Very rare decays at LHCb

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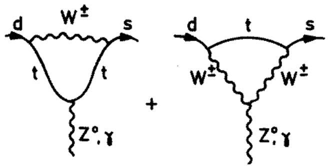
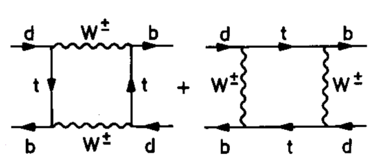
Why look for very rare decays? (1)

SM: vertices involving γ, Z^0 and G are flavour-conserving, no FCNC at tree level (GIM)

Only at one-loop level $\rightarrow$ suppressed processes.



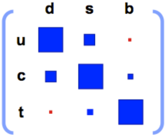
Penguin vertex



Box vertex

"Size" of the FCNC transition (effective vertex) depends on

- $\star$ masses of internal quarks/leptons
  $\Rightarrow$ D more suppressed than B, K decays
- $\star$ V_{CKM} elements
  $\Rightarrow$ $(b \rightarrow d)$ more suppressed than $(b \rightarrow s)$

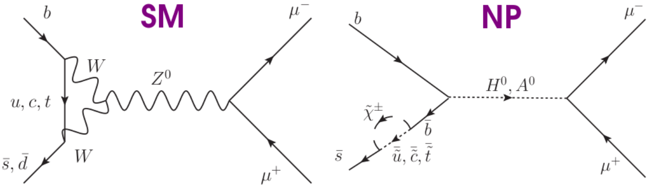


But

Why look for very rare decays? (2)

But!

- Purely leptonic final states: theoretical calculation clean, H_{eff} under control
  - low-energy hadronic matrix elements from leading semileptonic decays
  - perturbative QCD corrections recently improved
- New Physics can strongly modify the BR (new processes, new particles)



More on electroweak penguins on Thursday (K. Petridis)

Example: diagrams contributing to $B^0_{(s)} \to \mu^+\mu^-$.

LHCb analysis discussed

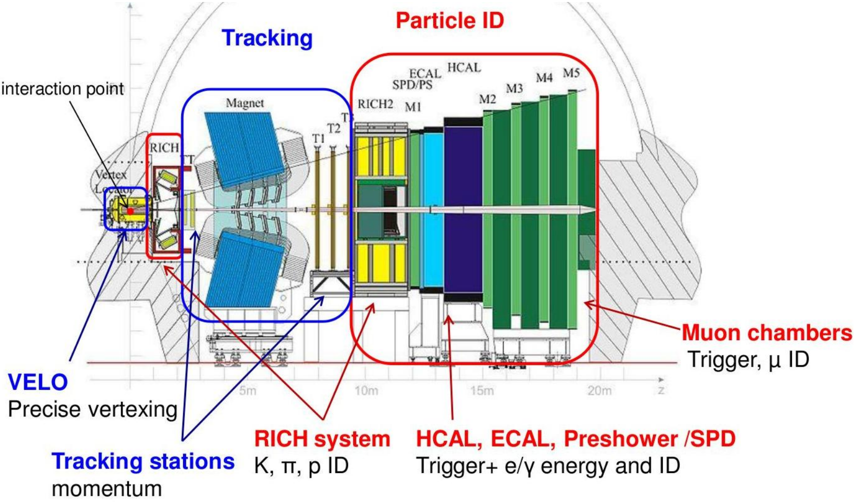
$D^0 \to \mu^+\mu^-$ → *R*-parity violating models

$K_S^0 \to \mu^+\mu^-$ → Models with new light scalars

$B^0_{(s)} \to \mu^+\mu^-\mu^+\mu^-$ → MSSM models with sgoldstino pairs production

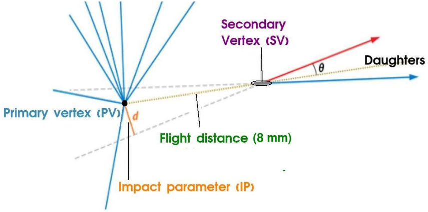
$B^0_{(s)} \to \mu^+\mu^-$ → Extended Higgs sector models

General analysis strategy: LHCb experiment



General analysis strategy: signal selection

- Triggers: mainly muon and dimuon lines
  (ϵ_{TRIG} ~70-90%)
- Particle Identification: μ for final states, h for control channels
  (ex. $\epsilon_{\mu\mu}$ ~98%, $\epsilon_{\pi\to\mu}$ ~0.6%)
- Meson mass requirements
  (ex. $\sigma(m)_{B_s^0\to\mu^+\mu^-} \sim 26$ MeV/c^2)
- Vertex criteria: tracks fitting, pointing, separation
  (σ_{vertex} ~16μm in x,y)



Backgrounds rejection

- **Combinatorial background → MultiVariate Analysis:**
  real leptons in the events, not coming from the same meson-decays
  MVA classifier is typically a Boosted Decision Tree (BDT)
- **"Peaking" backgrounds → MC/data-driven studies**
  exclusive decays with final state hadron(s) misId. as muon ($h \to \mu$) might peak in the signal search window

General analysis strategy: $\mathcal{BR}$ estimation

- **Normalisation** on a channel with same topology, to reduce uncertainties

$$\mathcal{BR}\ (signal) = \frac{N_{signal}}{N_{norm}} \frac{\epsilon_{signal}}{\epsilon_{norm}} \cdot \mathcal{BR}\ (norm)$$

Efficiencies ϵ from MC, data-driven corrections.

