

Searches for rare and forbidden decays in LHCb

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Rare & Forbidden decays at LHCb

- Searching for decays we **expect NOT to find**
 - **Forbidden** in SM
 - **Highly suppressed** in SM
 - Any signal = possible New Physics!
- LHCb can test different aspects of SM
 - Rare B and D decays
 - Also K^0 !
- **LHCb very suitable**
 - High vertex & mom. resolution
 - PID systems

Rare & Forbidden decays at LHCb

- Highly suppressed decays in SM
 - Higher order diagrams
 - **FCNC** box or penguin diagrams
- Forbidden decays
 - Lepton Flavour Violating (**LFV**)
 - e.g. $e^{\pm}\mu^{\mp}$ and $\tau^{\pm}\mu^{\mp}$
 - Baryon Number Violating (**BNV**)
 - e.g. $p\mu^{-}$

Rare & Forbidden decays at LHCb

\mathcal{B}

10^{-14}

$$K_{S/L}^0 \rightarrow \mu^+ \mu^- \mu^+ \mu^-$$

Suppressed FCNC

10^{-19}

$$D^{*0} \rightarrow \mu^+ \mu^-$$

Suppressed FCNC

$< 10^{-27}$

$$B_{(s)}^0 \rightarrow p \mu^-$$

Baryon number violating

10^{-50}

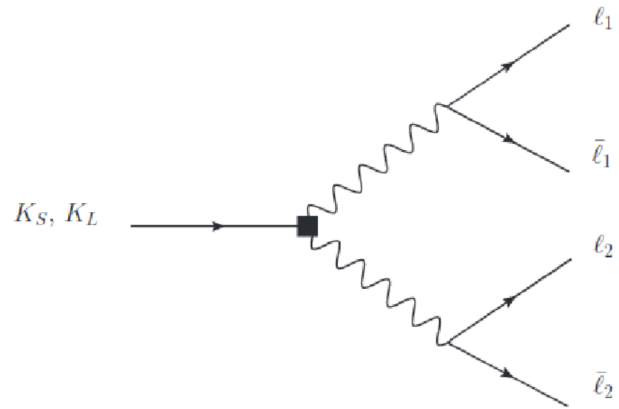
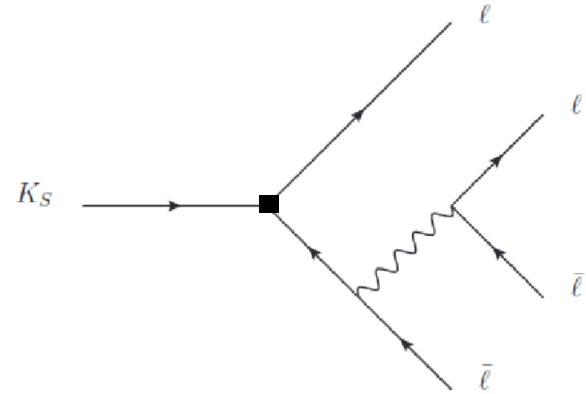
$$B^0 \rightarrow K^{*0} \mu^\pm e^\mp \quad \& \quad B_s^0 \rightarrow \phi \mu^\pm e^\mp$$

Lepton flavour violating

$$B^0 \rightarrow K^{*0} \tau^\pm \mu^\mp$$

$$K_{S/L}^0 \rightarrow \mu^+ \mu^- \mu^+ \mu^-$$

- FCNC decay
- SM expectation $\sim 10^{-14}$ (K_S^0) - 10^{-13} (K_L^0) [1]
 - LHCb K_L^0 acceptance $\sim 2 \times 10^{-3}$ lower than K_S^0 **due to lifetime**
- Measure relative to $K_S^0 \rightarrow \pi^+ \pi^-$ decays
- Measured in **different trigger categories**
- Use **BDT** to reject combinatorial background



[1] [Eur. Phys. J. C73 \(2013\) 2678](#)

