

Lepton flavour and number violation measurements at LHCb

Marcin Chrząszcz^{1,2}
on behalf of the LHCb collaboration



University of
Zurich^{UZH}



- ¹ University of Zurich,
² Institute of Nuclear Physics, Krakow

Heavy Quarks and Leptons 2014

August 25, 2014

1 LHCb detector

2 Lepton Flavour Violation

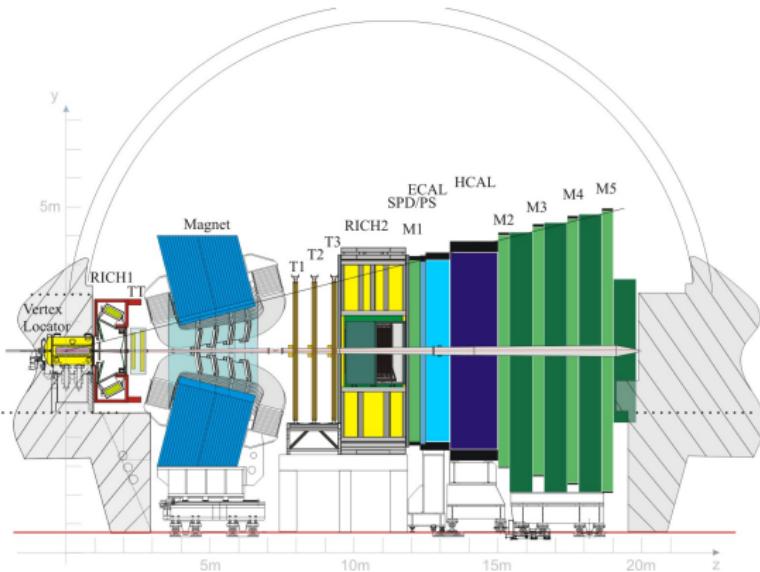
3 B decays

- $B^- \rightarrow h^+ \ell^- \ell^-$
- $B_{(s)} \rightarrow \ell_1^+ \ell_2^-$

4 τ decays

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

LHCb detector



LHCb is a forward spectrometer:

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



University of
Zurich

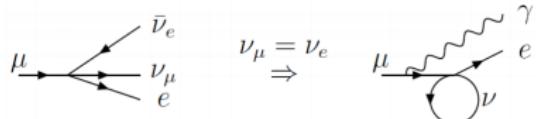


Lepton Flavour/Number Violation

Lepton Flavour Violation(LFV):

After μ^- was discovered it was natural to think of it as an excited e^- .

- Expected: $B(\mu \rightarrow e\gamma) \approx 10^{-4}$
- Unless another ν , in intermediate vector boson loop, cancels.



I.I.Rabi:

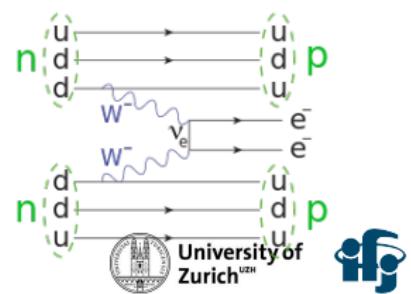
"Who ordered that?"



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

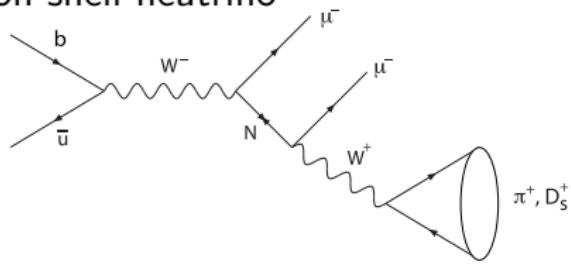
Lepton Number Violation (LNV)

- 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.

