# Tau physics

## Intensity Frontier Workshop

Argonne Nat. Lab., April 25-27, 2013

**Martín González-Alonso**

NPAC Theory Group

University of Wisconsin – Madison

# Tau physics: theory

**What Yuval said:** *"We would like to invite you to give a talk at the meeting. The idea of the talk will be to give an overview off tau physics, and we hope that you will put your personal interest into the talk and emphasis the things you feel are important."*

# Tau physics: theory

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**3 days before…**

**What I heard:** *Dear Martin, now you not only have to survive till April 26$^{th}$ without getting any sleep, but you also have to prepare an overview talk about tau physics…*

# Tau physics: theory

- Introduction;
- Lepton universality;
- Leptonic decays: Michel parameters;
- (Inclusive) Hadronic tau decays within the SM (and beyond!);
- LFV decays;
- CPV in tau decays;
- Lots of things left out:
  LNV in tau decays, tau physics in hadron colliders, tau g-2, tau EDM, …

Caveat:
very very personal
selections of topics!

# Introduction


Discovered in 1975 by M. Perl et al. at SLAC-LBL: **U particle**!

***"Evidence for, and properties of, the new charged heavy lepton"***
*(M. Perl @ XII Recontre de Moriond, 1977)*

1. INTRODUCTION

It is very likely that a mass 1.90 ± .10 GeV/$c^2$ charged heavy lepton has been found in $e^+e^-$ annihilation. This paper summarizes the evidence for the new lepton and then presents what we know so far about its properties. The summary of the evidence is very brief; the original papers must be consulted for details on the event selection criteria, on the elimination of conventional explanations, and for the background calculations.

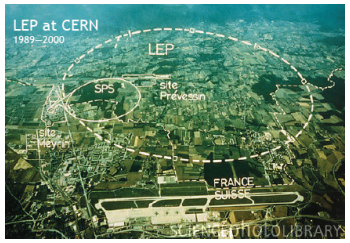
When we first found evidence for this new particle -- the $e\mu$ events in the data of the SLAC-LBL Magnetic Detector Collaboration[1] -- we called the particle U as a temporary name because its nature was unknown. Since there is now substantial evidence that it is a lepton, we wish to designate it by a lower case Greek letter. We use $\tau^{\pm}$ because it appears to be the third charged lepton to be found and τριτου means third in Greek. We feel the old use of τ to designate the three pion decay mode of the K is now obsolete.

# Introduction


Discovered in 1976 by M. Perl et al. at SLAC-LBL

- Mass: 1776.82(16) MeV (PDG2012)
- Lifetime: $2.096(10)\times10^{-13}$ s. (PDG2012)
- (Lots of) semileptonic decays!

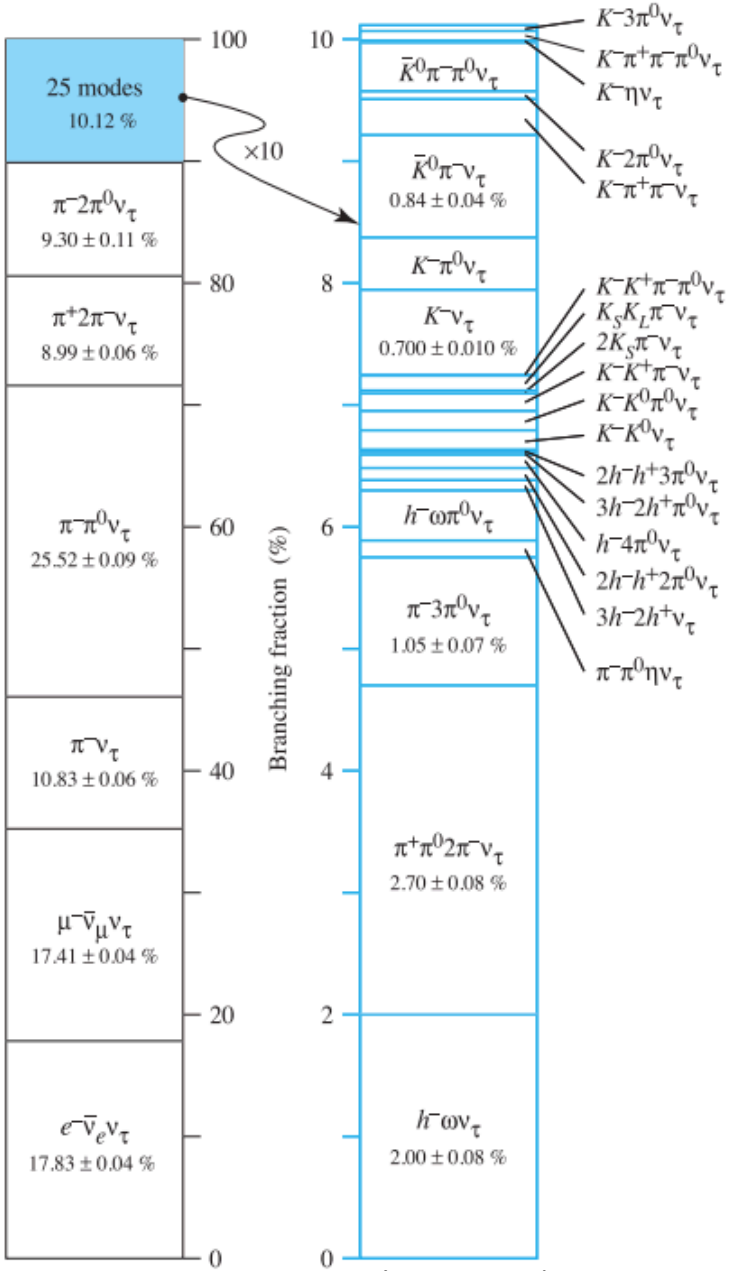
- Enormous progress in tau physics in since then! (CLEO, LEP, Babar, Belle, ...)
  - Early years: checking tau as a standard lepton;
  - Better data: det. of fundamental parameters & QCD studies;
  - Recently: tau = tool to search for NP (rare decays, final states in hadron colliders, ...)





| Experiment | Number of τ Pairs |
|---|---|
| LEP | $\sim3\times10^5$ |
| CLEO | $\sim1\times10^7$ |
| BaBar | $\sim5\times10^8$ |
| Belle | $\sim9\times10^8$ |

*Sw. Banerjee (TAU2010)*




*(PDG, 2012)*

# Outline

- Introduction; ✓
- Lepton universality;
- Leptonic decays: Michel parameters;
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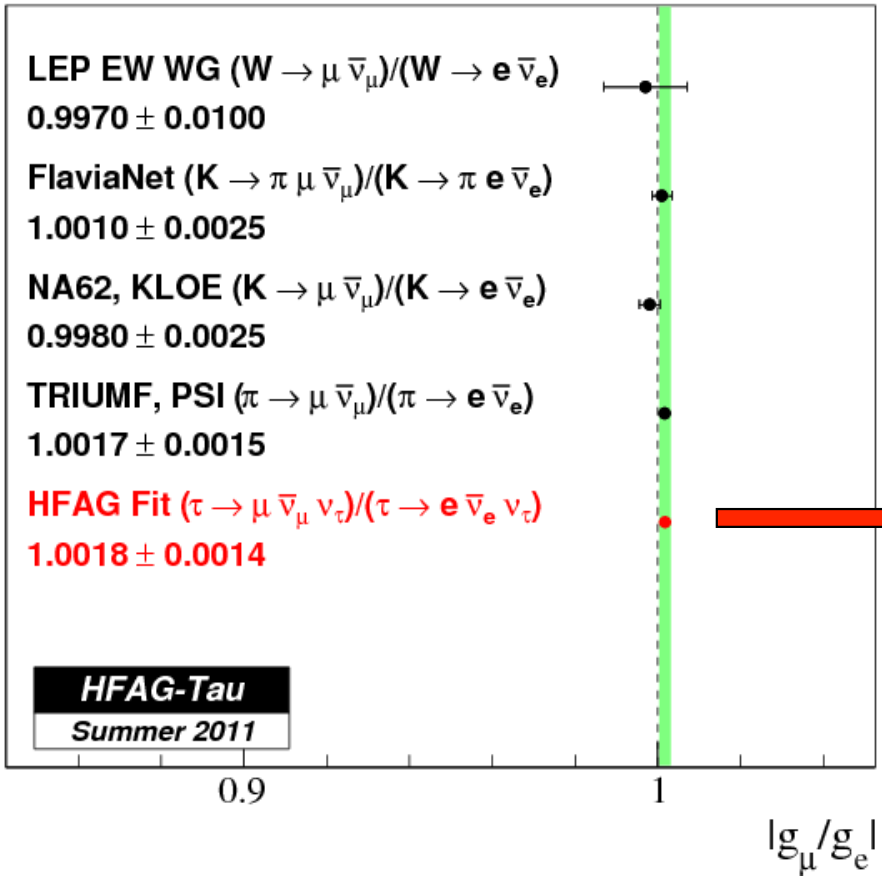
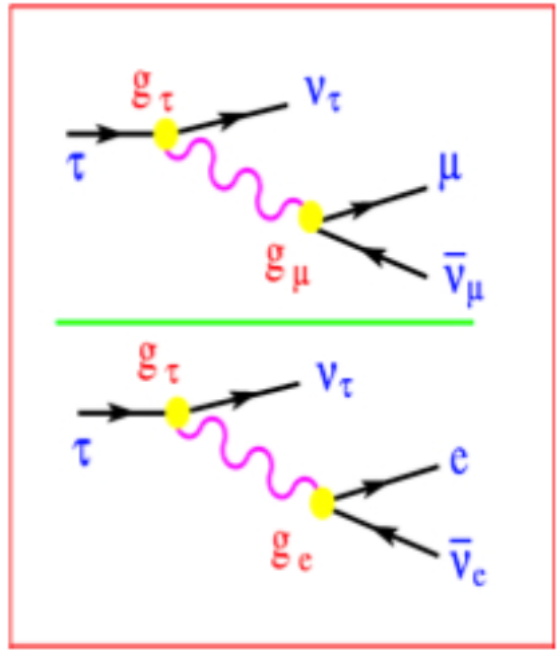
# Lepton universality

- E-mu universality tested at 0.14% from tau leptonic BRs (0.28% achieved in Z decays!)

