Searches for lepton flavour violation and baryon number violation at LHCb

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on behalf of the LHCb Collaboration

12th International Workshop on Tau Lepton Physics

Nagoya, Japan, 17th-21st September, 2012

MANCHESTER
1824

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

- $\tau^- \rightarrow \mu^- \mu^- \mu^+$ possible in SM + neutrino oscillations, but highly suppressed
 $\rightarrow \mathcal{B} \ll 10^{-40}$
- Rates enhanced by various new physics scenarios e.g. MSSM + massive neutrinos, RPV SUSY, Littlest Higgs with $\mathcal{T}$ -Parity
- Predicted branching fractions for some models **close to current experimental limits** for some regions of parameter spaces

Current status

- $\tau^- \rightarrow \mu^- \mu^- \mu^+$ yet to be observed
- Current experimental limits (at 90% C.L.):

Experiment	Upper limit	Number of $\tau^+\tau^-$ pairs
BaBar ¹	3.3×10^{-8}	430×10^6
Belle ²	2.1×10^{-8}	719×10^6

- But can also set limits at a hadron collider...
(See Diego's talk at 4pm tomorrow for more information on the LHCb detector)

¹Phys. Rev. D 81, 111101 (2010)

²Phys. Lett. B 687, 139-143 (2010)

Analysis strategy

- Inclusive τ cross section is $79.5 \pm 8.3 \mu\text{b}$ at $\sqrt{s} = 7 \text{ TeV}$ in LHCb acceptance
- 1.0 fb^{-1} collected in 2011
 $\rightarrow 8 \times 10^{10} \tau$ produced
- τ mainly from $D_s^- \rightarrow \tau^- \nu_{\bar{\tau}}$ decays (78%)
- Relative normalisation to $D_s^- \rightarrow \phi(\mu^+ \mu^-) \pi^-$
- Loose cut-based selection followed by 3D classification:
 - 1 Decay topology and kinematics
 - 2 Particle identification
 - 3 Invariant mass
- Classifiers trained on simulated signal and calibrated on control channels
- Limit from CL_s method (J. Phys. G: Nucl. Part. Phys. 28 2693)

τ production at LHCb

- Relative contributions to τ production calculated using **LHCb cross section measurements** and LEP/B-factory branching fractions :

Decay chain	Calc (%)
$D_S \rightarrow \tau$	77.9 ± 4.7
$D_s \rightarrow \tau$	67.8 ± 4.8
$B_X \rightarrow D_S \rightarrow \tau$	10.1 ± 2.1
$D^- \rightarrow \tau$	4.6 ± 4.4
$D^- \rightarrow \tau$	4.4 ± 4.2
$B_X \rightarrow D^- \rightarrow \tau$	0.3 ± 0.3
$B_X \rightarrow \tau$	17.5 ± 3.3

- Contributions from Z , W and Drell-Yan are found to be negligible
- Correct MC to agree via reweighting

Event selection

- Events required to pass **LHCb trigger** ($\sim 45\%$ efficient)
- Then selected via:

Cut	$\tau \rightarrow \mu\mu\mu$	$D_s \rightarrow \phi(\mu\mu)\pi$
$\mu^\pm$ and $\pi^\pm$		
p_τ	$> 300 \text{ MeV/c}$	
Track χ^2/N_{dof}	< 4	
IP χ^2/N_{dof}	> 9	
$\phi(1020)$		
Δm	-	$< 20 \text{ MeV/c}^2$
$\tau^\pm$ and $D_s^\pm$		
Δm	$< 400 \text{ MeV/c}^2$	$< 50 \text{ MeV/c}^2$
Vertex χ^2	< 15	
IP χ^2	< 225	
$c\tau$	$> 100\mu\text{m}$	
Lifetime fit χ^2	< 225	

- Also apply clone cut ($m(\mu^+\mu^+) > 250 \text{ MeV/c}^2$) and fiducial cuts
- Analysis performed blind** with $m(\tau) \pm 30 \text{ MeV/c}^2$ excluded initially

$D_s^- \rightarrow \phi(\mu^+\mu^-)\pi^-$ decays in data

- $\mathcal{B}(D_s \rightarrow \phi(\mu\mu)\pi)$ from:

$$\frac{\mathcal{B}(D_s \rightarrow \phi(KK)\pi)}{\mathcal{B}(\phi \rightarrow KK)} \mathcal{B}(\phi \rightarrow \mu\mu) = (1.33 \pm 0.12) \times 10^{-5}$$

