Searching for extremely rare decays at LHCb

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6-12 Aug 2023, ICISE, Quy Nhon

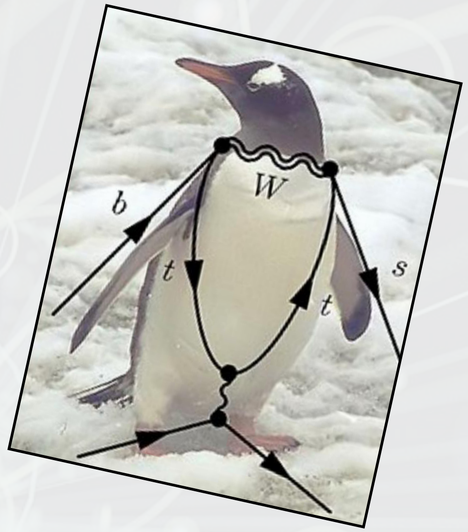
Maastricht University

LHCb

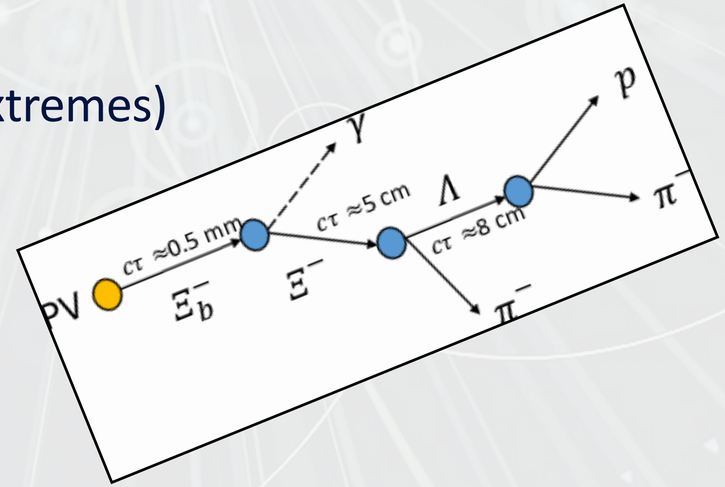
Nikhef

Extremely rare decays

- Rarer than ‘rare’: BR < 10^{-6}
- Test fundamental assumptions about the SM:
  Symmetries, new forces/scalars, flavour structure, …
- Indirect sensitivity to New Physics (quantum loops)
- 3rd generation relatively unexplored



- Are in principle ‘straightforward’
  (but maximal sensitivity —> push detector to extremes)
- Forbidden signal event = New Physics*
- No signal —> constrain coefficients in EFT



Define trigger

Topological/kinematic selection

Study backgrounds, apply PID, BDT

Model parameter of interest (usually Minv)

Unblind & fit, set limit with CLs / FC

Very rare menu

Baryon number violation

Lepton flavour violation

Dilepton decays

3-body dileptons

Multibody decays

Radiatives

Exotics

Disclaimers

- BR in LHCb normalised to channels known precisely from external measurements

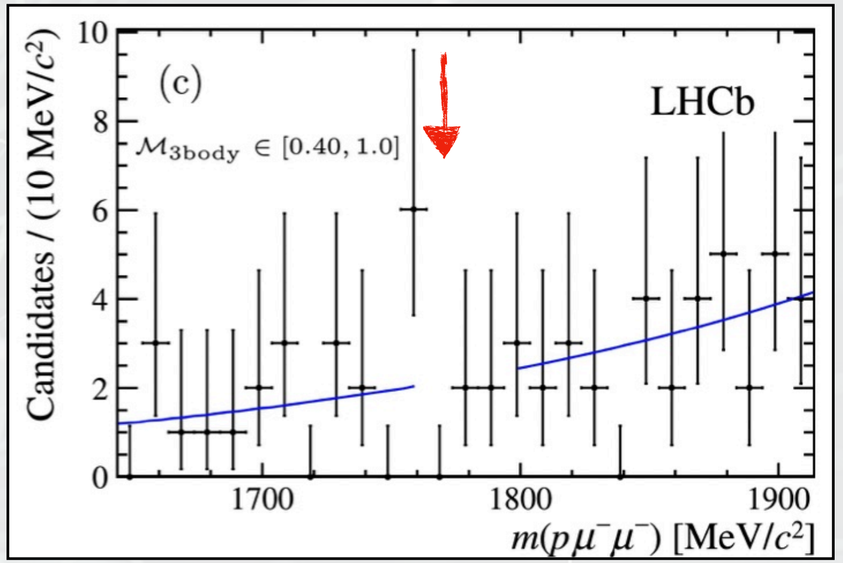
- Limits stated are at 95% CL

Baryon number violation

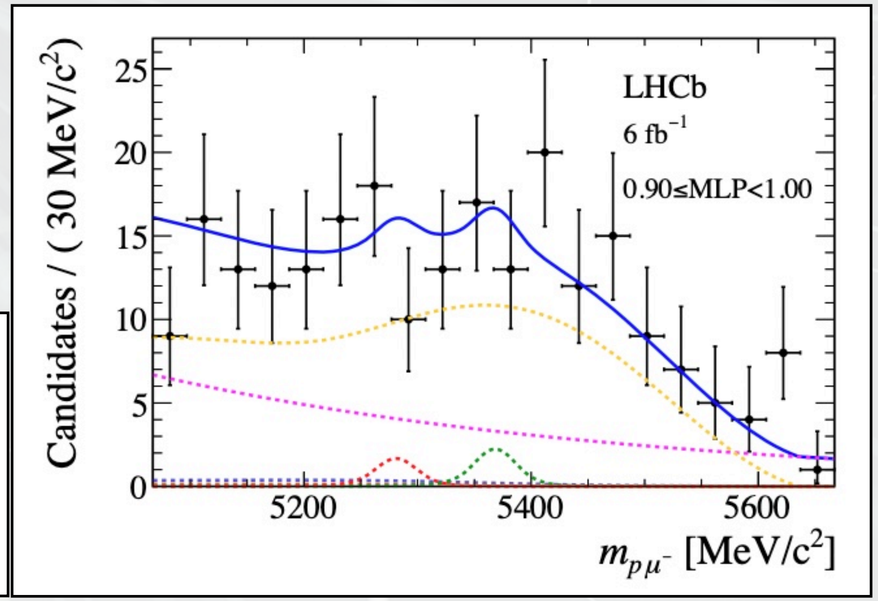
- Sakharov conditions for (EW) Baryogenesis
- Empirical symmetry that explains proton stability
- BSM models e.g. GUT add gauge bosons X and Y with B/LNV