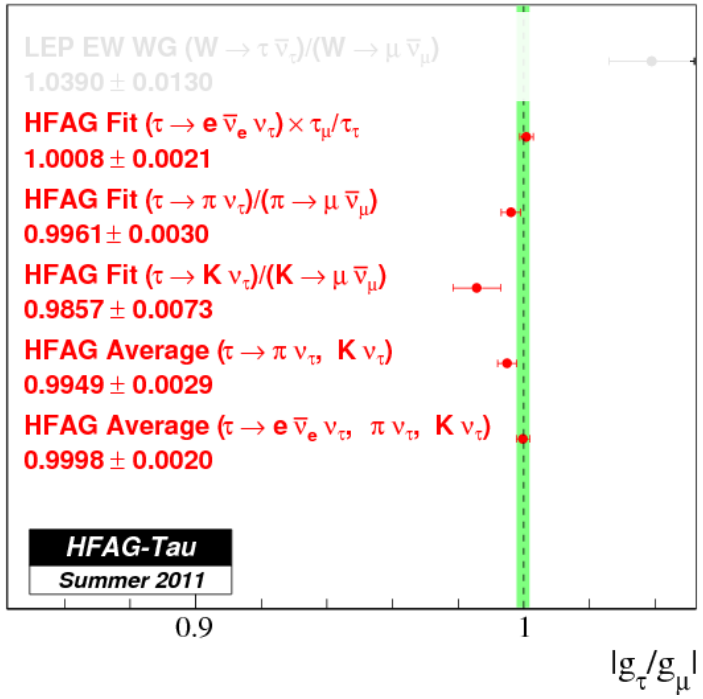


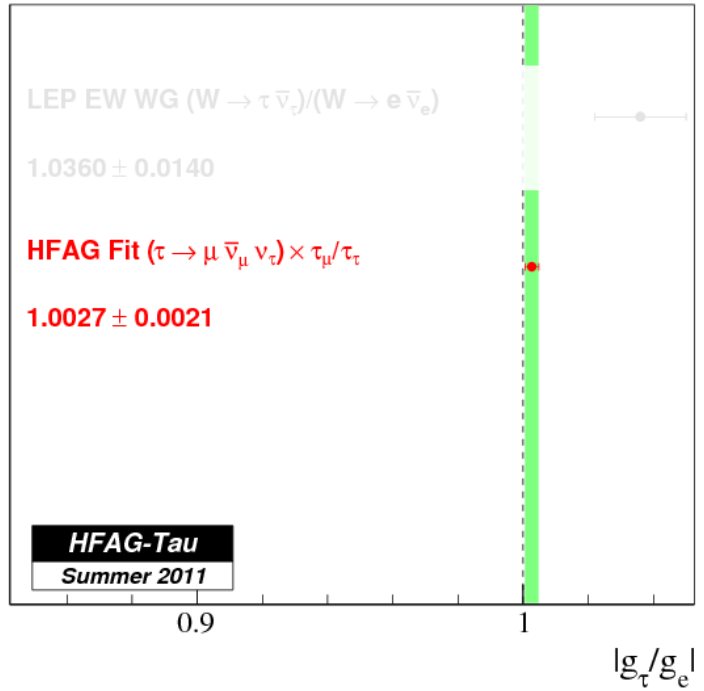



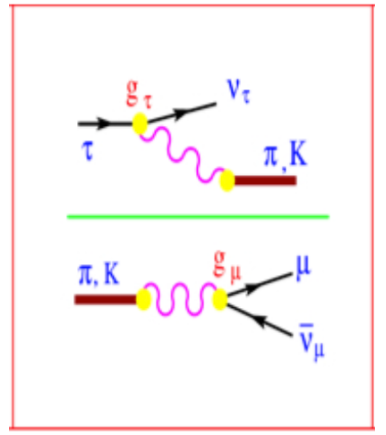

Banerjee (TAU2012)

# Lepton universality

- What about the third family?




Banerjee (TAU2012)

Summer: universality tested at the 0.1% level and good agreement…

… with too exceptions (~3 sigma level anomalies):

- Old one: W decay
- New one: B decay

$$R(D^{(*)}) = \frac{\Gamma\left(\overline{B} \to D^{(*)}\tau^-\overline{\nu}_\tau\right)}{\Gamma\left(\overline{B} \to D^{(*)}l^-\overline{\nu}_l\right)}$$

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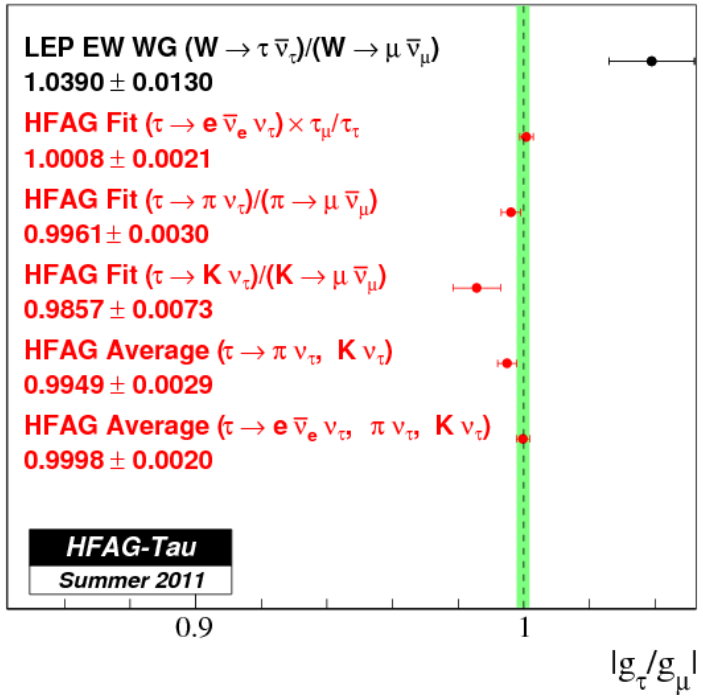


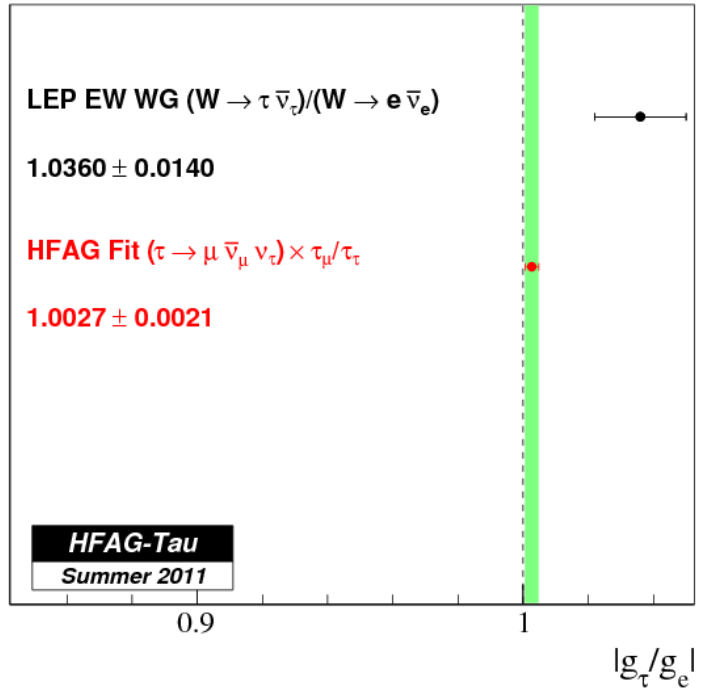


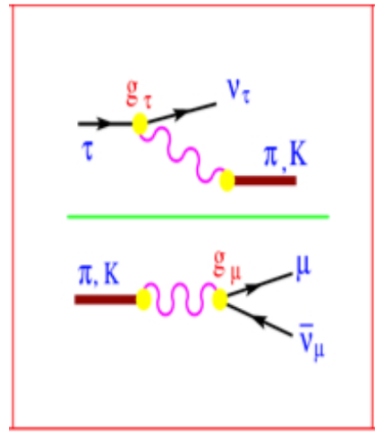


Banerjee (TAU2012)

Summary: universality tested at the 0.1% level and good agreement…
… with too exceptions (~3 sigma level anomalies):

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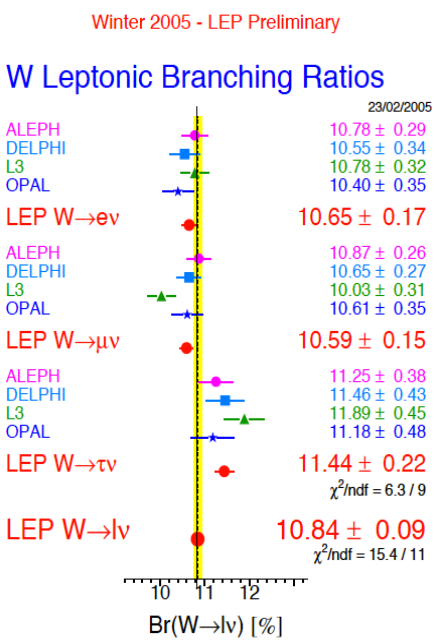
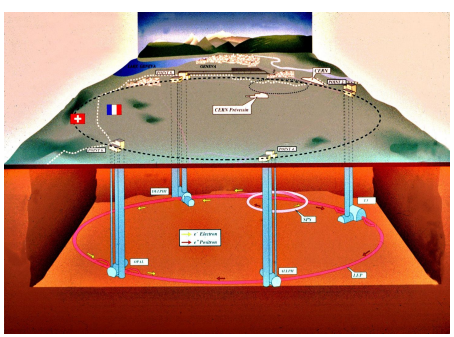
# Lepton universality: the LEP anomaly

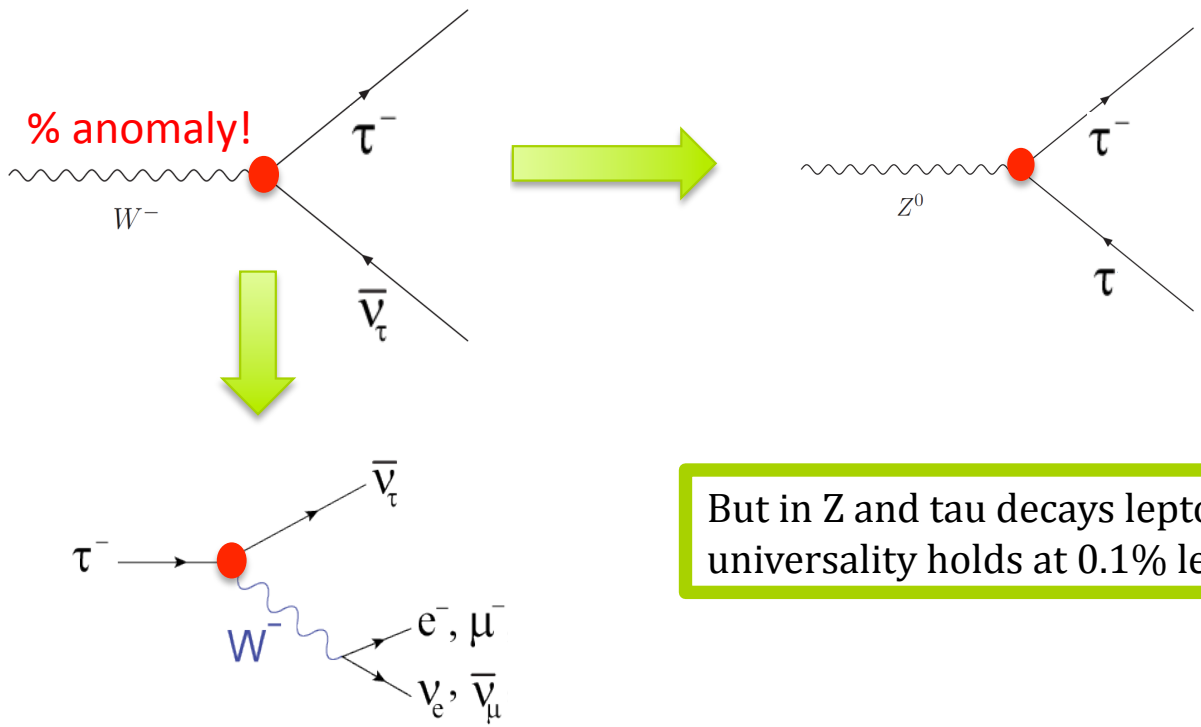
$$R^W_{\tau\ell} = \frac{2\,\mathrm{BR}\,(W \to \tau\,\overline{\nu}_\tau)}{\mathrm{BR}\,(W \to e\,\overline{\nu}_e) + \mathrm{BR}\,(W \to \mu\,\overline{\nu}_\mu)} = 1.077(26)$$

SM result: 0.999… **[2.8 σ]**



Why there aren't one thousand papers* in the arXiv explaining this anomaly?




