Experimental Review on
Lepton Universality tests
and
Lepton Flavour Violation tests
at the *B*-factories

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on behalf of the *BABAR* and Belle collaborations

Workshop on

Flavour changing and conserving processes

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Introduction

- **Lepton Universality** (LU) ⟶ traditional Standard Model electro-weak precision test
  - clean experimental test of Standard Model predictions
  - relatively challenging precision experimental measurement
  - LU violation can indicate New Physics
  - strong inheritance from LEP, modest progress with *B*-Factories
    - (main contribution Belle τ lifetime measurement)
- **Lepton Flavour Violation** (LFV) ⟶ powerful and clean New Physics probe
  - undetectably small in the Standard Model
  - relatively easy experimental measurement
  - experimental status dominated by *B*-Factories
- "No known symmetry principle protects lepton flavor conservation in the presence of lepton nonuniversality." Glashow-Guadagnoli-Lane, PRL 114, 091801 (2015)

Lepton Universality tests with lepton decays

Standard Model for leptons $\lambda, \rho = e, \mu, \tau$ (Marciano 1988)

$$\Gamma[\lambda \to \nu_\lambda \rho \bar{\nu}_\rho(\gamma)] = \Gamma_{\lambda\rho} = \Gamma_\lambda B_{\lambda\rho} = \frac{B_{\lambda\rho}}{\tau_\lambda} = \frac{G_\lambda G_\rho m_\lambda^5}{192\pi^3} f\left(\frac{m_\rho^2}{m_\lambda^2}\right) r_W^\lambda r_\gamma^\lambda ,$$

where

$$G_\lambda = \frac{g_\lambda^2}{4\sqrt{2}M_W^2} \qquad f(x) = 1 - 8x + 8x^3 - x^4 - 12x^2 \ln x \qquad f_{\lambda\rho} = f\left(\frac{m_\rho^2}{m_\lambda^2}\right)$$

$$r_W^\lambda = 1 + \frac{3}{5}\frac{m_\lambda^2}{M_W^2} \qquad r_\gamma^\lambda = 1 + \frac{\alpha(m_\lambda)}{2\pi}\left(\frac{25}{4} - \pi^2\right)$$

Tests of lepton universality from ratios or above partial widths:

$$\left(\frac{g_\tau}{g_\mu}\right) = \sqrt{\frac{B_{\tau e}}{B_{\mu e}}\frac{\tau_\mu m_\mu^5 f_{\mu e} r_W^\mu r_\gamma^\mu}{\tau_\tau m_\tau^5 f_{\tau e} r_W^\tau r_\gamma^\tau}} = 1.0011 \pm 0.0015 = \sqrt{\frac{B_{\tau e}}{B_{\tau e}^{\mathrm{SM}}}}$$

$$\left(\frac{g_\mu}{g_e}\right) = \sqrt{\frac{B_{\tau\mu}}{B_{\tau e}}\frac{f_{\tau e}}{f_{\tau\mu}}} = 1.0018 \pm 0.0014$$

$$\left(\frac{g_\tau}{g_e}\right) = \sqrt{\frac{B_{\tau\mu}}{B_{\mu e}}\frac{\tau_\mu m_\mu^5 f_{\mu e} r_W^\mu r_\gamma^\mu}{\tau_\tau m_\tau^5 f_{\tau\mu} r_W^\tau r_\gamma^\tau}} = 1.0029 \pm 0.0015 = \sqrt{\frac{B_{\tau\mu}}{B_{\tau\mu}^{\mathrm{SM}}}}$$

- precision: **0.20–0.23%** pre-*B*-Factories ➡ **0.14–0.15%** today
  thanks essentially to the Belle tau lifetime measurement, PRL 112 (2014) 031801
- $r_\gamma^\tau = 1 - 43.2 \cdot 10^{-4}$ and $r_\gamma^\mu = 1 - 42.4 \cdot 10^{-4}$ (Marciano 1988), M_W from PDG 2013

Coupling constants ratios uncertainties contributions

quantity	uncertainty	contribution
τ_τ	0.18%	0.09%
$B_{\tau\to\mu,e}$	0.23%	0.115%
m_τ	0.009%	0.022%

