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Low-energy constraints on heavy particles

Warszawa, 2 Grudnia 2017

Based on 1706.03783 with Martin Gonzalez-Alonso and Kin Mimouni

Energy

Theory

Experiment

1 TeV

SMEFT

LHC

100 GeV

LEP

TRISTAN

Fermi theory

10 GeV

ν beams

PVDIS

1 GeV

PVES

(...)

Pions et al

100 MeV

Moller

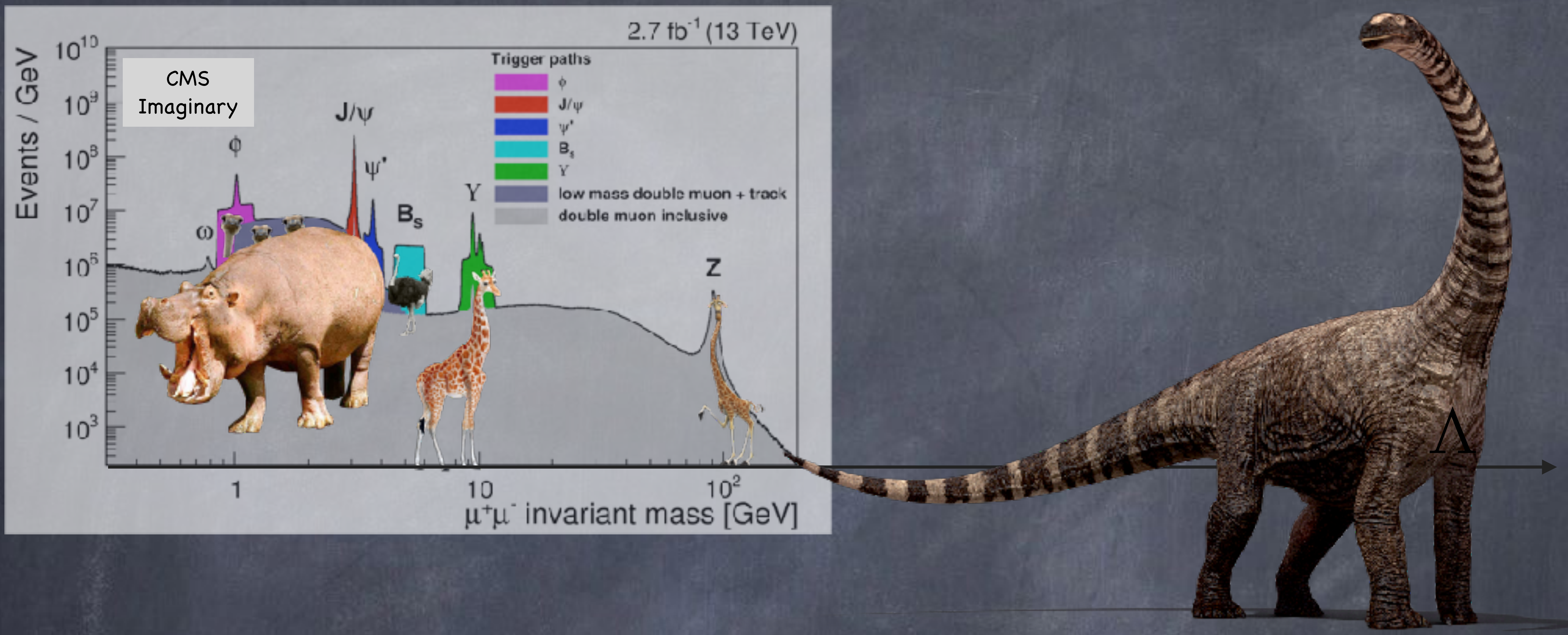
10 MeV

APV

1 MeV

E-H

Fantastic Beasts and Where To Find Them



x) It looks more and more likely that new degrees of freedom beyond the SM may not be directly available at the LHC or even at future colliders

x) However, even if it is not possible to see the head, it may be possible to see the tail...

Status report

- SM has been excessively successful in describing all collider and low-energy experiments. Discovery was 125 GeV Higgs boson is last piece of puzzle that falls into place. No more free parameters in SM
- We know physics beyond SM exists (neutrino masses, dark matter, inflation, baryon asymmetry). There are also some theoretical hints for new physics (strong CP problem, flavor hierarchies, gauge coupling unifications, naturalness problem)
- But there isn't one model or class of models that is strongly preferred, and all existing models addressing naturalness have certain tensions that cast doubt on whether they really describe nature
- We need to keep open mind on many possible forms of new physics that may show up in experiment. This requires a model-independent approach to complete other model-dependent searches

SMEFT

- Assume that the SM degrees of freedom is all there is below the TeV scale. But we treat the SM as an EFT, and call it the SMEFT
- In the SMEFT, the SM Lagrangian is treated as the lowest order approximation of the dynamics. Effects of heavy particles are encoded by new contact interactions of the SM particles added to the Lagrangian
- The SMEFT Lagrangian can be defined as an expansion in the inverse mass scale of heavy particles, which coincides with the expansion in operator dimensions
- Under certain (mild) assumptions, the SMEFT framework allows one to describe effects of new physics beyond the SM in a model independent way

+

SMEFT

Basic assumptions

- Much as in SM, relativistic QFT with linearly realized SU(3)xSU(2)xU(1) local symmetry spontaneously broken by VEV of Higgs doublet field
- SMEFT Lagrangian expanded in inverse powers of Λ, equivalently in operator dimension D

$$H \to LH, \qquad L \in SU(2)_L$$

$$H = \frac{1}{\sqrt{2}} \begin{pmatrix} \dots \\ v + h(x) + \dots \end{pmatrix}$$

$$v \ll \Lambda \ll \Lambda_L$$

$$\mathcal{L}_{\mathrm{SM\ EFT}} = \mathcal{L}_{\mathrm{SM}} + \frac{1}{\Lambda_L}\mathcal{L}^{D=5} + \frac{1}{\Lambda^2}\mathcal{L}^{D=6} + \frac{1}{\Lambda_L^3}\mathcal{L}^{D=7} + \frac{1}{\Lambda^4}\mathcal{L}^{D=8} + \dots$$

Lepton number or B-L violating, hence too small to probed at present and near-future colliders

Subleading wrt D=6 if Λ high enough

Generated by integrating out heavy particles with mass scale Λ
In large class of BSM models that conserve B-L, D=6 operators capture leading effects of new physics on collider observables at E << Λ

Buchmuller,Wyler (1986)   Grządkowski et al. 1008.4884   Alonso et al 1312.2014

(subset of) D=6 operators

In this talk, I will focus on a subset of D=6 operators
which contain 4 fermions and at least 2 leptons

