Rare Tau decays and CP violation searches with polarized beams

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Beijing, March 20, 2018
Outline:

1. Introduction and Motivation:
2. Lepton Flavour Violation
3. CP violation in tau decays
4. Conclusion and outlook
1.1 Quest for New Physics

- New era in particle physics: 
  (unexpected) **success of the Standard Model**: a successful theory of microscopic phenomena with no intrinsic energy limitation

- **Where do we look?** Everywhere! search for New Physics with broad search strategy given lack of clear indications on the SM-EFT boundaries (both in energies and effective couplings)

- Hint from B physics anomalies?
  \( b \rightarrow c \) charged currents: 
  \( \tau \) vs. light leptons (\( \mu, e \)) [\( R(D), R(D^*) \)]

\[
R(X) = \frac{\Gamma(B \rightarrow X\tau\bar{\nu})}{\Gamma(B \rightarrow X\ell\bar{\nu})}
\]
1.1 Quest for New Physics

- New era in particle physics:
  (unexpected) success of the Standard Model: a successful theory of microscopic phenomena with no intrinsic energy limitation

- Where do we look? Everywhere!
  search for New Physics with broad search strategy given lack of clear indications on the SM-EFT boundaries (both in energies and effective couplings)

- Hint from B physics anomalies?
  $b \rightarrow c$ charged currents:
  $\tau$ vs. light leptons ($\mu$, $e$) [R(D), R(D*)]

- Key unique role of Tau physics

\[ \Delta \chi^2 = 1.0 \text{ contours} \]

\[ \text{BaBar, PRL109,101802(2012)} \]
\[ \text{Belle, PRD92,072014(2015)} \]
\[ \text{LHCb, PRL115,111803(2015)} \]
\[ \text{Belle, PRD94,072007(2016)} \]
\[ \text{Belle, PRL118,211801(2017)} \]
\[ \text{LHCb, FPCP2017} \]

\[ \text{Average} \]

\[ \text{SM Predictions} \]

R(D)=0.300(8) HPQCD (2015)
R(D)=0.299(11) FNAL/MILC (2015)
R(D*)=0.252(3) S. Fajfer et al. (2012)

\[ \text{HFLAV} \]
\[ \text{FPCP 2017} \]

\[ P(\chi^2) = 71.6\% \]

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1.2 $\tau$ lepton as a unique probe of new physics

- In the quest of New Physics, can be sensitive to very high scale:
  - Kaon physics: $s\bar{d}s\bar{d}/\Lambda^2 \Rightarrow \Lambda \gtrsim 10^5 \text{ TeV}$
  - Tau Leptons: $\tau\rightarrow \mu\gamma$ $\Rightarrow \Lambda \gtrsim 10^2 \text{ TeV}$

- At low energy: lots of experiments e.g., *BaBar, Belle, BESIII, LHCb* important improvements on measurements and bounds obtained and more expected (*Belle II, HIEPA?*)

- In many cases no SM background: e.g., LFV, EDMs

- For some modes accurate calculations of hadronic uncertainties essential, e.g. CPV in hadronic Tau decays

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[Diagram showing energy levels $\Lambda_{NP}$ and $\Lambda_{LE}$ with $\tau$ lepton transitions.]
1.2 $\tau$ lepton as a unique probe of new physics

- A lot of progress in tau physics since its discovery on all the items described before important experimental efforts from LEP, CLEO, B factories: Babar, Belle, BES, VEPP-2M, LHCb, neutrino experiments,…

  More to come from LHCb, BES, VEPP-2M, Belle II, CMS, ATLAS, HIEPA?

- But $\tau$ physics has still potential "unexplored frontiers" deserve future exp. & th. efforts

- In the following, some selected examples

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Number of $\tau$ pairs</th>
</tr>
</thead>
<tbody>
<tr>
<td>LEP</td>
<td>$\sim 3 \times 10^5$</td>
</tr>
<tr>
<td>CLEO</td>
<td>$\sim 1 \times 10^7$</td>
</tr>
<tr>
<td>BaBar</td>
<td>$\sim 5 \times 10^8$</td>
</tr>
<tr>
<td>Belle</td>
<td>$\sim 9 \times 10^8$</td>
</tr>
<tr>
<td>Belle II</td>
<td>$\sim 10^{12}$</td>
</tr>
</tbody>
</table>
1.3 The Program

Muon LFC

\[ \mu^+ \rightarrow \mu^- e^+ \gamma \]

\[ \mu^+ \rightarrow \mu^- e^+ e^- \]

\[ \mu^- N \rightarrow e^- N \]

\[ \mu^- N \rightarrow e^+ N' \]

\[ \mu^+ e^- \rightarrow \mu^- e^+ \]

Neutrino Oscillations

\[ \nu_e \leftrightarrow \nu_\mu \]

\[ \nu_e \leftrightarrow \nu_\tau \]

\[ \nu_\mu \leftrightarrow \nu_\tau \]

Tau LFV

\[ \tau \rightarrow \ell \gamma \]

\[ \tau \rightarrow \ell^+ \ell^- \]

\[ \tau \rightarrow \ell + \text{hadrons} \]

CPV in \[ \tau \rightarrow K \pi \nu \]

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2. Charged Lepton-Flavour Violation
2.1 Introduction and Motivation

- Lepton Flavour Number is an « accidental » symmetry of the SM ($m_\nu=0$)

- In the $SM$ with massive neutrinos effective CLFV vertices are tiny
due to GIM suppression ➔ unobservably small rates!

E.g.: \( \mu \rightarrow e\gamma \)

\[
\begin{align*}
Br(\mu \rightarrow e\gamma) &= \frac{3\alpha}{32\pi} \left| \sum_{i=2,3} U_{\mu i}^* U_{ei} \frac{\Delta m_{1i}^2}{M_W^2} \right|^2
\end{align*}
\]

\(<10^{-54}\) \hspace{1cm}

Petcov’77, Marciano & Sanda’77, Lee & Shrock’77…

\[
\left[ Br(\tau \rightarrow \mu\gamma) < 10^{-40} \right]
\]

- Extremely clean probe of beyond SM physics

- In New Physics models: seazible effects
  Comparison in muonic and tauonic channels of branching ratios,
  conversion rates and spectra is model-diagnostic
2.1 Introduction and Motivation

- In New Physics scenarios CLFV can reach observable levels in several channels

<table>
<thead>
<tr>
<th></th>
<th></th>
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<tbody>
<tr>
<td>SUSY Higgs</td>
<td>Dedes, Ellis, Raidal, PLB 549 (2002) 159</td>
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</tr>
<tr>
<td></td>
<td>Brignole, Rossi, PLB 566 (2003) 517</td>
<td></td>
</tr>
<tr>
<td>SM + heavy Maj v&lt;sub&gt;R&lt;/sub&gt;</td>
<td>Cvetic, Dib, Kim, Kim, PRD66 (2002) 034008</td>
<td></td>
</tr>
<tr>
<td>Non-universal Z'</td>
<td>Yue, Zhang, Liu, PLB 547 (2002) 252</td>
<td></td>
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<tr>
<td></td>
<td>Fukuyama, Kikuchi, Okada, PRD 68 (2003) 033012</td>
<td></td>
</tr>
<tr>
<td>mSUGRA + Seesaw</td>
<td>Ellis, Gomez, Leontaris, Lola, Nanopoulos, EPJ C14 (2002) 319</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ellis, Hisano, Raidal, Shimizu, PRD 66 (2002) 115013</td>
<td></td>
</tr>
</tbody>
</table>

- But the sensitivity of particular modes to CLFV couplings is model dependent
- Comparison in muonic and tauonic channels of branching ratios, conversion rates and spectra is model-diagnostic
2.2 Tau LFV

- Several processes: $\tau \rightarrow \ell \gamma$, $\tau \rightarrow \ell_{\alpha} \bar{\ell}_{\beta} \ell_{\beta}$, $\tau \rightarrow \ell Y P$, $S$, $V$, $P \bar{P}$,...

