Search for the $B^0_{(s)} \to \pi\pi\mu\mu$ decay at LHCb.

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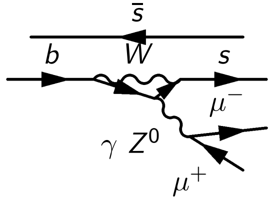
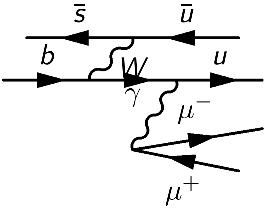
Why is it interesting to study $B^0_{(s)} \to \pi\pi\mu\mu$ decays?

$\rho(770)$, $f_0(980)$- light unflavored mesons decaying dominantly to $\pi\pi$



- $B^0_s \to f_0\mu^+\mu^-$: dominated by "penguin" and "box" $b \to s$ transition. Potentially sensitive to non-standard contribution, access similar physics of $B^0 \to K^*\mu^+\mu^-$and $B \to \phi\mu\mu$
- Allow to test non perturbative QCD models.
- $B^0 \to \rho\mu^+\mu^-$: dominated by $b \to d$ penguing and box transition in SM. Potentially sensitive to the non-SM physics, complementary w.r.t. $B^0_s \to f_0\mu^+\mu^-$.
- Both are not observed yet



Why do we study B^0 and B_s^0 together?

- Hard to disentangle $f_0(980)$ and $\rho(770)$. Additional resonances from the f family contribute also.
- Study $\pi\pi\mu\mu$ system with large $\pi\pi$ window [0.5, 1.3] GeV allows to see simultaneously $B_s^0 \to f_0\mu^+\mu^-$and $B^0 \to \rho\mu^+\mu^-$. Expected similar branching ratios.

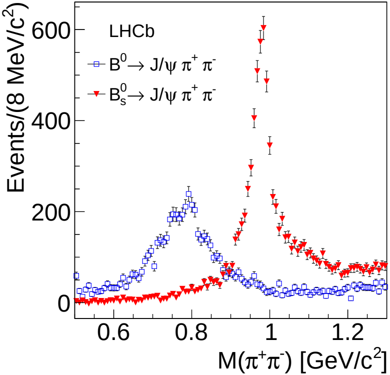


Figure: $\pi\pi$ mass distribution sWeighted from fit to $M(J/\psi\pi\pi)$

Brief overwiew

$$N^{observed\ B\to X} = 2\times L\times \sigma_{pp\to b+\dots}\times f_{s(d)}\times \mathrm{Br}(\mathrm{B}\to X)\times \epsilon_{detection}$$

- Search for $B_s^0 \to f_0\mu^+\mu^-$ and $B^0 \to \rho\mu^+\mu^-$ decays.
- measure their BR (or set an upper limit), normalised to $B^0 \to J/\psi K^*$:

$$\frac{Br(B^0_{(s)}\to\pi\pi\mu\mu)}{Br(B^0\to J/\psi K^*)} = \frac{N_{B^0_{(s)}\to\pi\pi\mu\mu}}{N_{B^0\to J/\psi K^*}}\times\frac{\epsilon_{B^0\to J/\psi K^*}}{\epsilon_{B^0_{(s)}\to\pi\pi\mu\mu}}(\times\frac{f_s}{f_d})$$

Here:

- ϵ - selection efficiency. Estimated from MC and data.
- $N_{B^0\to J/\psi K^*}$ - number of events in normalisation sample. Estimated from the fit of $M_{\pi K\mu\mu}$ spectrum.
- $N_{B^0_{(s)}}$ - number of signal events. Estimated from the fit of $M_{\pi\pi\mu\mu}$ spectrum. Fit of $J/\psi\pi\pi$ to check the fitting model and extract some shape parameters.

Basic selection

- Stripping v20(r1), B2XMuMu line
- Confirm trigger offline
- Mass constraint: $M_{\pi\pi} \in [0.5; 1.3]$ GeV + vetoed $\psi(1S, 2S)$ for the non-resonant sample

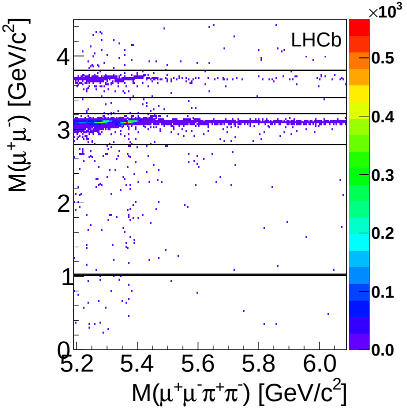


Figure: $M_{\pi\pi\mu\mu}$vs.$M_{\mu\mu}$ with indicated veto regions.