One flavor $(I = 1,2,3)$	Two flavors $(I < J = 1,2,3)$
$[O_{\ell\ell}]_{IIII} = \frac{1}{2}(\bar\ell_I \bar\sigma_\mu \ell_I)(\bar\ell_I \bar\sigma^\mu \ell_I)$	$[O_{\ell\ell}]_{IIJJ} = (\bar\ell_I \bar\sigma_\mu \ell_I)(\bar\ell_J \bar\sigma^\mu \ell_J)$
	$[O_{\ell\ell}]_{IJJI} = (\bar\ell_I \bar\sigma_\mu \ell_J)(\bar\ell_J \bar\sigma^\mu \ell_I)$
$[O_{\ell e}]_{IIII} = (\bar\ell_I \bar\sigma_\mu \ell_I)(e^c_I \sigma^\mu \bar e^c_I)$	$[O_{\ell e}]_{IIJJ} = (\bar\ell_I \bar\sigma_\mu \ell_I)(e^c_J \sigma^\mu \bar e^c_J)$
	$[O_{\ell e}]_{JJII} = (\bar\ell_J \bar\sigma_\mu \ell_J)(e^c_I \sigma^\mu \bar e^c_I)$
	$[O_{\ell e}]_{IJJI} = (\bar\ell_I \bar\sigma_\mu \ell_J)(e^c_J \sigma^\mu \bar e^c_I)$
$[O_{ee}]_{IIII} = \frac{1}{2}(e^c_I \sigma_\mu \bar e^c_I)(e^c_I \sigma^\mu \bar e^c_I)$	$[O_{ee}]_{IIJJ} = (e^c_I \sigma_\mu \bar e^c_I)(e^c_J \sigma^\mu \bar e^c_J)$

Chirality conserving $(I, J = 1,2,3)$	Chirality violating $(I, J = 1,2,3)$
$[O_{\ell q}]_{IIJJ} = (\bar\ell_I \bar\sigma_\mu \ell_I)(\bar q_J \bar\sigma^\mu q_J)$	$[O_{\ell equ}]_{IIJJ} = (\bar\ell^j_I \bar e^c_I)\epsilon_{jk}(\bar q^k_J \bar u^c_J)$
$[O^{(3)}_{\ell q}]_{IIJJ} = (\bar\ell_I \bar\sigma_\mu \sigma^i \ell_I)(\bar q_J \bar\sigma^\mu \sigma^i q_J)$	$[O^{(3)}_{\ell equ}]_{IIJJ} = (\bar\ell^j_I \bar\sigma_{\mu\nu} \bar e^c_I)\epsilon_{jk}(\bar q^k_J \bar\sigma_{\mu\nu} \bar u^c_J)$
$[O_{\ell u}]_{IIJJ} = (\bar\ell_I \bar\sigma_\mu \ell_I)(u^c_J \sigma^\mu \bar u^c_J)$	$[O_{\ell edq}]_{IIJJ} = (\bar\ell^j_I \bar e^c_I)(d^c_J q^j_J)$
$[O_{\ell d}]_{IIJJ} = (\bar\ell_I \bar\sigma_\mu \ell_I)(d^c_J \sigma^\mu \bar d^c_J)$	
$[O_{eq}]_{IIJJ} = (e^c_I \sigma_\mu \bar e^c_I)(\bar q_J \bar\sigma^\mu q_J)$	
$[O_{eu}]_{IIJJ} = (e^c_I \sigma_\mu \bar e^c_I)(u^c_J \sigma^\mu \bar u^c_J)$	
$[O_{ed}]_{IIJJ} = (e^c_I \sigma_\mu \bar e^c_I)(d^c_J \sigma^\mu \bar d^c_J)$	

However, implicitly assuming that all dimension-6 operators
are present simultaneously with arbitrary Wilson coefficients.
In particular, flavor structure is assumed to be completely generic

EFT below the weak scale

- This talk is focused on observables where characteristic energy scale is smaller than Z boson mass
- Below mZ the only SM degrees of freedom available are leptons, photon, gluons, and 5 flavors of quark, while H/W/Z bosons and top quark are integrated out
- I refer to it as the Fermi theory
- Fermi theory is an EFT with SU(3)xU(1) gauge group and fermionic matter spectrum, where the expansion parameter is 1/v, v = 246 GeV.
- There are 70 dimension-5 and 3631 dimension-6 operators preserving baryon and lepton number

  Jenkins et al
  1711.05270
- I focus here on flavor conserving 4-fermion operators coupling leptons and light quarks (flavor violating ones are of course equally or even more interesting but not discussed here)

(Subset of) Fermi theory Lagrangian

Charged current interactions of 2 leptons and 2 light quarks

$$\mathcal{L}_{\rm eff} \supset -\frac{2\tilde{V}_{ud}}{v^2}\Big[\left(1+\bar{\epsilon}_L^{de_J}\right)(\bar{e}_J\bar{\sigma}_\mu\nu_J)(\bar{u}\bar{\sigma}^\mu d) + \epsilon_R^{de}(\bar{e}_J\bar{\sigma}_\mu\nu_J)(u^c\sigma^\mu\bar{d}^c) + \frac{\epsilon_S^{de_J}+\epsilon_P^{de_J}}{2}(e_J^c\nu_J)(u^c d) + \frac{\epsilon_S^{de_J}-\epsilon_P^{de_J}}{2}(e_J^c\nu_J)(\bar{u}\bar{d}^c) + \epsilon_T^{de_J}(e_J^c\sigma_{\mu\nu}\nu_J)(u^c\sigma_{\mu\nu}d) + \mathrm{h.c.}\Big]$$

Neutral current interactions of 2 neutrinos and 2 light quarks

$$\mathcal{L}_{\rm eff} \supset -\frac{2}{v^2}(\bar{\nu}_J\bar{\sigma}^\mu\nu_J)\left(g_{LL}^{\nu_J q}\bar{q}\bar{\sigma}_\mu q + g_{LR}^{\nu_J q} q^c\sigma_\mu\bar{q}^c\right).$$

(Matching PDG Notation)

Neutral current interactions of 2 charged leptons and 2 light quarks

$$\mathcal{L}_{\rm eff} \supset \frac{1}{2v^2}\left[g_{AV}^{e_J q}(\bar{e}_J\gamma_\mu\gamma_5 e_J)(\bar{q}\gamma_\mu q) + g_{VA}^{e_J q}(\bar{e}_J\gamma_\mu e_J)(\bar{q}\gamma_\mu\gamma_5 q)\right] + \frac{1}{2v^2}\left[g_{VV}^{e_J q}(\bar{e}_J\gamma_\mu e_J)(\bar{q}\gamma_\mu q) + g_{AA}^{e_J q}(\bar{e}_J\gamma_\mu\gamma_5 e_J)(\bar{q}\gamma_\mu\gamma_5 q)\right]$$

4-lepton interactions

$$\mathcal{L}_{\rm eff} \supset -\frac{1}{v^2}(\bar{\nu}_J\bar{\sigma}_\mu\nu_J)\left[\left(g_{LV}^{\nu_J e_I}+g_{LA}^{\nu_J e_I}\right)(\bar{e}_I\bar{\sigma}_\mu e_I) + \left(g_{LV}^{\nu_J e_I}-g_{LA}^{\nu_J e_I}\right)(e_I^c\sigma_\mu\bar{e}_I^c)\right].$$

$$\mathcal{L}_{\rm eff} \supset \frac{1}{2v^2}g_{AV}^{ee}\left[-(\bar{e}\bar{\sigma}_\mu e)(\bar{e}\bar{\sigma}_\mu e) + (e^c\sigma_\mu\bar{e}^c)(e^c\sigma_\mu\bar{e}^c)\right]$$

