Theory of charged leptons

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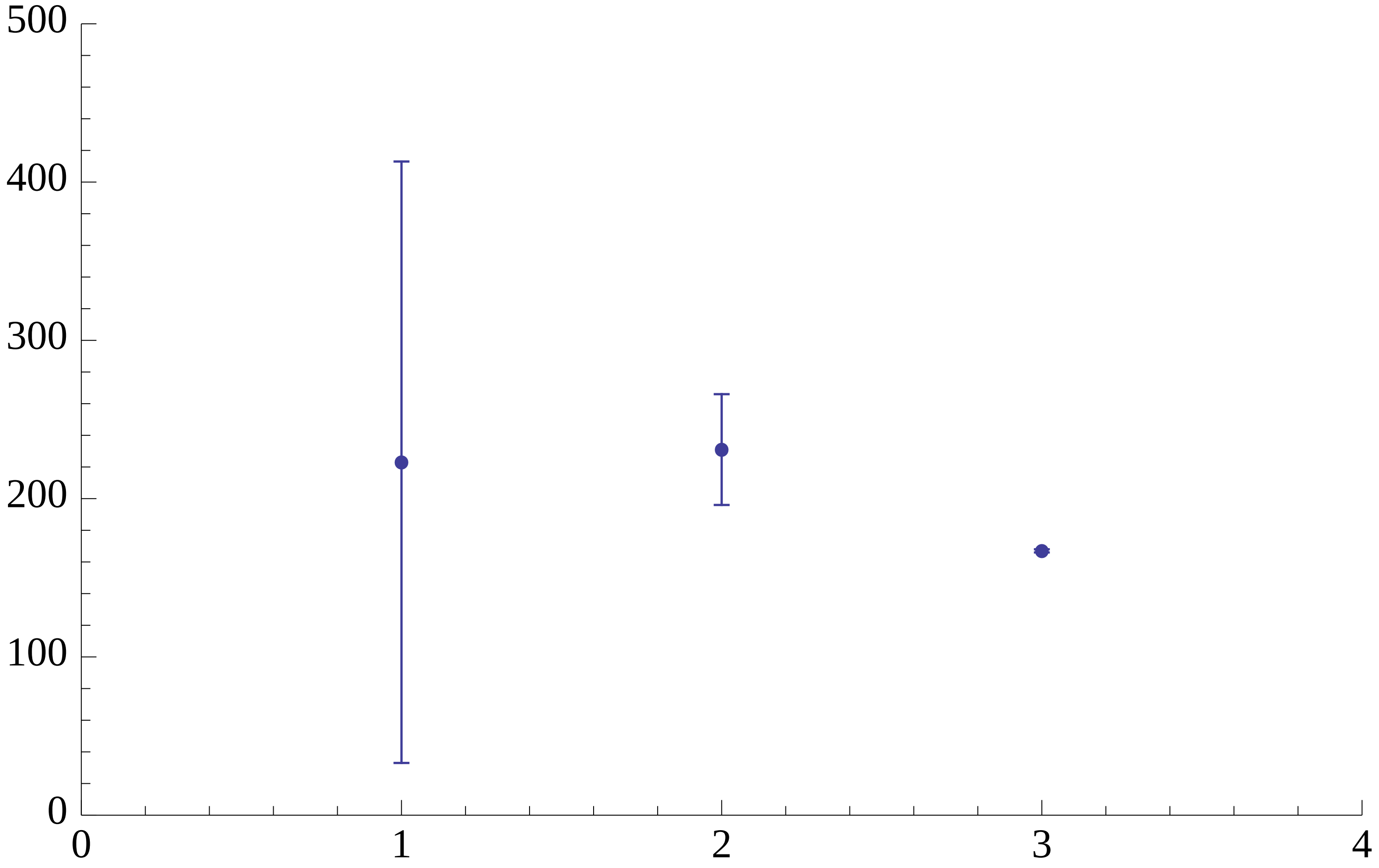
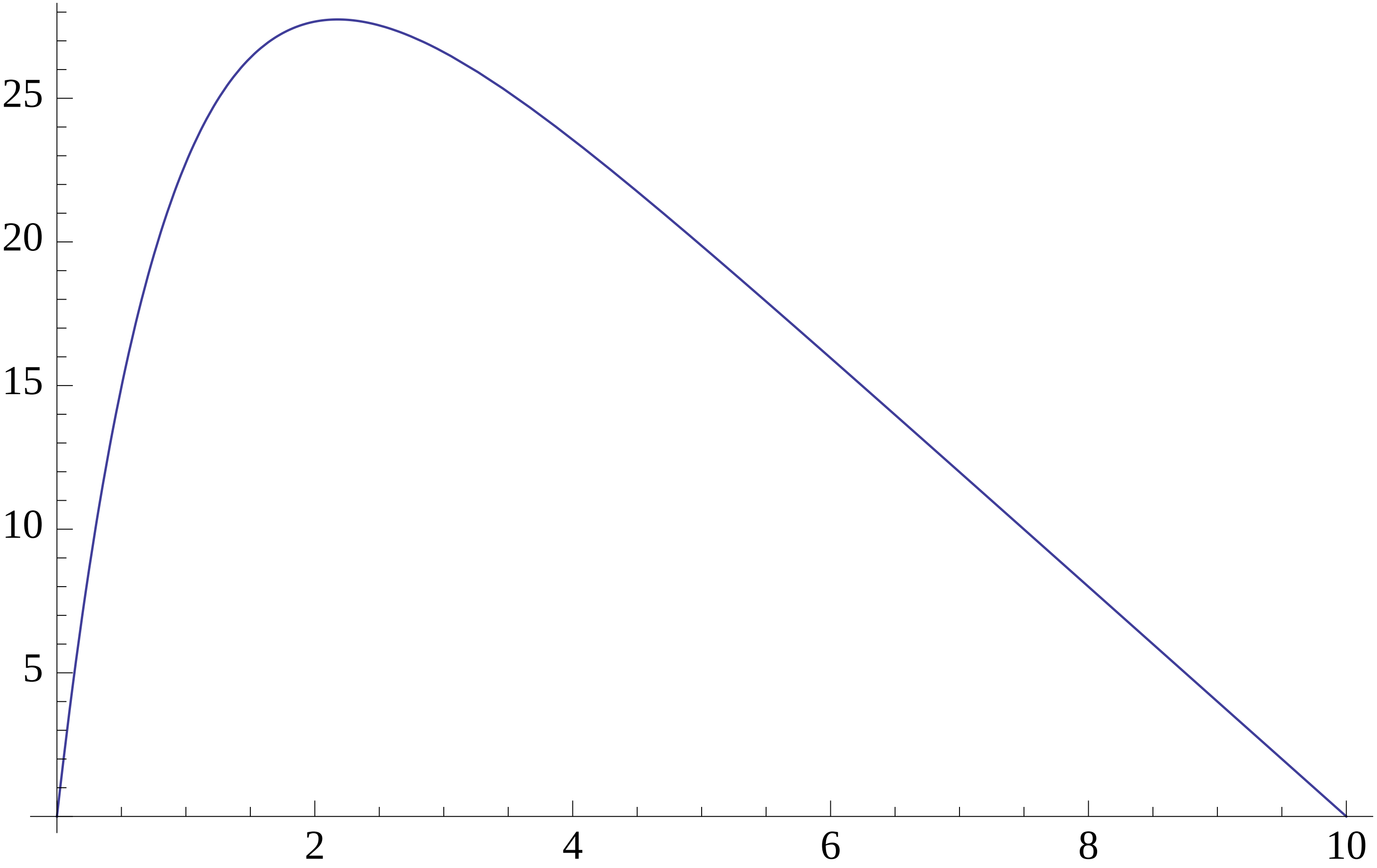
Why charged leptons?



