Rare Heavy Flavour Decays

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Rencontres du Vietnam

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Introduction

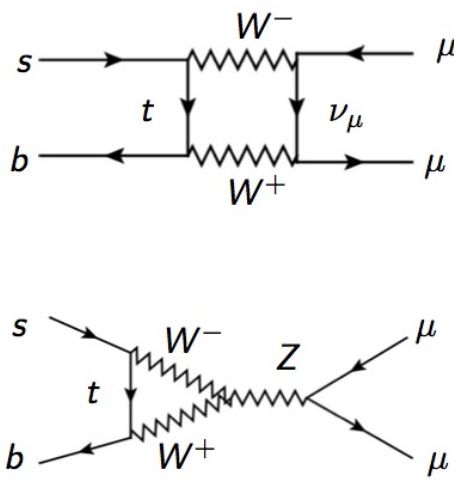
- **Rare decays**: mediated by electroweak flavour-changing neutral current (FCNC) processes in the Standard Model (SM)
- New Physics entering these decays $\Rightarrow$ large deviations from SM predictions
- **Complementary approach to direct searches**
  - higher energy ranges than directly accessible can be probed

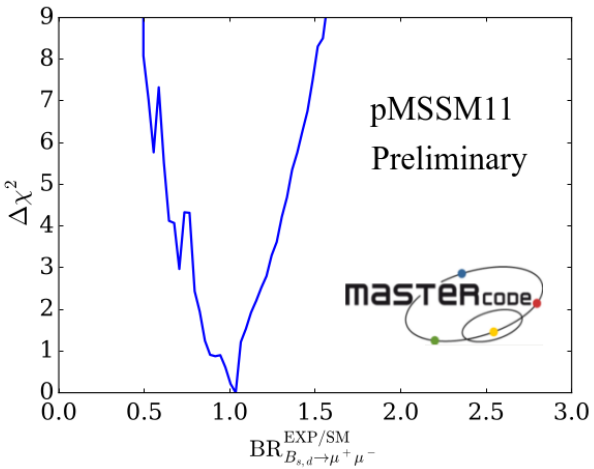
Covered in this Talk

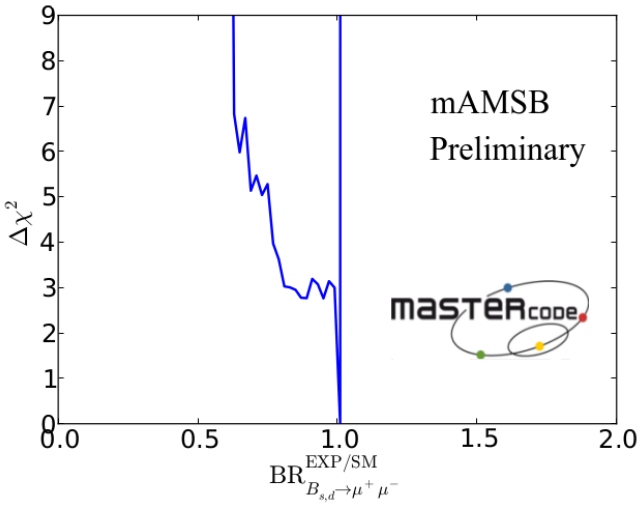
$B_s^0 \to \mu\mu$
$B_{(s)}^0 \to \mu^+\mu^-\mu^+\mu^-$
$B_{(s)}^0 \to \tau^+\tau^-$
$B_s \to \phi\gamma$
$B^0 \to K^*\mu^+\mu^-$
$D^0 \to e^\pm\mu^\mp$
$K_S^0 \to \mu^+\mu^-$
$K_S^0 \to \pi^0\mu^+\mu^-$ & $K_S^0 \to \pi^+\pi^-e^+e^-$
$\Sigma^+ \to p\mu^+\mu^-$

$B_s^0 \to \mu\mu$

- $\sim$4 decays for every billion B_s^0 mesons produced $\Rightarrow$ excepcionally sensitive to sources of BSM physics
  - for example, theories with additional Higgs bosons
- SM prediction: $\mathcal{B}(B_s^0 \to \mu\mu) = (3.66 \pm 0.23) \times 10^{-9}$;
  $\mathcal{B}(B^0 \to \mu\mu) = (1.06 \pm 0.09) \times 10^{-10}$ [Eur. Phys. J. **C72** (2012) 2172]







http://mastercode.web.cern.ch/mastercode/

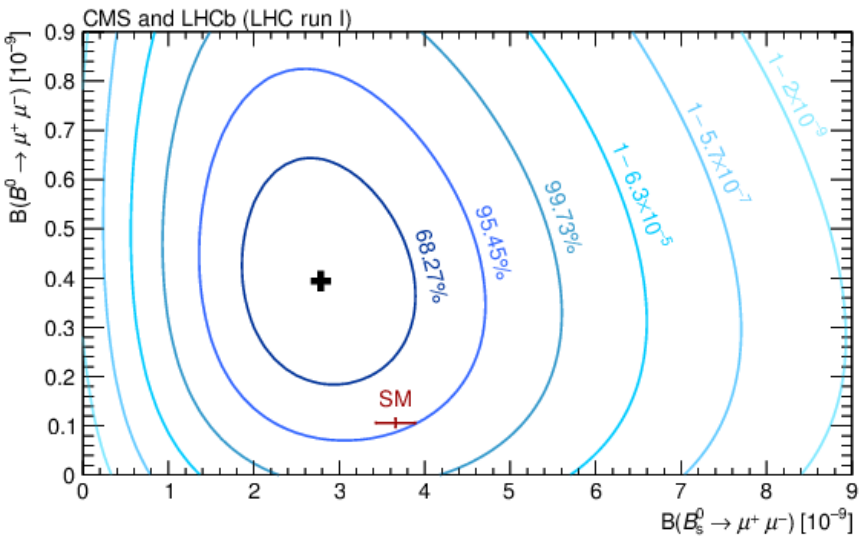
Nature 522, 68-72 (2015) [arXiv:1411.4413]

$B_s^0 \to \mu\mu$

$$\mathcal{B}(B_s^0 \to \mu\mu) = (2.8^{+0.7}_{-0.6}) \times 10^{-9},\ > 6\sigma \text{ significance}$$
$$\mathcal{B}(B^0 \to \mu\mu) = (3.9^{+1.6}_{-1.4}) \times 10^{-10}\ ,\ 3\sigma \text{ significance}$$

