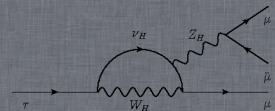
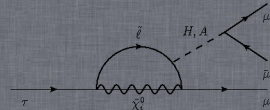
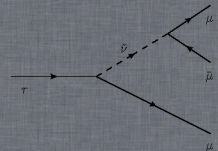
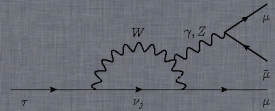


# Search for LFV and LNV decays at LHCb

Marcin Chrzęszcz

Institute of Nuclear Physics,  
Polish Academy of Science,  
on behalf of LHCb collaboration

29<sup>th</sup> September 2012



## B decays

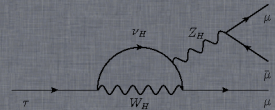
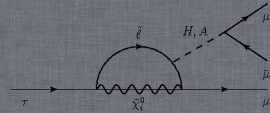
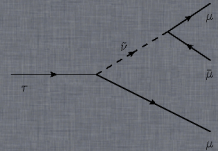
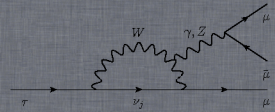
$$B^- \rightarrow h^+ l^- l^-$$

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

## $\tau$ decays

$$\tau^- \rightarrow \mu^- \mu^- \mu^+$$

$$\tau^- \rightarrow \bar{\nu} \mu^- \mu^+$$



# Overview of B and $\tau$ decays at LHCb

## ① LHCb optimised for B decays.

- Relatively low background.
- Efficient trigger.
- Analysis can be made using hard cuts (the case of LNF decays).

## ② $\tau$ decays at LHCb.

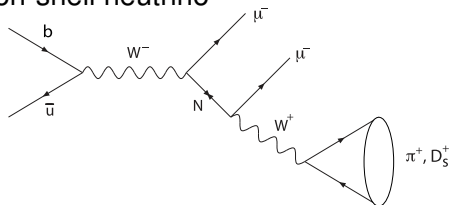
- Many  $\tau$  killed by trigger.
- Smaller cross section for production.
- Need complicated analysis strategy.

# LNV in bottom decays

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

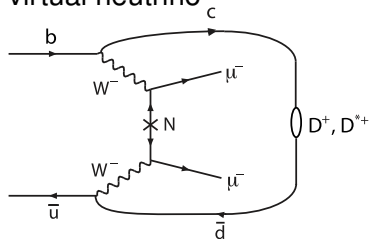
# LNV in bottom decays

on-shell neutrino



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

virtual neutrino

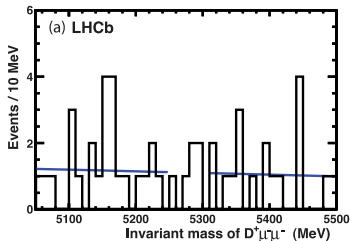


Special for B decays

Diagram without mass restriction  
Cabbibo favoured for  $B \rightarrow D$   
Analogous to double  $\beta$  decay.

# Virtual Majorana neutrinos

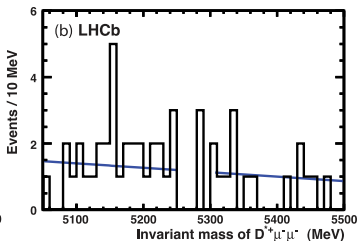
$$B^- \rightarrow D^+ \mu^- \mu^-$$



$$\mathcal{B}(B^- \rightarrow D^+ \mu^- \mu^-) < 6.9 \times 10^{-7}$$

@ 95% CL

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



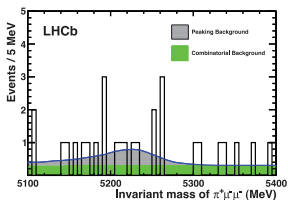
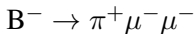
$$\mathcal{B}(B^- \rightarrow D^{*+} \mu^- \mu^-) < 2.4 \times 10^{-6}$$