Mass distribution before optimisation - too much combinatorial

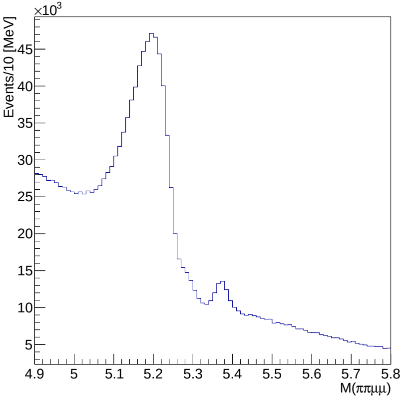


Figure: $J/\psi\pi\pi$ mass distribution before selection

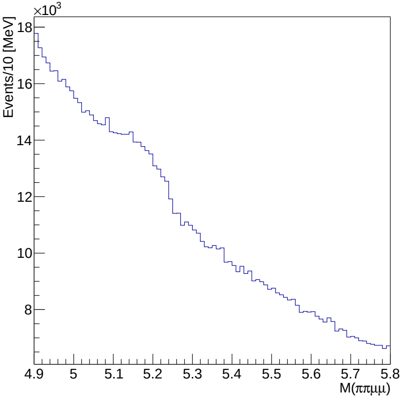
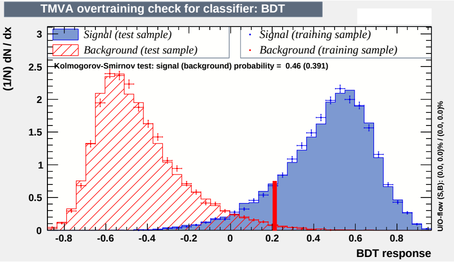
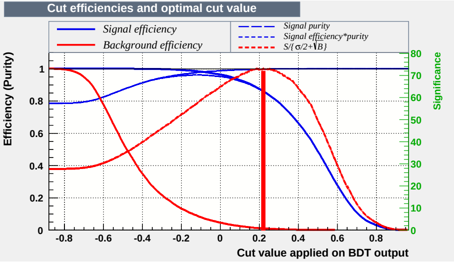


Figure: $\pi\pi\mu\mu$ mass distribution before selection

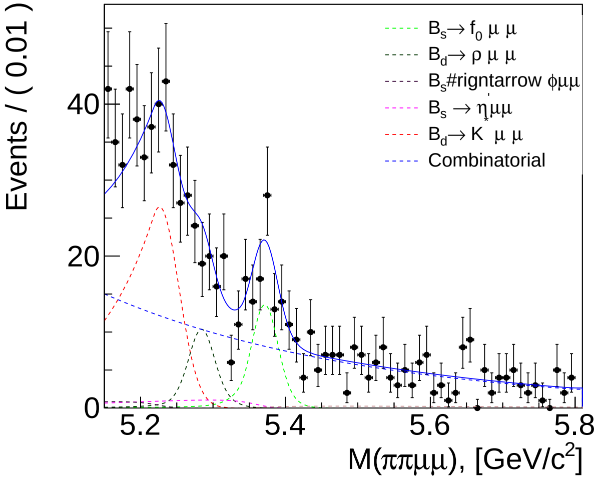
BDT selection

- Stripping v20(r1), B2XMuMu line
- Confirm trigger offline
- Mass constraint: $M_{\pi\pi} \in [0.5; 1.3]$ GeV + vetoed $\psi(1S, 2S)$ for the non-resonant sample
- BDT selection to suppress combinatorial





Distribution of invariant mass after BDT. (Do you see a problem?)



$K - \pi$ misid suppression

- B^0 signal region polluted by $B^0 \to K^* \mu^+ \mu^-$ decays from $\pi - K$ misidentification. B_s signal region not affected.
- Checked that BDT output is independent from DLL(K-π). Fixing BDT cut (already optimised to suppress combinatorial for $B_s^0 \to f_0 \mu^+ \mu^-$), can optimise the DLL cut alone.

DLL($\pi - K$) - characteristic of a track, telling if this track is more pion- or more kaon-like.

