Leptonic B decays - experimental status

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including results from CMS and LHCb

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Conference on Flavor Physics and CP Violation (FPCP 2019)
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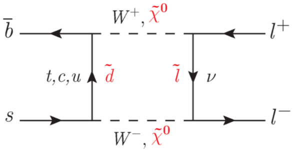
Leptonic B decays in SM and beyond

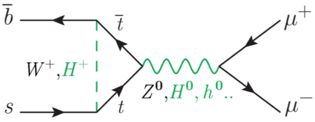
- $B \to \ell\ell$ decays not possible at tree level in the SM
  - also CKM and helicity suppressed $\to$ very rare decays
- theoretically very clean - QCD information only in f_q ($\sim$2% uncertainty)
  $\to$ branching ratios predicted in SM with small uncertainties

$$\mathcal{B}(B_s^0 \to e^+e^-) = (8.54 \pm 0.55) \times 10^{-14} \quad \mathcal{B}(B^0 \to e^+e^-) = (2.48 \pm 0.21) \times 10^{-15}$$
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.57 \pm 0.17) \times 10^{-9} \quad \mathcal{B}(B^0 \to \mu^+\mu^-) = (1.06 \pm 0.09) \times 10^{-10}$$
$$\mathcal{B}(B_s^0 \to \tau^+\tau^-) = (7.73 \pm 0.49) \times 10^{-7} \quad \mathcal{B}(B^0 \to \tau^+\tau^-) = (2.22 \pm 0.19) \times 10^{-8}$$

C. Bobeth et al., PRL 112(2014)101801, M. Beneke et al., PRL120(2018)011801

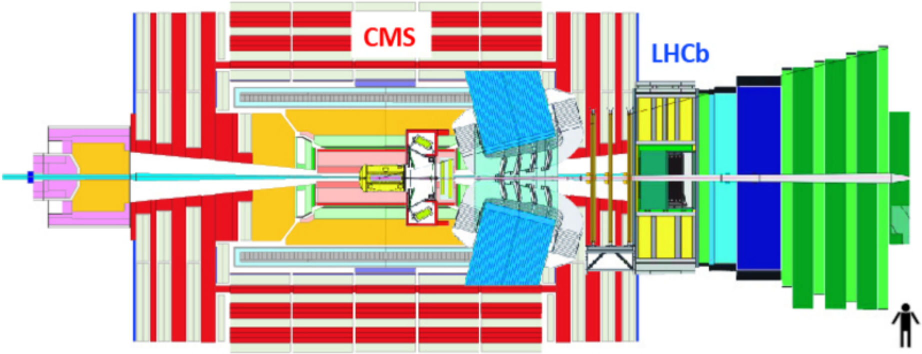
- new physics contributions could suppress/enhance BR $\to$ theory talks





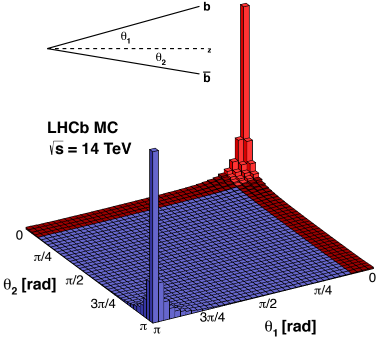
LHC detectors

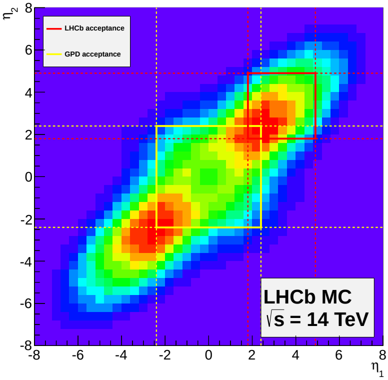
- important for $B \to \ell\ell$:
  - tracking and vertexing - impact paramenter resolution, dimuon invariant mass
  - particle ID: muon fake rejection
  - trigger: p_{T} threshold, bandwidth



Detectors for $B \to \ell\ell$

- b and $\overline{b}$ quarks produced in accpetance: LHCb 27%, GPD 49%
- b hadronisation: 40% B^0 , 40% B^+ , 10% B^0_s , baryons 10% (Λ_b etc)