But in Z and tau decays lepton universality holds at 0.1% level…

**Only 3…*
*Li & Ma, arXiv:hep-ph/0507017;*
*J.-h. Park, JHEP 0610 (2006) 077*
*R. Dermisek, arXiv:0807.2335*

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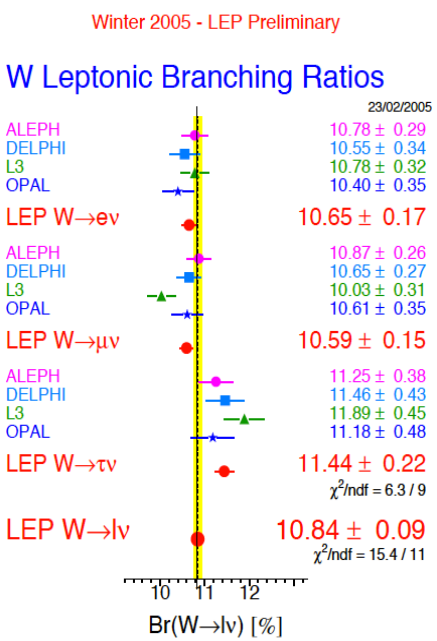


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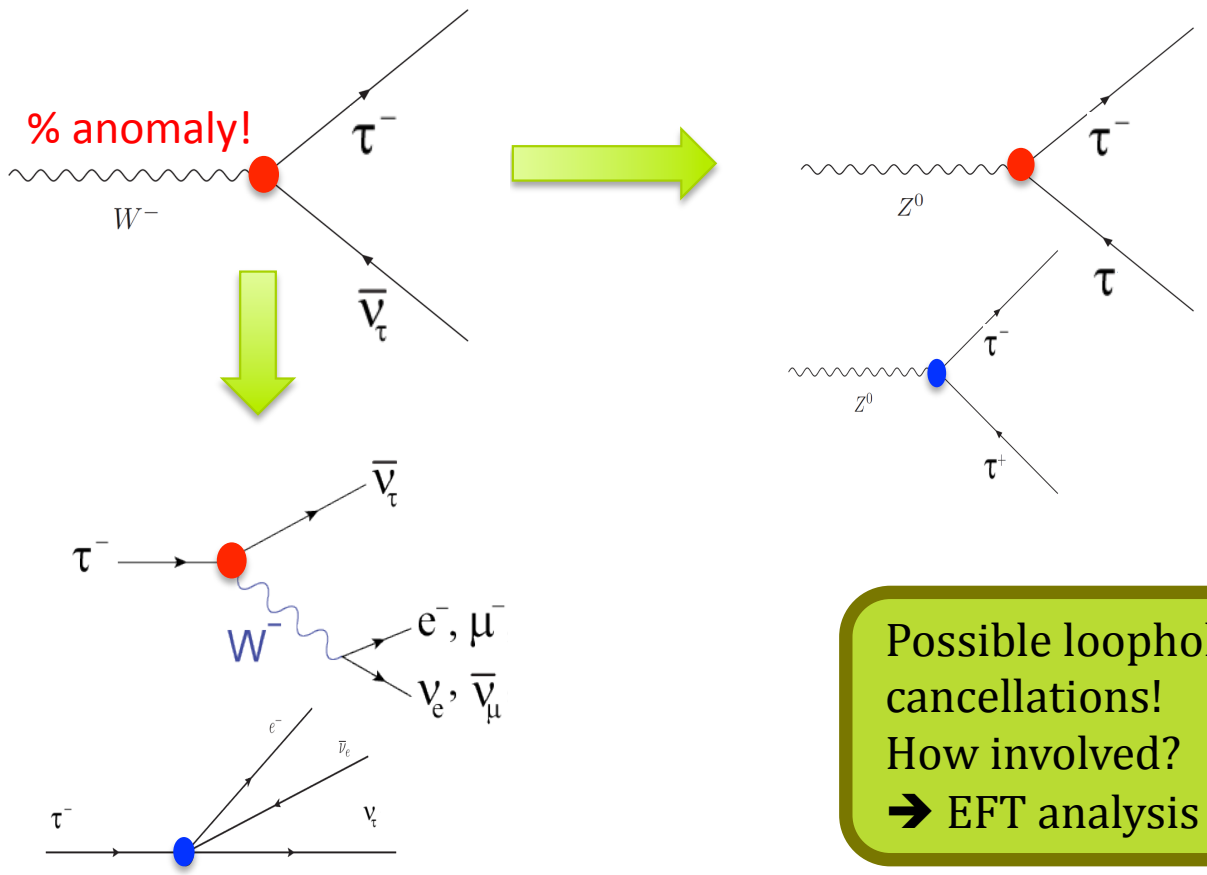
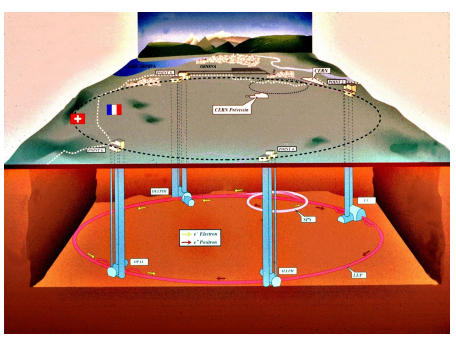


Possible loophole: cancellations! How involved?
➔ EFT analysis

# Lepton universality: the LEP anomaly

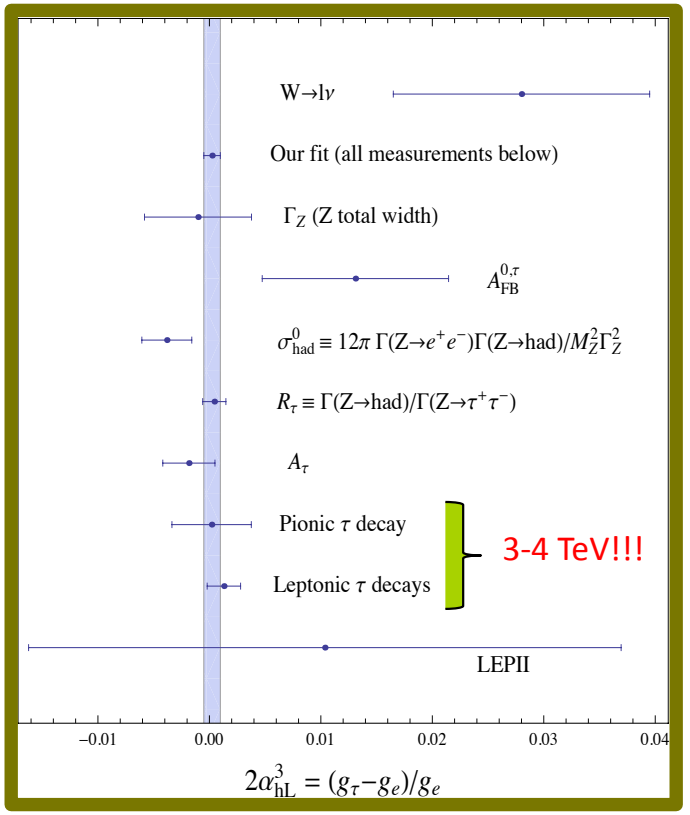
- EFT with [U(2)xU(1)]$^5$ flavor symmetry:

$$\mathcal{L}_{eff.} = \mathcal{L}_{SM} + \frac{1}{\Lambda^2}\sum \alpha_i \mathcal{O}_i \Rightarrow \Gamma\left(W \to \tau\,\overline{\nu}_\tau\right) = \frac{G_F\, M_W^3}{6\sqrt{2}\,\pi}\left(1 - w_\tau^2\right)^2 \left(1 + \frac{w_\tau^2}{2}\right)\left(1 + 4\alpha_{hL}^3\right)$$

*[Buchmüller & Wyler'86, Leung et al.'86]*

$$\left[O_{hL}^3 = i\left(h^\dagger D_\mu \tau^i h\right)\left(\overline{L}\,\gamma^\mu\,\tau^i\,L\right) + \text{h.c.}\right]$$

$$w_\tau = m_\tau / M_W$$




*(Filipuzzi, MGA & Portolés, 2012)*

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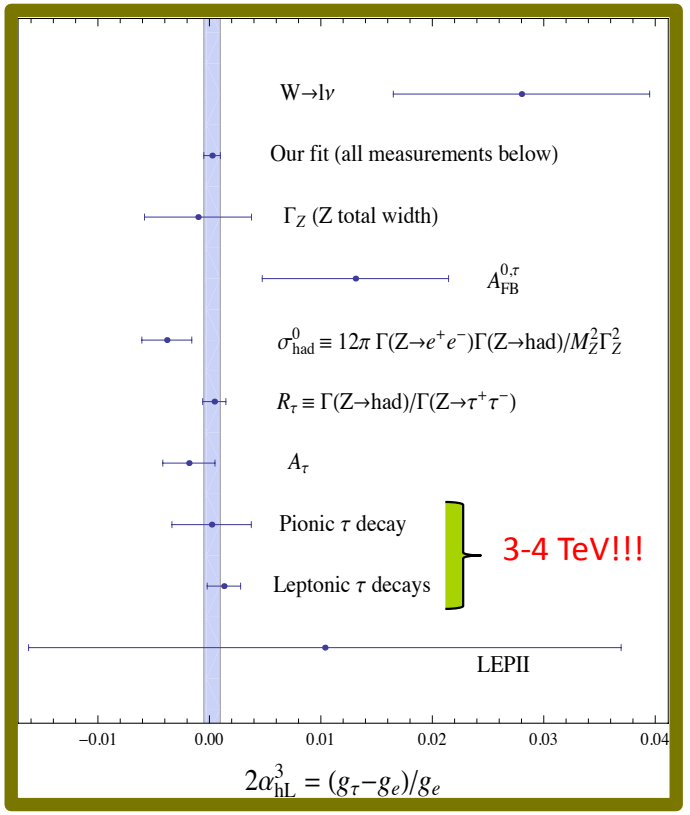


What if we have 2 (or more) operators?

All 17 operators that are [U(2)xU(1)]$^5$ inv. affecting the 3$^{rd}$ family are not able to accommodate the discrepancy!

Relaxing the symmetry to U(2)$^5$: 2 more operators… still no room!

$$O_{\tau B}^t = \left(\overline{L}\,\sigma^{\mu\nu}\,\tau\right) h\, B_{\mu\nu} + \text{h.c.}$$
$$O_{\tau W}^t = \left(\overline{L}\,\sigma^{\mu\nu}\,\tau^i\,\tau\right) h\, W_{\mu\nu}^i + \text{h.c.}$$

$$R_{\tau\ell}^W = 1.01 \pm 0.01$$

LEPII result: 1.077(26)

SM result: 0.999…

*(Filipuzzi, MGA & Portolés, 2012)*

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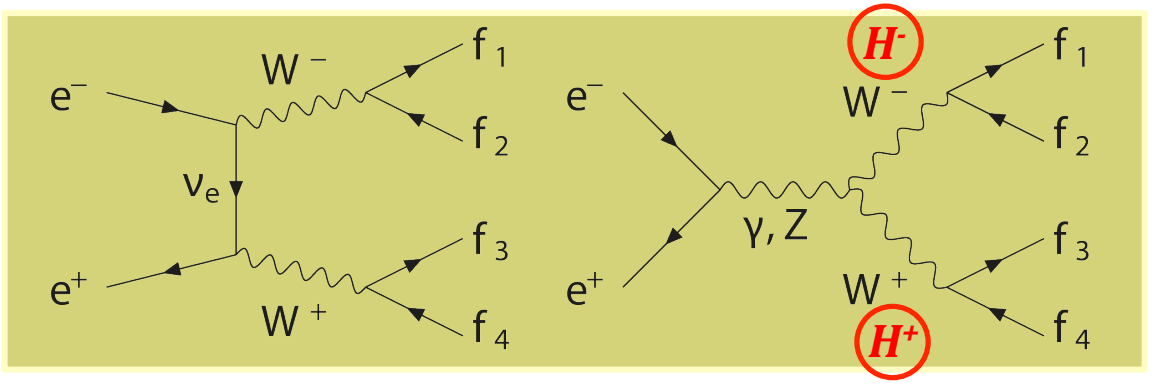
$$w_\tau = m_\tau / M_W$$

Conclusion:
The loophole in the naïve thinking (cancellations) is really small…

Thus…

- highly non-trivial flavor structure;
- EFT assumptions are wrong (e.g. new light fields)
- Or it's just a statistical fluctuation (or systematic…);

