Search for Charged Lepton Flavour Violation at LHCb experiment

Doctoral disertation

Marcin Chrząszcz
Supervisor: prof. dr hab. Tadeusz Lesiak
Auxiliary supervisor: dr hab. Alberto Lusiani

Henryk Niewodniczanski Institute of Nuclear Physics Polish Academy of Sciences, Cracow, Poland

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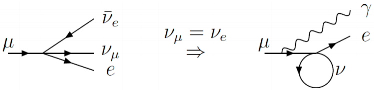
Outline

Lepton Flavour/Number Violation

Lepton Flavour Violation(LFV):
After μ^- was discovered (1936) it was natural to think of it as an excited e^-.

- Expected: $B(\mu \to e\gamma) \approx 10^{-4}$
- Unless there is a nother ν.

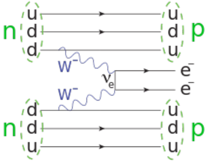


I.I.Rabi:
"Who ordered that?"

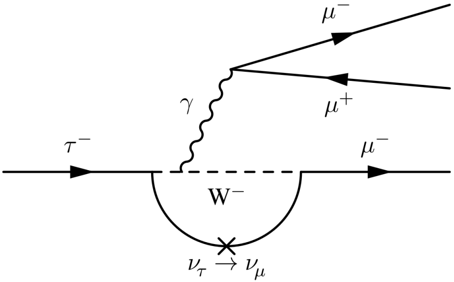
- Up to this day charged LFV is being searched for in various decay modes.
- LFV was already found in neutrino sector (oscillations).

Lepton Number Violation (LNV)

- Even with LFV, lepton number can be a conserved quantity.
- Many NP models predict LNV (Majorana neutrinos)
- LNV searched in s-called neutrinoless double β decays.



Status of searches for $\tau \to \mu\mu\mu$



- Charged Lepton Flavour Violation process.
- The Standard Model contribution: penguin diagram with neutrino oscillation

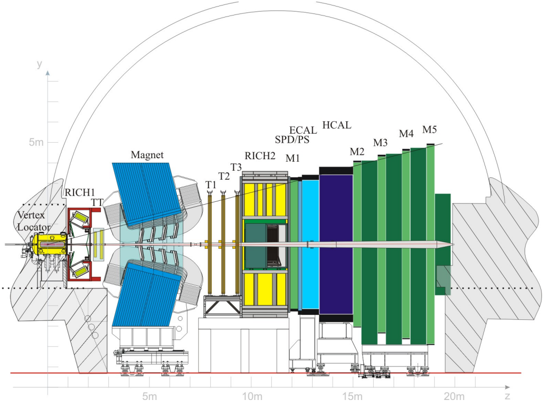
Current limits (90 % CL)

BaBar	3.3×10^{-8}
Belle	2.1×10^{-8}

Predictions

SM	$O(10^{-40})$
var. SUSY	10^{-10}
non universal Z′	10^{-8}
mSUGRA+seesaw	10^{-9}

and many more...



LHCb is a forward spectrometer:

- Excellent vertex resolution.
- Efficient trigger.
- High acceptance for τ and B.
- Superb particle identification (PID).

Strategy

1. Data sample: 1fb^{-1} 7 TeV and 2fb^{-1} 8TeV.
2. Normalization (control) decay channel: $D_s \rightarrow \phi(\mu\mu)\pi$.
3. Blind analysis.
4. Event selection:
   - Preselection of three tracks that combine to give a mass close to m_τ, with desplaised vertex.
   - Selection based on three classifiers:
     - Geometry and topology ($\mathcal{M}_{3body}$)
     - PID ($\mathcal{M}_{PID}$)
     - Three muon invariant mass ($m_{\mu\mu\mu}$)
5. Major background contributions:$D_s \rightarrow \eta(\mu\mu\gamma)\mu\nu$ and $D \rightarrow K\pi\pi$.
6. Evaluation of the upper limit on $\mathcal{B}(\tau \rightarrow \mu\mu\mu)$ using CL_s.