Lepton Universality tests with hadron decays

Standard Model:

$$\left(\frac{g_\tau}{g_\mu}\right)^2 = \frac{B(\tau \to h\nu_\tau)}{B(h \to \mu\bar{\nu}_\mu)} \frac{2m_h m_\mu^2 \tau_h}{(1+\delta_h) m_\tau^3 \tau_\tau} \left(\frac{1 - m_\mu^2/m_h^2}{1 - m_h^2/m_\tau^2}\right)^2 \qquad (h = \pi \text{ or } K)$$

rad. corr. $\delta_\pi = (0.16 \pm 0.14)\%$, $\delta_K = (0.90 \pm 0.22)\%$ (Decker 1994)

$$\left(\frac{g_\tau}{g_\mu}\right)_\pi = 0.9963 \pm 0.0027 \,, \qquad \left(\frac{g_\tau}{g_\mu}\right)_K = 0.9858 \pm 0.0071 \,.$$

(electron tests less precise because hadron two body decays to electrons are helicity-suppressed)

Averaging the three g_τ/g_μ ratios:

$$\left(\frac{g_\tau}{g_\mu}\right)_{\tau+\pi+K} = 1.0001 \pm 0.0014 \,,$$

accounting for statistical correlations

useful contribution from *BABAR* $\frac{B(\tau^- \to K^- \nu_\tau)}{B(\tau^- \to e^- \bar{\nu}_e \nu_\tau)}$ **measurement, PRL 105 (2010) 051602**

Some other Lepton Universality tests

$\left(\frac{g_\mu}{g_e}\right)$ from $\frac{B_{\pi\to\mu}}{B_{\pi\to e}}$ $\left(\frac{g_\mu}{g_e}\right)$ from $\frac{B_{K\to\mu}}{B_{K\to e}}$ $\left(\frac{g_\mu}{g_e}\right)$ from $\frac{B_{K\to\pi\mu}}{B_{K\to\pi e}}$

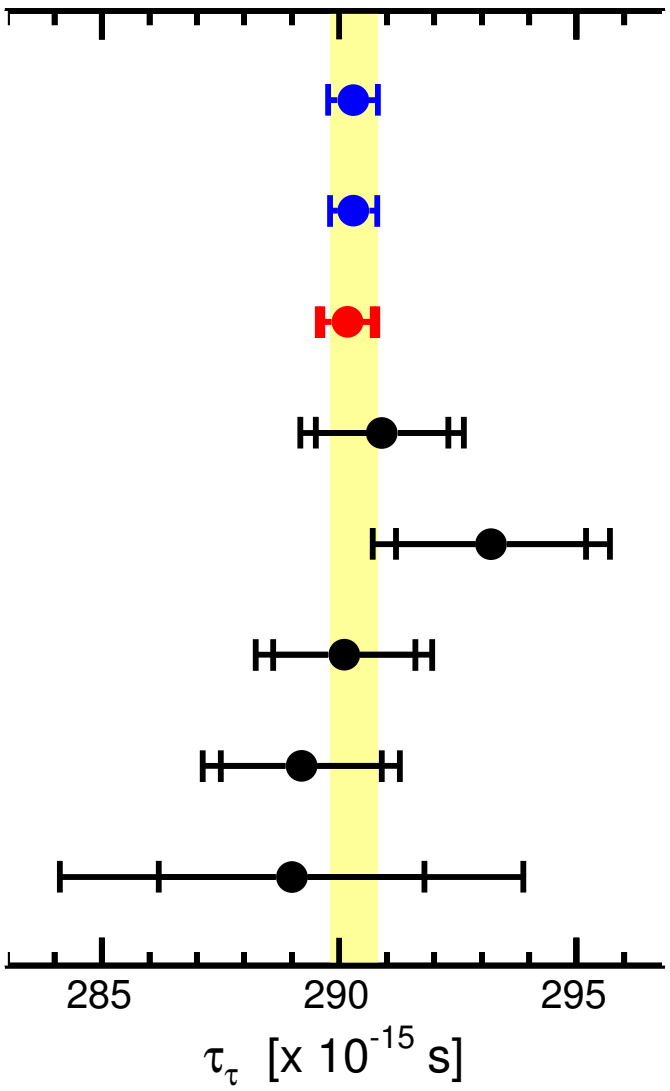
similar precision as previous ones

$\left(\frac{g_\tau}{g_\mu}\right)$ from $\frac{B_{W\to\tau}}{B_{W\to\mu}}$ $\left(\frac{g_\tau}{g_e}\right)$ from $\frac{B_{W\to\tau}}{B_{W\to e}}$ $\left(\frac{g_\mu}{g_e}\right)$ from $\frac{B_{W\to\mu}}{B_{W\to e}}$

