

Searches for Higgs and Higgs-like particles @ LHCb

Victor Coco, on behalf of the LHCb Collaboration

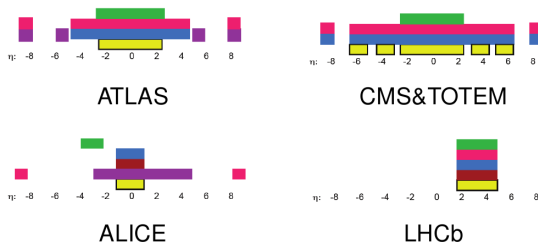
NIKHEF, Amsterdam

May 13, 2013



LHCP 2013, May 13-18th, Barcelona, Spain.

LHCb as a general purpose detector in the forward region

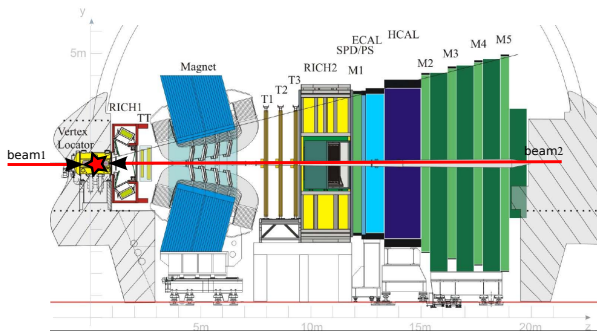


tracking, ECAL, HCAL, counters lumi, muon, hadron PID

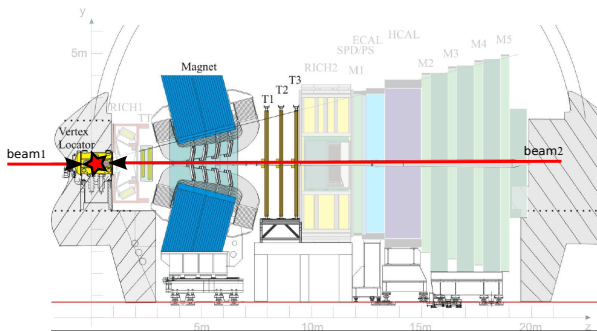
- LHCb experiment is fully instrumented over a unique region of pseudo rapidity at LHC.
- Several EW and QCD measurements in the forward region

see A. Grecu and R. Wallace talks.

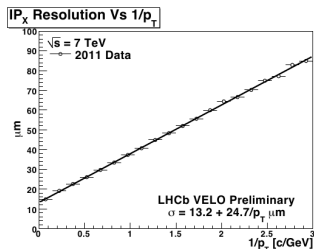
- In this talk:
 - Limits on neutral Higgs boson production in the forward region @ $\sqrt{s} = 7$ TeV, [arXiv:1304.2591](https://arxiv.org/abs/1304.2591).
 - Measurement of the central forward $b\bar{b}$ asymmetry, [LHCb-CONF-2013-001](https://arxiv.org/abs/1304.2591).
 - Search for Higgs-like bosons decaying into long-lived exotic particles, [LHCb-CONF-2012-014](https://arxiv.org/abs/1304.2591).



- Designed for CP violation studies in B decay and rare decays.
- Single arm spectrometer, $\sim 30\%$ of $b\bar{b}$ pairs produced in the acceptance.
- So far $\sim 1.1fb^{-1}$ recorded at $\sqrt{s} = 7\text{ TeV}$ and $\sim 2.2fb^{-1}$ at $\sqrt{s} = 8\text{ TeV}$.
- Data taking with luminosity levelling \rightarrow stable conditions with $\langle \text{pile-up} \rangle \sim 2$



- Tracking efficiency $\sim 95\%$
- $\delta p/p \sim 0.5\%$
- $20\mu\text{m}$ IP resolution at $p_T = 2\text{ GeV}$, important for b-jet tagging.



Limits on $\Phi_0 \rightarrow \tau^+ \tau^-$ production

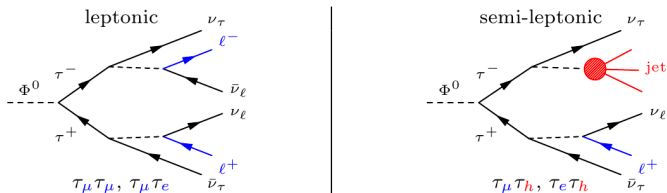
Selection

arXiv:1304.2591, submitted to JHEP

- Dataset: 1 fb^{-1} at $\sqrt{s} = 7 \text{ TeV}$.
- Reinterpretation of the data used for the $Z \rightarrow \tau\tau$ cross section measurement.

