Violation of Lepton Number, Lepton Flavour, Baryon Number and Lepton Universality in B and τ decays at BaBar and Belle

On behalf of the BaBar and Belle collaborations, CKM2016, Mumbai

Introduction/Motivation

- No fundamental symmetry explains the conservation of Lepton Flavour and Lepton Number in the Standard Model.
- New Physics models can enhance Lepton Flavour Violation LFV and Lepton Number Violation LNV up to current experimental limits at e^+e^- colliders.
- New Physics models can introduce different couplings to leptons and violate Lepton Universality (LUV).
- In GUT theories, quarks and leptons are part of the same multiplets so baryon number B and lepton number L are expected to be violated in almost all models.
- Experiments with higher mass leptons may be less precise than dedicated experiments but could see larger deviations.
- Many LFV, LNV and Baryon Number Violation (BNV) searches are simple additions to core analyses (e.g. rare decays $B^0 \to l^+l^-$ or FCNC in $B^- \to K^{(*)} l^+ l^-$).

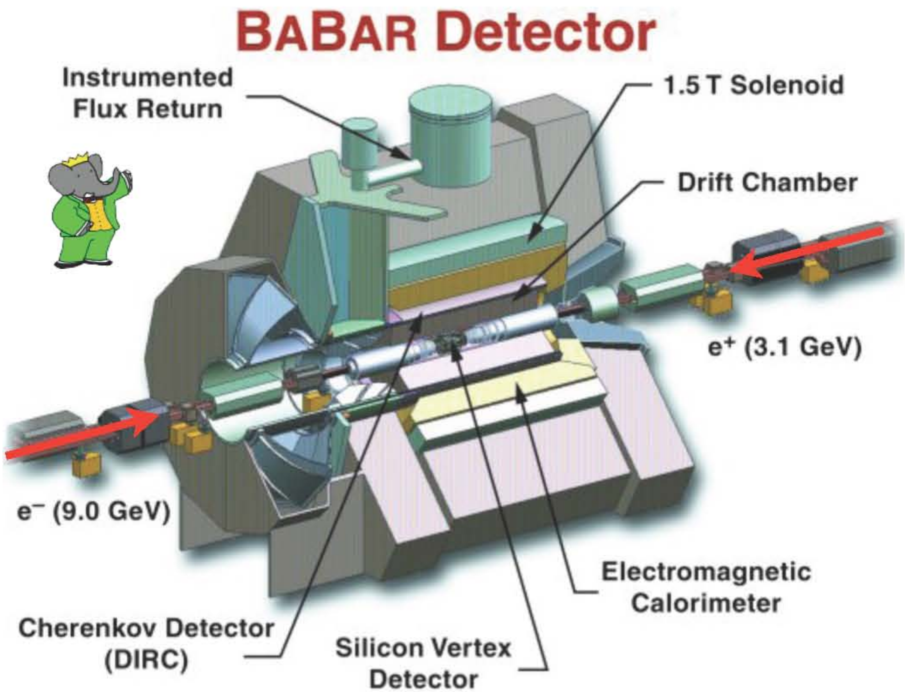
This Review

- Lepton Flavour Violation:
  - $\Upsilon(2,3S) \rightarrow e\tau/\mu\tau$
  - $B^0 \rightarrow e^+\mu^-$, $B \rightarrow K^* l^+ l'^-$, $B \rightarrow \pi e^+ \mu^-$
  - $B^\pm \rightarrow h^\pm \tau l$ and $B^0 \rightarrow l^+\tau^-$
- Lepton Number Violation:
  - $B^+ \rightarrow X^- l^+ l^+$
- Baryon Number Violation:
  - $B \rightarrow \Lambda l^+$
- Lepton Universality:
  - $B \rightarrow D^{(*)}\tau\upsilon$ / $B \rightarrow D^{(*)}l\upsilon$ ratio
  - $B \rightarrow K^{(*)}e^+e^-$ / $K^{(*)}\mu^+\mu^-$ ratio
- τ Lepton Flavour Violation
- τ Lepton Universality Status