less precise

no contribution from *B*-Factories

Tau Lifetime after Belle 2013 result



HFAG Summer 2014
290.29 ± 0.52

PDG 2014 average
290.30 ± 0.50

Belle 2013
290.17 ± 0.53 ± 0.33

Delphi 2004
290.90 ± 1.40 ± 1.00

L3 2000
293.20 ± 2.00 ± 1.50

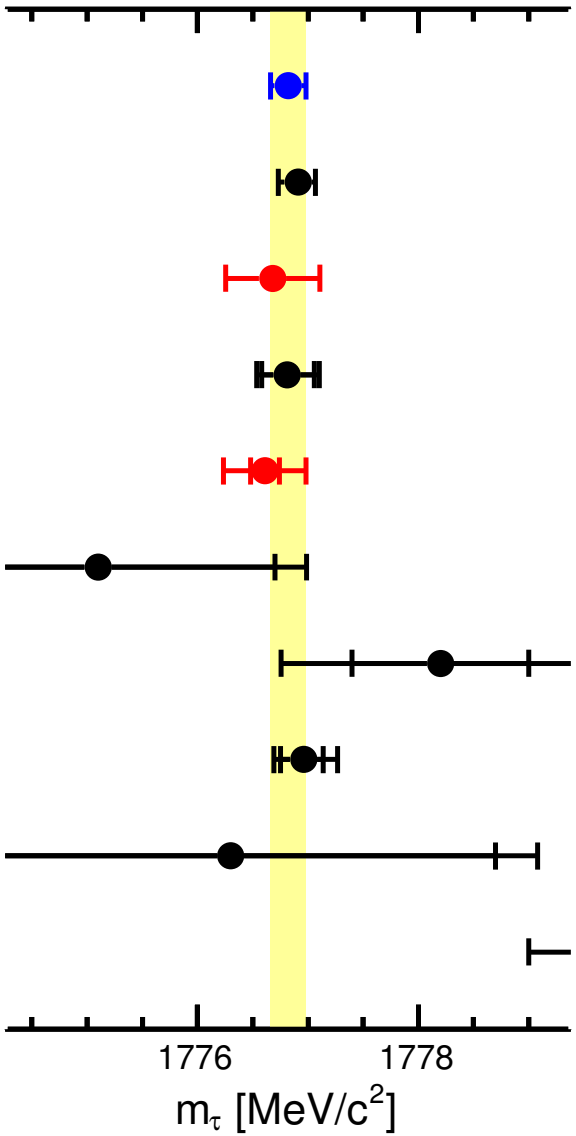
ALEPH 1997
290.10 ± 1.50 ± 1.10

OPAL 1996
289.20 ± 1.70 ± 1.20

CLEO 1996
289.00 ± 2.80 ± 4.00

HFAG-Tau
Summer 2014

Modest contribution of *B*-Factories to tau mass



PDG 2014 average
1776.82 ± 0.16

BES 2014 (not in PDG 2014)
$1776.91 \pm 0.12\ ^{+0.10}_{-0.13}$

BaBar 2009
$1776.68 \pm 0.12 \pm 0.41$

KEDR 2007
$1776.81\ ^{+0.25}_{-0.23} \pm 0.15$

Belle 2007
$1776.61 \pm 0.13 \pm 0.35$

OPAL 2000
$1775.10 \pm 1.60 \pm 1.00$

CLEO 1997
$1778.20 \pm 0.80 \pm 1.20$

BES 1996
$1776.96\ ^{+0.18}_{-0.21}\ ^{+0.25}_{-0.17}$

ARGUS 1992
$1776.30 \pm 2.40 \pm 1.40$

DELCO 1978
$1783.00\ ^{+3.00}_{-4.00}$

Tau leptonic branching fractions measurements

$\Gamma_5 = B(\tau^- \to e^- \overline{\nu}_e \nu_\tau)$	0.17817 ± 0.00041	HFAG 2014 prelim. fit
$0.17837 \pm 0.00080 \pm 0.00000$	ALEPH	Schael:2005am
$0.17760 \pm 0.00180 \pm 0.00000$	CLEO	Anastassov:1996tc
$0.17877 \pm 0.00155 \pm 0.00000$	DELPHI	Abreu:1999rb
$0.17806 \pm 0.00129 \pm 0.00000$	L3	Acciarri:2001sg
$0.17810 \pm 0.00108 \pm 0.00000$	OPAL	Abbiendi:1998cx
