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Unearthing the pattern of lepton flavour universality violations

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In collaboration with F. Conventi, G. D'ambrosio, M. Mangano, F. Piccinini, A.D. Polosa, E. Rossi,

In the context of Neutral current anomalies

Global fits including B- K* mu mu signal NP favouring coupling to muon

The consistency of global fits with the electron requires more fine tuning relative to the muon only.

However..

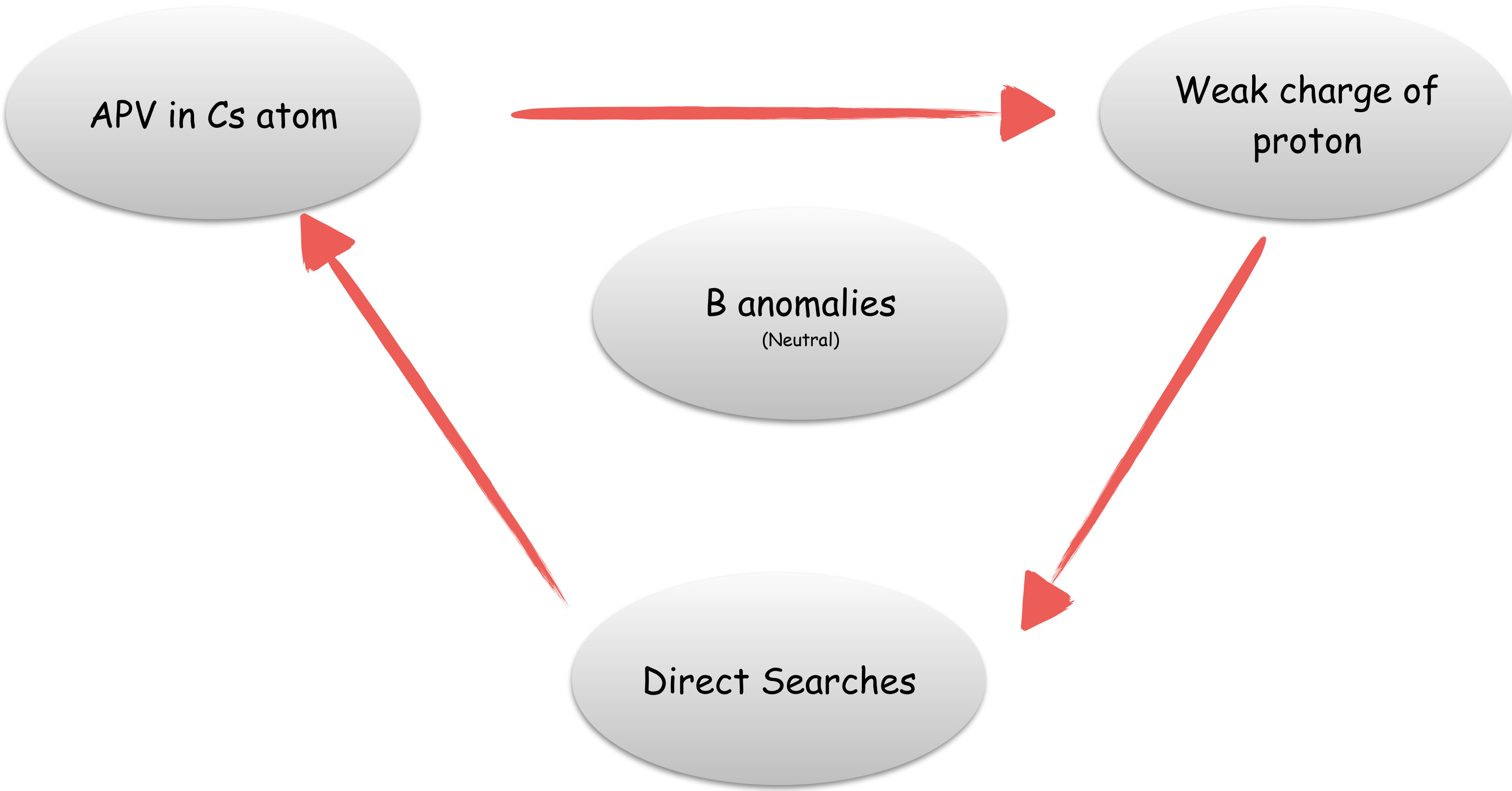
Including an electron contribution offers better fits to R_{K*}^{low}

Kumar, London
1901.04516

Let's look at the extreme possibility with electrons only!!

To develop the link with PV experiments

What is the goal of the talk?



Lets begin with the B anomalies

The fits to the data

$$\mathscr{H}_{\rm eff} = -V_{tb}V_{ts}^*\frac{\alpha_{\rm em}}{4\pi v^2}\sum_{\ell,X,Y} C_{b_X\ell_Y}\mathcal{O}_{b_X\ell_Y} + {\rm h.c.}\,, \qquad \mathcal{O}_{b_X\ell_Y} = (\bar{s}\gamma_\mu P_X b)(\bar{\ell}\gamma_\mu P_Y \ell).$$

The fits generally involve one operator at a time

$$R_K = \frac{|C_{b_{L+R}\mu_{L-R}}|^2 + |C_{b_{L+R}\mu_{L+R}}|^2}{|C_{b_{L+R}e_{L-R}}|^2 + |C_{b_{L+R}e_{L+R}}|^2}\ .$$

$$R_{K^*} = \frac{(1-p)(|C_{b_{L+R}\mu_{L-R}}|^2 + |C_{b_{L+R}\mu_{L+R}}|^2) + p\left(|C_{b_{L-R}\mu_{L-R}}|^2 + |C_{b_{L-R}\mu_{L+R}}|^2\right)}{(1-p)(|C_{b_{L+R}e_{L-R}}|^2 + |C_{b_{L+R}e_{L+R}}|^2) + p\left(|C_{b_{L-R}e_{L-R}}|^2 + |C_{b_{L-R}e_{L+R}}|^2\right)}$$

