Very rare B decays at LHCb

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on behalf of the LHCb Collaboration

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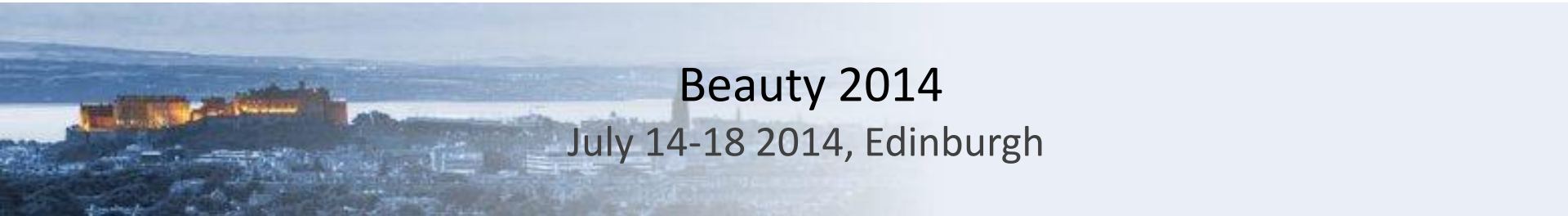


Beauty 2014
July 14-18 2014, Edinburgh

Outline

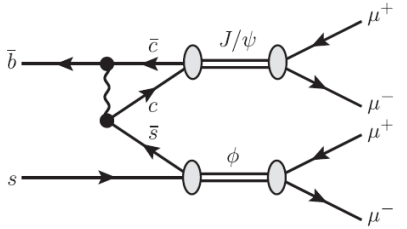
- Search for $B^0_{(s)} \to \mu^+\mu^-\mu^+\mu^-$ decays
- Search for $B^0_{(s)} \to e^\pm\mu^\mp$ decays
- $B^0_{(s)} \to \mu\mu$ decays

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

In Standard Model:

- Dominated by $B^0_s \to J/\psi(\to \mu^+\mu^-)\phi(\to \mu^+\mu^-)$
- BF=$(2.3 \pm 0.9) \times 10^{-8}$
- Main SM nonresonant contribution $B^0_{(s)} \to \mu^+\mu^-\,\gamma(\to \mu^+\mu^-)$, BF$< 10^{-10}$

$B^0_s \to J/\psi(\to \mu^+\mu^-)\phi(\to \mu^+\mu^-)$

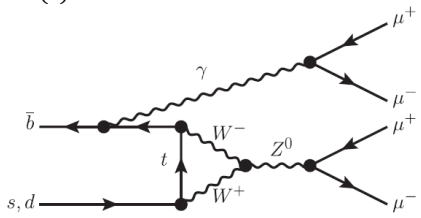


Beyond SM:

- BF can be significantly enhanced, for example in MSSM: $B \to S(\to \mu^+\mu^-)P(\to \mu^+\mu^-)$, S and P sgoldstino particles

[PRD85,077701 (2012)]

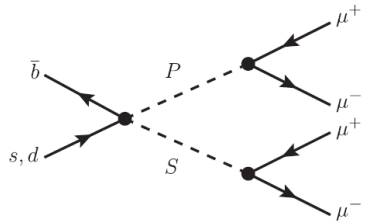
$B^0_{(s)} \to \mu^+\mu^-\,\mu^+\mu^-$



Interest also related to the evidence of $\Sigma^+ \to p\mu^+\mu^-$ by the HyperCP Collaboration consistent with existence of $P \to \mu^+\mu^-$ with M(P)=214.3 ± 0.5 MeV

[PRL94, 021801 (2005)]

SUSY decay channel



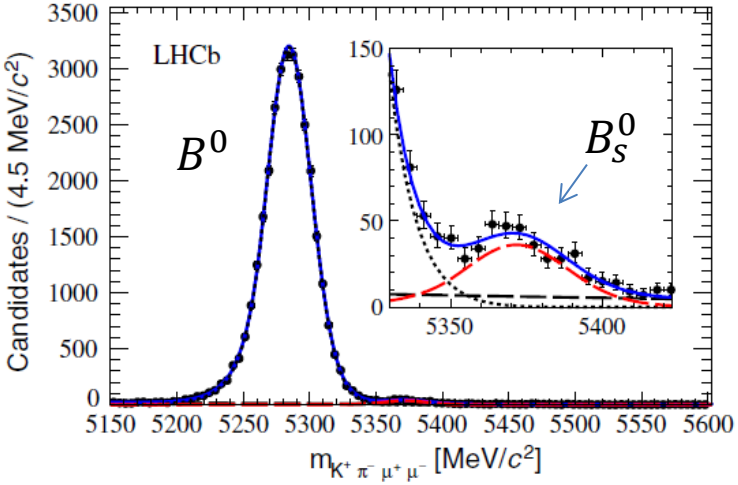
Search for $B^0_{(s)} \to \mu^+\mu^-\mu^+\mu^-$ decays

PRL 110, 211801 (2013)

Signal selection

- Dataset: 1 fb^{-1} , $\sqrt{s} = 7$ TeV
- Tight muon PID criteria ($\epsilon(\mu) = 78.5\%, \epsilon(\pi \to \mu) = 1.4\%$))
- 4 muons originating from single vertex and far from the primary vertex
- J/ψ and ϕ mass vetoes to remove the dominant $B_s \to J/\psi\,\phi$

normalization mode $B^0 \to J/\psi(\to \mu^+\mu^-)\,K^{*0}(\to K^+\pi^-)$



BF measurement

- $B^0 \to J/\psi(\to \mu^+\mu^-)\,K^{*0}(\to K^+\pi^-)$ used as normalization ($K\pi$ S-wave excluded)