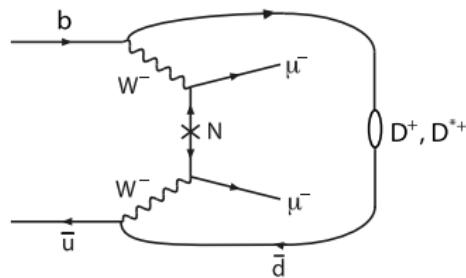


LNV in bottom decays

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)
- $m_4 = m_{\ell^-, \pi^+}$
- $m_\mu + m_\pi < m_4 < m_B - m_\mu$

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

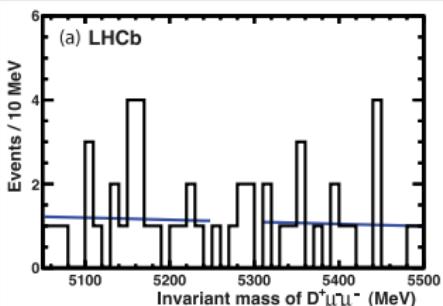


University of
Zurich

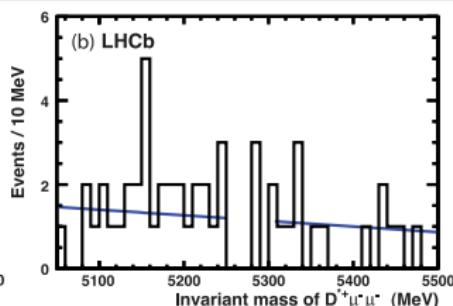


Virtual Majorana neutrinos

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



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



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

@ 95 % CL

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

@ 95 % CL

Based on 0.41 fb^{-1} 7 TeV data.

Phys. Rev.D85 (2012)
112004

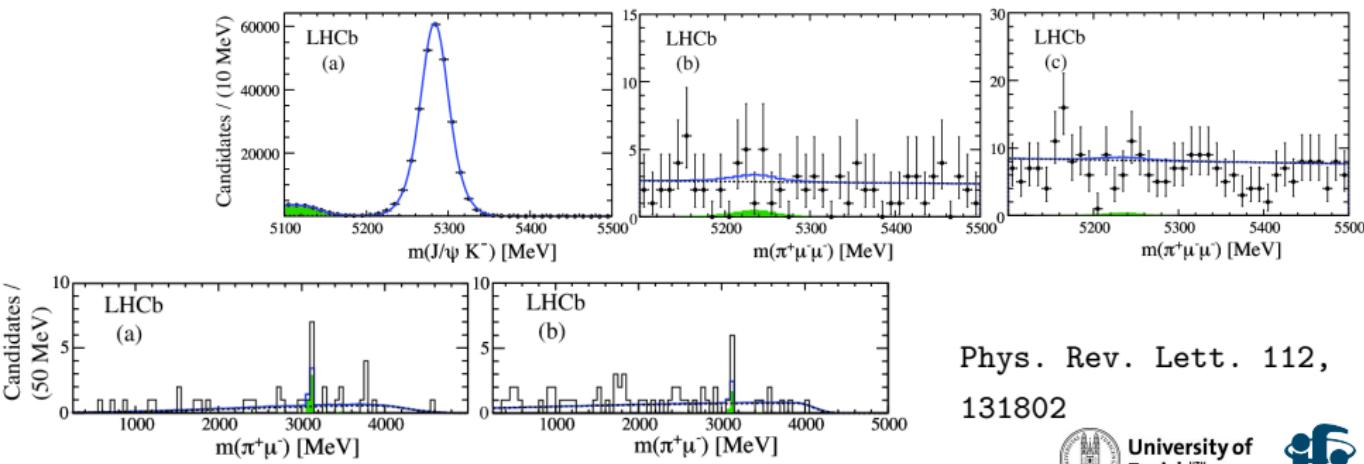


University of
Zurich



On-shell Majorana neutrinos

- $B^- \rightarrow \pi^+ \mu^- \mu^-$ searched with full data set 3 fb^{-1} .
- Cut based analysis.
- Normalization channel $B^+ \rightarrow J/\psi(\mu\mu)K^+$.
- Searches performed for two scenarios:
 - Short life-time neutrinos: $\tau_4 < 1 \text{ ps}$
 - Long life-time neutrinos: $\tau_4 \in (1, 1000) \text{ ps}$