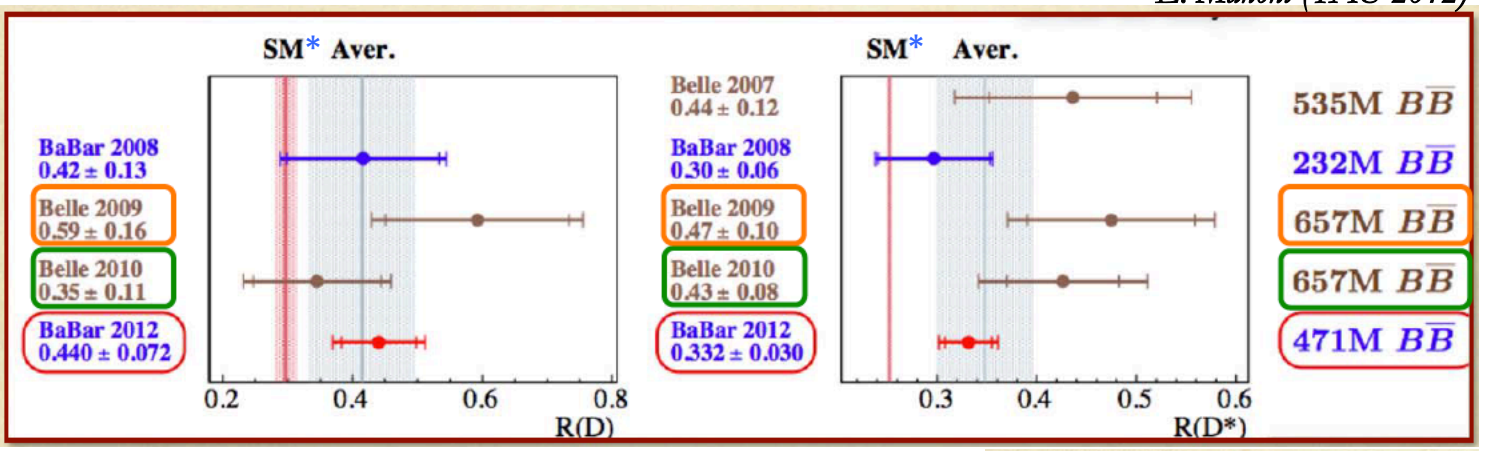



*(Park, 2006)*

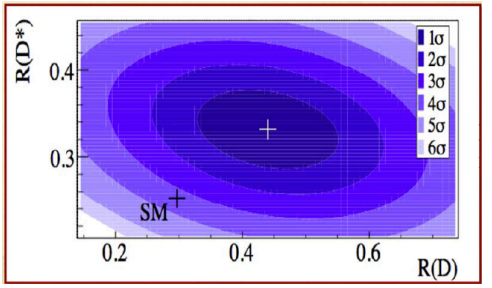
# Lepton universality in B decays

$$R(D^{(*)}) = \frac{\Gamma\left(\overline{B} \to D^{(*)}\tau^-\overline{\nu}_\tau\right)}{\Gamma\left(\overline{B} \to D^{(*)}l^-\overline{\nu}_l\right)}$$

*E. Manoni (TAU 2012)*




Averages do not include 2012 BaBar analysis




**3.4 sigma deviation!**

- BaBar & Belle agree!
- Statistical errors dominate for both exp!
- Updates expected for both exp! (& SuperBs!!)
- Also tensions in B➔τν (ameliorated by recent Belle result)

[*] Kamenik & Mescia'2008; Fajfer et al.'2012.

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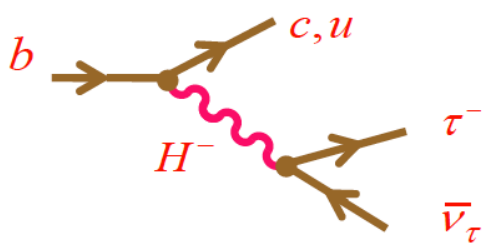


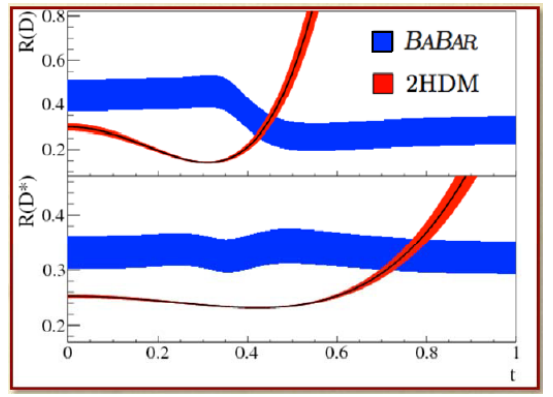


$t = \tan\beta / m_{H+}$ (GeV$^{-1}$)

- New physics?
  - Type II 2HDM excluded [*BaBar'2012*];
  - MSSM with MFV excluded [*Altmannshofer et al'2012*];
  - It can be accommodated in other SM extensions:
    type III 2HDM [*Crivellin et al.'2012*], Aligned 2HDM [*Celis et al.'2012*],
    EFT approach (within/beyond MFV) [*Fajfer et al.'2012, Datta et al.'2012, Biancofiore et al, 2013*], ..."

- Just SM?
  - Recent 2+1 flavor lattice calculation :
    $R(D)_{SM} = 0.316 \pm 0.012 \pm 0.007$, [*FNAL/MILC, 2012*];
  - Also: $R(D)_{SM} = 0.31 \pm 0.02$ [*Becirevic et al.'2012*];

    ➔ Discrepancy below 2σ!

| | R(D) | R(D*) |
|---|---|---|
| BABAR | 0.440 ± 0.071 | 0.332 ± 0.029 |
| SM | 0.297 ± 0.017 | 0.252 ± 0.003 |

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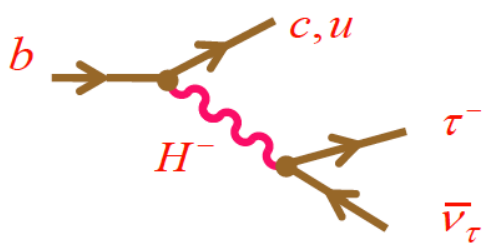


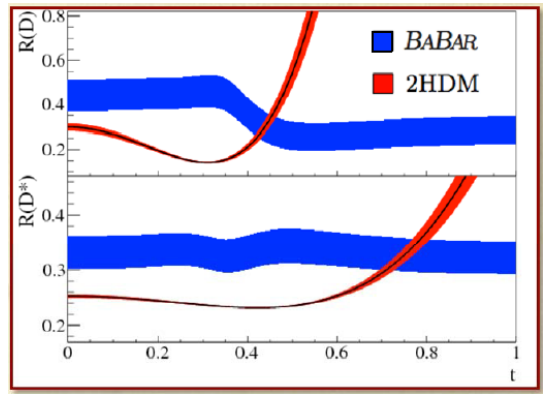


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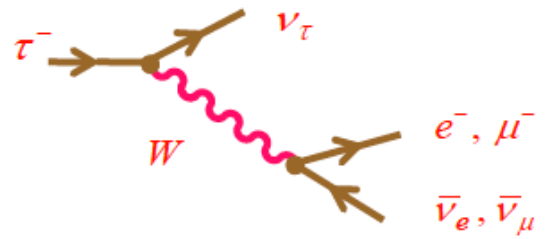
# Tau leptonic decays

- Observables:
  - Total rates ➔ lepton universality tests;
  - Angular & energy distribution (Michel parameters):




$$\frac{d^2\Gamma}{dx\,d(\cos\theta)} \propto x^2\left\{(3-3x)+\frac{2}{3}\rho(4x-3)+3\eta x_0\frac{(1-x)}{x}+\mathcal{P}_\mu\xi\cos\theta\left[(1-x)+\frac{2}{3}\delta(4x-3)\right]\right\},$$

*more parameters if the electron/muon polarization is measured

$$x=\frac{E_e}{E_{\max}}, \qquad x_0=\frac{m_e}{E_{\max}},$$

- Theory side:

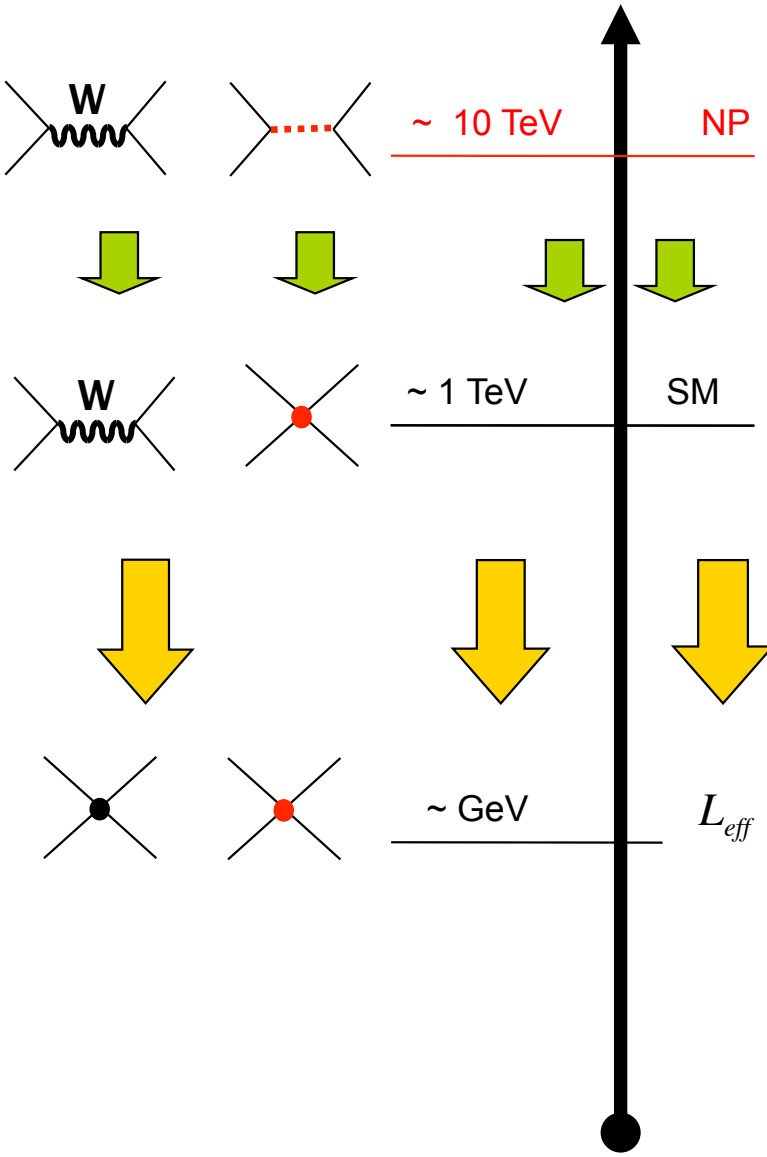
$$L_{eff} = -\frac{4G_F}{\sqrt{2}}\left[\bar{e}\gamma_\mu(1-\gamma_5)\nu_e\cdot\bar{\nu}_\tau\gamma_\mu(1-\gamma_5)\tau \;+\; \sum_i \varepsilon_i\,\bar{e}\,\Gamma\nu_e\cdot\bar{\nu}_\tau\Gamma\tau\right]$$

$\rho = 3/4 + f(\varepsilon_i)$
$\eta = 0 + f(\varepsilon_i)$
$\xi = 1 + f(\varepsilon_i)$
$\delta = 3/4 + f(\varepsilon_i)$

➔ **Agreement SM/exp ➔ bounds over epsilons.**

**In the 80s-90s, a few papers about the interest for specific NP models (Stahl'94, Pich & Silva'95, …)**

# Tau leptonic decays: an EFT approach




$$\mathcal{L}^{TeV}(x) = \mathcal{L}(\text{SM-fields, bSM-fields})$$

*[Buchmüller-Wyler'1986, Leung et al.'1986]*

$$\mathcal{L}_{eff.} = \mathcal{L}_{SM} + \frac{1}{\Lambda^2}\sum \alpha_i \mathcal{O}_i$$

*[Cirigliano, MGA, Jenkins'2010, Cirigliano, MGA, Graesser'2012]*

$$L_{eff} = -\frac{4G_F}{\sqrt{2}}\left[\bar{e}\gamma_\mu(1-\gamma_5)\nu_e \cdot \bar{\nu}_\tau\gamma_\mu(1-\gamma_5)\tau \;+\; \sum_i \varepsilon_i\, \bar{e}\,\Gamma\nu_e \cdot \bar{\nu}_\tau\Gamma\tau\right]$$

$$\boxed{\varepsilon_i = f(\alpha_j)}$$

**Relation between tau decay & collider observables!**
**(and also with NC processes)**

and muon!