@ 95% CL

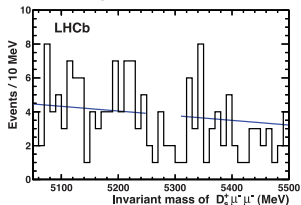
Phys. Rev.D85 (2012)  
112004

# On-shell Majorana neutrinos

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



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



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

Phys. Rev.D85 (2012)  
112004

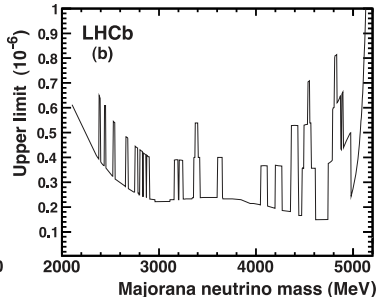
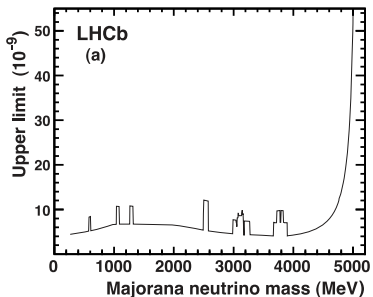
# Implications on Majorana mass

## mass spectrum

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

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

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



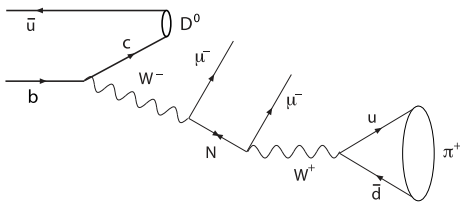
Phys. Rev.D85 (2012)

112004

M.Chrzyszcz 2012

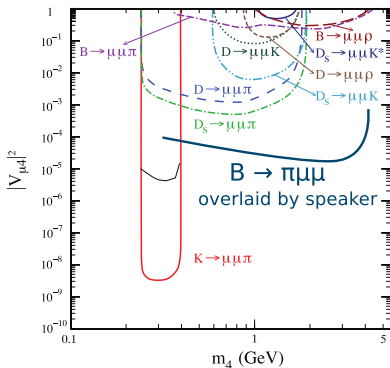
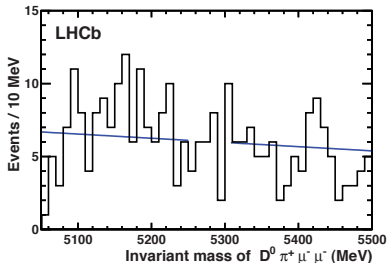
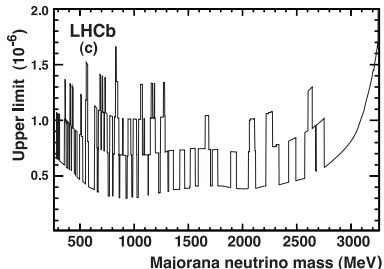


$$B^- \rightarrow D^0 \pi^+ \mu^- \mu^-$$



- 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 ( $260 \text{ MeV} < m_4 < 3.3 \text{ GeV}$ )
- first performed at LHCb













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



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

<sup>a</sup>LHCb, CERN-PH-EP-2012-006, arXiv:1

# Summary on LNV in B decays

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

<sup>a</sup>BaBar, Phys. Rev. D **85**, 071103 (2012)

<sup>b</sup>CLEO, Phys. Rev. D **65**, 111102 (2002)

<sup>c</sup>Belle, Phys. Rev. D **84**, 071106(R), (2011)

<sup>d</sup>LHCb, CERN-PH-EP-2012-006, arXiv:1201.5600 (2012)

<sup>e</sup>LHCb, Phys. Rev. Lett. **108** 101601 (2012)

# $\tau$ decays

$$\textcircled{1} \tau^- \rightarrow \mu^- \mu^- \mu^+$$

$$\textcircled{2} \tau^- \rightarrow \bar{p} \mu^- \mu^+$$

# LFV in $\tau^-$ sector

$$\tau^- \rightarrow \mu^- \mu^- \mu^+$$

# LFV in $\tau^-$ sector

- 1 In SM small  $\mathcal{B}(\tau^- \rightarrow \mu^- \mu^- \mu^+) \sim 10^{-50}$
- 2 NP can enhance  $\mathcal{B}$ .
- 3 Nature still hides  $\tau^- \rightarrow \mu^- \mu^- \mu^+$  from us.
- 4 Current limits:

Experiment	90% CL limit
BaBar	$3.3 \times 10^{-8}$
Belle	$2.1 \times 10^{-8}$

- 5 Can a hadron collider change the picture?

