Rare Decays at LHCb

Ricardo Vázquez Gómez
on behalf of the LHCb collaboration

LNF – INFN

Implications of LHCb measurements and future prospects
14-16 October 2013

Outline

- LHCb aims to study rare decays in three areas:
- 1) Very rare decays (this talk)
  - $B_s \to \mu\mu$ and $B_d \to \mu\mu$
  - Lepton Flavour Violation
  - Baryon Number Violation
  - Rare D decays
- 2) Radiative decays (this talk)
  - Study of the photon polarisation
- 3) Electroweak penguin decays (see C. Langenbruch's talk tomorrow)

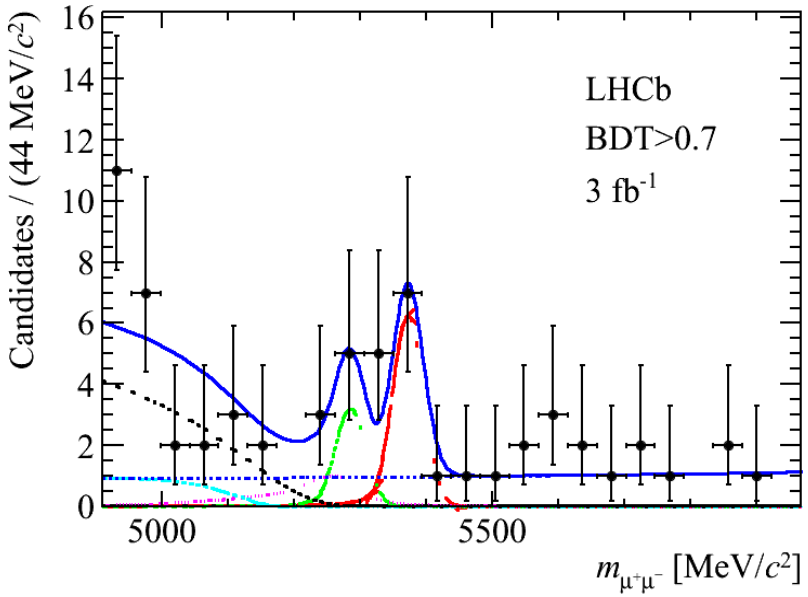
LHCb results (past and present)

- BR $B_{d,s} \to \mu\mu$ (4 papers + 5 conf-note) [Phys. Rev. Lett. 08 (2013) 117]
- Ratio of BR $(B \to K^*\gamma)/(Bs \to \phi\gamma)$ [Nucl. Phys. B 867 (2012) 1-18]
- BR of $B_{d,s} \to \mu\mu\mu\mu$ [Phys. Rev. Lett. 110 (2013) 1528276]
- BR $B \to \pi\mu\mu$ and $B \to D\mu\mu$ [Phys. Rev. D 85 (2012) 112004]
- BR $K_s \to \mu\mu$ [JHEP 01 (2013) 090]
- BR $D \to \mu\mu$ [Phys. Lett. B 725 (2013) 15-24]
- BR $D_{(s)} \to \pi\mu\mu$ [Phys. Lett. B 724 (2013) 203-212]
- BR $B_{d,s} \to e\mu$ [Phys. Rev. Lett. 102 (2009) 201801]
- BR of $\tau \to \mu\mu\mu$ [Phys. Lett. B 724 (2013) 36-45]
- BR of $\tau \to p\mu\mu$ [Phys. Lett. B 724 (2013) 36-45]
- Asymmetry in $B \to K\pi\pi\gamma$ [LHCb-CONF-2013-009]

Measurement of $B_s \to \mu\mu$ and search for $B_d \to \mu\mu$

$B_{d,s} \to \mu\mu$ updated result

- Update of the analysis with the full data sample of 3 fb^{-1}.



[Phys. Rev. Lett. 08 (2013) 117]

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (2.9^{+1.1}_{-1.0}(\text{stat})^{+0.3}_{-0.1}(\text{syst})) \times 10^{-9}, \quad 4\sigma$$

$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (3.7^{+2.4}_{-2.1}(\text{stat})^{+0.6}_{-0.4}(\text{syst})) \times 10^{-10} \quad 2\sigma$$

$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 7.4 \times 10^{-10} \text{ at } 95\% \text{ CL}$$

In good agreement within the current uncertainty with the SM predictions.
Keeps on providing strong constraints in NP scenarios.

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.56 \pm 0.30) \times 10^{-9}$$

$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (1.07 \pm 0.05) \times 10^{-10}$$

[Eur. Phys. J C72 (2012) 2172]
[Phys. Rev. Lett. 109 (2012) 041801]

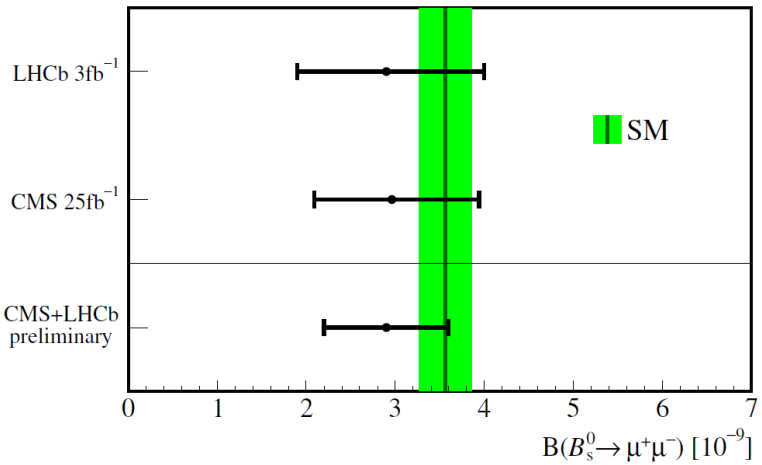
$B_{d,s} \to \mu\mu$ combination with CMS

