Lepton Flavour Violation at LHCb

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on behalf of the LHCb collaboration

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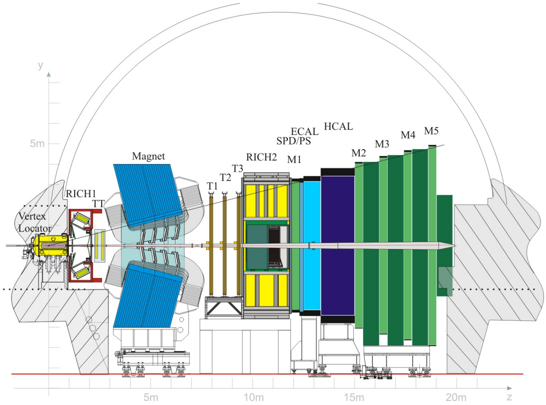
Outline

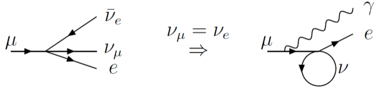


LHCb is a forward spectrometer:

- Excellent vertex resolution.
- Efficient trigger.
- High acceptance for τ and B.
- Great Particle ID

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 another ν, in intermediate vector boson loop, cancels.

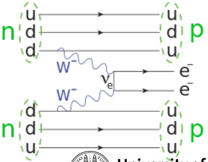


I.I.Rabi:
"Who ordered that?"

- 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) (see J. Harrison talk)

- Even with LFV, lepton number can be a conserved quantity.
- Many NP models predict it violation(Majorana neutrinos)
- Searched in so called Neutrinoless double β decays.



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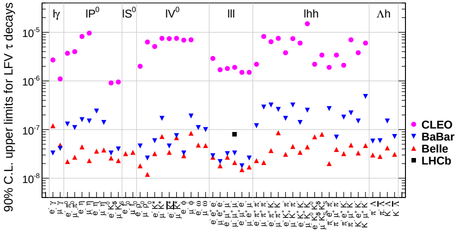
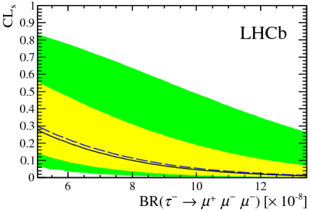
current limits (90 % CL)

BaBar	3.3×10^{-8}
Belle	2.1×10^{-8}
LHCb	8.0×10^{-8} $(1\mathrm{fb}^{-1})$





Today: Update with full LHCb data sample $(3\mathrm{fb}^{-1})$!

Strategy

- Blind analysis.
- Loose selection.
- Multivariate classification in: mass, PID($\mathcal{M}_{PID}$), geometry($\mathcal{M}_{3body}$).
- Binning optimisation.
- Consider 2012(8 TeV) and 2011(7 TeV) data separately.
- Relative normalisation ($D_s \to \phi(\mu\mu)\pi$).
- Invariant mass fit for expected background in each likelihood bin: fit in $|m - m_\tau| > 30$ MeV.
- "middle sidebands" for classifier evaluation and tests: ($20\ \text{MeV} < |m - m_\tau| < 30$ MeV).
- CLs for limit calculation.

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 $D^+ \to \tau$	$0.18 \pm 0.04\,\%$	$0.17 \pm 0.04\,\%$
$X_b \to \tau$	$15.5 \pm 2.7\,\%$	$14.7 \pm 2.3\,\%$

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

- 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[1]
- $\mathcal{O}(100)$ trigger lines.
- Lines change with data taking.
- Optimized choice of triggers based on $\frac{s}{\sqrt{b}}$ FOM.
- Evaluated different triggers used in 2012 data taking.
- Found negligible differences in trigger efficiencies.

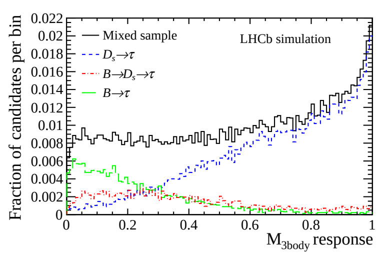
[1] arxiv 1211.3055

Geometric likelihood

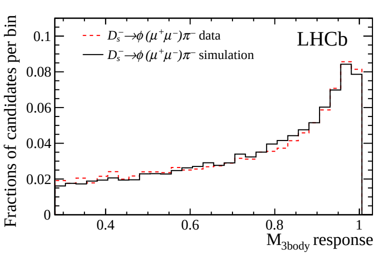
- As mentioned in LHC we have different production sources of τ's.
- Each source has different detector response signature.
- To maximise our performance we trained classifiers for each of the τ sources using:
  - Kinematic properties of τ candidate.
  - Geometric properties of τ candidate, like pointing 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!