# Analysis approach

$B$  factories

- ① Clean signal:  $e^+e^- \rightarrow \tau^+\tau^-$
- ② Calculate the thrust axis
- ③ "Partial tag" the other  $\tau$
- ④ Small cross section  $0.919nb$

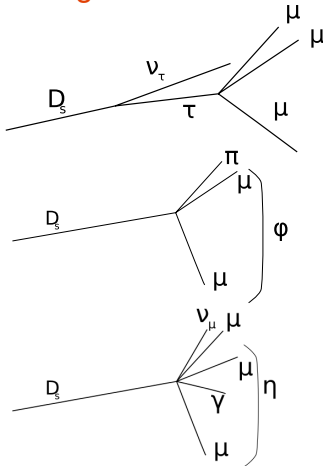
LHCb, (7TeV, 2011 data)

- ① Inclusive  $\tau$  cross section:  
 $79.5 \pm 8.3 \mu b$ .
- ②  $8 \times 10^{10} \tau$  produced.
- ③ Dominant contribution:  
 $D_s \rightarrow \tau \nu_\tau$  (78%)
- ④ No tag possible.

# 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
- Normalization with  $D_s \rightarrow \phi(\mu\mu)\pi$
- CLs method to extract the result

## Signal & Calibration & Background channel





# Signal likelihoods

## particle identification

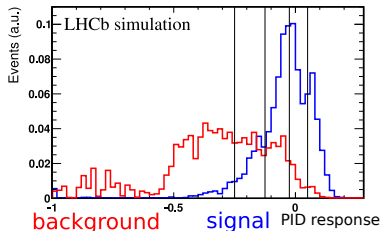
- hits in muon chambers
- energy in calorimeters
  - compatible with MIP
- RICH response

## 3 body decay likelihood

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

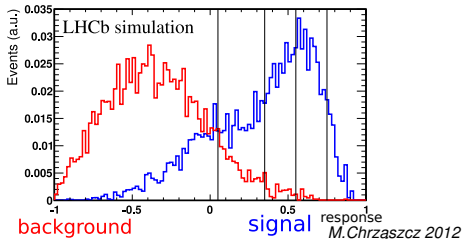
## Calibration

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



## Calibration

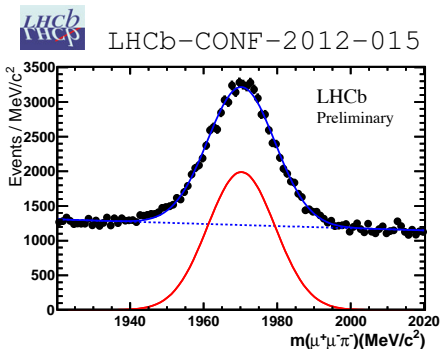
$$D_s \rightarrow \phi \pi$$



# Normalization channel $D_s^+ \rightarrow \phi(\mu^+\mu^-)\pi^+$

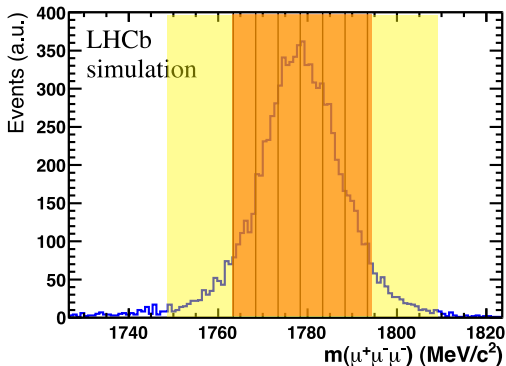
## Produced $\tau$ leptons

$$\mathcal{B}(\tau \rightarrow \mu\mu\mu) = \underbrace{\frac{\sigma(pp \rightarrow D_s \rightarrow \tau)}{\sigma(pp \rightarrow \tau)}}_{77.9\%} \frac{\mathcal{B}(D_s \rightarrow \phi(\mu\mu)\pi)}{\mathcal{B}(D_s \rightarrow \tau\nu_\tau)} \frac{\varepsilon_{norm}}{\varepsilon_{sig}} \frac{N_{\tau \rightarrow \mu\mu\mu}}{N_{D_s \rightarrow \phi(\mu\mu)\pi}}$$



# Invariant mass

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



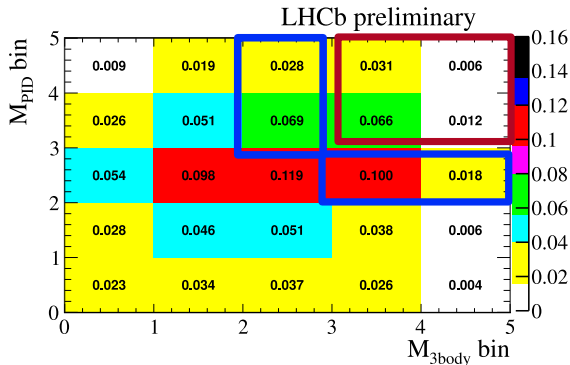
- Mass resolution and mass scale calibrated on data
- Blinded window
- Mass window
- Mass resolution:  $9.16\text{MeV}$

