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EFT perspective on future precision measurements

Based on work in progress with Martin Gonzalez-Alonso

Fahrplan

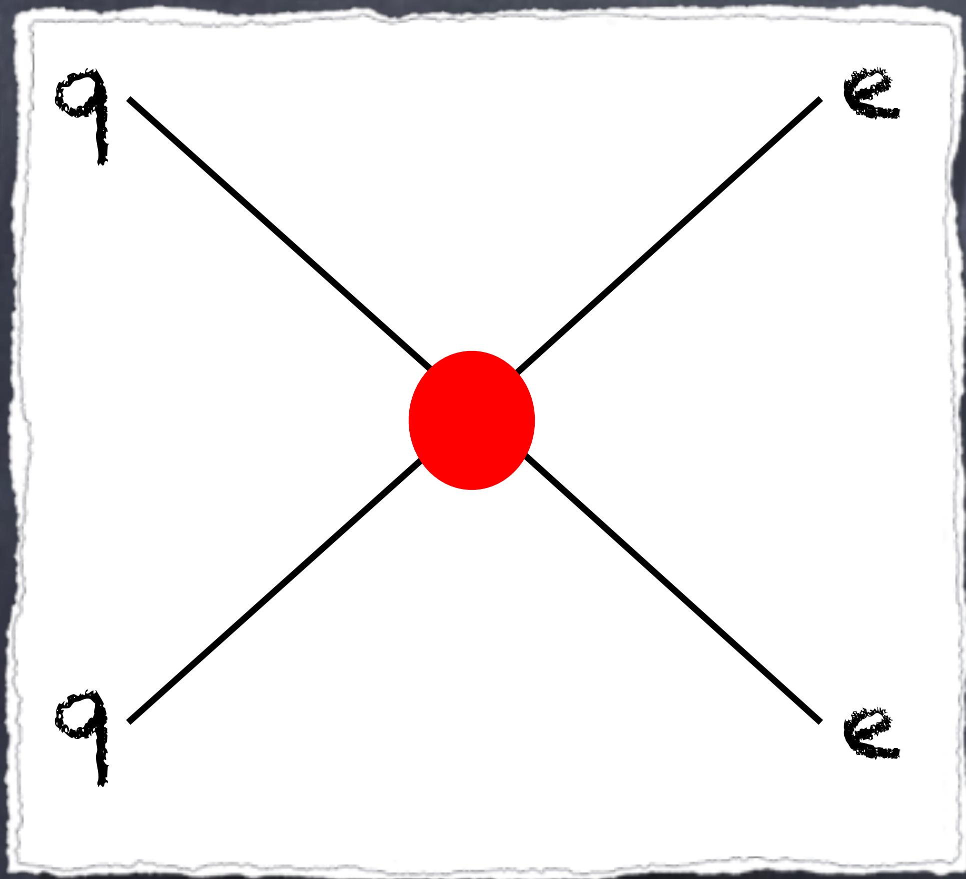
1. Effective field theory (EFT) formalism for low-energy precision measurements

2. EFT constraints: state of the art

3. Impact of future precision measurements (including P2 at Mainz)

4. Place of low-energy precision measurements in the **Bigger Picture**

Preview



Parity-violating electron scattering (PVES),
or atomic parity violation (APV) experiments
essentially probe 4-fermion *qqee* contact interactions,
where *q=u,d* are the light quarks and *e* are electrons

Thanks to the superior energy, the LHC is sensitive to qqee contact interactions with smaller coefficients than what can be currently (QWEAK, PVDIS, APV cesium) or in the near future (P2, SoLID, APV radium) achieved by low-energy experiments

Then what's the point going on
with the PVES and APV precision program ???

EFT Formalism

Status report

- The SM has been very successful in predicting the results of all collider and low-energy precision experiments. Discovery of the 125 GeV Higgs boson was the last piece of the puzzle falling into place. No more free parameters in the SM

- We know physics beyond the 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 unification, naturalness problem)

- But there isn't one model or a class of models that is strongly preferred. Myriads of models addressing neutrino masses, dark matter, inflation, baryon asymmetry, and even more models addressing the various theoretical issues of the SM...

- It is advantageous to keep an open mind on many possible forms of new physics that may show up in experiment. The best model-independent language for this purpose is that of effective field theories.

Effective field theories

- For observables at a given energy/momentum scale, retain only the degrees of freedom relevant at that scale and integrate out all heavier degrees of freedom
- Identify the symmetries of the low-energy theory and the small expansion parameters (typically, coupling constants and Energy_Scale/Heavy Mass_Scale)
- Write down most general interactions for the light degrees of freedom consistent with the symmetries and organize them in consistent expansion following some power counting with respect to the small parameter
- If the UV completion is known, connect its parameters to that of the effective theory by the matching procedure

Energy Scale	Theory	Experiment	Expansion Parameter
1 TeV	SMEFT	LHC	$\frac{E}{\Lambda}$
100 GeV		LEP	
	wEFT (aka Fermi theory, LEFT, WET)	TRISTAN	$\frac{E}{m_W}$
10 GeV		ν beams	
		PVDIS	
1 GeV	χPT	PVES	$\frac{E}{4\pi f_\pi}$
		Meson decays	
100 MeV		Moller scattering	
10 MeV	eQED		
1 MeV	nrQED	APV	$\frac{E}{m_e}$
	Euler-Heisenberg		

