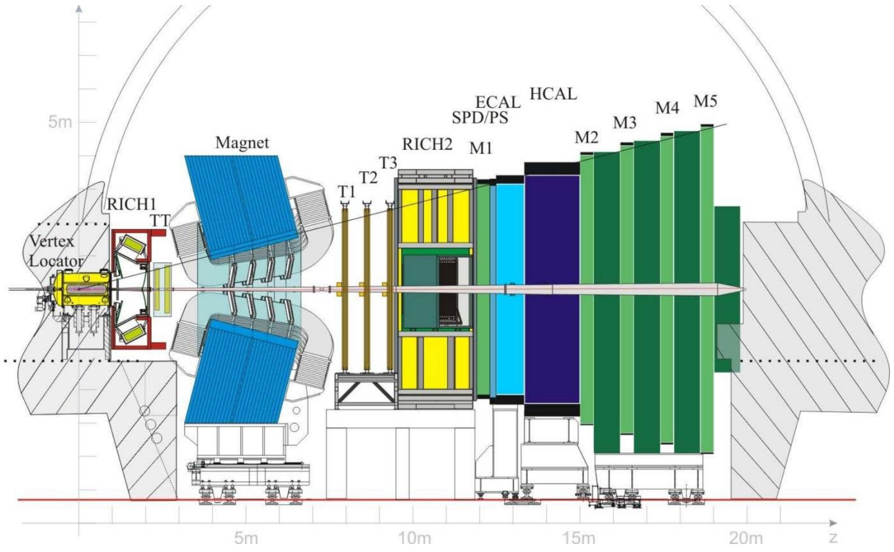
LHCb detector

[JINST 3 (2008) S08005]

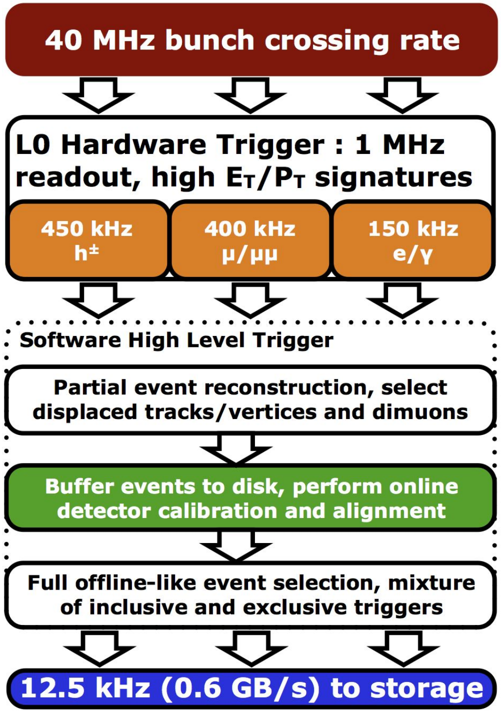


- Single-arm forward spectrometer
- Exploit large b-hadron cross-section in forward region
- Excellent tracking, vertexing and particle identification
- Momentum resolution ≅ 0.5%
- RICH detectors for π/K/p
- Very flexible trigger