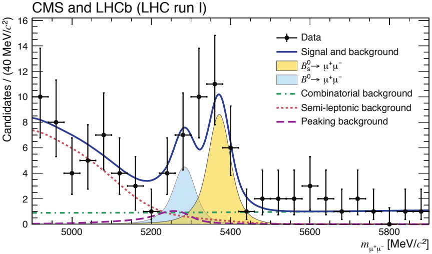


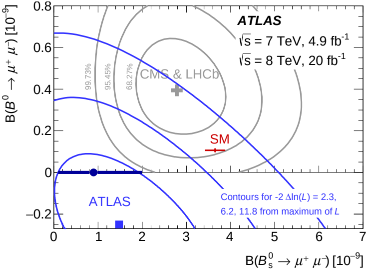
$B^0_{(s)} \to \mu^+\mu^-$

- LHCb+CMS combination:
  $\rightarrow$ first observation of $B_s^0 \rightarrow \mu^+\mu^-$ (6.2σ)
  $\rightarrow$ first evidence of $B^0 \rightarrow \mu^+\mu^-$ (3σ)

$$R = \frac{\mathcal{B}(B^0 \rightarrow \mu^+\mu^-)}{\mathcal{B}(B_s^0 \rightarrow \mu^+\mu^-)} = 0.14^{+0.08}_{-0.06}$$

  $\rightarrow$ R compatible with SM at 2.3σ
- ATLAS: $B_s^0 \rightarrow \mu^+\mu^-$ significance 1.4σ
  $\rightarrow$ compatible at 2σ with SM
  $\rightarrow$ tension between both results



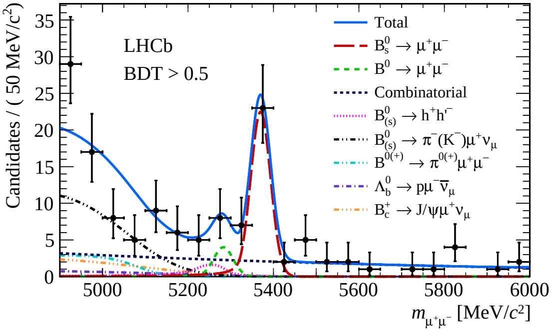


LHCb $B^0_{(s)} \to \mu^+\mu^-$

PRL 118(2017)191801

- using 3fb^{-1} of Run1 and 1.4fb^{-1} of Run2 data (2015+2016)
- BR analysis method similar to previous one with improvements:
  - improved combinatorial background rejection (BDT for track isolation)
  - tighter PID selection (helps to reduce $B \to h^+h'^-$ background)
  - better estimate of exclusive background yields
- main backgrounds: dimuon combinatorial events, peaking $B \to h^+h'^-$, $\Lambda^0_b \to p\mu^-\nu$, semileptonic $B^0_{(s)}$
- unbinned maximum likelihood fit of $m_{\mu\mu}$ simultaneously in 5 BDT bins
- normalisation channel $B^+ \to K^+J/\psi(\to \mu^+\mu^-)$
- calibration of signal peak position with $B^0_s \to K\pi$ and $B^0_s \to KK$
- fragmentation probabilities f_d/f_s estimated from $B^+ \to J/\psi K^+$ to $B^0_s \to J/\psi\phi$ ratio (assuming $f_d = f_u$)

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



- results compatible with SM, first single experiment observation

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.0 \pm 0.6^{+0.3}_{-0.2}) \times 10^{-9} \qquad \to 7.8\sigma$$

$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (1.5^{+1.2+0.2}_{-1.0-0.1}) \times 10^{-10} \qquad \to 1.6\sigma$$

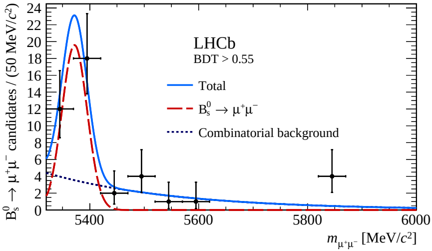
$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 3.4 \times 10^{-10} \text{at 95\% CL}$$

