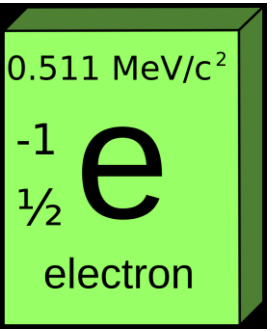
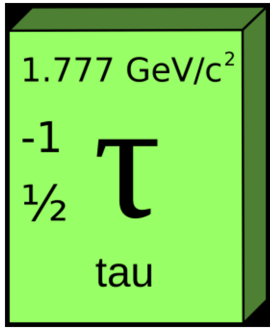
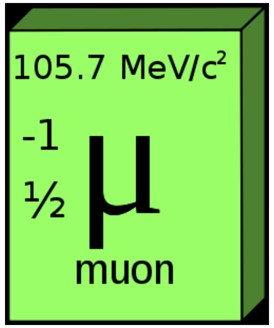
Charged leptons Physics: Precision BSM probes







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Cinvestav

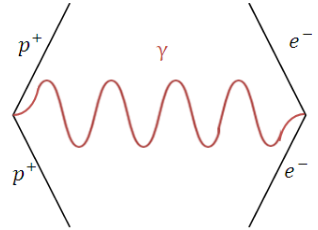
(See A. Pich's course at TAE 2018 and his several reviews on the topic available in inspires)

XVIII Mexican School of Particles & Fields

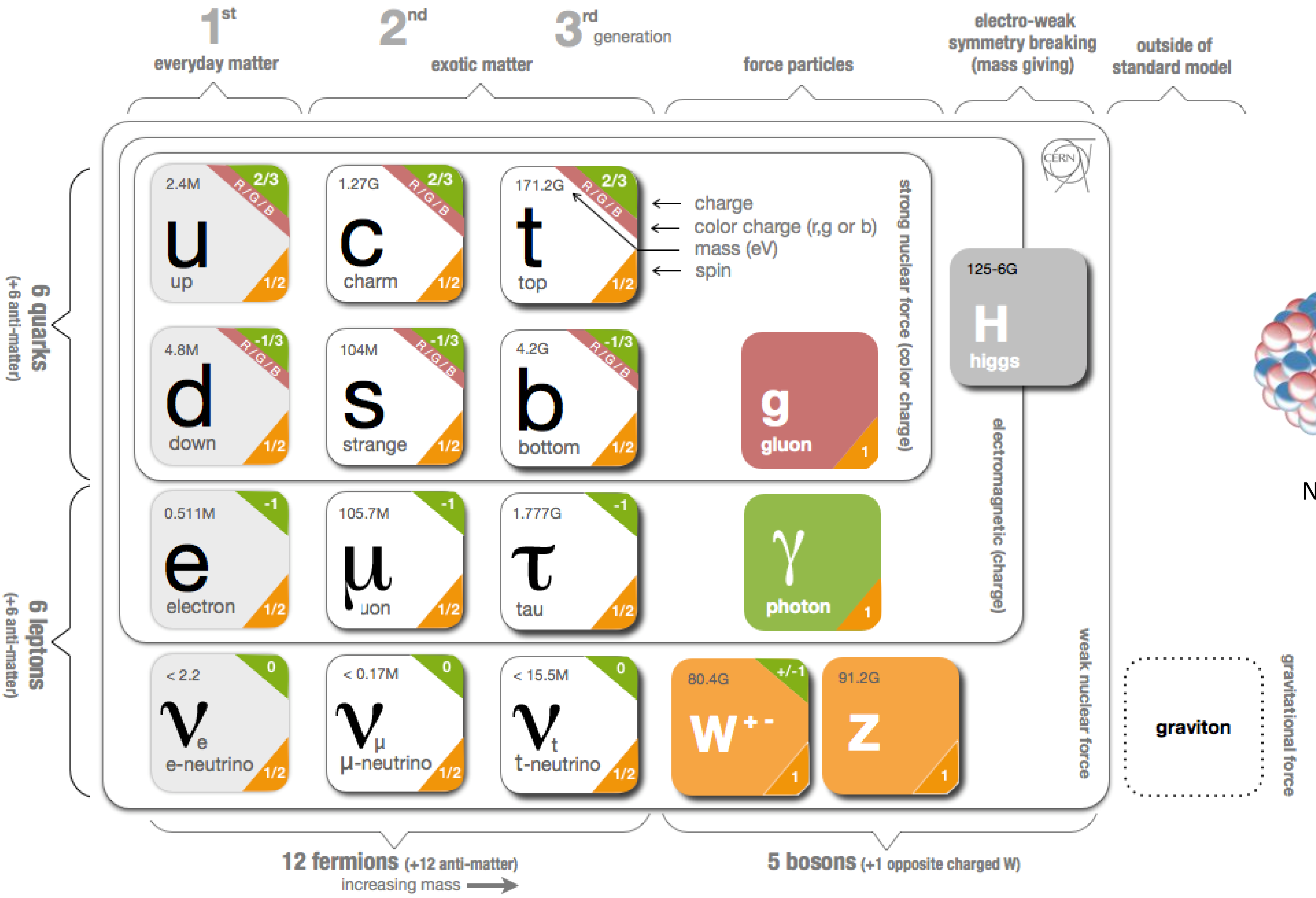
2018 University of Sonora School of High Energy Physics

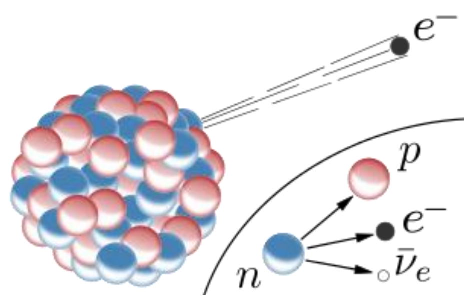
21-27 October 2018 Hermosillo, Sonora

BASICS

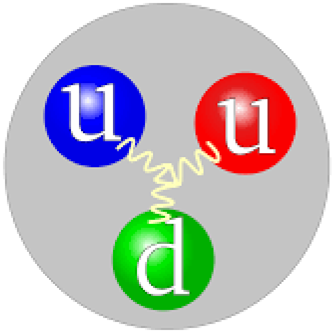


Electromagnetic interaction in the H atom





Nuclear β decay



Proton made up of quarks bond by gluon exchanges

BASICS

Matter content

$$\begin{bmatrix} \nu_e & u \\ e^- & d \end{bmatrix}, \qquad \begin{bmatrix} \nu_\mu & c \\ \mu^- & s \end{bmatrix}, \qquad \begin{bmatrix} \nu_\tau & t \\ \tau^- & b \end{bmatrix},$$

Generates flavor

Gauge symmetry & its breaking

$$SU(3)_C \otimes SU(2)_L \otimes U(1)_Y \xrightarrow{\text{SSB}} SU(3)_C \otimes U(1)_{QED}$$

$$\begin{bmatrix} \nu_l & q_u \\ l^- & q_d \end{bmatrix} \equiv \begin{pmatrix} \nu_l \\ l^- \end{pmatrix}_L, \quad \begin{pmatrix} q_u \\ q_d \end{pmatrix}_L, \quad l^-_R, \quad (q_u)_R, \quad (q_d)_R$$

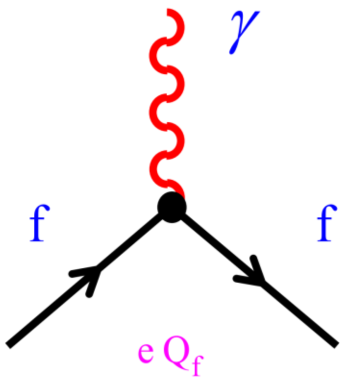
$\nu_{l\,R}$

$l = e, \mu, \tau$; $q_u = u, c, t$; $q_d = d, s, b$

BASICS

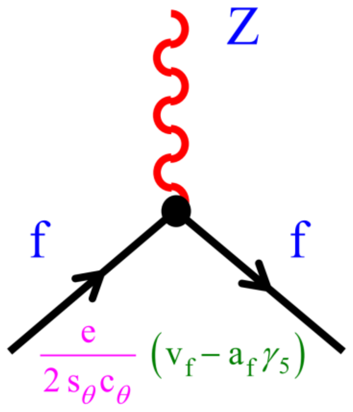
Universality: Family–Independent Couplings

Both in terms of flavor or mass eigenstates

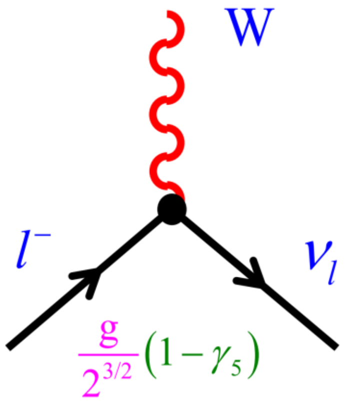


NEUTRAL CURRENTS

Flavour Conserving



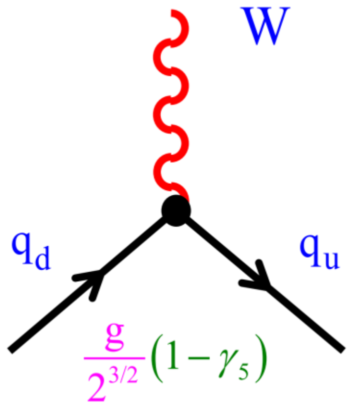
In terms of flavor eigenstates



CHARGED CURRENTS

Flavour Changing

Left Handed



In terms of mass eigenstates V_{CKM}/U_{PMNS} appear

Unitary if no extra matter

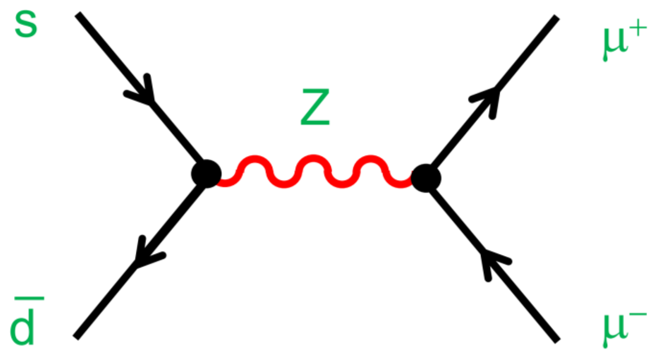
BASICS

Flavour Conserving Neutral Currents (GIM)

$$\mathcal{L}_{NC}^{Z} = -\frac{e}{2\sin\theta_W\cos\theta_W} Z_\mu \sum_f \bar{f}\,\gamma^\mu\left[v_f - a_f\,\gamma_5\right] f$$

They arise at one-loop in the SM (quantum phenomena)

What are the one-loop diagrams in the SM for $K^0 \to \mu\,\mu$?



NO

$$Br(K_L \to \mu^+\mu^-) = (6.84 \pm 0.11)\times 10^{-9} \quad , \quad Br(K_S \to \mu^+\mu^-) < 1.0\times 10^{-9} \quad (95\%\ \mathrm{CL})$$

LHCb, 1706.00758

$$K_L \to \pi^{0*} \to (\gamma\gamma)^* \to \mu^+\mu^-$$

$$K_S \to (\pi^+\pi^-)^* \to (\gamma\gamma)^* \to \mu^+\mu^-$$

BASICS

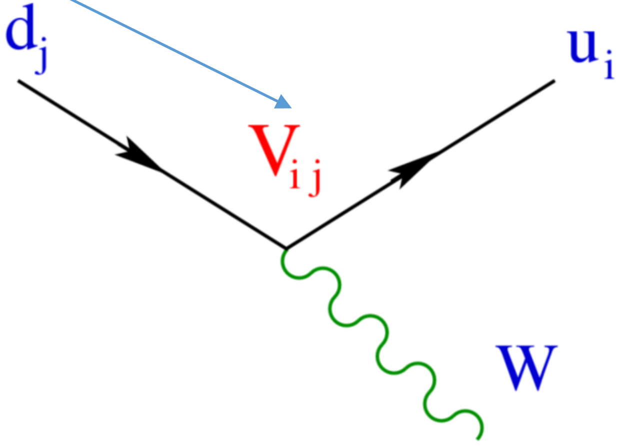
Flavour Changing Charged Currents

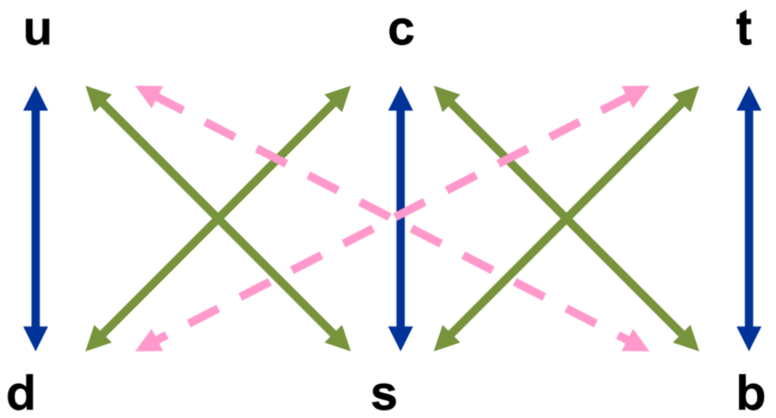
$$\mathcal{L}_{CC} = -\frac{g}{2\sqrt{2}}\, W^{\dagger}_{\mu} \left[\sum_{ij} \bar{u}_i \gamma^{\mu} (1-\gamma_5)\, \mathbf{V}_{ij}\, d_j + \sum_{l} \bar{\nu}_l \gamma^{\mu} (1-\gamma_5)\, l \right] + \text{h.c.}$$

$$\left(\bar{\nu}_{l_j} \equiv \bar{\nu}_i \; \mathbf{V}^{(l)}_{ij} \right)$$

It is mathematically analogous for leptons (for massive neutrinos)

Wolfenstein parametrization is very useful for grasping easily the associated Physics

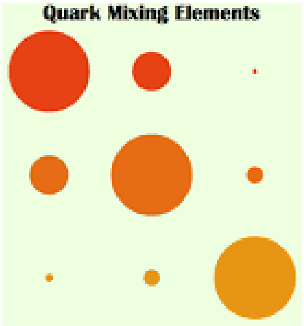


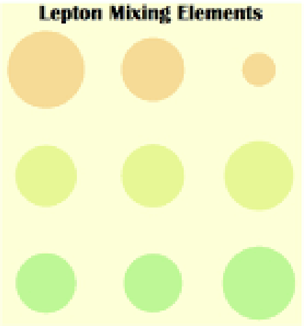


BASICS

Flavour Changing Charged Currents

$$\boxed{\mathcal{L}_{CC} = -\frac{g}{2\sqrt{2}} W_\mu^\dagger \left[\sum_{ij} \bar{u}_i \gamma^\mu (1-\gamma_5) \mathbf{V}_{ij} d_j + \sum_l \bar{\nu}_l \gamma^\mu (1-\gamma_5) l \right] + \text{h.c.}}$$





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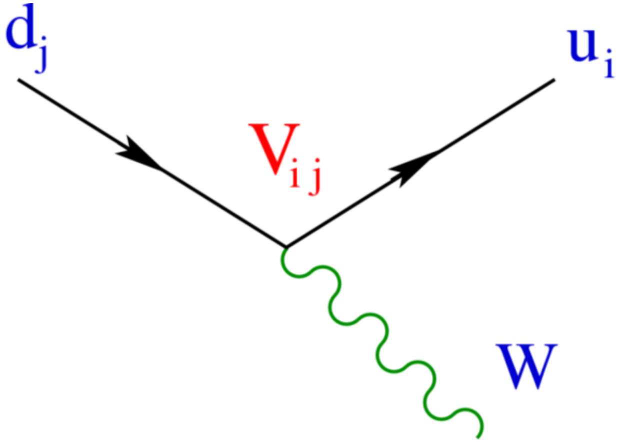
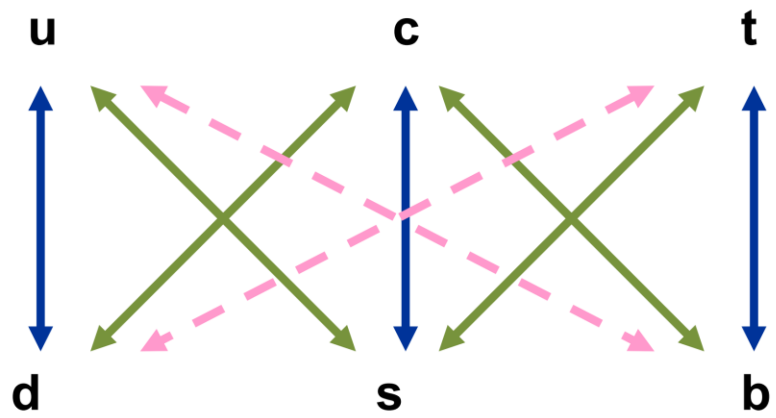
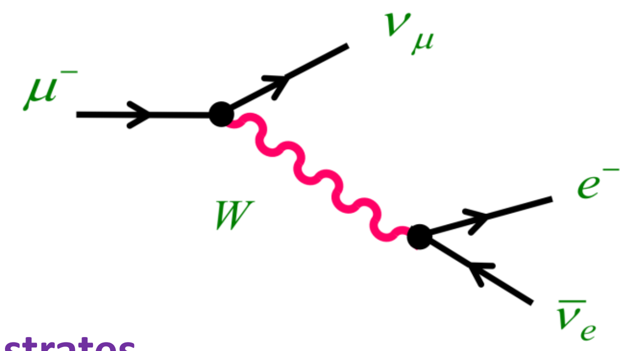
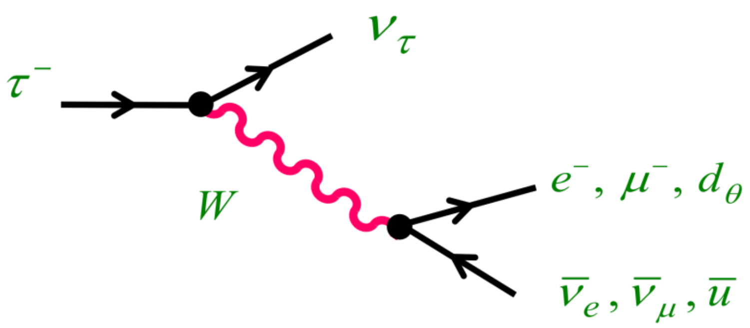
It is **mathematically** analogous for leptons (for massive neutrinos)

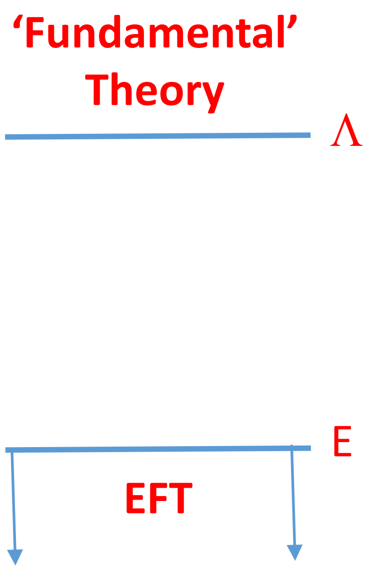




Weak Decays







This illustrates how an EFT works

$$T(l \to \nu_l\, l' \bar{\nu}_{l'}) \sim \frac{g^2}{M_W^2 - q^2} \xrightarrow{q^2 << M_W^2} \frac{g^2}{M_W^2} = 4\sqrt{2}\, G_F$$

Can you derive this dependence with dimensional analysis?

