Rare decays at LHCb

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on behalf of the LHCb Collaboration

INFN Pisa

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Outline

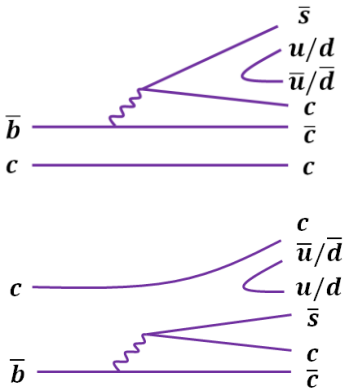
Selection of rare decay measurements

- Observation of $B_c^+ \to J/\psi D^{(*)} K^{(*)}$ decays
- Search for $B^0_{(s)} \to \mu^+\mu^-\mu^+\mu^-$
- Evidence for $\Sigma^+ \to p\mu^+\mu^-$
- Updated $K_s^0 \to \mu^+\mu^-$ BF upper limit
- Combined CMS/LHCb measurement of $B^0_{(s)} \to \mu^+\mu^-$
- Search for $B^0_{(s)} \to \tau^+\tau^-$

Other results on rare or SM-forbidden decays at LHCb are discussed in:
-) $b \to s l^+ l^-$ and radiative decays at LHCb, F. Polci (WG3, Monday)
-) Lepton universality, flavor and number violation in B and τ decays, P. Alvarez Cartelle (WG3, Tue afternoon)
-) $B_s^0 \to \phi\gamma$ time-dependent CPV, A. Oyanguren (WG4, Thursday)

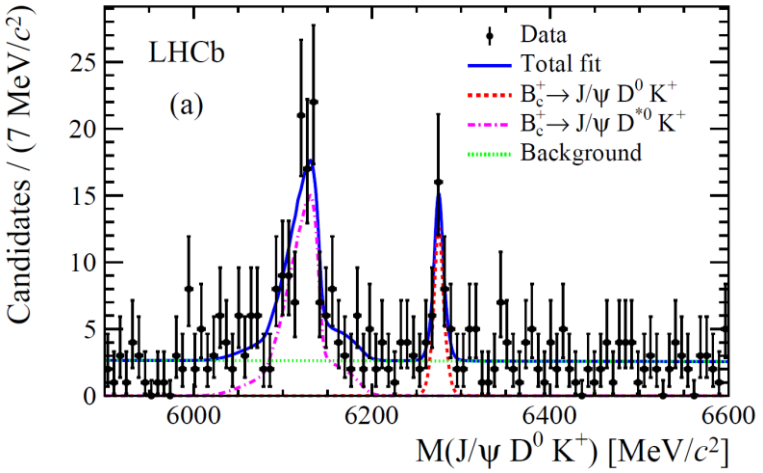
Observation of $B_c^+ \to J/\psi D^{(*)} K^{(*)}$ decays

- Opportunity to study D_{sJ}^+ states in the $D^{(*)}K^{(*)}$ system and search for possible exotic charmonium states in $J/\psi D^{(*)}$ (with more data)
- Branching fractions measured relative to $B_c^+ \to J/\psi\, \pi^+$
- Precise measurement of B_c^+ mass measurement



- Dataset: Run 1 (3 fb^{-1})
- $D^0 \to K^-\pi^+$ ($D^0 \to K^-\pi\pi\pi$); $K^{*0} \to K^+\pi^-$
- First observation of
  - $B_c^+ \to J/\psi D^0 K^+$ (6.3 σ)
  - $B_c^+ \to J/\psi D^{*0} K^+$ (10.3 σ, partial reconstruction)

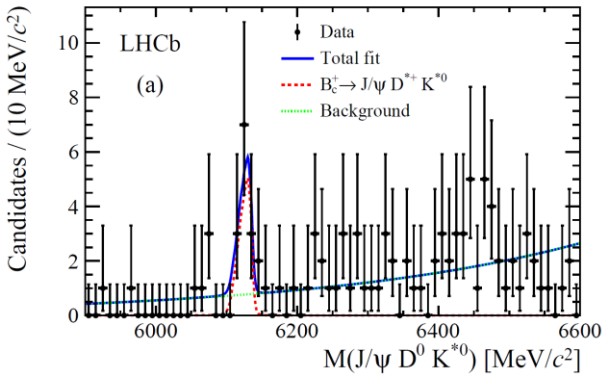
LHCb-PAPER-2016-055 in preparation

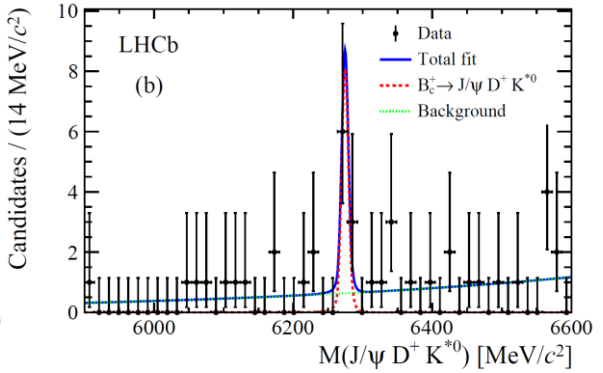


Observation of $B_c^+ \to J/\psi D^{(*)} K^{(*)}$ decays

LHCb-PAPER-2016-055 in preparation

- First evidence of
  - $B_c^+ \to J/\psi D^{*+} K^{*0}$ (4.0 σ, partial reconstruction)
  - $B_c^+ \to J/\psi D^{+} K^{*0}$ (4.4 σ)