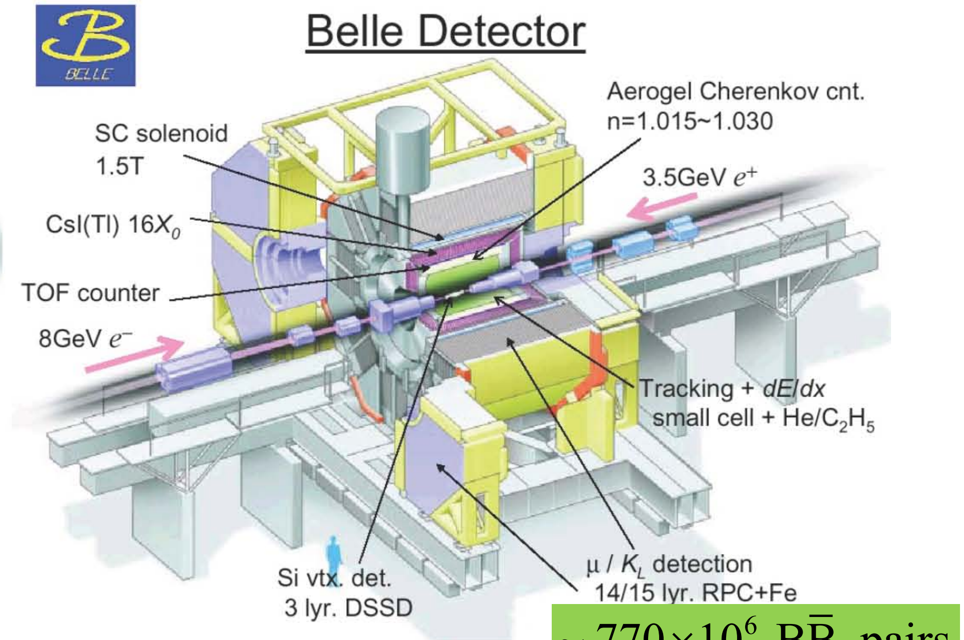
Results from 2008-2016

No discussion of charm decays

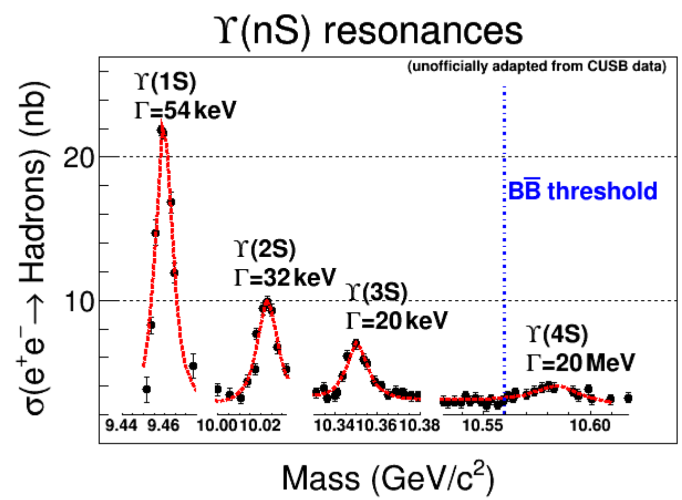
The BaBar and Belle Detectors



$\sim 470\times10^6\ \mathrm{B\bar{B}}\ \ \mathrm{pairs}$



$\sim 770\times10^6\ \mathrm{B\bar{B}}\ \ \mathrm{pairs}$



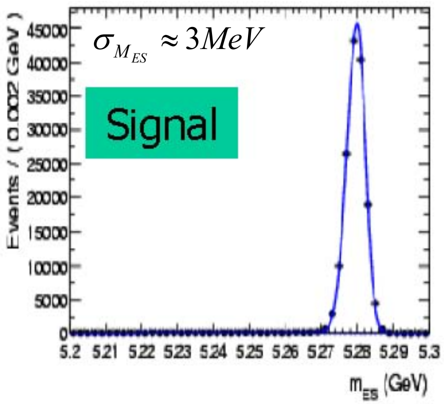
Common Features: asymmetric beam momenta, Υ(nS) production, low multiplicity, low background, π/K particle identification, hermetic, good muon and electron identification with wide coverage.

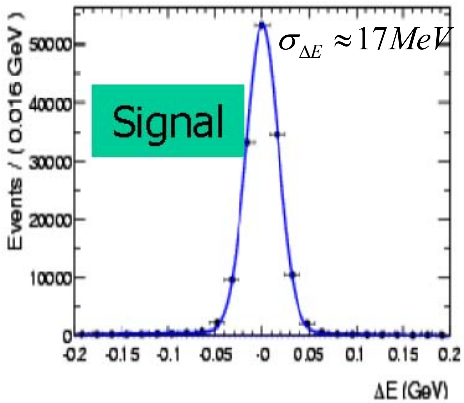
Typical Analysis Techniques

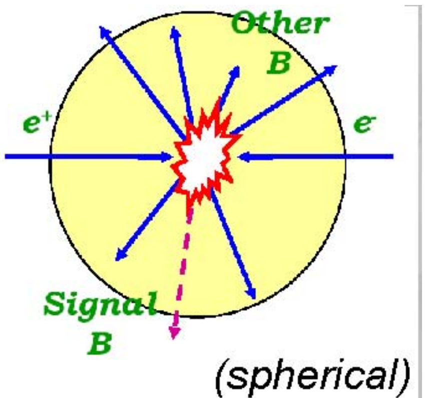
$$m_{ES} = m_{EC} = \sqrt{E^2_{beam} - p^2_{B/\tau}}$$

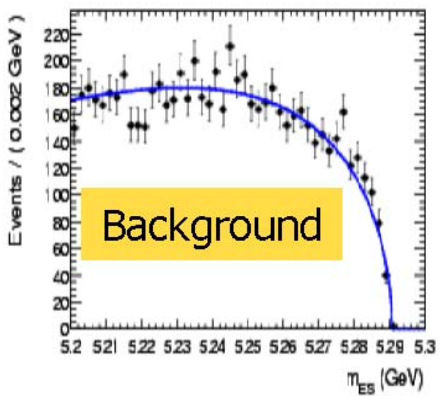
$$\Delta E = E_{B/\tau} - E_{beam}$$

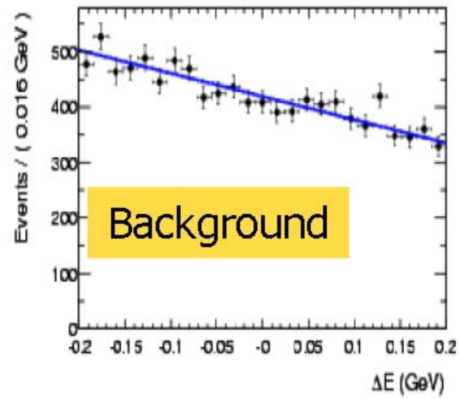
Event Topology

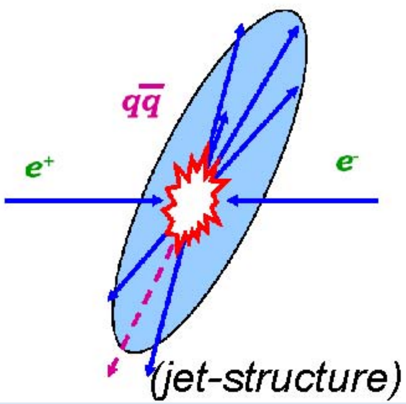












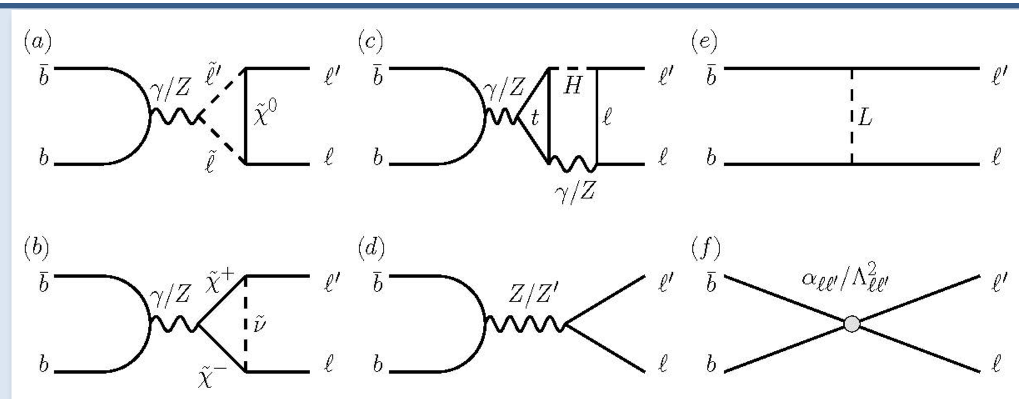
Plus Fisher Discriminants (F), Boosted Decision Trees (BDT), Neural Networks (NN) and unbinned Maximum Likelihood (ML) fits