τ production

- τ's in LHCb come from five main sources:

Mode	7 TeV	8 TeV
Prompt $D_s \to \tau$	$71.1 \pm 3.0\,\%$	$72.4 \pm 2.7\,\%$
Prompt $D^+ \to \tau$	$4.1 \pm 0.8\,\%$	$4.2 \pm 0.7\,\%$
Non-prompt $D_s \to \tau$	$9.0 \pm 2.0\,\%$	$8.5 \pm 1.7\,\%$
Non-prompt $D^+ \to \tau$	$0.18 \pm 0.04\,\%$	$0.17 \pm 0.04\,\%$
$X_b \to \tau$	$15.5 \pm 2.7\,\%$	$14.7 \pm 2.3\,\%$

- Pythia produces them in wrong propotions
- Channels were produced seperatly and added in the given proporitons.

$\mathcal{B}(\mathbf{D}^+ \to \boldsymbol{\tau})$

- There is no measurement of $\mathcal{B}(D^+ \to \tau)$.
- One can calculate it from: $\mathcal{B}(D^+ \to \mu\nu_\mu)$ + helicity suppression + phase space, `hep-ex:0604043`.
- $\mathcal{B}(D^+ \to \tau\nu_\tau) = (1.0 \pm 0.1) \times 10^{-3}$.

Triggers at LHCb

- LHCb uses complex trigger, $\mathcal{O}(100)$ trigger lines.
- Lines change with data taking.
- Optimized choice of triggers based on $\frac{s}{\sqrt{b}}$ FOM,

$$\varepsilon(\beta)'_{\text{evt},\text{line}} = \frac{N(\tau\ \text{MC(BKG) events triggered line, but not by any better line})}{N(\tau\ \text{MC(BKG) events triggered by any line})},$$

$$\text{CTFM} = \frac{\sqrt{\sum_{\text{trigger lines}} \beta'_{\text{evt},\text{line}}}}{\sum_{\text{trigger lines}} \varepsilon'_{\text{evt},\text{line}}}$$

- Evaluated different triggers used in 2012 data taking.
- Found negligible differences in trigger efficiencies.

name	ε'	β'	CTFM
Hlt2TriMuonTauDecision	0.880708	0.736182	0.974228
Hlt2DiMuonDetachedDecision	0.0669841	0.173396	1.00636
Hlt2CharmSemilep3bodyD2KMuMuDecision	0.0206816	0.0182935	0.99472
Hlt2CharmHadD2HHHDecision	0.00554351	0.00666405	0.992604
Hlt2CharmSemilep3bodyD2KMuMuSSDecision	0.00195444	0.00470404	0.993106
Hlt2CharmSemilep3bodyD2PiMuMuDecision	0.00206105	0.00679472	0.994591
Hlt2TopoMu3BodyBBDTDecision	0.00394442	0.0121521	0.996937

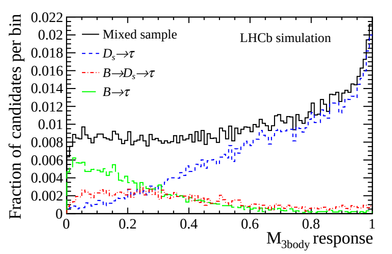
Geometric likelihood

- As mentioned in LHC we have different production sources of τ's.
- Each source has different detector response signature.
- To maximise our performance we trained classifiers for each of the τ sources using:
  - Kinematic properties of τ candidate.
  - Geometric properties of τ candidate, like pointing angle, DOCA, Vertex χ^2, flight distance.
  - Isolations, for vertex and individual tracks.
- After training the individual classifiers one that combines all this information in a single classifier on mixed sample of τ's.
- This technique is known as Blending or Ensemble learning.
- Using this approach we gain 6% sensitivity!

