

# Rare Decays at LHCb

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on behalf of the LHCb Collaboration

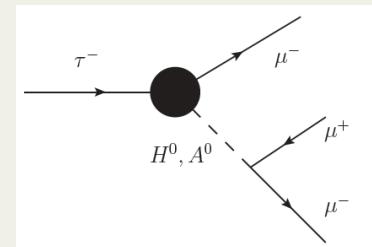
5<sup>th</sup> Workshop on Theory, Phenomenology and  
Experiments in Flavour Physics

23<sup>rd</sup>-25<sup>th</sup> May 2014

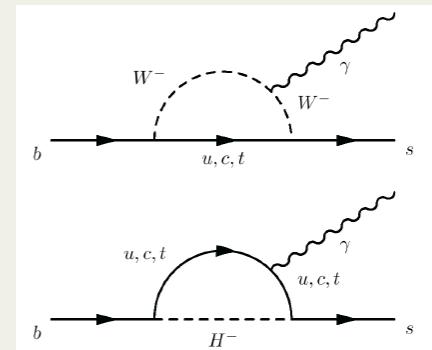


# What is a “rare decay” at LHCb

- A decay that is forbidden by a symmetry of the Standard Model (SM) or suppressed to such an extent that it cannot be observed in any plausible experiment (e.g. charged lepton flavour violation, baryon number violation)

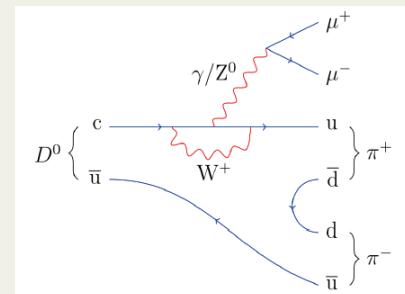
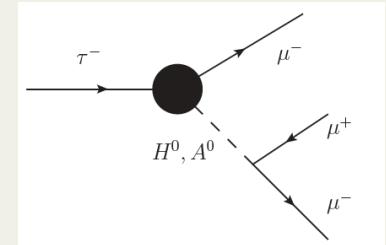


- A decay that occurs in the Standard Model only at loop level (e.g. penguin or box diagrams) and for which the BF and/or differential distributions of final state particles may be sensitive to new physics

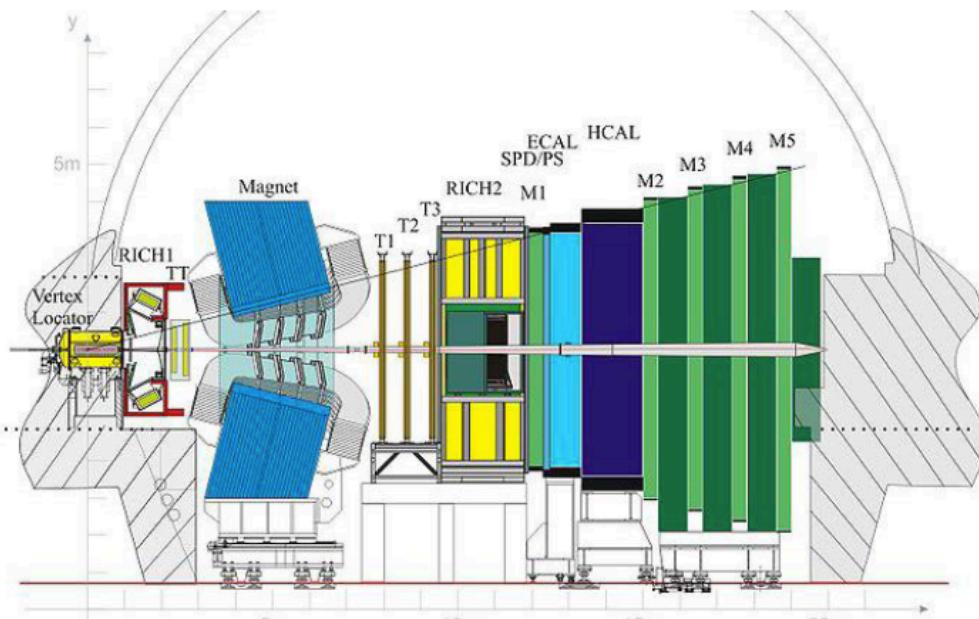


# Outline

- The LHCb experiment and datasets
- Searches for SM-forbidden decays at LHCb
  - Lepton flavour and baryon number violation in tau decays
  - Searches for heavy Majorana neutrinos in B and D meson decays
  - Lepton flavour violation in B and D meson decays
- Studies of SM-allowed rare decays at LHCb
  - $B_s \rightarrow \mu^+ \mu^-$  and  $B^0 \rightarrow \mu^+ \mu^-$  decays
  - Search for flavour-changing neutral current in  $D^0 \rightarrow \pi^+ \pi^- \mu^+ \mu^-$
  - Photon polarisation in  $b \rightarrow s \gamma$  transitions
  - Isospin asymmetries in  $B \rightarrow K^{(*)} \mu^+ \mu^-$  decays
  - Angular analysis of charged and neutral  $BB \rightarrow K \mu^+ \mu^-$  decays
  - Angular observables in  $B^0 \rightarrow K^{*0} \mu^+ \mu^-$
- Conclusions and outlook



# The LHCb detector and data



A dedicated **flavour physics** experiment in the forward region at the LHC

$3 \text{ fb}^{-1}$  of integrated luminosity from  $pp$  collisions at 7 and 8 TeV

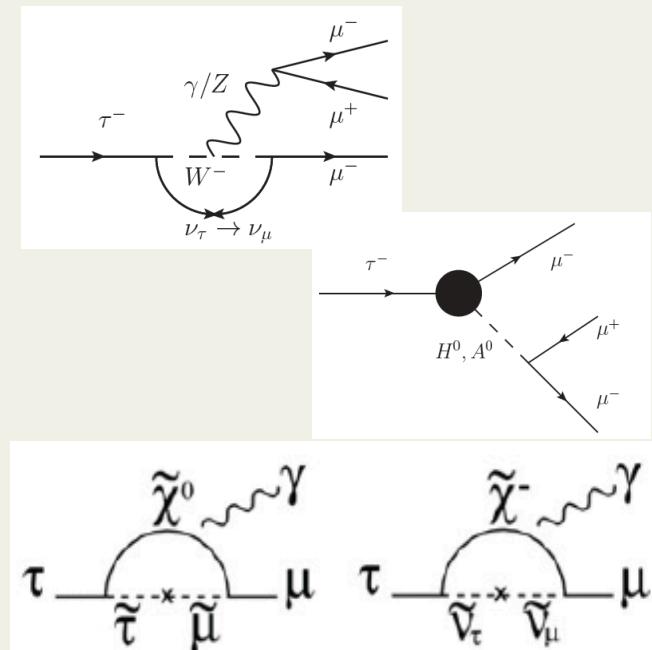
- Precise **vertex reconstruction**:  $< 10\mu\text{m}$  vertex resolution in  $x$  and  $y$
- Excellent **charged particle separation**:  $\pi^\pm$  misID of 10% for 95%  $K^\pm$  efficiency
- Clean **identification of muons**: misID of 1% for 98%  $\mu^\pm$  efficiency
- Excellent mass resolution: typically 7–20 MeV
- Flexible **low- $p_T$  trigger**: typically down to  $\sim 250$  MeV

# Searches for lepton flavour and baryon number violation in $\tau \rightarrow 3\mu$ and $\tau \rightarrow p\mu\mu$ at LHCb

*Phys.Lett. B724, 36-45 (2013)*

- Lepton flavour is conserved by construction in Standard Model
  - Now known to be violated, but suppressed by terms of order  $(\Delta m_\nu^2/M_W^2)^2$
  - Baryon number violation is required for baryogenesis
- Charged lepton flavour violation is expected in many New Physics (NP) extensions to the SM, with parameter spaces allowing rates up to the current experimental limits

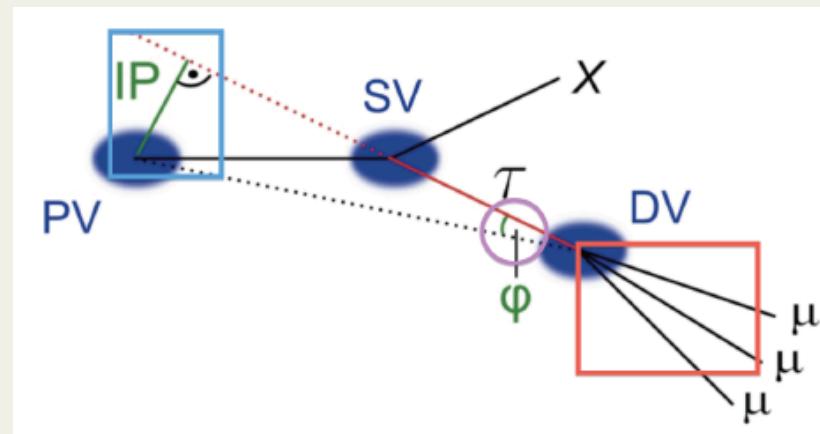
Model	References	$BF(\tau \rightarrow 3\mu)$
SM + $\nu$ mixing	Lee, Shrock, PRD 16,1444(1977) Cheng, Li, PRD 45,1908(1980)	$10^{-40}$
SUSY Higgs	Dedes, Ellis, Raidal, PLB 549,159(2002) Brignole, Rossi, PLB 566,517(2003)	$10^{-7}$
SM + heavy Majorana $\nu$	Cvetic, Dib, Kim, Kim, PRD 66,034008(2002)	$10^{-10}$
Non-universal $Z'$	Yue, Zhang,Liu, PLB 547,252(2002)	$10^{-8}$
SUSY SO(10)	Masiero, Vempati, Vives, NPB 649,189(2003) Fukuyama, Kikuchi, Okada, PRD 68,033012(2003)	$10^{-10}$
MSUGRA + Seesaw	Ellis et al., EPJ C14, 319(2002) Ellis, Hisano, Raidal, Shimizu, PRD 66,115013(2002)	$10^{-9}$



# LHCb searches for $\tau \rightarrow 3\mu$ and $\tau \rightarrow p\mu\mu$

Phys.Lett. B724, 36-45 (2013)