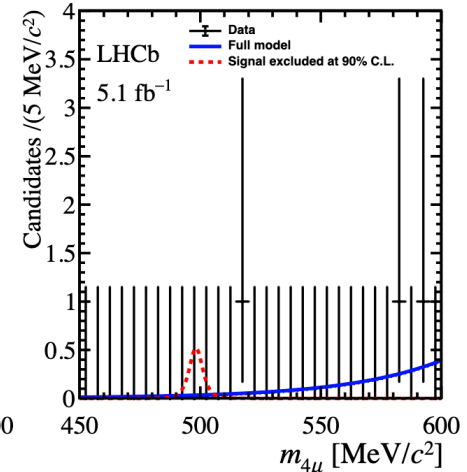
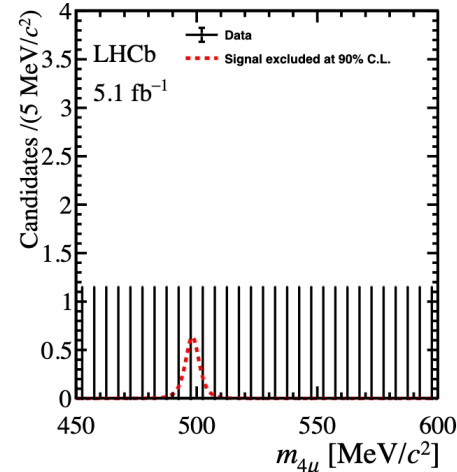
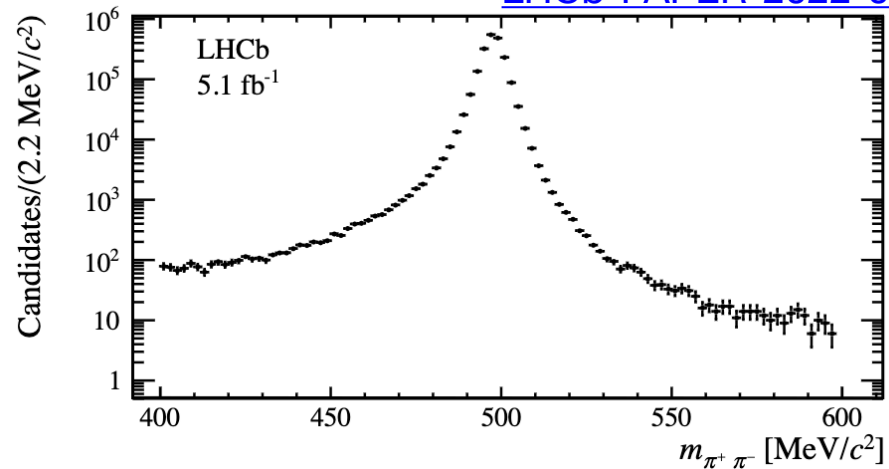
$$K_{S/L}^0 \rightarrow \mu^+ \mu^- \mu^+ \mu^-$$

- Abundant normalisation yield
- 90% C.L. by **integrating positive side of profile likelihood**

$$\mathcal{B}(K_S^0 \rightarrow \mu^+ \mu^- \mu^+ \mu^-) < 5.1 \times 10^{-12}$$

$$\mathcal{B}(K_L^0 \rightarrow \mu^+ \mu^- \mu^+ \mu^-) < 2.3 \times 10^{-9},$$

- Modelling of **trigger efficiency** is **leading systematic**



Search for $D^{*0} \rightarrow \mu^+ \mu^-$ decays

- FCNC decay
- D^{*0} decays strongly, in SM $\mathcal{B}(D^{*0} \rightarrow \mu^+ \mu^-) < 10^{-19}$ [1]
- Current best limit from CMD-3: $\mathcal{B}(D^{*0} \rightarrow e^+ e^-) < 10^{-6}$ [2]
- LHCb produced abundant D^{*0}
 - Large background in prompt sample
 - Search using $B^\pm \rightarrow D^{*0} \pi^\pm$ decays
 - Use displaced B^+ vertex for signal separation
- BDT against combinatorial background
- Simultaneous ML fit to $m(D^{*0})$ and $m(B^\pm)$

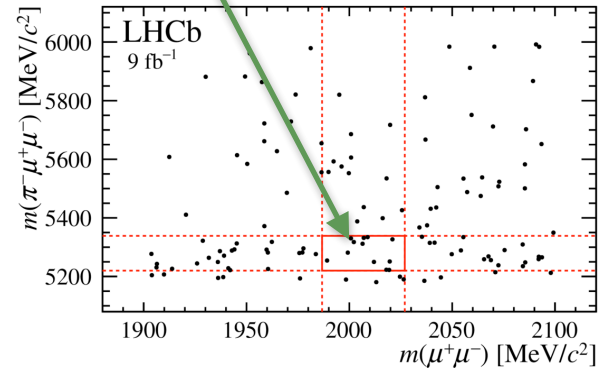
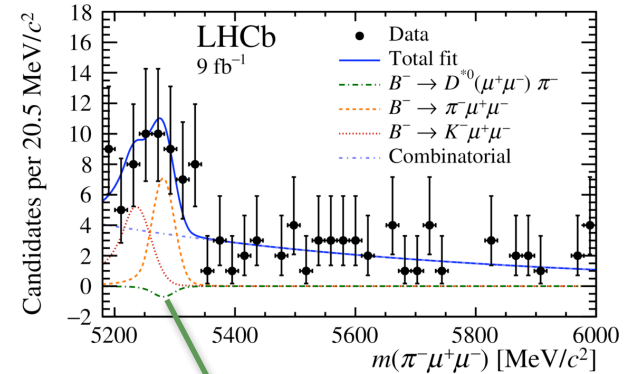
[1] [JHEP11\(2015\)142](#) [2] [PAN83.954\(2020\)](#)