This dependence is fundamental for LU tests

$$\boxed{\frac{1}{\tau_\mu} = \frac{G_F^2 m_\mu^5}{192\pi^3} f(m_e^2/m_\mu^2)\, r_{EW} \quad \Longrightarrow \quad G_F = (1.166\,378\,7 \pm 0.000\,000\,6) \times 10^{-5}\ \mathrm{GeV}^{-2}}$$

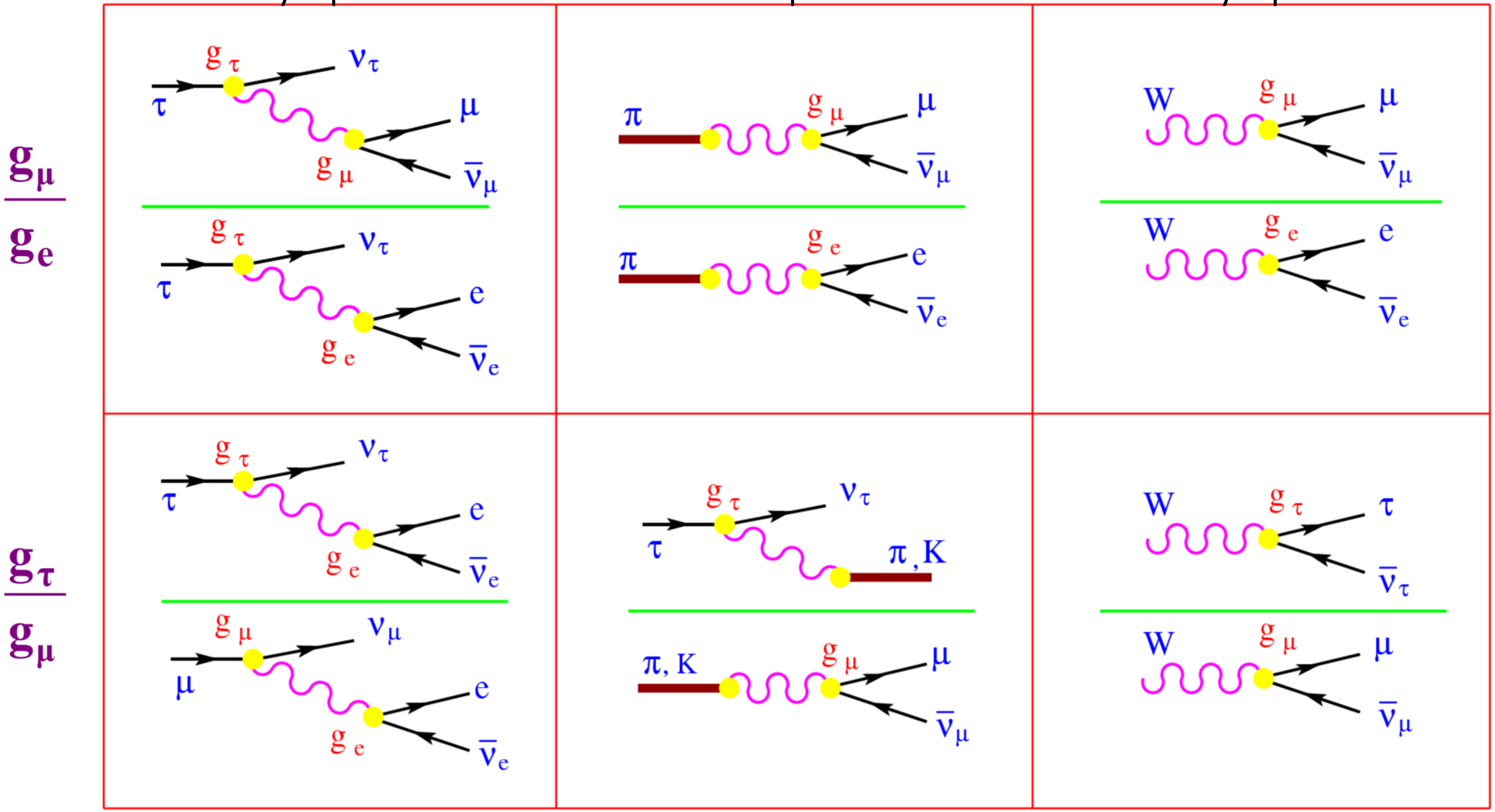
$$r_{EW} = \left[1 + \frac{\alpha(m_\mu)}{2\pi}\left(\frac{25}{4} - \pi^2\right) + C_2 \frac{\alpha(m_\mu)^2}{\pi^2}\right] = 0.9958 \qquad ; \qquad f(x) = 1 - 8x + 8x^3 - x^4 - 12x^2 \log x$$

BASICS

LEPTON UNIVERSALITY

Complementary Complementary

Only leptonic Semileptonic Only leptonic



BASICS

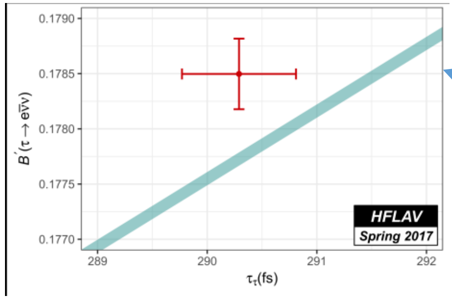
CHARGED CURRENT UNIVERSALITY

(I will discuss its Lorentz structure tomorrow)

$|g_\mu / g_e|$

$B_{\tau\to\mu}/B_{\tau\to e}$	1.0018 ± 0.0014
$B_{\pi\to\mu}/B_{\pi\to e}$	1.0021 ± 0.0016
$B_{K\to\mu}/B_{K\to e}$	0.9978 ± 0.0020
$B_{K\to\pi\mu}/B_{K\to\pi e}$	1.0010 ± 0.0025
$B_{W\to\mu}/B_{W\to e}$	0.996 ± 0.010

Belle-II Physics Book



How can this be possible?

$|g_\tau / g_\mu|$

$B_{\tau\to e}\ \tau_\mu/\tau_\tau$	1.0011 ± 0.0015
$\Gamma_{\tau\to\pi}/\Gamma_{\pi\to\mu}$	0.9962 ± 0.0027
$\Gamma_{\tau\to K}/\Gamma_{K\to\mu}$	0.9858 ± 0.0070
$B_{W\to\tau}/B_{W\to\mu}$	1.034 ± 0.013

Rad Cors not properly understood

$|g_\tau / g_e|$

$B_{\tau\to\mu}\ \tau_\mu/\tau_\tau$	1.0030 ± 0.0015
$B_{W\to\tau}/B_{W\to e}$	1.031 ± 0.013

Difficult to explain without spoiling other ratios

A. Pich, arXiv:1310.7922

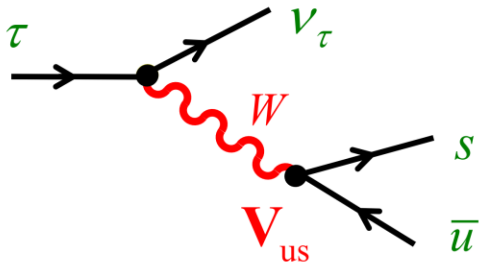
BASICS

Inclusive analysis of τ decay width

$\Gamma(K^+ \to \mu^+ \nu_\mu) / \Gamma(\pi^+ \to \mu^+ \nu_\mu)$

$$\frac{|V_{us}|}{|V_{ud}|} = 0.2313 \pm 0.007$$

$$R_{\tau,us} = \frac{\Gamma(\tau^- \to \nu_\tau X_s^-)}{\Gamma(\tau^- \to \nu_\tau e^- \bar{\nu}_e)}$$



$K \to \pi \ell \nu$

$$|V_{us}| = 0.2231 \pm 0.0007$$

Gámiz-Jamin-Pich-Prades-Schwab

$$\delta R_\tau \equiv \frac{R_{\tau,ud}}{|V_{ud}|^2} - \frac{R_{\tau,us}}{|V_{us}|^2} \approx 24 \frac{m_s^2(m_\tau^2)}{m_\tau^2} \Delta(\alpha_s) = 0.240 \pm 0.032$$

$$\boxed{|V_{us}|^2 = \frac{R_{\tau,S}}{\frac{R_{\tau,ud}}{|V_{ud}|^2} - \delta R_\tau^{th}}}$$

HFAG 2016: $R_{\tau,ud} = 3.4718 \pm 0.0072$; $R_{\tau,S} = 0.1633 \pm 0.0027$

$$\boxed{|V_{us}| = 0.2186 \pm 0.0018_{exp} \pm 0.0010_{th}}$$

Belle-II Physics Book

Replacing $\tau \to \nu K(\pi)$ by $K \to \nu \mu(\pi)$ data: $|V_{us}| = 0.2213 \pm 0.0023$

With better data, could give a very precise V_{us} determination

BASICS

Inclusive analysis of τ decay width

$\Gamma(K^+ \to \mu^+ \nu_\mu) / \Gamma(\pi^+ \to \mu^+ \nu_\mu)$

$$\frac{|V_{us}|}{|V_{ud}|} = 0.2313 \pm 0.007$$

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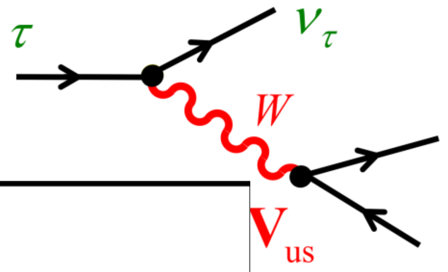


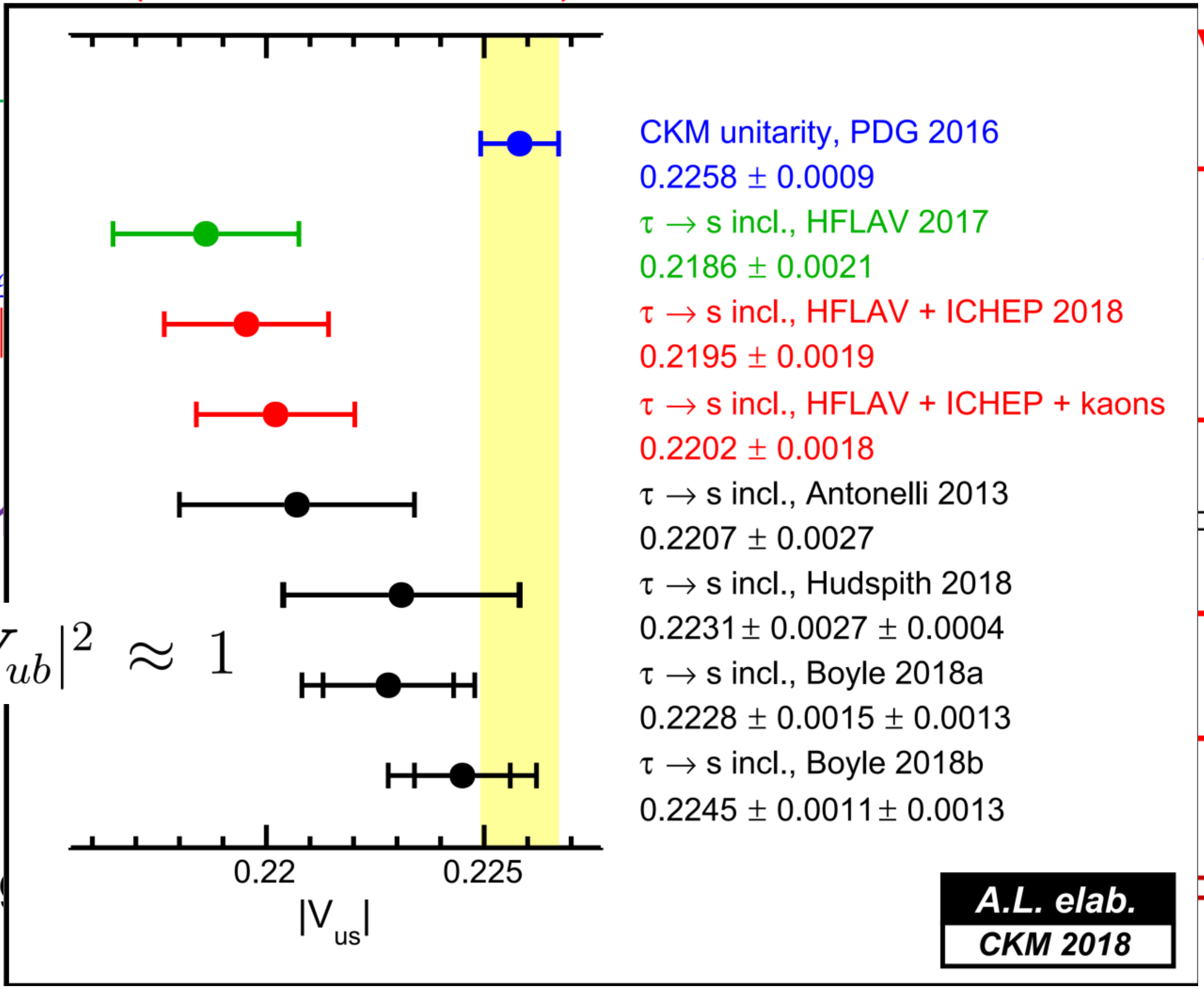
Gámiz-Jamin-

$$\delta R_\tau \equiv \frac{R_{\tau,ud}}{|V_{ud}|}$$

$$\frac{R_{\tau,S}}{\frac{R_{\tau,ud}}{|V_{ud}|^2} - \delta R_\tau^{\rm th}}$$

HFAG 201

± 0.0027



See, however, arXiv: 1807.10197(hep-ph)

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

UNITARITY

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Replacin

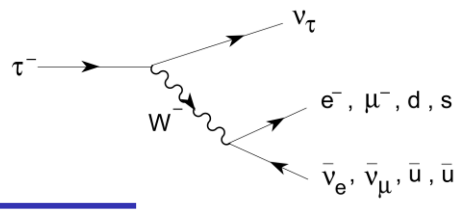
± 0.0023

With better data, could give a very precise V_{us} determination

$$R_\tau = \frac{\Gamma[\tau^- \to \nu_\tau \text{hadrons}]}{\Gamma[\tau^- \to \nu_\tau e^- \overline{\nu}_e]} = R_{\tau,V} + R_{\tau,A} + R_{\tau,S}$$

BASICS

Inclusive analysis of τ decay width



α_s at N^{3}LO from τ and Z

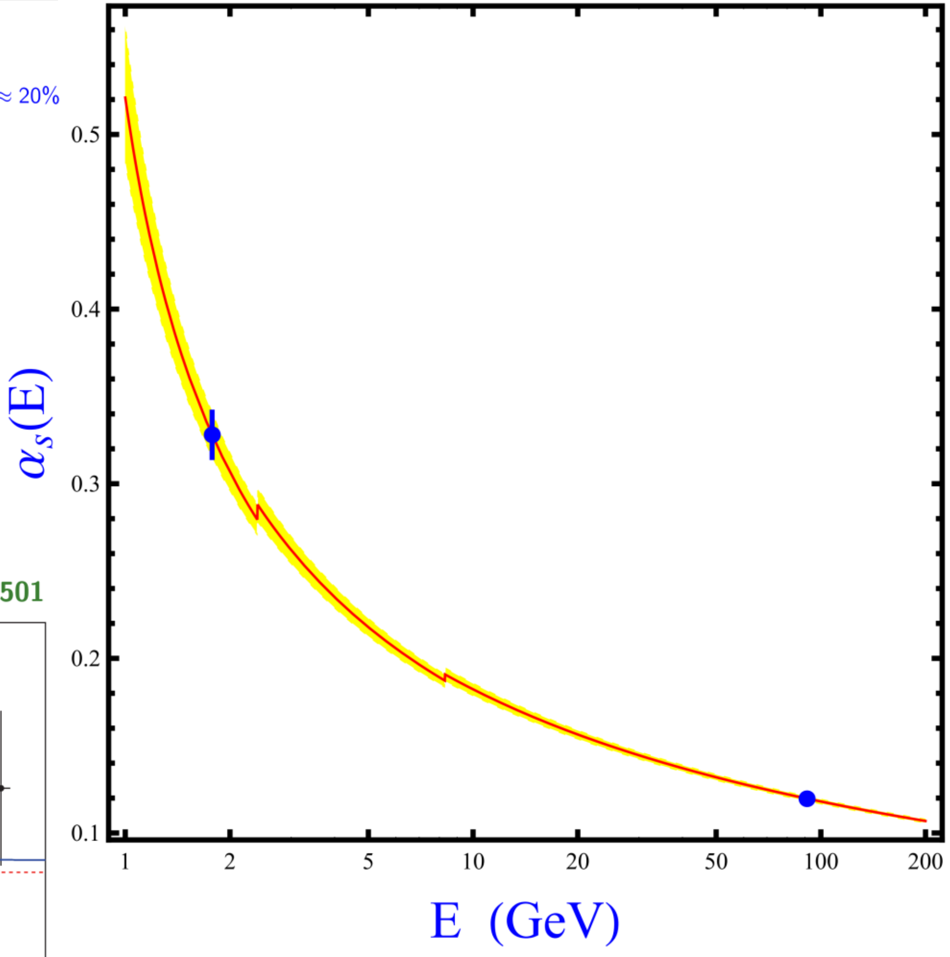
Braaten-Narison-Pich '92

$$\mathbf{R_\tau = N_C\, S_{EW}\, (1 + \delta_P + \delta_{NP})}$$

Baikov-Chetyrkin-Kühn '08

$\delta_P = a_\tau + 5.20\, a_\tau^2 + 26\, a_\tau^3 + 127\, a_\tau^4 + \cdots \approx 20\%$