LFV in $\Upsilon(2,3S)\rightarrow e\tau/\mu\tau$

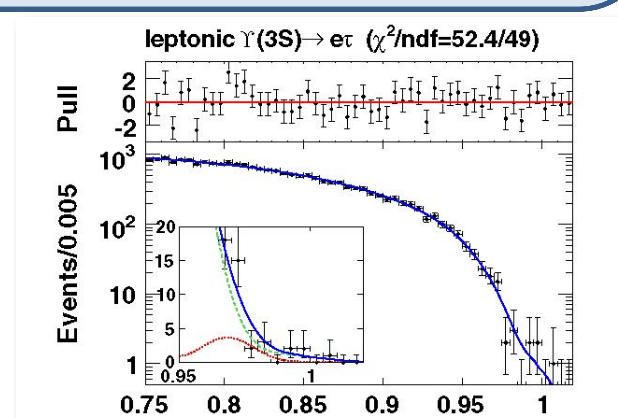
PRL 104, 151802 (2010)

- CLEO (PRL 101 (2008) 201601: $\Upsilon(2S)\rightarrow\mu\tau < 1.44 \times 10^{-5}$, $\Upsilon(3S)\rightarrow\mu\tau < 2.03 \times 10^{-5}$
- Theory: $$BF(\Upsilon(nS)\to l\tau) \le \frac{BF(\tau\to e^+e^-l)}{BF(\tau\to l^-\upsilon_\tau\bar{\upsilon}_l)}\frac{\Gamma(W\to l\upsilon)^2}{\Gamma(\Upsilon(nS))\Gamma(\Upsilon(nS)\to l^+l^-)}\left(\frac{M_{\Upsilon(nS)}}{M_W}\right)^6$$
$$< 5\times10^{-3}(\text{for }\Upsilon(nS)\to l\tau), < 3\times10^{-8}(\text{for }\Upsilon(nS)\to\mu e)$$

a) SUSY loops
b) SUSY loops
c) SUSY Higgs doublet H
d) Anomalous Z or Z'
e) Leptoquark L
f) Contact interaction
Probes 1-10 TeV



	$\mathcal{B}$ (10^{-6})	UL (10^{-6})
$\mathcal{B}(\Upsilon(2S)\to e^+\tau^-)$	$0.6^{+1.5+0.5}_{-1.4-0.6}$	< 3.2
$\mathcal{B}(\Upsilon(2S)\to \mu^+\tau^-)$	$0.2^{+1.5+1.0}_{-1.3-1.2}$	< 3.3
$\mathcal{B}(\Upsilon(3S)\to e^+\tau^-)$	$1.8^{+1.7+0.8}_{-1.4-0.7}$	< 4.2
$\mathcal{B}(\Upsilon(3S)\to \mu^+\tau^-)$	$-0.8^{+1.5+1.4}_{-1.5-1.3}$	< 3.1



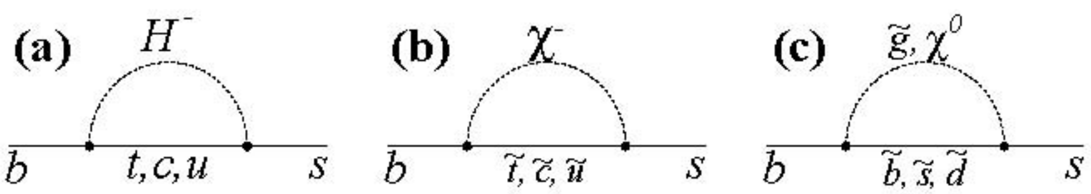
$x = |p_l|/E_B \quad \sigma_x \approx 0.01$

LFV in $B^0 \to e^+\mu^-$, $B \to K^* l^+ l'^-$, $B \to \pi e^+\mu^-$

- $B^0 \to e^+\mu^-$: like $D^0 \to e^+\mu^-$, part of FCNC search.
  - PRD 77, 032007 (2008)
  - PRD 77, 091104 (2008)
- $B \to K^* l^+ l^-$: FCNC, Branching Fractions, Polarisation, Asymmetries, Universality.
  - PRD 73, 092001 (2006)
  - PRD 85, 071103 (2012)
- $B \to \pi e^+\mu^-$: FCNC searches
  - PRL 99, 051801 (2007)

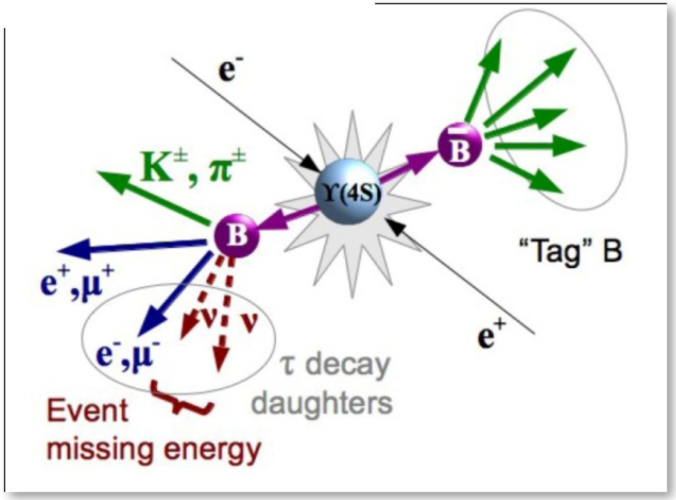
Decay Mode	$\mathcal{B}_{90\%}$ $(\times 10^{-8})$
$B^0 \to e^+ e^-$	11.3
$B^0 \to \mu^+ \mu^-$	5.2
$B^0 \to e\ \mu$	9.2
$B^+ \to \pi^+ e^\pm \mu^\mp$	17
$B^0 \to \pi^0 e^\pm \mu^\mp$	14
$B \to \pi e^\pm \mu^\mp$	9.2
$B^+ \to K^+ e^+ \mu^-$	9.1
$B^+ \to K^+ e^- \mu^+$	13
$B^+ \to K^+ e\ \mu$	9.1
$B^0 \to K^+ e\ \mu$	27
$B^0 \to K^{*0} e^+ \mu^-$	53
$B^0 \to K^{*0} e^- \mu^+$	34
$B^0 \to K^{*0} e\ \mu$	58
$B^+ \to K^{*+} e^+ \mu^-$	130
$B^+ \to K^{*+} e^- \mu^+$	99
$B^+ \to K^{*+} e\ \mu$	140
$B \to K e\ \mu$	3.8
$B \to K^* e\ \mu$	51