Search for $D^{*0} \rightarrow \mu^+ \mu^-$ decays

- Normalised to $B^\pm \rightarrow J/\psi(\rightarrow \mu^+ \mu^-)K^\pm$
- Non-resonant $B^\pm \rightarrow \pi^\pm \mu^+ \mu^-$ and mis-identified $B^\pm \rightarrow K^\pm \mu^+ \mu^-$ included in fit

$$N_{B^\pm \rightarrow D^{*0} \pi^\pm} = -2 \pm 3$$

- Under fluctuation of background in signal region



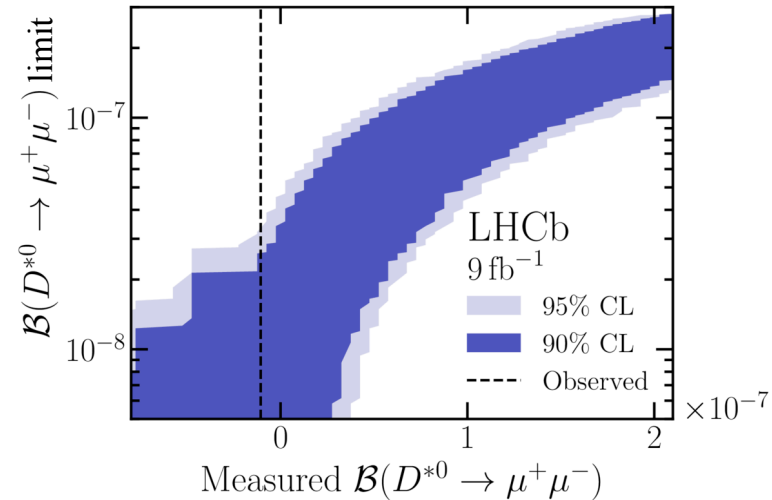
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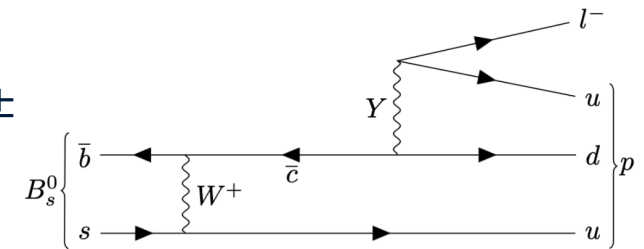
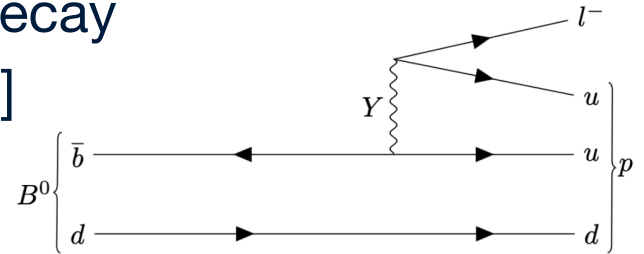
- Under fluctuation of background in signal region
- Upper limit using Feldman-Cousins

$$\mathcal{B}(D^{*0} \rightarrow \mu^+ \mu^-) < 2.6 (3.4) \times 10^{-8} \text{ at } 90 (95)\% \text{ CL}$$



