Searches for Lepton Flavour Violation and Lepton Number Violation in Hadron Decays

Paul Seyfert
on behalf of the LHCb collaboration
including results from the B factories

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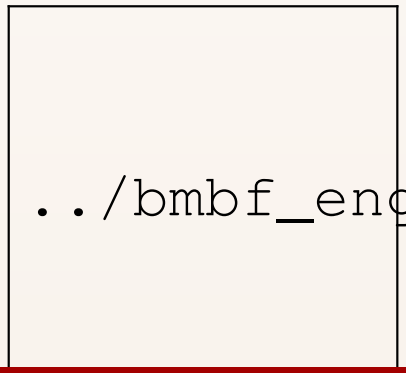
Flavour Physics and CP Violation 2012



Outline

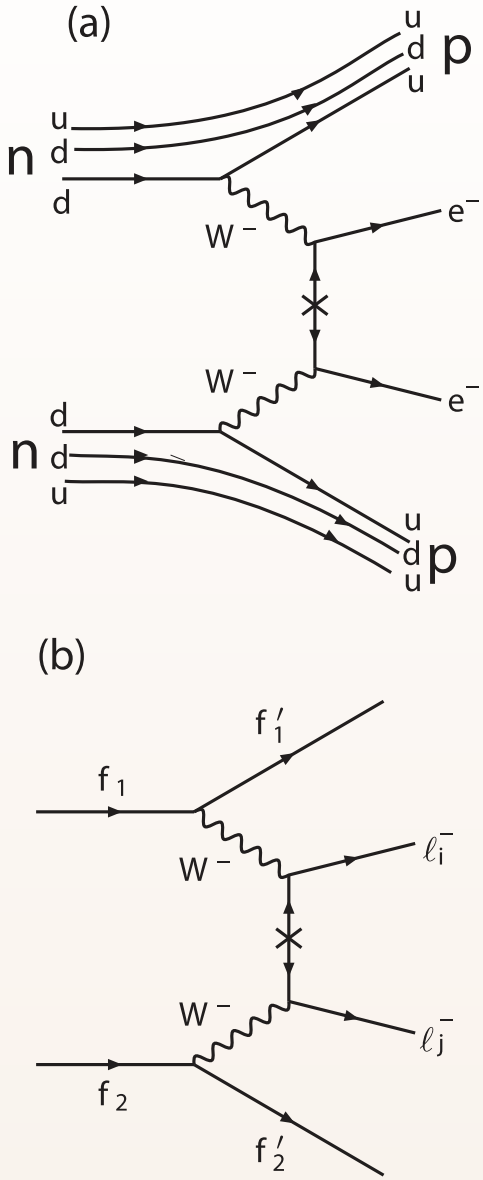
1. Lepton Number Violation
   - $\rightarrow \not{\ell}^{-}\ell^{-}$
   - $\rightarrow h^{+}\ell^{-}\ell^{-}$
   - $\rightarrow$
2. Lepton Flavour Violation
   - $\rightarrow h^{-}\ell^{+}\ell'^{-}$
   - $\rightarrow \not{\ell}^{\pm}\ell^{\mp}$
3. $\rightarrow$ at hadron colliders – first time shown!

Lepton Number Violation

- $\mathrm{D}^- \to \pi^+/\mathrm{K}^+\ell^-\ell^-$
- $\mathrm{B}^- \to h^+\ell^-\ell^-$
- $\mathrm{B}^- \to \mathrm{D}^0\pi^+\mu^-\mu^-$

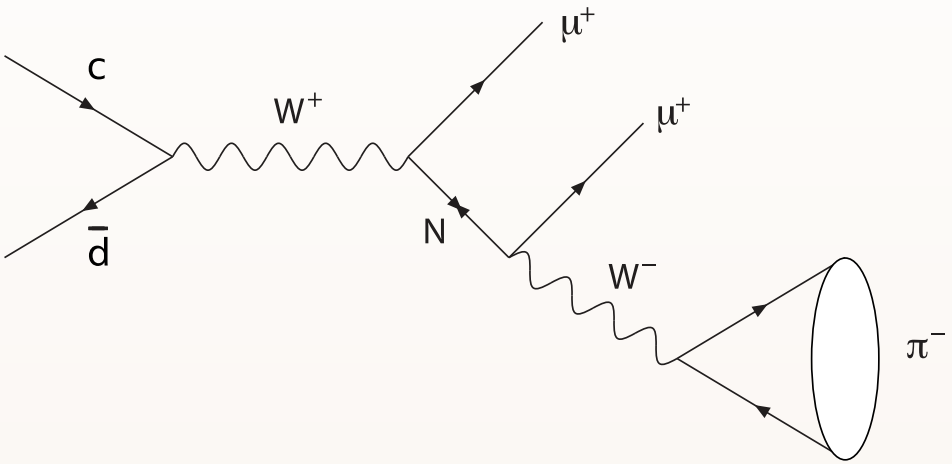
Lepton Number Violation

- Lepton number is conserved in the Standard Model
- Lepton number violation introduced in many New Physics models, e. g.:
  - 4$^{\text{th}}$ quark generation (arXiv:hep-ph/1106.0343)
  - *SO*(10) SUSY GUT (arXiv:hep-ph/9501298)
  - exotic Higgs (A. Zee, Phys. Lett. B93, 389 (1980))
- Majorana neutrinos violate Lepton Number classic search: neutrinoless double beta-decay (→Dongming Mei's talk)
- Similar fundamental process with mesons



LNV in meson decays

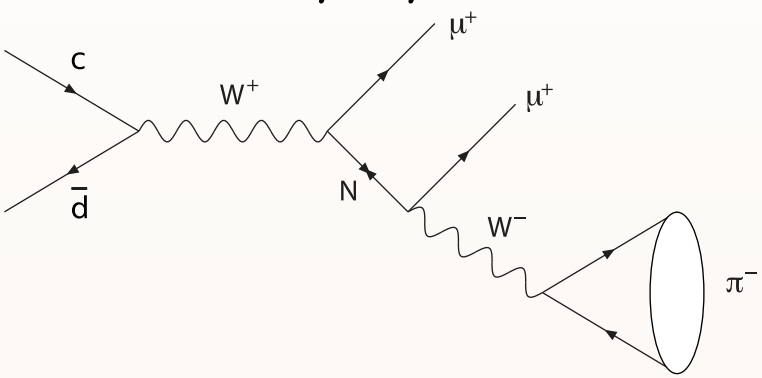
$$D^+ \to \pi^- \mu^+ \mu^+$$



- resonant production in accessible mass range
- rates depend on Majorana neutrino–lepton coupling $|V_{\mu 4}|$ (e.g. arXiv:0901.3589)
- $m_4 = m_{\ell^-,\pi^+}$

LNV in meson decays

$$D^+ \to \pi^- \mu^+ \mu^+$$



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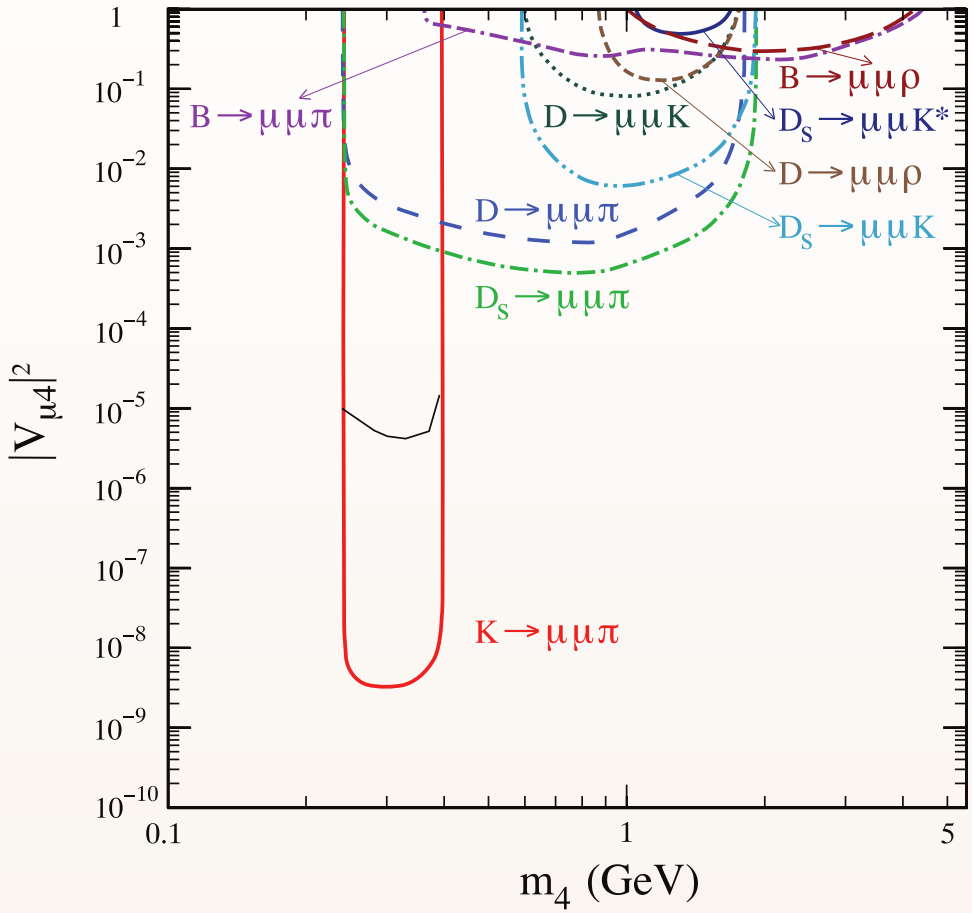


Status of 2009

arXiv:0901.3589

limits on LNV in charm decays

charm decays

- latest limits from BaBar
- includes Lepton Number and Flavour Violation
- comprehensive list of D^+, D_s^+, and Λ_c^+ decays

Decay mode	Yield (events)	Eff. (%)	BR UL 90% CL (10^{-4})	BF UL 90% CL (10^{-6})
$D^+ \to \pi^- e^+ e^+$	$4.7 \pm 4.7 \pm 0.5$	3.16	6.8	1.9
$D^+ \to \pi^- \mu^+ \mu^+$	$-3.1 \pm 1.2 \pm 0.5$	0.70	7.5	2.0
$D^+ \to \pi^- \mu^+ e^+$	$-5.1 \pm 4.2 \pm 2.0$	1.72	7.4	2.0
$D_s^+ \to \pi^- e^+ e^+$	$-5.7 \pm 14. \pm 3.4$	6.84	1.8	4.1
$D_s^+ \to \pi^- \mu^+ \mu^+$	$0.6 \pm 5.1 \pm 2.7$	1.05	6.2	14
$D_s^+ \to \pi^- \mu^+ e^+$	$-0.2 \pm 7.9 \pm 0.6$	2.23	3.6	8.4
$D^+ \to K^- e^+ e^+$	$-2.8 \pm 2.4 \pm 0.2$	2.67	3.1	0.9
$D^+ \to K^- \mu^+ \mu^+$	$7.2 \pm 5.4 \pm 1.6$	0.80	37	10
$D^+ \to K^- \mu^+ e^+$	$-11.6 \pm 4.0 \pm 3.1$	1.52	6.8	1.9
$D_s^+ \to K^- e^+ e^+$	$2.3 \pm 7.9 \pm 3.3$	4.10	2.1	5.2
$D_s^+ \to K^- \mu^+ \mu^+$	$-2.3 \pm 5.0 \pm 2.8$	0.98	5.3	13
$D_s^+ \to K^- \mu^+ e^+$	$-14.0 \pm 8.4 \pm 2.0$	2.26	2.4	6.1
$\Lambda_c^+ \to \overline{p} e^+ e^+$	$-1.5 \pm 4.2 \pm 1.5$	5.14	0.4	2.7
$\Lambda_c^+ \to \overline{p} \mu^+ \mu^+$	$-0.0 \pm 2.1 \pm 0.6$	0.94	1.4	9.4
$\Lambda_c^+ \to \overline{p} \mu^+ e^+$	$10.1 \pm 5.8 \pm 3.5$	2.50	2.3	16