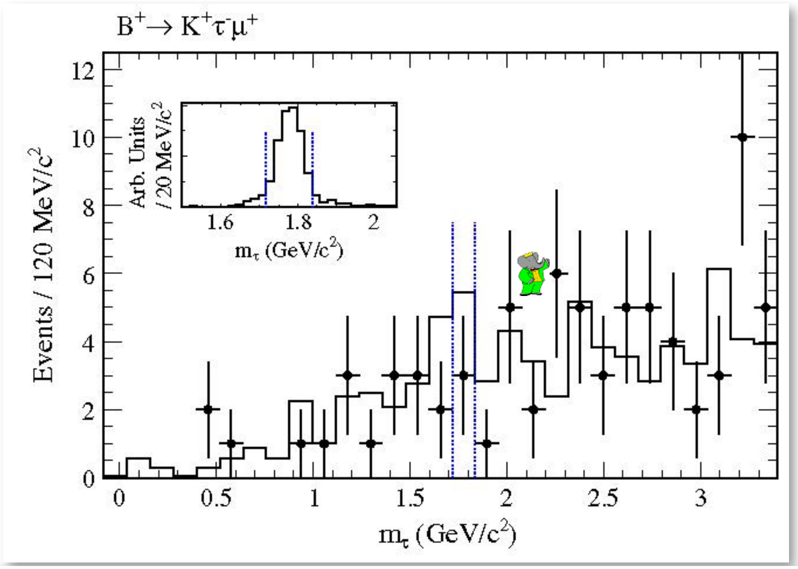
New Physics processes:

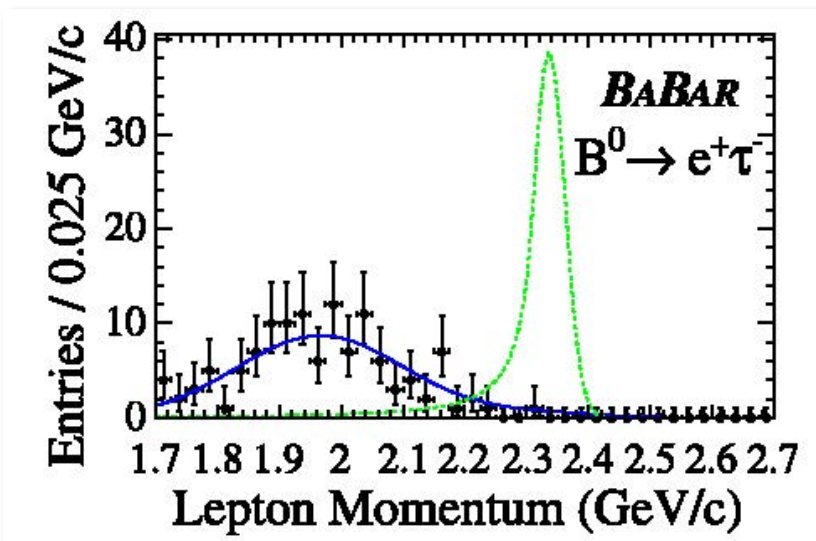


LFV in $B^{\pm} \rightarrow h^{\pm} \tau l$ and $B^0 \rightarrow l^+\tau^-$

Recoil method







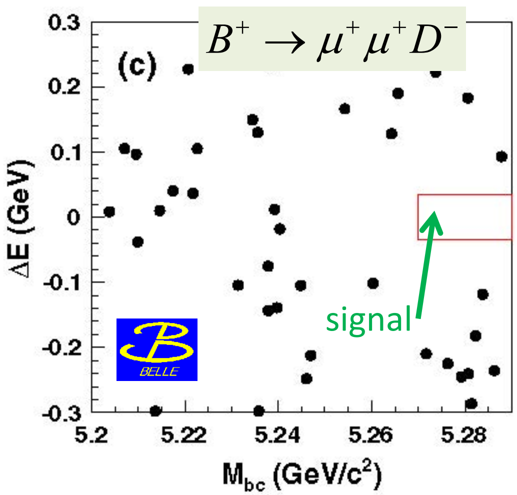
Decay Mode	Central Value $\times 10^{-5}$	$\mathcal{B}$ upper limit (90% CL) $\times 10^{-5}$
$B^+ \rightarrow K^+\tau^{\mp}\mu^{\pm}$	$0.0^{+2.7}_{-1.4}$	< 4.8
$B^+ \rightarrow K^+\tau^{\mp}e^{\pm}$	$-0.6^{+1.7}_{-1.4}$	< 3.0
$B^+ \rightarrow \pi^+\tau^{\mp}\mu^{\pm}$	$0.5^{+3.8}_{-3.2}$	< 7.2
$B^+ \rightarrow \pi^+\tau^{\mp}e^{\pm}$	$2.3^{+2.8}_{-1.7}$	< 7.5
$B^0 \rightarrow \tau^{\pm}e^{\mp}$	$0^{+1.5}_{-1.0}$	< 2.8
$B^0 \rightarrow \tau^{\pm}\mu^{\mp}$	$0^{+1.1}_{-0.7}$	< 2.2

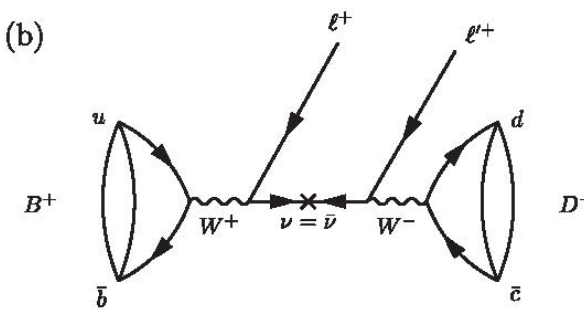
MSSM prediction $BF(B^0 \rightarrow l^+\tau^-) \sim 2 \times 10^{-10}$

LNV and Majorana υ in $B^+ \to X^- l^+ l^+$

PRD 89, 011102 (2014)
PRD 85, 071103 (2012)
PRD 84, 071106 (2011)

- LNV search in $B^+ \to h^- l^+ l^+$ (h=D/K/π, l=e/μ)
- Possible mechanism: exchange of Majorana υ (ΔL=2) or 4th neutrino generation. But mass and coupling are unknown.





Mode	$\epsilon(\%)$	N_{obs}	N_{exp}^{bkg}	$\mathcal{B}_{90\%}$ $(\times 10^{-6})$
$B^+ \to D^- e^+ e^+$	1.2	0	0.18 ± 0.13	< 2.6
$B^+ \to D^- e^+ \mu^+$	1.3	0	0.83 ± 0.29	< 1.8
$B^+ \to D^- \mu^+ \mu^+$	1.9	0	1.10 ± 0.33	< 1.1