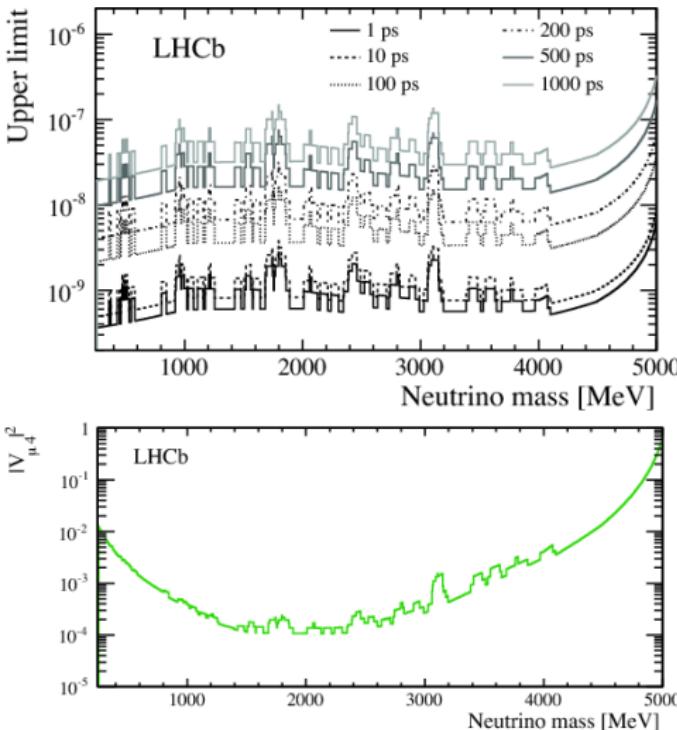
Phys. Rev. Lett. 112,
131802



University of
Zurich



On-shell Majorana neutrinos



- In absence of signal UL. were set.
- $Br(B^- \rightarrow \pi^+ \mu^- \mu^-)$ in range 10^{-9} .
- Limits also set for the coupling $|V_{\mu 4}|^2$

$$Br(B^- \rightarrow \pi^+ \mu^- \mu^-) = \frac{G_f^4 f_B^2 f_\pi^2}{128\pi\hbar} \tau_B m_B^5 |V_{ub} V_{ud}|^2 |V_{\mu 4}|^4 \left(1 - \frac{m_4^2}{m_B^2}\right) \frac{m_4}{\Gamma_{N_4}}$$

Summary on LNV in B decays

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

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

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

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

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

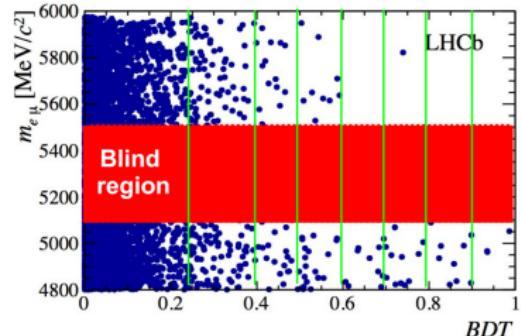
^eLHCb, Phys. Rev. Lett. **(112)** 131802 (2014)



University of
Zurich



- A separate physics interest is LFV B decays.
- Predicted by various NP models: lepto-quarks, SUSY, GUT.
- Analysis based on 1 fb^{-1} 2011 data.
- Analogous to our $B_s^0 \rightarrow \mu\mu$ analysis (PRL 111 (2013) 101804)



- ① Loose preselection based on topology and PID.
- ② Classifier trained on MC signal and $b\bar{b} \rightarrow \ell\ell X$
- ③ Calibration channel: $B_{(s)}^0 \rightarrow h^+ h^-$
- ④ Normalization Channel: $B^0 \rightarrow K^+ \pi^-$
- ⑤ CLs¹ method for limit extraction.