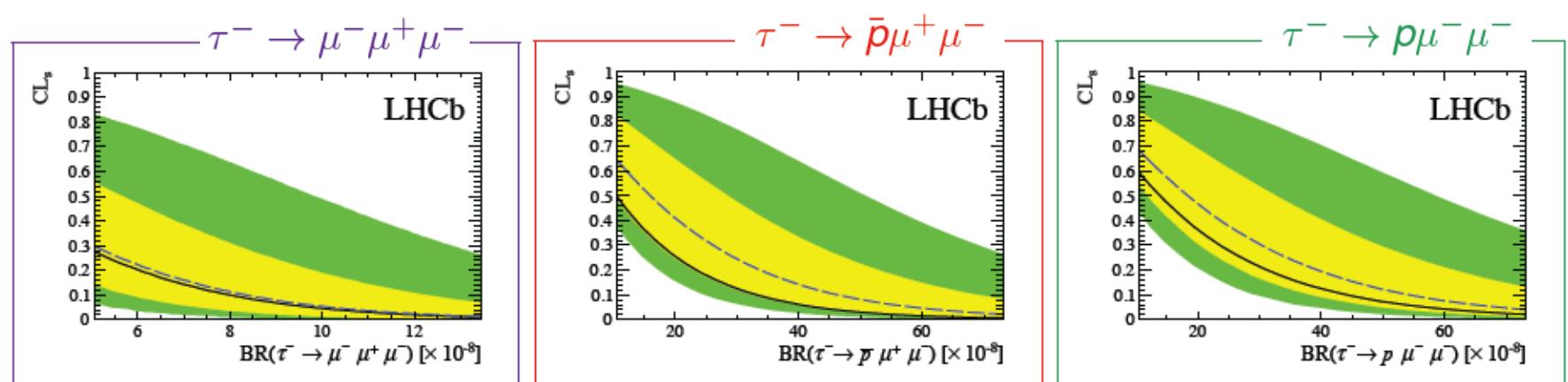
- About 70% of tau leptons produced at LHC are from  $D_s \rightarrow \tau \nu$ 
  - Inclusive  $\sigma(pp \rightarrow \tau + X) = 80 \pm 8 \text{ }\mu\text{b}$  at 7 TeV in the LHCb acceptance
  - $\sim 3.5 \times 10^{11}$  produced  $\tau$  in  $3 \text{ fb}^{-1}$  in 2011+12 LHC runs (c.f.  $3 \times 10^9 \tau$  produced in Belle+BaBar)
- LHCb, with forward geometry, low- $p_T$  triggers, vertex locator and good mass resolution is well suited for the  $\tau \rightarrow 3\mu$  and  $\tau \rightarrow p\mu\mu$  channels
- But high-multiplicity hadronic environments and lack of tau tagging makes analyses much more difficult than in  $e^+e^- \rightarrow \tau^+\tau^-$  at B factories
- Analysis uses two multivariate classifiers
- $\mathcal{M}_{3\text{body}}$  includes vertex and track fit qualities, vertex displacement, momentum direction (vertex pointing), vertex isolation,  $p_T$  of candidate
- Boosted decision tree with adaptive boosting, trained on MC for signal and background
- Response calibrated on  $D_s^- \rightarrow \phi(\mu^+\mu^-)\pi^-$  in data to account for data-MC differences



# LHCb searches for $\tau \rightarrow 3\mu$ and $\tau \rightarrow p\mu\mu$

*Phys.Lett. B724, 36-45 (2013)*

LHCb upper limits on BFs from  $1\text{fb}^{-1}$  (2011 data)

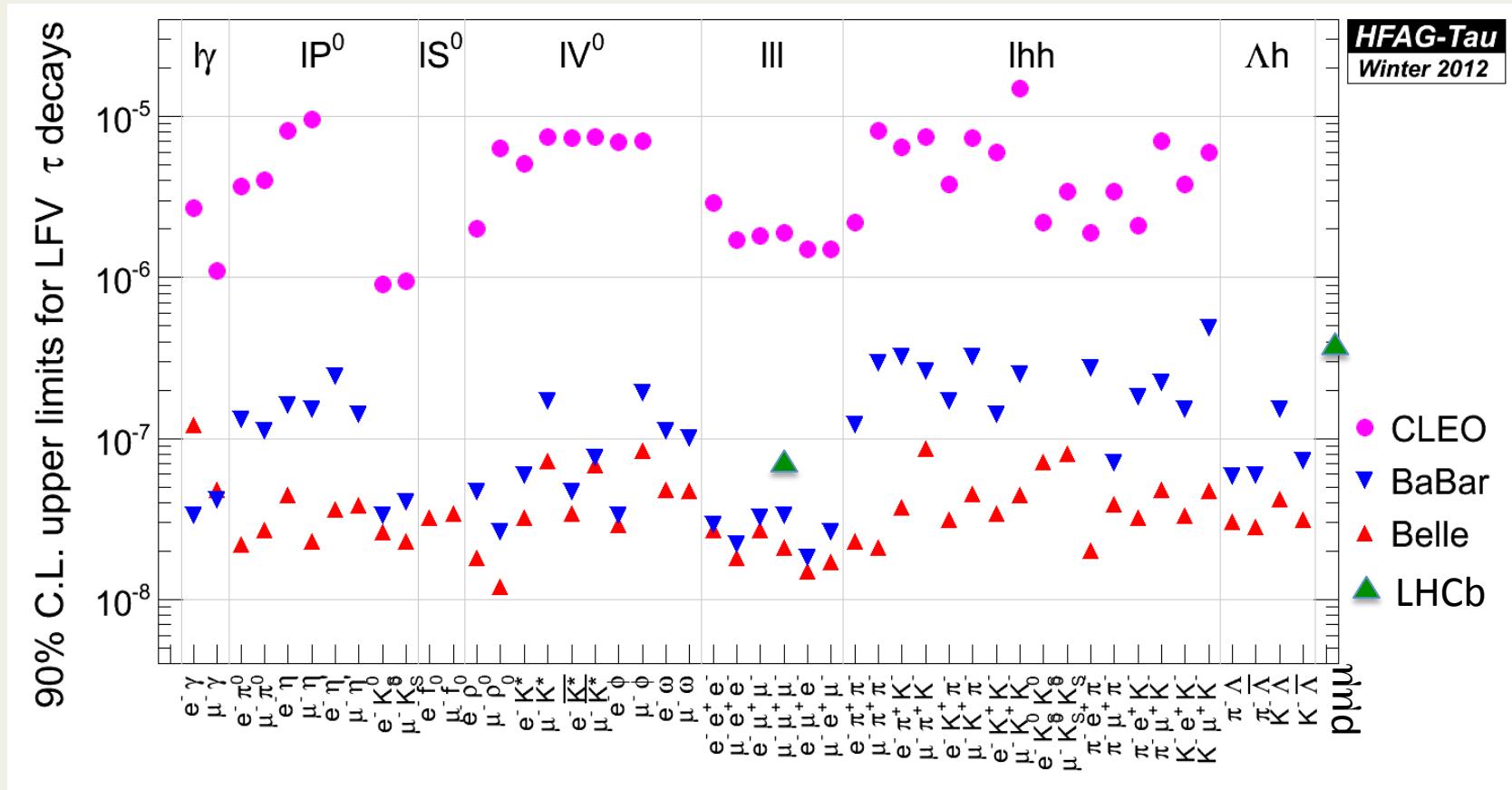


Channel	Expected (90% CL)	Observed (90% CL)
$\tau^- \rightarrow \mu^- \mu^+ \mu^-$	$8.3 \times 10^{-8}$	$8.0 \times 10^{-8}$
$\tau^- \rightarrow \bar{p} \mu^+ \mu^-$	$4.6 \times 10^{-7}$	$3.3 \times 10^{-7}$
$\tau^- \rightarrow p \mu^- \mu^-$	$5.4 \times 10^{-7}$	$4.4 \times 10^{-7}$

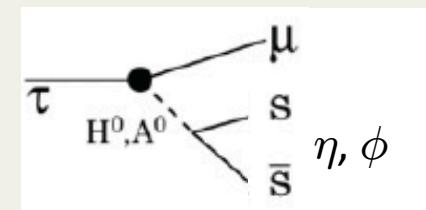
— Expected  
  $\pm \sigma$   
  $\pm 2\sigma$   
— Observed

- No previous limits existed for the  $\tau \rightarrow p\mu\mu$  modes, which violate both lepton and baryon number with  $\Delta(\text{B-L})=0$

# Compilation by Heavy Flavor Averaging Group of LFV limits for tau decays (supplemented with LHCb results)



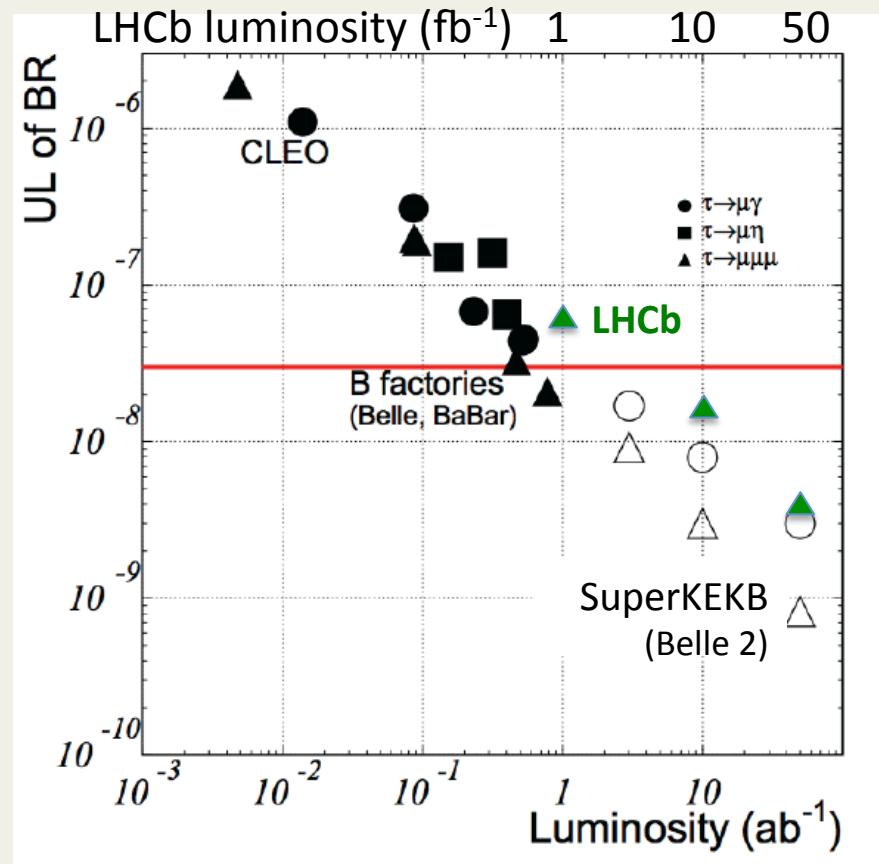
- The analyses are currently being updated using full  $3 \text{ fb}^{-1}$  Run 1 dataset
- Search started also for  $\tau \rightarrow \phi \mu$