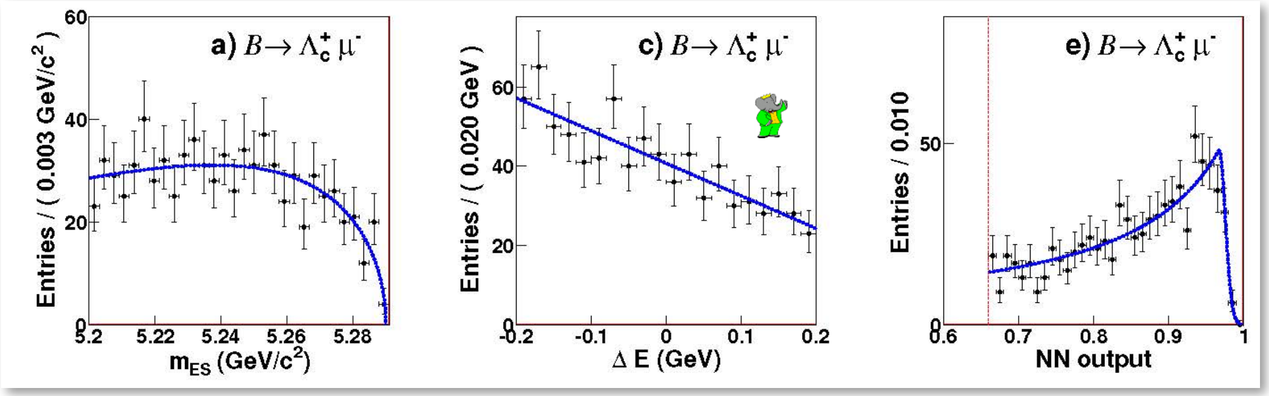
Decay Mode	$\mathcal{B}$ $(\times 10^{-6})$	$\mathcal{B}_{90\%}$ $(\times 10^{-6})$
$B^+ \to \pi^- e^+ e^+$	$0.27^{+1.1}_{-1.2} \pm 01$	< 2.3
$B^+ \to K^- e^+ e^+$	$0.49^{+1.3}_{-0.8} \pm 01$	< 3.0
$B^+ \to \pi^- \mu^+ \mu^+$	$0.03^{+5.1}_{-3.2} \pm 01$	< 10.7
$B^+ \to K^- \mu^+ \mu^+$	$0.45^{+3.2}_{-3.7} \pm 01$	< 6.7

Decay Mode	$\mathcal{B}$ $(\times 10^{-7})$	$\mathcal{B}_{90\%}$ $(\times 10^{-7})$
$B^+ \to K^{*-} e^+ e^+$	$1.7 \pm 1.4 \pm 0.1$	< 4.0
$K^{*-} \to K^- \pi^0$	$2.1 \pm 1.8 \pm 0.2$	< 5.1
$K^{*-} \to K^0_S \pi^-$	$0.6 \pm 2.9 \pm 0.2$	< 6.0
$B^+ \to K^{*-} e^+ \mu^+$	$-4.5 \pm 2.6 \pm 0.4$	< 3.0
$K^{*-} \to K^- \pi^0$	$-1.5 \pm 3.8 \pm 0.4$	< 6.5
$K^{*-} \to K^0_S \pi^-$	$-6.0 \pm 2.8 \pm 0.7$	< 4.2
$B^+ \to K^{*-} \mu^+ \mu^+$	$2.4 \pm 1.8 \pm 0.4$	< 5.9
$K^{*-} \to K^- \pi^0$	$2.0 \pm 1.8 \pm 0.2$	< 7.0
$K^{*-} \to K^0_S \pi^-$	$3.1 \pm 2.9 \pm 0.9$	< 9.8
$B^+ \to \rho^- e^+ e^+$	$-0.4 \pm 1.0 \pm 0.1$	< 1.7
$B^+ \to \rho^- e^+ \mu^+$	$1.0 \pm 2.4 \pm 0.2$	< 4.7
$B^+ \to \rho^- \mu^+ \mu^+$	$0.9 \pm 2.0 \pm 0.3$	< 4.2
$B^+ \to D^- e^+ e^+$	$8.8 \pm 8.6 \pm 1.5$	< 26
$B^+ \to D^- e^+ \mu^+$	$3.4 \pm 9.4 \pm 1.1$	< 21
$B^+ \to D^- \mu^+ \mu^+$	$-6.5 \pm 9.9 \pm 0.9$	< 17
$B^+ \to K^- e^+ \mu^+$	$0.6 \pm 0.5 \pm 0.1$	< 1.6
$B^+ \to \pi^- e^+ \mu^+$	$0.5 \pm 0.5 \pm 0.1$	< 1.5

BNV and LNV in $B \rightarrow \Lambda l^+$

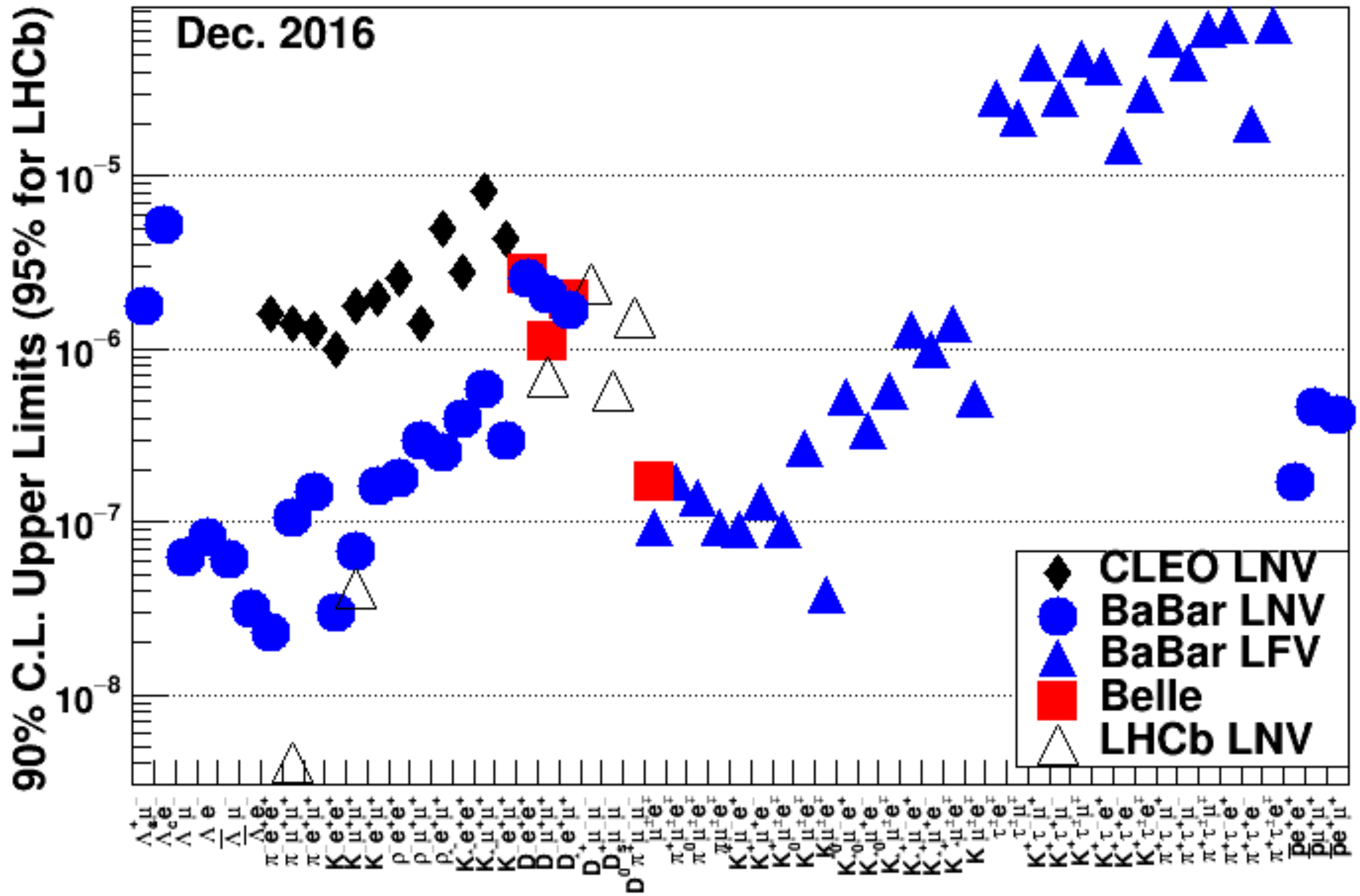
PRD 83, 091101 (2011)

