Lepton Universality, $|V_{us}|$ and Searches for Lepton Flavor Violation at B-Factories

Swagato Banerjee

University of Victoria | British Columbia Canada

Outline

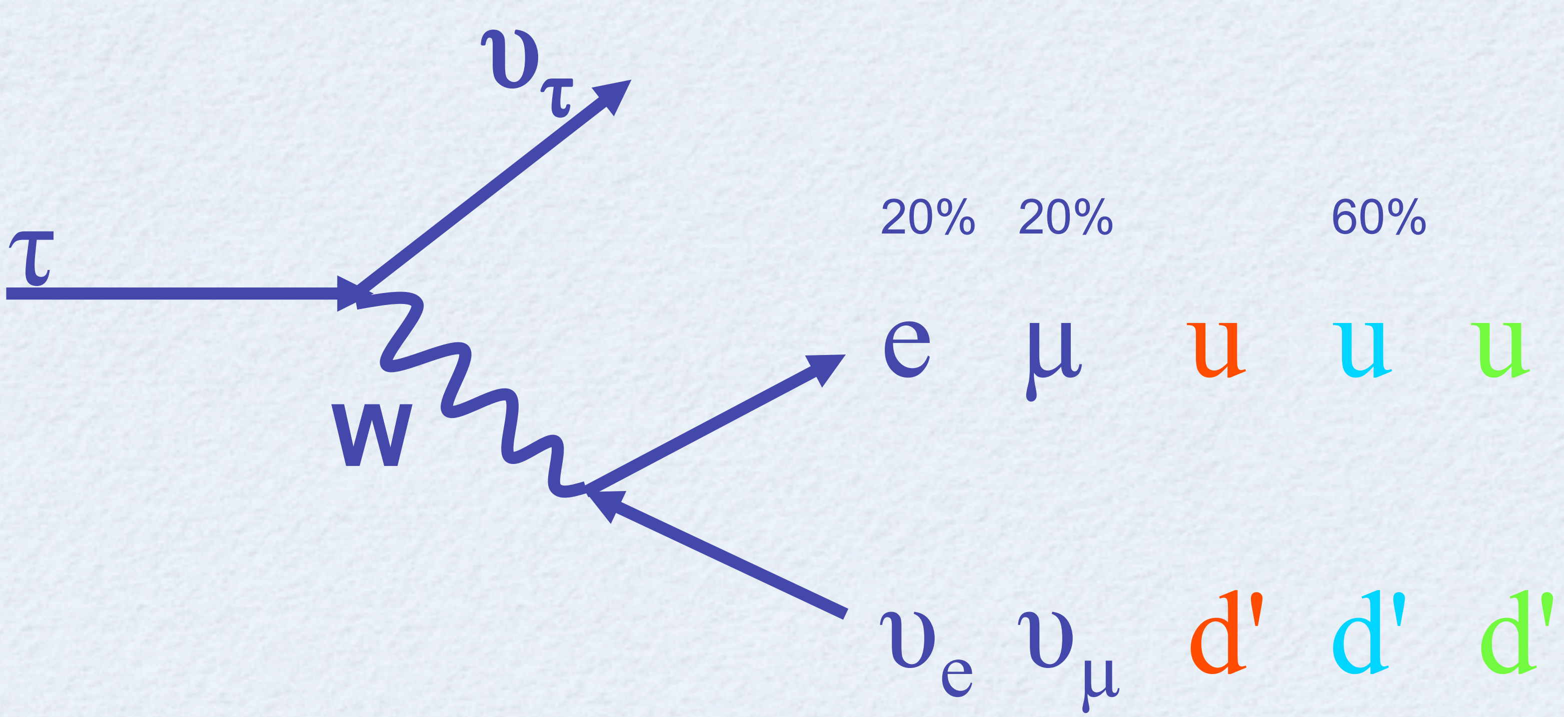
- High Precision Tests of SM and Search for New Physics
- B-Factories are also τ-Factories:
  - τ-pair and μ-pair production cross-section
  - Branching fractions for τ-decays
  - Tests of Lepton Universality
  - $|V_{us}|$ from τ decays:
    - Exclusive measurement of the K pole
    - Ratio of Exclusive measurements of K/π pole
    - Inclusive Sum of Strange Branching Fractions
  - Search for Lepton Flavor and Lepton Number Violation

Production and Decays

Production:

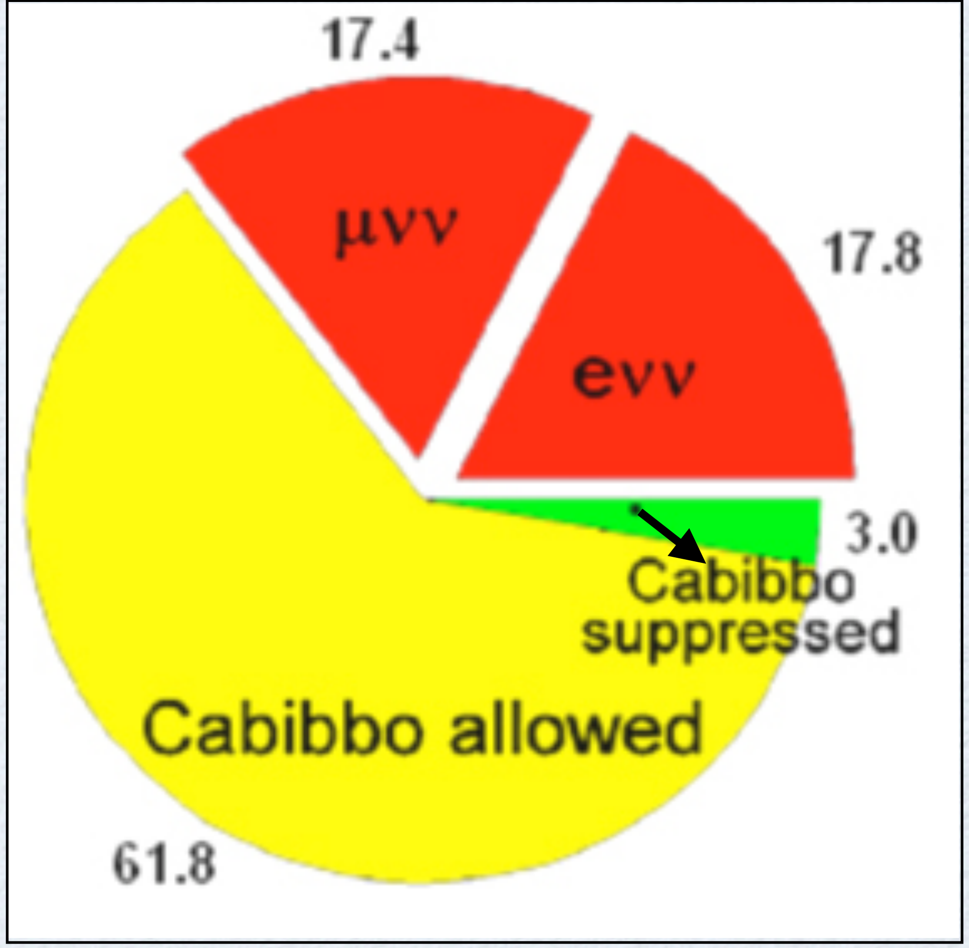
At $\Upsilon(4S)$: $e^+e^- \to Z^*/\gamma \to \tau^+\tau^-$. Also $e^+e^- \to \Upsilon(nS) \to \tau^+\tau^-$ for $n = 2, 3$

Decays:



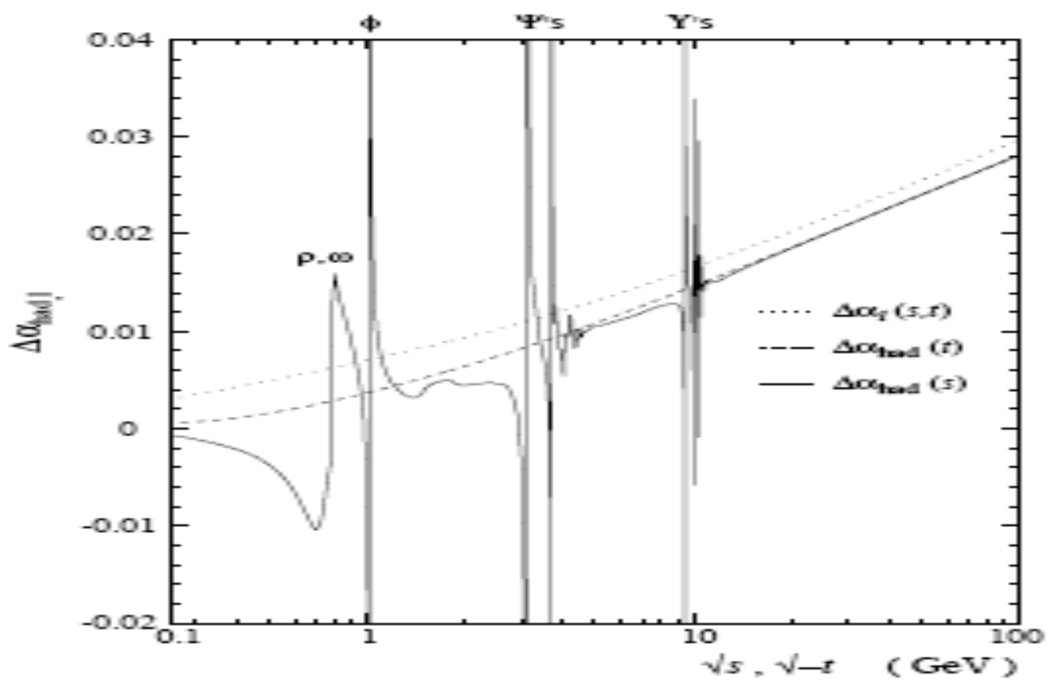
$$|d'\rangle = V_{ud}|d\rangle + V_{us}|s\rangle$$

Including QED & QCD corrections:

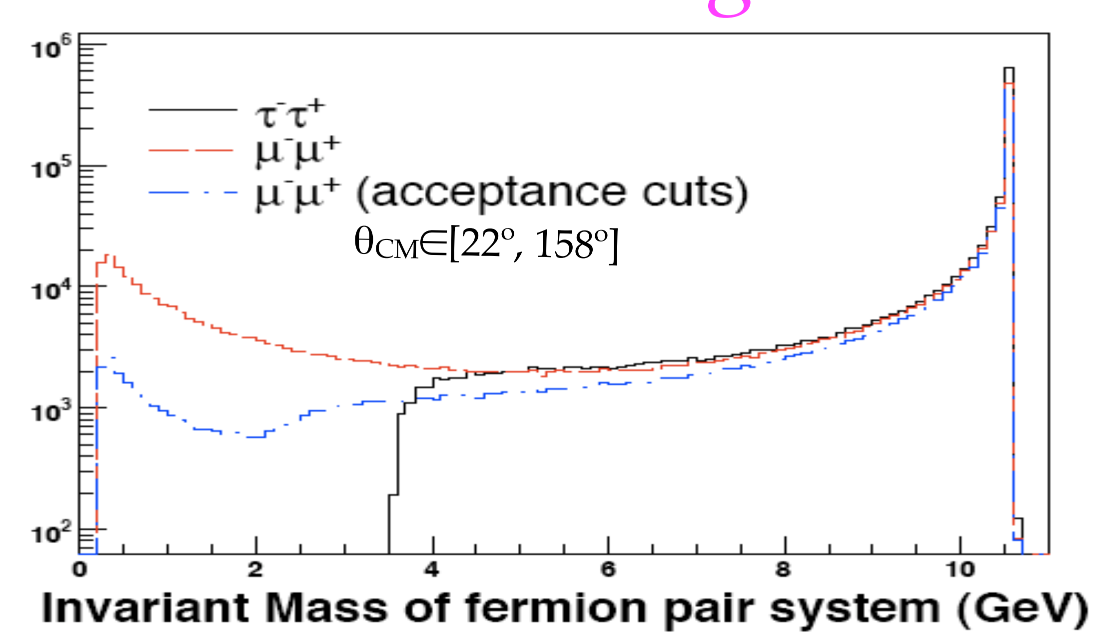


Revisiting Vacuum polarization

- *Until 2007:* $\sigma_{\tau\tau}^{\rm KORALB}$ = 0.91 nb, $\sigma_{\tau\tau}^{\rm KK2F}$ = 0.89 nb, $\Rightarrow \Delta\sigma_{\tau\tau}$ = 2.22 %
- *Default implementation of vacuum polarization in KK2F did NOT calculate the hadronic part for E < 40 GeV*
- *New input on* $R = (e^+e^- \to q\bar{q})/(e^+e^- \to \mu^+\mu^-)$ *from BES (2 to 5 GeV, 2002), Crystal Ball (5 to 7.4 GeV, 1990)*
- *Incorporating new calculation (REPI) of vacuum polarization into KORALB & KK2F makes them agree...*



[16] D. Karlen and H. Burkhardt, Eur. Phys. J. C **22**, 39 (2001) [arXiv:hep-ex/0105065].



$\Delta(\sigma_{\tau\tau}) = 0.18\%$
$\Delta(\sigma_{\mu\mu}) = 0.22\%$

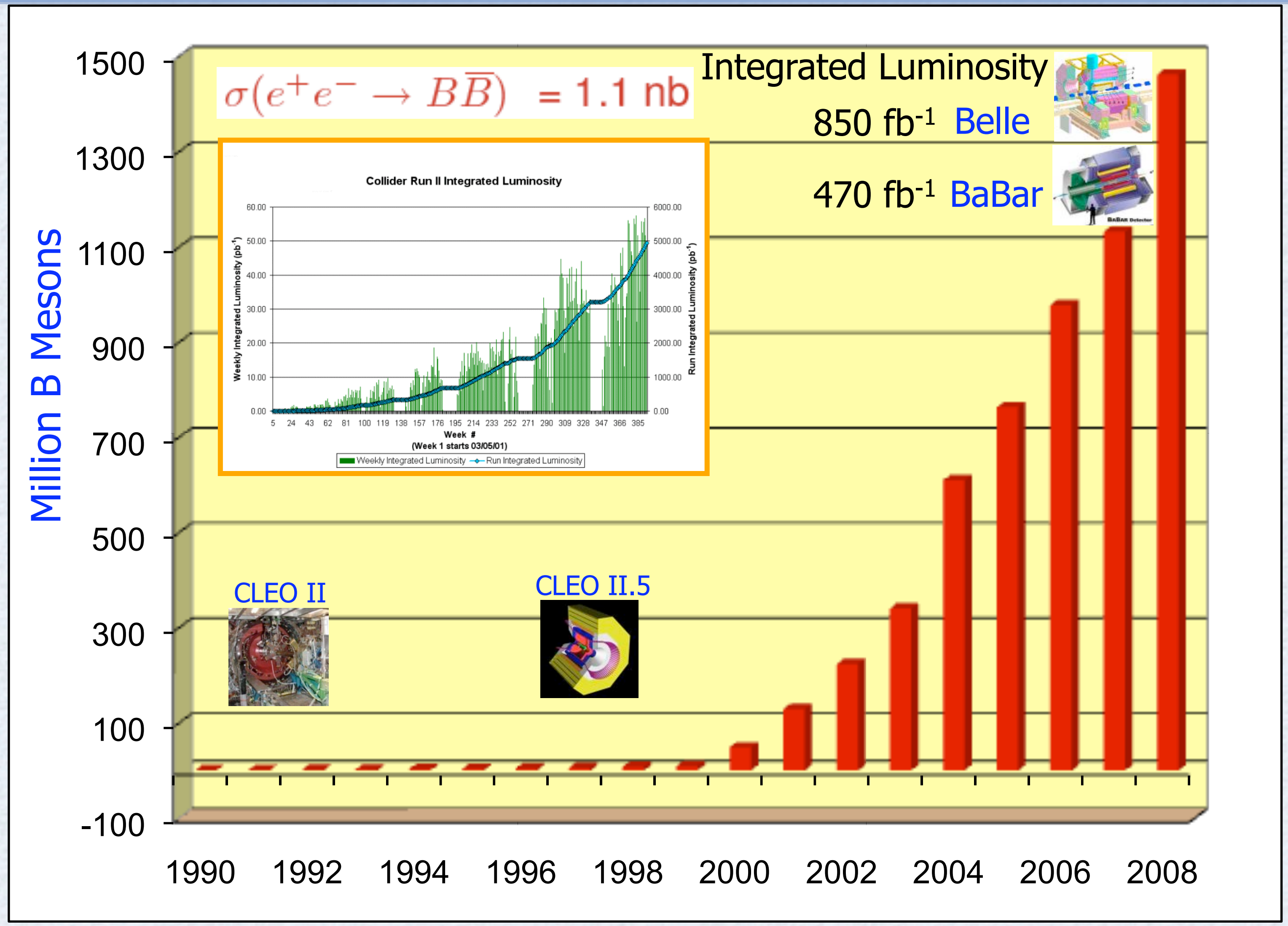
τ-pair and μ-pair cross-section at 10.58 GeV

PRD77, 054012 (2008) Swagato Banerjee, Bolek Pietrzyk, J. Michael Roney, Zbigniew Was

	$\sigma(\tau\tau)$	$\sigma(\mu\mu)$	$\sigma_{cuts}(\mu\mu)$	$\sigma(\tau\tau)/\sigma(\mu\mu)$
Vacuum Polarization	0.18%	0.22%	0.22%	0.05%
Bremsstrahlung	0.20%	0.20%	0.20%	0.20%
Interference	0.04%	0.04%	0.04%	0.04%
Vertex Corrections	0.15%	0.15%	0.15%	-
Vector Resonances	0.04%	0.12%	0.10%	-
Total	0.31%	0.36%	0.35%	0.21%

- $\sigma(e^+e^- \to \tau^+\tau^-) = (0.919 \pm 0.003)\,\text{nb}$
- $\sigma(e^+e^- \to \mu^+\mu^-) = (1.147 \pm 0.004)\,\text{nb}$
- $\sigma_{cuts}(e^+e^- \to \mu^+\mu^-) = (0.835 \pm 0.003)\,\text{nb}$
- $\sigma(\tau^+\tau^-)/\sigma_{cuts}(\mu^+\mu^-) = 1.100 \pm 0.002$

B-Factories are also τ-Factories

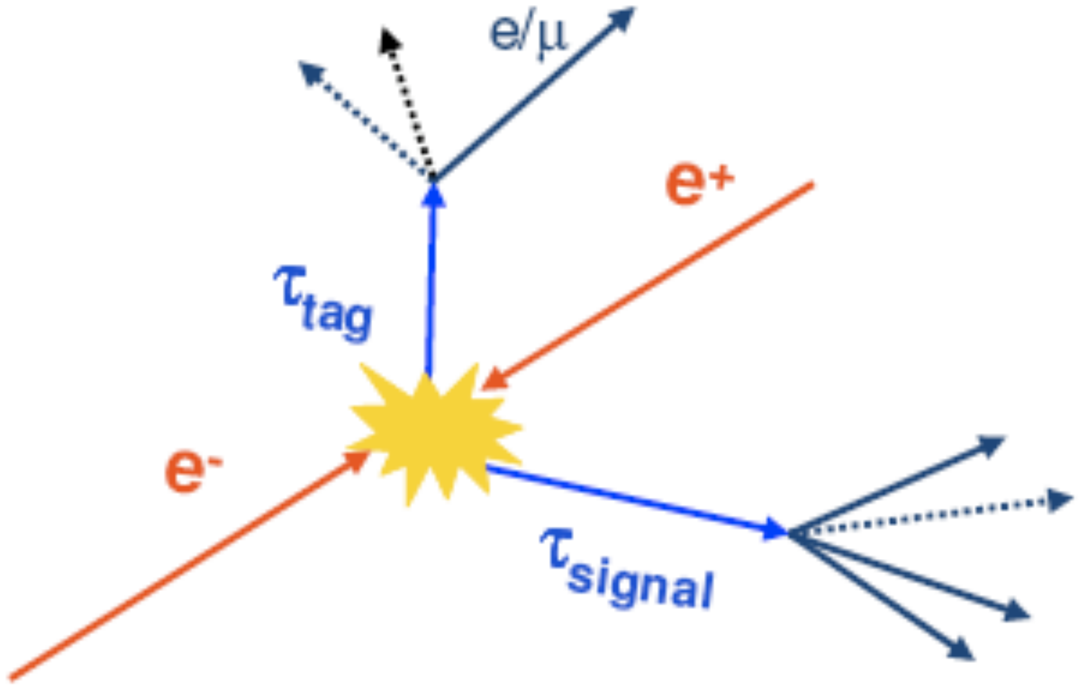


Cross Section at 10.58 GeV
$\sigma(\tau^+\tau^-)$=(0.919±0.003)nb
S. Banerjee, et. al. PRD77, 054012 (2008)