Matching Fermi theory to SMEFT

- One can match Fermi theory to SMEFT at μ = mZ to relate parameters of these 2 theories

Fermi theory

$$\mathcal{L}_{\rm eff} \supset -\frac{2}{v^2}(\bar\nu_J\bar\sigma^\mu\nu_J)\left(g_{LL}^{\nu_J q}\bar q\bar\sigma_\mu q + g_{LR}^{\nu_J q} q^c\sigma_\mu\bar q^c\right).$$

One example: $\nu\nu$qq operators

$$g_{LL}^{\nu_J u} = \frac{1}{2} - \frac{2s_\theta^2}{3} + \delta g_L^{Zu} + \left(1 - \frac{4s_\theta^2}{3}\right)\delta g_L^{Z\nu_J} - \frac{1}{2}([c_{lq}]_{JJ11} + [c_{lq}^{(3)}]_{JJ11}),$$

$$g_{LR}^{\nu_J u} = -\frac{2s_\theta^2}{3} + \delta g_R^{Zu} - \frac{4s_\theta^2}{3}\delta g_L^{Z\nu_J} - \frac{1}{2}[c_{lu}]_{JJ11},$$

$$g_{LL}^{\nu_J d} = -\frac{1}{2} + \frac{s_\theta^2}{3} + \delta g_L^{Zd} - \left(1 - \frac{2s_\theta^2}{3}\right)\delta g_L^{Z\nu_J} - \frac{1}{2}([c$$

$$g_{LR}^{\nu_J d} = \frac{s_\theta^2}{3} + \delta g_R^{Zd} + \frac{2s_\theta^2}{3}\delta g_L^{Z\nu_J} - \frac{1}{2}[c_{ld}]_{JJ11}.$$

SM contribution from Z exchange

Effect of shifted Z couplings

Trivial matching of 4-fermion operators

SMEFT

Chirality conserving $(I,J=1,2,3)$	C
$[O_{\ell q}]_{IIJJ} = (\bar\ell_I\bar\sigma_\mu\ell_I)(\bar q_J\bar\sigma^\mu q_J)$	
$[O_{\ell q}^{(3)}]_{IIJJ} = (\bar\ell_I\bar\sigma_\mu\sigma^i\ell_I)(\bar q_J\bar\sigma^\mu\sigma^i q_J)$	$[O$
$[O_{\ell u}]_{IIJJ} = (\bar\ell_I\bar\sigma_\mu\ell_I)(u_J^c\sigma^\mu\bar u_J^c)$	
$[O_{\ell d}]_{IIJJ} = (\bar\ell_I\bar\sigma_\mu\ell_I)(d_J^c\sigma^\mu\bar d_J^c)$	
$[O_{eq}]_{IIJJ} = (e_I^c\sigma_\mu\bar e_I^c)(\bar q_J\bar\sigma^\mu q_J)$	
$[O_{eu}]_{IIJJ} = (e_I^c\sigma_\mu\bar e_I^c)(u_J^c\sigma^\mu\bar u_J^c)$	
$[O_{ed}]_{IIJJ} = (e_I^c\sigma_\mu\bar e_I^c)(d_J^c\sigma^\mu\bar d_J^c)$	

RG running in Fermi theory

$$\mathcal{L}_{\text{eff}} \supset -\frac{2\tilde{V}_{ud}}{v^2}\Big[\left(1+\bar{\epsilon}_L^{de_J}\right)(\bar{e}_J\bar{\sigma}_\mu\nu_J)(\bar{u}\bar{\sigma}^\mu d)+\epsilon_R^{de}(\bar{e}_J\bar{\sigma}_\mu\nu_J)(u^c\sigma^\mu\bar{d}^c)$$
$$+\frac{\epsilon_S^{de_J}+\epsilon_P^{de_J}}{2}(e_J^c\nu_J)(u^c d)+\frac{\epsilon_S^{de_J}-\epsilon_P^{de_J}}{2}(e_J^c\nu_J)(\bar{u}\bar{d}^c)+\epsilon_T^{de_J}(e_J^c\sigma_{\mu\nu}\nu_J)(u^c\sigma_{\mu\nu}d)+\text{h.c.}\Big]$$

- Scalar and tensor operators experience significant running due to QCD loop corrections
- Electromagnetic running is most often negligible, unless it leads to mixing between stringently and weakly constrained operators

$$\begin{pmatrix}\epsilon_S^{d\ell}\\ \epsilon_P^{d\ell}\\ \epsilon_T^{d\ell}\end{pmatrix}_{(\mu=m_Z)} = \begin{pmatrix} 0.58 & 1.42\times10^{-6} & 0.017\\ 1.42\times10^{-6} & 0.58 & 0.017\\ 1.53\times10^{-4} & 1.53\times10^{-4} & 1.21\end{pmatrix}\begin{pmatrix}\epsilon_S^{d\ell}\\ \epsilon_P^{d\ell}\\ \epsilon_T^{d\ell}\end{pmatrix}_{(\mu=2\text{ GeV})}$$

Gonzalez-Alonso et al
1706.00410

see also Jenkins et al
1711.05270
for full set of anomalous dimensions

Workflow

1 Low-energy experiment

2 Constraints on Fermi theory coefficients

3 Constraints on SMEFT coefficients

Constraints on BSM model #1

Constraints on BSM model #2

…

Atomic Parity Violation

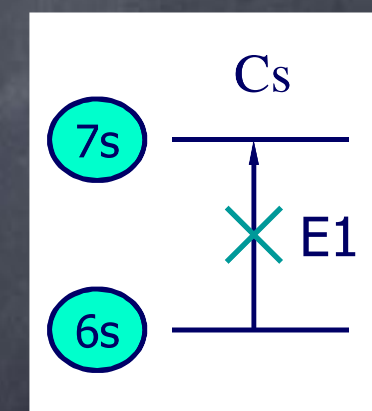
- Measurements of rate of rare parity-violating atomic transitions, for example 7s $\rightarrow$ 6s transition in cesium
- Results conveniently expressed in terms of atomic weak charge

$$Q_W(Z,N) = -2\left((2Z+N)g_{AV}^{eu} + (Z+2N)g_{AV}^{ed}\right)$$

Current most precise measurement from cesium (Z=55, N=78)

$$Q_W^{\mathrm{Cs}} = -72.62 \pm 0.43, \qquad Q_{W,\mathrm{SM}}^{\mathrm{Cs}} = -73.25 \pm 0.02$$

Wood et al (1997)



$$\mathcal{L}_{\mathrm{eff}} \supset \frac{1}{2v^2}\left[g_{AV}^{e_J q}(\bar{e}_J\gamma_\mu\gamma_5 e_J)(\bar{q}\gamma_\mu q) + g_{VA}^{e_J q}(\bar{e}_J\gamma_\mu e_J)(\bar{q}\gamma_\mu\gamma_5 q)\right]$$