90% CL upper limits on $\tau$ LFV decays

- 48 LFV modes studied at Belle and BaBar
2.2 Tau LFV

- Several processes: $\tau \rightarrow \ell \gamma$, $\tau \rightarrow \ell_\alpha \bar{\ell}_\beta \ell_\beta$, $\tau \rightarrow \ell Y$
- $P, S, V, P\bar{P},...$
- 90% CL upper limits on $\tau$ LFV decays

- Expected sensitivity $10^{-9}$ or better at LHCb, Belle II?
Overview of τ physics

Evolution of LFV limits

MarkII
ARGUS
DELPHI
CLEO
Belle
BaBar
LHCb
Belle II

mSUGRA + seesaw
SUSY + SO(10)
SM + seesaw
SUSY + Higgs

90% CL Upper Limit on Branching Ratio

γ → µγ
µη
µµ
µµµ

Reduced sensitivity by a factor ~7
Reduced sensitivity by a factor of 50

B(τ → µγ) < 10^{-9}
B(τ → µµµ) < 10^{-10}

δSUGRA + mSUGRA + mSUGRA
SUSY + SO(10)
SM + seesaw
SUSY + Higgs

Possible reach by Belle II (50 ab^{-1})

Belle II can reduce most of these limits by 1~2 orders of magnitude

Belle II physics prospect – tau LFV

I. Heredia

MWPF2015
2.3 Effective Field Theory approach

\[ \mathcal{L} = \mathcal{L}_{SM} + \frac{C^{(5)}}{\Lambda} O^{(5)} + \sum_i \frac{C_i^{(6)}}{\Lambda^2} O_i^{(6)} + \ldots \]

- Build all D>5 LFV operators:

  ➢ Dipole:

  \[ \mathcal{L}_{\text{eff}}^D \geq -\frac{C_D}{\Lambda^2} m_\tau \bar{\mu} \sigma^{\mu\nu} P_{L,R} \tau F_{\mu\nu} \]

See e.g.
Black, Han, He, Sher’02
Brignole & Rossi’04
Dassinger et al.’07
Matsuzaki & Sanda’08
Giffels et al.’08
Crivellin, Najjari, Rosiek’13
Petrov & Zhuridov’14
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  - Lepton-quark (Scalar, Pseudo-scalar, Vector, Axial-vector):
    \[ \mathcal{L}_{\text{eff}}^{S,V} \supset -\frac{C_{S,V}}{\Lambda^2} m_\tau m_q G_F \bar{\mu} \Gamma P_{L,R} \tau \bar{q} \Gamma q \]

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- Build all D>5 LFV operators:
  - Dipole: \[ \mathcal{L}_{\text{eff}}^{D} \supset - \frac{C_D}{\Lambda^2} m_\tau \bar{\mu} \sigma^{\mu\nu} P_{L,R} \tau F_{\mu\nu} \]
  - Lepton-quark (Scalar, Pseudo-scalar, Vector, Axial-vector):
  - Integrating out heavy quarks generates *gluonic operator*

\[ \frac{1}{\Lambda^2} \bar{\mu} P_{L,R} \tau Q \bar{Q} \rightarrow \mathcal{L}_{\text{eff}}^{G} \supset - \frac{C_G}{\Lambda^2} m_\tau G_F \bar{\mu} P_{L,R} \tau G^a_{\mu\nu} \]

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- Build all D>5 LFV operators:
  - Dipole: \[ \mathcal{L}^{D}_{\text{eff}} \supset -\frac{C_D}{\Lambda^2} m_\tau \bar{\mu}_\sigma^{\mu\nu} P_{L,R} \tau F_{\mu\nu} \]
  - Lepton-quark (Scalar, Pseudo-scalar, Vector, Axial-vector):
    - 4 leptons (Scalar, Pseudo-scalar, Vector, Axial-vector):
      \[ \mathcal{L}^{4\ell}_{\text{eff}} \supset -\frac{C_{SV}^{4\ell}}{\Lambda^2} \bar{\mu} \Gamma P_{L,R} \tau \bar{\mu} \Gamma P_{L,R} \mu \]

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Dipole: Dominant in SUSY -GUT and SUSY see-saw scenarios

Rich structure at dim=6

Dominant in RPV SUSY and RPC SUSY for large tan(\beta) and low m_A,

leptoquarks

\[ \Gamma \equiv 1, \gamma^\mu \]

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2.3 Effective Field Theory approach

\[ \mathcal{L} = \mathcal{L}_{SM} + \frac{C^{(5)}}{\Lambda} \mathcal{O}^{(5)} + \sum_i \frac{C^{(6)}_i}{\Lambda^2} \mathcal{O}^{(6)}_i + \ldots \]

- Build all D>5 LFV operators:
  - Dipole:
    \[ \mathcal{L}^D_{\text{eff}} \supset - \frac{C^D}{\Lambda^2} m_t \bar{\mu} \sigma^{\mu\nu} P_{L,R} \tau F_{\mu\nu} \]
  - Lepton-quark (Scalar, Pseudo-scalar, Vector, Axial-vector):
    \[ \mathcal{L}^S_{\text{eff}} \supset - \frac{C^S_{SV}}{\Lambda^2} m_t m_q G_F \bar{\mu} \Gamma P_{L,R} \tau \bar{q} \Gamma q \]
  - Lepton-gluon (Scalar, Pseudo-scalar):
    \[ \mathcal{L}^G_{\text{eff}} \supset - \frac{C^G}{\Lambda^2} m_t G_F \bar{\mu} P_{L,R} \tau G^a_{\mu\nu} G^{a\mu\nu} \]
  - 4 leptons (Scalar, Pseudo-scalar, Vector, Axial-vector):
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- Each UV model generates a *specific pattern* of them

See e.g.
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### 2.4 Model discriminating power of Tau processes

- **Summary table:**

<table>
<thead>
<tr>
<th></th>
<th>$\tau \rightarrow 3\mu$</th>
<th>$\tau \rightarrow \mu\gamma$</th>
<th>$\tau \rightarrow \mu\pi^+\pi^-$</th>
<th>$\tau \rightarrow \mu K\bar{K}$</th>
<th>$\tau \rightarrow \mu\pi$</th>
<th>$\tau \rightarrow \mu\eta^{(')}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$O_{S,V}^{4\ell}$</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$O_D$</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$O_V^{q}$</td>
<td>–</td>
<td>–</td>
<td>✓</td>
<td>✓</td>
<td>(I=0)</td>
<td>(I=0,1)</td>
</tr>
<tr>
<td>$O_S^{q}$</td>
<td>–</td>
<td>–</td>
<td>✓</td>
<td>✓</td>
<td>(I=0)</td>
<td>(I=0,1)</td>
</tr>
<tr>
<td>$O_{GG}$</td>
<td>–</td>
<td>–</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$O_{A}^{q}$</td>
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<td>–</td>
<td>–</td>
<td>–</td>
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<td>(I=1)</td>
</tr>
<tr>
<td>$O_{P}^{q}$</td>
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<td>–</td>
<td>–</td>
<td>–</td>
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<td>(I=1)</td>
</tr>
<tr>
<td>$O_{G\tilde{G}}$</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>✓</td>
</tr>
</tbody>
</table>

- In addition to leptonic and radiative decays, **hadronic decays** are very important sensitive to large number of operators!

- But need reliable determinations of the hadronic part: **form factors** and **decay constants** (e.g. $f_\eta$, $f_\eta'$)
2.4 Model discriminating power of Tau processes

- **Summary table:**

<table>
<thead>
<tr>
<th>( \tau \rightarrow 3\mu )</th>
<th>( \tau \rightarrow \mu \gamma )</th>
<th>( \tau \rightarrow \mu \pi^+\pi^- )</th>
<th>( \tau \rightarrow \mu K\bar{K} )</th>
<th>( \tau \rightarrow \mu \pi )</th>
<th>( \tau \rightarrow \mu \eta^{(i)} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( O_{S,V}^{4\ell} )</td>
<td>✅</td>
<td>✅</td>
<td>✅</td>
<td>✅</td>
<td>✅</td>
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<tr>
<td>( O_D )</td>
<td>✅</td>
<td>✅</td>
<td>✅</td>
<td>✅</td>
<td>✅</td>
</tr>
<tr>
<td>( O_V^q )</td>
<td>✅</td>
<td>✅</td>
<td>✅</td>
<td>✅</td>
<td>✅</td>
</tr>
<tr>
<td>( O_S^q )</td>
<td>✅</td>
<td>✅</td>
<td>✅</td>
<td>✅</td>
<td>✅</td>
</tr>
<tr>
<td>( O_{GG} )</td>
<td>✅</td>
<td>✅</td>
<td>✅</td>
<td>✅</td>
<td>✅</td>
</tr>
<tr>
<td>( O_{A}^q )</td>
<td>✅</td>
<td>✅</td>
<td>✅</td>
<td>✅</td>
<td>✅</td>
</tr>
<tr>
<td>( O_{P}^q )</td>
<td>✅</td>
<td>✅</td>
<td>✅</td>
<td>✅</td>
<td>✅</td>
</tr>
<tr>
<td>( O_{G\tilde{G}} )</td>
<td>✅</td>
<td>✅</td>
<td>✅</td>
<td>✅</td>
<td>✅</td>
</tr>
</tbody>
</table>