New physics in the muon sector									
Wilson coeff.	Best-fit			1-σ range			$\sqrt{\chi^2_{\rm SM} - \chi^2_{\rm best}}$		
	'clean'	'dirty'	all	'clean'	'dirty'	all	'clean'	'dirty'	all
$C^{\rm BSM}_{b_L\mu_L}$	−1.33	−1.33	−1.33	−0.99 −1.70	−1.01 −1.68	−1.10 −1.58	4.1	4.6	6.2
$C^{\rm BSM}_{b_L\mu_R}$	0.68	−0.73	−0.35	1.27 0.10	−0.40 −1.03	−0.03 −0.65	1.2	2.1	1.1
$C^{\rm BSM}_{b_R\mu_L}$	0.03	−0.20	−0.15	0.32 −0.26	−0.04 −0.29	−0.01 −0.25	0.1	1.3	1.1
$C^{\rm BSM}_{b_R\mu_R}$	−0.44	0.41	0.29	0.14 −1.00	0.61 0.18	0.50 0.07	0.8	1.7	1.3

New physics in the electron sector									
Wilson coeff.	Best-fit			1-σ range			$\sqrt{\chi^2_{\rm SM} - \chi^2_{\rm best}}$		
	'clean'	'dirty'	all	'clean'	'dirty'	all	'clean'	'dirty'	all
$C^{\rm BSM}_{b_Le_L}$	1.72	0.15	0.99	2.31 1.21	0.69 −0.39	1.30 0.70	4.1	0.3	3.5
$C^{\rm BSM}_{b_Le_R}$	−5.15	−1.70	−3.46	−4.23 −6.10	0.33 −2.83	−2.81 −4.05	4.3	0.9	3.6
$C^{\rm BSM}_{b_Re_L}$	0.085	−0.51	0.02	0.39 −0.21	0.29 −1.55	0.30 −0.25	0.3	0.7	0.1
$C^{\rm BSM}_{b_Re_R}$	−5.60	2.10	−3.63	−4.66 −6.56	3.52 −2.70	−2.65 −4.43	4.2	0.5	2.5

G. D'Amico et al.
1704.05438

Table 1: *Best fits assuming a single chiral operator at a time, and fitting only the 'clean'* R_K, R_{K^*}, *and* $\mathrm{BR}(B_s \to \mu^+\mu^-)$, *or only the 'dirty' observables as discussed in the text, or combining them in a global fit. As far as the electron case is concerned, we only add to the 'clean' set the observables data from* $\mathrm{BR}(B^+ \to X_s e^+ e^-)$ *and* $\mathrm{BR}(B^+ \to K^+ e^+ e^-)$, *as illustrated in appendix A. The data affected by dominant theoretical uncertainties are dubbed as 'dirty': the significance quoted here would be rescaled by a factor* λ *if the theoretical uncertainties, adopted from state-of-the-art studies, were under-estimated by the same factor.*

From Anomalies to Parity Violation Experiments

These experiments can be classified into:

Atomic parity violation experiments in Cs

CS Wood et, al

Weak neutral current

Parity violation due to electron scattering of liquid hydrogen target

Jefferson Lab Collab

Both these experiments measure the weak charge of the Cs Nucleus and proton respectively

In SM model parametrization

$$\mathcal{L}_{Q_W,Q_P} = \frac{\bar{e}\gamma_\mu\gamma_5 e}{2v^2} \sum_{q=u,d} C_{1q}\bar{q}\gamma^\mu q$$

where

$$C_{1u} = -\frac{1}{2} + \frac{4}{3}\sin^2_{\theta_W}$$
$$C_{1d} = \frac{1}{2} - \frac{2}{3}\sin^2_{\theta_W}$$

$$Q_W^p = -2\left[2C_{1u} + C_{1d}\right]$$
$$Q_W^{Cs} = -2\left[55(2C_{1u} + C_{1d}) + 78(C_{1u} + 2C_{1d})\right]$$

$$C_{1u}^{SM} = -0.1887 \pm 0.0022$$
$$C_{1d}^{SM} = 0.3419 \pm 0.0025$$

C.S. Wood et al.
Dzuba et. al 1207.5864

Atomic parity violation experiments in Cs

In the absence of weak neutral current, the s-s spectroscopic transition is forbidden by the parity selection rule

WNC interaction violated parity and mixed the P and S states resulting in parity violation

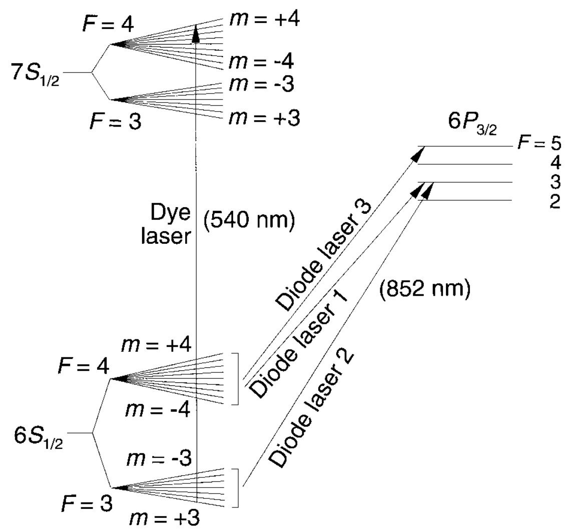


Fig. 1. Partial cesium energy-level diagram including the splitting of S states by the magnetic field. The case of 540-nm light exciting the $F = 3$, $m = 3$ level is shown. Diode lasers 1 and 2 optically pump all of the atoms into the (3, 3) level, and laser 3 drives the $6S_{F=4}$ (F_{det}) to $6P_{F=5}$ transition to detect the $7S$ excitation. PNC is also measured for excitation from the (3, −3), (4, 4), and (4, −4) 6S levels. The diode lasers excite different transitions for the latter two cases.

The PNC amplitude of an electric dipole transition between the $6s$ and $7s$ states of cesium can be written as

$$E_{\rm PNC} = \sum_n \left[\frac{\langle 6s|H_{\rm PNC}|np_{1/2}\rangle\langle np_{1/2}|\boldsymbol{d}|7s\rangle}{E_{6s}-E_{np_{1/2}}} + \frac{\langle 6s|\boldsymbol{d}|np_{1/2}\rangle\langle np_{1/2}|H_{\rm PNC}|7s\rangle}{E_{7s}-E_{np_{1/2}}} \right], \qquad (1)$$

$$H_{\rm PNC} = -\frac{G_F}{2\sqrt{2}} Q_W \gamma_5 \rho(\boldsymbol{r}) ,$$

How does this come about in terms of effective theory due to Z exchange?