Assumption: below ~1 TeV scale, no new degrees of freedom beyond those of the SM

wEFT: EFT below the weak scale

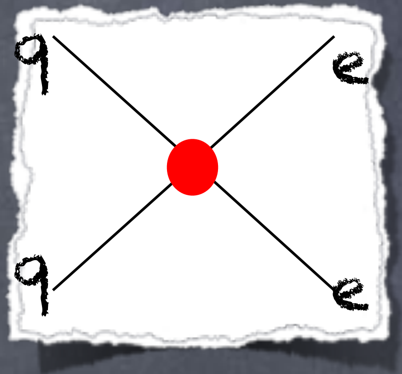
- In this workshop, the focus is on precision observables where the characteristic energy scale is much smaller than the Z boson mass
- Below mZ the only SM degrees of freedom available are leptons, photon, gluons, and 5 flavors of quark, while H/W/Z bosons and top quark are integrated out
- I refer to it as the wEFT (also known as Fermi theory, WET, LEFT ,...)
- wEFT is an EFT with SU(3)xU(1) gauge group and fermionic matter spectrum, where the expansion parameter is E/mW, mW≈80 GeV.
- There are 70 dimension-5 and 3631 dimension-6 operators preserving baryon and lepton number Jenkins et al 1711.05270
- I focus on parity-violating 4-fermion effective interactions between electron and light quarks and on electron self-interactions (other effective interactions can of course be equally or even more interesting but they are not discussed in this talk)

(Subset of) wEFT Lagrangian

Parity-violating neutral current interactions of 2 electron and 2 light quarks

$$\mathcal{L}_{\rm wEFT} \supset -\frac{1}{2v^2}\sum_{q=u,d} g_{AV}^{eq}(\bar{e}\,\bar{\sigma}_\rho e - e^c\sigma_\rho\bar{e}^c)(\bar{q}\,\bar{\sigma}^\rho q + q^c\sigma^\rho\bar{q}^c)$$

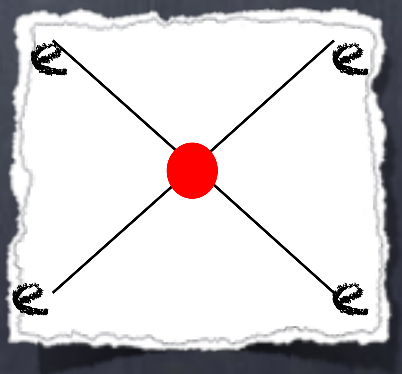
$$-\frac{1}{2v^2}\sum_{q=u,d} g_{VA}^{eq}(\bar{e}\,\bar{\sigma}_\rho e + e^c\sigma_\rho\bar{e}^c)(\bar{q}\,\bar{\sigma}^\rho q - q^c\sigma^\rho\bar{q}^c)$$



Closely following PDG notation

Parity-violating 4-electron interactions

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



$$v \equiv \frac{1}{\sqrt{\sqrt{2}G_F}} \approx 246\ \mathrm{GeV}$$

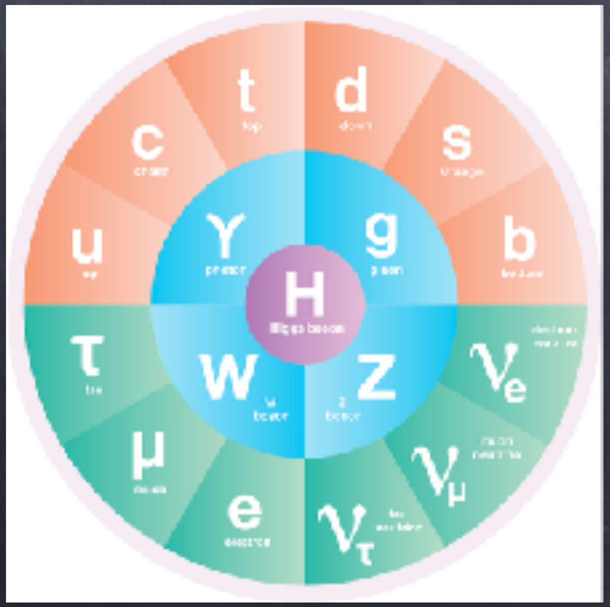
SMEFT

- Assume that the SM degrees of freedom are all there is below the TeV scale. But we treat the SM as an EFT, and we 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 some (mild) assumptions, the SMEFT framework allows one to describe effects of new physics beyond the SM in a model independent way

- Convenient for BSM practitioners because it is easy to connect SMEFT constraints to constraints on specific models. Automation of that process is ongoing



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SMEFT

Basic assumptions

- Much as in the SM, relativistic QFT with linearly realized SU(3)xSU(2)xU(1) local symmetry spontaneously broken by VEV of Higgs doublet field

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

- SMEFT Lagrangian expanded in inverse powers of Λ, equivalently in operator dimension D

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

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

Generated by integrating out lepton number or B-L violating heavy particles with mass scale Λ_L, responsible for neutrino masses

$\Lambda_L \lesssim$ 10^15 GeV

Subleading wrt D=5/6 if Λ_L/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

TeV $\lesssim \Lambda \lesssim$?

Buchmuller,Wyler (1986)

Grządkowski et al. 1008.4884

Dimension-6 operators

Warsaw basis

Grządkowski et al. 1008.4884

Bosonic CP-even		Bosonic CP-odd	
O_H	$(H^\dagger H)^3$		
$O_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$		
O_{HD}	$\left\lvert H^\dagger D_\mu H\right\rvert^2$		
O_{HG}	$H^\dagger H\, G^a_{\mu\nu}G^a_{\mu\nu}$	$O_{H\widetilde{G}}$	$H^\dagger H\, \widetilde{G}^a_{\mu\nu}G^a_{\mu\nu}$
O_{HW}	$H^\dagger H\, W^i_{\mu\nu}W^i_{\mu\nu}$	$O_{H\widetilde{W}}$	$H^\dagger H\, \widetilde{W}^i_{\mu\nu}W^i_{\mu\nu}$
O_{HB}	$H^\dagger H\, B_{\mu\nu}B_{\mu\nu}$	$O_{H\widetilde{B}}$	$H^\dagger H\, \widetilde{B}_{\mu\nu}B_{\mu\nu}$
O_{HWB}	$H^\dagger\sigma^i H\, W^i_{\mu\nu}B_{\mu\nu}$	$O_{H\widetilde{W}B}$	$H^\dagger\sigma^i H\, \widetilde{W}^i_{\mu\nu}B_{\mu\nu}$
O_W	$\epsilon^{ijk}W^i_{\mu\nu}W^j_{\nu\rho}W^k_{\rho\mu}$	$O_{\widetilde{W}}$	$\epsilon^{ijk}\widetilde{W}^i_{\mu\nu}W^j_{\nu\rho}W^k_{\rho\mu}$
O_G	$f^{abc}G^a_{\mu\nu}G^b_{\nu\rho}G^c_{\rho\mu}$	$O_{\widetilde{G}}$	$f^{abc}\widetilde{G}^a_{\mu\nu}G^b_{\nu\rho}G^c_{\rho\mu}$

Table 2.2: Bosonic D=6 operators in the Warsaw basis.