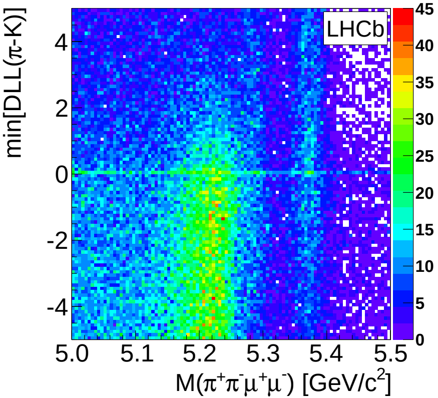
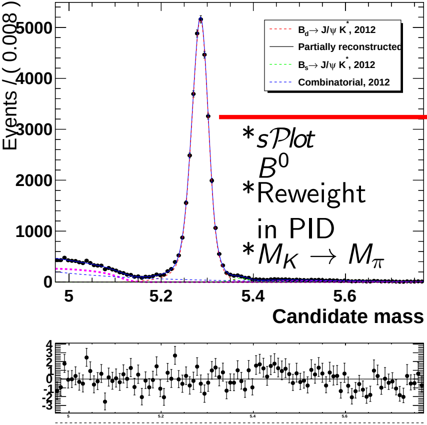
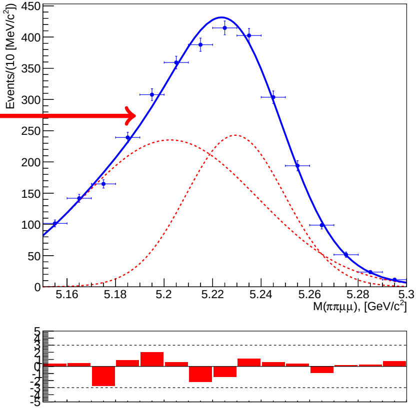


Figure: DLL($\pi - K$)vs$M_{\pi\pi\mu\mu}$

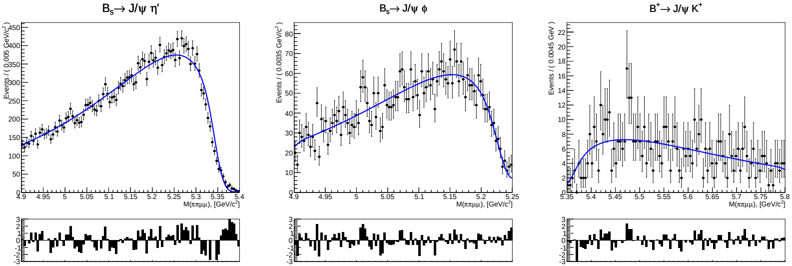
Remaining $\pi - K$ misId



- *sPlot B^0
- *Reweight in PID
- *$M_K \to M_\pi$



Other backgrounds: partially reconstructed



Three possible partially reconstructed backgrounds.

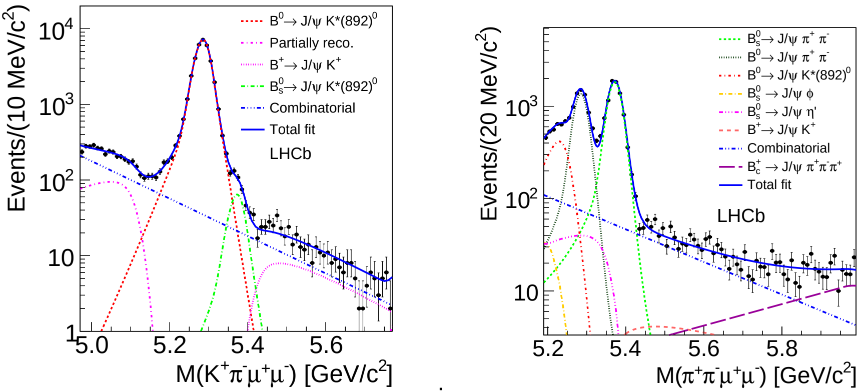
- $B_s - \gamma$, leading component - $B_s \to \eta^{(\prime)}(\to \pi\pi\gamma)\mu\mu$
  - exp. yield ~1.5 events
- $B_s - \pi$, leading component - $B_s \to \phi(\to \pi\pi\pi)\mu\mu$
  - exp. yield ~0.5 events
- Overreconstructed events, leading component - $B^+ \to K(+\pi)\mu\mu$
  - exp. yield ~5 events