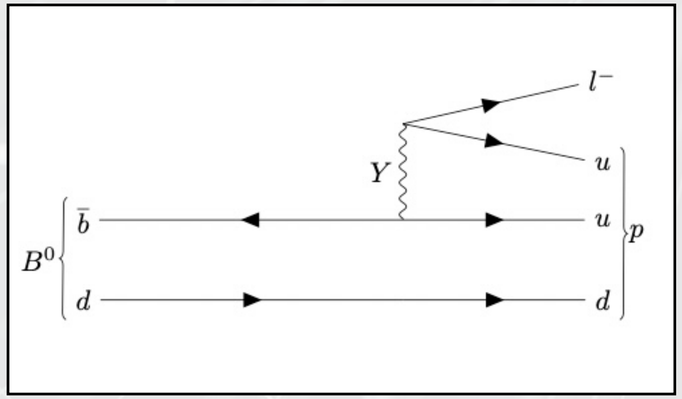
- Search for $\tau^- \to p\mu\mu^-$, BR < (4.3-5.7) x 10^{-7}
- Search for $B^0_{(s)} \to p\mu^-$, BR < 3.1 (14.0) x 10^{-9} 2022
- Limited by statistics, partially reconstructed / misID'd backgrounds

Phys. Lett. B 724, 36-45



arXiv:2210.10412

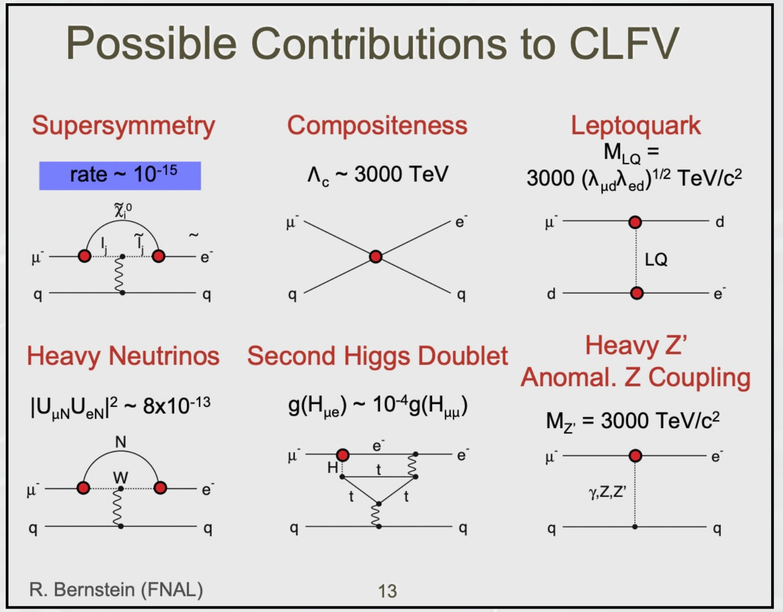




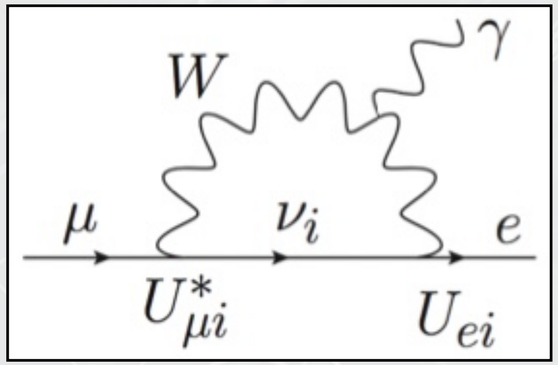
R. Bernstein (RdV 2016)

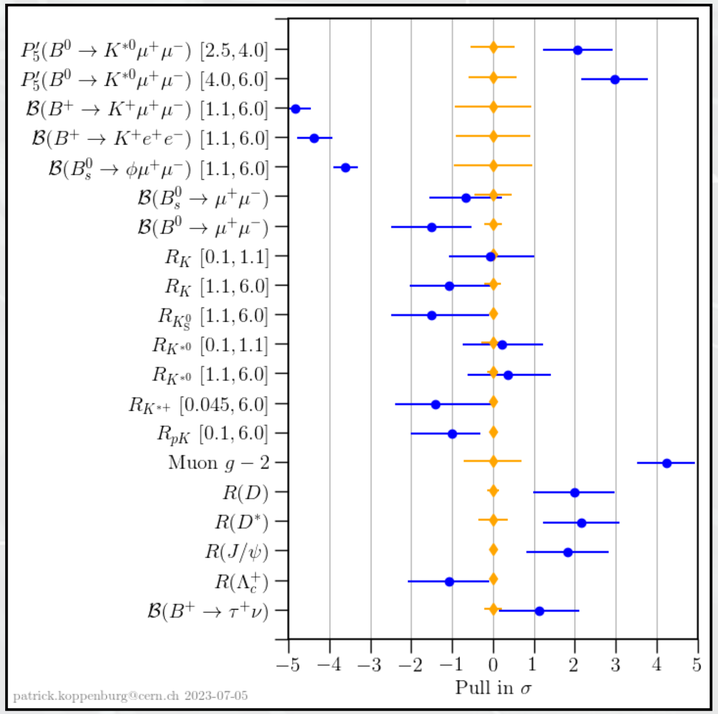
Lepton flavour violation I

- Neutrino oscillations -> LFV in charged sector (BR < 10^{-40})
- BSM models enhanced cLFV, some focus on 3rd generation (eg extended Higgs sectors)



- LF vs Lepton Universality: 'accidental' symmetries of SM
  New mediators to violate universality (eg LQ, Z') also do LFV.
  (see e.g. Phys. Rev. Lett. 114, 091801)
- LHCb's Flavour anomaly measurements
  (see talk by Marie-Hélène Schune) -> LFV test in orthogonal way



