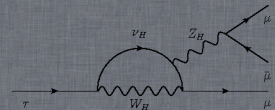
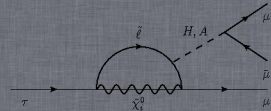


Rare decays @ LHCb

Marcin Chrzęszcz

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

7th January 2013



Overview of LHCbs rare decays

Lepton Number Violation

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

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

τ decays

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

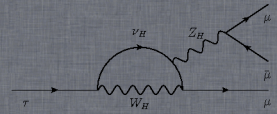
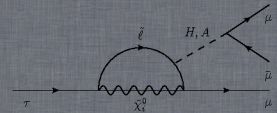
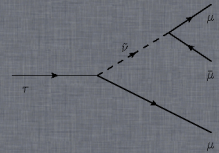
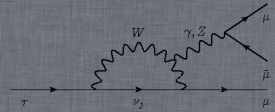
$$\tau^- \rightarrow \bar{p} \mu^- \mu^+, \tau^- \rightarrow p \mu^- \mu^-$$

Higgs Penguins

$$K_S^0 \rightarrow \mu\mu$$

$$D^0 \rightarrow \mu\mu$$

$$B_s^0 \rightarrow \mu\mu, B^0 \rightarrow \mu\mu$$



Rare decays LHCb

- ① Lepton Flavour Lepton/Baryon Number Violating B, τ decays.
- ② Precision tests of Higgs penguins.
 - Purely leptonic B, D, K decays.
- ③ Radiative decays.
 - CP asymmetry in $B^0 \rightarrow K^* \gamma$
- ④ New Vector or Axial couplings in EW Penguins
 - Angular analysis and CP asymmetry in $b \rightarrow s \mu \mu$ transitions.
 - Isospin asymmetry in $b \rightarrow s \mu \mu$ transitions.
 - First observation of $b \rightarrow d \mu \mu$ transition.

Discussed decays

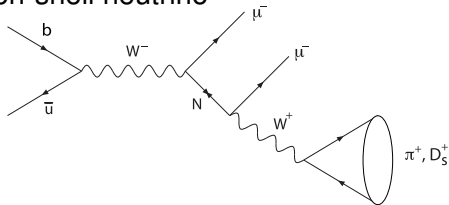
- ① Lepton Flavour Lepton/Baryon Number Violating B, τ decays.
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 - First observation of $b \rightarrow d \mu \mu$ transition.

$$\mathbf{B}^- \rightarrow h^+ \mu^- \mu^-$$

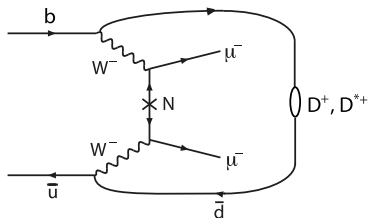
$$\mathbf{B}^- \rightarrow h^+ \ell^- \ell^-$$

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

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 $B \rightarrow D$
Analogous to double β decay.

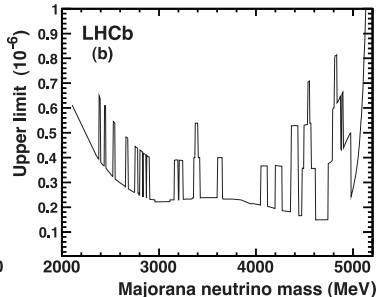
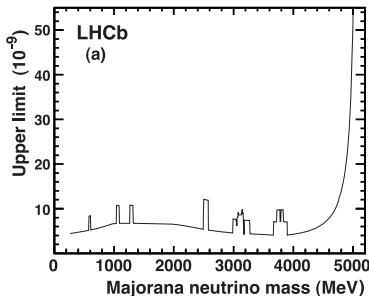
Implications on Majorana mass

mass spectrum

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

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

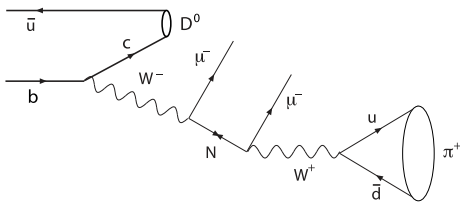
$$B^- \rightarrow D_s^+ \mu^- \mu^-$$



Phys. Rev. D85 (2012)