JHEP01(2013)111, see Ronan Wallace talk on Friday.

- 5 independent datasets: $\tau_\mu\tau_\mu$, $\tau_\mu\tau_e$, $\tau_e\tau_\mu$, $\tau_\mu\tau_h$ and $\tau_e\tau_h$



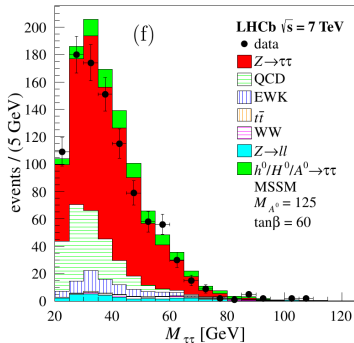
- Selection:
 - $p_{T1} > 20 \text{ GeV}$, $p_{T2} > 5 \text{ GeV}$, $2 < \eta_{1,2} < 4.5$.
 - Track displaced from PV in $\tau_\mu\tau_\mu$, $\tau_\mu\tau_h$ and $\tau_e\tau_h$.
 - $\Delta\phi > 2.7$ and $m_{1,2} > 20 \text{ GeV}$.
 - Lepton isolation.
 - In $\tau_\mu\tau_\mu$, momentum asymmetry and exclusion of $m_{\mu\mu} \in [80; 100 \text{ GeV}]$

Limits on $\Phi_0 \rightarrow \tau^+\tau^-$ production

Signal and Backgrounds

arXiv:1304.2591, submitted to JHEP

- Neutral Higgs $\Phi_0 \rightarrow \tau^+\tau^-$ signal.
 - Mass shape from gluon fusion production simulation.
 - MSSM cross section using m_0^{max} scenario:
 - gg fusion production (HIGLU and GGH@NLO)
 - associated $b\bar{b}$ production (BBH@NNLO)
 - Efficiencies from data as for $Z \rightarrow \tau\tau$.
- Shapes and normalisation of backgrounds:
 - QCD, shape and normalisation from data.
 - $Z \rightarrow \ell\ell$, shape and normalisation from data.
 - EWK, shape from simulation and normalisation from data.
 - top/WW from simulation.
 - $Z \rightarrow \tau\tau$ Shape from simulation, theoretical cross sections.

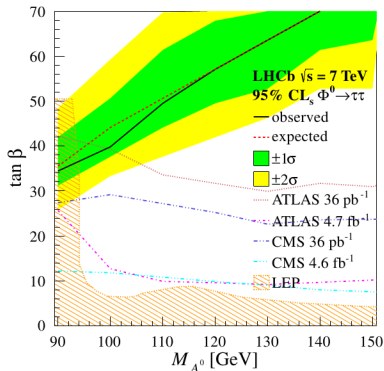
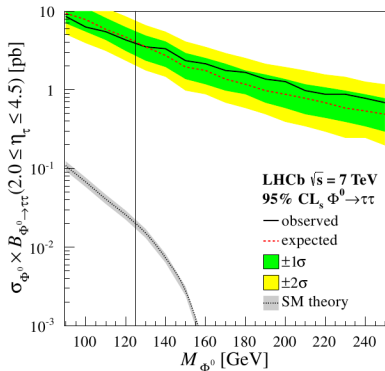


Limits on $\Phi_0 \rightarrow \tau^+\tau^-$ production

Results

arXiv:1304.2591, submitted to JHEP

- Asymptotic limit from profile ratio of extended likelihood using mass shape, upper limit calculated at $CL_s = 95\%$



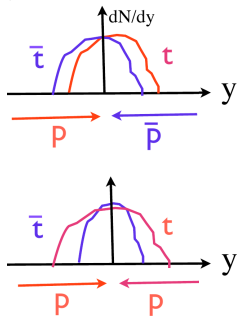
- Important for investigating models with enhanced forward production.

