# Rare decays in the beauty, charm and strange sector

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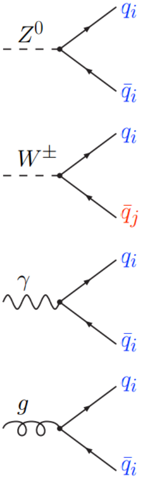
# Outline

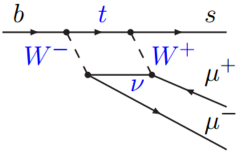
1. Beauty decays
   - $\Lambda_b \to \Lambda\mu\mu$
   - $\bar{B}^0_s \to K^*\mu\mu$
   - $B_{(s)} \to e\mu$
   - $B \to K^* e\mu$.
2. Charm decays
   - $\Lambda_c \to p\mu\mu$
   - $D \to hh\mu\mu$
3. Strange decays
   - $K^0_S \to \mu\mu$
   - $\Sigma \to p\mu\mu$

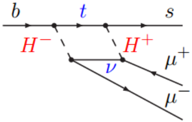
# Why rare decays?

- The SM allows only charged interactions to change flavour.
  - Other interactions are flavour conserving.
- One can escape this constraint and produce $b \to s$ and $b \to d$ at loop level.
  - These kinds of processes are suppressed in the SM $\to$ Rare decays.
  - New Physics can enter in the loops.

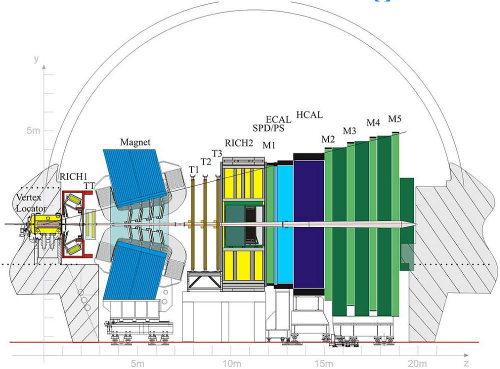


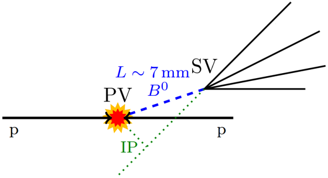




# LHCb detector - tracking

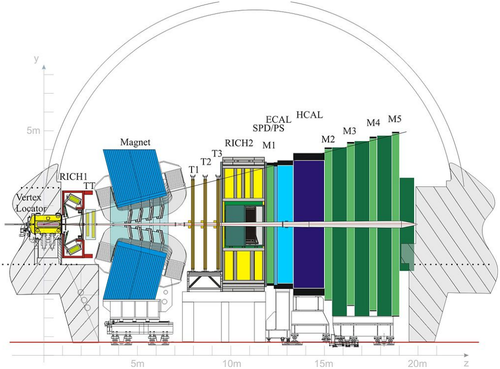


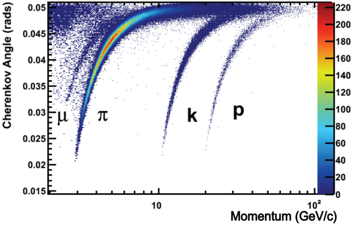




- Excellent Impact Parameter (IP) resolution ($20\ \mu\mathrm{m}$).
  $\Rightarrow$ Identify secondary vertices from heavy flavour decays
- Proper time resolution $\sim\ 40-50$ fs.
  $\Rightarrow$ Good separation of primary and secondary vertices.
- Excellent momentum ($\delta p/p \sim 0.5-1.0\%$) and inv. mass resolution.
  $\Rightarrow$ Low combinatorial background.

# LHCb detector - PID

*Int. J. Mod. Phys. A30 (2015) 1530022*




- Excellent Muon identification $\epsilon_{\mu\to\mu} \sim 97\%$, $\epsilon_{\pi\to\mu} \sim 1-3\%$
- Good $K-\pi$ separation via RICH detectors, $\epsilon_{K\to K} \sim 95\%$, $\epsilon_{\pi\to K} \sim 5\%$.
  $\Rightarrow$ Reject peaking backgrounds.
- High trigger efficiencies, low momentum thresholds.
  $B \to J/\psi X$: Trigger $\sim 90\%$.