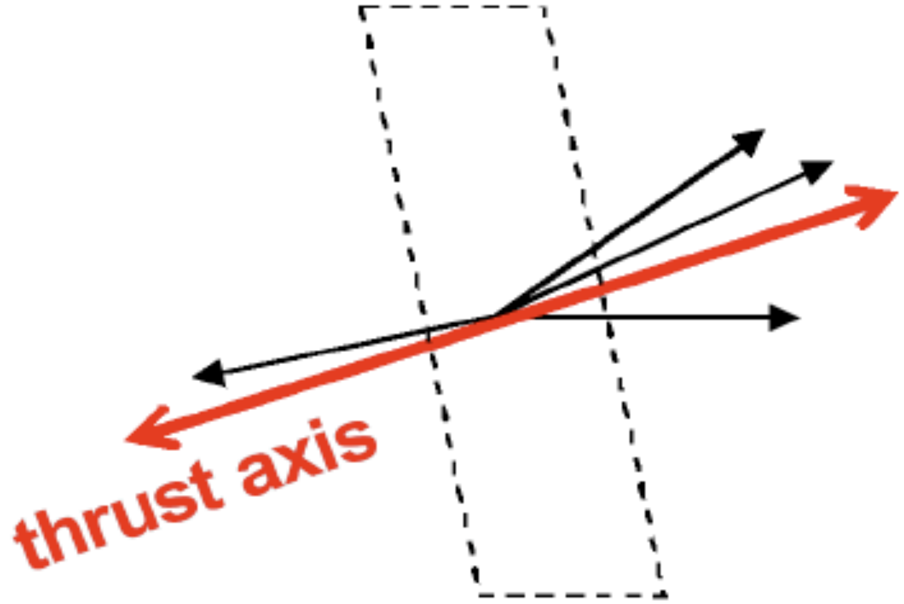
Experiment	Number of τ Pairs
LEP	~3×10^5
CLEO	~1×10^7
BaBar	~5×10^8
Belle	~9×10^8

τ-pair Event Topology

- Well separated in space

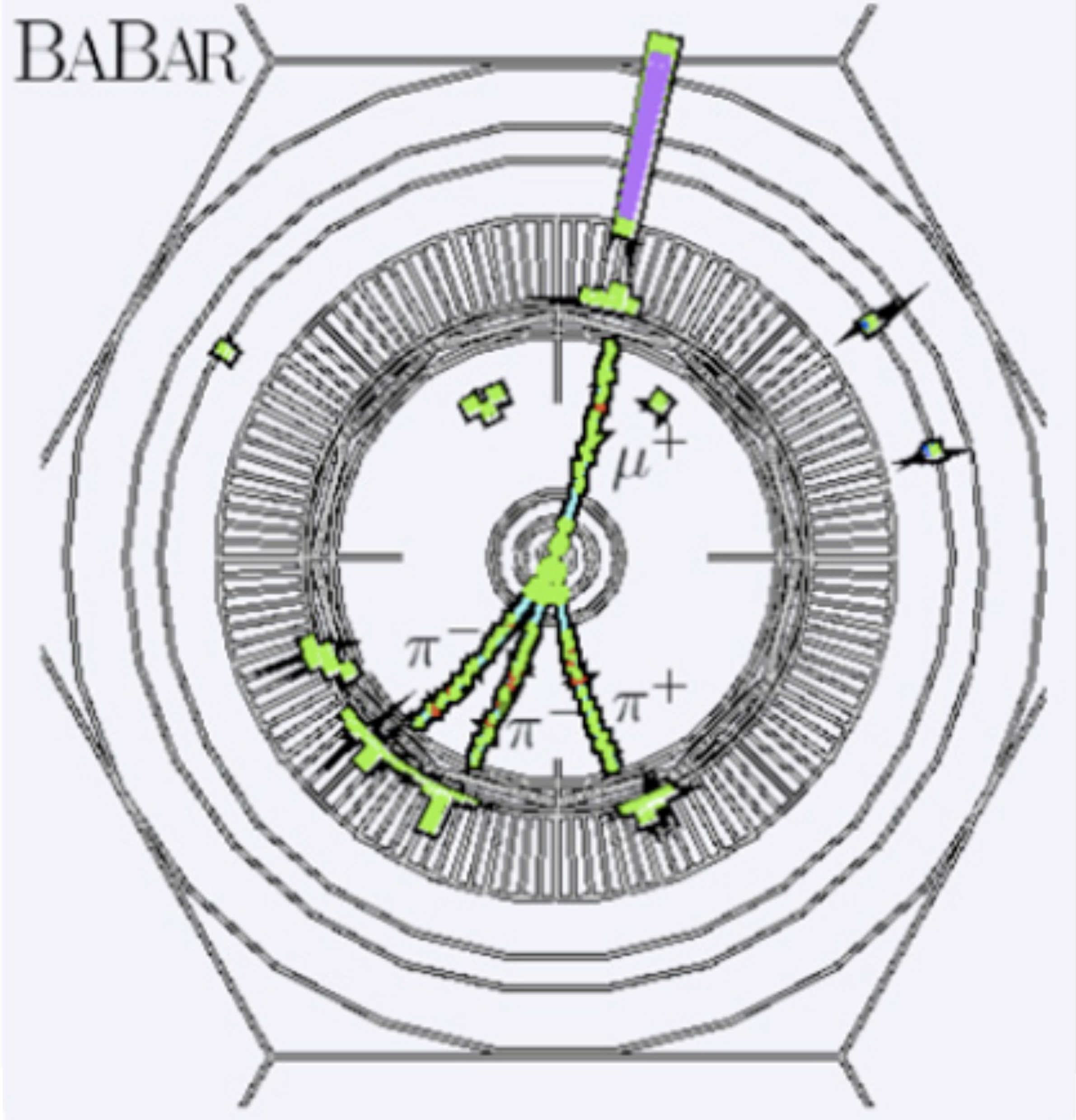


- Divide event into 2 hemispheres in CM frame ⊥ to thrust axis



☛ unique signature:
Leptonic + Hadronic decay

$$e^+e^- \to \tau^+(\to \mu^+\bar{\nu}_\tau\nu_\mu)\tau^-(\to \pi^-\pi^-\pi^+\nu_\tau)$$



☞ most analyses use leptonic tags

Mandate

HFAG: Tau Physics Parameters

Purpose:

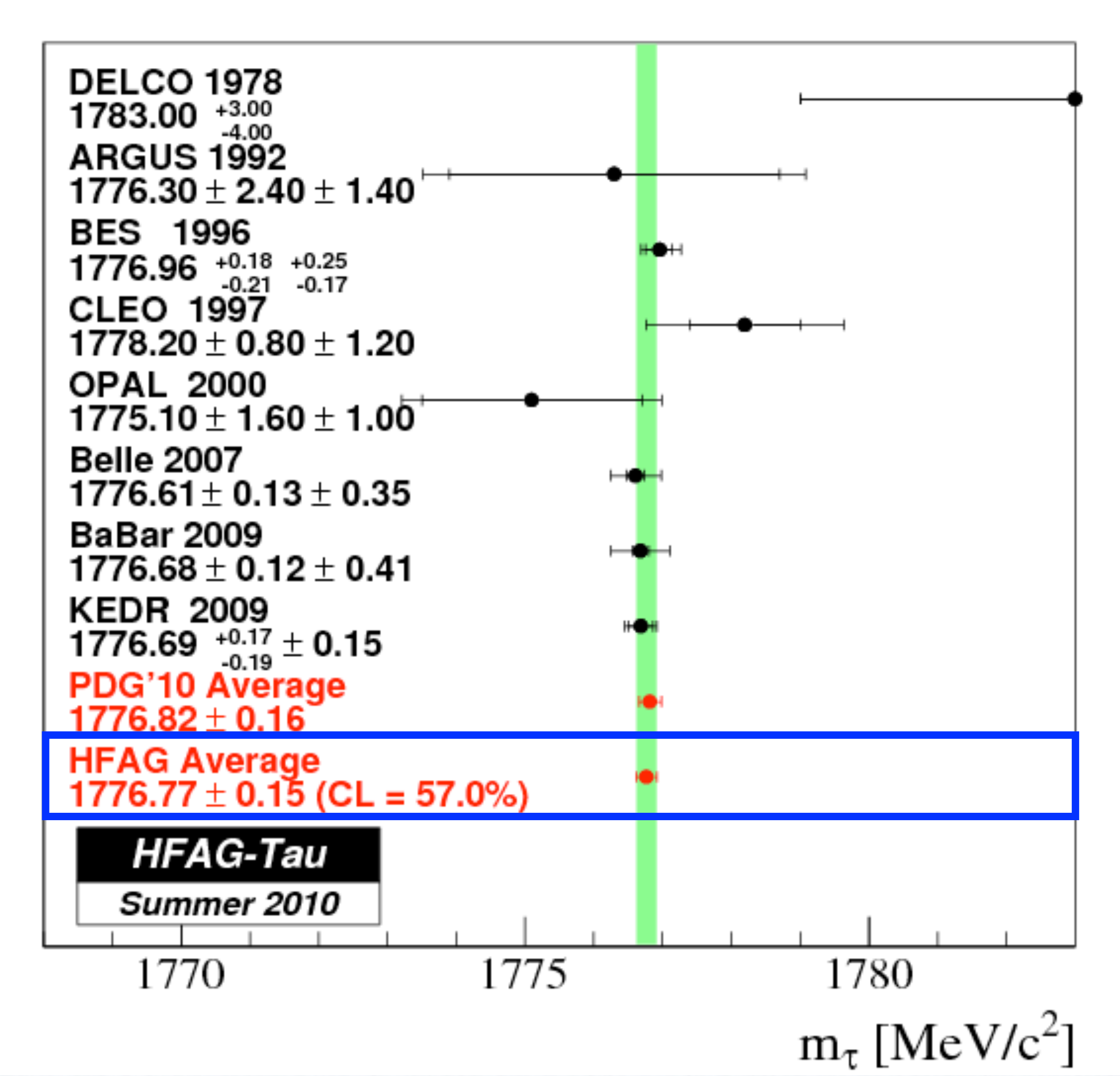
Provide latest results and averages of Branching Fractions and Upper Limits of the Tau Lepton

Scope:

- Tau Mass
- Leptonic Branching Fractions
- Strange Branching Fractions
- Non-Strange Branching Fractions
- Extraction of |Vus|
- Lepton Flavour Violating Upper Limits

http://www.slac.stanford.edu/xorg/hfag/tau/index.html

Tau Mass



Tau Mass:

Decay Mode	Experiment	Reference	Result
$\tau^- \to \pi^- \pi^- \pi^+ \nu$	BaBar	Phys.Rev.D80:092005,2009	$(1776.68 \pm 0.12 \pm 0.41)$ MeV
	Belle	Phys.Rev.Lett.99:011801,2007	$(1776.61 \pm 0.13 \pm 0.35)$ MeV
	KEDR	Tau08	$(1776.69\ ^{+0.17}_{-0.19} \pm 0.15)$ MeV
			(Top of the Page)

Averaging Branching Fractions

- Most of the branching fractions are highly correlated.
- Sources of correlation between the same experiment:
  - Track reconstruction ~ 1% for 1-vs-1 topology
  - Secondary vertex reconstruction ~ 1.5% for K_S
  - Calorimeter bump reconstruction ~ 3% for π^0
  - Particle identification ~ 2-4 %
  - Luminosity uncertainty ~ 1%

Sources of correlation between different experiments:
  - Tau-pair cross-section uncertainty ~ 0.36%
  - Uncertainty on Branching Fractions of backgrounds

➡ Simultaneous averaging of all branching fractions

Averaging Branching Fractions

- Global Fit performed on 151 measurements:
  - 37 from ALEPH
  - 2 from ARGUS
  - 11 from BaBar
  - 10 from Belle
  - 1 from CELLO
  - 35 from CLEO
  - 6 from CLEO3
  - 14 from DELPHI
  - 2 from HRS
  - 11 from L3
  - 19 from OPAL
  - 3 from TPC

PDG was kind to provide
"their" list of 124 measurements
from pre B-Factory era
used for their averages and global fits:

THANKS!

Using these inputs, we are able to
reproduce the PDG averages as well as
global fit values, errors and
their S-Factor estimates to within $\sim 10^{-5}$.

Methodology

- PDG averages published results, subject to a cut off date.
- HFAG also uses preliminary results, and tries to update at least once a year. Preliminary results not published over a long period of time (~2 years) are discarded.
- HFAG tries to take into account correlations between measurements, as well as dependence on common external parameters such as tau-pair cross-section and background normalization errors between experiments.
- As much as possible, HFAG tries to avoid inflating measured uncertainties using PDG-style scale factors to account for spread between the different measurements. Instead, a confidence level (CL) for the average is quoted.

Special Handling of ALEPH inputs

242 *ALEPH Collaboration / Physics Reports 421 (2005) 191–284*

Table 15
Correlation matrix of the statistical errors on the branching fractions

	μ	h	$h\pi^0$	$h2\pi^0$	$h3\pi^0$	$h4\pi^0$	$3h$	$3h\pi^0$	$3h2\pi^0$	$3h3\pi^0$	$5h$	$5h\pi^0$
e	−0.21	−0.15	−0.25	−0.09	−0.01	0.00	−0.15	−0.10	0.03	−0.06	0.00	0.01
μ	1.00	−0.13	−0.21	−0.07	−0.06	0.00	−0.09	−0.07	0.00	−0.02	0.00	−0.04
h		1.00	−0.31	−0.02	0.01	−0.06	−0.12	−0.06	−0.02	0.01	−0.01	0.02
$h\pi^0$			1.00	−0.40	0.05	0.00	−0.11	−0.06	−0.02	0.00	−0.04	−0.04
$h2\pi^0$				1.00	−0.51	0.26	−0.09	0.01	−0.07	0.06	−0.01	0.03
$h3\pi^0$					1.00	−0.75	0.01	−0.03	0.05	−0.02	−0.01	0.01
$h4\pi^0$						1.00	−0.02	−0.02	−0.03	0.01	0.02	−0.03
$3h$							1.00	−0.33	0.08	−0.05	−0.04	0.00
$3h\pi^0$								1.00	−0.45	0.19	−0.02	−0.02
$3h2\pi^0$									1.00	−0.65	0.03	0.02
$3h3\pi^0$										1.00	−0.01	−0.04
$5h$											1.00	−0.24
$5h\pi^0$												1.00

ALEPH quotes the correlation matrix for hadronic modes, but PDG translates the matrix into pion modes, which are obtained by subtracting the kaon contribution. We use the total hadronic branching fraction also quoted in the paper.

B-Factory measurements in the Global Fit

11 measurements from the BaBar collaboration:

$$\frac{\mathcal{B}(\tau^- \to \mu^- \overline{\nu}_\mu \nu_\tau)}{\mathcal{B}(\tau^- \to e^- \overline{\nu}_e \nu_\tau)} = (0.9796 \pm 0.0016 \pm 0.0036)\ [567],$$
$$\frac{\mathcal{B}(\tau^- \to \pi^- \nu_\tau)}{\mathcal{B}(\tau^- \to e^- \overline{\nu}_e \nu_\tau)} = (0.5945 \pm 0.0014 \pm 0.0061)\ [567],$$
$$\frac{\mathcal{B}(\tau^- \to K^- \nu_\tau)}{\mathcal{B}(\tau^- \to e^- \overline{\nu}_e \nu_\tau)} = (0.03882 \pm 0.00032 \pm 0.00057)\ [567],$$
$$\mathcal{B}(\tau^- \to K^- \pi^0 \nu_\tau) = (0.416 \pm 0.003 \pm 0.018)\%\ [568]$$
$$\mathcal{B}(\tau^- \to \overline{K}^0 \pi^- \nu_\tau) = (0.840 \pm 0.004 \pm 0.023)\%\ [569]$$
$$\mathcal{B}(\tau^- \to \overline{K}^0 \pi^- \pi^0 \nu_\tau) = (0.342 \pm 0.006 \pm 0.015)\%\ [570]$$
$$\mathcal{B}(\tau^- \to \pi^- \pi^- \pi^+ \nu_\tau\ (\text{ex. } K^0)) = (8.834 \pm 0.007 \pm 0.127)\%\ [571]$$
$$\mathcal{B}(\tau^- \to K^- \pi^- \pi^+ \nu_\tau\ (\text{ex. } K^0)) = (0.273 \pm 0.002 \pm 0.009)\%\ [571]$$
$$\mathcal{B}(\tau^- \to K^- \pi^- K^+ \nu_\tau) = (0.1346 \pm 0.0010 \pm 0.0036)\%\ [571]$$
$$\mathcal{B}(\tau^- \to K^- K^- K^+ \nu_\tau) = (1.58 \pm 0.13 \pm 0.12) \times 10^{-5}\ [571]$$
$$\mathcal{B}(\tau^- \to 3h^- 2h^+ \nu_\tau\ (\text{ex. } K^0)) = (8.56 \pm 0.05 \pm 0.42) \times 10^{-4}\ [572]$$

10 measurements from the Belle collaboration:

$$\mathcal{B}(\tau^- \to h^- \pi^0 \nu_\tau) = (25.67 \pm 0.01 \pm 0.39)\%\ [573]$$
$$\mathcal{B}(\tau^- \to \overline{K}^0 \pi^- \nu_\tau) = (0.808 \pm 0.004 \pm 0.026)\%\ [574]$$
$$\mathcal{B}(\tau^- \to \pi^- \pi^- \pi^+ \nu_\tau\ (\text{ex. } K^0)) = (8.420 \pm 0.003\ ^{+0.260}_{-0.250})\%\ [575]$$
$$\mathcal{B}(\tau^- \to K^- \pi^- \pi^+ \nu_\tau\ (\text{ex. } K^0)) = (0.330 \pm 0.001\ ^{+0.016}_{-0.017})\%\ [575]$$
$$\mathcal{B}(\tau^- \to K^- \pi^- K^+ \nu_\tau) = (0.155 \pm 0.001\ ^{+0.006}_{-0.005})\%\ [575]$$
$$\mathcal{B}(\tau^- \to K^- K^- K^+ \nu_\tau) = (3.29 \pm 0.17\ ^{+0.19}_{-0.20}) \times 10^{-5}\ [575]$$
$$\mathcal{B}(\tau^- \to \pi^- \pi^0 \eta \nu_\tau) = (1.35 \pm 0.03 \pm 0.07) \times 10^{-3}\ [576]$$
$$\mathcal{B}(\tau^- \to K^- \eta \nu_\tau) = (1.58 \pm 0.05 \pm 0.09) \times 10^{-4}\ [576]$$
$$\mathcal{B}(\tau^- \to K^- \pi^0 \eta \nu_\tau) = (0.46 \pm 0.11 \pm 0.04) \times 10^{-4}\ [576]$$
$$\mathcal{B}(\tau^- \to \overline{K}^0 \pi^- \eta \nu_\tau) = (0.88 \pm 0.14 \pm 0.04) \times 10^{-4}\ [576]$$