- Low luminosity, limited acceptance but excellent spatial resolution of the vertex locator: $H(W, Z) \rightarrow b\bar{b} + \ell$ is the best candidate.
- $\sim 5(11)\%$ of SM Higgs decays have 2 b's in the acceptance at $\sqrt{s} = 7(14) \text{ TeV}$.
- Sensitivity studies on-going at $\sqrt{s} = 7 \text{ TeV}$ and 8 TeV .
- Triggered development of new tools:
 - Jet reconstruction and calibration.
 - b-jet tagging.
- On this path, measurements in the $b\bar{b}$ sector have been performed:
 - Measurement of $\sigma_{b\bar{b}}$ with inclusive final states ([LHCb-CONF-2013-002](#))
Highlight: high efficiency B seeds reconstruction ($\sim 82\%$) can be used as b-tagger.
 - **Measurement of the central forward $b\bar{b}$ asymmetry $A_{FC}^{b\bar{b}}$ ([LHCb-CONF-2013-001](#))**

Central forward $b\bar{b}$ asymmetry $A_{FC}^{b\bar{b}}$

Motivation

- CDF and D0 observe $A_{FB}^{t\bar{t}}$ 3 to 4 times larger than the SM prediction ($\sim 5\%$).
- $\sim 2.5\sigma$ discrepancy with SM
- LHC can only measure A_{FC} .
- $A_{FC}^{b\bar{b}} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}$, $\Delta y = |y_b| - |y_{\bar{b}}|$



- Depending on new physics flavour structure, it can also show up in the bottom sector.

Kahawala, Krohn, Strassler, [arXiv:1108.3301](https://arxiv.org/abs/1108.3301).

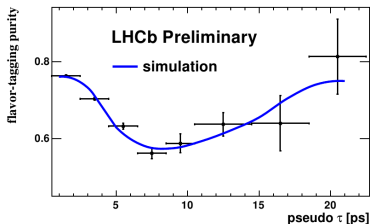
- No precise SM prediction for $A_{FC}^{b\bar{b}}$, expected to be $O(1\%)$ for $m_{b\bar{b}} > 100$ GeV and $O(0.1\%)$ over the whole mass range.

Central forward $b\bar{b}$ asymmetry $A_{FC}^{b\bar{b}}$

Selection and flavour tagging

LHCb-CONF-2013-001

- Dataset: 1 fb^{-1} at $\sqrt{s} = 7 \text{ TeV}$.
- Di-jets events ($p_{T,1,2} > 15 \text{ GeV}$, $2 < \eta_{1,2} < 4.5$, $\Delta\phi > 2.5 \text{ rad}$), jets reconstructed with anti-kT ($R=0.5$) and corrected back to quark level.
- b-jet tagging using topological B mesons trigger information [LHCb-PUB-2011-002](#):
→ very high purity, $c\bar{c}$ contamination $O(0.01\%)$.
- b and \bar{b} are discriminated by the charge of a hard, displaced muon.

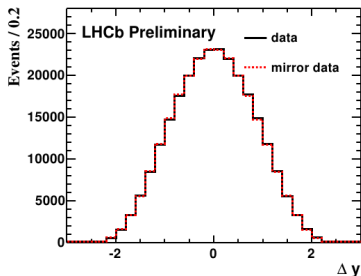


- Raw asymmetry is corrected for the time dependent impurity of the flavour tagging (b vs. \bar{b}).
- Time integrated purity: $70.7 \pm 0.4\%$ from double tag data sample.

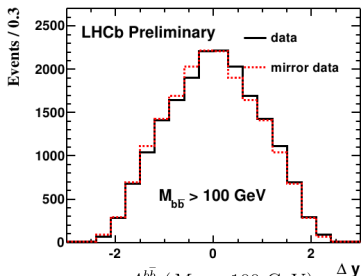
Central forward $b\bar{b}$ asymmetry $A_{FC}^{b\bar{b}}$

Results

LHCb-CONF-2013-001



$$A_{FC}^{b\bar{b}} = (0.5 \pm 0.5 \text{ (stat)} \pm 0.5 \text{ (syst)})\%$$



$$A_{FC}^{b\bar{b}}(M_{b\bar{b}} > 100 \text{ GeV}) = (4.3 \pm 1.7 \text{ (stat)} \pm 2.4 \text{ (syst)})\%$$

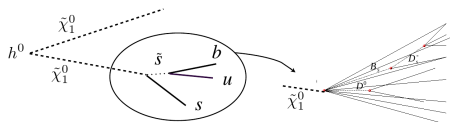
- Systematic errors from the flavour-tagging purity and detector asymmetry.
- $\sigma_{m_{b\bar{b}}} \sim 15 - 20\%$, no unfolding \rightarrow Migration to $m_{b\bar{b}} > 100 \text{ GeV}$ dilutes $A_{FC}^{b\bar{b}}$ by few percent (not taken into account in preliminary analysis).
- Work on-going on data driven method for mass unfolding and improved b-tagging efficiency.
- With addition of the 2012 data, a factor ~ 6 more events are expected for $m_{b\bar{b}} > 100 \text{ GeV}$.
- Capacity of reconstruction di-b jets and tagging them with high purity.