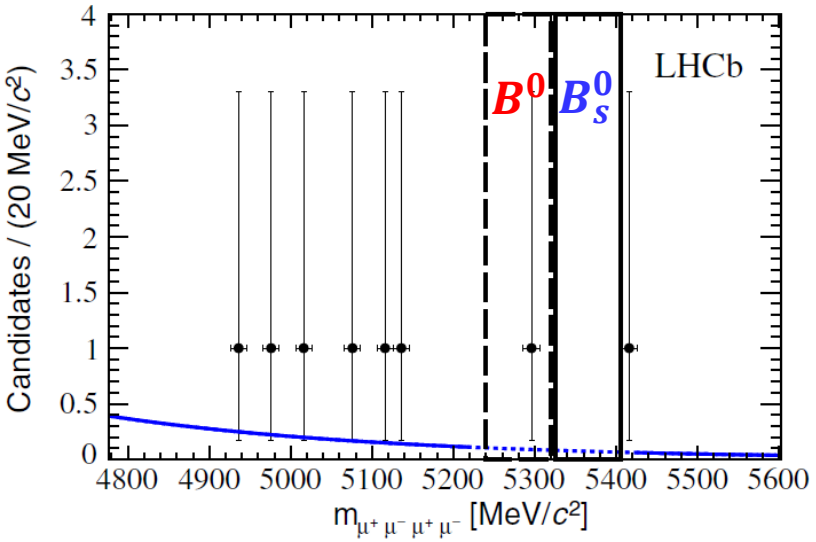
- $$\mathcal{B}(B^0_{(s)} \to \mu^+\mu^-\mu^+\mu^-) = \mathcal{B}(B^0 \to J/\psi K^{*0}) \times \frac{\epsilon_{B^0 \to J/\psi K^{*0}}}{\epsilon_{B^0_{(s)} \to \mu^+\mu^-\mu^+\mu^-}} \frac{N_{B^0_{(s)} \to \mu^+\mu^-\mu^+\mu^-}}{N_{B^0 \to J/\psi K^{*0}}} \left(\frac{f_{d(s)}}{f_d}\right)^{-1} \kappa$$

$\epsilon_{B^0 \to \mu^+\mu^-\mu^+\mu^-} = 0.349 \pm 0.003$ %
$\epsilon_{B^0_s \to \mu^+\mu^-\mu^+\mu^-} = 0.359 \pm 0.003$ %
$\epsilon_{B^0 \to J/\psi K^{*0}} = 0.273 \pm 0.003$ %
$\kappa = 1.09 \pm 0.09$ correction for the S-wave exclusion
$f_s/f_d = 0.256 \pm 0.020$ B^0/B^0_s production fraction

[JHEP 1304 (2013) 001, LHCb-CONF-2013-011]

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

PRL 110, 211801 (2013)



1 event in B^0 mass window,
0 event in B^0_s mass window
Consistent with background expectation

Set 90% (95%) CL upper limits with phase space model:

$BF(B^0_s \to \mu^+\mu^-\mu^+\mu^-) < 1.2(1.6) \times 10^{-8}$

$BF(B^0 \to \mu^+\mu^-\mu^+\mu^-) < 5.3(6.6) \times 10^{-9}$

Set 90% (95%) CL upper limits for MSSM model with $m_{P(S)} = 214.3$ MeV (2.5 GeV) (*):

$BF(B^0_s \to SP \to 4\mu) < 1.2(1.6) \times 10^{-8}$

$BF(B^0 \to SP \to 4\mu) < 5.1(6.3) \times 10^{-9}$

(*) compared to phase space model: tiny change of reconstruction efficiency due to different **p** distribution of muons

Search for $B^0_{(s)} \to e^{\pm}\mu^{\mp}$ decays

Lepton flavor violating process forbidden in SM

Decay allowed in several NP scenarios including models with heavy singlet Dirac neutrinos, SUSY and the Pati-Salam model

The Pati-Salam model predicts a new interaction to mediate transitions between leptons and quarks via exchange of spin-1 gauge bosons (Pati-Salam leptoquarks, LQ)

[PRD 10 (1974) 275]

Direct searches for pair production of 1st and 2nd generation scalar LQ at ATLAS and CMS exclude LQ mass ranges $\lesssim 1$ TeV

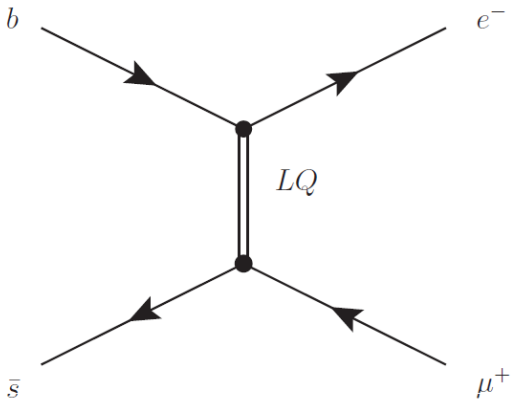
Previous branching fraction limits from CDF:

$BF\left(B_s^0 \to e^{\pm}\mu^{\mp}\right) < 2.0(2.6)\ 10^{-7}$ @ 90(95)% CL

$BF\left(B^0 \to e^{\pm}\mu^{\mp}\right) < 6.4(7.9)\ 10^{-8}$ @ 90(95)% CL

[PRL 102,201801(2009)]

LQ coupling to leptons and quarks of different generations

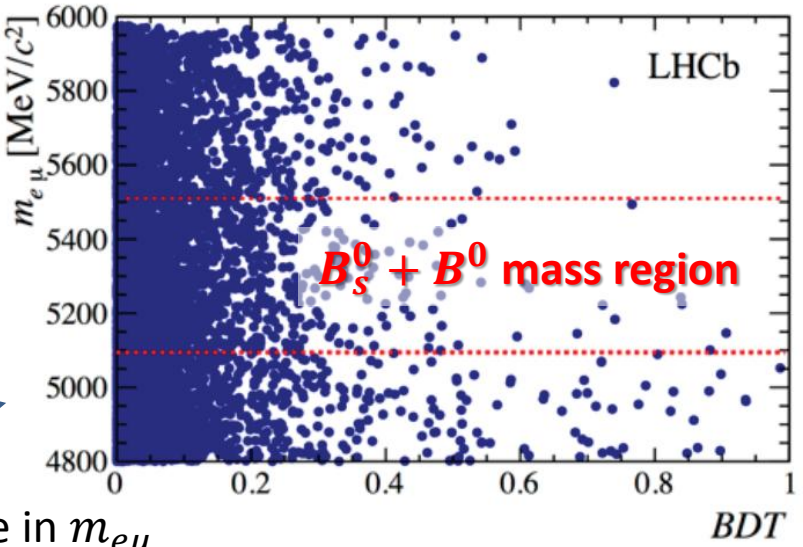


Search for $B^0_{(s)} \to e^{\pm}\mu^{\mp}$ decays

[PRL 111,141801 (2013)]

