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

Basem Khanji
On behalf of the LHCb collaboration

Milano-Bicocca, INFN-CERN

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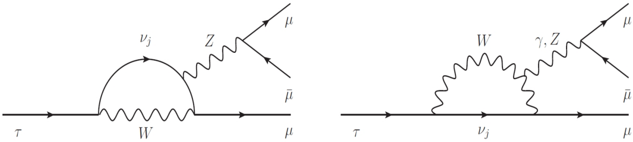
Implications of LHCb measurements and future prospects-CERN

Outline

Introduction

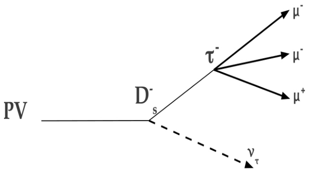
- $\tau^- \rightarrow \mu^+\mu^-\mu^-$: Charged Lepton Flavour Violation
- Penguin level with neutrino oscillation



- SM: $\mathcal{B} < 10^{-40}$ (Eur. Phys. J. C57 (2008) 13): beyond experimental reach
- Enhanced in New Physics: $\mathcal{B} \sim 10^{-8}$ (JHEP 05 (2007) 013): within experimental reach

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

- Large τ cross section
  - Main production sources:
    $\mathrm{D_s} \to \tau\ (\sim 70\%), \mathrm{B} \to \mathrm{D_s} \to \tau, \mathrm{B} \to \tau$



- Excellent μ $\mathcal{M}_{\rm PID}$ & detection at LHCb
  - $\epsilon(\mu\mathrm{ID}) \sim 97\%$,
  - $(1-3)\%$ $\pi \to \mu$ misID probability
  - μ trigger: $\sim 90\%$ efficient

State of the art

- Search at B factories:
  - $\mathcal{B}(\tau^- \to \mu^+\mu^-\mu^-) < 2.1 \times 10^{-8}$ at 90% $\mathrm{C.L.}$ Belle (World best) (Phys. Lett. B 687, 139 (2010))
  - $\mathcal{B}(\tau^- \to \mu^+\mu^-\mu^-) < 3.3 \times 10^{-8}$ at 90% $\mathrm{C.L.}$ BaBar (Phys. Rev. D 81, 111101(R) (2010))
- At LHCb: (Phys. Lett. B724, 36-45, 2013) $(1\,\mathrm{fb}^{-1})$
  - $\mathcal{B}(\tau^- \to \mu^+\mu^-\mu^-) < 8.0 \times 10^{-8}$ at 90% $\mathrm{C.L.}$ $(1\,\mathrm{fb}^{-1})$, first from a hadron collider

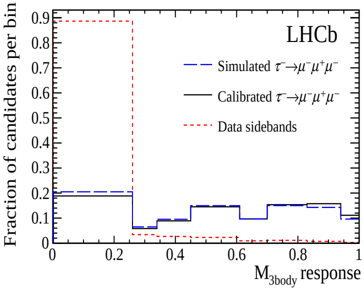
$\tau^- \to \mu^+\mu^-\mu^-$ decay has not been observed

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

- Loose selection
- Discrimination between signal and backgrounds:
  - $\mathcal{M}_{\rm 3body}$: multivariate likelihood based on decay topology & kinematics
  - $\mathcal{M}_{\rm PID}$: multivariate likelihood based on muon PID
  - Invariant mass of $\mu^-\mu^+\mu^-$
- Search in bins of $\mathcal{M}_{\rm 3body}$, $\mathcal{M}_{\rm PID}$ & mass
- Use normalization/control channel $D_s^- \to \phi(\mu^+\mu^-)\pi^-$
- CLs method to estimate the upper limit

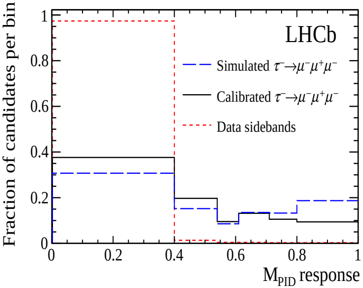
$\mathcal{M}_{\rm 3body}$: Geometric Likelihood