Search for $B_{(s)}^0 \rightarrow p\mu^-$ decays

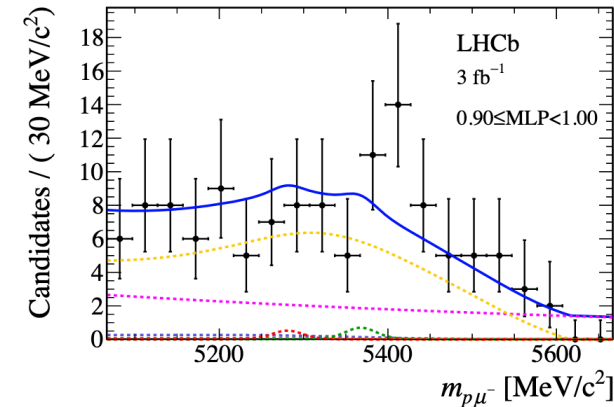
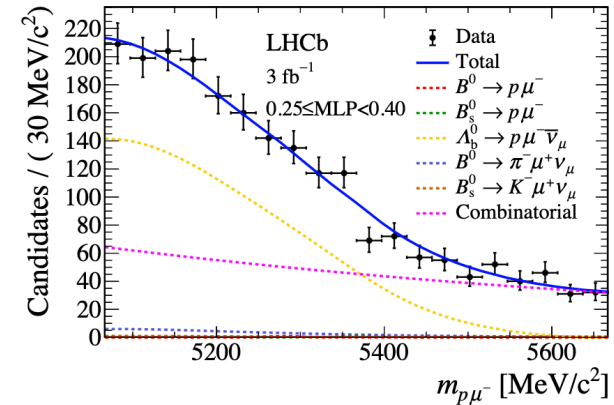
- Lepton number & baryon number violating decay
 - Proton decay $\mathcal{B}(\bar{b} \rightarrow uu\ell^-) < 10^{-27}$ [1]
 - **First search!**
- Use PID to reject hadron misID candidates
- **MLP** to reject combinatorial background
- Normalised using $B^\pm \rightarrow J/\psi(\rightarrow \mu^+\mu^-)K^\pm$
- Signal extraction using fit on $m(p\mu^-)$
 - **Binned in MLP response**



[1] [PRD.72.095001](https://arxiv.org/abs/hep-ex/0501067)

Search for $B_{(s)}^0 \rightarrow p\mu^-$ decays

- Signal extraction using fit on $m(p\mu^-)$
 - Binned in MLP response
 - Dominant background: semi-leptonic decays



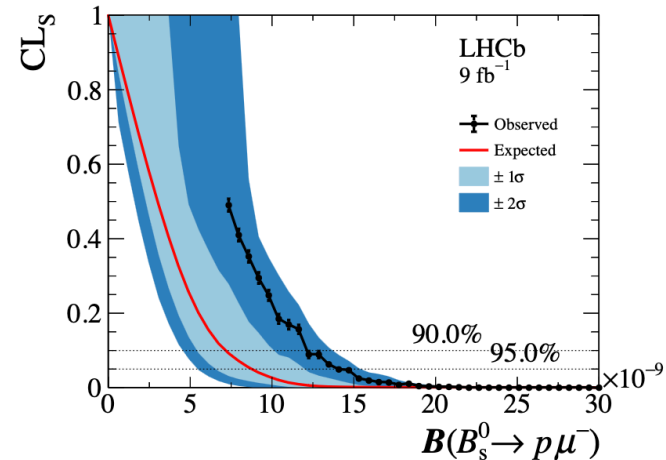
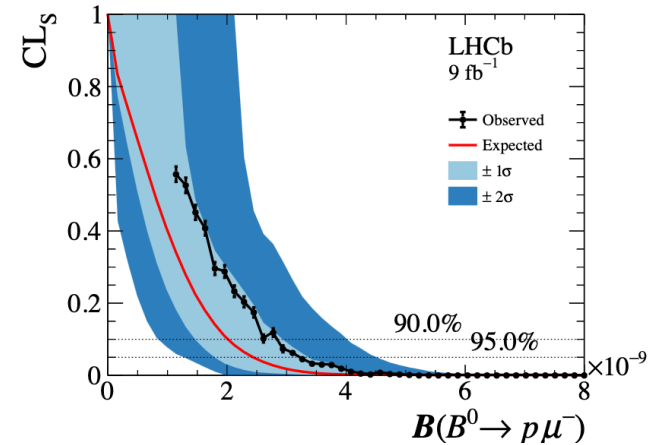
Search for $B_{(s)}^0 \rightarrow p\mu^-$ decays

- Signal extraction using fit on $m(p\mu^-)$
 - Binned in MLP response
 - Dominant background: semi-leptonic decays

- Upper limit obtained using **CLs method**

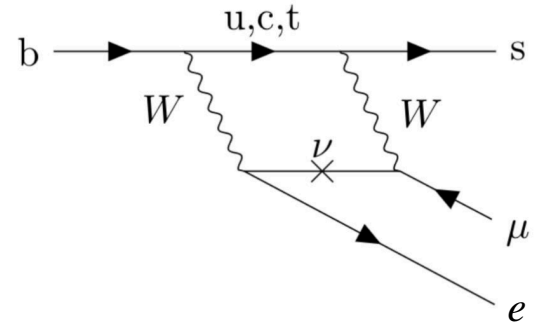
$$\mathcal{B}(B^0 \rightarrow p\mu^-) < 2.6 \text{ (3.1)} \times 10^{-9}$$