Signal selection

- Dataset: 1 fb^{-1} , $\sqrt{s} = 7$ TeV
  $B^0 \to K^+\pi^-$ used as normalization channel
  Main background from $b\bar{b} \to e^{\pm}\mu^{\mp}X$ decays
  Final signal/background discrimination through BDT (multivariate classifier) and $m_{e\mu}$



signal: flat in BDT, peaks at $m_{B^0_{(s)}}$ in $m_{e\mu}$

background: peaks at 0 in BDT, exponential shape in $m_{e\mu}$

Result:

Events in signal region consistent with the expected background

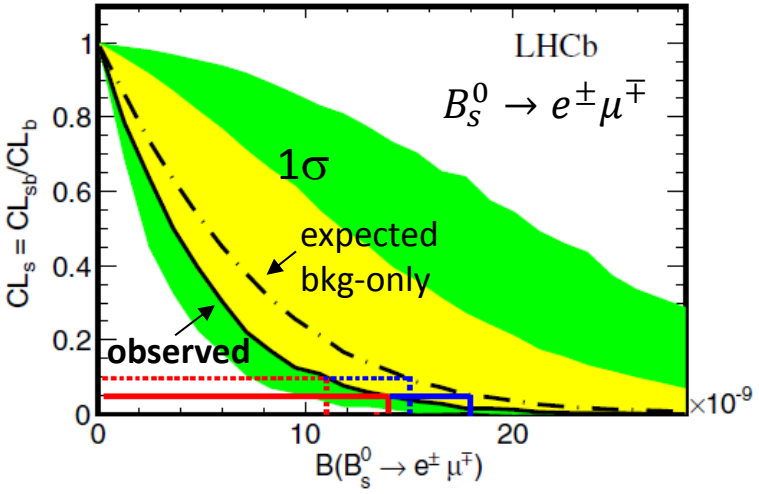
$$\mathcal{B}(B^0_{(s)} \to e^{\pm}\mu^{\mp}) = \frac{\mathcal{B}_{\text{norm}}\,\epsilon_{\text{norm}} f_d}{N_{\text{norm}}\,\epsilon_{\text{sig}} f_{d(s)}} \times N_{B^0_{(s)} \to e^{\pm}\mu^{\mp}}$$

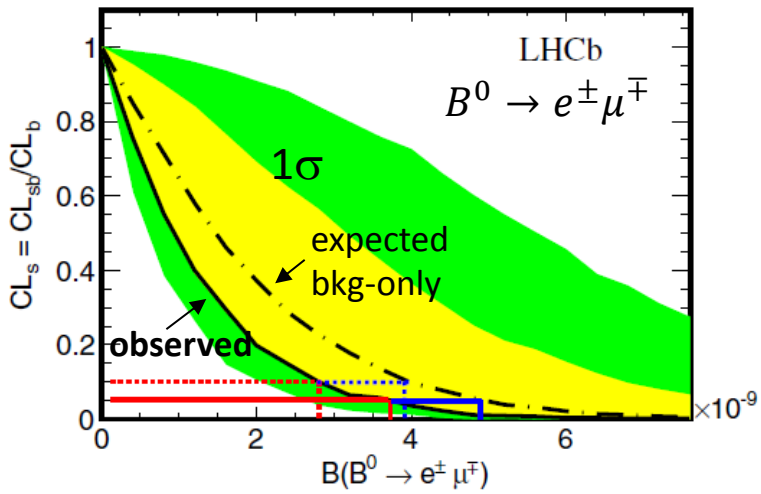
norm = $B^0 \to K^+\pi^-$
$f_s/f_d = 0.256 \pm 0.020$ B^0/B^0_s production fraction

Upper limit on $B(B^0_{(s)} \to e^{\pm}\mu^{\mp})$ evaluated with the CLs method

Search for $B^0_{(s)} \to e^{\pm}\mu^{\mp}$ decays

[PRL 111,141801 (2013)]





	$B^0_s \to e\mu$ at 90%(95%) CL	$B^0 \to e\mu$ at 90%(95%) CL
Previous (CDF 2fb^{-1})	$20.0\ (20.6)10^{-8}$	$64.0\ (79.0)10^{-9}$
Expected (LHCb 1fb^{-1})	$1.5\ (1.8)10^{-8}$	$3.8\ (4.8)10^{-9}$
Observed (LHCb 1fb^{-1})	$1.1\ (1.4)10^{-8}$	$2.8\ (3.7)10^{-9}$

Lower limits on Pati-Salam leptoquark masses [PRD50, 6843 (1994)]

