Charged Lepton Flavor Violation at LHCb

Basem Khanji
On behalf of the LHCb collaboration

Milano-Bicocca, INFN, Italy

8-May-2013

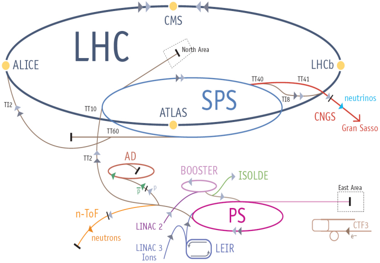
1st Conference on Charged Lepton Flavor Violation , 6-8 May 2013, Lecce (Italy)

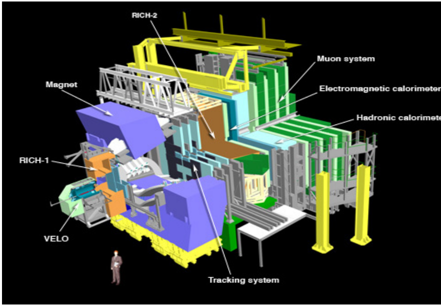
Outlines

1. LHCb experiment
2. Charged Lepton Flavour Violation in τ decays
3. Lepton Number Violation in D & B decays
4. Conclusion

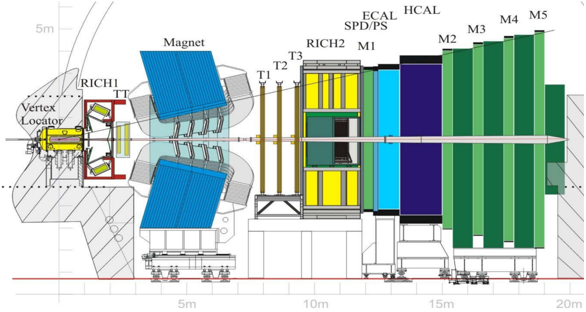
LHCb

- One of LHC four experiments
- LHCb physics:
  - Indirect search for New Physics: probe effects of new particles in loops
  - Designed to search for CP violation & Rare decays in Beauty & Charm
    - $\sigma(b\bar{b}) = (288 \pm 4 \pm 48)\ \mu b^{-1}$
      Eur. Phys. J. C71 (2011) 1645
    - $\sigma(c\bar{c}) = (1419 \pm 12 \pm 116 \pm 65)\ \mu b^{-1}$
      Nucl. Phys. B871 (2013)
- LHCb experiment:
  - Single-arm forward spectrometer
  - Unique η coverage ($2 < \eta < 5$), complementary to ATLAS & CMS



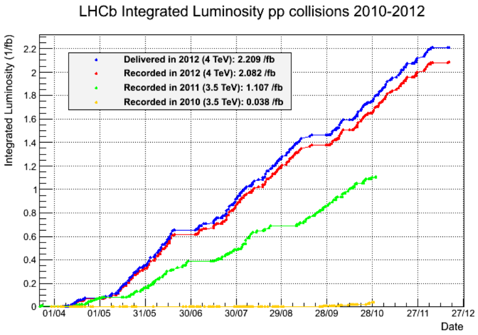


LHCb detector



- VELO: proper time measurement ($\sigma(t) \sim 50$ fs)
- Tracking system & magnet: reconstruct tracks & momentum ($\delta(p)/p \sim 0.4\%$)
- RICH system: $K - \pi$ identification ($2 \rightarrow 100\,\mathrm{GeV}/c$)
- Calorimeter: Energy measurement, identify π^0,γ
- Muon detector: $\epsilon(\mu\mathrm{ID}) \sim 97\%$, low $h \rightarrow \mu$ misID rate
- Trigger: ($40\,\mathrm{MHz} \rightarrow 5\,\mathrm{kHz}$)
  - L0(hardware): lepton, hadron and photon with high p_{T}
  - HLT1(software): partial reconstruction(high IP & p_{T})
  - HLT2(software): full reconstruction, inclusive/exclusive selections

LHCb luminosity



- 2011: $1.0\,\text{fb}^{-1}$ (data taking eff. $\sim 91\%$, $\sqrt{s} = 7\,\text{TeV}$)
- 2012: $2.0\,\text{fb}^{-1}$ (data taking eff. $\sim 94\%$, $\sqrt{s} = 8\,\text{TeV}$)

Results shown in this talk are based on 2011 data sample

Charged Lepton Flavour Violation in τ decays

$$\tau^- \to \mu^+\mu^-\mu^-$$
$$\tau^- \to \bar{p}\mu^+\mu^-$$
$$\tau^- \to p\mu^-\mu^-$$

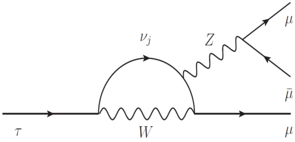
$\tau^- \to \mu^+\mu^-\mu^-$ and $\tau \to p\mu\mu$ @ LHCb