# Rare beauty decays

## $b \to s\ell\ell$ family

- $B \to K^{*}\mu\mu$
- $B_s^0 \to \phi\mu\mu$
- $\Lambda_b \to pK\mu\mu$
- LUV: $R_K$, $R_{K^*}$

## $b \to s\gamma$ family

- $B \to J/\psi\gamma$
- $B \to K\pi\pi\gamma$

## $b \to d\ell\ell$ family

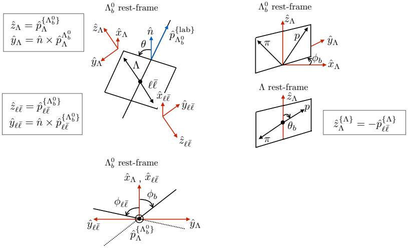
- $B \to \pi\pi\mu\mu$
- $\bar{B}_s^0 \to K^{*}\mu\mu$
- $\Lambda_b \to p\pi\mu\mu$

## Purely leptonic family

- $B \to \ell\ell$
- LFV: $B \to \ell\ell'$
- LFV in $\tau$

$\Rrightarrow$ Too many results to be covered in one talk! Please see A. Oyanguren's talk for more!

⇛ $b \rightarrow s\mu\mu$ in baryon sector.
⇛ Because of spin $1/2$ nature of the baryon there the system has to be described by 5 angles: 1710.00746
⇛ Impossible to perform a likelihood fit. Need to use moments:



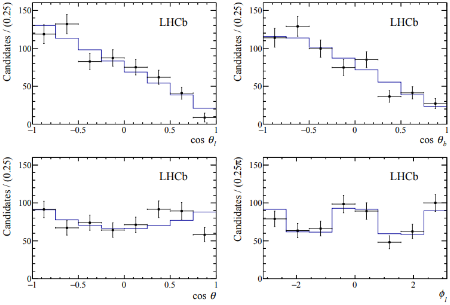

$$M_i = \frac{3}{32\pi^2} \int \sum_{i=1}^{34} K_i(q^2) f(\overrightarrow{\Omega}) d\overrightarrow{\Omega}$$

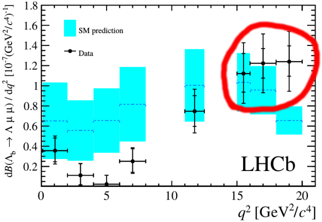
⇛ In total we have 34 observables!

# $\Lambda_b \to \Lambda\mu\mu$

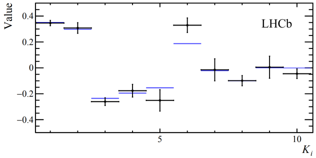
*LHCb-PAPER-2018-029*

- ⇛ Update with $5\ \mathrm{fb}^{-1}$.
- ⇛ 610 events observed at high $q^2$.
- ⇛ Angular efficiency modelled in 6D.



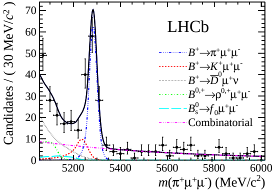

⇛ The results:



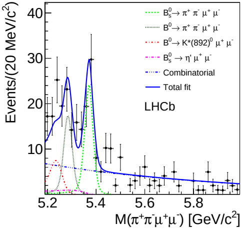
# $b \to d$ transitions

⇛ The $b \to d$ is further suppressed by $|V_{td}|/|V_{ts}| \to \ \mathcal{B} \sim \mathcal{O}(10^{-8})$.