Yukawa

$[O^\dagger_{eH}]_{IJ}$	$H^\dagger H e^c_I H^\dagger \ell_J$
$[O^\dagger_{uH}]_{IJ}$	$H^\dagger H u^c_I \widetilde{H}^\dagger q_J$
$[O^\dagger_{dH}]_{IJ}$	$H^\dagger H d^c_I H^\dagger q_J$

Vertex

$[O^{(1)}_{H\ell}]_{IJ}$	$i\bar\ell_I\bar\sigma_\mu\ell_J H^\dagger \overleftrightarrow{D}_\mu H$
$[O^{(3)}_{H\ell}]_{IJ}$	$i\bar\ell_I\sigma^i\bar\sigma_\mu\ell_J H^\dagger\sigma^i \overleftrightarrow{D}_\mu H$
$[O_{He}]_{IJ}$	$ie^c_I\sigma_\mu\bar e^c_J H^\dagger \overleftrightarrow{D}_\mu H$
$[O^{(1)}_{Hq}]_{IJ}$	$i\bar q_I\bar\sigma_\mu q_J H^\dagger \overleftrightarrow{D}_\mu H$
$[O^{(3)}_{Hq}]_{IJ}$	$i\bar q_I\sigma^i\bar\sigma_\mu q_J H^\dagger\sigma^i \overleftrightarrow{D}_\mu H$
$[O_{Hu}]_{IJ}$	$iu^c_I\sigma_\mu\bar u^c_J H^\dagger \overleftrightarrow{D}_\mu H$
$[O_{Hd}]_{IJ}$	$id^c_I\sigma_\mu\bar d^c_J H^\dagger \overleftrightarrow{D}_\mu H$
$[O_{Hud}]_{IJ}$	$iu^c_I\sigma_\mu\bar d^c_J \widetilde{H}^\dagger D_\mu H$

Dipole

$[O^\dagger_{eW}]_{IJ}$	$e^c_I\sigma_{\mu\nu}H^\dagger\sigma^i\ell_J W^i_{\mu\nu}$
$[O^\dagger_{eB}]_{IJ}$	$e^c_I\sigma_{\mu\nu}H^\dagger\ell_J B_{\mu\nu}$
$[O^\dagger_{uG}]_{IJ}$	$u^c_I\sigma_{\mu\nu}T^a\widetilde{H}^\dagger q_J\, G^a_{\mu\nu}$
$[O^\dagger_{uW}]_{IJ}$	$u^c_I\sigma_{\mu\nu}\widetilde{H}^\dagger\sigma^i q_J\, W^i_{\mu\nu}$
$[O^\dagger_{uB}]_{IJ}$	$u^c_I\sigma_{\mu\nu}\widetilde{H}^\dagger q_J\, B_{\mu\nu}$
$[O^\dagger_{dG}]_{IJ}$	$d^c_I\sigma_{\mu\nu}T^a H^\dagger q_J\, G^a_{\mu\nu}$
$[O^\dagger_{dW}]_{IJ}$	$d^c_I\sigma_{\mu\nu}\bar{H}^\dagger\sigma^i q_J\, W^i_{\mu\nu}$
$[O^\dagger_{dB}]_{IJ}$	$d^c_I\sigma_{\mu\nu}H^\dagger q_J\, B_{\mu\nu}$

Table 2.3: Two-fermion D=6 operators in the Warsaw basis. The flavor indices are denoted by I, J. For complex operators (O_{Hud} and all Yukawa and dipole operators) the corresponding complex conjugate operator is implicitly included.

$(\bar RR)(\bar RR)$

O_{ee}	$\eta(e^c\sigma_\mu\bar e^c)(e^c\sigma_\mu\bar e^c)$
O_{uu}	$\eta(u^c\sigma_\mu\bar u^c)(u^c\sigma_\mu\bar u^c)$
O_{dd}	$\eta(d^c\sigma_\mu\bar d^c)(d^c\sigma_\mu\bar d^c)$
O_{eu}	$(e^c\sigma_\mu\bar e^c)(u^c\sigma_\mu\bar u^c)$
O_{ed}	$(e^c\sigma_\mu\bar e^c)(d^c\sigma_\mu\bar d^c)$
O_{ud}	$(u^c\sigma_\mu\bar u^c)(d^c\sigma_\mu\bar d^c)$
O'_{ud}	$(u^c\sigma_\mu T^a\bar u^c)(d^c\sigma_\mu T^a\bar d^c)$

$(\bar LL)(\bar RR)$

$O_{\ell e}$	$(\bar\ell\bar\sigma_\mu\ell)(e^c\sigma_\mu\bar e^c)$
$O_{\ell u}$	$(\bar\ell\bar\sigma_\mu\ell)(u^c\sigma_\mu\bar u^c)$
$O_{\ell d}$	$(\bar\ell\bar\sigma_\mu\ell)(d^c\sigma_\mu\bar d^c)$
O_{eq}	$(e^c\sigma_\mu\bar e^c)(\bar q\bar\sigma_\mu q)$
O_{qu}	$(\bar q\bar\sigma_\mu q)(u^c\sigma_\mu\bar u^c)$
O'_{qu}	$(\bar q\bar\sigma_\mu T^a q)(u^c\sigma_\mu T^a\bar u^c)$
O_{qd}	$(\bar q\bar\sigma_\mu q)(d^c\sigma_\mu\bar d^c)$
O'_{qd}	$(\bar q\bar\sigma_\mu T^a q)(d^c\sigma_\mu T^a\bar d^c)$