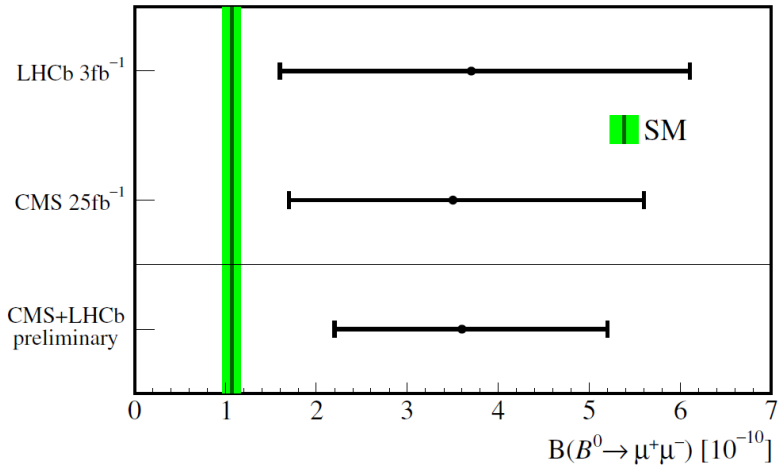
- Combination of CMS results for $B_{d,s} \to \mu\mu$ [Phys. Rev. Lett. 111 (2013) 101804]
- Taking into account the common sources of uncertainties, the combined limits are

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (2.9 \pm 0.7) \times 10^{-9} \quad \text{,> 5}\sigma$$

$$\mathcal{B}(B^0 \to \mu^+\mu^-) = \left(3.6\,^{+1.6}_{-1.4}\right) \times 10^{-10} \quad \text{, < 3}\sigma$$

[LHCb-CONF-2013-012, CMS-PAS-BPH-13-007]





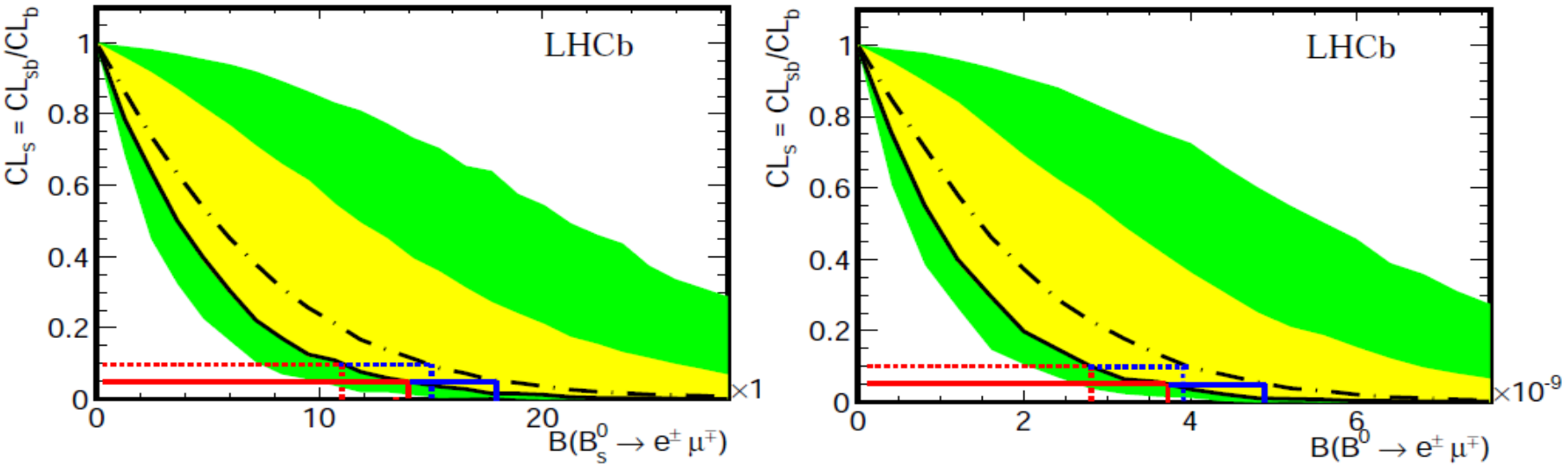
LHCb will now focus on measuring the ratio $BR(B_d \to \mu^+\mu^-)/BR(B_s \to \mu^+\mu^-)$

Lepton Flavour Violating decays

Results on $B_{d,s} \to e\mu$

Using 1 fb^{-1} of data from 2011 at 7 TeV

[Phys. Rev. Lett. 111 (2013) 141801]



$$\mathcal{B}(B_s^0 \to e^\pm \mu^\mp) < 1.1(1.4) \times 10^{-8} \text{ at } 90(95)\% \text{ CL}$$

$$\mathcal{B}(B^0 \to e^\pm \mu^\mp) < 2.8(3.7) \times 10^{-8} \text{ at } 90(95)\% \text{ CL}$$

Limits on BR 20 times smaller than previous results from CDF

[Phys. Rev. Lett. 102 (2009) 201801]