- Violate both Baryon and Lepton Number conservation.
- Expected to be highly suppressed ($< 4 \times 10^{-29}$).
- $B^- \rightarrow \bar{\Lambda}\, l^-$ violates (B-L).
- Only look at electron and muon modes.
- $\Lambda^+_c \rightarrow pK^-\pi^+$, $\Lambda \rightarrow p\pi^-$. Constrain tracks to a vertex and mass compatible with $\Lambda_{(c)}$.
- Use m_{ES}, ΔE, and neural net to identify signal.



Decay Mode	N_{cand}	$\mathcal{B}(\times 10^{-8})$	$\epsilon(\%)$	$\mathcal{B}_{90\%}(\times 10^{-8})$
$B^0 \rightarrow \Lambda_c^+ \mu^-$	814	-4^{+71}_{-56}	26.3 ± 0.9	180
$B^0 \rightarrow \Lambda_c^+ e^-$	651	190^{+130}_{-90}	25.7 ± 0.7	520
$B^- \rightarrow \Lambda \mu^-$	320	$-2.3^{+3.5}_{-2.5}$	28.7 ± 0.9	6.2
$B^- \rightarrow \Lambda e^-$	194	$1.2^{+3.7}_{-2.6}$	27.2 ± 0.6	8.1
$B^- \rightarrow \bar{\Lambda} \mu^-$	192	$1.5^{+2.6}_{-1.7}$	31.3 ± 1.0	6.1
$B^- \rightarrow \bar{\Lambda} e^-$	74	$-0.9^{+0.7}_{-0.0}$	30.0 ± 0.6	3.2

B-meson LFV and LNV Summary



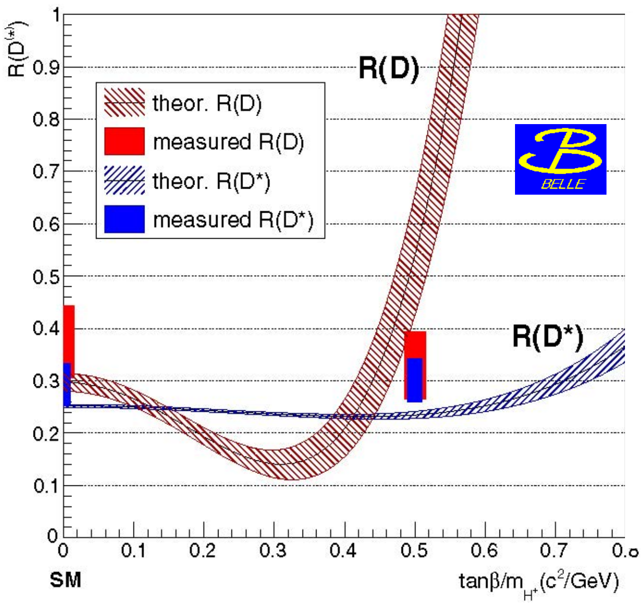
B→ D$^{(*)}$τυ / B→ D$^{(*)}$lυ ratio

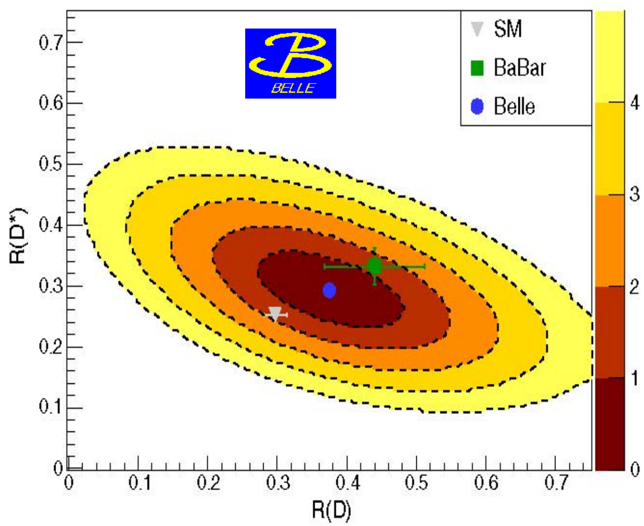
PRD 94, 072007 (2016) ,PRD 92, 072014 (2015)
PRL 109, 101802 (2012), PRD 88 072012 (2013)

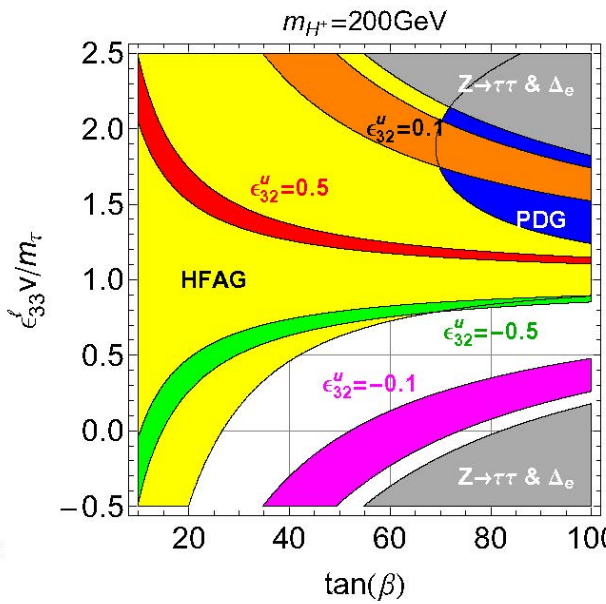
- Often interpreted in terms of SM plus a charged Higgs.
- In disagreement with 2HDM Type II predictions
- But couplings to leptons could be different.
- Belle have used both hadronic (2015) and semileptonic (2016) tags

There are models available to account for discrepancies:

- Leptoquarks
- 2HDM variations
- ….