$(\bar LL)(\bar LL)$

$O_{\ell\ell}$	$\eta(\bar\ell\bar\sigma_\mu\ell)(\bar\ell\bar\sigma_\mu\ell)$
O_{qq}	$\eta(\bar q\bar\sigma_\mu q)(\bar q\bar\sigma_\mu q)$
O'_{qq}	$\eta(\bar q\bar\sigma_\mu\sigma^i q)(\bar q\bar\sigma_\mu\sigma^i q)$
$O_{\ell q}$	$(\bar\ell\bar\sigma_\mu\ell)(\bar q\bar\sigma_\mu q)$
$O'_{\ell q}$	$(\bar\ell\bar\sigma_\mu\sigma^i\ell)(\bar q\bar\sigma_\mu\sigma^i q)$

$(\bar LR)(\bar LR)$

O_{quqd}	$(u^c q^j)\epsilon_{jk}(d^c q^k)$
O'_{quqd}	$(u^c T^a q^j)\epsilon_{jk}(d^c T^a q^k)$
$O_{\ell equ}$	$(e^c\ell^j)\epsilon_{jk}(u^c q^k)$
$O'_{\ell equ}$	$(e^c\bar\sigma_{\mu\nu}\ell^j)\epsilon_{jk}(u^c\bar\sigma^{\mu\nu}q^k)$
$O_{\ell edq}$	$(\bar\ell\bar e^c)(d^c q)$

Table 2.4: Four-fermion D=6 operators in the Warsaw basis. Flavor indices are suppressed here to reduce the clutter. The factor η is equal to 1/2 when all flavor indices are equal (e.g. in $[O_{ee}]_{1111}$), and $\eta = 1$ otherwise. For each complex operator the complex conjugate should be included.

Full set has 2499 distinct operators, including flavor structure and CP conjugates

Enough fun for everyone :)

Alonso et al 1312.2014, Henning et al 1512.03433

More intuitive parametrization (Higgs basis)

Effect of dimension-6 operators: vertex corrections to Z and W boson interactions with fermions

$$\mathcal{L}_{vff} = \frac{g_L}{\sqrt{2}}\left(W_\mu^+ \bar{u}\bar{\sigma}_\mu (V_{\rm CKM} + \delta g_L^{Wq}) d + W_\mu^+ u^c \sigma_\mu \delta g_R^{Wq} \bar{d}^c + W_\mu^+ \bar{\nu}\bar{\sigma}_\mu (I + \delta g_L^{W\ell}) e + \text{h.c.}\right)$$
$$+ \sqrt{g_L^2 + g_Y^2} Z_\mu \left[\sum_{f \in u,d,e,\nu} \bar{f}\bar{\sigma}_\mu (T_f^3 - s_\theta^2 Q_f + \delta g_L^{Zf}) f + \sum_{f^c \in u^c,d^c,e^c} f^c \sigma_\mu (-s_\theta^2 Q_f + \delta g_R^{Zf}) \bar{f}^c\right]$$

$$\begin{aligned}
\delta g_L^{W\ell} &= c_{H\ell}^{(3)} + f(1/2,0) - f(-1/2,-1),\\
\delta g_L^{Z\nu} &= \frac{1}{2}c_{H\ell}^{(3)} - \frac{1}{2}c_{H\ell}^{(1)} + f(1/2,0),\\
\delta g_L^{Ze} &= -\frac{1}{2}c_{H\ell}^{(3)} - \frac{1}{2}c_{H\ell}^{(1)} + f(-1/2,-1),\\
\delta g_R^{Ze} &= -\frac{1}{2}c_{He} + f(0,-1),
\end{aligned}$$

$$\begin{aligned}
\delta g_L^{Wq} &= \left(c_{Hq}^{(3)} + f(1/2,2/3) - f(-1/2,-1/3)\right) V_{\rm CKM},\\
\delta g_R^{Wq} &= +\frac{1}{2}c_{Hud},\\
\delta g_L^{Zu} &= \frac{1}{2}c_{Hq}^{(3)} - \frac{1}{2}c_{Hq}^{(1)} + f(1/2,2/3),\\
\delta g_L^{Zd} &= -\frac{1}{2}V_{\rm CKM}^\dagger c_{Hq}^{(3)} V_{\rm CKM} - \frac{1}{2}V_{\rm CKM}^\dagger c_{Hq}^{(1)} V_{\rm CKM} + f(-1/2,-1/3),\\
\delta g_R^{Zu} &= -\frac{1}{2}c_{Hu} + f(0,2/3),\\
\delta g_R^{Zd} &= -\frac{1}{2}c_{Hd} + f(0,-1/3),
\end{aligned}$$

$$\begin{aligned}
f(T^3,Q) &= -I_3 Q \frac{g_L g_Y}{g_L^2 - g_Y^2} c_{HWB}\\
&+ I_3 \left(\frac{1}{4}[c_{\ell\ell}]_{1221} - \frac{1}{2}[c_{H\ell}^{(3)}]_{11} - \frac{1}{2}[c_{H\ell}^{(3)}]_{22} - \frac{1}{4}c_{HD}\right)\left(T^3 + Q\frac{g_Y^2}{g_L^2 - g_Y^2}\right)
\end{aligned}$$

Not all vertex corrections are independent

$$\delta g_L^{Z\nu} = \delta g_L^{Ze} + \delta g_L^{W\ell}$$
$$\delta g_L^{Wq} = \delta g_L^{Zu} V_{\rm CKM} - V_{\rm CKM} \delta g_L^{Zd}$$