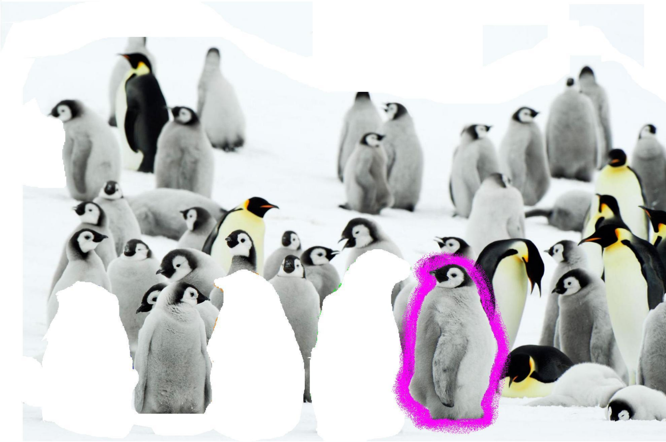
- **Blind approach**: signal region examined only after analysis and strategy for systematics extraction are optimised

- **Limit** determination: CL_s method for compatibility of observation with expectations, significance (typically set using CL_b estimator) [J. Phys. G28 2693]

- **Branching fraction** estimation: unbinned likelihood fit to mass spectra

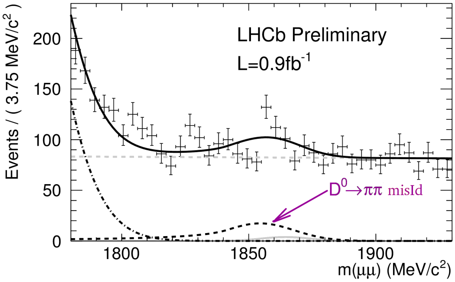
LHCb analyses discussed

$D^0 \to \mu^+\mu^-$ → *R*-parity violating models

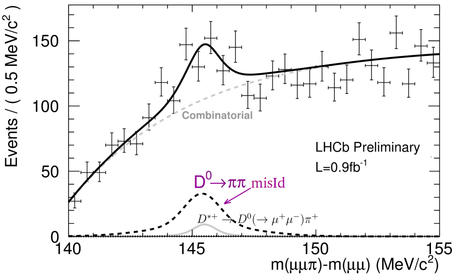


Analysis of 0.9 fb^{-1} at LHCb (2011)

- Use D^0 from D^{*+} decays ($D^{*+} \to D^0(\to \mu^+\mu^-)\pi^+$)
- Main backgrounds: combinatorial + peaking from $D^0 \to h^+h^-$ (mainly double misidentified $D^0 \to \pi\pi$)
- Normalisation on $D^0 \to \pi^+\pi^-$
- Unbinned extended maximum likelihood fit in 2D ($m(\mu\mu)$, Δm=$m_{(D^{*+})}$-$m_{(D^0)}$)



$1780 < m(\mu\mu) < 1810$ MeV/c^2

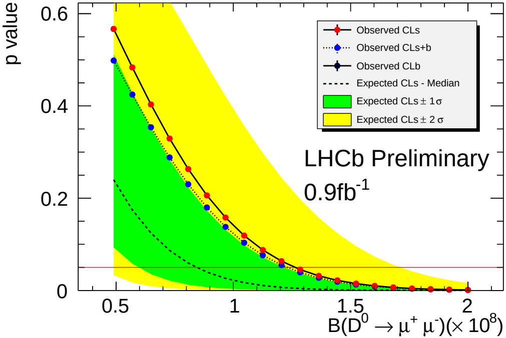


$142 < \Delta m < 149$ MeV/c^2

$D^0 \to \mu^+\mu^-$: best new limit

SM: strong GIM suppressions, $\mathcal{BR}_{SM} \sim 6{\cdot}10^{-11}$ at 90%C.L. [Phys. Rev. D66 (2002)]
Best experimental limit (Belle) was: $\mathcal{BR}_{exp} < 1.4{\cdot}10^{-7}$ at 90% C.L.

Observation compatible with expected background, limit extraction with CL_s



$\text{BR}(D^0 \to \mu^+\mu^-) < 1.3\ (1.1) \cdot 10^{-8}$ at 95(90)% C.L.

Still orders of magnitude larger than SM, paper in preparation with improved analysis.

LHCb analyses discussed

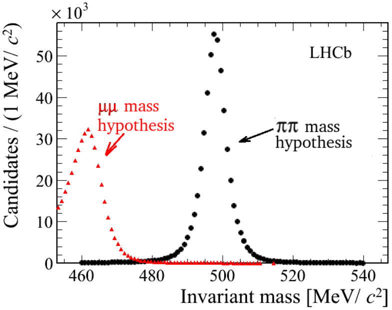
$D^0 \to \mu^+\mu^-$

$K^0_S \to \mu^+\mu^-$ $\to$ Models with new light scalars

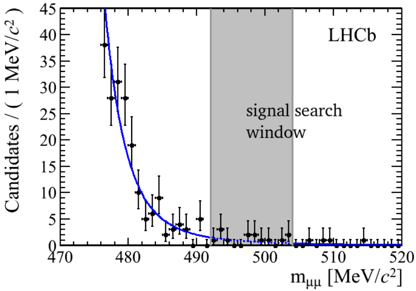
Analysis of 1 fb^{-1} at LHCb (2011)