Negligible backgrounds

Other backgrounds were also considered:

- $B^0 \to D^-(\to \rho\mu^- X)\mu + X$. Out of fit range.
- $B^0 \to D^-(\to \phi(\to \mu\mu)\pi)\pi$ vetoed by dimuon invariant mass
- $B^0 \to J/\psi\omega(\to \pi\pi\pi))$. Out of dipion mass range
- Double misidentified $B_s^0 \to J/\psi f_0$ events are vetoed by dipion mass.
- $\Lambda_b^0 \to hh\mu\mu$-negligeble after selection.
- $B_s \to J/\psi(\to \gamma\mu\mu)f_0$ - vetoed by dimuon mass.
- $B_c \to J/\psi\pi\pi\pi$ - Included wit floating yield to the resonant fit model.

Fitting data. Noralisation and check of the model



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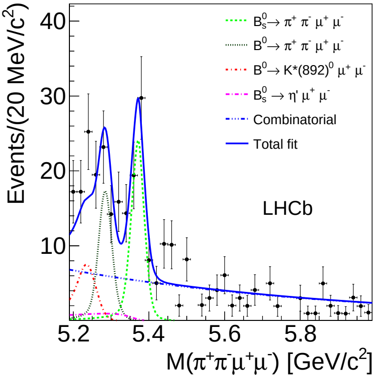
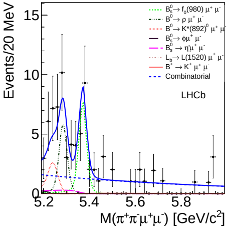
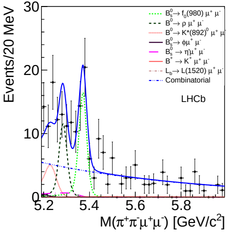
Mass distribution of $B \to J/\psi K\pi$ and $B \to J/\psi \pi\pi$ candidates with fit projections overlaid.

Signal sample.







Mass distributions of the sample with fit projections overlaid, zoomed in the range 5.19–6.0 GeV.

Results

	B_s
$N_{candidates}$	$55 \pm 10 \pm 5$
R	$(1.67 \pm 0.29 \pm 0.13) \times 10^{-3}$
Br	$(8.6 \pm 1.5 \pm 0.7 \pm 0.7\,(\text{norm})) \times 10^{-8}$
Significance	7.3σ

	B_d
$N_{candidates}$	$40 \pm 10 \pm 3$
R	$(0.41 \pm 0.10 \pm 0.03) \times 10^{-3}$
Br	$(2.11 \pm 0.51 \pm 0.15 \pm 0.16\,(\text{norm})) \times 10^{-8}$
Significance	4.8σ

Backup

Theoretical predictions

$Br(B_s^0 \to f_0\mu^+\mu^-)$	Ref.
$\left(5.21^{+3.23}_{-2.06}\right) \times 10^{-7}$	[ARXIV:0811.2648]
$\left(9.5^{+3.1}_{-2.6}\right) \times 10^{-8}$	[ARXIV:1002.2880]
$(1.67 \pm 0.61) \times 10^{-7}$	[ARXIV:1002.2880]
$(0.81 - 2.02) \times 10^{-8}$	[PhysRevD81,016012]
$(0.63 - 3.37) \times 10^{-9}$	[PhysRevD81,016012]

$Br(B^0 \to \rho\mu^+\mu^-)$	Ref.
$\left(5.0^{+2.1}_{-2.6}\right) \times 10^{-8}$	[HEP-PH/9706247] and [HEP-PH/9609503]
$\left(8.6^{+3.4}_{-4.5}\right) \times 10^{-8}$	[HEP-PH/9706247] and [HEP-PH/9609503]
$\sim 10^{-7}$	[HEP-PH/9807256]
6×10^{-8}	[HEP-PH/9812272]
$(2.8 - 8.4) \times 10^{-8}$	[PhysRevD77,014017]