In the following,
parametrizing the relevant space of
dimension-6 operators using
the independent vertex corrections
and coefficients of 4-fermion operators

Also, rescaling c→c Λ^2/v^2,

so that dimension-6 operators in Lagrangian
normalized by the scale 1/v^2

Matching wEFT to SMEFT

One can match wEFT to SMEFT at μ = mZ to relate parameters of the 2 effective theories

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

$$g_{AV}^{ee} = \frac{1}{2} - 2s_\theta^2 - 2\left(1 - 2s_\theta^2\right)\delta g_L^{Ze} - 4s_\theta^2 \delta g_R^{Ze} - \frac{1}{2}[c_{\ell\ell}]_{1111} + \frac{1}{2}[c_{ee}]_{1111}$$

SM contribution from Z exchange

Effect of shifted Z couplings

Trivial matching of 4-fermion operators

$$\mathcal{L}_{\rm SMEFT} \subset \frac{g_L}{\sqrt{2}}\left(W_\mu^+ \bar{u}\bar{\sigma}_\mu (V_{\rm CKM} + \delta g_L^{Wq}) d + W_\mu^+ u^c \sigma_\mu \delta g_R^{Wq} \bar{d}^c + W_\mu^+ \bar{\nu}\bar{\sigma}_\mu (I + \delta g_L^{W\ell}) e + \text{h.c.}\right)$$
$$+ \sqrt{g_L^2 + g_Y^2} Z_\mu \left[\sum_{f \in u,d,e,\nu} \bar{f}\bar{\sigma}_\mu (T_f^3 - s_\theta^2 Q_f + \delta g_L^{Zf}) f + \sum_{f^c \in u^c,d^c,e^c} f^c \sigma_\mu (-s_\theta^2 Q_f + \delta g_R^{Zf}) \bar{f}^c \right]$$

One flavor $(I = 1,2,3)$
$[O_{\ell\ell}]_{IIII} = \frac{1}{2}(\bar{\ell}_I \bar{\sigma}_\mu \ell_I)(\bar{\ell}_I \bar{\sigma}^\mu \ell_I)$
$[O_{\ell e}]_{IIII} = (\bar{\ell}_I \bar{\sigma}_\mu \ell_I)(e_I^c \sigma^\mu \bar{e}_I^c)$
$[O_{ee}]_{IIII} = \frac{1}{2}(e_I^c \sigma_\mu \bar{e}_I^c)(e_I^c \sigma^\mu \bar{e}_I^c)$

Matching wEFT to SMEFT

One can match wEFT to SMEFT at μ = mZ to relate parameters of the 2 effective theories

$$g_{AV}^{eu} = -\frac{1}{2} + \frac{4}{3}s_\theta^2 - \left(\delta g_L^{Zu} + \delta g_R^{Zu}\right) + \frac{3-8s_\theta^2}{3}\left(\delta g_L^{Ze} - \delta g_R^{Ze}\right) + \frac{1}{2}\left[c_{lq}^{(3)} - c_{lq} - c_{lu} + c_{eq} + c_{eu}\right]_{1111}$$

$$g_{AV}^{ed} = \frac{1}{2} - \frac{2}{3}s_\theta^2 - \left(\delta g_L^{Zd} + \delta g_R^{Zd}\right) - \frac{3-4s_\theta^2}{3}\left(\delta g_L^{Ze} - \delta g_R^{Ze}\right) + \frac{1}{2}\left[-c_{lq}^{(3)} - c_{lq} - c_{ld} + c_{eq} + c_{ed}\right]_{1111}$$

$$g_{VA}^{eu} = -\frac{1}{2} + 2s_\theta^2 - \left(1-4s_\theta^2\right)\left(\delta g_L^{Zu} - \delta g_R^{Zu}\right) + \left(\delta g_L^{Ze} + \delta g_R^{Ze}\right) + \frac{1}{2}\left[c_{lq}^{(3)} - c_{lq} + c_{lu} - c_{eq} + c_{eu}\right]_{1111}$$

$$g_{VA}^{ed} = \frac{1}{2} - 2s_\theta^2 - \left(1-4s_\theta^2\right)\left(\delta g_L^{Zd} - \delta g_R^{Zd}\right) - \left(\delta g_L^{Ze} + \delta g_R^{Ze}\right) + \frac{1}{2}\left[-c_{lq}^{(3)} - c_{lq} + c_{ld} - c_{eq} + c_{ed}\right]_{1111}$$

SM contribution from Z exchange

Effect of shifted Z couplings

Trivial matching of 4-fermion operators

$$\mathcal{L}_{\rm wEFT} \supset -\frac{1}{2v^2}\sum_{q=u,d} g_{AV}^{eq}\left(\bar{e}\,\bar{\sigma}_\rho e - e^c\sigma_\rho\bar{e}^c\right)\left(\bar{q}\,\bar{\sigma}^\rho q + q^c\sigma^\rho\bar{q}^c\right)$$
$$-\frac{1}{2v^2}\sum_{q=u,d} g_{VA}^{eq}\left(\bar{e}\,\bar{\sigma}_\rho e + e^c\sigma_\rho\bar{e}^c\right)\left(\bar{q}\,\bar{\sigma}^\rho q - q^c\sigma^\rho\bar{q}^c\right)$$