Quality of Global Fit

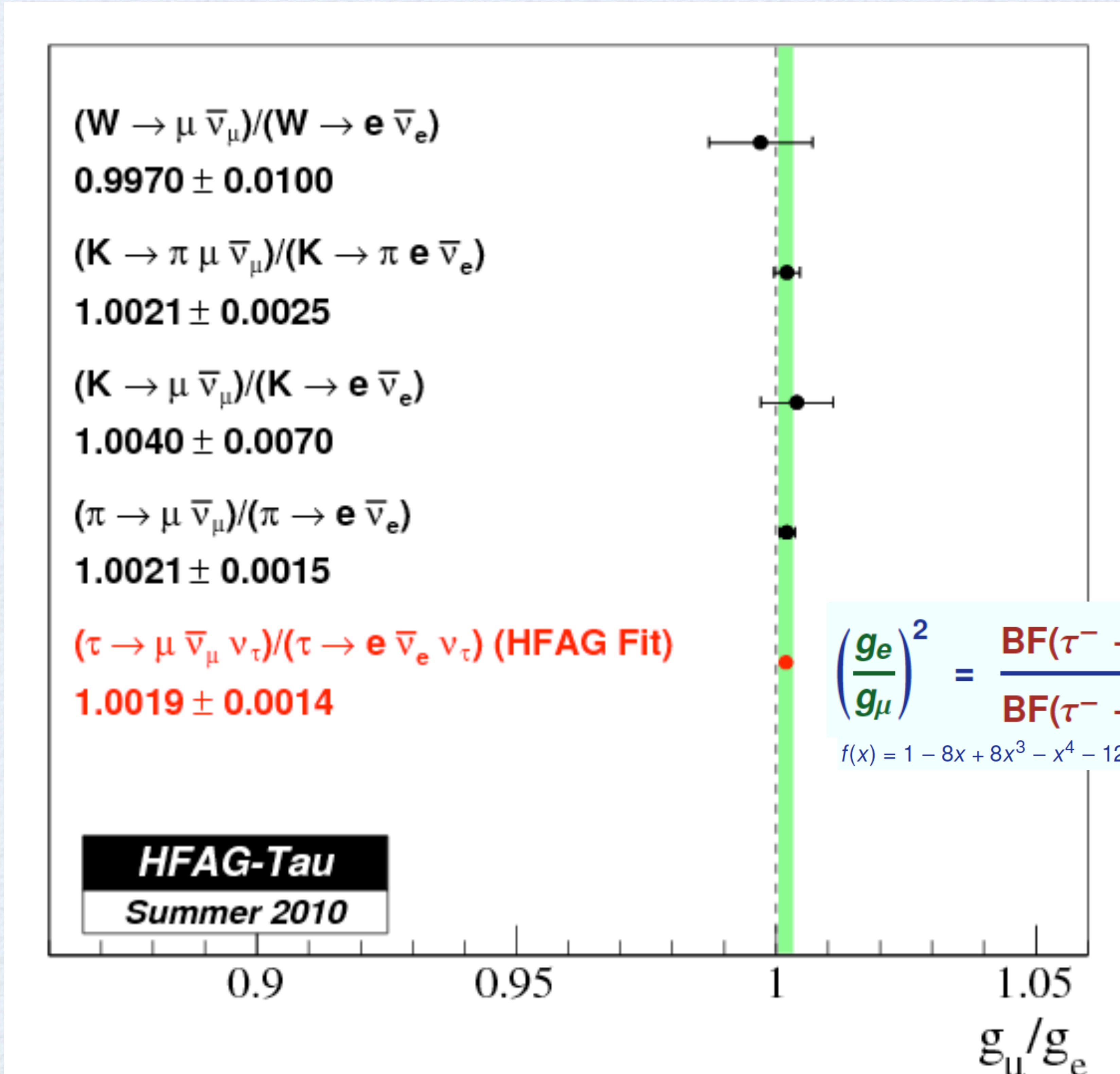
Using pre B-Factory era measurements:
sum of all branching fractions from unconstrained fit
= 0.2 σ lower than unity.
χ^2 of unconstrained fit = 78.1/94 d.o.f. ⇒ CL = 88.2%
χ^2 of constrained fit = 78.2/95 d.o.f. ⇒ CL = 89.5%

Including measurements from B-Factories era:
sum of all branching fractions from unconstrained fit
= 1.5 sigma lower than unity.
χ^2 of unconstrained fit = 132.8/114 d.o.f. ⇒ CL = 11.0%
χ^2 of constrained fit = 135.2/115 d.o.f. ⇒ CL = 9.6%

Results from unitarity constrained HFAG Fit

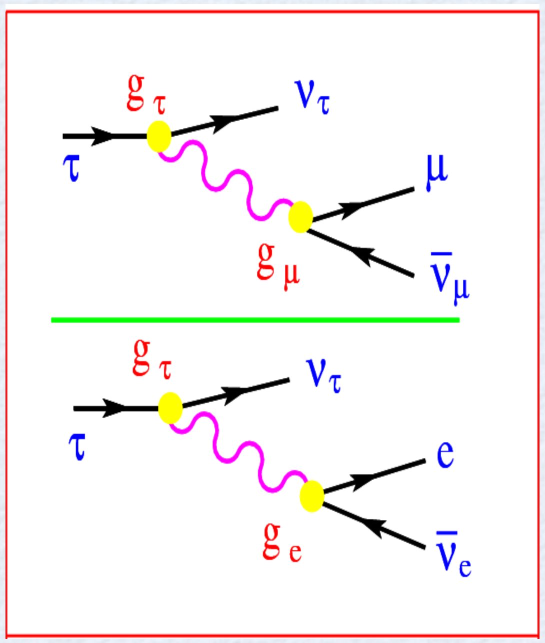
Base modes from τ^- decay	No B-Factory Data	With B-Factory Data
leptonic modes		
$e^-\overline{\nu}_e\nu_\tau$	17.836 ± 0.048	17.831 ± 0.040
$\mu^-\overline{\nu}_\mu\nu_\tau$	17.351 ± 0.046	17.407 ± 0.039
non-strange modes		
$\pi^-\nu_\tau$	10.901 ± 0.064	10.830 ± 0.051
$\pi^-\pi^0\nu_\tau$	25.493 ± 0.095	25.530 ± 0.090
$\pi^-2\pi^0\nu_\tau$ (ex. K^0)	9.234 ± 0.099	9.278 ± 0.097
$\pi^-3\pi^0\nu_\tau$ (ex. K^0)	1.028 ± 0.075	1.043 ± 0.074
$h^-4\pi^0\nu_\tau$ (ex. K^0,η)	0.100 ± 0.039	0.109 ± 0.039
$K^-K^0\nu_\tau$	0.153 ± 0.016	0.160 ± 0.016
$K^-K^0\pi^0\nu_\tau$	0.155 ± 0.020	0.162 ± 0.019
$\pi^-K^0_SK^0_S\nu_\tau$	0.024 ± 0.005	0.024 ± 0.005
$\pi^-K^0_SK^0_L\nu_\tau$	0.110 ± 0.024	0.121 ± 0.024
$\pi^-\pi^-\pi^+\nu_\tau$ (ex. K^0,ω)	8.945 ± 0.061	8.982 ± 0.050
$\pi^-\pi^-\pi^+\pi^0\nu_\tau$ (ex. K^0,ω)	2.723 ± 0.069	2.726 ± 0.068
$h^-h^-h^+2\pi^0\nu_\tau$ (ex. K^0,ω,η)	0.091 ± 0.036	0.100 ± 0.036
$h^-h^-h^+3\pi^0\nu_\tau$	0.022 ± 0.005	0.022 ± 0.005
$\pi^-K^-K^+\nu_\tau$	0.153 ± 0.007	0.144 ± 0.003
$\pi^-K^-K^+\pi^0\nu_\tau$	0.006 ± 0.002	0.006 ± 0.002
$3h^-2h^+\nu_\tau$ (ex. K^0)	0.081 ± 0.005	0.083 ± 0.003
$3h^-2h^+\pi^0\nu_\tau$ (ex. K^0)	0.018 ± 0.003	0.018 ± 0.003
$\pi^-\pi^0\eta\nu_\tau$	0.175 ± 0.024	0.139 ± 0.007
$\pi^-\omega\nu_\tau$	1.953 ± 0.064	1.960 ± 0.064
$h^-\omega\pi^0\nu_\tau$	0.404 ± 0.042	0.409 ± 0.042
strange modes		
$K^-\nu_\tau$	0.686 ± 0.022	0.697 ± 0.010
$K^-\pi^0\nu_\tau$	0.453 ± 0.027	0.431 ± 0.015
$K^-2\pi^0\nu_\tau$ (ex. K^0)	0.057 ± 0.023	0.060 ± 0.022
$K^-3\pi^0\nu_\tau$ (ex. K^0,η)	0.036 ± 0.022	0.039 ± 0.022
$\overline{K}^0\pi^-\nu_\tau$	0.889 ± 0.037	0.831 ± 0.018
$\overline{K}^0\pi^-\pi^0\nu_\tau$	0.359 ± 0.035	0.350 ± 0.015
$\overline{K}^0\pi^-2\pi^0\nu_\tau$	0.024 ± 0.023	0.031 ± 0.023
$\overline{K}^0h^-h^-h^+\nu_\tau$	0.024 ± 0.020	0.029 ± 0.020
$K^-\pi^-\pi^+\nu_\tau$ (ex. K^0)	0.335 ± 0.023	0.294 ± 0.007
$K^-\pi^-\pi^+\pi^0\nu_\tau$ (ex. K^0,η)	0.075 ± 0.012	0.078 ± 0.012
$K^-\phi\nu_\tau(\phi \to KK)$		0.004 ± 0.001
$K^-\eta\nu_\tau$	0.027 ± 0.006	0.016 ± 0.001
$K^-\pi^0\eta\nu_\tau$	0.018 ± 0.009	0.005 ± 0.001
$\overline{K}^0\pi^-\eta\nu_\tau$	0.022 ± 0.007	0.009 ± 0.001
$K^-\omega\nu_\tau$	0.042 ± 0.009	0.042 ± 0.009
Sum of strange modes	3.0460 ± 0.0731	2.9155 ± 0.0510
Sum of all modes	100	100.00

Tests of Lepton Universality

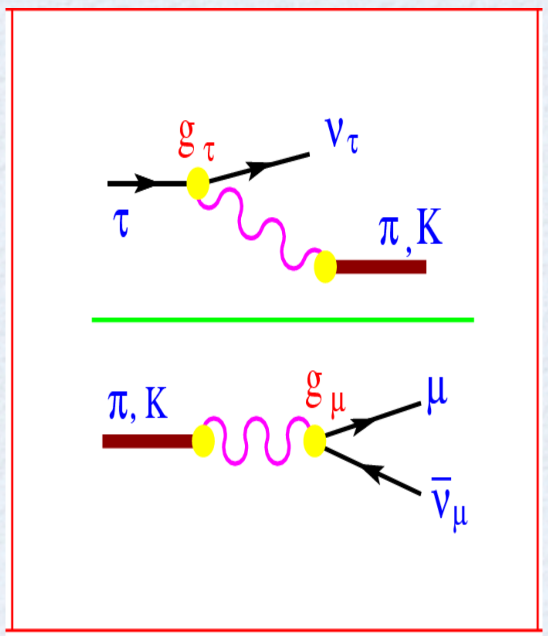


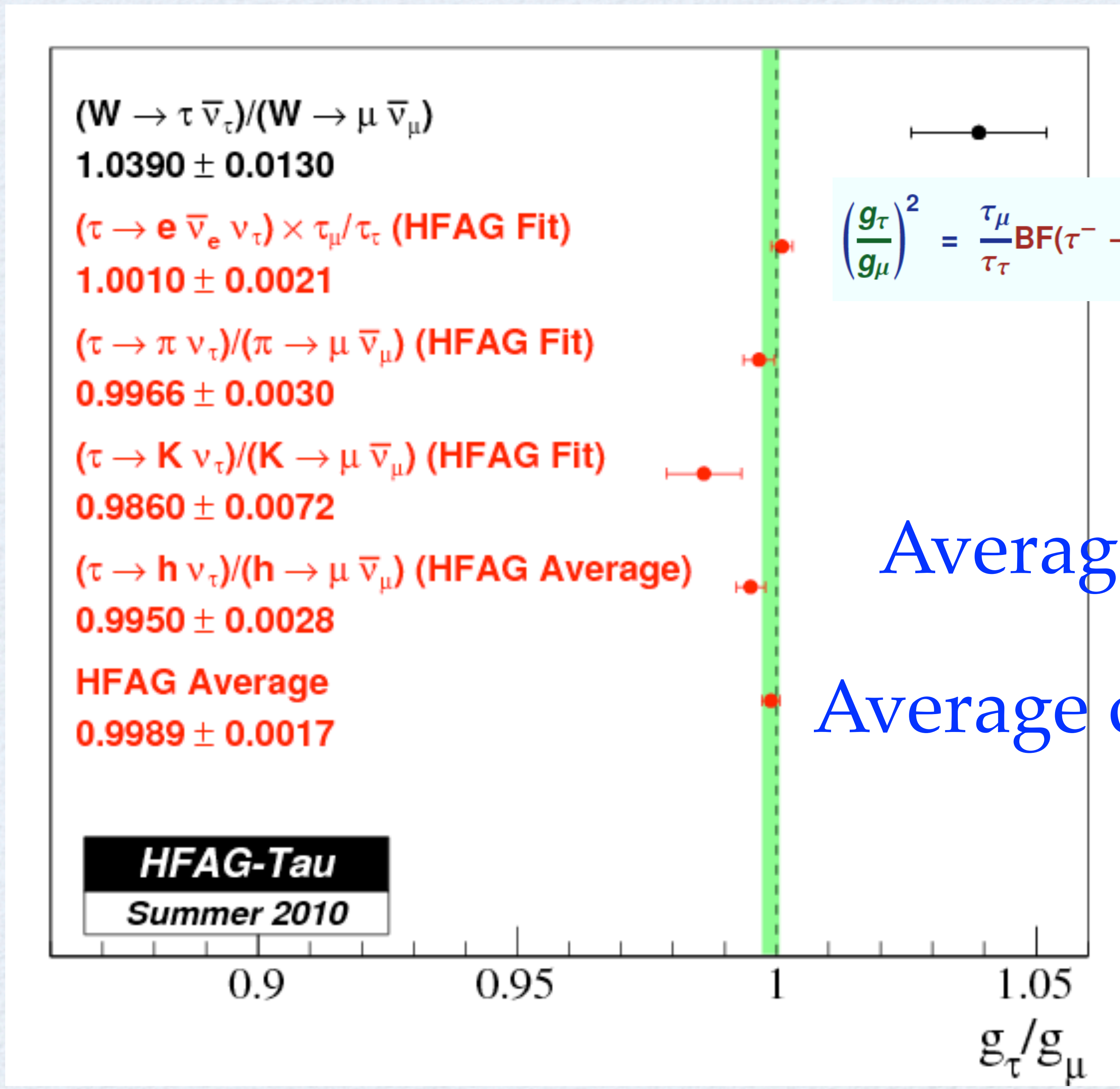
$$\left(\frac{g_e}{g_\mu}\right)^2 = \frac{BF(\tau^- \to e^- \overline{\nu_e} \nu_\tau)}{BF(\tau^- \to \mu^- \overline{\nu_\mu} \nu_\tau)} \frac{f(m_\mu^2/m_\tau^2)}{f(m_e^2/m_\tau^2)}$$

$f(x) = 1 - 8x + 8x^3 - x^4 - 12x \ln x$ (approximating all $m_\nu = 0$)



Tests of Lepton Universality



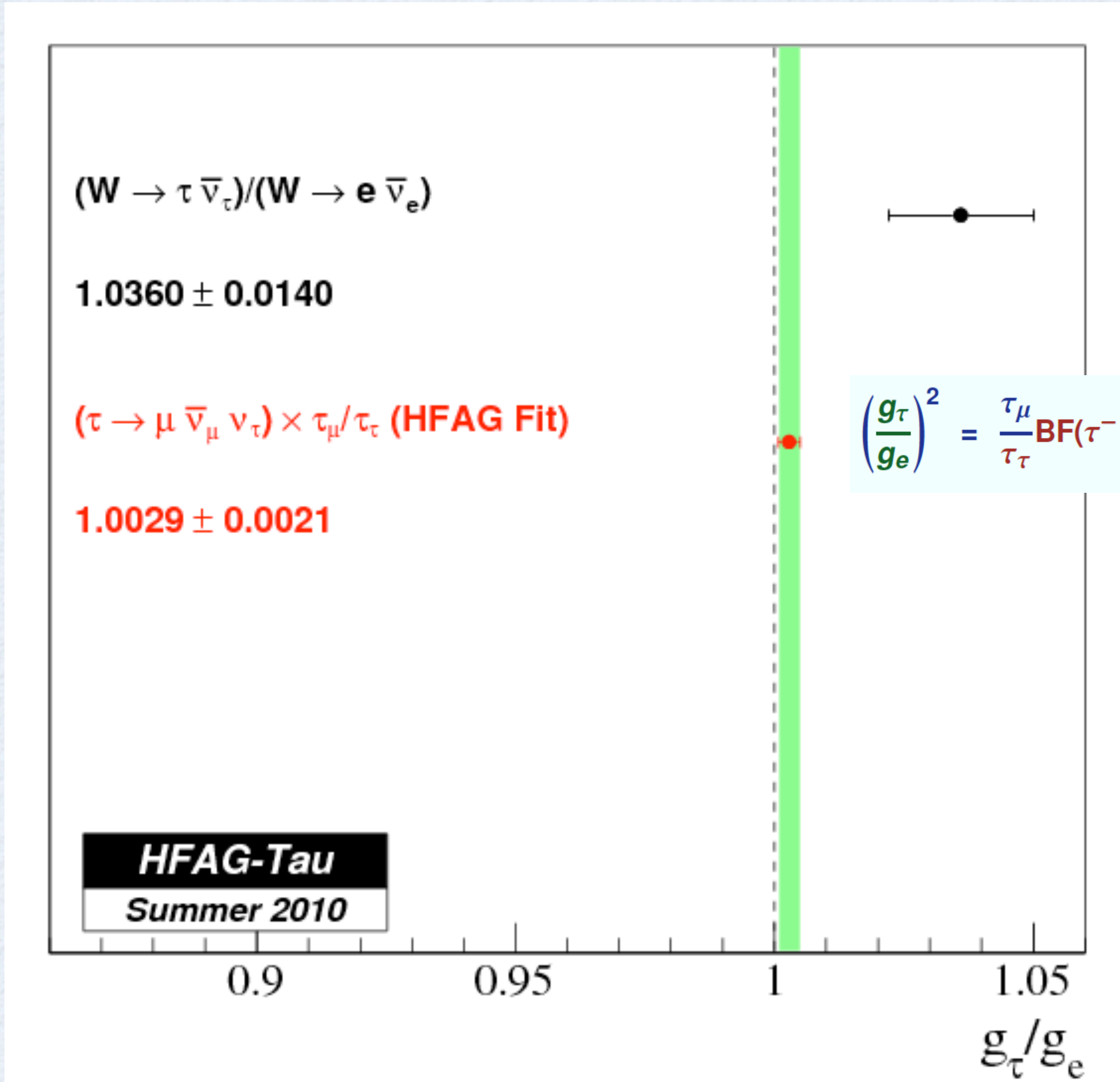


$$\left(\frac{g_\tau}{g_\mu}\right)^2 = \frac{\tau_\mu}{\tau_\tau} BF(\tau^- \to e^- \overline{\nu_e} \nu_\tau) \left(\frac{m_\mu}{m_\tau}\right)^5 \frac{f(m_e^2/m_\mu^2) r_{EW}^\mu}{f(m_e^2/m_\tau^2) r_{EW}^\tau}$$

Average of π and K

Average of e, π and K

Tests of Lepton Universality



$$\left(\frac{g_\tau}{g_e}\right)^2 = \frac{\tau_\mu}{\tau_\tau} BF(\tau^- \to \mu^- \overline{\nu_\mu} \nu_\tau) \left(\frac{m_\mu}{m_\tau}\right)^5 \frac{f(m_e^2/m_\mu^2) r^\mu_{EW}}{f(m_\mu^2/m_\tau^2) r^\tau_{EW}}$$

Unitarity of the CKM matrix

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \sim \begin{pmatrix} 1 & \lambda & \lambda^3 \\ \lambda & 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix}$$

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$$

- $|V_{ud}| = 0.97425 \pm 0.00022$ from (nuclear β decays)

  J.C.Hardy & I.S.Towner, PRC 79, 055502 (2009)

- $|V_{ub}| = (3.93 \pm 0.36) \times 10^{-3}$ (from $B \to X_u \ell \nu$ decays)