$$\mathcal{B}(B_s^0 \rightarrow p\mu^-) < 12.1 \text{ (14.0)} \times 10^{-9}$$



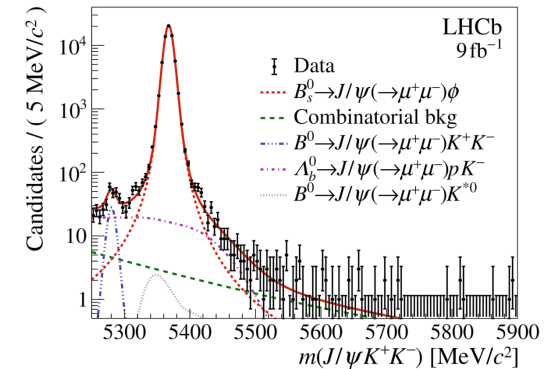
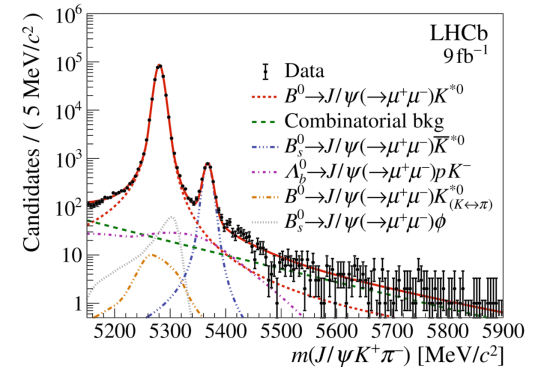
Search for LFV $B^0 \rightarrow K^{*0} \mu^\pm e^\mp$ & $B_s^0 \rightarrow \phi \mu^\pm e^\mp$ decays

- Lepton flavour violating decays
 - Only possible in SM through **neutrino mixing**
 - Branching fractions of $\mathcal{O}(10^{-50})$
- Potentially enhanced by **leptoquarks or Z'**
- **First limit** for $B_s^0 \rightarrow \phi \mu^\pm e^\mp$!
- Semi-leptonic backgrounds rejected with **vetos**
- **BDT** to reject combinatorial background



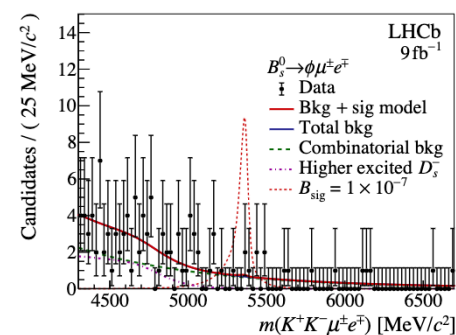
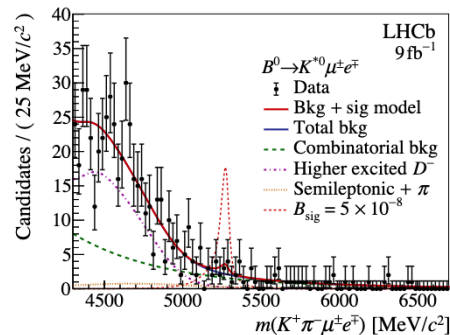
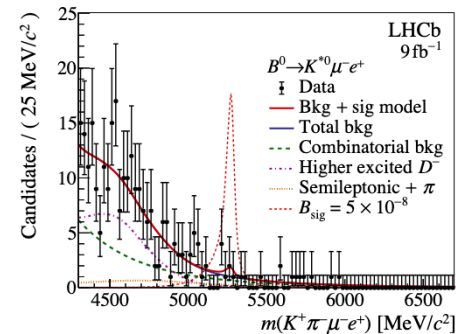
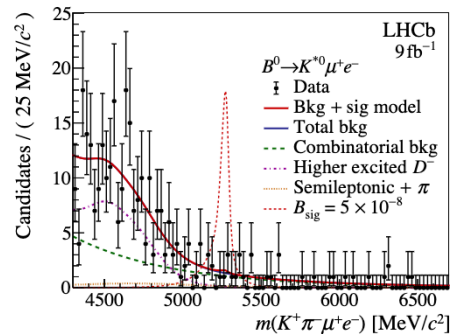
Search for LFV $B^0 \rightarrow K^{*0} \mu^\pm e^\mp$ & $B_s^0 \rightarrow \phi \mu^\pm e^\mp$ decays