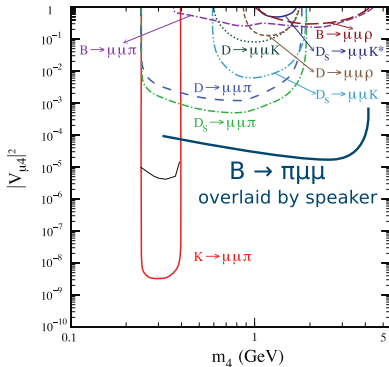
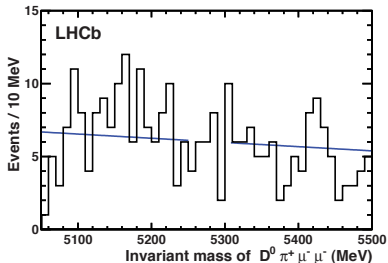
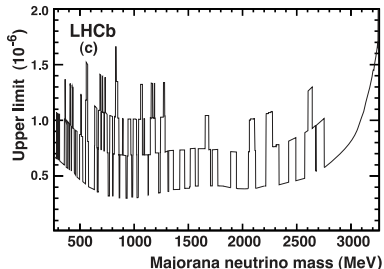
112004, 0.5 fb^{-1} M. Chrzęszcz 2013

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



- 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

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



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

^aLHCb, CERN-PH-EP-2012-006,
arXiv:1201.5600

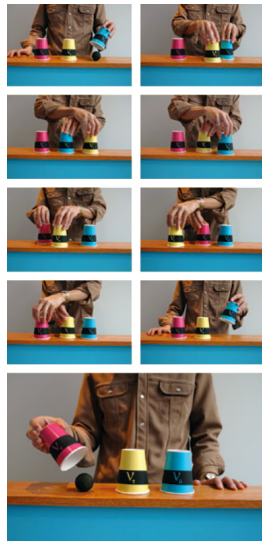
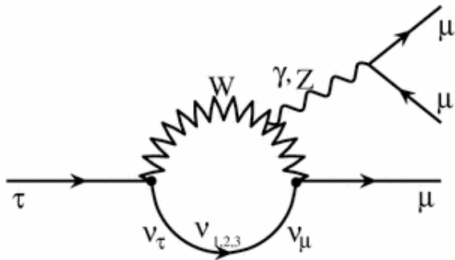
τ decays

① $\tau^- \rightarrow \mu^- \mu^- \mu^+$

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

LFV in τ^- sector

$$\tau \rightarrow \mu\mu\mu$$



LFV in τ^- 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:

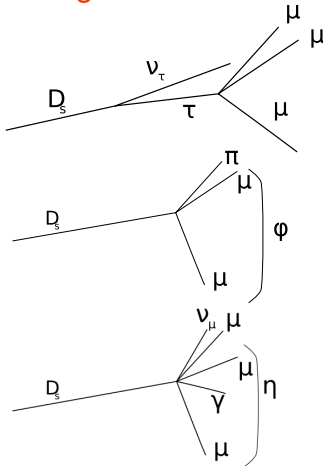
Experiment	90% CL limit
BaBar	3.3×10^{-8}
Belle	2.1×10^{-8}

- ⑤ Can a hadron collider change the picture?

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

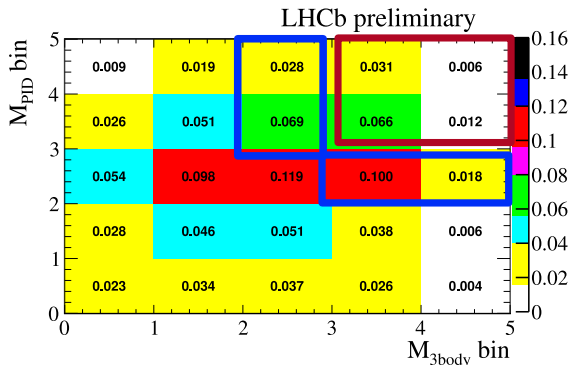


Signal likelihoods

combined signal distribution

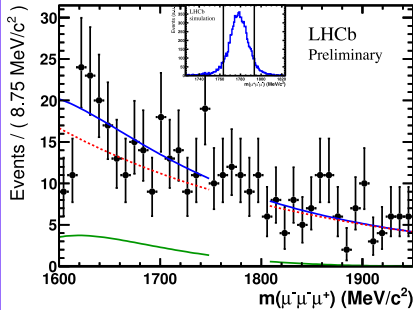
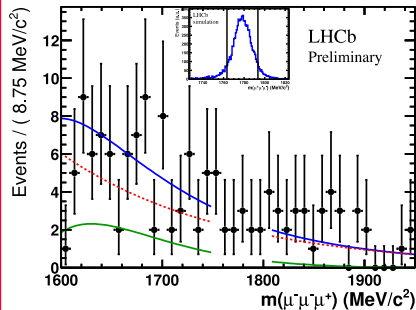
- events distributed over 25 likelihood bins
- background estimate from mass sidebands