- Negligible contribution of non-resonant events in data ($< 2\%$)
- $N_{D_s \rightarrow \phi\pi} = 45\,520 \pm 920$ from a gaussian fit to data
- $\phi(1020)$ reconstructed with a low background level
- Ingredients for normalisation factor (see later)

Signal and background discrimination

- Two multivariate classifiers, $\mathcal{M}_{3\text{body}}$ and $\mathcal{M}_{\text{PID}}$
- Use boosted decision trees with adaptive boosting
- $\mathcal{M}_{3\text{body}}$ includes: vertex and track fit quality, vertex displacement, vertex pointing, vertex isolation and τ p_T

- Trained on signal and background MC
- Calibrated on $D_s^- \rightarrow \phi\pi^-$ data

Signal and background discrimination - $\mathcal{M}_{\text{PID}}$

- $\mathcal{M}_{\text{PID}}$ includes: information from **RICH**, **ECAL**, **HCAL** and **muon chambers**

- Trained on **signal** and **background** MC
- Calibrated on $J/\psi \rightarrow \mu^+ \mu^-$ data

Binning optimisation

- We optimise both the **number** of bins and the **position** of the bin boundaries in the BDTs
- Use an iterative procedure to find the optimum of the figure of merit:

$$\Delta LQ = 2\ln(Q_{SB}) - 2\ln(Q_B)$$

where,

$$Q_{SB} = \prod \frac{P(s_i + b_i, s_i + b_i)}{P(s_i + b_i, b_i)}$$

$$Q_B = \prod \frac{P(b_i, s_i + b_i)}{P(b_i, b_i)}$$

- **5 bins** for both BDTs found to be optimal
- Detailed in arXiv:hep-ex/9706016

$\mu^-\mu^-\mu^+$ mass binning

- Signal mass window defined as $m(\tau) \pm 15\text{MeV}/c^2$
- Divided into 6 equally spaced bins
- Contains $\sim 90\%$ of $\tau^- \rightarrow \mu^-\mu^-\mu^+$ decays

- Both central value of mass window and mass resolution corrected according to measured resolution and scaling at LHCb
- Signal shape in mass window from fit to $D_s^- \rightarrow \phi\pi^-$ events in data

Normalisation factor

$$\mathcal{B}(\tau \rightarrow \mu\mu\mu) = \mathcal{B}(D_s \rightarrow \phi(\mu\mu)\pi) \times \frac{f_{D_s}^\tau}{\mathcal{B}(D_s \rightarrow \tau\nu_\tau)} \times \frac{\epsilon_{D_s \rightarrow \phi\pi}}{\epsilon_{\tau \rightarrow \mu\mu\mu}} \times \frac{N_{\tau \rightarrow \mu\mu\mu}}{N_{D_s \rightarrow \phi\pi}}$$

- $f_{D_s}^\tau$ is the fraction of τ from D_s (78%), from LHCb cross section measurements and LEP/B-factory branching fractions
- $\mathcal{B}(D_s \rightarrow \tau\nu_\tau)$ from arXiv:hep-ex/1201.2401
- ϵ are the efficiencies to select signal and normalisation events, calculated using MC
- **Systematics cancel** in ratio of efficiencies
- $\mathcal{B}(D_s \rightarrow \phi(\mu\mu)\pi)$ and $N_{D_s \rightarrow \phi\pi}$ described earlier

Peaking background: $D_s^- \rightarrow \eta(\mu^+\mu^-\gamma)\mu^-\bar{\nu}_\mu$

- Backgrounds at LHCb from decays of heavy mesons with either:
 - 1 Three real final state muons
 - 2 One or two real muons and one or two mis-identified particles
- Most significant physical background from $D_s^- \rightarrow \eta(\mu^+\mu^-\gamma)\mu^-\bar{\nu}_\mu$
- Consider as a **separate background PDF** in limit calculation with a fixed normalisation
- Shape and magnitude from MC
- Total background PDF is then a **combination** of the above plus an additional **exponential**

Background fits

- Background estimate in signal region from data sidebands
- 4 highest (left), and second 4 highest (right) bins merged
- Combinatorial, $D_s^- \rightarrow \eta(\mu^+\mu^-\gamma)\mu^-\bar{\nu}_\mu$ and combined backgrounds