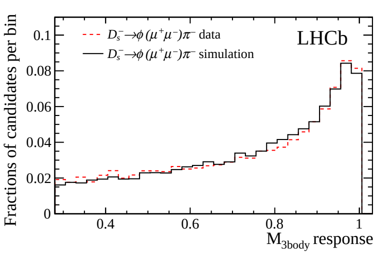
Performance of Blend classifier

- Classifier prefers τ's from prompt D_s, the dominant channel.

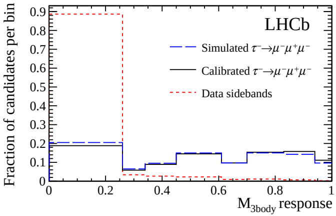
MC response for different τ production channels



Response for $D_s \to \phi\pi$ data and MC



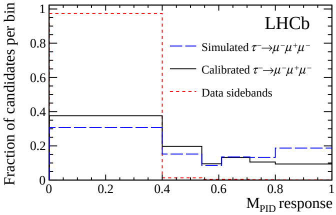
- Assume all differences between $\tau \to \mu\mu\mu$ and $D_s \to \phi\pi$ come from kinematics (mass, resonance, decay time), which is correct in MC.
- Get correction $D_s \rightsquigarrow \tau$ from MC.
- Apply corrections to $D_s \to \phi\pi$ on data.



- $D_s \to \phi\pi$ well modelled in MC.

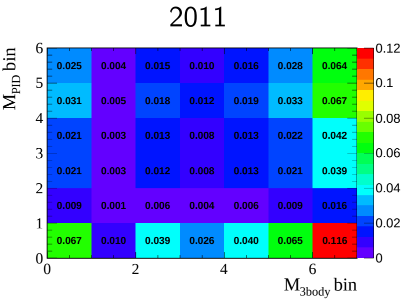
Particle Identification (PID)

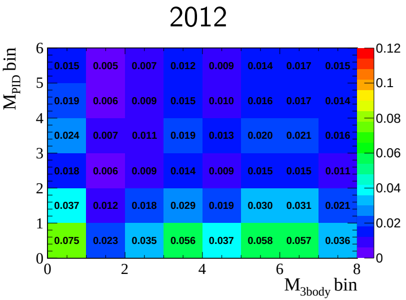
- Classifier trained on inclusive MC sample.
- Using information from: RICH, Calorimeters, Muon system and tracking.
- Correct for the MC efficiency using control channel: $\mathrm{D_s} \rightarrow \phi(\mu\mu)\pi$ and $\mathrm{B} \rightarrow \mathrm{J}/\psi(\mu\mu)\mathrm{K}$



Binning optimisation

- Events are distributed among $\mathcal{M}_{3body}, \mathcal{M}_{PID}$ plane.
- In 2D we group the events in groups(bins)
- Bins are optimised using CL_s method.
- The lowest bins are rejected, because they do not contribute to the limit sensitivity.
- In rest of the bins a fit to mass side-bands is performed in order to estimate number of expected background in signal window.

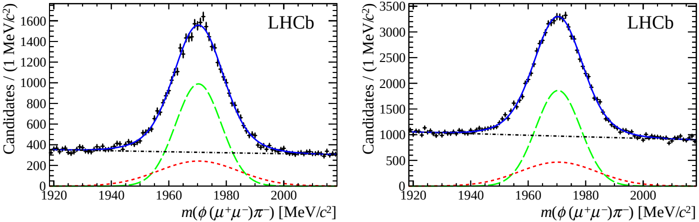




Mass shape

- Double-Gaussian with fixed fraction (70 % inner Gaussian).
- Fix fraction to ease calibration.
- Correct mass by MC:

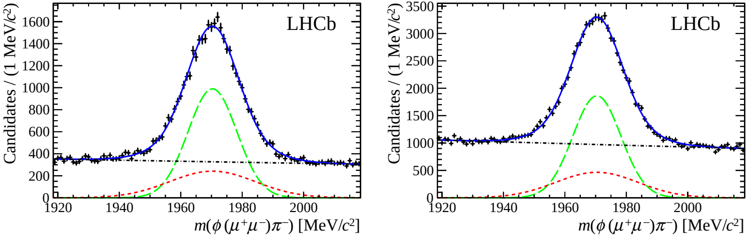
$$\sigma^{\tau}_{data} = \frac{\sigma^{\tau}_{MC}}{\sigma^{D_s}_{MC}} \times \sigma^{D_s}_{data}$$



Calibrated τ Mass shape	7 TeV	8 TeV
Mean (MeV)	1779.1 ± 0.1	1779.0 ± 0.1
σ_1 (MeV)	7.7 ± 0.1	7.6 ± 0.1
σ_2 (MeV)	12.0 ± 0.8	11.5 ± 0.5

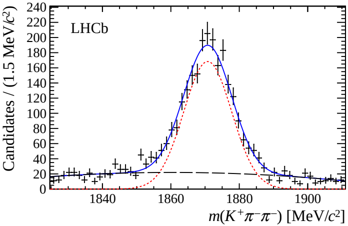
$$\mathcal{B}(\tau \to \mu\mu\mu) = \frac{\mathcal{B}(D_s \to \phi\pi)}{\mathcal{B}(D_s \to \tau\nu_\tau)} \times f^{\tau}_{D_s} \times \frac{\varepsilon_{\text{norm}}}{\varepsilon_{\text{sig}}} \times \frac{N_{\text{sig}}}{N_{\text{norm}}} = \alpha \times N_{\text{sig}}$$

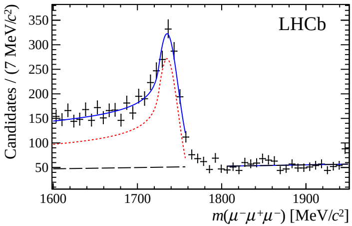
- where ε stands for trigger, reconstruction, selection efficiency.
- $f^{\tau}_{D_s}$ is the fraction of τ coming from D_s.
- norm = normalisation channel $D_s \to \phi\pi$
  i.e. (83 ± 3) % for 2012.

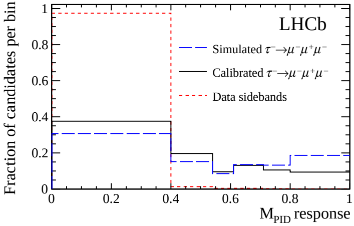


Misidentification

- Most dominant: $D^+ \to K\pi\pi$.
- Also seen $D^+ \to \pi\pi\pi$ and $D_s \to \pi\pi\pi$.
- All contained in the lowest $\mathcal{M}_{PID}$ bin.

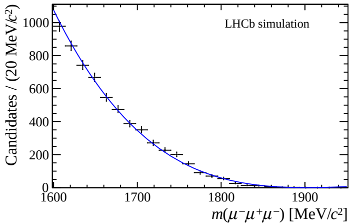


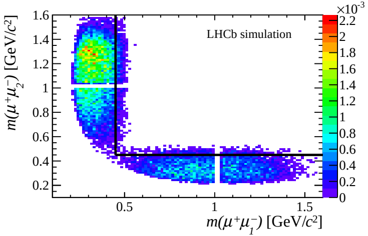




Dangerous backgrounds

- $\phi \to \mu\mu + X$: narrow veto on dimuon mass.
- $D_s \to \eta(\mu\mu\gamma)\mu\nu_\mu$: not so easy:
    - Model it
    - Remove it with dimuon mass cut:
        - Fits better understood.
        - Sensitivity unchanged when removing veto.
        - Smaller uncertainty on expected background.