$\Gamma_3 = B(\tau^- \to \mu^- \overline{\nu}_\mu \nu_\tau)$	0.17391 ± 0.00040	HFAG 2014 prelim. fit
$0.17319 \pm 0.00077 \pm 0.00000$	ALEPH	Schael:2005am
$0.17325 \pm 0.00122 \pm 0.00000$	DELPHI	Abreu:1999rb
$0.17342 \pm 0.00129 \pm 0.00000$	L3	Acciarri:2001sg
$0.17340 \pm 0.00108 \pm 0.00000$	OPAL	Abbiendi:2002jw
$\frac{\Gamma_3}{\Gamma_5} = \frac{B(\tau^- \to \mu^- \overline{\nu}_\mu \nu_\tau)}{B(\tau^- \to e^- \overline{\nu}_e \nu_\tau)}$	0.97610 ± 0.00278	HFAG 2014 prelim. fit
$0.99700 \pm 0.05315 \pm 0.00000$	ARGUS	Albrecht:1991rh
$0.97960 \pm 0.00390 \pm 0.00053$	BaBar	Aubert:2009qj
$0.97770 \pm 0.01074 \pm 0.00000$	CLEO	Anastassov:1996tc

Most relevant *B*-Factories contributions for Lepton Universality tests

- Belle tau lifetime, PRL 112 (2014) 031801
- *BABAR* $B_{\tau\to\mu,\pi,K}/B_{\tau\to e}$, PRL 105 (2010) 051602
- *BABAR* tau mass, PRD D80 (2009) 092005
- Belle tau mass, PRL 99 (2007) 011801
- several other BRs were measured, which had only minor impact
- *B*-Factories less successful than LEP on all large tau BRs
  - cannot select tau events with just one hemisphere with good efficiency and purity
  - lower hadronic multiplicity ➞ more difficult to discriminate between tau pairs and hadrons
  - less precise knowledge of the luminosity