LHCb

$m_{LQ}(B^0_s \to e^{\pm}\mu^{\mp}) > 107$ TeV @90% CL

$m_{LQ}(B^0 \to e^{\pm}\mu^{\mp}) > 135$ TeV @90% CL

CDF

$m_{LQ}(B^0_s \to e^{\pm}\mu^{\mp}) > 47.8$ TeV @90% CL

$m_{LQ}(B^0 \to e^{\pm}\mu^{\mp}) > 59.3$ TeV @90% CL

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

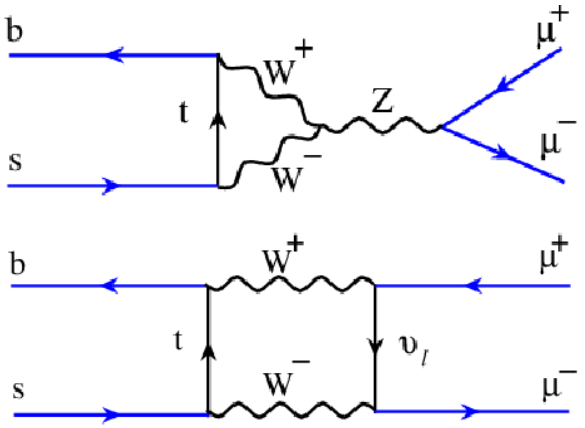
SM prediction

FCNC processes, additional helicity suppression, theoretically clean

$B^0_s \to \mu\mu$: $(3.65 \pm 0.23)\ 10^{-9}$

$B^0 \to \mu\mu$: $(1.06 \pm 0.09)\ 10^{-10}$

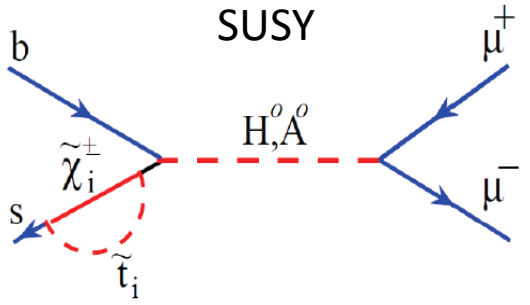
[A.J. Buras et al, EPJC 72 2172 (2012), Bobeth et al, PRL112, 101801 (2014)]



beyond the SM

The branching fraction can be significantly enhanced in a number of NP models. SUSY, 2HDM, SM4, …

Especially sensitive to contributions in the scalar/pseudoscalar sector



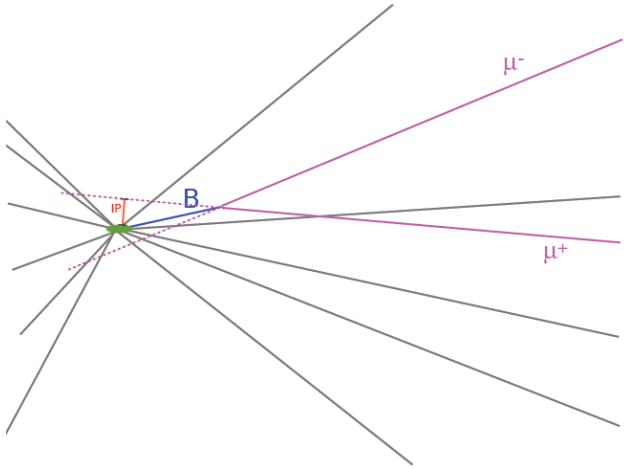
for the future: $BF(B^0 \to \mu\mu)/BF(B^0_S \to \mu\mu)$ sensitive probe of the MFV hypothesis

Analysis strategy

[PRL111, 101805 (2013)]

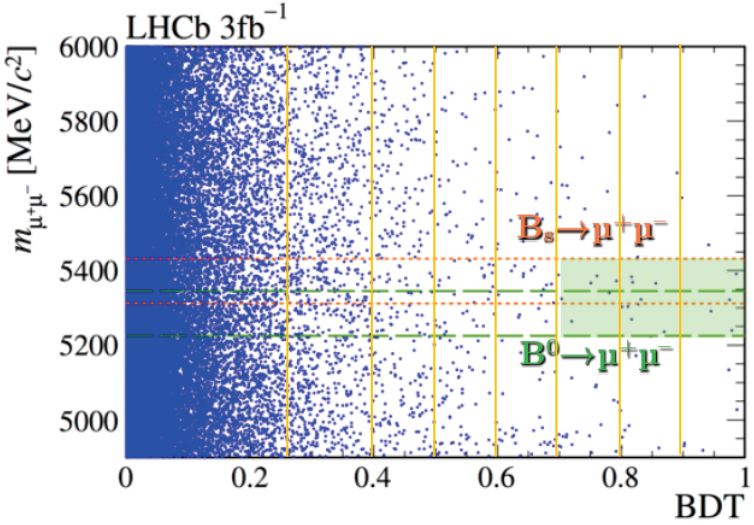
Loose selection

- Dataset: 3 fb^{-1} (1.0 at $\sqrt{s} = 7$ TeV, 2.0 at $\sqrt{s} = 8$ TeV)
- 2 muons from vertex displaced from the IP
- Additional requirements on tracks and B candidate
- $m(\mu\mu)$ in [4900,6000] MeV



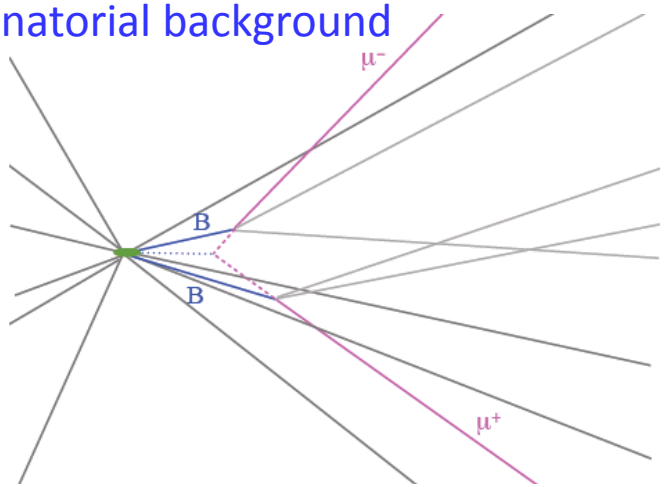
Signal extraction in $m(\mu\mu)$ vs BDT plane

- BDT: multivariate classifier based on 12 kinematic and 'geometric' variables
- Signal: flat in BDT, peaks at $m_{B_s^0}$ or m_{B^0}
- Background: strongly peaking at 0 in BDT, exponential or peaking in $m(\mu\mu)$
- Extract $B^0_{(s)} \to \mu\mu$ yields from fit of $m(\mu\mu)$ in 8 BDT subregions