- Large τ cross section ($\sim 10^{11}$ τ per 1 fb^{-1})
  - Inclusive τ cross section: $\sim 80\,\mu\mathrm{b}^{-1}$
  - $\sim 80\%$ from D_s
- Muons provide clear signal in the detector
- RICH gives an excellent proton identification

$$\tau^- \to \mu^+ \mu^- \mu^-$$

Physics case

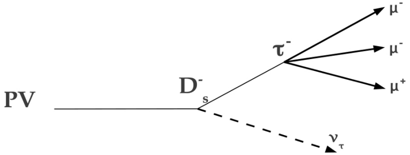
- Neutrino oscillation $\rightarrow$ Charged Lepton Flavour Violation
- cLFV decays through loops
  - $\mathcal{B} < 10^{-50}$, enhanced in New Physics ($\mathcal{B} \sim 10^{-8} - 10^{-10}$)
  - $\mu^- \rightarrow e^-\gamma$, $\tau^- \rightarrow \mu^+\mu^-\mu^-$



- No cLFV τ-decay has yet been observed
  - $\mathcal{B}(\tau^- \rightarrow \mu^+\mu^-\mu^-) < 2.1 \times 10^{-8}$ at 90% C.L. @ Belle (Phys.Lett. B687 (2010) 139-143)

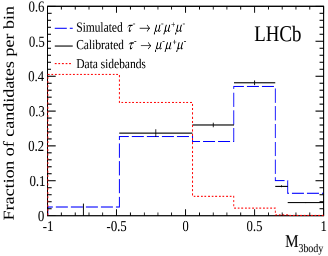
Analysis Strategy

- Trigger + Loose Selections cuts
- Discrimination between signal and backgrounds:
  - $\mathcal{M}_{\mathrm{3body}}$: multivariate likelihood based on decay topology & kinematics
  - $\mathcal{M}_{\mathrm{PID}}$: multivariate likelihood based on 3μ PID
  - Invariant Mass
- Perform the search in bins of $\mathcal{M}_{\mathrm{3body}}$, $\mathcal{M}_{\mathrm{PID}}$ and mass
- Normalization/control channel: $\mathrm{D_s^-} \to \phi(\mu^+\mu^-)\pi^-$
- $\mathrm{CL_s}$ method to set an upper limit on $\mathcal{B}$
- arXiv:1304.4518



$\mathcal{M}_{3\text{body}}$: Geometrical likelihood

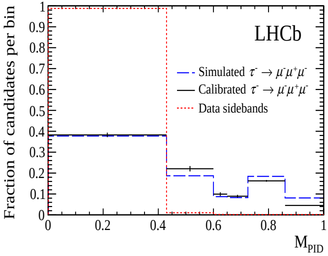
- Uses BDT (adaptive boosting) to separate signal from background
  - Topological information: vertex displacement, pointing & isolation
  - Kinematic information: τ transverse momentum
- Use MC samples (background & signal) to train the classifier



- Calibrated on data using $D_s^- \to \phi(\mu^+\mu^-)\pi^-$
- Binning: Iterative optimization of bin boundaries and location of the bins

$\mathcal{M}_{\text{PID}}$: PID likelihood

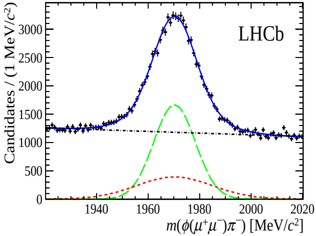
- Use Neural Net to separate signal from background
- Combines information from PID sub-detectors(RICH, Muon system and Calorimeter)
- Use MC samples (background & signal) to train the classifier



- Calibration using $J/\psi \to \mu\mu$ sample
- Binning: Iterative optimization of bin boundaries and location of the bins

$\tau^- \to \mu^+\mu^-\mu^-$ mass Pdf

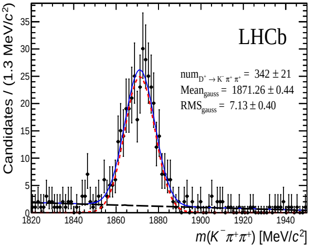
- Mass shape is taken from the $D_s^- \to \phi(\mu^+\mu^-)\pi^-$ in data
- Sum of two Gaussian (one is restricted to be narrower than the second and contribute 70%)
- Offline cuts for $\tau^- \to \mu^+\mu^-\mu^-$



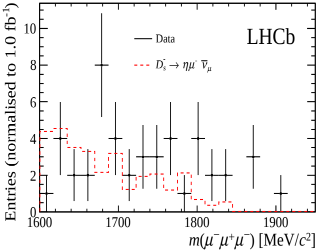
- Fit is also used to get the $D_s^- \to \phi(\mu^+\mu^-)\pi^-$ yield for the normalization

Backgrounds for $\tau^- \to \mu^+\mu^-\mu^-$

- Dominated by combinatorial
- Processes with three mis-ID particles $D^+ \to K^-\pi^+\pi^+$ (peaking background)
  - Concentrated in the lowest $\mathcal{M}_{\text{PID}}$ bin (dropped from the analysis)
- Processes with 3 real muons: $D_s^+ \to \eta(\mu^+\mu^-\gamma)\mu^+\nu_\mu$
  - Can not be removed by $\mathcal{M}_{\text{3body}}$ or $\mathcal{M}_{\text{PID}}$
  - Removed applying a cut on $m_{\mu^+\mu^-} > 450\,\text{MeV}/c^2$ ($\epsilon_{sig} \sim 83\%$)