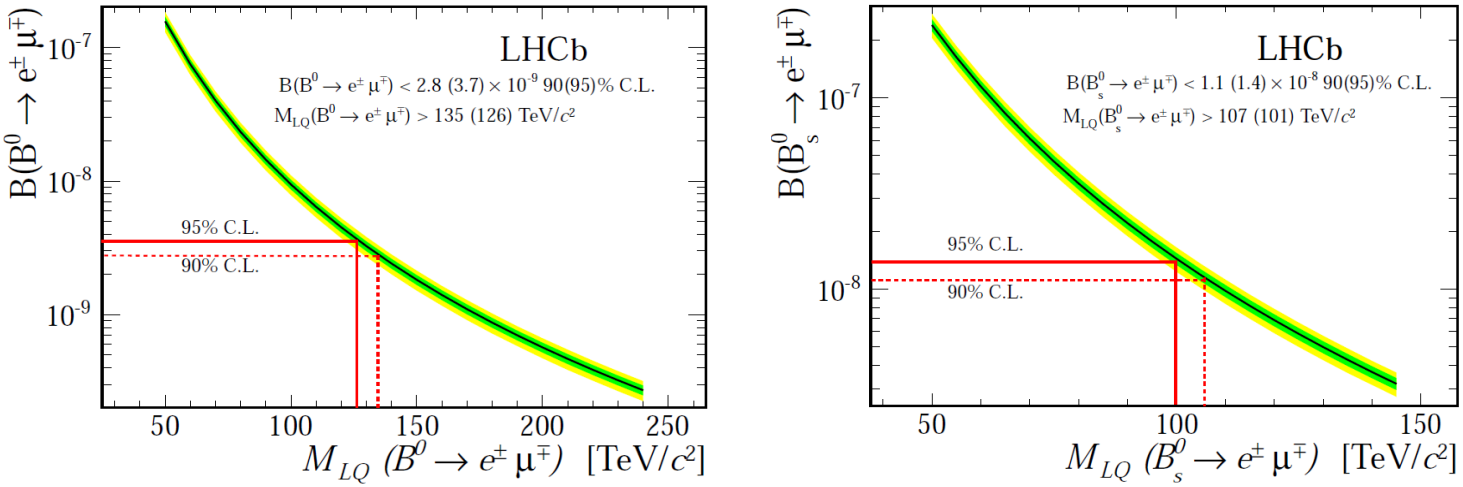
Lepton Flavour Violation interpretations

- 1) Pati-Salam leptoquarks.
  - GPD limits in range [0.4 – 0.9] TeV **same generation couplings**

ATLAS [Eur. Phys. J. C72 (2012) 2151, Phys. Lett. B 709 (2012) 158, JHEP 06 (2013) 033]

CMS [Phys. Rev. D 86 (2012) 052013, JHEP 12 (2012) 055, Phys. Rev. Lett. 110 (2013) 081801]

  - LHCb looks for couplings of **different generations.**



  - **How do the two sets of measurements compare?**

- 2) 2HDM model of type III (LFV Higgs decays)
- Plan to study B→τμ, B→τe: at which level are they ruled out by $\tau \to \mu\gamma$, $\mu \to e\gamma$, electron EDM limits?

LFV in τ decays

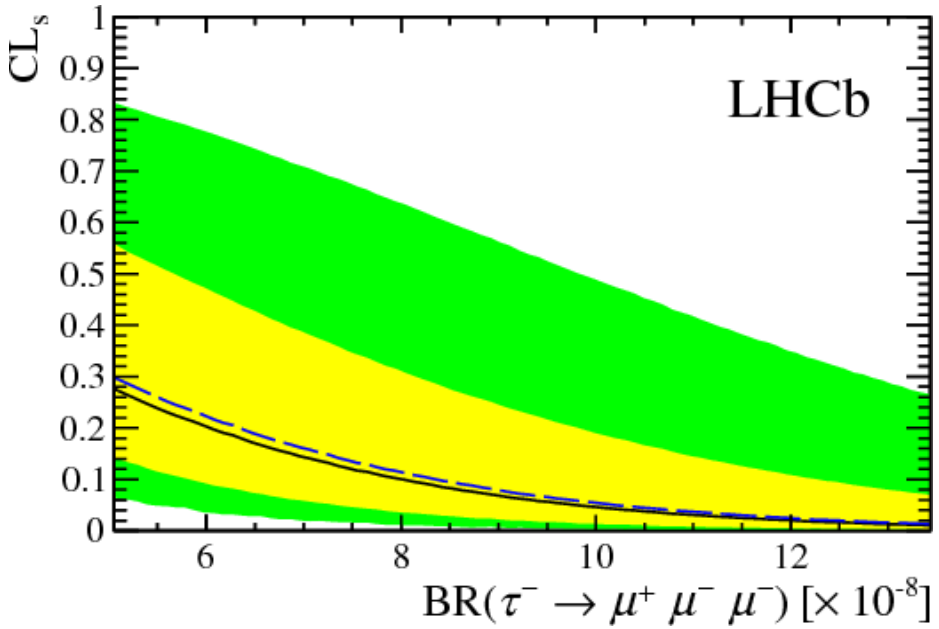
- BSM models predict that the amount of LFV in τ decays is larger than in μ decays. [Ann. Rev. Nucl. Part. Sci 58 (2008) 315]
- Latest MEG result $\mathcal{B}(\mu^{\pm} \to e^{\pm}\gamma) < 5.7 \times 10^{-13}$ at 90% CL [arXiv:1303.0754] dramatically constrains the phase-space of physics BSM.
- What can we learn from LFV τ decays? (see talk by P. Paradisi)