Parity Violating Scattering

- Polarization asymmetry of low-energy scattering of electrons on protons
- Results can also expressed in terms of proton weak charge (Z=1, N=0)

$$Q_W(Z,N) = -2\left((2Z+N)g_{AV}^{eu} + (Z+2N)g_{AV}^{ed}\right)$$

$$Q_W^{\mathrm{p}} = 0.064 \pm 0.012 \qquad Q_{W,\mathrm{SM}}^{\mathrm{p}} = 0.0708 \pm 0.0003$$

Qweak
1507.3275

- To constrain gVA coefficients, one needs to include results of deep inelastic parity violating scattering from PVDIS and SAMPLE experiments

$$\begin{pmatrix} \delta g_{AV}^{eu} \\ \delta g_{AV}^{ed} \\ \delta g_{VA}^{eu} \\ \delta g_{VA}^{ed} \end{pmatrix} = \begin{pmatrix} 0.0033 \pm 0.0054 \\ -0.0047 \pm 0.0051 \\ -0.041 \pm 0.081 \\ -0.032 \pm 0.11 \end{pmatrix}, \qquad \rho = \begin{pmatrix} & -0.98 & -0.37 & -0.27 \\ & & 0.37 & 0.27 \\ & & & 0.94 \\ & & & \end{pmatrix}$$

$$\mathcal{L}_{\mathrm{eff}} \supset \frac{1}{2v^2}\left[g_{AV}^{e_J q}(\bar{e}_J\gamma_\mu\gamma_5 e_J)(\bar{q}\gamma_\mu q) + g_{VA}^{e_J q}(\bar{e}_J\gamma_\mu e_J)(\bar{q}\gamma_\mu\gamma_5 q)\right]$$

Neutrino Scattering

Experiments can precisely measure ratios of NC/CC neutrino and anti-neutrino scattering on nuclei

$$R_{\nu_i} = \frac{\sigma(\nu_i N \to \nu X)}{\sigma(\nu_i N \to \ell_i^- X)}, \qquad R_{\bar{\nu}_i} = \frac{\sigma(\bar{\nu}_i N \to \bar{\nu} X)}{\sigma(\bar{\nu}_i N \to \ell_i^+ X)}$$

$$\mathcal{L}_{\rm eff} \supset -\frac{2}{v^2}(\bar{\nu}_J \bar{\sigma}^\mu \nu_J)\left(g_{LL}^{\nu_J q}\bar{q}\bar{\sigma}_\mu q + g_{LR}^{\nu_J q} q^c \sigma_\mu \bar{q}^c\right).$$

For isoscalar nuclei we have Llewellyn-Smith relation

$$R_{\nu_i} = (g_L^{\nu_i})^2 + r(g_R^{\nu_i})^2, \qquad R_{\bar{\nu}_i} = (g_L^{\nu_i})^2 + r^{-1}(g_R^{\nu_i})^2 \qquad (g_{L/R}^{\nu_J})^2 \equiv \frac{(g_{LL/LR}^{\nu_J u})^2 + (g_{LL/LR}^{\nu_J d})^2}{\left(1+\bar{\epsilon}_L^{de_J}\right)^2}$$

Experiments use mostly muon neutrinos
(though some rather imprecise results exist for electron neutrinos too

Experiment	Observable	Experimental value	SM value	Ref.
CHARM ($r = 0.456$)	R_{ν_μ}	0.3093 ± 0.0031	0.3156	[74]
	$R_{\bar{\nu}_\mu}$	0.390 ± 0.014	0.370	[74]
CDHS ($r = 0.393$)	R_{ν_μ}	0.3072 ± 0.0033	0.3091	[75]
	$R_{\bar{\nu}_\mu}$	0.382 ± 0.016	0.380	[75]
CCFR	κ	0.5820 ± 0.0041	0.5830	[76]

PDG combination

$$\begin{aligned} (g_L^{\nu_\mu})^2 &= 0.3005 \pm 0.0028, & (g_R^{\nu_\mu})^2 &= 0.0329 \pm 0.0030, \\ \theta_L^{\nu_\mu} &= 2.50 \pm 0.035, & \theta_R^{\nu_\mu} &= 4.56^{+0.42}_{-0.27}. \end{aligned}$$

Neutrino Scattering

Precise results exist also for muon neutrino scattering on electrons

Experiment	Ref.	$g_{LV}^{\nu_\mu e}$	$g_{LA}^{\nu_\mu e}$
CHARM-II	[39]	-0.035 ± 0.017	-0.503 ± 0.0017
CHARM	[38]	-0.06 ± 0.07	-0.54 ± 0.07
BNL-E734	[40]	-0.107 ± 0.045	-0.514 ± 0.036

PDG combination

$$g_{LV}^{\nu_\mu e} = -0.040 \pm 0.015, \qquad g_{LA}^{\nu_\mu e} = -0.507 \pm 0.014,$$

$$\mathcal{L}_{\rm eff} \supset -\frac{1}{v^2}(\bar\nu_J \bar\sigma_\mu \nu_J)\left[(g_{LV}^{\nu_J e_I} + g_{LA}^{\nu_J e_I})(\bar e_I \bar\sigma_\mu e_I) + (g_{LV}^{\nu_J e_I} - g_{LA}^{\nu_J e_I})(e_I^c \sigma_\mu \bar e_I^c)\right].$$

Moller Scattering

SLAC E158 experiment made a precise measurement of parity-violating asymmetry in Møller scattering $e^- e^- \to e^- e^-$ at very low energy (below GeV)

$$\mathcal{L}_{\rm eff} \supset \frac{1}{2v^2} g^{ee}_{AV} \left[-(\bar{e}\bar{\sigma}_\mu e)(\bar{e}\bar{\sigma}_\mu e) + (e^c \sigma_\mu \bar{e}^c)(e^c \sigma_\mu \bar{e}^c)\right]$$

$$g^{ee}_{AV} = 0.0190 \pm 0.0027.$$

Also including

- Tau decays (leptonic only for the moment)
- Trident muon production
- Electron-positron collisions below Z-pole in TRISTAN
- ...