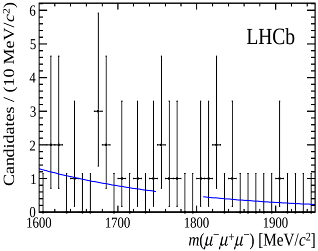
$K^-\pi^+\pi^+$ hypothesis



Dimuon mass

Background yield estimation

- Unbinned extended likelihood fit to the mass sidebands in each bin
- Simple exponential as no specific background survives
- Interpolate to the signal region [1759.18, 1799.18]



- Plot shown here contains 4 bins with the highest S/B

Normalization

- Relative normalization: Convert the signal yield into $\mathcal{B}$ $\rightarrow$ normalize to $\mathrm{D_s^-} \rightarrow \phi(\mu^+\mu^-)\pi^-$
- No lumi or absolute cross section measurements

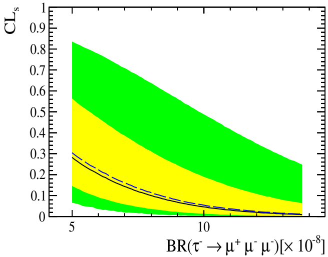
$$\mathcal{B}(\tau^- \rightarrow \mu^+\mu^-\mu^-) = \frac{\mathcal{B}(\mathrm{D_s^-} \rightarrow \phi(\mu^+\mu^-)\pi^-)}{\mathcal{B}(D_s^- \rightarrow \tau^-\nu_{\mp})} \times f^{\tau}_{D_s} \times \frac{\epsilon_{\mathrm{cal}}{}^{\mathrm{REC\&SEL}}\epsilon_{\mathrm{cal}}{}^{\mathrm{TRIG|SEL}}}{\epsilon_{\mathrm{sig}}{}^{\mathrm{REC\&SEL}}\epsilon_{\mathrm{sig}}{}^{\mathrm{TRIG|SEL}}} \times \frac{N_{\mathrm{sig}}}{N_{\mathrm{cal}}} = \alpha \times N_{\mathrm{sig}}$$

	$\tau^- \rightarrow \mu^+\mu^-\mu^-$
$\mathcal{B}(\mathrm{D_s^-} \rightarrow \phi(\mu^+\mu^-)\pi^-)$(PDG)	$(1.33 \pm 0.12) \times 10^{-5}$
$\mathcal{B}(D_s^- \rightarrow \tau^-\nu_{\mp})$(PDG)	0.0561 ± 0.0024
$f^{\tau}_{D_s}$ (LHCb, LEP)	0.78 ± 0.05
$\epsilon_{\mathrm{cal}}{}^{\mathrm{REC\&SEL}}/\epsilon_{\mathrm{sig}}{}^{\mathrm{REC\&SEL}}$(MC)	1.49 ± 0.12
$\epsilon_{\mathrm{cal}}{}^{\mathrm{TRIG}}/\epsilon_{\mathrm{sig}}{}^{\mathrm{TRIG}}$(MC)	0.753 ± 0.037
N_{cal}(Data)	$48\,076 \pm 840$
α	$(4.34 \pm 0.65) \times 10^{-9}$

- New LHCb $\mathrm{c\bar{c}}$, $\mathrm{b\bar{b}}$ cross sections $\rightarrow$ re-weight τ, D_s MC
- Reconstruction and selection efficiencies calculated from MC
  - Systematics evaluated due to re-weighting
  - correction factors to account for MC/data differences

Results

- Expected & observed limit as a function of branching fraction
  - yellow 68% region, green 95% region
- Limits are quoted for the phase-space model of τ decay
  - Variation of efficiencies in Dimuon mass range is small ($< 20\%$)
- Upper limits:



$$\mathcal{B}(\tau^- \to \mu^+\mu^-\mu^-) \quad < \quad 8.3(10.2) \times 10^{-8} \text{ at } 90\% \text{ } (95\%) \text{ CL}$$

little worse than Belle, first upper limit for $\tau^- \to \mu^+\mu^-\mu^-$ in proton collider

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

Physics case

- $\tau^- \to \bar{p}\mu^+\mu^-$ and $\tau^- \to p\mu^-\mu^-$
  - Charged flavour violation & baryon number violation
  - Angular momentum is conserved ($|\Delta(B-L)| = 0$)
  - Observation of those decays is a sign for New Physics
- No measurements exist for the $\tau^- \to \bar{p}\mu^+\mu^-$ and $\tau^- \to p\mu^-\mu^-$ decays