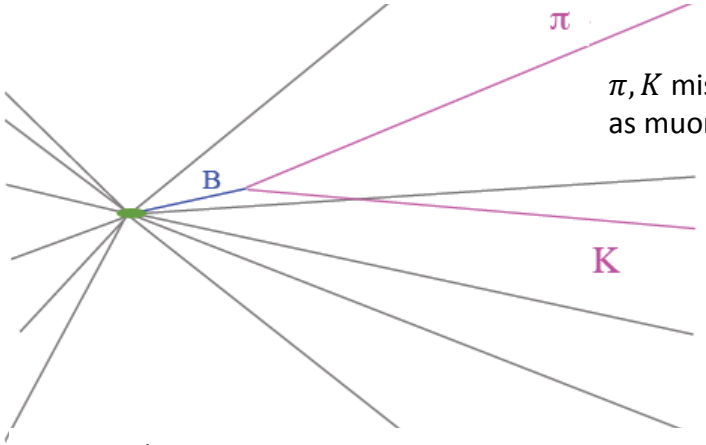
$B^0_{(s)} \to \mu\mu$ backgrounds

combinatorial background



good muons, bad B direction, bad isolation, random mass, very high yield (10^8 x signal)

$B \to h'^+h^-$ and other 'exclusive' backgrounds



π, K misidentified as muons

$B \to h'^+h^-$: bad muons, good B direction, good isolation, peaking mass, yield 10^4 x signal

- Main background from $b\bar{b} \to \mu^+\mu^- X$ (μ^+, μ^- from different B decays)
- $B \to h'^+h^-$ ($h = \pi, K$): peak in $m(\mu\mu)$ and overlap the $B^0_{(s)}$ mass region
- Exclusive backgrounds included as separate components in $m(\mu\mu)$ fit except for $\Lambda_b^0 \to p\mu^-\bar{\nu}_\mu$

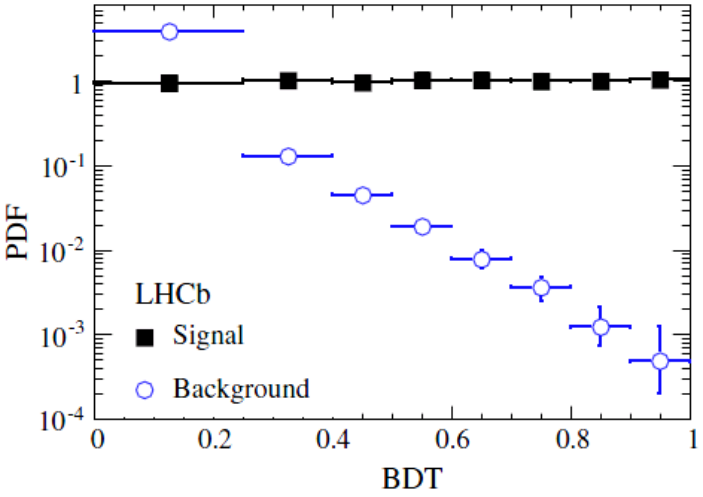
Expected yield of main exclusive backgrounds in 3 fb^{-1} with $m(\mu\mu)$ in [4900,6000] MeV

	Yield in full BDT range	Fraction with BDT > 0.7 [%]
$B^0_{(s)} \to h^+h'^-$	15 ± 1	28
$B^0 \to \pi^-\mu^+\nu_\mu$	115 ± 6	15
$B_s^0 \to K^-\mu^+\nu_\mu$	10 ± 4	21
$B^{0(+)} \to \pi^{0(+)}\mu^+\mu^-$	28 ± 8	15
$\Lambda_b^0 \to p\mu^-\bar{\nu}_\mu$	70 ± 30	11

Calibration and normalization

Calibration

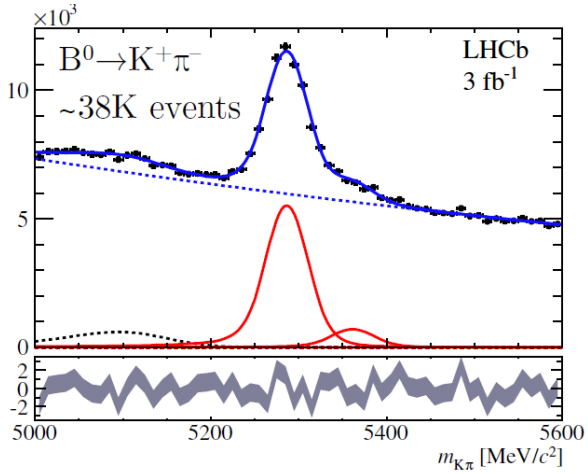
- signal BDT shape: calibrated from $B_{(s)} \to h'^{+}h^{-}$
- signal $m(\mu\mu)$ shape: 'CrystalBall' function, mean from $B_{(s)} \to h'^{+}h^{-}$, resolution extrapolated from charmonium/bottomonium$\to \mu\mu$ decays



Branching fraction

$$\mathcal{B}(B^0_{(s)} \to \mu^+\mu^-) = \frac{\mathcal{B}_{\rm norm}\epsilon_{\rm norm} f_{\rm norm}}{N_{\rm norm}\epsilon_{\rm sig} f_{d(s)}} \times N_{B^0_{(s)}\to\mu^+\mu^-} = \alpha_{(s)} \times N_{B^0_{(s)}\to\mu^+\mu^-}$$

- Normalization channels: $B^+ \to J/\psi(\to \mu\mu)K^+$, $B^0 \to K^+\pi^-$
- $\epsilon_{norm}/\epsilon_{sig}$ from MC and corrected for data/MC diff
- $f_{norm} = f_d; f_s/f_d = 0.259 \pm 0.015$
- $\alpha_{(s)}$ compatible for the two channels and averaged