$a_\tau \equiv \alpha_s(m_\tau^2)/\pi$



$$\alpha_s(m_\tau^2) = 0.328 \pm 0.013$$

Rodríguez-Sánchez, Pich, arXiv:1605.06830

$$\alpha_s(M_Z^2) = 0.1197 \pm 0.0015$$

$$\alpha_s(M_Z^2)_{\text{Z width}} = 0.1196 \pm 0.0030$$

A very precise test of Asymptotic Freedom

$$\boxed{\alpha_s^\tau(M_Z^2) - \alpha_s^Z(M_Z^2) = 0.0001 \pm 0.0015_\tau \pm 0.0030_Z}$$

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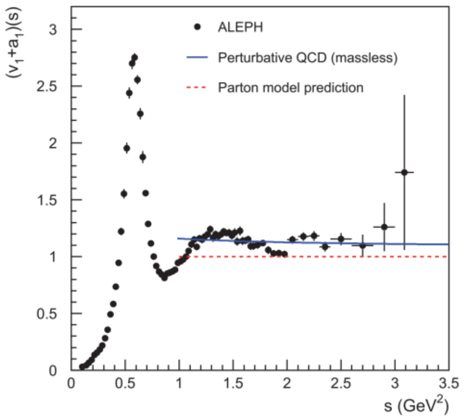
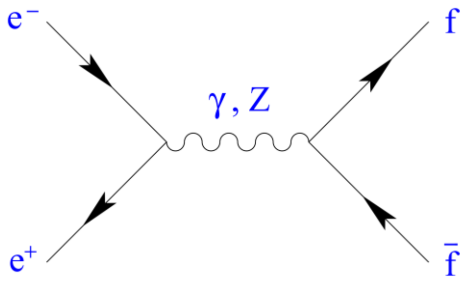
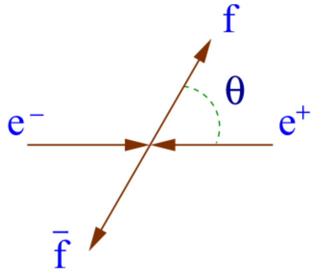
Davier et al, 1312.1501



$$\alpha_s(M_Z^2)_{\text{Lattice}} = 0.11852 \pm 0.00084$$

(ALPHA, arXiv:1706.03821)





BASICS

Neutral current couplings of leptons

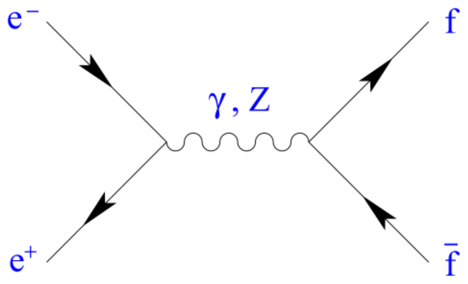
$$v_f = T_3^f (1 - 4\,|Q_f|\,\sin^2\theta_W) \qquad a_f = T_3^f$$

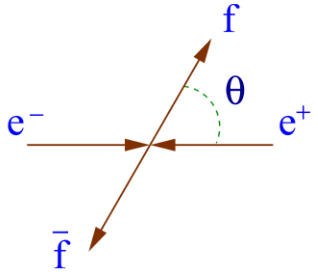
$$\mathcal{L}_{\rm NC}^{Z} = -\frac{g}{2\cos\theta_W}\, Z_\mu \sum \bar{f}\gamma^\mu (v_f - a_f\gamma_5) f\,,$$

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{8s}\,\left\{A\,(1+\cos^2\theta) + B\,\cos\theta - h_\ell\,\left[C\,(1+\cos^2\theta) + D\cos\theta\right]\right\},$$

$$\begin{aligned}
A &= 1 + 2\,v_e v_\ell\,\mathrm{Re}(\chi) + \left(v_e^2 + a_e^2\right)\left(v_\ell^2 + a_\ell^2\right)|\chi|^2\,,\\
B &= 4\,a_e a_\ell\,\mathrm{Re}(\chi) + 8\,v_e a_e v_\ell a_\ell|\chi|^2\,,\\
C &= 2\,v_e a_l\,\mathrm{Re}(\chi) + 2\left(v_e^2 + a_e^2\right) v_\ell a_\ell|\chi|^2\,,\\
D &= 4\,a_e v_\ell\,\mathrm{Re}(\chi) + 4\,v_e a_e\left(v_\ell^2 + a_\ell^2\right)|\chi|^2\,,
\end{aligned}$$

$$\chi = \frac{G_F M_Z^2}{2\sqrt{2}\pi\alpha}\,\frac{s}{s - M_Z^2 + is\Gamma_Z/M_Z}\,.$$





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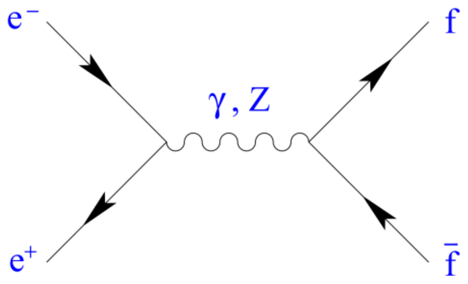
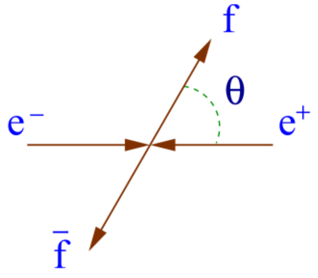
$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{8s} \left\{ A\,(1+\cos^2\theta) + B\,\cos\theta - h_\ell \left[C\,(1+\cos^2\theta) + D\cos\theta \right] \right\},$$

Experimental determination of the previous coefficients is possible:

$$\sigma(s) = \frac{4\pi\alpha^2}{3s} A\,, \quad \mathcal{A}_{\rm FB}(s) \equiv \frac{N_F - N_B}{N_F + N_B} = \frac{3}{8}\frac{B}{A}\,, \quad \mathcal{A}_{\rm Pol}(s) \equiv \frac{\sigma^{(h_\ell=+1)} - \sigma^{(h_\ell=-1)}}{\sigma^{(h_\ell=+1)} + \sigma^{(h_\ell=-1)}} = -\frac{C}{A}\,,$$

$$\mathcal{A}_{\rm FB,Pol}(s) \equiv \frac{N_F^{(h_\ell=+1)} - N_F^{(h_\ell=-1)} - N_B^{(h_\ell=+1)} + N_B^{(h_\ell=-1)}}{N_F^{(h_\ell=+1)} + N_F^{(h_\ell=-1)} + N_B^{(h_\ell=+1)} + N_B^{(h_\ell=-1)}} = -\frac{3}{8}\frac{D}{A}\,.$$





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$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{8s}\left\{A\,(1+\cos^2\theta) + B\,\cos\theta - h_\ell\left[C\,(1+\cos^2\theta) + D\cos\theta\right]\right\},$$

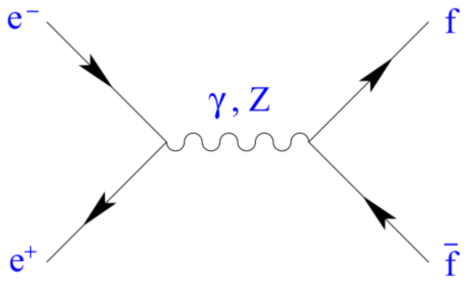
At the Z-peak (LEP), these simplify and get related:

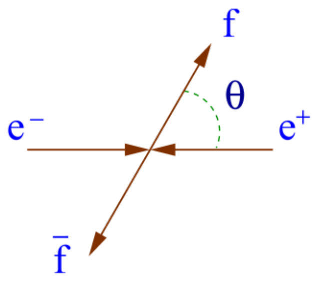
$$\sigma^{0,\ell} \equiv \sigma(M_Z^2) = \frac{12\pi}{M_Z^2}\frac{\Gamma_e\Gamma_\ell}{\Gamma_Z^2}\,, \qquad \mathcal{A}_{\rm FB}^{0,\ell} \equiv \mathcal{A}_{FB}(M_Z^2) = \frac{3}{4}\mathcal{P}_e\mathcal{P}_\ell\,,$$

$$\mathcal{P}_\ell \equiv \frac{-2v_\ell a_\ell}{v_\ell^2 + a_\ell^2}$$

$$\mathcal{A}_{\rm Pol}^{0,\ell} \equiv \mathcal{A}_{\rm Pol}(M_Z^2) = \mathcal{P}_\ell\,, \qquad \mathcal{A}_{\rm FB,Pol}^{0,\ell} \equiv \mathcal{A}_{\rm FB,Pol}(M_Z^2) = \frac{3}{4}\mathcal{P}_e\,,$$

$$\Gamma_\ell \equiv \Gamma(Z\to\ell^+\ell^-) = \frac{G_F M_Z^3}{6\pi\sqrt{2}}\,(v_\ell^2 + a_\ell^2)\,\left(1+\delta_{\rm RC}^Z\right)$$





BASICS

Neutral current couplings of leptons

$$v_f = T_3^f (1 - 4|Q_f| \sin^2\theta_W) \qquad a_f = T_3^f$$

$$\mathcal{L}_{\rm NC}^{Z} = -\frac{g}{2\cos\theta_W} Z_\mu \sum \bar{f}\gamma^\mu (v_f - a_f\gamma_5) f\,,$$

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{8s}\left\{A\,(1+\cos^2\theta) + B\,\cos\theta - h_\ell\left[C\,(1+\cos^2\theta) + D\cos\theta\right]\right\},$$

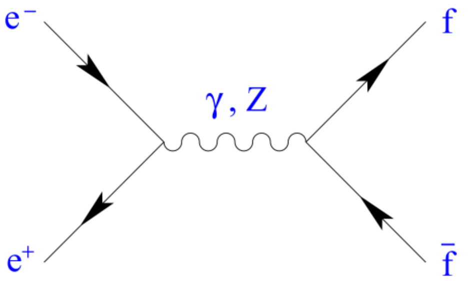
With polarized e-beams (SLC) one can further measure:

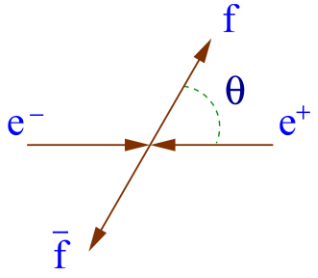
$$\mathcal{A}_{\rm LR}^{0} \equiv \mathcal{A}_{\rm LR}(M_Z^2) = \frac{\sigma_L(M_Z^2) - \sigma_R(M_Z^2)}{\sigma_L(M_Z^2) + \sigma_R(M_Z^2)} = -\mathcal{P}_e\,, \qquad \mathcal{A}_{\rm FB,LR}^{0,\ell} \equiv \mathcal{A}_{\rm FB,LR}(M_Z^2) = -\frac{3}{4}\mathcal{P}_\ell\,.$$

$$\mathcal{P}_\ell \equiv \frac{-2v_\ell a_\ell}{v_\ell^2 + a_\ell^2}$$

BASICS

Neutral current couplings of leptons





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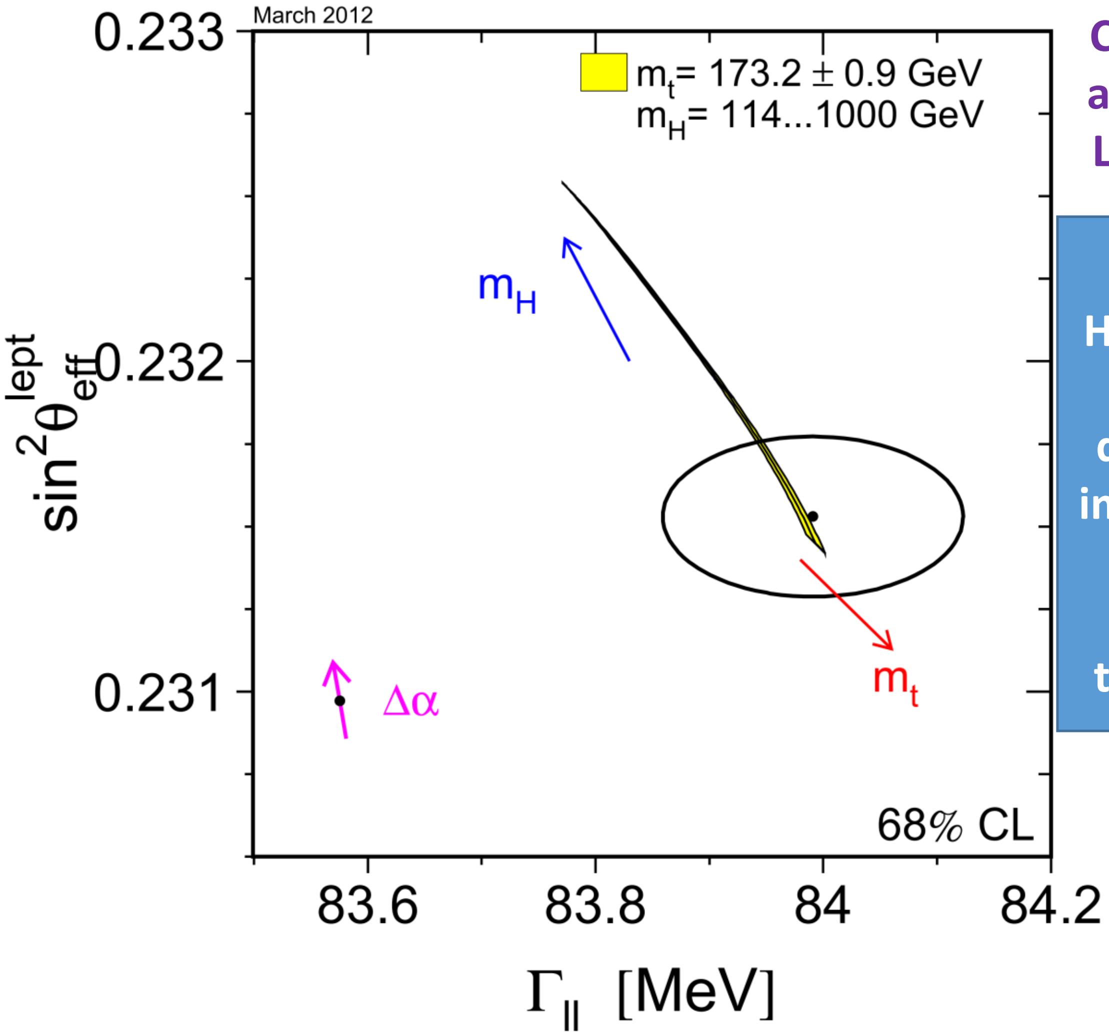
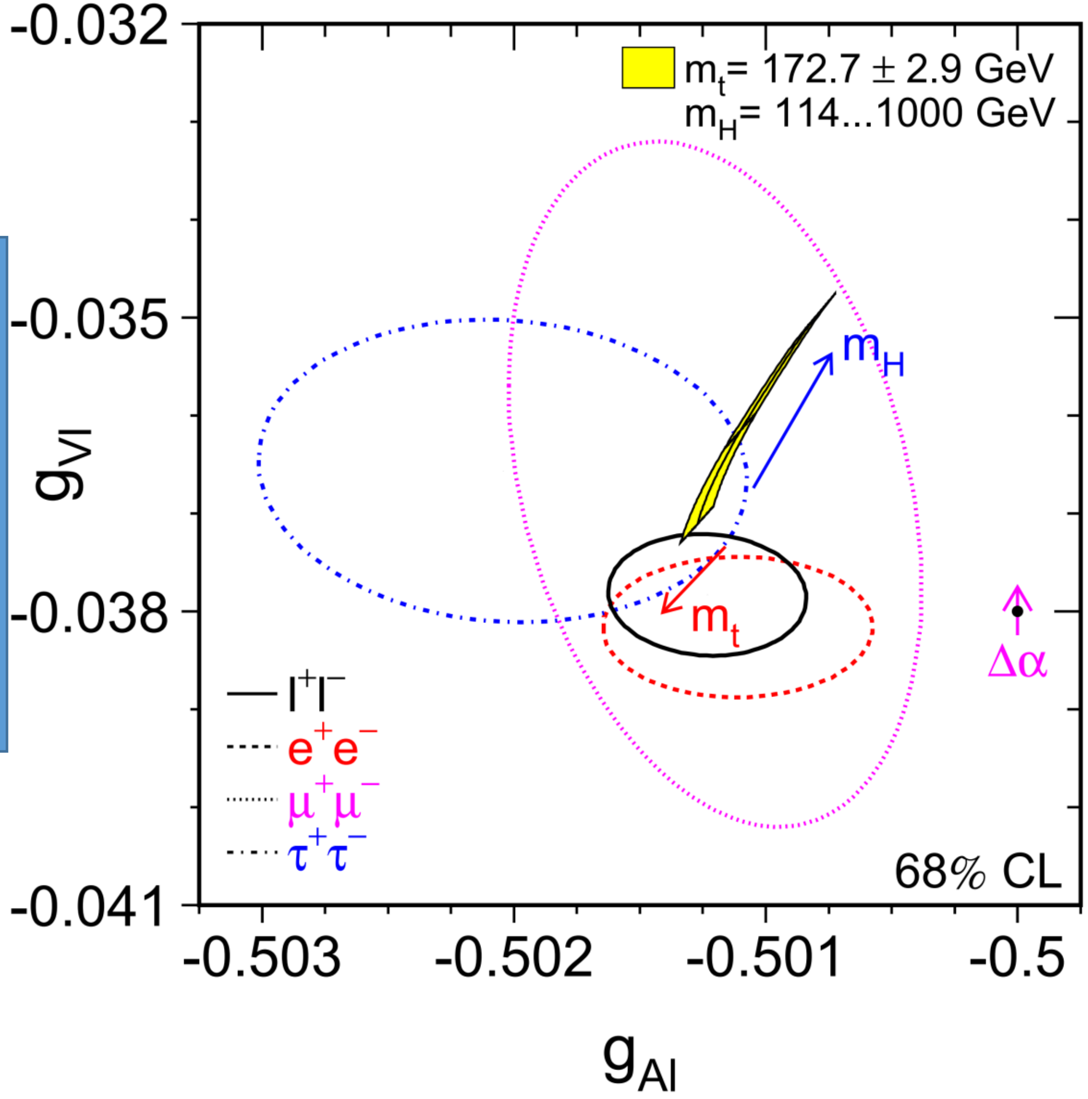


Combined analysis of LEP & SLD

And the Higgs boson was discovered immediately , where hinted by these plots



CONTENTS

- μ and e anomalous magnetic moments (a_μ, a_e): Are **BOTH** anomalies real?
- Charged lepton flavor violation: **Any observation is New Physics**
- Semileptonic tau decays: **From the Fermi-like theory to the SMEFT**
- Michel parameters in leptonic lepton decays: **Not only muons matter**

a_μ & a_e : Are **BOTH** anomalies real?