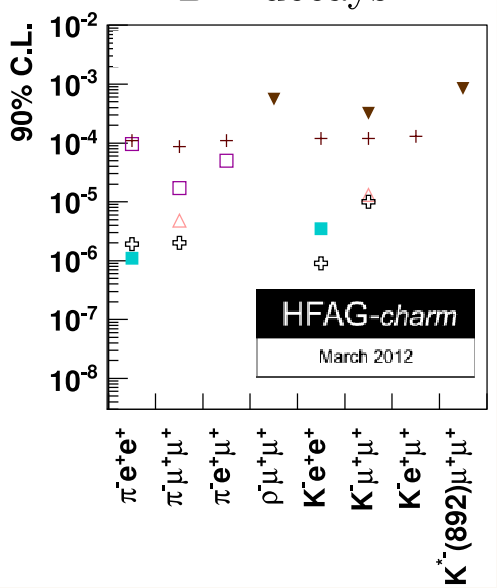
Phys. Rev. D **84**, 072006 (2011)

limits on LNV in charm decays

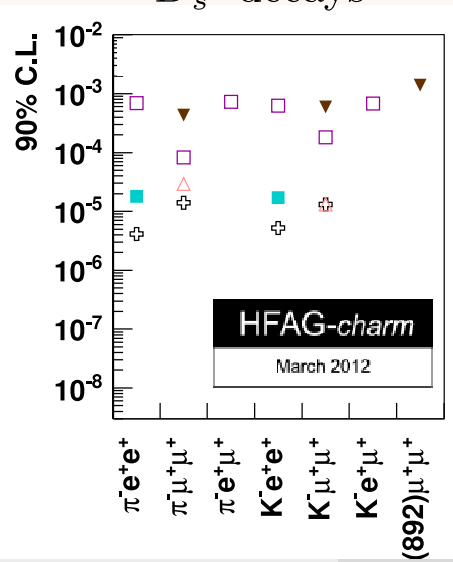
charm decays

- latest limits from BaBar
- includes Lepton Number and Flavour Violation
- comprehensive list of D^+, D_s^+, and Λ_c^+ decays
- best limit for most channels

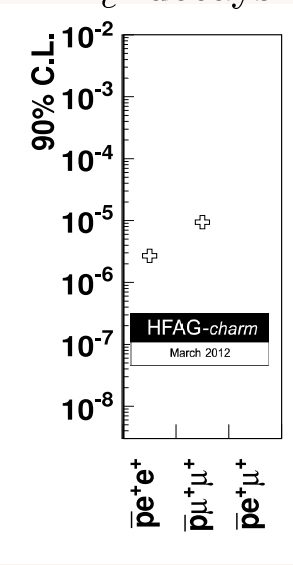
D^+ decays



D_s^+ decays



Λ_c^+ decays

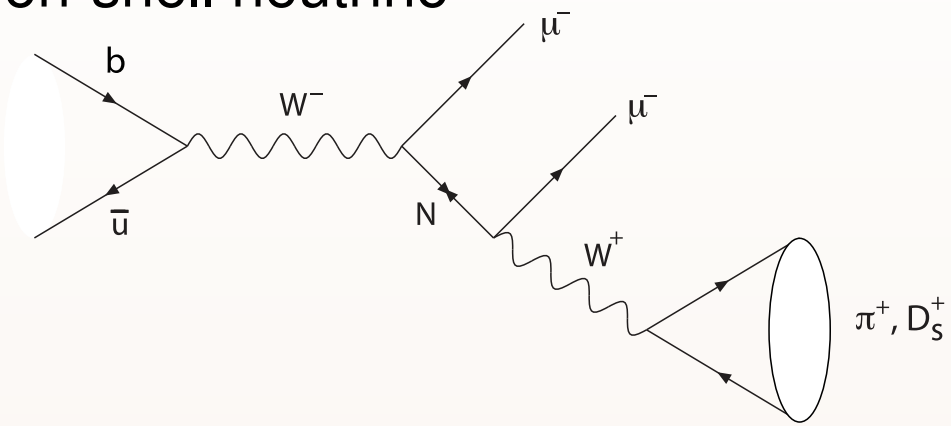


LNV in bottom decays

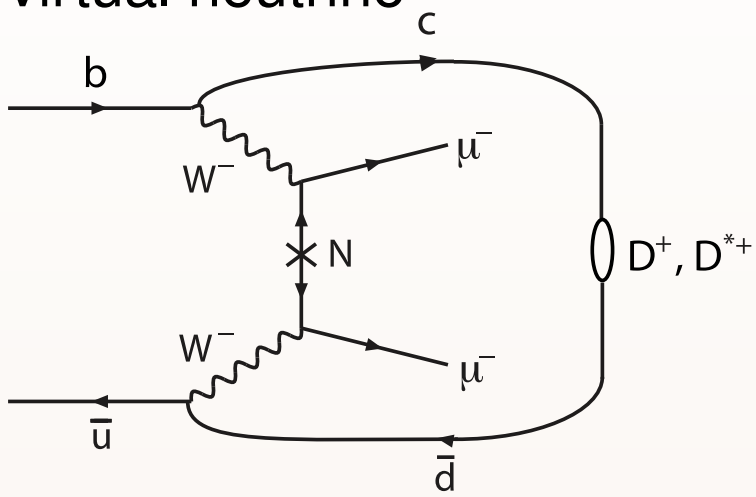
$$B^- \to h^+ \ell^- \ell^-$$

LNV in bottom decays

on-shell neutrino



virtual neutrino



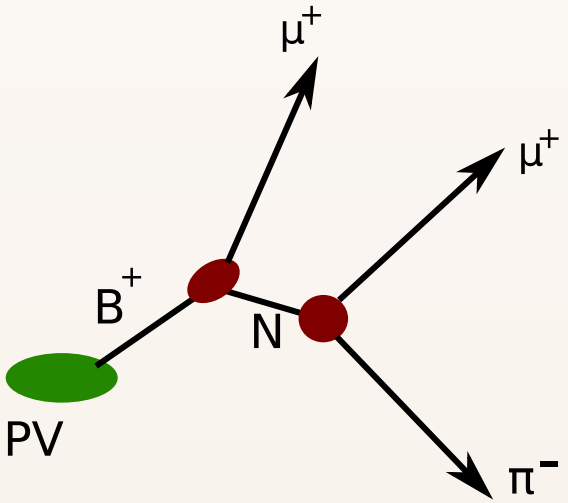
- resonant production in accessible mass range
- rates depend on Majorana neutrino–lepton coupling $|V_{\mu 4}|$ (e.g. arXiv:0901.3589)
- $m_4 = m_{\ell^-,\pi^+}$

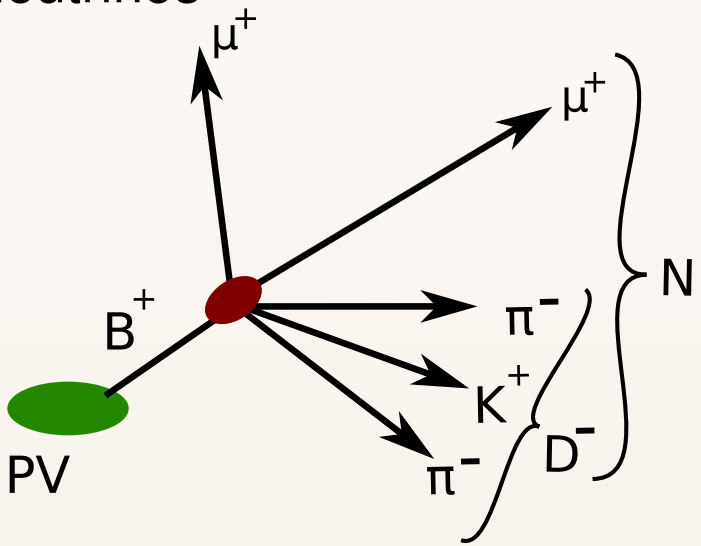
special for B decays

diagram without mass restriction
Cabbibo favoured for $B \to D$

search for Majorana neutrinos at LHCb

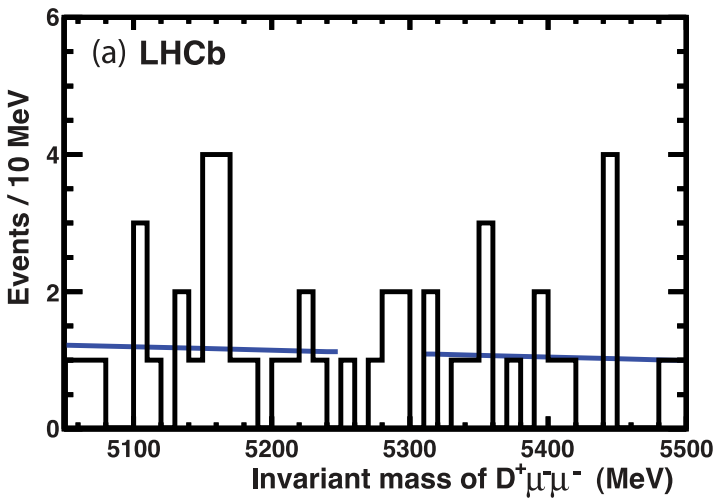
- searches at B factories in Liang Sun's talk
- LHCb: search for
  - $B^- \to \pi^+ \mu^- \mu^-$
  - $B^- \to D^+ \mu^- \mu^-$
  - $B^- \to D_s^+ \mu^- \mu^-$
  - $B^- \to D^{*+} \mu^- \mu^-$
- consider topology in reconstruction
  - allow for flight distance for on-shell neutrinos
  - common vertex for virtual neutrinos