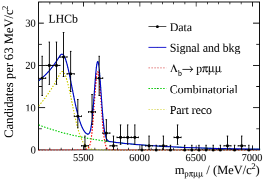
⇛ Already lots of results in Run1:




[JHEP 10 (2015) 034]




[PHYS. LETT. B743 (2015) 46]



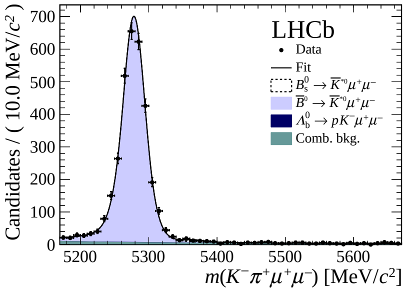

[JHEP 04 (2017) 029]

⇛ The ratio between the $b \to s$ and $b \to d$ can be used to determine some CKM elements:

$$\frac{\mathcal{B}(B \to \pi\mu\mu)}{\mathcal{B}(B \to K\mu\mu)} \sim |V_{td}/V_{ts}| = 0.20 \pm 0.02$$

⇛ Large improvements expected in Run2.

- ⇛ $4.6\ \mathrm{fb}^{-1}$ of data!
- ⇛ Analysis in 4 bins of NN response.
- ⇛ Signal yield determined from a simultaneous fit to the NN response bins.
- ⇛ Normalized to $B \to K^* J/\psi$.
- ⇛ First evidence with $3.4\ \sigma$.




- ⇛ The measured branching fraction:

$$\mathcal{B}(\bar{B}^0_s \to K^* \mu\mu) = (2.9 \pm 1.0(\mathrm{stat}) \pm 0.2(\mathrm{syst}) \pm 0.3(\mathrm{norm})) \times 10^{-8}$$

- ⇛ For now consistent with SM predictions arXiv:1803.05876

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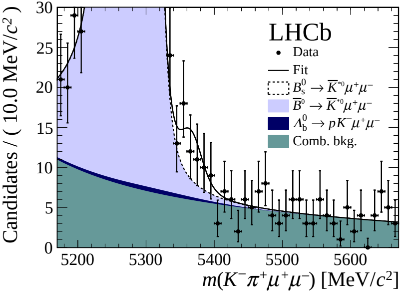


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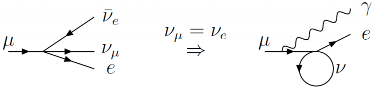
# Lepton Flavour/Number Violation

arxiv::1609.08895

Lepton Flavour Violation(LFV):

⇛ After $\mu^-$ was discovered it was logical to think of it as an excited $e^-$.

- Expected: $B(\mu \to e\gamma) \approx 10^{-4}$
- Unless another $\nu$, in intermediate vector boson loop cancels.




**I.I.Rabi:**

"Who ordered that?"

- Up to this day charged LFV is being searched for in various decay modes.
- LFV was already found in neutrino sector.

⇛ Anomalies may suggest connections between LUV and LFV.

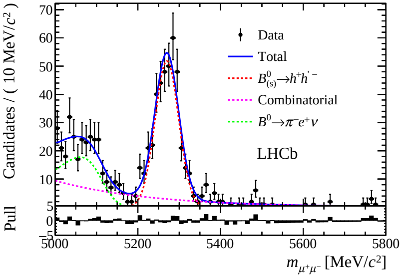
$$\mathcal{B}(B \to Ke\mu) \sim 3 \cdot 10^{-8} \left(\frac{1-R_K}{0.23}\right) \qquad \mathcal{B}(B \to K\mu\tau) \sim 2 \cdot 10^{-8} \left(\frac{1-R_K}{0.23}\right)$$

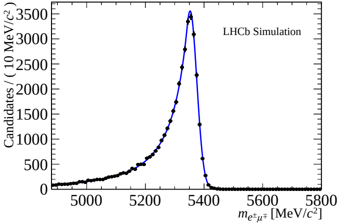
$$\frac{\mathcal{B}(B_s^0 \to e\mu)}{\mathcal{B}(B_s^0 \to \mu\mu)} \sim 0.01 \left(\frac{1-R_K}{0.23}\right) \qquad \frac{\mathcal{B}(B_s^0 \to \tau\mu)}{\mathcal{B}(B_s^0 \to \mu\mu)} \sim 4 \left(\frac{1-R_K}{0.23}\right)$$

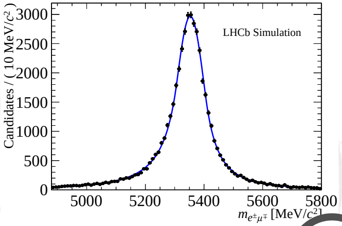
⇛ Need to deal with bremsstrahlung: different efficiency and mass shapes.