Selection summary

Variable	Requirement
BDT	> 0.25 (2011), > 0.15(2012)
DLL($\pi - K$)	> 1
DLL($\pi - \mu$)	> -1
DLL($\pi - p$)	> 0
ProbNN(μ)	> 0.25
$M_{\pi\pi}$	$\in [0.5, 1.3]\,\mathrm{GeV}$
$M_{\mu\mu}$ non-resonant	$\in [0.212, 2.796] \cup [3.216, 3.436] \cup [3.806, 5.05]\,\mathrm{GeV}$
$M_{\mu\mu}$ resonant	$\in [2.796, 3.216]\,\mathrm{GeV}$
$M_{\pi^+\pi^-\mu^+\mu^-}$	$\in [5.19, 6.99]\,\mathrm{GeV}$
$M_{\pi\leftrightarrow\mu}$	$\notin [3.036, 3.156] \cup [3.625, 3.745]\,\mathrm{GeV}$
DLL$(K - \pi)_K$	> 5

Efficiencies

Sample	$\varepsilon_{\rm acc}$(%)	$\varepsilon_{\rm trig}\ \varepsilon_{\rm pres}\ \varepsilon_{\rm BDT}$(%)	$\varepsilon_{\rm PID}$ (%)	Total (%)
		2011		
$B_s^0 \to f_0\mu^+\mu^-$	14.26 ± 0.076	5.026 ± 0.033	50.345 ± 0.092	0.3608 ± 0.0031
$B^0 \to \rho\mu^+\mu^-$	14.49 ± 0.049	4.211 ± 0.015	48.755 ± 0.05	0.2975 ± 0.0015
$B^0 \to J/\psi K^*$	14.87 ± 0.039	7.4619 ± 0.0089	8.407 ± 0.043	0.0933 ± 0.0005
		2012		
$B_s^0 \to f_0\mu^+\mu^-$	15.48 ± 0.076	5.174 ± 0.032	46.062 ± 0.096	0.3689 ± 0.0030
$B^0 \to \rho\mu^+\mu^-$	15.64 ± 0.049	4.103 ± 0.029	42.813 ± 0.11	0.2748 ± 0.0022
$B^0 \to J/\psi K^*$	16.05 ± 0.039	6.688 ± 0.027	9.075 ± 0.056	0.0974 ± 0.0008

- $\varepsilon_{\rm acc}$ - geometry efficiency, value and uncertainty extracted from generator statistics.
- $\varepsilon_{\rm trig}\ \varepsilon_{\rm pres}\ \varepsilon_{\rm BDT}$ - selection efficiency, estimated from Monte-Carlo simulation.
- $\varepsilon_{\rm PID}$ - PID selection efficiency, estimated from data and MC sample using PIDCalib package.

Normalisation: Fit of $B^0 \to J/\psi K^*$

Parameter	2011 sample	2012 sample
Yield of $B^0 \to J/\psi K^*$	10493 ± 110	25129 ± 176
width of first CB $[\mathrm{GeV}/c^2]$	0.01896 ± 0.00018	
ratio of CB widths	0.741 ± 0.044	
Ratio of CB	0.741 ± 0.015	
Part.reco'd Argus shape$c$	-19 ± 11	
Part.reco'd Argus starting point $[\mathrm{GeV}/c^2]$	5.1235 ± 0.0063	
mass $[\mathrm{GeV}/c^2]$	5.28521 ± 0.00022	
Combinatorial slope	-5.49 ± 0.75	-5.77 ± 0.47
Yield of partially reconstructed	349 ± 79	911 ± 142
Combinatorial yield	938 ± 119	2712 ± 227
Yield of $_s \to J/\psi K^*(892)^0$	100 ± 18	219 ± 31
Yield of $_u \to J/\psi K^+$	48 ± 26	131 ± 44

Table: Results of the fit to the $B^0 \to J/\psi K^*$ data.

Yields of $B^0 \to J/\psi K^*$ need to be corrected in order to substract S-wave.
P-wave is$\sim 96\%$ in our $M_{K\pi}$ mass range according to [PRD 88, 052002 (2013)]

Fit of the $\mu\mu\pi\pi$ sample

- Fit range: $5.19 - 6.99$ *GeV*
- Signal shapes: Double crystal ball with tail parameters fixed from MC and common width parameter.
- Signal yields: $N^{year}_{signal} = N^{year}_{B_d \to J/\psi K^*} \times \frac{Br(signal) \times \varepsilon^{year}_{signal}}{Br(B_d \to J/\psi K^*) \times \varepsilon^{year}_{B_d \to J/\psi K^*}} \times (\frac{f_s}{f_d})$
- Combinatorial component is described by exponent and is free
- Partially reconstructed componants are fitted with MC-defined argus shape with yields, fixed from expectations.
- MISID shapes are fixed from data.
- M_{misid} is free, MISID yield is under gaussian constraint.