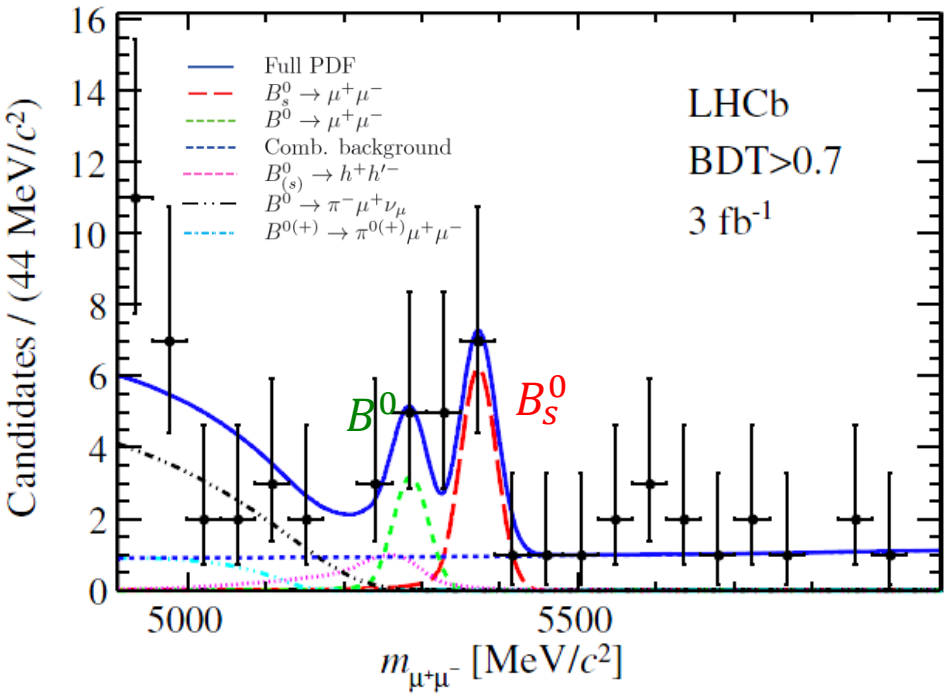


$BF(B^0_{(s)} \to \mu\mu)$

[PRL111, 101805 (2013)]

Fit

- Simultaneous unbinned ML fit to $m(\mu\mu)$ in each of the 8 BDT regions
- Free yields: B^0_s, B^0 and combinatorial background
- Yields of main exclusive backgrounds constrained according to their expected values and uncertainties



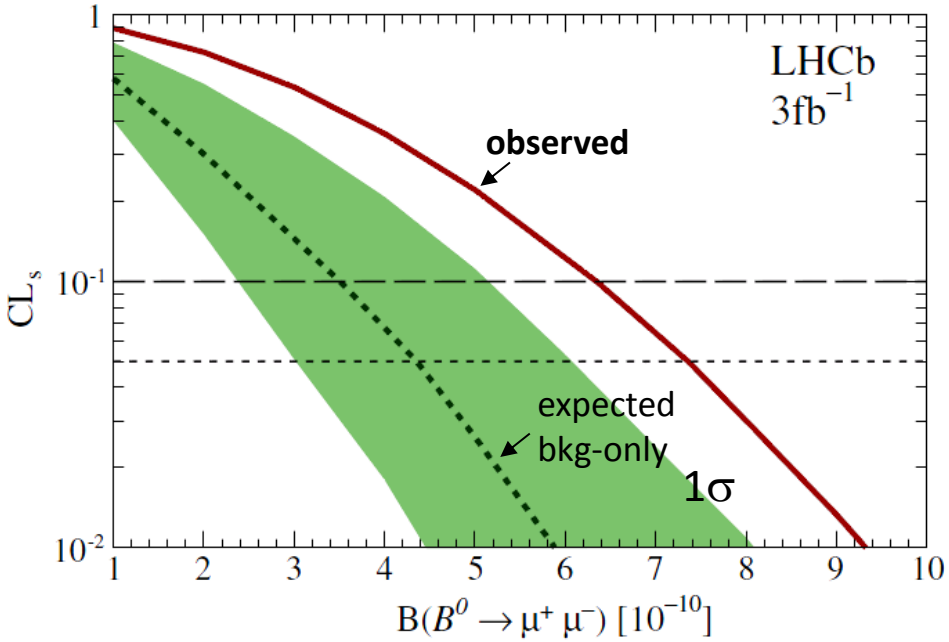
Results

$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = (2.9^{+1.1}_{-1.0}(\text{stat})^{+0.3}_{-0.1}(\text{syst})) \times 10^{-9}$$ significance: 4.0 σ

$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (3.7^{+2.4}_{-2.1}(\text{stat})^{+0.6}_{-0.4}(\text{syst})) \times 10^{-10}$$ significance: 2.0 σ

In agreement with the SM predictions

$B^0 \to \mu^+\mu^-$ upper limit



[PRL111, 101805 (2013)]

expected and observed CLs values as a function of $BF(B^0 \to \mu^+\mu^-)$

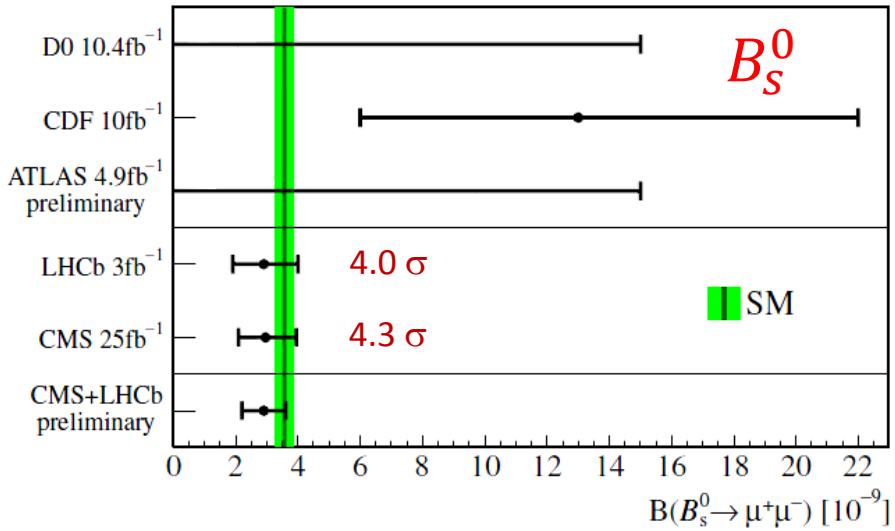
Since no significant excess of $B^0 \to \mu^+\mu^-$ found