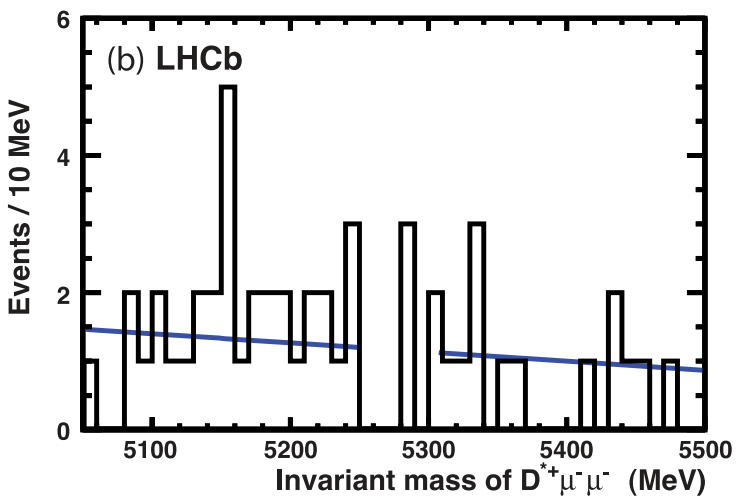


virtual Majorana neutrinos

$B^- \to D^+ \mu^- \mu^-$



$B^- \to D^{*+} \mu^- \mu^-$



$\mathcal{B}(B^- \to D^+ \mu^- \mu^-) < 6.9 \times 10^{-7}$
@ 95 % CL

$\mathcal{B}(B^- \to D^{*+} \mu^- \mu^-) < 2.4 \times 10^{-6}$
@ 95 % CL

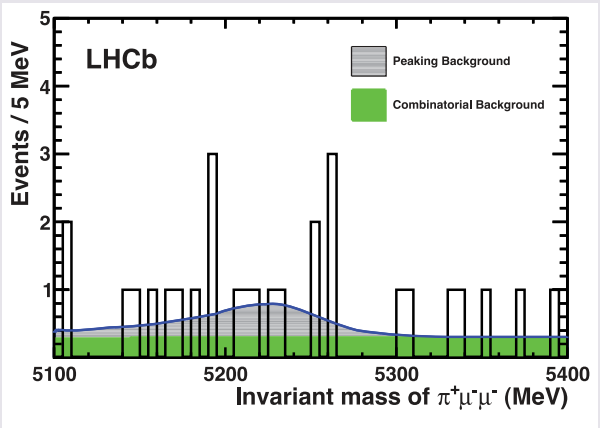
$0.41\ \text{fb}^{-1}$

arXiv:1201.5600

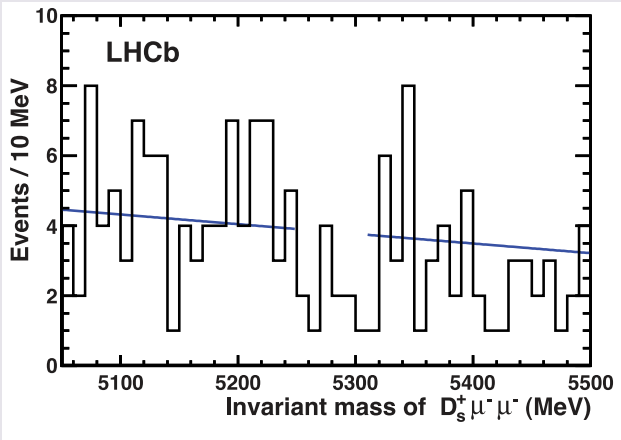
on-shell Majorana neutrinos

- mis-identification rates from data with mass shape from simulation

$B^- \to \pi^+ \mu^- \mu^-$



$B^- \to D_s^+ \mu^- \mu^-$



assuming B^- phase space decay:

$\mathcal{B}(B^- \to \pi^+ \mu^- \mu^-) < 1.3 \times 10^{-8}$ @ 95 % CL

$\mathcal{B}(B^- \to D_s \mu^- \mu^-) < 5.8 \times 10^{-7}$ @ 95 % CL

$0.41\ \text{fb}^{-1}$

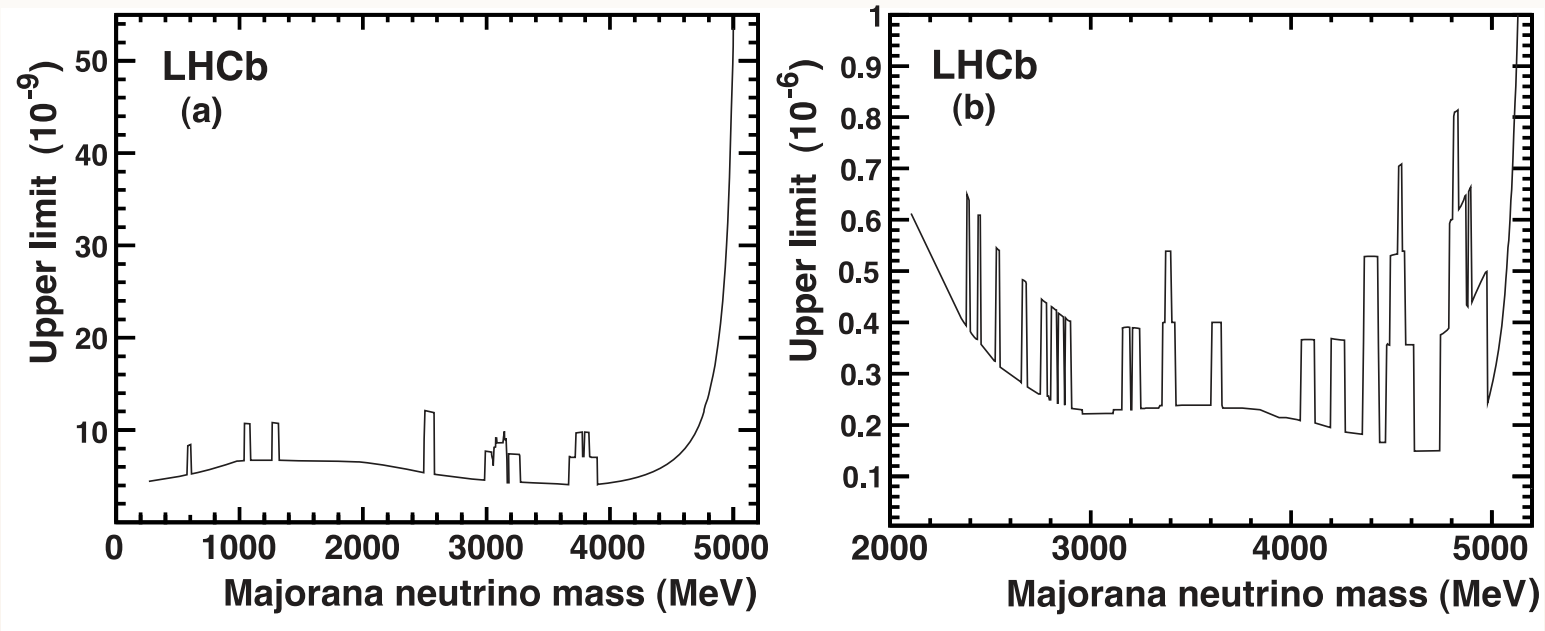
arXiv:1201.5600

implications on Majorana mass

mass extraction

Determine limit as function of $h^+\mu^-$ mass

$$B^- \to \pi^+ \mu^- \mu^- \qquad B^- \to D_s^+ \mu^- \mu^-$$

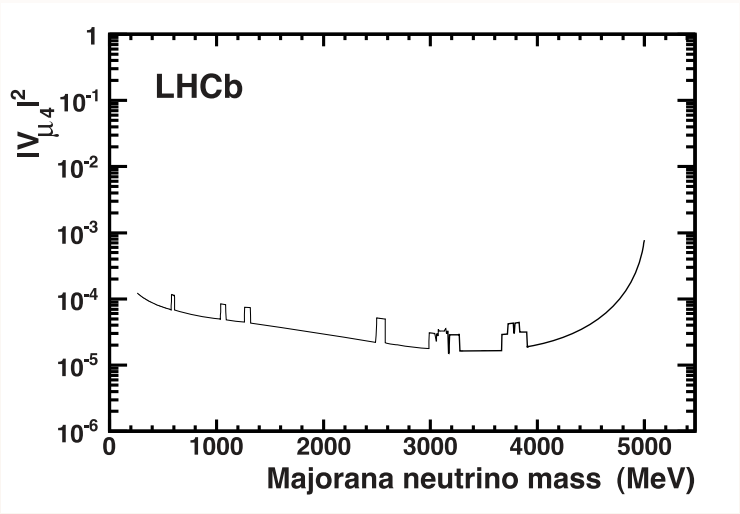


0.41 fb^{-1}

arXiv:1201.5600

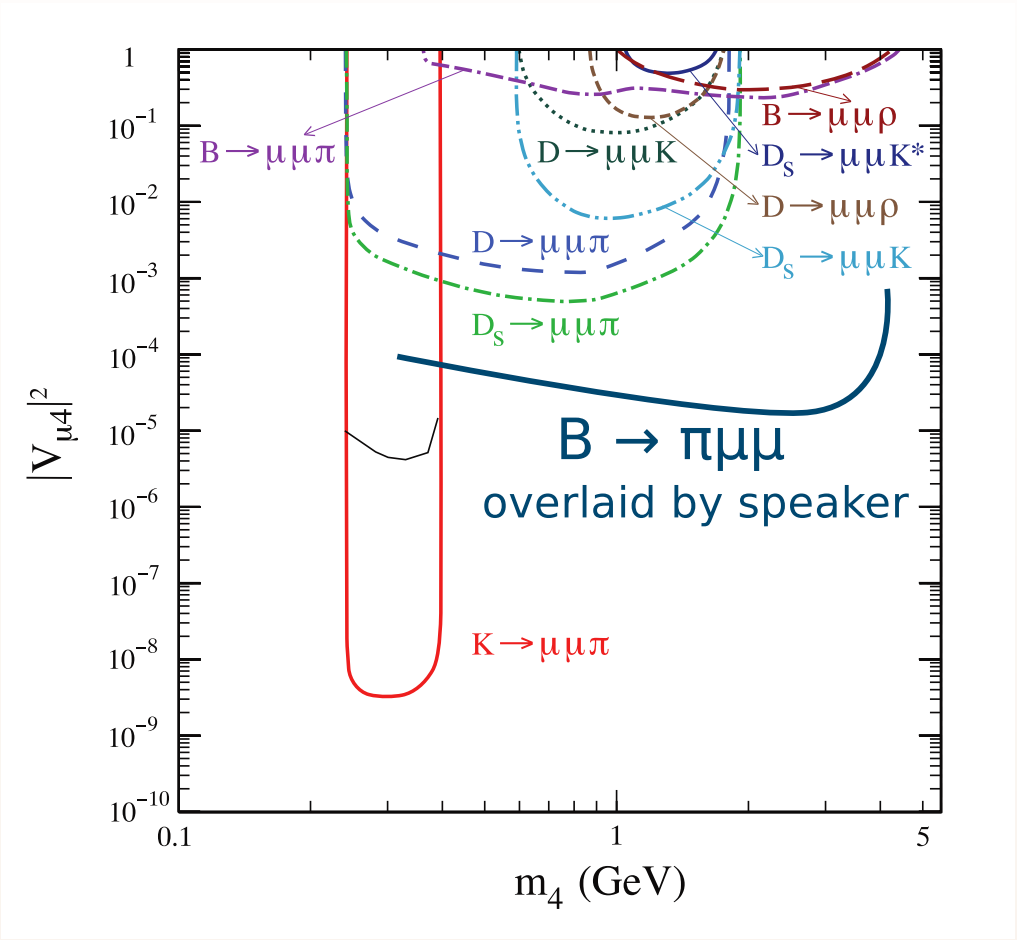
new bounds for on shell Majorana neutrinos