Current measurements statistically compatible with the SM prediction

$\Rightarrow$ **Stringent constraints on BSM Physics**

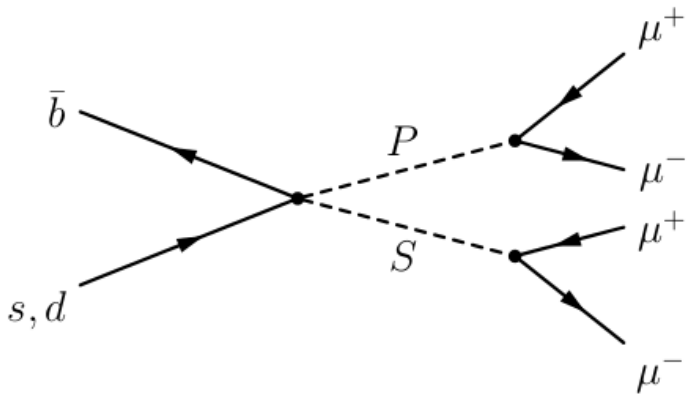


- **CMS**: $\mathcal{B}(B_s^0 \to \mu\mu) = (3.0^{+1.0}_{-0.9}) \times 10^{-9}$, $\mathcal{B}(B^0 \to \mu\mu) < 1.1 \times 10^{-9}$ at 95% CL [Phys. Rev. Lett. 111 (2013) 101804]
- **LHCb**: $\mathcal{B}(B_s^0 \to \mu\mu) = (2.9^{+1.1}_{-1.0}) \times 10^{-9}$, $\mathcal{B}(B^0 \to \mu\mu) < 7.4 \times 10^{-10}$ at 95% CL [Phys. Rev. Lett. 111, 101805 (2013)]
- **ATLAS**: $\mathcal{B}(B_s^0 \to \mu\mu) = (0.9^{+1.1}_{-0.8}) \times 10^{-9}$, $\mathcal{B}(B^0 \to \mu\mu) < 4.2 \times 10^{-10}$ at 95% CL [arXiv:1604.04263]

Nature 522, 68-72 (2015) [arXiv:1411.4413]

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

- Excess of events found by HyperCP for the decay $\Sigma^+ \to pP(\to \mu^+\mu^-)$ [PRL 94 (2005) 021801]
  - $\mathcal{B}(B^0_{(s)} \to \mu^+\mu^-\mu^+\mu^-) \sim \times 10^{-11}$ [Phys. Rev. Lett **B556** (2003) 169]
  - interpreting the HyperCP events as MSSM decays $\Rightarrow$ large $\mathcal{B}(P \to \mu^+\mu^-)$ (m(P)$\sim$ 214 MeV) [Phys. Rev. D 8, 1240 (1973)]
- Decays of short lived scalar (S) and pseudoscalar (P) goldstinos to $\mu^+\mu^-$



- Previous LHCb limits with 1 fb^{-1} were already world best [Phys. Rev. Lett **110** (2013) 211801]

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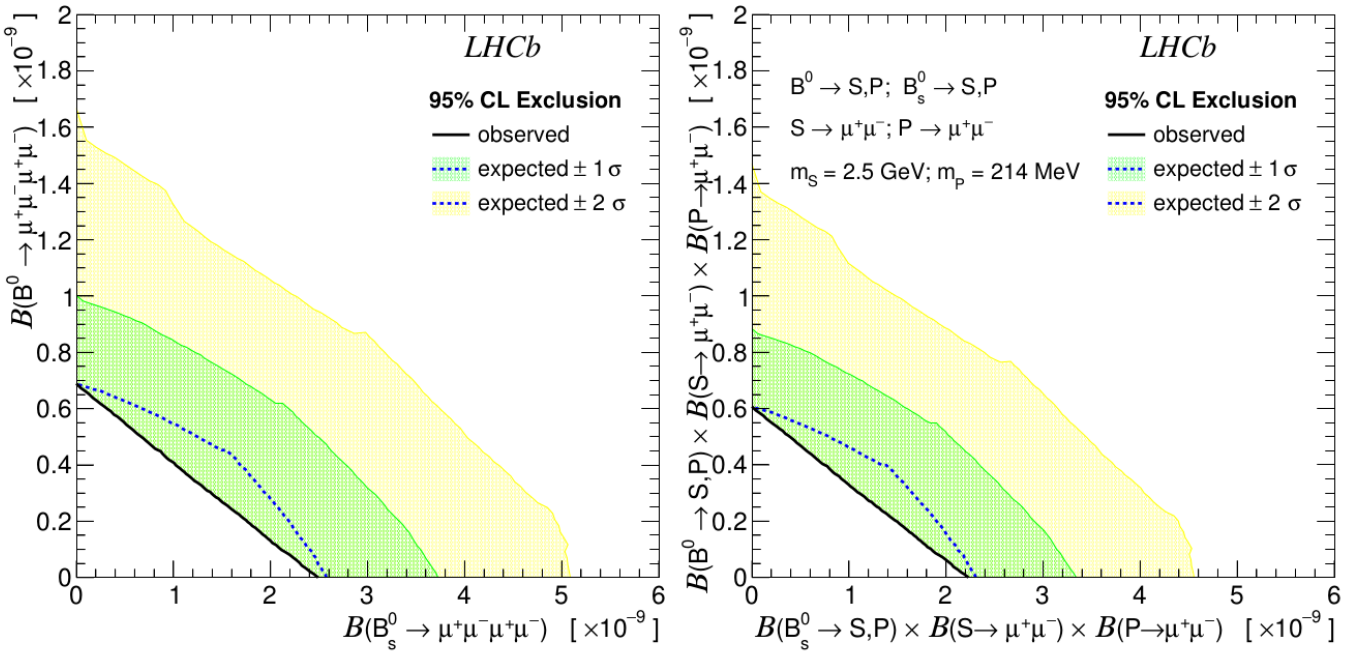
$B^0_{(s)} \to \mu^+\mu^-\mu^+\mu^-$

3fb^{-1} analysis (95% CL):

$$\begin{aligned}
\mathcal{B}(B^0_s \to \mu^+\mu^-\mu^+\mu^-) &< 2.5 \times 10^{-9} \\
\mathcal{B}(B^0_s \to S(\mu^+\mu^-)P(\mu^+\mu^-)) &< 2.2 \times 10^{-9} \\
\mathcal{B}(B^0 \to \mu^+\mu^-\mu^+\mu^-) &< 6.9 \times 10^{-9} \\
\mathcal{B}(B^0 \to S(\mu^+\mu^-)P(\mu^+\mu^-)) &< 6.0 \times 10^{-9}
\end{aligned}$$



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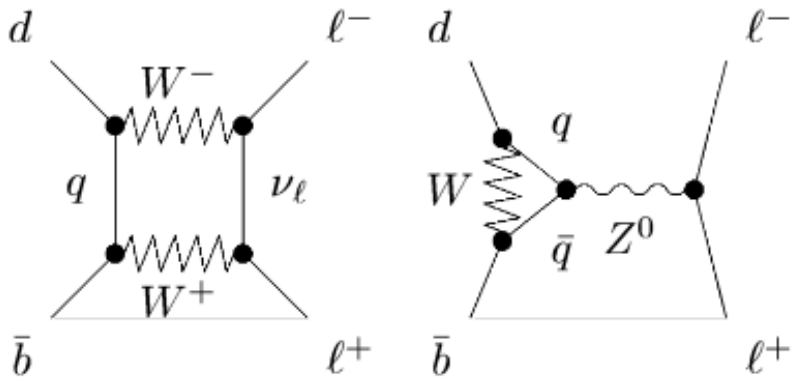
$B^0_{(s)} \to \tau^+\tau^-$