# Tau leptonic decays: an EFT approach

$$L_{eff} \approx -\frac{4G_F}{\sqrt{2}}\left(1+2\,\mathrm{Re}\,\varepsilon_L\right)\left[\bar{e}\gamma_\mu(1-\gamma_5)\nu_e \cdot \bar{\nu}_\tau\gamma_\mu(1-\gamma_5)\tau \;+\; \varepsilon_R\,\bar{e}(1-\gamma_5)\nu_e \cdot \bar{\nu}_\tau(1+\gamma_5)\tau\right]$$

**Deviations from (quark-)lepton universality**

$$\varepsilon_R = +2[\hat{\alpha}_{le}]_{2112}$$

$$O_{le} = \left(\bar{l}\gamma^\mu l\right)(\bar{e}\gamma_\mu e),$$

**Energy & angular distribution (Michel parameters!)**

**Remarkably simple result! Consequences:**

1) **Only some Michel parameters are "interesting"**
2) **We can calculate the precision needed to compete with LEP**
   **[interesting for (super)-B factories]**

$$O_{le} = \left(\bar{l}\gamma^\mu l\right)(\bar{e}\gamma_\mu e), \;= \bar{\nu}_\tau\gamma_\mu(1-\gamma_5)\nu_e \cdot \bar{e}\gamma^\mu(1+\gamma_5)\tau \;+\; \bar{\tau}\gamma_\mu(1-\gamma_5)e \cdot \bar{e}\gamma^\mu(1+\gamma_5)\tau$$

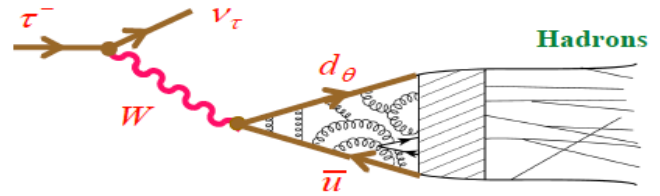
$$\bar{\tau}_L\,\tau_R \cdot \bar{e}_R e_L$$

*(Cirigliano & MGA, 2010)*

# Outline

- Introduction; ✓
- Lepton universality; ✓
- Leptonic decays: Michel parameters; ✓
- (Inclusive) Hadronic tau decays within the SM (and beyond!);
- LFV decays;
- CPV in tau decays;
- Lots of things left out:
  LNV in tau decays, tau physics in hadron colliders, tau g-2, tau EDM, …

# Hadronic tau decays

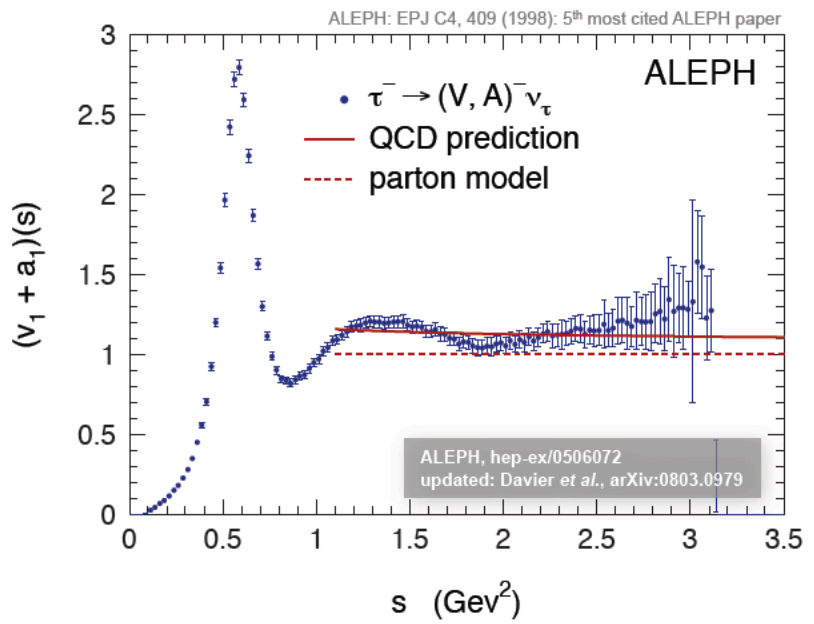



- The tau is the only lepton heavy enough to decay hadronically.
  Moreover, its mass is significantly larger than QCD scale!!! (key point)
  ➔ This allows precise analytical studies of inclusive observables (via OPE):
  $\alpha_S$, $V_{us}$ and low-energy parameters.

- I'll focus on the following inclusive observables:

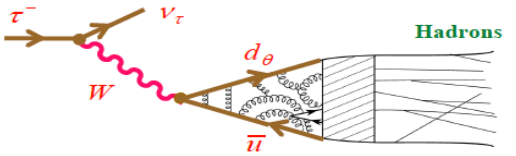
$$\Gamma\left(\tau \to \nu_\tau + hadrons_{S=0}\right)$$
$$\Gamma\left(\tau \to \nu_\tau + hadrons_{S\neq 0}\right)$$

LEP measured with precision not only the total BRs but also the energy distribution of the hadronic system (spectral functions!!).
This triggered enormous QCD activity!




- Very active field: experimentally and theoretically;

# (Inclusive) Hadronic tau decays

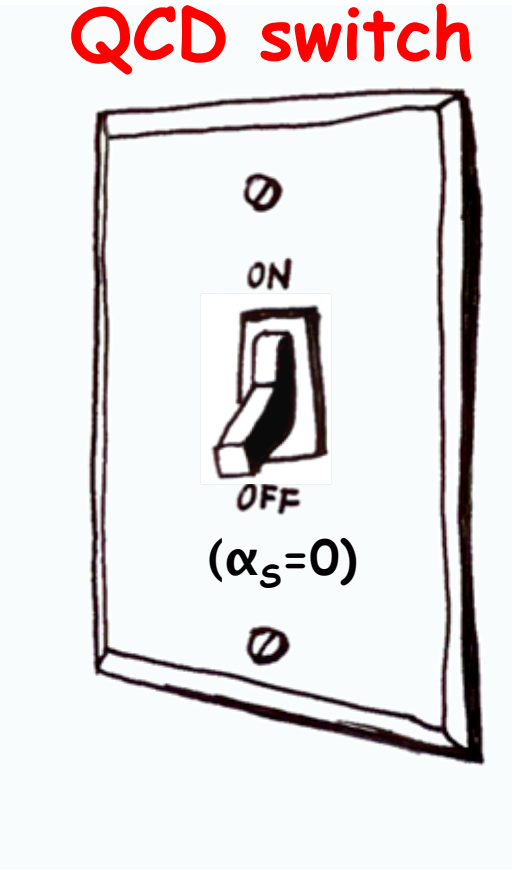



- Extraction of $\alpha_S$ and $V_{us}$. The idea is simple:

$$R_\tau \equiv \frac{\Gamma(\tau \to \nu_\tau + hadrons)}{\Gamma(\tau \to \nu_\tau\, e^-\, \nu_e)} \approx N_C$$

$$R_\tau = R_\tau^{S=0} + R_\tau^{S\neq 0} \approx N_C |V_{ud}|^2 + N_C |V_{us}|^2 \approx 2.85 + 0.15$$

$$\frac{|V_{us}|^2}{|V_{ud}|^2} \approx \frac{R_\tau^{S\neq 0}}{R_\tau^{S=0}} \longrightarrow |V_{us}|^2$$



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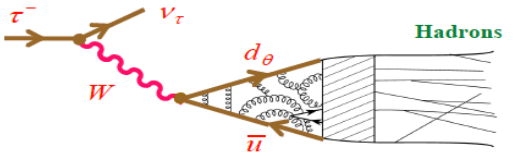


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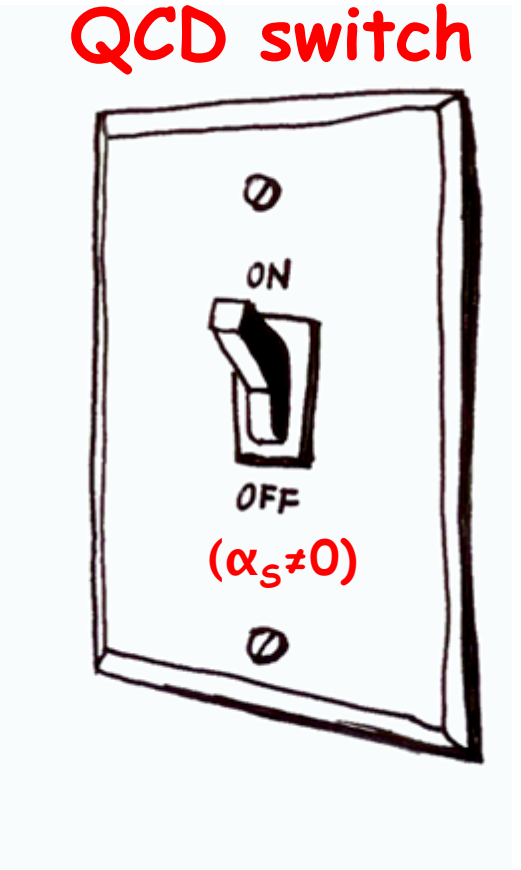
$$R_\tau = R_\tau^{S=0} + R_\tau^{S\neq 0} \approx N_C |V_{ud}|^2 + N_C |V_{us}|^2 \approx 2.85 + 0.15$$

[exp: ~3.467(8) + 0.161(3)]

$$\frac{|V_{us}|^2}{|V_{ud}|^2} \approx \frac{R_\tau^{S\neq 0}}{R_\tau^{S=0}} \quad \text{+ corr.} \quad \Rightarrow \quad |V_{us}|^2$$

$$R_\tau^{S=0} \approx N_C |V_{ud}|^2 + O(\alpha_s) \quad \Rightarrow \quad \alpha_s$$

The complication is here!