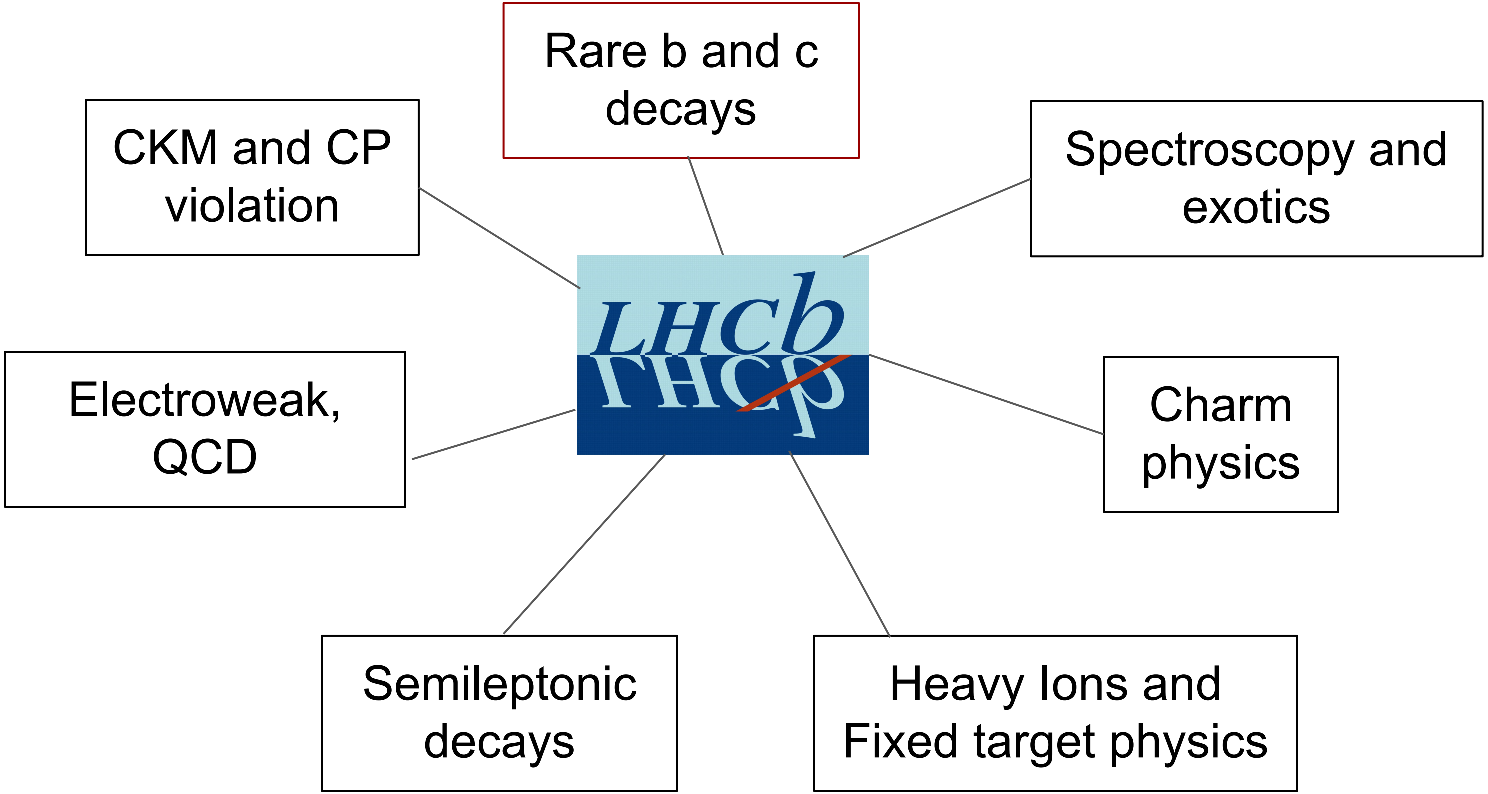
LHCb data and trigger

- Two stage trigger, which is efficient for hadrons and muons
- Detector calibration/alignment before running HTL2
- Offline quality reconstruction in HLT2
- No hardware trigger in Run 3
- Integrated luminosity about 9 fb^{-1} during Run 1 and Run 2
- In Runs 3–4 aim at 50 fb^{-1}

Run 2 trigger



LHCb physics program



FCNC decays

- Flavour Changing Neutral Currents (FCNCs) ($b \to sll$) are good candidates to probe new physics (NP)
- FCNC is suppressed in Standard Model (SM) (cannot happen at tree level, loop level - Glashow-Iliopoulos-Maiani (GIM) mechanism)
- NP processes compete with SM in tree level and can modify the effective couplings
- Typically such decays have complex angular structure offering variety of observables
- Past measurements show some discrepancies, but there is long-standing debate what they exactly mean
- Decays described by effective hamiltonian, Wilson coefficients C_i encode the short-distance physics:

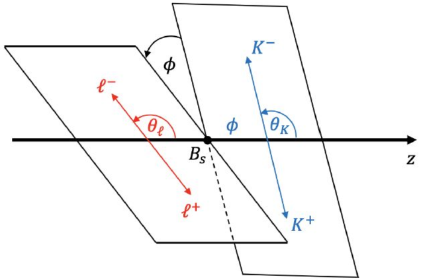
$$H_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{ts}^* V_{tb} \sum_{i=1}^{10} C_i(\mu) \mathcal{O}_i(\mu)$$

Angular formalism

Differential decay rate can be expanded in an orthonormal basis of angular functions:

$$\frac{d\Gamma}{dq^2 d\Omega} = \mathcal{C} \times \left\{ \sum_{i=1}^{41} f_i(\Omega)\Gamma_i(q^2) \right\}$$

$$d\Omega = d\cos\theta_\ell d\cos\theta_K d\phi$$



Ortonormality implies: $\int f_i(\Omega) f_j(\Omega) d\Omega = \delta_{ij}$

For a generic rate function constructed out of a set orthonormal basis functions $\frac{dN}{d\Omega} = \sum_i b_i f_i(\Omega)$

the moments b_i can be measured from data as $b_i = \tilde{f}_i = \sum_{k=1}^{N_\mathrm{data}} f_i(\Omega_k)$

Analysis strategy

- Goal: perform a differential branching fraction measurement and an angular analysis of $B^0 \to K^+ \pi^- \mu^+ \mu^-$ candidates in the $1330 < m_{K\pi} < 1530$ MeV/c^2 region,
- The differential branching fraction measurement, is performed as a function of q^2 in the 5 q^2 bins,
- Angular analysis is performed in a single q^2 bin, [1.1, 6.0] GeV^2/c^4