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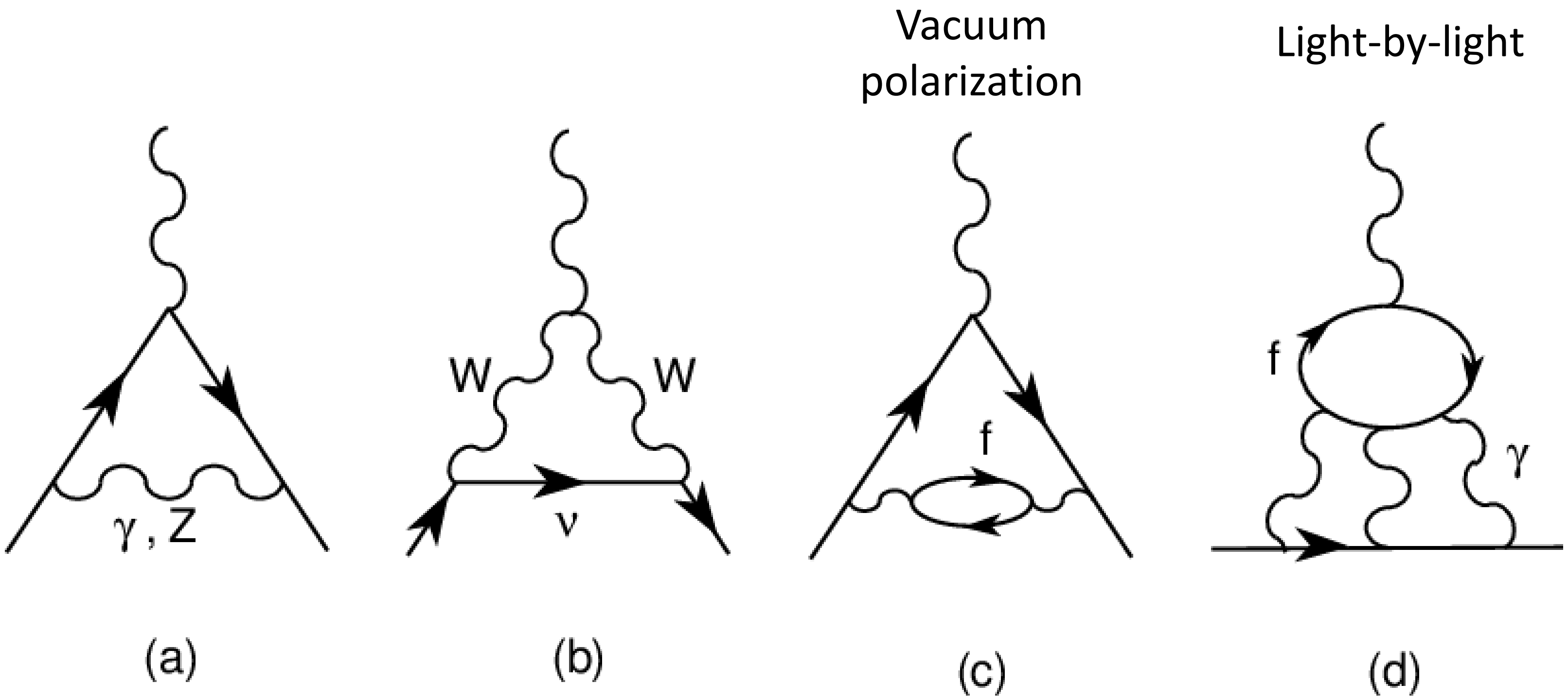

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$\vec{\mu}_l = g_l\, e/(2\, m_l)\, \vec{S}_l$, $g_l = 2\,(1+a_l)$, $a_l = \alpha/(2\,\pi)+\ldots$

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Until half a year ago, there was just **ONE** possible anomaly, summarized as: $\vec{\mu}_l = g_l\, e/(2\, m_l)\, \vec{S}_l$, $g_l = 2\,(1+a_l)$, $a_l = \alpha/(2\,\pi)+\ldots$

$$\Delta a_\mu = a_\mu^{exp} - a_\mu^{SM} = 274(63)(37)\times 10^{-11} \quad (3.7\sigma)$$

But the picture has drastically changed as an exp. in Berkeley announced a new ultraprecise measurement of α using interferometry techniques (ScienceMag Vol. 360, Issue 6385, pp. 191-195). They have really measured the mass of the Cs 133 atom and used

$$\alpha^2 = \frac{2R_\infty}{c}\frac{m_{\mathrm{At}}}{m_{\mathrm{e}}}\frac{h}{m_{\mathrm{At}}}$$

to determine α.

Knowing α, a_e is a series in α (Aoyama, Hayakawa, Kinoshita & Nio, PRL 109, 11807 (2012) & PRD 96 019901 (2017)).

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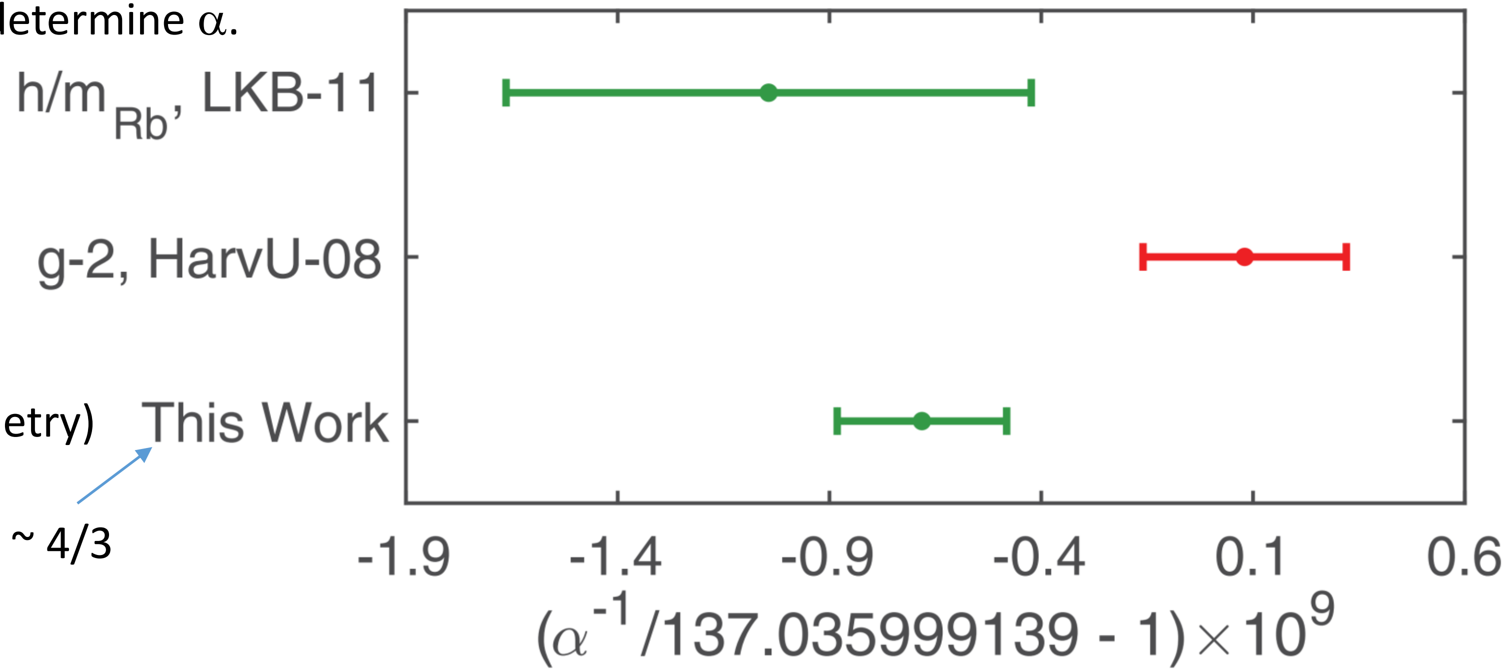

(Matter-wave interferometry)

Statistical error/Systematical error ~ 4/3

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Berkeley

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$$\delta a = a_{\mathrm{meas}} - a(\alpha) = -0.88(0.36)\times 10^{-12}$$

Harvard

Hanneke, Fowler & Gabrielse (PRL 100 (2008) 120801).

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In general, 'natural' NP models tend to contribute to a_l with the same sign for l=e, μ. Particularly, the Berkeley result **rules out dark photon explanations of the a_μ anomaly** at the 99%C.L.

a_μ & a_e : Are **BOTH** anomalies real?

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$$\Delta a_\mu = a_\mu^{exp} - a_\mu^{SM} =$$

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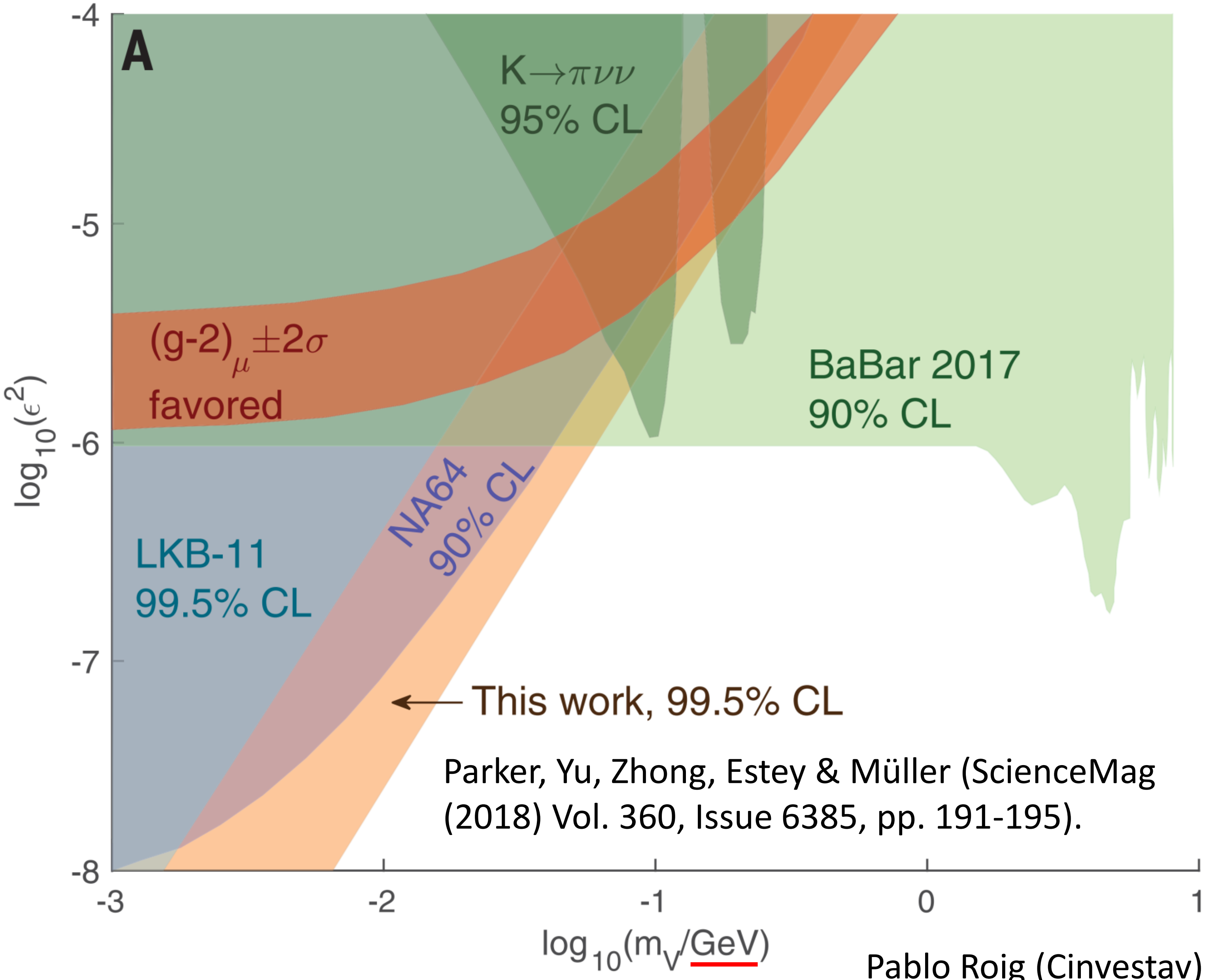

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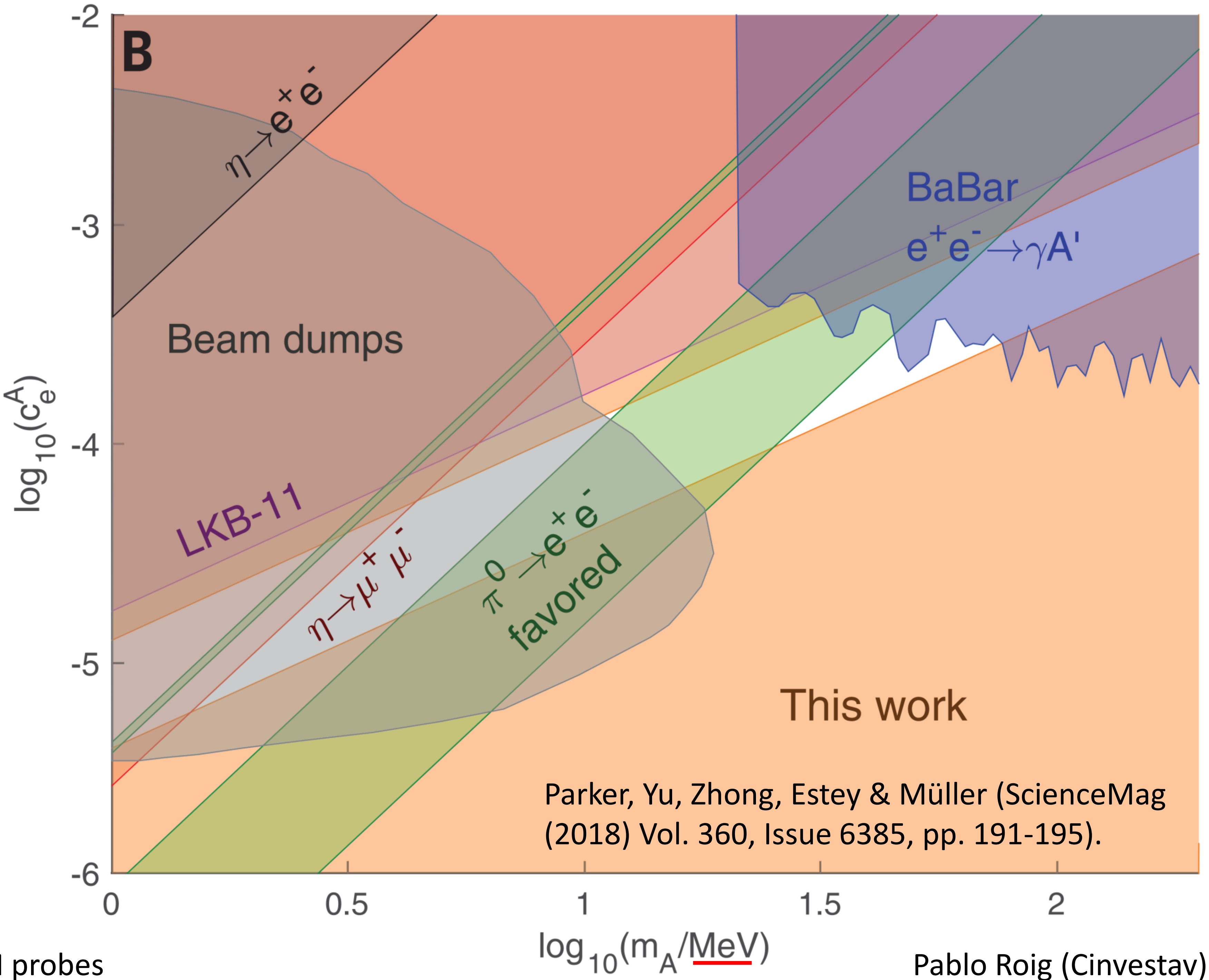

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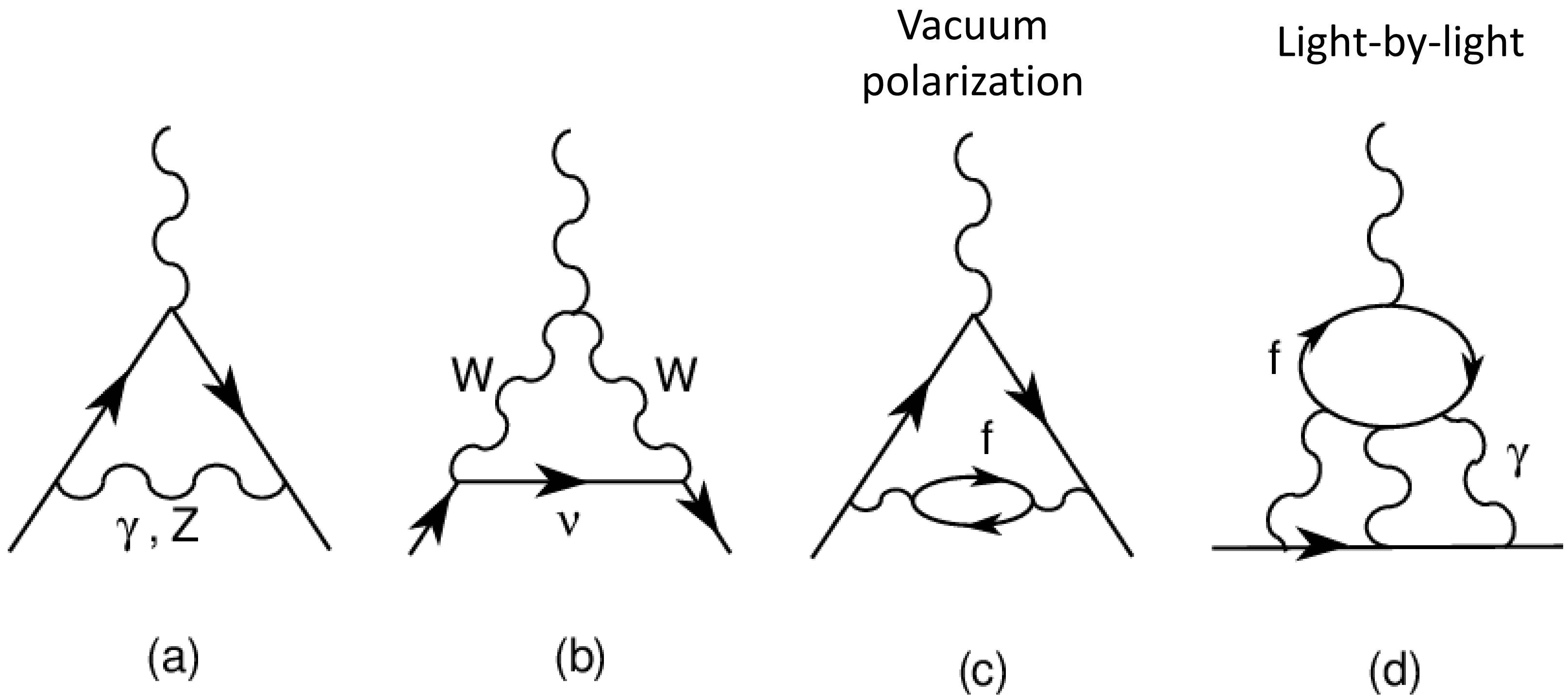
My personal view: $\Delta \mathbf{a_e}$ is not that significant and **will be reduced with more precise measurements** of g_e.
$\Delta \mathbf{a_\mu}$ is mainly a result of present **insufficient knowledge of the hadronic non-perturbative contributions**.

a_μ & a_e : Are BOTH anomalies real?