- Normalised using $B^0 \rightarrow J/\psi(\rightarrow \mu^+ \mu^-) K^{*0}$ and $B_s^0 \rightarrow J/\psi(\rightarrow \mu^+ \mu^-) \phi$ resonant modes
- Models different misID backgrounds
- Signal fit split by lepton charges
 - Simultaneous ML fit to $m(K^+ \pi^- \mu^+ e^-)$ or $m(K^+ K^- \mu^+ e^-)$



Search for LFV $B^0 \rightarrow K^{*0} \mu^\pm e^\mp$ & $B_s^0 \rightarrow \phi \mu^\pm e^\mp$ decays

- No significant signal observed
- Upper limits set using **CLs** method

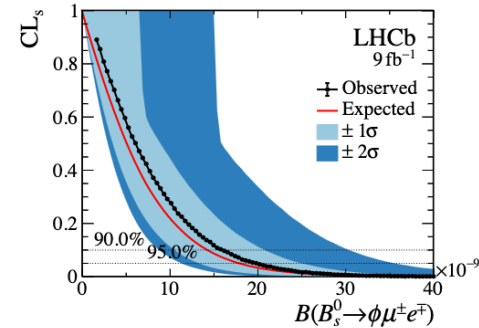
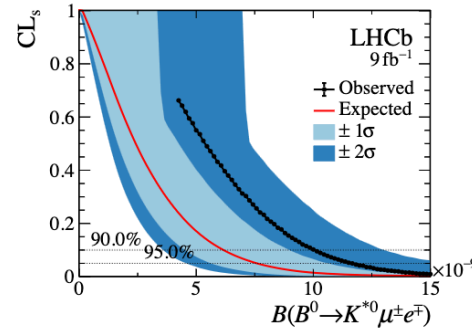
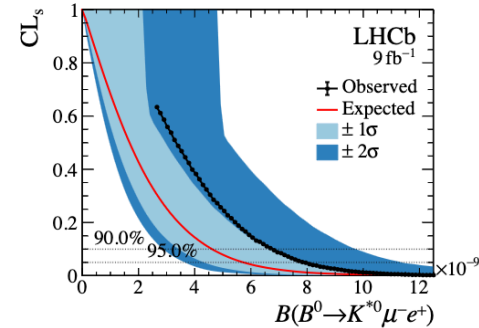
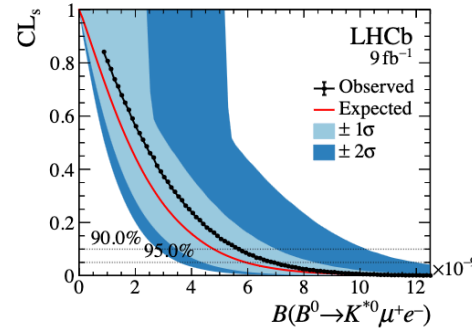


Search for LFV $B^0 \rightarrow K^{*0} \mu^\pm e^\mp$ & $B_s^0 \rightarrow \phi \mu^\pm e^\mp$ decays

- No significant signal observed
- Upper limits set using **CLs method**

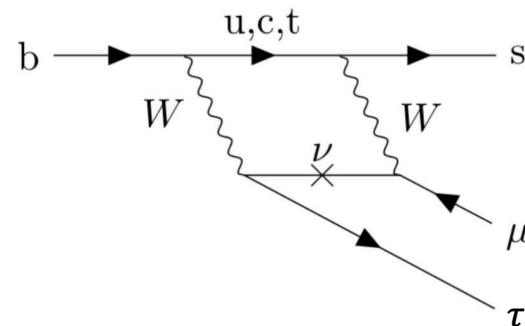
$$\begin{aligned}
 \mathcal{B}(B^0 \rightarrow K^{*0} \mu^+ e^-) &< 5.7 \times 10^{-9} \quad (6.9 \times 10^{-9}), \\
 \mathcal{B}(B^0 \rightarrow K^{*0} \mu^- e^+) &< 6.8 \times 10^{-9} \quad (7.9 \times 10^{-9}), \\
 \mathcal{B}(B^0 \rightarrow K^{*0} \mu^\pm e^\mp) &< 10.1 \times 10^{-9} \quad (11.7 \times 10^{-9}), \\
 \mathcal{B}(B_s^0 \rightarrow \phi \mu^\pm e^\mp) &< 16.0 \times 10^{-9} \quad (19.8 \times 10^{-9})
 \end{aligned}$$

- First limit for $B_s^0 \rightarrow \phi \mu^\pm e^\mp$
- World's **most stringent limit** for $B^0 \rightarrow K^{*0} \mu^\pm e^\mp$