Why charged leptons? (again)



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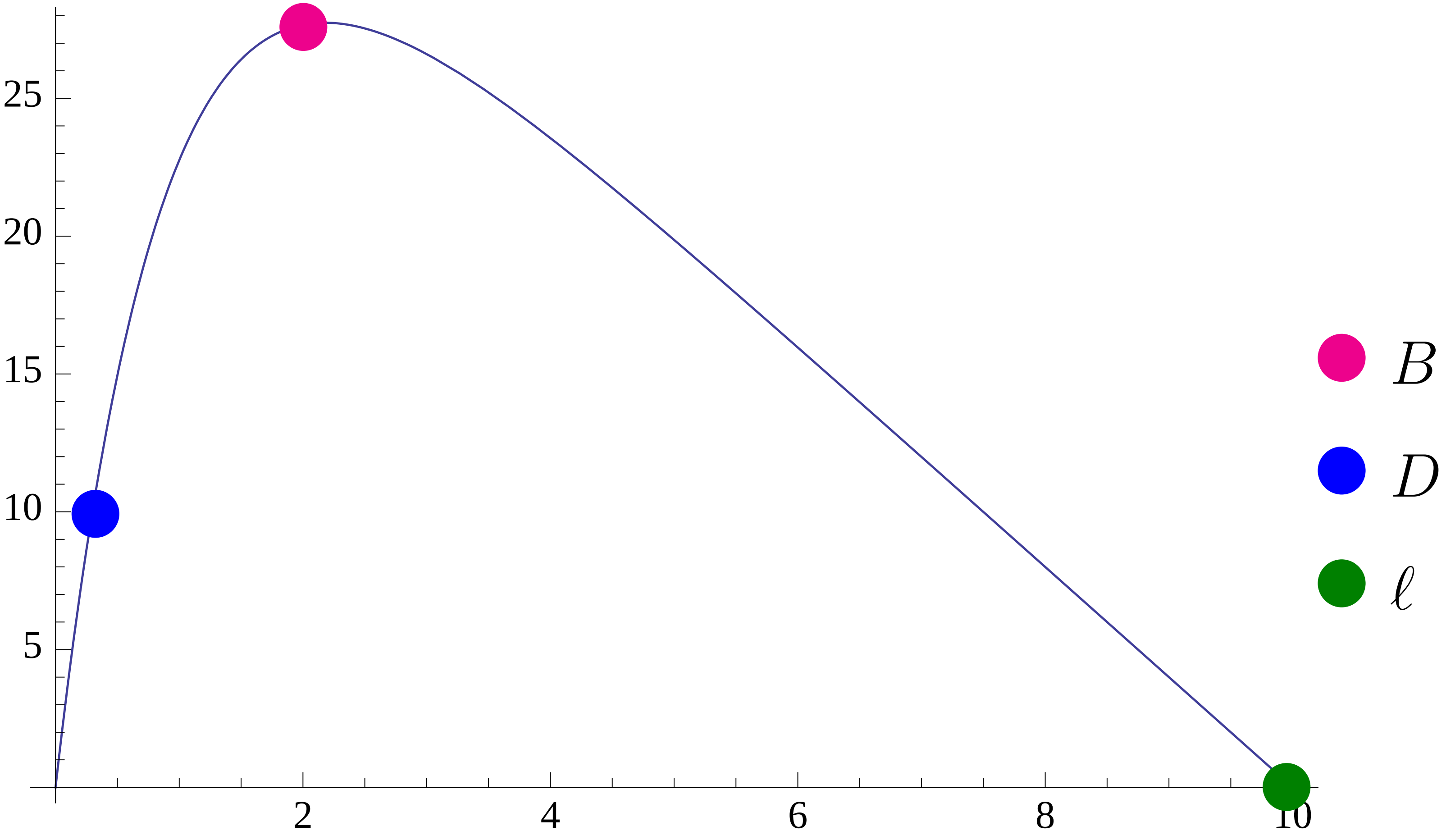