- Classifier prefers τ's from prompt $\mathrm{D_s}$, the dominant channel.

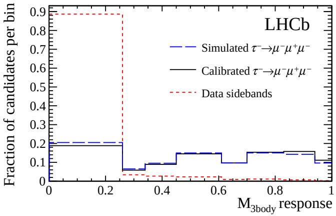
MC response for different τ production channels



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

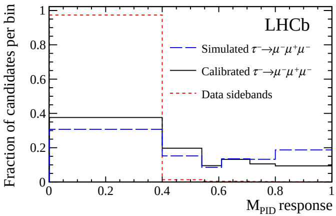


- Assume all differences between $\tau \to \mu\mu\mu$ and $D_s \to \phi\pi$ come from kinematics (mass, resonance, decay time), which is correct in MC.
- Get correction $D_s \rightsquigarrow \tau$ from MC.
- Apply corrections to $D_s \to \phi\pi$ on data.

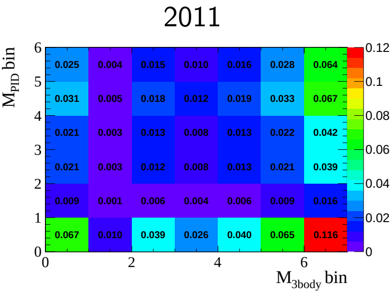


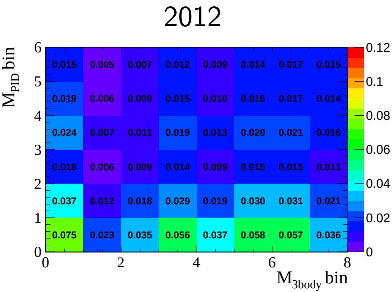
- $D_s \to \phi\pi$ well modelled in MC.

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



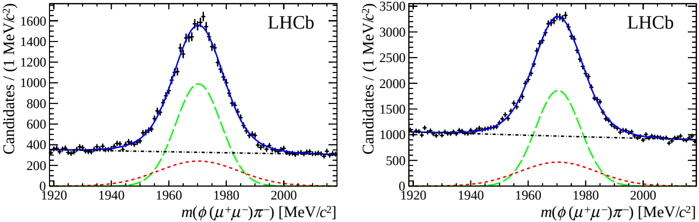
- Events are distributed among $\mathcal{M}_{3body}, \mathcal{M}_{PID}$ plane.
- In 2D we group the events in groups(bins)
- Bins are optimised using CL_s method.
- The lowest bins are rejected, because they do not contribute to the limit sensitivity.
- In rest of the bins a fit to mass side-bands is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





- 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

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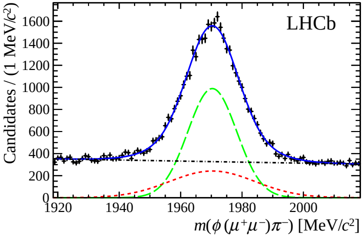
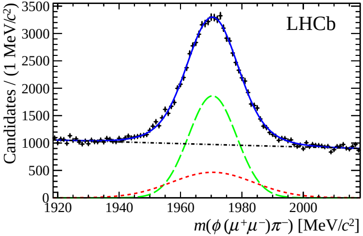
Relative normalisation

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

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





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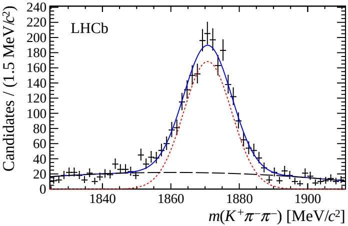
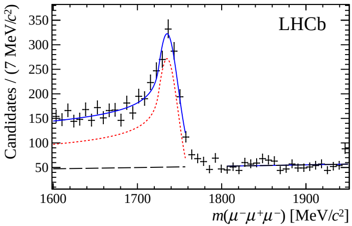
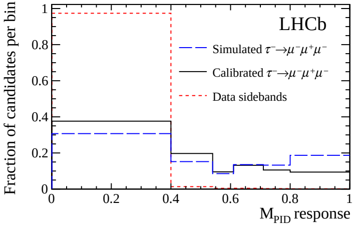
Misidentification

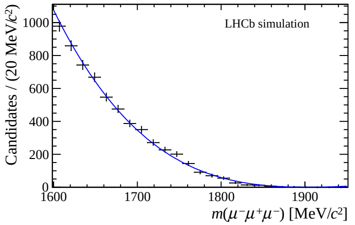
- Most dominant: $D^+ \to K\pi\pi$.
- Also seen $D^+ \to \pi\pi\pi$ and $D_s \to \pi\pi\pi$.
- All contained in the lowest $\mathcal{M}_{PID}$ bin.