- **Form factors for \( \tau \rightarrow \mu(e)\pi\pi \) determined using **dispersive techniques**

- **Hadronic part:**

\[
H_{\mu} = \langle \pi\pi | \left(V_{\mu} - A_{\mu}\right)e^{il_{QCD}} | 0 \rangle = \left(Lorentz \ struct.\right)_{\mu}^{i} F_{i}(s)
\]

with

\[
s = \left(p_{\pi^+} + p_{\pi^-}\right)^2
\]

- **2-channel unitarity condition is solved with**  
  \( l=0 \) S-wave \( \pi\pi \) and KK scattering data as input

\[
ImF_{n}(s) = \sum_{m=1}^{2} T_{nm}^{*}(s)\sigma_{m}(s)F_{m}(s)
\]

*Celis, Cirigliano, E.P.’14*

*Donoghue, Gasser, Leutwyler’90*

*Moussallam’99*

*Daub et al’13*

*Celis, Cirigliano, E.P.’14*
2.4 Model discriminating power of Tau processes

• Summary table:

<table>
<thead>
<tr>
<th>Process</th>
<th>$\tau \rightarrow 3\mu$</th>
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<th>$\tau \rightarrow \mu K\bar{K}$</th>
<th>$\tau \rightarrow \mu\pi$</th>
<th>$\tau \rightarrow \mu\eta^{(i)}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$O^{4\ell}_{S,V}$</td>
<td>✓</td>
<td>−</td>
<td>−</td>
<td>−</td>
<td>−</td>
<td>−</td>
</tr>
<tr>
<td>$O_D$</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>−</td>
<td>−</td>
</tr>
<tr>
<td>$O^q_V$</td>
<td>−</td>
<td>−</td>
<td>✓ (I=1)</td>
<td>✓ (I=0,1)</td>
<td>−</td>
<td>−</td>
</tr>
<tr>
<td>$O^q_S$</td>
<td>−</td>
<td>−</td>
<td>✓ (I=0)</td>
<td>✓ (I=0,1)</td>
<td>−</td>
<td>−</td>
</tr>
<tr>
<td>$O_{GG}$</td>
<td>−</td>
<td>−</td>
<td>✓</td>
<td>✓</td>
<td>−</td>
<td>−</td>
</tr>
<tr>
<td>$O^q_A$</td>
<td>−</td>
<td>−</td>
<td>−</td>
<td>✓ (I=1)</td>
<td>✓ (I=0)</td>
<td>−</td>
</tr>
<tr>
<td>$O^q_P$</td>
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<td>−</td>
<td>−</td>
<td>✓ (I=1)</td>
<td>✓ (I=0)</td>
<td>−</td>
</tr>
<tr>
<td>$O_{GG}$</td>
<td>−</td>
<td>−</td>
<td>−</td>
<td>−</td>
<td>−</td>
<td>✓</td>
</tr>
</tbody>
</table>

The notion of “best probe” (process with largest decay rate) is model dependent.

If observed, compare rate of processes key handle on relative strength between operators and hence on the underlying mechanism.
2.5 Handles

- Two handles:
  - Branching ratios: \[ R_{F,M} \equiv \frac{\Gamma(\tau \rightarrow F)}{\Gamma(\tau \rightarrow F_M)} \] with F_M dominant LFV mode for model M.
  - Spectra for > 2 bodies in the final state: \[ \frac{dBR(\tau \rightarrow \mu\mu\mu)}{d\sqrt{s}} \]

- Benchmarks:
  - Dipole model: \( C_D \neq 0, C_{\text{else}} = 0 \)
  - Scalar model: \( C_S \neq 0, C_{\text{else}} = 0 \)
  - Vector (gamma,Z) model: \( C_V \neq 0, C_{\text{else}} = 0 \)
  - Gluonic model: \( C_{GG} \neq 0, C_{\text{else}} = 0 \)
2.6 Model discriminating of BRs

- Two handles:
  - Branching ratios: 
    \[ R_{F,M} = \frac{\Gamma(\tau \rightarrow F)}{\Gamma(\tau \rightarrow F_M)} \]
    with $F_M$ dominant LFV mode for model M

<table>
<thead>
<tr>
<th></th>
<th>$\mu\pi^+\pi^-$</th>
<th>$\mu\rho$</th>
<th>$\mu f_0$</th>
<th>$3\mu$</th>
<th>$\mu\gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>D</td>
<td>$R_{F,D}$</td>
<td>$0.26 \times 10^{-2}$</td>
<td>$0.22 \times 10^{-2}$</td>
<td>$0.13 \times 10^{-3}$</td>
<td>$0.22 \times 10^{-2}$</td>
</tr>
<tr>
<td>BR</td>
<td>$&lt; 1.1 \times 10^{-10}$</td>
<td>$&lt; 9.7 \times 10^{-11}$</td>
<td>$&lt; 5.7 \times 10^{-12}$</td>
<td>$&lt; 9.7 \times 10^{-11}$</td>
<td>$&lt; 4.4 \times 10^{-8}$</td>
</tr>
<tr>
<td>S</td>
<td>$R_{F,S}$</td>
<td>1</td>
<td>0.28</td>
<td>0.7</td>
<td>-</td>
</tr>
<tr>
<td>BR</td>
<td>$&lt; 2.1 \times 10^{-8}$</td>
<td>$&lt; 5.9 \times 10^{-9}$</td>
<td>$&lt; 1.47 \times 10^{-8}$</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$V(\gamma)$</td>
<td>$R_{F,V(\gamma)}$</td>
<td>1</td>
<td>0.86</td>
<td>0.1</td>
<td>-</td>
</tr>
<tr>
<td>BR</td>
<td>$&lt; 1.4 \times 10^{-8}$</td>
<td>$&lt; 1.2 \times 10^{-8}$</td>
<td>$&lt; 1.4 \times 10^{-9}$</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Z</td>
<td>$R_{F,Z}$</td>
<td>1</td>
<td>0.86</td>
<td>0.1</td>
<td>-</td>
</tr>
<tr>
<td>BR</td>
<td>$&lt; 1.4 \times 10^{-8}$</td>
<td>$&lt; 1.2 \times 10^{-8}$</td>
<td>$&lt; 1.4 \times 10^{-9}$</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>G</td>
<td>$R_{F,G}$</td>
<td>1</td>
<td>0.41</td>
<td>0.41</td>
<td>-</td>
</tr>
<tr>
<td>BR</td>
<td>$&lt; 2.1 \times 10^{-8}$</td>
<td>$&lt; 8.6 \times 10^{-9}$</td>
<td>$&lt; 8.6 \times 10^{-9}$</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

* Celis, Cirigliano, E.P.'14

Benchmark
Emilie Passemar
2.6 Model discriminating of BRs

- Studies in specific models

<table>
<thead>
<tr>
<th>ratio</th>
<th>LHT</th>
<th>MSSM (dipole)</th>
<th>MSSM (Higgs)</th>
<th>SM4</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \frac{\text{Br}(\mu^--\mu^+\mu^-)}{\text{Br}(\tau^--\mu^+\mu^-)} )</td>
<td>0.02...1</td>
<td>( \sim 6 \times 10^{-3} )</td>
<td>( \sim 6 \times 10^{-3} )</td>
<td>0.06...2.2</td>
</tr>
<tr>
<td>( \frac{\text{Br}(\mu^-\rightarrow e^-\mu^+\mu^-)}{\text{Br}(\tau^-\rightarrow e^-\mu^+\mu^-)} )</td>
<td>0.04...0.4</td>
<td>( \sim 1 \times 10^{-2} )</td>
<td>( \sim 1 \times 10^{-2} )</td>
<td>0.07...2.2</td>
</tr>
<tr>
<td>( \frac{\text{Br}(\tau^--\mu^-\rightarrow e^-\mu^+\mu^-)}{\text{Br}(\tau^-\rightarrow \mu^-\rightarrow e^-\mu^+\mu^-)} )</td>
<td>0.04...0.3</td>
<td>( \sim 2 \times 10^{-3} )</td>
<td>0.06...0.1</td>
<td>0.06...2.2</td>
</tr>
<tr>
<td>( \frac{\text{Br}(\tau^-\rightarrow e^-\mu^+\mu^-)}{\text{Br}(\tau^-\rightarrow e^-\mu^+\mu^-)} )</td>
<td>0.04...0.3</td>
<td>( \sim 2 \times 10^{-3} )</td>
<td>0.02...0.04</td>
<td>0.03...1.3</td>
</tr>
<tr>
<td>( \frac{\text{Br}(\tau^-\rightarrow \mu^-\rightarrow e^-\mu^+\mu^-)}{\text{Br}(\tau^-\rightarrow \mu^-\rightarrow e^-\mu^+\mu^-)} )</td>
<td>0.8...2</td>
<td>( \sim 5 )</td>
<td>0.3...0.5</td>
<td>1.5...2.3</td>
</tr>
<tr>
<td>( \frac{\text{Br}(\tau^-\rightarrow \mu^-\rightarrow e^-\mu^+\mu^-)}{\text{Br}(\tau^-\rightarrow \mu^-\rightarrow e^-\mu^+\mu^-)} )</td>
<td>0.7...1.6</td>
<td>( \sim 0.2 )</td>
<td>5...10</td>
<td>1.4...1.7</td>
</tr>
<tr>
<td>( \frac{\text{Br}(\mu\rightarrow e\gamma)}{\text{Br}(\mu\rightarrow e\gamma)} )</td>
<td>( 10^{-3} \ldots 10^2 )</td>
<td>( \sim 5 \times 10^{-3} )</td>
<td>0.08...0.15</td>
<td>( 10^{-12} \ldots 26 )</td>
</tr>
</tbody>
</table>