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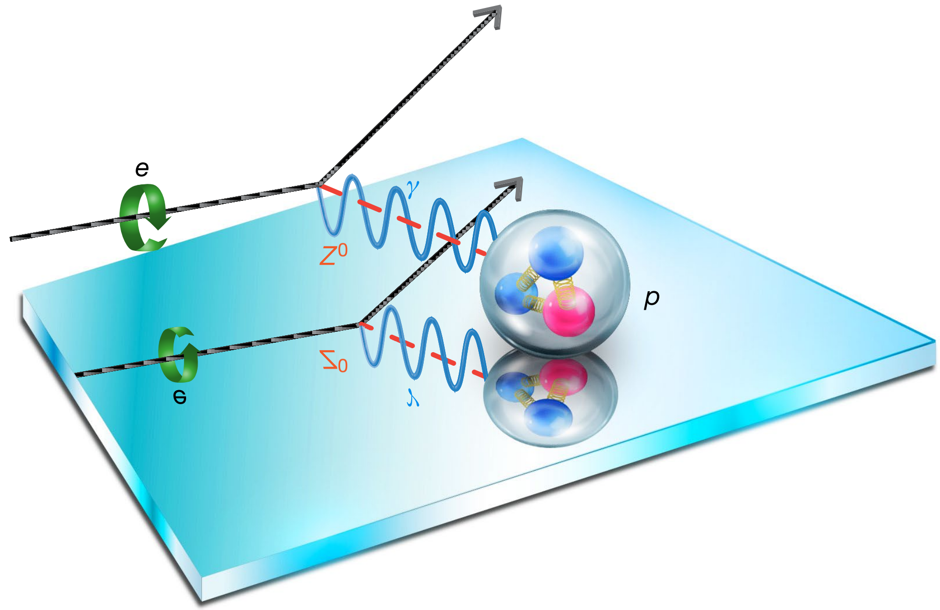
Nature

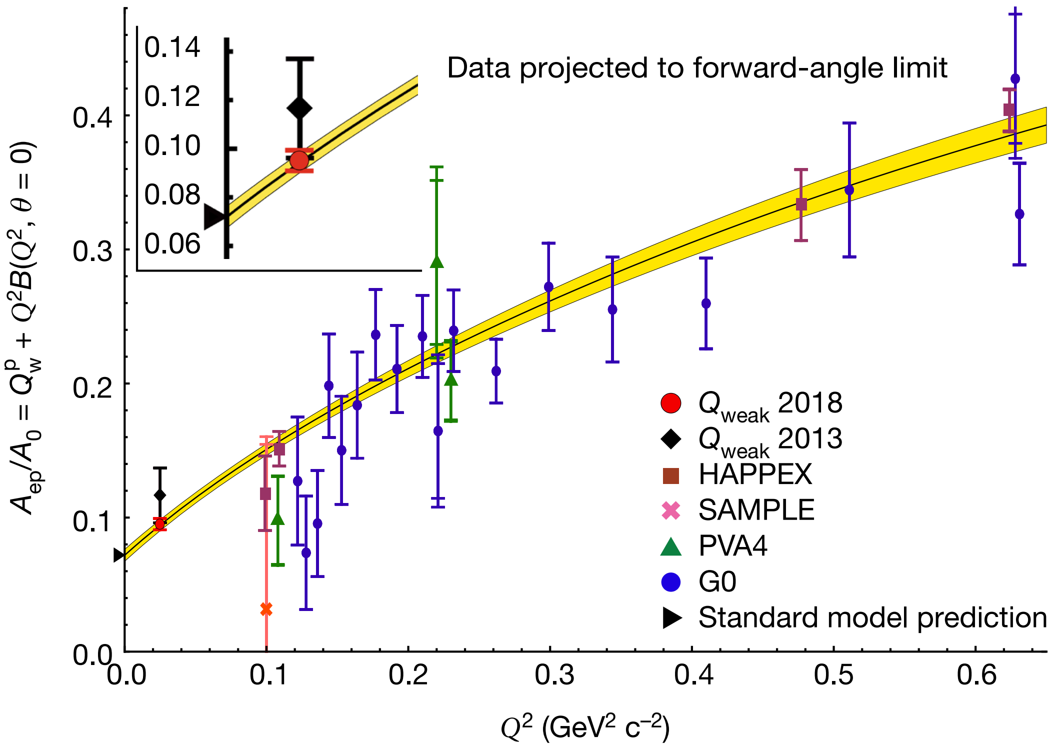
Electron Scattering experiments

Interference between photon and weak charge leads to the parity violation asymmetry