Phys. Rev. Lett.
111, 141801 (2013)



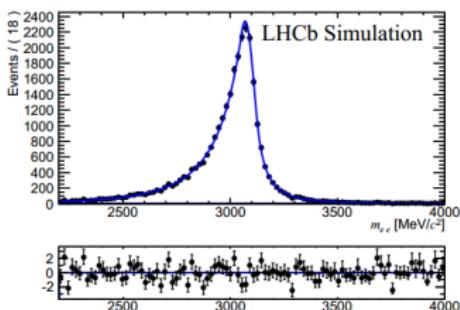
¹A.L.Read, The CLs technique,
Journal of Physics G (2012)

$B_{(s)} \rightarrow e^- \mu^+$ mass calibration

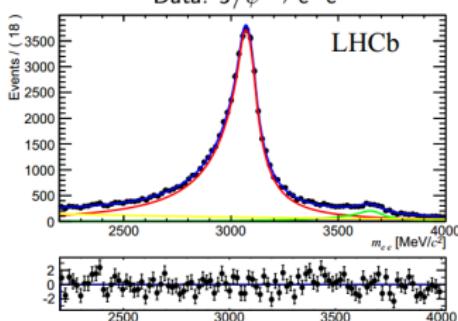
LHCb philosophy: data driven approach when/where possible.

- Electrons undergo Bremsstrahlung → recover the lost energy.
- Re-weight MC to match event multiplicity.
- Parametrize signal shape by Crystal Ball.
- Validate the approach on $J/\psi \rightarrow e^- e^+$.
- Observe agreement between data and MC J/ψ line shape.

Simulation: $J/\psi \rightarrow e^+ e^-$ (not re-weighted)



Data: $J/\psi \rightarrow e^+ e^-$



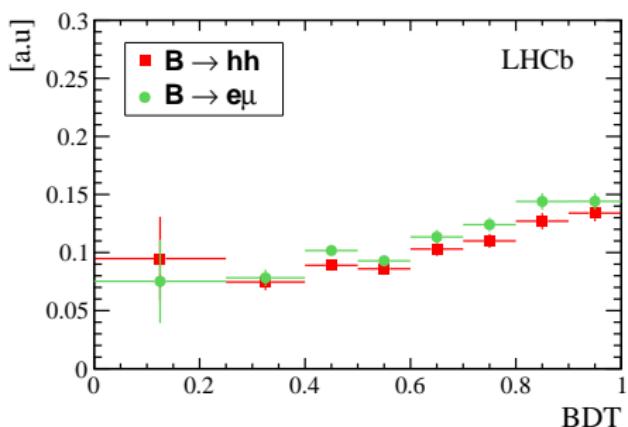
University of
Zurich



$B_{(s)} \rightarrow e^- \mu^+$ BDT calibration

- Hadronic two body B decays are an excellent proxy!
- Same topology and kinematics.
- Select and inclusive sample of $B_{(s)} \rightarrow h^+ h'^-$
- Apply BDT to selected hadronic sample and correct MC signal efficiency:

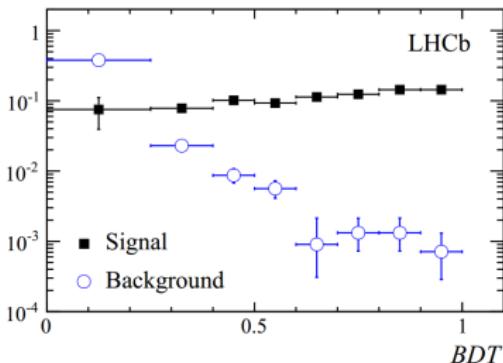
$$\epsilon_{DATA}^{sig} = \frac{\epsilon_{DATA}^{norm}}{\epsilon_{MC}^{norm}} \times \epsilon_{MC}^{sig} \quad (1)$$



- ① $B_{(s)} \rightarrow h^+ h'^-$ BDT shape in data.
- ② $B_{(s)} \rightarrow e\mu$ BDT shape after corrections.