- New Physics can enhance the value the branching ratio in this channel
  - Models with leptoquarks, W'/Z' bosons and two-Higgs-doublet models
- $\mathcal{B}_{SM}(B^0 \to \tau^+\tau^-) = (2.22 \pm 0.19) \times (10^{-8})$;
  $\mathcal{B}_{SM}(B^0_s \to \tau^+\tau^-) = (7.73 \pm 0.49) \times (10^{-7})$ [Phys. Rev. Lett. 112, 101801 (2014)]
- **Strategy:** reconstruction via the $\tau \to \pi\pi\pi\nu_\tau$ decay
  - 2 neutrinos present: B invariant mass cannot be a discriminating variable $\Rightarrow$ decay times of the τ leptons an of the B candidate + functions of observables
- Previous experimental limits:

$\mathcal{B}(B^0 \to \tau^+\tau^-) < 4.1 \times 10^{-3}$ by BaBar [Phys. Rev. Lett. **96** (2006) 241802];
$\mathcal{B}(B^0_s \to \tau^+\tau^-)$: never measured



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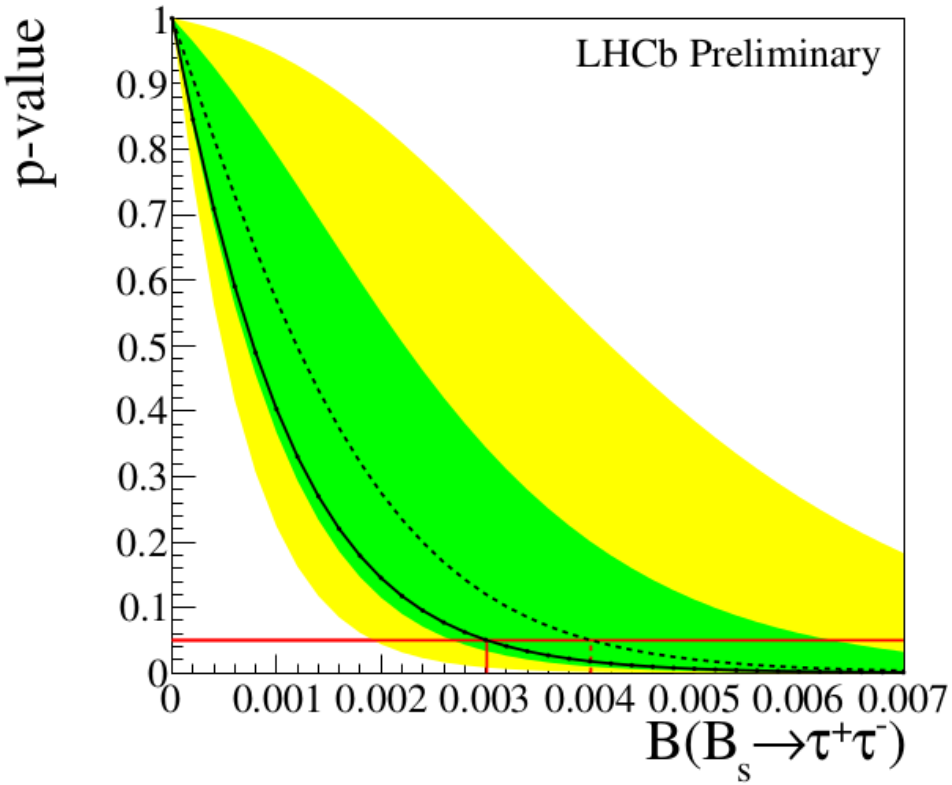
$B^0_{(s)} \to \tau^+\tau^-$

Preliminary limits at 90% (95%) CL:

$\mathcal{B}(B^0 \to \tau^+\tau^-) = 1.0(1.3) \times 10^{-3}$

$\mathcal{B}(B^0_s \to \tau^+\tau^-) = 2.4(3.0) \times 10^{-3}$

- Model-dependent. Selection efficiency (efficiency of the offline selection) relies on model that uses CLEO results for $\tau^- \to \pi^-\pi^0\nu_\tau$ [Phys.Rev.D61:112002,2000]



- - : expected values

– : observed values

68 % CL

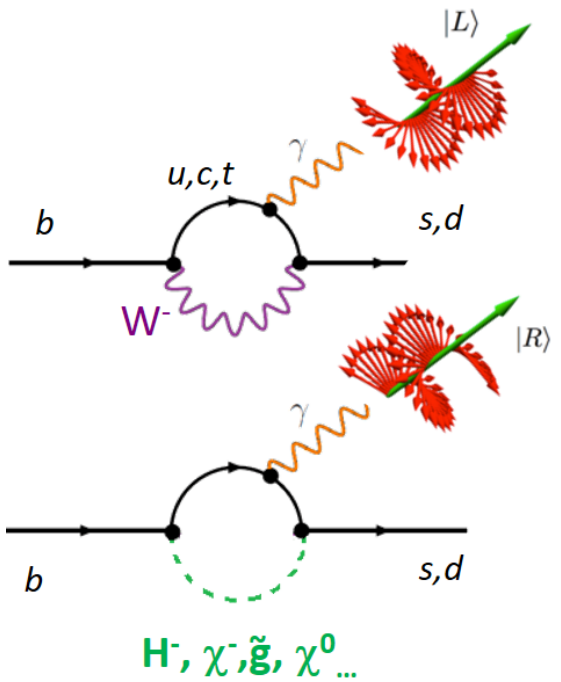
95 % CL

Limit at 95 % CL

$B_s \to \phi\gamma$

- Photons emitted in $b \to s\gamma$ are predominantly **left-handed** in the SM
  - + small amount of right-handed photons $\propto \left(\frac{m_s}{m_b}\right)$
- NP can enhance right-handed contributions $\Rightarrow$ observable effects in mixing-induced CP asymmetries and time-dependent decay rates of radiative B^0 and B_s^0

- Photon polarization previously measured by BaBar and Belle for B^0 system [arXiv:1412.7515]
- LHCb has **first result on photon polarization in radiative B_s^0 decays**
  - $B^0 \to K^{*0} e^+ e^-$ decays sensitive to the photon polarization too [JHEP04(2015)064]



arXiv:1609.02032

$B_s \to \phi\gamma$

- Rate at which B_s^0 or $\bar{B}_s^0$ decay to a common final state that contains a photon, proportional to:
  $\exp(-\Gamma_s t)[\cosh(\Delta\Gamma_s t/2) - \mathcal{A}^\Delta \sinh(\Delta\Gamma_s t/2) + \zeta\mathcal{C}\cos\Delta m_s t - \zeta\mathcal{S}\sin\Delta m_s t]$
  - $\Delta\Gamma_s$ and Δm_s: width and mass differences between the light and heavy B_s^0 mass eigenstates
  - Γ_s: mean decay width
  - ζ: $+1$ for an initial B_s^0 state, -1 for $\bar{B}_s^0$
  - $\mathcal{C}, \mathcal{S}, \mathcal{A}^\Delta$: functions of the left- and right-handed photon polarization amplitudes.

  $\mathcal{C}, \mathcal{S}$ cancel out when the flavour of the B_s^0 is not taken into account

  In the B_s^0 system, the sizeable width difference allows $\mathcal{A}^\Delta$ to be measured.