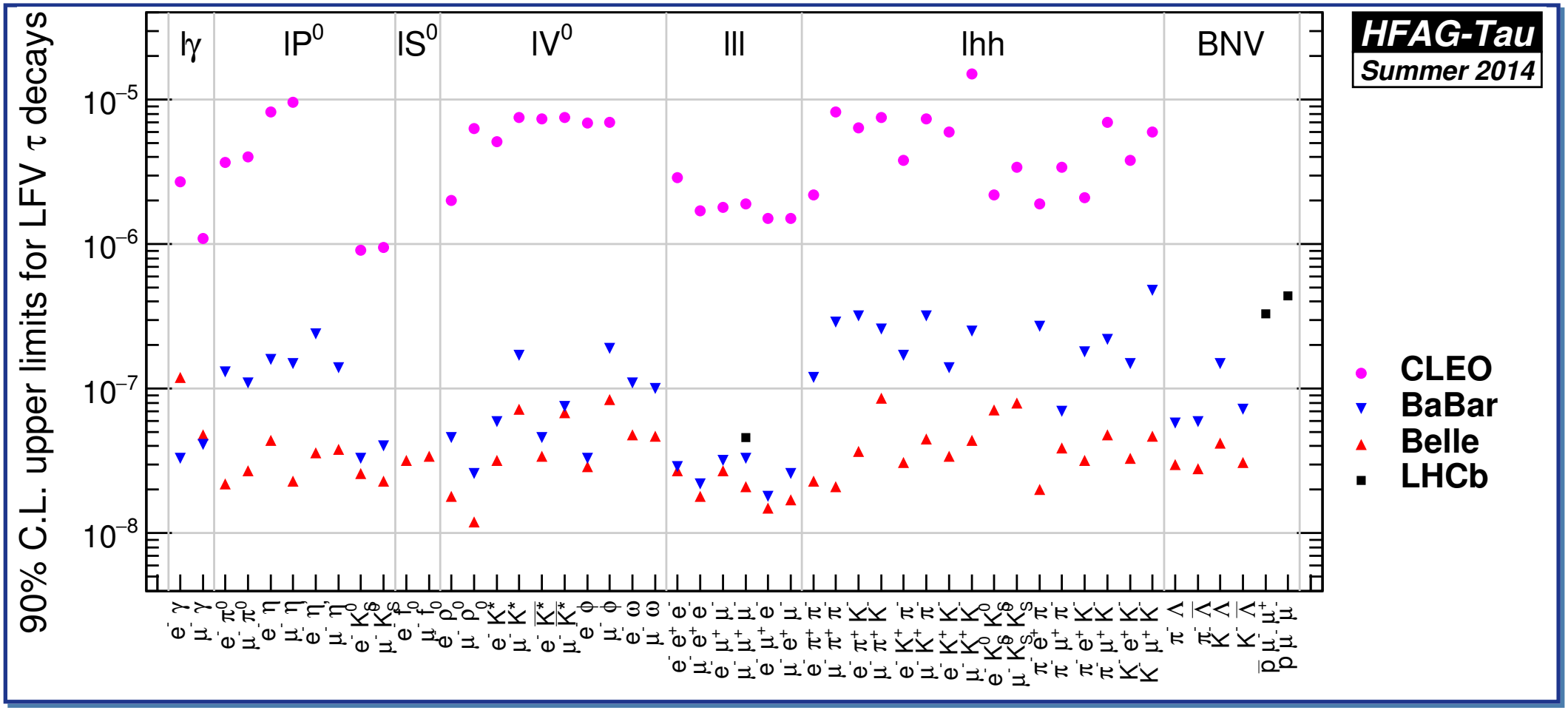
Lepton Flavour Violation searches at the *B*-Factories

- *B*-Factories are best facilities to search for LFV tau decay searches
- neutrinoless tau decays (e.g. $\tau \to \mu\gamma$, $\tau^+ \to f_1^+ f_2^+ f_3^-$) cannot conserve tau lepton number
  - ► easiest tau decay to detect
    - no undetected neutrinos
    - decay products invariant mass peaks at tau mass
    - reconstructed tau energy in CM-frame is half the event energy
- $B^+ \to \Lambda \ell^+$, $B^+ \to h^- \ell^+ \ell'^+$ (also lepton number violation)