LHCb limit on $|V_{\mu 4}|$



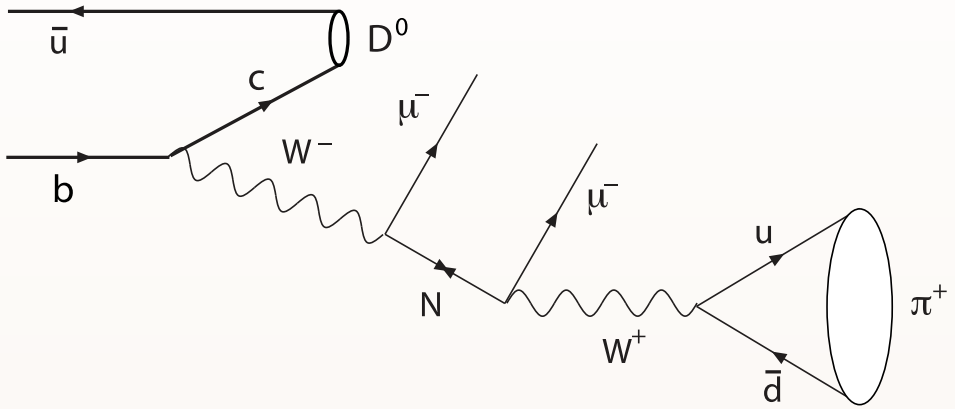
arXiv:1201.5600

Status of 2009



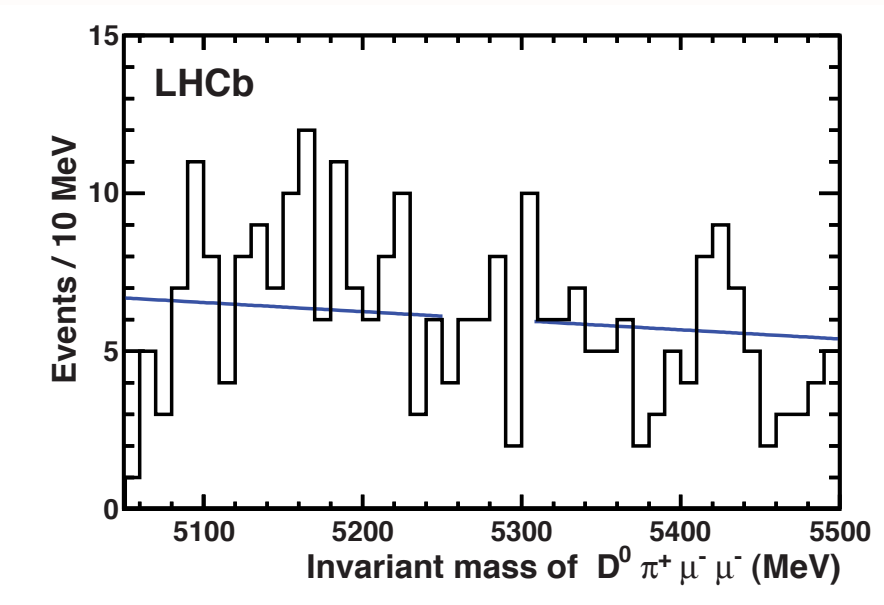
arXiv:0901.3589

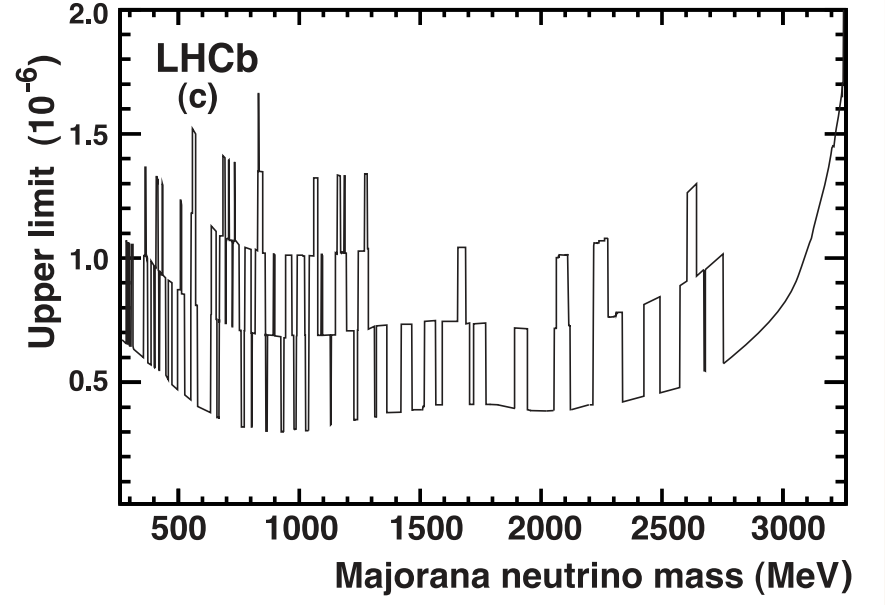
$B^- \to D^0\pi^+\mu^-\mu^-$



- Four body B decay complementary to three body decay (arXiv:1108.6009)
- $m_4 = m(\pi^+\mu^-)$
- \+ enhanced by W couplings
- \- smaller mass range accessible (260 MeV $< m_4 <$ 3.3 GeV)
- first performed at LHCb

$B^- \to D^0\pi^+\mu^-\mu^-$





$\mathcal{B}(B^- \to D^0\pi^+\mu^-\mu^-) < 1.5 \times 10^{-6}$ @95 % CL [a]

Less restrictive than $B^- \to \pi^+\mu^-\mu^-$ on $|V_{\mu 4}|^2$

[a] LHCb, CERN-PH-EP-2012-006, arXiv:1201.5600

Summary on LNV in B decays

channel	limit		
$\mathcal{B}(B^- \to \pi^+ e^- e^-)$	$< 2.3 \times 10^{-8}$	@90 % CL	 [a]
$\mathcal{B}(B^- \to K^+ e^- e^-)$	$< 3.0 \times 10^{-8}$	@90 % CL	 [a]
$\mathcal{B}(B^- \to K^{*+} e^- e^-)$	$< 2.8 \times 10^{-6}$	@90 % CL	 [b]
$\mathcal{B}(B^- \to \rho^+ e^- e^-)$	$< 2.6 \times 10^{-6}$	@90 % CL	 [b]
$\mathcal{B}(B^- \to D^+ e^- e^-)$	$< 2.6 \times 10^{-6}$	@90 % CL	 [c]
$\mathcal{B}(B^- \to D^+ e^- \mu^-)$	$< 1.8 \times 10^{-6}$	@90 % CL	 [c]
$\mathcal{B}(B^- \to \pi^+ \mu^- \mu^-)$	$< 1.3 \times 10^{-8}$	@95 % CL	[d]
$\mathcal{B}(B^- \to K^+ \mu^- \mu^-)$	$< 5.4 \times 10^{-7}$	@95 % CL	[e]
$\mathcal{B}(B^- \to D^+ \mu^- \mu^-)$	$< 6.9 \times 10^{-7}$	@95 % CL	[d]
$\mathcal{B}(B^- \to D^{*+} \mu^- \mu^-)$	$< 2.4 \times 10^{-6}$	@95 % CL	[d]
$\mathcal{B}(B^- \to D_s^+ \mu^- \mu^-)$	$< 5.8 \times 10^{-7}$	@95 % CL	[d]
$\mathcal{B}(B^- \to D^0 \pi^- \mu^- \mu^-)$	$< 1.5 \times 10^{-6}$	@95 % CL	[d]

[a] BaBar, Phys. Rev. D **85**, 071103 (2012)
[b] CLEO, Phys. Rev. D **65**, 111102 (2002)
[c] Belle, Phys. Rev. D **84**, 071106(R), (2011)
[d] LHCb, CERN-PH-EP-2012-006, arXiv:1201.5600 (2012)
[e] LHCb, Phys. Rev. Lett. 108 101601 (2012)

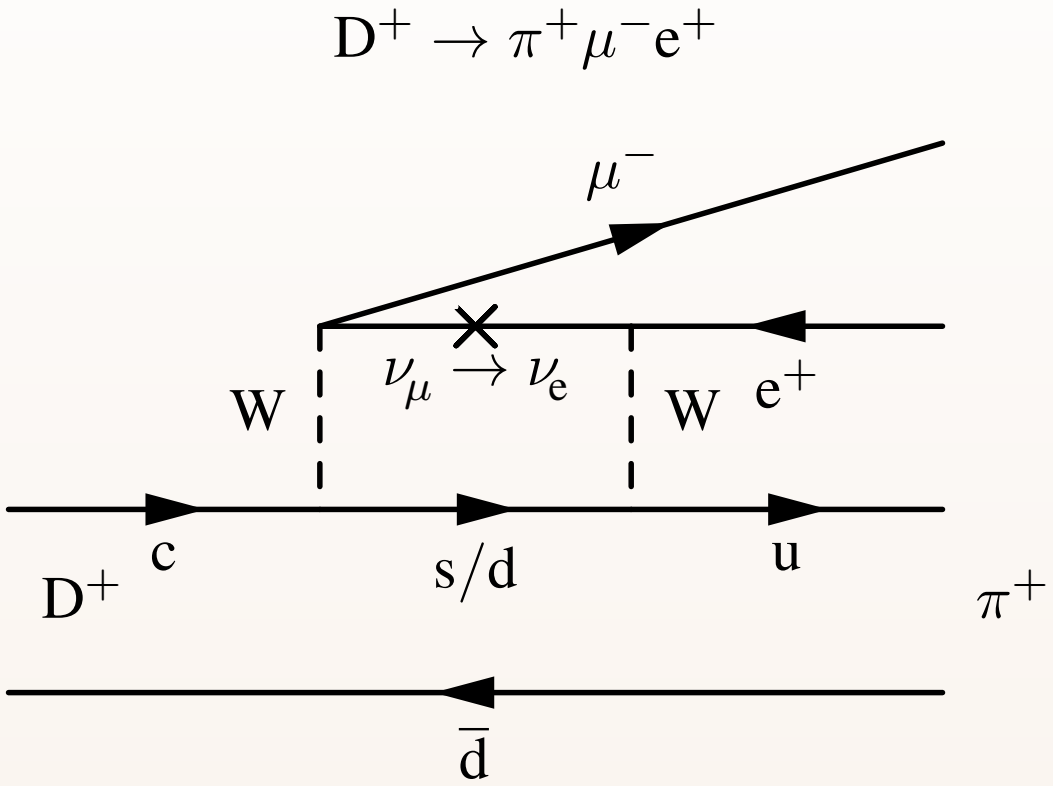
Lepton Flavour Violation

- $\mathrm{D}^- \to h^- \ell^+ \ell'^-$
- $\mathrm{B}^- \to \pi^-/\mathrm{K}^- \tau^\pm \ell^\mp$
- $\tau^- \to \mu^- \mu^- \mu^+$

Lepton Flavour Violation

- established for neutrinos
- can enter charged sector in loops
- predicted rates unmeasurable small

