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Strategies for $\tau \rightarrow lhh'$ *analyses*

Tau LFV brainstorming, 03/06/2021

CENTRE DE PHYSIQUE DES PARTICULES DE MARSEILLE CPPM

Aix*Marseille université Initiative d'excellence

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Belle II

erc

BaBar strategy

Search for Lepton-Flavor and Lepton-Number Violation in the Decay $\tau^{-} \to \ell \quad h^{\pm} h'^{-}$

(2005)

https://arxiv.org/abs/hep-ex/0506066v1

Reconstruction and background suppression

- 1×3 topology: four tracks with zero net charge, coming from a common region, 3-prong in one hemisphere and 1-prong in the other using plane perpendicular to thrust.
- Particle identification: one of 3-prong tracks must be an electron or muon and the two others either a pion or kaon.
- Photon conversion: ignored if e^+e^- inv. mass < 30 MeV/c^2.
- Against qqbar & SM $\tau^+\tau^-$: no photon with $E_\gamma < 100$ MeV.
- Against two-photon & Bhabha bkg: event's $p_T^{CM} < 0.2$ GeV/c and $\theta_{miss}^{CM} \in [0.25, 2.4]$ rad.
- Against qqbar & two-photon bkg: $M_{1\text{-prong}} \in [0.6, 1.9]$ GeV/c^2 for ehh' and $[0.8, 1.9]$ GeV/c^2 for μhh'.
- Against Bhabha bkg: $p_{1\text{-prong}}^{CM} < 4.5$ GeV/c for e$\pi\pi$, leptons and pions must not pass kaon identification for all modes, 1-prong must not be identified as electron for electronic modes (except eKK) .

Signal region and background estimation method

Blind analysis, with a **signal region** defined in 2D-space ΔM ($= M_{rec} - m_\tau$) - ΔE ($= E_{rec}^{CM} - E_{beam}^{CM}$):

- ehh': $\Delta M \in [-30, +20]$ MeV/c^2 and $\Delta E \in [-100, +50]$ MeV
- μhh': $\Delta M \in [-20, +20]$ MeV/c^2 and $\Delta E \in [-100, +50]$ MeV

} optimised in simulation, smallest expected upper limits on Br in background-only hypothesis

PDF determined for **each background type** by fit on MC and **each decay mode**, then normalised according to an unbinned maximum likelihood fit to the data in the **side-band region** (excluding signal region):

- ehh': $\Delta M \in [-700, +400]$ MeV/c^2 and $\Delta E \in [-700, +400]$ MeV
- μhh': $\Delta M \in [-400, +400]$ MeV/c^2 and $\Delta E \in [-700, +400]$ MeV

} Dominant background: low multiplicity qqbar, SM $\tau^+\tau^-$. Negligible background: Bhabha, μμ, two-photon events.

PDFs are defined in the ($\Delta M'$-$\Delta E'$) space, slightly rotated from (ΔM-ΔE), as the product of:

- $P_{M'}(\Delta M')$ = Gaussian distribution for qqbar **or** sum of 2 asymmetric Gaussians for $\tau^+\tau^-$
- $P_{E'}(\Delta E') = (1 - x/\sqrt{[1 + x^2]})(1 + a_1 x + a_2 x^2 + a_3 x^3)$, where $x = (\Delta E' - a_4)/a_5$

Uncertainties and results

Analysis performed using 221.4 fb^{-1} of data.

- **Signal selection efficiencies**: 85 % Br for 1-prong τ decays, 40 % for topology requirement, 20-70 % for PID criteria.
- PID efficiencies and misID rates measured in control samples.
- Main **signal systematic uncertainty** from measuring PID efficiencies (0.7-3.8 %), then modeling of tracking efficiency (2.5 %), restriction on extra photons (2.4 %).
- Main **background systematic uncertainty** from finite amount of data in SB region, additional 10 % from varying the fit procedure and form of PDFs.