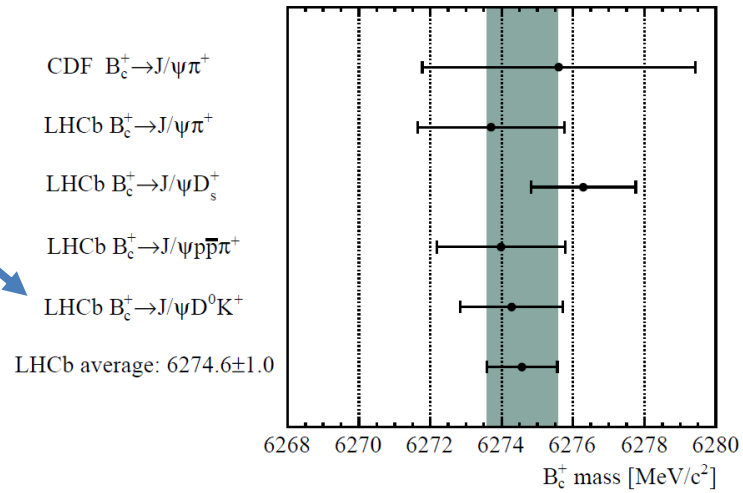


- Most precise B_c^+ mass measurement made using $B_c^+ \to J/\psi D^0 K^+$

$M(B_c^+) = 6274.28 \pm 1.40 \pm 0.32$ MeV/c²

New LHCb average:

$M(B_c^+) = 6274.6 \pm 1.0$ MeV/c²

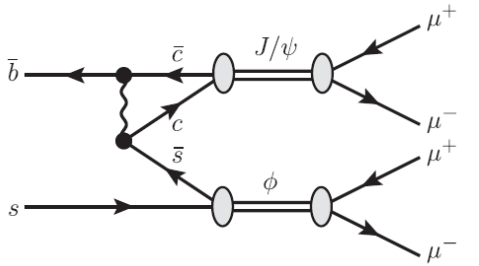


Search for $B^0_{(s)} \to \mu^+\mu^-\mu^+\mu^-$ decays

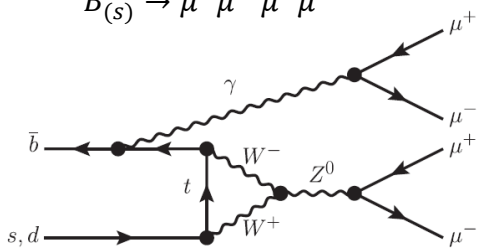
In Standard Model:

- Dominated by $B^0_s \to J/\psi(\to \mu^+\mu^-)\phi(\to \mu^+\mu^-)$
  BF = $(1.84 \pm 0.20) \times 10^{-8}$
- SM B^0_s non-resonant BF $\sim 3.5 \times 10^{-10}$
  $B^0_{(s)} \to \mu^+\mu^-\,\gamma(\to \mu^+\mu^-)$

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



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



Beyond SM:

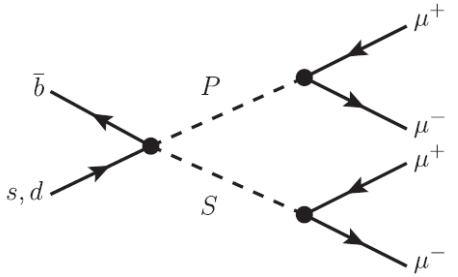
- BF can be significantly enhanced, for example in MSSM: $B \to S(\to \mu^+\mu^-)P(\to \mu^+\mu^-)$, S and P sgoldstino particles

[PRD85,077701 (2012)]

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



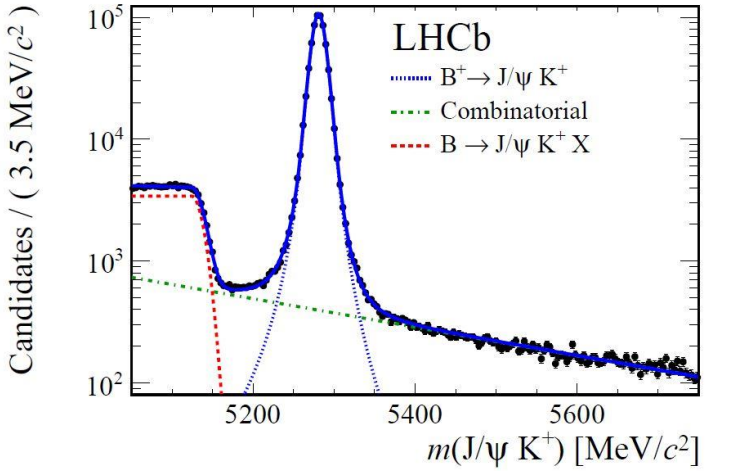
Search for $B^0_{(s)} \to \mu^+\mu^-\mu^+\mu^-$ decays

arxiv:1611.07704 subm. to JHEP

Signal selection

- Dataset: 3 fb^{-1} (Run1)
- 4 muon candidates originating from single vertex and far from the primary vertex
- J/ψ, $\psi(2S)$ and ϕ mass vetoes to remove the dominant SM resonant decays
- Multivariate classifier (B kinematic and position w.r.t. primary vertex) to reject background

normalization mode $B^+ \to J/\psi(\to \mu^+\mu^-)\, K^+$



BF measurement

- $B^+ \to J/\psi(\to \mu^+\mu^-)\, K^+$ used as normalization channel
- $$\mathcal{B}(B^0_{(s)} \to \mu^+\mu^-\mu^+\mu^-) = N(B^0_{(s)} \to \mu^+\mu^-\mu^+\mu^-) \times \frac{\varepsilon(B^+ \to J/\psi(\to \mu^+\mu^-)K^+) \times \mathcal{B}(B^+ \to J/\psi(\to \mu^+\mu^-)K^+)}{\varepsilon(B^0_{(s)} \to \mu^+\mu^-\mu^+\mu^-) \times N(B^+ \to J/\psi(\to \mu^+\mu^-)K^+)} \times \frac{f_u}{f_{d,s}}$$