- Normalisation on $K^0_S \rightarrow \pi^+\pi^-$
- Combinatorial background (exponential) + peaking $K^0_S \rightarrow \pi^+\pi^-$ with double misId (power law function)

Selected $K^0_S \rightarrow \pi^+\pi^-$ events:



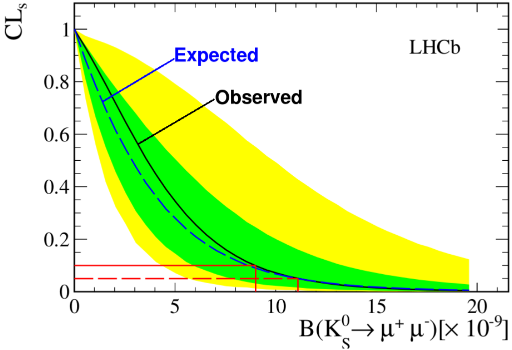
Background model fitted to data:



$K_S \to \mu^+\mu^-$: world's best limit.

SM expectation: $\mathcal{BR}_{SM} = (5.1 \pm 1.5) \cdot 10^{-12}$ [NuPh B366(1991)189] [JHEP 0401(2004)009]
Best experimental limit (1973) was: $\mathcal{BR}_{exp} < 3.2 \cdot 10^{-7}$ at 90% C.L.

Results: candidates consistent with expected background, limit extraction



$\mathcal{BR}(K_S^0 \to \mu^+\mu^-) < 11(9) \cdot 10^{-9}$ at 95(90)% C.L.

Factor 30 improvement on limit!

LHCb analyses discussed

$D^0 \rightarrow \mu^+\mu^-$

$K^0_S \rightarrow \mu^+\mu^-$

$B^0_{(s)} \rightarrow \mu^+\mu^-\mu^+\mu^-$ $\rightarrow$ MSSM models with sgoldstino pairs production

$B^0_{(s)} \to \mu^+\mu^-\mu^+\mu^-$

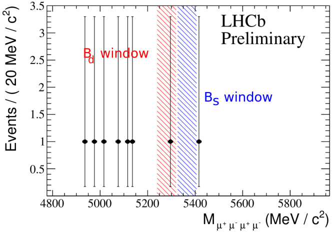
SM: $\mathcal{BR}$ of non-resonant mode $(B^0_q \to \mu^+\mu^-\gamma^*(\mu^+\mu^-)) < 10^{-10}$

[Phys.Rev. D70(2004)114028]

No experimental limits before this analysis.

Analysis of 1 fb^{-1} at LHCb

- Selection to maximise signal and remove resonant mode $B^0_s \to J/\psi\phi$
- Normalisation on $B^0 \to J/\psi(\to \mu\mu)K^{*0}(\to K\pi)$



- Result: 1 event observed in B^0_d window, 0 in B^0_s. Consistent with expected background
- Limits at 95(90)% C.L.:

$$\mathcal{BR}\ (B_s \to 4\mu) < 1.3\ (1.0)\ \cdot 10^{-8}$$
$$\mathcal{BR}\ (B_d \to 4\mu) < 5.4\ (4.3)\ \cdot 10^{-8}$$

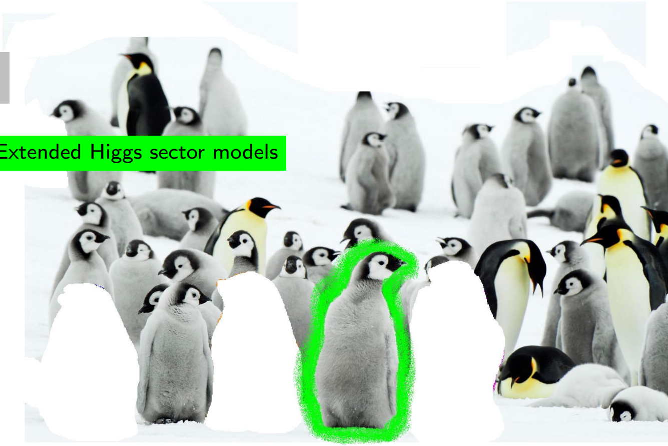
LHCb analyses discussed

$D^0 \to \mu^+\mu^-$

$K^0_S \to \mu^+\mu^-$

$B^0_{(s)} \to \mu^+\mu^-\mu^+\mu^-$

$B^0_{(s)} \to \mu^+\mu^-$ $\to$ Extended Higgs sector models



$B^0_{(s)} \to \mu^+\mu^-$: SM and beyond

SM prediction

- FCNC (Z-penguin, W-box) + helicity suppressions
- Effective calculation with QCD correction [Buras et al., arXiv:1208.0934]:

$$\mathcal{BR}\,(B^0 \to \mu^+\mu^-)_{SM} = \mathbf{(1.07{\pm}0.10){\cdot}10^{-10}}$$
$$\mathcal{BR}\,(B^0_s \to \mu^+\mu^-)_{SM} = (3.23{\pm}0.27){\cdot}10^{-9}$$

- Time integrated correction, accounting for the finite width $\Delta\Gamma(B_s)$ [LHCb-CONF-2012-002] [De Bruyn et al., PRL 109, 041801]:

$$\mathcal{BR}\,(B^0_s \to \mu^+\mu^-)^{\Delta\Gamma}_{SM} = \mathbf{(3.54{\pm}0.30){\cdot}10^{-9}}$$