$$A_{ep} = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}$$

In the limit of low momentum transfer



$$A_{ep}/A_0 = Q_w^p + Q^2 B(Q^2, \theta)$$

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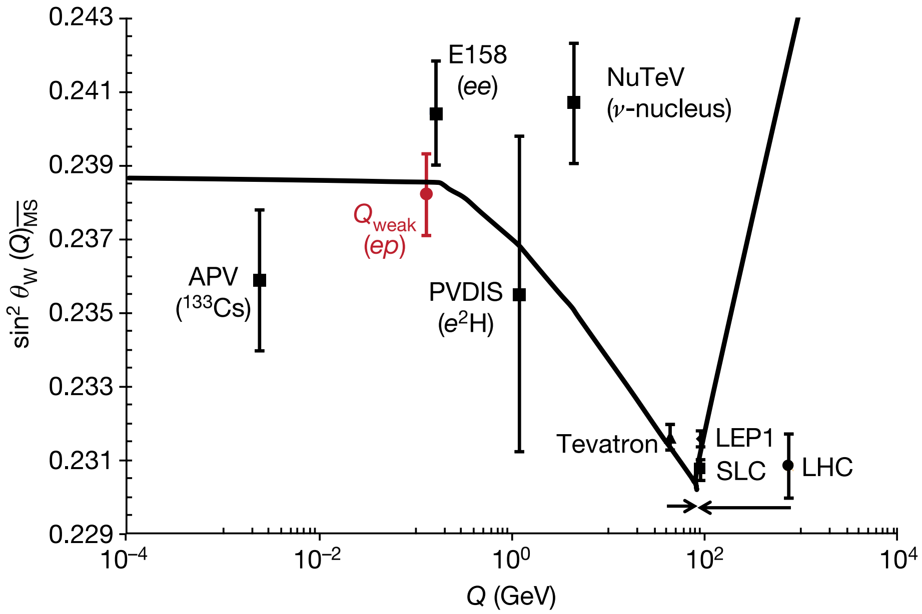
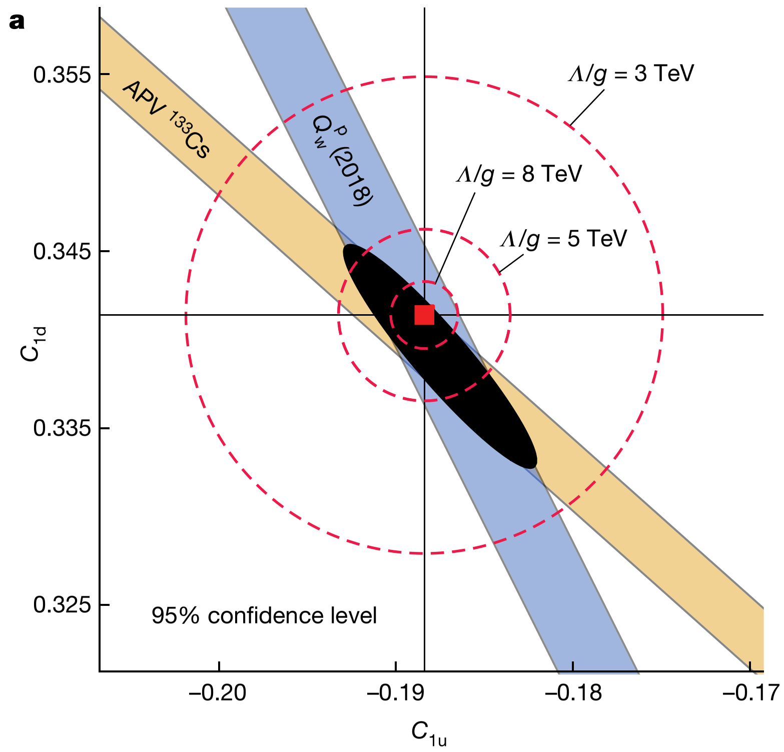
Lets combine the experiments (Parity Violating ones)





extraction of the weinberg angle from these measurements

So far:

We discussed the anomalies in the B decays and the fits to different operators chiralities

We also discussed the two parity violation experiments which measure the axiol vector electron and vector quark coupling to the Z boson

How are these connected?

Lets go back to the effective lagrangian description of both

Anomalies

$$\mathcal{H}_{eff} = -\frac{G_f \alpha}{\sqrt{2}\pi} V_{tb} V_{ts}^* \sum_i \mathcal{O}_{XY} C_{XY}$$

$$\mathcal{O}_{b_X \ell_Y} = (\bar{s}\gamma_\mu P_X b)(\bar{\ell}\gamma_\mu P_Y \ell).$$

$$C_{XY} = C_{XY}^{SM} + C_{XY}^{NP}.$$

Heavy quarks and chiral lepton current

A priori there is be no relation bet light and heavy quark coupling to NP

PV experiments

$$\mathcal{L} = \frac{\bar{e}\gamma_\mu\gamma_5 e}{2v^2} \sum_{q=u,d} C_{1q}^{eff} \bar{q}\gamma^\mu q$$

$$C_{1q}^{eff} = C_{1q}^{SM} + C_{1q}^{NP}$$

Light quarks and chiral lepton current

The effective Lagrangian with Z'

$$\mathcal{L} = \frac{Z'^{\mu}}{2\cos\theta_w}\Big[g_e(g'_e)\bar{e}\gamma_\mu P_{L(R)}e + g_\mu(g'_\mu)\bar{\mu}\gamma_\mu P_{L(R)}\mu$$
$$+ \sum_q (g_q\bar{q}\gamma_\mu P_L q + g'_q\bar{q}\gamma_\mu P_R q)$$
$$+ (g_t - g_q)V^*_{ts}V_{tb}\bar{s}\gamma_\mu P_{L,R}b + \dots\Big]$$

From this lagrangian we can identify the additional contribution to the WC contributing to B anomalies as well as PV experiments

Since the fits for anomalies involve only on WC at a time, we consider the following three cases

	WC	operator	Best fit	2 σ
Case A	C_{LL}	$(\bar{s}_L\gamma^\mu b_L)(\bar{e}_L\gamma_\mu e_L)$	0.99	[0.37,1.61]
Case B	C_{LR}	$(\bar{s}_L\gamma^\mu b_L)(\bar{e}_R\gamma_\mu e_R)$	-3.46	[-4.76,-2.16]
Case C	C_{RR}	$(\bar{s}_R\gamma^\mu b_R)(\bar{e}_R\gamma_\mu e_R)$	-3.63	[-5.5,-2.67]

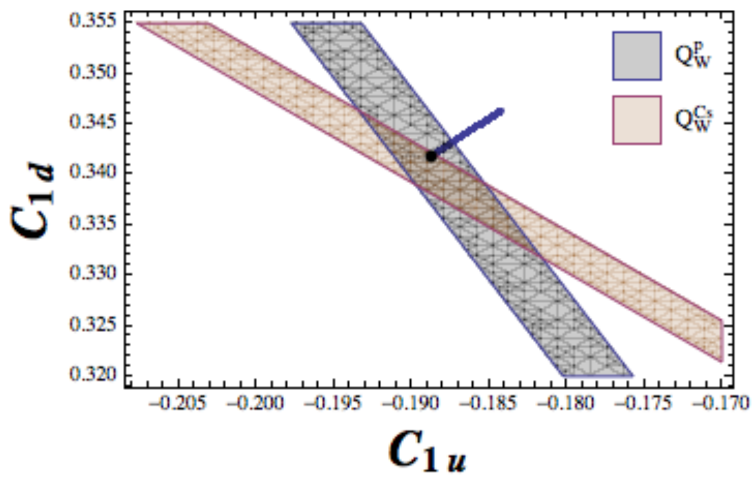
TABLE I. 2σ ranges used for the fits to Wilson coefficients in the case where only electron couples to New Physics.