- Objective: select 3-body displaced decays
- Use geometry and kinematic variables to construct $\mathcal{M}_{\rm 3body}$
  - Use several multivariate classifiers
  - Tailored for each of τ's production mode
- Correct $\mathcal{M}_{\rm 3body}$ for data/MC differences using $D_s^- \to \phi(\mu^+\mu^-)\pi^-$



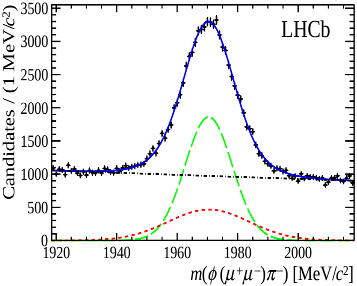
$\mathcal{M}_{\mathrm{PID}}$: μ Particle identification

- Objective: distinguish real 3μ particles in the final state
- Information from the RICH detectors, calorimeters and the muon detectors
- Calibrated using $\mathrm{J}/\psi(\mu\mu)$ and cross-checked in $D_s^- \to \phi(\mu^+\mu^-)\pi^-$ in data



Mass

- 3μ invariant mass
- Shape is taken from $D_s^- \to \phi(\mu^+\mu^-)\pi^-$ in data
- Correct mass resolution for differences between $\tau^- \to \mu^+\mu^-\mu^-$ and $D_s^- \to \phi(\mu^+\mu^-)\pi^-$ in the simulation



Normalization

- Convert the signal yield into $\mathcal{B}$
- No luminosity or absolute cross section measurements
- Normalization channel: similar to signal topology $\rightarrow$ normalize to $D_s^- \rightarrow \phi(\mu^+\mu^-)\pi^-$

$$\mathcal{B}(\tau^- \rightarrow \mu^+\mu^-\mu^-) =$$

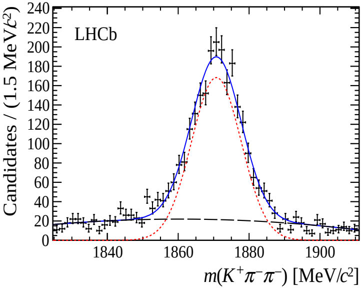
$$\frac{\mathcal{B}(D_s^- \rightarrow \phi(\mu^+\mu^-)\pi^-)}{\mathcal{B}(\mathrm{D_s} \rightarrow \tau\nu)} \times f_{D_s}^{\tau} \times \frac{\epsilon_{\mathrm{norm}}{}^{\mathrm{REC\&SEL}}\epsilon_{\mathrm{norm}}{}^{\mathrm{TRIG|SEL}}}{\epsilon_{\mathrm{sig}}{}^{\mathrm{REC\&SEL}}\epsilon_{\mathrm{sig}}{}^{\mathrm{TRIG|SEL}}} \times \frac{N_{\mathrm{sig}}}{N_{\mathrm{norm}}}$$

$$= \alpha \times N_{\mathrm{sig}}$$

- $\alpha = (1.72 \pm 0.23) \times 10^{-9}$, systematic uncertainties are included

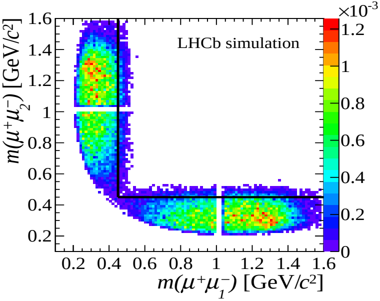
Backgrounds

- $D^+ \to K^-\pi^+\pi^+$: π, K are misidentified as μ
- Rejected by applying a cut on $\mathcal{M}_{\rm PID}$



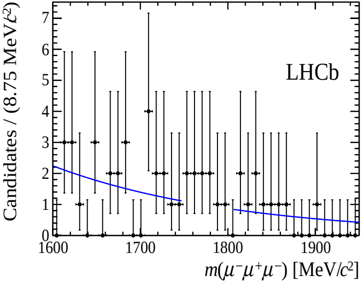
Backgrounds

- $D_s^- \to \eta(\mu^+\mu^-\gamma)\mu^-\nu_\mu$ background
- Similar to signal $\to$ difficult
- Rejected by applying a cut on $\mu^+\mu^-$ mass