For  $\tau \rightarrow 3\mu$  LHCb Run 2 may overtake the Belle limit  
... but should eventually be overtaken by Belle 2

In terms of sensitivity for  $\tau \rightarrow 3\mu$

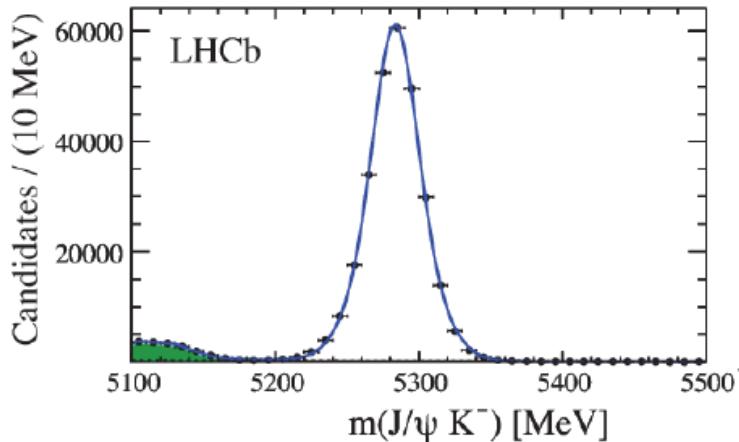
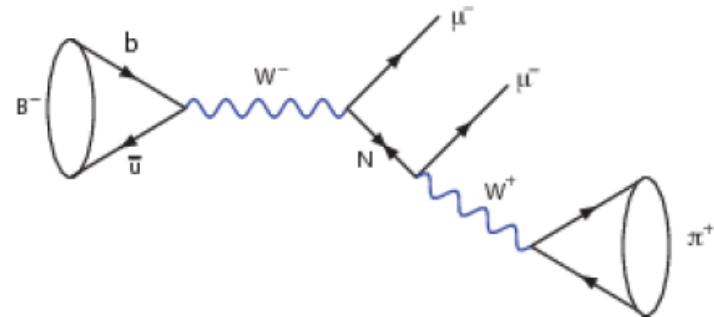
- $1 \text{ fb}^{-1}$  at LHCb is equivalent to  $1 \text{ ab}^{-1}$  at an  $e^+e^-$  B/charm/tau factory



# Search for Majorana neutrinos in $B^- \rightarrow \pi^+ \mu^- \mu^-$ at LHCb

*Phys. Rev. Lett. 112, 131802 (2014)*

- Forbidden LNV decay probes Majorana neutrino masses between 250 and 5000 MeV
- Search valid for neutrino lifetimes between 0 and 1000 ps

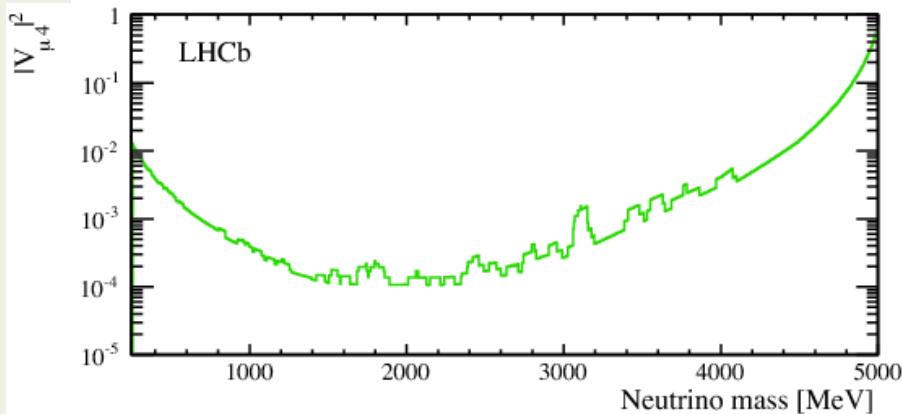
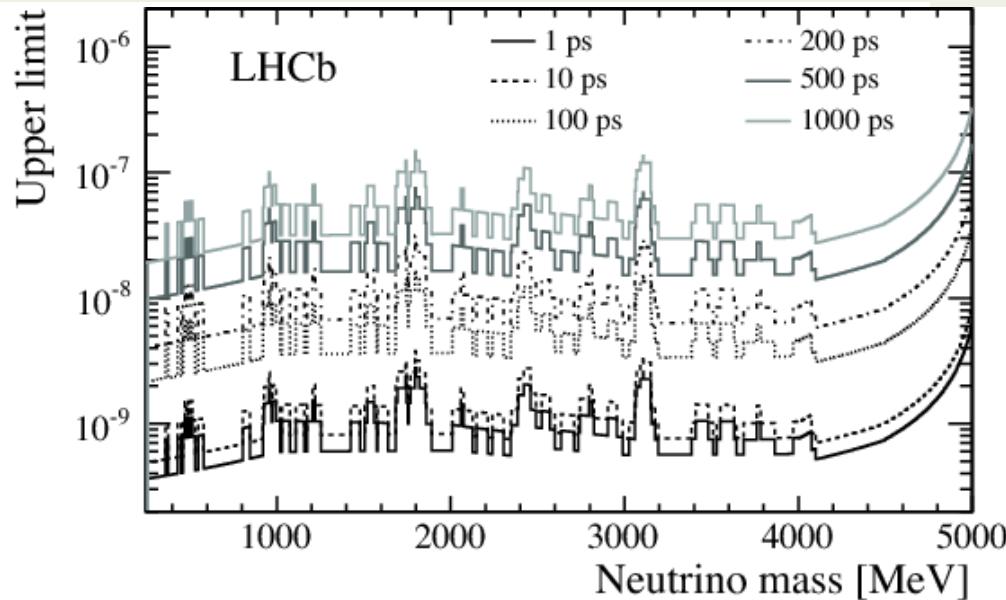


- Normalise to  $B^- \rightarrow J/\psi K^-$
- Combinatorial background from sideband fit, peaking backgrounds from MC
- Previous LHCb measurement (LHCb-PAPER-2011-038) updated with full  $3 \text{ fb}^{-1}$

# Search for Majorana neutrinos in $B^- \rightarrow \pi^+ \mu^- \mu^-$ at LHCb

Phys.Rev.Lett. 112, 131802 (2014)

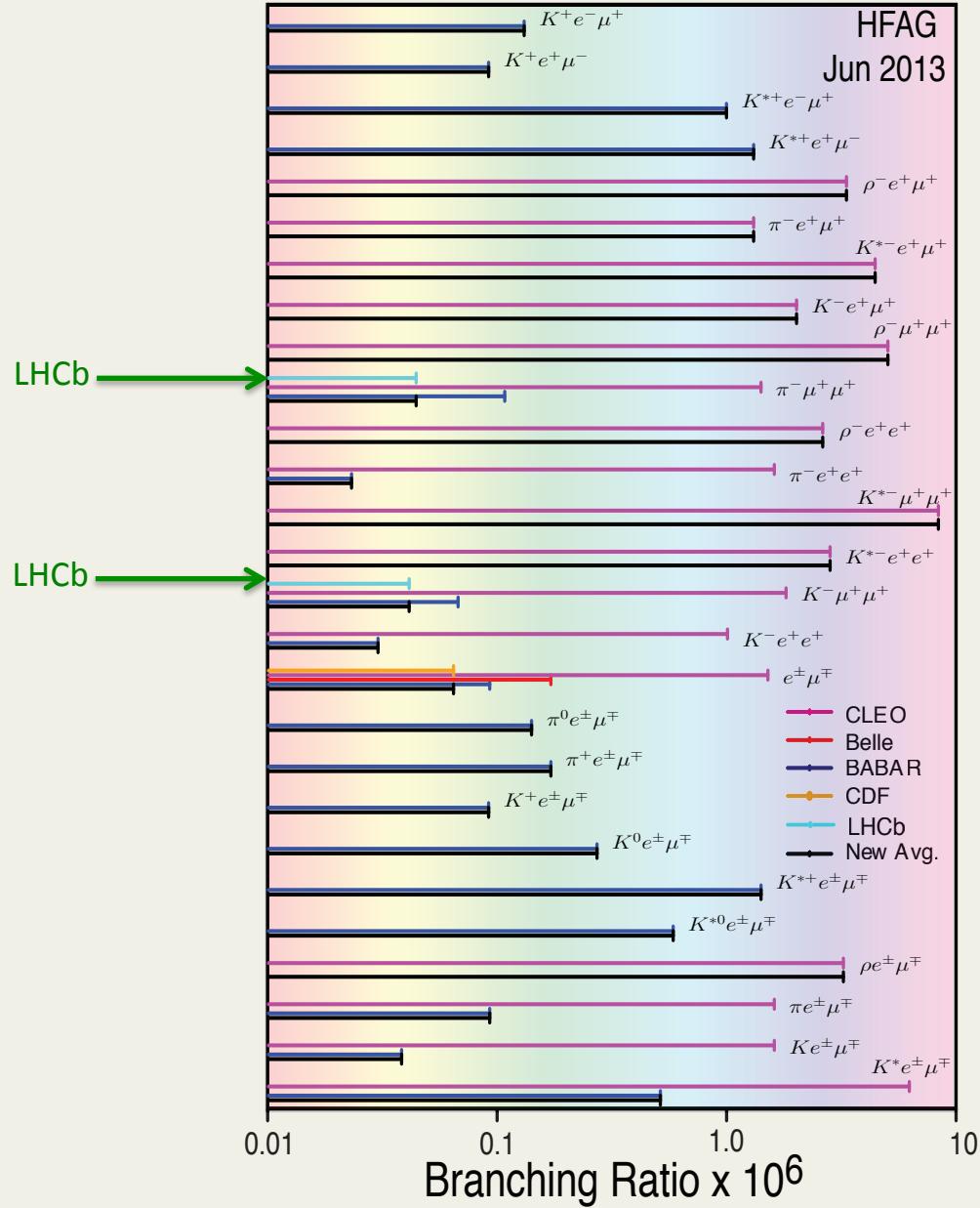
- No signal observed
  - Limits as a function of  $m_\nu$  and  $\tau_\nu$  using  $CL_s$  method
- Signal efficiency is highest for short lifetimes
- $BF(B^- \rightarrow \pi^+ \mu^- \mu^-) < 4.0 \times 10^{-9}$  at 95% CL for 1 ps lifetime