Analysis Strategy for $\tau^- \to \bar{p}\mu^+\mu^-$, $\tau^- \to p\mu^-\mu^-$

- Same as $\tau^- \to \mu^+\mu^-\mu^-$ except:
  - Trigger + Loose Selections cuts
  - Discrimination between signal and backgrounds:
    - $\mathcal{M}_{3\text{body}}$: multivariate likelihood based on decay topology & kinematics
    - PID: Set of cuts applied to the p, μ particles
    - Invariant Mass
  - Normalization/control channel: $D_s^- \to \phi(\mu^+\mu^-)\pi^-$
  - C.L. method to set an upper limit on $\mathcal{B}$
  - arXiv:1304.4518

PID likelihood

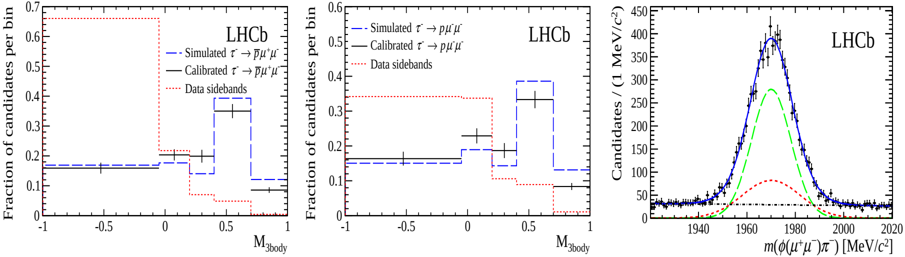
- DLL: difference in the log-likelihood for different particle mass hypotheses
- Optimize cuts according to $\frac{S}{1+\sqrt{B}}$

Cut ($\tau \to p\mu\mu$)
DLL$(\mu - \pi) > 1$
DLL$(\mu - K) > 20$
DLL$(\mathrm{p} - \pi) > 15$
DLL$(\mathrm{p} - K) > 9$

- Optimization: use signal from simulation and background from data sidebands

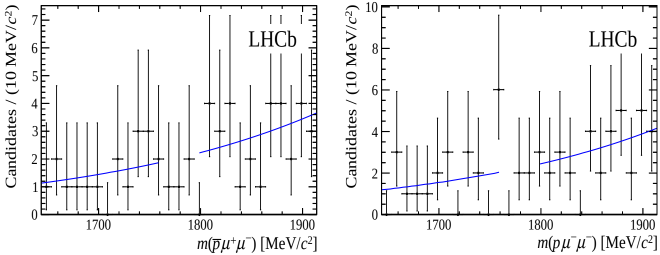
Binning $\tau^- \to \bar{p}\mu^+\mu^-, \tau^- \to p\mu^-\mu^-$

- $\mathcal{M}_{3\text{body}}$ and the mass variables
  - $\mathcal{M}_{3\text{body}}$ binning optimization yields 5 bins
- Mass shape is obtained from $D_s^- \to \phi(\mu^+\mu^-)\pi^-$ mass fit in data



Backgrounds for $\tau^- \to \bar{p}\mu^+\mu^-, \tau^- \to p\mu^-\mu^-$

- Light mesons and an extra pion, kaon or muon
- Contributions from photon conversion in the $\mu^+\mu^-$, muon tracks identified as proton are found negligible
- Expect no peaking backgrounds
- Estimation of Background yield: from $p\mu\mu$ mass side bands



- Plots shown here contains 4 bins with the highest S/B

Normalization

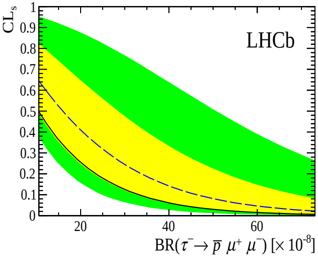
- Relative normalization: Convert the signal yield into $\mathcal{B} \rightarrow$ normalize to $D_s^- \rightarrow \phi(\mu^+\mu^-)\pi^-$
- No lumi or absolute cross section measurements

$$\mathcal{B}(\tau \rightarrow p\mu\mu) = \frac{\mathcal{B}(D_s^- \rightarrow \phi(\mu^+\mu^-)\pi^-)}{\mathcal{B}(D_s^- \rightarrow \tau^-\nu_{\mp})} \times f_{D_s}^{\tau} \times \frac{\epsilon_{\rm cal}{}^{\rm REC\&SEL}\,\epsilon_{\rm cal}{}^{\rm TRIG|SEL}\,\epsilon_{\rm cal}{}^{\rm PID}}{\epsilon_{\rm sig}{}^{\rm REC\&SEL}\,\epsilon_{\rm sig}{}^{\rm TRIG|SEL}\,\epsilon_{\rm sig}{}^{\rm PID}} \times \frac{N_{\rm sig}}{N_{\rm cal}} = \alpha \times N_{\rm sig}$$