Low-energy flavor

- Probing charge current QQLL interactions in low-energy flavor transitions
- Using $\pi \to e\nu$, $\pi \to \mu\nu$, superallowed nuclear decays, semi-leptonic kaon decays, and differential distributions in $\pi \to e\nu\gamma$ decays
- Entangled with determination of SM parameters: CKM matrix elements Vud and Vus, so careful analysis needed

Gonzalez-Alonso, Martin Camalich
1605.07114

$$\begin{pmatrix} \tilde{V}_{ud} \\ \Delta_{\rm CKM} \\ \epsilon_R^{de} \\ \epsilon_S^{de} \\ \epsilon_P^{de} \\ \epsilon_T^{de} \\ \Delta_{LP}^{d} \end{pmatrix} = \begin{pmatrix} 0.97451(38) \\ -(1.2 \pm 8.4) \cdot 10^{-4} \\ -(1.3 \pm 1.7) \cdot 10^{-2} \\ (1.4 \pm 1.3) \cdot 10^{-3} \\ (4.0 \pm 7.8) \cdot 10^{-6} \\ (1.0 \pm 8.0) \cdot 10^{-4} \\ (1.9 \pm 3.8) \cdot 10^{-2} \end{pmatrix}, \quad \rho = \begin{pmatrix} 1. & 0.88 & 0. & 0.82 & 0.01 & 0. & 0.01 \\ 0.88 & 1. & 0. & 0.73 & 0.01 & 0. & 0.01 \\ 0. & 0. & 1. & 0. & -0.87 & 0. & -0.87 \\ 0.82 & 0.73 & 0. & 1. & 0.01 & 0. & 0.01 \\ 0.01 & 0.01 & -0.87 & 0.01 & 1. & 0. & 0.9995 \\ 0. & 0. & 0. & 0. & 0. & 1. & 0. \\ 0.01 & 0.01 & -0.87 & 0.01 & 1. & 0. & 1. \end{pmatrix}$$

Among most precise measurements!

$$\begin{aligned} \mathcal{L}_{\rm eff} \supset\; & -\frac{2\tilde{V}_{ud}}{v^2}\Big[\left(1+\bar{\epsilon}_L^{de_J}\right)(\bar{e}_J\bar{\sigma}_\mu\nu_J)(\bar{u}\bar{\sigma}^\mu d) + \epsilon_R^{de}(\bar{e}_J\bar{\sigma}_\mu\nu_J)(u^c\sigma^\mu\bar{d}^c) \\ & + \frac{\epsilon_S^{de_J}+\epsilon_P^{de_J}}{2}(e_J^c\nu_J)(u^c d) + \frac{\epsilon_S^{de_J}-\epsilon_P^{de_J}}{2}(e_J^c\nu_J)(\bar{u}\bar{d}^c) + \epsilon_T^{de_J}(e_J^c\sigma_{\mu\nu}\nu_J)(u^c\sigma_{\mu\nu}d) + \text{h.c.}\Big] \end{aligned}$$

Constraints on SMEFT

- Follow program started 13 years ago by Skiba and Han, however allowing for arbitrary flavor structure

Han, Skiba
hep-ph/0412166

- Combine low-energy measurements with input from LEP and LEP-2

Efrati,AA,Soreq
1503.07782

- LEP constrains Z boson couplings to fermion with per-mille to percent precision

- LEP-2 constrains some linear combinations of 4-lepton and 2-quark-2-lepton operators

AA,Mimouni
1511.07434

- 264 experimental inputs constraining 61 combinations of SMEFT Wilson coefficients

- Most often, enough handles to lift flat directions among concerned operators

$$
\begin{aligned}
g_{LL}^{\nu_J u} &= \frac{1}{2} - \frac{2s_\theta^2}{3} + \delta g_L^{Zu} + \left(1 - \frac{4s_\theta^2}{3}\right)\delta g_L^{Z\nu_J} - \frac{1}{2}([c_{lq}]_{JJ11} + [c_{lq}^{(3)}]_{JJ11}), \\
g_{LR}^{\nu_J u} &= -\frac{2s_\theta^2}{3} + \delta g_R^{Zu} - \frac{4s_\theta^2}{3}\delta g_L^{Z\nu_J} - \frac{1}{2}[c_{lu}]_{JJ11}, \\
g_{LL}^{\nu_J d} &= -\frac{1}{2} + \frac{s_\theta^2}{3} + \delta g_L^{Zd} - \left(1 - \frac{2s_\theta^2}{3}\right)\delta g_L^{Z\nu_J} - \frac{1}{2}([c_{lq}]_{JJ11} - [c_{lq}^{(3)}]_{JJ11}), \\
g_{LR}^{\nu_J d} &= \frac{s_\theta^2}{3} + \delta g_R^{Zd} + \frac{2s_\theta^2}{3}\delta g_L^{Z\nu_J} - \frac{1}{2}[c_{ld}]_{JJ11}.
\end{aligned}
$$

and so on...

Constraints on SMEFT

AA, Gonzalez-Alonso, Mimouni
1706.03783

$$
\begin{pmatrix}
\delta g_L^{We} \\ \delta g_L^{W\mu} \\ \delta g_L^{W\tau} \\ \delta g_L^{Ze} \\ \delta g_L^{Z\mu} \\ \delta g_L^{Z\tau} \\ \delta g_R^{Ze} \\ \delta g_R^{Z\mu} \\ \delta g_R^{Z\tau} \\ \delta g_L^{Zu} \\ \delta g_L^{Zc} \\ \delta g_L^{Zt} \\ \delta g_R^{Zu} \\ \delta g_R^{Zc} \\ \delta g_L^{Zd} \\ \delta g_L^{Zs} \\ \delta g_L^{Zb} \\ \delta g_R^{Zd} \\ \delta g_R^{Zs} \\ \delta g_R^{Zb} \\ \delta g_R^{Wq_1} \\ [c_{\ell\ell}]_{1111} \\ [c_{\ell e}]_{1111} \\ [c_{ee}]_{1111} \\ [c_{\ell\ell}]_{1221} \\ [c_{\ell\ell}]_{1122} \\ [c_{\ell e}]_{1122} \\ [c_{\ell e}]_{2211} \\ [c_{ee}]_{1122} \\ [c_{\ell\ell}]_{1331} \\ [c_{\ell\ell}]_{1133} \\ [c_{\ell e}]_{1133} \\ [c_{\ell e}]_{3311} \\ [c_{ee}]_{1133} \\ [\hat{c}_{\ell\ell}]_{2222} \\ [c_{\ell\ell}]_{2332}
\end{pmatrix}
=
\begin{pmatrix}
-1.00 \pm 0.64 \\ -1.36 \pm 0.59 \\ 1.95 \pm 0.79 \\ -0.023 \pm 0.028 \\ 0.01 \pm 0.12 \\ 0.018 \pm 0.059 \\ -0.033 \pm 0.027 \\ 0.00 \pm 0.14 \\ 0.042 \pm 0.062 \\ -0.8 \pm 3.1 \\ -0.15 \pm 0.36 \\ -0.3 \pm 3.8 \\ 1.4 \pm 5.1 \\ -0.35 \pm 0.53 \\ -0.9 \pm 4.4 \\ 0.9 \pm 2.8 \\ 0.33 \pm 0.17 \\ 3 \pm 16 \\ 3.4 \pm 4.9 \\ 2.30 \pm 0.88 \\ -1.3 \pm 1.7 \\ 1.01 \pm 0.38 \\ -0.22 \pm 0.22 \\ 0.20 \pm 0.38 \\ -4.8 \pm 1.6 \\ 1.5 \pm 2.1 \\ 1.5 \pm 2.2 \\ -1.4 \pm 2.2 \\ 3.4 \pm 2.6 \\ 1.5 \pm 1.3 \\ 0 \pm 11 \\ -2.3 \pm 7.2 \\ 1.7 \pm 7.2 \\ -1 \pm 12 \\ -2 \pm 21 \\ 3.0 \pm 2.3
\end{pmatrix}
\times 10^{-2},
\qquad
\begin{pmatrix}
[c_{\ell q}^{(3)}]_{1111} \\ [\hat{c}_{eq}]_{1111} \\ [\hat{c}_{\ell u}]_{1111} \\ [\hat{c}_{\ell d}]_{1111} \\ [\hat{c}_{eu}]_{1111} \\ [\hat{c}_{ed}]_{1111} \\ [\hat{c}_{\ell q}^{(3)}]_{1122} \\ [c_{\ell u}]_{1122} \\ [\hat{c}_{\ell d}]_{1122} \\ [c_{eq}]_{1122} \\ [c_{eu}]_{1122} \\ [\hat{c}_{ed}]_{1122} \\ [\hat{c}_{\ell q}^{(3)}]_{1133} \\ [c_{\ell d}]_{1133} \\ [c_{eq}]_{1133} \\ [c_{ed}]_{1133} \\ [c_{\ell q}^{(3)}]_{2211} \\ [c_{\ell q}]_{2211} \\ [c_{\ell u}]_{2211} \\ [c_{\ell d}]_{2211} \\ [\hat{c}_{eq}]_{2211} \\ [c_{\ell equ}]_{1111} \\ [c_{\ell edq}]_{1111} \\ [c_{\ell equ}^{(3)}]_{1111} \\ \epsilon_P^{d\mu}(2\ \mathrm{GeV})
\end{pmatrix}
=
\begin{pmatrix}
-2.2 \pm 3.2 \\ 100 \pm 180 \\ -5 \pm 11 \\ -5 \pm 23 \\ -1 \pm 12 \\ -4 \pm 21 \\ -61 \pm 32 \\ 2.4 \pm 8.0 \\ -310 \pm 130 \\ -21 \pm 28 \\ -87 \pm 46 \\ 270 \pm 140 \\ -8.6 \pm 8.0 \\ -1.4 \pm 10 \\ -3.2 \pm 5.1 \\ 18 \pm 20 \\ -1.2 \pm 3.9 \\ 1.3 \pm 7.6 \\ 15 \pm 12 \\ 25 \pm 34 \\ 4 \pm 41 \\ -0.080 \pm 0.075 \\ -0.079 \pm 0.074 \\ -0.02 \pm 0.19 \\ -0.02 \pm 0.15
\end{pmatrix}
\times 10^{-2}.
$$