G. D'Ambrosio, A.I, F.Piccinini, A Polosa
1902.00893

Case A

$$C_{LL} = \frac{\sqrt{2}\pi g_e (g_t - g_q)}{4\cos^2\theta_W m_{Z'}^2 G_F \alpha}$$

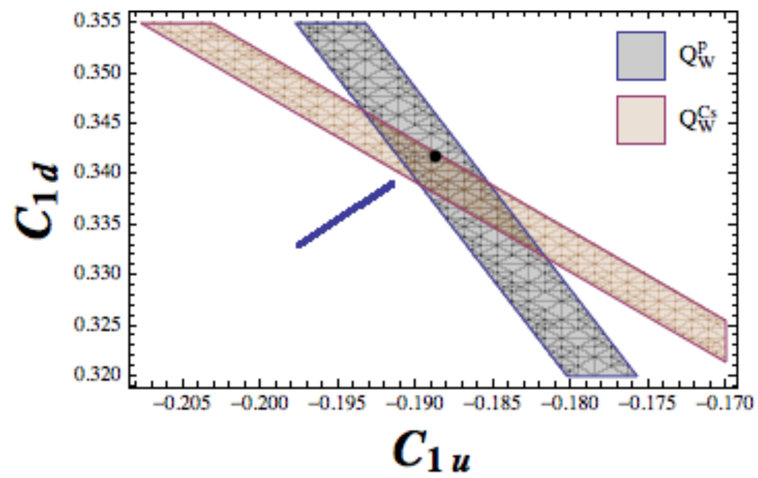
$$C_{1q}^{eff} = C_{1q}^{SM} + \frac{2v^2 g_e g_q}{8\cos^2\theta_W m_{Z'}^2}$$



Case B

$$C_{LR} = \frac{\sqrt{2}\pi g_e' (g_t - g_q)}{4\cos^2\theta_W m_{Z'}^2 G_F \alpha}$$

$$C_{1q} = C_{1q}^{SM} - \frac{2v^2 g_e' g_q}{8\cos^2\theta_W m_{Z'}^2}$$



For light quark we assume

$$g_q = g_q'$$

Has implications for direct searches!!

Non-universality at Colliders

Can we say something about the structure of the solutions at the colliders?

This non universality in the couplings should in principle also show up in a collider.

For a Z’ resonant production, traditional searches are in the form of a “bump hunt”

Consider the case, when both partial decay into electron and muon final states is narrow width

Consider the on-shell production of Z' at colliders and consider the following ratio

$$\delta = \frac{\sigma_{Z'}\lambda_\mu^2 \mathcal{L}\epsilon_\mu}{\sigma_{Z'}\lambda_e^2 \mathcal{L}\epsilon_e} = \frac{N_\mu}{N_e}$$

Now the electron and muon are in general associated with different acceptance efficiencies

Is there a way for the above ratio to roughly reflect the ratio of WC

Its clear that if $\epsilon_\mu \simeq \epsilon_e$ then

$$\delta \simeq \frac{\lambda_\mu^2}{\lambda_e^2} = \left(\frac{C_9^\mu}{C_9^e}\right)^2$$

We construct the modified ratio:

$$\delta = \sqrt{\frac{2(S_\mu + B_\mu)\log\left[1+\frac{S_\mu}{S_\mu}\right] - 2S_\mu}{2(S_e + B_e)\log\left[1+\frac{S_e}{B_e}\right] - 2S_e}}$$

In the limit S<<<B

$$\delta = \frac{\frac{S_\mu}{\sqrt{B_\mu}}}{\frac{S_e}{\sqrt{B_e}}} \propto \left(\frac{g_\mu}{g_e}\right)^2$$

$$= \sqrt{\frac{\epsilon_e^B}{\epsilon_\mu^B}} \frac{\epsilon_\mu}{\epsilon_e} \left(\frac{g_\mu}{g_e}\right)^2$$

If the reconstruction efficiencies are same, then the ratio is ratio of square of Wilson coefficients

From indirect searches to colliders

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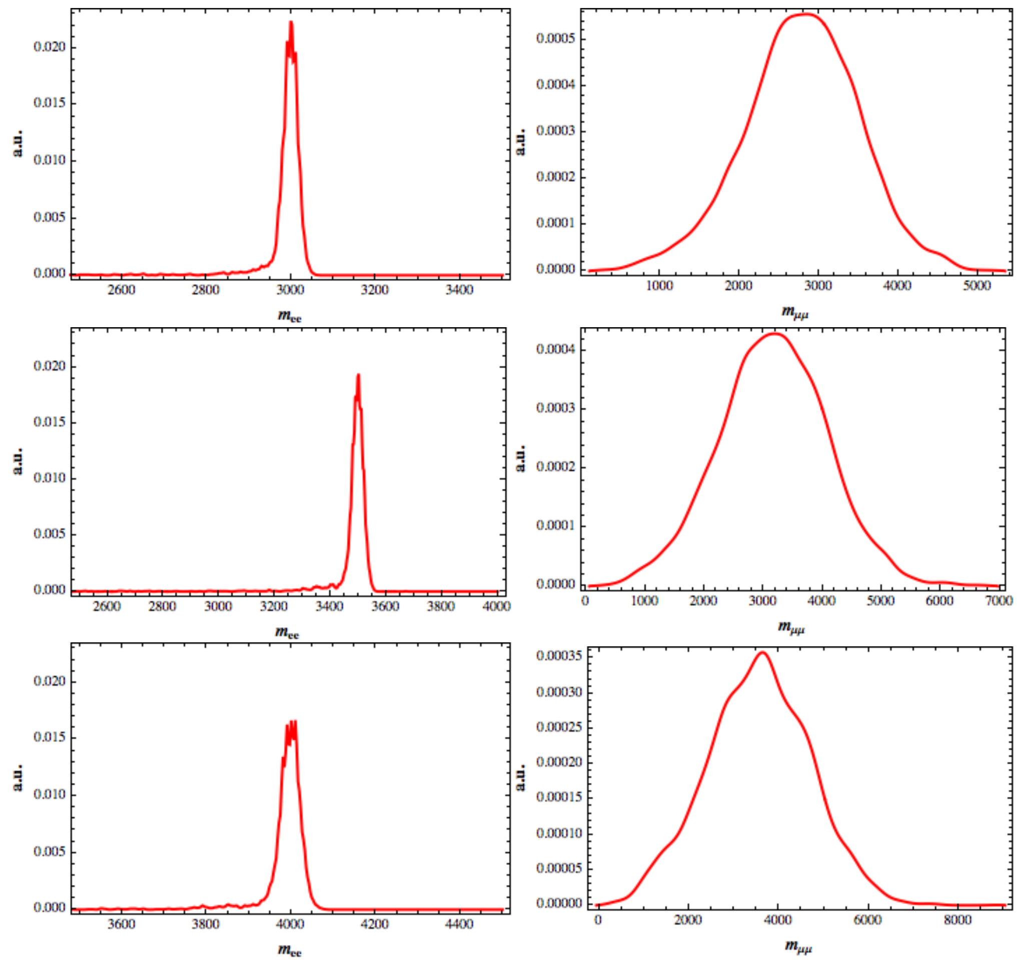
To appear

What are the prospects of an electron only solution in comparison to a muon only solution?