Search for Higgs-like bosons decaying into long lived particles

Motivation

LHCb-CONF-2012-014

- Long lived neutral massive particles (LLP) arise from many new physics models.
- Pair production through Higgs-like boson accessible with early LHC data.
- mSUGRA with R parity and baryon number violation
 - Carpenter, Kaplan and Rhee, [Phys. Rev. Lett. 99 \(2007\) 211801](#)
 - $h^0 \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow 3jets + 3jets$, $\sim 70\%$ of the decay have a b quark.
 - For $m_{h^0} = 125 \text{ GeV}$, $m_{\tilde{\chi}_1^0} = 48 \text{ GeV}$ and $\tau_{\tilde{\chi}_1^0} = 10 \text{ ps}$ (BV48), $\sim 25\%$ of the events have a LLP in LHCb acceptance.
 - $\tilde{\chi}_1^0$ is the LLP, mass range $20 - 60 \text{ GeV}/c^2$ and lifetime $3 - 25 \text{ ps}$.



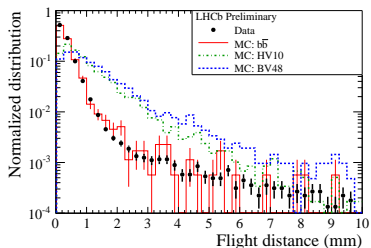
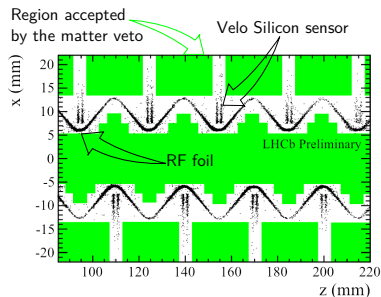
- Similar topology in some Hidden Valley models
 - Strassler, Zurek [Phys. Lett. B651 \(2007\) 374](#)
 - $h_0 \rightarrow \pi_v^0 \pi_v^0 \rightarrow b\bar{b}b\bar{b}$
 - π_v^0 is the LLP (HV10).

Search for Higgs-like bosons decaying into long lived particles

Selections

LHCb-CONF-2012-014

- Dataset: 36 pb^{-1} at $\sqrt{s} = 7 \text{ TeV}$.
- Trigger and reconstruction of LLP based on an inclusive displaced vertex algorithm.
- $h^0 \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0$ candidates:
 - Vertex outside matter region.
 - $m_{\text{vertex}} > 4 \text{ GeV}$, $R > 0.4 \text{ mm}$ and $N_{tr} \geq 4$
 - back to back $\tilde{\chi}_1^0$ candidates pointing to the same PV
 - Shape and yields compatible with $b\bar{b}$ backgrounds:
(75 ± 13)k $b\bar{b}$ expected, 59k observed.
- Final selection to reject all $b\bar{b}$ MC:
 - $m_{\text{vertex}} > 6 \text{ GeV}$, $N_{tr} \geq 3$
 - Good quality vertex.
- No candidate observed in data.



Search for Higgs-like bosons decaying into long lived particles

Results

LHCb-CONF-2012-014

- Overall selection efficiency on BV48: $0.384 \pm 0.017(\text{stat.}) \pm 0.085(\text{syst.})\%$.
- Main systematic uncertainties on the detection efficiency: trigger efficiency (15%) and vertex reconstruction (12%)
- $\sigma_{h0} \times BR(h^0 \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0)$ 95%CL upper limit: 32 pb.
- A fast simulation of the analysis chain allow to extend the probed phase space.

m_{LLP}	30	35	40	48	55
m_{h^0}					
100	101	58	44	58 ⁶⁴	
105	100	75	44	39	
110	132	75	56	34	
114	128	91	47	32 ³²	46
120	148	93	58	34	31
125	179	90	61	41 ⁴²	29