Buras et al.’10

Disentangle the underlying dynamics of NP
Figure 3: Dalitz plot for $\tau^- \rightarrow \mu^- \mu^+ \mu^-$ decays when all operators are assumed to vanish with the exception of $C_{DL,DR} = 1$ (left) and $C_{SLL,SRR} = 1$ (right), taking $\Lambda = 1$ TeV in both cases. Colors denote the density for $d^2\text{BR}/(dm_{\mu^+} dm_{\mu^-})$, small values being represented by darker colors and large values in lighter ones. Here $m_{\mu^+}^2$ represents $m_{12}^2$ or $m_{23}^2$, defined in Sec. 3.1.

Figure 4: Dalitz plot for $\tau^- \rightarrow \mu^- \mu^+ \mu^-$ decays when all operators are assumed to vanish with the exception of $C_{VRL,VLR} = 1$ (left) and $C_{VLL,VRR} = 1$ (right), taking $\Lambda = 1$ TeV in both cases. Colors are defined as in Fig. 3.
2.7 Discriminating power of $\tau \rightarrow \mu (e) \pi \pi$ decays

Celis, Cirigliano, E.P.'14
2.7 Discriminating power of $\tau \to \mu (e) \pi \pi$ decays

\[ \mathcal{L}_{\text{eff}}^D \supset -\frac{C_D}{\Lambda^2} m_\tau \bar{\mu} \sigma^{\mu\nu} P_{L,R} \tau F_{\mu\nu} \]

Dipole model:
- $C_D \neq 0$
- $C_{\text{else}} = 0$

\[ \mathcal{L}_{\text{eff}}^S \supset -\frac{C_S}{\Lambda^2} m_\tau m_q G_{F,\tau} \bar{\mu} P_{L,R} \tau \bar{q} q \]

Scalar model:
- $C_S = 1$
- $C_{\text{else}} = 0$, $\Lambda = 1$ TeV

Emilie Passemar
2.7 Discriminating power of $\tau \to \mu(e)\pi\pi$ decays

Different distributions according to the operator!
2.8 Non standard LFV Higgs coupling

\[ \Delta \mathcal{L}_Y = -\frac{\lambda_{ij}}{\Lambda^2} \left( \bar{f}_L^i f_R^j H \right) H^* H \]

- **High energy**: LHC

```
\begin{array}{c}
\text{p} \\
\text{h} \\
\text{p} \\
\end{array}
```

- **Low energy**: D, S operators

```
\begin{array}{c}
l_i \\
\text{h} \\
l_j \\
\end{array}
```

In the SM:

\[ Y_{ij}^{h_{SM}} = \frac{m_i}{\tau} \delta_{ij} \]

Hadronic part treated with perturbative QCD

Goudelis, Lebedev, Park’11
Davidson, Grenier’10
Harnik, Kopp, Zupan’12
Blankenburg, Ellis, Isidori’12
McKeen, Pospelov, Ritz’12
Arhrib, Cheng, Kong’12

Emilie Passemam
2.8 Non standard LFV Higgs coupling

- $\Delta L_Y = -\frac{\lambda_{ij}}{\Lambda^2} \left( \bar{f}_L^i f_R^j H \right) H^+ H$

- High energy: LHC

- Low energy: D, S, G operators

In the SM: $Y_{ij}^{hSM} = \frac{m_i}{v} \delta_{ij}$

Hadronic part treated with perturbative QCD

Reverse the process

Hadronic part treated with non-perturbative QCD

Goudelis, Lebedev, Park’11
Davidson, Grenier’10
Harnik, Kopp, Zupan’12
Blankenburg, Ellis, Isidori’12
McKeen, Pospelov, Ritz’12
Arhrib, Cheng, Kong’12
Constraints in the $\tau\mu$ sector

- At low energy

  $\tau \rightarrow \mu \pi \pi$

  Dominated by $\rho(770)$ (photon mediated)
  $f_0(980)$ (Higgs mediated)
Constraints in the $\tau\mu$ sector

- **Constraints from LE:**
  - $\tau \rightarrow \mu\gamma$: best constraints but loop level sensitive to UV completion of the theory
  - $\tau \rightarrow \mu\pi\pi$: tree level diagrams robust handle on LFV

- **Constraints from HE:**
  - $LHC$ wins for $\tau\mu$!
  - Opposite situation for $\mu e$!
  - For LFV Higgs and nothing else: LHC bound

- **Summary:**
  - $BR(\tau \rightarrow \mu\gamma) < 2.2 \times 10^{-9}$
  - $BR(\tau \rightarrow \mu\pi\pi) < 1.5 \times 10^{-11}$
Hint of New Physics in $h \rightarrow \tau \mu$?

Figure 5: Constraints on the flavour violating Yukawa couplings, $|Y_{\mu \tau}|$ and $|Y_{\tau \mu}|$. The black dashed lines are contours of $B(H \rightarrow \mu \tau)$ for reference. The expected limit (red solid line) with one standard deviation (green) and two standard deviation (yellow) bands, and observed limit (black solid line) are derived from the limit on $B(H \rightarrow \mu \tau)$ from the present analysis. The shaded regions are derived constraints from null searches for $t \rightarrow 3\mu$ (dark green) and $t \rightarrow \mu g$ (lighter green). The light blue region indicates the additional parameter space excluded by our result. The purple diagonal line is the theoretical naturalness limit $Y_{ij} Y_{ji} \ll m_i m_j / v^2$.

Conclusions

A direct search for lepton flavour violating decays of the Higgs boson in the $H \rightarrow \mu \tau$ channel is described. The data sample used in the search was collected in proton-proton collisions at $p_s = 13$ TeV with the CMS experiment at the LHC and corresponds to an integrated luminosity of 2.3 fb$^{-1}$. No excess is observed. The best-fit branching fraction is $B(H \rightarrow \mu \tau) = 0.76^{+0.81}_{-0.84}$% and an upper limit of $B(H \rightarrow \mu \tau) < 1.20$% (1.62% expected) is set at 95% CL.

At $p_s = 8$ TeV a small excess was observed, corresponding to 2.4 $\sigma$, with an analysis based on an integrated luminosity of 19.7 fb$^{-1}$ that yielded an expected 95% CL limit on the branching fraction of 0.75%. More data are needed to make definitive conclusions on the origin of that excess.
Hint of New Physics in $h \to \tau\mu$?