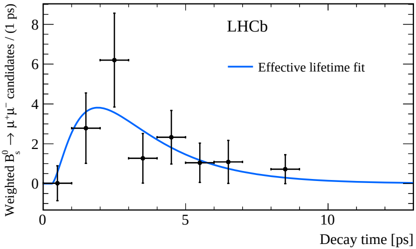
- main syst. uncertainties:
  - $\mathcal{B}(B_s^0 \to \mu^+\mu^-)$: f_s/f_d
  - $\mathcal{B}(B^0 \to \mu^+\mu^-)$: exclusive backgrounds

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

- first measurement of effective lifetime $\tau_{\mu\mu} \equiv \frac{\int_0^\infty t\langle\Gamma(B^0_s(t)\to\mu\mu)\rangle dt}{\int_0^\infty \langle\Gamma(B^0_s(t)\to\mu\mu)\rangle dt}$
- similar selection as for BR, simplified BDT and looser PID cut
- 2 step process validated with $B^0 \to K^+\pi^-$:
  - fit $m_{\mu\mu}$ to get weights for *sPlot* and subtract background
  - fit the weighted signal decay time distribution to measure $\tau_{\mu\mu}$

$$\tau(B^0_s \to \mu^+\mu^-) = 2.04 \pm 0.44 \pm 0.05 \text{ ps}$$





- SM $\tau = 1.510 \pm 0.005$ ps (HFAG summer 2016 average)

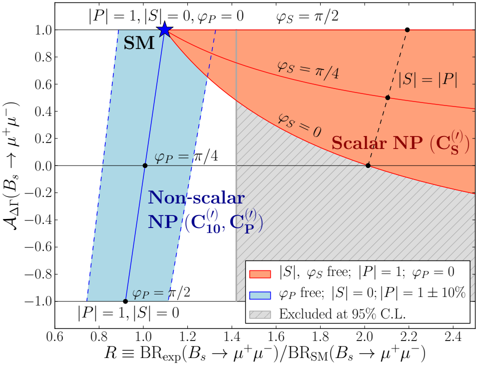
LHCb $B^0_{(s)} \to \mu^+\mu^-$

- in SM only the heavy mass eigenstate decays to $\mu^+ \mu^-$

$$\tau_{\mu\mu} \approx \tau_{B_s^0}(1 + y_s A_{\Delta\Gamma}), \quad y_s = 0.062 \pm 0.006$$

$$A_{\Delta\Gamma} = \frac{\Gamma(B_s^H \to \mu^+\mu^-) - \Gamma(B_s^L \to \mu^+\mu^-)}{\Gamma(B_s^H \to \mu^+\mu^-) + \Gamma(B_s^L \to \mu^+\mu^-)} = +1 \text{ (SM)}, \quad [-1,1] \text{ (NP)}$$

- measurement consistent with $A_{\Delta\Gamma} = 1(-1)$ at 1σ (1.4σ)