Model	$\tau \to \ell\gamma$	$\tau \to \ell\ell\ell$
SM with lepton CKM	10^{-40}	10^{-14}
SM with left-handed heavy Dirac neutrino	$< 10^{-18}$	$< 10^{-18}$
SM with right-handed heavy Majorana neutrino	$< 10^{-9}$	$< 10^{-10}$
SM with left- and right-handed neutral singlets	10^{-8}	10^{-9}
MSSM with right-handed heavy Majorana neutrino	10^{-10}	10^{-9}
MSSM with seesaw	10^{-7}	
left-right SUSY	10^{-10}	10^{-10}
SUSY SO(10)	10^{-8}	
SUSY-GUT	10^{-8}	
SUSY with neutral Higgs	10^{-10}	$10^{-10} - 10^{-7}$
SUSY with Higgs triplet		10^{-7}
gauge mediated SUSY breaking	10^{-8}	
MSSM with universal soft SUSY breaking	10^{-7}	10^{-9}
MSSM with non-universal soft SUSY breaking	10^{-10}	10^{-6}
Non universal Z' (technicolor)	10^{-9}	10^{-8}
two Higgs doublet III	10^{-15}	10^{-17}
seesaw with extra dimensions	10^{-11}	

[arXiv:hep-ph/0503261] and references therein

Result on $\tau \to \mu\mu\mu$

Using $1 fb^{-1}$ of data collected at 7 TeV. [Phys. Lett. B 724 (2013) 36-45]



$$\mathcal{B}(\tau^{\pm} \to \mu^{\pm}\mu^{\mp}\mu^{\pm}) < 8.0(9.8) \times 10^{-8} \text{ at } 90(95)\% \text{ C.L.}$$

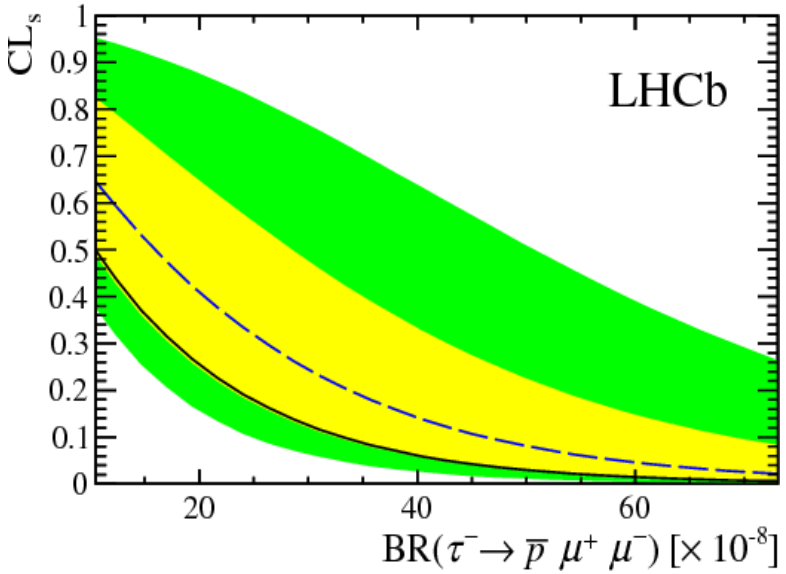
$\tau \to \mu\mu\mu$ limit is comparable with previous results $<2.1 \times 10^{-8}$ at 90% CL from Belle [Phys. Lett. B 687 (2010) 139].

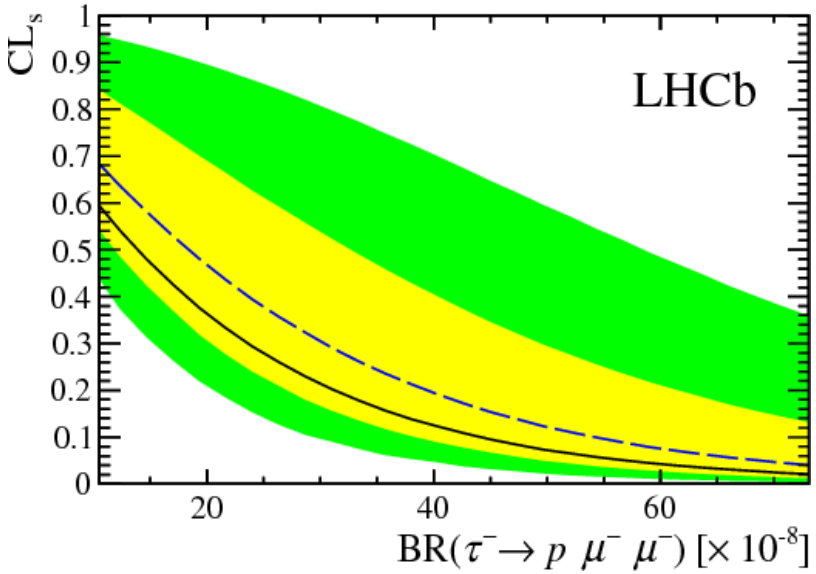
Conservatively, the limit evolves with sqrt(L) → competitive by end 2018.

Search for bayon number violating τ decays

Results $\tau^- \to p^- \mu^+ \mu^-$ and $\tau^- \to p \mu^- \mu^-$

Using $1 fb^{-1}$ of data collected at 7 TeV. [Phys. Lett. B 724 (2013) 36-45]





$$\mathcal{B}(\tau^- \to \bar{p}\mu^+\mu^-) < 3.3(4.3) \times 10^{-7} \text{ at } 90(95)\% \text{ C.L.}$$

$$\mathcal{B}(\tau^- \to p\mu^-\mu^-) < 4.4(5.7) \times 10^{-7} \text{ at } 90(95)\% \text{ C.L.}$$