CMS Preliminary

$35.9 \text{ fb}^{-1} (13 \text{ TeV})$

<table>
<thead>
<tr>
<th>Process</th>
<th>Expected (Median)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu^+_\text{had}$, 0 Jets</td>
<td>1.04% (1.14%)</td>
</tr>
<tr>
<td>$\mu^+_\text{had}$, 1 Jet</td>
<td>1.74% (1.26%)</td>
</tr>
<tr>
<td>$\mu^+_\text{had}$, 2 Jets</td>
<td>1.65% (2.12%)</td>
</tr>
<tr>
<td>$\mu^+_\text{VBF}$</td>
<td>1.30% (1.41%)</td>
</tr>
<tr>
<td>$\mu^-\text{had}$, 0 Jets</td>
<td>1.08% (1.01%)</td>
</tr>
<tr>
<td>$\mu^-\text{had}$, 1 Jet</td>
<td>1.35% (1.47%)</td>
</tr>
<tr>
<td>$\mu^-\text{had}$, 2 Jets</td>
<td>3.33% (3.23%)</td>
</tr>
<tr>
<td>$\mu^-\text{VBF}$</td>
<td>1.40% (1.73%)</td>
</tr>
<tr>
<td>$H \to \mu\tau$</td>
<td>0.51% (0.49%)</td>
</tr>
</tbody>
</table>

95% CL Limit on $\text{Br}(H \to \mu\tau)$, %

CMS Preliminary

$35.9 \text{ fb}^{-1} (13 \text{ TeV})$

CMS 8TeV

$\tau \to 3\mu$

$\tau \to \mu\gamma$

Emilie Passemar
3. LFC processes: CPV in tau decays
3.1 Introduction

- CP violation measured in K and B decays in agreement with SM
- Not enough CP violation to explain asymmetry matter/anti-matter
- Look elsewhere:
  - Neutrinos
  - Charged leptons
  - Electric dipole moments

- Aim: pin down new sources of CPV in the lepton sector and discriminating between NP scenarios

- Study of tau decays:
  - CPV in tau pair production \((e^+e^- \rightarrow \tau^+\tau^-)\) EDM
  - CPV in hadronic tau decays
    - SM source: K-Kbar mixing
    - NP source: In the vertex
3.2 EDM of the Tau

- Probe to test new sources of CP violation

- CPV in tau pair production ($e^+e^- \rightarrow \tau^+\tau^-$)

- Very challenging measurement for $\tau$

- Measured using spin correlations of decay product the taus

- Help of polarized beams?

No SM background

P and T violation:

$$\mathcal{H} \sim d \vec{J} \cdot \vec{E}$$

EDMs in $e \cdot cm$

<table>
<thead>
<tr>
<th>System</th>
<th>current</th>
<th>projected</th>
<th>SM (CKM)</th>
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<tr>
<td>$e$</td>
<td>$\sim 10^{-28}$</td>
<td>$10^{-29}$</td>
<td>$\sim 10^{-38}$</td>
</tr>
<tr>
<td>$\mu$</td>
<td>$\sim 10^{-19}$</td>
<td>$\sim 10^{-35}$</td>
<td>$\sim 10^{-34}$</td>
</tr>
<tr>
<td>$\tau$</td>
<td>$\sim 10^{-16}$</td>
<td><strong>$10^{-29}$</strong></td>
<td><strong>$10^{-34}$</strong></td>
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<tr>
<td>$n$</td>
<td>$\sim 10^{-26}$</td>
<td>$10^{-28}$</td>
<td>$\sim 10^{-31}$</td>
</tr>
<tr>
<td>$p$</td>
<td>$\sim 10^{-23}$</td>
<td>$10^{-29}$ **</td>
<td>$\sim 10^{-31}$</td>
</tr>
<tr>
<td>$^{199}\text{Hg}$</td>
<td>$\sim 10^{-29}$</td>
<td>$10^{-30}$</td>
<td>$\sim 10^{-33}$</td>
</tr>
<tr>
<td>$^{129}\text{Xe}$</td>
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<td>$10^{-29}$</td>
<td>$\sim 10^{-33}$</td>
</tr>
<tr>
<td>$^{225}\text{Ra}$</td>
<td>$\sim 10^{-23}$</td>
<td>$10^{-26}$</td>
<td>$\sim 10^{-33}$</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
</tbody>
</table>
3.2 EDM of the Tau

- The squared spin density matrix for $e^+(p)\ e^-(p) \rightarrow \gamma^* \rightarrow \tau^+(k,S_+) \ \tau^-(k,S_-)$

$$\mathcal{M}^2 = \mathcal{M}_{SM}^2 + \text{Re}(d_\tau)\mathcal{M}_{Re}^2 + \text{Im}(d_\tau)\mathcal{M}_{Im}^2 + |d_\tau|^2\mathcal{M}_{d2}^2$$

- Study of spin momentum correlations:

$$\mathcal{M}_{Re}^2 \propto (S_+ \times S_-) \cdot \hat{k}, \quad (S_+ \times S_-) \cdot \hat{p},$$

$$\mathcal{M}_{Im}^2 \propto (S_+ - S_-) \cdot \hat{k}, \quad (S_+ - S_-) \cdot \hat{p},$$

- Polarized beams will help since the decay products of only one tau could be studied \textit{Bernabeu, Gonzalez-Sprinberg, Vidal’04,’07}

$$-0.22 < \text{Re} (d_\tau) < 0.45 \quad (10^{-16} e \cdot cm) \quad \text{and} \quad -0.25 < \text{Im} (d_\tau) < 0.08 \quad (10^{-16} e \cdot cm)$$

- Radiative decay possibility \textit{Eidelman, Epifanov, Fael, Mercolli, Passera’16}
3.3 $\tau \to K\pi\nu_\tau$ CP violating asymmetry

- $A_Q = \frac{\Gamma(\tau^+ \to \pi^+ K^0_S \bar{\nu}_\tau) - \Gamma(\tau^- \to \pi^- K^0_S \nu_\tau)}{\Gamma(\tau^+ \to \pi^+ K^0_S \bar{\nu}_\tau) + \Gamma(\tau^- \to \pi^- K^0_S \nu_\tau)}$

  $= |p|^2 - |q|^2 \approx (0.36 \pm 0.01)\%$ in the SM

  Bigi & Sanda’05

  Grossman & Nir’11

- Experimental measurement: BaBar’11

  $A_{Q_{\text{exp}}} = (-0.36 \pm 0.23_{\text{stat}} \pm 0.11_{\text{syst}})\% \quad \Rightarrow \quad 2.8\sigma \quad \text{from the SM!}$

- CP violation in the tau decays should be of opposite sign compared to the one in D decays in the SM

  $A_D = \frac{\Gamma(D^+ \to \pi^+ K^0_S) - \Gamma(D^- \to \pi^- K^0_S)}{\Gamma(D^+ \to \pi^+ K^0_S) + \Gamma(D^- \to \pi^- K^0_S)} = (-0.54 \pm 0.14)\%$

  Belle, Babar, CLEO, FOCUS

Grossman & Nir’11

Emilie Passemar
3.3 $\tau \rightarrow K\pi\nu_\tau$ CP violating asymmetry

- New physics? Charged Higgs, $W_L$-$W_R$ mixings, leptoquarks, tensor interactions (Devi, Dhargyal, Sinha’14, Cirigliano, Crivellin, Hoferichter’17)?

- Need to investigate how large can be the prediction in realistic new physics models: it looks like a tensor interaction can explain the effect but in conflict with bounds from neutron EDM and $D\bar{D}$ mixing

Bigi’Tau12

Very difficult to explain!

- light BSM physics?

Cirigliano, Crivellin, Hoferichter’17
3.3 $\tau \rightarrow K\pi\nu_\tau$ CP violating asymmetry

- In this measurement, need to know hadronic part form factors

$$\langle K\pi | \bar{s}\gamma_\mu u | 0 \rangle = \left[ (p_K - p_\pi)_{\mu} + \frac{\Delta_{K\pi}}{s} (p_K + p_\pi)_{\mu} \right] f_+ (s) - \frac{\Delta_{K\pi}}{s} (p_K + p_\pi)_{\mu} f_0 (s)$$

with $s = Q^2 = (p_K + p_\pi)^2$

$\Delta_{K\pi} = (M_K^2 - M_\pi^2)$

- $f_+$ vector
- $f_0$ scalar
3.3 $\tau \rightarrow K\pi\nu_\tau$ angular CP violating asymmetry

- Measurement of the angular CP asymmetry from Belle:

\[
\frac{d\Gamma(\tau^- \rightarrow K\pi^-\nu_\tau)}{d\sqrt{Q^2}d\cos\theta \ d\cos\beta} = \left[A(Q^2) - B(Q^2) \left(3\cos^2\psi - 1\right)\left(3\cos^2\beta - 1\right)\right]|f_+(s)|^2
\]

\[
+ m_{\tau}^2|f_0(s)|^2 - C(Q^2)\cos\psi \cos\beta \Re\left(f_+(s)f_0^*(s)\right)
\]

- $A(Q^2)$, $B(Q^2)$, $C(Q^2)$: kinematic factors

- Angles:
  - in $K\pi$ rest frame
    - $\beta$: angle between kaon and $e^+e^-$ CMS frame
    - $\Psi$: angle between $\tau$ and CMS frame
  - in $\tau$ rest frame
    - $\theta$: angle between $\tau$ direction in CMS and direction of $K\pi$ system (dependence with $\Psi$)