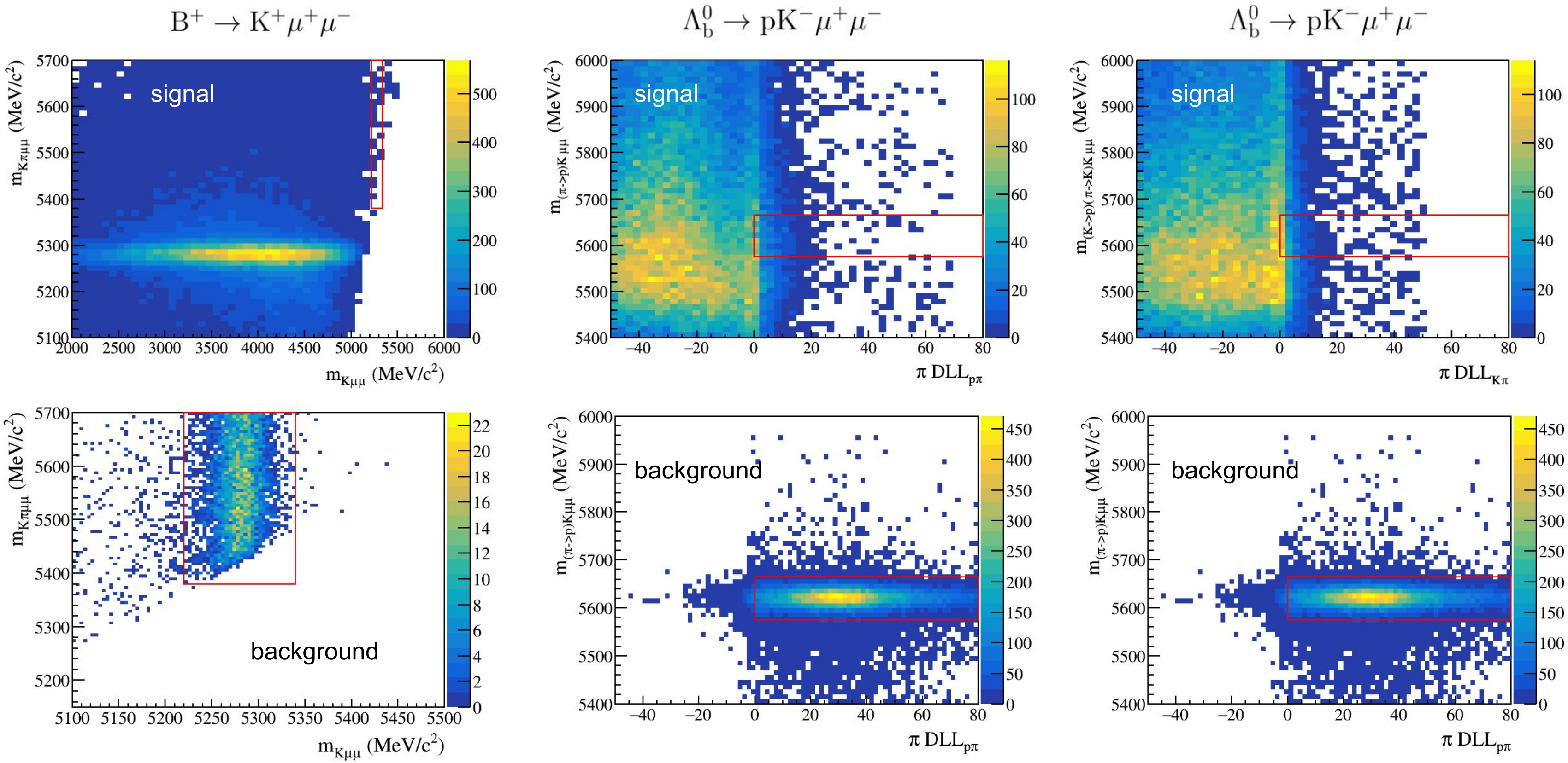
The q^2 binning scheme for the differential branching fraction measurement.

Bin	q^2 [GeV^2/c^4]
1	[0.10, 0.98]
2	[1.10, 2.50]
3	[2.50, 4.00]
4	[4.00, 6.00]
5	[6.00, 8.00]

Analysis pipeline

- Preselection cuts
- Vetoing peaking backgrounds
- Multivariate classifier
- Data - simulation agreement reweighting
- Acceptance correction
- Diferential branching fraction measurement
- Angular observables measurement

Peaking background vetoes - cuts



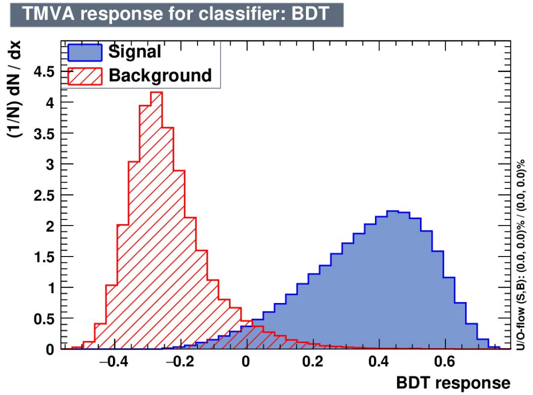
BDT classifier

$B^0 \to K^{*0} J/\psi$ data candidates - **signal**

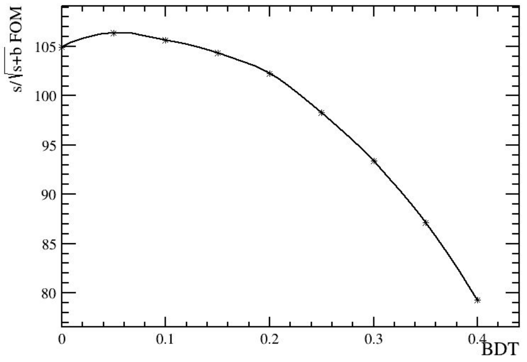
Upper mass sideband ([5350, 7000] MeV/c^2) of the $B^0 \to K^{*0}\mu^+\mu^-$ candidates - **background**

Variables used in training:

- the B^0 candidate lifetime, momentum and transverse momentum,
- cosine of the angle between the direction of B^0 meson flight and the vector between the primary vertex and the B^0 decay vertex, □
- the $K^+\pi^-\mu^+\mu^-$ vertex χ^2, which represents the quality of the fit of the hypothesis that the final state particles originated from a common vertex,
- particle identification variables of kaon, pion and muons □
- the isolation variables, describing the separation of the signal tracks from tracks originating from other sources.