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

- Limit calculated using CL_s method
- First τ LFV result at a hadron collider
- Detailed in LHCb-CONF-2012-015
- Further improvements expected in 2012

LHCb preliminary

	Expected	Observed
90% C.L.	8.2×10^{-8}	6.3×10^{-8}
95% C.L.	9.9×10^{-8}	7.8×10^{-8}

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

- Search for **baryon number violation** processes so far unsuccessful, but must have occurred in the early universe
- Conservation of angular momentum requires spin 1/2 transfer when nucleon decays to lepton: $\Delta B = \pm\Delta L$, allowing for either $\Delta(B - L) = 0$ or $|\Delta(B - L)| = 2$ transitions, with the former required in the SM and most of its extensions
- Limits on $\tau \rightarrow \Lambda h$ and $B \rightarrow \Lambda l$ in the range $10^{-7} - 10^{-8}$ from BaBar³ and Belle⁴
- Adapt $\tau^- \rightarrow \mu^-\mu^-\mu^+$ analysis to search for $\tau^- \rightarrow \bar{p}\mu^+\mu^-$ and $\tau^- \rightarrow p\mu^-\mu^-$, which are both $\Delta(B - L) = 0$

³Phys. Rev. D 83 (2011) 091101

⁴arXiv:hep-ex/1207.1158

Differences between the analyses

- Use $\mathcal{M}_{3\text{body}}$ with $\tau^- \rightarrow \mu^- \mu^- \mu^+$ tuning
- Apply **hard PID cuts** to reject background, optimised on **signal MC** and **outer data sidebands**
- Bin in $5 \times \mathcal{M}_{3\text{body}}$
 (top: $\tau^- \rightarrow \bar{\rho} \mu^+ \mu^-$,
 middle: $\tau^- \rightarrow \rho \mu^- \mu^-$)
 and $6 \times p\mu\mu$ **mass** (bottom: both)
- Normalisation factor is $\sim 25 \times$ **larger** due to lower trigger efficiency and use of PID cuts instead of BDT
- No peaking backgrounds expected

Background fits for $\tau \rightarrow \rho \mu \mu$

$\mathcal{M}_{3\text{body}}: 0.4 - 0.7$

$\mathcal{M}_{3\text{body}}: 0.7 - 1.0$

- Highest bins in $\mathcal{M}_{3\text{body}}$ for $\tau^- \rightarrow \bar{\rho} \mu^+ \mu^-$ (left) and $\tau^- \rightarrow \rho \mu^- \mu^-$ (right)

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

LHCb preliminary

	Expected	Observed
90% C.L.	$4.7(5.4) \times 10^{-7}$	$3.4(4.6) \times 10^{-7}$
95% C.L.	$5.9(6.9) \times 10^{-7}$	$4.5(6.0) \times 10^{-7}$

- Detailed in LHCb-CONF-2012-027
- **First limits** for these decays!

Summary

- LHCb has made the **first LFV measurements** at a hadron collider with $\tau^- \rightarrow \mu^- \mu^- \mu^+$
- Expect to reach/exceed B-factory limits in coming years
- First ever measurements of $\tau^- \rightarrow \bar{p} \mu^+ \mu^-$ and $\tau^- \rightarrow p \mu^- \mu^-$

Channel	Expected (90% C.L.)	Observed (90% C.L.)
$\tau^- \rightarrow \mu^- \mu^- \mu^+$	8.2×10^{-8}	6.3×10^{-8}
$\tau^- \rightarrow \bar{p} \mu^+ \mu^-$	4.7×10^{-7}	3.4×10^{-7}
$\tau^- \rightarrow p \mu^- \mu^-$	5.4×10^{-7}	4.6×10^{-7}

- LHCb can make **significant contributions** to the searches for LFV and BNV

LHCb performance in 2012

- Since the start of 2012 LHCb is collecting data at $\sqrt{s} = 8$ TeV
- Charm cross-section is $\sim 15\%$ higher

- Aiming to collect $\sim 2\text{fb}^{-1}$ before the 2013–2014 shutdown

Systematics

- Normalisation factor contains systematic uncertainties from (in order of relative magnitude):
 - 1 τ production reweighting
 - 2 Particle ID cut efficiencies
 - 3 Trigger efficiency
 - 4 Background subtracted $D_s \rightarrow \phi\pi$ yield
 - 5 LHCb muon identification efficiency
 - 6 Track reconstruction efficiency
 - 7 Vertex IP resolution smearing in MC
- Difference between exponential and linear background fits included as systematic on background PDF