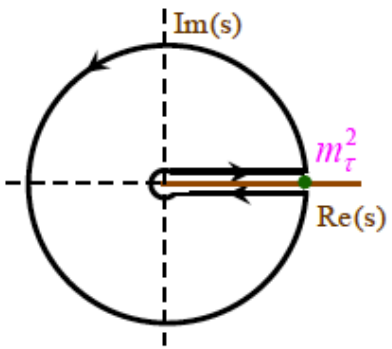
# (Inclusive) Hadronic tau decays

*(Braaten et al, 1992)*

$$R_\tau \equiv \frac{\Gamma(\tau^- \to \nu_\tau + \text{had})}{\Gamma(\tau^- \to \nu_\tau e^- \bar{\nu}_e)} = 12\pi \int_0^1 dx\,(1-x)^2 \left[(1+2x)\,\text{Im}\,\Pi^{(1)}(x m_\tau^2) + \text{Im}\,\Pi^{(0)}(x m_\tau^2)\right]$$

$$= 6\pi i \oint_{|x|=1} dx\,(1-x)^2 \left[(1+2x)\,\Pi^{(0+1)}(x m_\tau^2) - 2x\,\Pi^{(0)}(x m_\tau^2)\right]$$

$$x \equiv \frac{s}{m_\tau^2}$$




$$= N_C\, S_{\text{EW}} \left(1 + \delta_{\text{P}} + \delta_{\text{NP}}\right)$$

$$\Pi^{(J)}(s) = \sum_{D=2n} \frac{C_D^{(J)}(s,\mu)\,\langle O_D(\mu)\rangle}{(-s)^{D/2}}$$

$S_{\text{EW}} = 1.0201\ (3)$ Marciano-Sirlin, Braaten-Li, Erler

$\delta_{\text{P}} = a_\tau + 5.20\, a_\tau^2 + 26\, a_\tau^3 + 127\, a_\tau^4 + \ldots \approx 20\%$

$a_\tau \equiv \alpha_s(m_\tau)/\pi$

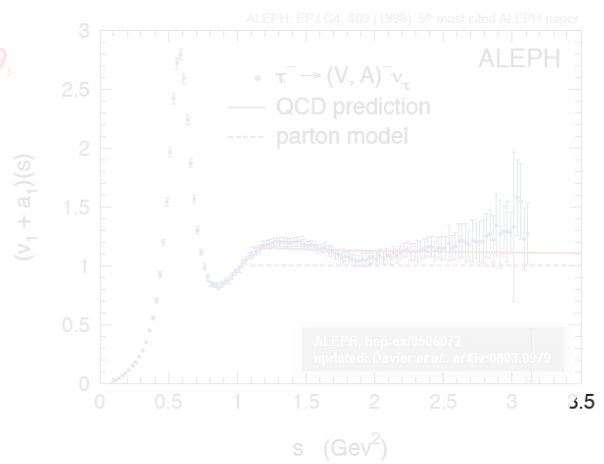
$\delta_{\text{NP}} = -0.0059 \pm 0.0014$

*(Baikov et al.,'08)*

Fitted from data (Davier et al)

- Intense theoretical activity!!!
  *Davier et al'08, Maltman & Yavin'08, Beneke & Jamin'08, Maltman'09, Menke'09, Caprini & Fischer'09, Descotes-Genon & Malaescu'09, Cvetic et al'10, Abbas et al.'12, Beneke et al'12, Boito et al'12, ...*

- Exp: still using LEP data!
  A more precise measurement of the spectral functions would be welcome;



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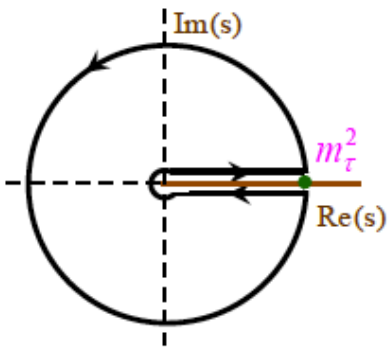


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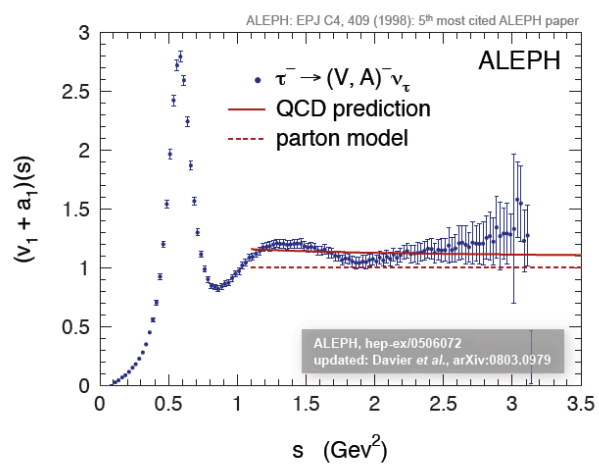


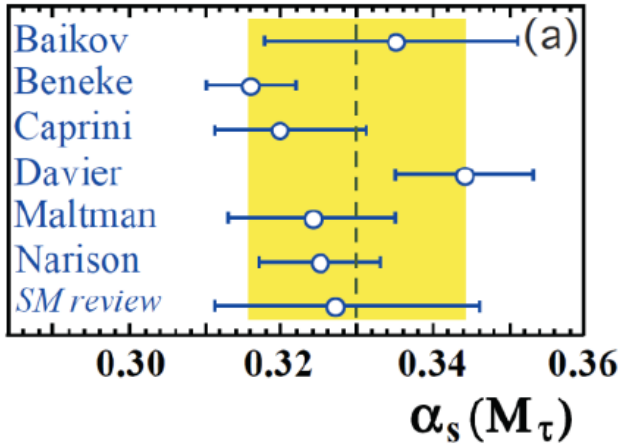
# (Inclusive) Hadronic tau decays

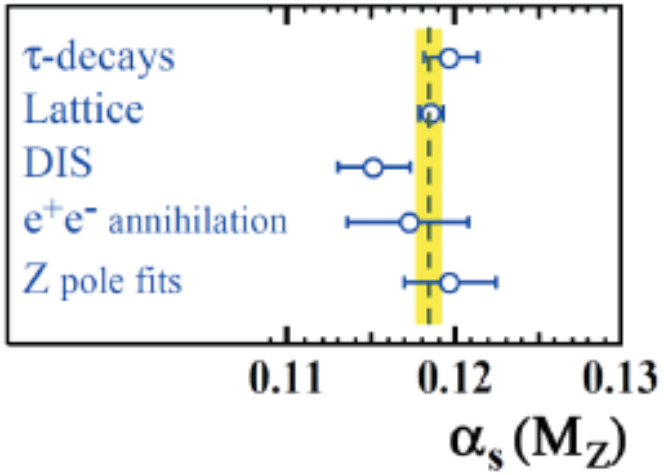
$$\alpha_s\left(m_\tau^2\right) = 0.329(13) \longrightarrow \alpha_s\left(M_Z^2\right) = 0.1198(15)$$

*A. Pich (TAU2012)*

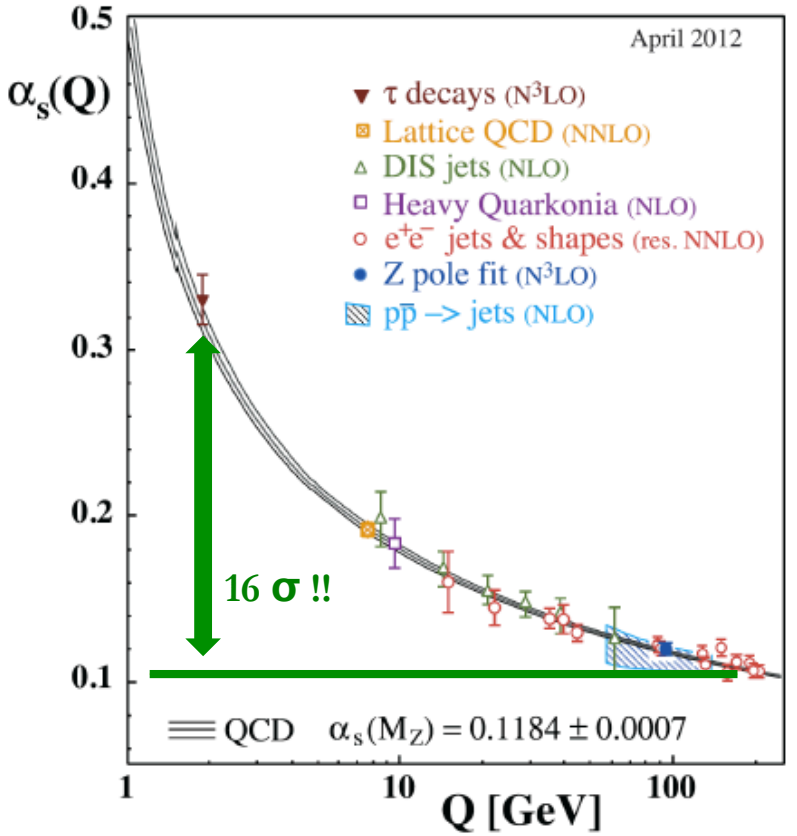
$$\alpha_s\left(M_Z^2\right) = 0.1197(28)$$

**Beautiful test of the QCD running!**




**PDG2012**



# (Inclusive) Hadronic tau decays

$$R_\tau^{S=0} \approx N_C |V_{ud}|^2 (1+\delta)$$

$$R_\tau^{S\neq 0} \approx N_C |V_{us}|^2 (1+\delta) - \delta R_\tau$$

**SU(3) breaking correction!**
**Calculable theoretically = f($m_s$)**
**[Pich & Prades'98,'99]**

$$\delta R_\tau = 0.239(30)$$

**[Gamiz'2013]**
**[Maltman'2010: larger error]**

$$|V_{us}|^2 = \frac{R_\tau^{S\neq 0}}{\frac{R_\tau^{S=0}}{|V_{ud}|^2} - \delta R_\tau}$$

*[Gamiz et al'03, '05, '08]*

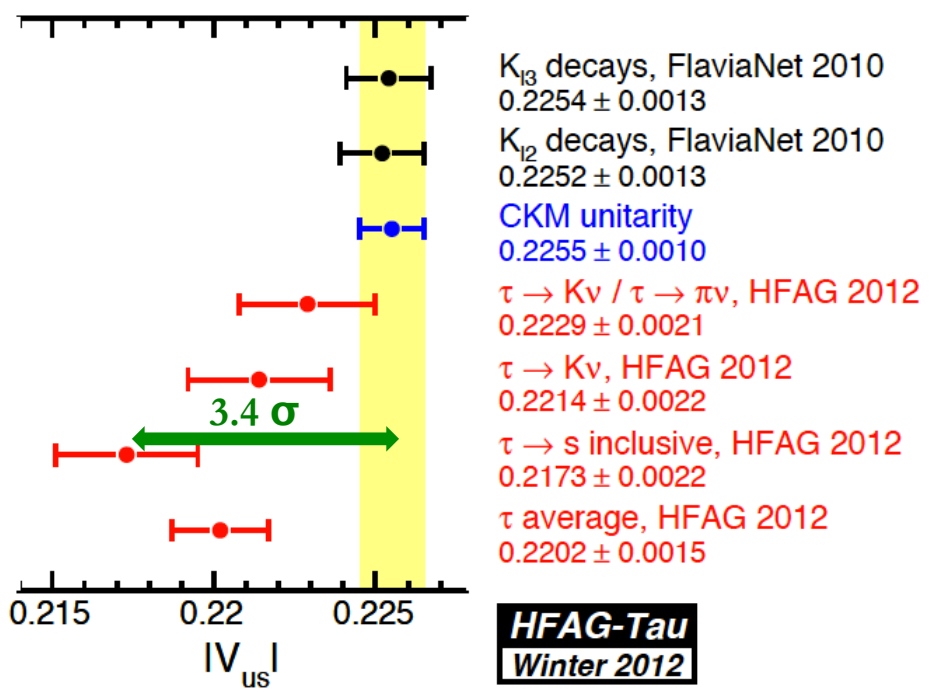
$$|V_{us}| = 0.2173 \pm 0.0020_{\text{exp}} \pm 0.0010_{\text{th}}$$

$$|V_{us}| = 0.2255(13) \quad [\text{from } K_{l3}]$$

$$R^{00}_{\tau,S} = 0.1612\ (28)$$

$$R^{00}_{\tau,V+A} = 3.4671\ (84)$$

$$|V_{ud}| = 0.97425\ (22)$$




**NOTE:**
BRs from B-factories are smaller than previous world averages!

# [Interlude: CKM unitarity test]

- Apart from the importance per se (fundamental parameter!!!), it is important for NP searches: CKM unitarity tests!