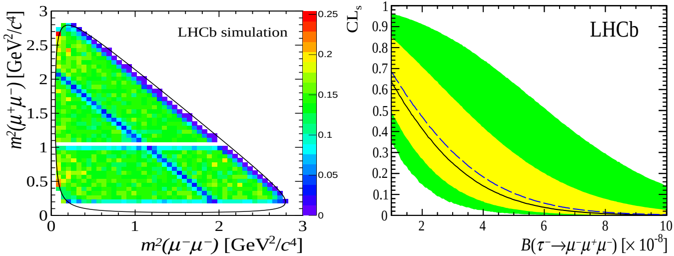
Backgrounds

- Combinatorial: estimated from the sidebands of the $\mu\mu\mu$ mass distribution data



Results

- No significant excess of events over the expected background estimates
- Upper limit is set assuming a flat phase-space model of $\tau^- \to \mu^+\mu^-\mu^-$



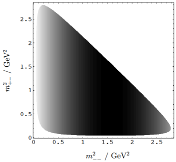
$\mathcal{B}(\tau^- \to \mu^+\mu^-\mu^-) < 4.6 \times 10^{-8}$ at 90% C.L. arXiv:1409.8548

Combination with B-factories

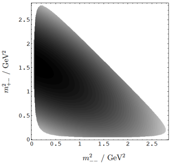
- LHCb + BaBar + Belle: $\mathcal{B}(\tau^- \to \mu^+\mu^-\mu^-) < 1.2 \times 10^{-8}$ at 90% $\mathrm{C.L.}$
  HFAG Preliminary
  - BaBar + Belle: $\mathcal{B}(\tau^- \to \mu^+\mu^-\mu^-) < 1.4 \times 10^{-8}$
- LHCb limit adds $+15\%$ sensitivity to the world upper limit

Model dependence

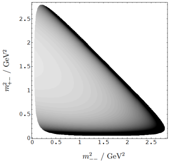
- Kinematic dependence on New Physics models introducing the LFV
- Model-independent analysis: JHEP 10 (2007) 039
  - New Physics with different chirality structure
  - 2 purely leptonic operators, 1 radiative operator, 2 interference operators
  - Dalitz plot for each operator



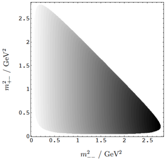
$\rho_V^{(LL)(LL)}$



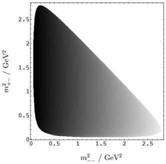
$\rho_V^{(LL)(RR)}$



$\rho_{radiative}^{(LR)}$



$\rho_{mix}^{(LL)(LL)}$



$\rho_{mix}^{(LL)(RR)}$

Model dependence

- We studied variation of our limit for each operator

Operator	$\rho_V^{(LL)(LL)}$	$\rho_V^{(LL)(RR)}$	$\rho_{radiative}^{(LR)}$	$\rho_{mix}^{(LL)(LL)}$	$\rho_{mix}^{(LL)(RR)}$
Limit $\times 10^{-8}$ (90% C.L.)	4.2	4.1	6.8	4.4	4.6

- Lower sensitivity for the $\rho_{radiative}^{(LR)}$ due to requirement on $\mu^+\mu^-$ mass
  - Do we need to be sensitive to $\rho_{radiative}^{(LR)}$ for prominent New Physics models ?
  - Interpretation of model independent limits?

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

- MSSM: large $\mathcal{B}(\tau^- \to \mu^+\mu^-\mu^-)$ (i.e interesting experimentally) favors large $\tan(\beta)$ ranges (arXiv 0304081)
  - ... But recent results in $B_s^0 \to \mu^+\mu^-$ exclude this region
- Higgs induced $\tau^- \to \mu^+\mu^-\mu^-$ (e.g LHT) received constrains from Higgs discovery in ATLAS & CMS
  - Small scale parameter (f) makes $\mathcal{B}(\tau^- \to \mu^+\mu^-\mu^-)$ large (arXiv 0906.5454)
  - ...but small f means $m_{higgs} > 500\,\mathrm{GeV}$ (arXiv 0506042)