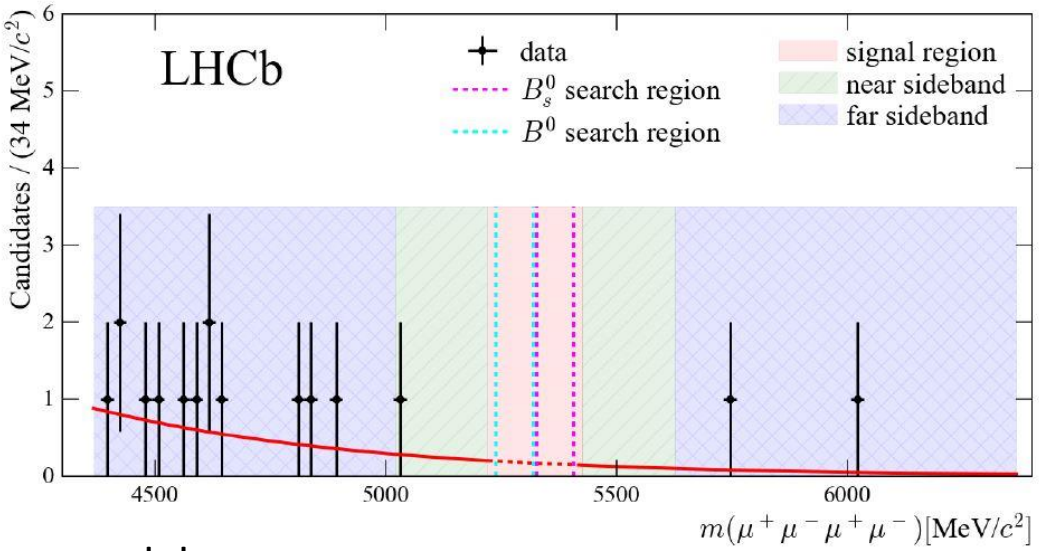
$f_s/f_d = 0.259 \pm 0.015$ B^0/B^0_s production fraction

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

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

arxiv:1611.07704 subm. to JHEP

0 events in B^0 and B^0_s signal regions
Consistent with background expectation



Set 95% CL upper limits with phase space model:

$BF(B^0_s \to \mu^+\mu^-\mu^+\mu^-) < 2.5 \times 10^{-9}$

$BF(B^0 \to \mu^+\mu^-\mu^+\mu^-) < 6.9 \times 10^{-10}$

Improved by a factor 6.4 (B^0_s) and 9.5 (B^0) compared to previous limits

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

$BF(B^0_s \to SP \to 4\mu) < 2.2 \times 10^{-9}$

$BF(B^0 \to SP \to 4\mu) < 6.0 \times 10^{-10}$

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

Search for $\Sigma^+ \to p\mu^+\mu^-$ decays

- FCNC process, in SM [1]

  $1.6 \times 10^{-8} < BF(\Sigma^+ \to p\mu^+\mu^-) < 9.0 \times 10^{-8}$

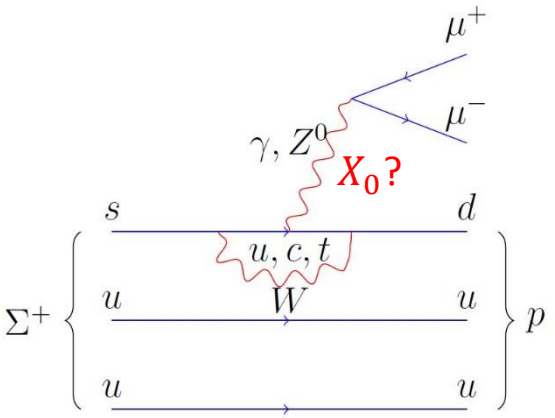
  He, Tandean,Valencia, PRD72 (2005), 074003

- Three signal candidates by HyperCP experiment

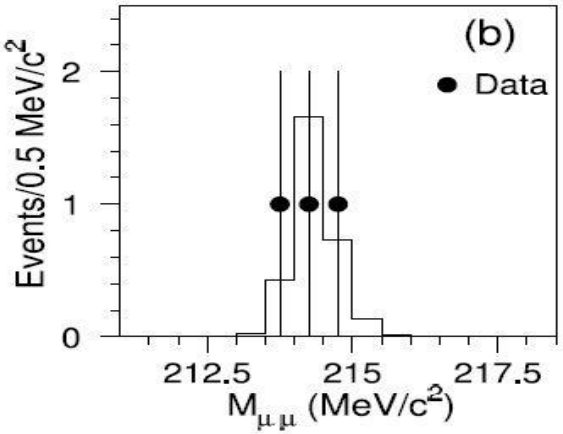
  $BF(\Sigma^+ \to p\mu^+\mu^-) = (8.6^{+6.6}_{-5.4} \pm 5.5) \times 10^{-8}$

- Very similar $m_{\mu\mu}$, $\mathrm{m}(\mu^+\mu^-) = 214 \pm 0.3$ MeV

- Indication of $\Sigma^+ \to p\, X^0(\to \mu^+\mu^-)$?