### In hadronic rest frame

- cms
- $K$
- $\beta$
- $\psi$
- $\tau$
- $\pi$

Emilie Passemar
### 3.3 $\tau \rightarrow K\pi\nu_\tau$ angular CP violating asymmetry

- Measurement of the angular CP asymmetry from Belle:

$$
\frac{d\Gamma(\tau^- \rightarrow K\pi^-\nu_\tau)}{d\sqrt{Q^2} d\cos\theta d\cos\beta} = \left[ A(Q^2) - B(Q^2) \left( 3\cos^2\psi - 1 \right) \left( 3\cos^2\beta - 1 \right) \right] |f_+(s)|^2
$$

$$
+ m_\tau^2 |\tilde{f}_0(s)|^2 - C(Q^2)\cos\psi\cos\beta \text{Re}(f_+(s)\tilde{f}_0^*(s))
$$

- $A(Q^2)$, $B(Q^2)$, $C(Q^2)$: kinematic factors

#### Charged Higgs contribution

$$
\tilde{f}_0(s) = f_0(s) + \frac{\eta^2}{m_\tau^2} f_H(s)
$$

with

$$
f_H(s) = \frac{s}{m_u - m_s} f_0(s)
$$

Khün & Mirkes’ 05
3.3 $\tau \to K\pi\nu_\tau$ angular CP violating asymmetry

- Belle uses sum of BWs to fit the invariant mass distribution \textit{Belle’08}

\[ F_V = \frac{1}{1 + \beta + \chi} \left[ BW_{K^*(892)}(s) + \beta BW_{K^*(1410)}(s) + \gamma BW_{K^*(1680)}(s) \right] \]
\[ F_S = \kappa \frac{s}{M^2_{K^*(800)}} BW_{K^*_0(800)}(s) + \gamma \frac{s}{M^2_{K^*_0(1430)}} BW_{K^*_0(1430)}(s) \]

- Can be justified for the vector but not for the scalar!
  - Use a parametrization relying on dispersion relations instead:
    - Resum all final state $K\pi$ rescattering
    \[
    \begin{array}{c}
    \text{K} \\
    \text{K} \\
    \text{K} \\
    \text{K} \\
    \hline
    \pi \\
    \pi
    \end{array}
    =
    \begin{array}{c}
    \times \\
    \times \\
    \times \\
    \times \\
    \hline
    \pi \\
    \pi
    \end{array}
    +
    \begin{array}{c}
    \circ \\
    \circ \\
    \circ \\
    \circ \\
    \hline
    \pi \\
    \pi
    \end{array}
    +
    \begin{array}{c}
    \times \\
    \times \\
    \times \\
    \times \\
    \hline
    \pi \\
    \pi
    \end{array}
    +
    \begin{array}{c}
    \times \\
    \times \\
    \times \\
    \times \\
    \hline
    \pi \\
    \pi
    \end{array}
    +
    \begin{array}{c}
    \times \\
    \times \\
    \times \\
    \times \\
    \hline
    \pi \\
    \pi
    \end{array}
    + \ldots
    
  - Allow to combine with $K \to \pi\nu_1$ precise measurements

- Several theoretical parametrizations proposed: All rely on analyticity and unitarity and crossing symmetry \textit{Jamin, Pich, Portolés’06,’08, Moussallam’08, Boito, Escribano, Jamin’09,’10, Bernard, Boito, E.P.’11, Bernard’14}
3.3 $\tau \rightarrow K\pi\nu_\tau$ angular CP violating asymmetry

$N_{\text{events}} \propto N_{\text{tot}} b_w \frac{1}{\Gamma_{K\pi}} \frac{d\Gamma_{K\pi}}{d\sqrt{s}}$

Bernard, Boito, E.P.'11
Antonelli, Cirigliano, Lusiani, E.P.'13

$f_\theta(s) = \exp\left[ P_2(s) + \frac{s^2(s-\Delta_{K\pi})}{\pi (m_\pi + m_\pi)^2 s'^2} \frac{ds'}{s'^2} \frac{\phi_0(s')}{(s'-s-i\epsilon)} \right]$
3.3 $\tau \to K\pi\nu_\tau$ CP violating asymmetry

- In this measurement, need to know hadronic part form factors

$$\langle K\pi | \bar{s}\gamma_\mu u | 0 \rangle = \left[ (p_K - p_\pi)_{\mu} + \frac{\Delta_{K\pi}}{s} (p_K + p_\pi)_{\mu} \right] f_+(s) - \frac{\Delta_{K\pi}}{s} (p_K + p_\pi)_{\mu} f_0(s)$$

with $s = Q^2 = (p_K + p_\pi)^2$

- Up to now know from decay spectrum but difficult to disentangle scalar and vector form factor consider the FB asymmetry instead

$$A_{FB} = \frac{d\Gamma(\cos \theta) - d\Gamma(-\cos \theta)}{d\Gamma(\cos \theta) + d\Gamma(-\cos \theta)}$$

Beldjoudi & Truong’94 Moussallam, B2TIP

- Formula: can disentangle scalar and vector FF easily

$$A_{FB}(s) = \frac{3\Delta_{\pi^+K^0}}{\sqrt{\lambda_{\pi^+K^0}(s)|f^K_{V\pi}(s)||f^K_{0\pi}(s)|}} \frac{\cos(\delta^{1/2}_{i} - \delta^{1/2}_{0})}{\lambda_{\pi^+K^0}(s)(1 + 2s/m^2_\tau) + 3|f^K_{0\pi}(s)|^2 \Delta^2_{\pi^+K^0}}.$$ 

vanishes at threshold

Never done before: Feasible at HIEPA?
3.3 \( \tau \rightarrow K\pi\nu_\tau \) CP violating asymmetry

- Measurement of the direct contribution of NP in the angular CP violating asymmetry done by CLEO and Belle

Belle does not see any asymmetry at the 0.2 - 0.3% level

Belle’11

- Problem with this measurement? It would be great to have other experimental measurements from Belle II or HIEPA

\[ A_{\text{CP}} \] vs. \( W \) (GeV/c^2)
3.3 $\tau \rightarrow K\pi\nu_\tau$ CP violating asymmetry

- The angular CP asymmetry from Belle:

$$\frac{d\Gamma(\tau^- \rightarrow K\pi^-\nu_\tau)}{d\sqrt{Q^2} \, d\cos\theta \, d\cos\beta} = \left[ A(Q^2) - B(Q^2) \left( 3\cos^2\psi - 1 \right) \left( 3\cos^2\beta - 1 \right) \right] |f_+(s)|^2$$

$$+ m_\tau^2 \left| \tilde{f}_0(s) \right|^2 - C(Q^2)\cos\psi\cos\beta \Re \left( f_+(s)\tilde{f}_0^*(s) \right)$$

- When integrating on the angle the interference term between scalar and vector vanishes

$$\frac{d\Gamma}{d\sqrt{Q^2}} = \frac{G_F^2 \sin^2\theta_c m_\tau^3}{3 \times 2^5 \times \pi^3 Q^2} \left( 1 - \frac{Q^2}{m_\tau^2} \right)^2 \left( 1 + \frac{2Q^2}{m_\tau^2} \right)$$

$$\times q_1(Q^2) \left\{ q_1(Q^2)^2 |F_V|^2 + \frac{3}{4} \frac{Q^2}{1 + 2Q^2 / m_\tau^2} |F_S|^2 \right\}$$
3.3 $\tau \to K\pi\nu_\tau$ CP violating asymmetry

- We need a tensor interaction to get some interference:

$$\mathcal{H}_T^{\text{eff}} \equiv G'(s\sigma_{\mu\nu}u)(\nu_\tau (1 + \gamma_5)\sigma^{\mu\nu}T)$$

with

$$G' = \frac{G_F}{\sqrt{2}} C_T, \quad C_T = |C_T| e^{i\phi_T}$$

- When integrating the interference term between vector and tensor does not vanish:

$$\frac{d\Gamma}{dQ^2} = \frac{d\Gamma_{SM}^T}{dQ^2} + \frac{d\Gamma_T}{dQ^2} + \frac{d\Gamma_{V-T}^T}{dQ^2}$$

$$\frac{d\Gamma_{V-T}^T}{dQ^2} = G_F^2 \sin^2 \theta_C \frac{m_\tau^3}{32\pi^3} \left( \frac{m_\tau^2 - Q^2}{m_\tau^2} \right)^2 \frac{q_1^3}{Q^2} \frac{Q^2}{m_\tau^2} \times |C_T| \left| F_V(s) \right| \left| F_T(s) \cos (\delta_T(s) - \delta_V(s) + \phi_T) \right|$$

In conflict with bounds from neutron EDM and DD mixing

Cirigliano, Crivellin, Hoferichter’17
3.4 Three body CP asymmetries

- Ex: $\tau \rightarrow K\pi\pi\nu_\tau$

- A variety of CPV observables can be studied: $\tau \rightarrow K\pi\pi\nu_\tau$, $\tau \rightarrow \pi\pi\pi\nu_\tau$ rate, angular asymmetries, triple products, ...