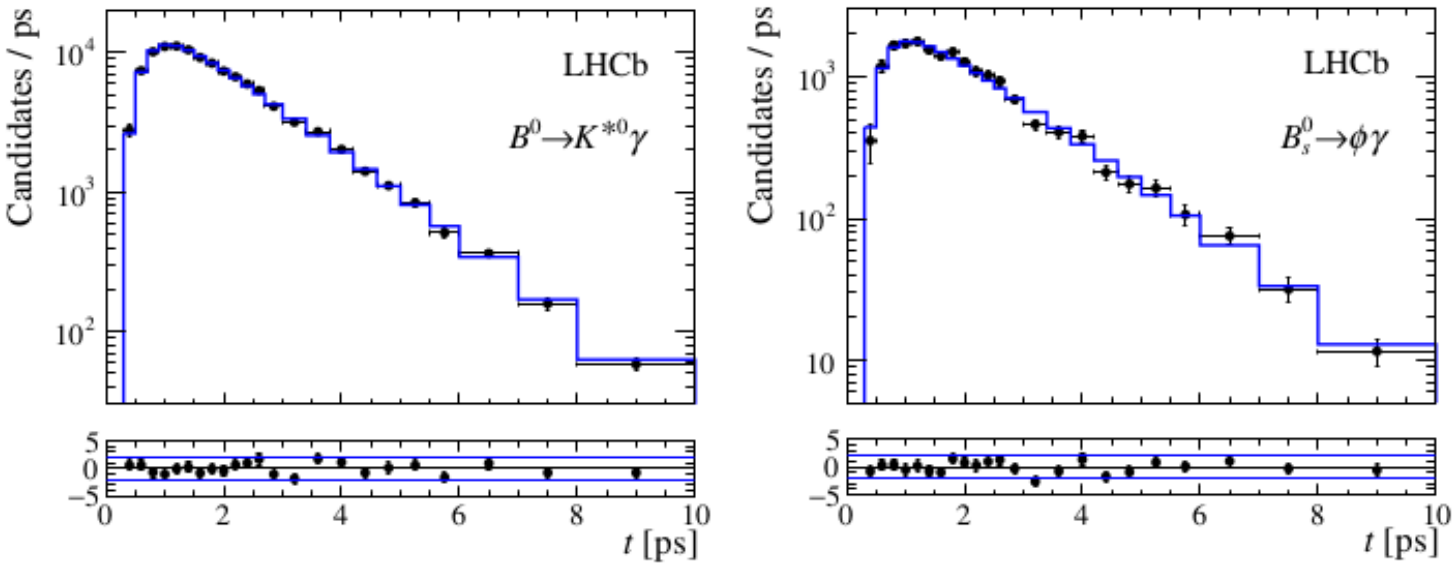
- in the SM: $\mathcal{A}^\Delta_{SM} = \sin(2\psi), \tan\psi \equiv \frac{A(\bar{B}_s^0 \to \phi\gamma_R)}{A(\bar{B}_s^0 \to \phi\gamma_L)} \Rightarrow \mathcal{A}^\Delta_{SM} = 0.047^{+0.029}_{-0.025}$
  [arXiv:0802.0876]

arXiv:1609.02032

$B_s \to \phi\gamma$

- More than 4000 $B_s \to \phi\gamma$ reconstructed, $B_s \to K^{*0}\gamma$ ~6 times larger
- Simultaneous unbinned maximum likelihood fit to $B_s \to \phi\gamma$ and $B_s \to K^{*0}\gamma$ (control channel)
- Result compatible with SM expectation, within two standard deviations

$$\mathcal{A}^{\Delta} = -0.98^{+0.46}_{-0.52}(\text{stat.})^{+0.23}_{-0.20}(\text{syst.})$$



arXiv:1609.02032

$B^0 \to K^* \mu^+ \mu^-$

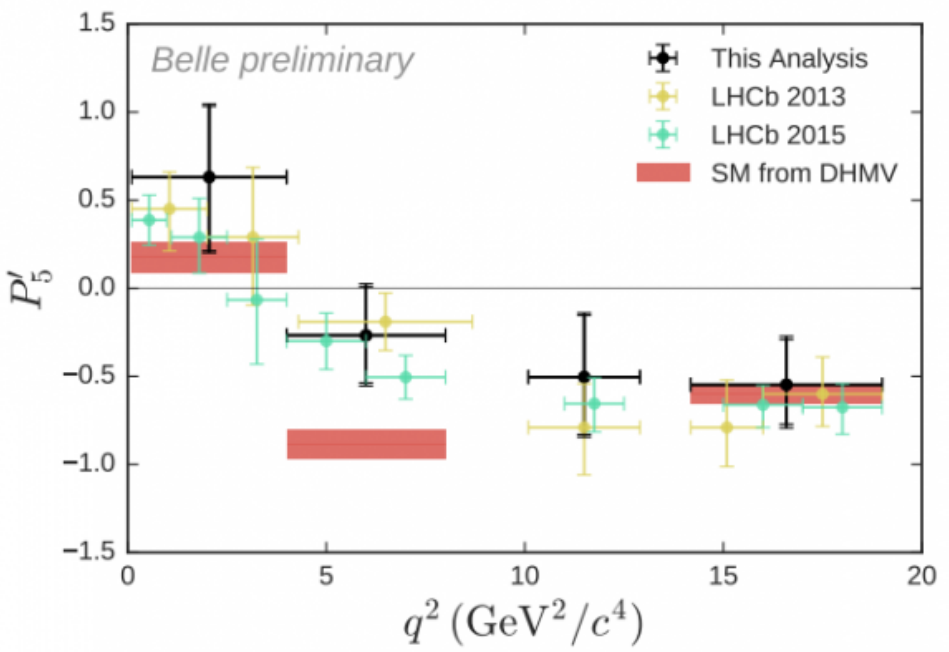
- Flavour-Changing Neutral Current process
  - In the SM via electroweak penguin or box diagrams
  - New heavy particles can contribute to them $\Rightarrow$ modify observables
- **Analysis:**
  1. Angular analysis of $B^0 \to K^* \mu^+ \mu^-$ [JHEP02(2016)104]
  2. $B^0 \to K^*(892)^0 \mu^+ \mu^-$ Differential BF + angular analysis
     S-wave fraction in $B^0 \to K^+ \pi^- \mu^+ \mu^-$[arXiv:1606.04731]
  3. $B^0 \to K^*_{0,2}(1430)^0 \mu^+ \mu^-$ Differential BF + angular analysis
     S-wave,P-wave,D-wave contributions[arXiv:1609.04736]
- Final state fully described y three decay angles $(\theta_l, \theta_K, \phi)$, $m(K^+\pi^-)$ and q^2
- $B^0 \to J/\psi K^*(892)^0$ used for normalisation

$B^0 \to K^* \mu^+ \mu^-$

- Anomaly (compatible with the SM at 3.7σ) found in one of the angular observables:

$$P_5' = \frac{S_5}{\sqrt{F_L(1-F_L)}}$$

[JHEP, 1301:048, 2013]