HyperCP Collab, PRL 94 (2005), 021801



Search for $\Sigma^+ \to p\mu^+\mu^-$ decays

LHCb-CONF-2016-013

Signal selection

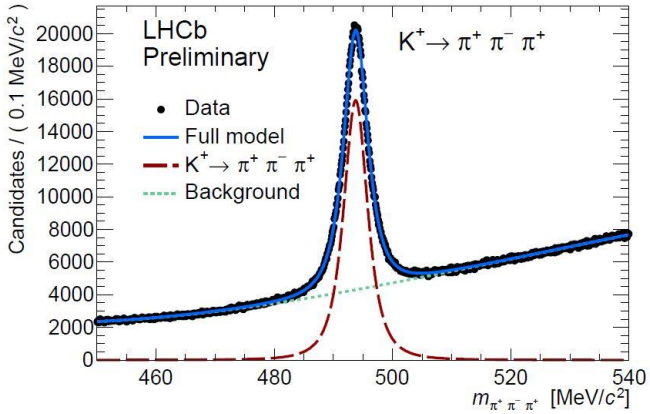
- Dataset: 3 fb^{-1} (Run1)
- Selection of $\Sigma^+ \to p\mu^+\mu^-$ candidates optimized using multivariate classifier (BDT). $\Lambda \to p\pi$ veto.
- $K^+ \to \pi^+\pi^+\pi^-$ used as calibration channel
- Two trigger selections:
  - 'inclusive' selection to search for $\Sigma^+ \to p\mu^+\mu^-$ evidence
  - trigger independently of signal (TIS) to measure the BF (better control of trigger efficiency)

BF measurement

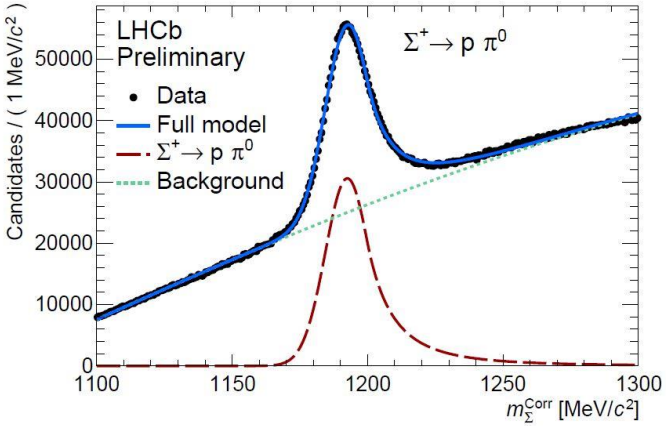
- Measured in TIS sample
- $\Sigma^+ \to p\pi^0$ used as normalization channel

$$\mathcal{B}(\Sigma^+ \to p\mu^+\mu^-) = \frac{\varepsilon_{\Sigma^+\to p\pi^0}}{\varepsilon_{\Sigma^+\to p\mu^+\mu^-}} \frac{N_{\Sigma^+\to p\mu^+\mu^-}}{N_{\Sigma^+\to p\pi^0}} \mathcal{B}(\Sigma^+ \to p\pi^0)$$

invariant mass of $K^+ \to \pi^+\pi^-\pi^+$ candidates

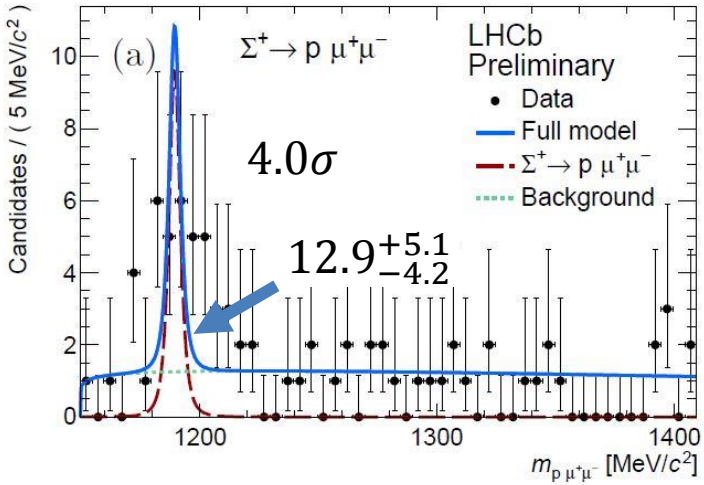


invariant mass of $\Sigma^+ \to p\pi^0$ candidates



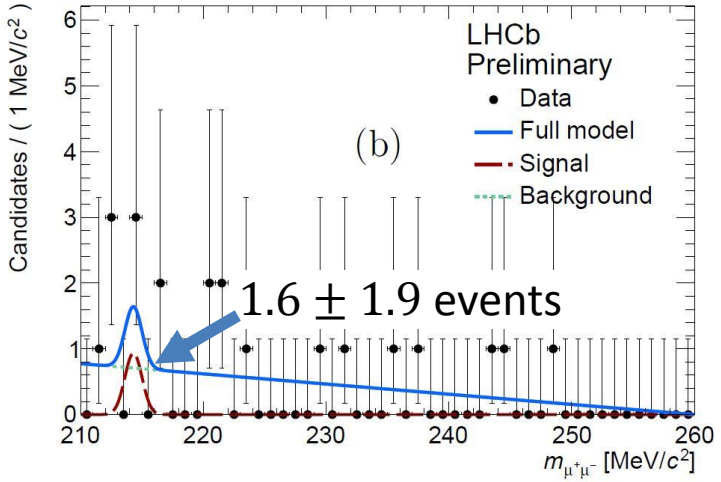
Search for $\Sigma^+ \to p\mu^+\mu^-$ decays