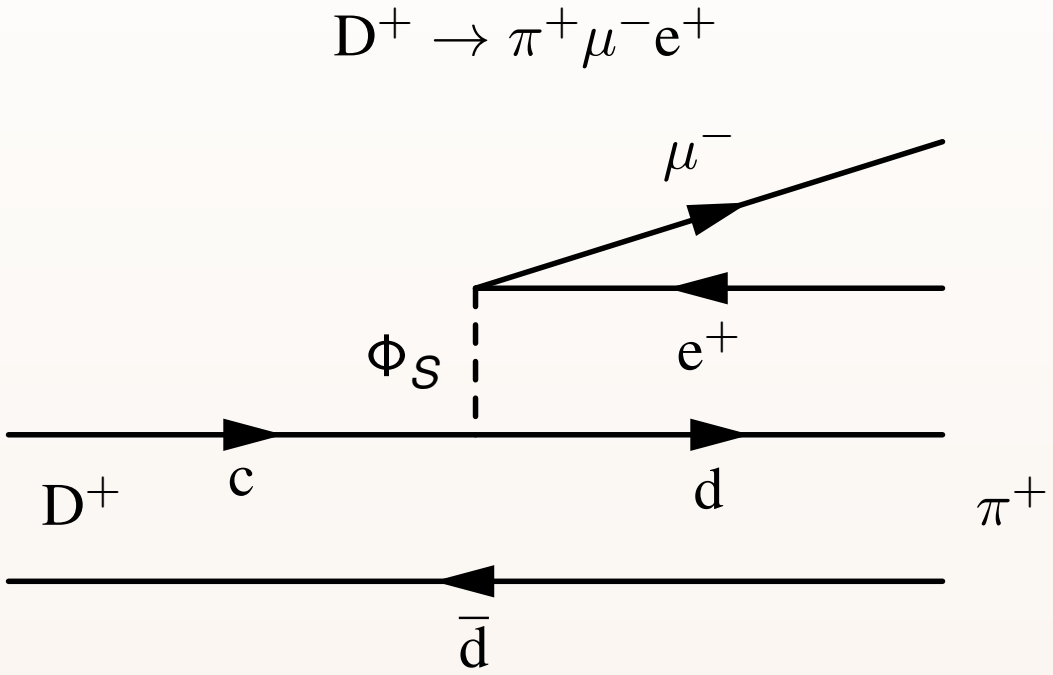
Standard Model + neutrino oscillation



Lepton Flavour Violation

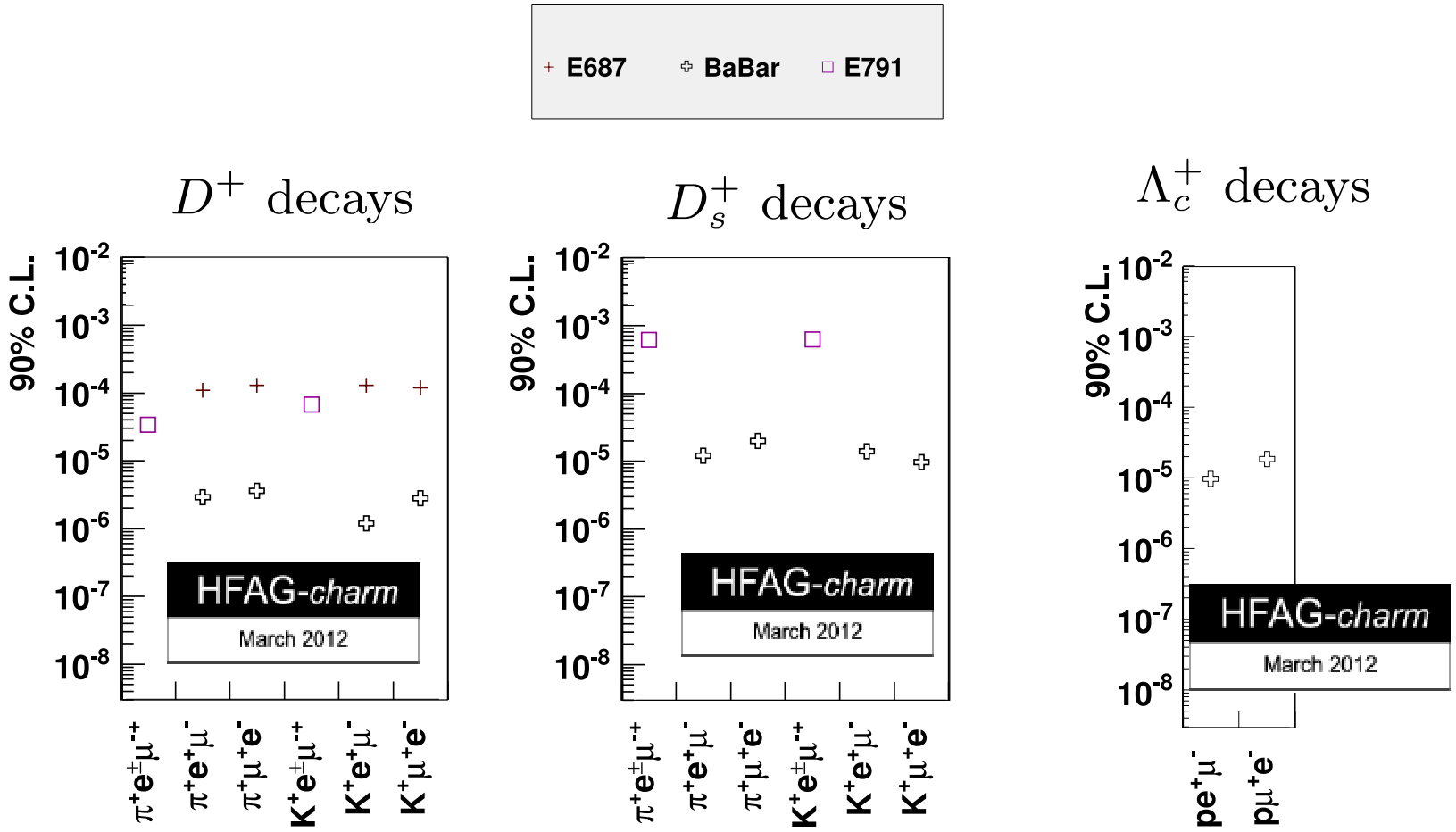
- established for neutrinos
- can enter charged sector in loops
- predicted rates unmeasurable small
- enhancement predicted in many New Physics models, e.g.
  - multi-Higgs extensions[1]
  - leptoquarks[2]
  - low scale seesaw models[3]

extended Higgs



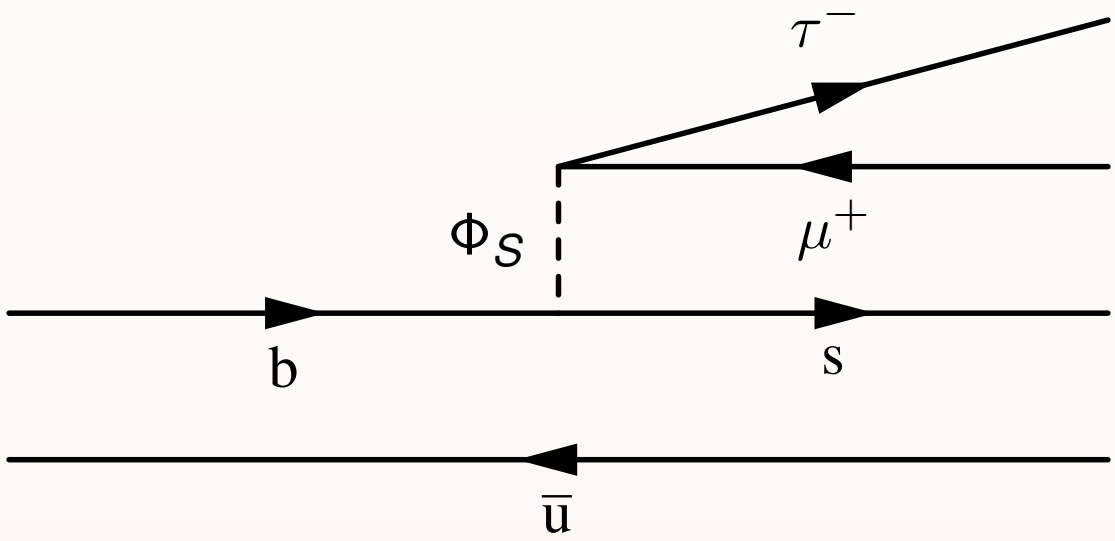
[1] Phys. Rev. D **44**, 1461
[2] Z. Phys. C **61**, 613
[3] Phys. Rev. D **73**, 074011

LFV in charm decays



[HFAG]

LFV in bottom decays



- LFV τ sector not probed by D decays
- enough energy available in B decays
- multi Higgs models enhance $B \to h\tau\mu$ over other channels[4]
- challenging: neutrino in τ decay similar to $B \to X\ell\nu$

[4] Phys. Rev. D **44** 1461

LFV in bottom decays

channel	limit	
$\mathcal{B}(B^+ \to K^+\tau^-\mu^+)$	$< 4.5 \times 10^{-5}$	BABAR a
$\mathcal{B}(B^+ \to K^+\tau^+\mu^-)$	$< 2.8 \times 10^{-5}$	BABAR a
$\mathcal{B}(B^+ \to K^+\tau^-e^+)$	$< 4.3 \times 10^{-5}$	BABAR a
$\mathcal{B}(B^+ \to K^+\tau^+e^-)$	$< 1.5 \times 10^{-5}$	BABAR a
$\mathcal{B}(B^+ \to \pi^+\tau^-\mu^+)$	$< 6.2 \times 10^{-5}$	BABAR a
$\mathcal{B}(B^+ \to \pi^+\tau^+\mu^-)$	$< 4.5 \times 10^{-5}$	BABAR a
$\mathcal{B}(B^+ \to \pi^+\tau^-e^+)$	$< 7.4 \times 10^{-5}$	BABAR a
$\mathcal{B}(B^+ \to \pi^+\tau^+e^-)$	$< 2.0 \times 10^{-5}$	BABAR a
$\mathcal{B}(B^+ \to \pi^+\mu^\pm e^\mp)$	$< 1.7 \times 10^{-7}$	BABAR b
$\mathcal{B}(B^+ \to K^+\mu^+e^-)$	$< 9.1 \times 10^{-8}$	BABAR b

details in talk of Giovanni Marchiori

LFV energy scale

$\Lambda_{\bar{b}d}$:

2.2 TeV $\to$ 11 TeV

$\Lambda_{\bar{b}s}$:

2.6 TeV $\to$ 15 TeV

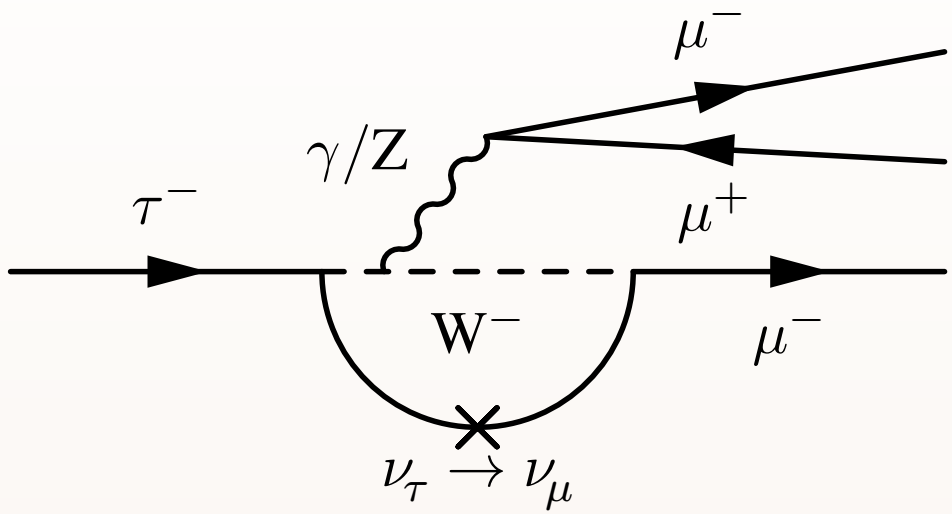
a: BaBar, arXiv:1204.2852, 429 fb^{-1}

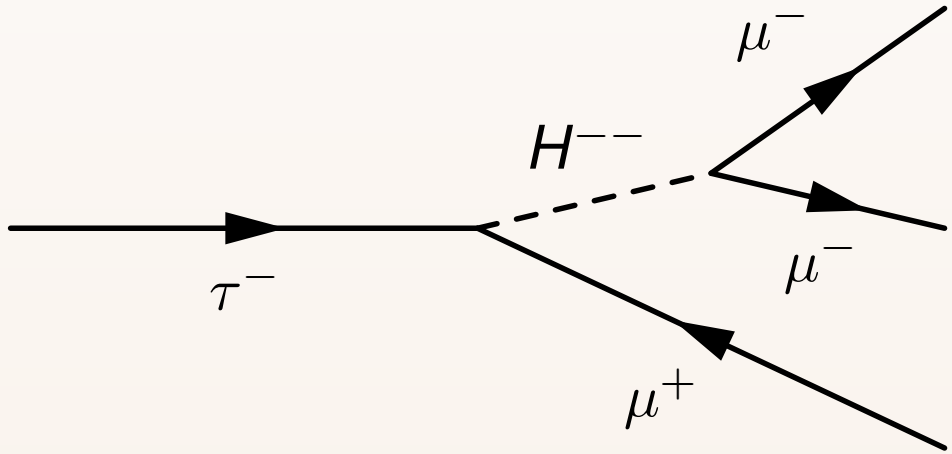
b: BaBar, Phys. Rev. Let. **99**, 051801 (2007), 209 fb^{-1}