	$\tau^- \rightarrow \bar{p}\mu^+\mu^-$	$\tau^- \rightarrow p\mu^-\mu^-$
$\mathcal{B}(D_s^- \rightarrow \phi(\mu^+\mu^-)\pi^-)$(PDG)	$(1.33 \pm 0.12) \times 10^{-5}$	
$\mathcal{B}(D_s^- \rightarrow \tau^-\nu_{\mp})$(PDG)	0.0561 ± 0.0024	
$f_{D_s}^{\tau}$(LHCb, LEP)	0.78 ± 0.05	
$\epsilon_{\rm cal}{}^{\rm REC\&SEL}/\epsilon_{\rm sig}{}^{\rm REC\&SEL}$(MC)	1.35 ± 0.12	1.36 ± 0.12
$\epsilon_{\rm cal}{}^{\rm TRIG}/\epsilon_{\rm sig}{}^{\rm TRIG}$(MC)	1.68 ± 0.10	2.03 ± 0.13
$\epsilon_{\rm cal}{}^{\rm PID}/\epsilon_{\rm sig}{}^{\rm PID}$(MC)	1.43 ± 0.07	1.42 ± 0.08
N_{cal}(Data)	$8\,145 \pm 180$	
α	$(7.4 \pm 1.2) \times 10^{-8}$	$(9.0 \pm 1.5) \times 10^{-8}$

Results

- Expected & observed limit as a function of branching fraction
- Limits are quoted for the phase-space model of τ decay
- Upper limits:



$$\mathcal{B}(\tau^- \to \bar{p}\mu^+\mu^-) < 4.6(5.9) \times 10^{-7} \text{ at } 90\% \ (95\%)\text{CL}$$
$$\mathcal{B}(\tau^- \to p\mu^-\mu^-) < 5.4(6.9) \times 10^{-7} \text{ at } 90\% \ (95\%)\text{CL}$$

First upper limit for $\tau \to p\mu\mu$ ever

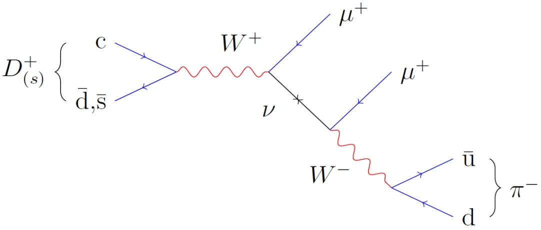
Lepton Number Violation in D & B decays

Lepton Number Violation in D decays

$D^+_{(s)} \to \pi^- \mu^+ \mu^+$

Physics case

- Lepton Number violation is suppressed in $D^+_{(s)} \to \pi^- \mu^+ \mu^+$
- Occur through lepton mixing, mediated by Majorana neutrinos



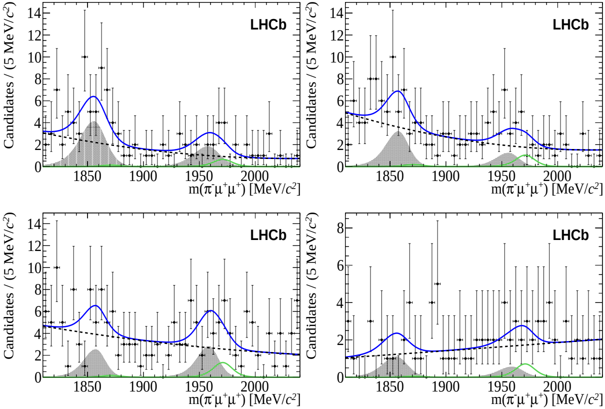
- $\mathcal{B}(D^+ \to \pi^- \mu^+ \mu^+) < 2 \times 10^{-6}$ at 90% C.L. @ BaBar
- $\mathcal{B}(D^+_s \to \pi^- \mu^+ \mu^+) < 14 \times 10^{-6}$ at 90% C.L. @ BaBar

Analysis Strategy

- Trigger + Loose selection
- BDT classifier disentangles signal from background
  - Use topological & kinematic information
- Optimize cuts on BDT & μ PID
- Use $D^+_{(s)} \to \phi(\mu^+\mu^-)\pi^-$ as normalization & control channels
- Fit invariant mass (background-only & signal + background)
- Use CL_s to determine the upper limit
- arXiv:1304.6365

Invariant mass fit

- Split signal sample into 4 bins of $m_{\pi^-\mu^+}$ to increase significance
- Peaking background shape: from $D^+_{(s)} \to \pi^-\pi^+\pi^+$ data sample
- Simultaneous fit amongst 4 bins and the two control & signal sample



Results

- No signal observed, Upper limit is set (assuming phase-space model)
- Systematic uncertainties are included

Bin description	$m(\mu^+\pi^-)$ [MeV/c^2]	90(95)%D^+	90(95)% D_s
bin 1	250 – 1140	1.4(1.7)	6.2(7.6)
bin 2	1140 – 1340	1.1(1.3)	4.4(5.3)
bin 3	1340 – 1550	1.3(1.5)	6.0(7.3)
bin 4	1540 – 2000	1.3(1.5)	7.5(8.7)