Mode	Efficiency [%]	N_{bgd}	N_{obs}	UL at 90% CL
$e^-K^+K^-$	3.77 ± 0.16	0.22 ± 0.06	0	$1.4 \cdot 10^{-7}$
$e^-K^+\pi^-$	3.08 ± 0.13	0.32 ± 0.08	0	$1.7 \cdot 10^{-7}$
$e^-\pi^+K^-$	3.10 ± 0.13	0.14 ± 0.06	1	$3.2 \cdot 10^{-7}$
$e^-\pi^+\pi^-$	3.30 ± 0.15	0.81 ± 0.13	0	$1.2 \cdot 10^{-7}$
$\mu^-K^+K^-$	2.16 ± 0.12	0.24 ± 0.07	0	$2.5 \cdot 10^{-7}$
$\mu^-K^+\pi^-$	2.97 ± 0.16	1.67 ± 0.29	2	$3.2 \cdot 10^{-7}$
$\mu^-\pi^+K^-$	2.87 ± 0.16	1.04 ± 0.18	1	$2.6 \cdot 10^{-7}$
$\mu^-\pi^+\pi^-$	3.40 ± 0.19	2.99 ± 0.41	3	$2.9 \cdot 10^{-7}$
$e^+K^-K^-$	3.85 ± 0.16	0.04 ± 0.04	0	$1.5 \cdot 10^{-7}$
$e^+K^-\pi^-$	3.19 ± 0.14	0.16 ± 0.06	0	$1.8 \cdot 10^{-7}$
$e^+\pi^-\pi^-$	3.40 ± 0.15	0.41 ± 0.10	1	$2.7 \cdot 10^{-7}$
$\mu^+K^-K^-$	2.06 ± 0.11	0.07 ± 0.10	1	$4.8 \cdot 10^{-7}$
$\mu^+K^-\pi^-$	2.85 ± 0.16	1.54 ± 0.25	1	$2.2 \cdot 10^{-7}$
$\mu^+\pi^-\pi^-$	3.30 ± 0.18	1.46 ± 0.27	0	$0.7 \cdot 10^{-7}$

$\mathbf{Br = N^{90}_{UL} / (2\, \varepsilon\, \mathcal{L}\, \sigma_{\tau\tau})}$, where N^{90}_{UL} = 90 % CL upper limit on number of signal events when N_{obs} events observed and N_{bkg} background events expected.

Following:

R. D. Cousins and V. L. Highland, Nucl. Instr. Methods Phys. Res., Sect. A 320, 331 (1992)

R. Barlow, Comput. Phys. Commun. 149, 97 (2002)

Belle strategy

Search for Lepton-Flavor and Lepton-Number-Violating $\tau \rightarrow \ell h h'$ Decay Modes

(2013)

https://arxiv.org/abs/1206.5595v2

Reconstruction and background suppression

- 1×3 topology: four tracks with zero net charge, coming from region $dr < 0.5$ cm and $dz < 3$ cm, 3-prong in one hemisphere and 1-prong in the other using plane perpendicular to thrust.
- Further requirements: $-0.866 < \cos\theta < 0.956$, tracks with $p_T > 0.1$ GeV/c and photons with $E_\gamma > 0.1$ GeV.
- Particle identification: $P(e) > 0.9$, $p > 0.6$ GeV/c for electrons | $P(\mu) > 0.95$, $p > 1.0$ GeV/c for muons.
- Bremsstrahlung correction: electron's momentum corrected with momentum of every photon within 0.05 rad cone.
- Kaon and pion vetoes: $P(K/\pi) > (0.6 - 0.9)$, $P(p/K) < 0.6$ for kaons | $P(K/\pi) < 0.6$ for pions.
- Missing momentum: $\cos\theta^{CM}_{tag\text{-}miss} \in [0, 0.96]$ for electronic modes (against Bhabha, two-photons events, inelastic vector meson-photoproduction) | $\cos\theta^{CM}_{tag\text{-}miss} \in [0, 0.85]$ for muonic modes if hadron in tag side (against qqbar).
- Missing neutrinos: $|p^t_{miss}| > 0.7\ (0.5)$ GeV/c for electronic (muonic) modes, > 1.5 GeV/c for $\tau^- \to e^- \pi^+ \pi^-$, direction points into fiducial volume of detector.