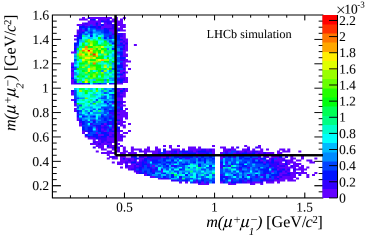






- $\phi \to \mu\mu + X$: narrow veto on dimuon mass.
- $\mathrm{D_s} \to \eta(\mu\mu\gamma)\mu\nu_\mu$: not so easy:
  - Model it
  - Remove it with dimuon mass cut:
    - Fits better understood.
    - Sensitivity unchanged when removing veto.
    - Smaller uncertainty on expected background.



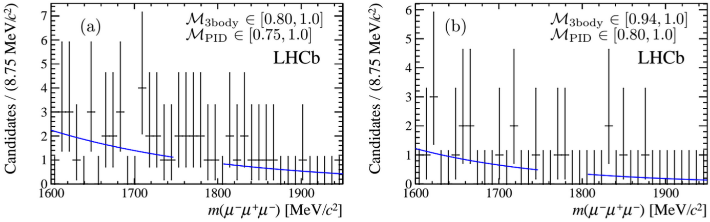


Remaining backgrounds

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

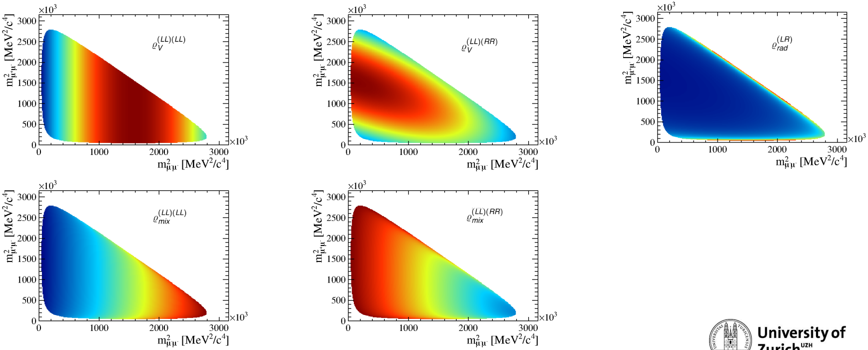
$\rightarrow$ Compatible results blinding only ± 20 MeV[2]

Example of most sensitive regions in 2011 and 2012



[2] partially used in classifier development

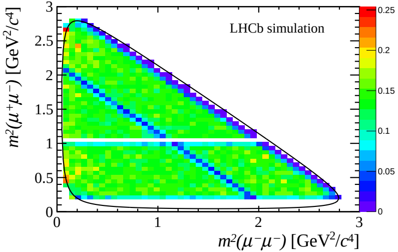
- η veto $\Rightarrow$ our limit not constraining to New Physics with small $m_{\mu^+\mu^-}$.
- Model description in arXiv:0707.0988 by S.Turczyk.
- 5 relevant Dalitz distributions: 2 four-point operators, 1 radiative operator, 2 interference terms.

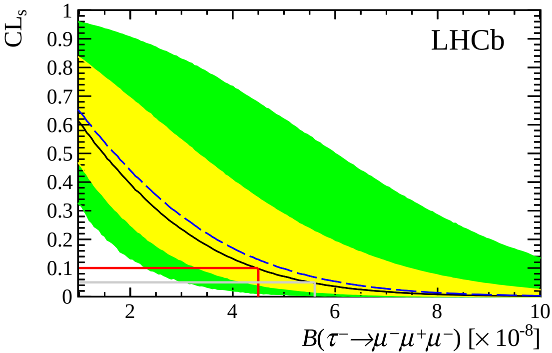


Model dependence

- 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.

- 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)

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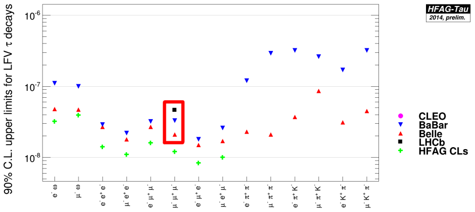
"The Rule of Three"

$\tau \to \mu\mu\mu$ 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}



From A.Lusiani talk

To conclude:

- LHCb updated $\tau \to \mu\mu\mu$ with full data set.
- We are getting close to B-factories.
- Thanks to 3 experiments we have a world limit: $\mathcal{B}(\tau \to \mu\mu\mu) < 1.2 \times 10^{-8}$ at 90% CL.