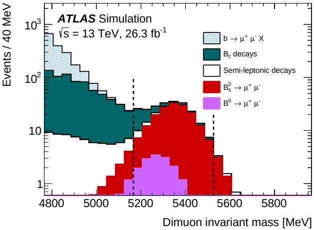


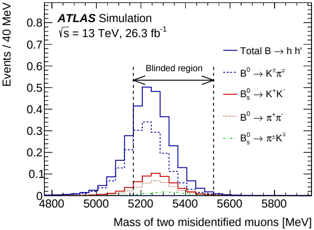
PRL 109(2012)041801

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

JHEP 04(2019)098

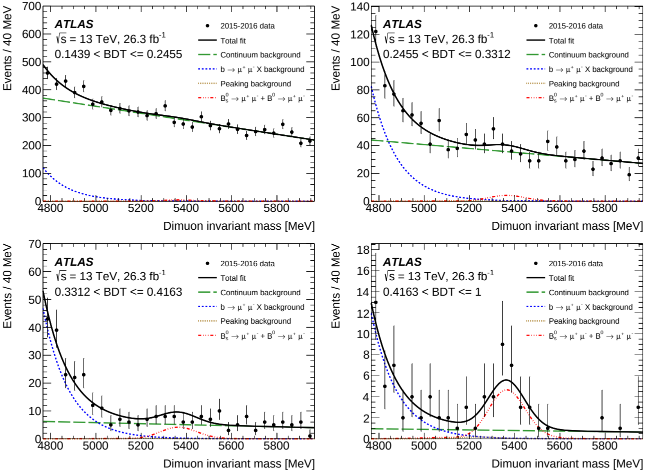
- combining 2015+2016 data = $26.3\ \mathrm{fb}^{-1}$
- select $\mu^+\mu^-$ pair consistent with $B^0_{(s)}$
- background: combinatorial, partially reconstructed, semileptonic
- multivariate BDT to reduce combinatorial background
- N(signal) normalised to $B^+ \to J/\psi\ K^+$





ATLAS $B^0_{(s)} \to \mu^+\mu^-$ details in W. Walkowiak's talk, Thu 5:45PM

- unbinned maximum-likelihood fit in 4 bins of BDT
- observed: 80±20 B^0_s , -12 ± 20 B^0_d candidates
- expected in SM: 91 B^0_s , 10 B^0_d



- likelihood maximum of Run2 data:

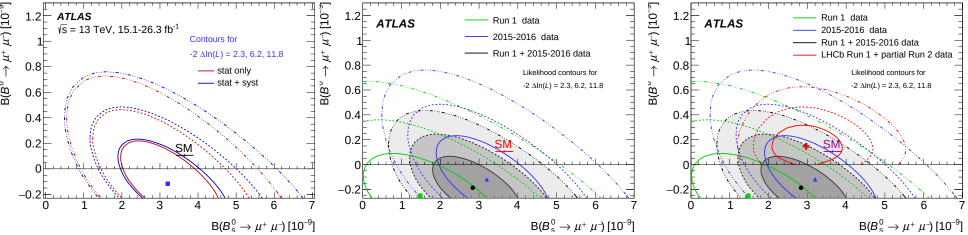
$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = (3.21^{+0.90+0.48}_{-0.83-0.31}) \times 10^{-9} \quad \mathcal{B}(B^0 \to \mu^+\mu^-)(-1.3^{+2.2+0.7}_{-1.9-0.8}) \times 10^{-10}$$

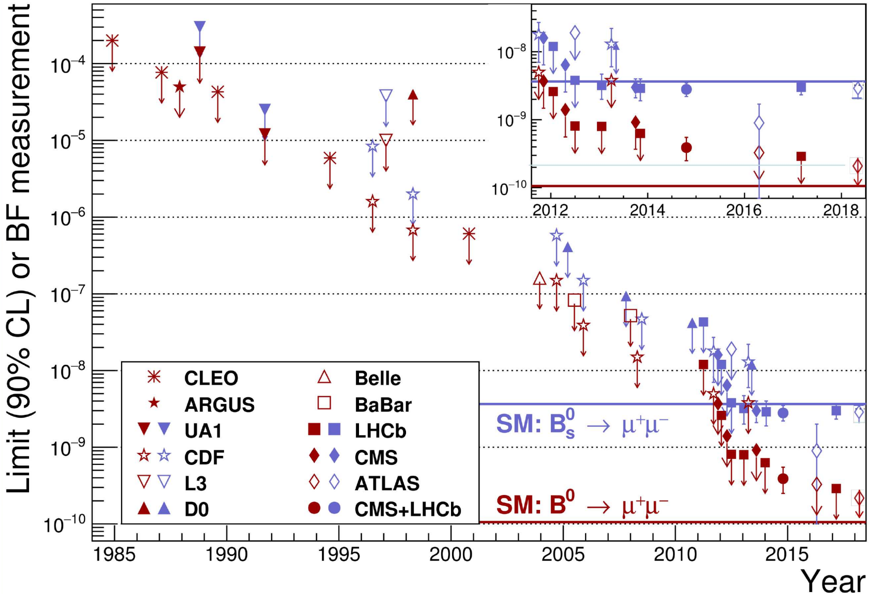
- Run1 + Run2 (2015+16) combination:

$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = (2.8^{+0.8}_{-0.7}) \times 10^{-9} \qquad \mathcal{B}(B^0 \to \mu^+\mu^-) < 2.1 \times 10^{-10} \text{at 95\% CL}$$