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a_μ & a_e : Are BOTH anomalies real?

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$$a_e(\mathrm{NLO\ had.\ v.p.}) = -0.2234\ (12)_{\mathrm{exp}}\ (7)_{\mathrm{rad}} \times 10^{-12},$$

$$a_e(\mathrm{NNLO\ had.\ v.p.}) = 0.028\ (1) \times 10^{-12},$$

$$a_e(\mathrm{had.}\ l\text{-}l) = 0.035\ (10) \times 10^{-12}.$$

a_μ & a_e : Are BOTH anomalies real?

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$$a_e(\mathrm{electroweak}) = 0.0297\ (5) \times 10^{-12}.$$

$$a_e(\mathrm{theory}) = 1\ 159\ 652\ 181.643\ (25)(23)(16)(763) \times 10^{-12},$$

Only QED matters for a_e!!

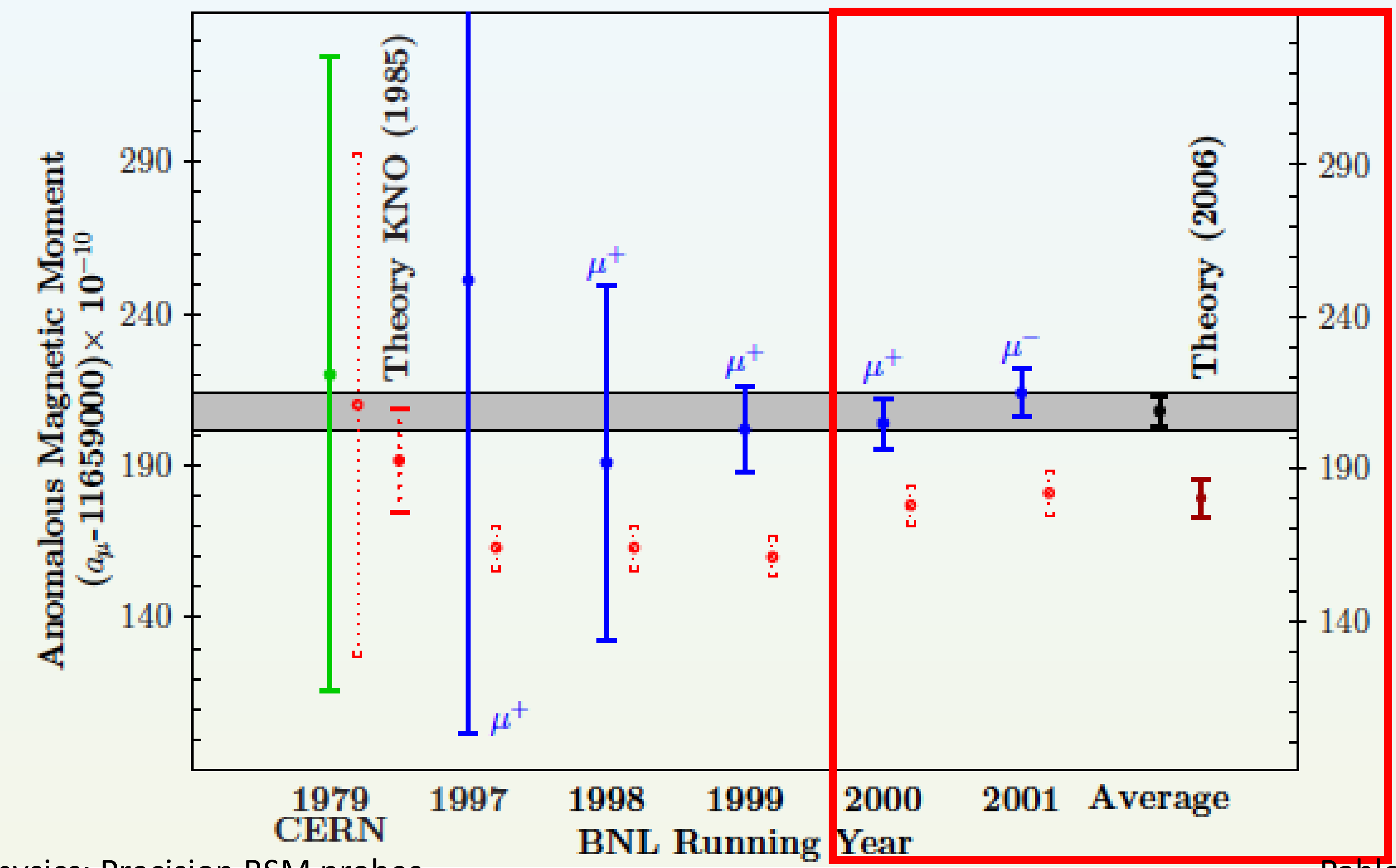
This gives a reasonable UL for heavy NP contributions

They can't explain Δa_e at one-loop

Uncertainty on α

a_μ & a_e : Are BOTH anomalies real?

In the muon case the theoretical uncertainty is completely dominated by the hadronic contributions



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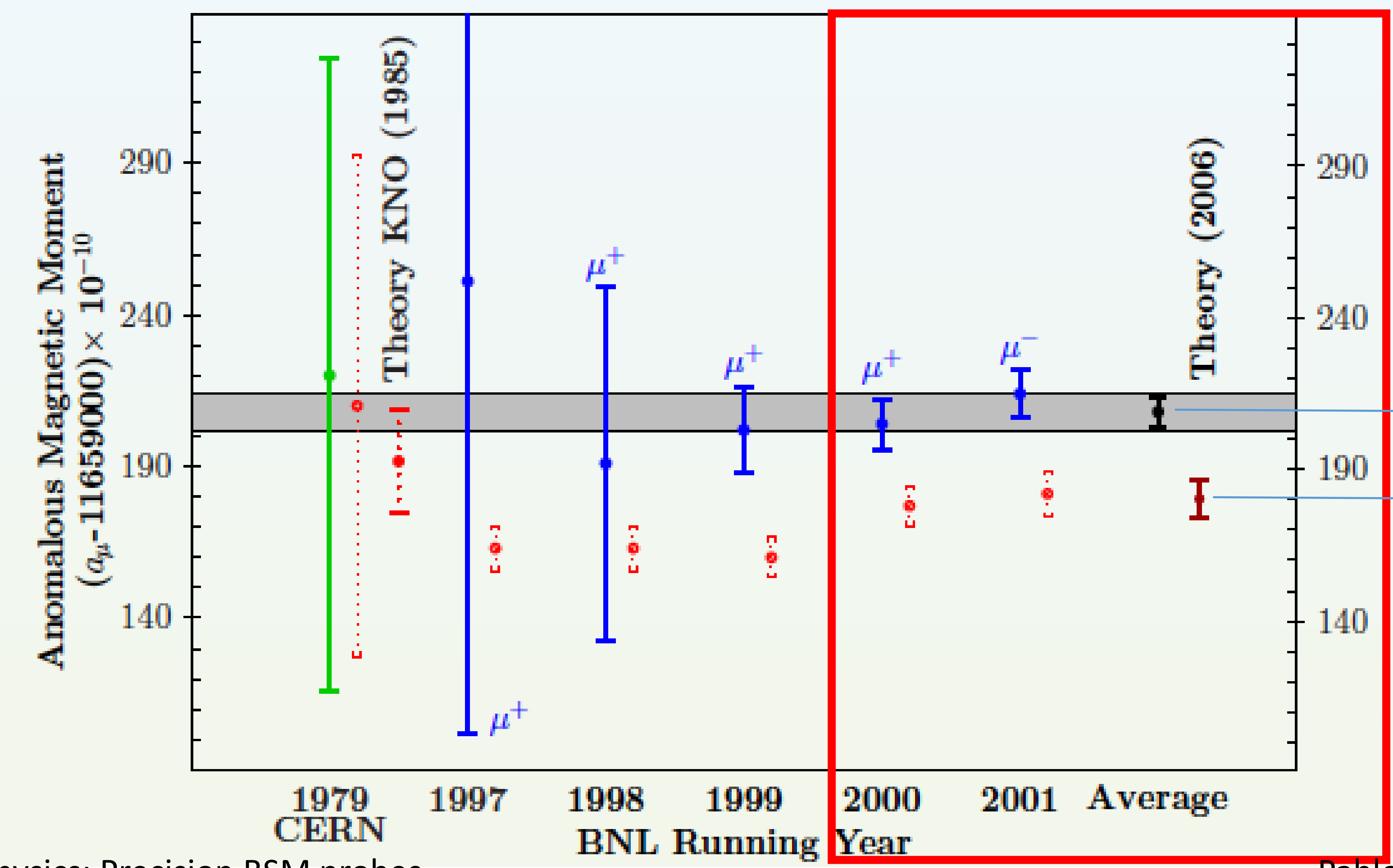

Fourfold improvement on error by FNAL in 2021!!

Muon g-2 Theory Initiative

a_μ & a_e : Are **BOTH** anomalies real?

In the muon case the theoretical uncertainty is completely dominated by the hadronic contributions

$a_\mu^{QED}=\underline{116584718.92(3)\times10}^{-11}$ Very Precise!

$a_\mu^{EW}=\underline{154(1)\times10}^{-11}$ Non Controversial

$a_\mu^{Had}(V.P.)^{LO}=\underline{6923(37)}\times10^{-11}$

$a_\mu^{Had}(V.P.)^{NLO+NNLO} = -86(1)\times10^{-11}$

$a_\mu^{Had}(LBL) = 105(26)\times10^{-11}$ (Consensus?)

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Current developments are focused on improving HVP determination (data-driven & lattice) & the HLbL part (efforts directed towards data-driven determination, lattice and other analytic approaches: large-Nc, ChPT, DSE, Rational approximants, …)

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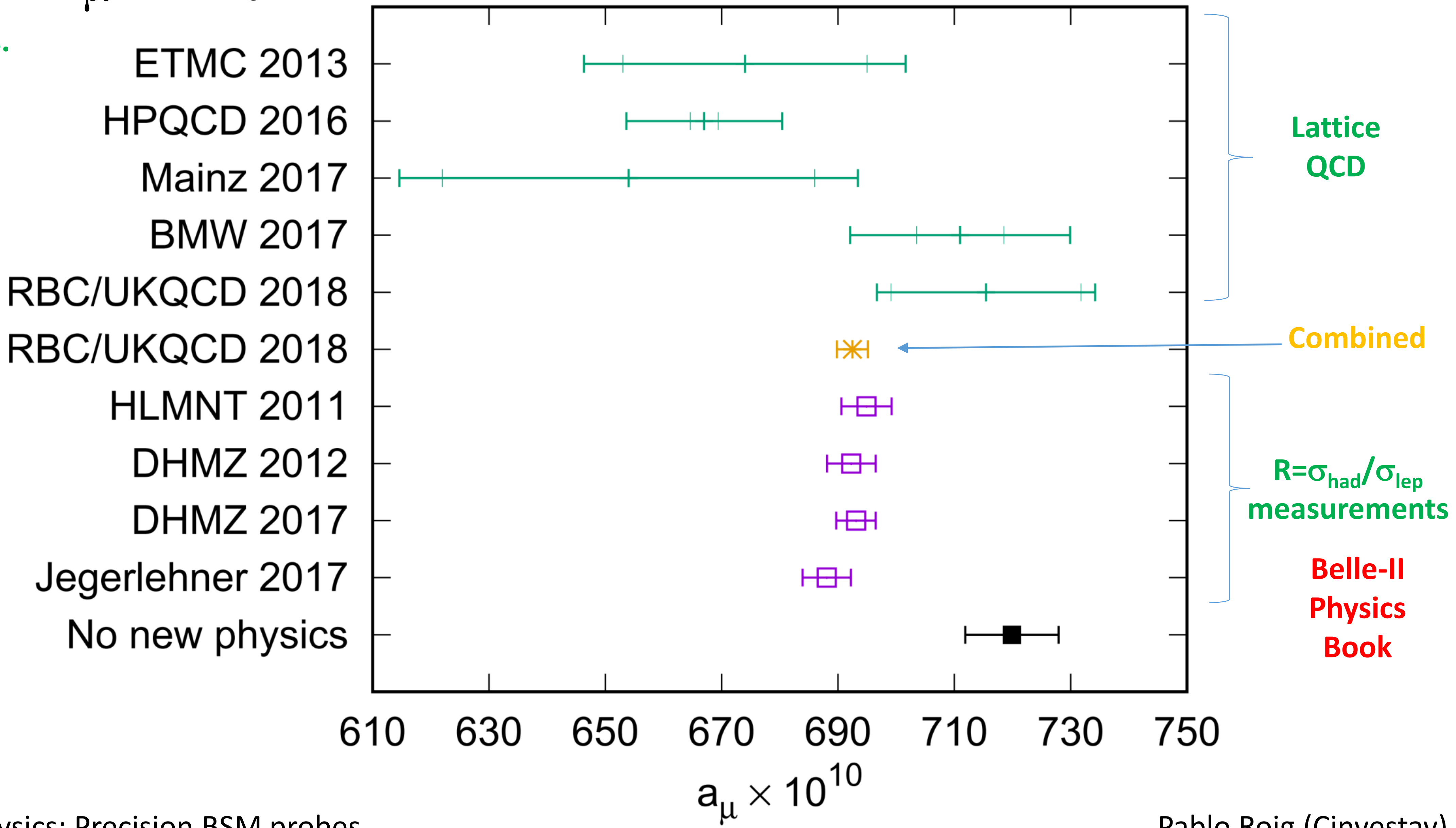
RBC & UKQCD Colls.
PRL 121 (2018)
no.2, 022003

See also Meyer & Wittig's review
1807.09370



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(It supersedes previous result by Roig, Guevara & López-Castro PRD'14)

π^0 gives the most important contribution

Guevara, Roig & Sanz-Cillero, JHEP'18

$$a_\mu^{\pi^0,HLbL} = (5.81 \pm 0.09 \pm 0.09^{+0.5}_{-0}) \cdot 10^{-10}$$

Hoferichter et. al. PRL & JHEP '18

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K. Raya, Bashir & Roig, DSE, to appear soon…

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A.S. Fomin, A.Yu. Korchin, A. Stocchi, S. Barsuk, P. Robbe

What about a_τ?