Beyond SM

$$\mathcal{BR} \propto |C_s - C_s'|^2 \,(1\text{-}\frac{4m_\mu^2}{m_{B_s}^2}) + |\,(C_P - C_P') + \frac{2m_\mu}{m_{B_s}^2}(C_{10} - C_{10}')|^2$$

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Beyond SM

$$\mathcal{BR} \propto |C_s - C'_s|^2 \left(1 - \frac{4m^2_\mu}{m^2_{B_s}}\right) + \left| \left(C_P - C'_P \right) + \frac{2m_\mu}{m^2_{B_s}} \left(C_{10} - C'_{10} \right) \right|^2$$

- New particles & diagrams: SM coupling and NP couplings

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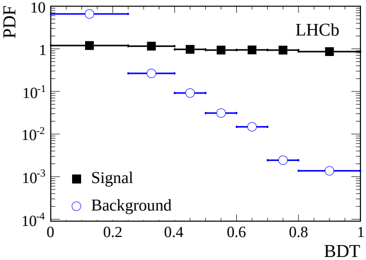
- New particles & diagrams: SM coupling and NP couplings
- Axial contributions suppressed with respect to (pseudo-)scalar

$\Rightarrow B^0_{(s)} \to \mu^+\mu^-$ sensitive to NP in the **scalar sector**.

$B^0_{(s)} \to \mu^+\mu^-$: 2012 analysis

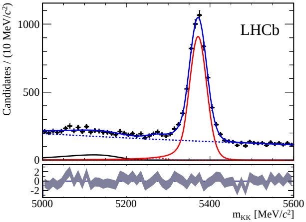
Signal/background classification

- Selection: pairs of μ^+ μ^-, displaced vertex, $m(\mu\mu) \in$ [4900-6000]MeV/c^2
- **BDT**: discrimination of combinatorial background, real μ's from $b\bar{b} \to \mu\mu X$
  - trained on MC samples
  - calibrated on data (exclusive $B^0 \to hh$ for **signal**, dimuon mass sidebands for **bkgd**)



Signal Invariant Mass (IM)

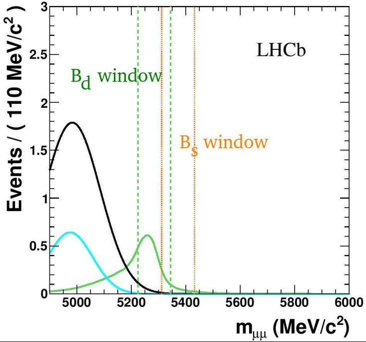
- Pdf: Crystal ball function
- Peak position: from exclusive $B^0 \to hh$ decays (h=K, π)
- Resolution: from interpolation of dimuon resonances (J/ψ, ϕ, Υ, ...), in agreement with exclusive $B^0 \to hh$ result



Normalisation on two independent channels: $B^\pm \to J/\psi K^\pm$ and $B^0 \to K\pi$, averaged.
Ratio of b-**fragmentation fractions** $f_s/f_d = 0.256 \pm 0.020$ [LHCb-PAPER-2012-037]

$B^0_{(s)} \to \mu^+\mu^-$: backgrounds for 2012 analysis

Combinatorial	contaminates mass windows *exponential model from sidebands interpolation*
$B^0 \to hh$, **double misId**	**peaking** in mass windows (particularly B_d) *shape from MC, folded with misId from data*
Exclusive semileptonic decays, single $h \to \mu$ misId	negligible in mass windows; some included in the sidebands fit, to avoid an interpolation bias *shape from MC, normalisation with misId from data*



Exclusive backgrounds dedicated study (improved in 2012):

$B^0_d \to \pi^-\mu^+\nu$

$B^0_d \to K^-\mu^+\nu$

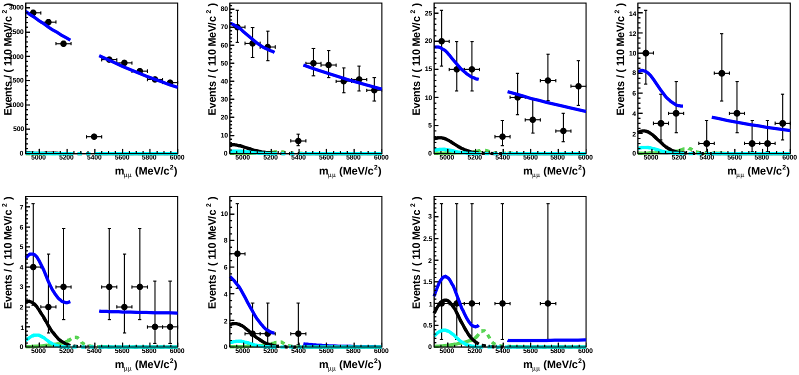
$\Lambda^0_b \to p\mu^-\nu$

$B^{0(+)} \to \pi^{0(+)}\mu^+\mu^-$

$B^+_c \to J/\psi(\mu^+\mu^-)\mu^+\nu$

$B^0_{(s)} \to \mu^+\mu^-$: 2012 blind data [LHCb-PAPER-2012-043, arXiv:1211.2674]

Mass sidebands fit for 8 TeV data, 7 BDT bins:

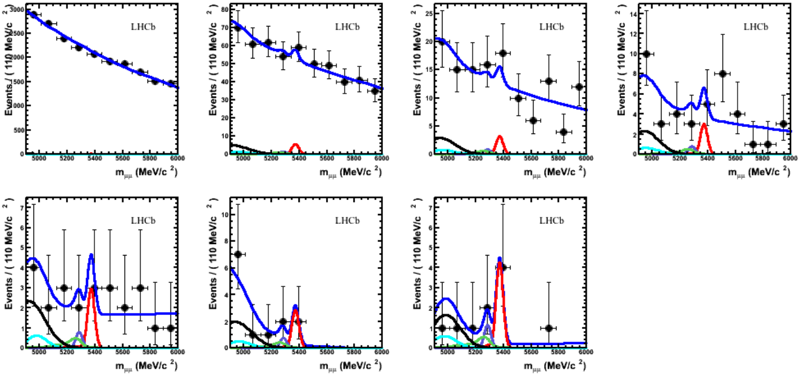


All background pdf's are included in the global fit of the blind data sidebands:

$B^0_d \to \pi^-\mu^+\nu_\mu$	$B^{0(\pm)}_{d(u)} \to \pi^{0(\pm)}\mu^+\mu^-$	$B^0_{(s)} \to h^+h^-$	Total

$B^0_{(s)} \to \mu^+\mu^-$: unblind!

Fit to unblinded 8 TeV data, 7 BDT bins:



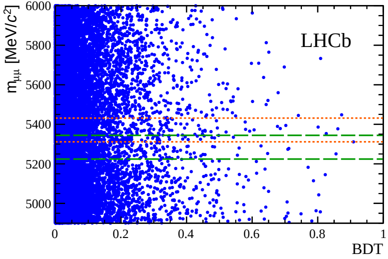
$B^0_s \to \mu^+\mu^-$	$B^0 \to \mu^+\mu^-$	$B^0_d \to \pi^-\mu^+\nu_\mu$
$B^{0(\pm)}_{d(u)} \to \pi^{0(\pm)}\mu^+\mu^-$	$B^0_{(s)} \to h^+h^-$	Total

$B^0_{(s)} \to \mu^+\mu^-$: Combined results 2011+2012 (1.0+1.1fb^{-1})

NB: analysis on 2011 data repeated with 2012 strategy.

Observations vs Expectations.

- observed candidates in 2012 dataset, binned [IM, BDT] plane (B_d window, B_s window):



- comparison of N_{obs} with N^{SM}_{exp} and N^{bkd}_{exp}
- CL_s method to assess significance.

$B^0_{(s)} \to \mu^+\mu^-$: Combined results 2011+2012 ($1.0+1.1 fb^{-1}$)

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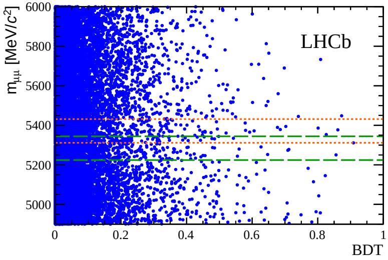


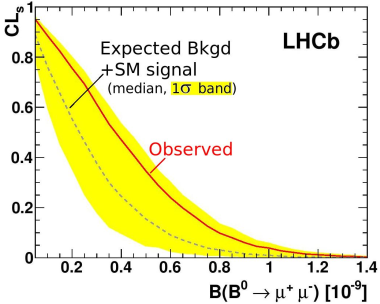
- comparison of N_{obs} with N^{SM}_{exp} and N^{bkd}_{exp}
- CL_s method to assess significance.

$B^0 \to \mu^+\mu^-$: No excess.

Combined 2011+2012: new world best limit!

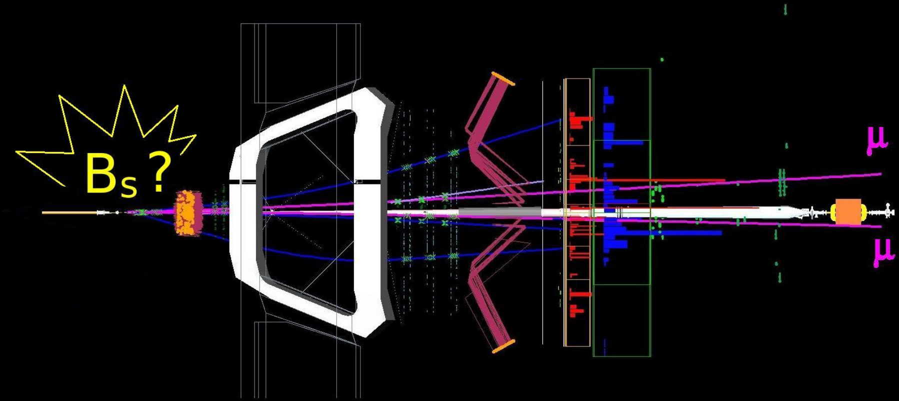
$\mathcal{BR}\ (B^0 \to \mu^+\mu^-)_{exp} < 7.1\cdot 10^{-10}$ at 95% C.L.

$\mathcal{BR}\ (B^0 \to \mu^+\mu^-)_{obs} < 9.4\cdot 10^{-10}$ at 95% C.L.