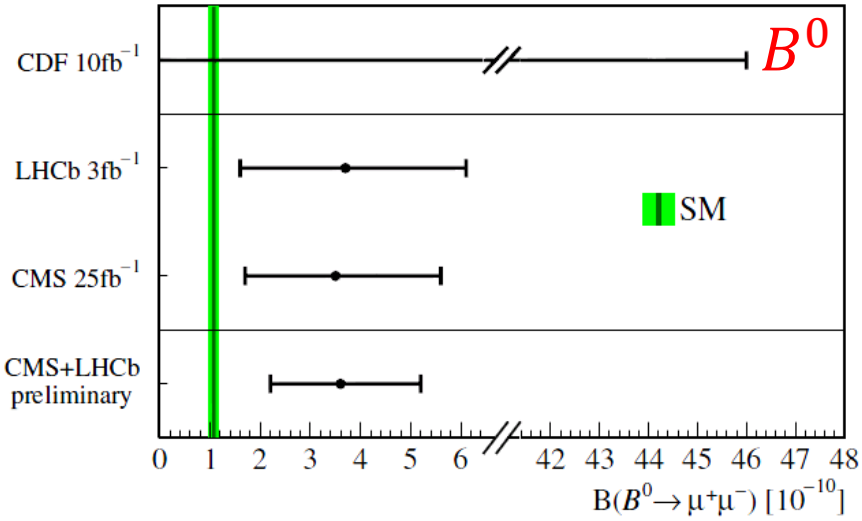
➡ upper limit calculated with the CLs method

	90% C.L.	95% C.L.
Expected bkg	3.5×10^{-10}	4.4×10^{-10}
Expected bkg + SM	4.5×10^{-10}	5.4×10^{-10}
Observed	6.3×10^{-10}	7.4×10^{-10}

LHCb-CMS combination

[LHCb-CONF-2013-012, CMS-PAS-BPH-13-007]





Simplified combination procedure using asymmetric Gaussian errors

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (2.9 \pm 0.7) \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = \left(3.6\,^{+1.6}_{-1.4}\right) \times 10^{-10}$$

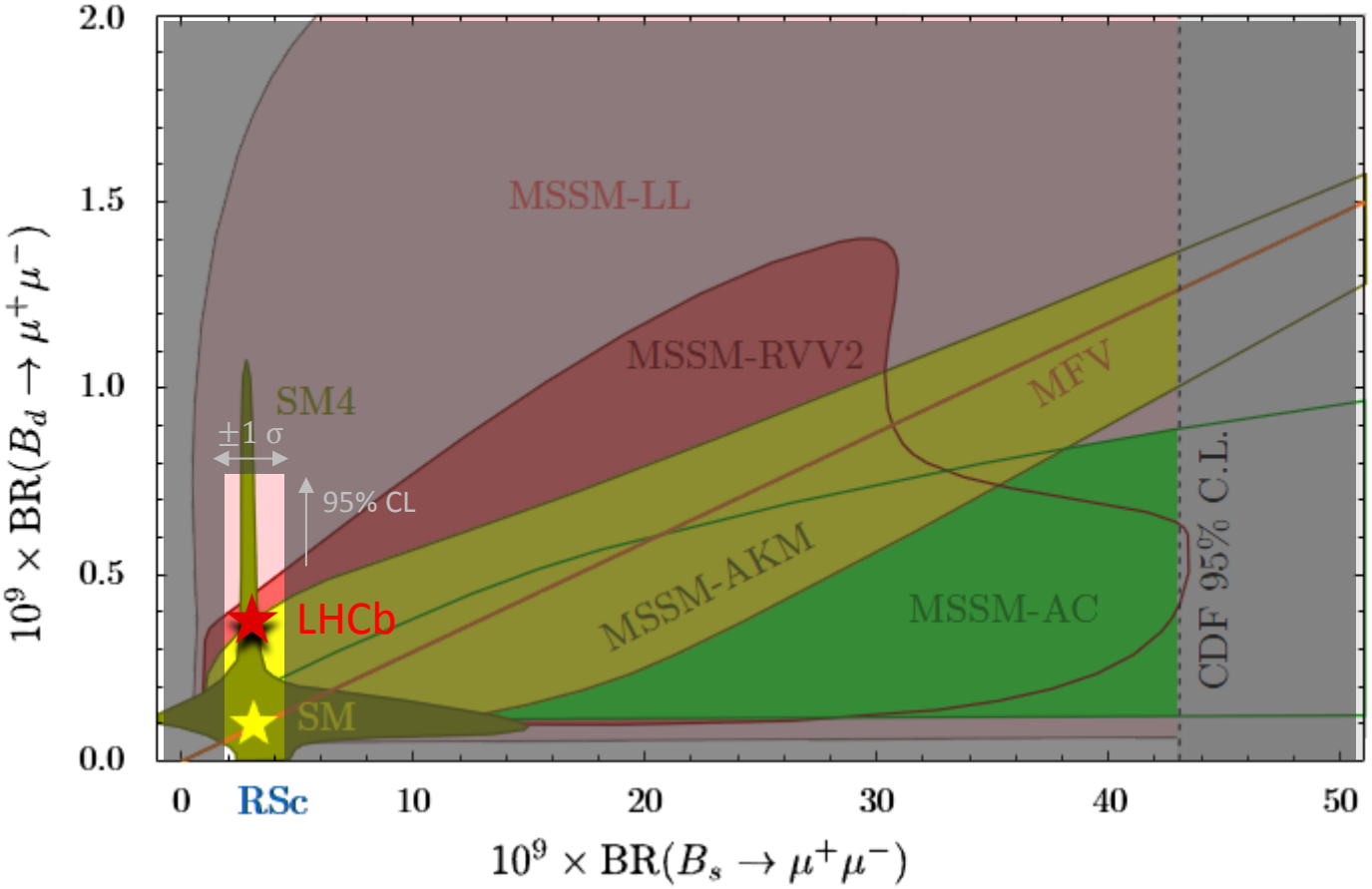
consistent with SM

Combined signal significance not evaluated

Rigorous combination from simultaneous fit to LHCb and CMS datasets will be available soon