- Limits on fourth generation couplings,  $|V_{\mu 4}|^2$ , as a function of neutrino mass

Using model of A. Atre et al., JHEP 05(2009)030

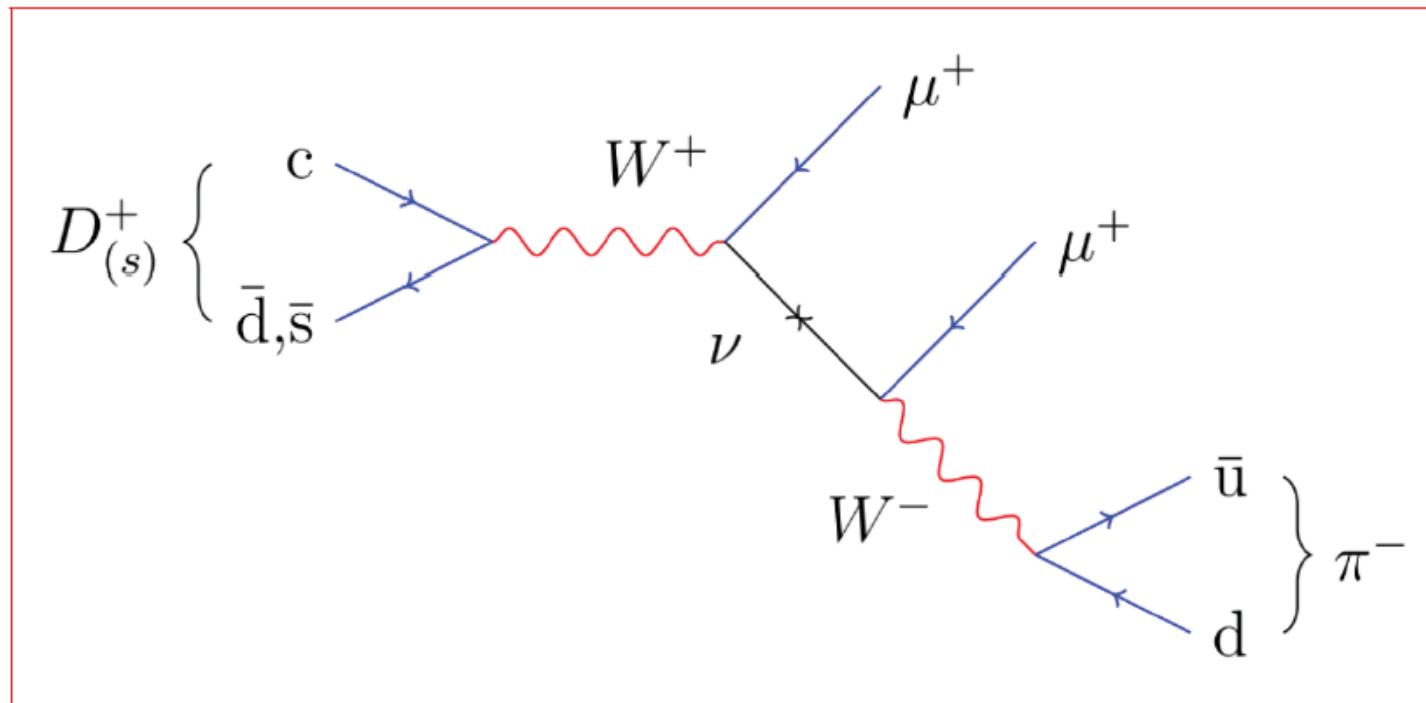
# Lepton Number Violating Charmless B Decays



# LHCb search for $D^+_{(s)} \rightarrow \pi^- \mu^+ \mu^+$

Phys.Lett. B274, 203-212 (2013)

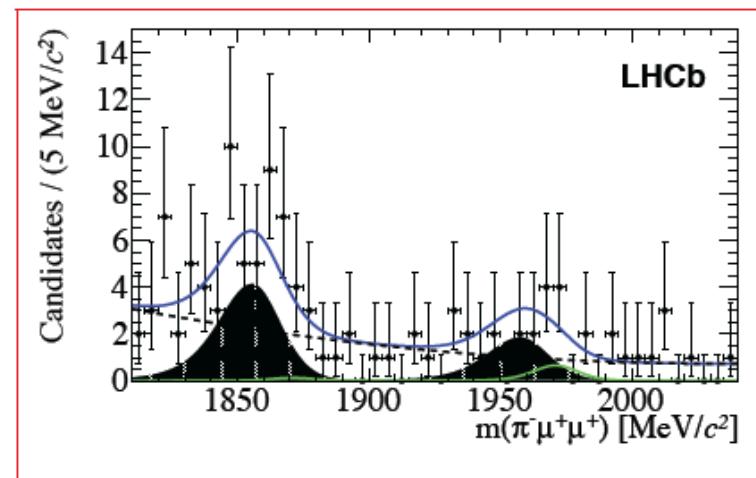
- $D^+_{(s)} \rightarrow \pi^- \mu^+ \mu^+$  decays can occur through leptonic mixing via a **Majorana neutrino** (*Phys.Rev. D84, 072006(2012)*)
- World's best experimental limits from BaBar of  $2 \times 10^{-6}$  and  $1.4 \times 10^{-5}$  for  $D^+ \rightarrow \pi^- \mu^+ \mu^+$  and  $D_s^+ \rightarrow \pi^- \mu^+ \mu^+$  respectively



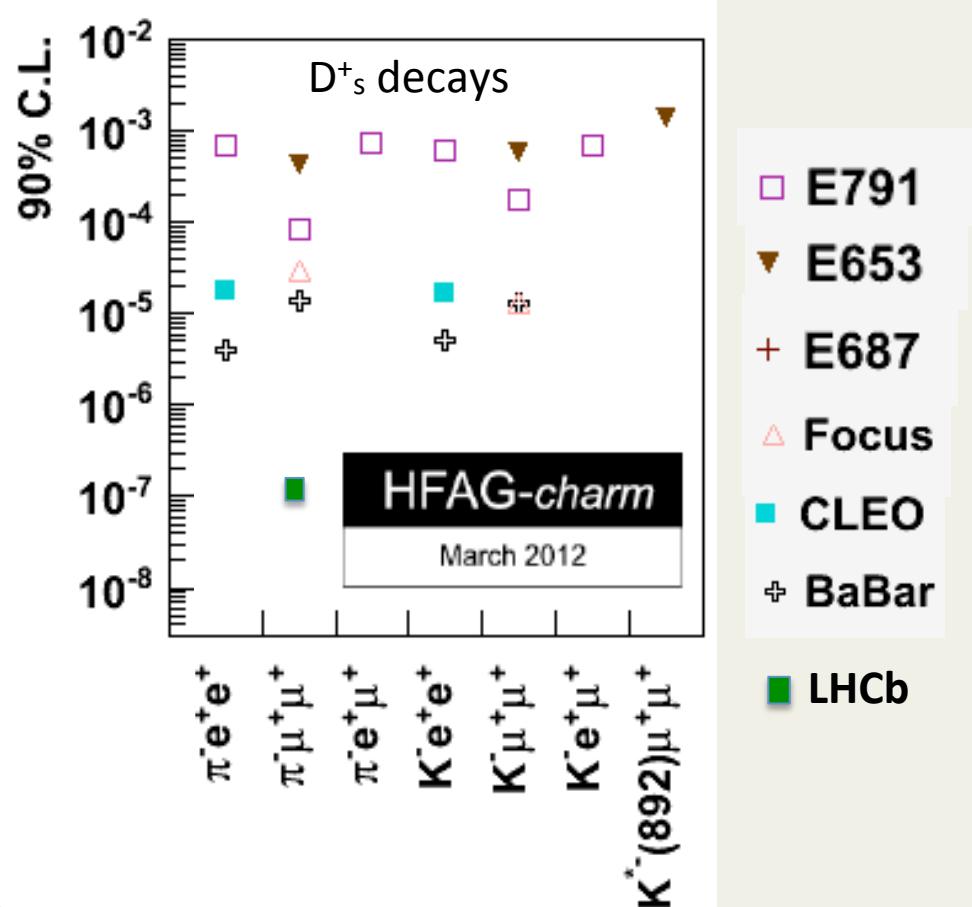
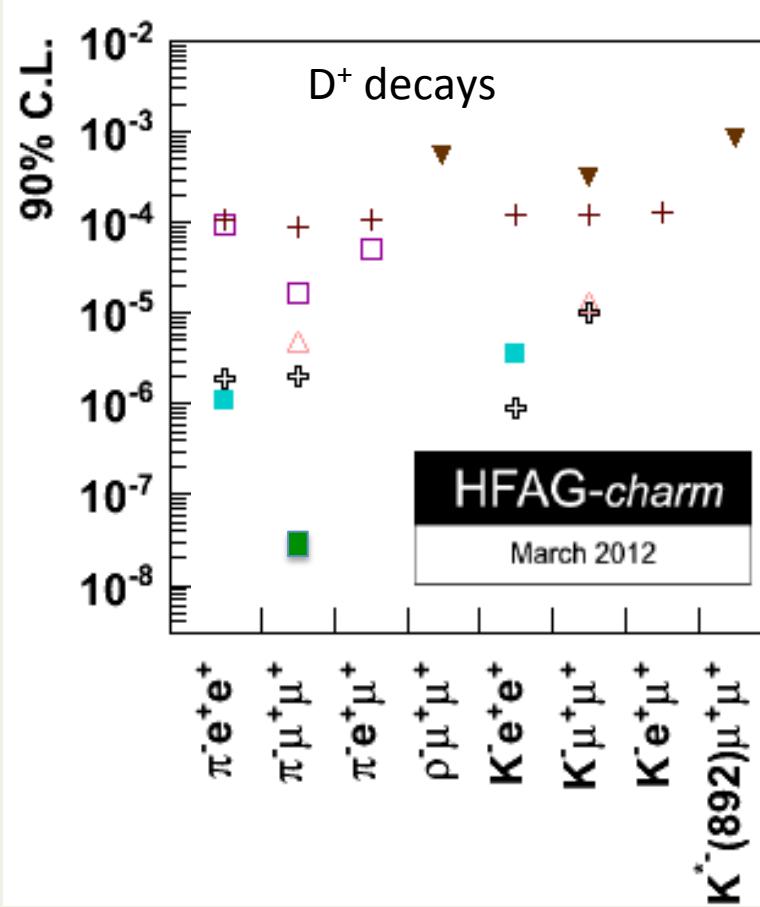
# LHCb search for $D^+_{(s)} \rightarrow \pi^- \mu^+ \mu^+$