⇛ Fit performed separately in bremsstrahlung categories.

⇛ Primary background: $B \to hh$:



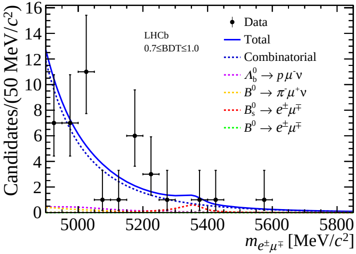




⇛ Estimated with the data driven method to be $< 6$ events.

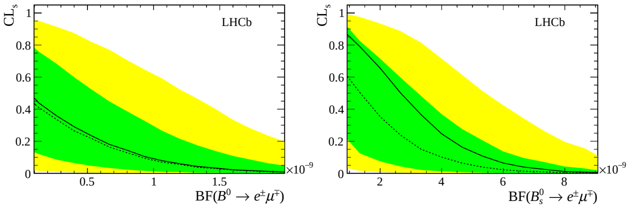
# $B_{(s)} \to e\mu$

[JHEP 1803 (2018) 078]

- $\Rightarrow$ With $3\ \mathrm{fb}^{-1}$ data.
- $\Rightarrow$ Fit the $m_{e\mu}$ mass and calculate $\mathrm{CL_s}$.




$$\mathcal{B}(B^0 \to e^\pm\mu^\mp) < 1.3(1.0)\cdot 10^{-8}$$




$$\mathcal{B}(B_s^0 \to e^\pm\mu^\mp) < 6.3(5.4)\cdot 10^{-9} \quad \text{if light eigenstate dominates}$$

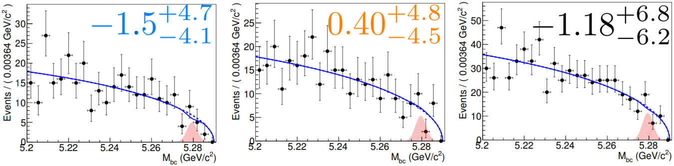
$$\mathcal{B}(B_s^0 \to e^\pm\mu^\mp) < 7.2(6.0)\cdot 10^{-9} \quad \text{if heavy eigenstate dominates}$$

# $B \to K^* e\mu$

[Belle, arxiv::1807.03267]

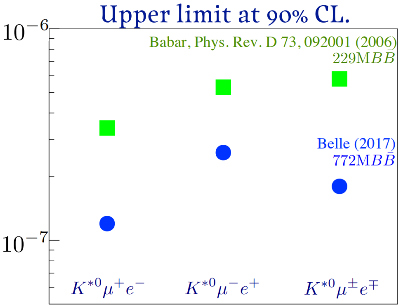
⇛ Fit to $M_{bc}$:

$$M_{bc} = \sqrt{(E_{beam})^2 - (p_B)^2}$$




⇛ No statistically significant events observed, upper limits set

⇛ The best UL but order of magnitude above the LUV model predictions.



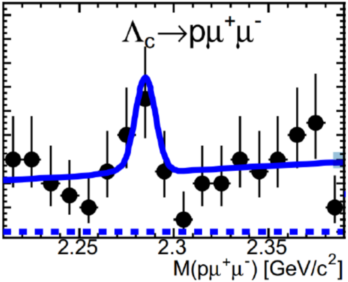
# $\Lambda_c \to p\mu\mu$

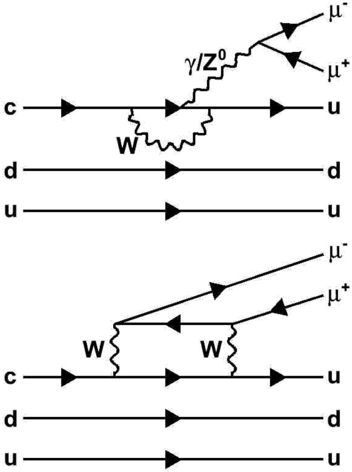
[Phys. Rev D 84 072006]