$B_{(s)} \rightarrow e^- \mu^+$ background

- Number of expected background candidates extrapolated from side bands: $[4, 9, 5.0] \cup [5.5, 5.9]$ GeV
- Peaking backgrounds:
 - $B_{(s)} \rightarrow h^+ h^-$, model using miss ID rates.
Expect 4 events in the full BDT range.
- Semileptonic backgrounds:
 - $\Lambda_b \rightarrow p \mu \nu$
 - $B \rightarrow \pi \mu \nu$
 - $B_c^+ \rightarrow J/\psi(\mu\mu) e\nu$
 - $B_c^+ \rightarrow J/\psi(ee) \mu\nu$
- Can be modelled in a fit

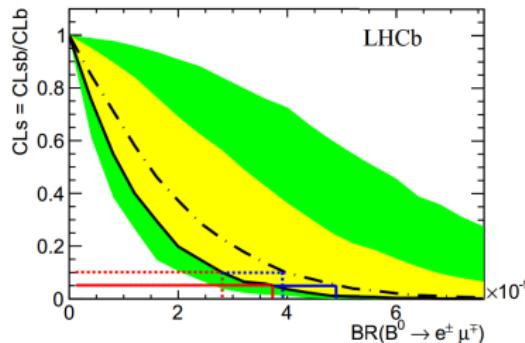
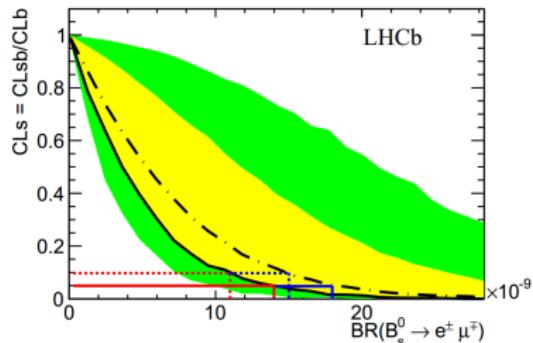


BDT	Expected from sideband fit	$B_{(s)}^0 \rightarrow h^+ h^-$	Observed
0-0.25	2222 ± 51	0.67 ± 0.12	2332
0.25-0.4	$80.9^{+10.1}_{-9.4}$	0.47 ± 0.09	90
0.4-0.5	$20.4^{+5.0}_{-4.5}$	0.40 ± 0.08	19
0.5-0.6	$13.2^{+3.9}_{-3.6}$	0.37 ± 0.06	4
0.6-0.7	$2.1^{+2.9}_{-1.4}$	0.45 ± 0.08	3
0.7-0.8	$3.1^{+1.9}_{-1.4}$	0.49 ± 0.08	3
0.8-0.9	$3.1^{+1.9}_{-1.4}$	0.57 ± 0.09	3
0.9-1.0	$1.7^{+1.4}_{-1.0}$	0.54 ± 0.12	1



University of
Zurich





Upper limits

	$Br(B \rightarrow e\mu)$ @ 90(95)% CL	$Br(B_s \rightarrow e\mu)$ at 90(95)% CL
Expected	$3.8(4.8) \times 10^{-9}$	$1.5(2.0) \times 10^{-8}$
Observed	$1.5(1.8) \times 10^{-9}$	$1.1(1.4) \times 10^{-8}$