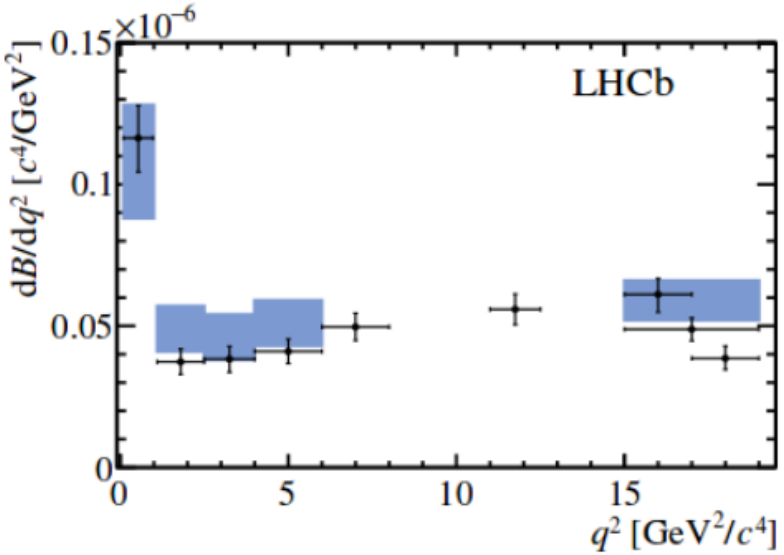


[arXiv:1604.04042]

(see Julian Heeck's talk)

$B^0 \to K^*\mu^+\mu^-$

2 : $796 < m(K^+\pi^-) < 996\ \mathrm{MeV/c^2}$

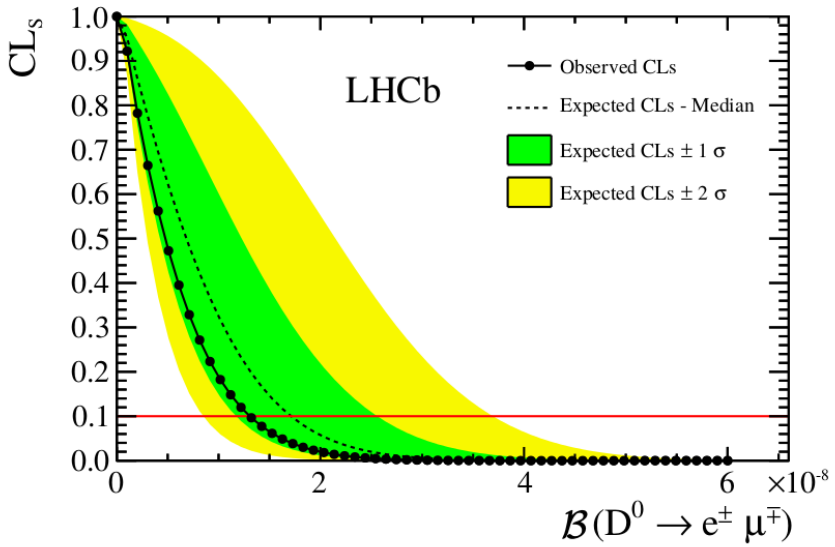


3 : $1330 < m(K^+\pi^-) < 1530\ \mathrm{MeV/c^2}$

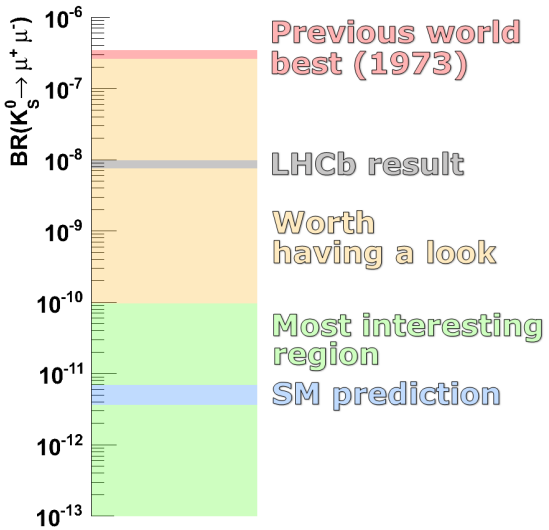
- Large interference effects between the S- and P- or D-wave contributions
- D-wave fraction: $F_D < 0.25$ at 95% CL

Lepton Flavour Violation ($D^0 \to e^{\pm}\mu^{\mp}$)

- Not present in the SM, allowed in nature (at least) through neutrino mixing [PRL 81 (1998) 1562]
- Large LFV is expected in numerous New Physics scenarios (Supersymmetry, Extra Dimension, Little Higgs))
- Subset of LFV searches done @ LHCb : $B_{(s)} \to e^{\pm}\mu^{\mp}, D^0 \to e^{\pm}\mu^{\mp}, \tau \to \mu\mu\mu$
  - Charm decays: stronger GIM suppression
- Previous result for $D^0 \to e^{\pm}\mu^{\mp}$ from Belle: $\mathcal{B}(D^0 \to e^{\pm}\mu^{\mp}) < 2.6 \times 10^{-7}$ at 90% CL [Phys. Rev. D 81, 091102(R) (2010)];
  $\mathcal{B}(D^0 \to e^{\pm}\mu^{\mp}) < 1.3 \times 10^{-8}$ at 90% CL



$K_S^0 \to \mu^+\mu^-$

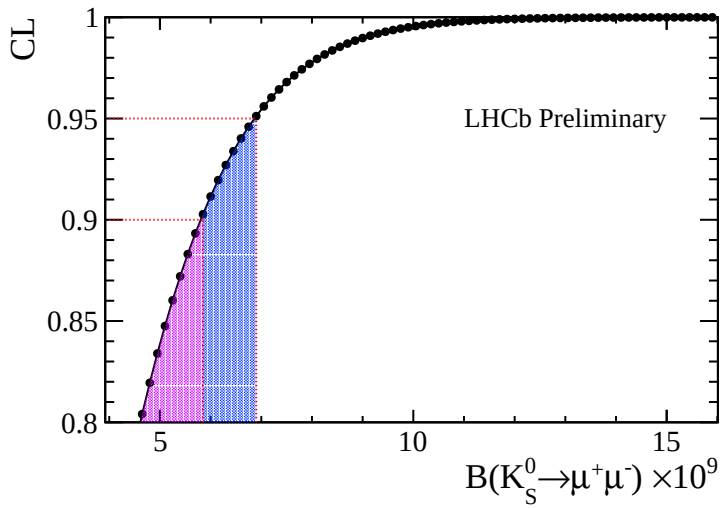


- Strongly suppressed decay in the SM, new light scalars can affect $\mathcal{B}(K_S^0 \to \mu^+\mu^-)$
- Previous results, far from the SM prediction[a]:

$$\mathcal{B}(K_S^0 \to \mu^+\mu^-) = (5.0 \pm 0.2) \times 10^{-12}$$

[a] [NPB366 (1991) 189] , [JHEP 01 (2004) 009]

Preliminary result:
$\mathcal{B}(K_S^0 \to \mu^+\mu^-) <$
$6.9(5.8) \times 10^{-9}$ at 95(90)% CL