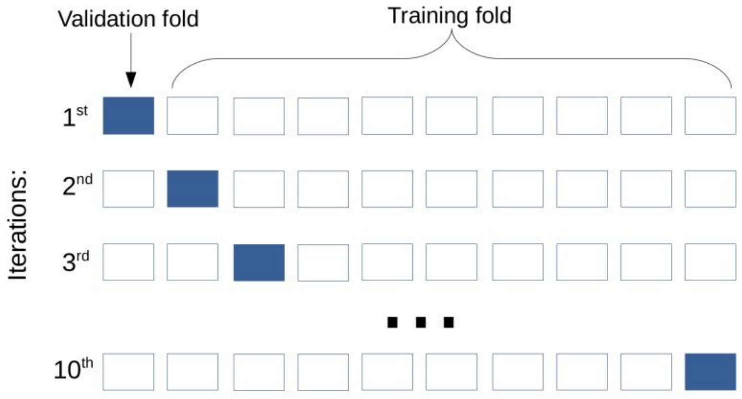
BDT response for one fold of the test set.



BDT optimization

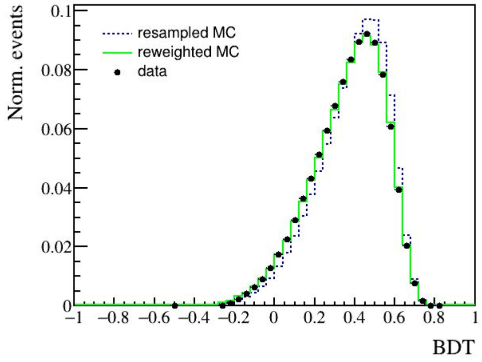
K-folding technique

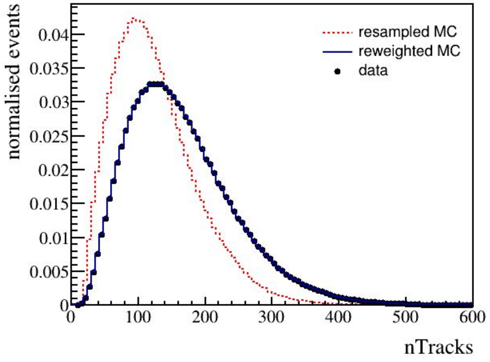
The whole data sample is split randomly into 10 subsets. The MVA for the first sample (blue) is trained and tested on rest of the samples (white), then this response is evaluated on this one sample. This method allows 90% of the dataset for every BDT training to be used in an unbiased way.

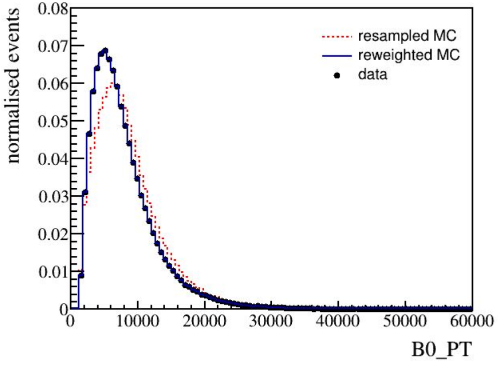


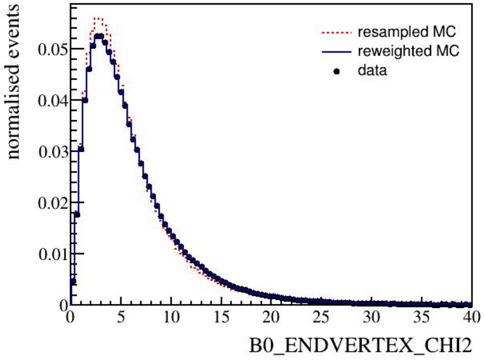
Data - simulation agreement

Reweighting candidates to account for residual differences (weights derived by comparing sWeighted $B^0 \to K^{*0} J/\psi$ data and $B^0 \to K^{*0} J/\psi$ MC)