$\tau^- \to \mu^-\mu^-\mu^+$ at hadron colliders

- in Standard Model + neutrino oscillation introduced in penguin diagrams
- highly suppressed ($\mathcal{B} \ll 10^{-50}$)
- enhanced by e.g. charged Higgs
- best measurements conducted at B factories (Francesco Renga's talk)

! also possible at hadron colliders





$\tau \to \mu\mu\mu$ in hadron collisions

τ sources at B factories

- $e^+e^- \to \tau^+\tau^-$
- allows τ tag

τ sources at the LHC

- inclusive τ cross section 79.5 ± 8.3 µb at $\sqrt{s} = 7$ TeV in the LHCb acceptance

$\to$ 7.9×10^{10} τ produced

- dominant: $D_s \to \tau\nu_\tau$ (78%)

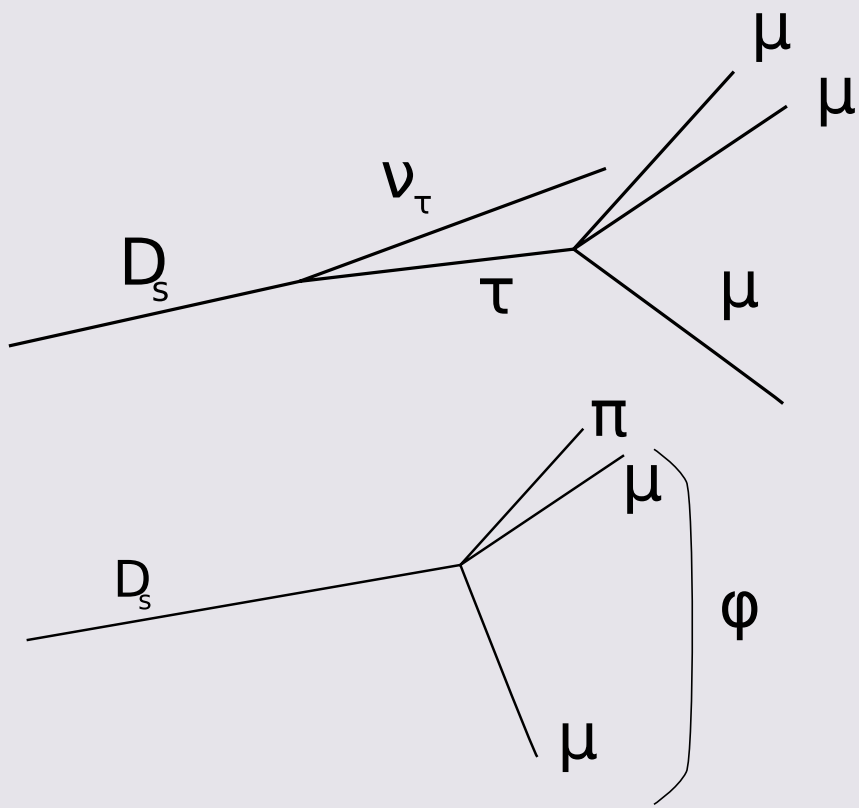
! no τ tag possible

- standard τ signatures very similar to D decays ($D^+ \to \pi^+\pi^-\pi^+\pi^0$ vs. $\tau^+ \to \pi^+\pi^-\pi^+\overline{\nu}_\tau$)

Strategy

- Loose cut based selection
- Classification in 3D space:
  - invariant mass
  - decay topology (multivariate)
  - particle identification (multivariate)
- Classifier trained on simulation
- Calibration with control channel
- Normalisation with D_s
- CLs method to extract the result

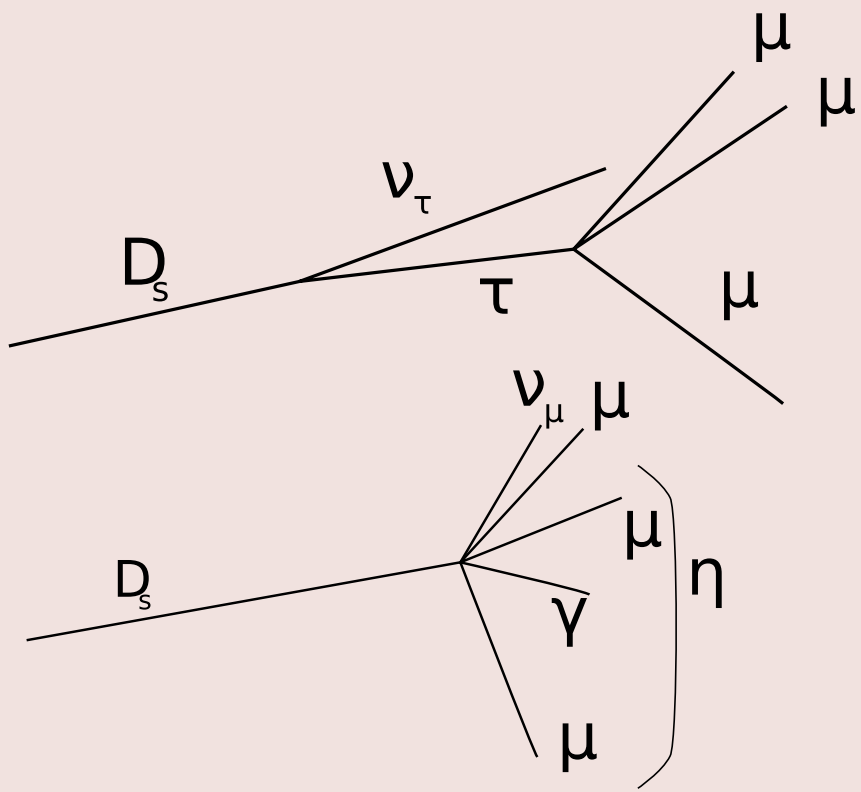
Signal & Calibration channel



Strategy

- Loose cut based selection
- Classification in 3D space:
  - invariant mass
  - decay topology (multivariate)
  - particle identification (multivariate)
- Classifier trained on simulation
- Calibration with control channel
- Normalisation with D_s
- CLs method to extract the result

Signal & peaking background



Normalisation channel $D_s^+ \to \phi(\mu^+\mu^-)\pi^+$

produced τ leptons

$$\mathcal{B}(\tau \to \mu\mu\mu) = \frac{\sigma(pp \to D_s \to \tau)}{\sigma(pp \to \tau)} \frac{\mathcal{B}(D_s \to \phi(\mu\mu)\pi)}{\mathcal{B}(D_s \to \tau\nu_\tau)} \frac{\varepsilon_{norm}}{\varepsilon_{sig}} \frac{N_{\tau\to\mu\mu\mu}}{N_{D_s\to\phi(\mu\mu)\pi}}$$

ingredients

- $b\bar{b}$ and $c\bar{c}$ production measurements from LHCb
- $B \to \tau$ and $D \to \tau$ branching ratios from LEP / B factories
- $\mu\mu\pi$ final state

$\to$ systematics cancel

- trigger
- reconstruction
- selection

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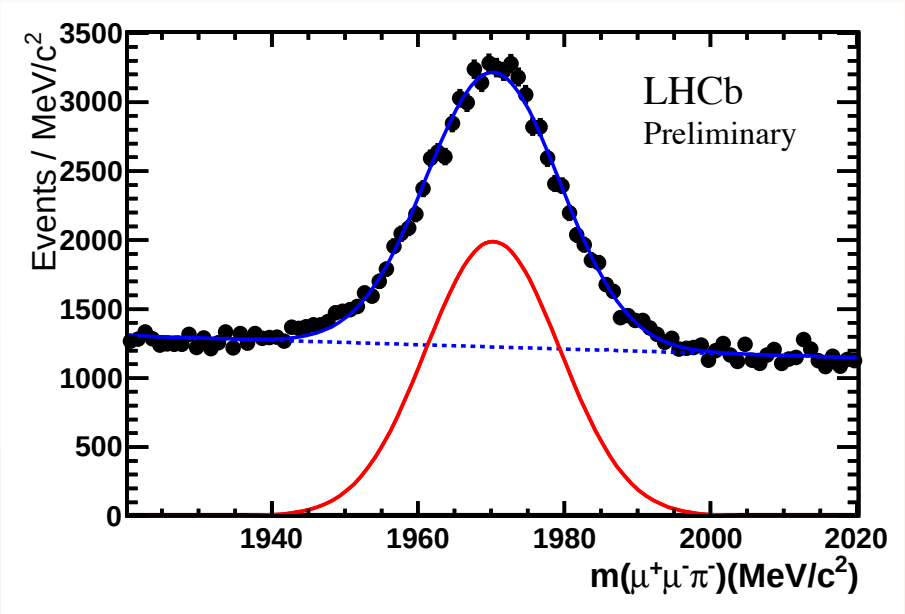

45 515 $D_s \to \phi(\mu^+\mu^-)\pi$ decays

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- $\mu\mu\pi$ final state

$\to$ systematics cancel

- non resonant contribution $< 2\,\%$

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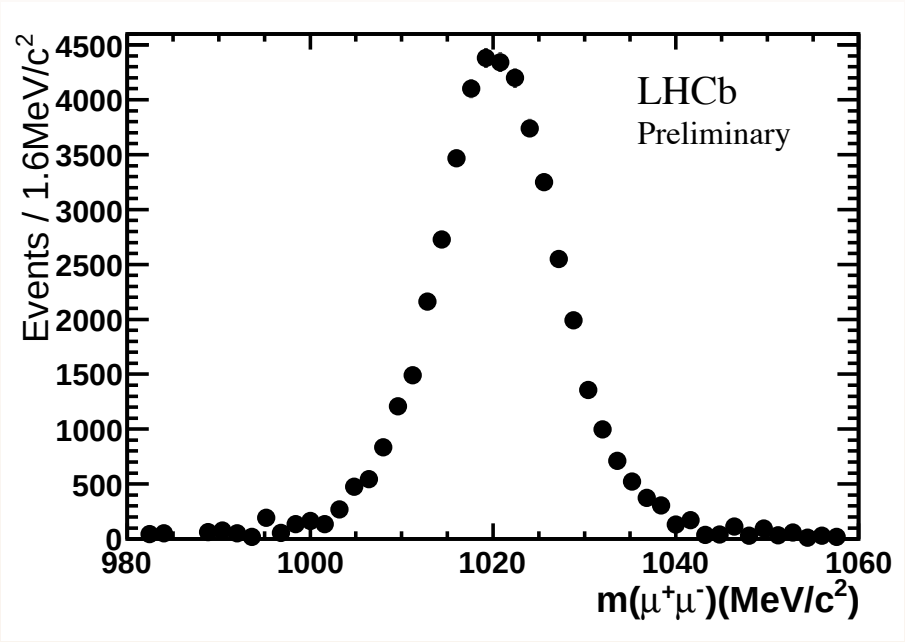


background substracted $\mu^+\mu^-$ mass

signal likelihoods

3 body decay likelihood

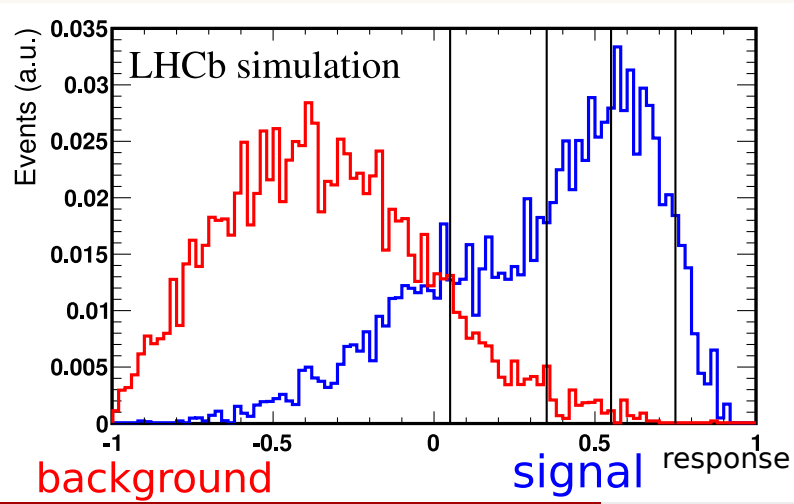
- vertex properties
  - vertex fit, pointing
- track quality
- isolation

particle identification

- hits in muon chambers
- energy in calorimeters
  - compatible with MIP
- RICH information