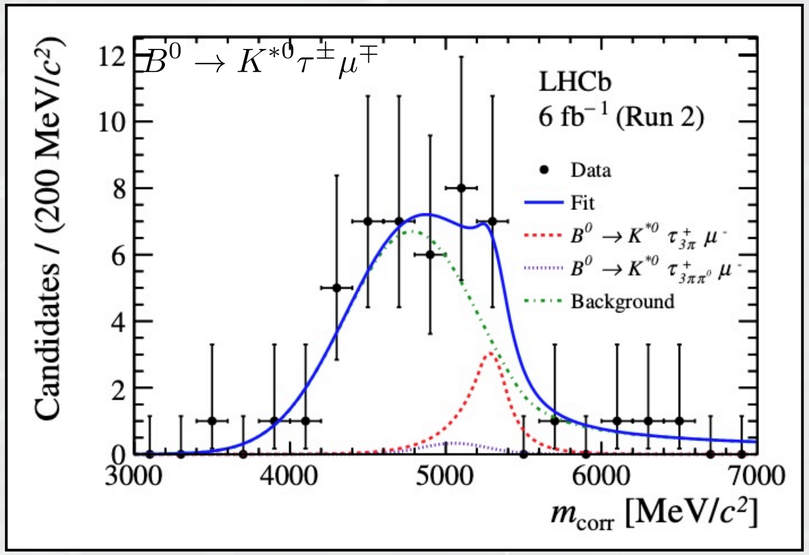


LFV/LFU Snowmass 2021
pkoppenb/anomalies

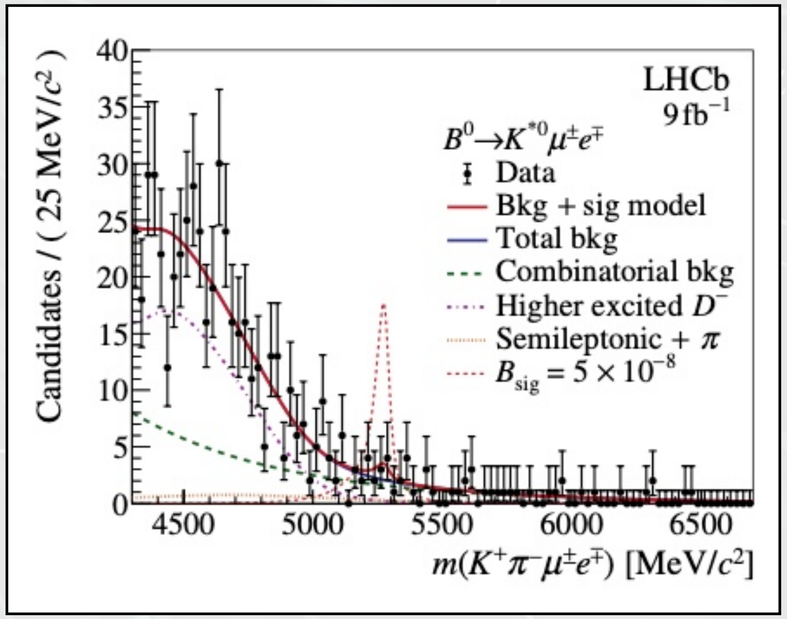
Lepton flavour violation II

- Search for $B^0 \to K^{*0}\tau^{\pm}\mu^{\mp}$ BR < (0.1-1.2) x 10^{-6} 2022
- $B^0 \to K^{*0}\mu^{\pm}e^{\mp}$ BR < (1.9-11.7) x 10^{-9} 2022
- $B_s^0 \to \phi\mu^{\pm}e^{\mp}$ BR < 19.8 x 10^{-9} 2022
- $B_s^0 \to \phi\mu^{\pm}\tau^{\mp}$ WIP
  $\Lambda_b^0 \to \Lambda e^{\pm}\mu^{\mp}$ WIP
- $D^+_{(s)} \to h^+ e^{\pm}\mu^{\mp}$ BR < 10^{-6} - 10^{-7} JHEP 6 (2021) 044

JHEP 2306 (2023) 143



JHEP 2306 (2023) 073



- Tau reconstruction tau->3pi (pi0), missing energy.
  Utilise tau flight distance χ^2 and a^0 decay kinematics
  Fit corrected mass with missing pT.
- Electron reconstruction with Bremsstrahlung recovery
  Background from SL D$^{(*)}$ and misID $J/\psi X$

Lepton flavour violation III

- Same b->sll' but different topology, no form factors, different backgrounds / systematics
- Search for $B^0_{(s)} \to \tau^{\pm}\mu^{\mp}$, BR < (1.4-4.2) x 10^{-5}
- Search for $B^0_{(s)} \to e^{\pm}\mu^{\mp}$, BR < (1.3-7.2) x 10^{-9}

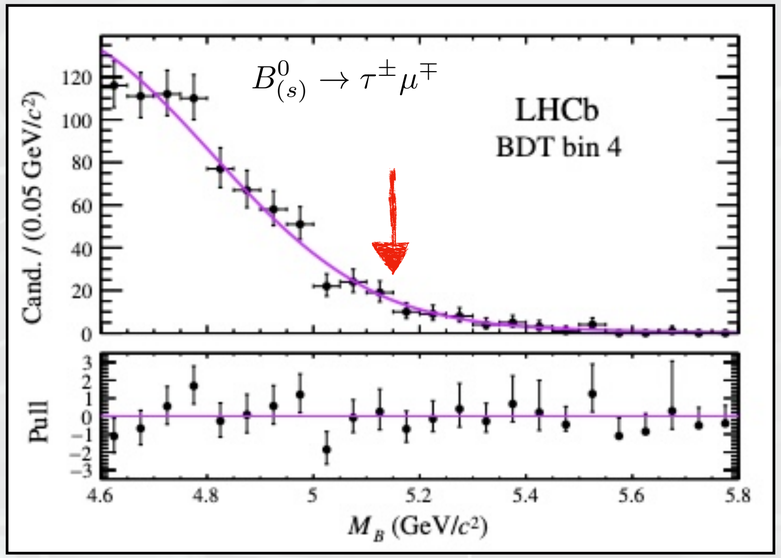
Update WIP

- LQ enhancement of BR($\tau\mu$) up to 10^{-5}, Pati-Salam 10^{-4}
  BR($e\mu$) mode up to 10^{-11}.