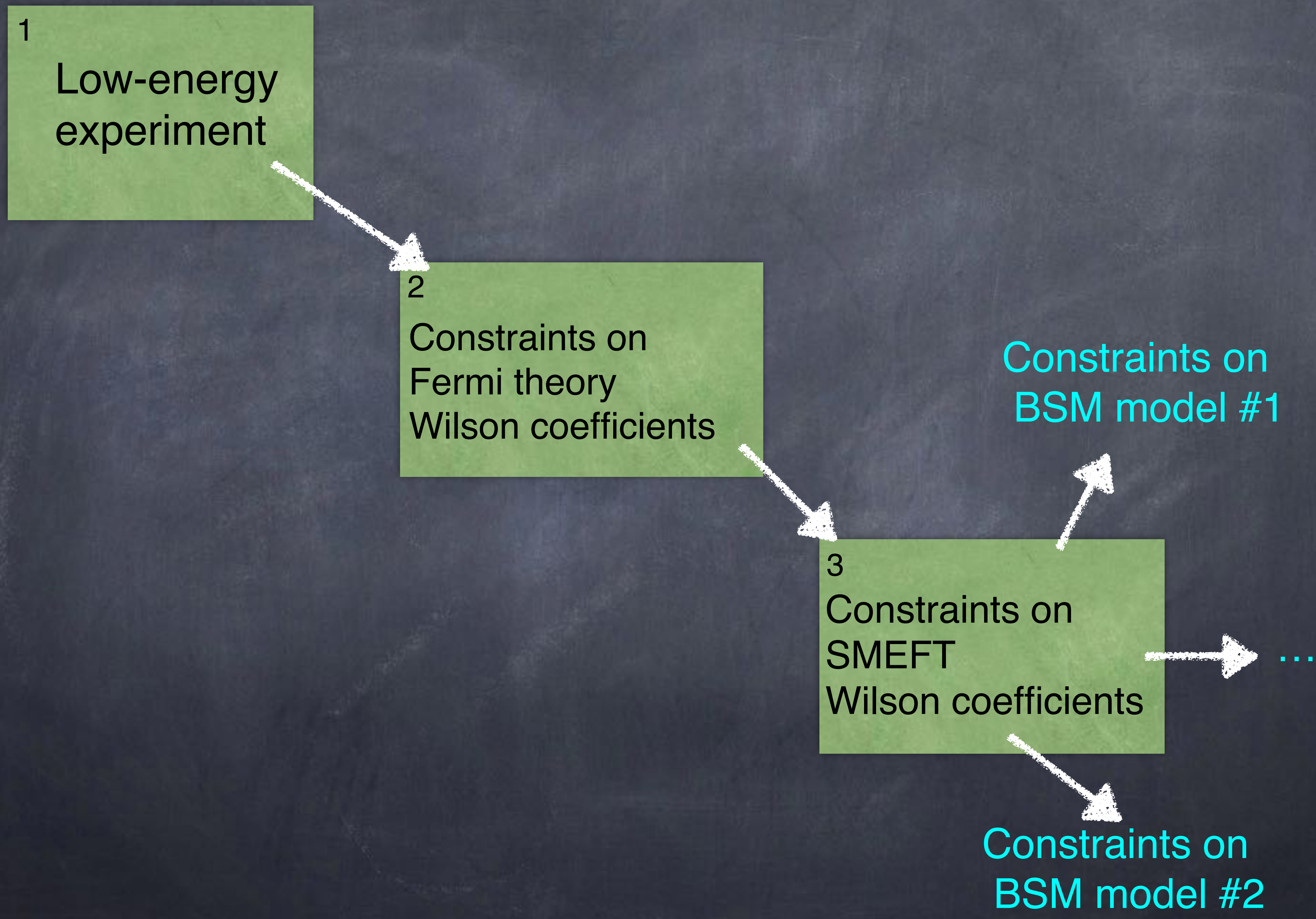
$$\mathcal{L}_{\rm SMEFT} \subset \frac{g_L}{\sqrt{2}}\left(W_\mu^+\bar{u}\bar{\sigma}_\mu(V_{\rm CKM} + \delta g_L^{Wq})d + W_\mu^+ u^c\sigma_\mu\delta g_R^{Wq}\bar{d}^c + W_\mu^+\bar{\nu}\bar{\sigma}_\mu(I + \delta g_L^{W\ell})e + \text{h.c.}\right)$$
$$+\sqrt{g_L^2+g_Y^2}Z_\mu\left[\sum_{f\in u,d,e,\nu}\bar{f}\bar{\sigma}_\mu(T_f^3 - s_\theta^2 Q_f + \delta g_L^{Zf})f + \sum_{f^c\in u^c,d^c,e^c} f^c\sigma_\mu(-s_\theta^2 Q_f + \delta g_R^{Zf})\bar{f}^c\right]$$

SMEFT

Chirality conserving $(I, J = 1,2,3)$

$$[O_{\ell q}]_{IIJJ} = (\bar{\ell}_I\bar{\sigma}_\mu\ell_I)(\bar{q}_J\bar{\sigma}^\mu q_J)$$
$$[O_{\ell q}^{(3)}]_{IIJJ} = (\bar{\ell}_I\bar{\sigma}_\mu\sigma^i\ell_I)(\bar{q}_J\bar{\sigma}^\mu\sigma^i q_J)$$
$$[O_{\ell u}]_{IIJJ} = (\bar{\ell}_I\bar{\sigma}_\mu\ell_I)(u_J^c\sigma^\mu\bar{u}_J^c)$$
$$[O_{\ell d}]_{IIJJ} = (\bar{\ell}_I\bar{\sigma}_\mu\ell_I)(d_J^c\sigma^\mu\bar{d}_J^c)$$
$$[O_{eq}]_{IIJJ} = (e_I^c\sigma_\mu\bar{e}_I^c)(\bar{q}_J\bar{\sigma}^\mu q_J)$$
$$[O_{eu}]_{IIJJ} = (e_I^c\sigma_\mu\bar{e}_I^c)(u_J^c\sigma^\mu\bar{u}_J^c)$$
$$[O_{ed}]_{IIJJ} = (e_I^c\sigma_\mu\bar{e}_I^c)(d_J^c\sigma^\mu\bar{d}_J^c)$$

Workflow


1
Low-energy experiment
2
Constraints on Fermi theory Wilson coefficients
3
Constraints on SMEFT Wilson coefficients
Constraints on BSM model #1
...
Constraints on BSM model #2