Fixed LLP lifetime = 10 ps

units in pb

Fixed Higgs mass = 114 GeV/c²

m_{LLP}	30	35	40	48	55
τ_{LLP}					
3	210	156	136	168 ⁶⁶	410
5	145	101	68	58 ⁶⁶	137
10	129	91 ⁸⁴	47	32 ³²	46
15	155	90	49	31	33
20	131	93	63	32	31
25	142	100	61	34	25

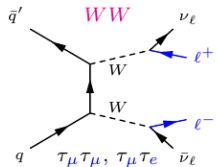
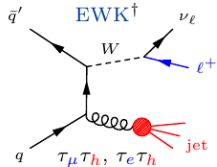
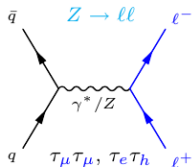
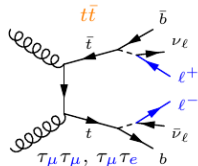
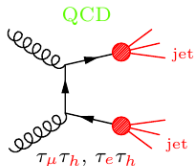
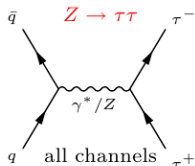
- Update of the analysis including jet reconstruction and ~ 80 times more data on-going.
- Analysis strategy will also allow single LLP search.

- Set limits on neutral Higgs production in the forward region.
- Preliminary searches of long lived exotic particles from Higgs-like boson decay.
- Preliminary measurements of $A_{FC}^{b\bar{b}}$ compatible with SM.
- Tools have been developed for reconstruction of jets and b-tagging them with good efficiency and purity
→ Open new fields of research at LHCb.
- Higgs searches at LHCb will benefit from higher \sqrt{s} and more integrated luminosity.

Limits on $\Phi_0 \rightarrow \tau^+ \tau^-$ production

Backgrounds

arXiv:1304.2591, submitted to JHEP



[†] EWK is a single hard lepton from an EWK boson and does not include $Z \rightarrow \tau\tau, Z \rightarrow \ell\ell, t\bar{t}, WW$

Limits on $\Phi_0 \rightarrow \tau^+ \tau^-$ production

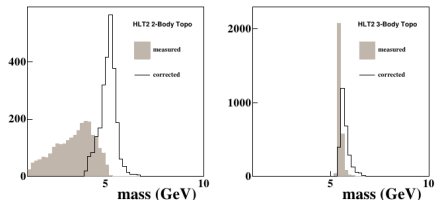
Number of events

arXiv:1304.2591, submitted to JHEP

Table 1: Estimated number of events for each background component and their sum, together with the observed number of candidates and the expected number of SM signal events for $M_H = 125$ GeV, separated by analysis category.

	$\tau_\mu \tau_\mu$	$\tau_\mu \tau_e$	$\tau_e \tau_\mu$	$\tau_\mu \tau_h$	$\tau_e \tau_h$
$Z \rightarrow \tau\tau$	79.8 ± 5.6	288.2 ± 26.2	115.8 ± 12.7	146.1 ± 9.7	62.1 ± 8.0
QCD	11.7 ± 3.4	72.4 ± 2.2	54.0 ± 3.0	41.9 ± 0.5	24.5 ± 0.6
EWK	0.0 ± 3.5	40.3 ± 4.3	0.0 ± 1.3	10.8 ± 0.5	9.3 ± 0.5
$t\bar{t}$	$< 0.1 \pm 0.1$	3.6 ± 0.4	1.0 ± 0.1	$< 0.1 \pm 0.1$	0.7 ± 0.4
WW	$< 0.1 \pm 0.1$	13.3 ± 1.2	1.6 ± 0.2	0.2 ± 0.1	$< 0.1 \pm 0.1$
$Z \rightarrow \ell\ell$	29.8 ± 7.0	—	—	0.4 ± 0.1	2.0 ± 0.2
Total	121.4 ± 10.2	417.9 ± 26.7	172.4 ± 13.1	199.3 ± 9.7	98.7 ± 8.0
Observed	124	421	155	189	101
SM Higgs $\times 100$	3.9 ± 0.5	11.9 ± 1.6	3.8 ± 0.5	9.7 ± 1.3	4.2 ± 0.6

$$m_{\text{corrected}} = \sqrt{m^2 + |p'_{T\text{missing}}|^2 + |p'_{T\text{missing}}|}$$