The impact of a ‘negative’ result

original plot from D. M. Straub, arxiv:1012.3893

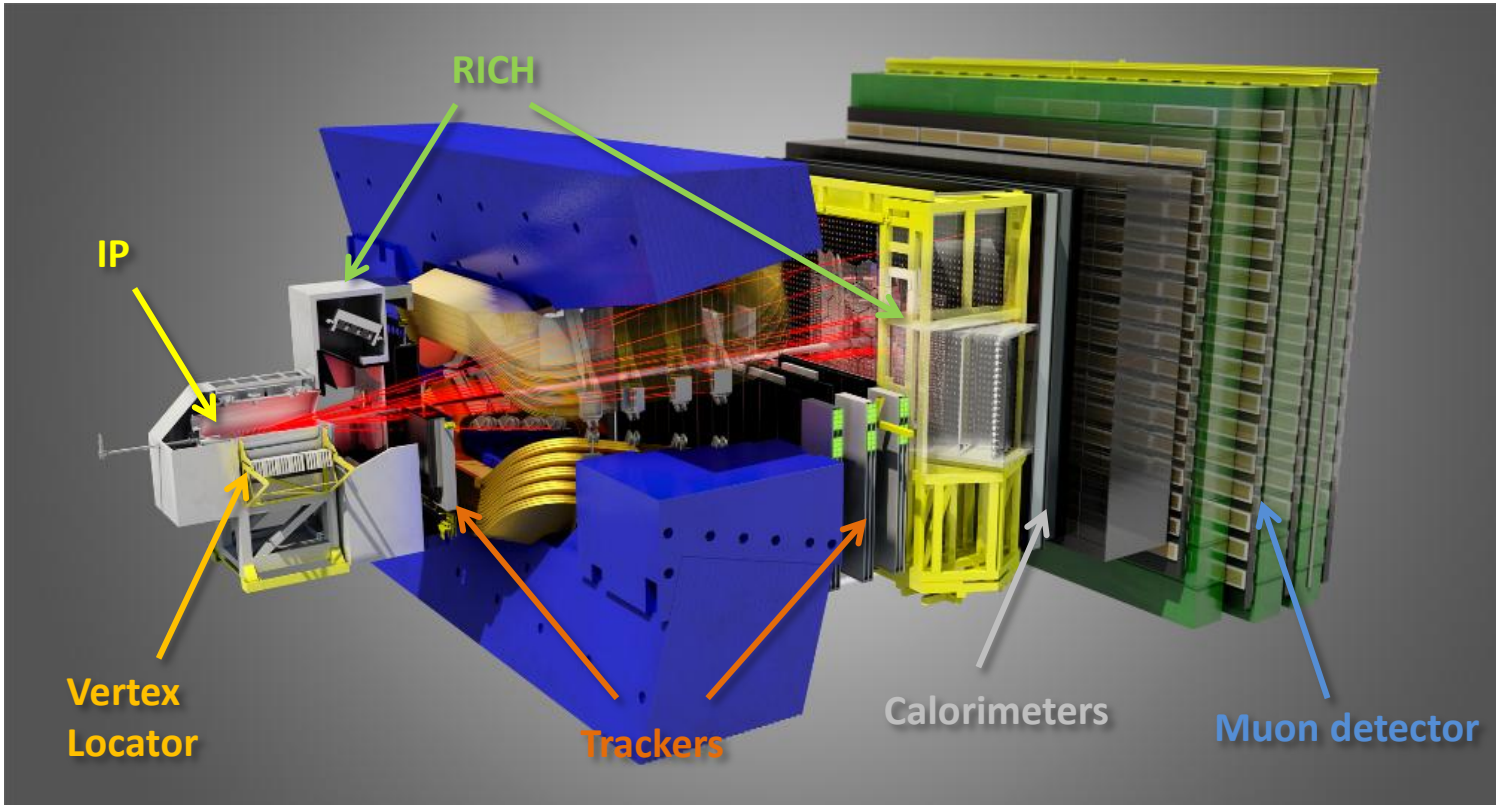


Summary

- First limits on $B^0_{(s)} \to \mu^+\mu^-\mu^+\mu^-$ decays
- Limits on $B^0_{(s)} \to e^{\pm}\mu^{\mp}$ decays improved by factor 20 compared to previous measurement
- Confirmed evidence of $B^0_s \to \mu\mu$, no evidence yet for $B^0 \to \mu\mu$
- All results consistent with SM predictions
- Next update coming soon: LHCb+CMS $B^0_{(s)} \to \mu^+\mu^-$ combination

backup

The LHCb detector



Vertex and IP resolution

$\sigma(IP) \approx 24\ \mu m$ at $p_T = 2$ GeV

$\sigma_{BV} \approx 16\ \mu m$ in x,y

Trigger

$\epsilon_\mu = 90\%$

Momentum resolution

$\sigma(p)/p = 0.4 - 0.6\ \%$ for p in [0,100] GeV

$\sigma(m_B) \sim 26$ MeV for two-body decays

Muon identification

$\epsilon_\mu \sim 98\%$, $\epsilon_{\pi\to\mu} \sim 0.5\%$, $\epsilon_{K\to\mu} \sim 0.3\%$, $\epsilon_{p\to\mu} \sim 0.3\%$

Leptoquark mass limit from $BF(B^0_{(s)} \to e^{\pm}\mu^{\mp})$

$$\mathcal{B}(B^0_{(s)} \to e^{\pm}\mu^{\mp}) = \pi \frac{\alpha_S^2(M_{\mathrm{LQ}})}{M_{\mathrm{LQ}}^4} F^2_{B^0_{(s)}} m^3_{B^0_{(s)}} R^2 \frac{\tau_{B^0_{(s)}}}{\hbar}$$

$$R = \frac{m_{B^0_{(s)}}}{m_b}\left(\frac{\alpha_S(M_{\mathrm{LQ}})}{\alpha_S(m_t)}\right)^{-(4/7)}\left(\frac{\alpha_S(m_t)}{\alpha_S(m_b)}\right)^{-(12/23)}$$

$F_{B^0_{(s)}}$ = decay constants

[PRL 111,141801 (2013); PRD50, 6843 (1994]