Same principle as in charm, see Bevan’15

Difficulty: Treatment of the hadronic part
Hadronic final state interactions have to be taken into account!
- Disentangle weak and strong phases

- More form factors, more asymmetries to build but same principles as for 2 bodies

References:
- e.g., Choi, Hagiwara and Tanabashi’98
- Kiers, Little, Datta, London et al.,’08
- Mileo, Kiers and, Szynkman’14
4. Conclusion and outlook
Conclusion and outlook

• Direct searches for new physics at the TeV-scale at LHC by ATLAS and CMS energy frontier

• Probing new physics orders of magnitude beyond that scale and helping to decipher possible TeV-scale new physics requires to work hard on the intensity and precision frontiers

• Charged leptons and in particular tau physics offer an important spectrum of possibilities:
  ➢ LFV measurement has SM-free signal
  ➢ Current experiments and mature proposals promise orders of magnitude sensitivity improvements (Belle II, Tau-Charm factory, etc.)
  ➢ There is a hint of new dynamics in CPV asymmetries in the tau sector
  ➢ Progress towards a better knowledge of hadronic uncertainties
  ➢ New physics models usually strongly correlate the flavours sectors
Conclusion and outlook

- We show how CLFV decays offer excellent model discriminating tools giving indications on
  - the mediator (operator structure)
  - the source of flavour breaking (comparison $\tau \mu$ vs. $\tau e$ vs. $\mu e$)

- Interplay low energy and collider physics: LFV of the Higgs boson

- We discussed the possibilities to look for CP violation in the tau sector: BaBar result does not agree with SM expectation but needs to be confirmed. A lot of new measurements possible ($A_{CP}$, $A_{FB}$, etc.) to shed light on CP violation in the tau sector: combine strong and weak phase determination

- EDM of the tau also very interesting to study but difficult

- Several topics extremely interesting to study at the tau-charm factories that I did not address:
  - $\alpha_S$, $|V_{us}|$ and $m_s$ from hadronic tau decays
  - Lepton universality tests, Michel parameters…

- A lot of very interesting physics remains to be done in the tau sector!
5. Back-up
3.5 Results

![Graph showing Br(τ → μ ± π ± π ±)]

Bound:

\[ \sqrt{|Y_{\mu\tau}^h|^2 + |Y_{\tau\mu}^h|^2} \leq 0.13 \]

Less stringent but more robust handle on LFV Higgs couplings

| Process | (BR. x 10^8) 90% CL | \( \sqrt{|Y_{\mu\tau}^h|^2 + |Y_{\tau\mu}^h|^2} \) | Operator(s) |
|---------|---------------------|---------------------------------|-------------|
| \( \tau \to \mu \gamma \) | < 4.4 [88] | < 0.016 | Dipole |
| \( \tau \to \mu \mu \mu \) | < 2.1 [89] | < 0.24 | Dipole |
| \( \tau \to \mu \pi^+\pi^- \) | < 2.1 [86] | < 0.13 | Scalar, Gluon, Dipole |
| \( \tau \to \mu \rho \) | < 1.2 [85] | < 0.13 | Scalar, Gluon, Dipole |
| \( \tau \to \mu \pi^0\pi^0 \) | < 1.4 x 10^3 [87] | < 6.3 | Scalar, Gluon |

Belle’08’11’12 except last from CLEO’97
3.5 What if $\tau \to \mu(e)\pi\pi$ observed?

Reinterpreting Celis, Cirigliano, E.P’14

- $\tau \to \mu(e)\pi\pi$ sensitive to $Y_{\mu\tau}$
  but also to $Y_{u,d,s}$!

- $Y_{u,d,s}$ poorly bounded

- For $Y_{u,d,s}$ at their SM values:
  \[
  Br(\tau \to \mu\pi^+\pi^-) < 1.6 \times 10^{-11}, Br(\tau \to \mu\pi^0\pi^0) < 4.6 \times 10^{-12}
  \]
  \[
  Br(\tau \to e\pi^+\pi^-) < 2.3 \times 10^{-10}, Br(\tau \to e\pi^0\pi^0) < 6.9 \times 10^{-11}
  \]

- But for $Y_{u,d,s}$ at their upper bound:
  \[
  Br(\tau \to \mu\pi^+\pi^-) < 3.0 \times 10^{-8}, Br(\tau \to \mu\pi^0\pi^0) < 1.5 \times 10^{-8}
  \]
  \[
  Br(\tau \to e\pi^+\pi^-) < 4.3 \times 10^{-7}, Br(\tau \to e\pi^0\pi^0) < 2.1 \times 10^{-7}
  \]

below present experimental limits!

- If discovered among other things upper limit on $Y_{u,d,s}$!
  Interplay between high-energy and low-energy constraints!

Talk by J. Zupan @ KEK-FF2014FALL
3.1 Constraints from $\tau \to \mu \pi \pi$

- Photon mediated contribution requires the pion vector form factor:

$$\langle \pi^+(p_{\pi^+})\pi^-(p_{\pi^-})|\frac{1}{2}((\bar{u}\gamma^\alpha u - \bar{d}\gamma^\alpha d)|0\rangle \equiv F_V(s)(p_{\pi^+} - p_{\pi^-})^\alpha$$

- Dispersive parametrization following the properties of analyticity and unitarity of the Form Factor

Gasser, Meißner ’91
Guerrero, Pich ’97
Oller, Oset, Palomar ’01
Pich, Portolés ’08
Gómez Dumm&Roig ’13
...

- Determined from a fit to the Belle data on $\tau^- \to \pi^-\pi^0\nu_{\tau}$

Celis, Cirigliano, E.P.’14
Determination of $F_V(s)$

- Vector form factor
  - Precisely known from experimental measurements
    
    $e^+ e^- \rightarrow \pi^+ \pi^-$ and $\tau^- \rightarrow \pi^0 \pi^- \nu_{\tau}$ (isospin rotation)
  
  - Theoretically: Dispersive parametrization for $F_V(s)$

\[
F_V(s) = \exp\left[ \lambda_1 \frac{s}{m_{\pi}^2} + \frac{1}{2} \left( \lambda_2 - \lambda_2^2 \right) \left( \frac{s}{m_{\pi}^2} \right)^2 + \frac{s^3}{\pi} \int_{4m_{\pi}^2}^{\infty} ds' \frac{ds'}{s'^3} \frac{\phi_V(s')}{(s' - s - i\varepsilon)} \right]
\]

- Subtraction polynomial + phase determined from a fit to the

  $Belle$ data $\tau^- \rightarrow \pi^0 \pi^- \nu_{\nu_{\tau}}$

Extracted from a model including 3 resonances $\rho(770)$, $\rho'(1465)$ and $\rho''(1700)$ fitted to the data

**Guerrero, Pich’98, Pich, Portolés’08, Gomez, Roig’13**
Determination of $F_{\gamma}(s)$

Determination of $F_{\gamma}(s)$ thanks to precise measurements from Belle!
3.1 Constraints from $\tau \rightarrow \mu \pi \pi$

- Tree level Higgs exchange

$$\langle \pi^+ \pi^- | m_u \bar{u} u + m_d \bar{d} d | 0 \rangle \equiv \Gamma_\pi(s)$$

$$\langle \pi^+ \pi^- | \theta^\mu | 0 \rangle \equiv \theta_\pi(s)$$

$$\langle \pi^+ \pi^- | m_s \bar{s} s | 0 \rangle \equiv \Delta_\pi(s)$$

$$\frac{d\Gamma(\tau \rightarrow \mu \pi^+ \pi^-)}{d\sqrt{s}} = \frac{(m^2_\tau - s)^2 \sqrt{s - 4m^2_\pi}}{256\pi^3m^3_\tau} \left( |Y^h_{\tau\mu}|^2 + |Y^h_{\mu\tau}|^2 \right) \frac{M^4_h v^2}{\sqrt{s}} |K_\Delta \Delta_\pi(s) + K_\Gamma \Gamma_\pi(s) + K_{\theta} \theta_\pi(s)|^2$$