LHCb-CONF-2016-013



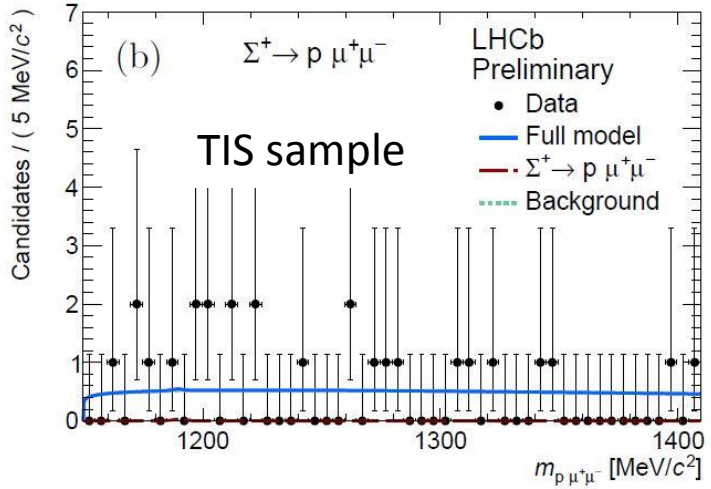
no enhancement at 214.3 MeV

$m(\mu^+\mu^-)$ in $\mathrm{m}(\Sigma^+)$ signal region



- $\Sigma^+ \to p\mu^+\mu^-$ 4.0σ evidence with full selection
- No enhancement at $m(\mu^+\mu^-) = 214.3$ MeV
- No significant signal in TIS sample (see sl. 7):

  $BF(\Sigma^+ \to p\mu^+\mu^-) < 6.3 \times 10^{-8}$ @ 95% CL



Search for $K_s^0 \to \mu^+\mu^-$

- FCNC process, dominated by long distance contribution through $K^0 \to \gamma\gamma$, in absence of CP violation it can proceed only through P wave

- SM prediction:

  $BF(K_S^0 \to \mu^+\mu^-) = (5.0 \pm 1.5) \times 10^{-12}$

  JHEP 01 (2004), 009

- Branching ratio can be enhanced by new physics contributions, for example from new light scalars

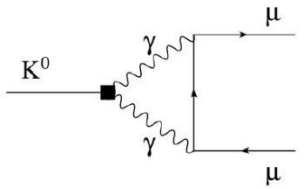
- Current limit set by LHCb on 1fb^{-1} of Run1:

  $BF(K_S^0 \to \mu^+\mu^-) < 9 \times 10^{-9}$ @90% CL

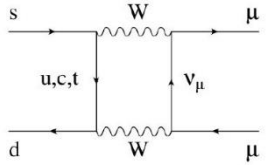
  LHCb 2011 dataset (1 fb^{-1}), JHEP 01 (2013) 090

- New update on remaining 2fb^{-1} of Run1

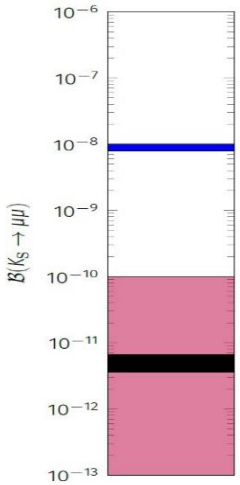
long distance contribution



example of short distance contribution



JHEP 01 (2004), 009



current limit (LHCb)

most interesting region

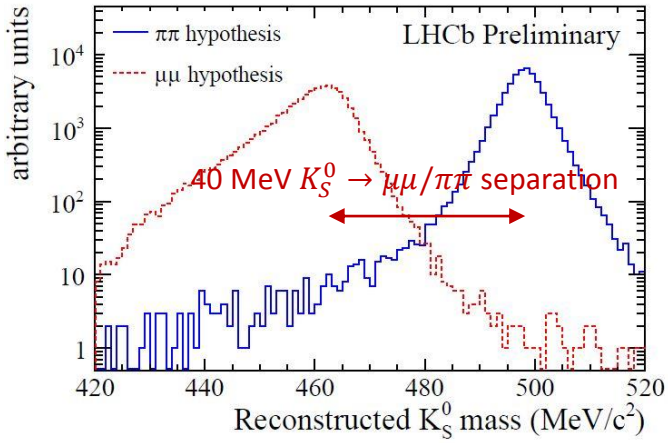
SM prediction

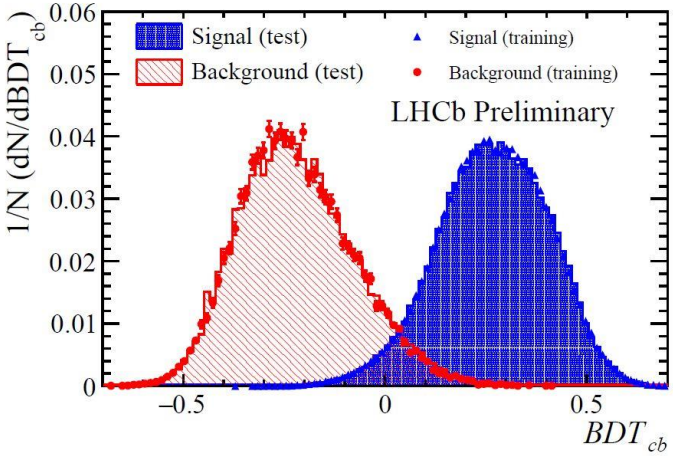
plot from A. Puig

Search for $K_s^0 \to \mu^+\mu^-$

- Data sample split in three subsets depending on trigger selection. Trigger efficiency $\sim$ 2.5%, limited by low p,pT of muons.
- $K_S^0 \to \pi^+\pi^-$ used as calibration and normalization mode. Main background source together with the combinatorial background.
- BDT based on kinematic, geometric, topologic quantities to suppress combinatorial background (one BDT for each trigger category, each one hen split in 10 bins)
- BDT based on particle ID quantities to reduce misidentified $K_S^0 \to \pi^+\pi^-$ (x 4 suppression improvement w.r.t. previous measurement)