$\rightarrow$ compatible with SM at 2.4σ

$\rightarrow$ most stringent limit on $B^0 \to \mu^+\mu^-$ to date

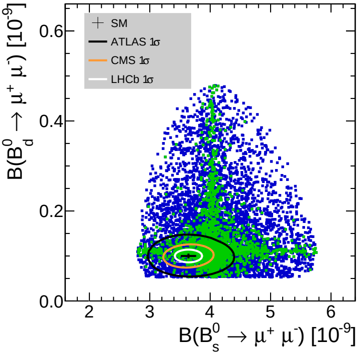


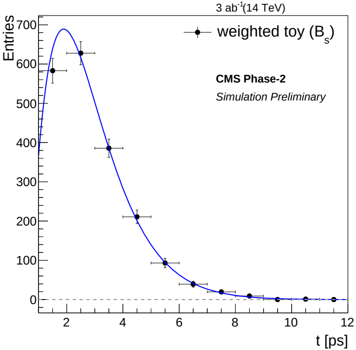


Limit (90% CL) or BF measurement
Year
CLEO
ARGUS
UA1
CDF
L3
D0
Belle
BaBar
LHCb
CMS
ATLAS
CMS+LHCb
SM: $B^0_s \to \mu^+\mu^-$
SM: $B^0 \to \mu^+\mu^-$

Expected sensitivity with HL-LHC dataset

- uncertainty of $B_s^0 \to \mu^+\mu^-$ will be dominated by f_s/f_d
- improved trackers $\to$ better mass resolution
- add information from effective lifetime and time-dependent CP asymmetry





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

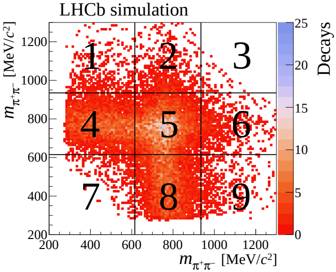
LHCb search for $B^0_{(s)} \to \tau^+\tau^-$

PRL 118(2017)251802

- FCNC process similar to $B^0_{(s)} \to \mu^+\mu^-$ but much less suppressed

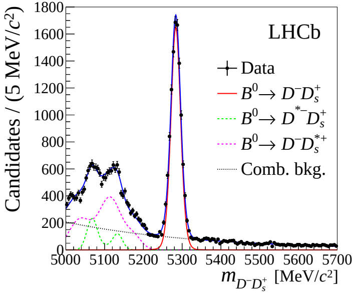
$$\frac{\mathcal{B}(B^0_{(s)} \to \tau^+\tau^-)}{\mathcal{B}(B^0_s \to \mu^+\mu^-)} = \frac{m_\tau^2}{m_\mu^2} \times \sqrt{\frac{m_B^2 - 4m_\tau^2}{m_B^2 - 4m_\mu^2}} \sim 210$$

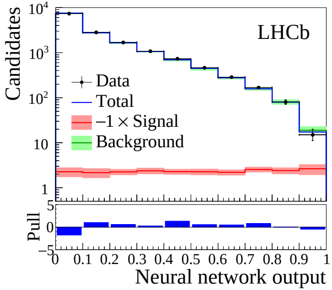
- Run1 dataset, selecting $\tau^- \to a_1(1260)^-\bar{\nu}_\tau \to \rho(770)^0\pi^-\bar{\nu}_\tau \to \pi^+\pi^-\pi^-\bar{\nu}_\tau$
  $\to$ experimentally very challenging because of 2 neutrinos
- B^0 and B^0_s cannot be separated by mass
  $\to$ assumptions on one decay impact the limit on the other
- define regions in $m_{\pi^+\pi^-}$ for opposite-charge pion combinations:
  - signal = both τ in 5
  - control = one τ in (4,5,8), other in (4,8)
  - background = one or both τ in (1,3,7,9)