Phys.Lett. B274, 203-212 (2013)

- Normalisation to  $D^+_{(s)} \rightarrow \phi(\mu^+ \mu^-) \pi^+$
- Classification of signal and background from PID cuts and a BDT using kinematic and geometric variables, trained on 2010 data
- **Peaking background** from  $D^+_{(s)} \rightarrow \pi^+ \pi^+ \pi^-$  decays with shape (grey) measured from data
- Fit in bins of  $m(\pi^- \mu^+)$  to improve statistical significance
- Limit of  $2.2 \times 10^{-8}$  and  $1.2 \times 10^{-7}$  for  $D^+$  and  $D_s^+$  decays respectively are a factor of fifty improvement over previous best limits



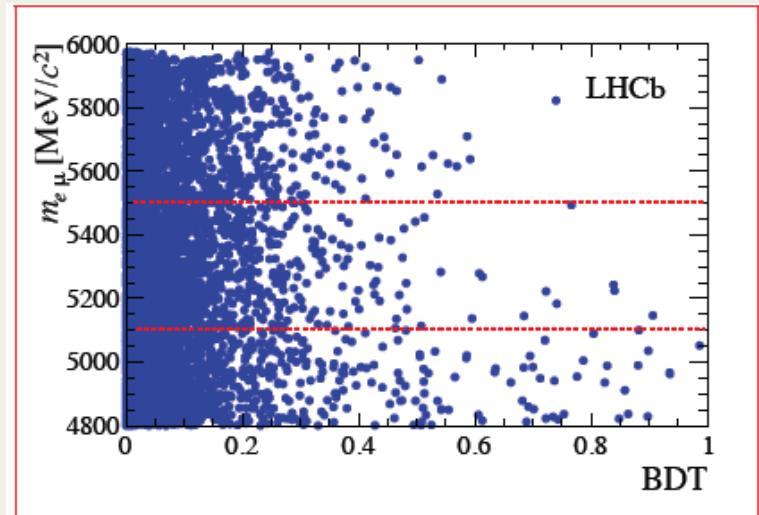
# Compilation by Heavy Flavor Averaging Group of LNV limits for $D^+$ and $D_s^+$ decays (supplemented with LHCb results)



# Direct search for lepton flavour violation in $B^0_{(s)} \rightarrow e^\pm \mu^\mp$

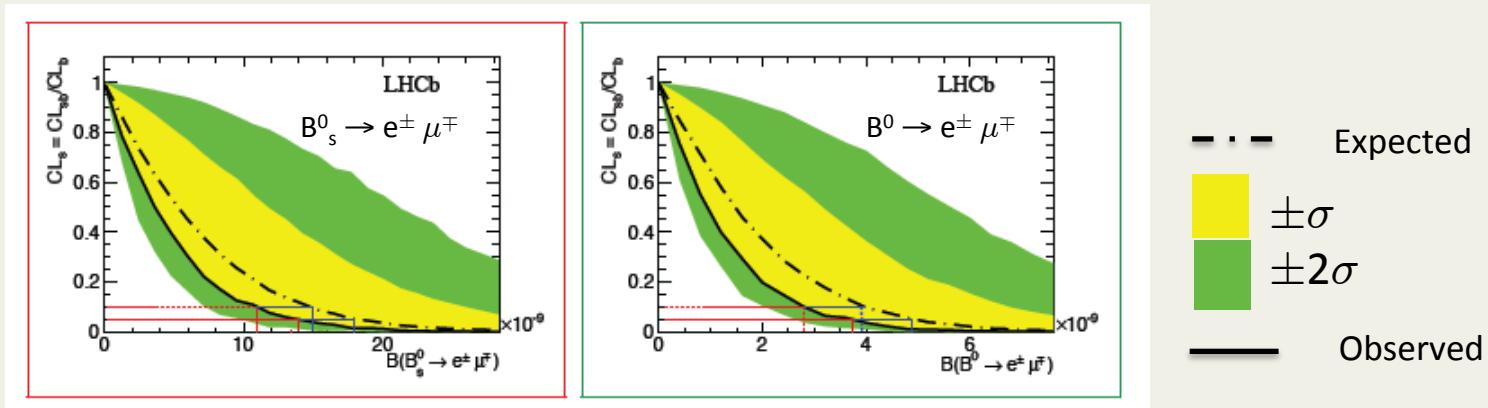
*Phys.Rev.Lett. 111, 141801 (2013)*

- These decays are allowed in several BSM models
  - Heavy singlet Dirac neutrinos (e.g. A. Ilakovic, Phys. Rev. D62, 036010 (2000))
  - RPV and LNV SUSY models (e.g. R.A. Diaz et al., Eur. Phys. J C41, 305 (2005))
  - Leptoquarks coupling leptons and quarks of different generations (Pati-Salam) (J.C Pati and A. Salam, Phys. Rev. D10, 275 (1974))
- Analysis uses  $1 \text{ fb}^{-1}$  of 7 TeV data (2011 sample)
- Potential signal normalised to  $B^0 \rightarrow K^+ \pi^-$  with  $B^0_{(s)} \rightarrow h^+ h^-$  as control channel
- Main backgrounds from semileptonic b decays:  $b\bar{b} \rightarrow e^\pm \mu^\mp X$  and from particle misid
- Candidates classified by  $e\mu$  mass and output of a geometrical BDT with 9 variables



# Direct search for lepton flavour violation in $B^0_{(s)} \rightarrow e^\pm \mu^\mp$

*Phys.Rev.Lett. 111, 141801 (2013)*



## Limits on branching fractions

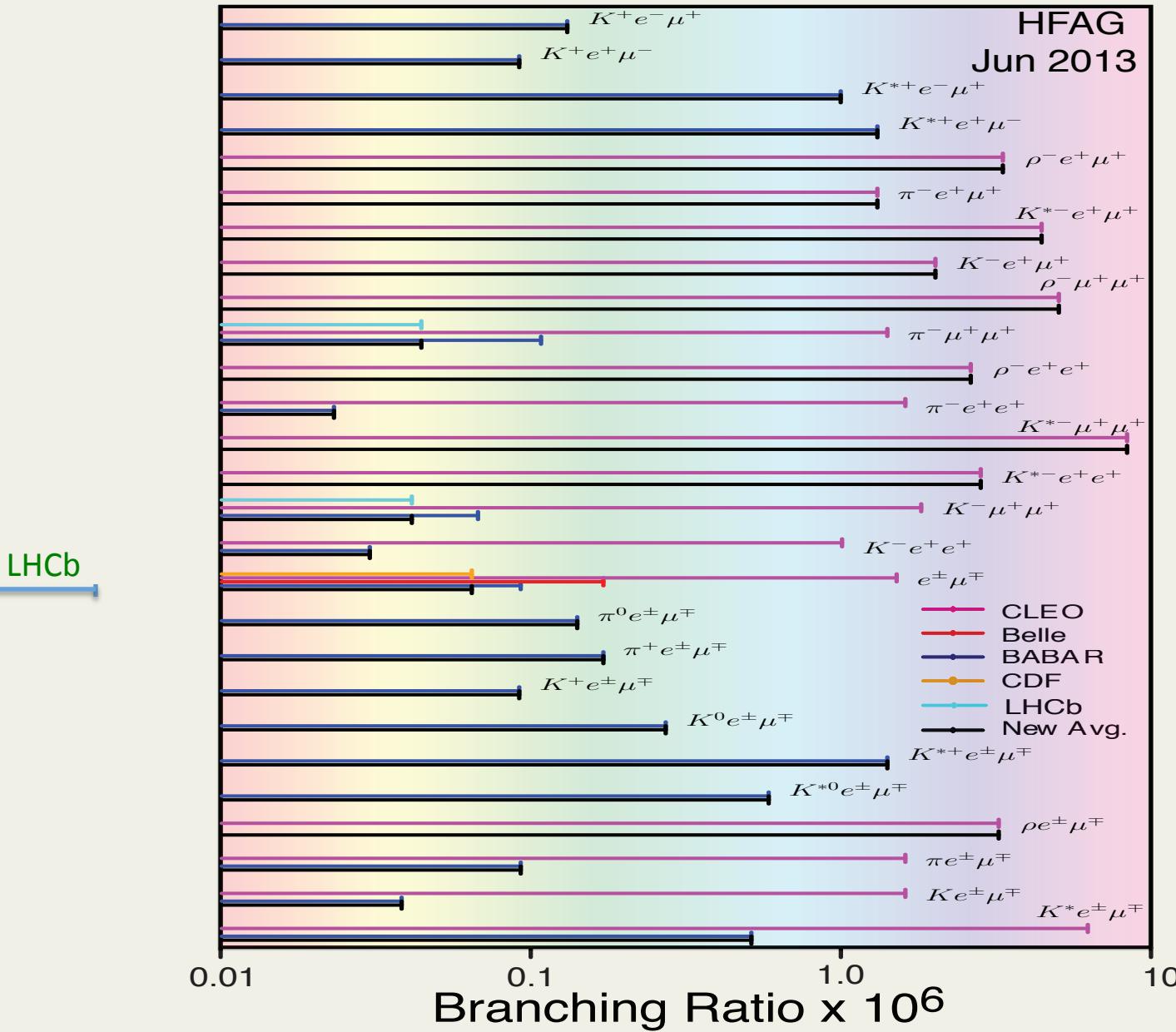
Channel	Observed (90% CL)	Observed (95% CL)
$B_s^0 \rightarrow e^\pm \mu^\mp$	$1.1 \times 10^{-8}$	$1.4 \times 10^{-8}$
$B^0 \rightarrow e^\pm \mu^\mp$	$2.8 \times 10^{-9}$	$3.7 \times 10^{-9}$