First limits in $\tau^- \to p^- \mu^+ \mu^-$ and $\tau^- \to p \mu^- \mu^-$

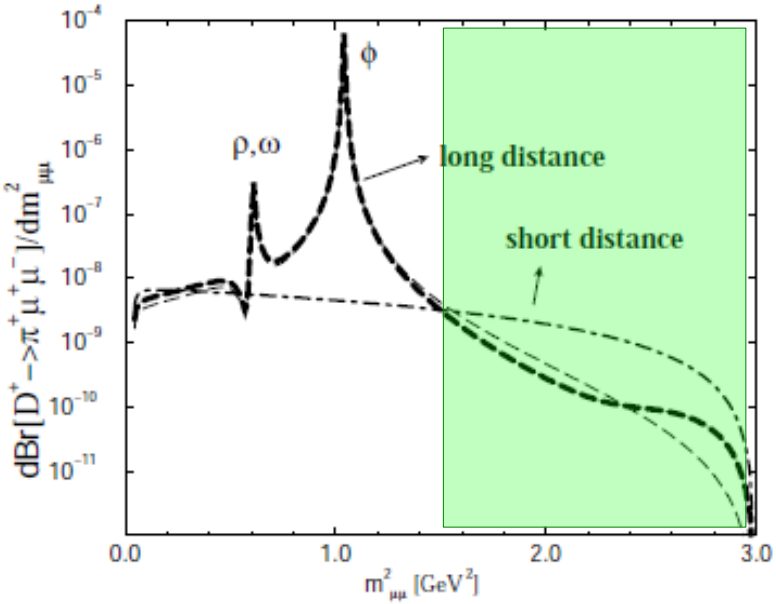
No evidence of baryon number violation.

Does the proton lifetime measurement already rule out decays like $\tau \to p\mu\mu$?

Search for rare D decays

Rare D decays

- Search for non-resonant $D^+ \to \pi^+ \mu^+ \mu^-$ with $1 fb^{-1}$ of 2011 data at 7 TeV. Will prove the FCNC $c \to u l^+ l^-$ transition.
- The SM predicts it to be $O(10^{-9})$, $b \to s l^+ l^-$ $O(10^{-7})$, $s \to d l^+ l^-$ $O(10^{-8})$.
- Dominated by long distance contribution around the V-meson resonance masses (ρ,ω,ϕ). Short distance contribution present at large di-μ masses.



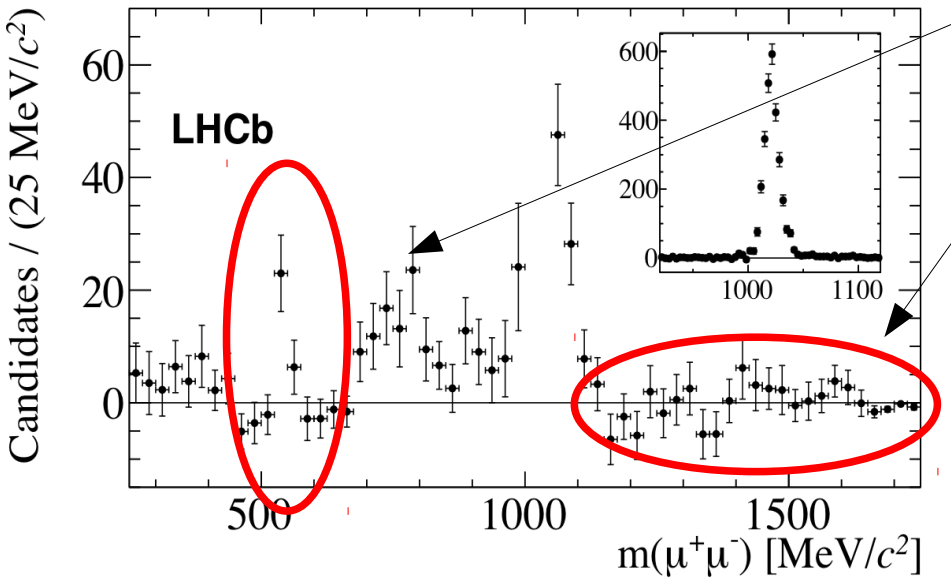
Region where FCNC dominates

[Phys. Rev. D 64 (2001) 114009]

Limit on BR

- Candidates are split in 5 bins of m(μμ). The most relevant are the first [250-525] MeV and last [1250-2000] MeV.

[Phys. Lett. B 724 (2013) 203-212]



Significance of 6.1σ for D→πη

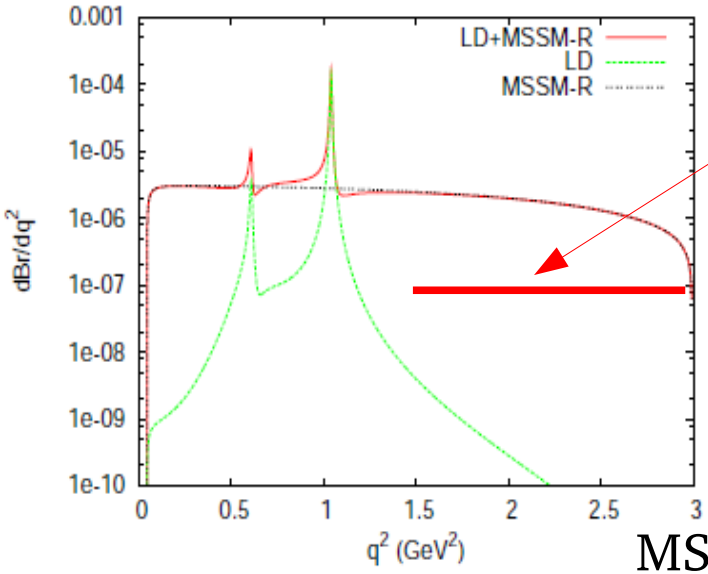
No excess of candidates seen in the high di-μ mass region.

$$\mathcal{B}(D^+ \to \pi^+\mu^+\mu^-) < 7.3(8.3) \times 10^{-8} \text{ at } 90(95)\% \text{ CL}$$

Factor **50** improvement in the limit wrt D0 result
[Phys. Rev. Lett. 100 (2008) 101801].