Outline

- A general view on particle physics
- Synergy within charged leptons
- Probing the lepton sector with neutrinos
- Probing the flavor sector with quarks
- Probing new physics together with the rest of the world

$$e \qquad \mu \qquad \tau$$

The big picture

Why do we think there is NP?

Two types of reasons: data and beauty

- Data
    - Dark matter
    - Baryogenesis
    - Neutrino masses (?)
- Beauty
    - Cosmological constant
    - Hierarchy problem
    - Flavor hierarchy problem(s)
    - The strong CP problem
    - All the hints for a GUT

The simple flavor problem

Why flavor?

Flavor is interesting

- Fermion masses are (mainly) small and hierarchical
- FCNCs are very small
- The charged current is universal
- Quark mixing angles are small and hierarchical
- The patterns of leptons and quark flavors are different

Flavor seems to have a lot to tell us

The new physics flavor problem

The SM flavor puzzle: why the masses and mixing angles exhibit hierarchy. This is not what we refer to here

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The SM flavor structure is special

- Universality of the charged current interaction
- FCNCs are highly suppressed

Any NP model must reproduce these successful SM features

The new physics flavor scale

- K physics: ϵ_K

$$\frac{s\bar{d}s\bar{d}}{\Lambda^2} \quad \Rightarrow \quad \Lambda \gtrsim 10^5 \text{ TeV}$$

- Charged leptons: $\mu \to e\gamma$, $\mu \to e$, etc.

$$\frac{\mu\bar{e}f\bar{f}}{\Lambda^2} \quad \Rightarrow \quad \Lambda \gtrsim 10^3 \text{ TeV}$$

- There is no exact symmetry that can forbid such operators
- All other bounds on NP, like proton decay, maybe due to exact symmetry

Flavor and the hierarchy problem

There is tension:

- The hierarchy problem $\Rightarrow \Lambda \sim 1$ TeV
- Flavor bounds $\Rightarrow \Lambda > 10^5$ TeV

This tension is the NP flavor problem

Any TeV scale NP has to deal with the flavor bounds

$$\Downarrow$$

Such NP cannot have a generic flavor structure

Where is the tail?

Solution to the NP flavor problem

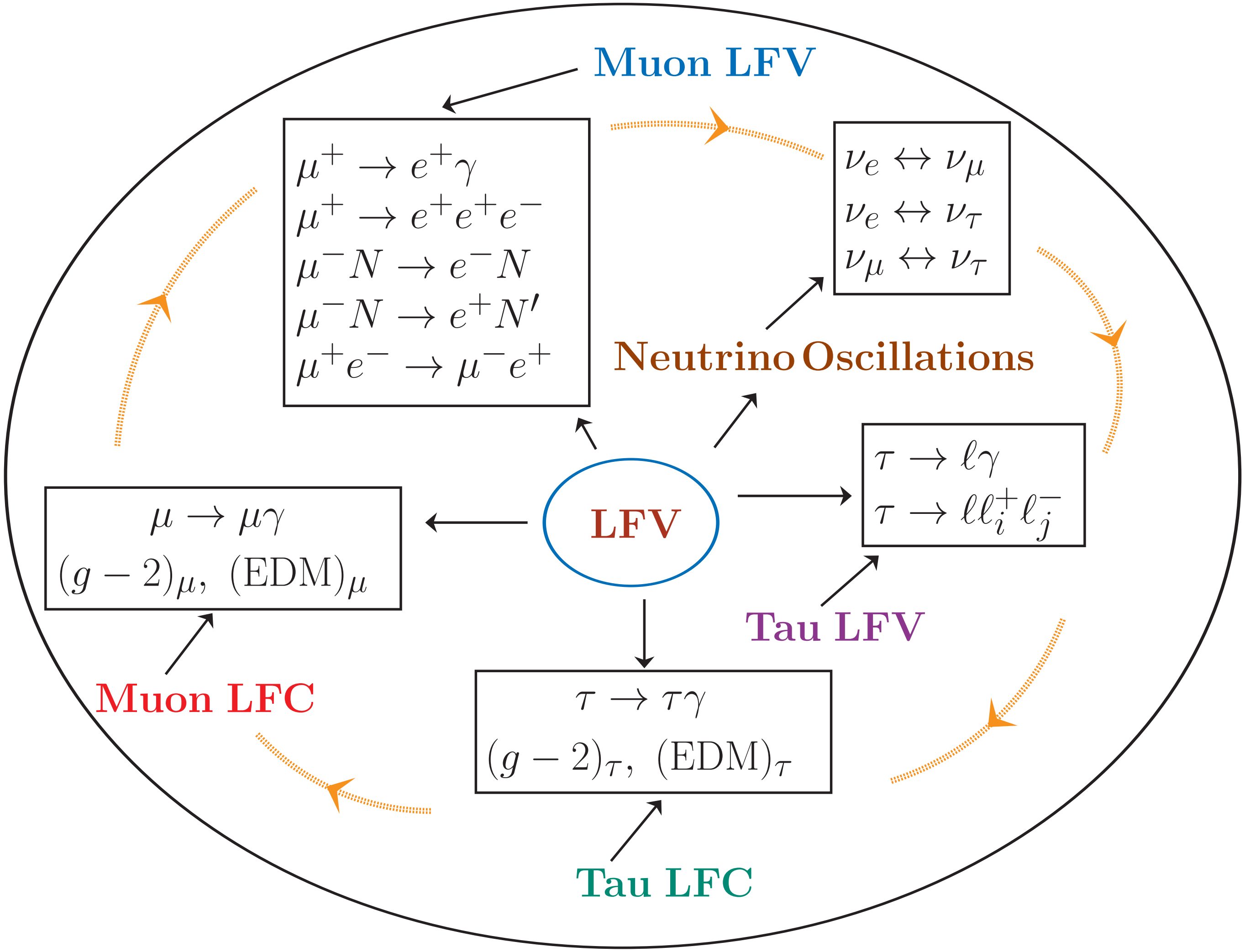
- No NP at the TeV
- There must be a structure in the TeV NP
    - Degeneracy
    - Alignment
    - Only top partners are light