2HDM Type X model: A. Crivellin et al. PRL 116, 081801 (2016)

$$R_{SM}(D) = 0.297 \pm 0.017$$

$$R_{SM}(D^*) = 0.252 \pm 0.003$$

PRD 85, 094025 (2012)
LQCD for $R_{SM}(D)$ similar

$$R_{exp}(D) = 0.391 \pm 0.041 \pm 0.028$$

$$R_{exp}(D^*) = 0.322 \pm 0.018 \pm 0.012$$

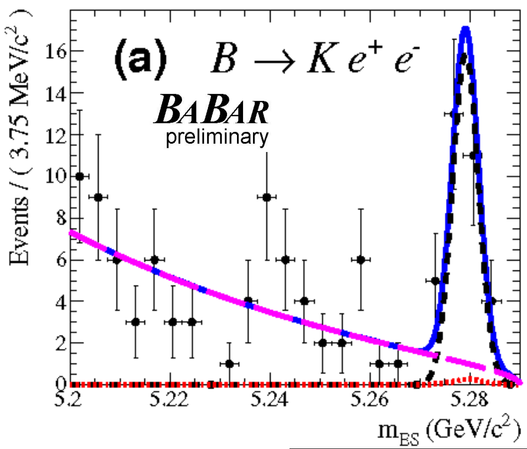
Combined BaBar/Belle/LHCb deviation is 3.9σ

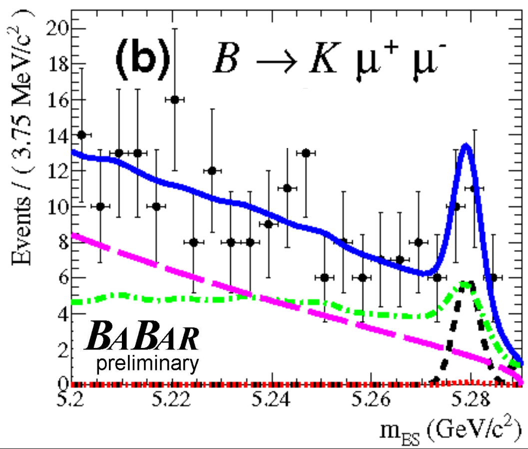
Lepton Universality in $B\to K\, l^+ l^-$

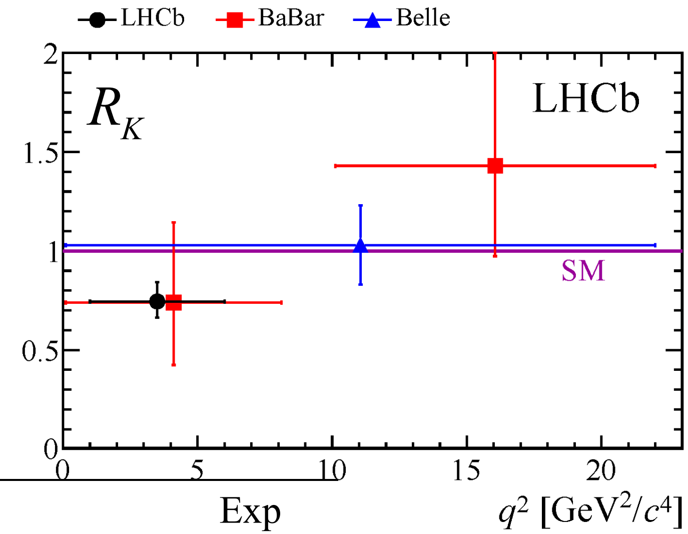
PRD 86, 032012 (2012)
PRL 103, 171801 (2009)
To be submitted to PRD (2017)

- An output from $B\to K^{(*)} l^+ l^-$ angular analyses.
- SM prediction $R_K \approx 1.0 \pm \sim 0.01$
- Combine B^0 and B^+ decays.
- Use $1.0<q^2<6.0$ GeV^2 region where theory uncertainties are lowest.

$$R_X = \frac{\int_{q^2_{\min}}^{q^2_{\max}} \frac{d\Gamma(B\to X\mu^+\mu^-)}{dq^2}\, dq^2}{\int_{q^2_{\min}}^{q^2_{\max}} \frac{d\Gamma(B\to X e^+ e^-)}{dq^2}\, dq^2}$$