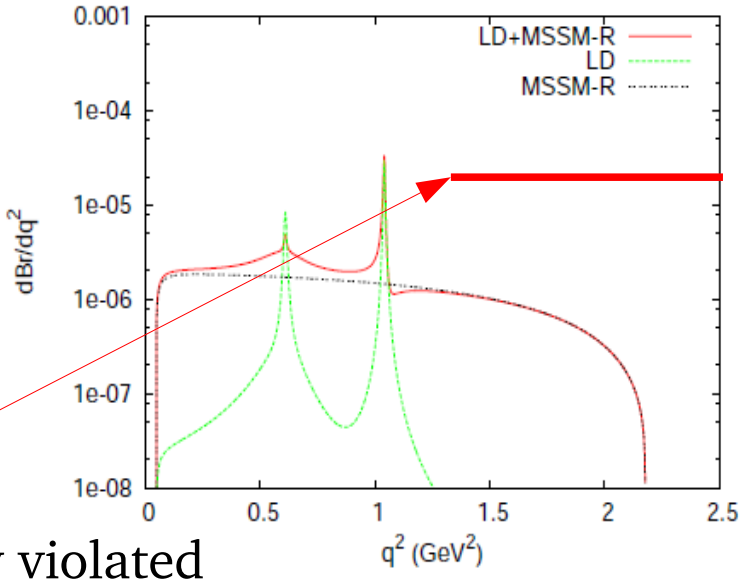
Constraints on NP

$D^+ \to \pi^+\mu^+\mu^-$ [Phys. Rev. D 76 (2007) 074010] $D_s^+ \to K^+\mu^+\mu^-$



LHCb result

BaBar result



MSSM with R parity violated

Current limit on $D_s^+ \to K^+\mu^+\mu^-$ is from BaBar with ~80% of the total data sample

$BR < 2\times10^{-5}$ at 90% C.L.

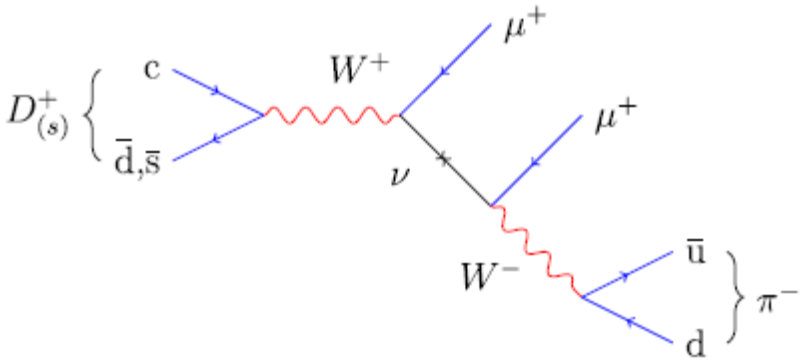
[Phys. Rev. D 84 (2011) 072006]

What do we learn more in studying the $D_s^+ \to K^+\mu^+\mu^-$ decay with respect to the $D^+ \to \pi^+\mu^+\mu^-$ one? (See talk by N. Kosnik)

Search for Lepton Number Violating decays

Majorana neutrinos in D decays

Search for same-sign muons in the decay $D_{(s)}^{+} \to \pi^{-}\mu^{+}\mu^{+}$ → Lepton Number Violating decay that can be mediated via a Majorana neutrino.



Using 1fb-1 of data at 7 TeV LHCb sets these limits to [Phys. Lett. B 724 (2013) 203-212]

$$\mathcal{B}(D^+ \to \pi^-\mu^+\mu^+) < 2.2(2.5) \times 10^{-8} \text{ at } 90(95)\% \text{ CL}$$

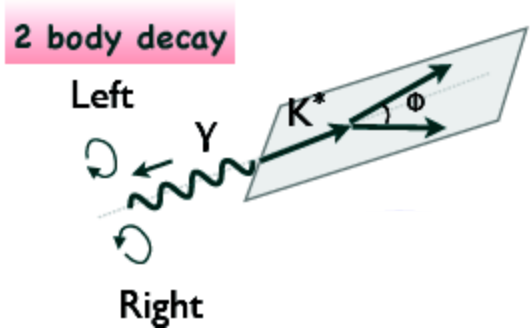
$$\mathcal{B}(D_s^+ \to \pi^-\mu^+\mu^+) < 1.2(1.4) \times 10^{-7} \text{ at } 90(95)\% \text{ CL}$$

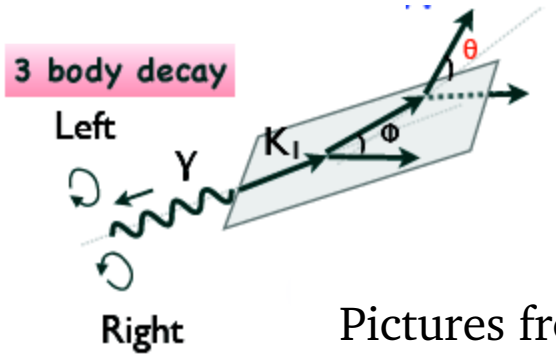
A factor 100 lower than previous BaBar limits [Phys. Rev. D 84 (2011) 072006]

Photon polarisation in $B^+ \to K^+ \pi^+ \pi^- \gamma$ decays

The importance of the 3-body

- Probe the photon polarisation in the transition b→sγ.
- In the SM, photons are predominantly left-handed, although never confirmed experimentally.





Pictures from E. Kou

Two-body decays are symmetric along the helicity axis. No left-right distinction.

Three-body decays can make an angle wrt the helicity axis.