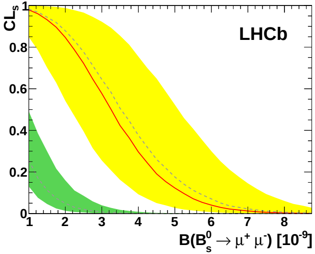
Compatibility with bkg only hypothesis:
p-value = 0.11

In the B_s mass window, at high BDT...



$B^0_{(s)} \to \mu^+\mu^-$: Combined results 2011+2012 (1.0+1.1fb^{-1})

$B^0_s \to \mu^+\mu^-$ excess!

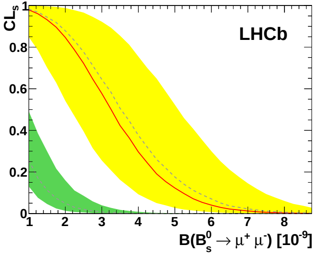


- Compatibility with bkg only hypothesis:

  p-value $= 5.3{\cdot}10^{-4} \Rightarrow$ **3.5σ excess**
- Compatible with bkg+signal !
- Double sided limit, at 95% C.L.: $1.1{\cdot}10^{-9} < \mathcal{BR}\ (B^0_s \to \mu^+\mu^-) < 6.4{\cdot}10^{-9}$

$B^0_{(s)} \to \mu^+\mu^-$: Combined results 2011+2012 (1.0+1.1fb^{-1})

$B^0_s \to \mu^+\mu^-$ excess!



- Compatibility with **bkg only** hypothesis:

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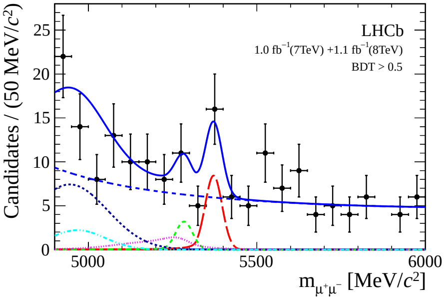
- Double sided limit, at 95% C.L.: $1.1{\cdot}10^{-9} < \mathcal{BR}\ (B^0_s \to \mu^+\mu^-) < 6.4{\cdot}10^{-9}$

$B^0_s \to \mu^+\mu^-\ \mathcal{BR}$ extraction

Unbinned maximum likelihood fit in [4900-6000] MeV/c^2, see slide 21:

- $\mathcal{BR}\ (B^0_s \to \mu^+\mu^-)$, $\mathcal{BR}\ (B^0 \to \mu^+\mu^-)$ and combinatorial bkd are free parameters



$$\mathcal{BR}\ (B^0_s \to \mu^+\mu^-) = (\ \mathbf{3.2}\ ^{+1.4}_{-1.2}\ (\text{stat})\ ^{+0.5}_{-0.3}\ (\text{syst})\ ) \cdot 10^{-9}$$

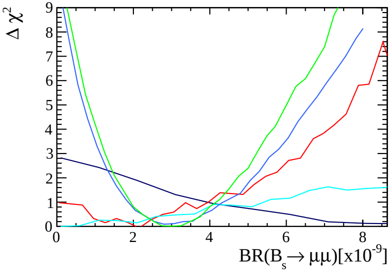
Summary

- Rare decays: interesting probes of new physics.
- LHCb analyses presented, common general strategy (limits at 95% C.L.):
  - $D^0 \to \mu^+\mu^-$: $\mathcal{BR} < \mathbf{1.3 \cdot 10^{-8}}$ new world best limit
  - $K_S^0 \to \mu^+\mu^-$: $\mathcal{BR} < \mathbf{11 \cdot 10^{-9}}$ new world best limit
  - $B^0_{(s)} \to \mu\mu\mu\mu$: $\mathcal{BR} < \mathbf{1.3\ (5.4)} \cdot 10^{-8}$ first limits
  - $B^0 \to \mu^+\mu^-$: $\mathcal{BR} < \mathbf{9.4 \cdot 10^{-10}}$ new world best limit
  - $B_s^0 \to \mu^+\mu^-$: $\mathcal{BR} = \mathbf{(3.2^{+1.5}_{-1.2}) \cdot 10^{-9}}$ **first evidence**!
- More on LHCb rare searches on Thursday (Harnew)
- What next?
  Experimental bounds closing in on the SM $\mathcal{BR}$'s, but still space for NP!
  New variables to investigate, ex: ratio of $\mathcal{BR}$ $(B_s^0 \to \mu^+\mu^-)/\mathcal{BR}$ $(B^0 \to \mu^+\mu^-)$,effective lifetime...

Backup

Impact of $B_s^0 \to \mu^+\mu^-$ result on NP [MasterCode webpage]

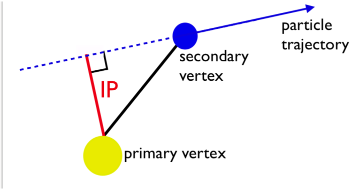
- MasterCode: Markov Chain MonteCarlo method to construct a global likelihood function that receives contributions from full set of electroweak precision observables
- A SM-like $\mathcal{BR}$ $(B_s^0 \to \mu^+\mu^-)$ is expected in constrained SUSY models, as CMSSM or NUHM1
- new $\mathcal{BR}$ $(B_s^0 \to \mu^+\mu^-)$ result is still quite consistent with SUSY
- the favoured regions in the parameter space of these models do not change significantly after the inclusion of the new constraint

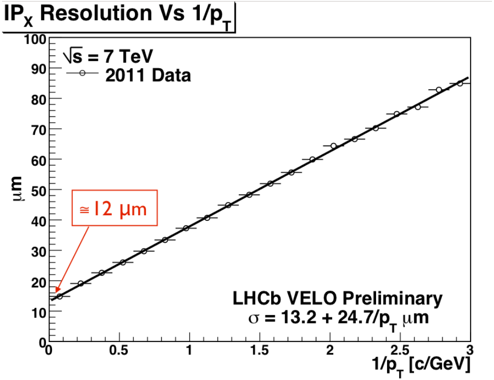


Combination of $\mathcal{BR}$ $(B_s^0 \to \mu^+\mu^-)$ measurements: ATLAS (Winter 2012), CDF (ASPEN 2012), CMS (Winter 2012), LHCb (HCP 2012), and combined likelihood.