Other searches for cLFV in τ decays

- Search for $\tau \to p\mu\mu$:
  - cLFV + Baryon Number Violation
  - At LHCb: first upper limits ever
    - $\mathcal{B}(\tau^- \to \bar{p}\mu^+\mu^-) < 3.3 \times 10^{-7}$ at 90% CL (Phys. Lett. B724, 36-45, 2013)
    - $\mathcal{B}(\tau^- \to p\mu^-\mu^-) < 4.4 \times 10^{-7}$ at 90% CL (Phys. Lett. B724, 36-45, 2013)
  - Limits on this decay from proton lifetime are more stringent than LHCb search
  - Lack of clear theoretical motivation/predictions for such process
- Investigating $\tau \to \mu^-\mu^- e^+$
  - No radiative operators
  - But experimentally challenging at LHCb
- Advice for interesting/model-constraining channels to be investigated?

Future

- Prospects of $\tau^- \to \mu^+\mu^-\mu^-$ search at LHCb end of Run II:
  - @$13\,\mathrm{TeV}$, $\sim 8\,\mathrm{fb}^{-1}$ end of Run II
  - $\mathcal{B}(\tau^- \to \mu^+\mu^-\mu^-) \sim 2.8 \times 10^{-8}$ at 90% $\mathrm{C.L.}$ (simple scaling)
- Upgrade (Run III+Run IV):
  - @$14\,\mathrm{TeV}$, $\sim 50\,\mathrm{fb}^{-1}$ end of Run IV
  - $\mathcal{B}(\tau^- \to \mu^+\mu^-\mu^-) \sim 9 \times 10^{-9}$ at 90% $\mathrm{C.L.}$ (simple scaling)
- How much improvement would $\mathcal{O}(10^{-9})$ bring to the theory?

Conclusion

- cLFV $\tau^- \to \mu^+\mu^-\mu^-$ decay is an important probe for New Physics
- LHCb set the first upper limit on $\tau^- \to \mu^+\mu^-\mu^-$ at a hadron collider with 2011 data
- LHCb produced a new limit using the full data set from Run I $(3\,\mathrm{fb}^{-1})$
- $\mathcal{B}(\tau^- \to \mu^+\mu^-\mu^-) < 4.6 \times 10^{-8}$ at 90% $\mathrm{C.L.}$
  - LHCb lowered the world limit from 1.4×10^{-8} to 1.2×10^{-8}
- Investigating $\tau \to p\mu\mu$, $\tau \to \mu^-\mu^-e^+$
- Other cLFV and LNV in Beauty & Charm at LHCb:
  - LNV in Charm: $\mathrm{D}^+_{(\mathrm{s})} \to \pi^-\mu^+\mu^+$ (Phys. Lett. B724 (2013) 203-212)
  - cLFV in Beauty: $\mathrm{B}_{\mathrm{s,d}} \to e^\pm\mu^\mp$ (Phys. Rev. Lett. 111, 141801)
  - LNV in Beauty: $\mathrm{B}^+ \to \pi^-\mu^+\mu^+$ (Phys. Rev. Lett.108 (2012) 101601)
- Plans to pursue cLFV in τ decays in Run II and beyond

Backups

Model independent operators

$$H_{\text{eff}}^{\text{rad}} = \frac{e}{4\pi}\frac{v}{\Lambda^2}\sum_{h,s} g_{\text{rad}}^{(s,h)}\left(\bar{\mu}(-i\sigma_{\mu\nu})\tau_s\right)F^{\mu\nu}$$

$$H_{\text{eff}}^{(LL)(LL)} = g_V^{(LL)(LL)}\frac{(\bar{\mu}_L\gamma_\mu\tau_L)(\bar{\mu}_L\gamma^\mu\mu_L)}{\Lambda^2}$$

$$H_{\text{eff}}^{(LL)(RR)} = g_V^{(LL)(RR)}\frac{(\bar{\mu}_L\gamma_\mu\tau_L)(\bar{\mu}_R\gamma^\mu\mu_R)}{\Lambda^2}$$