- The average value of the triple product $\vec{p}_\gamma \cdot (\vec{p}_1 \times \vec{p}_2)$ has one sign for left-handed photons and the opposite for right-handed.

Photon polarisation

- The amplitude of the process and the photon polarisation are defined as

$$|A(\bar{B} \to \bar{K}_1\gamma, \bar{K}_1 \to \bar{K}\pi\pi)|^2 = |c_L|^2|\mathcal{M}_L|^2 + |c_R|^2|\mathcal{M}_R|^2$$

$$\lambda_\gamma = \frac{|c_R|^2 - |c_L|^2}{|c_R|^2 + |c_L|^2} = \frac{|\mathcal{C}'_{7\gamma}|^2 - |\mathcal{C}_{7\gamma}|^2}{|\mathcal{C}'_{7\gamma}|^2 + |\mathcal{C}_{7\gamma}|^2}$$

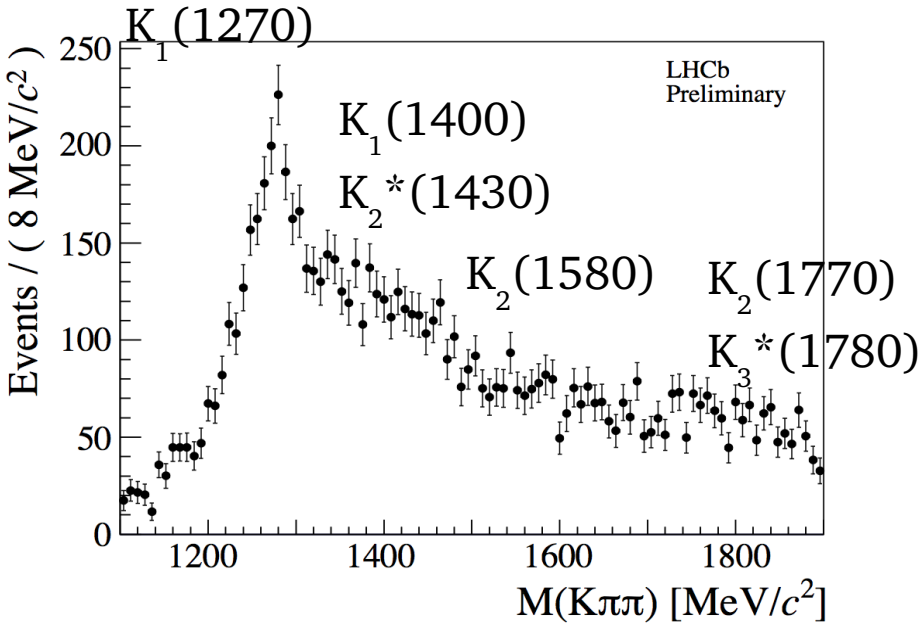
- The decay distribution for $B \to K_1(K\pi\pi)\gamma$ is given by:

$$\frac{d\Gamma}{ds_{13}ds_{23}d\cos\theta} \propto \frac{1}{4}|\vec{J}^2|(1+\cos^2\theta) + \frac{\lambda_\gamma}{2} Im\left(\hat{n}\cdot(\vec{J}\times\vec{J}^*)\right)\cos\theta$$

The polarisation information is not only in the **angular distribution**, but also on the Dalitz distribution.(see talk by E. Kou)

This is true **if and only if** there is only **one** single resonance. With more resonances strong theoretical input is needed.

Kππ mass spectra



Can't isolate individual components. The measurement must be **inclusive**.

Restrict the analysis to the regions **[1100,1300] MeV + [1400-1600] MeV**

Define the Up-Down asymmetry for **one single resonance** as

$$\mathcal{A}_{\rm ud} \equiv \frac{\int_0^1 {\rm dcos}\,\tilde{\theta}\frac{{\rm d}\Gamma}{{\rm dcos}\,\tilde{\theta}} - \int_{-1}^0 {\rm dcos}\,\tilde{\theta}\frac{{\rm d}\Gamma}{{\rm dcos}\,\tilde{\theta}}}{\int_{-1}^1 {\rm dcos}\,\tilde{\theta}\frac{{\rm d}\Gamma}{{\rm dcos}\,\tilde{\theta}}} = \frac{3}{4}\lambda_\gamma \frac{\int {\rm d}s\,{\rm d}s_{13}\,{\rm d}s_{23}{\rm Im}\left[\vec{n}\cdot(\vec{\mathcal{T}}\times\vec{\mathcal{T}}^*)\right]}{\int {\rm d}s\,{\rm d}s_{13}\,{\rm d}s_{23}|\mathcal{T}|^2}$$

Photon polarisation

Helicity amplitude (from theory)

How is the up-down asymmetry related to the polarisation for more than one resonance?