LHCb-CONF-2016-012

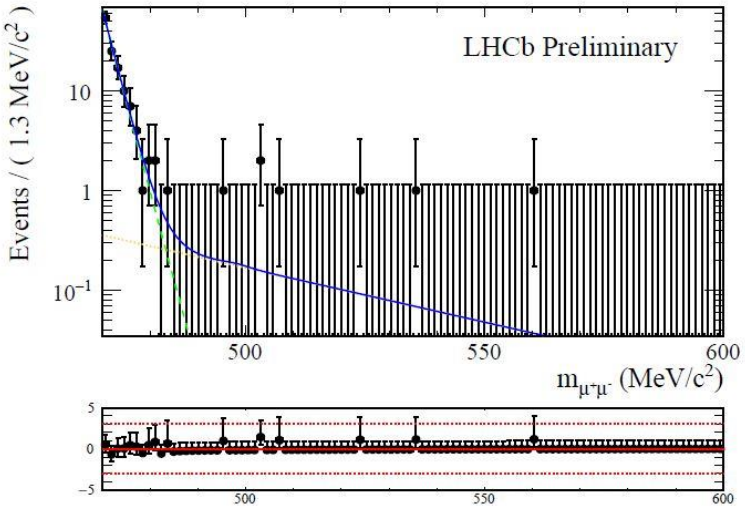




Search for $K_s^0 \to \mu^+\mu^-$

- Simultaneous unbinned maximum likelihood fit of $m(\mu^+\mu^-)$ in all BDT bins and trigger categories
- Three components: signal, misID $K_S^0 \to \pi^+\pi^-$, combinatorial background

LHCb-CONF-2016-012



Branching ratio from:

$$\mathcal{B}(K_S^0 \to \mu^+\mu^-) = \mathcal{B}(K_S^0 \to \pi^+\pi^-) \cdot \frac{\epsilon^{\pi\pi}}{\epsilon^{\mu\mu}} \cdot \frac{N^{\mu\mu}}{N^{\pi\pi}}$$

$$\frac{\epsilon^{\pi\pi}}{\epsilon^{\mu\mu}} = \frac{\epsilon^{\pi\pi}_{sel}}{\epsilon^{\mu\mu}_{sel}} \times \frac{\epsilon^{\pi\pi}_{trig}}{\epsilon^{\mu\mu}_{trig}} \times \frac{1}{\epsilon^{\mu\mu}_{BDT}} \times \frac{1}{\epsilon_{\mu\mathrm{ID}}}$$

No signal found, upper limit:

$$BF\left(K_S^0 \to \mu^+\mu^-\right) < 5.8(6.9) \times 10^{-9} \text{ @ 90(95)\% CL}$$

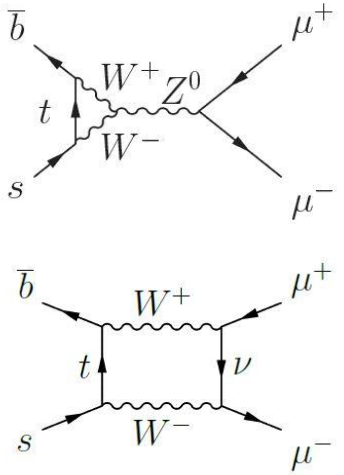
$\sim$ 2 times improvement compared to previous limit

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

- FCNC processes, additional helicity suppression, theoretically clean

  $BF(B_s^0 \to \mu^+\mu^-): (3.65 \pm 0.23)10^{-9}$
  $BF(B^0 \to \mu^+\mu^-): (1.06 \pm 0.09)10^{-10}$

  Bobeth et al, PRL112, 101801 (2014)



- The BF can be significantly affected in a number of NP models. Especially sensitive to contributions in scalar/pseudoscalar sector

- Latest measurements by LHCb, CMS and ATLAS

  $BF(B_s^0 \to \mu^+\mu^-): (2.9^{+1.1}_{-1.0}) \times 10^{-9}$ $4.0\ \sigma$
  $BF(B^0 \to \mu^+\mu^-) < 7.4 \times 10^{-10}$ @ 95% CL

  LHCb PRL 111 (2013) 101805

  $BF(B_s^0 \to \mu^+\mu^-): (3.0^{+1.0}_{-0.9}) \times 10^{-9}$ $4.3\ \sigma$
  $BF(B^0 \to \mu^+\mu^-) < 7.4 \times 10^{-10}$ @ 95% CL

  CMS PRL 111 (2013) 101804

  $BF(B_s^0 \to \mu^+\mu^-): (0.9^{+1.1}_{-0.8}) \times 10^{-9}$
  $BF(B^0 \to \mu^+\mu^-) < 4.2 \times 10^{-10}$ @ 95% CL

  ATLAS EPJ C76 (2016) no 9, 513

consistent with SM

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

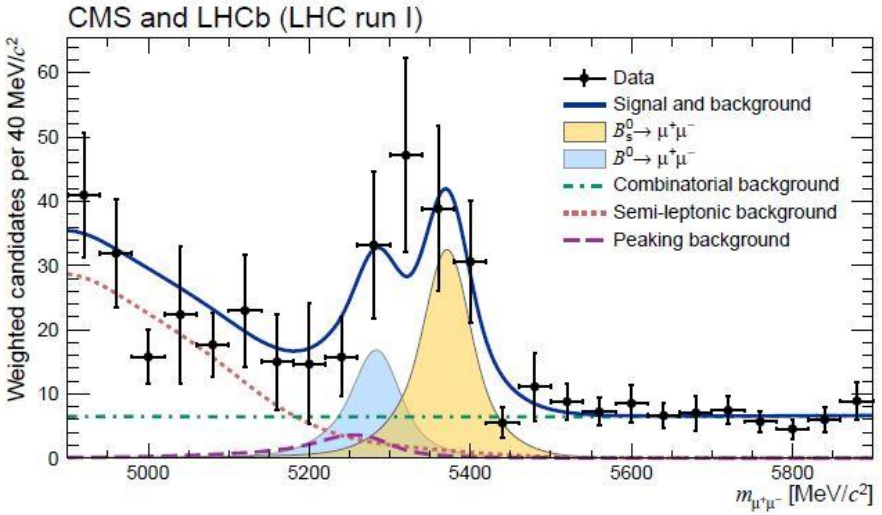
Nature 522, 68-72

CMS-LHCb combination

- Combined analysis of LHCb and CMS Run1 datasets
- Observation of $B^0_s \to \mu^+\mu^-$ decay