Even if we find NP at the LHC, we have a problem: the inverse LHC problem

- We need flavor physics in either way

Synergy within charged leptons

The very basic of charged leptons



Muon LFV

$\mu^+ \to e^+\gamma$
$\mu^+ \to e^+e^+e^-$
$\mu^- N \to e^- N$
$\mu^- N \to e^+ N'$
$\mu^+ e^- \to \mu^- e^+$

$\nu_e \leftrightarrow \nu_\mu$
$\nu_e \leftrightarrow \nu_\tau$
$\nu_\mu \leftrightarrow \nu_\tau$

Neutrino Oscillations

LFV

$\mu \to \mu\gamma$
$(g-2)_\mu,\ (\mathrm{EDM})_\mu$

$\tau \to \ell\gamma$
$\tau \to \ell\ell_i^+\ell_j^-$

Tau LFV

Muon LFC

$\tau \to \tau\gamma$
$(g-2)_\tau,\ (\mathrm{EDM})_\tau$

Tau LFC

Thanks to Babu

Basic ideas

- No (or very small) hadronic uncertainties
- In many cases there is no “SM background”
- Large diversity of processes

$$
\begin{gathered}
g-2, \quad \mu \to e\gamma, \quad \mu \to eee, \\
\mu^- + A \to e^- + A, \quad \mu^- + A \to e^+ + A', \quad \mu^+ e^- \to \mu^- e^+, \\
\tau \to e\gamma, \quad \tau \to \mu\gamma, \quad \tau \to eee, \\
\tau \to \mu\mu\mu, \quad \tau^+ \to e^+\mu^+\mu^-, \quad \tau^+ \to \mu^+ e^+ e^-, \\
\tau \to \mu\pi, \quad \tau \to e\pi, \quad \tau \to \mu K_S,
\end{gathered}
$$

and more

The program

- A lot of related measurements
- This is similar to LHC or B factories, but
  - Multi-purpose experiments have one big apparatus and many analyses that are interconnected
  - Charged leptons experiments are smaller, but all of them together have much to probe
- Huge improvements in probing power are possible
  - The next 10-20 years we can improve different bounds by 2-5 orders of magnitude
  - Basically no theoretical uncertainties

Charged leptons and children

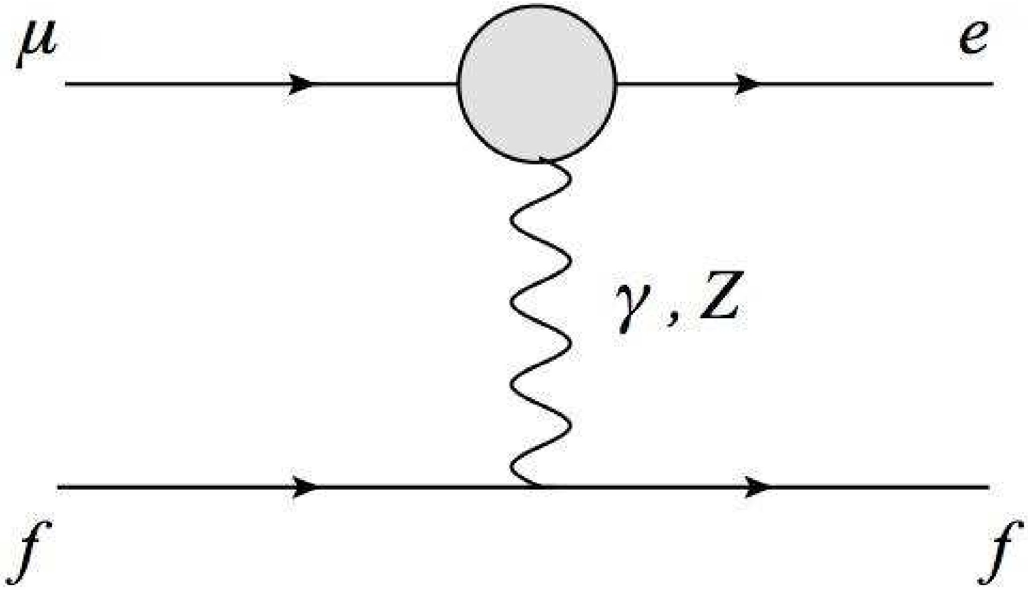
What I had in my fortune cookie:

Charged lepton processes are like your children:

they have a lot in common
and you love them all
but each is very different
and together it is much more fun

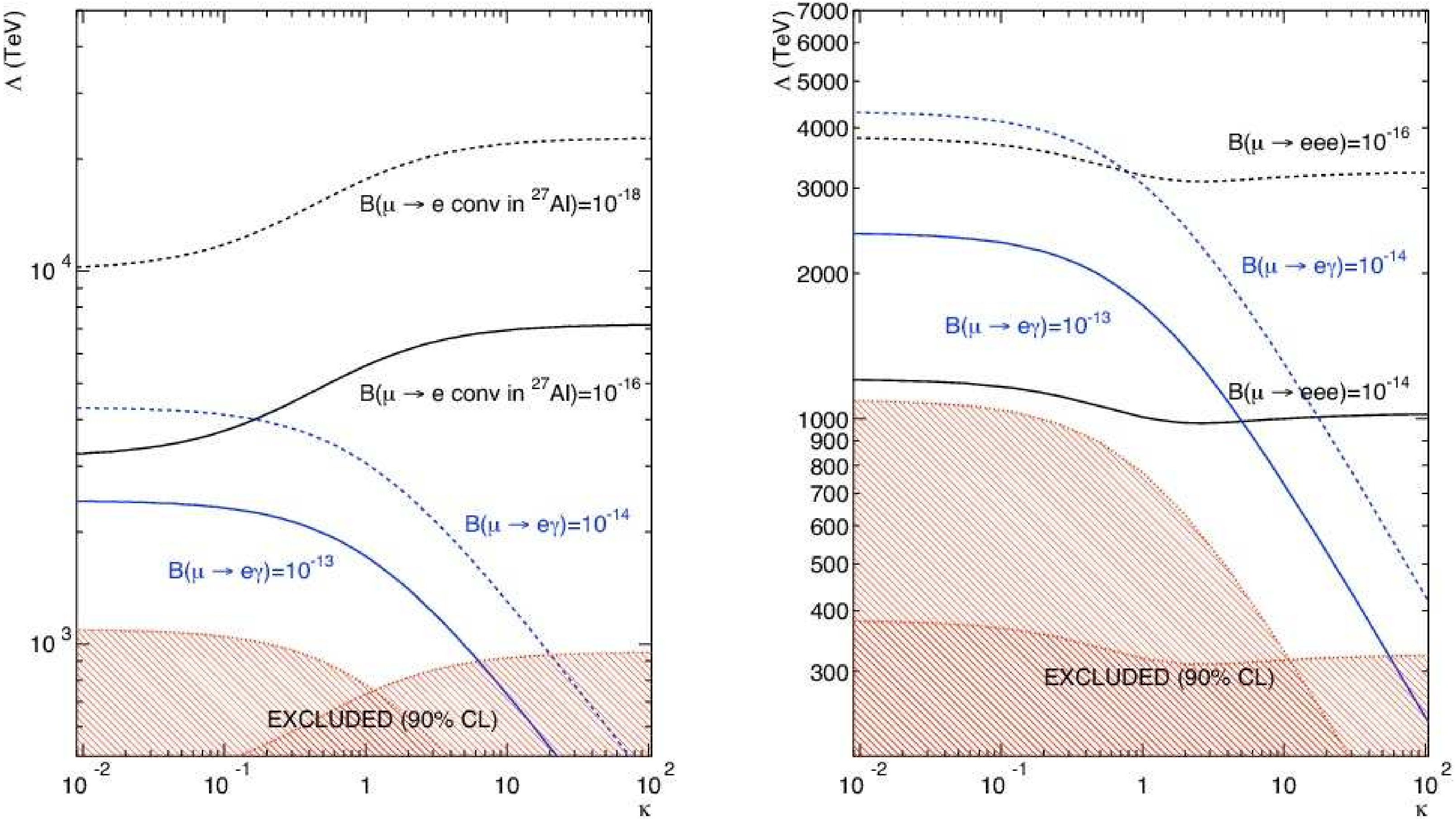
Interplay within the charged leptons

- There are many operators. Each mode is sensitive to a different set of them
- Example: $\mu \to e\gamma$ vs $\mu \to eee$ vs $\mu \to e$ conversion