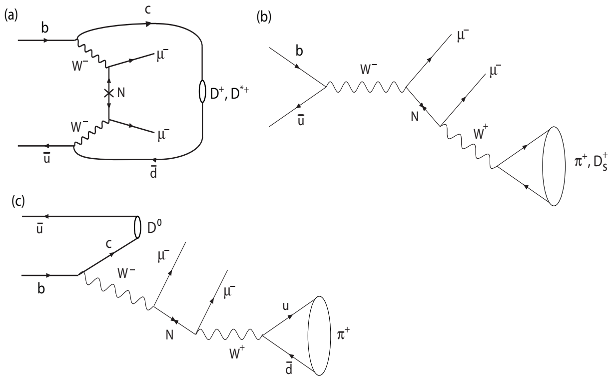
$$\mathcal{B}(D^+ \to \pi^-\mu^+\mu^+) < 2.2(2.5)\times 10^{-8} \text{ at } 90\% \ (95\%) \text{ CL}$$
$$\mathcal{B}(D_s \to \pi^-\mu^+\mu^+) < 1.2(1.4)\times 10^{-7} \text{ at } 90\% \ (95\%) \text{ CL}$$

World best upper limit

Lepton Number Violation in B decays

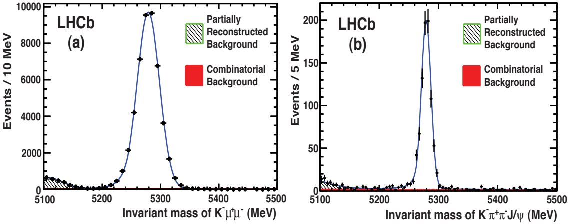
Physics case

- Lepton Number violating B decays which are forbidden in Standard Model
  - $B^- \to D^{(*)+}\mu^-\mu^-$, $B^- \to \pi^+(D_s^+)\mu^-\mu^-$, $B^- \to D^0\pi^+\mu^-\mu^-$
- Virtual/on-shell contributions from Majorana neutrino allow for such decays



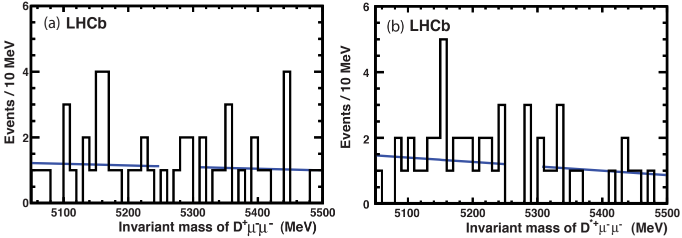
Analysis strategy

- Data sample used: 0.41 fb^{-1}
- cut-based analysis
- Normalization: well known channels with same number of muons and equal track multiplicities
  - final states with 3 tracks $\mathrm{B}^+ \to \mathrm{J}/\psi(\mu\mu)\mathrm{K}^+$
  - final states with 5tracks $\mathrm{B}^+ \to (\psi(2S) \to \pi\pi \mathrm{J}/\psi(\mu\mu)\ )K^+$
- Estimate Background using a fit to the invariant mass
- Phys. Rev. D 85 (2012) 112004



Results: $B^- \to D^{(*)+}\mu^-\mu^-$

- Background: mis-reconstructed B decays(negligible) & combinatorial (dominant)



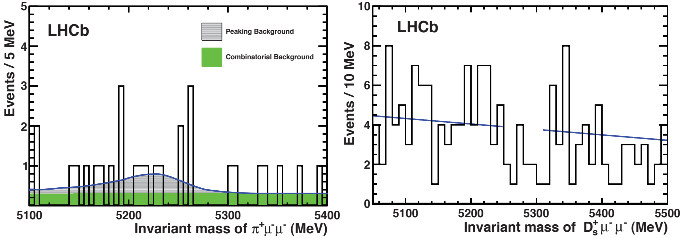
- Systematic error: $\sim 8\%$ dominated by trigger

$$\mathcal{B}(B^- \to D^+\mu^-\mu^-) < 6.9 \times 10^{-7} \text{ at } 95\% \text{ CL}$$
$$\mathcal{B}(B^- \to D^*\mu^-\mu^-) < 2.4 \times 10^{-6} \text{ at } 95\% \text{ CL}$$

Most stringent upper limit for D^+ and the first limit on D^*

Results: $B^- \to \pi^+(D_s^+)\mu^-\mu^-$

- $B^- \to \pi^+\mu^-\mu^-$ Background: misidentified $B^+ \to J/\psi(\mu\mu)K^+$ & combinatorial (dominant)
- $B^- \to D_s^+\mu^-\mu^-$ Background: combinatorial



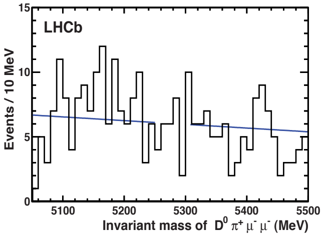
- Systematic error: $(14 - 13.)\%$ dominated by efficiency modeling

$$\mathcal{B}(B^- \to \pi^+\mu^-\mu^-) < 1.3 \times 10^{-8} \text{ at } 95\% \text{ CL}$$
$$\mathcal{B}(B^- \to D_s^+\mu^-\mu^-) < 5.8 \times 10^{-7} \text{ at } 95\% \text{ CL}$$