Current Lepton mass reconstruction efficiencies



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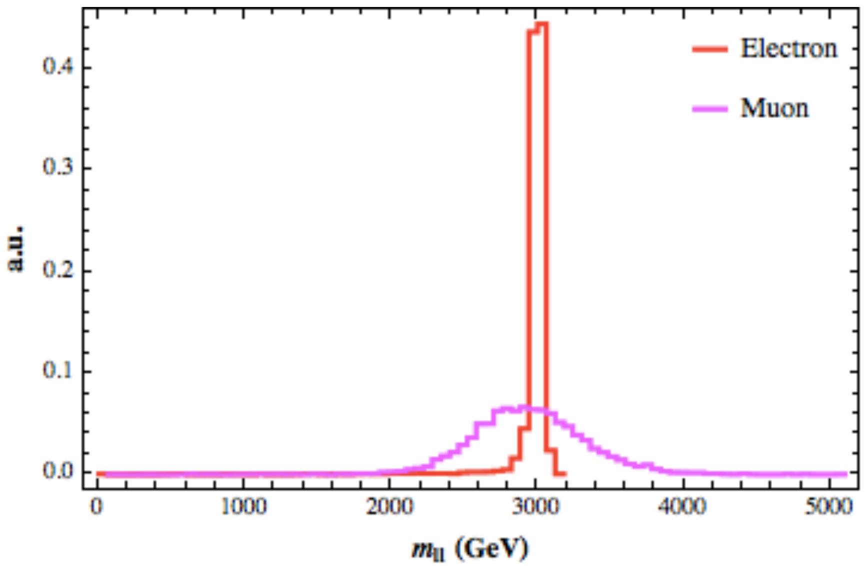