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

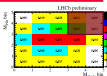


- 11 % signal efficiency
- 21 % signal efficiency
- for illustration: high likelihood range shown

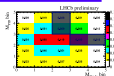
Observed events



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 fb^{-1}

LHCb-CONF-2012-015

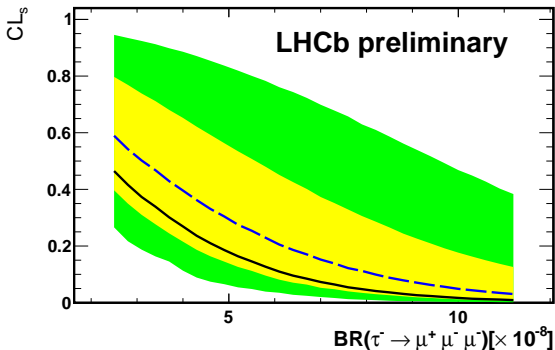
Extracted upper limit



1 fb⁻¹

LHCb-CONF-
2012-015

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



LNV & BNV in τ^- sector

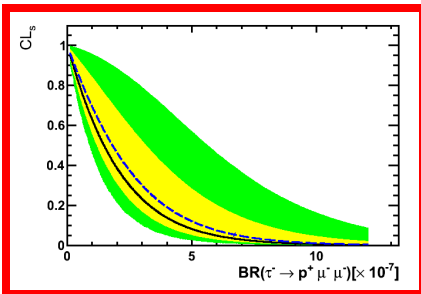
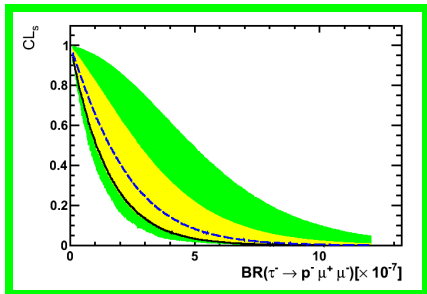
$$\tau^- \rightarrow \bar{\nu} \mu^- \mu^+$$

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


LNV & BNV in τ^- 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 $\tau^- \rightarrow \Lambda h^-$, previously 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 $\tau^- \rightarrow \mu^-\mu^-\mu^+$

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



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

 1 fb^{-1}

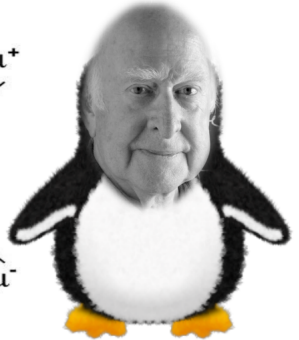
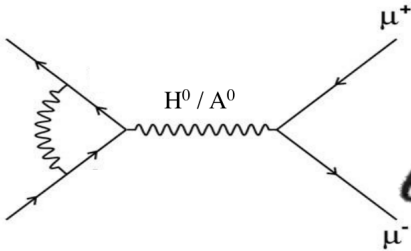
LHCb-CONF-2012-015

First time measured!!

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Purely leptonic decay

$K_s, D^0,$
 B_0, B_s



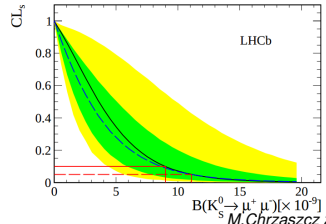
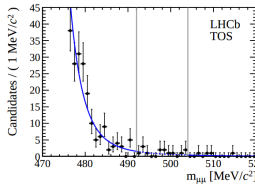
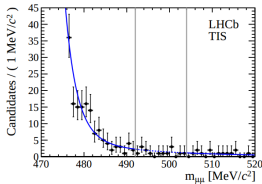
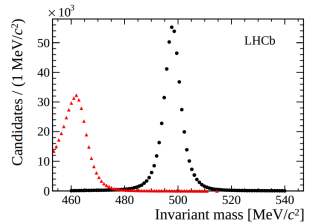
$K_S^0 \rightarrow \mu\mu$