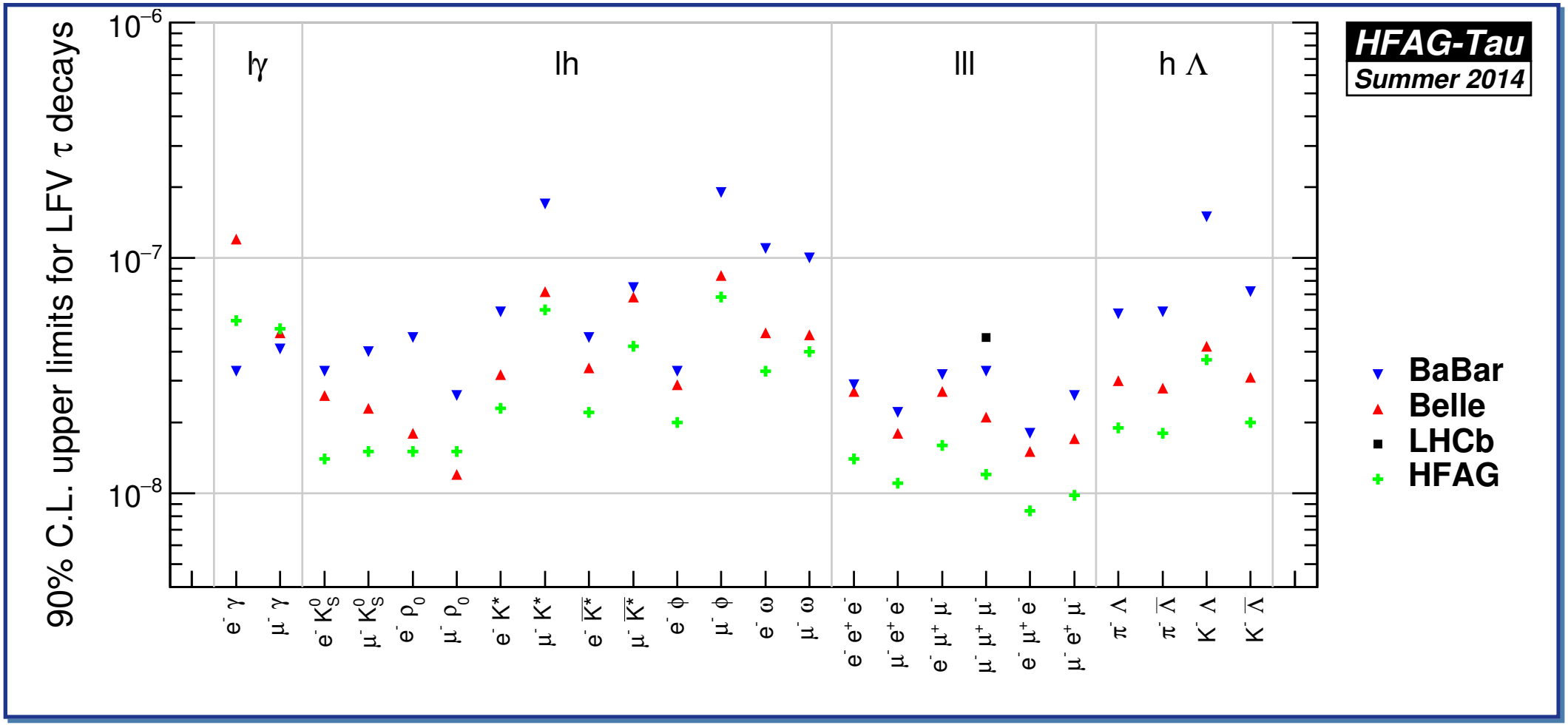
Most recent LFV searches results from the *B*-Factories

- BaBar $\tau \to 3$ leptons, PRD 81 (2010) 111101
- Belle $\tau \to 3$ leptons, PLB 687 (2010) 139
- Belle $\tau \to \ell K_S^0$, $\tau \to \ell K_S^0 K_S^0$, PLB 692 (2010) 4
- Belle $\tau \to \ell V$, PLB 699 (2011) 251
- Belle $\tau \to \ell h h'$, PLB 719 (2013) 346
- eagerly waiting for Belle $\tau \to e, \mu\gamma$ with complete data sample