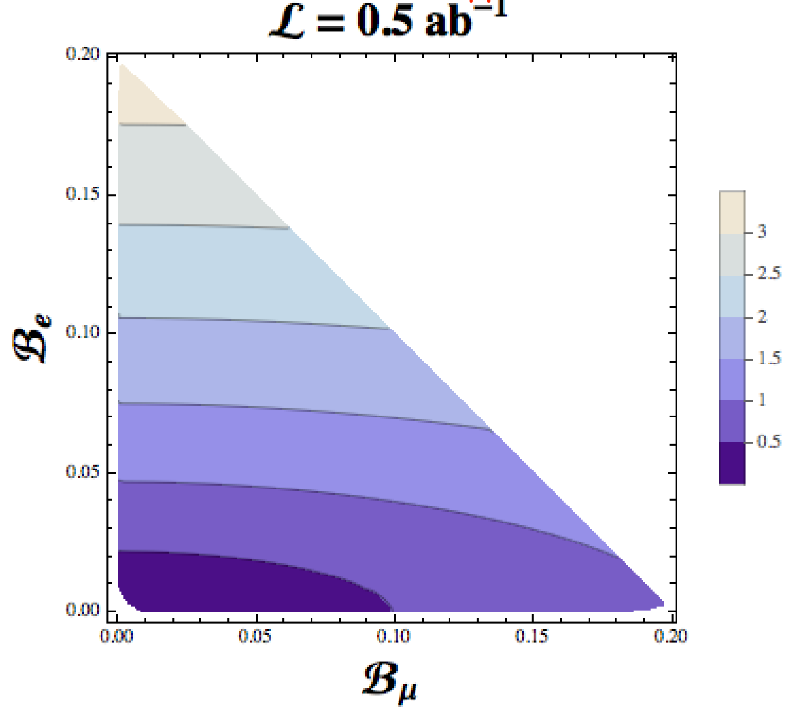

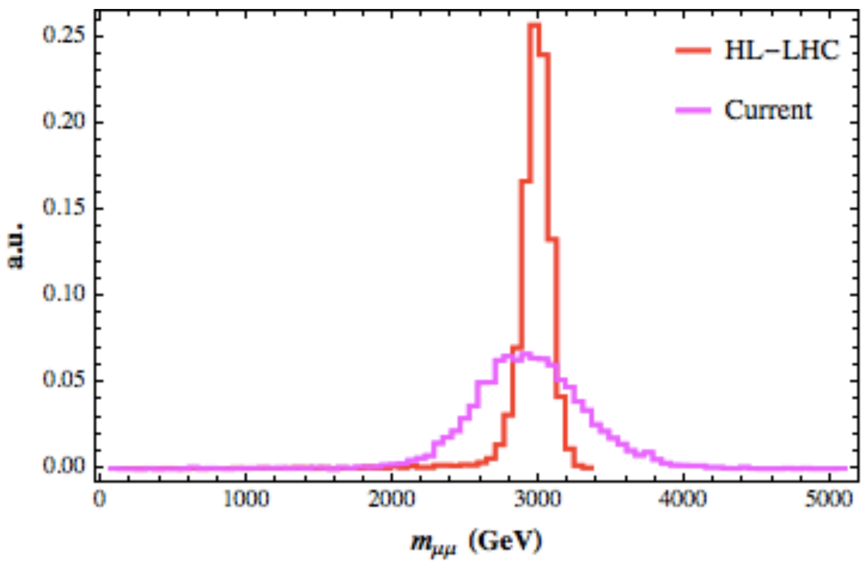

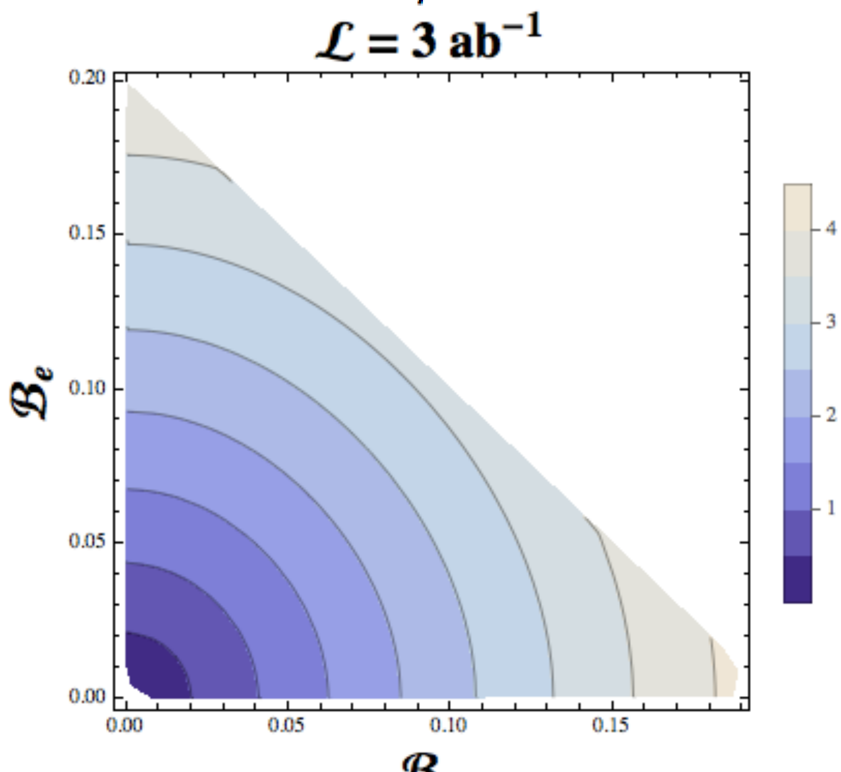

Test of universality

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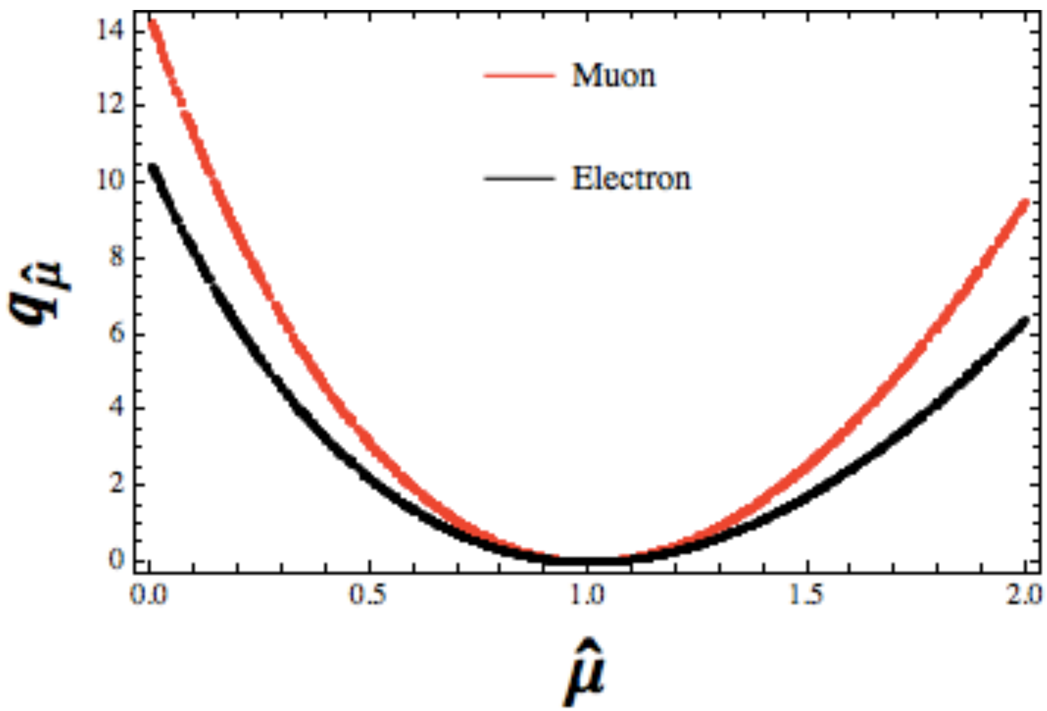
Consider a general test statistic

$$q_{\hat{\mu}} = -2\log\left[\frac{\hat{\mu}s + b}{s + b}\right]$$

Its defined separately for both the electrons and muons such that

$$\hat{\mu}_e + \hat{\mu}_\mu = 2$$



$$0 \le \hat{\mu} \le 2.$$

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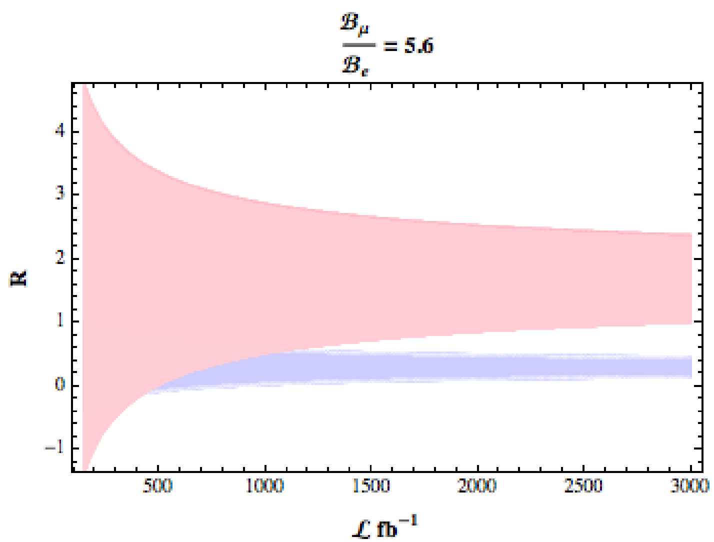
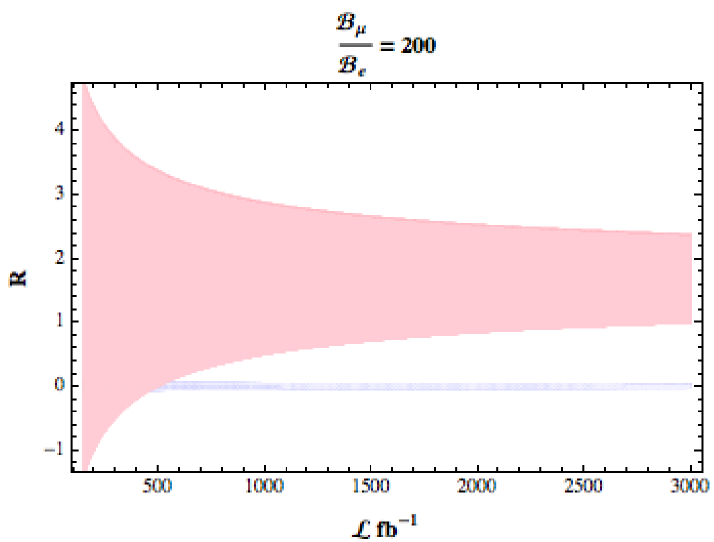
The computation of the individual significances can be further extended to take their ratios