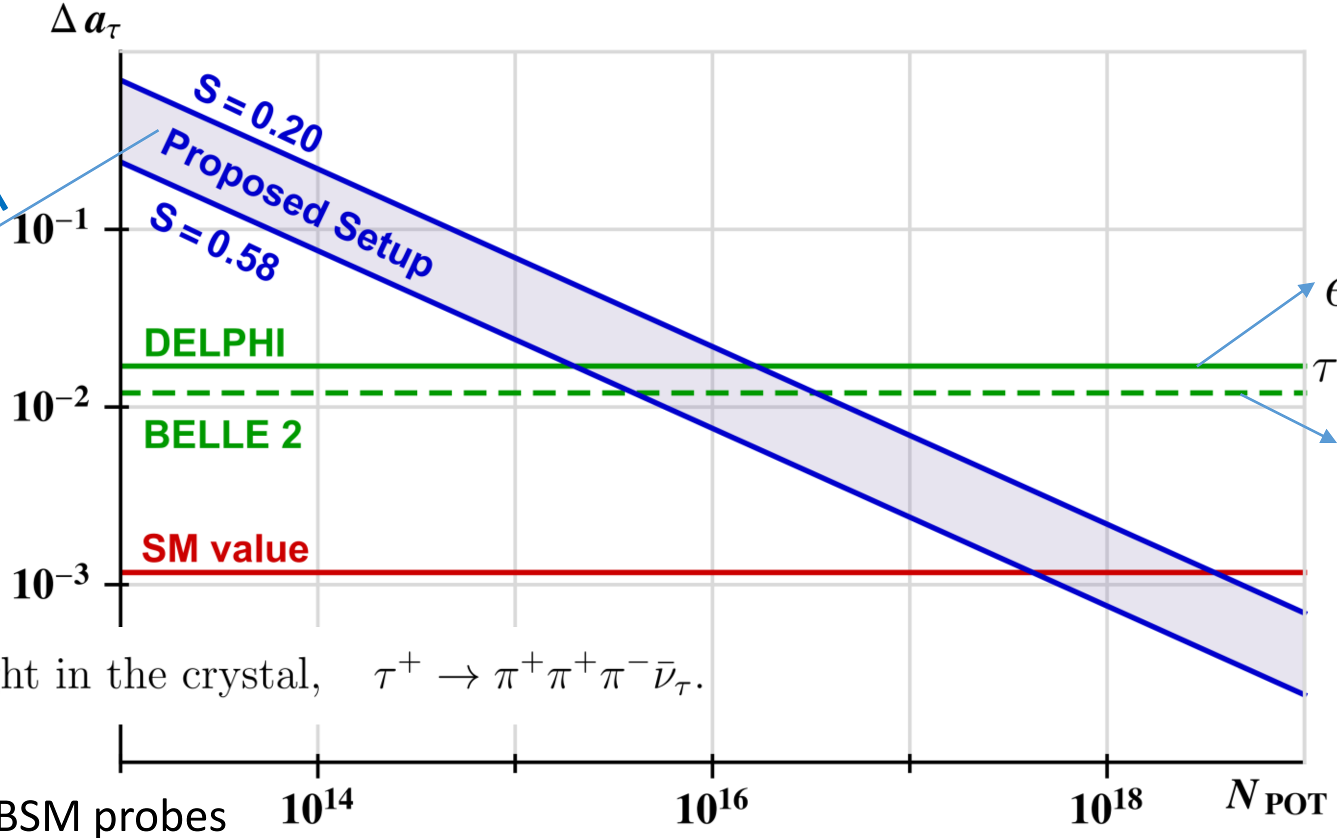
arXiv:1810.06699 (hep-ph)

The sensitivity of a_l to heavy NP scales as m_l^2/M_{NP}^2 so τ is **the most interesting one theoretically**. However, $\tau_\tau \sim 3{\cdot}10^{-11}$ s makes impossible measurement as for the μ or e.

$$a_{\tau,\,\mathrm{SM}} = 0.00117721(5)$$

Eidelman & Passera '07

Spin precession in a bent crystal



$$p\,p \to D_s^+ X, \quad D_s^+ \to \tau^+ \nu_\tau, \quad \tau^+ \text{ flight in the crystal}, \quad \tau^+ \to \pi^+ \pi^+ \pi^- \bar{\nu}_\tau.$$

$$e^+e^- \to e^+e^-\tau^+\tau^-$$

$$\tau^- \to \ell^- \nu_\tau \bar{\nu}_\ell \gamma \;\; (\ell = e,\, \mu)$$

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But it will still only be probing the Schwinger contribution ☹

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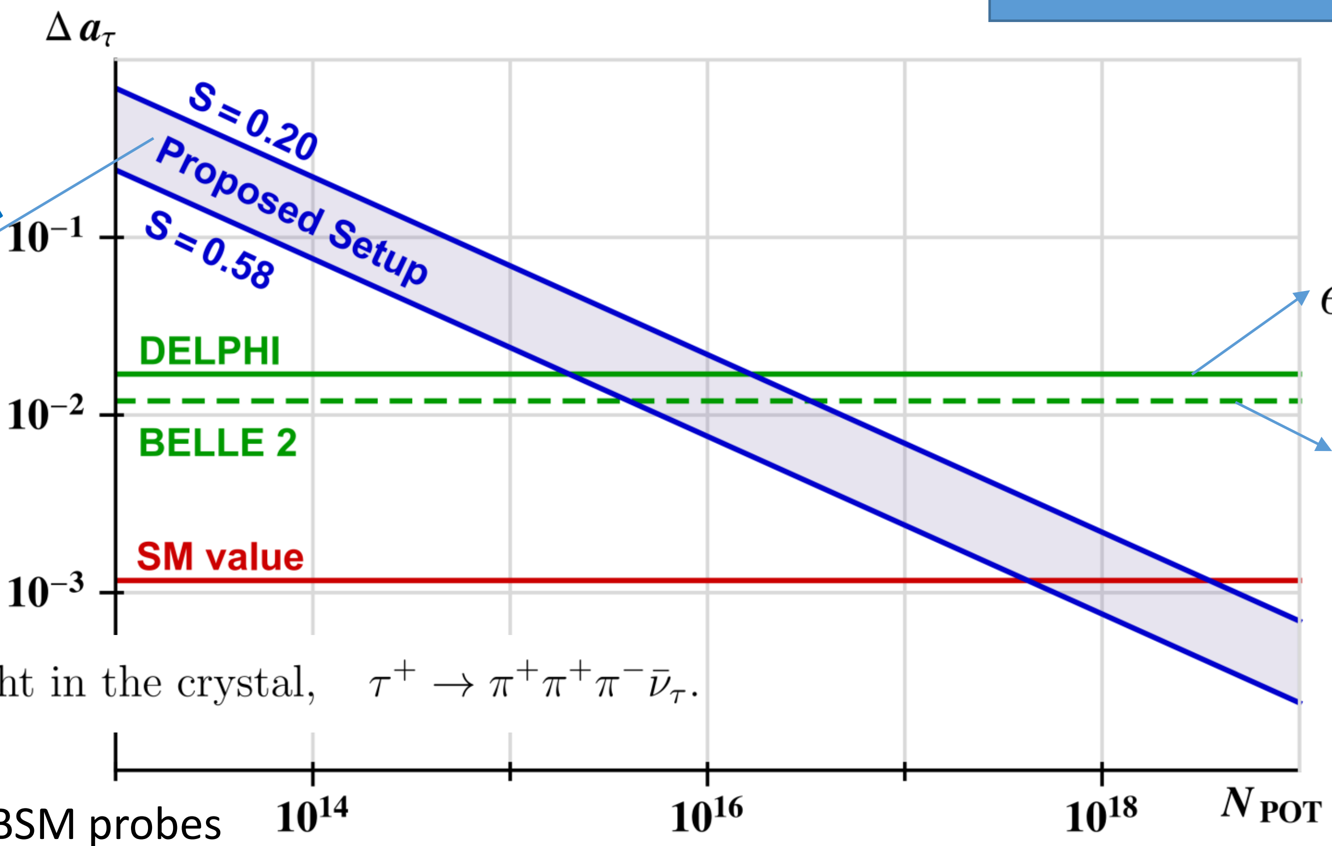

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CHARGED LEPTON FLAVOR VIOLATION (cLFV):
Any observation is New Physics

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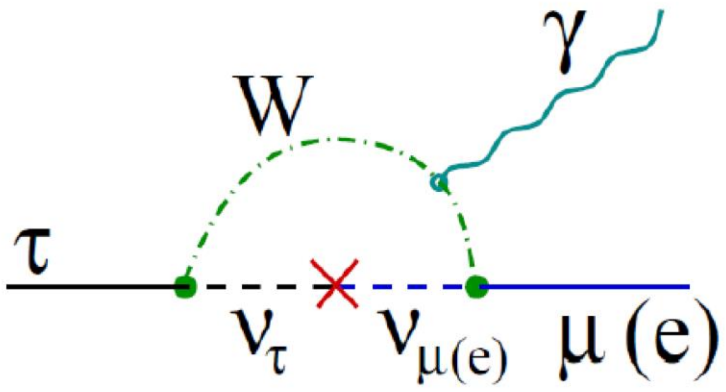
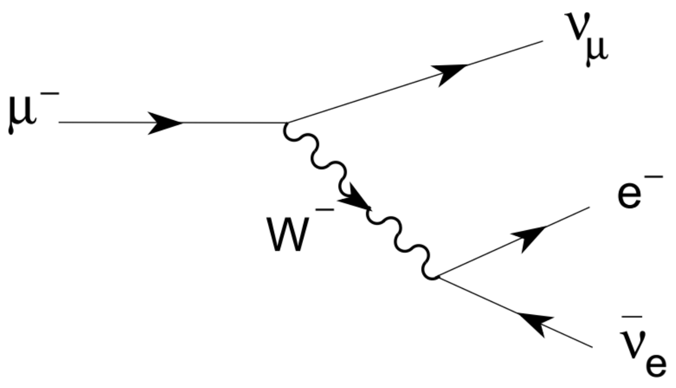


cLFV is forbidden in the limit of massless neutrinos (Lepton flavor is conserved).
cLFV smallness is due to neutrinos running in the loop (GIM suppression) and the KLN theorem (no IR divs associated with intermediate or final-state particles can appear).

$$BR(\mu\to e\gamma)\simeq\frac{\Gamma(\mu\to e\gamma)}{\Gamma(\mu\to e\nu\bar\nu)}=\frac{3\alpha}{32\pi}\left|\sum_{k=1,3}\frac{U_{\mu k}U^*_{ek}m^2_{\nu k}}{m^2_W}\right|^2\sim 10^{-54}.$$

- T. P. Cheng and L. F. Li, Gauge Theory Of Elementary Particle Physics



Analogously, a similar suppresion **has to** arise in other cLFV processes.

$BR(Z\to\ell'\ell)\sim 10^{-54}$

- Phys. Rev. D 63, 053004 (2001)

$BR(h\to\ell'\ell)\sim 10^{-55}$

- Phys. Rev. D 71, 035011 (2005)

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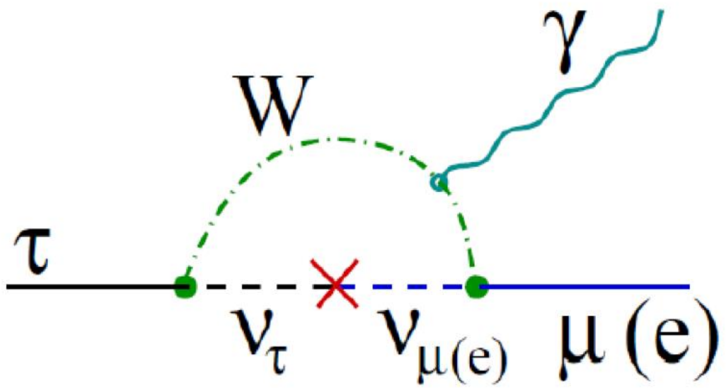

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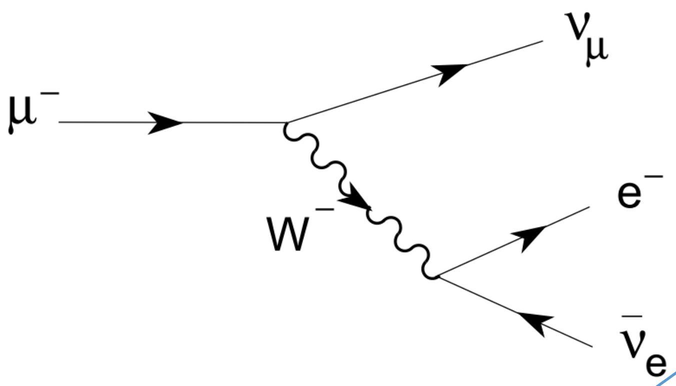


Analogously, a similar suppresion **has to** arise in other cLFV processes. **However**

$BR(\tau^\pm \to \mu^\pm \ell^\pm \ell^\mp) > 10^{-14}$

$$\mathcal{M} \sim \sum_{j=1}^3 U^*_{\mu j}U_{\tau j}\log\left(\frac{m^2_W}{m^2_j}\right).$$

- X. Y. Pham, Eur. Phys. J. C 8, 513 (1999).

$BR(\mu^\pm \to e^\pm e^\pm e^\mp) \sim 10^{-53}$ (updated input)

$$\mathcal{M} \sim \sum_{j=1}^{3} U^*_{ej}U_{\mu j}\frac{m^2_j}{m^2_W}\log\left(\frac{m^2_W}{m^2_j}\right)$$

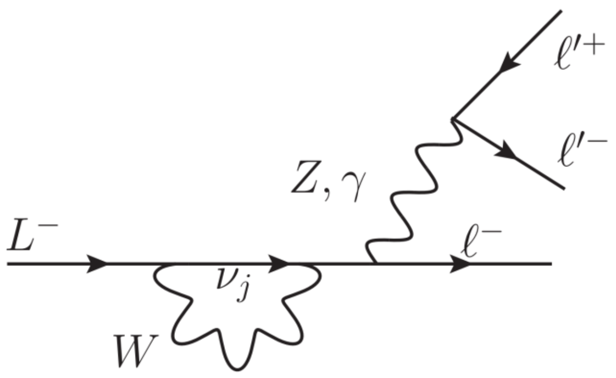
- S. T. Petcov, Sov. J. Nucl. Phys. 25, 340 (1977).

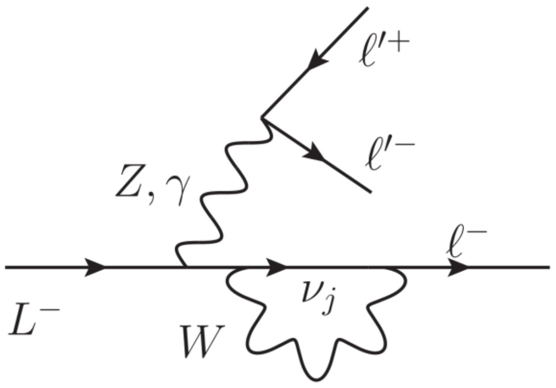
It has been cited over the years as the SM prediction by ATLAS, BaBar, Belle & CMS despite it violates KLN Theorem.

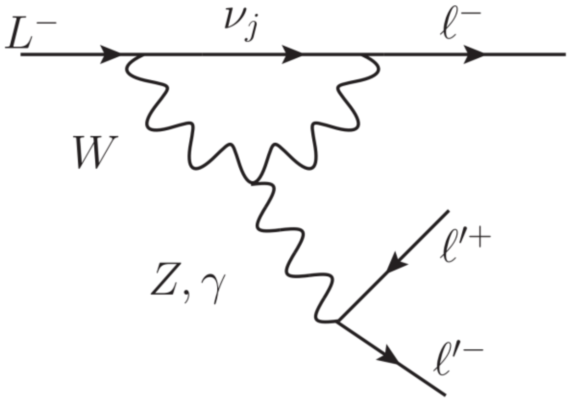
CHARGED LEPTON FLAVOR VIOLATION (cLFV): **Any observation is New Physics**

G. Hernández-Tomé*, G. López-Castro* and P. Roig*
* CINVESTAV, MÉXICO

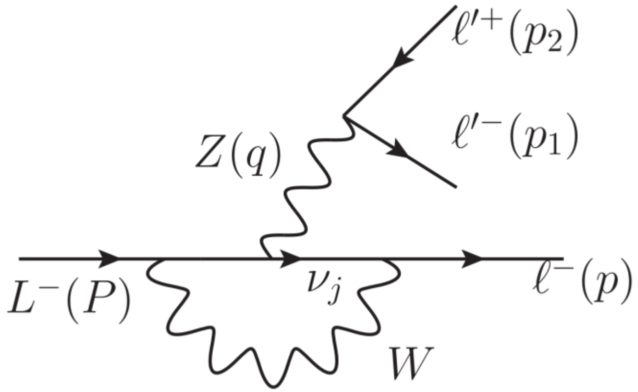
arXiv:1807.06050

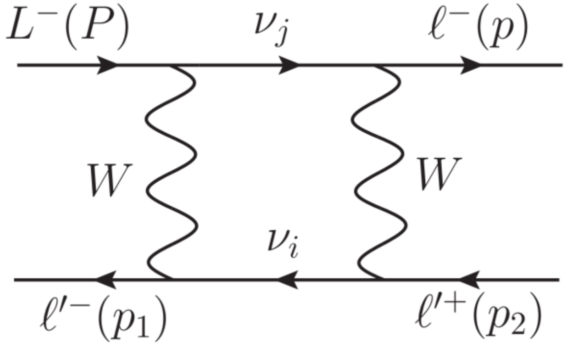






Diagrams with 2 ν propagators dominate





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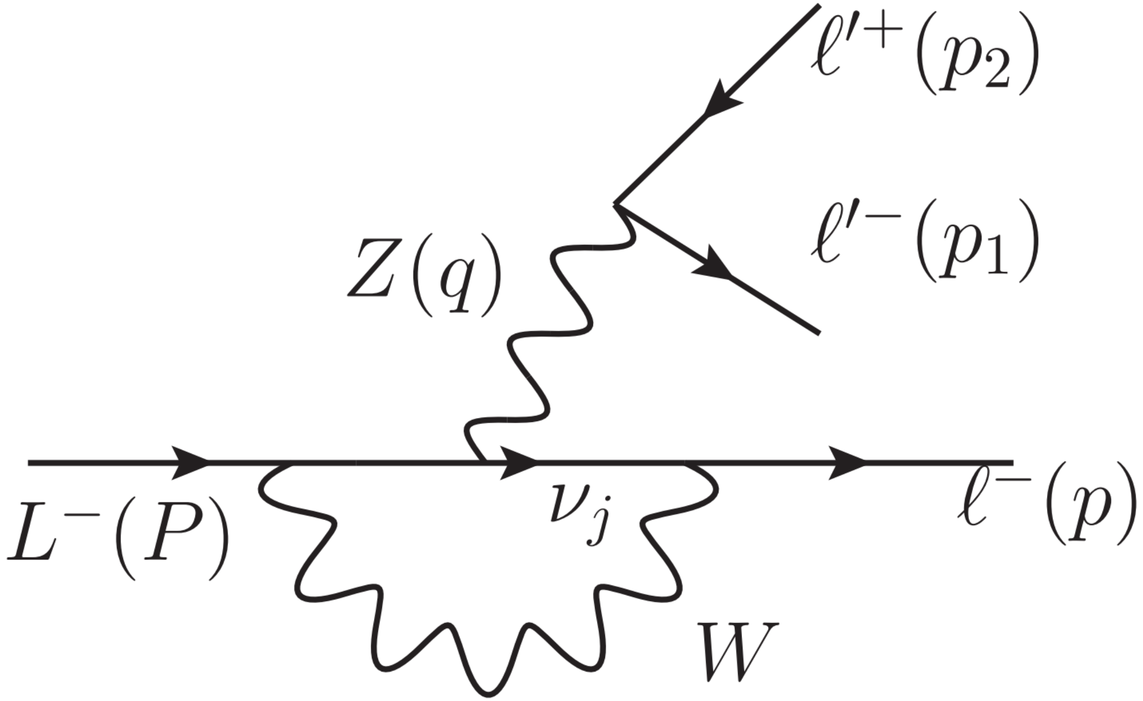
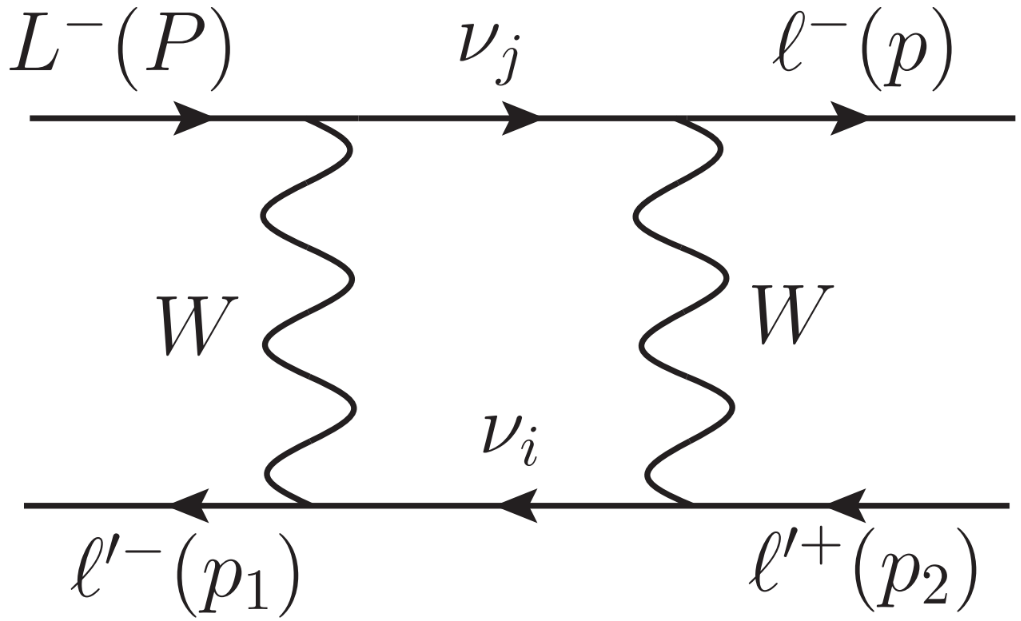
*** CINVESTAV, MÉXICO**

arXiv:1807.06050





Two different analytical evaluations: With Feynman parameters & with PaVe functions.
Two different numerical computations: Fully numerical with PaVe and after expansion around m_ν=0.
We have kept for the first time external momenta & masses: This changes results by at least one order of magnitude (depending on the channel). Petcov's formulae are reproduced when external p's are neglected.