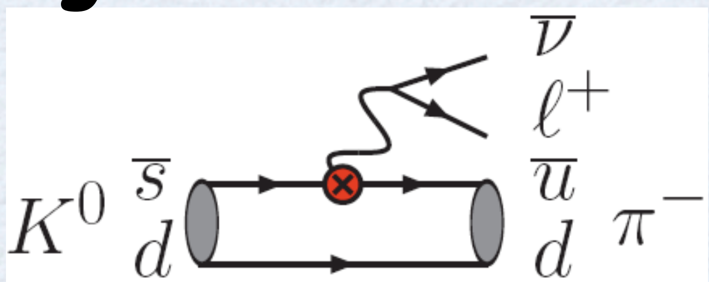
  Particle Data Group

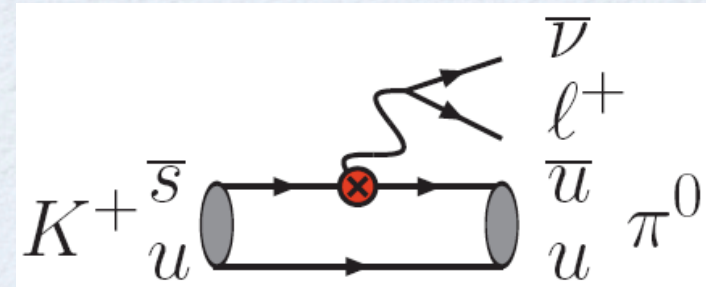
$\Rightarrow |V_{us}| = 0.2255 \pm 0.0010$

Precision measurement of $|V_{us}|$ is a test of CKM unitarity

Approaches to $|V_{us}|$

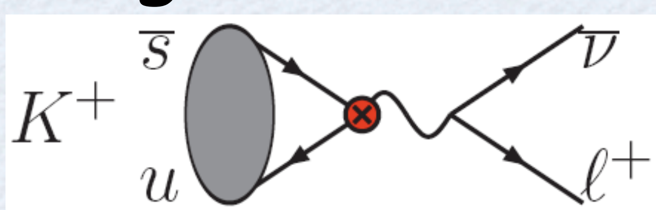
Kl3 decays:

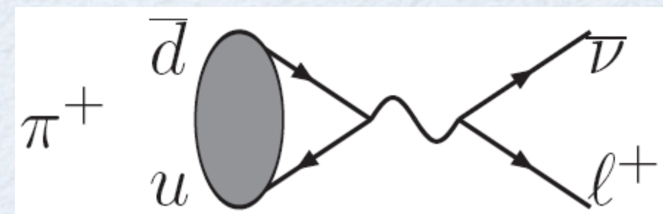




$\Rightarrow |V_{us}| f_+(0)$

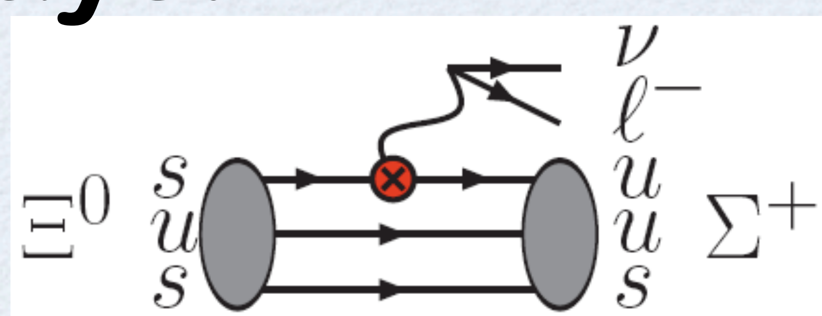
Kl2 decays:





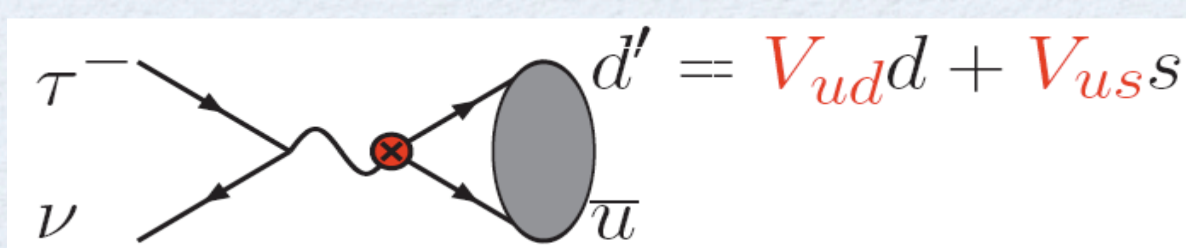
$\Rightarrow \frac{|V_{us}|}{|V_{ud}|} \frac{F_K}{F_\pi}$

Hyperon decays:



$\Rightarrow |V_{us}| f_1(0)$

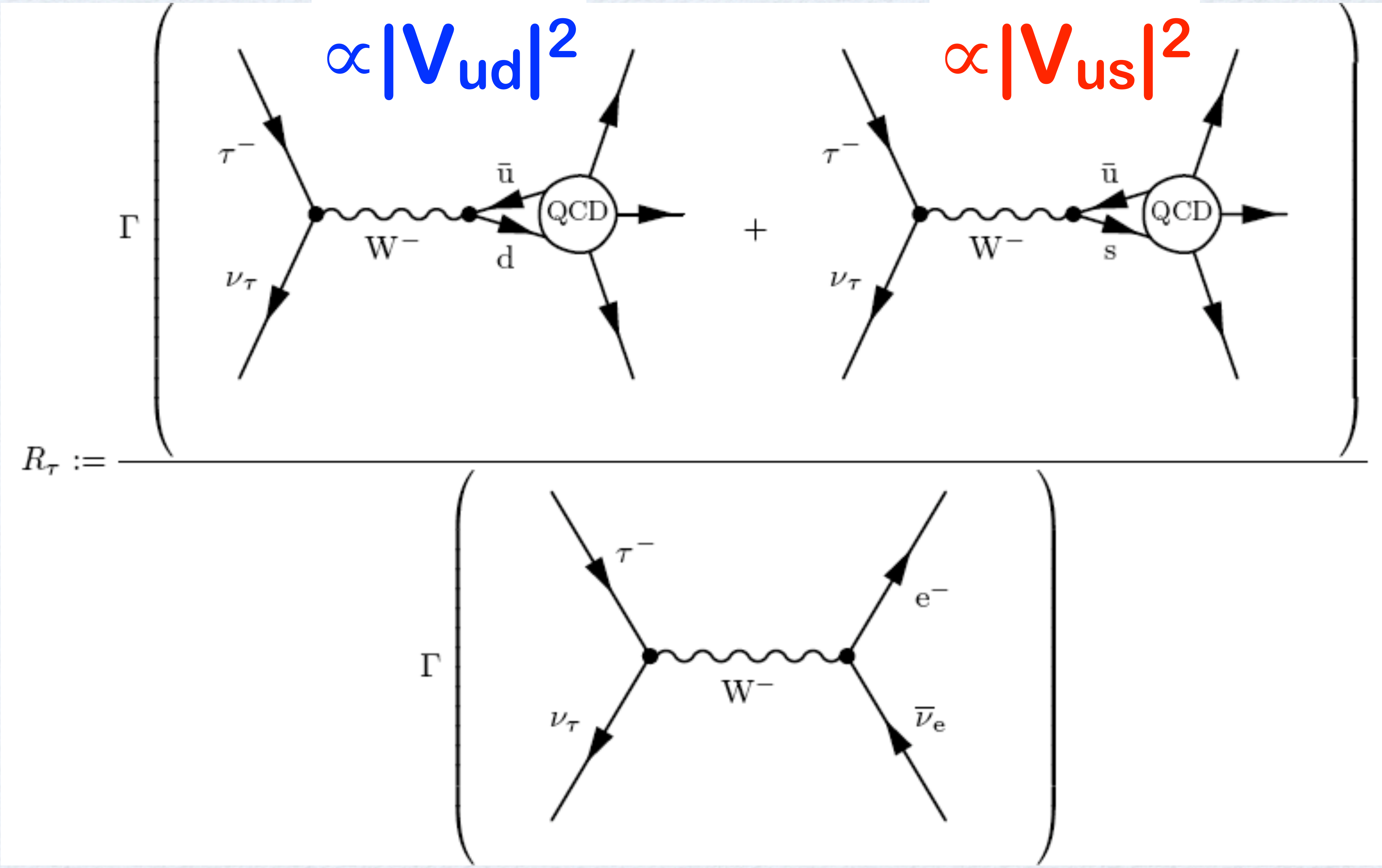
τ decays:



$\Rightarrow m_s, |V_{us}|$

τ Hadronic Width

$$R_\tau = \frac{\Gamma(\tau^- \to \text{hadrons}\ \nu_\tau\,(\gamma))}{\Gamma(\tau^- \to e^- \overline{\nu}_e \nu_\tau\,(\gamma))} = R_{\tau,ns} + R_{\tau,s}$$



$|V_{us}|$ with Fixed m_s

$$|V_{us}|^2 = \frac{R_{\tau,\text{strange}}}{\left(R_{\tau,\text{non-strange}} / |V_{ud}|^2\right) - \delta R_{\tau,\text{theory}}}$$

- QCD Sum rules, Lattice:

$$m_s(2\,\text{GeV}) = 94 \pm 6\ \text{MeV}$$

M. Jamin et. al., PRD74, 074009 (2006)

- Smallest uncertainity on (0,0) moment

$$\delta R^{00}_{\tau,\text{th}} = 0.1544\,(37) + 9.3\,(3.4)\,m_s^2 + 0.0034\,(28) = 0.240\,(32)$$

E. Gamiz et. al. (hep-ph/0612154) (Tau06)

- $$\delta R_{\tau,theory} << R_\tau$$

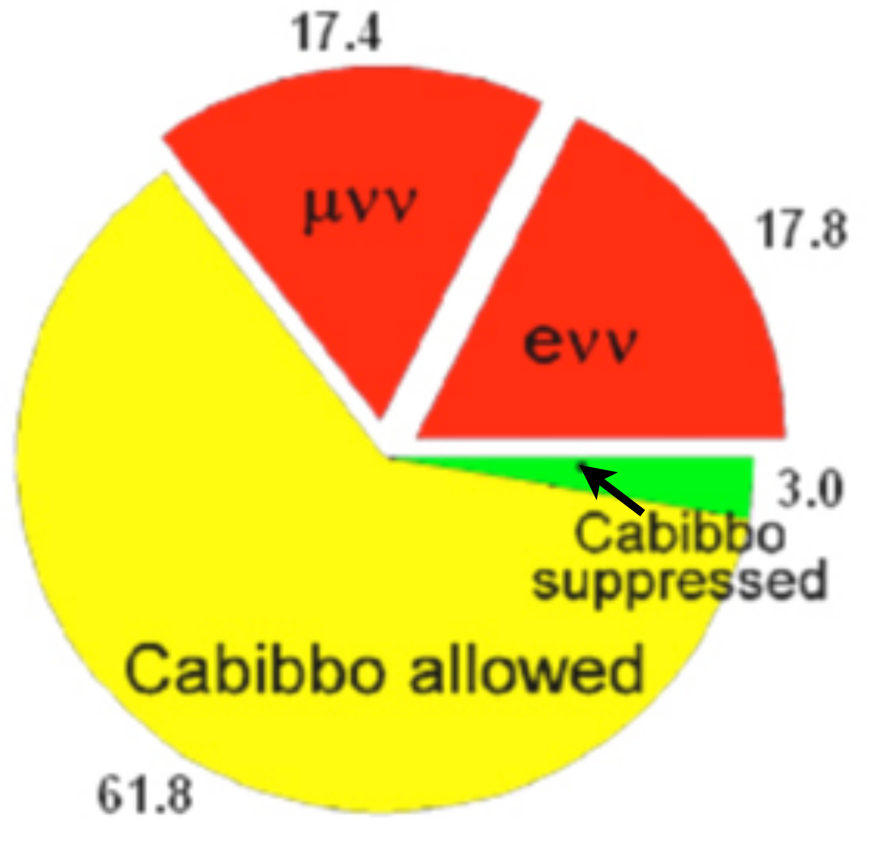
$$\Rightarrow \text{modest } \Delta(\delta \mathrm{R}_{\tau,\text{theory}}) \equiv 13\% \text{ gives } 0.5\% \text{ error on } |\mathrm{V}_{\text{us}}|$$

Route to Vus from τ decays

- Direct measurement averaged with $\mathcal{B}_e$ from $\mathcal{B}_\mu$ & τ_τ:

$$\mathcal{B}_e^{\rm uni} = (17.851 \pm 0.027)\%$$

- $$\mathcal{B}_{\rm had} = 1 - \mathcal{B}_e - \mathcal{B}_\mu$$
$$= 1 - 1.97257\,\mathcal{B}_e^{\rm uni}$$



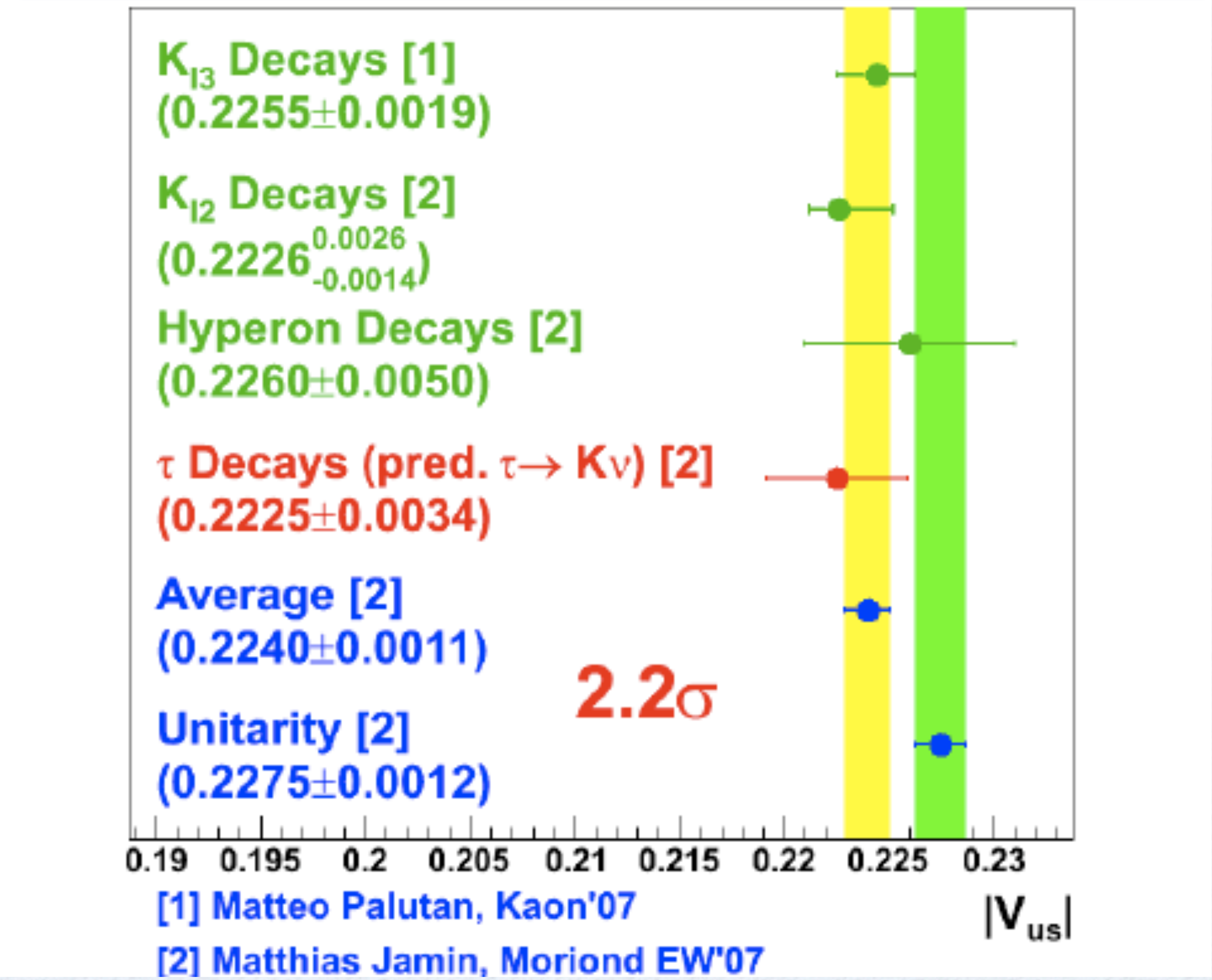
- $$R_{\tau,\rm had} = 3.6294 \pm 0.0086$$

- Strange τ decays:

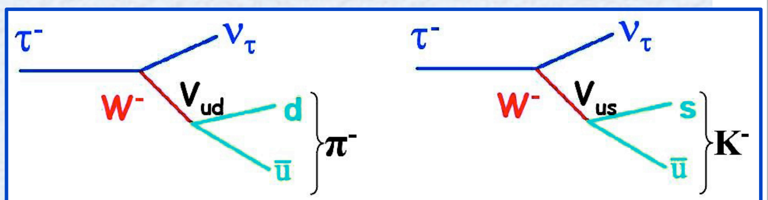
  Measure them all...

- $$R_{\tau,non-strange} = R_\tau - R_{\tau,strange}$$

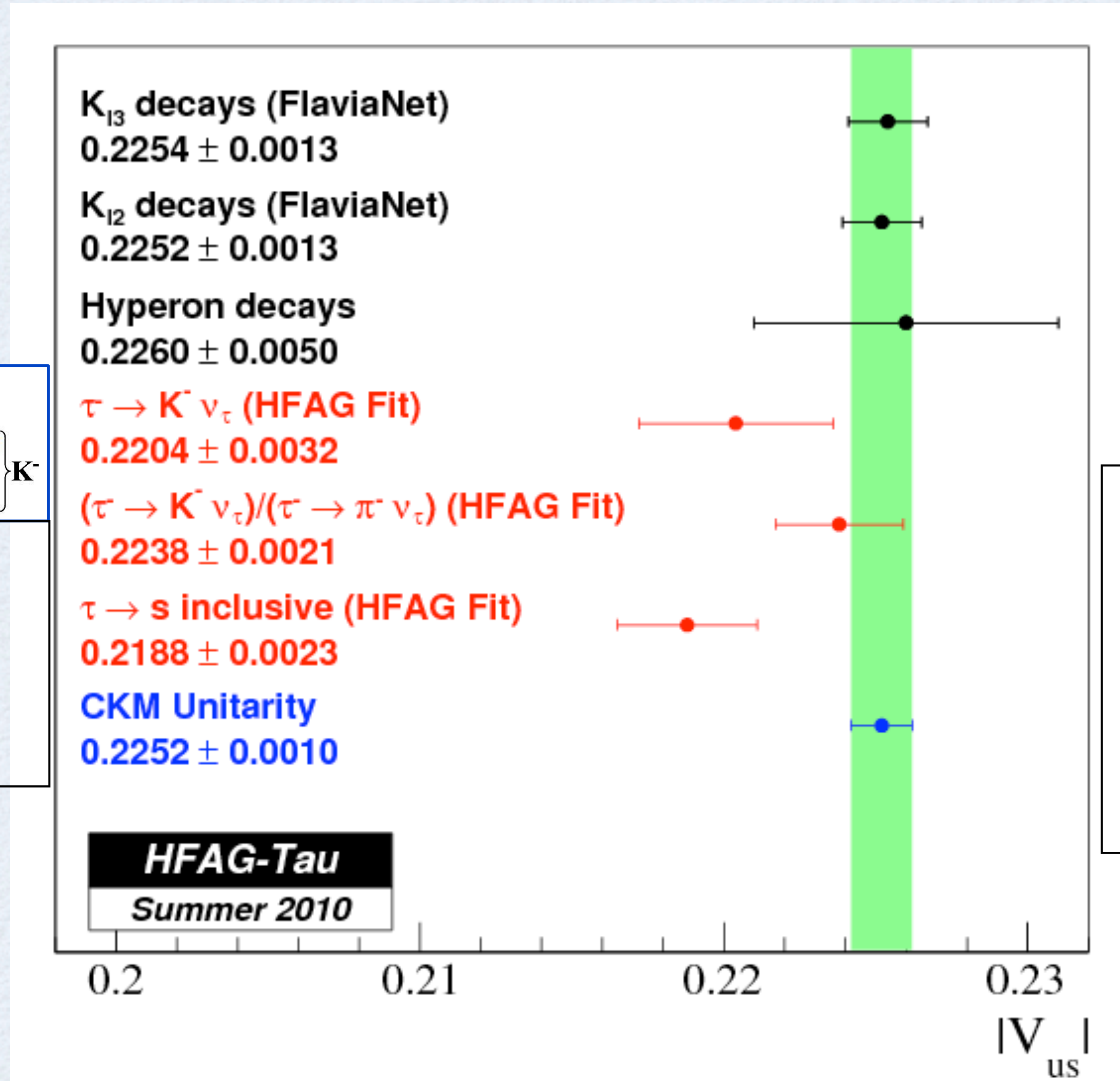
Status of $|V_{us}|$ (2007)