Reconstruction and background suppression

Mode	$\mathcal{P}(K/\pi)$	T
$\tau \to \mu\pi\pi$	–	$0.90 < T < 0.98$
$\tau \to \mu K\pi$	> 0.9	$0.92 < T < 0.98$
$\tau \to \mu KK$	> 0.8	$0.92 < T < 0.98$
$\tau \to e\pi\pi$	–	$0.90 < T < 0.97$
$\tau \to eK\pi$	> 0.8	$0.90 < T < 0.97$
$\tau \to eKK$	> 0.6	$0.90 < T < 0.98$

- Against qqbar & Bhabha & μμ: thrust magnitude follows →
- Against qqbar: $n_\gamma^{tag} \leq 2$ (hadronic tag) and $n_\gamma^{tag} \leq 1$ (leptonic tag), $m_{tag} < 1$ GeV/c² (photons included).
- Signal side: one additional photon allowed.
- Against photon conversion and other bkgs: in electronic modes, inv. masses of $e^-h^+/h^+h'^-$ (for $\tau^- \to e^- h^+ h'^-$) or $e^+h^-/e^+h'^-$ (for $\tau^- \to e^+ h^- h'^-$) required to be > 0.2 GeV/c².
- Against K decaying into μ: in muonic modes, $P(K/\pi) < 0.6$ on muon candidates if hadronic tag side.
- Against di-baryon production with proton in tag: $P(p/\pi) < 0.6$ and $P(p/K) < 0.6$ on tag tracks.
- Additional requirements depending on decay channel (on $M_{\pi\pi\pi}$, m^2_{miss}, ...).

Signal region and background estimation method

Blind analysis, with a **signal region** defined in 2D-space ($M_{lhh'}$-ΔE), fitting signal MC distributions with an asymmetric Gaussian. SR defined as a 3σ ellipse:

coord. center of ellipse

$$\frac{((M_{\ell hh'} - M^0_{\ell hh'})\cos\theta - (\Delta E - \Delta E^0)\sin\theta)^2}{(3\sigma_{M_{\ell hh'}})^2} + \frac{((M_{\ell hh'} - M^0_{\ell hh'})\sin\theta + (\Delta E - \Delta E^0)\cos\theta)^2}{(3\sigma_{\Delta E})^2} = 1$$

average of high & low widths

Mode	$\sigma^{high}_{M_{\ell hh'}}$	$\sigma^{low}_{M_{\ell hh'}}$	$\sigma^{high}_{\Delta E}$	$\sigma^{low}_{\Delta E}$
$\tau^- \to \mu^-\pi^+\pi^-$	5.3	5.8	14.1	20.1
$\tau^- \to \mu^+\pi^-\pi^-$	5.4	5.7	14.2	20.1
$\tau^- \to e^-\pi^+\pi^-$	5.7	6.2	14.3	22.0
$\tau^- \to e^+\pi^-\pi^-$	5.6	6.3	14.4	22.3
$\tau^- \to \mu^-K^+K^-$	3.4	3.6	12.9	17.2
$\tau^- \to \mu^+K^-K^-$	3.4	3.3	12.9	17.3
$\tau^- \to e^-K^+K^-$	4.4	4.4	13.3	19.8
$\tau^- \to e^+K^-K^-$	3.8	4.2	12.4	19.9
$\tau^- \to \mu^-\pi^+K^-$	4.4	4.8	14.2	18.8
$\tau^- \to e^-\pi^+K^-$	4.8	5.5	14.0	21.0
$\tau^- \to \mu^-K^+\pi^-$	4.6	5.1	14.3	18.7
$\tau^- \to e^-K^+\pi^-$	4.9	5.4	13.9	21.2
$\tau^- \to \mu^+K^-\pi^-$	4.5	4.7	14.7	18.6
$\tau^- \to e^+K^-\pi^-$	5.0	5.4	14.0	21.2

Ellipse parameters optimised to give highest sensitivity: $\mathrm{FOM} = \varepsilon_{sig}/\sqrt{N_{bkg}}$

Background estimated in $\pm 5\sigma_{\Delta E}$ **side-band region**, projected onto $M_{lhh'}$ axis.