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

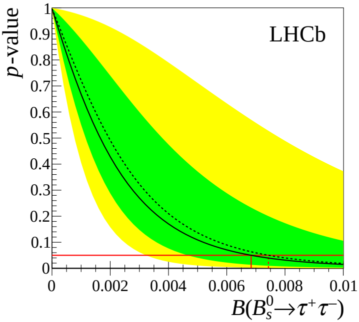
- normalisation channels
  $B^0 \to D^-(K^+\pi^-\pi^+)D_s^+(K^+K^-\pi^+)$
- after preselection, build NN from 7 kinematic variables: τ masses and decay times, π and B isolation from tracks
- $m_{\tau\tau}$ gives a weak discrimination
  $\to$ build second NN from kinematic and geometric variables
- fit its output with binned ML fit in signal region
  $B_s^0 \to \tau^+\tau^-$ fit $\to$

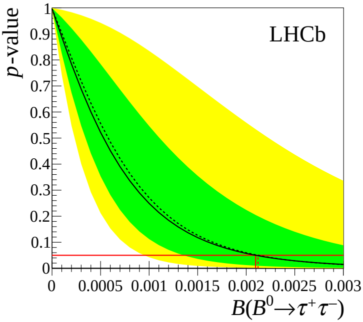




LHCb $B^0_{(s)} \to \tau^+\tau^-$

- $\mathcal{B}(B^0_s \to \tau^+\tau^-) < 5.2(6.8) \times 10^{-3}$ at 90 (95)% CL
- assuming signal dominated by B^0 :
  $$\mathcal{B}(B^0 \to \tau^+\tau^-) < 1.6(2.1) \times 10^{-3} \text{ at 90 (95)\% CL}$$
- 2.6-times better wrt previous result form BaBar but still far from SM ($\mathcal{B}(B^0_s \to \tau^+\tau^-) \sim 7 \times 10^{-7}, \mathcal{B}(B^0 \to \tau^+\tau^-) \sim 2 \times 10^{-8}$)

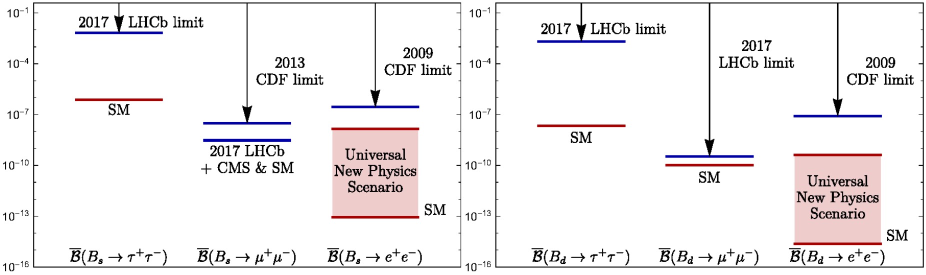




$B^0_{(s)} \to e^+ e^-$

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

- last measurement published by CDF in 2009: $\mathcal{B} < 2.8 \times 10^7$
  PRL 102(2009)201801
- no measurement from Belle or LHC experiments yet
- problems with electrons: brems, low-p_{T} trigger, selection, identification