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9999 \pm 0.0006$$

Shown in specific NP scenarios, and within an EFT approach (with MFV):

*[Barbieri et al. (1985), Marciano & Sirlin (1987), Hagiwara et al. (1995), Kurylov & Ramsey-Musolf (2002), Bauman, Erler & Ramsey-Musolf (2012) ...]*

$$\Delta_{CKM} = 4\left(-\hat{\alpha}^{(3)}_{\varphi l} + \hat{\alpha}^{(3)}_{\varphi q} - \hat{\alpha}^{(3)}_{lq} + \hat{\alpha}^{(3)}_{ll}\right) = -(1 \pm 6)\cdot 10^{-4}$$

$$\Lambda_i^{eff} > 11\text{TeV (90\% CL)}$$

*[Cirigliano, MGA & Jenkins, 2010]*

**5x stronger than the constraint from LEP & other EWPO!!!**

$$O^{(3)}_{ll} = \frac{1}{2}(\bar{l}\gamma^\mu\sigma^a l)(\bar{l}\gamma_\mu\sigma^a l)$$
$$O^{(3)}_{lq} = (\bar{l}\gamma^\mu\sigma^a l)(\bar{q}\gamma_\mu\sigma^a q)$$
$$O^{(3)}_{\varphi l} = i(h^\dagger D^\mu\sigma^a\varphi)(\bar{l}\gamma_\mu\sigma^a l) + \text{h.c.},$$
$$O^{(3)}_{\varphi q} = i(\varphi^\dagger D^\mu\sigma^a\varphi)(\bar{q}\gamma_\mu\sigma^a q) + \text{h.c.}$$

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**Critical assumption!**
**NP contamination of $V_{ij}$ is channel-independent.**
**No explanation for the current $V_{us}$ "tension"**

# NP in $V_{us}$ extractions?

*[Cirigliano & MGA, work in progress]*

- EFT with a more general NP flavor structure (beyond MFV)

$$V_{us}^{pheno}\Big|_{Kl3} \neq V_{us}^{pheno}\Big|_{\tau(excl)} \neq V_{us}^{pheno}\Big|_{\tau(incl)}$$

Is it possible to accommodate the current tensions without spoiling collider & EWPO?

  - Identification of relevant operators;
  - Bounds on those operators from EWPO;
  - Calculation of the effect of those operators on the $V_{us}$ extraction;

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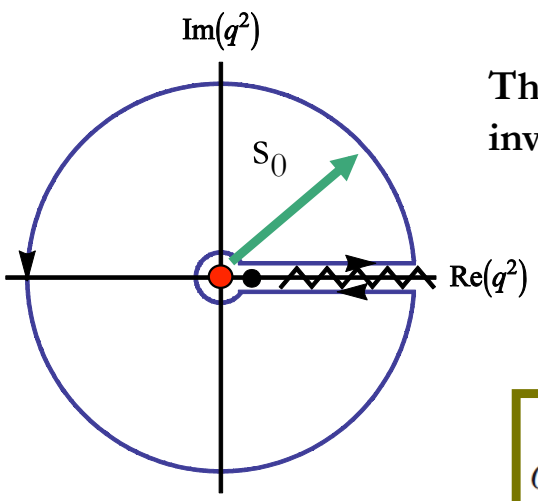
***Not trivial in the case of inclusive tau decays!***
***[By-product: NP in the extraction of $a_s$?]***




**The QCDSR derivation involves new correlators!!**

$$\delta R_\tau \equiv \frac{R_{\tau,nS}}{|V_{ud}|^2} - \frac{R_{\tau,S}}{|V_{us}|^2}$$

$$\begin{aligned} R_\tau = \; & 6\pi i |V_{ud}|^2 \oint_{|s|=m_\tau^2} \frac{ds}{m_\tau^2}\left(1-\frac{s}{m_\tau^2}\right)^2 \times \\ & \times \Bigg\{ |\kappa_V|^2 \left[\left(1+\frac{2s}{m_\tau^2}\right)\Pi_{VV}^{(1)}(s) + \Pi_{VV}^{(0)}(s)\right] \\ & + |\kappa_A|^2 \left[\left(1+\frac{2s}{m_\tau^2}\right)\Pi_{AA}^{(1)}(s) + \Pi_{AA}^{(0)}(s)\right] \\ & + 2\,\mathrm{Re}(\kappa_V \kappa_S^*)\frac{\Pi_{VS}(s)}{m_\tau} + 2\,\mathrm{Re}(\kappa_A \kappa_P^*)\frac{\Pi_{AP}(s)}{m_\tau} \\ & + 6 \times 2\,\mathrm{Re}(\kappa_V \kappa_T^*)\frac{\Pi_{VT}(s)}{m_\tau}\Bigg\} \times \left[1 - 2\tilde{v}_L\right], \end{aligned}$$

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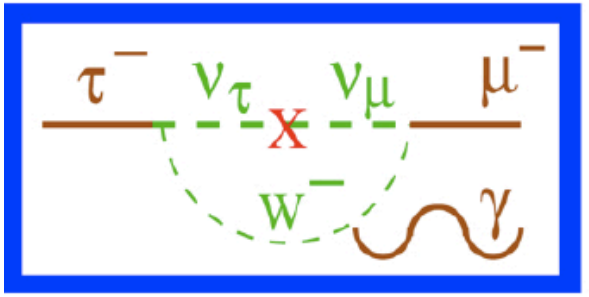
# Lepton Flavor Violation

- LFV is an "accidental" symmetry in the SM ($m_\nu$=0)
  This accident does not occur in general in bSM theories.

- Neutrino have mass ➔ LFV! ➔ Charged LFV… but zero for all practical purposes.




$$B(\tau \to \mu\gamma) \sim \left(\frac{\Delta m_{23}^2}{M_W^2}\right)^2 \leq O\left(10^{-54}\right)$$

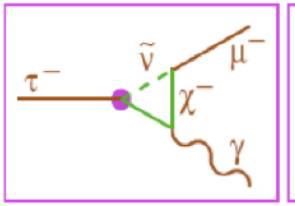
*[Lee & Shrock, 1977]*

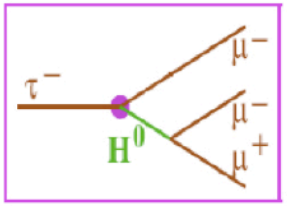
**Perfect smoking gun for NP!!!**

- LFV processes probe physics at scales Λ>>TeV.
  Moreover, realistic NP models often produce LFV at visible rates.

- Muon-LFV is more constrained experimentally… but we don't know the NP flavor structure!!
  **Tau/muon LFV is model-dependent ➔ model-diagnostic!!**
  Several NP models find interesting tau/muon LFV correlations.
  *This will become a key issue if MEG finds a NP signal.*

# Lepton Flavor Violation

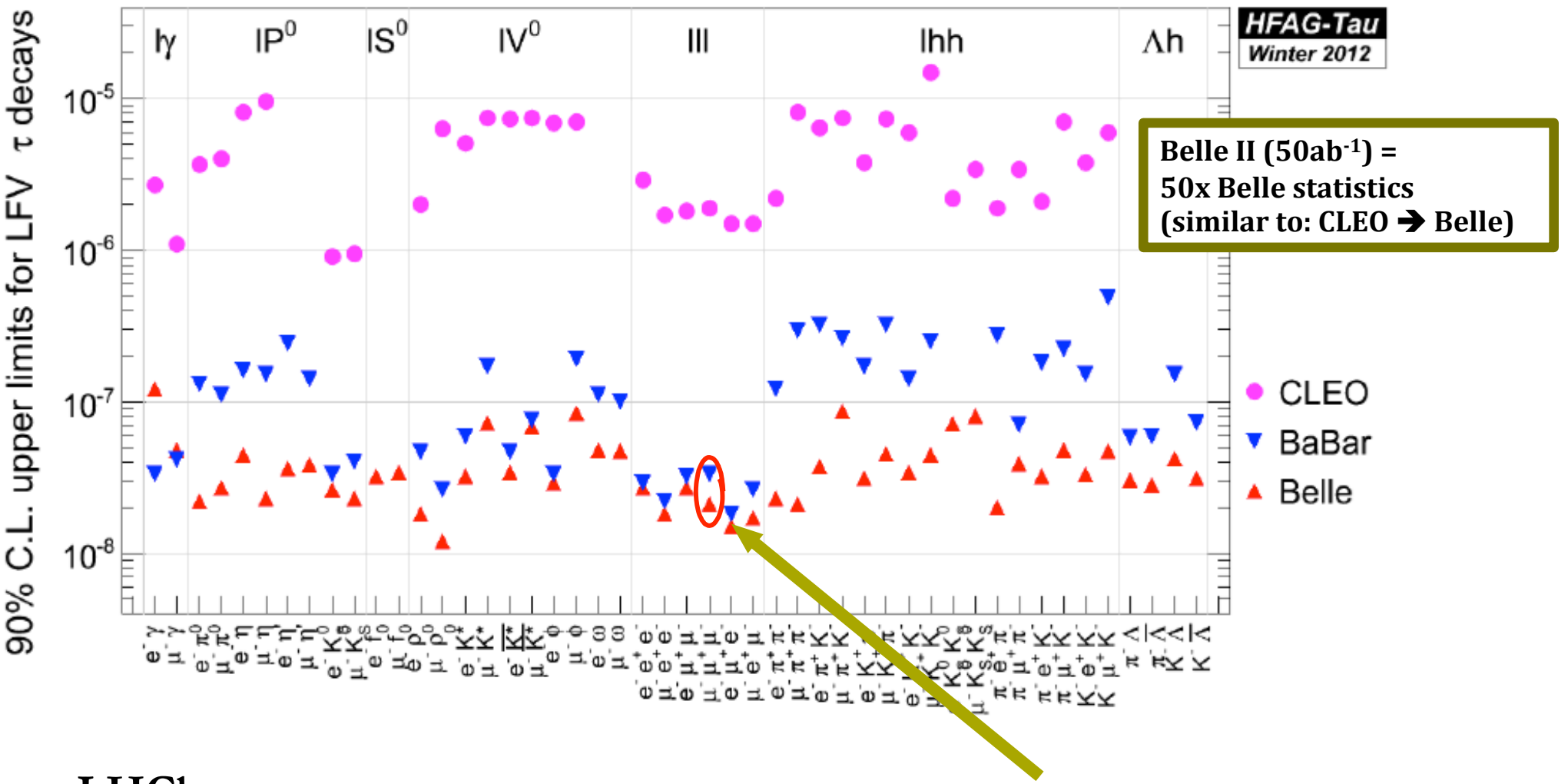



- Different tau-LFV processes are also model-diagnostic!

| LFV in example models (Hitlin, IF2011) | | $\tau \to \mu\gamma$ | $\tau \to \ell\ell\ell$ |
|---|---|---|---|
| SM + ν mixing | Lee, Shrock, PRD 16 (1977) 1444<br>Cheng, Li, PRD 45 (1980) 1908 | Undetectable | |
| SUSY Higgs | Dedes, Ellis, Raidal, PLB 549 (2002) 159<br>Brignole, Rossi, PLB 566 (2003) 517 | $10^{-10}$ | $10^{-7}$ |
| SM + heavy Maj $\nu_R$ | Cvetic, Dib, Kim, Kim , PRD66 (2002) 034008 | $10^{-9}$ | $10^{-10}$ |
| Non-universal Z' | Yue, Zhang, Liu, PLB 547 (2002) 252 | $10^{-9}$ | $10^{-8}$ |
| SUSY SO(10) | Masiero, Vempati, Vives, NPB 649 (2003) 189<br>Fukuyama, Kikuchi, Okada, PRD 68 (2003) 033012 | $10^{-8}$ | $10^{-10}$ |
| mSUGRA + Seesaw | Ellis, Gomez, Leontaris, Lola, Nanopoulos, EPJ C14 (2002) 319<br>Ellis, Hisano, Raidal, Shimizu, PRD 66 (2002) 115013 | $10^{-7}$ | $10^{-9}$ |

# Lepton Flavor Violation




**LHCb**
**(7 TeV, 1 fb$^{-1}$)**

$B(\tau^- \to \mu^-\mu^+\mu^-) \leq 6.3 \cdot 10^{-8}$ (90%CL)

**Catching up B-factories!** $B(\tau^- \to \mu^-\mu^+\mu^-) \leq (2.1 - 3.3) \cdot 10^{-8}$

EIC would improve the limits on LFV (e/tau). *[Gonderinger & Ramsey-Musolf, 2010]*

# CPV in tau decays;

- Tau physics offers a variety of CPV observables (rate, angular asymmetries, triple products, …) that can be studied to search for new sources of CPV.