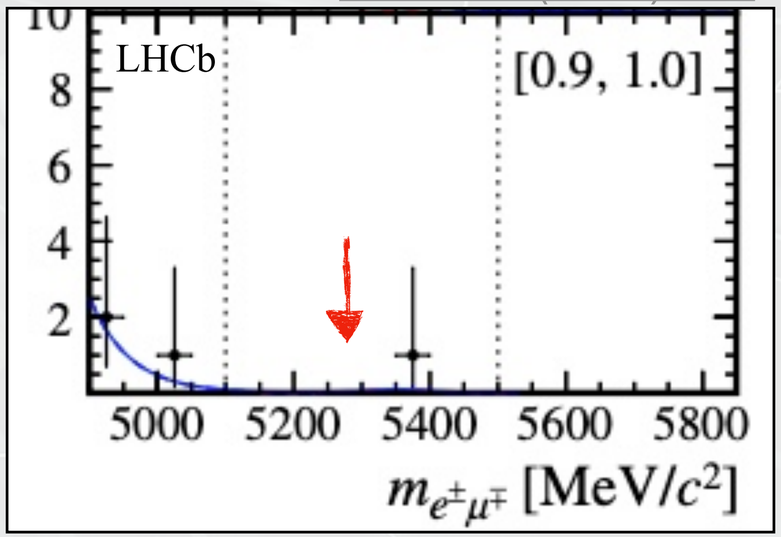
- $D^0 \to e^{\pm}\mu^{\mp}$, BR < 1.3 x 10^{-8} (@90% CL) Phys. Lett. B 754, 167
  Using $D^* \to D^0\pi^+$. BR Could be up to 10^{-6} in mSUSY.
- $\tau^- \to \mu^+\mu^-\mu^-$, BR < 4.6 x 10^{-8} JHEP 02 (2015) 121
  3rd gen, lepton-lepton

Update WIP

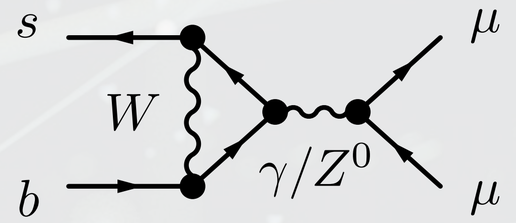
Phys. Rev. Lett. 123 211801



JHEP 03 (2018) 078



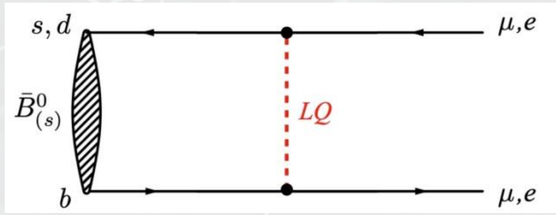
Dileptons



- b → sll transitions in two-body decays: extremely suppressed!

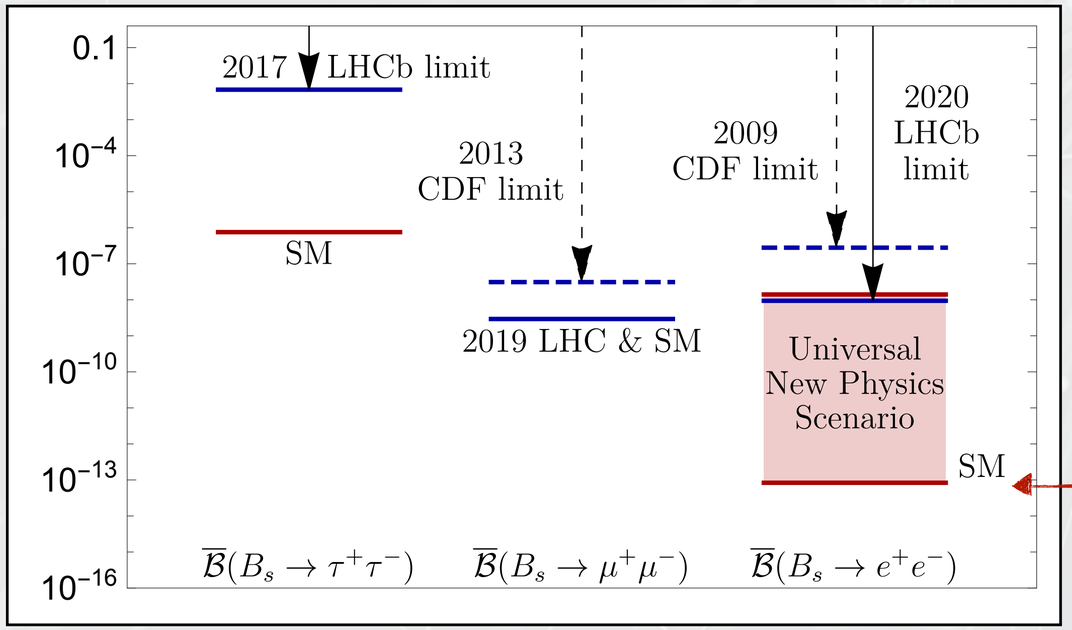
helicity suppression!

$$\mathcal{B} \propto |V_{tb}V_{tq}|^2 \left[(1 - \frac{4m_\mu^2}{M_B^2}) |C_S - C_S'|^2 + |(C_P - C_P') + \boxed{\frac{2m_\mu}{M_B}} (C_{10} - C_{10}')|^2 \right]$$



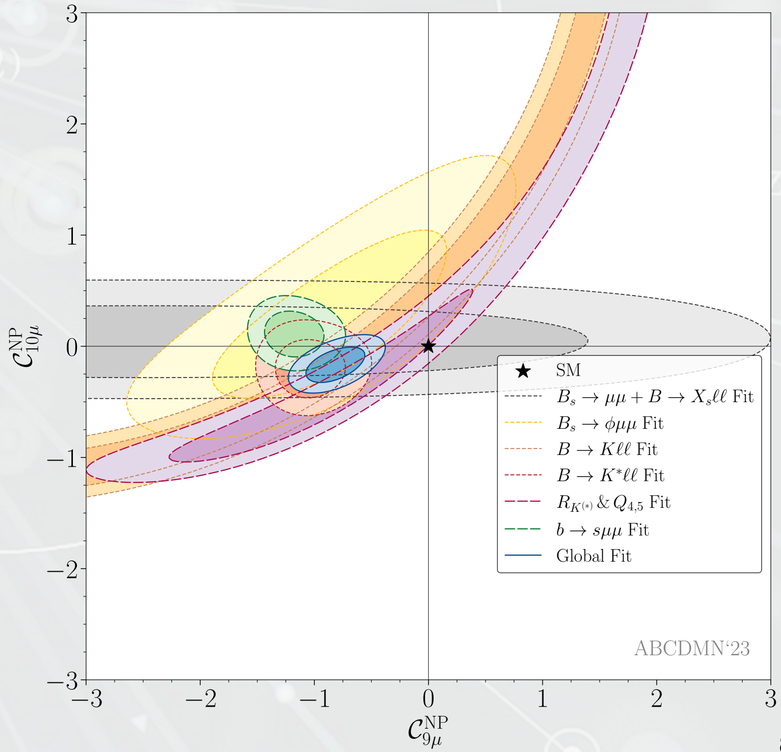
- Sensitive to (pseudo)scalar and axial vector (C_{10}) contributions

J. High Energ. Phys. 05, 156 (2017)



$B_s \to e^+e^-$ even more suppressed!

