Tau Analysis:

Tau in 3 leptons & 3 prongs

Group Meeting

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Belle

Search for Lepton Flavor Violating Tau Decays into Three Leptons with 719 Million Produced Tau+Tau- Pairs (2010)

http://arxiv.org/abs/1001.3221

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Updated search for Lepton Flavor Violating tau Decays into Three Leptons (Belle note)

Belle Method
Event selection

- 3X1 Topology: Signal τ decay into 3 leptons, Tag τ into one charged track (**4 charged tracks with zero net charge**) and add any nb of photons and neutrinos.

- 6 signal modes: $\tau^- \rightarrow e^-e^+e^-,\ \mu^-\mu^+\mu^-,\ e^-\mu^+\mu^-,\ \mu^-e^+e^-,\ \mu^-e^+\mu^-,\ e^-\mu^+e^-$;
  mode by mode selection optimization.

- Events selections: fiducial volume $-0.866 < cos\theta < 0.956$;
  $p_T > 0.1\ GeV/c$ for charged tracks;
  $E_\gamma > 0.1\ GeV$ for photons; $|dr| < 0.5\ cm$ and $|dz| < 3\ cm$.

- Event's particle separated in 2 hemispheres (plane perpendicular to the trust axis).

- Particle identification: Electrons $P(e) = \frac{L_e}{L_e + L_x} > 0.9\ \ for\ p > 0.3\ GeV/c$ (eff 91%, pion misid 0.5%),
  Muons $P(\mu) = \frac{L_\mu}{L_\mu + L_\pi + L_K} > 0.9\ for\ p > 0.6\ GeV/c$ (eff 85%, pion misid 2%).

- Missing particles: Ensure to be neutrinos $\vec{p}_{miss} > 0.4GeV/c$ and is **in fiducial volume**, must be in tag side $0.0 < cos\theta^{CM}_{tag-miss} < 0.98$ (reject Bhabha, μμ & γ conversion); $m_{tag} < 1.78\ GeV/c^2$.

Belle Method
Background rejection

- Reject $q\bar{q}$ bkg by: Thrust magnitude cuts $\mathbf{0.90 < T < 0.96}$ **for eee**, $\mathbf{0.90 < T < 0.97}$ **else**, Total Visible energy $\mathbf{5.29 < E_{vis}^{CM} < 9.5GeV}$ (3 leptons, tag prong & photons).

- Reject γ conversion and Bhabhas: ee invariant mass $\boldsymbol{M_{ee} > 0.2GeV/c^2}$ for eee & μee;
  Tag side prong $\boldsymbol{P(e) < 0.1}$ for eee & eμμ (also suppress bhabha);
  Reject events if tag track is in ECL barrel/endcap gaps.

- Reduce Bhabha & μμ bkg with material interaction: $\boldsymbol{p_{tag}^{CM} < 4.5\ Gev/c}$ for eee & μee.

- Reject generic ττ & $q\bar{q}$ bkg:

Mode	Hadronic tag	Leptonic tag
$\tau^- \to \mu^-\mu^+\mu^-$ $\tau^- \to \mu^-e^+e^-$ $\tau^- \to e^-\mu^+\mu^-$	$p_{\rm miss} > -3.0\ m^2_{\rm miss} - 1.0$ $p_{\rm miss} > 3.0\ m^2_{\rm miss} - 1.5$	$p_{\rm miss} > -2.5\ m^2_{\rm miss}$ $p_{\rm miss} > 1.3\ m^2_{\rm miss} - 1.0$
$\tau^- \to e^-e^+e^-$	$p_{\rm miss} > -3.0\ m^2_{\rm miss} - 1.0$ $p_{\rm miss} > 4.2\ m^2_{\rm miss} - 1.5$	$p_{\rm miss} > -2.5\ m^2_{\rm miss}$ $p_{\rm miss} > 2.0\ m^2_{\rm miss} - 1.0$
$\tau^- \to e^+\mu^-\mu^-$ $\tau^- \to \mu^+e^-e^-$	not applied	not applied

- Optimisation by looking in the number of events needed to obtain a 99% CL evidence (N^{99}_{obs}); the number of bkg (N_{BG}).

Belle Method
Signal Region & Backgoround estimation

Signal region define in ($M_{3l}, \Delta E$) 2D plane:

M_{3l} & ΔE resolutions are extracted from asymmetric gaussian fits on signal MC samples;
Then elliptical SR are optimised to have the minimum area with 90% of signal (after all selections).