- Interesting recent result:

$$A_\tau \equiv \frac{\Gamma(\tau^+ \to \pi^+ K_S \bar{\nu}_\tau) - \Gamma(\tau^- \to \pi^- K_S \nu_\tau)}{\Gamma(\tau^+ \to \pi^+ K_S \bar{\nu}_\tau) + \Gamma(\tau^- \to \pi^- K_S \nu_\tau)} = (-3.6 \pm 2.3 \pm 1.1) \cdot 10^{-3}$$

*(BaBar'2011)*

$$A_\tau^{SM} = (3.6 \pm 0.1) \cdot 10^{-3}$$

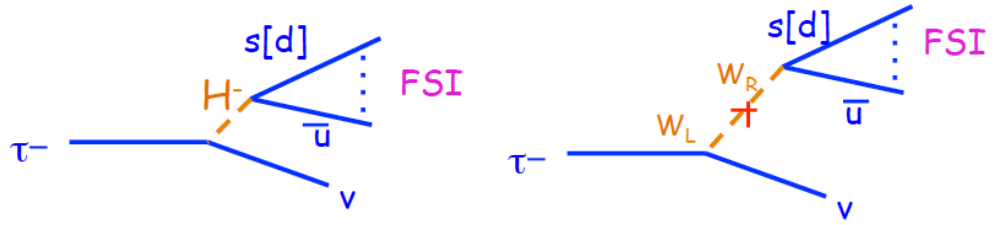
(due to $K^0 - \bar{K}^0$ mixing)

*[Bigi & Sanda, 2005]*
*[Grossman & Nir, 2011]*

**2.8σ discrepancy!**

- Belle has also searched for CPV in this decay mode through a difference in the angular distributions, finding a null result at the 0.2–0.3% level [*Belle, 2011*].

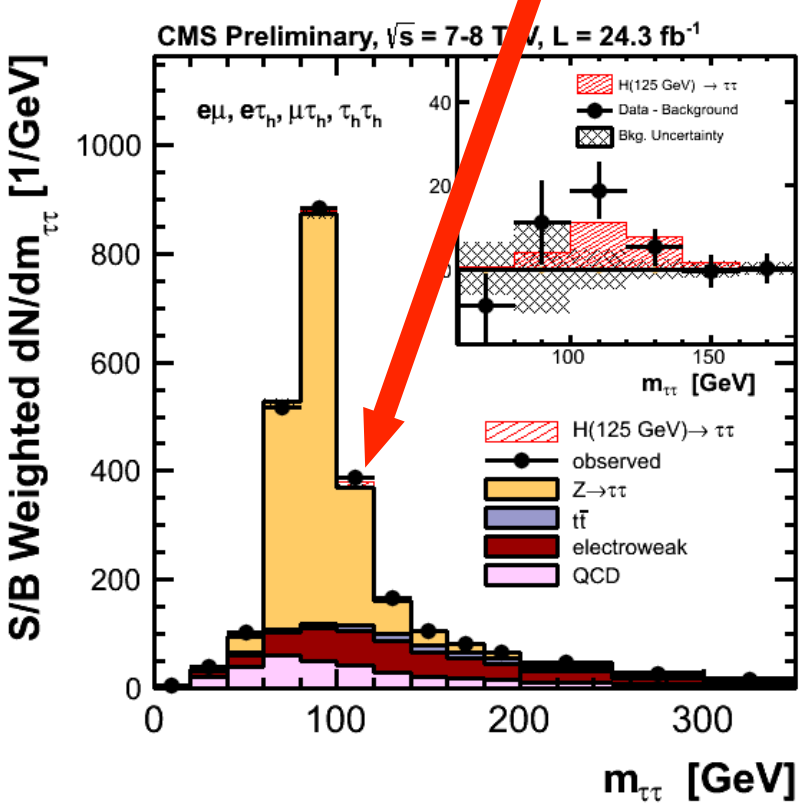
- NP explanations? *[Bigi, 2012]*
  - Charged Higgs?
  - $W_L$-$W_R$ mixing?
  - LQ?

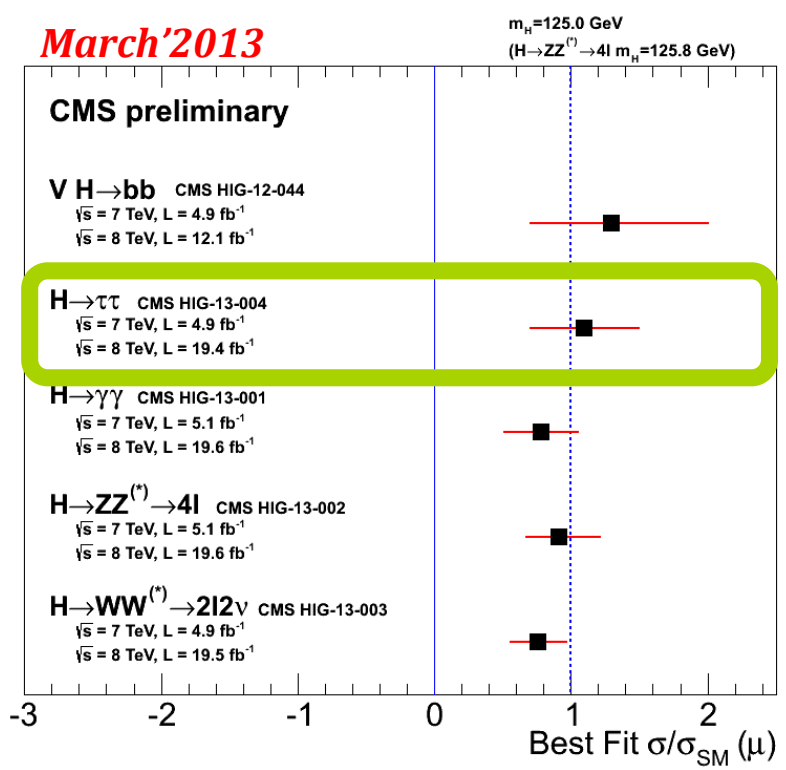


# Tau physics in colliders

- Excellent tool for New Physics searches: MSSM Higgses, Z' boson, …
- Largest Higgs-lepton coupling (4th Higgs BR)

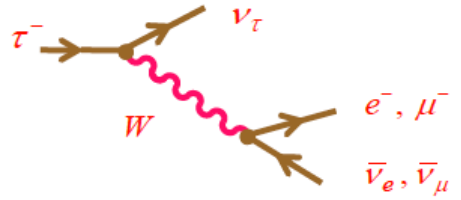
*2.9 sigma local significance*



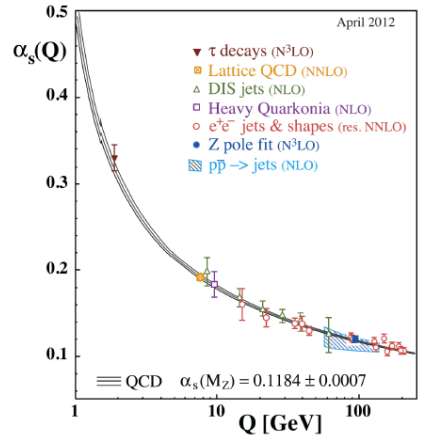



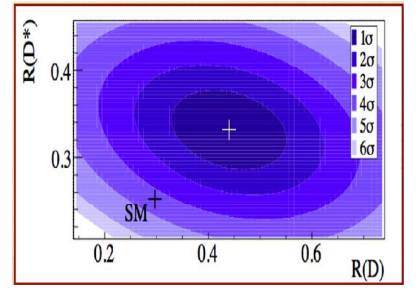

*ATLAS results is less precise (less statistics)*

# Summary/Outlook

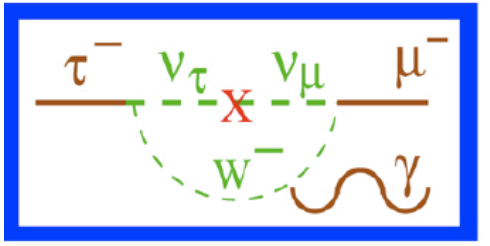



- Very exciting future in tau physics: Belle II, BESIII, LHCb, …
- Several intriguing anomalies:
  *Lepton universality (W and B decays), $V_{us}$ extraction, CPV, …*
- Lot of theory work to do too:
  *QCD analysis of inclusive hadronic tau decays (pQCD, DV, OPE, …), New Physics studies, …*
- Crowning jewel: tau-LFV searches;
- Lots of (very interesting) topics not addressed in this talk:
  *low-energy QCD studies, $(g\text{-}2)_{tau/muon}$, $EDM_{tau}$, collider studies, …*




**3.4 sigma deviation!**



# Backup slides

# Lepton universality

- NP flavor structure?

$$O_{\varphi l}^{(3)} \equiv i(\varphi^\dagger D^\mu \sigma^a \varphi)(\bar{l}\,\gamma_\mu \sigma^a l) + h.c.$$

Structure?

$$\alpha_{\varphi l}^{(3)} O_{\varphi l}^{(3)} \equiv \sum_{\alpha,\beta=1}^{3} [\alpha_{\varphi l}^{(3)}]_{\alpha\beta} [O_{\varphi l}^{(3)}]_{\alpha\beta} + h.c. \quad = i(\varphi^\dagger D^\mu \sigma^a \varphi)\left( \begin{pmatrix} \bar{l}_e & \bar{l}_\mu & \bar{l}_\tau \end{pmatrix} \gamma_\mu \sigma^a \begin{pmatrix} \alpha_{11} & \alpha_{12} & \alpha_{13} \\ \alpha_{21} & \alpha_{22} & \alpha_{23} \\ \alpha_{31} & \alpha_{32} & \alpha_{33} \end{pmatrix} \begin{pmatrix} l_e \\ l_\mu \\ l_\tau \end{pmatrix} \right) + h.c.$$

- Symmetry of the SM for $m_{f1}=m_{f2}=m_{f3}=0$ ➔ $U(3)^5$

$$\alpha_{\varphi l}^{(3)} = \begin{pmatrix} \alpha_{11} & \alpha_{12} & \alpha_{13} \\ \alpha_{21} & \alpha_{22} & \alpha_{23} \\ \alpha_{31} & \alpha_{32} & \alpha_{33} \end{pmatrix} = \bar{\alpha}_{\varphi l}^{(3)} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Lepton univ. holds by def.

- A way of singularizing the 3rd family is relaxing the symmetry to $[U(2)xU(1)]^5$.

$$\alpha_{\varphi l}^{(3)} = \begin{pmatrix} \alpha_{11} & \alpha_{12} & \alpha_{13} \\ \alpha_{21} & \alpha_{22} & \alpha_{23} \\ \alpha_{31} & \alpha_{32} & \alpha_{33} \end{pmatrix} = \begin{pmatrix} \alpha_{h\ell}^3 & 0 & 0 \\ 0 & \alpha_{h\ell}^3 & 0 \\ 0 & 0 & \alpha_{hL}^3 \end{pmatrix}$$

$$\begin{pmatrix} l_e \\ l_\mu \\ l_\tau \end{pmatrix}, \begin{pmatrix} e \\ \mu \\ \tau \end{pmatrix}, \begin{pmatrix} q_u \\ q_c \\ q_t \end{pmatrix}, \begin{pmatrix} u \\ c \\ t \end{pmatrix}, \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

- "Less symmetry": $U(2)^5$ [SM symmetry for $m_{f1}=m_{f2}=0$, but $m_{f3}\neq 0$]