⇛ SM predictions:
$\mathcal{O}(10^{-8})$

⇛ Long distance effects:
$\mathcal{O}(10^{-6})$

⇛ Previous measurement done by Babar:
$\mathrm{Br}(\Lambda_c^+ \to p\mu^+\mu^-) < 4.4 \cdot 10^{-5}$ at 90% CL



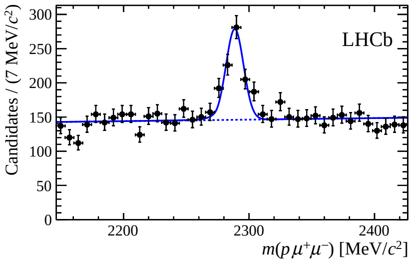



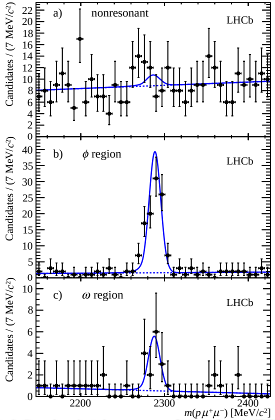

LHCb analysis with $3\ \mathrm{fb}^{-1}$

# $\Lambda_c \to p\mu\mu$



- $\Rrightarrow$ Blind analysis with the normalization to the $\Lambda_c \to p\phi(\mu\mu)$.
- $\Rrightarrow$ BDT to reduce combinatorial background.
- $\Rrightarrow$ The dominant background: $\Lambda_c \to p\pi\pi$: $2.0 \pm 1.1$ events



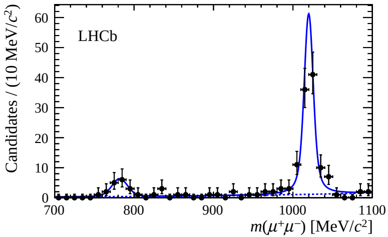




Analysis performed in 3 mass windows:

- $\phi$ region: $m_{\mu\mu} \in [985, 1055]\ \mathrm{MeV/c^2}$
- $\omega$ region: $m_{\mu\mu} \in [759, 805]\ \mathrm{MeV/c^2}$
- nonresonant: rest of phase-space.

# $\Lambda_c \to p\mu\mu$






$\Rrightarrow$ It's the first observation of $\Lambda_c \to p\mu\mu$ in the $\omega$ region, with $5.0\ \sigma$ significance.

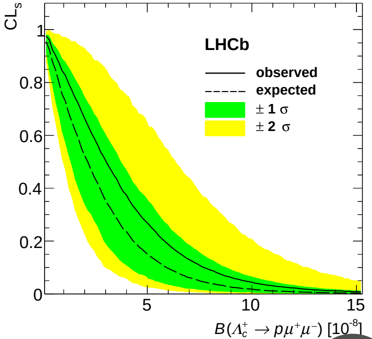
$\Rrightarrow$ The corresponding branching fraction reads:

$$\mathcal{B}(\Lambda_c \to p\omega) = (9.4 \pm 3.2 \pm 1.0 \pm 2.0) \cdot 10^{-4}$$

$\Rrightarrow$ No significant excess observed in the nonresonant region:

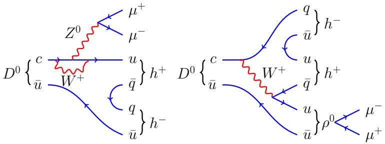
$$\mathcal{B}(\Lambda_c \to p\mu\mu) < 7.7(9.6) \times 10^{-8}$$

$\Rrightarrow$ Improving BaBar result by 3 orders of magnitude!



# $D \rightarrow hh\mu\mu$

[PHYS. REV. LETT. 119, 181805 (2017)]




⇛ First observation with $2\ \text{fb}^{-1}$ of data!

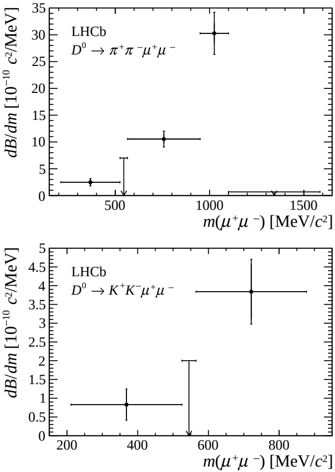
⇛ Dominated by long distance contributions.