Mode	$\sigma_{M_{3\ell}}^{\text{high}}$ (MeV/c^2)	$\sigma_{M_{3\ell}}^{\text{low}}$ (MeV/c^2)	$\sigma_{\Delta E}^{\text{high}}$ (MeV)	$\sigma_{\Delta E}^{\text{low}}$ (MeV)
$\tau^- \to \mu^-\mu^+\mu^-$	5.0/5.2	5.1/5.4	13.5/13.9	16.1/16.7
$\tau^- \to e^-e^+e^-$	5.3/5.3	7.2/7.6	12.9/15.6	26.6/24.9
$\tau^- \to e^-\mu^+\mu^-$	6.0/5.2	5.0/6.2	12.5/14.3	19.6/20.9
$\tau^- \to \mu^-e^+e^-$	5.0/5.3	6.9/7.0	13.2/13.5	22.8/23.4
$\tau^- \to e^+\mu^-\mu^-$	5.1/5.0	6.6/6.6	12.8/14.0	20.7/20.9
$\tau^- \to \mu^+e^-e^-$	5.5/5.8	6.4/6.9	13.8/16.5	24.0/23.7

Blind Analysis:
Signal efficiency evaluated outside SR.
Bkg number is done with loser PID cut, in M_{3l} sidebands (excluding SR) and then extrapolate to the SR assuming bkg is uniform.

Belle Method Results

Systematic Uncertainties:

- lepton identification 2.2% (e) & 2.0% (μ);
- Charged track finding 1.0%;
- Electron veto (eee, eμμ) same as lepton ID;
- MC stat & Luminosity (0.5-0.9)% and 1.4%.

Mode	ε (%)	N_{BG}	σ_{syst} (%)	N_{obs}	$\mathcal{B}(\times 10^{-8})$
$\tau^- \to e^- e^+ e^-$	6.0	0.21±0.15	9.8	0	<2.7
$\tau^- \to \mu^- \mu^+ \mu^-$	7.6	0.13±0.06	7.4	0	<2.1
$\tau^- \to e^- \mu^+ \mu^-$	6.1	0.10±0.04	9.5	0	<2.7
$\tau^- \to \mu^- e^+ e^-$	9.3	0.04±0.04	7.8	0	<1.8
$\tau^- \to e^+ \mu^- \mu^-$	10.1	0.02±0.02	7.6	0	<1.7
$\tau^- \to \mu^+ e^- e^-$	11.5	0.01±0.01	7.7	0	<1.5

Branching fraction: $Br < \frac{s_{90}}{2\varepsilon N_{\tau\tau}}$;

s_{90} the 90% CL upper limit of signal events (include sys uncertainties) obtained by the POLE program

$N_{\tau\tau}$ the number of ττ pairs from 782fb^{-1}

Babar

Limits on τ Lepton-Flavor Violating Decays in Three Charged Leptons (2010)

http://arxiv.org/abs/1002.4550

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Improved Limits on the Lepton-Flavor Violating Decays $\tau^- \to l^- l^+ l^-$ (2007)

https://arxiv.org/pdf/0708.3650.pdf

Babar Method
Event selection

- 3X1 Topology: Signal τ decay into 3 leptons, Tag τ into one charged track (**4 charged tracks & zero net charge**) and add any nb of photons and neutrinos.

- 6 signal modes: $\tau^- \rightarrow e^-e^+e^-,\ \mu^-\mu^+\mu^-,\ e^-\mu^+\mu^-,\ \mu^-e^+e^-,\ \mu^-e^+\mu^-,\ e^-\mu^+e^-$

- Particle identification: Particle's identified as e or μ with invariant mass & energy equal to τ parent;
  Electrons: Multivariate algo → $\boldsymbol{E/p}$, $\boldsymbol{dE/dx}$ & calorimeter shower's shape; (eff 91%, pion misid 2.4%),
  Muons: BDT algo → IFR hit's number, interaction lengths traversed's number, calorimeter energy deposition, inner trackers info (for low momentum μ < $500\ MeV/c$); (eff 77%, pion misid 2.1%).

- Events selections: pointing to a common region consistent with ττ production;
  polar angles in the colorimeter acceptance range.

- Event's particle separated in 2 hemispheres (plane perpendicular to the trust axis):
  Signal side with exactly 3 tracks with $\boldsymbol{m < 3.5\ GeV/c^2}$,
  Tag side with exactly 1 tracks and neutral energy deposits.

- γ conversion reduction: Two couples of oppositely charge required $\boldsymbol{m_{inv} > 30\ MeV/c^2}$ for eee & eμμ, $\boldsymbol{m_{inv} > 20\ MeV/c^2}$ else.

Babar Method
Background rejection

- **Main bkg suppression performed by the particle identfication.**

- Tag selection: momentum $p < 4.8\ GeV/c$; τ mass $0.2 < m_{inv} < 3.0\ GeV/c^2$ for eee, μee, eμμ & $0.1 < m_{inv} < 3.5\ GeV/c^2$ else.