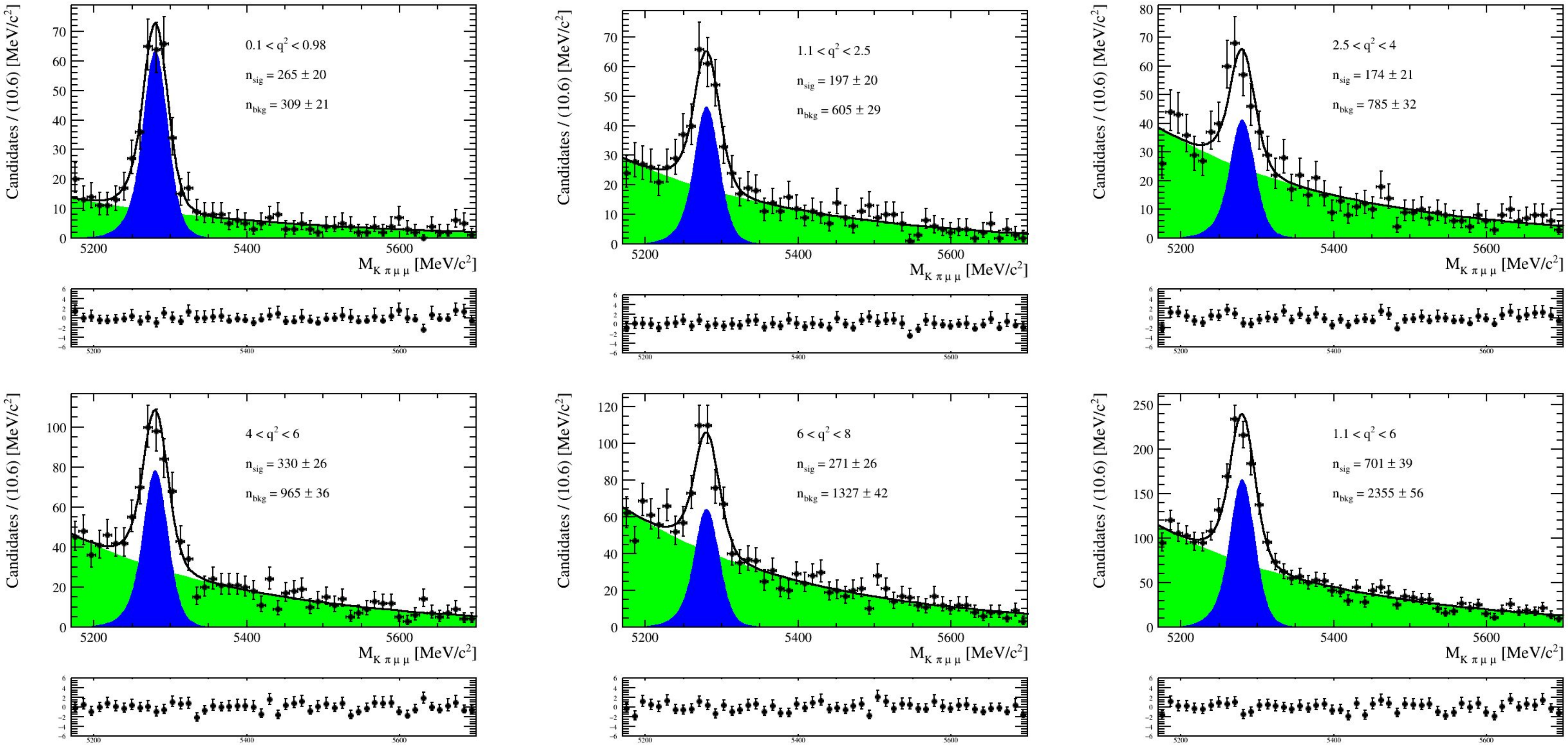








Mass fits



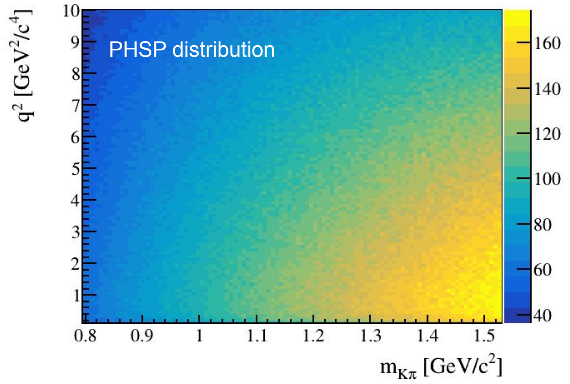
Candidates / (10.6) [MeV/c²]
M_{K π μ μ} [MeV/c²]
0.1 < q² < 0.98
n_sig = 265 ± 20
n_bkg = 309 ± 21
1.1 < q² < 2.5
n_sig = 197 ± 20
n_bkg = 605 ± 29
2.5 < q² < 4
n_sig = 174 ± 21
n_bkg = 785 ± 32
4 < q² < 6
n_sig = 330 ± 26
n_bkg = 965 ± 36
6 < q² < 8
n_sig = 271 ± 26
n_bkg = 1327 ± 42
1.1 < q² < 6
n_sig = 701 ± 39
n_bkg = 2355 ± 56

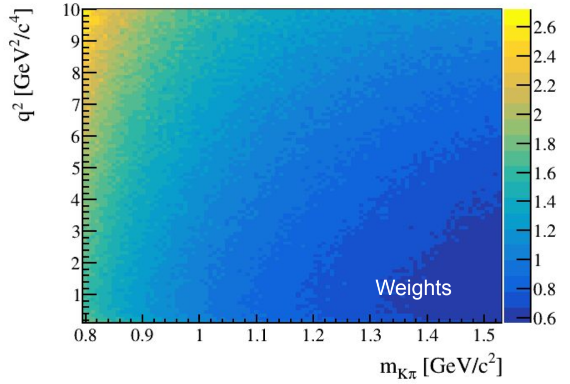
Acceptance correction

The triggering, reconstruction and selection of signal candidates cause distortions to the distributions of q^2, $\cos\theta_l$, $\cos\theta_K$, φ and $m_{K\pi}$ which need to be corrected for. This can be done with weights:

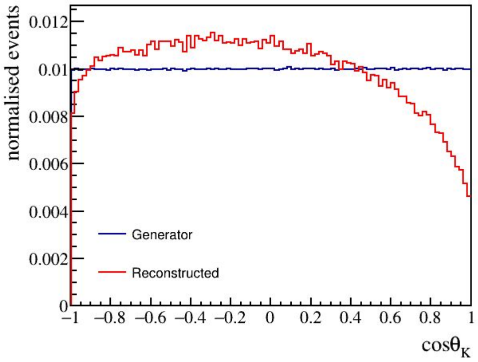
$$\omega = \frac{1}{\epsilon(q^2, cos\theta_K, cos\theta_\ell, \phi, m_{K\pi})}$$

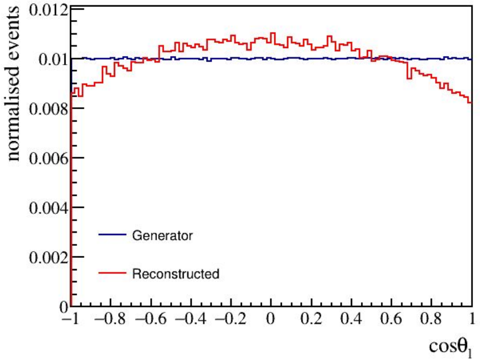
where $\varepsilon(q^2, \cos\theta_l, \cos\theta_K, \varphi, m_{K\pi})$ is a five dimensional efficiency parameterisation determined from simulated events, parametrized by Legendre polynomials.

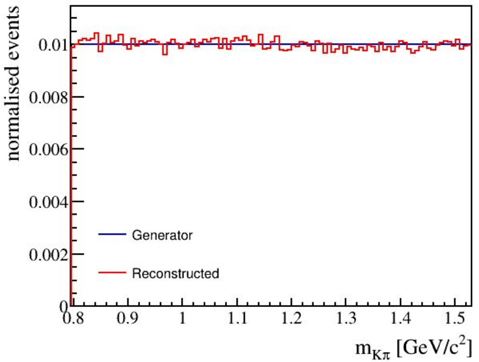


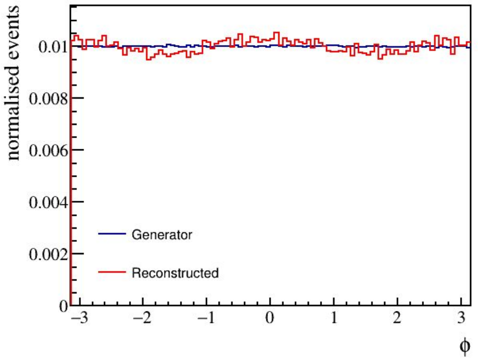


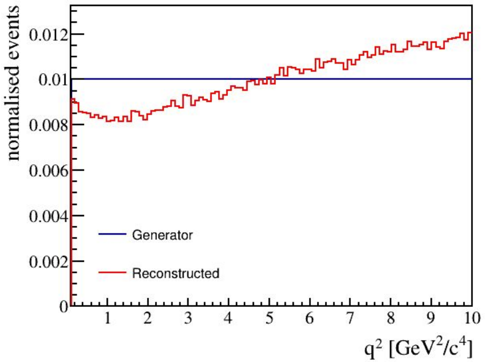
Acceptance correction - reweighted distributions