Discriminating power

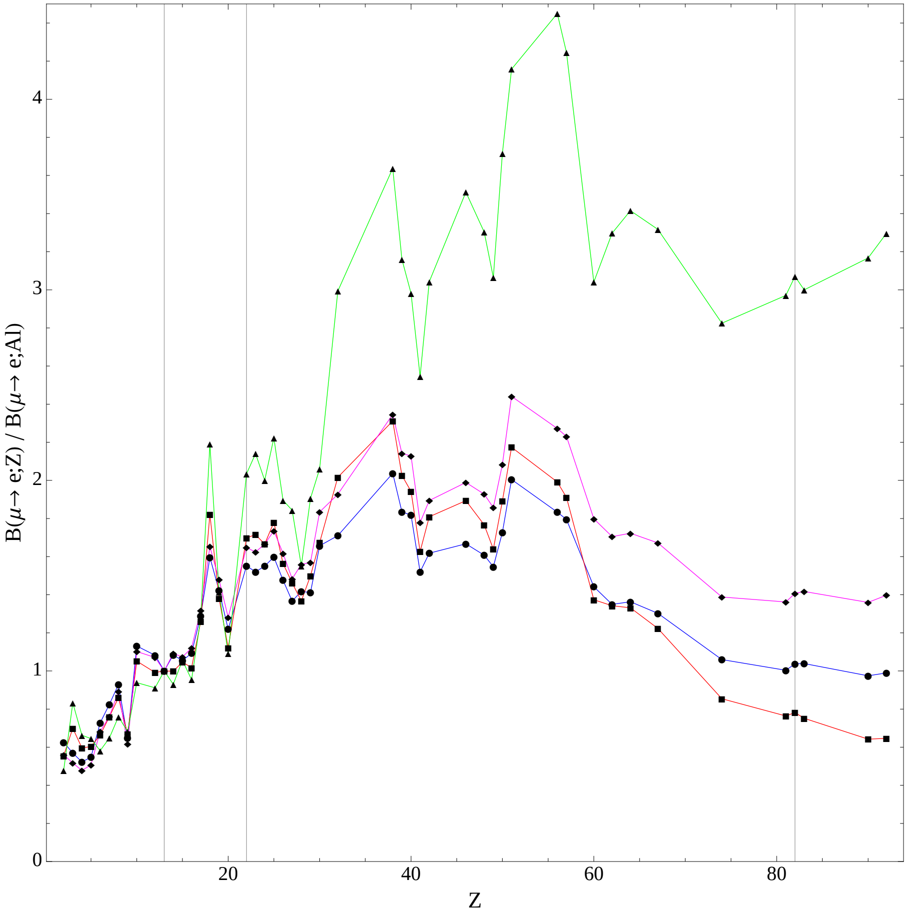
DeGouvea, Vogel, 2013



$\kappa \sim C_1/C_2$ ratio of two operators

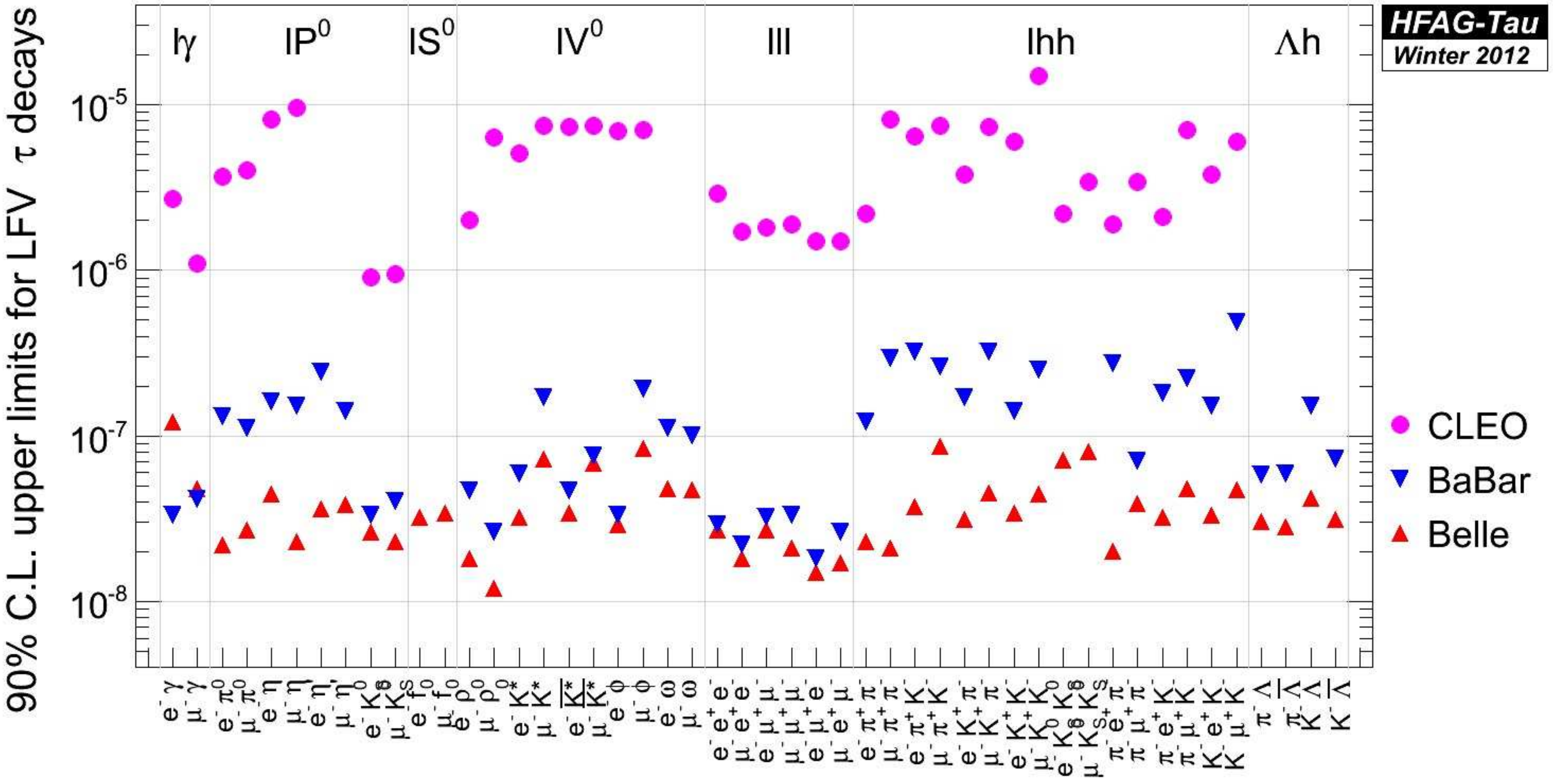
The power of $\mu \to e$

Cirigliano, Kitano, Okada, Tuzon, 2009



Al *Ti* *Pb*

Similar story for taus



Relation to neutrinos

Symmetries

Both charged leptons and neutrinos probe LFV, but they probe different operators

- Neutrino masses arise from the dim-5 $LLHH$ operator
- Charged leptons processes probe dim-6 operators, for example, μeee
- The fact that we established $m_\nu \neq 0$ implies that lepton flavor is a broken symmetry
- We promote the SM into the νSM

Charged leptons and neutrinos

- neutrino oscillations imply the breaking of lepton flavor symmetry