$s = (p_{\pi^+} + p_{\pi^-})^2$

$\theta^\mu = -9\frac{\alpha_s}{8\pi} G^a_{\mu\nu} G^{a\mu\nu} + \sum_{q=u,d,s} m_q \bar{q} q$

Voloshin’85
Determination of the form factors: $\Gamma_{\pi}(s), \Delta_{\pi}(s), \theta_{\pi}(s)$

- No experimental data for the other FFs up to $\sqrt{s} \sim 1.4$ GeV
  Inputs: $I=0$, S-wave $\pi\pi$ and KK data

- Unitarity:

\[
\text{Disc}_{\pi\pi, KK} = \text{Im} F_n(s) = \sum_{m=1}^{2} T_{nm}^*(s) \sigma_m(s) F_m(s)
\]

\[n = \pi\pi, K\bar{K}\]

\textit{Coupled channel analysis} \\
Donoghue, Gasser, Leutwyler’90 \\
Moussallam’99 \\
Daub et al’13
Determination of the form factors: $\Gamma_\pi(s), \Delta_\pi(s), \theta_\pi(s)$

- Inputs: $\pi\pi \rightarrow \pi\pi, KK$

- A large number of theoretical analyses Descotes-Genon et al.'01, Kaminsky et al.'01, Buttiker et al.'03, Garcia-Martin et al.'09, Colangelo et al.'11 and all agree

- 3 inputs: $\delta_\pi(s), \delta_K(s), \eta$ from B. Moussallam \(\Rightarrow\) reconstruct $T$ matrix
3.4.4 Determination of the form factors: $\Gamma_\pi(s), \Delta_\pi(s), \theta_\pi(s)$

- General solution:

\[
\begin{pmatrix}
F_\pi(s) \\
\frac{2}{\sqrt{3}} F_K(s)
\end{pmatrix} =
\begin{pmatrix}
C_1(s) & D_1(s) \\
C_2(s) & D_2(s)
\end{pmatrix}
\begin{pmatrix}
P_F(s) \\
Q_F(s)
\end{pmatrix}
\]

Canonical solution

Polynomial determined from a matching to ChPT + lattice

- Canonical solution found by solving the dispersive integral equations iteratively starting with Omnès functions

\[
X(s) = C(s), D(s)
\]

\[
\text{Im} X_n^{(N+1)}(s) = \sum_{m=1}^{2} \text{Re} \left\{ T_{nm}^* \sigma_m(s) X_m^{(N)} \right\}
\]

\[
\text{Re} X_n^{(N+1)}(s) = \frac{1}{\pi} \int_{4m^2_\pi}^{\infty} \frac{ds'}{s' - s} \text{Im} X_n^{(N+1)}
\]
Determination of the polynomial

- **General solution**

\[
\begin{pmatrix}
F_\pi(s) \\
\frac{2}{\sqrt{3}} F_K(s)
\end{pmatrix}
= \begin{pmatrix}
C_1(s) & D_1(s) \\
C_2(s) & D_2(s)
\end{pmatrix}
\begin{pmatrix}
P_F(s) \\
Q_F(s)
\end{pmatrix}
\]

- **Fix the polynomial with requiring** \[ F_p(s) \to 1/s \] (Brody & Lepage) + ChPT:

**Feynman-Hellmann theorem:**

\[
\Gamma_P(0) = \left( m_u \frac{\partial}{\partial m_u} + m_d \frac{\partial}{\partial m_d} \right) M_P^2
\]

\[
\Delta_P(0) = \left( m_s \frac{\partial}{\partial m_s} \right) M_P^2
\]

- **At LO in ChPT:**

\[
M_{\pi^+}^2 = (m_u + m_d) B_0 + O(m^2)
\]

\[
M_{K^+}^2 = (m_u + m_s) B_0 + O(m^2)
\]

\[
M_{K^0}^2 = (m_d + m_s) B_0 + O(m^2)
\]

\[
P_\Gamma(s) = \Gamma_{\pi}(0) = M_{\pi}^2 + \cdots
\]

\[
Q_{\Gamma}(s) = \frac{2}{\sqrt{3}} \Gamma_{K}(0) = \frac{1}{\sqrt{3}} M_{\pi}^2 + \cdots
\]

\[
P_{\Delta}(s) = \Delta_{\pi}(0) = 0 + \cdots
\]

\[
Q_{\Delta}(s) = \frac{2}{\sqrt{3}} \Delta_{K}(0) = \frac{2}{\sqrt{3}} \left( M_K^2 - \frac{1}{2} M_{\pi}^2 \right) + \cdots
\]
Determination of the polynomial

- General solution

\[
\begin{pmatrix}
F_\pi(s) \\
\frac{2}{\sqrt{3}} F_K(s)
\end{pmatrix} =
\begin{pmatrix}
C_1(s) & D_1(s) \\
C_2(s) & D_2(s)
\end{pmatrix}
\begin{pmatrix}
P_F(s) \\
Q_F(s)
\end{pmatrix}
\]

- At LO in ChPT:

\[
\begin{align*}
M_{\pi^+}^2 &= (m_u + m_d) B_0 + O(m^2) \\
M_{K^+}^2 &= (m_u + m_s) B_0 + O(m^2) \\
M_{K^0}^2 &= (m_d + m_s) B_0 + O(m^2)
\end{align*}
\]

\[
\begin{align*}
P_\Gamma(s) &= \Gamma_\pi(0) = M_\pi^2 + \cdots \\
Q_\Gamma(s) &= \frac{2}{\sqrt{3}} \Gamma_K(0) = \frac{1}{\sqrt{3}} M_\pi^2 + \cdots \\
P_\Delta(s) &= \Delta_\pi(0) = 0 + \cdots \\
Q_\Delta(s) &= \frac{2}{\sqrt{3}} \Delta_K(0) = \frac{2}{\sqrt{3}} \left( M_K^2 - \frac{1}{2} M_\pi^2 \right) + \cdots
\end{align*}
\]

- Problem: large corrections in the case of the kaons!

Use lattice QCD to determine the SU(3) LECs

\[
\begin{align*}
\Gamma_K(0) &= (0.5 \pm 0.1) M_\pi^2 \\
\Delta_K(0) &= 1^{+0.15}_{-0.05} (M_K^2 - 1/2 M_\pi^2)
\end{align*}
\]

*Bernard, Descotes-Genon, Toucas’12
*Dreiner, Hanart, Kubis, Meissner’13
Determination of the polynomial

- General solution

\[
\begin{pmatrix}
F_\pi(s) \\
\frac{2}{\sqrt{3}} F_K(s)
\end{pmatrix}
= \begin{pmatrix}
C_1(s) & D_1(s) \\
C_2(s) & D_2(s)
\end{pmatrix}
\begin{pmatrix}
P_F(s) \\
Q_F(s)
\end{pmatrix}
\]

- For \(\theta_p\) enforcing the asymptotic constraint is not consistent with ChPT. The unsubtracted DR is not saturated by the 2 states.

Relax the constraints and match to ChPT.

\[
\begin{align*}
P_{\theta}(s) &= 2M_\pi^2 + \left(\dot{\theta}_\pi - 2M_\pi^2 \dot{C}_1 - \frac{4M_K^2}{\sqrt{3}} \dot{D}_1\right) s \\
Q_{\theta}(s) &= \frac{4}{\sqrt{3}} M_K^2 + \frac{2}{\sqrt{3}} \left(\dot{\theta}_K - \sqrt{3} M_\pi^2 \dot{C}_2 - 2M_K^2 \dot{D}_2\right) s
\end{align*}
\]
\[ \langle \pi^+ \pi^- | m_\mu \bar{u} u + m_\mu \bar{d} d | 0 \rangle \equiv \Gamma_\pi(s) \]

\[ \langle \pi^+ \pi^- | m_s \bar{s} s | 0 \rangle \equiv \Delta_\pi(s) \]

\[ \langle \pi^+ \pi^- | \theta_\mu | 0 \rangle \equiv \theta_\pi(s) \]
- Uncertainties:
  - Varying $s_{\text{cut}}$ (1.4 GeV$^2$ - 1.8 GeV$^2$)
  - Varying the matching conditions
  - T matrix inputs
Comparison with ChPT

ChPT, EFT only valid at low energy for $E < E_m$.

Emilie Passemard