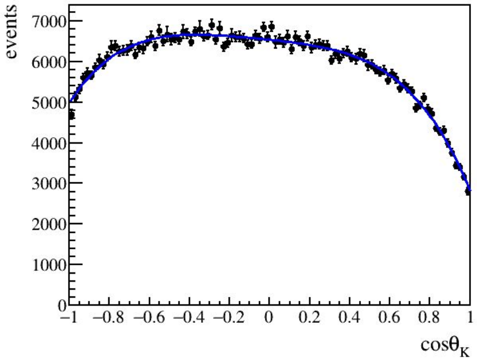


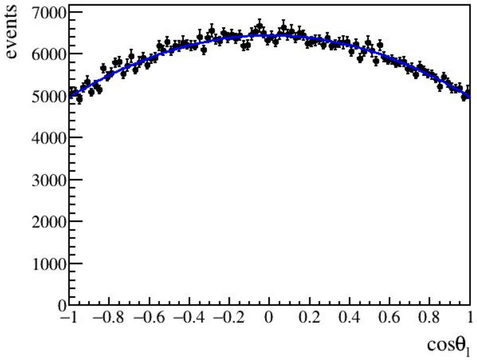


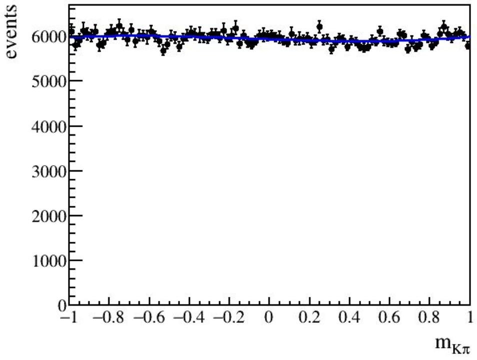


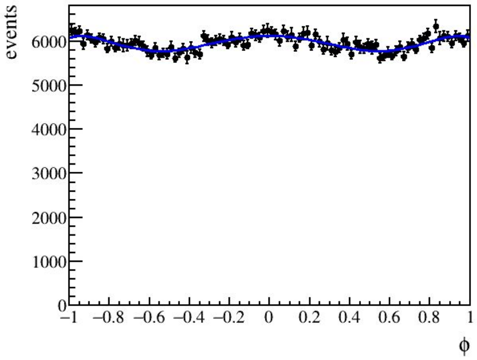


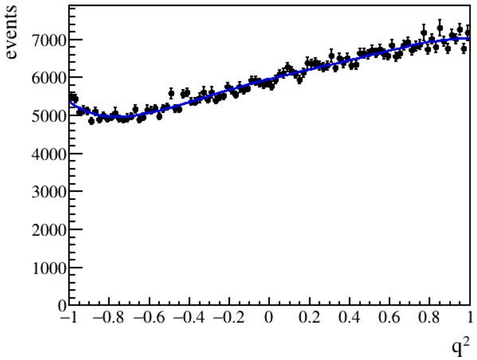
Acceptance correction - Legendre polynomials parametrization



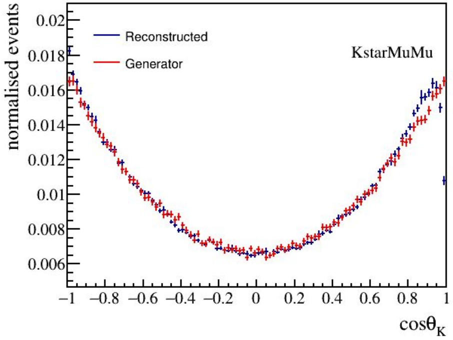


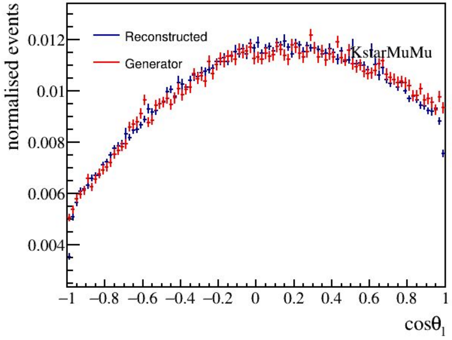


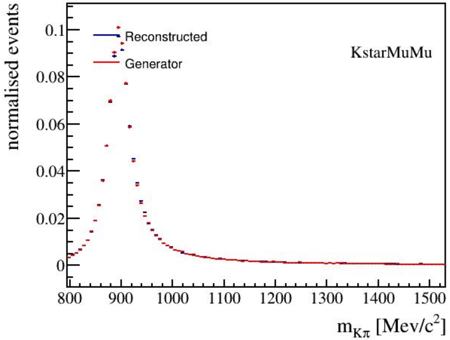


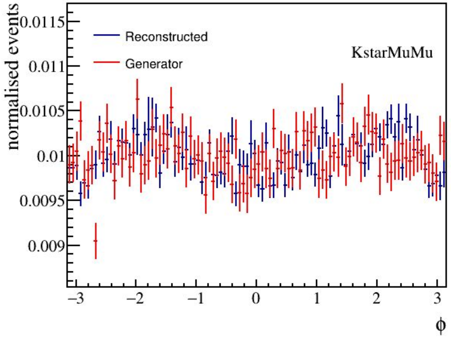


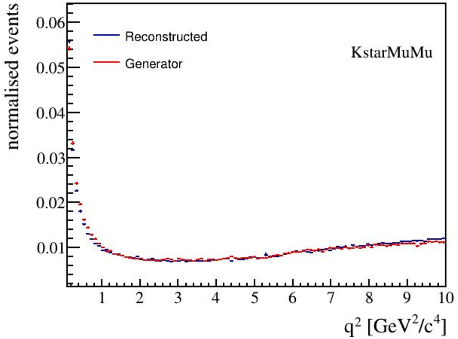
Acceptance correction - crosscheck with $B^0 \to K^{*0}\mu^+\mu^-$ events











Backup

Data and MC samples

- Analysis is performed with data collected at centre-of-mass energy of 13 TeV in 2016-2018:

year	Integrated luminosity	Reconstruction	Stripping
2016	1.67/fb	reco16	Stripping28r1
2017	1.71/fb	reco17	Stripping29
2018	2.19/fb	reco18	Stripping34

- All simulated samples were produced with SimType Sim09:

No.	Decay	Event type	Model	Number of candidates
1	$B^0 \to K^+\pi^-\mu^+\mu^-$	TGenPhaseSpace	PHSP	100 M
2	$B^0 \to K^+\pi^-\mu^+\mu^-$	11114000	PHSP	11.4 M
3	$\mathrm{B}^0 \to \mathrm{K}^{*0}\mathrm{J}/\psi$	11144001	Phys	4.0 M
4	$\mathrm{B}^0 \to \mathrm{K}^{*0}\mu^+\mu^-$	11114002	Phys	9.2 M
5	$\mathrm{B}^0 \to \mathrm{J}/\psi\mathrm{K}\pi$	11144050	PHSP	9.8 M
6	$\mathrm{B}^0 \to \psi(2\mathrm{S})\mathrm{K}\pi$	11144051	PHSP	5.2 M
7	$B^+ \to K^+\mu^+\mu^-$	12113002	Phys	0.6 M
8	$\Lambda_b \to pK\mu^+\mu^-$	15114011	PHSP	1.9 M
9	$B_s^0 \to \phi\mu^+\mu^-$	13114002	Phys	3.1 M