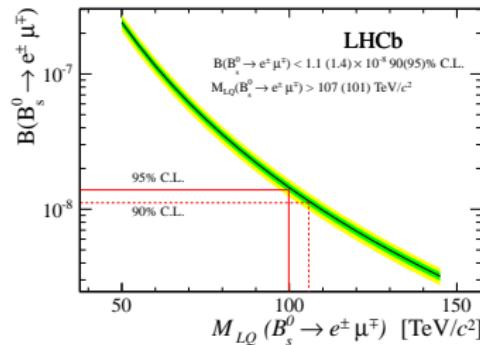
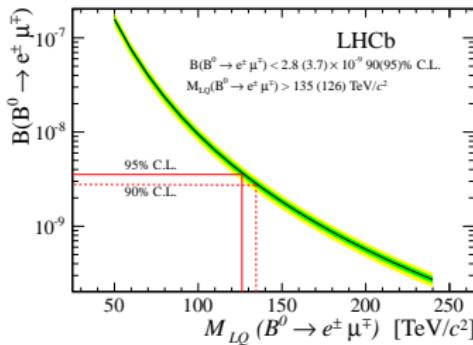


University of
Zurich



$B_{(s)} \rightarrow e^- \mu^+$ Implications

- LHCb limits two times better than previous ones from CDF².
- CDF implications to lepto-quarks mass³.
 - $m_{LQ}(B_s^0 \rightarrow e\mu) > 47.8(44.9)$ TeV 90(95%) @CL.
 - $m_{LQ}(B^0 \rightarrow e\mu) > 59.3(56.3)$ TeV 90(95%) @CL.



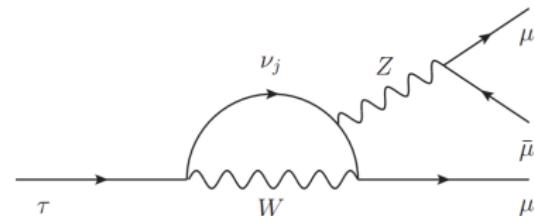
LHCb limits:

- $m_{LQ}(B_s^0 \rightarrow e\mu) > 107(101)$ TeV 90(95%) @CL.
- $m_{LQ}(B^0 \rightarrow e\mu) > 135(126)$ TeV 90(95%) @CL.

²Phys. Rev. Lett. 102 (2009) 201801

³Theoretical formula Phys. Rev. D 50 (1994) 6843

- ➊ In SM small $\mathcal{B}(\tau^- \rightarrow \mu^-\mu^-\mu^+) \sim 10^{-40}$
- ➋ NP can enhance \mathcal{B} .
- ➌ Nature still hides $\tau^- \rightarrow \mu^-\mu^-\mu^+$ from us.
- ➍ Current limits:



Experiment	90% CL limit
BaBar ⁴	3.3×10^{-8}
Belle ⁵	2.1×10^{-8}

- Can a hadron collider change the picture?

⁴Phys. Rev. D81:111101(R), 2010

⁵Phys. Lett. B687:139-143, 2010

Analysis approach

\mathcal{B} factories

- ① signal: $e^+e^- \rightarrow \tau^+\tau^-$
- ② $1.2 \times 10^9 \tau$ pairs
- ③ Calculate the thrust axis
- ④ Tag the other τ
- ⑤ Small cross section $0.919 nb$

LHCb, (7 TeV, 2011 data)

- ① Inclusive τ 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 partial tag possible.



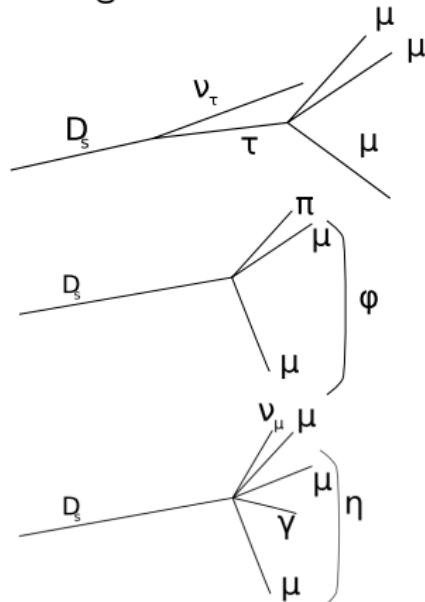
University of
Zurich



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:



University of
Zurich



Signal likelihoods

particle identification

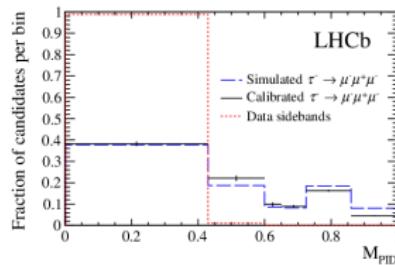
- hits in muon chambers
- energy in calorimeters
 - compatible with MIP
- RICH response

3 body decay likelihood

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

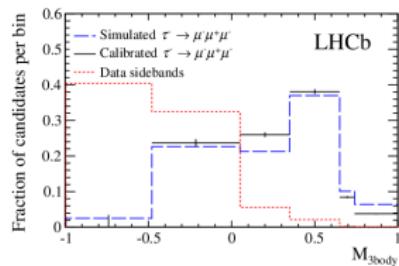
Calibration

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



Calibration

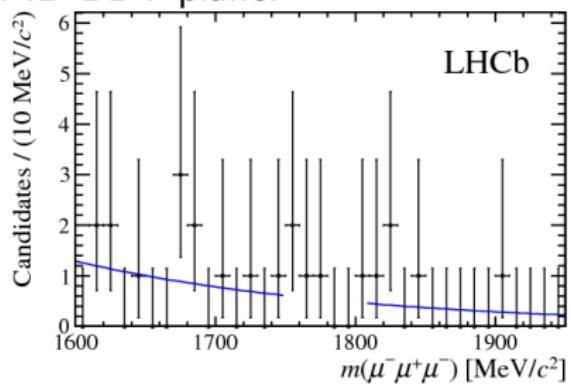
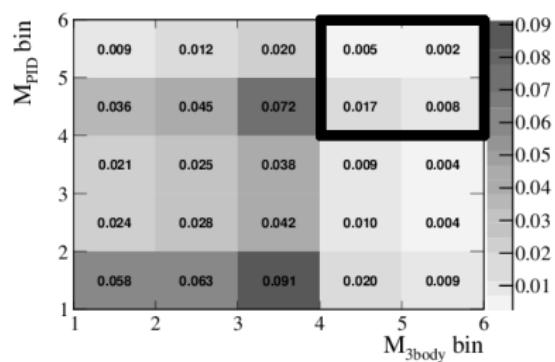
$D_s \rightarrow \phi\pi$



combined signal distribution

- events distributed over 25 likelihood bins
- background estimate from mass side-bands

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



University of
Zurich



Extracted upper limit

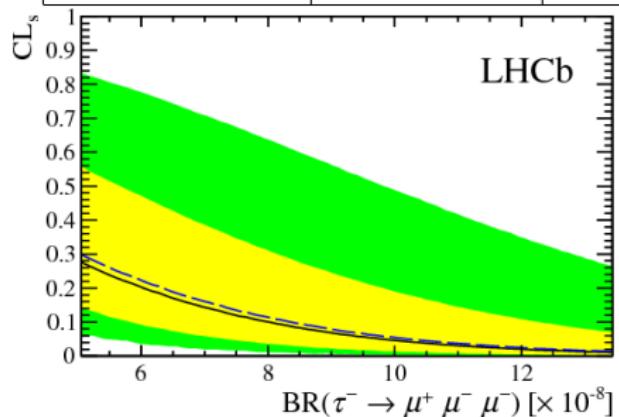
LHCb
THCP

1 fb⁻¹

PLB 724

(2013) 36-45

Upper limits			
	observed	expected	CL
$\mathcal{B}(\tau \rightarrow \mu\mu\mu)$	8.0×10^{-8}	8.3×10^{-8}	90%
	9.8×10^{-8}	10.2×10^{-8}	95%



University of
Zurich



Summary

- Analyses of LFV and LNV processes are going very well in LHCb
- We already have a number of best limits in our hands.
- Stay tuned, more new results coming up soon.