$$BF(B^0_s \to \mu^+\mu^-) = (2.8^{+0.7}_{-0.6}) \times 10^{-9}$$

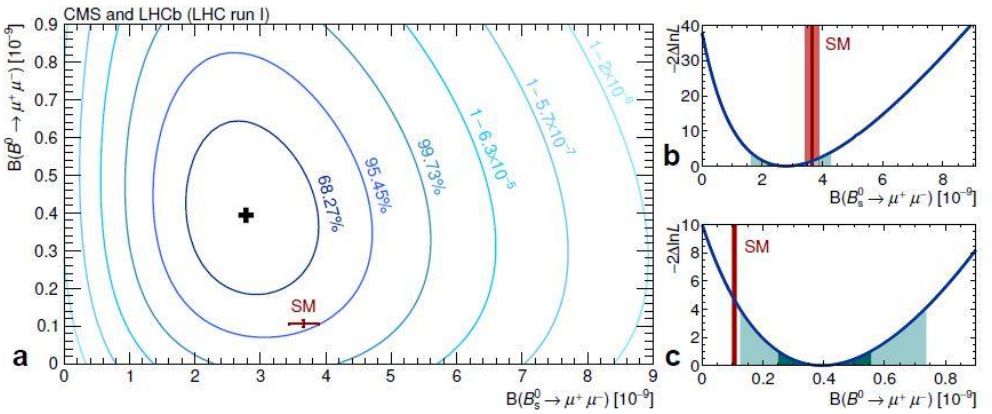
6.2 σ stat significance
compatibility with SM at 1.2σ level



- Evidence of $B^0 \to \mu^+\mu^-$ decay

$$BF(B^0 \to \mu^+\mu^-) = (3.9^{+1.6}_{-1.4}) \times 10^{-10}$$

3.0 σ stat significance
compatibility with SM at 2.2σ level

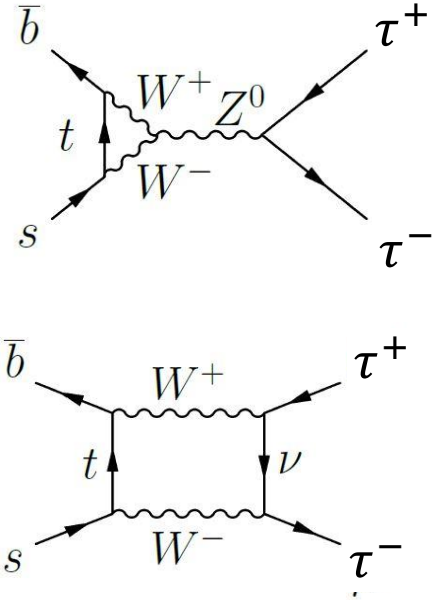


Search for $B^0_{(s)} \to \tau^+\tau^-$ decays

- FCNC processes, analogous to $B^0_{(s)} \to \mu^+\mu^-$ (but much less helicity-suppressed)
- With $B^0_{(s)} \to \mu^+\mu^-$ they can test lepton flavor universality
- SM time-integrated BF:

$$BF(B_s^0 \to \tau^+\tau^-) = (7.73 \pm 0.49) \times 10^{-7}$$
$$BF(B^0 \to \tau^+\tau^-) = (2.22 \pm 0.19) \times 10^{-8}$$

Bobeth et al, PRL 112 (2014), 101801



- τ leptons selected in $\tau^+ \to \pi^+\pi^-\pi^+\bar{\nu}_\tau$. Decay model tuned on CLEO data

PRD61 (2000), 112002

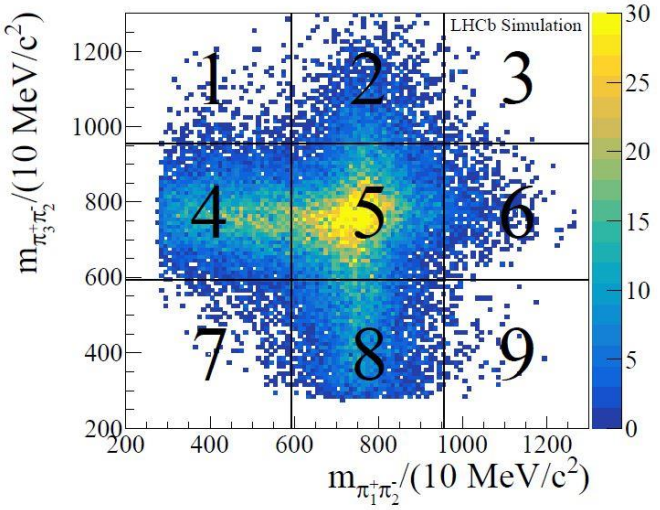
- Experimentally VERY challenging due to two neutrinos in final state
- B_s^0 and B^0 cannot be separated: assumption on one decay needed to extract limit on the other