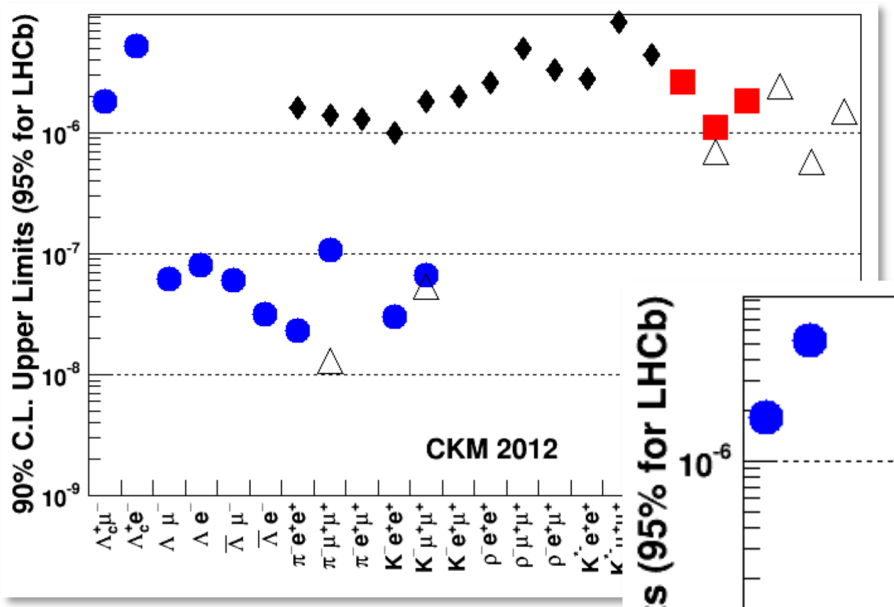
Tau LFV upper limits



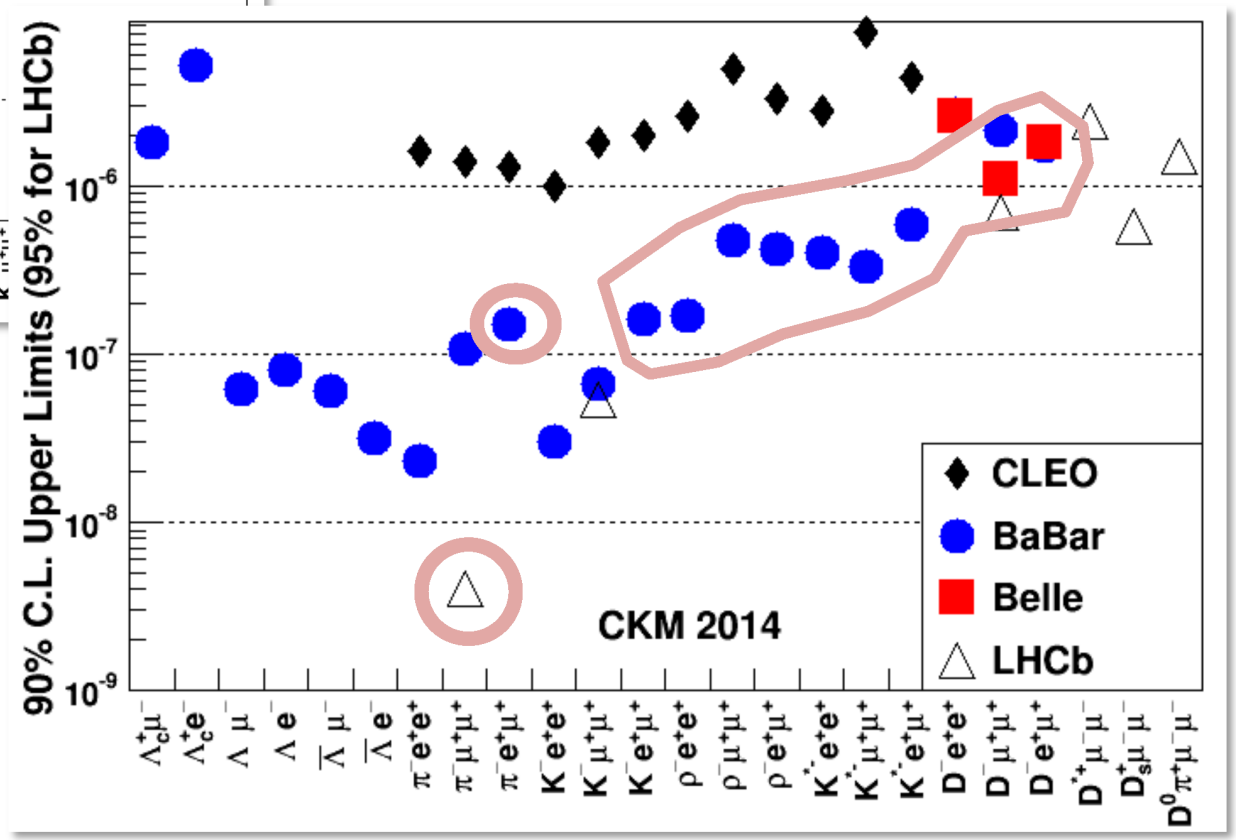
HFAG combined a subset of tau LFV upper limits