Status of $|V_{us}|$ (2010)



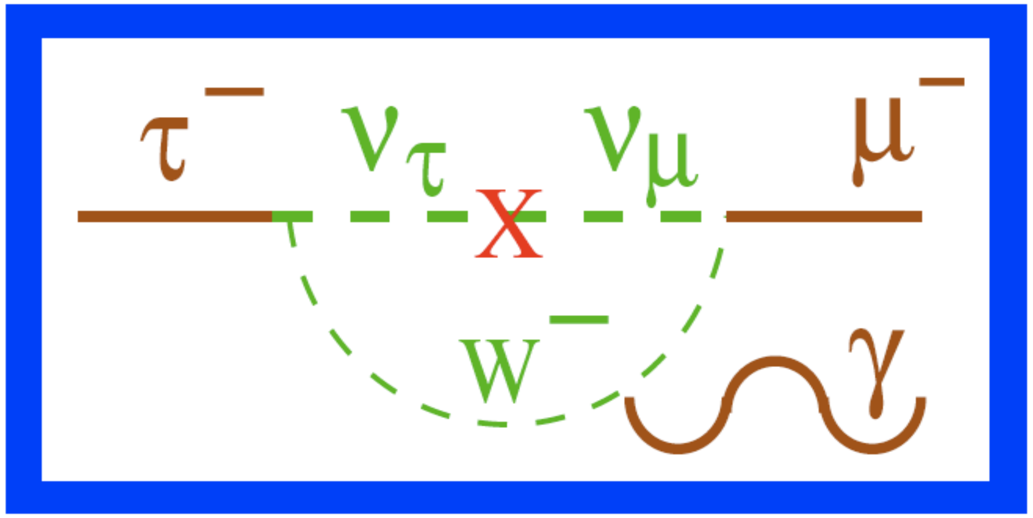
Using meson decay constants from Lattice, $|V_{us}|$ agrees with CKM unitarity



$|V_{us}|$ from inclusive strange decays ~ 2.7 σ lower than CKM unitarity using QCD sum rules in the OPE framework

Lepton Flavor Violation in Tau Decays

- Lepton flavor violation (LFV)
  - not forbidden by SM gauge symmetry
  - most new models naturally include LFV vertex
- In SM, LF is conserved for zero degenerate ν masses
- Now we have clear indication that ν's have finite mass
  $\Rightarrow$ Lepton Flavor is violated in Nature: but by how much?
- SM extended to include finite ν mass and mixing predicts LFV



$\mathcal{B}(\tau^\pm \to \mu^\pm\gamma)$ [Lee-Shrock, Phys. Rev. D **16**, 1444 (1977)]

$$= \frac{3\alpha}{128\pi}\left(\frac{\Delta m^2_{23}}{M^2_W}\right)^2 \sin^2 2\theta_{\mathrm{mix}}\mathcal{B}(\tau \to \mu\bar{\nu}_\mu\nu_\tau)$$

With $\Delta \sim 10^{-3}\,\mathrm{eV}^2$, $M_W \sim \mathcal{O}(10^{11})\,\mathrm{eV}$

$\approx \mathcal{O}(10^{-54})$ $(\theta_{\mathrm{mix}}$: max)

... many orders below experimental sensitivity!

- Observation for LFV $\Rightarrow$ unambiguous signature of new physics

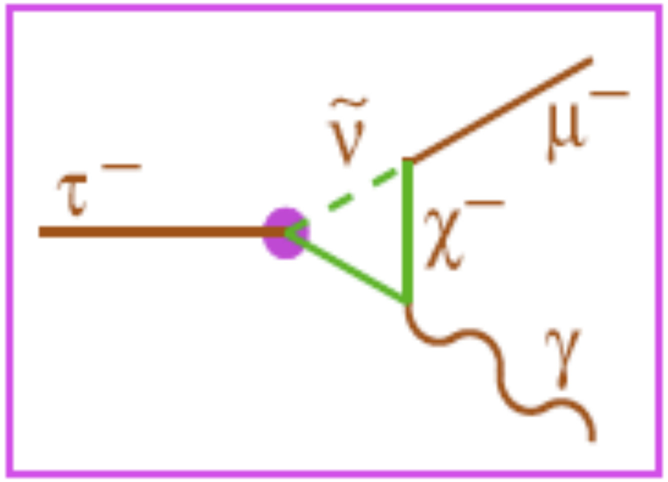
Lepton Flavor Violation in Tau Decays

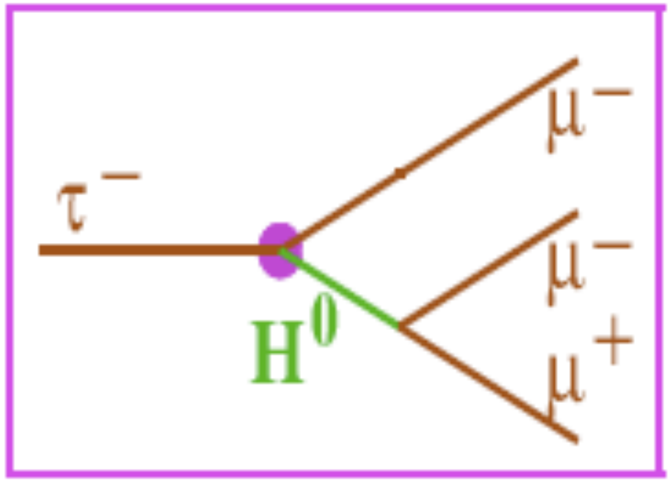
- Some models predict LFV upto existing experimental bounds

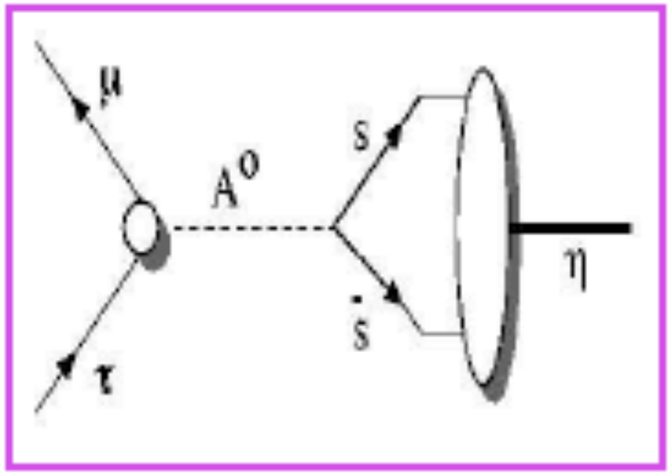
	$\mathcal{B}(\tau \to \ell\gamma)$	$\mathcal{B}(\tau \to \ell\ell\ell)$
SM+ν-mixing (PRL95(2005)41802,EPJC8(1999)513)	10^{-54}	10^{-54}
SUSY Higgs (PLB549(2002)159, PLB566(2003)217)	10^{-10}	10^{-7}
SM+Heavy Majorana ν_R (PRD66(2002)034008)	10^{-9}	10^{-10}
Non-Universal Z$'$ (PLB547(2002)252)	10^{-9}	10^{-8}
SUSY SO(10) (NPB649(2003)189, PRD68(2003)033012)	10^{-8}	10^{-10}
mSUGRA+seesaw (EPJC14(2000)319, PRD66(2002)115013)	10^{-7}	10^{-9}

MSSM+seesaw (PRD66 (2002) 057301) $\mathcal{B}(\tau \to \mu\gamma)$: $\mathcal{B}(\tau \to \mu\mu\mu)$: $\mathcal{B}(\tau \to \mu\eta)$ = 1.5 : 1 : 8.4

Illustrations:





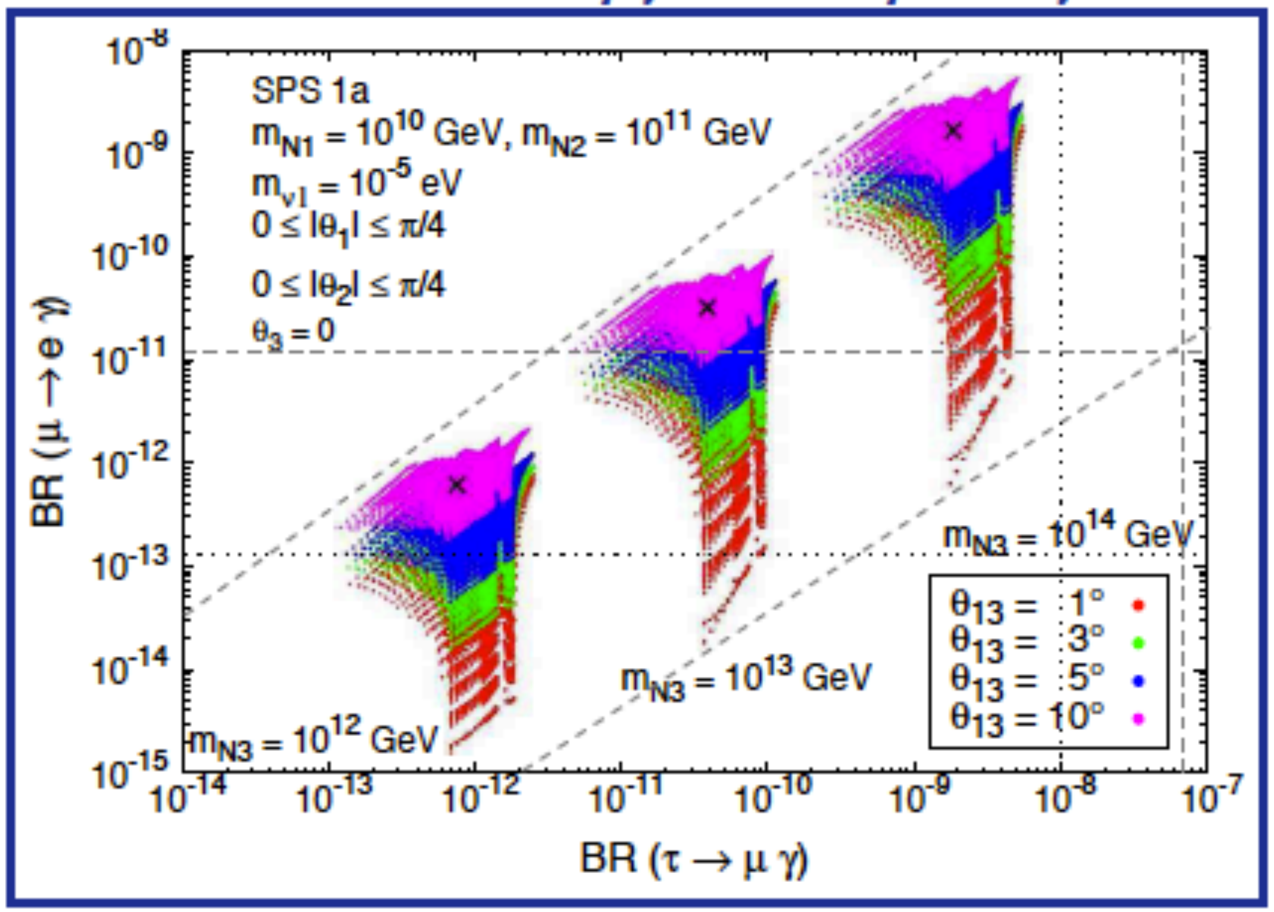


Search for $\tau \to \ell\gamma/\pi^0/\eta/\eta'$, $\tau \to \ell\ell\ell$, $\tau \to \ell h h'$ $(\ell = e, \mu; h = \pi, K)$

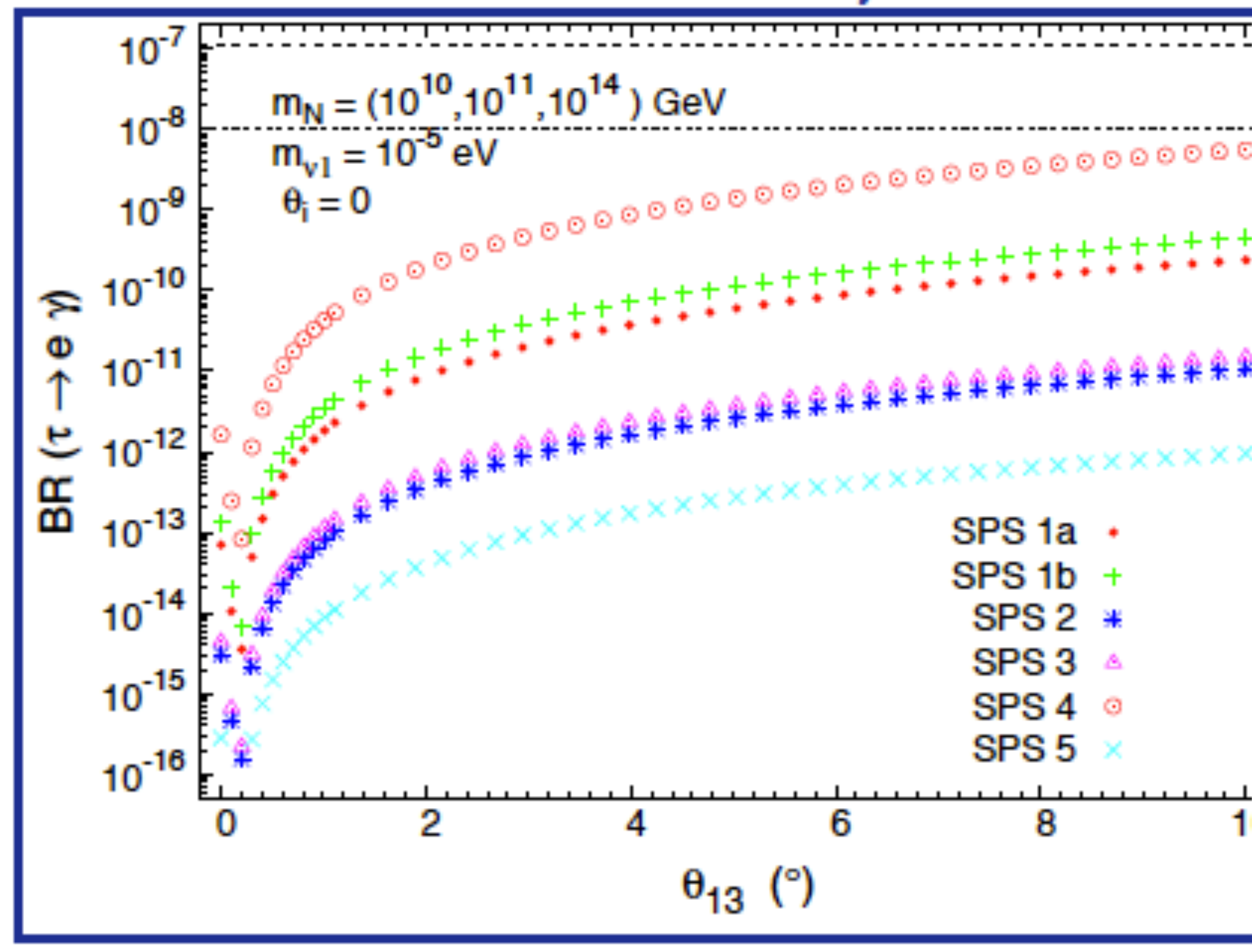
LFV Expectations in Tau Decays

Specially interesting in view of recent MEG results (ICHEP10)

CMSSM BF($\tau \to \mu\gamma$) vs. BF($\mu \to e\gamma$)



CMSSM BF($\tau \to e\gamma$)



N_i = right-handed neutrinos

ν_i = left-handed neutrinos

θ_i = N complex mixing angles

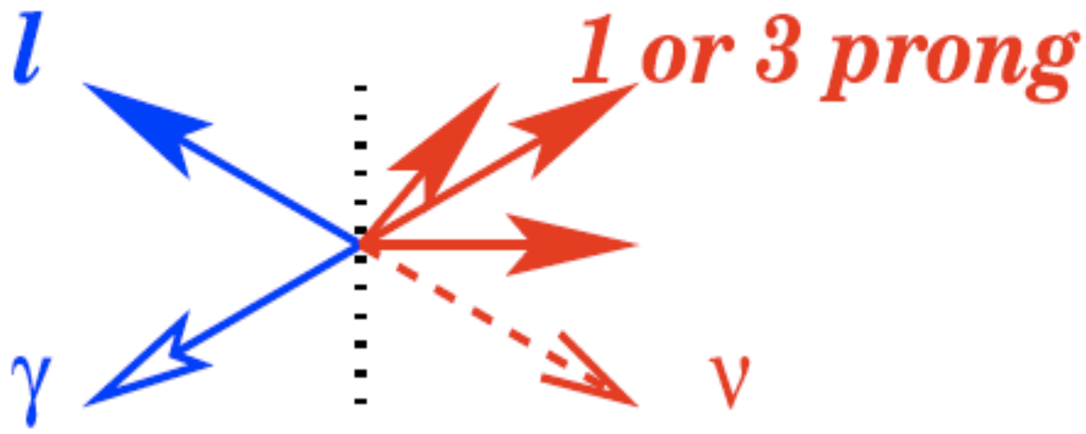
θ_{13} refers to PNMS mixing matrix

other info on JHEP11(2006)090

- tau LFV decays up to present limits for some SPS points
- $\tau \to \mu\gamma$ complementary to θ_{13}-sensitive $\mu \to e\gamma$

$e^+e^- \to \tau^+\tau^-$: Clean Environment

$\tau \to \ell\gamma$

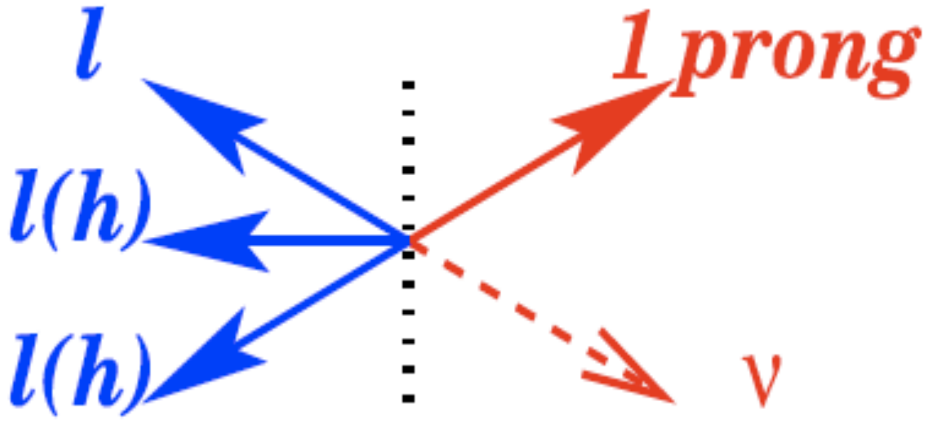


Signal–Side **Tag–Side**

Backgrounds:

- $\tau \to e\gamma\ (\tau \to \mu\gamma)$:
  - Radiative Bhabha (di-muon)
  - $\tau^+\tau^-\gamma(\tau \to \ell\nu\overline{\nu})$
  - $q\overline{q}\ (\gamma)$