Algueró et al, arXiv:2304.07330



Dileptons - results

- $B^0_{(s)} \to \mu^+\mu^-$, BR = (3.1 +- 0.5) x 10^{-9}
  Phys. Rev. D 105 012010
  Phys. Rev. Lett. 128 041801

- $B^0_{(s)} \to e^+e^-$, BR < (3.0-11.2) x 10^{-9}
  Phys. Rev. Lett. 124 211802

- $B^0_{(s)} \to \tau^+\tau^-$, BR < (2.1-6.8) x 10^{-3}
  Phys. Rev. Lett. 118 251802

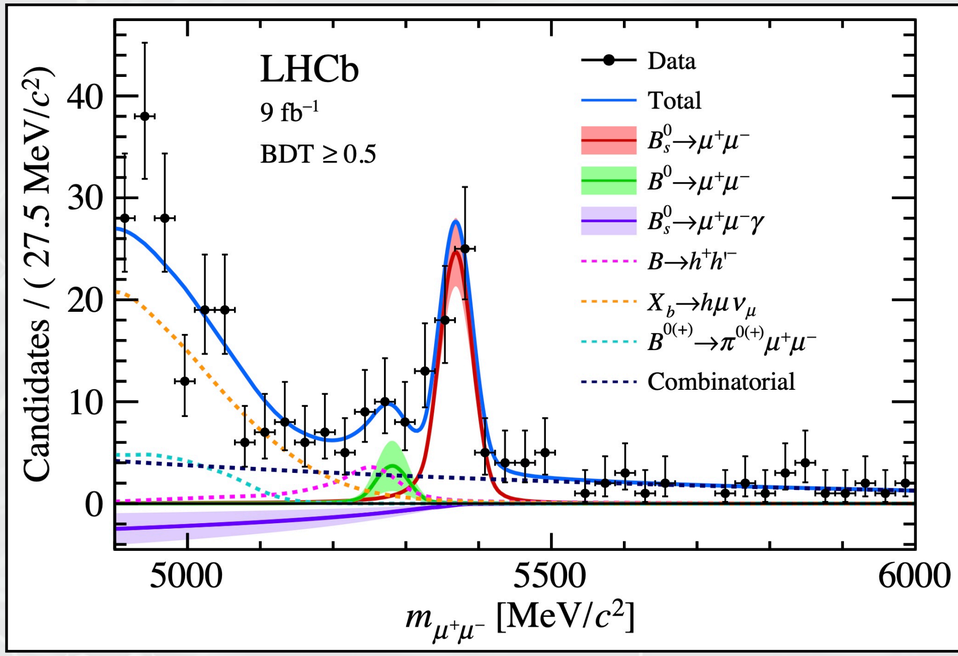
- $D^{*0} \to \mu^+\mu^-$, BR < 3.4 x 10^{-8}
  arXiv:2304.01981

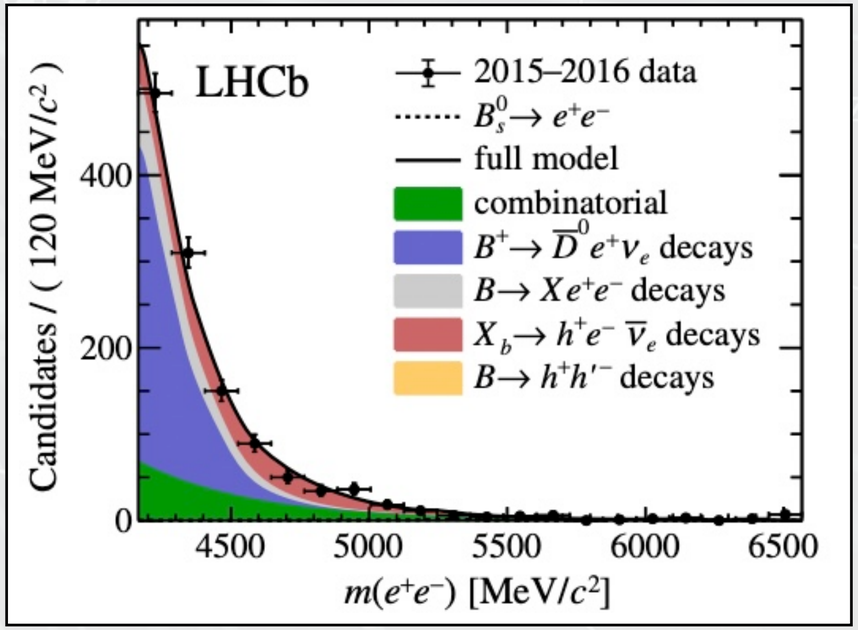
  $D^0 \to \mu^+\mu^-$, BR < 7.6 x 10^{-9}
  Phys. Lett. B 725 15

- $K^0_S \to \mu^+\mu^-$, BR < 2.4 x 10^{-10}
  Phys. Rev. Lett. 125 231801

Update WIP

2023





3-body dileptons

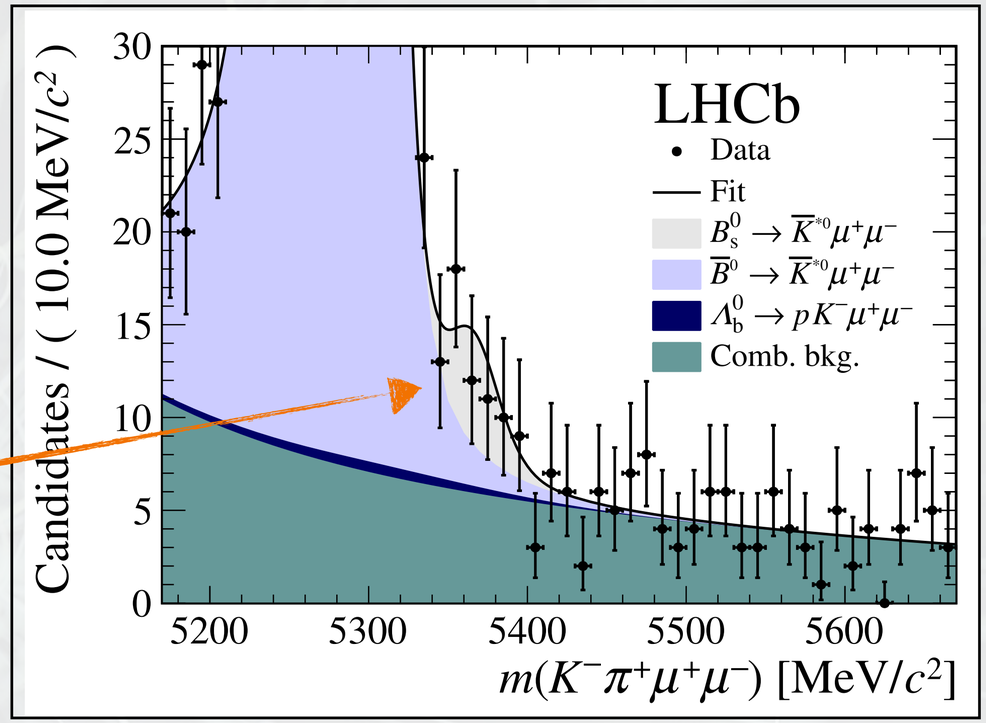
- FCNC with flavour anomalies observed:
  R-ratio measurements, BR, angular…
- Rarer searches supplement, add additional sensitivity, test QCD assumptions