⇛ Normalized to $D \rightarrow K\pi[\mu\mu]_{\omega/\rho}$

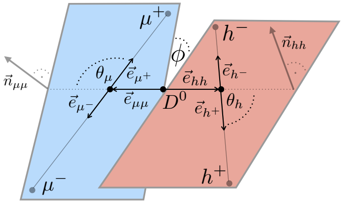
⇛ LHCb has measured the branching fractions:

$$\mathcal{B}(D \rightarrow \pi\pi\mu\mu) = (9.64 \pm 0.48 \pm 0.51 \pm 0.97) \cdot 10^{-7}$$

$$\mathcal{B}(D \rightarrow KK\mu\mu) = (1.54 \pm 0.27 \pm 0.09 \pm 0.16) \cdot 10^{-7}$$



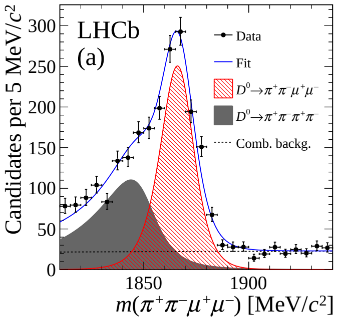
⇛ The challenge is to disentangle the SD and LD.
⇛ Angular observables can help:




$$A_{FB} = \frac{\Gamma(\cos\theta_\mu > 0) - \Gamma(\cos\theta_\mu < 0)}{\Gamma(\cos\theta_\mu > 0) + \Gamma(\cos\theta_\mu < 0)}$$

$$A_{2\phi} = \frac{\Gamma(\sin 2\phi > 0) - \Gamma(\sin 2\phi < 0)}{\Gamma(\sin 2\phi > 0) + \Gamma(\sin 2\phi < 0)}$$

$$A_{CP} = \frac{\Gamma(D \to hh\mu\mu) - \Gamma(\bar{D} \to hh\mu\mu)}{\Gamma(D \to hh\mu\mu) + \Gamma(\bar{D} \to hh\mu\mu)}$$



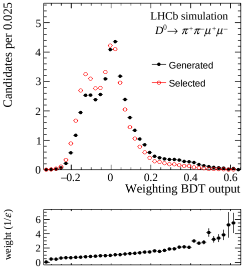

Analysis with $5\ \mathrm{fb}^{-1}$.
See M. Gersabeck talk for more details!

# $D \to hh\mu\mu$

[arXiv:1806.10793]

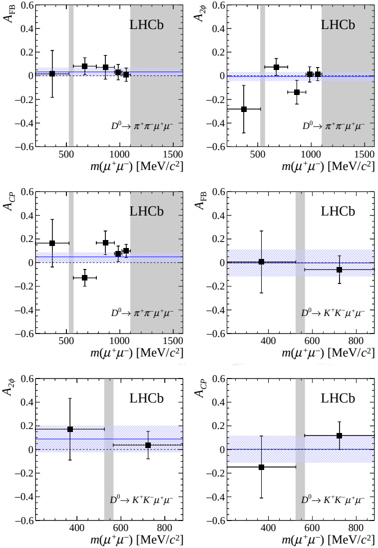
⇛ Need to perform a 4D acceptance correction.

⇛ BDT technique used to determine it.




⇛ Yields done by a weighted likelihood fit.

**All observables consistent with 0!**

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# $K^0_S \to \mu\mu$



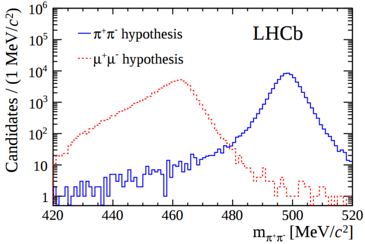
⇛ $pp$ collisions create enormous amount of strange mesons.