- Thus, we must have CLFV
- If all the breaking is from he operator that give neutrino masses, charged lepton flavor violation is tiny

$$\Gamma(\mu \to e\gamma) \propto \left(\frac{m_\nu}{m_W}\right)^4 \sim 10^{-54}$$

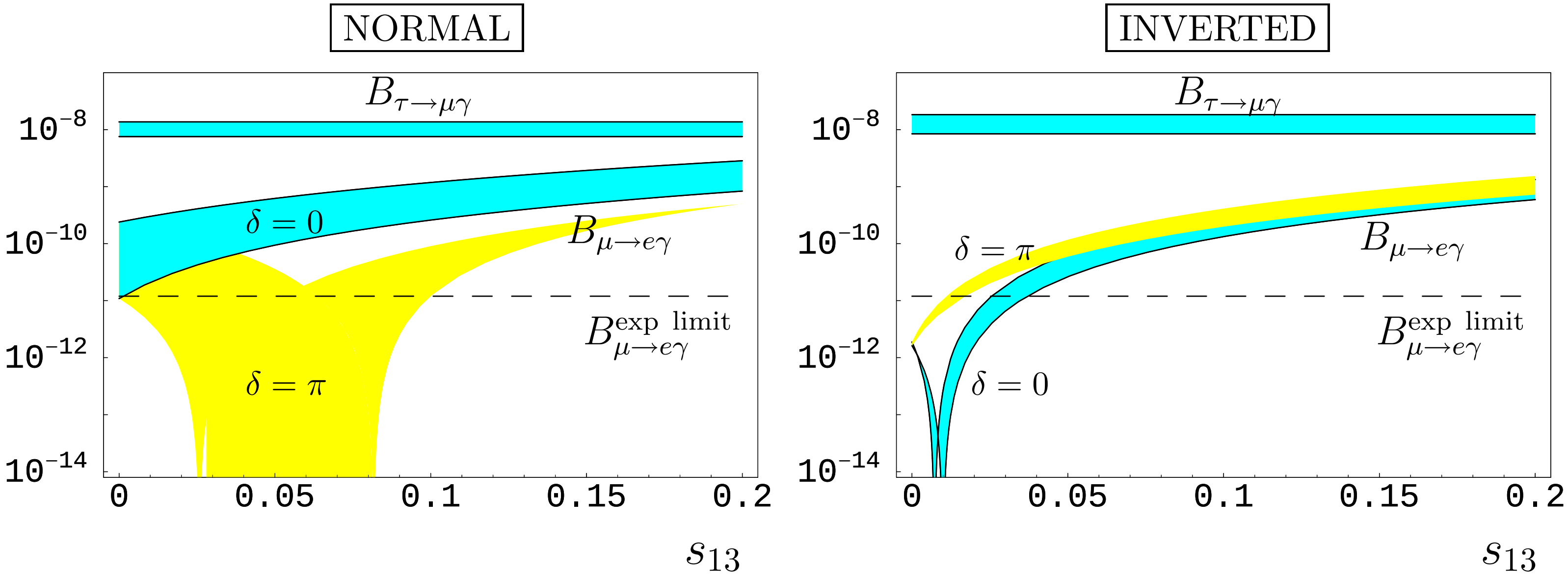
- More generally, if the scale of the dim-5 and dim-6 operators is the same, CLFV is tiny

CLFV probes physics beyond the νSM

Model relations

- While the operators for masses and CLFV decays are different they can be the same in specific models
- GUT, lepton MFV, RS, ...
- Example of MFV

Cirigliano, Grinstein, Isidori, Wise, 2005



BνSM, CLFV and NSI

If we find $\tau \to eee$, will it affect neutrino oscillation?