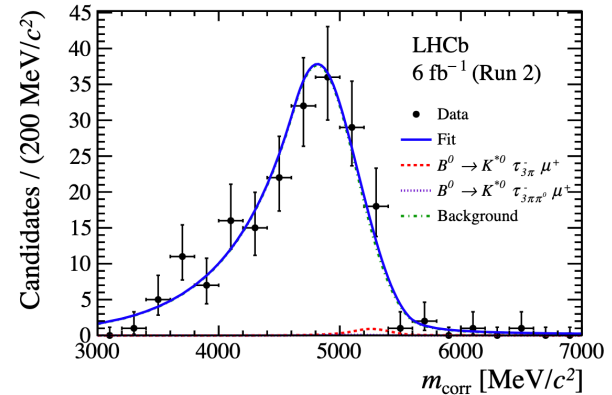
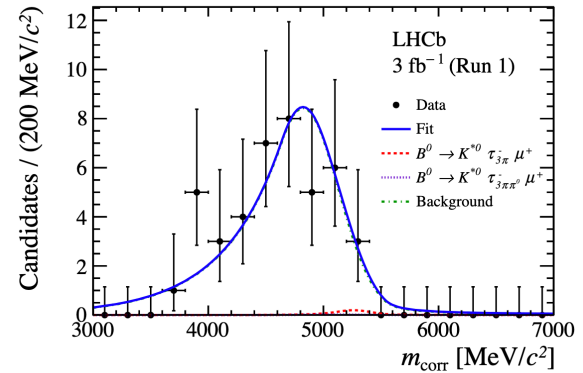
Search for LFV $B^0 \rightarrow K^{*0} \tau^\pm \mu^\mp$ decays

- Similar to $B^0 \rightarrow K^{*0} \mu^\pm e^\mp$
 - $\tau^\pm \rightarrow 3\pi^\pm \pi^0$
 - First search!
- Challenging tau reconstruction!
 - 3 pion vertex
 - missing neutrino energy
- Norm. $B^0 \rightarrow D^-(\rightarrow K^+ \pi^- \pi^-) D_s^+(\rightarrow K^+ K^- \pi^+)$
- 1 BDT for comb. + 1 BDT for $D^{(*)} \rightarrow \tau$ misID
- Use PID to further veto D backgrounds



Search for LFV $B^0 \rightarrow K^{*0} \tau^\pm \mu^\mp$ decays

- Model background in control region
 - Choice of control region = largest syst.
- Fit to $m_{\text{cor}} = \sqrt{p_\perp + m_{K^* \tau \mu}^2} + p_\perp$
 - p_\perp = missing mom. perpendicular to B^0

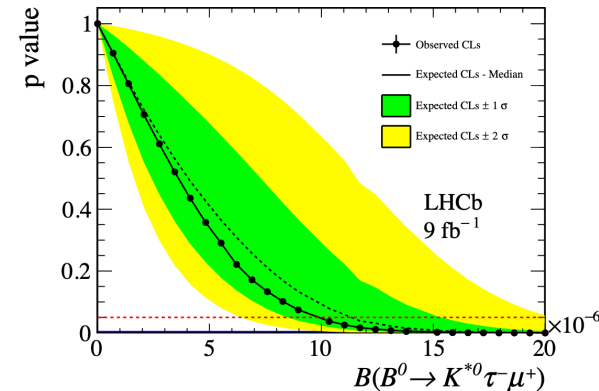
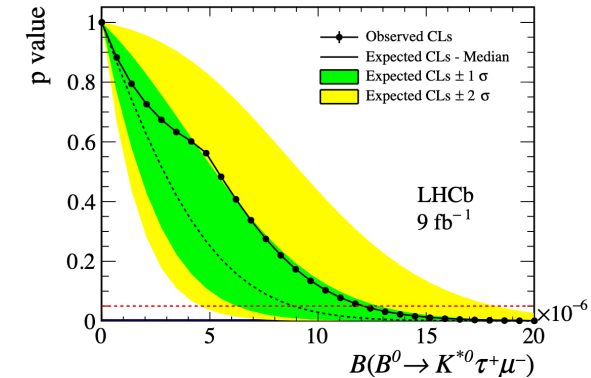


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- Fit to $m_{\text{cor}} = \sqrt{p_\perp + m_{K^* \tau \mu}^2 + p_\perp}$
 - p_\perp = missing mom. perpendicular to B^0
- Set limits using CLs method

$$\mathcal{B}(B^0 \rightarrow K^{*0} \tau^+ \mu^-) < 1.0 \text{ (1.2)} \times 10^{-5}$$

$$\mathcal{B}(B^0 \rightarrow K^{*0} \tau^- \mu^+) < 8.2 \text{ (9.8)} \times 10^{-6}$$