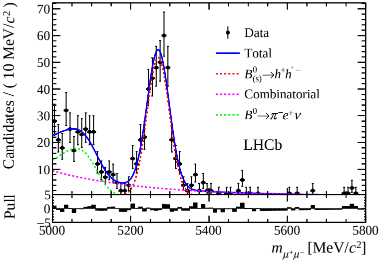
R. Fleischer et al., arXiv:1703.10160

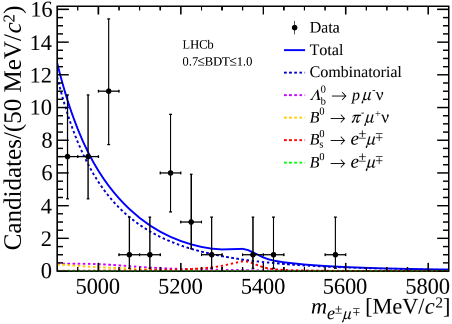
Search for LFV decays

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

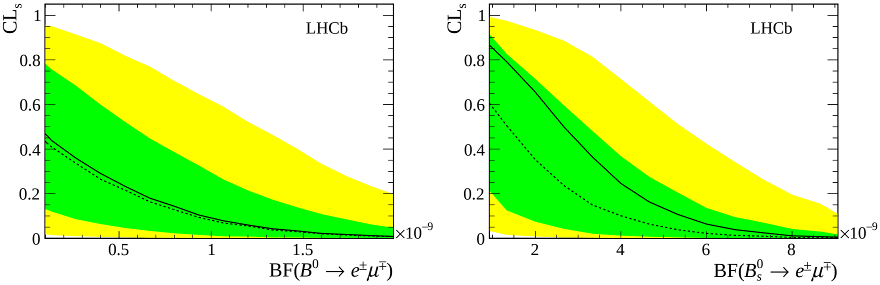
JHEP 1803 (2018) 078

- Run1 dataset - 3fb^{-1}
- primary background: $B \to h^+ h'^-$ estimated by data-driven method to N<6
- electron bremsstrahlung $\to$ different efficiency and mass shape
- fit of $m_{e\mu}$ separately in brems categories





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



- fit results:

$$\mathcal{B}(B^0 \to e^\pm \mu^\mp) < 1.3(1.0) \times 10^{-9} \text{at 95 (90)\% CL}$$
$$\mathcal{B}(B^0_s \to e^\pm \mu^\mp) < 6.3(5.4) \times 10^{-9} \text{at 95 (90)\% CL for heavy eigenstate}$$
$$\mathcal{B}(B^0_s \to e^\pm \mu^\mp) < 7.2(6.0) \times 10^{-9} \text{at 95 (90)\% CL for light eigenstate}$$

Other searches

- LHCb search for $B^0 \to 4\mu$ (JHEP 03(2017)001, Run1 data):

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-\mu^+\mu^-) < 2.5 \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-\mu^+\mu^-) < 6.9 \times 10^{-10} \text{ at 95\% CL}$$

- LHCb search for $B^+ \to \mu^+\mu^-\mu^+\nu_\mu$ (arXiv:1812.06004)

$$\mathcal{B} < 1.6 \times 10^{-8} \text{ at 95\% CL}$$

- updated results from Belle search for $B^0 \to \mu\nu_\mu$
$\to$ talk by Eiasha Waheed (Wed at 10:15AM)

Conclusions

- updated measurements of leptonic B decays are consistent with SM
- but there is still room for NP
  - $B^0 \to \mu^+\mu^-$ ATLAS and LHCb dataset up to 2016, CMS Run1
  - $B^0 \to \tau^+\tau^-$ LHCb with Run1 data
  - LFV $B^0_{(s)} \to e^\pm\mu^\mp$ LHCb Run1
- bigger datasets and improved techniques promise smaller uncertainties
- analyses of whole Run2 dataset ongoing, Belle2 starting

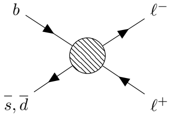
$\to$ Stay tuned for updates!

Backup slides

Effective field theory

- model independent Hamiltonian for $|\Delta B| = |\Delta S| = 1$ transitions

$$\mathcal{H}_{eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{\alpha}{4\pi} \sum_i [C_i \mathcal{O}_i + C_i' \mathcal{O}_i']$$



i = 1,2 tree,
i = 3-6,8 gluon penguin,
i = 7 photon penguin,
i = 9, 10 EW penguin
i = S scalar penguin (H)
i = P pseudoscalar penguin

- heavy fields $(t, Z, W^{\pm}, H, Z')$ are integrated out in perturbative short-distance couplings $\rightarrow$ Wilson coefficients C_i, C_i'
- non-perturbative long-distance physics $\rightarrow$ operators
- in SM only C_{10} contributes to $B \rightarrow \ell\ell$
- sensitivity to NP is larger for C_S and C_P (no helicity suppression)