CHARGED LEPTON FLAVOR VIOLATION (cLFV): Any observation is New Physics

G. Hernández-Tomé*, G. López-Castro* and P. Roig*
*** CINVESTAV, MÉXICO**

arXiv:1807.06050

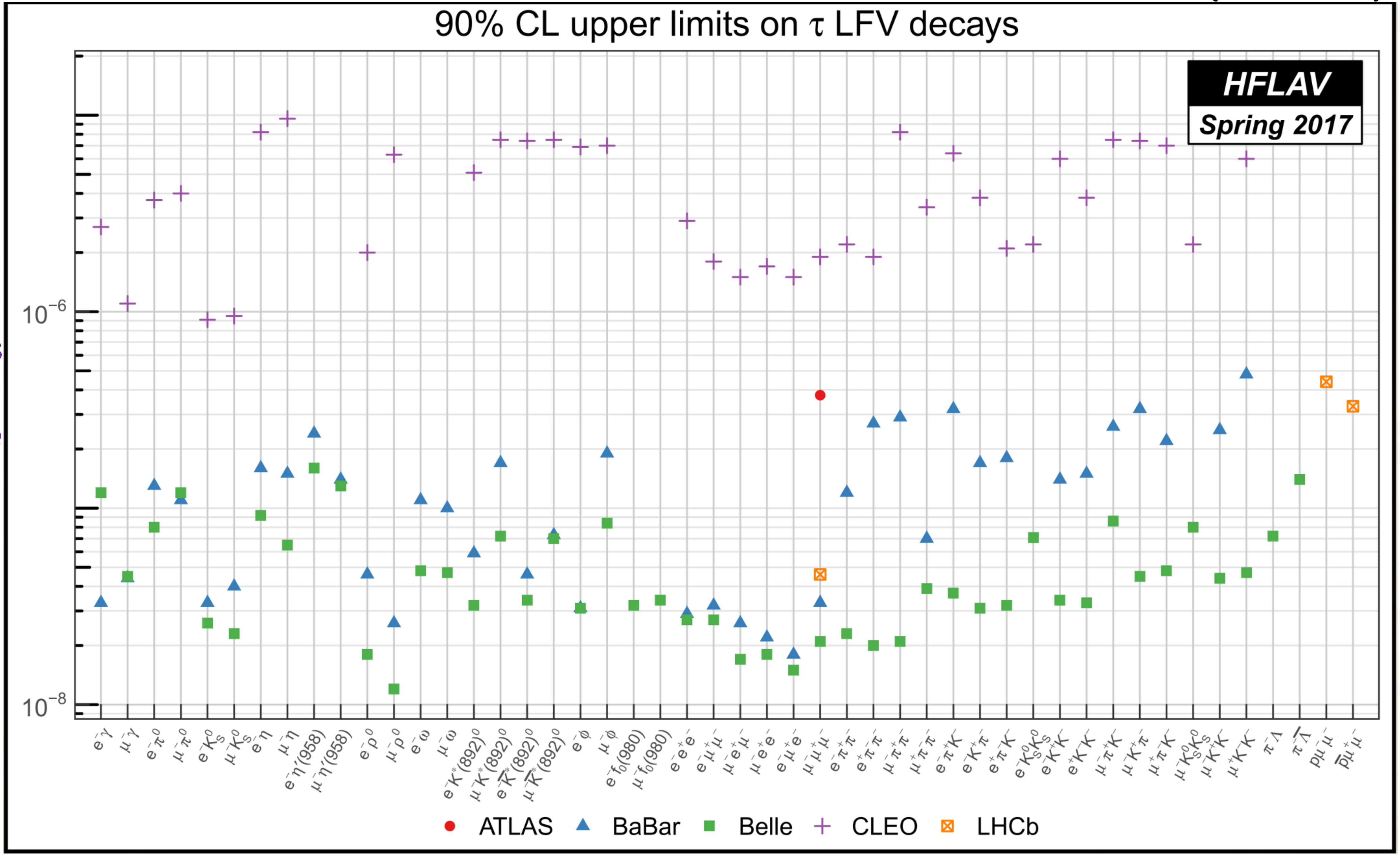
(* Updated input)

Decay channel	Our Result	Petcov's Result*
$\mu^- \to e^- e^+ e^-$	$7{,}4 \cdot 10^{-55}$	$8{,}5 \cdot 10^{-54}$
$\tau^- \to e^- e^+ e^-$	$3{,}2 \cdot 10^{-56}$	$1{,}4 \cdot 10^{-54}$
$\tau^- \to \mu^- \mu^+ \mu^-$	$6{,}4 \cdot 10^{-55}$	$3{,}2 \cdot 10^{-53}$
$\tau^- \to e^- \mu^+ \mu^-$	$2{,}1 \cdot 10^{-56}$	$9{,}4 \cdot 10^{-55}$
$\tau^- \to \mu^- e^+ e^-$	$5{,}2 \cdot 10^{-55}$	$2{,}1 \cdot 10^{-53}$

Are there other processes where the inaccuracy of neglecting external momenta and masses may become an issue?

CHARGED LEPTON FLAVOR VIOLATION (cLFV):

Belle-II could improve two orders of magnitude w.r.t. BaBar & Belle (it depends on the channel)



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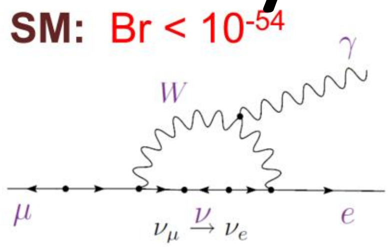
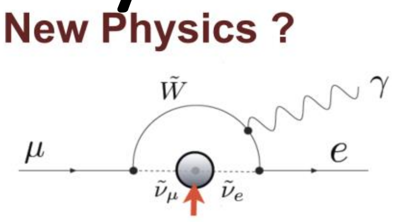
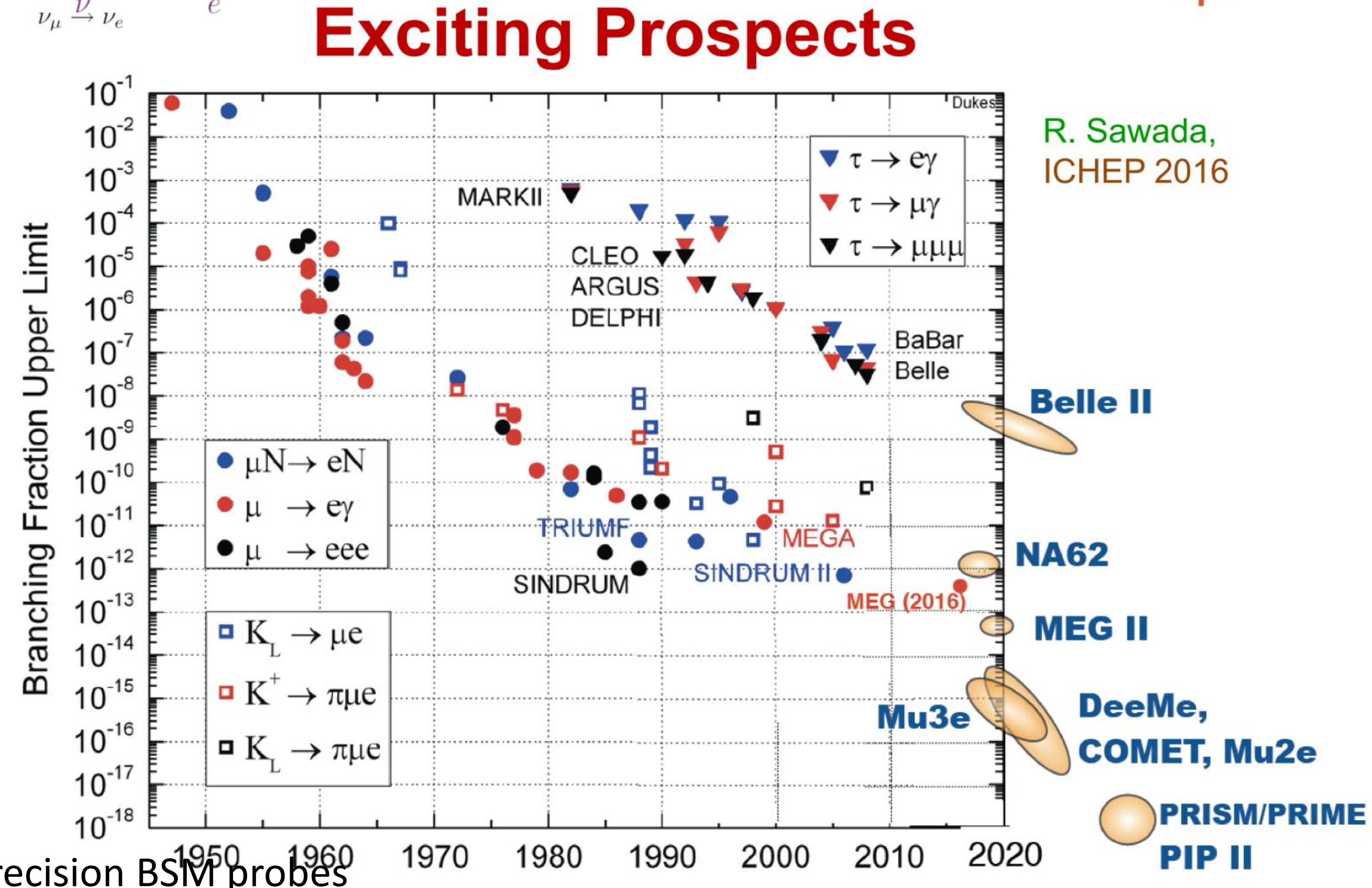
CHARGED LEPTON FLAVOR VIOLATION (cLFV):
Any observation is New Physics





(see Marcela's poster for unconventional searches)



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SEMILEPTONIC TAU DECAYS:

From the Fermi-like theory to the SMEFT

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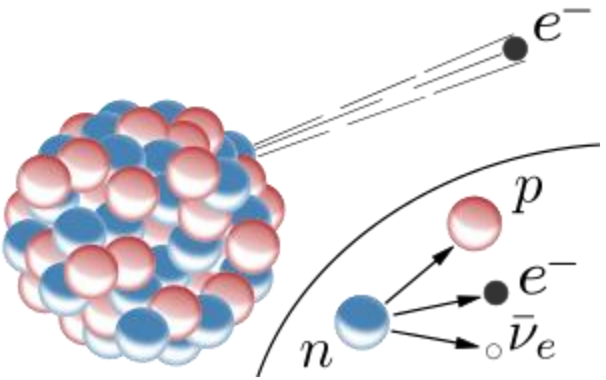


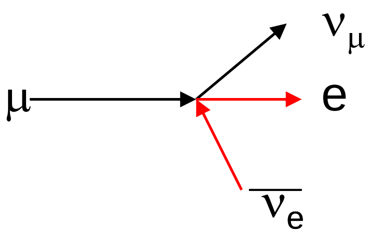
Apparent non-conservation of energy & angular momentum & violation of the spin-statistics connection in nuclear β decays lead Pauli postulate the ν.

Fermi implemented a vector contact interaction (QED-like) between fermion currents as a theory for β decays including the ν.

With a modern perspective, Fermi's theory is only one of the possible contributions allowed by symmetries in the EFT framework and applies also to leptonic lepton decays and semileptonic decays involving light quarks (u,d,s).

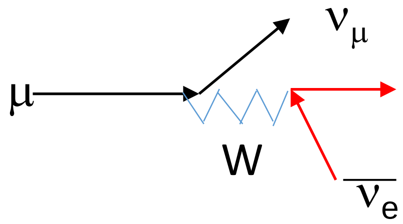
$(e\,\Gamma^n\,\nu_e)(\nu_\mu\,\Gamma_n\,\mu)$ + h.c.

$$\Gamma^n \in \left(I_4\,,\, i\gamma_5\,,\, \gamma^\mu\,,\, \gamma_5\gamma^\mu\,,\, \sigma^{\mu\nu}\right)$$



EFT
Fermi-like theory

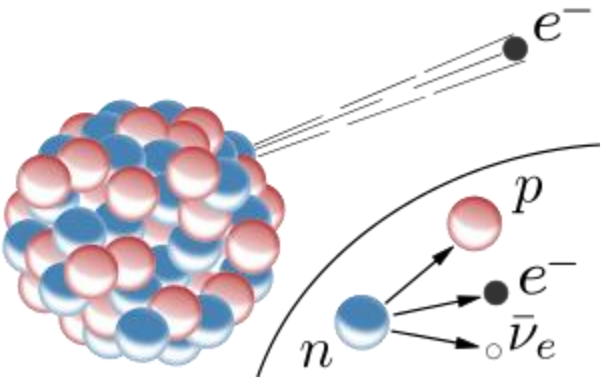
$-1/(Q^2-M_W^2) \sim 1/M_W^2$



'Fundamental theory'
SM

SEMILEPTONIC TAU DECAYS:

From the Fermi-like theory to the SMEFT



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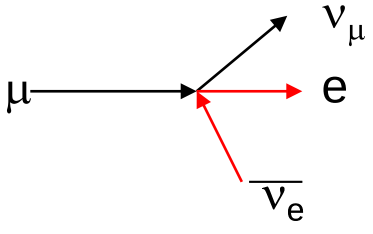

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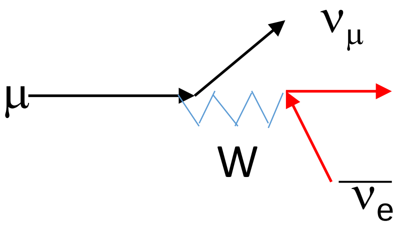

'Fundamental theory'
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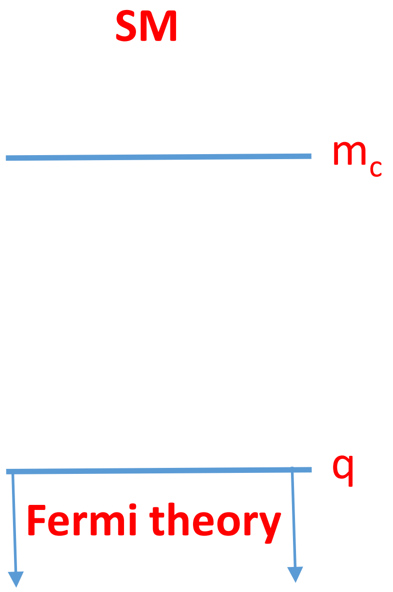

SEMILEPTONIC TAU DECAYS:

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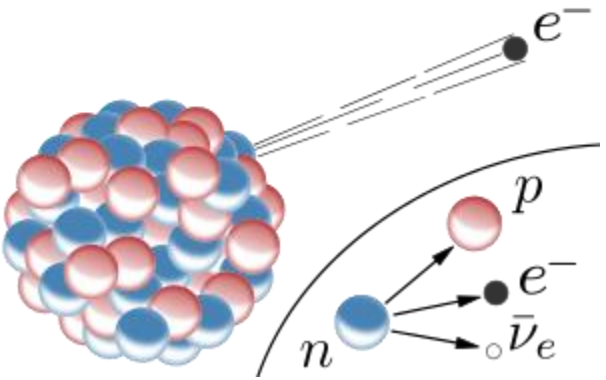
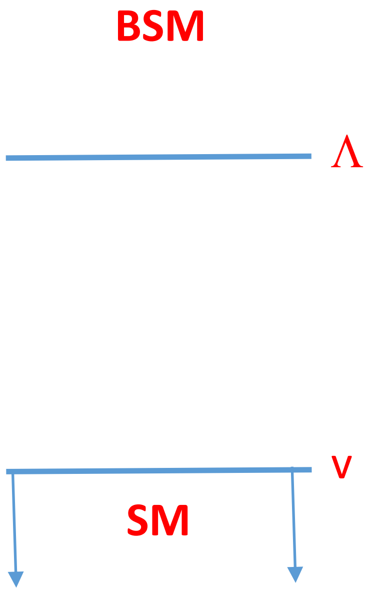