- Inclusive vertexing of 2, 3 or 4 displaced high p_T tracks.
- Mass corrected for missing p_T .
- Multivariate classifier

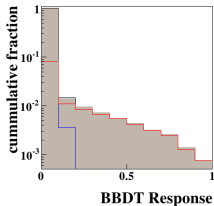


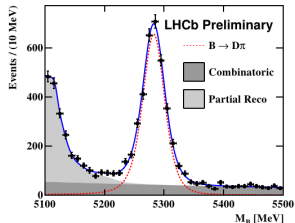
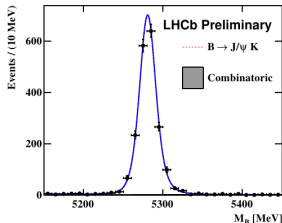
Figure 10: Response from the BBDT for minimum bias LHCb 2010 data (shaded grey), $pp \rightarrow c\bar{c}X$ Monte Carlo (blue), $pp \rightarrow b\bar{b}X$ Monte Carlo (red) and all minimum bias Monte Carlo (black). The Monte Carlo is not normalized to the data (see text for details). *N.b.*, no muon or electron requirements were used when making this plot.

Central forward $b\bar{b}$ asymmetry $A_{FC}^{b\bar{b}}$

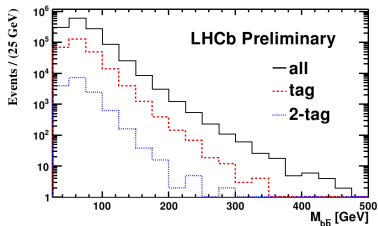
Flavour tagging purity

LHCb-CONF-2013-001

- Predicted to be $73 \pm 2\%$
- Checked with self-tagged exclusive decay $B^+ \rightarrow J/\psi K^+$ and $B^+ \rightarrow \bar{D}^0 \pi^+$, $71.5 \pm 4\%$



- $70.7 \pm 0.4\%$ from double tag data sample.

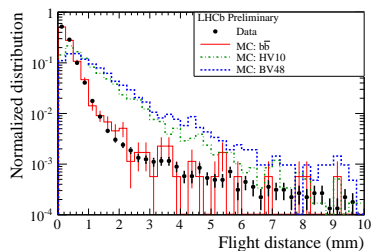
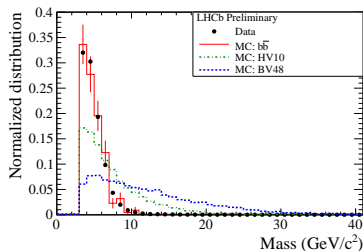
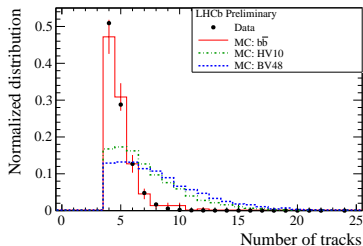


Search for Higgs-like bosons decaying into long lived particles

Single LLP pre-selection

LHCb-CONF-2012-014

- LLP vertex outside matter veto,
 $m_{vertex} > 4 \text{ GeV}$, $R > 0.4 \text{ mm}$ and $N_{tr} \geq 4$.
- Assuming $\sigma_{b\bar{b}} = 287 \pm 40 \mu\text{b}$,
(75 ± 13) k $b\bar{b}$ events expected, 59 k observed.
- Shape and yields compatible with $b\bar{b}$ backgrounds.

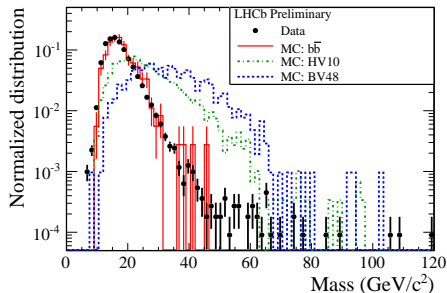
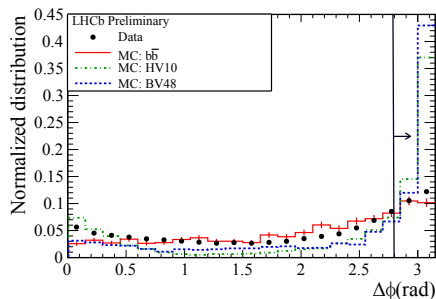


Search for Higgs-like bosons decaying into long lived particles

h_0 candidate pre-selection

LHCb-CONF-2012-014

- For $h_0 \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0$, LLP candidates are expected to be back-to-back and pointing to the same PV.
- Pairs of LLP with $\Delta\phi > 2.8$ are combined to form the h_0 candidate.