# Signal likelihoods

## combined signal distribution

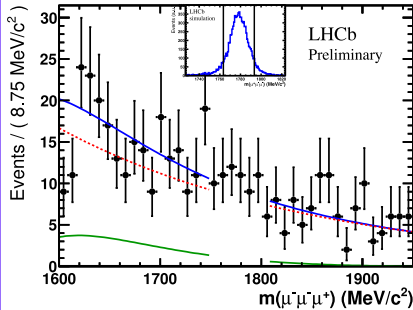
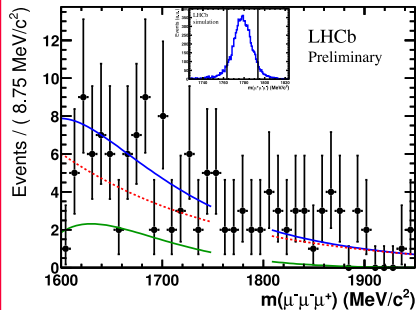
- events distributed over 25 likelihood bins
- background estimate from mass sidebands

Signal efficiency in 3-BODY BDT vs PID BDT plane.

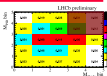


- 11 % signal efficiency
- 21 % signal efficiency
- for illustration: high likelihood range shown

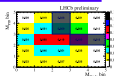
# Observed events



11 % of the signal  
0.03 % of the background



21 % of the signal  
0.14 % of the background



red dashed combinatorial background  
green  $D_s^+ \rightarrow \eta(\mu^- \mu^+ \gamma)\mu^+ \nu_\mu$   
blue combined background



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

LHCb-CONF-2012-015

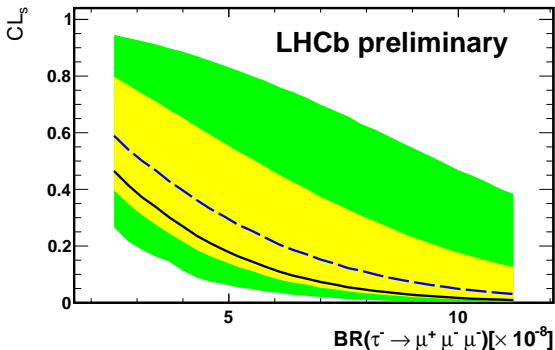
# Extracted upper limit



1 fb<sup>-1</sup>

LHCb-CONF-  
2012-015

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



# LNV & BNV in $\tau^-$ sector

$$\tau^- \rightarrow \bar{\nu} \mu^- \mu^+$$

$$\tau^- \rightarrow \nu \mu^- \mu^-$$

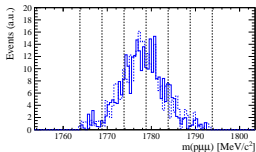
# LNV & BNV in $\tau^-$ sector

- ① Search for baryon number violation processes so far unsuccessful, but must have occurred in the early universe
- ② Decay fall into  $|B - L| = 0$  category, which is predicted by many NP models.
- ③ Similar decays  $\tau^- \rightarrow \Lambda \ell^-$ , previous studied in  $\mathcal{B}$  factories.
- ④ Two possible decay and new physics modes:  $\tau^- \rightarrow \bar{p} \mu^- \mu^+$ ,  
 $\tau^- \rightarrow p \mu^- \mu^-$ .
- ⑤ Analysis adopted from  $\tau^- \rightarrow \mu^- \mu^- \mu^+$



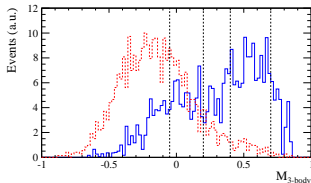
# Differences

## Mass distribution

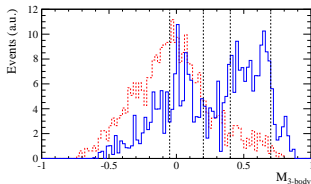


- Use the same  $\mathcal{M}_{3body}$  BDT as for  $\tau^- \rightarrow \mu^- \mu^- \mu^+$
- Instead of PID BDT use hard PID cut optimised on MC and Data.
- Worse normalization factor, due to hard PID cuts.
- Only combinatorial background expected.