EFT operators relevant for rare B decays

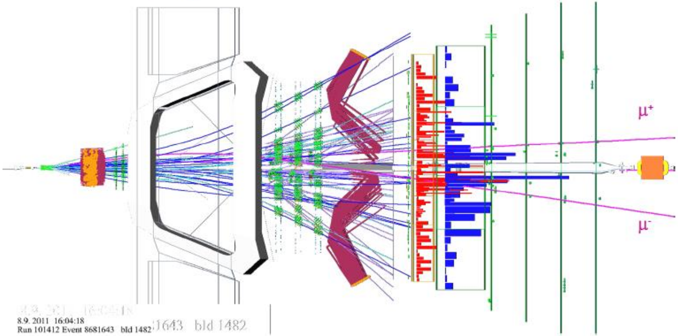
$$
\begin{aligned}
\mathcal{O}_7 &= \tfrac{m_b}{e}(\bar{s}\sigma^{\mu\nu}P_R b)F_{\mu\nu} & \mathcal{O}_7' &= \tfrac{m_b}{e}(\bar{s}\sigma^{\mu\nu}P_L b)F_{\mu\nu} \\
\mathcal{O}_8 &= g_s\tfrac{m_b}{e^2}(\bar{s}\sigma^{\mu\nu}P_R T^a b)G^a_{\mu\nu} & \mathcal{O}_8' &= g_s\tfrac{m_b}{e^2}(\bar{s}\sigma^{\mu\nu}P_L T^a b)G^a_{\mu\nu} \\
\mathcal{O}_9 &= (\bar{s}\gamma_\mu P_L b)\,(\bar{\ell}\gamma^\mu \ell) & \mathcal{O}_9' &= (\bar{s}\gamma_\mu P_R b)\,(\bar{\ell}\gamma^\mu \ell) \\
\mathcal{O}_{10} &= (\bar{s}\gamma_\mu P_L b)\,(\bar{\ell}\gamma^\mu \gamma_5 \ell) & \mathcal{O}_{10}' &= (\bar{s}\gamma_\mu P_R b)\,(\bar{\ell}\gamma^\mu \gamma_5 \ell)
\end{aligned}
$$

$$
\begin{aligned}
\mathcal{O}_{\mathrm{S}} &= (\bar{s}P_R b)\,\bar{\ell}\ell & \mathcal{O}_{\mathrm{S}}' &= (\bar{s}P_L b)\,\bar{\ell}\ell \\
\mathcal{O}_{\mathrm{P}} &= (\bar{s}P_R b)\,(\bar{\ell}\gamma_5 \ell) & \mathcal{O}_{\mathrm{P}}' &= (\bar{s}P_L b)\,(\bar{\ell}\gamma_5 \ell) \\
\mathcal{O}_{\mathrm{T}} &= (\bar{s}\sigma_{\mu\nu} b)\,(\bar{\ell}\sigma^{\mu\nu} \ell) & \mathcal{O}_{\mathrm{T5}} &= (\bar{s}\sigma_{\mu\nu} b)\,(\bar{\ell}\sigma^{\mu\nu}\gamma_5 \ell)
\end{aligned}
$$

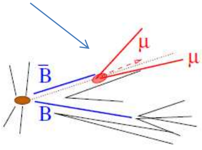
$$
\begin{aligned}
\mathcal{O}_{\mathrm{LL}} &= (\mathcal{O}_9 - \mathcal{O}_{10})/2 & \mathcal{O}_{\mathrm{LR}} &= (\mathcal{O}_9 + \mathcal{O}_{10})/2 \\
\mathcal{O}_{\mathrm{RL}} &= (\mathcal{O}_9' - \mathcal{O}_{10}')/2 & \mathcal{O}_{\mathrm{RR}} &= (\mathcal{O}_9' + \mathcal{O}_{10}')/2
\end{aligned}
$$

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

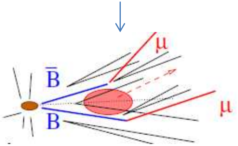
$B_s \rightarrow \mu^+\mu^-$ event in LHCb



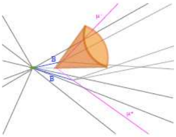
Signal



Combinatorial background



Discriminated via isolation variable



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

Analysis strategy:

- opposite sign muon pair in $m_{\mu\mu}$ = [4900, 6000] MeV
- BDT: kinematics, geometrical, isolation variables
- S/B classification in $m_{\mu\mu}$ vs. BDT score plane
- background estimation: data driven, MC samples, theory inputs
- yields: 1.9×10^6 $B^+ \to J/\psi K^+$, 6.2×10^3 $B^0 \to K\pi$