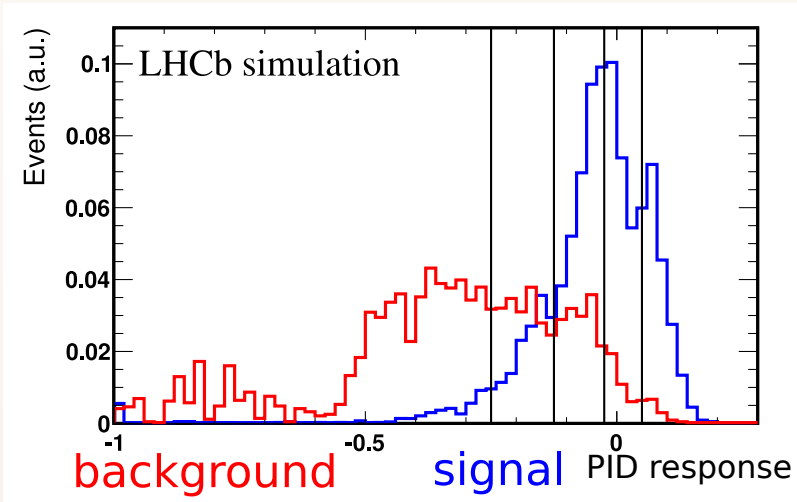
Calibration

$D_s \to \phi\pi$



Calibration

$J/\psi \to \mu^+\mu^-$



invariant mass

two fold role

- background estimation in sidebands
- different signal likelihood inside signal region

1 fb^{-1}

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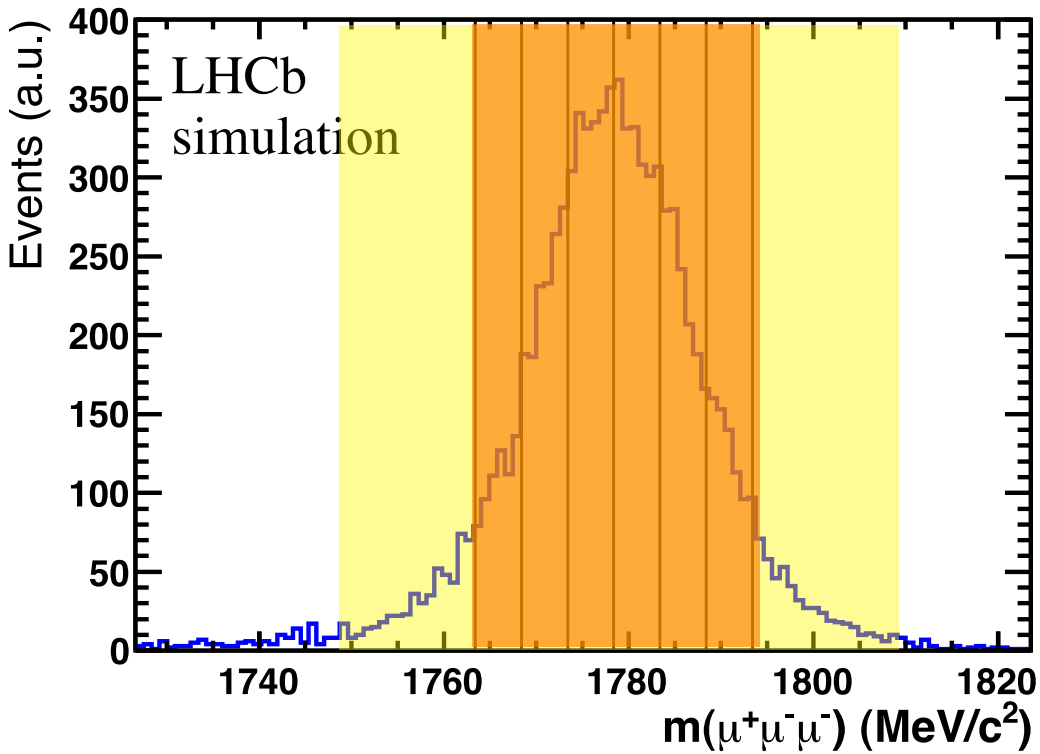

- mass resolution and mass scale calibrated on data

signal likelihoods

combined signal distribution

- events distributed over 25 likelihood bins
- background estimate from mass sidebands

1 fb^{-1}

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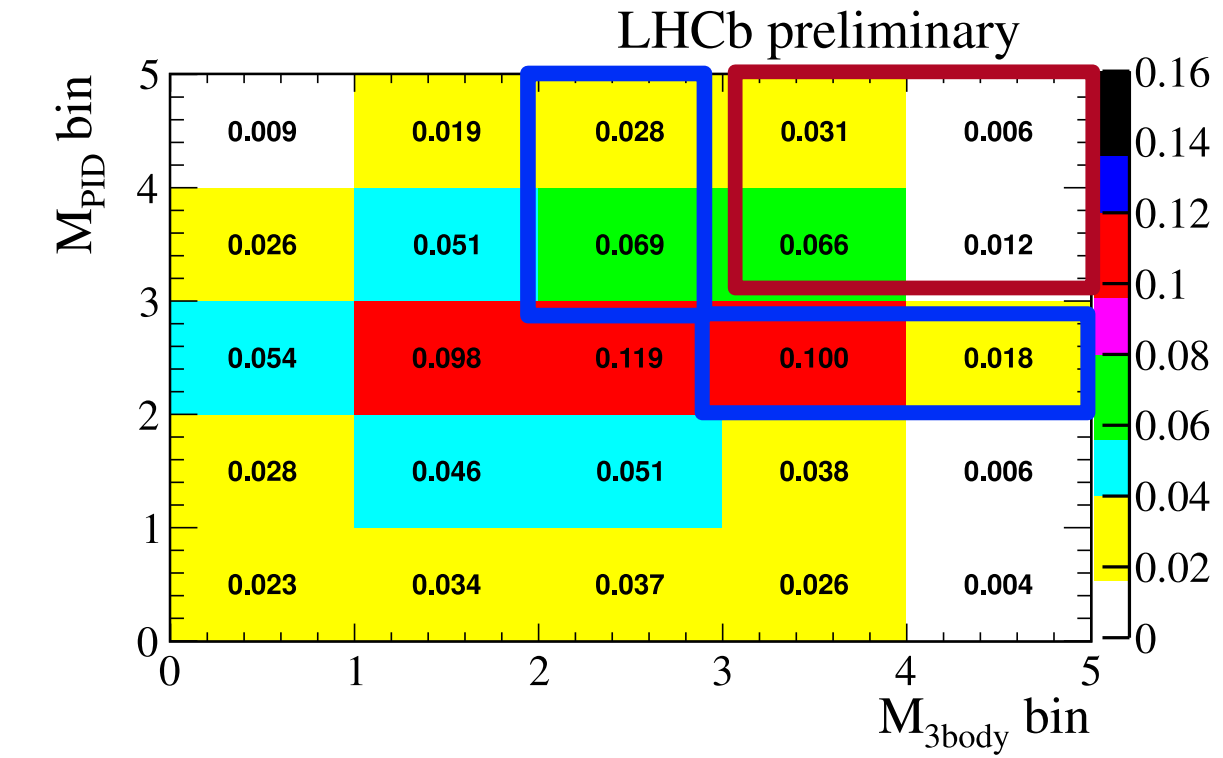
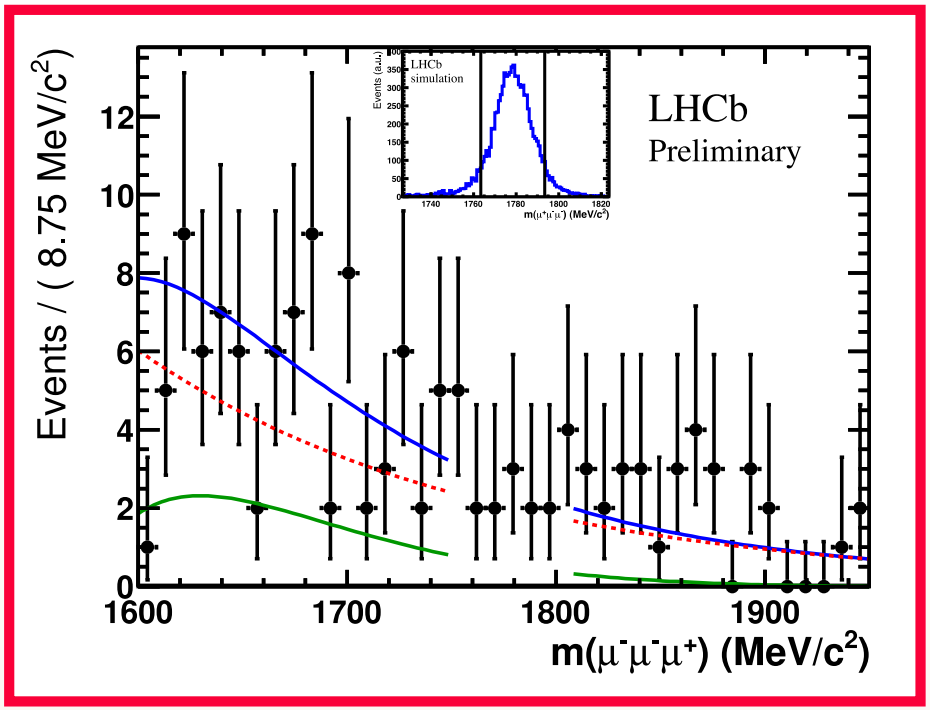
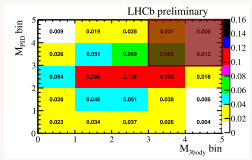