$\tau \to \ell\ell\ell\ (\tau \to \ell h h')$



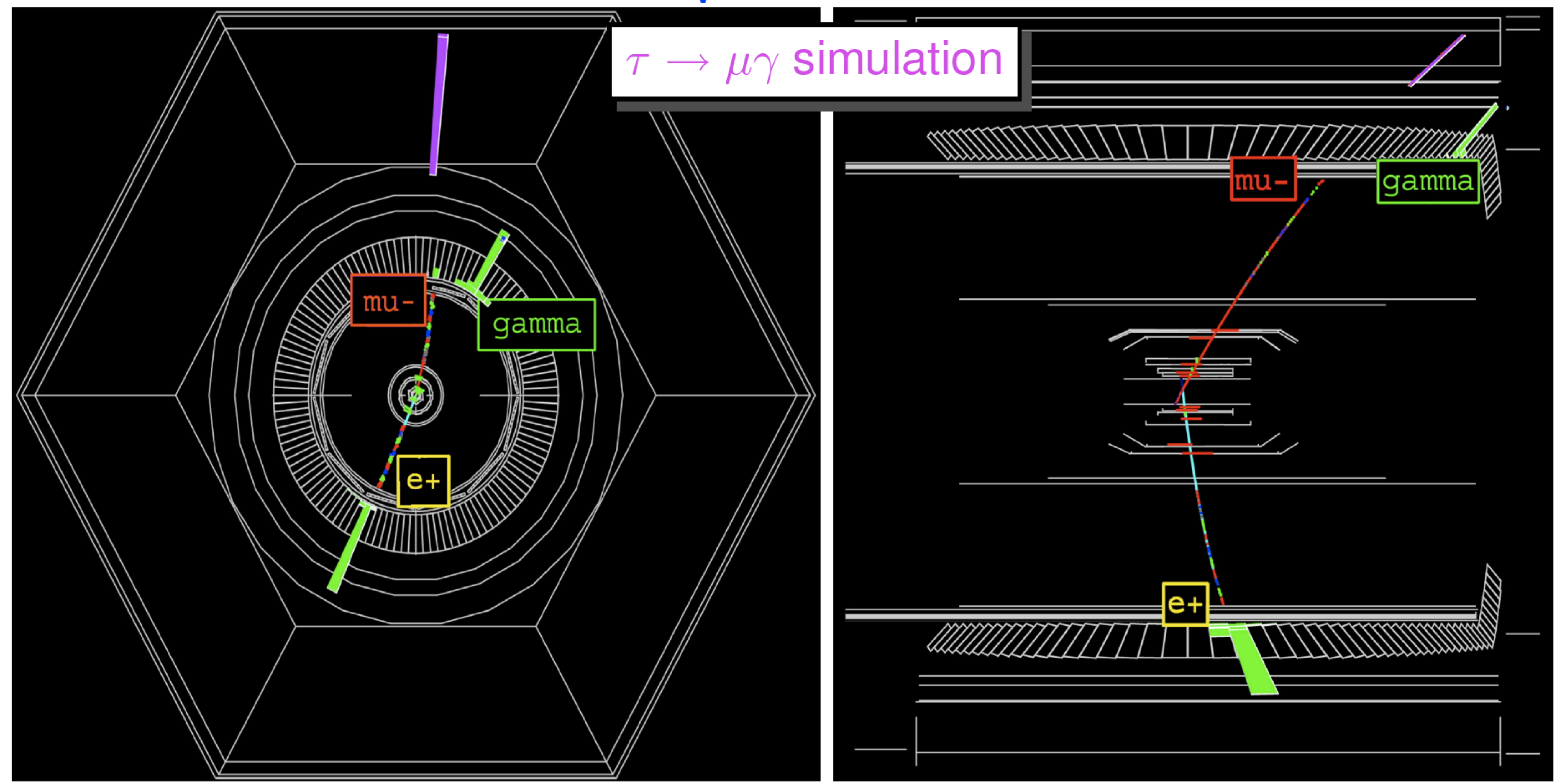
Signal–Side **Tag–Side**

Backgrounds:

- $\tau^- \to \ell'^-\ell^+\ell^-$:
  - Bhabha, di-muon
- $\tau^- \to \ell^+\ell'^-\ell'^-,\ \tau \to \ell h h'$:
  - $\tau^+\tau^-,\ q\overline{q}$

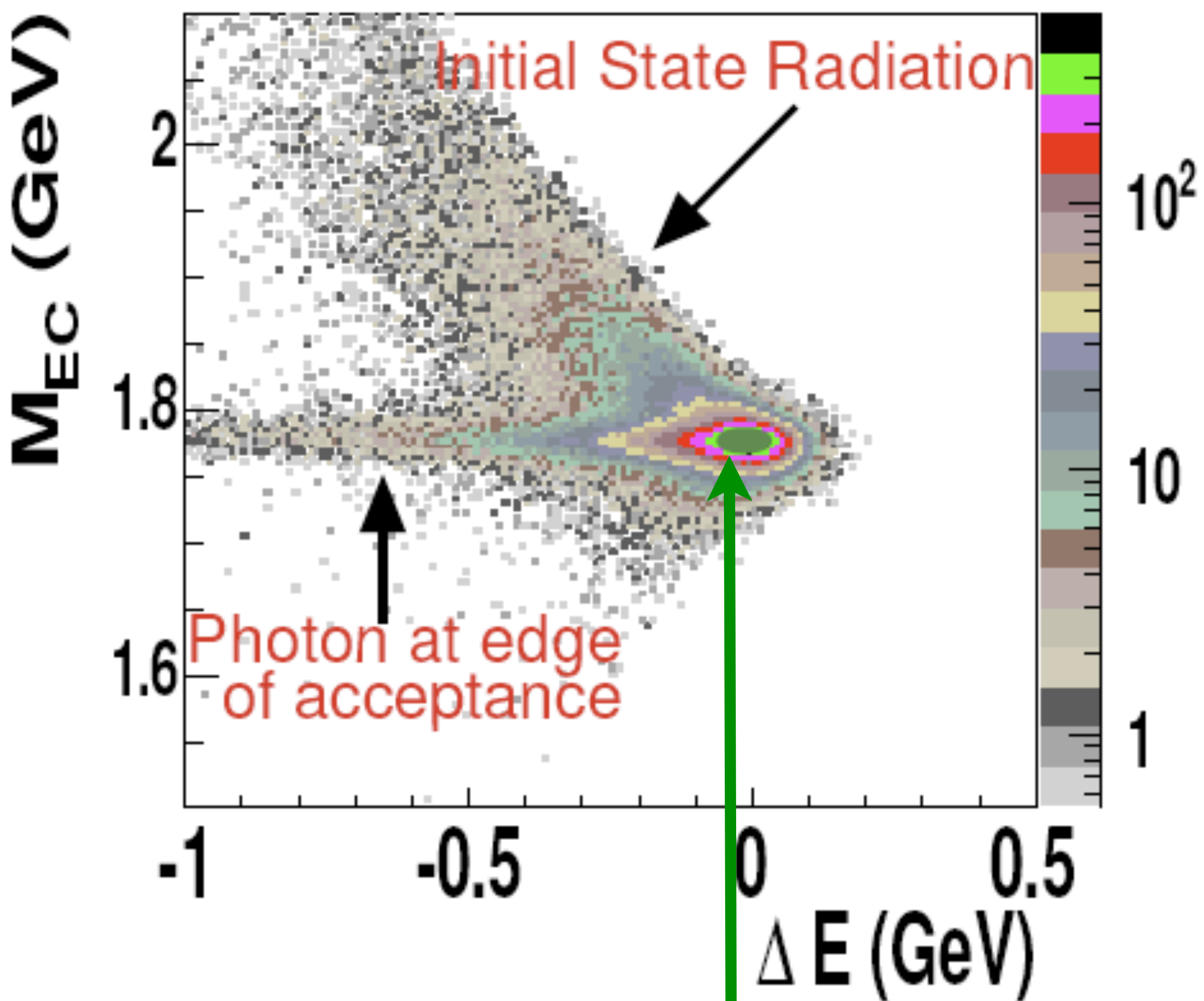
$\tau^- \to \mu^- \gamma$: Signal Characteristics

- $m_{\mu\gamma} \sim m_\tau$
- CM Frame: $\Delta E = \sqrt{P_\mu^2 + m_\mu^2} + E_\gamma - \sqrt{s}/2 \sim 0$



$\tau^- \to \mu^- \gamma$: Signal Characteristics

- (Energy, Mass)$_{\text{daughters}} \sim (\frac{\sqrt{s}}{2}, m_\tau)$ (upto resolution & radiation)



$\tau \to \mu\gamma$ simulation

$\Delta E = E_{rec} - \frac{\sqrt{s}}{2} \sim 0$

$\sigma(\Delta E) \sim 42\,\text{MeV}$

M_{EC} ($\sigma \sim 8.3$MeV)

Beam energy constrained mass after vertexing

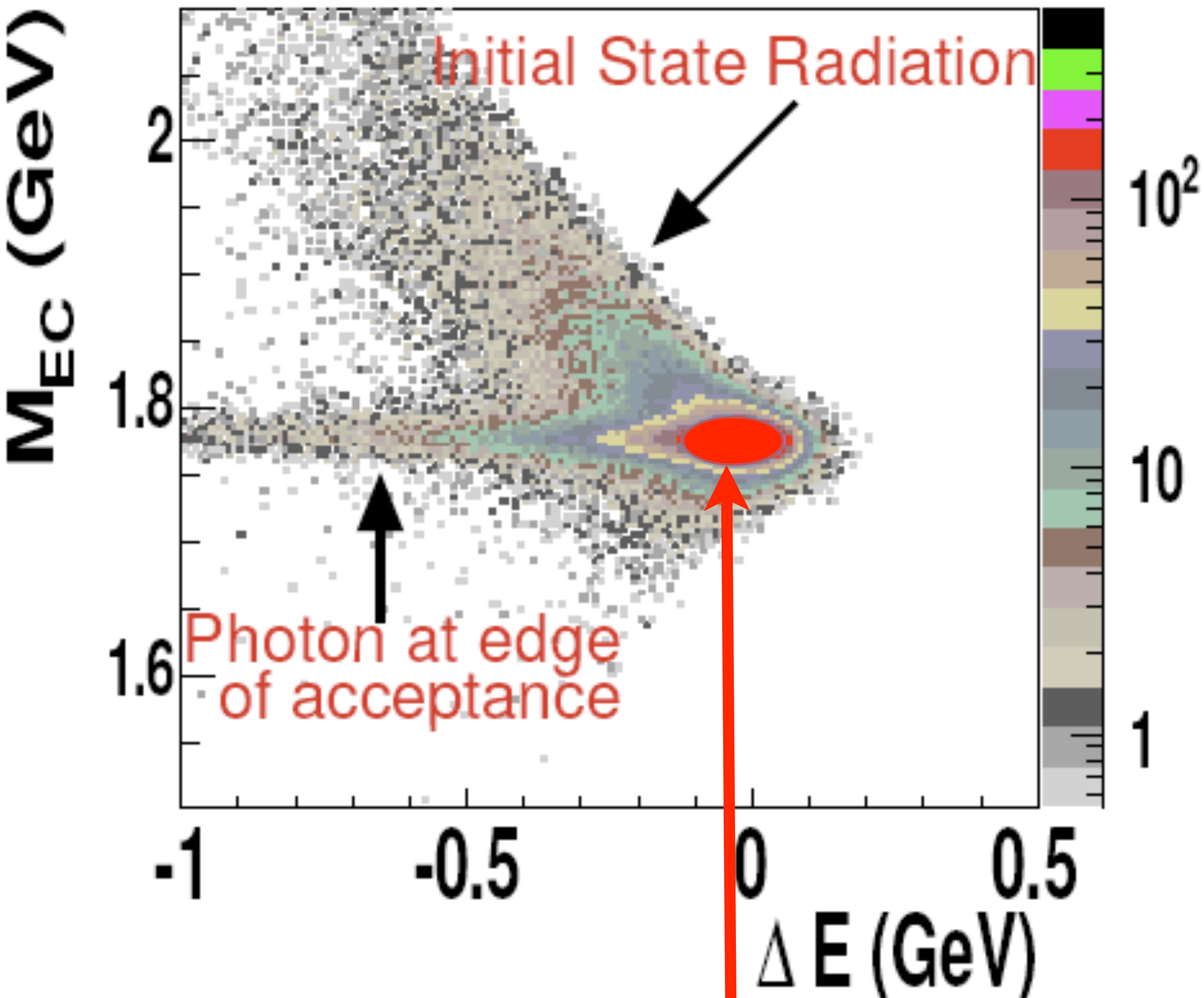
γ at μ POCA(XY)

[Inv. mass: $\sigma \sim 18\,\text{MeV}$]

☞ Signal Region: $\pm$ 2 σ around $(\langle\Delta E\rangle, \langle M_{EC}\rangle)$

$\tau^- \to \mu^- \gamma$: Signal Characteristics

- (Energy, Mass)$_{\text{daughters}} \sim (\frac{\sqrt{s}}{2}, m_\tau)$ (upto resolution & radiation)



$\tau \to \mu\gamma$ simulation

$\Delta E = E_{rec} - \frac{\sqrt{s}}{2} \sim 0$

$\sigma(\Delta E) \sim 42\,\text{MeV}$

M_{EC} ($\sigma \sim 8.3$MeV)

Beam energy constrained mass after vertexing

γ at μ $_{\text{POCA(XY)}}$

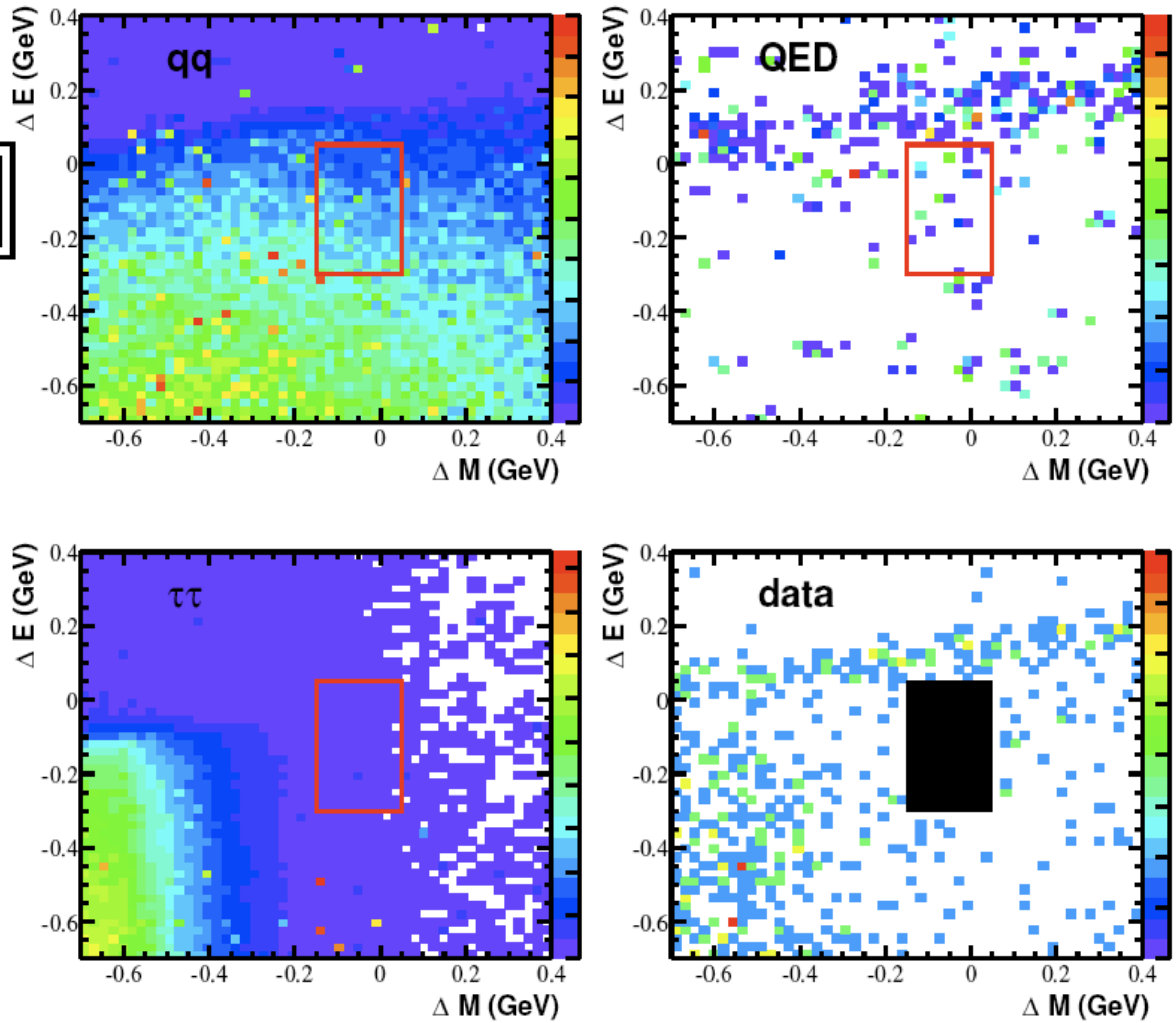
[Inv. mass: $\sigma \sim 18\,\text{MeV}$]

☛ Blinded Region: $\pm$ 3 σ around $(\langle\Delta E\rangle, \langle M_{EC}\rangle)$

Typical Background Distributions

$q\bar{q}$: uniform

QED: $\Delta E \approx 0$



$\tau^+\tau^-$:
$\Delta M \ll 0$
$\Delta E \ll 0$

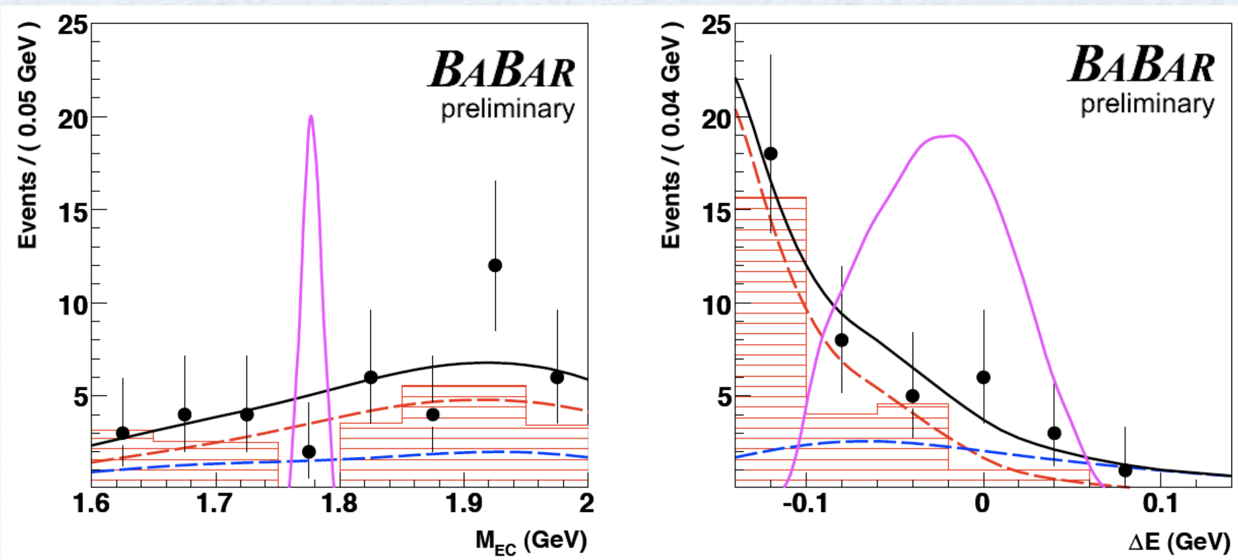
$\tau \to \ell\ell\ell$:
after PID &
Preselection