- Good prospects to enter the most interesting region in the future

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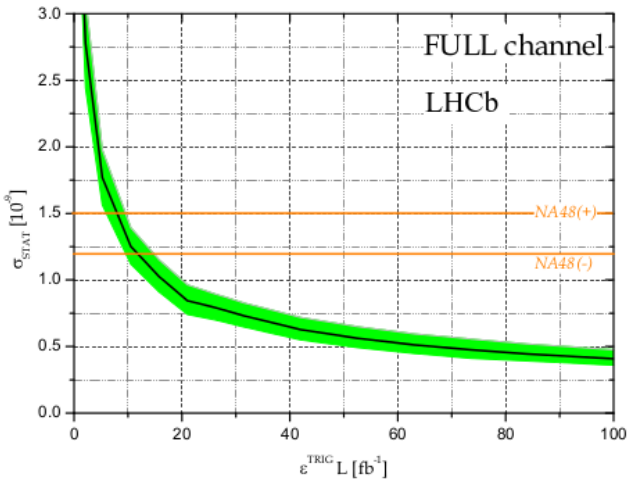
Prospects for other K_S^0 decays

$K_S^0 \to \pi^0 \mu^+ \mu^-$

[CERN-LHCb-PUB-2016-017]

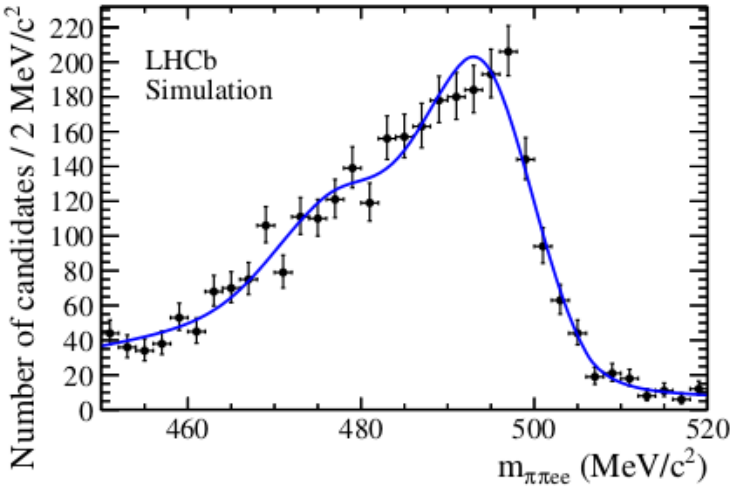
- $K_L^0 \to \pi^0 l^+ l^-$ sensitive to NP (Extra Dimensions models); $K_S^0 \to \pi^0 \mu^+ \mu^-$ sensitive to C_9
- SM prediction unprecise due to a factor that comes from $\mathcal{B}(K_S^0 \to \pi^0 \mu^+ \mu^-)$
- NA48 50% relative error [Phys. Lett. **B599** (2004) 197]
- Good prospects for the LHCb upgrade



$K_S^0 \to \pi^+ \pi^- e^+ e^-$

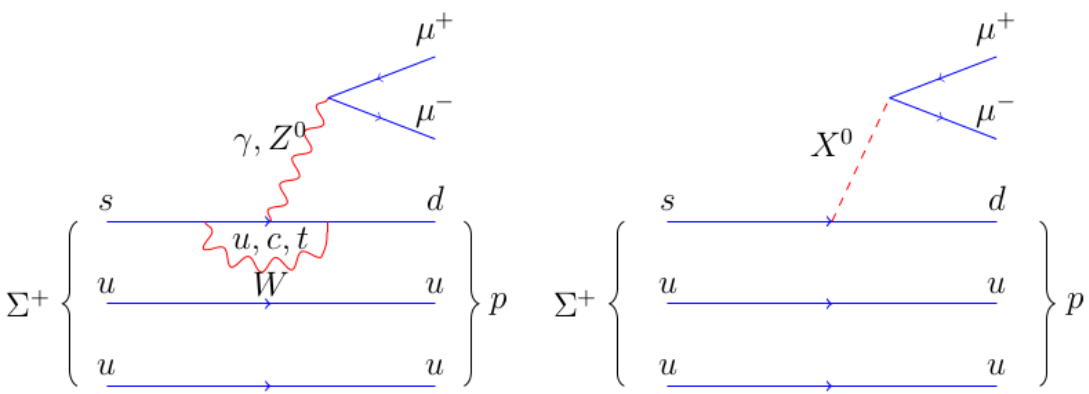
[CERN-LHCb-PUB-2016-016]

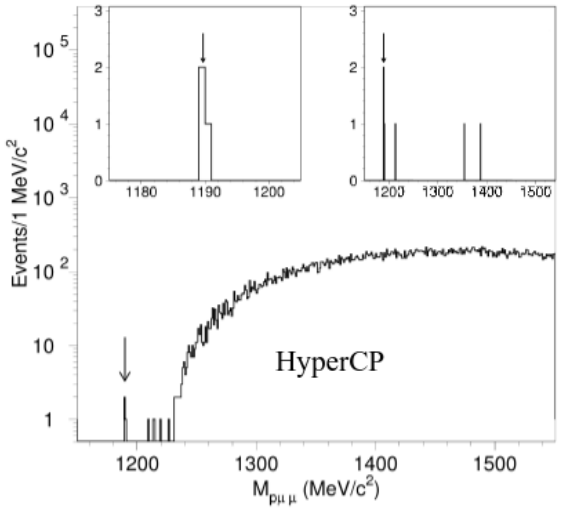
- Important background for $K_s^0 \to 4l$ (sensitive to NP)
- Interesting for light dark matter searches [PRD 92 (2015) no. 11 115017]
- Expected yield: $N_{sig}/\text{fb}^{-1} \sim 100$
- Evidence/observation feasible with the LHCb Run I dataset



$\Sigma^+ \to p\mu^+\mu^-$

- Hyperons are copiously produced at LHC
- $\Sigma^+ \to p\mu^+\mu^-$ is a FCNC process, allowed only at loop level in the SM
- Evidence of this decay found by HyperCP [PRL 94 (2005) 021801]
  - $\mathcal{B}(\Sigma^+ \to p\mu^+\mu^-) = (8.6^{+6.6}_{-5.4}) \times 10^{-8}$
  - 3 observed signal events with almost the same dimuon pair invariant mass $\Rightarrow$ possibility of an intermediate resonance $\Sigma^+ \to pX^0(\to \mu\mu)$