Scale suppressing these dimension-6 operators between 250 GeV and tens of TeV

Magic Notebook

Full likelihood in different SMEFT bases available in electronic form
in publicly available Mathematica notebook
https://www.dropbox.com/s/26nh71oebm4o12k/SMEFTlikelihood.nb?dl=0

```
    δgZdL -> δgWB[-cpHq11/2 - cHq11/2, -1/2, -1/3], δgZsL -> δgWB[-cpHq22/2 - cHq22/2, -1/2, -1/3],
    δgZbL -> δgWB[-cpHq33/2 - cHq33/2, -1/2, -1/3],
    δgWq1R → -1/2 cHud11
   } /. {gL → 0.6484551965717312`, gY → 0.357970638062825O3`};

χsqGeneralWarsaw = χsqGeneralNohat /. HiggsBasisToWarsawBasis // Expand

62.8281 + 1393.2 ced1111 + 259 242. ced1111^2 - 276.078 ced1122 + 15 337.9 ced1111 ced1122 + 7668.94 ced1122^2 + 414.671 ced1133 +
 6757.97 ced1111 ced1133 + 6757.97 ced1122 ced1133 + 26 074.8 ced1133^2 - 0.521255 ced2211 - 1.78692 × 10^-10 ced1111 ced2211 +
 6.21342 × 10^-12 ced1122 ced2211 + 4.22925 × 10^-12 ced1133 ced2211 + 6.62281 ced2211^2 - 979.149 cee1111 + 1.57248 × 10^-8 ced1111 cee1111 -
 8.86316 × 10^-5 ced1122 cee1111 - 3.2819 × 10^-9 ced1133 cee1111 + 1.34598 × 10^-12 ced2211 cee1111 + 125 140. cee1111^2 + 433.888 cee1122 -
 1.7747 × 10^-8 ced1111 cee1122 + 4.13489 × 10^-8 ced1122 cee1122 + 2.14934 × 10^-8 ced1133 cee1122 - 5.81473 × 10^-12 ced2211 cee1122 -
 8.62973 × 10^-11 cee1111 cee1122 + 103 752. cee1122^2 - 86.3308 cee1133 + 5.08607 × 10^-7 ced1111 cee1133 + 7.87446 × 10^-8 ced1122 cee1133 +
 3.49777 × 10^-8 ced1133 cee1133 + 7.90683 × 10^-13 ced2211 cee1133 - 5.07191 × 10^-9 cee1111 cee1133 - 2.39942 × 10^-8 cee1122 cee1133 +
 52 381.2 cee1133^2 + 3428.96 ceq1111 + 947 689. ced1111 ceq1111 - 15 337.9 ced1122 ceq1111 - 6757.97 ced1133 ceq1111 -
 3.40017 × 10^-10 ced2211 ceq1111 + 5.66526 × 10^-8 cee1111 ceq1111 - 1.51814 × 10^-7 cee1122 ceq1111 + 7.46588 × 10^-7 cee1133 ceq1111 +
 940 962. ceq1111^2 + 296.807 ceq1122 - 15 146.9 ced1111 ceq1122 - 15 146.9 ced1122 ceq1122 - 6566.97 ced1133 ceq1122 -
 7.63715 × 10^-12 ced2211 ceq1122 + 9.63746 × 10^-9 cee1111 ceq1122 - 4.48648 × 10^-8 cee1122 ceq1122 - 7.97512 × 10^-8 cee1133 ceq1122 +
 15 146.9 ceq1111 ceq1122 + 7582.1 ceq1122^2 - 65.7757 ceq1133 - 5113.45 ced1111 ceq1133 - 5113.45 ced1122 ceq1133 -
 40 176.9 ced1133 ceq1133 - 3.8385 × 10^-12 ced2211 ceq1133 + 2.84528 × 10^-5 cee1111 ceq1133 - 1.56085 × 10^-8 cee1122 ceq1133 -
 2.6511 × 10^-8 cee1133 ceq1133 + 5113.45 ceq1111 ceq1133 + 4965.31 ceq1122 ceq1133 + 22 125.5 ceq1133^2 - 0.521255 ceq2211 -
 1.78692 × 10^-10 ced1111 ceq2211 + 6.21342 × 10^-12 ced1122 ceq2211 + 4.22925 × 10^-12 ced1133 ceq2211 + 13.2456 ced2211 ceq2211 +
 1.34598 × 10^-12 cee1111 ceq2211 - 5.81473 × 10^-12 cee1122 ceq2211 + 7.90683 × 10^-13 cee1133 ceq2211 - 3.40017 × 10^-10 ceq1111 ceq2211 -
 7.63715 × 10^-12 ceq1122 ceq2211 - 3.8385 × 10^-12 ceq1133 ceq2211 + 6.62281 ceq2211^2 + 2051.31 ceu1111 + 428 577. ced1111 ceu1111 -
 30 675.8 ced1122 ceu1111 - 13 515.9 ced1133 ceu1111 - 1.78641 × 10^-10 ced2211 ceu1111 + 4.09439 × 10^-8 cee1111 ceu1111 -
 1.33774 × 10^-7 cee1122 ceu1111 + 2.37735 × 10^-7 cee1133 ceu1111 + 934 795. ceq1111 ceu1111 + 30 293.8 ceq1122 ceu1111 +
 10 226.9 ceq1133 ceu1111 - 1.78641 × 10^-10 ceq2211 ceu1111 + 253 974. ceu1111^2 + 654.624 ceu1122 - 28 780.4 ced1111 ceu1122 -
 28 780.4 ced1122 ceu1122 - 11 620.5 ced1133 ceu1122 - 1.42289 × 10^-11 ced2211 ceu1122 + 2.55536 × 10^-8 cee1111 ceu1122 -
 1.19239 × 10^-7 cee1122 ceu1122 - 1.67269 × 10^-7 cee1133 ceu1122 + 28 780.4 ceq1111 ceu1122 + 29 833.6 ceq1122 ceu1122 +
 8713.5 ceq1133 ceu1122 - 1.42289 × 10^-11 ceq2211 ceu1122 + 57 560.8 ceu1111 ceu1122 + 34 160.7 ceu1122^2 + 1.04251 ceu2211 +
```