2-dim PDF's: shape from MC/control sample, rate fitted to Data

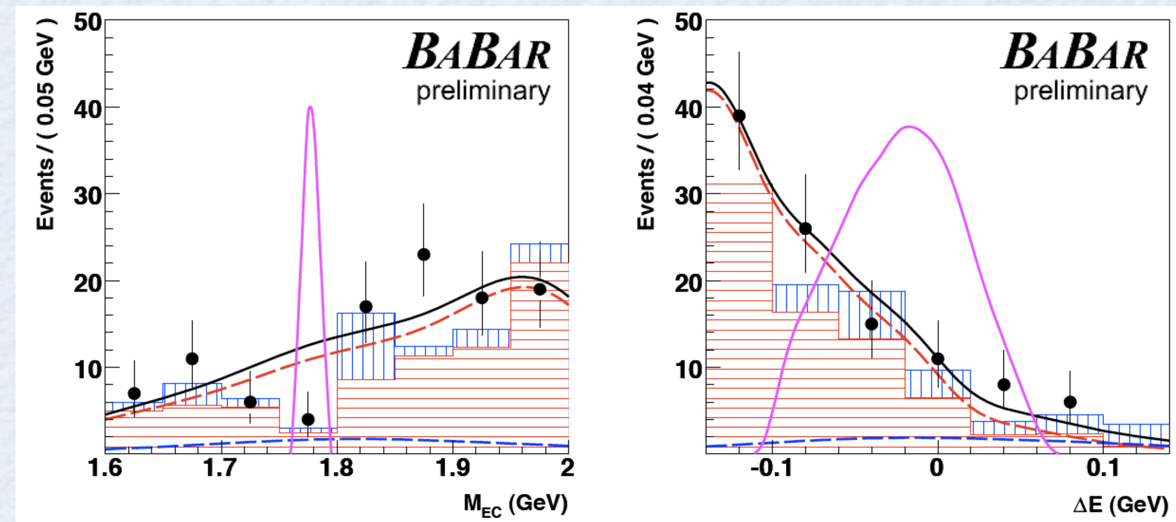
2-dim Fit with Background PDFs only

$$PDF_{tot} = (f_{e^+e^-/\mu^+\mu^-} \times PDF_{e^+e^-/\mu^+\mu^-}) + ([1 - f_{e^+e^-/\mu^+\mu^-}] \times PDF_{\tau})$$

$\tau^{\pm} \to e^{\pm}\gamma$:



$\tau^{\pm} \to \mu^{\pm}\gamma$:



The number of background events ($N_{2\sigma}^{data}$) inside the $\pm 2\sigma$ ellipse is estimated as:

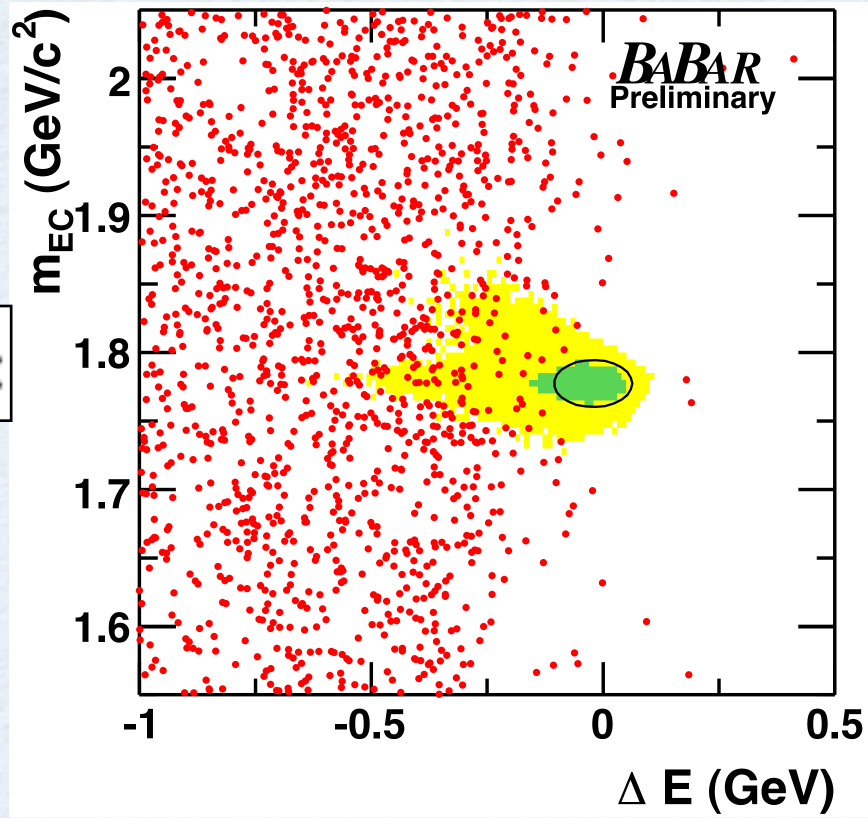
$$N_{2\sigma}^{data} = \frac{\int_{2\sigma} PDF_{tot}}{\int_{FitBox-3\sigma} PDF_{tot}} \times N_{FitBox-3\sigma}^{data}$$

Cross-check neighbouring ellipses shifted in the mass variable:

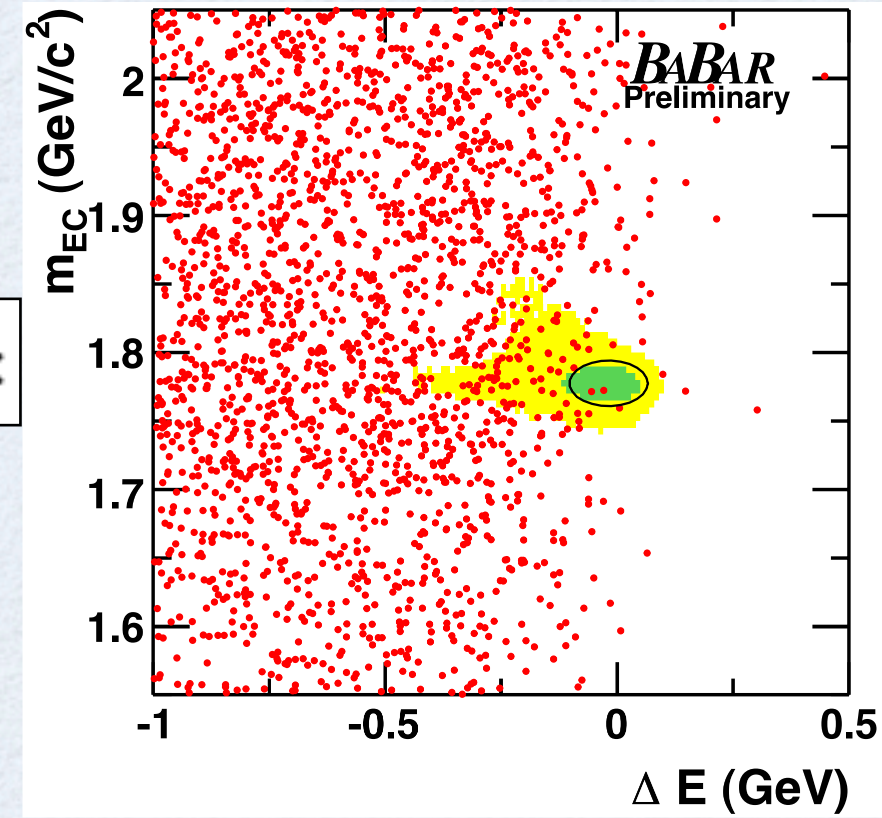
Decay modes	# of events	-9σ	$-5\ \sigma$	0	$+5\ \sigma$	$+9\ \sigma$
$\tau^{\pm} \to e^{\pm}\gamma$	Observed	2	1	?	2	2
	Expected	1.2±0.2	1.4±0.2	1.6±0.3	1.9 ±0.3	2.1±0.3
$\tau^{\pm} \to \mu^{\pm}\gamma$	Observed	3	1	?	4	6
	Expected	2.8±0.3	3.1±0.3	3.6±0.4	4.2±0.4	4.8±0.5

$\tau^- \to e^-/\mu^- \gamma$: Unblinded results

$\tau^\pm \to e^\pm\gamma$:



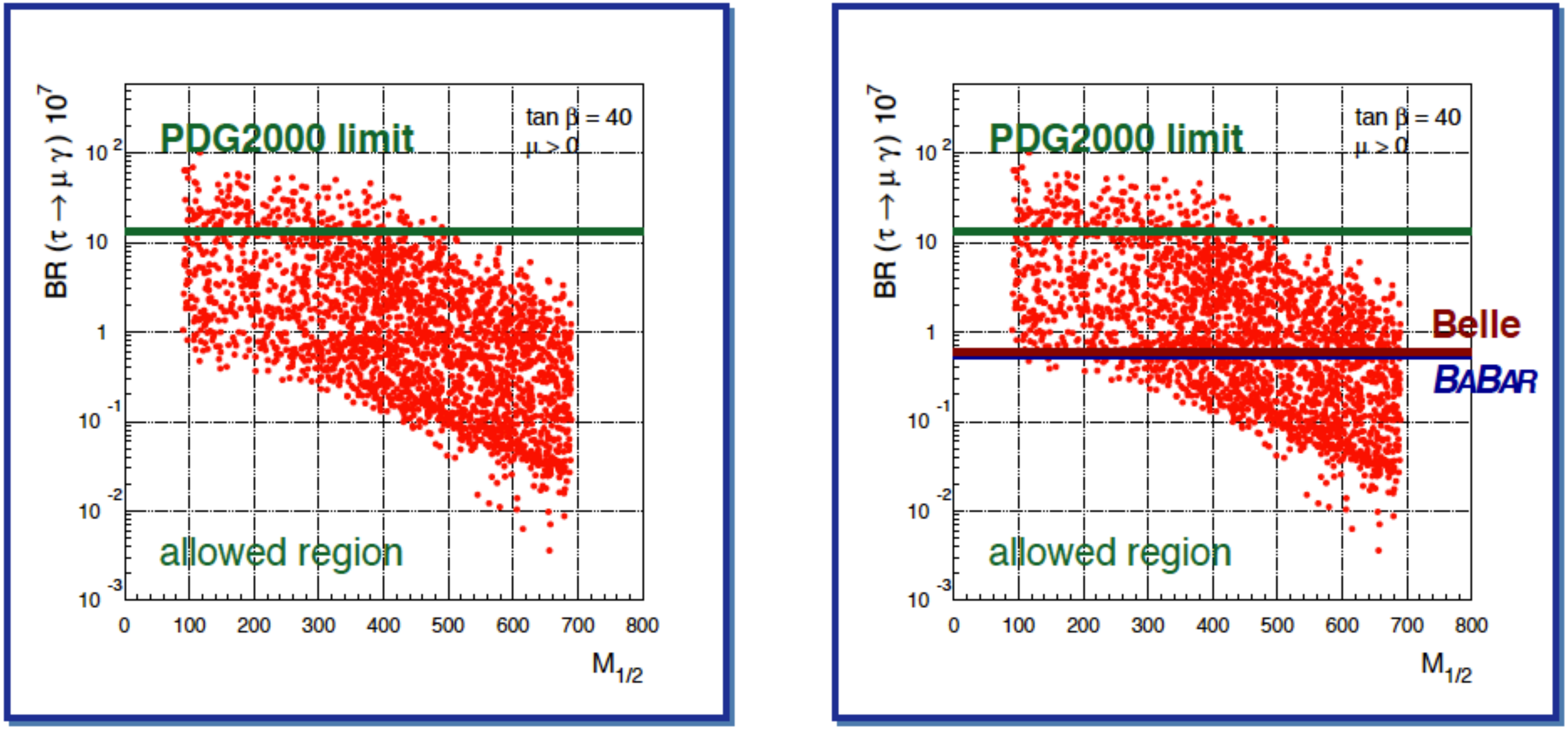
$\tau^\pm \to \mu^\pm\gamma$:



N_τ	$(963 \pm 7) \times 10^6$
$\tau^\pm \to e^\pm\gamma$ search	
Number of background events expected in 2σ signal ellipse	(1.6 ± 0.4)
Efficiency in 2σ signal ellipse	$(3.9 \pm 0.3)\%$
Expected Feldman & Cousins Upper Limit (w/o systmatics)	$\mathcal{B}(\tau^\pm \to e^\pm\gamma) < 9.8 \times 10^{-8}$ at 90% CL
Expected Feldman & Cousins Upper Limit (with systmatics)	$\mathcal{B}(\tau^\pm \to e^\pm\gamma) < 9.8 \times 10^{-8}$ at 90% CL
Numbers of events observed in 2σ signal ellipse	0
Observed Feldman & Cousins Upper Limit	$\mathcal{B}(\tau^\pm \to e^\pm\gamma) < 3.3 \times 10^{-8}$ at 90% CL
$\tau^\pm \to \mu^\pm\gamma$ search	
Number of background events expected in 2σ signal ellipse	(3.6 ± 0.7)
Efficiency in 2σ signal ellipse	$(6.1 \pm 0.5)\%$
Expected Feldman & Cousins Upper Limit (w/o systmatics)	$\mathcal{B}(\tau^\pm \to \mu^\pm\gamma) < 7.9 \times 10^{-8}$ at 90% CL
Expected Feldman & Cousins Upper Limit (with systmatics)	$\mathcal{B}(\tau^\pm \to \mu^\pm\gamma) < 8.2 \times 10^{-8}$ at 90% CL
Numbers of events observed in 2σ signal ellipse	2
Observed Feldman & Cousins Upper Limit	$\mathcal{B}(\tau^\pm \to \mu^\pm\gamma) < 4.4 \times 10^{-8}$ at 90% CL

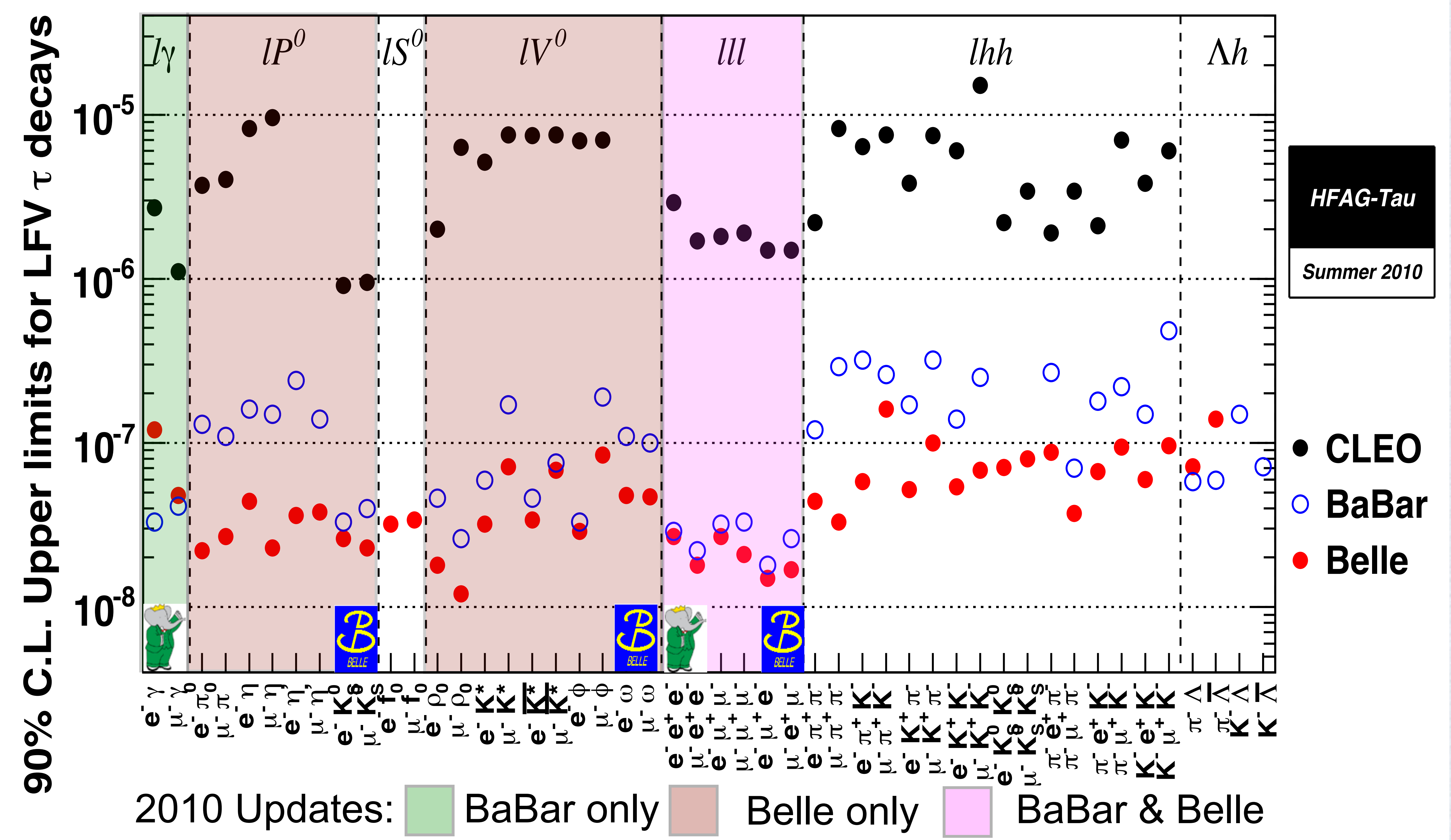
PRL 104, 021802 (2010)

Evolution of $\tau^- \to \mu^- \gamma$ limits



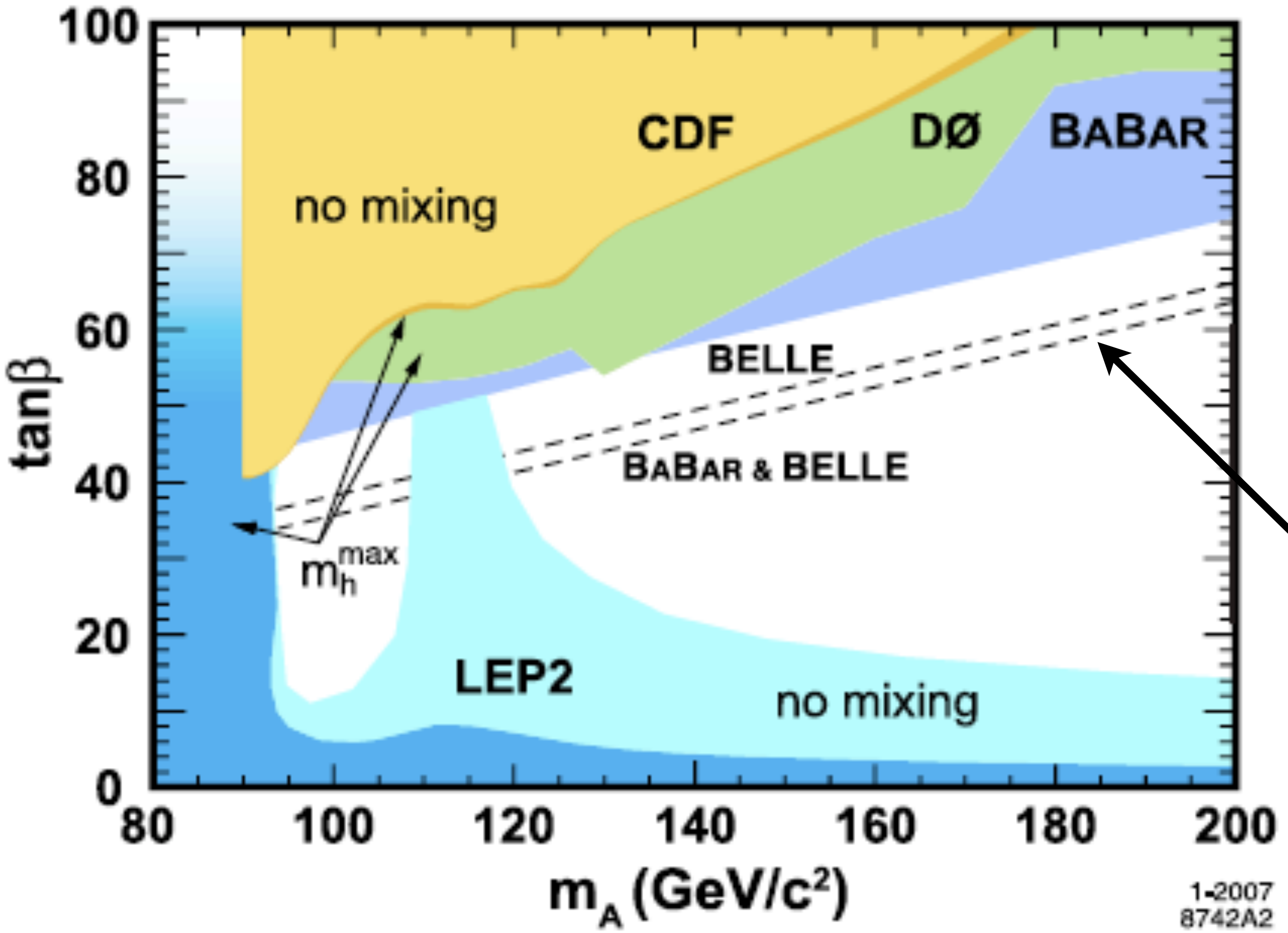
SUSY SO(10) + seesaw – Masiero et al., NJP 6 (2004) 202