Now
Now
Now
Now
Now
Now
Now
Now
Now
Now
Now
Now
Present

Current wEFT constraints from APV and PVES

PDG combination of (old) QWEAK, PVDIS, and APV cesium experiments:

$$\begin{pmatrix} \delta g^{eu}_{AV} \\ \delta g^{ed}_{AV} \\ 2\delta g^{eu}_{VA} - \delta g^{ed}_{VA} \end{pmatrix} = \begin{pmatrix} 3.3 \pm 5.5 \\ -4.7 \pm 5.1 \\ -49 \pm 68 \end{pmatrix} \times 10^{-3}$$

$$g^{eu}_{AV,\mathrm{SM}} = -\,0.1887$$
$$g^{ed}_{AV,\mathrm{SM}} = +\,0.3419$$
$$g^{eu}_{VA,\mathrm{SM}} = -\,0.0351$$
$$g^{ed}_{VA,\mathrm{SM}} = +\,0.0247$$

PDG

wEFT parameters

$$g^{eq}_{AV} = g^{eq}_{AV,\mathrm{SM}} + \delta g^{eq}_{AV}$$
$$g^{eq}_{VA} = g^{eq}_{VA,\mathrm{SM}} + \delta g^{eq}_{VA}$$

Contain the difficult part (loop corrections)

BSM part treated at leading order

$$\mathcal{L}_{\mathrm{wEFT}} \supset -\frac{1}{2v^2}\sum_{q=u,d} g^{eq}_{AV}(\bar{e}\,\bar{\sigma}_\rho e - e^c\sigma_\rho \bar{e}^c)(\bar{q}\,\bar{\sigma}^\rho q + q^c\sigma^\rho \bar{q}^c)$$
$$-\frac{1}{2v^2}\sum_{q=u,d} g^{eq}_{VA}(\bar{e}\,\bar{\sigma}_\rho e + e^c\sigma_\rho \bar{e}^c)(\bar{q}\,\bar{\sigma}^\rho q - q^c\sigma^\rho \bar{q}^c)$$

Current wEFT constraints from APV and PVES

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$$\begin{pmatrix} \delta g_{AV}^{eu} \\ \delta g_{AV}^{ed} \\ 2\delta g_{VA}^{eu} - \delta g_{VA}^{ed} \end{pmatrix} = \begin{pmatrix} 3.3 \pm 5.5 \\ -4.7 \pm 5.1 \\ -49 \pm 68 \end{pmatrix} \times 10^{-3}$$

PDG

Updating with the final QWEAK measurement: $Q_W(p) = 0.0719 \pm 0.0045$

$$\begin{pmatrix} \delta g_{AV}^{eu} \\ \delta g_{AV}^{ed} \\ 2\delta g_{VA}^{eu} - \delta g_{VA}^{ed} \end{pmatrix} = \begin{pmatrix} 0.74 \pm 2.2 \\ -2.1 \pm 2.5 \\ -39 \pm 54 \end{pmatrix} \times 10^{-3}$$

Current wEFT constraints from Moller scattering

SLAC E158 measurement of parity-violating asymmetry

in Møller scattering $e^- e^- \to e^- e^-$

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

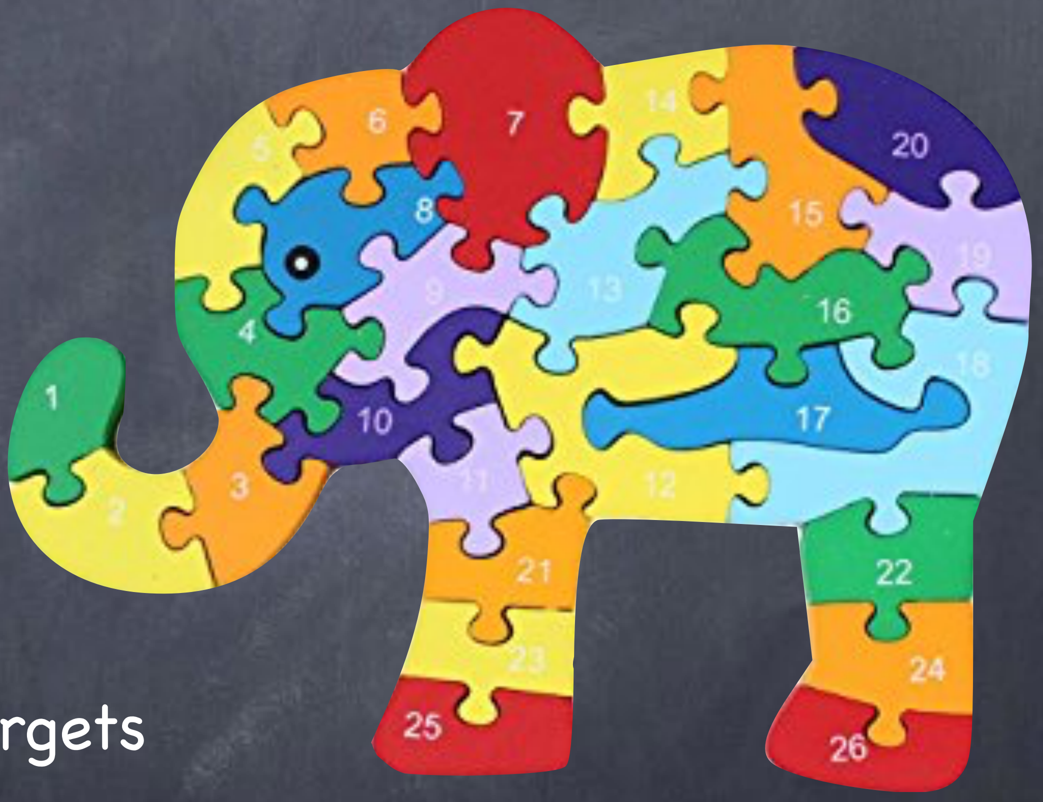
$$g_{AV}^{ee} = 0.0190 \pm 0.0027.$$

PDG

Global constraints on SMEFT

Combining multiple low-energy measurements of flavor-conserving observables

- Electron-positron collisions at LEP, LEP-2 and TRISTAN
- APV and PVES
- Pion decays
- Nuclear beta decays
- Tau decays
- Moller scattering
- Neutrino scattering on electron and nucleon targets
- Trident muon production
- ...