More on LHCb: VELO IP resolution

Impact Parameter (IP):

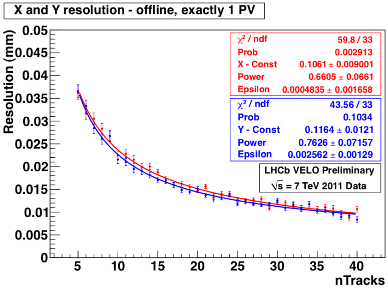




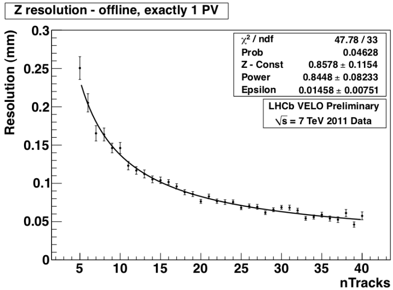
IP resolution $< 35\ \mu m$ for tracks with p>1 GeV/c

More on LHCb: VELO Vertex resolution

Primary Vertex resolution in (x, y):



Primary Vertex resolution in z:



For a 25-tracks vertex: in transverse plane $= 13\ \mu m$, in z-direction $= 71\ \mu m$

More on muonID at LHCb

Muon Identification

- `isMuon` requirement:
  - track extrapolated from tracking to muon stations
  - look for (muon station) hits in a defined field of interest (FOI)
  - combination of requirements on track p and number of hits found
- muon hypothesis test:
  - information from muon system, RICH and CALO combined to build a muon likelihood $L(\mu)$ and a non-muon one $L(K)$, $L(\pi)$
  - global DLL ($\Delta LogL$) used as discriminating variable for the muon test

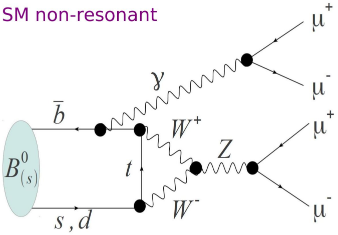
Calibration and efficiencies determined on data (tag&probe methods): $J/\psi \to \mu\mu$, $D \to K\pi$, $K_s \to \pi\pi$, etc

Ex, $B^0_{(s)} \to \mu^+\mu^-$analysis: simultaneous cuts of $DLL(\mu - \pi)$ >-5 and $DLL(K - \pi)$ <10 reduce (by a factor ~5) the rate of $B \to hh$ events with double hadron misidentification

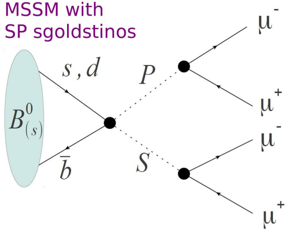
More on $B^0_{(s)} \to \mu^+\mu^-\mu^+\mu^-$

- In SuSy extensions of SM, goldstino superpartners (S and P sgoldstinos) can be light enough for emerging in decays of SM particles [arXiv:1112.5230v2]
- Sgoldstino coupling to SM fields are prop to the SuSy breaking parameters
- Prominent signature of sgoldstino pair production is 2 muon pairs!
- $\mathcal{BR}\ (B_s \to SP < 10^{-4})$
- LHCb search sensitive to $B_s \to SP$ with m(P) similar to that reported by HyperCP [PRL 94, 021801]

SM non-resonant



MSSM with SP sgoldstinos



$B^0_{(s)} \to \mu^+\mu^-$: Status at today

Status at June 2012 (LHC):

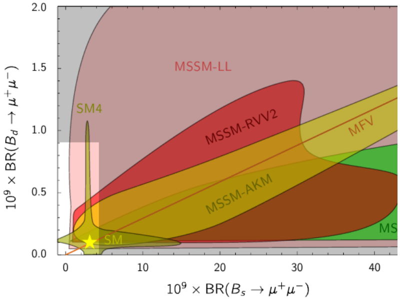
$\mathcal{BR}\ (B^0_s \to \mu^+\mu^-) < 4.2{\cdot}10^{-9}$ at 95% C.L.
$\mathcal{BR}\ (B^0 \to \mu^+\mu^-) < 8.1{\cdot}10^{-10}$ at 95% C.L.

[LHC combination note]

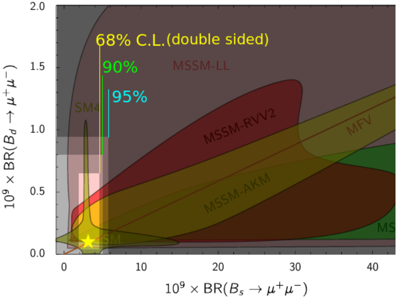
Status at November 2012 (LHCb only):

$\mathcal{BR}\ (B^0_s \to \mu^+\mu^-) = (3.2^{+1.5}_{-1.2}){\cdot}10^{-9}$
$\mathcal{BR}\ (B^0 \to \mu^+\mu^-) < 9.4{\cdot}10^{-10}$ at 95% C.L.