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

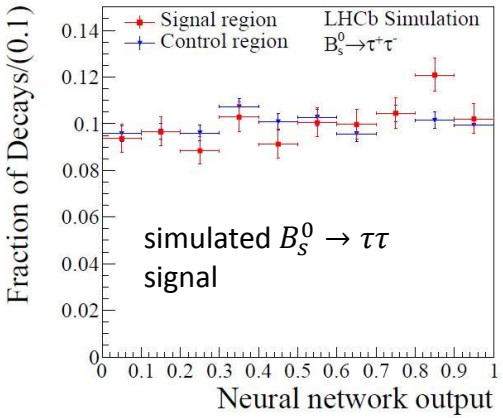
LHCb-CONF-2016-011

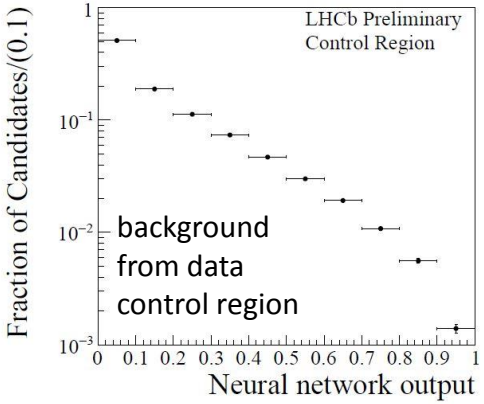
- Approximate reconstruction of $B \to \tau\tau$ decay chain by exploiting geometrical and mass constraints
- Definition of *signal*, *control* and *background* samples based on $(m_{\pi_1^\pm\pi_2^\mp}, m_{\pi_3^\pm\pi_2^\mp})$ of $\tau^\pm \to \pi_1^\pm\pi_2^\mp\pi_3^\pm\nu_\tau$ decays
  - signal region: both $\tau^\pm$ in 5
  - control region: one τ in 4 or 8, the other in 4, 5 or 8
- After pre-selection, neural network (NN) built with geometric, kinematic and isolation variables to separate signal and background

$B_s^0 \to \tau^+\tau^-$ signal MC



signal NN distribution uniform in [0,1], background peaks at 0





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

- $B^0 \to D^+[K^-\pi^+\pi^+]D_s^-[K^+K^-\pi^-]$ used as calibration and normalisation channel
- Signal extracted from fit to NN in signal region:

$$N_{B_s\to\tau\tau} = -46 \pm 51$$

- $\mathcal{B}(B_s^0 \to \tau^+\tau^-) =$

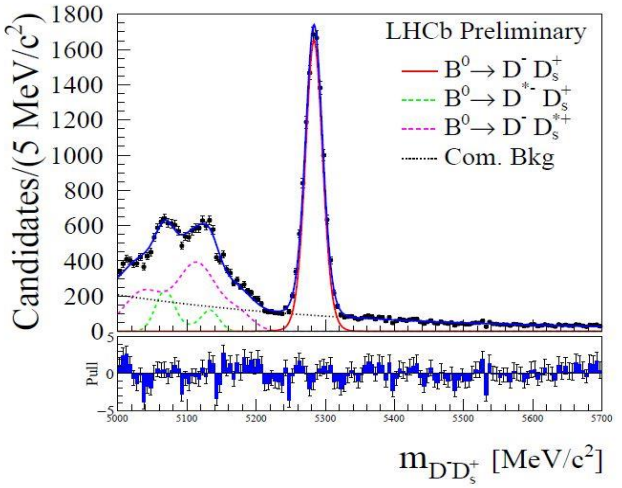
$$\frac{\epsilon^{D^-D_s^+} \cdot \mathcal{B}(B^0 \to D^+D_s^-) \cdot \mathcal{B}(D^+ \to K^-\pi^+\pi^+) \cdot \mathcal{B}(D_s^+ \to K^+K^-\pi^+)}{N^{\text{obs}}_{D^-D_s^+} \cdot \epsilon^{\tau^+\tau^-} \cdot [\mathcal{B}(\tau^- \to \pi^-\pi^+\pi^-\nu_\tau)]^2} \cdot \frac{f_d}{f_s}$$

$BF(B_s^0 \to \tau^+\tau^-) < 2.4(3.0) \times 10^{-3}$ at 90(95)% CL

assuming signal fully dominated by B^0:

$BF(B^0 \to \tau^+\tau^-) < 1.0(1.3) \times 10^{-3}$ at 90 (95%) CL

x 4 improvement w.r.t. previous result from BaBar (PRL 96 (2006) 241802)



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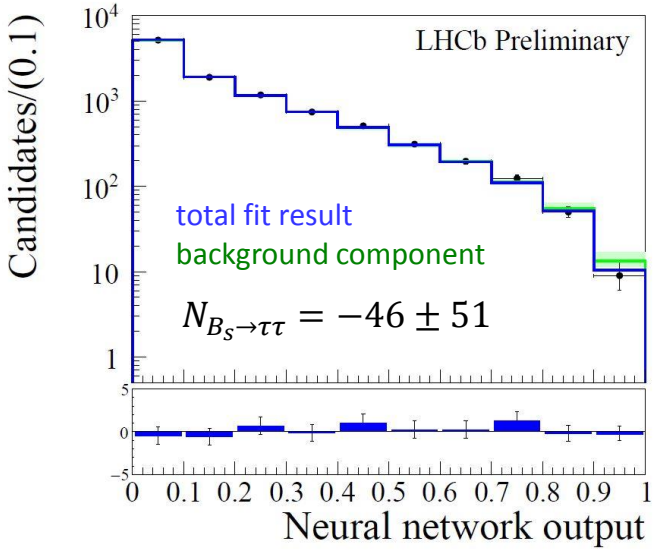

Summary

- First observation of $B_c^+ \to J/\psi D^{(*)} K^{(*)}$ decays and precise measurement of B_c^+ mass
- Evidence of $\Sigma^+ \to p\mu^+\mu^-$ does not confirm $\mu^+\mu^-$ enhancement at 214.3 MeV seen by HyperCP
- Improved BF upper limit of $B^0_{(s)} \to \mu^+\mu^-\mu^+\mu^-$ and $K^0_S \to \mu^+\mu^-$decays
- Combined CMS+LHCb analysis of $B^0_{(s)} \to \mu^+\mu^-$ decays leads to evidence of $B^0 \to \mu^+\mu^-$, to be confirmed with future measurements
- First search for $B^0_s \to \tau^+\tau^-$ decays