Constrained scenarios

- Full likelihood can be easily used to constrain more specific BSM scenarios by replacing general Wilson coefficients with appropriate model dependent expressions and minimizing likelihood wrt new variables

Barbieri et al
hep-ph/0405040

- For example, we can constrain SMEFT to well-known oblique corrections scenario

$$\delta g_{L/R}^{Zf} = \alpha \left\{ T^3_{f_{L/R}} \frac{T - W - \frac{g_Y^2}{g_L^2} Y}{2} + Q_f \frac{2 g_Y^2 T - (g_L^2 + g_Y^2) S + 2 g_Y^2 W + \frac{2 g_Y^2 (2 g_L^2 - g_Y^2)}{g_L^2} Y}{4(g_L^2 - g_Y^2)} \right\}$$

$$\delta g_L^{We} = \frac{\alpha}{2(g_L^2 - g_Y^2)} \left(- \frac{g_L^2 + g_Y^2}{2} S + g_L^2 T - (g_L^2 - 2 g_Y^2) W + g_Y^2 Y \right),$$

$$c_{\ell\ell}^{(3)} = c_{\ell q}^{(3)} = c_{qq}^{(3)} = -\alpha W, \qquad c_{f_1 f_2} = -4 Y_{f_1} Y_{f_2} \frac{g_Y^2}{g_L^2} \alpha Y ,$$

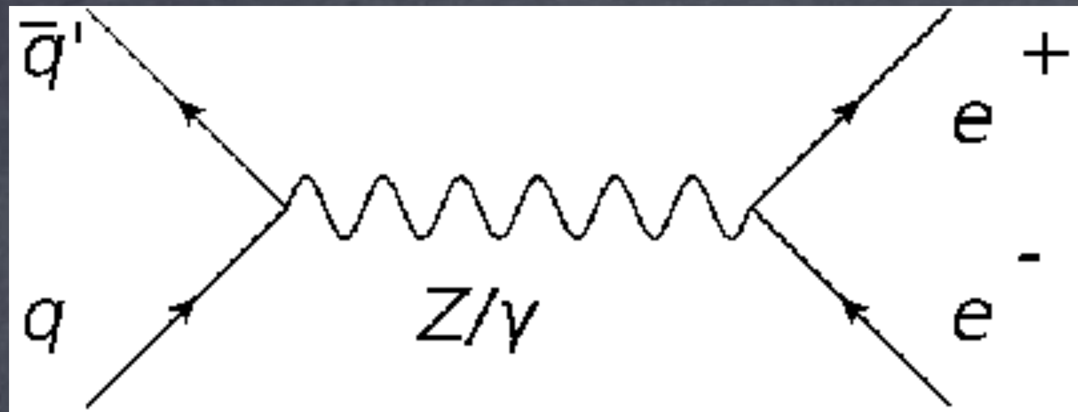
Wells Zhang
1510.08462

Our low-energy oblique parameters fit

$$\begin{pmatrix} S \\ T \\ Y \\ W \end{pmatrix} = \begin{pmatrix} -0.10 \pm 0.13 \\ 0.02 \pm 0.08 \\ -0.15 \pm 0.11 \\ -0.01 \pm 0.08 \end{pmatrix}, \qquad \rho = \begin{pmatrix} 1. & 0.86 & 0.70 & -0.12 \\ . & 1. & 0.39 & -0.06 \\ . & . & 1. & -0.49 \\ . & . & . & 1. \end{pmatrix}$$

AA, Gonzalez-Alonso, Mimouni
1706.03783

Comparing LHC and low-energy bounds



Using precision measurements of electron and muon Drell-Yan differential cross-sections in ATLAS run-1

ATLAS 1606.01736

see also next talk by Andrea Wulzer

$(ee)(qq)$

	$[c^{(3)}_{\ell q}]_{1111}$	$[c_{\ell q}]_{1111}$	$[c_{\ell u}]_{1111}$	$[c_{\ell d}]_{1111}$	$[c_{eq}]_{1111}$	$[c_{eu}]_{1111}$	$[c_{ed}]_{1111}$
Low-energy	0.45 ± 0.28	1.6 ± 1.0	2.8 ± 2.1	3.6 ± 2.0	-1.8 ± 1.1	-4.0 ± 2.0	-2.7 ± 2.0
$\mathrm{LHC}_{1.5}$	$-0.70^{+0.66}_{-0.74}$	$2.5^{+1.9}_{-2.5}$	$2.9^{+2.4}_{-2.9}$	$-1.6^{+3.4}_{-3.0}$	$1.6^{+1.8}_{-2.2}$	$1.6^{+2.5}_{-1.5}$	$-3.1^{+3.6}_{-3.0}$
$\mathrm{LHC}_{1.0}$	$-0.84^{+0.85}_{-0.92}$	$3.6^{+3.6}_{-3.7}$	$4.4^{+4.4}_{-4.7}$	$-2.4^{+4.8}_{-4.7}$	$2.4^{+3.0}_{-3.2}$	$1.9^{+2.5}_{-1.9}$	$-4.6^{+5.4}_{-4.1}$
$\mathrm{LHC}_{0.7}$	$-1.0^{+1.4}_{-1.5}$	5.9 ± 7.2	7.4 ± 9.0	-3.6 ± 8.7	3.8 ± 5.9	$2.1^{+3.8}_{-2.9}$	-8 ± 10