[LHCb-PAPER-2012-043]



[Straub, Moriond EWK 2012]

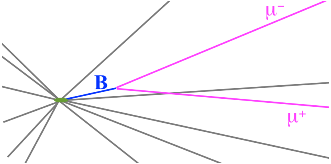


More on $B^0_{(s)} \to \mu^+\mu^-$: selection

see [CERN seminar Nov12]

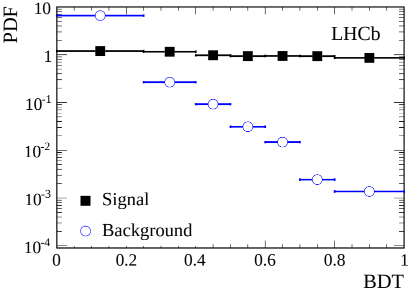
After selection:

- pairs of opposite charged muons
- secondary vertex displaced
- $m(\mu\mu)$ in the range [4900-6000] MeV/c^2
- loose cut on MVA discriminant



Signal/background separation: BDT

Discrimination of combinatorial background (2 real muons from $b\bar{b} \to \mu\mu X$)



- 9 input variables,uncorrelated with inv mass
- training on MC signal and background samples
- signal shape (calibration) from exclusive $B^0 \to hh$ channels
- background shape from dimuon mass sidebands

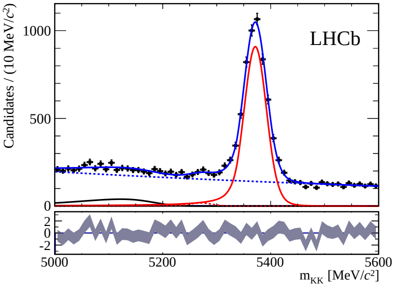
More on $B^0_{(s)} \to \mu^+\mu^-$: Invariant Mass

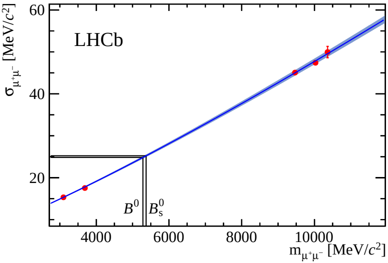
Signal invariant mass

- Pdf: Crystal ball function
- Peak position: from exclusive $B^0 \to hh$ decays (h=K, π)
- Resolution: from interpolation of dimuon resonances (J/ψ, ϕ, Υ, ...) and from exclusive $B^0 \to hh$; results in agreement.

$$\sigma(B^0) = (24.63 \pm 0.13_{stat} \pm 0.36_{syst}) MeV/c^2$$

$$\sigma(B^0_s) = (25.04 \pm 0.18_{stat} \pm 0.36_{syst}) MeV/c^2$$





More on $B^0_{(s)} \to \mu^+\mu^-$: Normalisation

$$\mathcal{BR}_{B^0_{(s)}\to\mu^+\mu^-} = \mathcal{BR}_{norm} \frac{\epsilon^{RECO}_{norm}}{\epsilon^{RECO}_{B^0_{(s)}\to\mu^+\mu^-}} \frac{\epsilon^{SEL/RECO}_{norm}}{\epsilon^{SEL/RECO}_{B^0_{(s)}\to\mu^+\mu^-}} \frac{\epsilon^{TRG/SEL}_{norm}}{\epsilon^{TRG/SEL}_{B^0_{(s)}\to\mu^+\mu^-}} \frac{f_{norm}}{f_{B^0_q}} \frac{N_{B^0_{(s)}\to\mu^+\mu^-}}{N_{norm}} = \alpha \cdot N_{B^0_{(s)}\to\mu^+\mu^-}$$

Normalisation strategy

- two independent channels: $B^\pm \to J/\psi K^\pm$ and $B^0 \to K\pi$, averaged
- selection and reconstruction efficiencies from MC with some data inputs:
  - IP smearing to make MC more similar to data
  - Muon ID efficiency from data
  - Invariant mass cut efficiency corrected for data resolution
  - Tracking efficiency corrected from data
  - Trigger efficiency from data
- stability of the yields N_{norm} checked throughout the year dataset
- ratio of b-fragmentation fractions from last LHCb result: $f_s/f_d = 0.256 \pm 0.020$
  f_s/f_d p_T dependence checked on data 2012, stable within 1.5σ

More on $B^0_{(s)} \to \mu^+\mu^-$ backgrounds: $B \to hh$ double misId

- misId probability ($\epsilon_{hh\to\mu\mu}$) for kaons and pions with tag&probe from $D^+ \to D^0(\to K\pi^+)\pi^+$, in p and p_T bins
- total number of misId decays extracted from number of triggered ones with
  - misId probability correction
  - trigger correction (difference between $B^0_{(s)} \to hh$and $B^0_{(s)} \to \mu^+\mu^-$triggers)
- Invariant Mass shape extracted from data, cross-checked with $B^0_{(s)} \to hh$exclusive
- BDT shape corrected for a BDT-dependent misId rate