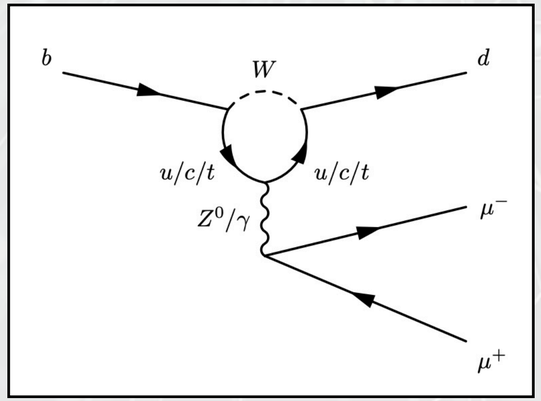
- $B_s^0 \to \bar{K}^{*0}\mu^+\mu^-$: BR = (2.9 +- 1.1) x 10^{-8} (3.4 σ)
  JHEP 07 (2018) 020
- $B^\pm \to \pi^\pm\mu^+\mu^-$: BR = (1.8 +- 0.3) x 10^{-8}
  JHEP 10 (2015) 034
- $\Sigma^+ \to p\mu^+\mu^-$: BR = (2.2 +- 1.8) x 10^{-8} (4.1 σ)
  Phys. Rev. Lett. 120 221803

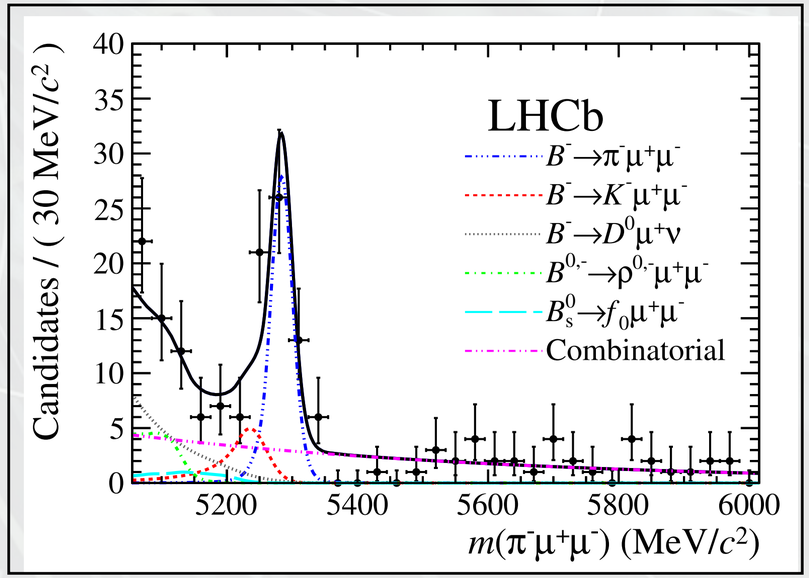
Update Run2 WIP

- $D^+ \to h^+\mu^+\mu^-$: BR < (2.5-8.3) x 10^{-8}
  JHEP 6 (2021) 044
- $\Lambda_c^+ \to p\mu^+\mu^-$: BR < 9.6 x 10^{-8}

Phys. Rev. D 97 091101





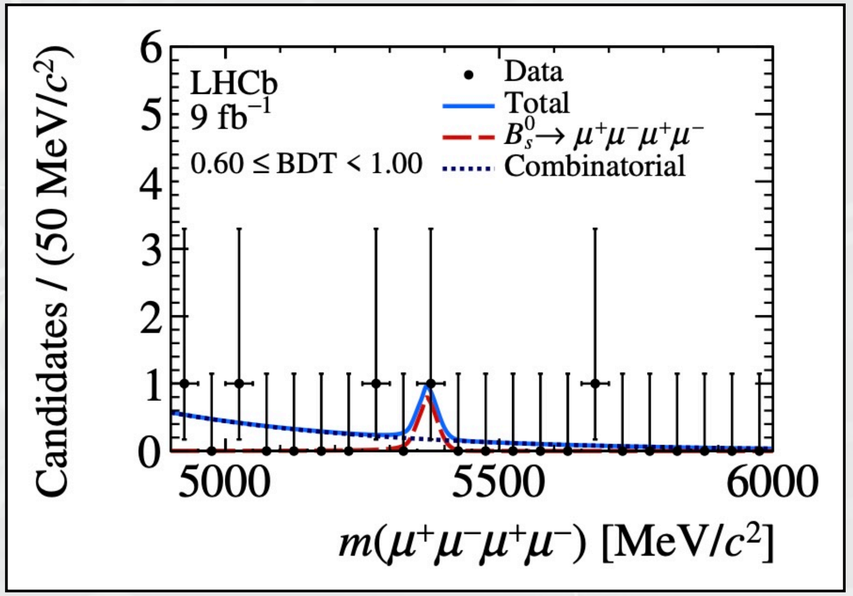


Multibody final states

- Rare FCNC modes, can generically be enhanced by various BSM physics

- $B^0_{(s)} \to \mu^+\mu^-\mu^+\mu^-$, BR < (1.8-26) x 10^{-10}
  JHEP 2203 (2022) 109

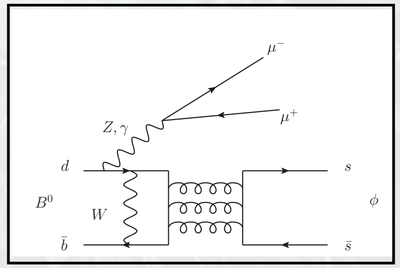
Update WIP



- $K^0_S \to \mu^+\mu^-\mu^+\mu^-$, BR < 5.1 x 10^{-12} (@90% CL)
  arXiv:2212.04977