$(\mu\mu)(qq)$

	$[c^{(3)}_{\ell q}]_{2211}$	$[c_{\ell q}]_{2211}$	$[c_{\ell u}]_{2211}$	$[c_{\ell d}]_{2211}$	$[c_{eq}]_{2211}$	$[c_{eu}]_{2211}$	$[c_{ed}]_{2211}$
Low-energy	-0.2 ± 1.2	4 ± 21	18 ± 19	-20 ± 37	40 ± 390	-20 ± 190	40 ± 390
$\mathrm{LHC}_{1.5}$	$-1.22^{+0.62}_{-0.70}$	1.8 ± 1.3	2.0 ± 1.6	-1.1 ± 2.0	1.1 ± 1.2	$2.5^{+1.8}_{-1.4}$	-2.2 ± 2.0
$\mathrm{LHC}_{1.0}$	$-0.72^{+0.81}_{-0.87}$	$3.2^{+4.0}_{-3.5}$	$3.9^{+4.8}_{-4.4}$	$-2.3^{+4.9}_{-4.7}$	$2.3^{+3.1}_{-3.2}$	$1.6^{+2.3}_{-1.8}$	-4.4 ± 5.3
$\mathrm{LHC}_{0.7}$	$-0.7^{+1.3}_{-1.4}$	$3.2^{+10.3}_{-4.8}$	$4.3^{+12.5}_{-6.4}$	-3.6 ± 9.0	3.8 ± 6.2	$1.6^{+3.4}_{-2.7}$	-8 ± 11

Chirality-violating operators ($\mu = 1$ TeV)

	$[c_{\ell equ}]_{1111}$	$[c_{\ell edq}]_{1111}$	$[c^{(3)}_{\ell equ}]_{1111}$	$[c_{\ell equ}]_{2211}$	$[c_{\ell edq}]_{2211}$	$[c^{(3)}_{\ell equ}]_{2211}$
Low-energy	$(-0.6 \pm 2.4)10^{-4}$	$(0.6 \pm 2.4)10^{-4}$	$(0.4 \pm 1.4)10^{-3}$	$0.014(49)$	$-0.014(49)$	$-0.09(29)$
$\mathrm{LHC}_{1.5}$	0 ± 2.0	0 ± 2.6	0 ± 0.91	0 ± 1.2	0 ± 1.6	0 ± 0.56
$\mathrm{LHC}_{1.0}$	0 ± 2.9	0 ± 3.7	0 ± 1.4	0 ± 2.9	0 ± 3.7	0 ± 1.4
$\mathrm{LHC}_{0.7}$	0 ± 5.3	0 ± 6.6	0 ± 2.6	0 ± 5.5	0 ± 6.9	0 ± 2.6

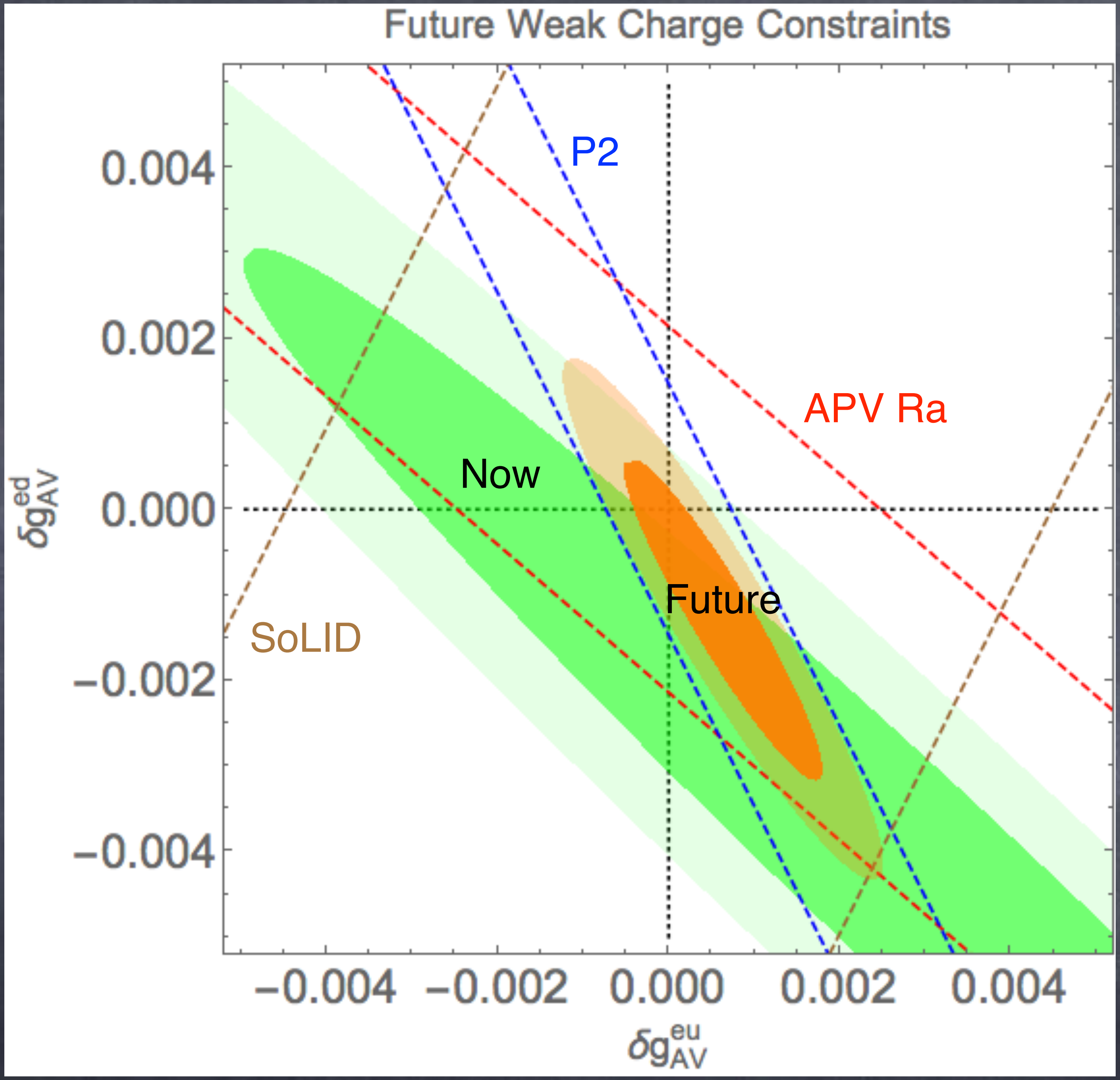
Low-energy and LHC comparable for chirality-preserving eeqq operators

LHC superior for chirality-preserving qq operators $\mu\mu$qq operators

Low-energy superior for chirality-violating operators

Future now

work in progress with
Giovanni Grilli di Cortona
and Zahra Tabrizi



In the near future, a lot of progress can be achieved,
both my more precise low-energy measurements,
as well as by including larger class of observables