Observed and expected pattern of events: $\tau^- \rightarrow \mu^- \mu^- \mu^+$

$\mathcal{M}_{PID}$	$\mathcal{M}_{3body}$	expected background	observed events
-1.0, -0.25	-1.0, 0.05	24372 ± 50	23763
-1.0, -0.25	0.05, 0.35	1563 ± 13	1454
-1.0, -0.25	0.35, 0.55	407.7 ± 6.4	298
-1.0, -0.25	0.55, 0.75	144.8 ± 3.7	86
-1.0, -0.25	0.75, 1.0	12.9 ± 1.0	11
-0.25, -0.125	-1.0, 0.05	4530 ± 22	4410
-0.25, -0.125	0.05, 0.35	361.5 ± 6.1	340
-0.25, -0.125	0.35, 0.55	87.8 ± 3.9	67
-0.25, -0.125	0.55, 0.75	32.7 ± 1.8	21
-0.25, -0.125	0.75, 1.0	2.79 ± 0.53	3
-0.125, -0.025	-1.0, 0.05	2103 ± 15	2061
-0.125, -0.025	0.05, 0.35	209.0 ± 4.8	194
-0.125, -0.025	0.35, 0.55	56.8 ± 2.4	54
-0.125, -0.025	0.55, 0.75	19.8 ± 1.2	29
-0.125, -0.025	0.75, 1.0	3.28 ± 0.58	1
-0.025, 0.05	-1.0, 0.05	463.7 ± 6.9	460
-0.025, 0.05	0.05, 0.35	49.1 ± 2.2	43
-0.025, 0.05	0.35, 0.55	15.4 ± 1.2	13
-0.025, 0.05	0.55, 0.75	7.10 ± 0.82	3
-0.025, 0.05	0.75, 1.0	0.46 ± 0.17	1
0.05, 1.0	-1.0, 0.05	106.2 ± 3.3	107
0.05, 1.0	0.05, 0.35	8.59 ± 1.8	11
0.05, 1.0	0.35, 0.55	5.85 ± 0.74	5
0.05, 1.0	0.55, 0.75	2.12 ± 0.40	4
0.05, 1.0	0.75, 1.0	0.49 ± 0.20	0

- Lowest likelihood bins found to have no effect on the limit

Model dependence: $\tau^- \rightarrow \mu^- \mu^- \mu^+$

- Branching fraction depends on new physics model which is assumed
- MC samples generated assuming a flat phase space distribution
- Combined selection & trigger efficiency found to remain constant within 15% across the whole dimuon mass spectrum
- BDT response is also flat as a function of dimuon mass

Observed and expected pattern of events: $\tau \rightarrow p\mu\mu$

$\mathcal{M}_{3body}$	Expected background	Observed events
-1.00, -0.05	85.2 ± 3.3	91
-0.05, 0.20	29.5 ± 2.0	32
0.20, 0.40	9.8 ± 1.1	5
0.40, 0.70	5.48 ± 0.85	4
0.70, 1.00	0.78 ± 0.32	0

$\mathcal{M}_{3body}$	Expected background	Observed events
-1.00, -0.05	47.4 ± 2.5	69
-0.05, 0.20	32.0 ± 2.0	33
0.20, 0.40	9.0 ± 1.1	7
0.40, 0.70	6.1 ± 0.90	4
0.70, 1.00	0.65 ± 0.11	0

- Lowest likelihood bin found to have no effect on the limit

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

- $\tau^- \rightarrow \bar{p}\mu^+\mu^-$ and $\tau^- \rightarrow p\mu^-\mu^-$ can probe different NP models:

Channel	$\Delta(\tau)$	$\Delta(\mu)$	$\Delta(\text{baryon})$
$\tau^- \rightarrow \bar{p}\mu^+\mu^-$	-1	0	-1
$\tau^- \rightarrow p\mu^-\mu^-$	-1	+2	+1

- $\tau^- \rightarrow \bar{p}\mu^+\mu^-$ similar to channels studied at BaBar and Belle
- Differences in upper limits due to:
 - 1 LHCb trigger
 - 2 Detector acceptance to pairs of tracks of opposite or same charge
 $\rightarrow \tau^- \rightarrow \bar{p}\mu^+\mu^-$ has slightly better mass resolution
 - 3 Nature of combinatorial background