- LHCb results give an order of magnitude improvement over previous limits (CDF)
- Limits also set on masses of Pati-Salam leptoquarks

$$M_{LQ}(B_s^0 \rightarrow e^\pm \mu^\mp) > 107 \text{ TeV at 90% CL}$$

$$M_{LQ}(B^0 \rightarrow e^\pm \mu^\mp) > 135 \text{ TeV at 90% CL}$$

# Lepton Number Violating Charmless B Decays



# Measurement of $\text{BF}(B_s^0 \rightarrow \mu^+ \mu^-)$ and search for $B^0 \rightarrow \mu^+ \mu^-$

LHCb, Phys.Rev.Lett. 111, 101805 (2013)

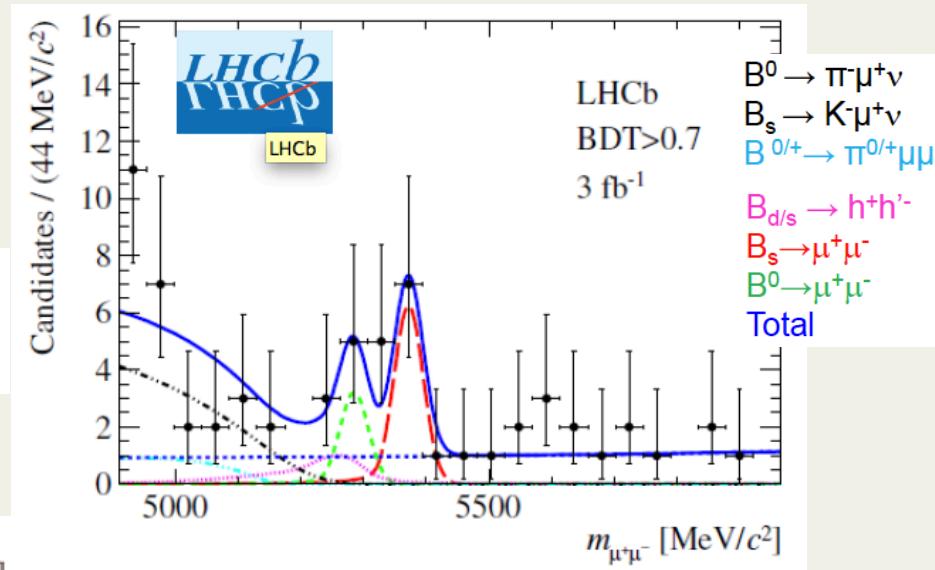
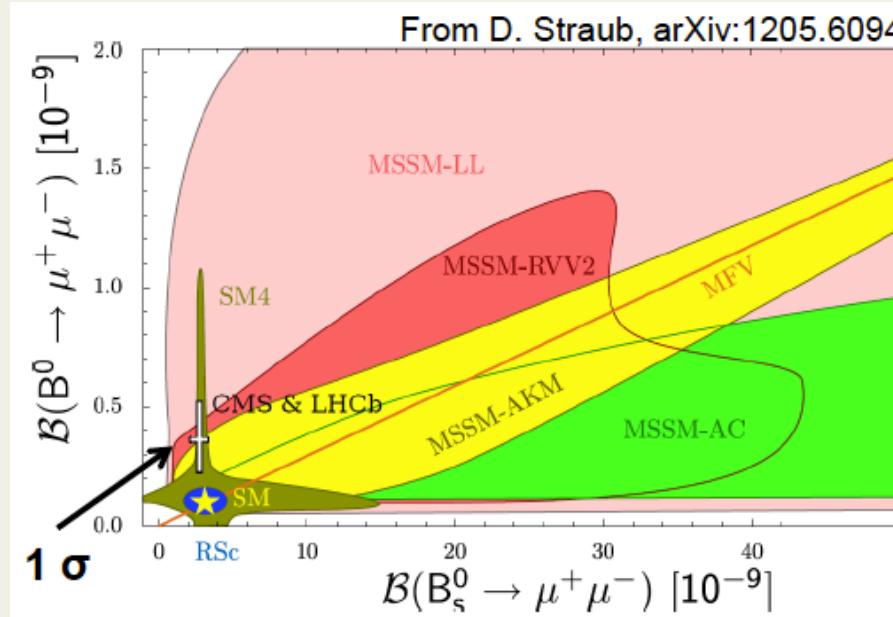
CMS, Phys.Rev.Lett. 111, 101804 (2013)

Combined LHCb and CMS results:

CERN-LHCb-CONF-2013-012

$$\text{BR}(B_s^0 \rightarrow \mu^+ \mu^-) = (2.9 \pm 0.7) \times 10^{-9}$$

$$\text{BR}(B^0 \rightarrow \mu^+ \mu^-) = (3.6^{+1.6}_{-1.4}) \times 10^{-10}$$



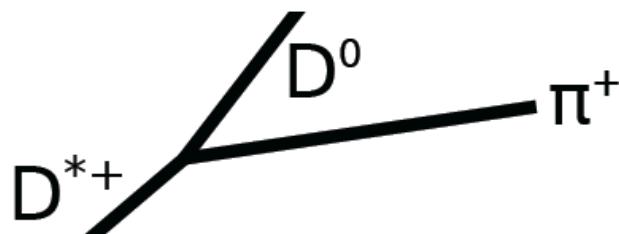
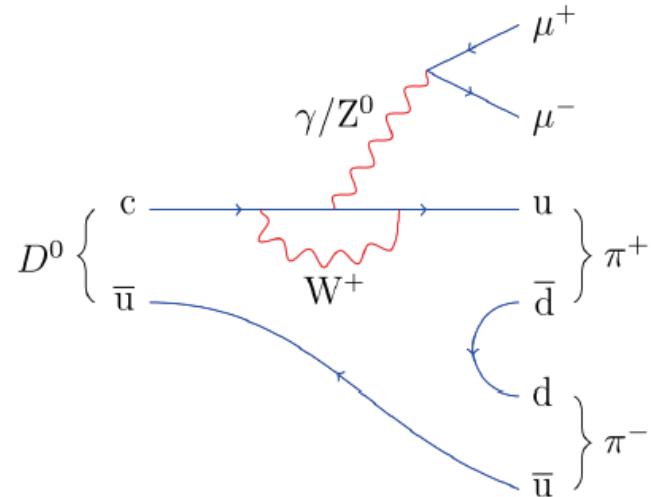
Current SM calculation of  $\text{BF}(B_s \rightarrow \mu^+ \mu^-)$  has 10% uncertainty

Would be useful for theory errors to be reduced before full LHC Run2 results

# LHCb search for FCNC decay $D^0 \rightarrow \pi^+ \pi^- \mu^+ \mu^-$

Phys.Lett. B728, 234-243 (2014)

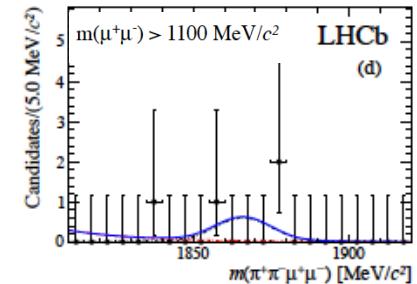
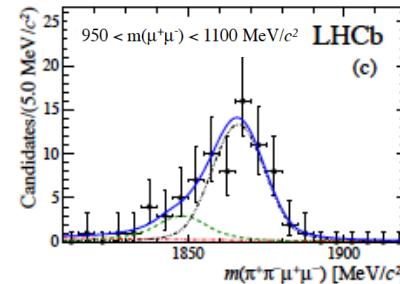
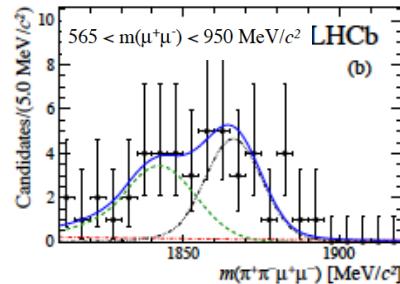
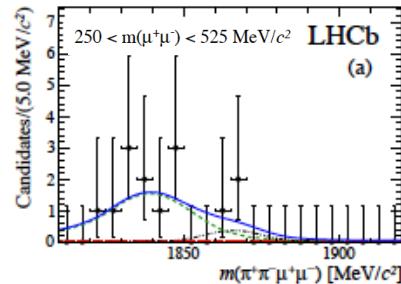
- GIM suppression is more effective in charm than in  $b$ -decays
- Expected BF for  $D^0 \rightarrow \pi^+ \pi^- \mu^+ \mu^-$  of  $\sim 10^{-9}$  in the SM
- Could be enhanced by new physics



- Analyse 1  $\text{fb}^{-1}$  of  $D^0$  from  $D^{*+} \rightarrow D^0 \pi^+$
- Normalise to  $D^0 \rightarrow \pi^+ \pi^- \phi(\mu^+ \mu^-)$
- Fit signal yield in four bins of  $\mu\mu$  mass:

# LHCb search for FCNC decay $D^0 \rightarrow \pi^+ \pi^- \mu^+ \mu^-$

*Phys.Lett. B728, 234-243 (2014)*



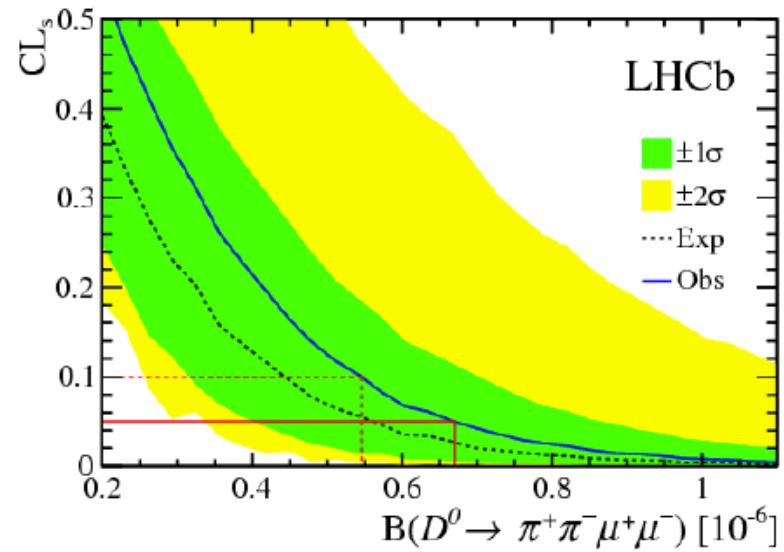
Low  $m_{\mu\mu}$

$\rho/\omega$  region

$\phi$  region

High  $m_{\mu\mu}$

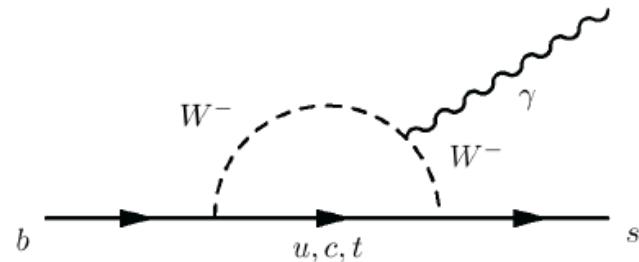
Combined limit of  
 $\text{BF}(D^0 \rightarrow \pi^+ \pi^- \mu^+ \mu^-) < 5.5 \times 10^{-7}$   
 at 90% CL from the signal yields in  
 the low  $m_{\mu\mu}$  + high  $m_{\mu\mu}$  bins  
 → 50× improvement on previous  
 limit



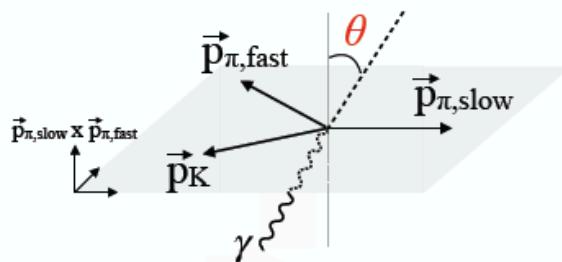
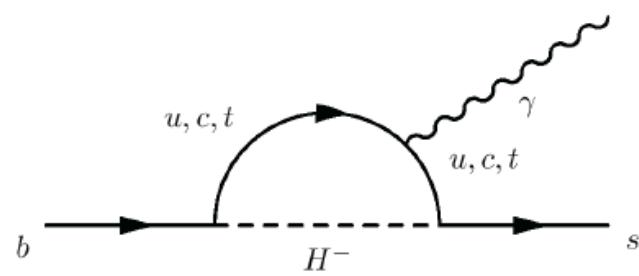
# Photon polarization in $b \rightarrow s\gamma$ transitions

Phys.Rev.Lett. 112, 161801 (2014)

- Photons from  $b \rightarrow s\gamma$  transitions are predominantly left-handed in the SM



- NP contributions to loops may introduce a right-handed component



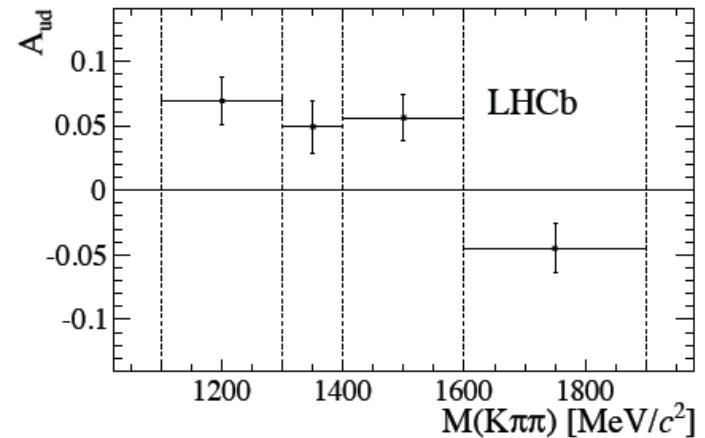
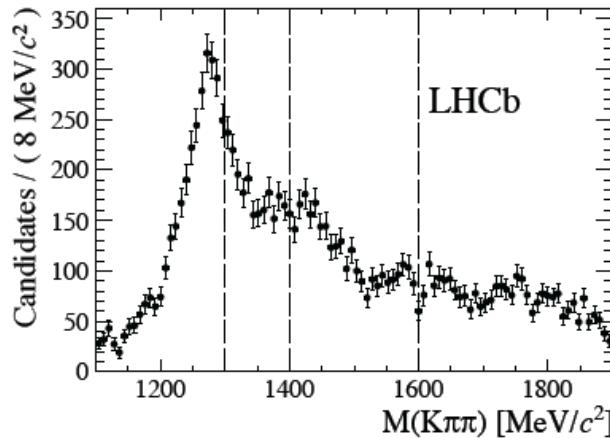
- Up-down asymmetry,  $A_{ud}$ , proportional to photon polarisation

- Fit  $\cos\theta$  distribution from  $B^+ \rightarrow K^+\pi^-\pi^+\gamma$  in bins of  $K^+\pi^-\pi^+$  mass

# Photon polarisation in $b \rightarrow s\gamma$ transitions

Phys.Rev.Lett. 112, 161801 (2014)

Four independent measurements of  $A_{ud}$ :



Non-zero up-down asymmetry at  $5.2\sigma$  based on  $3 \text{ fb}^{-1}$  of LHCb data

→ First observation of photon polarisation in  $b \rightarrow s\gamma$   
LHCb-PAPER-2014-001

However, limited knowledge of  $K^+\pi^-\pi^+$  mass spectrum prevents calculation of a value for the photon polarisation

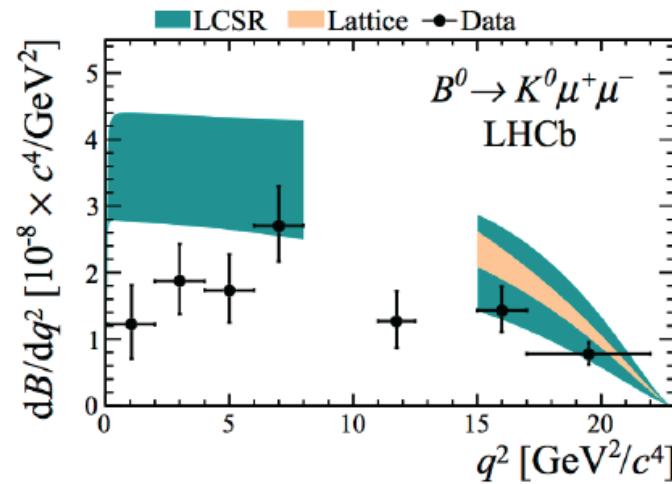
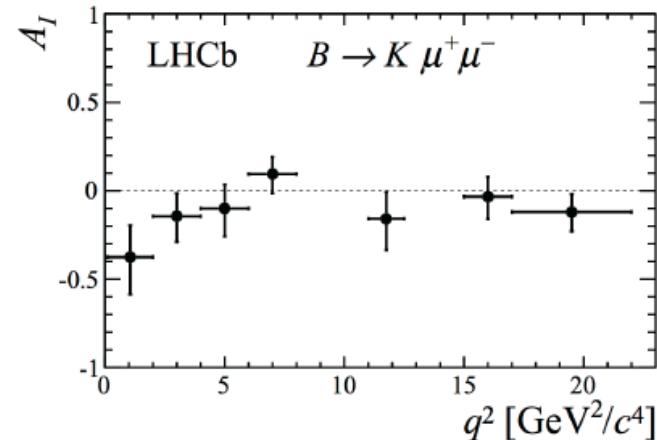
# Isospin asymmetry in $B \rightarrow K^{(*)}\mu^+\mu^-$ decays

arXiv:1403.8044, submitted to JHEP

- Update of previous  $1 \text{ fb}^{-1}$  result, which found a  $4.4\sigma$  discrepancy in  $A_I$  for  $K\mu\mu$  from SM

$$A_I = \frac{\Gamma(B^0 \rightarrow K^{(*)0}\mu^+\mu^-) - \Gamma(B^+ \rightarrow K^{(*)+}\mu^+\mu^-)}{\Gamma(B^0 \rightarrow K^{(*)0}\mu^+\mu^-) + \Gamma(B^+ \rightarrow K^{(*)+}\mu^+\mu^-)}$$

- Latest result on  $A_I$  consistent with SM
- Shapes of differential branching fractions consistent with SM, but systematically below light-cone sum rule and lattice predictions

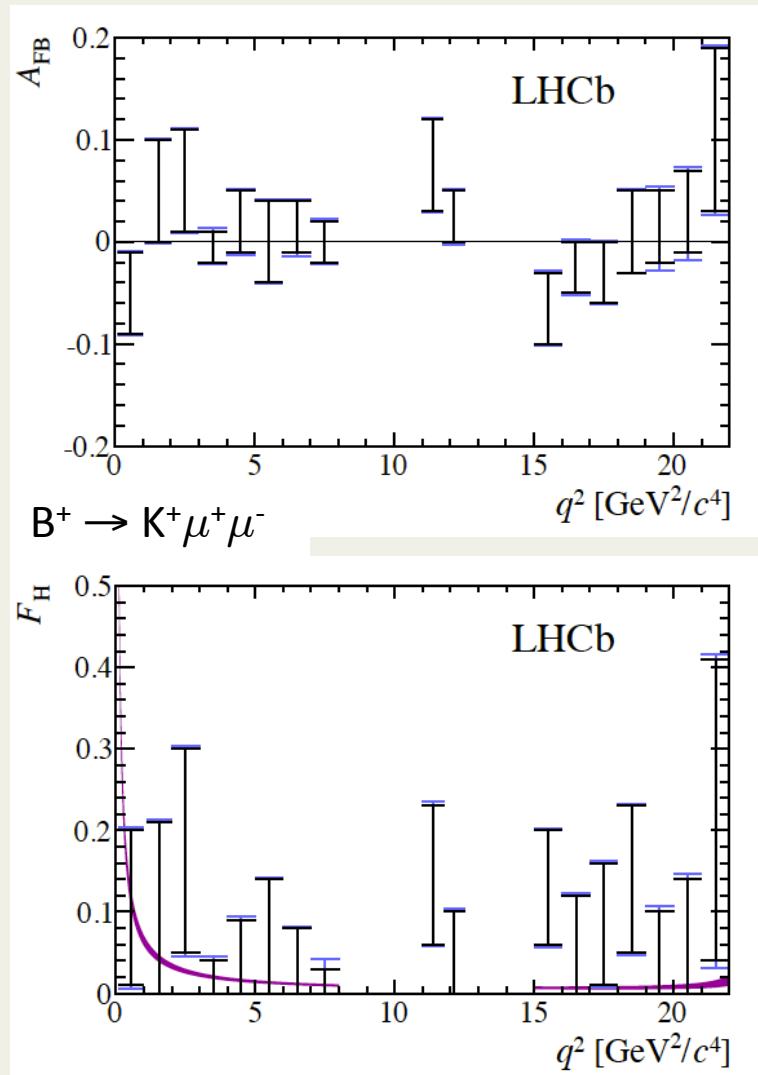


# Angular analysis of charged and neutral $B \rightarrow K\mu^+\mu^-$ decays

arXiv:1403.8045, submitted to JHEP

$$\frac{1}{\Gamma} \frac{d\Gamma}{d \cos \theta_l} = \frac{3}{4}(1 - F_H)(1 - \cos^2 \theta_l) + \frac{1}{2}F_H + A_{FB} \cos \theta_l$$