Stage	Trigger lines
L0	L0Muon
HLT1	Hlt1TrackAllL0 or Hlt1TrackMuon
HLT2	Hlt2Topo[2,3,4]BodyBBDT, Hlt2TopoMu[2,3,4]BodyBBDT, Hlt2SingleMuon or Hlt2DiMuonDetached

Stripping and preselection

- All $B^0 \to K^+\pi^-\mu^+\mu^-$ candidates are required to pass the stripping requirements contained in StrippingB2XMuMu stripping line. Each data sample from 2016, 2017 and 2018 corresponds to different stripping and reconstruction versions

Selection criteria in StrippingB2XMuMu for stripping 28r1, 29 and 34.

Candidate	Stripping 28r1, 29 and 34
B^0	IP $\chi^2 < 16$ (best PV) flight distance $\chi^2 > 121$ vertex $\chi^2/\text{ndf} < 8$ DIRA angle <14 mrad $4900 < m < 7000$ MeV/c^2
K^{*0}	$m(K\pi) < 6200$ MeV/c^2 vertex $\chi^2/\text{ndf} < 12$ flight distance $\chi^2 > 16$
$\mu^+\mu^-$	$m(\mu^+\mu^-) < 7100$ MeV/c^2 vertex $\chi^2/\text{ndf} < 9$
tracks hadron muon	ghost Prob <0.5 min IP $\chi^2 > 6$ min IP $\chi^2 > 9$
muon	IsMuon $\text{DLL}_{\mu\pi} > -3$
GEC	SPD Mult.<600

Preselection cuts applied to stripped candidates.

Candidate	Selection
B^0	$4960 < m < 6000$ MeV/c^2 $p_T > 1500$ MeV/c
K^{*0}	$630 < m(K\pi) < 1630$ MeV/c^2
track Track Pairs	$0 < \theta < 400$ mrad $\theta_{\text{pair}} > 1$ mrad
K	hasRich True $\text{DLL}_{K\pi} > -5$
π	hasRich True $\text{DLL}_{K\pi} < 25$
$\mu^+\mu^-$	IsMuon True
PV	$\lvert X - \langle X \rangle \rvert < 5$ mm $\lvert Y - \langle Y \rangle \rvert < 5$ mm $\lvert Z - \langle Z \rangle \rvert < 200$ mm

Peaking background vetoes - cuts

$$\Lambda_b^0 \to pK^-\mu^+\mu^-$$

$$(5575 < m_{(\pi\to p)K\mu\mu} < 5665)\ \mathrm{MeV/c^2}\ \text{and}\ \pi\mathrm{DLL}_{p\pi} > 0$$
$$(5575 < m_{(K\to p)(\pi\to K)\mu\mu} < 5665)\ \mathrm{MeV/c^2}\ \text{and}\ \pi\mathrm{DLL}_{K\pi} > 0$$

$$B_s^0 \to \phi\mu^+\mu^-$$

$$5321 < m_{(\pi\to K)K\mu\mu} < 5411\ \mathrm{MeV/c^2}\ \text{and}\ 1010 < m_{(\pi\to K)K} < 1030\ \mathrm{MeV/c^2} \quad \mathrm{DLL}_{K\pi} > -10$$

$$5321 < m_{(\pi\to K)K\mu\mu} < 5411\ \mathrm{MeV/c^2}\ \text{and}\ 1030 < m_{(\pi\to K)K} < 1050\ \mathrm{MeV/c^2} \quad \mathrm{DLL}_{K\pi} > 10$$

$$B^+ \to K^+\mu^+\mu^-$$

$$m_{K\pi\mu\mu} > 5380\ \mathrm{MeV/c^2}\ \text{and}\ 5220 < m_{K\mu\mu} < 5340\ \mathrm{MeV/c^2}$$

$$B^0 \to J/\psi K\pi$$

$$2996 < m_{(\pi\to\mu)\mu} < 3196\ \mathrm{MeV/c^2}\ \text{and}\ (\pi\mathrm{IsMuon}||\pi\mathrm{DLL}_{\mu\pi} > 0.0)$$
$$2996 < m_{(K\to\mu)\mu} < 3196\ \mathrm{MeV/c^2}\ \text{and}\ (\mathrm{KIsMuon}||\mathrm{KDLL}_{\mu\pi} > 0.0)$$

$$B^0 \to \psi(2S)K\pi$$

$$3626 < m_{(\pi\to\mu)\mu} < 3746\ \mathrm{MeV/c^2}\ \text{and}\ (\pi\mathrm{IsMuon}||\pi\mathrm{DLL}_{\mu\pi} > 5.0)$$
$$3626 < m_{(K\to\mu)\mu} < 3746\ \mathrm{MeV/c^2}\ \text{and}\ (\mathrm{KIsMuon}||\mathrm{KDLL}_{\mu\pi} > 5.0)$$

$$B^0 \to K^+\pi^-\mu^+\mu^-$$

$$\mathrm{KDLL}_{K\pi} - \pi\mathrm{DLL}_{K\pi} > 10$$