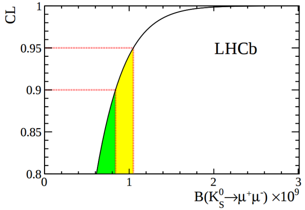
⇛ Can be used to search for $K^0_S \to \mu\mu$.

⇛ SM prediction:
$\mathrm{Br}(K^0_S \to \mu\mu) = (5.0 \pm 1.5) \times 10^{-12}$

⇛ Dominated by the long distance effects.

⇛ Bkg dominated by $K^0_S \to \pi\pi$.



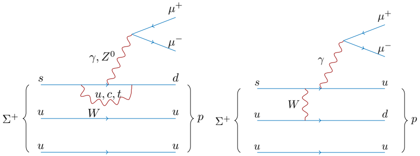




⇛ No significant enhancement of signal has been observed and UL was set:

$\mathrm{Br}(K^0_S \to \mu\mu) <$ $0.8(1.0) \times 10^{-9}$ at $90(95)\%$ CL

# $\Sigma \to p\mu\mu$

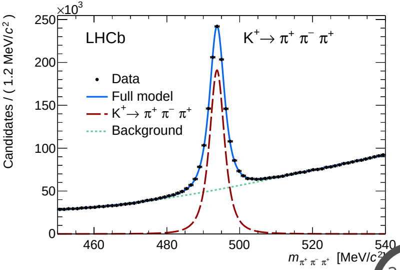
⇛ $\Sigma \to p\mu\mu$ is a $s \to d$ transition, which in SM are dominated by LD: $\mathcal{O}(10^{-8})$.



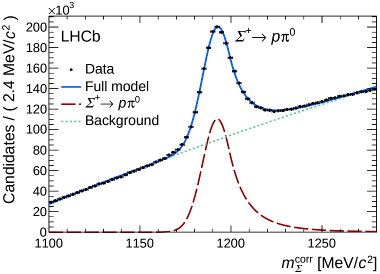

⇛ Previously HyperCP collaboration reported evidence of this decay:
$\mathcal{B}(\Sigma \to p\mu\mu) = \left(8.6^{+6.6}_{-5.4} \pm 5.5\right) \cdot 10^{-8}$ [Phys Rev Lett 94 021801, 2005]

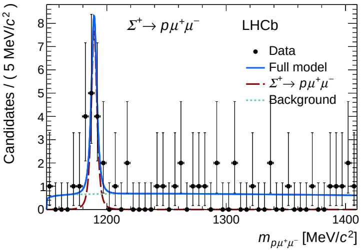
⇛ Calibrated with $K \to \pi\pi\pi$: resolution of $4.28\ \mathrm{MeV/c^2}$.

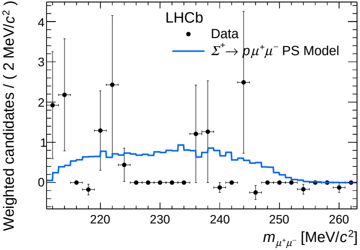
Used $3\ \mathrm{fb}^{-1}$ of data.



⇛ Normalize to $\Sigma \to p\gamma$.




⇛ Evidence with $4.1\ \sigma$ significance.

⇛ Branching fraction measured:

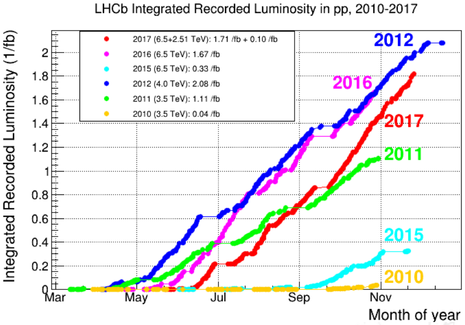
$$\mathcal{B}(\Sigma \to p\mu\mu) = \left(2.2^{+1.8}_{-1.3}\right) \cdot 10^{-8}$$

# Summary

⇛ FCNC processes provide powerful constraints on extensions of the SM.

⇛ Large $b\bar{b}$ cross-section provides a large sample of ”rare” decay processes.

⇛ More results being updated with Run2 data.




⇛ Stay tuned for more results!

# Backup