2022

- $B^0_d \to \phi\mu^+\mu^-$, BR < 3.2 x 10^{-9} (@90% CL)
  JHEP 05 (2022) 067

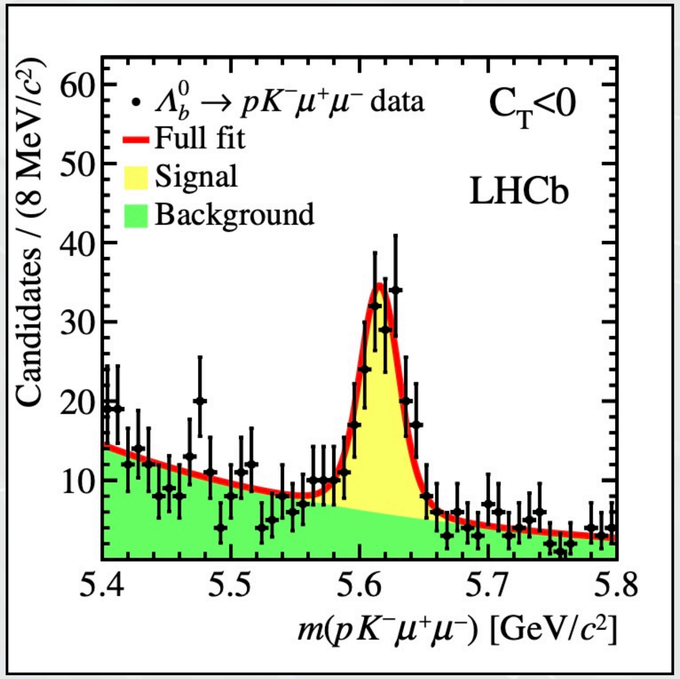


- First observations at 10^{-7}, limits at 10^{-8} for semi-hadronic modes, probing flavour structure, hadronic resonances, CPV…

$B^{0(+)} \to (K^+)\pi^+\pi^-\mu^+\mu^-$,

$D^0 \to \{\pi^-\pi^+, K^-\pi^+, K^-K^+\}\mu^-\mu^+$,

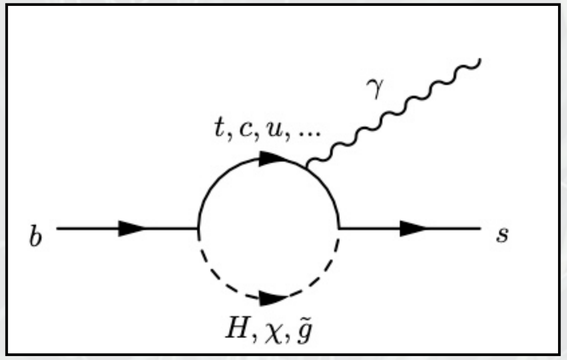
$\Lambda_b \to p\{\pi^-, K^-\}\mu^+\mu^-$

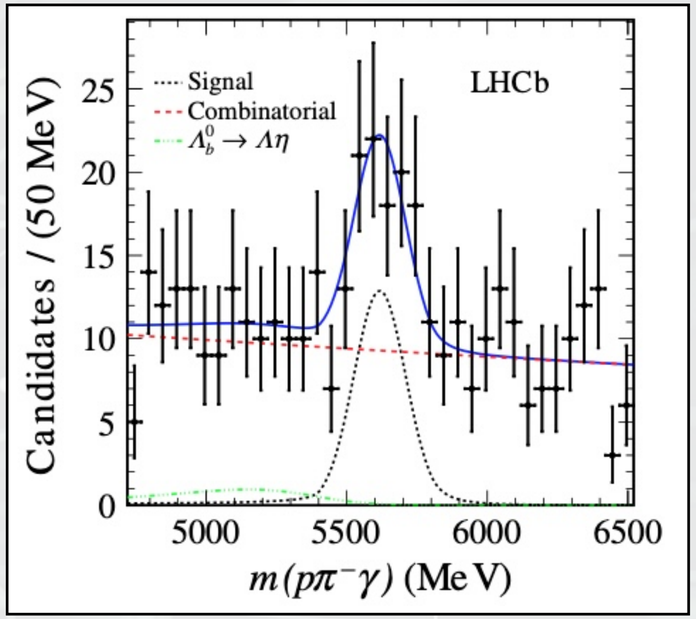


Phys. Lett. B 743 46 JHEP 10 (2014) 064
Phys. Rev. Lett. 119 181805 Phys. Lett. B 757 558
JHEP 04 (2017) 029 JHEP 1706 (2017) 108

Radiatives

- Varying $b \to s\gamma$ topologies, probing photon coupling $C_7^{(\prime)}$.
- Reconstruction challenging

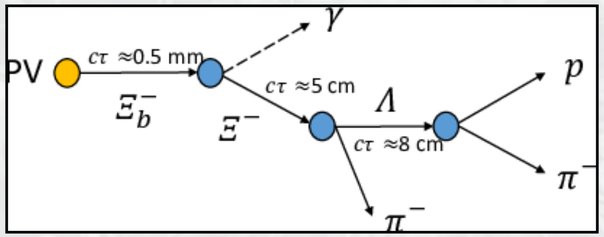




- $\Lambda_b^0 \to \Lambda\gamma$

  First observation, BR = (7.1 +- 1.8) x 10^{-6}

  Phys. Rev. Lett. 123 031801



- $\Xi_b^- \to \Xi^-\gamma$, BR < 1.3 x 10^{-4}

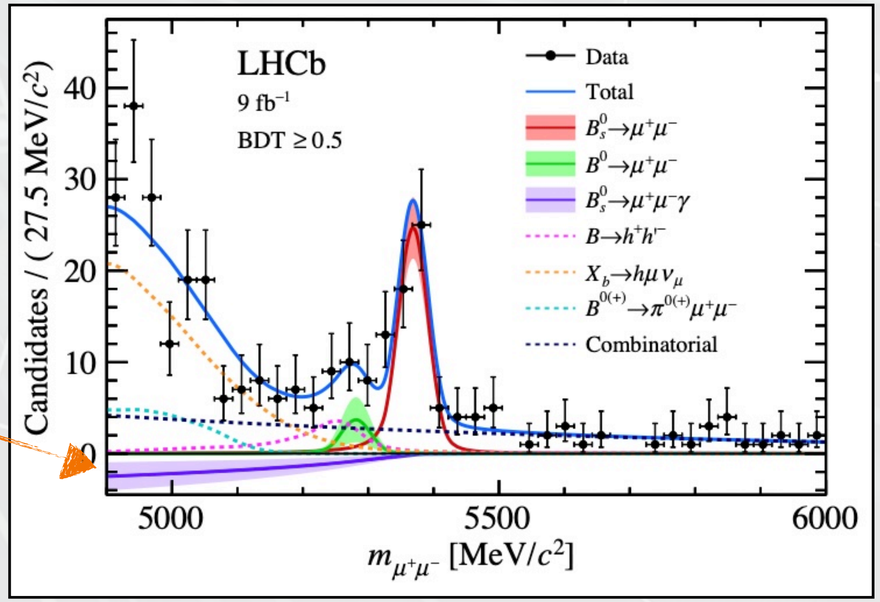
  JHEP 2201 (2022) 069

- $B_{(s)}^0 \to \mu^+\mu^-\gamma$, BR < 2.0 x 10^{-9}

  ISR large photon momentum

  Phys. Rev. Lett. 128 041801

Update WIP



- Testing QCD factorisation

  $B_{(s)}^0 \to J/\psi\gamma$: BR < (1.5-7.3) x 10^{-6} (@90% CL)