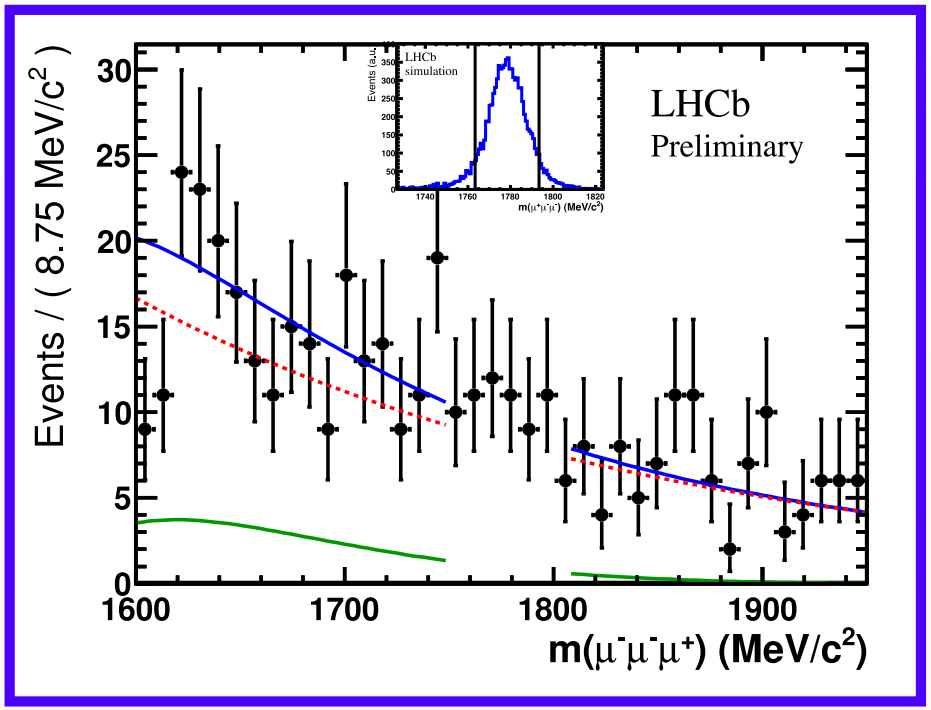
- 11 % signal efficiency
- 21 % signal efficiency
- for illustration: high likelihood range shown

observed events

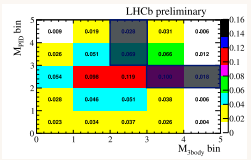


11 % of the signal
0.03 % of the background





21 % of the signal
0.14 % of the background



red dashed combinatorial background

green $D_s^+ \to \eta(\mu^-\mu^+\gamma)\mu^+\nu_\mu$

blue combined background

1 fb^{-1}

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extracted limit

result (preliminary)

	observed	expected
$\mathcal{B}(\tau \to \mu\mu\mu)$	$< 6.3 \times 10^{-8}$	8.2×10^{-8} @ 90 % *CL*
	$< 7.8 \times 10^{-8}$	9.9×10^{-8} @ 95 % *CL*

1 fb^{-1}

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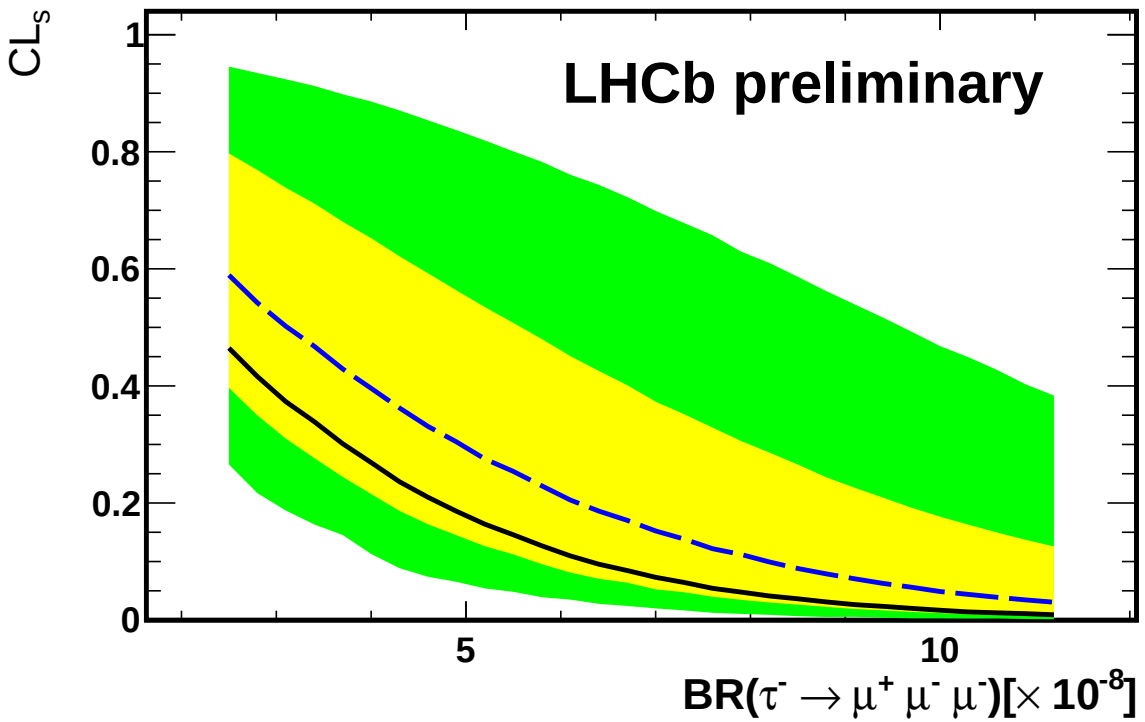


Belle $2.1x10^{-8}$ @ 90 % CL
Phys. Lett. B **687**, 139 (2010)

BaBar $3.3x10^{-8}$ @ 90 % CL
Phys. Rev. D **81**, 111101(R) (2010)

Summary

- neither lepton number violation nor lepton flavour violation observed (yet)
- hadron decays provide good probes for Lepton Number & Flavour Violation
- excellent sensitivity achieved at B factories
  - LNV and LFV excluded to 10^{-5} for D decays
- LHCb extends knowledge on forbidden B decays
  - LNV excluded to $10^{-6\cdots-8}$
- LHCb approaching B factories for $\tau \to \mu\mu\mu$

$\Rightarrow$ first time done at hadron colliders

BACKUP

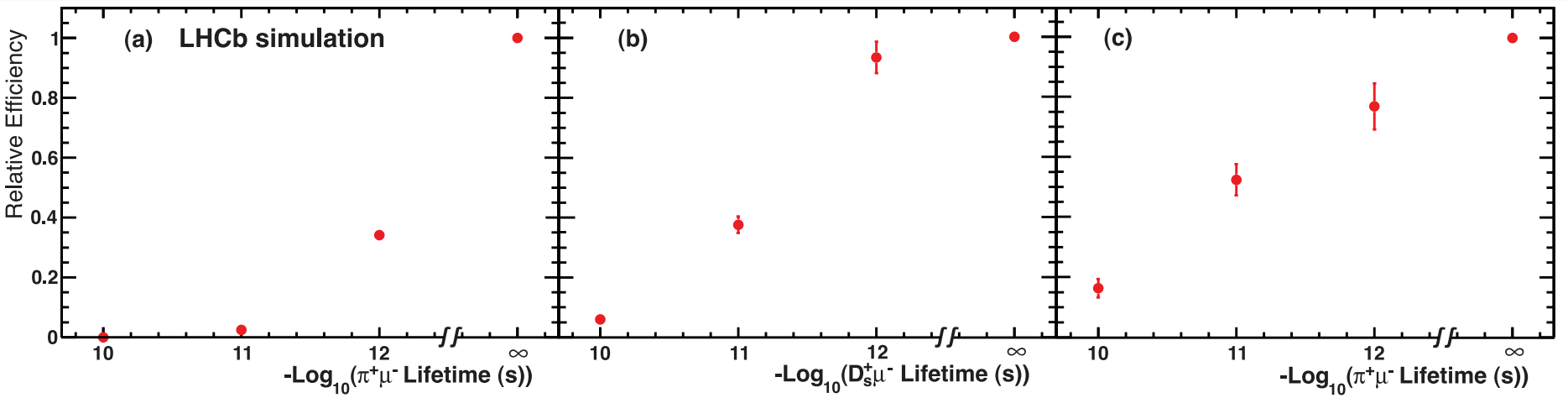
Sensitivity to long lived Majorana neutrinos

- analysis allows for neutrino flight distance
- probes only Majorana neutrinos decaying inside the detector
- sensitivity to lifetime provided

a) $B^- \to \pi^+ \mu^- \mu^-$
250 MeV $< m_4 <$ 5 GeV

b) $B^- \to D_s{}^+ \mu^- \mu^-$
2.1 GeV $< m_4 <$ 5.15 GeV

c) $B^- \to D^0 \pi^+ \mu^- \mu^-$
260 MeV $< m_4 <$ 3.3 GeV



- sensitive to lifetimes $< 10^{-10}$ s
- $B^- \to D^0 \pi^+ \mu^- \mu^-$ better sensitive to "large" lifetimes

model dependence

$$\tau^- \to \mu^- \mu^- \mu^+$$

possible problem

if the selection efficiency is different for various models, the limit could be higher or lower than the one we quote.

crosschecks

We tested the

- trigger efficiency
- preselection
- multivariate classifier

as a function of the invariant dimuon mass(es).
$\Rightarrow$ these are constant within 15 %

Prospects

When will LHCb catch up with the B factories on $\tau^- \to \mu^-\mu^-\mu^+$?

short answer

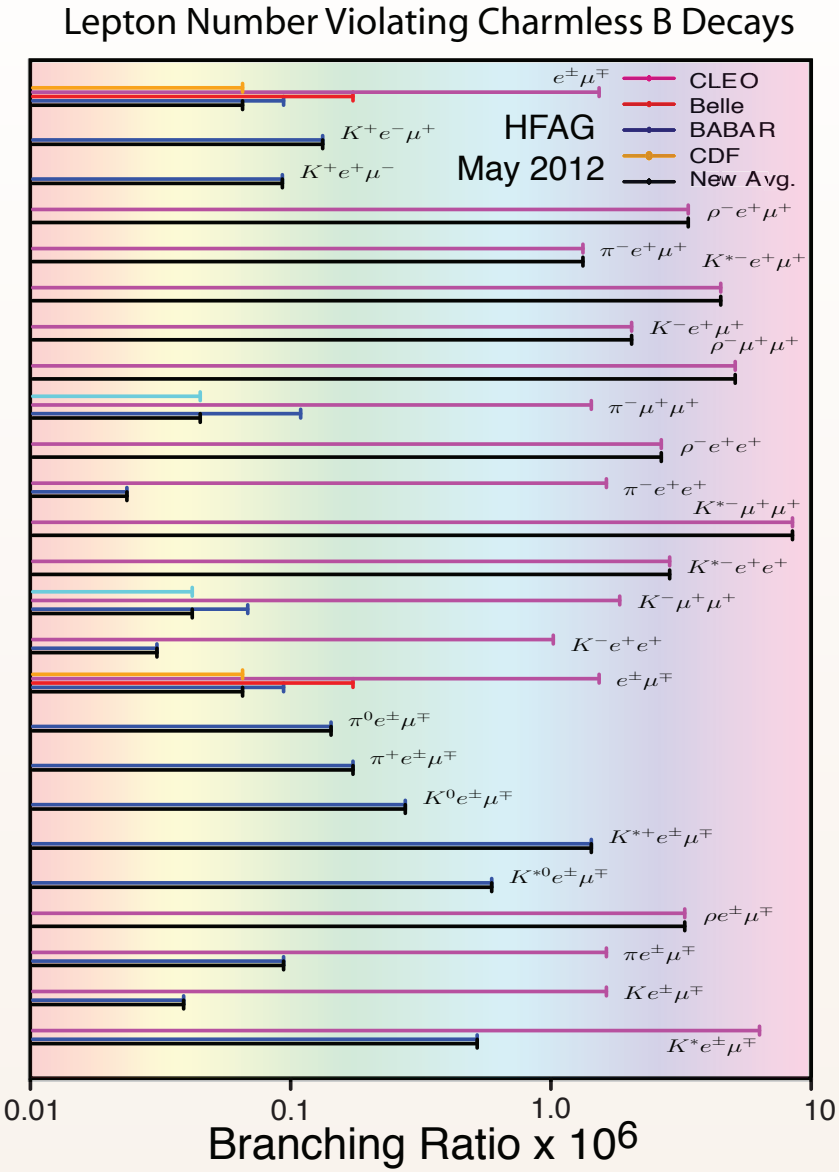
not studied so far

long answer

Judge yourself:

- used: 1 fb^{-1} @ 7 TeV
- 2012: 1.5 fb^{-1} @ 8 TeV (charm cross section $\sim$ 15 % higher)
- 2013-1014: long shutdown 1
- 2014-2017: running at higher energies

HFAG limits for bottom decays



[HFAG]