- Electronic modes: small amount of background, mainly from two-photon processes. Extrapolating to SR as linear function of $M_{lhh'}$.

- Muonic modes: main background from qqbar ($\tau \to \mu\pi\pi$), $\tau^+\tau^-$ ($\tau \to \mu\pi K$), or both ($\tau \to \mu KK$). Extrapolating to SR by fitting the SB using the sum of an exponential ($\tau^+\tau^-$) and a first-order polynomial function (qqbar) for $\tau \to \mu\pi\pi$. For $\tau \to \mu\pi K/\mu KK$, linear function of $M_{lhh'}$.

Uncertainties and results

Analysis performed using 854 fb^{-1} of data.

Main **systematic uncertainty** from :

- resolutions of $M_{lhh'}$ and ΔE due to data/MC differences (3.7-4.8 %),
- lepton identification (1.9-2.2 %), hadron identification (1.3-1.8 %),
- 1.4 % for charged track findind, same for integrated luminosity.
- Total for all modes: (5.5-6.7 %).

Main **background systematic uncertainty** from statistics of sample and shape of distribution (less than 20 %, smaller than statistical error).

Mode	ε (%)	N_{BG}	σ_{syst} (%)	N_{obs}	s_{90}	$\mathcal{B}$ (10^{-8})
$\tau^- \to \mu^-\pi^+\pi^-$	5.83	0.63 ± 0.23	5.7	0	1.87	2.1
$\tau^- \to \mu^+\pi^-\pi^-$	6.55	0.33 ± 0.16	5.6	1	4.01	3.9
$\tau^- \to e^-\pi^+\pi^-$	5.45	0.55 ± 0.23	5.7	0	1.94	2.3
$\tau^- \to e^+\pi^-\pi^-$	6.56	0.37 ± 0.19	5.5	0	2.10	2.0
$\tau^- \to \mu^-K^+K^-$	2.85	0.51 ± 0.19	6.1	0	1.97	4.4
$\tau^- \to \mu^+K^-K^-$	2.98	0.25 ± 0.13	6.2	0	2.21	4.7
$\tau^- \to e^-K^+K^-$	4.29	0.17 ± 0.10	6.7	0	2.29	3.4
$\tau^- \to e^+K^-K^-$	4.64	0.06 ± 0.06	6.5	0	2.39	3.3
$\tau^- \to \mu^-\pi^+K^-$	2.72	0.72 ± 0.28	6.2	1	3.65	8.6
$\tau^- \to e^-\pi^+K^-$	3.97	0.18 ± 0.13	6.4	0	2.27	3.7
$\tau^- \to \mu^-K^+\pi^-$	2.62	0.64 ± 0.23	5.7	0	1.86	4.5
$\tau^- \to e^-K^+\pi^-$	4.07	0.55 ± 0.31	6.2	0	1.97	3.1
$\tau^- \to \mu^+K^-\pi^-$	2.55	0.56 ± 0.21	6.1	0	1.93	4.8
$\tau^- \to e^+K^-\pi^-$	4.00	0.46 ± 0.21	6.2	0	2.03	3.2

$Br = s_{90} / (2 N_{\tau\tau} \varepsilon)$, where s_{90} = 90 % CL upper limit on number of signal events, based on number of observed events, number of expected background events and systematic uncertainties.

Following:

G. J. Feldman and R. D. Cousins, Phys. Rev. D 57, 3873 (1998)
J. Conrad et al., Phys. Rev. D 67, 012002 (2003)