Search for Higgs-like bosons decaying into long lived particles

h_0 candidate selection and efficiencies

LHCb-CONF-2012-014

- Rejection of all $b\bar{b}$ MC for:
 - Both LLP: $N_{tr} \geq 6$, $m_{vertex} > 6$ GeV, Matter veto
 - Vertex position error: $\sigma_r < 0.05$ mm and $\sigma_z < 0.24$ mm.
 - Di-LLP: $\Delta\phi > 2.8$, same PV.
- **No events survive the selection in data.**
- Signal efficiency is obtained from MC (here $m_{h_0} = 114$ GeV, $m_{\tilde{\chi}_1^0} = 48$ GeV and $\tau_{\tilde{\chi}_1^0} = 10$ ps).

Detection efficiencies

	Source	ϵ [%]
1	one LLP in acceptance (generator cut)	29.4
2	LLP preselection	44.1
3	Trigger	35.5
4	Matter veto	95.8
5	LLP selection	66.4
7	two LLP found	19.1
8	$ \Delta\phi $ cut	68.4
	Total	0.384
	Total without trigger	0.589

Systematic uncertainties

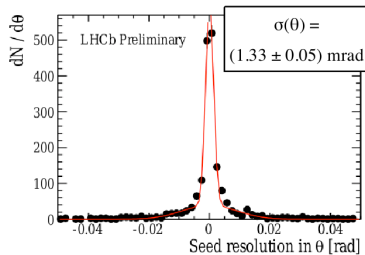
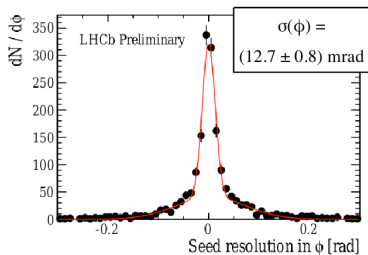
	Source	%
1	Integrated Luminosity	4
2	Trigger	15
3	Track reconstruction	7
4	Vertex reconstruction	12
5	p_T and mass calibration	6
6	Matter veto	4
7	Beam line position	1
	Total	22

Measurement of $\sigma_{b\bar{b}}$ with inclusive final states

Selection

LHCb-CONF-2013-002

- 2.6 pb^{-1} at $\sqrt{s} = 7 \text{ TeV}$, only events with one PV.
- Partial B hadron reconstruction using 2 or 3 track seed.
- Merging procedure.
- Good approximation of the B hadron direction



- Selection: events with exactly 2 seeds within $2.5 < \eta < 4$ and $p_T > 5 \text{ GeV}$.

Measurement of $\sigma_{b\bar{b}}$ with inclusive final states

Result

LHCb-CONF-2013-002

- B seeds efficiency:
 - MC: $81.6 \pm 0.7\%$
 - Data: $82.5 \pm 3.0\%$ (event tagged with the other side B)
- Global efficiency for b events 8×10^{-4} , for c events 1.8×10^{-5} .
- Fraction of $b\bar{b}$ and $c\bar{c}$ from template fit of a BDT variable.
- Shape of the BDT cross checked with other side $B \rightarrow D\pi$ and $D \rightarrow K\pi\pi$.

- Preliminary results:

- $\sigma_{b\bar{b}, 2.5 < \eta_{b,\bar{b}} < 4., p_{T_{b,\bar{b}}} > 5 \text{ GeV}} = (7.7 \pm 0.12(\text{stat}) \pm 0.84(\text{syst})) \mu\text{b}$
- $\sigma_{c\bar{c}, 2.5 < \eta_{c,\bar{c}} < 4., p_{T_{c,\bar{c}}} > 5 \text{ GeV}} = (104.6 \pm 2.7(\text{stat}) \pm 11.4(\text{syst})) \mu\text{b}$
- For reference, extrapolation to the full phase space with POWHEG, gives $364 \mu\text{b}$ and $3353 \mu\text{b}$ resp.