- Reject Bhabha:
  Reject events where two opposite sign tracks is consistant with γ conversion, $\boldsymbol{M_{ee} < 200\ MeV/c^2}$ for all except $\boldsymbol{M_{ee} < 300\ MeV/c^2}$ for μeμ;
  For eee & eμμ, 1 prong track required energy deposit inconsistent with e, and not identified as e;
  For eμe, μee & μμμ, 1 prong track not identified as μ;
  Missing momentum, $\boldsymbol{p_{miss} > 300\ MeV/c}$ for eee & eμμ, $\boldsymbol{p_{miss} > 200\ MeV/c}$ for μee & μμμ & $\boldsymbol{p_{miss} > 100\ MeV/c}$ for μeμ & eμe;
  Opening angle, $\boldsymbol{cos(\theta_{13}) > -0.995}$ for eee & $\boldsymbol{cos(\theta_{13}) > -0.997}$ for μee.

- For μee & eμμ, both - tracks can satisfied e & μ PID, so both mass hypothesis 2D plane are computed but only one hypothesis fall into $\boldsymbol{\Delta M_{rec} \in]-600, 400[\ MeV/c^2}$ & $\boldsymbol{\Delta E \in]-700, 400[\ MeV}$

- Remaining Bkg are low multiplicity $q\bar{q}$ events, QED events (Bhabha or μμ depending on mode) & generic ττ;
  With distinct distributions in the 2D plane $(\Delta M_{rec}; \Delta E)$.

Babar Method
Event selection

- Signal Region define in 2D plane ($\Delta M_{ec};\Delta E$):
  with $\Delta E \equiv E^{CM}_{rec} - E^{CM}_{beam}$ and $\Delta M_{ec} \equiv M_{ec} - m_\tau$ where $M^2_{ec} \equiv \frac{E^{CM\,2}_{beam}}{c^4} - \frac{|\vec{p}^{CM}_{3l}|^2}{c^2}$
  Optimise by minimizing expected UL when no LFV signal is present, expected UL estimated with MC & data control samples.
- Blind analysis is performed.
- Expected Bkg rate determine by fitting in ($\Delta M_{ec};\Delta E$) separatly for each modes (crosschecks with sidebands method).
- **q$\overline{\text{q}}$ bkg:**
  Rotated ($\Delta M_{ec};\Delta E$) call ($\Delta M';\Delta E'$), rotation parameters included in fit params;
  $\Delta M'$ pdf = bifurcated Gaussian;
  $\Delta E'$ pdf = $(1 - x/\sqrt{1+x^2})(1 + ax + bx^2 + cx^3)$, with $x = (\Delta E' - d)/e$.
- **generic ττ bkg:**
  $(\Delta M'';\Delta E'')$, $\Delta M'' = cos\beta_1 \Delta M_{ec} + sin\beta_1 \Delta E$ & $\Delta E'' = cos\beta_2 \Delta E + sin\beta_2 \Delta M_{ec}$;
  $\Delta M''$ pdf = 2 Gauss sum (common mean);
  $\Delta E''$ pdf same as $q\overline{q}$.

Mode	ΔM_{rec} (MeV/c 2)	ΔE (MeV)
μμμ	-25, 30	-200, 100
eee	-30, 30	-300, 100
eμμ	-30, 30	-300, 50
μee	-30, 30	-300, 50
μeμ	-30, 30	-350, 100
eμe	-30, 30	-350, 100

- **QED bkg:**
  Rotated 2D Plane;
  eee, eμe & eμμ samples produced by passing all selection except lepton tag veto but identified as μ (eμe) or e;
  μee: tag tracks identified as μ and $0.5 < m_{1prong} < 2.5\ GeV/c^2$ and $p_{1prong} > 4.8GeV/c$;
  $\Delta M'$ pdf = 3rd order polynomial;
  $\Delta E'$ pdf = Crystal Ball;

Systematics Uncertainties on SGN EFF:

- PID dominates error 1.8-7.8%;
- Tracking efficiency 1%;
- All other smaller than 0.1%.

Systematics Uncertainties on BKG ESTIMATION:

- Estimated from fits;
- «to varying PDF parameters by their uncertainties, alternative functional forms are used to determine the uncertainty on the expected background yield in the SR»

Mode	Eff. [%]	$N_{\rm bgd}$	$\rm UL_{90}^{exp}$	$N_{\rm obs}$	$\rm UL_{90}^{obs}$
$e^-e^+e^-$	8.6 ± 0.2	0.12 ± 0.02	3.4	0	2.9
$\mu^-e^+e^-$	8.8 ± 0.5	0.64 ± 0.19	3.7	0	2.2
$\mu^+e^-e^-$	12.7 ± 0.7	0.34 ± 0.12	2.2	0	1.8
$e^+\mu^-\mu^-$	10.2 ± 0.6	0.03 ± 0.02	2.8	0	2.6
$e^-\mu^+\mu^-$	6.4 ± 0.4	0.54 ± 0.14	4.6	0	3.2
$\mu^-\mu^+\mu^-$	6.6 ± 0.6	0.44 ± 0.17	4.0	0	3.3

$$UL_{90}^{exp} = N_{UL}^{90}/2\varepsilon L \sigma_{\tau\tau}$$

by Cousins & Highland method