Most stringent upper limit

Results: $B^- \to D^0\pi^+\mu^-\mu^-$

- Background:combinatorial



- systematic error: 13% dominated by trigger

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

Most stringent upper limit

Conclusion

- LHCb searches for Lepton Flavour violation, Lepton Number Violation & Baryon Number Violation
- First limits on the cLFV decay mode $\tau^- \to \mu^+\mu^-\mu^-$ at a hadron collider
- First limits ever on cLFV & BNV $\tau^- \to \bar{p}\mu^+\mu^-$ and $\tau^- \to p\mu^-\mu^-$ decay modes
- World best limit for $\mathrm{D}^+_{(\mathrm{s})} \to \pi^-\mu^+\mu^+$
- World best limit for: $\mathrm{B}^- \to \mathrm{D}^{(*)+}\mu^-\mu^-$, $\mathrm{B}^- \to \pi^+(\mathrm{D}^+_s)\mu^-\mu^-$, $\mathrm{B}^- \to \mathrm{D}^0\pi^+\mu^-\mu^-$
- More to come:
  - 2012: 2 fb^{-1} + higher τ cross section
  - Other cLFV searches ($\mathrm{B}_{\mathrm{s,d}} \to e^\pm\mu^\mp$,...) on going

Backups

Selection

	$\tau^- \to \mu^+\mu^-\mu^-$	$D_s^- \to \phi(\mu^+\mu^-)\pi^-$
$\mu^\pm$ and $\pi^\pm$		
pT	> 300 MeV/c	
Track χ^2/ndf	< 4	
IP χ^2/ndf	> 9	
$\phi(1020)$		
Δm	> 20 MeV/c^2	< 20 MeV/c^2
$\tau^\pm$ and D_s		
Δm	< 400 MeV/c^2	< 50 MeV/c^2
Vertex χ^2	< 15	
IP χ^2	< 225	
$c\tau$	$> 100\ \mu$m	
Lifetime fit χ^2	< 225	
cos α	> 0.99	
Lifetime	> -0.01 ns & < 0.025 ns	
$m_{\mu^+\mu^-}$	> 450 MeV/c^2	-
$m_{\mu^+\mu^+}$	> 250 MeV/c^2	-

	$\tau \to p\mu\mu$	$D_s^- \to \phi(\mu^+\mu^-)\pi^-$
$\mu^\pm$,p and $\pi^\pm$		
pT	> 300 MeV/c	
p	> 5 GeV/c & < 100 GeV/c	
Track χ^2/ndf	< 3	
IP χ^2/ndf	> 9	
DLL$(\mu - \pi)$	> -5	
DLL$(\mu - K)$	> 0	
DLL$(p - \pi)$	> -5	
$\phi(1020)$		
Δm	-	< 20 MeV/c^2
$\tau^\pm$ and D_s		
Δm	< 250 MeV/c^2	< 50 MeV/c^2
p_T	> 4 GeV/c^2	
Vertex χ^2	< 15	
IP χ^2	< 225	
cos α	> 0.999	
$c\tau$	$> 100\ \mu$m	
Lifetime fit χ^2	< 225	
Lifetime	> -0.01 ns & < 0.025 ns	
$m_{\mu^+\mu^+}$	> 250 MeV/c^2	-

- Stripping & offline selection for the four channels

Definitions of Geometrical Likelihood variables

- Cone isolation: The sum of the three track isolation.
  - Exclude muons candidates
  - tracks satisfy: $\sqrt{\delta eta^2 + \delta\phi^2} < 1$ where $(\delta\eta = \eta_\tau - \eta_{track})$
  - $I = \frac{pT_\tau}{pT_\tau + \sum_{tracks} pT(tracks)}$
- Track isolation: Number of tracks defined as:
  - take each muon candidate and performed for long tracks that can make "good" vertex with this muon
  - $\alpha < 0.27$rad, DOCA$< 130\,\mu$m, PVdis> 0.5cm, 30 >SVdis> -0.15cm
  - Sum of the momenta between muon and track<0.6

Geometrical likelihood calibration

- $\mathcal{M}_{\text{3body}}$ is calibrated exploiting the similarity between signal and calibration modes.
- To correct for the differences:
  - corrections from MC applied to the control distribution in data
- Cross checked:
  - Take correction factors from unsmeared MC and treat the smeared control MC as data.
  - compare to signal MC-true in smeared MC
- Assign systematic uncertainty 1.3% to account for biases below the sensitivity of the cross check.