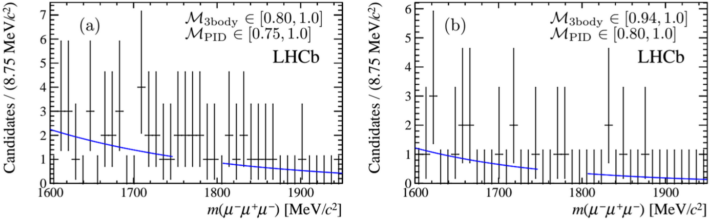




- Fit exponential to invariant mass spectrum in each likelihood bin.
- Don't use blinded region (± 30 MeV).

$\rightarrow$ Compatible results blinding only ± 20 MeV[1]

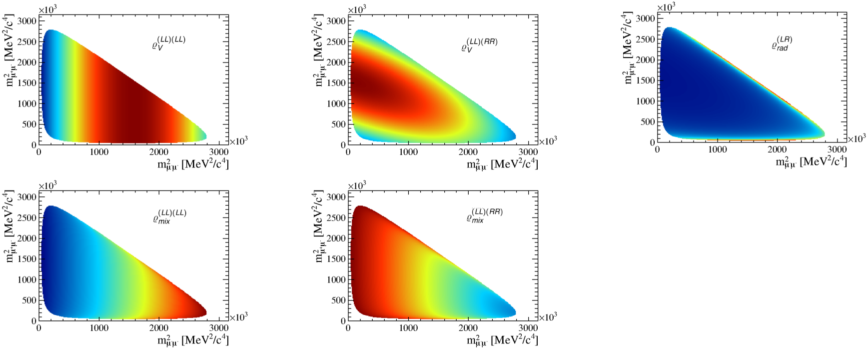
Example of most sensitive regions in 2011 and 2012



[1] partially used in classifier development

Model dependence

- η veto $\Rightarrow$ our limit not constraining to New Physics with small $m_{\mu^+\mu^-}$.
- Model description in arXiv:0707.0988 by S.Turczyk.
- 5 relevant Dalitz distributions: 2 four-point operators, 1 radiative operator, 2 interference terms.



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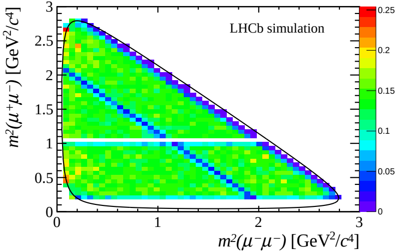
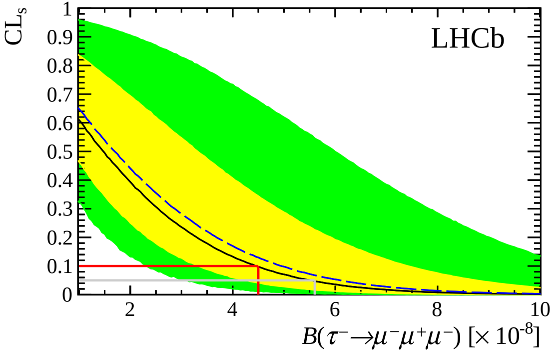
- With radiative distribution limit gets worse by a factor of 1.5 (dominantly from the η veto).
- The other four Dalitz distributions behave nicely (within 7 %).





Limits(PHSP):

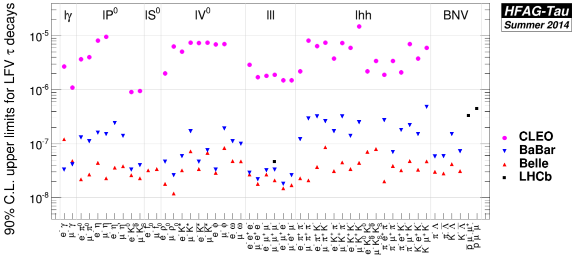
Observed(Expected)

$4.6\ (5.0) \times 10^{-8}$ at 90% CL

$5.6\ (6.1) \times 10^{-8}$ at 95% CL

Dalitz distribution	$\times 10^{-8}$
$\varrho_V^{(LL)(LL)}$	4.2 (4.7)
$\varrho_V^{(LL)(RR)}$	4.1 (4.6)
$\varrho_{rad}^{(LR)}$	6.8 (7.6)
$\varrho_{mix}^{(LL)(LL)}$	4.4 (5.1)
$\varrho_{mix}^{(LL)(RR)}$	4.6 (5.0)