Status of LFV Searches at B-Factories



Indirect Search for Charged CP-odd Higgs

- Mixing between left-handed smuons and staus with $m_{\nu_R} = 10^{14}$ GeV via seesaw $\Rightarrow \tau^\pm \to \mu^\pm \eta$ limit translates into exclusion plot in $\tan\beta$ vs. m_A plane (M.Sher, PRD66 (2002) 057301)



Light and dark shade: $m_h^{\max}$ and no-mixing stop mixing benchmark models (M. Carena et.al, hep-ph/9912223)

Combination of BaBar& Belle LFV Limits
S. Banerjee (Tau06)
Nucl. Phys. Proc. Suppl. 169, 199 (2007)

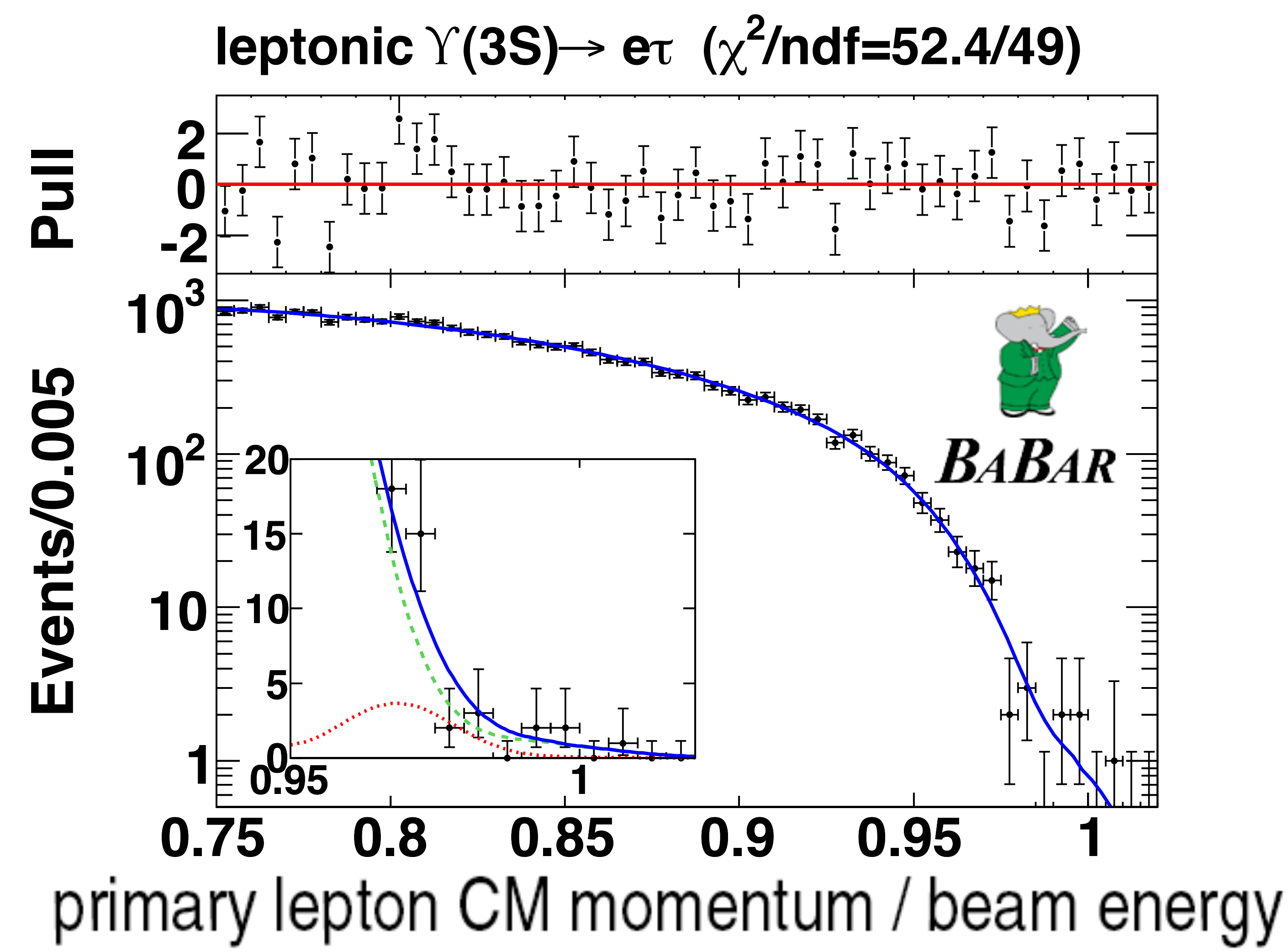
- 95% C.L. from BABAR-BELLE competitive with direct searches at CDF: Higgs $\to \tau^+\tau^-$ (310 pb^{-1}), D0: Higgs $\to b\bar{b}$ (260 pb^{-1}), $\tau^+\tau^-$ (325 pb^{-1}); complementary to region excluded by LEP2

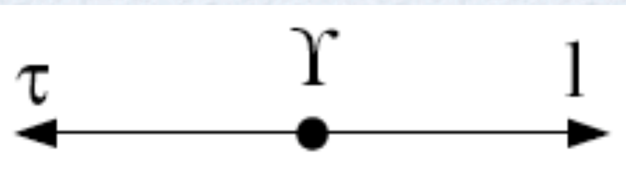
LFV in $\Upsilon(nS) \to l\tau$ ($l=e,\mu$) decays

Process	τ Decay	Channel
$\Upsilon(3S) \to e\tau$	$\tau \to \mu\nu\nu$	leptonic $e\tau$
$\Upsilon(3S) \to e\tau$	$\tau \to \pi^{\pm}\pi^{0}\nu / \pi^{\pm}\pi^{0}\pi^{0}\nu$	hadronic $e\tau$
$\Upsilon(3S) \to \mu\tau$	$\tau \to e\nu\nu$	leptonic $\mu\tau$
$\Upsilon(3S) \to \mu\tau$	$\tau \to \pi^{\pm}\pi^{0}\nu / \pi^{\pm}\pi^{0}\pi^{0}\nu$	hadronic $\mu\tau$

BaBar, PRL 104, 151802 (2010)

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

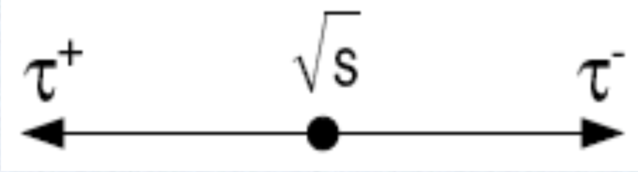


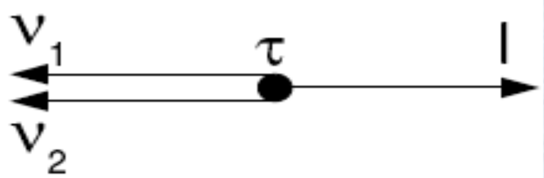


$$E_l = (m_\Upsilon^2 - m_\tau^2 + m_l^2)/(2m_\Upsilon)$$

$$p_l/E_B = \sqrt{4(E_l^2 - m_l^2)/m_\Upsilon^2}$$

Signal: peak ~ 0.97



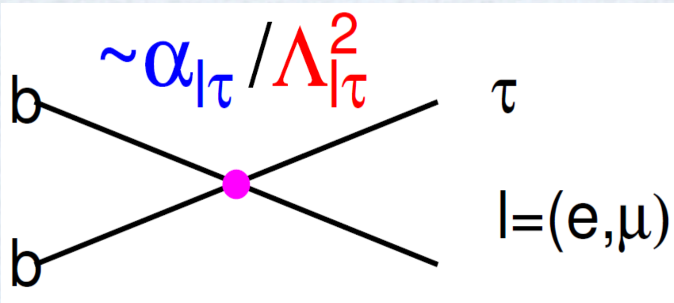


Bhabha/Mu-pair Background: peak ~ 1.0

Tau-pair Background: Kinematic cut-off ~ 0.97

Limits on Contact Interaction

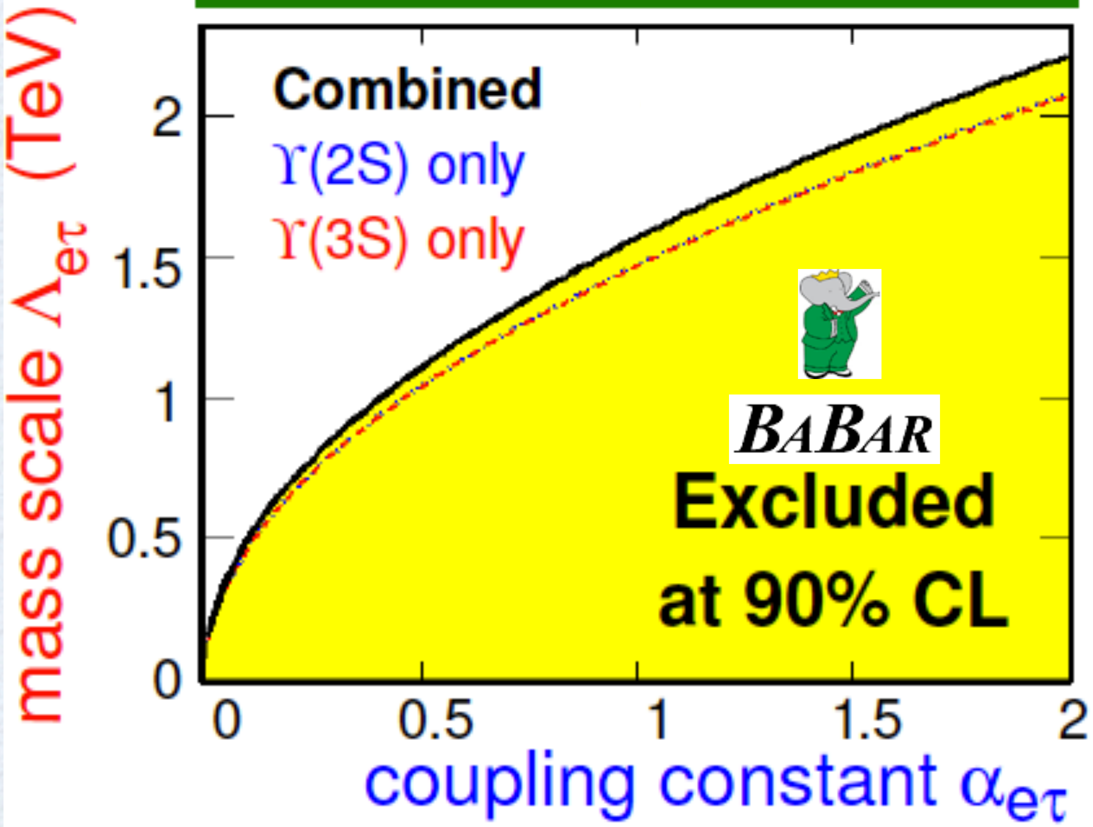
Constraints on *coupling constant* and *mass scale*:



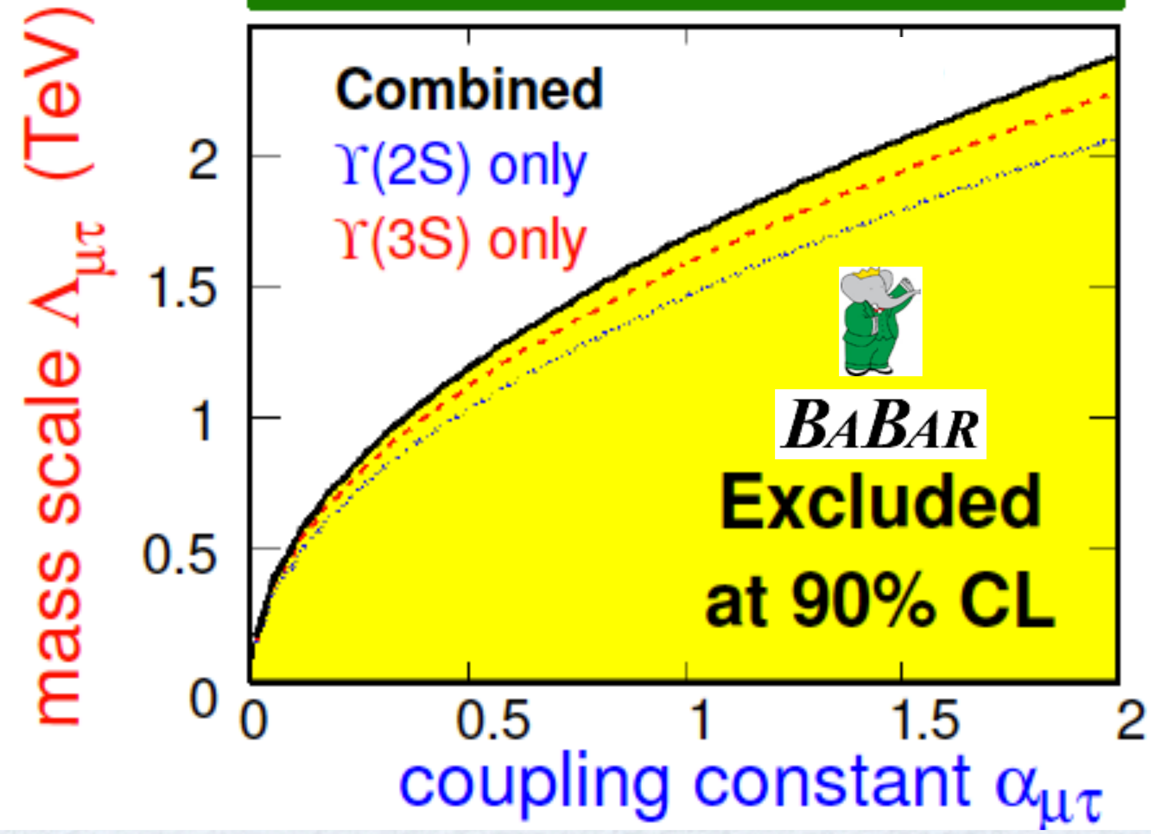
$$\frac{\alpha_{l\tau}^2}{\Lambda_{l\tau}^4} = \frac{BF(\Upsilon(3S)\to l\tau)}{BF(\Upsilon(3S)\to ll)} \frac{2q_b\alpha^2}{(M_{\Upsilon(nS)})^4}$$

Silagadze Phys. Scripta 64.128 & Black et al. PRD 66.053002

$\alpha_{e\tau} = 1 \rightarrow \Lambda_{e\tau} > 1.6$ TeV



$\alpha_{\mu\tau} = 1 \rightarrow \Lambda_{\mu\tau} > 1.7$ TeV



Future Prospects

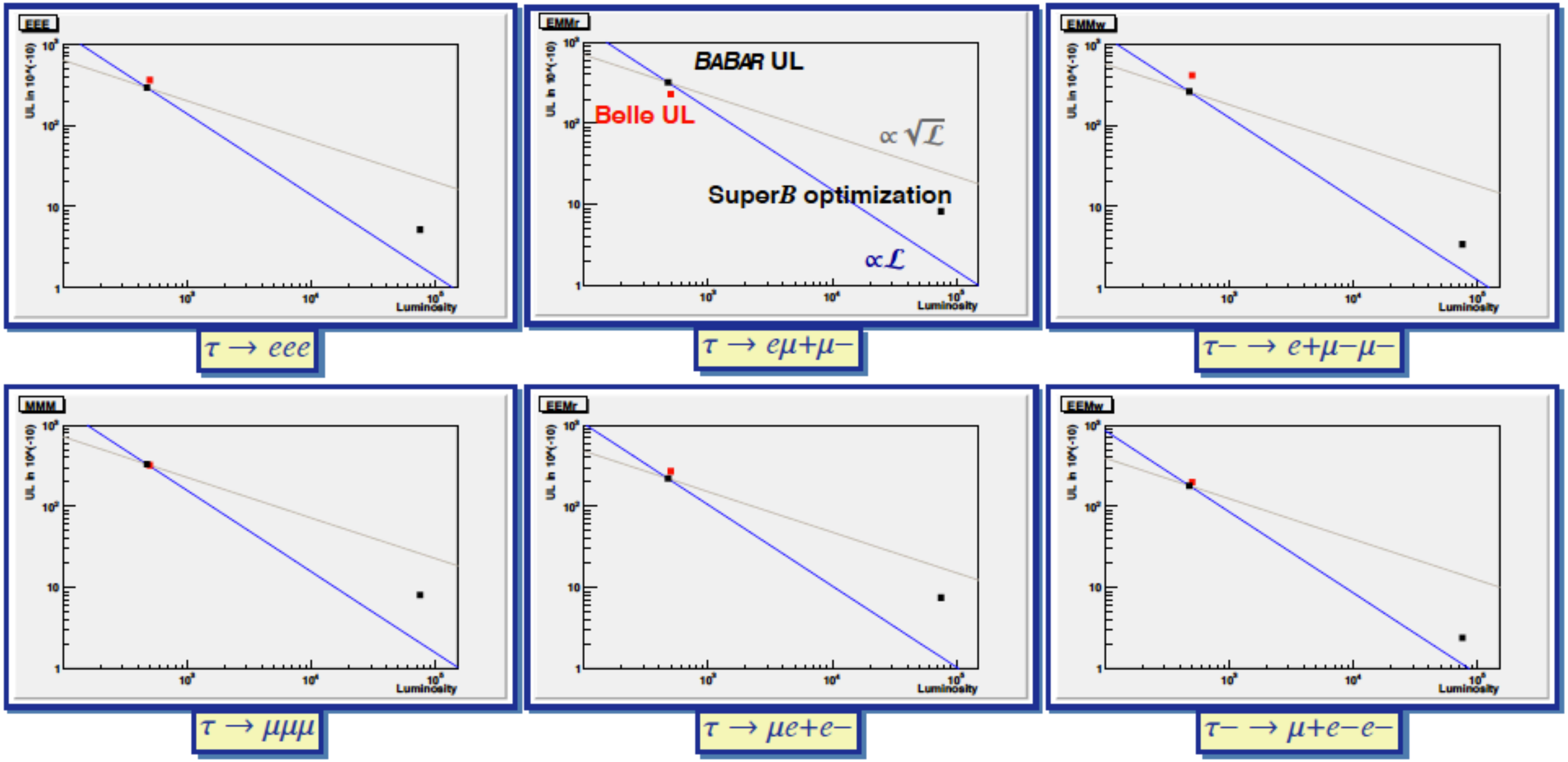
- Belle2 and Super*B* promise integrated luminosities in the range of 50–75 ab^{-1}
- Super*B* LFV reach studied in recent **2010 Super*B* Physics Report**, arXiv:1008.1541v1 [hep-ex]
- repeating B-factories analysis → LVF reach increases $\sqrt{\mathcal{L}_{SuperB}/\mathcal{L}_{BABAR}} \approx \sqrt{150} \approx 12$
  - improves with hermeticity, PID, tracking/neutrals efficiency
  - worsens with beam background
- if exp. bkg $\lesssim$1 events at constant signal efficiency → LVF reach increases $\mathcal{L}_{SuperB}/\mathcal{L}_{BABAR} \approx 150$

Super*B* LFV reach summary

Process	Expected 90% CL upper limit	3σ evidence reach
$BF(\tau \rightarrow \mu\gamma)$	$2.4 \cdot 10^{-9}$	$5.4 \cdot 10^{-9}$
$BF(\tau \rightarrow e\gamma)$	$3.0 \cdot 10^{-9}$	$6.8 \cdot 10^{-9}$
$BF(\tau \rightarrow \ell\ell\ell)$	$2.3–8.2 \cdot 10^{-10}$	$1.2–4.0 \cdot 10^{-9}$

Future Prospects

Super$B$ $\tau \to 3\ell$ 90% CM upper limit extrapolations: $\propto \mathcal{L}$ vs. $\propto \sqrt{\mathcal{L}}$ vs. re-optimization



Summary

Many interesting topics still waiting to be studied:

- The Mystery of |Vus| in τ decays
- Second Class Currents in $\tau^- \to \eta\pi^-\nu$ decays
- Search for CPV in $\tau^- \to K_S\pi^-\nu$ decays

B-Factories are more than precision machine: Discovery of New Physics hopeful...