PID Likelihood for $\tau^- \to \mu^+\mu^-\mu^-$

- A neural net combining inputs from the PID subdetectors, kinematic variables.
- There is one of these classifier for each particle hypothesis
- For the muon case in $\mathcal{M}_{\text{PID}}$: flat distributed between 0 and 1, while for all other particles peaks at 0.
- To efficiently suppress background candidates from $\mu\mu$X combinations, min(p1_$\mathcal{M}_{\text{PID}}$, p2_$\mathcal{M}_{\text{PID}}$, p3_$\mathcal{M}_{\text{PID}}$)

$\mathcal{M}_{\rm PID}$ calibration

- J/$\psi(\mu\mu)$sample without requirements on DLL or ProbNN variables is used to obtain the selection efficiency for any given DLL or ProbNN cut as a function of track momentum, pseudo-rapidity, and track multiplicity.
- For each track in the signal MC, efficiency (to pass a $\mathcal{M}_{\rm PID}$ cut) is evaluated on the calibration sample.
- kinematic correlations between all final state tracks accounted for

Mass

- $D_s^- \to \phi(\mu^+\mu^-)\pi^-$ mass resolution in data

	$\tau^- \to \mu^+\mu^-\mu^-$	$\tau \to p\mu\mu$
N_{cal}	$48,076 \pm 760 \pm 357$	$8,145 \pm 127 \pm 128$
Mean (MeV/c^2)	1970.29 ± 0.08	1970.1 ± 0.1
σ_1 (MeV/c^2)	8.10 ± 0.09	8.15 ± 0.20
σ_2 (MeV/c^2)	14.8 ± 0.9	11.92 ± 0.84

- $D_s^- \to \phi(\mu^+\mu^-)\pi^-$ mass resolution in data is considerably different from MC
- widths of the data-resolution gaussians are determined by correcting the MC widths by the ratio of data/MC widths

	$\tau^- \to \mu^+\mu^-\mu^-$	$\tau^- \to \bar{p}\mu^+\mu^-$	$\tau^- \to p\mu^-\mu^-$
Mean (MeV/c^2)	1779.18 ± 0.04	1778.0 ± 0.1	1778.0 ± 0.1
σ_1 (MeV/c^2)	8.1 ± 0.1	4.5 ± 0.2	4.6 ± 0.2
σ_2 (MeV/c^2)	16 ± 1	7.7 ± 0.7	8.0 ± 0.7

Binning

- Data is binned in $\mathcal{M}_{\rm 3body}$, $\mathcal{M}_{\rm PID}$ and the mass variables
- Binning optimization following procedure
  - *Preliminary* binning in $\mathcal{M}_{\rm PID}$ variable to identify bins bounderies
  - Remove the lowest bin
  - Optimize $\mathcal{M}_{\rm 3body}$ on the remaining sample
  - Same procedure for $\mathcal{M}_{\rm PID}$
  - Found 6 sensitive bins in $\mathcal{M}_{\rm 3body}$ and another 6 in $\mathcal{M}_{\rm PID}$

Binning optimisation

- number of bins and the position of the bin boundaries are numerically optimized according to the figure of merit:

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

where,

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

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

- $P(a, e)$ is the probability to observe a when the quantity has a Poisson distribution with expectation value e
- that the probabilities are computed for each bin i.
- The s_i indicate signal events in bin i, while b_i indicate background events.

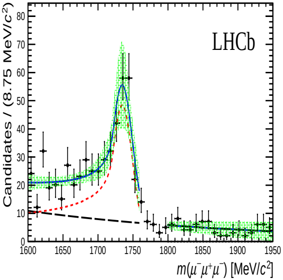
Data/MC comparison

- get $D_s^- \to \phi(\mu^+\mu^-)\pi^-$ from data using sPlot: An unbinned maximum likelihood fit to the $\mu\mu\pi$ mass
- good agreement between data and MC
- differences observed in track match χ^2 and the cone isolation (Not used in the selection)
- $\mathcal{M}_{\mathrm{3body}}$ is calibrated on data in any case

Model Dependence

- particle kinematics depend on NP models which introduce LFV
- results are correct for a flat phase space(due to MC)
- how much the result needs to be corrected for other distributions?
  - determine eff. of trigger and selections in bins of dimuon mass (constant within $\sim 15\%$)
  - $\mathcal{M}_{3\mathrm{body}}$ response in dimuon mass is flat

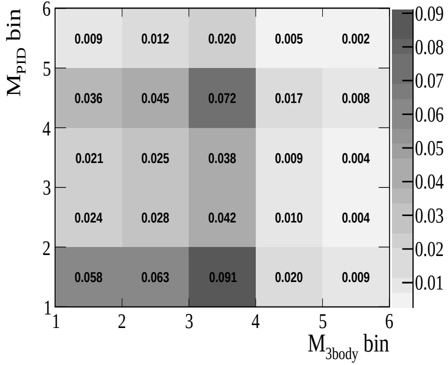
Kpipi Mass



LHCb
Candidates / (8.75 MeV/c^2)
0
10
20
30
40
50
60
70
80
1600
1650
1700
1750
1800
1850
1900
1950
$m(\mu^-\mu^+\mu^-)$ [MeV/c^2]

$\tau^- \to \mu^+\mu^-\mu^-$ $\mathcal{M}_{3\text{body}}$ & $\mathcal{M}_{\text{PID}}$ Pdf

- For $\tau^- \to \mu^+\mu^-\mu^-$ the correlation between $\mathcal{M}_{3\text{body}}$ and $\mathcal{M}_{\text{PID}}$ is considered
- Pdf used for the limit calculation



$V_{\mu 4}$ vs Majorana mass from $B^- \to \pi^+ \mu^- \mu^-$