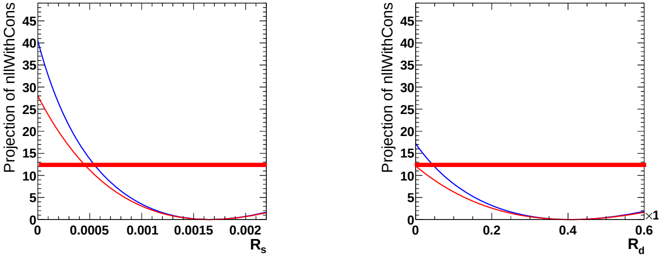
Fit of the $\mu\mu\pi\pi$ sample

Parameter	2011 sample	2012 sample
$\mathcal{R}_d$'	$(0.387 \pm 0.093) \times 10^{-3}$	
$\mathcal{R}_s$'	$(0.404 \pm 0.071) \times 10^{-3}$	
$N(\mathrm{B}_s^0 \to J/\psi f_0)$	2675 ± 59	6218 ± 92
$N(\mathrm{B}^0 \to J/\psi \rho)$	1980 ± 67	4425 ± 100
$M(B^0)$ $[\mathrm{GeV}/c^2]$	5.28459 ± 0.00039	5.28438 ± 0.00027
M_{misid} $[\mathrm{GeV}/c^2]$	5.2036 ± 0.0027	5.2141 ± 0.0018
signal width $[/c^2]$	17.96 ± 0.35	19.86 ± 0.35
N_{comb} resonant	796 ± 70	1895 ± 104
slope comb. resonant $[\mathrm{GeV}^{-1}]$	-4.31 ± 0.37	-3.83 ± 0.19
N_{comb} non-resonant	56.2 ± 9.2	172 ± 16
slope comb. non-resonant $[\mathrm{GeV}^{-1}]$	-1.22 ± 0.36	-1.44 ± 0.21
$N(B_c^+ \to J/\psi\, \pi^+\pi^-\pi^+)$	167 ± 25	361 ± 39
$N(\mathrm{B}^0 \to J/\psi K^*)$	762 ± 20	1858 ± 34
$N(\mathrm{B}^0 \to K^*\mu^+\mu^-)$	7.1 ± 1.0	15.8 ± 1.5

Table: Results of the fit to the data.

1D Likelihood profile

$\sigma(B_s) = 7.3$
$\sigma(B_d) = 4.8$



Likelihood profile of R($B_s^0 \to f_0\mu^+\mu^-$) (left) and R($B^0 \to \rho\mu^+\mu^-$) (right), where R is $Br(B_{(s)}^0 \to \pi\pi\mu\mu)/Br(\mathrm{B}^0 \to J/\psi K^*)$

The red line corresponds to the profile-likelihood, where, for each point probed in R, all other parameters are floating; the blue line corresponds to the likelihood scan along to R, where all the others parameters are fixed to their values at the minimum of the likelihood.

2D Likelihood profiles

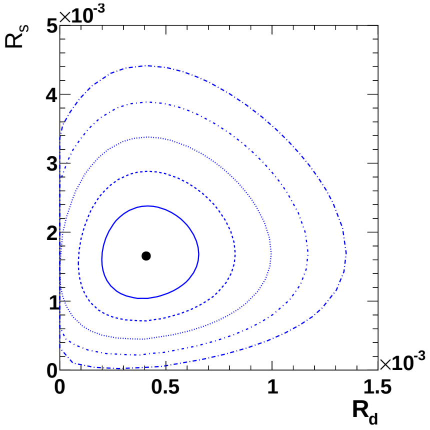
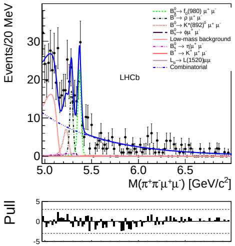


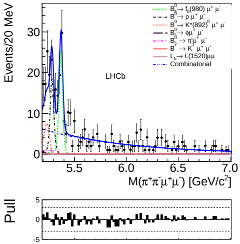
Figure: Likelihood levels (1..5σ) of R($B_s^0 \to f_0\mu^+\mu^-$) and R($B^0 \to \rho\mu^+\mu^-$).