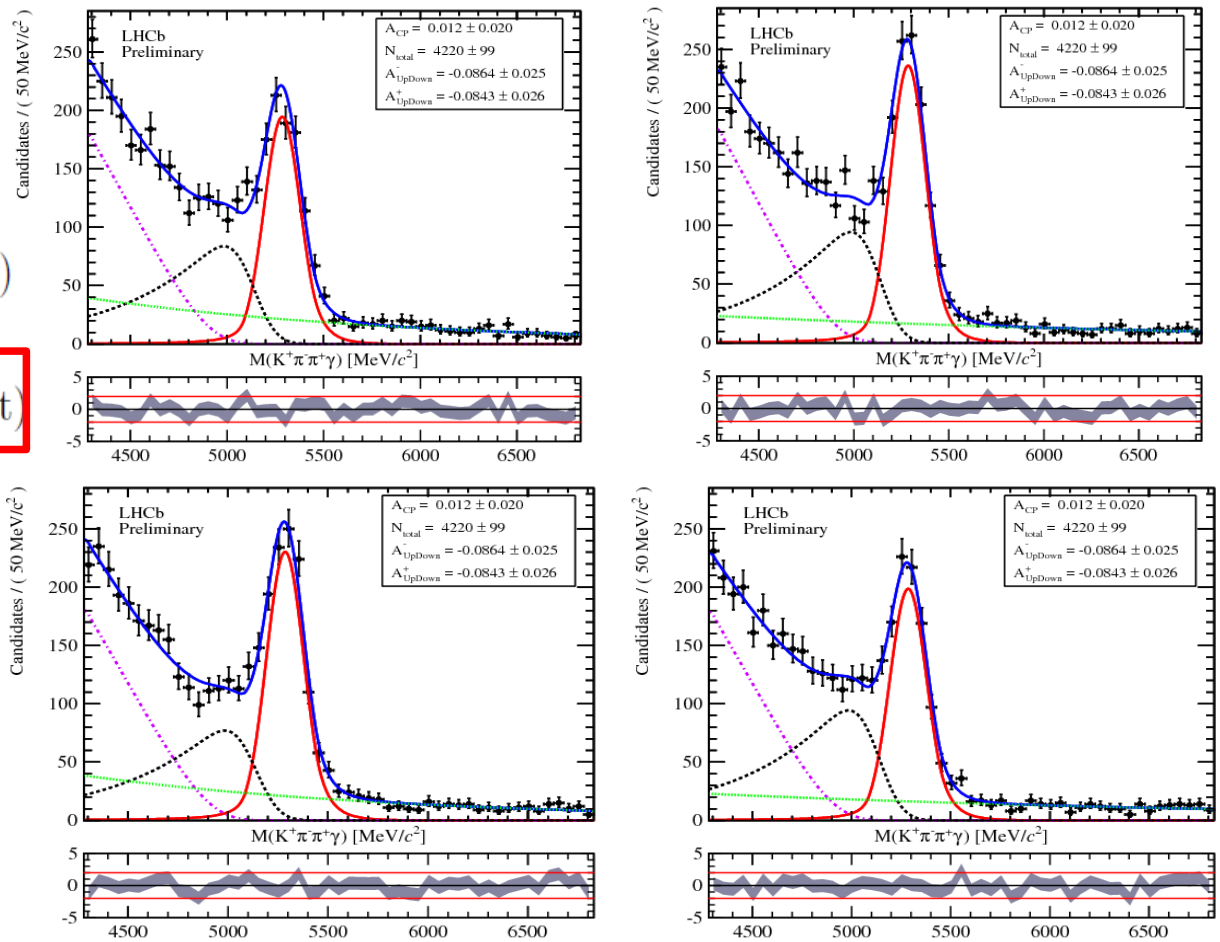
Mass fits and result

- Simultaneous fit to 4 event categories: photon direction (up, down) and charge (+,-).

[LHCb-CONF-2013-009]

$$\mathcal{A}^+ = -0.084 \pm 0.026\,(\text{stat})\,{}^{+0.004}_{-0.003}\,(\text{syst})\,,$$
$$\mathcal{A}^- = -0.086 \pm 0.025\,(\text{stat}) \pm 0.002\,(\text{syst})$$

$$\mathcal{A}_{\text{ud}} = -0.085 \pm 0.019\,(\text{stat}) \pm 0.003\,(\text{syst})$$



4.6σ significance wrt to 0.
First evidence of the photon to be polarised.

Update with full dataset is foreseen in short time → expect 5σ observation.

LHCb measurements (the future) ~1year

- Combination of BR($B_s \to \mu^+\mu^-$) with CMS.
- Search for $D^0 \to \pi^+\pi^-\mu^+\mu^-$ [will appear shotly in arXiv]
- Optimised measurement for BR($B_d \to \mu^+\mu^-$)/BR($B_s \to \mu^+\mu^-$).
- Search for BR($B_s \to \tau^+\tau^-$) and LFV BR($B_s \to \tau^+\mu^-$), BR($B_s \to \tau^+e^-$)
- Search for $\Lambda_b \to K^+\mu^-$
- Search for $\Sigma^+ \to p\mu^+\mu^-$
- Search for Majorana neutrinos in $B^- \to \pi^+\mu^-\mu^-$ decays (update with $3fb^{-1}$)
- Study the photon polarisation in $B^+ \to K^+\pi^+\pi^-\gamma$ and in $B_s \to \phi\gamma$
- Simultaneous BR measurements $B_s \to \phi\gamma$, $B \to K^*\gamma$, $B \to \rho\gamma$, $\Lambda_b \to \Lambda^*\gamma$
- Rare K_s decays ($K_s \to \mu^+\mu^-$, $K_s \to \mu^+\mu^-\mu^+\mu^-$, $K_s \to \pi^+\pi^-\mu^+\mu^-$, etc..)
- Other suggestions?

Wrapping up the questions

- In the Pati-Salam framework, how the results from GPD (same generation couplings) and LHCb (different generation couplings) compare?
- Plan to study $B \to \tau\mu$, $B \to \tau e$: at which level are they ruled out by $\tau \not\to \mu\gamma$, $\mu \not\to e\gamma$, electron EDM limits?
- What can we learn from LFV τ decays?
- Does the proton lifetime measurement already rule out decays like $\tau \not\to p\mu\mu$?
- What else do we learn in studying the $D_s^+ \to K^+\mu^+\mu^-$ decay with respect to the $D^+ \to \pi^+\mu^+\mu^-$ one?
- For the photon polarization, how to interpret up-down asymmetry when multiple resonances are present? Any suggestions for cleaner measurements?
- Suggestions on other worth-studying decays.