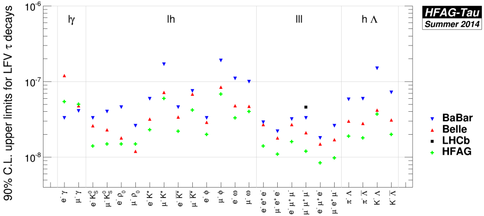
- Searches for LFV in τ sector is a domain of B factories.
- Over last years both BaBar and Belle set very strong limits on branching fractions of several rare τ decays.



- Since thouse limits are used to constraint NP models, their "official" combination is of paramount importance.
- Various methods of limit computation used in Belle and BaBar's studies.
- The HFAQ group recomputed consistently all estimates using the CL_s method and the the same approach was involved in the average evaluation.

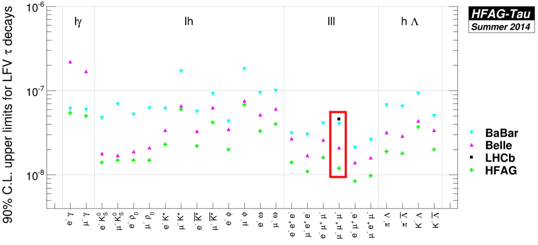
- For each measurement take integrated luminosity ($\mathcal{L}$), cross section ($\sigma_{\tau\tau}$), efficiencies (ϵ), background expected(b) and all systematics.
- Calculate number of signal: $s = \mathcal{L}\sigma_{\tau\tau}\epsilon^{tot}\mathcal{B}(\tau \to LFV)$.
- Scan the CL_s wrt. $\mathcal{B}(\tau \to LFV)$:

$$CL_s = \frac{\prod_{i=1}^{N_{\rm chan}} \sum_{n=0}^{n_i} \frac{e^{-(s_i+b_i)}(s_i+b_i)^n}{n!}}{\prod_{i=1}^{n_{\rm chan}} \sum_{n=0}^{n_i} \frac{e^{-b_i} b_i^n}{n!}},$$



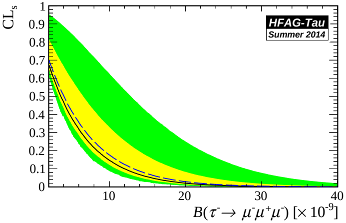
$\tau \to \mu\mu\mu$ limits (90 % CL)

BaBar(FC)	3.3×10^{-8}
Belle(FC)	2.1×10^{-8}
LHCb(CLs)	4.6×10^{-8}
HFAG(CLs)	1.2×10^{-8}



To conclude:

- LHCb is reaching B-factories limits.
- Many new techniques developed to perform this analysis.
- Combination of UL within HFAG gave the best sensitivity for $\mathcal{B}(\tau \to \mu\mu\mu) < 1.2 \times 10^{-8}$ at 90% CL.



Backup

Prof. J.Ciborowski comments

1. Podrozdział (4.10) ten jest de facto zapowiedzią większej pracy. Szkoda, że materiał tu przedstawiony potraktowany został bardzo skrótowo, co wymusiło na mnie konieczność kilkakrotnego przeczytania tego podrozdziału i utrudniło docenienie wyniku otrzymanego przez autora w konfrontacji z przewidywaniami teoretycznymi.

    - The theory part of this was presented in detail in 2.3.4. This chapter is just a showing how to reweight the distributions to a given NP model, thats why I tried to keep it short, but I agree I over did it.

Prof. J.Ciborowski comments

1. Jedyne rzucające się w oczy uchybienie redakcyjne to pomyłki w numerach rozdziałów, których zawartość wymieniona jest pod koniec Wstępu.

- Mea Cupla. Completly missed that.