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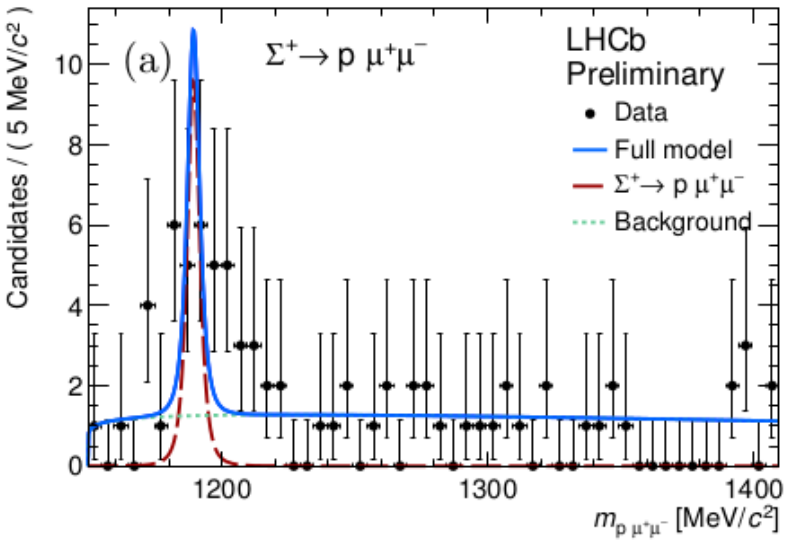
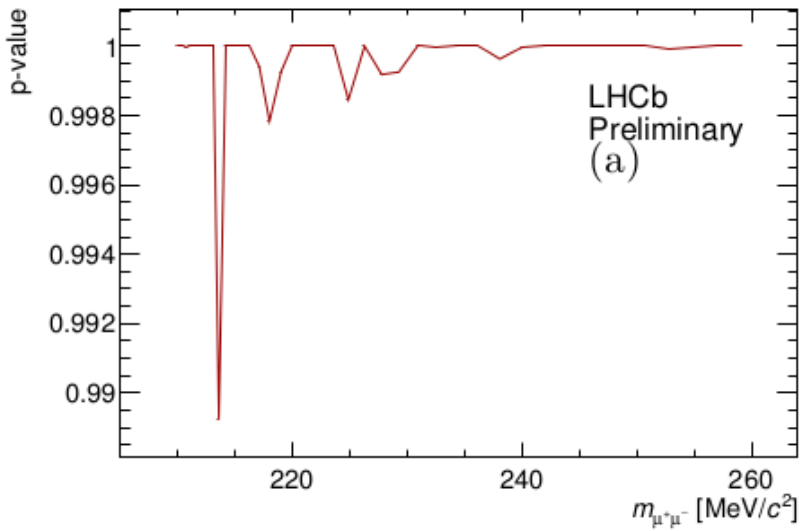
$\Sigma^+ \to p\mu^+\mu^-$

- Data is divided in 2 trigger strategies
  - Excess corresponding to $\Sigma^+ \to p\mu^+\mu^-$ decay seen in one category, not found in the other (limit on the BR: $\mathcal{B}(\Sigma^+ \to p\mu^+\mu^-) < 7.9 \times 10^{-8}$)
- No significant structure in the dimuon invariant mass distribution





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Summary & Outlook

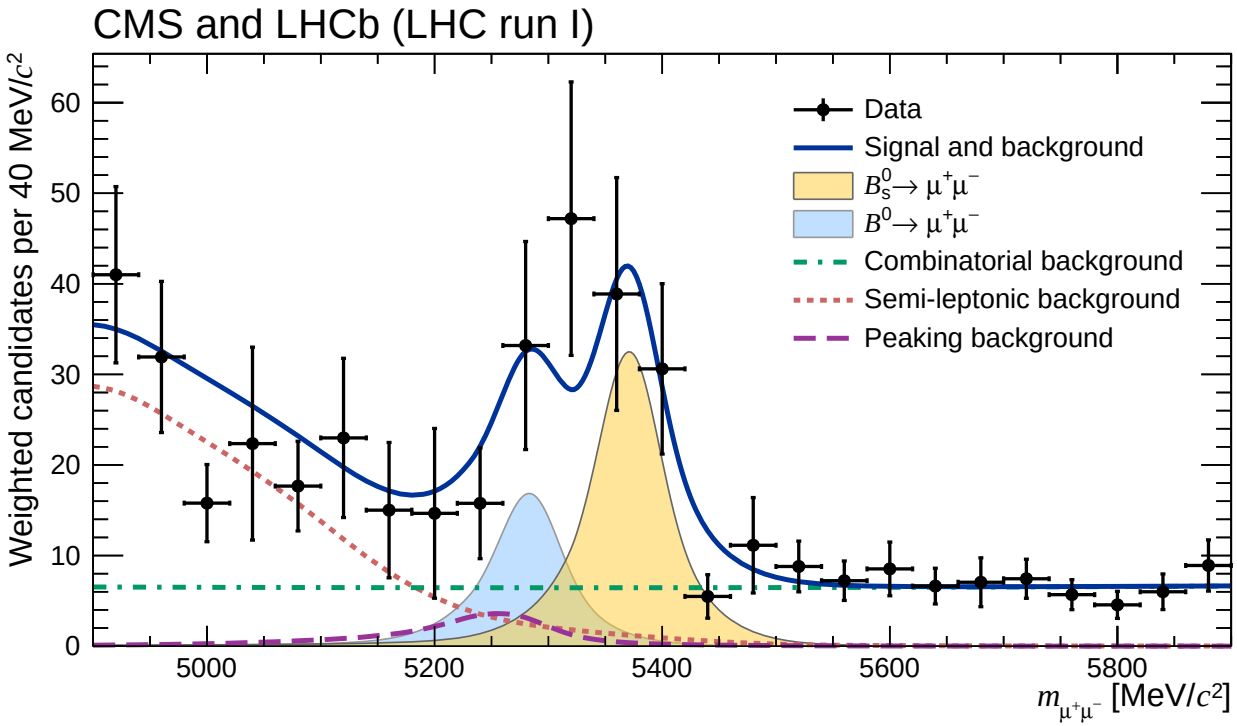
- Rare heavy flavour decays provide an excellent framework to look for New Physics
- Many interesting results presented for different channels
  - No significant NP evidence so far
  - Interesting anomalies found!
- Tight limits in NP models
- Interesting prospects ahead!

Stay tuned for more results!

Thanks for your attention!

$B_s^0 \to \mu\mu$

- Branching ratio measured both by CMS and LHCb collaborations
  - First evidence reported by LHCb [Phys. Rev. Lett **110** (2013) 021801]
- Centre-of-mass energy: 7 and 8 TeV
- $B^+ \to J/\psi K^+$ as normalisation channel
- 25fb^{-1} for CMS, 3fb^{-1} for LHCb



Nature 522, 68-72 (2015) [arXiv:1411.4413]

$K_S^0 \to \mu^+\mu^-$

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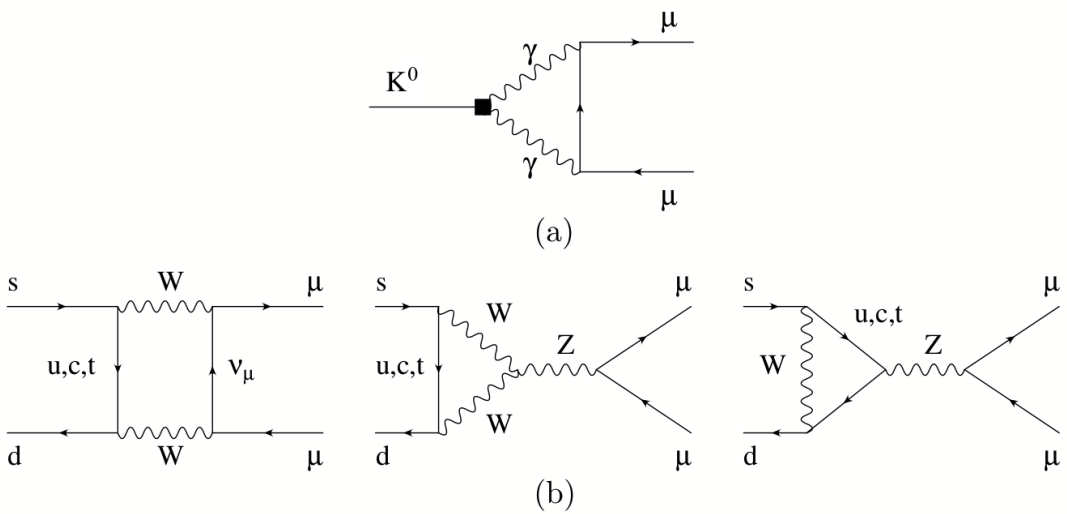
- LHCb was not firstly designed to study kaons, but they are largely produced in the detector
- Trigger modifications during the upgrade: efficiencies up to 100 % are feasible for Kaon decays.