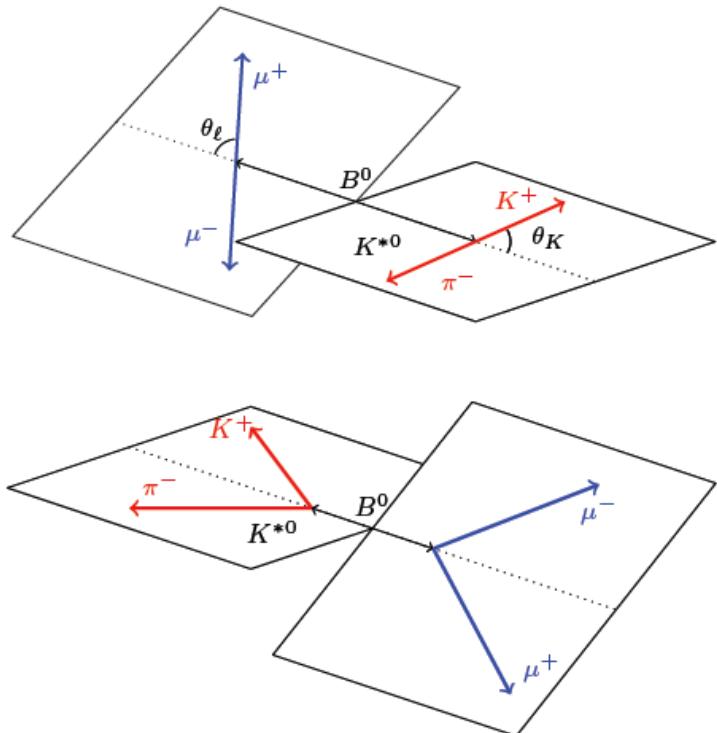
- Angular analysis to determine the forward-backward asymmetry,  $A_{FB}$ , and the flat parameter  $F_H$ , which together define the differential angular decay rate for  $B^+ \rightarrow K^+\mu^+\mu^-$  and  $B^0 \rightarrow K_s^0\mu^+\mu^-$  decays
- All results consistent with SM



# Angular observables in $B^0 \rightarrow K^{*0} \mu^+ \mu^-$

Phys.Rev.Lett. 111, 191801 (2013)

- Angular distribution of FCNC decay  $B^0 \rightarrow K^{*0} \mu^+ \mu^-$  described by angles  $\theta_I$ ,  $\theta_K$  and  $\phi$
- Depends on Wilson coefficients (short distance) and form factors (long distance)
- Study variables  $P'_4$ ,  $P'_5$ ,  $P'_6$  and  $P'_8^{-1}$  free from form factor uncertainties, using  $1 \text{ fb}^{-1}$  of LHCb data



$\phi$  is the angle between decay planes in the  $B^0$  rest frame

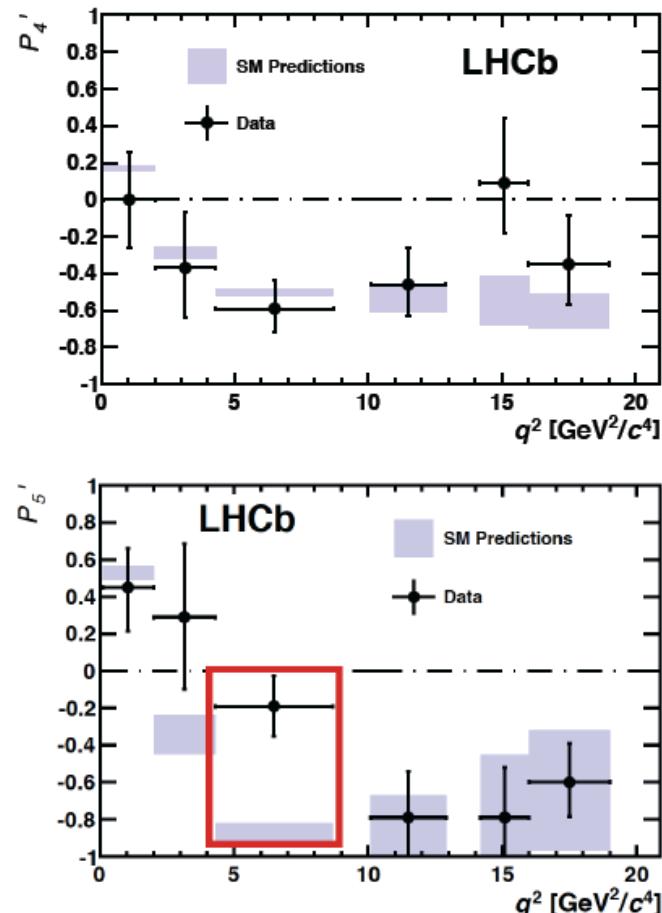
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<sup>1</sup>S. Descotes-Genon, T. Hurth, J. Matias and J. Virto, JHEP, 05, 2013, 137

# Angular observables in $B^0 \rightarrow K^{*0} \mu^+ \mu^-$

Phys.Rev.Lett. 111, 191801 (2013)

- Measure each observable in six  $q^2(\mu\mu)$  bins
- $3.7\sigma$  discrepancy in  $P'_5$  in  $4.3 < q^2 < 8.68 \text{ GeV}^2$  bin  
→ 0.5% probability of such a discrepancy in 24 independent measurements
- $2.5\sigma$  discrepancy in  $P'_5$  in  $1 < q^2 < 6 \text{ GeV}^2$  bin
- Possible interpretation as a NP contribution to Wilson coefficient  $C_9$ <sup>2</sup>

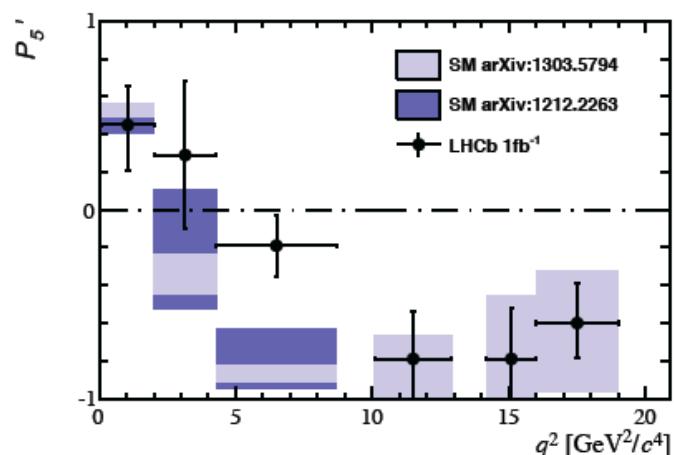


<sup>2</sup><http://arxiv.org/abs/1307.5683>, <http://arxiv.org/abs/1308.1501>

# Angular observables in $B^0 \rightarrow K^{*0} \mu^+ \mu^-$

Phys.Rev.Lett. 111, 191801 (2013)

- Some disagreement about the handling of uncertainties
- New SM predictions from S. Jäger and J. Camalich<sup>3</sup>
  - show reduced tension with the data
- Update to  $3 \text{ fb}^{-1}$  in progress



<sup>3</sup><http://uk.arxiv.org/abs/1212.2263>

## Rare Decays at LHCb: Conclusions

- Already LHCb has improved on previous limits for a number of LFV and LNV channels and has made various studies of rare decays that could be sensitive to new physics
- No significant deviations from the SM have been seen
- Studies of rare and forbidden decays at LHCb form a vital strand in the search for new Physics
- It should be out there, so we will keep pushing back the frontiers ... at LHC Run II and on to the LHCb upgrade



## Additional material

Angular observables in  $B^0 \rightarrow K^{*0} \mu^+ \mu^-$

$$\frac{1}{d\Gamma/dq^2} \frac{d^4\Gamma}{d\cos\theta_\ell d\cos\theta_K d\phi dq^2} = \frac{9}{32\pi} \left[ \frac{3}{4}(1 - F_L)\sin^2\theta_K + F_L\cos^2\theta_K + \frac{1}{4}(1 - F_L)\sin^2\theta_K \cos 2\theta_\ell - F_L\cos^2\theta_K \cos 2\theta_\ell + S_3\sin^2\theta_K \sin^2\theta_\ell \cos 2\phi + S_4\sin 2\theta_K \sin 2\theta_\ell \cos \phi + S_5\sin 2\theta_K \sin\theta_\ell \cos \phi + S_6\sin^2\theta_K \cos\theta_\ell + S_7\sin 2\theta_K \sin\theta_\ell \sin \phi + S_8\sin 2\theta_K \sin 2\theta_\ell \sin \phi + S_9\sin^2\theta_K \sin^2\theta_\ell \sin 2\phi \right],$$

$$P'_{i=4,5,6,8} = \frac{S_{j=4,5,7,8}}{\sqrt{F_L(1 - F_L)}}.$$