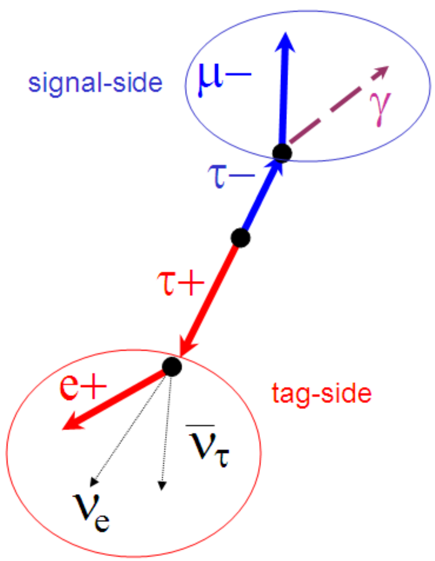


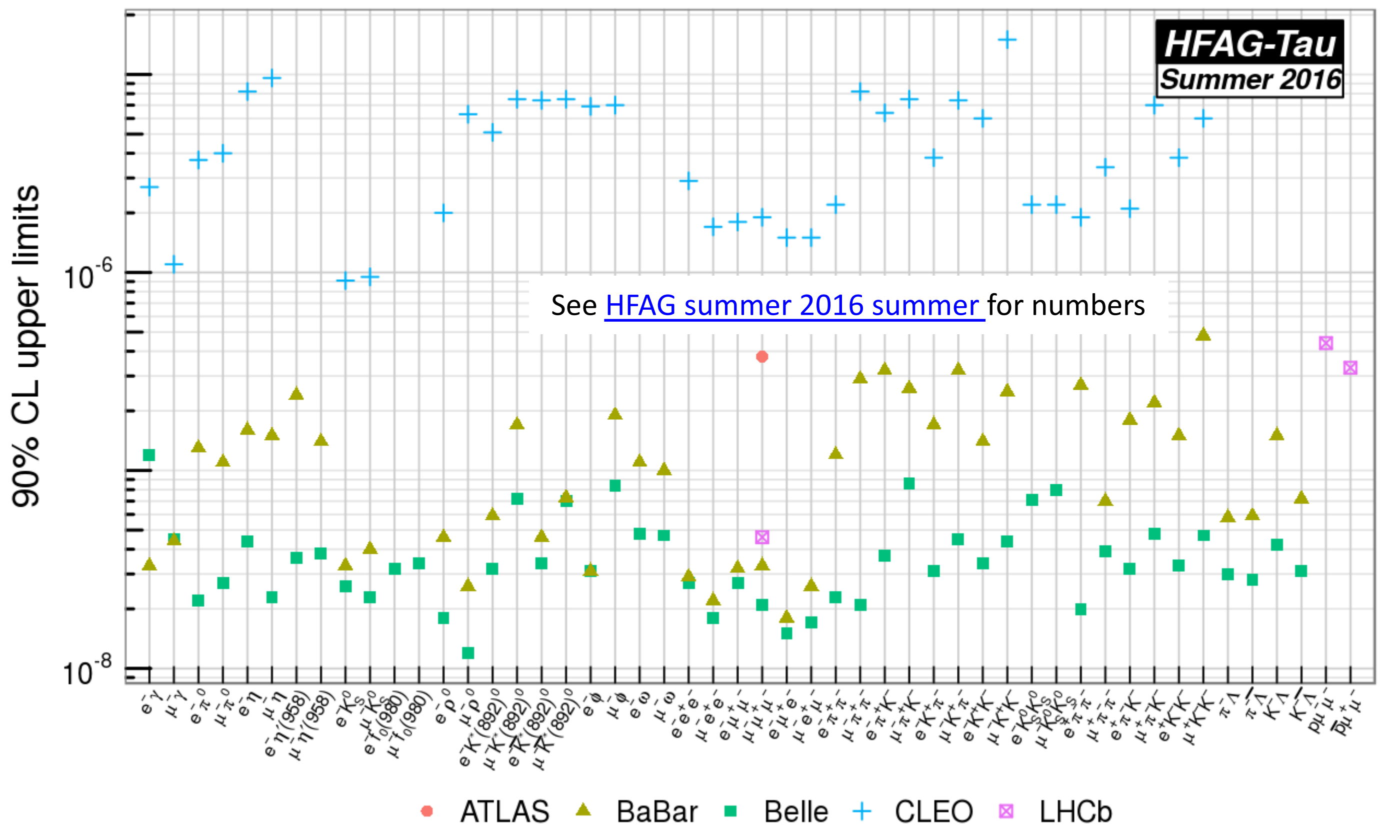
Ratio	Value	Range	Publication	Exp
$R_{K^{(+,*)}}$	$0.64^{+0.39}_{-0.30} \pm 0.06$	$1.0-6.0$	To be submitted	BaBar
R_{K^+}	$1.03 \pm 0.19 \pm 0.06$	$0.1-25.0$	PRL 103, 171801(2009)	Belle
R_{K^*}	$0.83 \pm 0.17 \pm 0.08$	$0.1-25.0$	PRL 103, 171801(2009)	Belle
R_K	$0.74^{+0.40}_{-0.31} \pm 0.06$	$0.1-8.1$	PRD 86, 032012 (2012)	BaBar
R_{K^+}	$0.745^{+0.090}_{-0.074} \pm 0.036$	$1.0-6.0$	PRL 113,151601(2014)	LHCb

Results consistent between BaBar and Belle, SM and LHCb

Tau LFV summary

- Even with bounds on μ->eγ, some models predict τ->μγ accessible at current experimental sensitivities.
- Different models predict different rates and hierarchies for the tau decays so need to measure as many decay modes as possible.
- Some modes are background free (e.g τ→eee, $\tau^- \to l^- h^0$); others are not (τ→μγ).

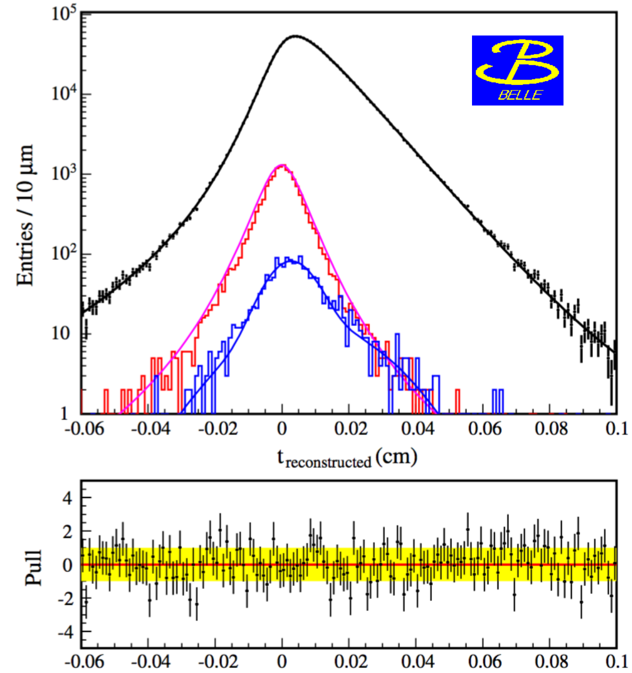




No LFV observed. Limits in the range 10^{-8} to 2×10^{-7}

Tau Lepton Universality summary

- Little change since 2014. Belle τ lifetime measurement last significant update:
  - $\tau_\tau = (290.13 \pm 0.53 \pm 0.33) \times 10^{-15}$ s



$$\frac{B(\tau \to l\nu\bar{\nu})}{\tau_\tau} = \Gamma(\tau \to l\nu\bar{\nu}) \propto g_\tau^2 g_l^2 m_\tau^5 f(m_l^2 / m_\tau^2)\delta_w \delta_\gamma$$

$$\left(\frac{g_\tau}{g_\mu}\right) = 1.0010 \pm 0.0015$$

$$\left(\frac{g_\tau}{g_e}\right) = 1.0029 \pm 0.0015$$

$$\left(\frac{g_\mu}{g_e}\right) = 1.0019 \pm 0.0014$$

} Leptonic processes only

$$\left(\frac{g_\tau}{g_\mu}\right)_{K+\pi+\tau} = 1.0000 \pm 0.0014$$

} Leptonic + $\tau^- \to h^- \nu$

See HFAG summer 2016 summer for more details

Conclusion

- Lepton Number, Lepton Flavour, and Baryon Number Violation have not been seen.
- Limits have improved by two orders of magnitude over the last decade.
- Some of the more optimistic New Physics models and/or parameter space have been deprecated.
- Many of the deviations continue to be seen at LHCb.
- Some deviations from SM predictions in branching fraction ratios can be interpreted as Lepton Universality Violation.
- Interesting time for LFV, LNV, LUV:
  - New dedicated experiments coming on line (e.g. mu2e, mu3e).
  - LHCb upgrade (50 fb^{-1})
  - Belle II (50 ab^{-1})