- $\mathcal{B}(K_S^0 \rightarrow \mu\mu)_{SM} = (5.0 \pm 1.5) \times 10^{-12}$
- Good mass resolution enables to separate $K_S^0 \rightarrow \pi\pi$ MisID peak.
- Previous limit $\mathcal{B} < 3.2 \times 10^{-7}$, PLB44 (1973) 217.
- BDT used, trained and calibrated on data.
- Background estimated from upper side bands.
- Normalization $K_S^0 \rightarrow \pi\pi$.
- New LIMIT: $\mathcal{B} < 9 \times 10^{-9}$



1 fb⁻¹

arXiv :1209.4029



M.Chrzęszcz 2013

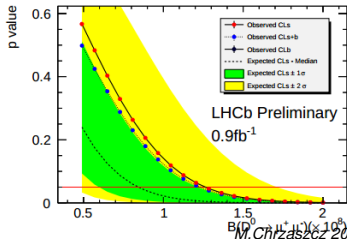
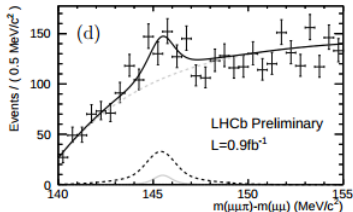
$$D^0 \rightarrow \mu\mu$$



0.9 fb⁻¹

LHCb-CONF-2012-005

- BDT used, Good separation between c and b decays.
- Background estimated from upper side bands.
- Normalization $D^0 \rightarrow \pi\pi$, CLs method for the limit.
- 2D fit to $m(D^0)$ and $m(D^{0*} - D^0)$
- Limit: 1.3×10^{-8} 90% CL.



M. Chrzaszcz 2013

A 25 years journey

DEUTSCHES ELEKTROEN - SYNCHROTRON

DESY

DESY 87-111
September 1987



B MESON DECAYS INTO CHARMONIUM STATES

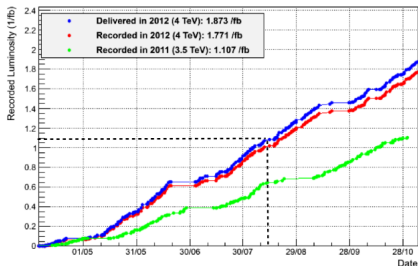
ABSTRACT. Using the ARGUS detector at the e^+e^- storage ring DORIS II, we have studied the colour-suppressed decays $B \rightarrow J/\psi X$ and $B \rightarrow \psi' X$. We find the inclusive branching ratios for these two channels to be $(1.07 \pm 0.16 \pm 0.19)\%$ and $(0.46 \pm 0.17 \pm 0.11)\%$ respectively. From a sample of reconstructed exclusive events the masses of the B^0 and B^+ mesons are determined to be $(5279.5 \pm 1.6 \pm 3.0) \text{ MeV}/c^2$ and $(5278.5 \pm 1.8 \pm 3.0) \text{ MeV}/c^2$ respectively. Branching ratios are determined from five events of the type $B^0 \rightarrow J/\psi K^{*0}$ and three of $B^+ \rightarrow J/\psi K^+$. In the same data sample a search for $B^0 \rightarrow e^+e^-$, $\mu^+\mu^-$ and $\mu^\pm e^\mp$ leads to upper limits for such decays.

Table 2 Upper limits for exclusive dilepton decays.

decay channel	upper limit with 90% CL
$B^0 \rightarrow e^+e^-$	$8.5 \cdot 10^{-5}$
$B^0 \rightarrow \mu^+\mu^-$	$5.0 \cdot 10^{-5}$
$B^0 \rightarrow e^\pm\mu^\mp$	$5.0 \cdot 10^{-5}$

Datasets

- Analyses done using 2011 and 2012 data.
 - 2011: 1.0 fb^{-1} at 7 TeV
 - 2012: 1.1 fb^{-1} at 8 TeV
- Previous analyses done with 2011 data only.
- Published PRL108(2012)231801
- Results:
 - $\mathcal{B}(B_s^0 \rightarrow \mu\mu) < 4.9 \times 10^{-9}$
 - $\mathcal{B}(B^0 \rightarrow \mu\mu) < 1.0 \times 10^{-9}$
- New analysis implements improvements.



Analysis

1 Selection

- Loose selection, for reducing data size.
- Similar for control channels.