Fit checks: Fit variations

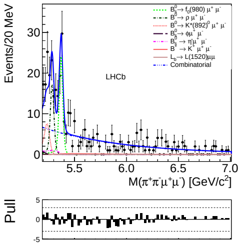
As an additional check with alternative fit models



extending fit range ([5.0-7.0] GeV)



fixing exponent from the right sideband ([5.5-6.97] GeV)



Combinatorial function was described by line.

Fit checks: Fit variations

	default fit	Extended fit range	fixing combinatorial	Linear combinatorial
$\mathcal{R}_s(\times 10^{-3})$	1.55 ± 0.26	1.51 ± 0.26	1.59 ± 0.25	1.75 ± 0.26
$\mathcal{R}_d(\times 10^{-3})$	0.329 ± 0.072	0.318 ± 0.072	0.345 ± 0.068	0.406 ± 0.072

Table: Values of $\mathcal{R}_s$ and $\mathcal{R}_d$ from the fit to data in different configurations to check the stability of the results.

Systematics

Main sources of systematics:

- Yield of $B^0 \to J/\psi K^*$ signal
  - Statistics and dependence on signal shape
- Efficiency
  - Statistics of MC sample
  - Dependence on model (compared with efficiency, of "dummy" model)
  - Difference with data - defined for BDT and trigger (TISTOS) efficiencies. Found from comparision of efficiency found on MC with efficiency found on reference sample.
- Signal shapes
  - Since shapes were fixed from MC, we had to consider the effect from "wrong shape".

In all cases, uncertinty of parameter was transfered to the systematics in two steps:

- Perform set of fits with examined parameter varied within error
- Define systematics as RMS of the distribution of obtained R_s and R_d

Systematics

Source	$\sigma(\mathcal{R}_s)$	$\sigma(\mathcal{R}_d)$
$B^0 \to K^* \mu^+ \mu^-$ shape	1	4
Partially- and over- rec. backg.	1	4
Signal shapes	7	14
Efficiencies	19	13
Yields of $B^0 \to J/\psi K^*$	18	13
S-wave in $B^0 \to J/\psi K^*$	6	4
f_s/f_d	32	–
total	43	26

Table: Systematic uncertainties of $\mathcal{R}_s$ and $\mathcal{R}_d$ relative to their statistical uncertainties.

Fit checks: Toys

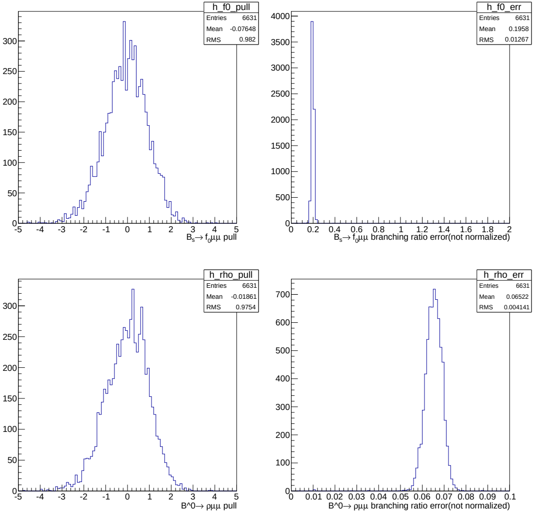
Three toy datasets were generated using fitting PDF:

- "Default" - values of generation parameters as ones from fit to data.
- "No Bd" - default, but R_d set to 0
- "No Bs" - default, but R_s set to 0

Parameter	Gen. value	Mean fit value	Mean fit error	Pull mean	Pull RMS	s_{stat}
$\mathcal{R}_s$	1.132	1.126	0.196	-0.076 ± 0.012	0.98	7.5
$\mathcal{R}_d$	0.292	0.294	0.065	-0.019 ± 0.012	0.98	5.4
$\mathcal{R}_s$	0.0	-0.009	0.099	-0.227 ± 0.014	1.14	0.7
$\mathcal{R}_d$	0.292	0.284	0.064	-0.173 ± 0.012	1.00	5.3
$\mathcal{R}_s$	1.132	1.118	0.195	-0.118 ± 0.012	0.97	7.5
$\mathcal{R}_d$	0.0	-0.011	0.041	-0.377 ± 0.014	1.15	0.8

Table: Results of the pseudo-experiments. The second column report the values used in the generation of the pseudo-experiments for $\mathcal{R}_s$ and $\mathcal{R}_d$; all other parameters are generated with values close to the ones found in the fit to data, see Tab. 22.

Fit checks: Toys ("As is" parameter distributions)



Significance checks