## 3-body BDT distribution for $\tau^- \rightarrow \bar{p} \mu^- \mu^+$

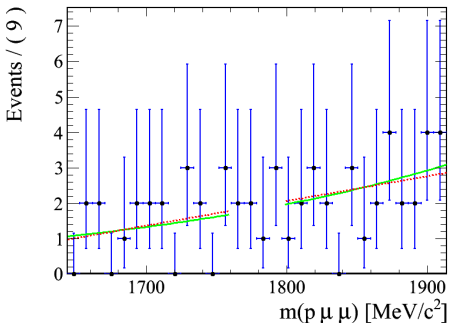


## 3-body BDT distribution for $\tau^- \rightarrow p \mu^- \mu^-$

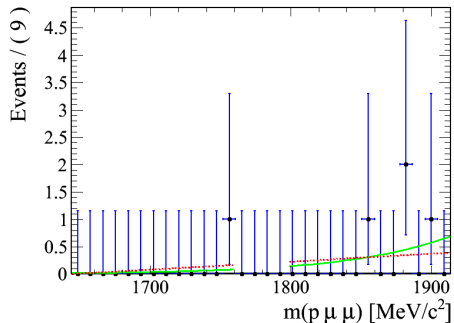


# Background Fits

$$\tau^- \rightarrow p\mu^-\mu^-$$



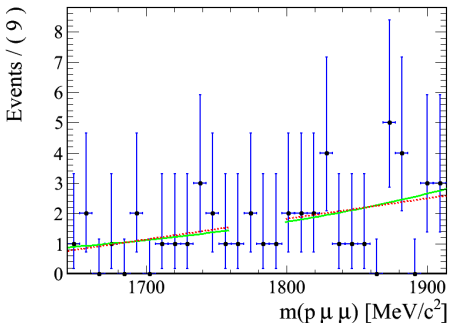
3-body BDT (0.4, 0.7)



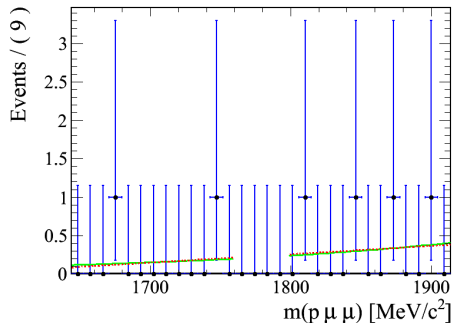
3-body BDT (0.7, 1.0)

# Background Fits

$$\tau^- \rightarrow \bar{p} \mu^- \mu^+$$

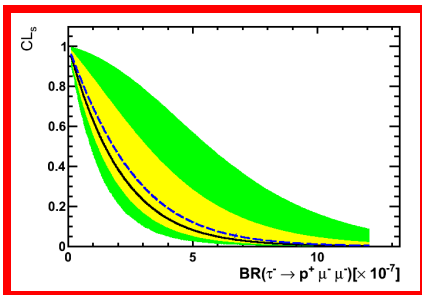
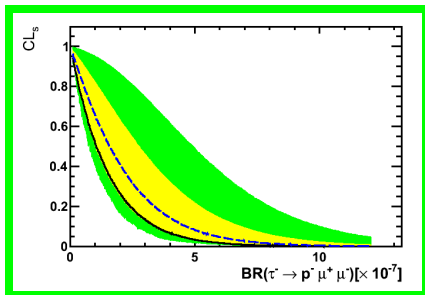


3-body BDT (0.4, 0.7)



3-body BDT (0.7, 1.0)

# Limits on $\tau^- \rightarrow \bar{p}\mu^-\mu^+$ and $\tau^- \rightarrow p\mu^-\mu^-$



CL	Observed	Expected
90%	$3.4 \times 10^{-7}$ $4.6 \times 10^{-7}$	$4.7 \times 10^{-7}$ $5.4 \times 10^{-7}$
95%	$4.5 \times 10^{-7}$ $6.0 \times 10^{-7}$	$5.9 \times 10^{-7}$ $6.9 \times 10^{-7}$

First time measured!!

# Summary

- ① LNV, LFV and BNV still hidden from us.
- ② First upper limits for  $\tau$  LFV and LNV in hadron colliders.
- ③ LHCb catching up  $\mathcal{B}$  factories.
- ④ First search for  $\mathcal{B}(\tau \rightarrow p\mu\mu)$ .

Thank you for your attention.

Work partially funded by the Polish Ministry of Science and Higher Education under the "Diamond Grant"

# Backup Slides