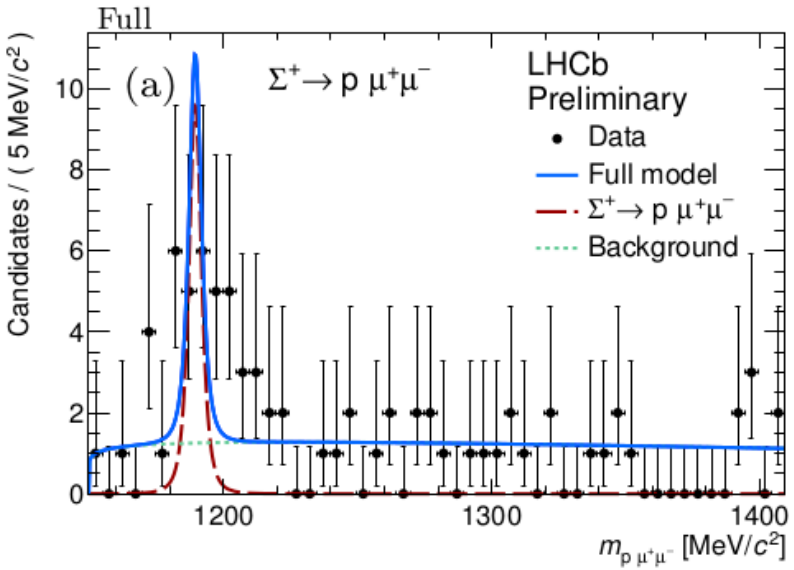
The $K_S^0 \to \mu^+\mu^-$ decay is:

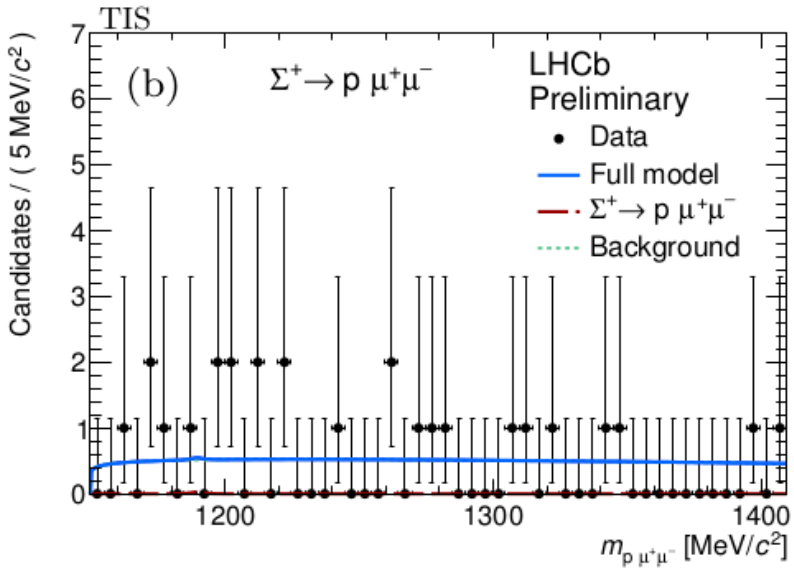
- Flavour-changing neutral current (FCNC) transition.
- Notably new light scalars can affect K_S^0 exclusively.



(a): Long distance contribution. (b) Short distance contributions. [JHEP 01 (2004) 009]

$\Sigma^+ \to p\mu^+\mu^-$





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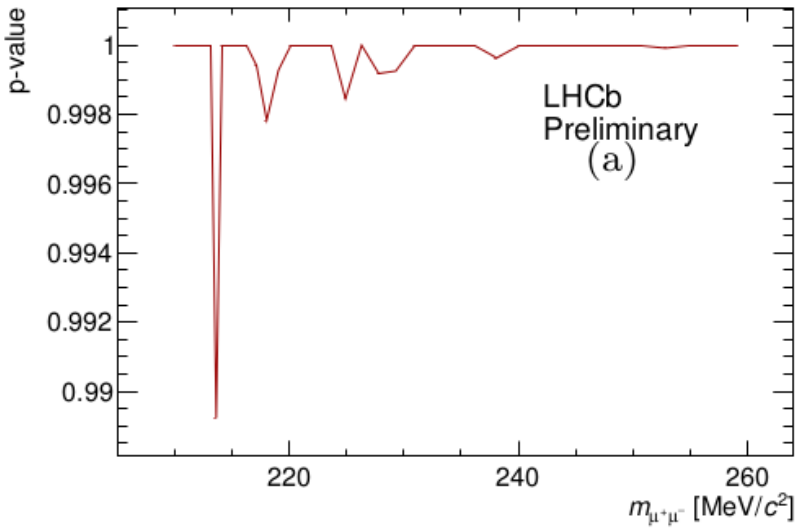
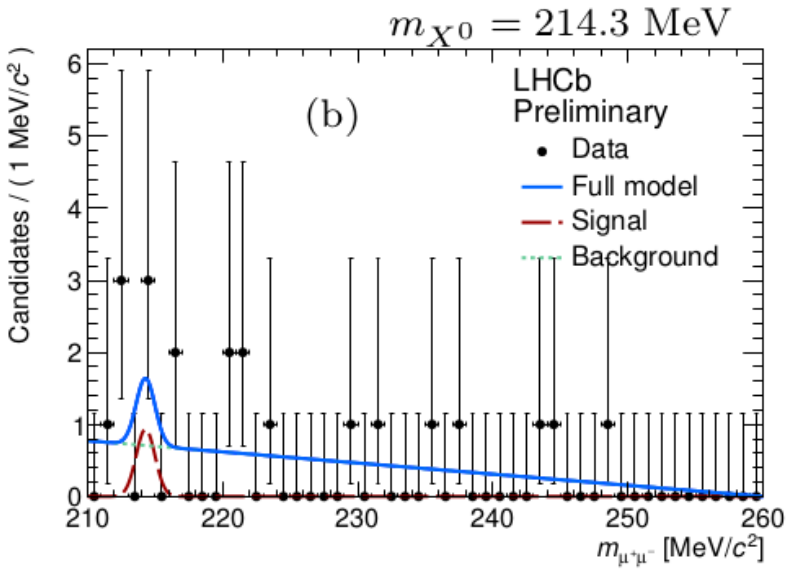
$\Sigma^+ \to p\mu^+\mu^-$





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