Summary and conclusion

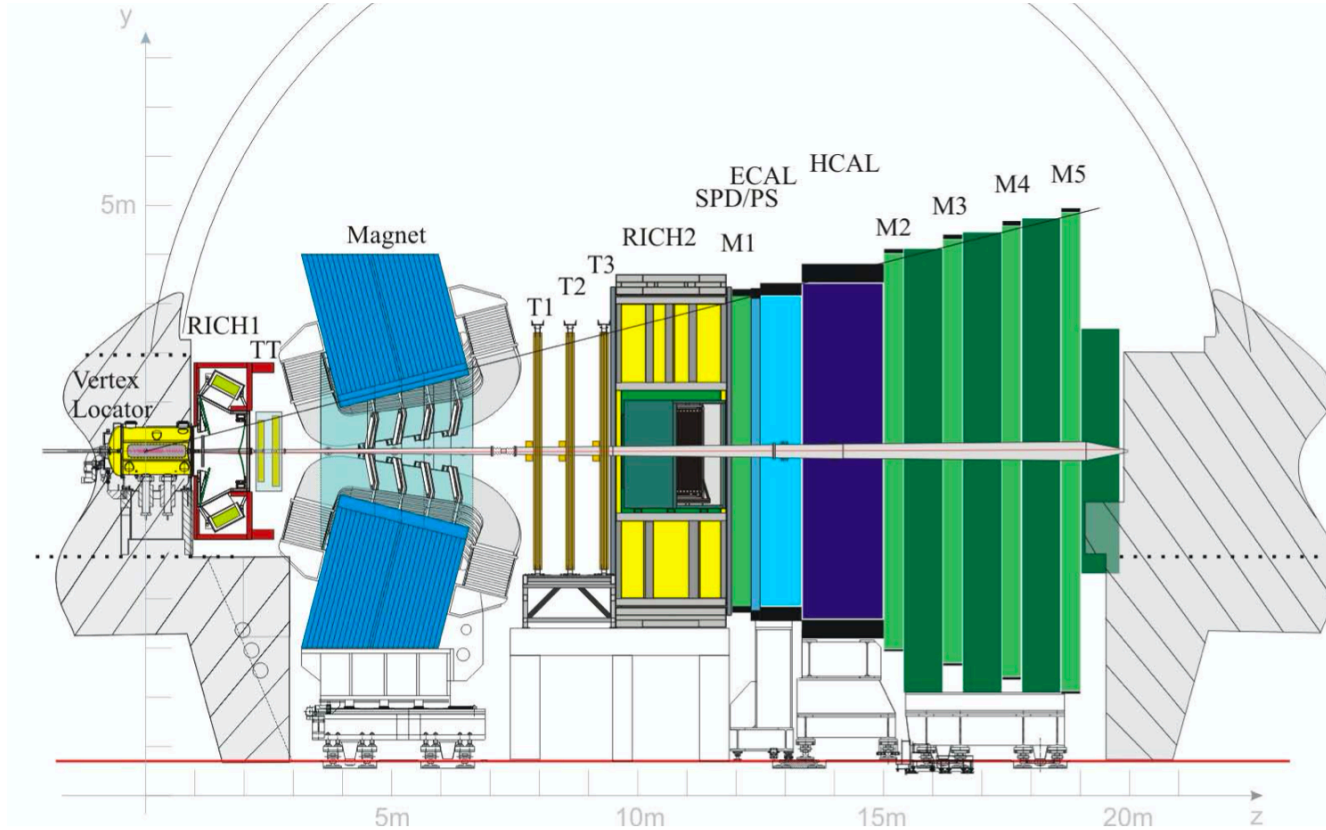
- Very rare and forbidden decays provide a **wide variety of SM tests and NP searches**
- LHCb sets many **world's-best limits**
 - 4 analyses presented here today
 - Many more done and still to come!
- Recent LHCb upgrade
 - **More data expected**
 - Often limiting factor in precision
 - Exciting times ahead!



BACKUP



The LHCb detector



$$K_{S/L}^0 \rightarrow \mu^+ \mu^- \mu^+ \mu^-$$

Table 1: Summary of systematic uncertainties.

Source	Relative effect (%)
$\mathcal{B}(K_S^0 \rightarrow \pi^+ \pi^-)$	0.07
s_{MB}	0.30
Variations in data taking	1
Data/simulation differences	4.40
$K_S^0 \rightarrow \pi^+ \pi^-$ yield	1
PID	3.30
Tracking	1.20
ϵ^{L0}	10 (TIS), 21 (xTOS)
$\epsilon^{\text{HLT/L0}}$	11
Total	16 (TIS), 24 (xTOS)