This would actually extract the universality

$$\delta \simeq \frac{g_e^2}{g_\mu^2} = \left(\frac{C_9^e}{C_9^\mu}\right)^2 \longleftrightarrow R = \sqrt{\frac{2(S_l + B_l)\log\left[1+\frac{S_l}{B_l}\right] - 2S_l}{2(S_{l'} + B_{l'})\log\left[1+\frac{S_{l'}}{B_{l'}}\right] - 2S_{l'}}}$$

$$\sqrt{\frac{\epsilon_{l'}^B}{\epsilon_l^B}\frac{\epsilon_l}{\epsilon_{l'}}}\left(\frac{g_l}{g_{l'}}\right)^2$$





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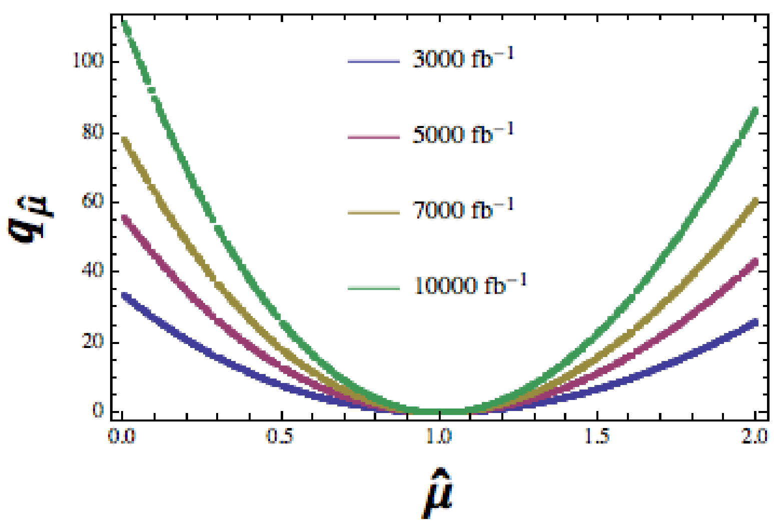
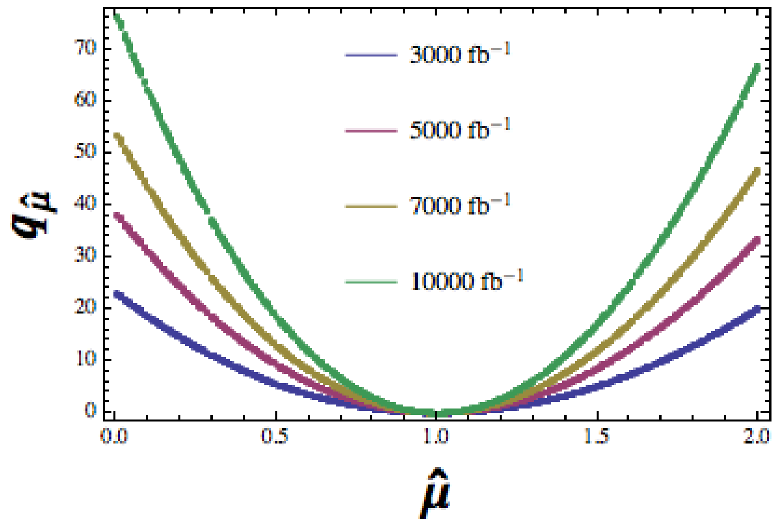
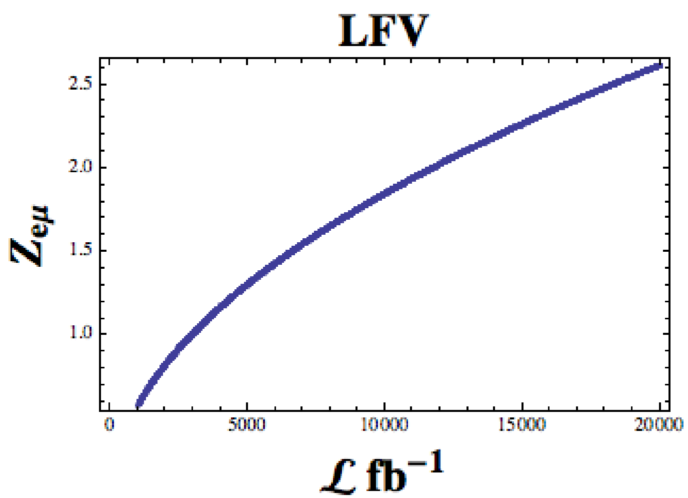
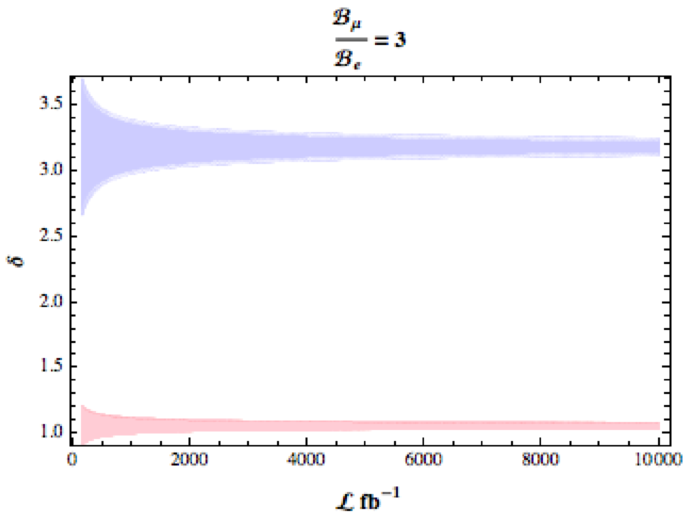
A few comments about FCC-100 TeV





Does LFUV imply LFV?





To Conclude

The current and future experiments may hold the key to unravelling the anomalies

Coupled with direct searches at the HL and (possibly) FCC, a bigger picture may emerge

K physics is also an interesting prospect with the advent of NA62

D'Ambrosio,Iyer 2017