LFV and LNV searches in *B* decays

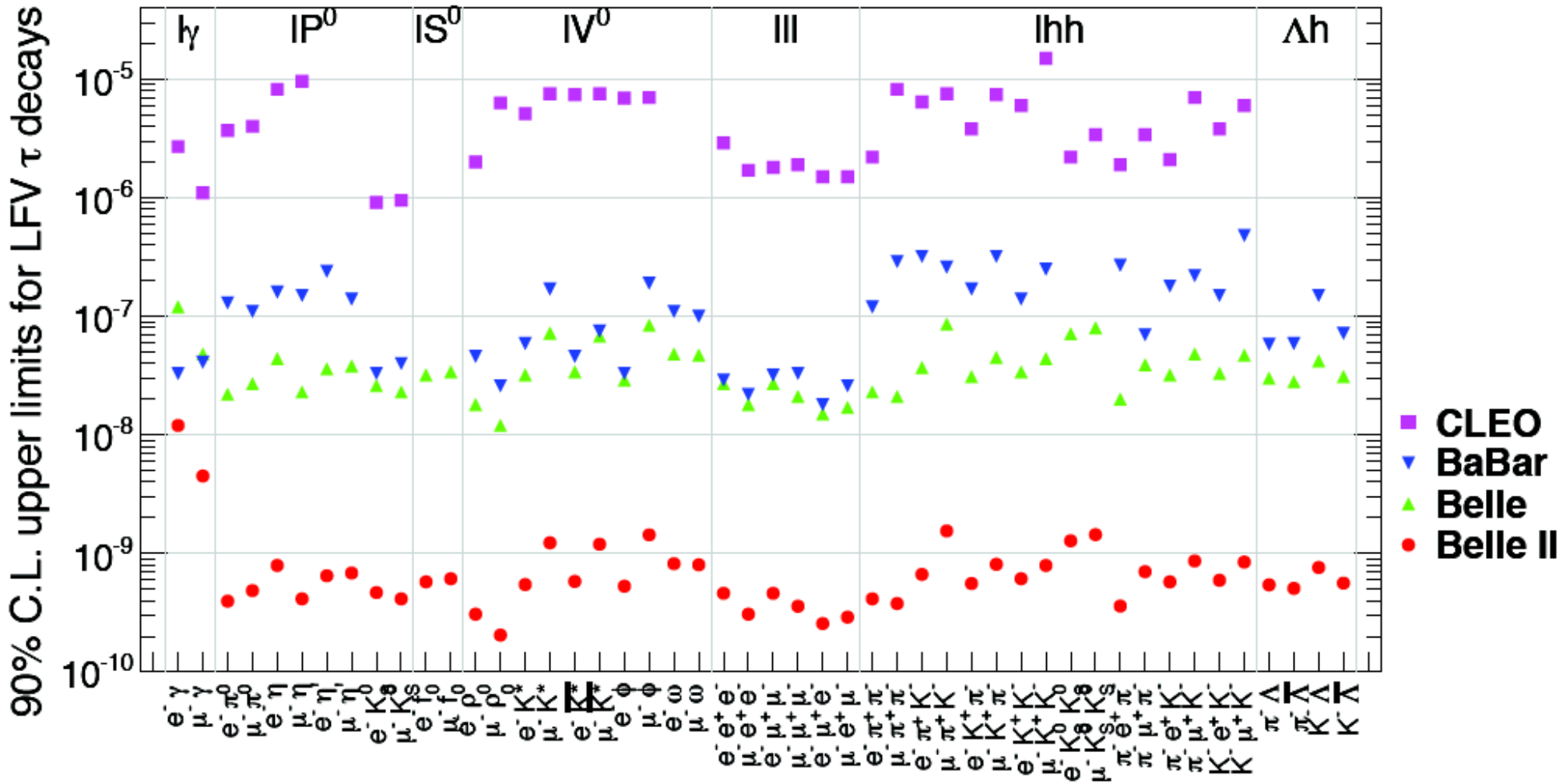


plots from F. Wilson, CKM 2014



CLEO: PRD 65, 111102 (2002)
Belle: PRD 84, 071106 (2011)
BaBar: PRD 85, 071102 (2012)
LHCb: PRL 108, 106601 (2012)
LHCb: PRD 85,112004 (2012)
BaBar: PRD 89, 011102 (2014)
LHCb: PRL 112, 131802 (2014)

Tau LFV expected upper limits for BelleII



plot from M. Barret, FPCP 2015

Conclusions and prospects

- Lepton Universality tests
  - Belle tau lifetime improved LU tests
  - limited additional improvements from *B*-Factories tau BR measurements
- Lepton Flavour Violation Searches
  - *B*-Factories improved tau LFV limits by about 2 orders of magnitude
  - BelleII will further improve LFV limits by 1-2 orders of magnitude