With an even more modern perspective (in apparent absence of NP up to a few TeVs) we can consider the SM itself as an EFT: SMEFT (Büchmuller-Wyler ‘85; Grzadkowski, Iskrzynski, Misiak & Rosiek ’10, …)

(See Cirigliano, Jenkins & González-Alonso Nucl.Phys. B830 (2010) 95-115 for semileptonic decays involving light quarks in SMEFT)

$$\mathcal{L}^{(\text{eff})} = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \frac{1}{\Lambda^3}\mathcal{L}_7 + \ldots$$

$$\mathcal{L}_n = \sum_i \alpha_i^{(n)}\, O_i^{(n)} \,,$$



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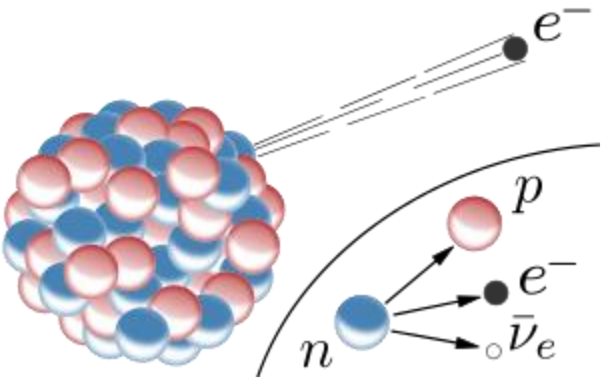

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Proceeding this way (Garcés, Hernández-Villanueva, López-Castro & PR, JHEP 1712 (2017) 027):

1st pointed out that $\tau \to \nu_\tau$ hads could be competitive with nuclear β & radiative π decay in restricting NP in charged weak currents

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$$\mathcal{L}_{\rm CC} = -\frac{G_F V_{ud}}{\sqrt{2}} \Big(1 + \epsilon_L + \epsilon_R\Big) \Big[\bar{\ell}\gamma_\mu(1-\gamma_5)\nu_\ell \cdot \bar{u}\Big[\gamma^\mu - (1-2\tilde{\epsilon}_R)\gamma^\mu\gamma_5\Big]d$$

$$+ \bar{\ell}(1-\gamma_5)\nu_\ell \cdot \bar{u}\Big[\tilde{\epsilon}_S - \tilde{\epsilon}_P\gamma_5\Big]d + 2\tilde{\epsilon}_T\, \bar{\ell}\sigma_{\mu\nu}(1-\gamma_5)\nu_\ell \cdot \bar{u}\sigma^{\mu\nu}d\Big] + \text{h.c.},$$

$$\tilde{\epsilon}_i \equiv \epsilon_i/(1+\epsilon_L+\epsilon_R) \text{ for } i = R, S, P, T.$$

SEMILEPTONIC TAU DECAYS:

From the Fermi-like theory to the SMEFT

Garcés, Hernández-Villanueva, López-Castro & PR, JHEP 1712 (2017) 027 1st pointed out that $\tau \to \nu_\tau$ hads could be competitive with nuclear β & radiative π decay in restricting NP in charged weak currents

$\tau \to \nu_\tau\, \eta\, \pi$: For ε_S

$\tau \to \nu_\tau\, \pi\, \pi$: For ε_T in Miranda & PR, 1806.09547 → $\hat{\epsilon}_T = \left(-1.3^{+1.5}_{-2.2}\right) \cdot 10^{-3}$

Hadronization from Escribano et al. PRD'16 & Dumm & PR EPJC'13

Previous decay channels + inclusive analysis + **$\tau \to \nu_\tau\, \pi$ + $a_\mu^{\pi\pi}$** in Cirigliano, Falkowski, González-Alonso & Rodríguez-Sánchez, 1809.01161

$$\begin{pmatrix} \epsilon_L^\tau - \epsilon_L^e + \epsilon_R^\tau - \epsilon_R^e \\ \epsilon_R^\tau \\ \epsilon_S^\tau \\ \epsilon_P^\tau \\ \epsilon_T^\tau \end{pmatrix} = \begin{pmatrix} 1.0 \pm 1.1 \\ 0.2 \pm 1.3 \\ -0.6 \pm 1.5 \\ 0.5 \pm 1.2 \\ -0.04 \pm 0.46 \end{pmatrix} \cdot 10^{-2}$$

[MS-bar at μ = 2 GeV]

SEMILEPTONIC TAU DECAYS:
From the Fermi-like theory to the SMEFT

Channel	$\widehat{\epsilon}_S$	$\widehat{\epsilon}_T$	Source
$\tau^- \to \pi^-\pi^0\nu_\tau$	$(-5.2, 5.2)$	$(-0.79, 0.013)$	BR Belle $\star$
	$< 8 \cdot 10^{-3}$ (input)	$\boxed{(-1.3^{+1.5}_{-2.2}) \cdot 10^{-3}}$	$\pi\pi$ spectrum Belle $\star$
$\tau^- \to \pi^-\eta\nu_\tau$	$\boxed{(-8.3, 3.7) \cdot 10^{-3}}$	$(-0.55, 0.50)$	BR Babar UL $\dagger$
	$(-6 \pm 15) \cdot 10^{-3}$	–	arXiv 1809.01161
semileptonic τ	-	$(-0.4 \pm 4.6) \cdot 10^{-3}$	arXiv 1809.01161
$\frac{\Gamma(\pi\to e\nu(\gamma))}{\Gamma(\pi\to\mu\nu(\gamma))}$ & β decays	$\boxed{< 8 \times 10^{-3}}$	$\boxed{< 10^{-3}}$	Cirigliano et al JHEP 2013

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$\star$ **E. Garcés et al, JHEP 12, (2017)**

$\dagger$ **J. Miranda and P. Roig, 1806.09547**

To appear in JHEP
(see Álex poster)

Analysis for Kπ decay modes is in progress (see Javier's poster)

MICHEL PARAMETERS IN LEPTONIC LEPTON DECAYS:

Not only muons matter

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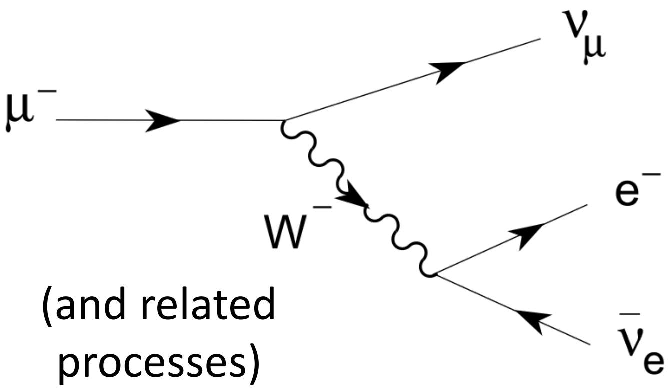

(and related processes)

$$n = S, V, T$$

$$\Gamma^S = 1,\ \Gamma^V = \gamma^\mu,\ \Gamma^T = \frac{i}{2\sqrt{2}}(\gamma^\mu\gamma^\nu - \gamma^\nu\gamma^\mu)$$

$$\mathcal{H} = 4\frac{G_{\ell'\ell}}{\sqrt{2}}\sum_{n,\epsilon,\omega} g^n_{\epsilon\omega}\left[\overline{\ell'_\epsilon}\Gamma^n(\nu_{\ell'})_\sigma\right]\left[\overline{(\nu_\ell)_\lambda}\Gamma_n\ell_\omega\right]$$

$\epsilon, \omega, \sigma, \lambda$ label the chiralities

$$\frac{d^2\Gamma_{\ell\to\ell'}}{dx\, d\cos\theta} = \frac{m_\ell\, \omega^4}{2\pi^3} G^2_{\ell'\ell}\sqrt{x^2 - x_0^2}\left\{F(x) - \frac{\xi}{3}\mathcal{P}_\ell\sqrt{x^2 - x_0^2}\cos\theta\, A(x)\right\},$$

$E_{l'}^{max}$

$$x \equiv E_{\ell'}/\omega$$

$$x_0 \equiv m_{\ell'}/\omega$$

MICHEL PARAMETERS IN LEPTONIC LEPTON DECAYS:

Not only muons matter

$$\frac{d^2\Gamma_{\ell\to\ell'}}{dx\, d\cos\theta} = \frac{m_\ell\, \omega^4}{2\pi^3} G^2_{\ell'\ell} \sqrt{x^2 - x_0^2} \left\{ F(x) - \frac{\xi}{3} \mathcal{P}_\ell \sqrt{x^2 - x_0^2} \cos\theta\, A(x) \right\},$$

$E_{l'}^{max}$ $\quad x \equiv E_{\ell'}/\omega \quad x_0 \equiv m_{\ell'}/\omega$

$$F(x) = x(1-x) + \frac{2}{9}\rho(4x^2 - 3x - x_0^2) + \eta x_0 (1-x),$$

In the SM: $\rho = \frac{3}{4}$, $\eta = 0$, $\xi = 1$, $\delta = \frac{3}{4}$

$$A(x) = 1 - x + \frac{2}{3}\delta\left(4x - 4 + \sqrt{1 - x_0^2}\right).$$

Michel parameters for muon decay (unpolarized daugther lepton, 5 additional independent parameters if measured)
They are bilinear combinations of the effective $g^n_{\varepsilon\omega}$ couplings.

MICHEL PARAMETERS IN LEPTONIC LEPTON DECAYS:

Not only muons matter

Assumes LU

	$\mu^- \to e^- \bar{\nu}_e \nu_\mu$	$\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau$	$\tau^- \to e^- \bar{\nu}_e \nu_\tau$	$\tau^- \to \ell^- \bar{\nu}_\ell \nu_\tau$
ρ	0.74979 ± 0.00026	0.763 ± 0.020	0.747 ± 0.010	0.745 ± 0.008
η	0.057 ± 0.034	0.094 ± 0.073	—	$\boxed{0.013 \pm 0.020}$
ξ	$1.0009\,^{+\,0.0016}_{-\,0.0007}$	1.030 ± 0.059	0.994 ± 0.040	0.985 ± 0.030
$\xi\delta$	$0.7511\,^{+\,0.0012}_{-\,0.0006}$	0.778 ± 0.037	0.734 ± 0.028	0.746 ± 0.021
ξ'	1.00 ± 0.04	—	—	—
ξ''	0.65 ± 0.36	—	—	—

A. Pich, Prog.Part.Nucl.Phys. 75 (2014) 41-85

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MICHEL PARAMETERS IN LEPTONIC LEPTON DECAYS:

Not only muons matter

$$\Gamma_{\ell\to\ell'} = \frac{\widehat{G}^2_{\ell'\ell} m_\ell^5}{192\pi^3} f\left(m^2_{\ell'}/m^2_\ell\right) \left(1+\delta^{\ell'\ell}_{\mathrm{RC}}\right) ,$$

Low-E parameter

$$\widehat{G}_{\ell'\ell} \equiv G_{\ell'\ell} \sqrt{1 + 4\,\eta\, \frac{m_{\ell'}}{m_\ell} \frac{g\left(m^2_{\ell'}/m^2_\ell\right)}{f\left(m^2_{\ell'}/m^2_\ell\right)}}$$

MICHEL PARAMETERS IN LEPTONIC LEPTON DECAYS:

Not only muons matter

Achieving competitive accuracy in the Michel parameters carrying information on the daughter lepton polarization is difficult in tau decays. Since the photon it emits is sensitive to this information, Michel parameters have been/are being measured using radiative tau decays at Belle.

$\mu \rightarrow e\, e^+ e^- \nu_\mu \nu_e$ was discovered by SINDRUM ('85) & $\mu \rightarrow e\, \gamma\, \nu_\mu \nu_e$ by MEG ('16)
but Michel parameters were not measured.

a_τ

The corresponding Michel parameters have been measured in $\tau \rightarrow l\, \gamma\, \nu_\tau \nu_l$

Belle(prelim.): $\bar{\eta} = -1.3 \pm 1.5 \pm 0.8$, $\xi\kappa = 0.5 \pm 0.4 \pm 0.2$; arXiv:1609.08280

And will be published soon for $\tau \rightarrow l\, l'^+ l'^- \nu_\mu \nu_e$ using our Michel parameters formalism (A. Flores-Tlalpa, Gabriel López-Castro & PR, JHEP 1604 (2016) 185) (***mention private communication***)

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DISCLAIMER

I have not discussed other very interesting NP searches that can be performed through charged leptons physics. Namely:

- **Electron & muon electric dipole moments**
- **$\mu\, e \to \mu\, e$ for $a_\mu^{HVP,LO}$**
- **Dark photons** *(for obvious reasons)*
- **LU anomalies in semileptonic decays of heavy mesons**
- **Antimatter gravity with muonium**
- **LNV**
- **LFV in nuclei**
- **Baryogenesis through leptogenesis**
- **…**

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SUMMARY

Charged leptons Physics are Precision BSM probes. Some examples:

- μ and e anomalous magnetic moments (a_μ, a_e): Are **BOTH** anomalies real?
- Charged lepton flavor violation: **Any observation is New Physics**
- Semileptonic tau decays: **From the Fermi-like theory to the SMEFT**
- Michel parameters in leptonic lepton decays: **Not only muons matter**

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Charged leptons Physics are Precision BSM probes. Some examples:

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- Michel parameters in leptonic lepton decays: **Not only muons matter**

Looking for NP, go as leptonic (clean) as possible

BACKUP

FERMION GENERATIONS

$N_G = 3$ **Identical Copies** **Masses are the only difference**

$$\begin{matrix} Q=0 \\ Q=-1 \end{matrix} \qquad \begin{pmatrix} \nu'_j & u'_j \\ l'_j & d'_j \end{pmatrix} \qquad \begin{matrix} Q=+2/3 \\ Q=-1/3 \end{matrix} \qquad (j=1,\cdots,N_G)$$

WHY ?

$$\mathcal{L}_Y = -\sum_{jk} \left\{ \left(\bar{u}'_j, \bar{d}'_j\right)_L \left[c^{(d)}_{jk} \begin{pmatrix} \phi^{(+)} \\ \phi^{(0)} \end{pmatrix} d'_{kR} + c^{(u)}_{jk} \begin{pmatrix} \phi^{(0)\dagger} \\ -\phi^{(+)\dagger} \end{pmatrix} u'_{kR} \right] - \left(\bar{\nu}'_j, \bar{l}'_j\right)_L c^{(l)}_{jk} \begin{pmatrix} \phi^{(+)} \\ \phi^{(0)} \end{pmatrix} l'_{kR} \right\} + \text{h.c.}$$

$$\Big\Downarrow \ \textbf{SSB}$$

$$\mathcal{L}_Y = -\left(1+\frac{H}{v}\right) \left\{ \bar{d}'_L \cdot \mathbf{M}'_d \cdot d'_R + \bar{u}'_L \cdot \mathbf{M}'_u \cdot u'_R + \bar{l}'_L \cdot \mathbf{M}'_l \cdot l'_R + \text{h.c.} \right\}$$

Arbitrary Non-Diagonal Complex Mass Matrices

$$\left[\mathbf{M}'_d , \mathbf{M}'_u , \mathbf{M}'_l \right]_{jk} = \left[c^{(d)}_{jk} , c^{(u)}_{jk} , c^{(l)}_{jk} \right] \frac{v}{\sqrt{2}}$$

DIAGONALIZATION OF MASS MATRICES

$$\mathbf{M}'_d = \mathbf{H}_d \cdot \mathbf{U}_d = \mathbf{S}_d^\dagger \cdot \mathcal{M}_d \cdot \mathbf{S}_d \cdot \mathbf{U}_d \qquad \mathbf{H}_f = \mathbf{H}_f^\dagger$$

$$\mathbf{M}'_u = \mathbf{H}_u \cdot \mathbf{U}_u = \mathbf{S}_u^\dagger \cdot \mathcal{M}_u \cdot \mathbf{S}_u \cdot \mathbf{U}_u \qquad \mathbf{U}_f \cdot \mathbf{U}_f^\dagger = \mathbf{U}_f^\dagger \cdot \mathbf{U}_f = 1$$

$$\mathbf{M}'_l = \mathbf{H}_l \cdot \mathbf{U}_l = \mathbf{S}_l^\dagger \cdot \mathcal{M}_l \cdot \mathbf{S}_l \cdot \mathbf{U}_l \qquad \mathbf{S}_f \cdot \mathbf{S}_f^\dagger = \mathbf{S}_f^\dagger \cdot \mathbf{S}_f = 1$$

$$\boxed{\begin{array}{c} \mathcal{L}_Y = -\left(1+\frac{H}{v}\right)\left\{\bar{d}\cdot\mathcal{M}_d\cdot d + \bar{u}\cdot\mathcal{M}_u\cdot u + \bar{l}\cdot\mathcal{M}_l\cdot l\right\} \\[1em] \mathcal{M}_u = \mathrm{diag}\,(m_u, m_c, m_t) \;\; ; \;\; \mathcal{M}_d = \mathrm{diag}\,(m_d, m_s, m_b) \;\; ; \;\; \mathcal{M}_l = \mathrm{diag}\,(m_e, m_\mu, m_\tau) \end{array}}$$

$$d_L \equiv \mathbf{S}_d \cdot d'_L \quad ; \quad u_L \equiv \mathbf{S}_u \cdot u'_L \quad ; \quad l_L \equiv \mathbf{S}_l \cdot l'_L$$

$$d_R \equiv \mathbf{S}_d \cdot \mathbf{U}_d \cdot d'_R \quad ; \quad u_R \equiv \mathbf{S}_u \cdot \mathbf{U}_u \cdot u'_R \quad ; \quad l_R \equiv \mathbf{S}_l \cdot \mathbf{U}_l \cdot l'_R$$

Mass Eigenstates
$\neq$
Weak Eigenstates

$$\bar{f}'_L\, f'_L = \bar{f}_L\, f_L \quad ; \quad \bar{f}'_R\, f'_R = \bar{f}_R\, f_R \quad \longrightarrow \quad \mathcal{L}'_{NC} = \mathcal{L}_{NC}$$

$$\bar{u}'_L\, d'_L = \bar{u}_L \cdot \mathbf{V} \cdot d_L \quad ; \quad \mathbf{V} \equiv \mathbf{S}_u \cdot \mathbf{S}_d^\dagger \quad \longrightarrow \quad \mathcal{L}'_{CC} \neq \mathcal{L}_{CC}$$

QUARK MIXING