2 Normalization

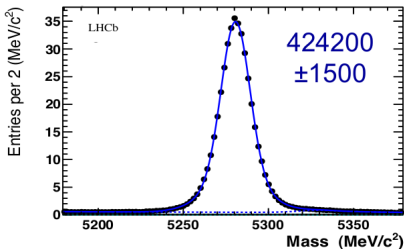
- Makes result more stable.
- Channels: $B^+ \rightarrow J/\psi K^+$ and $B^+ \rightarrow hh$

3 Signal likelihoods

- Same as for 2011 analysis.

4 Invariant mass resolutions:

- $\sigma(B_s^0 \rightarrow \mu\mu) = 25.04 \pm 0.4$
- $\sigma(B^0 \rightarrow \mu\mu) = 24.63 \pm 0.38$
- comparable to 2011.



- Calibration channel & yield.
- Main bck $bb \rightarrow \mu\mu\gamma$
- Number of expected bck extrapolated from sidebands.
- Improved description of peaking background.

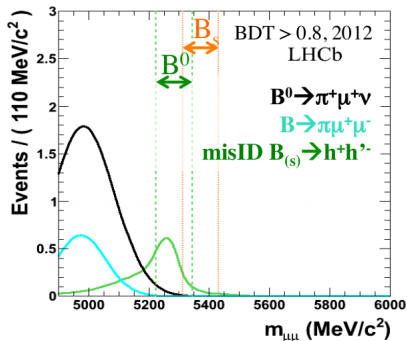
Peaking background

1 Improvement of combinatorial background interpolation by inclusion of exclusive decays in the fit.

- Only $B_s^0 \rightarrow hh$ in the mass window (same as 2011).
- Mass shapes different from exponential
 - $B^0 \rightarrow \pi\mu\nu$
 - $B^+ \rightarrow \pi^+\mu\mu, B^0 \rightarrow \pi^0\mu\mu$
- Negligible contribution to signal window.

2 Exclusive background parameters used in fit as priors.

- Mass shape from MC
- Normalized to $B^+ \rightarrow J/\psi K^+$



Results

- **RESULT:**

$$\mathcal{B}(B_s^0 \rightarrow \mu\mu) = 3.2_{-1.2}^{+1.5} \times 10^{-9}$$

$$\mathcal{B}(B^0 \rightarrow \mu\mu) < 9.4 \times 10^{-10}$$

SM predictions:

$$\mathcal{B}(B_s^0 \rightarrow \mu\mu) = 3.54 \pm 0.3 \times 10^{-9}$$

Buras, Isidori: arXiv:1208.0934

$$\mathcal{B}(B^0 \rightarrow \mu\mu) = 0.1 \pm 0.01 \times 10^{-9}$$

Buras, Isidori: arXiv:1012.1447

- 3.5σ significance.

- Double sided limit 95% CL.

$$1.1 \times 10^{-9} < \mathcal{B}(B_s^0 \rightarrow \mu\mu) <$$

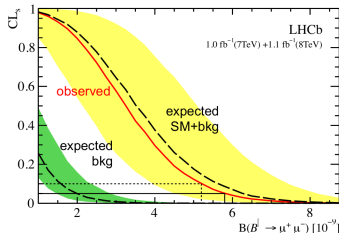
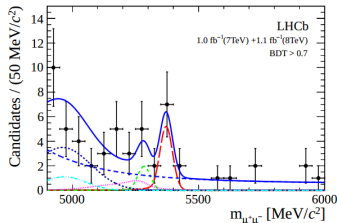
$$6.4 \times 10^{-9}$$

- **FIRST EVIDENCE OF SIGNAL**



2.1 fb⁻¹

arXiv : 1211.2674



Summary













- ① First Evidence of $B_s^0 \rightarrow \mu\mu$, after 25 years of searches.
- ② World's best limits for $B^0 \rightarrow \mu\mu$, $D^0 \rightarrow \mu\mu$, $K_S^0 \rightarrow \mu\mu$
- ③ Strongest constraints on Majorana neutrino coupling.
- ④ First searches for LFV in hadron colliders.
- ⑤ First search for $\mathcal{B}(\tau \rightarrow p\mu\mu)$.
- ⑥ Stay tuned for new results!

Thank you for your attention.

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

Backup Slides

Summary on LNV in B decays

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

^aBaBar, Phys. Rev. D **85**, 071103 (2012)

^bCLEO, Phys. Rev. D **65**, 111102 (2002)

^cBelle, Phys. Rev. D **84**, 071106(R), (2011)

^dLHCb, CERN-PH-EP-2012-006, arXiv:1201.5600 (2012)

^eLHCb, Phys. Rev. Lett. **108** 101601 (2012)