BνSM, CLFV and NSI

If we find $\tau \to eee$, will it affect neutrino oscillation?

Yes

- Neutrino oscillations are sensitive to Non Standard Interactions (NSIs)
- They can show up in matter effects or in the production or detection processes
- The effect in oscillations scale like the amplitude and not like the rate $\Rightarrow$ Enhanced sensitivity in neutrino oscillation experiments

NSI in neutrinos

- If the new operators involve the lepton doublets, it must be that

$$\mathcal{A}(\tau \to \mu) \sim \mathcal{A}(\nu_\tau \to \nu_\mu) = \varepsilon$$

- For neutrino oscillation we have interference

$$\Gamma(\tau \to \mu X) \propto |\varepsilon|^2 \qquad P(\nu_\mu \to \nu_\tau) \propto |\exp(-i\Delta E t) + \varepsilon|^2$$

- For small $x = \Delta m^2 L/(4E)$ we get

$$P(\nu_\mu \to \nu_\tau) \propto |\varepsilon|^2 + x^2 + 2xIm(\varepsilon)$$

Neutrinos and charged leptons

$$P(\nu_\mu \to \nu_\tau) \propto |\varepsilon|^2 + x^2 + 2xIm(\varepsilon) \qquad \Gamma(\tau \to \mu X) \propto |\varepsilon|^2$$

- NSIs affect oscillation experiments by changing the L/E dependence
- Both neutrinos and charged leptons can be relevant (linear vs quadratic)
- Charged lepton decays and neutrino oscillations can probe the same flavor violating operators
- The bound on muon CLFV are too strong to make NSIs in the $\mu - e$ sector relevant to neutrino oscillations
- Neutrino oscillations “win” on flavor conserving operators, like $ee\tau\tau$

Relation to the rest of physics

The connection to quarks

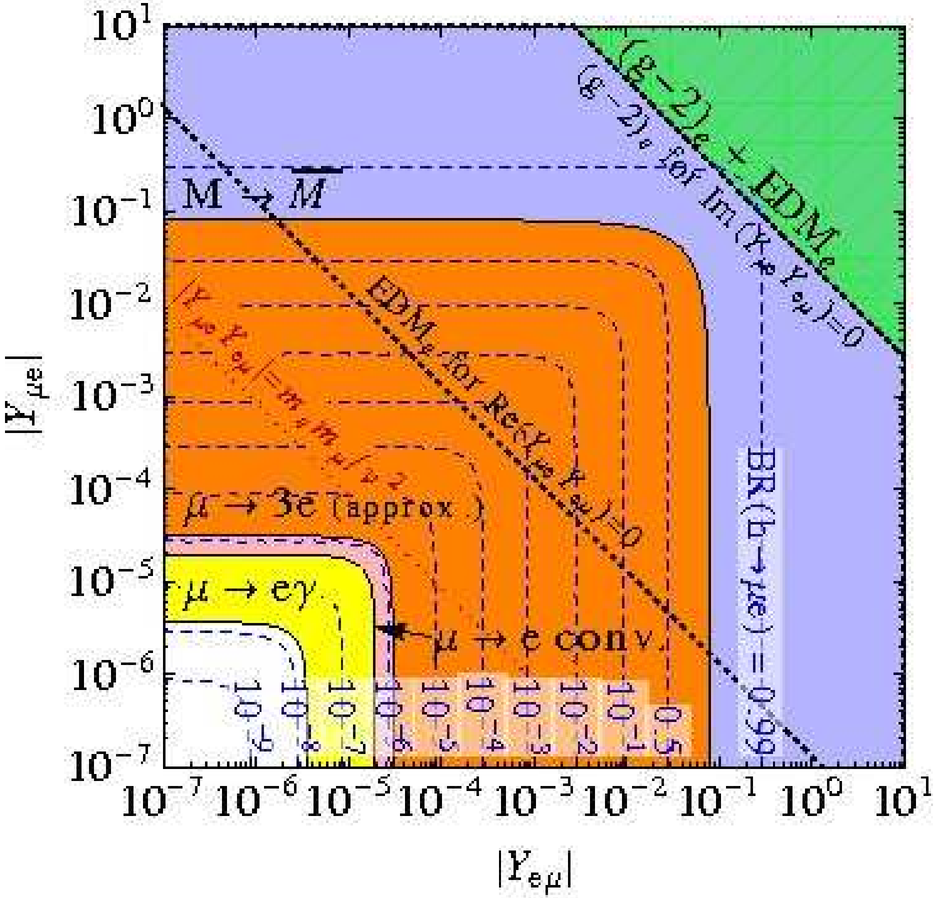
- Both quarks and leptons probe high energy scale via flavor violation
- For hadrons we have QCD. It makes it hard and interesting
- Charged leptons BRs are much smaller
- Why hadrons “win” in probing power?
- In meson we probe the amplitude, in charged leptons the rates
- Of course, quarks and leptons probe different operators

Connection to flavor at the LHC

- We can probe LFV operators at the LHC
- Hopefully, we will find NP that violate flavor
- How about $Z' \to e\mu$?
- CLFV low energy processes can help in finding more about the source of LFV
- We can also look for LFV effects in Higgs decays

Connection to flavor at the LHC

Harnik, Kopp, Zupan, 2012



Conclusions

Conclusion

- Theorists and experimentalist do not need to work on similar things
- Charged lepton flavor violation is so clean, so just go and measure it