  Phys. Rev. D 92 112002

  $W^+ \to D_s^+\gamma\,(Z \to D^0\gamma)$: BR < 6.5 x 10^{-4} (2.1 x 10^{-3})

  2022

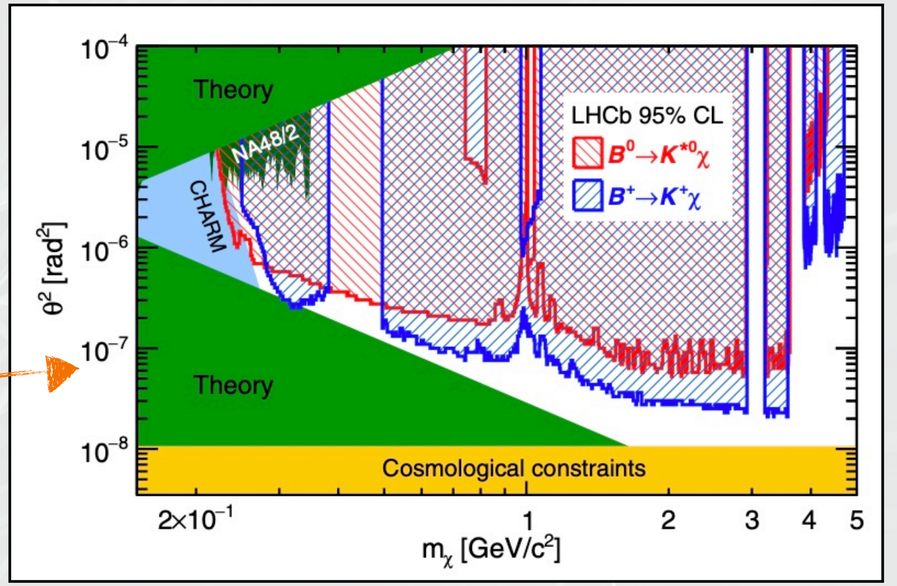
  arXiv:2212.07120

Exotics

- Search for ‘BSM’ decay signatures directly,
  set limits as mass vs decay time / coupling
- Hidden-Sector Bosons in long-lived dimuon resonances:
  $B^{0(+)} \to K^{*0(+)}\mu^+\mu^-$

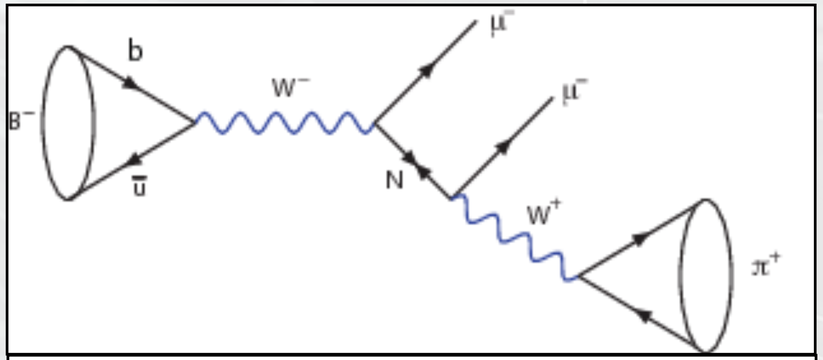
  Phys. Rev. D 95 071101

  Phys. Rev. Lett. 115 161802



- Long-lived particles in $e^{\pm}\mu^{\mp}\nu$, $\mu^{\pm}q_iq_j$ Eur. Phys. J. C 81, 261 Eur. Phys. J. C82 373
- Heavy Neutral Leptons in $W^+ \to \mu^+\mu^{\pm}jet$

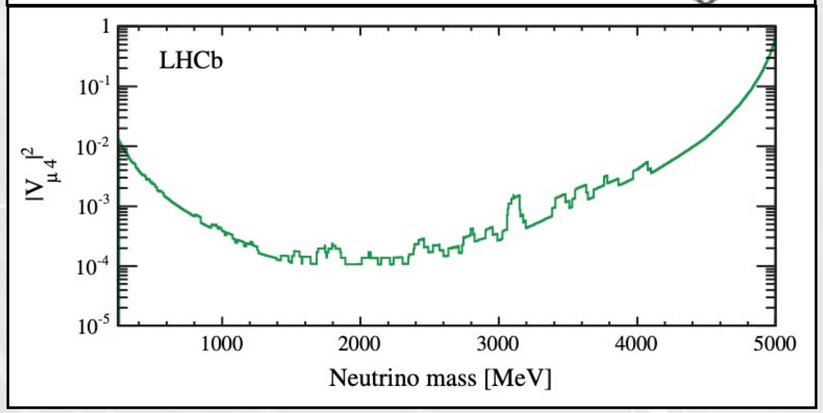
  Eur. Phys. J. C81 248



- Majorana neutrino’s in $B^- \to \pi^+\mu^-\mu^-$
  ‘$0\nu\beta\beta$’, limits at BR < 4.0 x 10^{-9} for τ_N < 1 ps.

  Phys. Rev. Lett. 112 131802

Update with D WIP



- Strong CP Violation in $\eta \to \pi^+\pi^-$,
  BR < 1.6 x 10^{-5} (@90% CL) Phys. Lett. B 764 233
- (long-lived) dimuon resonances at low mass, Υ mass, dark photons

  JHEP 10 (2020) 156 Phys. Rev. Lett. 124, 041801

  JHEP 09 (2018) 147

Conclusions

J. Phys.: Conf. Ser. 878 012012

LHCb is an excellent laboratory for very rare decays

Very rare decays provide an extensive physics programme,
- testing SM assumptions, searching for BSM physics
- Model (in-)dependent contributions

Many limits close to NP expectations,
many observations statistically limited for further studies