QWEAK, PVDIS, and APV
are pieces of the puzzle
in the bigger picture

Global constraints on SMEFT

$$
\begin{pmatrix}
\delta g_L^{We} \\ \delta g_L^{W\mu} \\ \delta g_L^{W\tau} \\ \delta g_L^{Ze} \\ \delta g_L^{Z\mu} \\ \delta g_L^{Z\tau} \\ \delta g_R^{Ze} \\ \delta g_R^{Z\mu} \\ \delta g_R^{Z\tau} \\ \delta g_L^{Zu} \\ \delta g_L^{Zc} \\ \delta g_L^{Zt} \\ \delta g_R^{Zu} \\ \delta g_R^{Zc} \\ \delta g_L^{Zd} \\ \delta g_L^{Zs} \\ \delta g_L^{Zb} \\ \delta g_R^{Zd} \\ \delta g_R^{Zs} \\ \delta g_R^{Zb} \\ \delta g_R^{Wq_1} \\ [c_{\ell\ell}]_{1111} \\ [c_{\ell e}]_{1111} \\ [c_{ee}]_{1111} \\ [c_{\ell\ell}]_{1221} \\ [c_{\ell\ell}]_{1122} \\ [c_{\ell e}]_{1122} \\ [c_{\ell e}]_{2211} \\ [c_{ee}]_{1122} \\ [c_{\ell\ell}]_{1331} \\ [c_{\ell\ell}]_{1133} \\ [c_{\ell e}]_{1133} \\ [c_{\ell e}]_{3311} \\ [c_{ee}]_{1133} \\ [\hat{c}_{\ell\ell}]_{2222} \\ [c_{\ell\ell}]_{2332}
\end{pmatrix}
=
\begin{pmatrix}
-1.00 \pm 0.64 \\ -1.36 \pm 0.59 \\ 1.95 \pm 0.79 \\ -0.023 \pm 0.028 \\ 0.01 \pm 0.12 \\ 0.018 \pm 0.059 \\ -0.033 \pm 0.027 \\ 0.00 \pm 0.14 \\ 0.042 \pm 0.062 \\ -0.8 \pm 3.1 \\ -0.15 \pm 0.36 \\ -0.3 \pm 3.8 \\ 1.4 \pm 5.1 \\ -0.35 \pm 0.53 \\ -0.9 \pm 4.4 \\ 0.9 \pm 2.8 \\ 0.33 \pm 0.17 \\ 3 \pm 16 \\ 3.4 \pm 4.9 \\ 2.30 \pm 0.88 \\ -1.3 \pm 1.7 \\ 1.01 \pm 0.38 \\ -0.22 \pm 0.22 \\ 0.20 \pm 0.38 \\ -4.8 \pm 1.6 \\ 1.5 \pm 2.1 \\ 1.5 \pm 2.2 \\ -1.4 \pm 2.2 \\ 3.4 \pm 2.6 \\ 1.5 \pm 1.3 \\ 0 \pm 11 \\ -2.3 \pm 7.2 \\ 1.7 \pm 7.2 \\ -1 \pm 12 \\ -2 \pm 21 \\ 3.0 \pm 2.3
\end{pmatrix}
\times 10^{-2},
$$

$$
\begin{pmatrix}
[c_{\ell q}^{(3)}]_{1111} \\ [\hat{c}_{eq}]_{1111} \\ [\hat{c}_{\ell u}]_{1111} \\ [\hat{c}_{\ell d}]_{1111} \\ [\hat{c}_{eu}]_{1111} \\ [\hat{c}_{ed}]_{1111} \\ [\hat{c}_{\ell q}^{(3)}]_{1122} \\ [c_{\ell u}]_{1122} \\ [\hat{c}_{\ell d}]_{1122} \\ [c_{eq}]_{1122} \\ [c_{eu}]_{1122} \\ [\hat{c}_{ed}]_{1122} \\ [\hat{c}_{\ell q}^{(3)}]_{1133} \\ [c_{\ell d}]_{1133} \\ [c_{eq}]_{1133} \\ [c_{ed}]_{1133} \\ [c_{\ell q}^{(3)}]_{2211} \\ [c_{\ell q}]_{2211} \\ [c_{\ell u}]_{2211} \\ [c_{\ell d}]_{2211} \\ [\hat{c}_{eq}]_{2211} \\ [c_{\ell equ}]_{1111} \\ [c_{\ell edq}]_{1111} \\ [c_{\ell equ}^{(3)}]_{1111} \\ \epsilon_P^{d\mu}(2\ \mathrm{GeV})
\end{pmatrix}
=
\begin{pmatrix}
-2.2 \pm 3.2 \\ 100 \pm 180 \\ -5 \pm 11 \\ -5 \pm 23 \\ -1 \pm 12 \\ -4 \pm 21 \\ -61 \pm 32 \\ 2.4 \pm 8.0 \\ -310 \pm 130 \\ -21 \pm 28 \\ -87 \pm 46 \\ 270 \pm 140 \\ -8.6 \pm 8.0 \\ -1.4 \pm 10 \\ -3.2 \pm 5.1 \\ 18 \pm 20 \\ -1.2 \pm 3.9 \\ 1.3 \pm 7.6 \\ 15 \pm 12 \\ 25 \pm 34 \\ 4 \pm 41 \\ -0.080 \pm 0.075 \\ -0.079 \pm 0.074 \\ -0.02 \pm 0.19 \\ -0.02 \pm 0.15
\end{pmatrix}
\times 10^{-2}.
$$

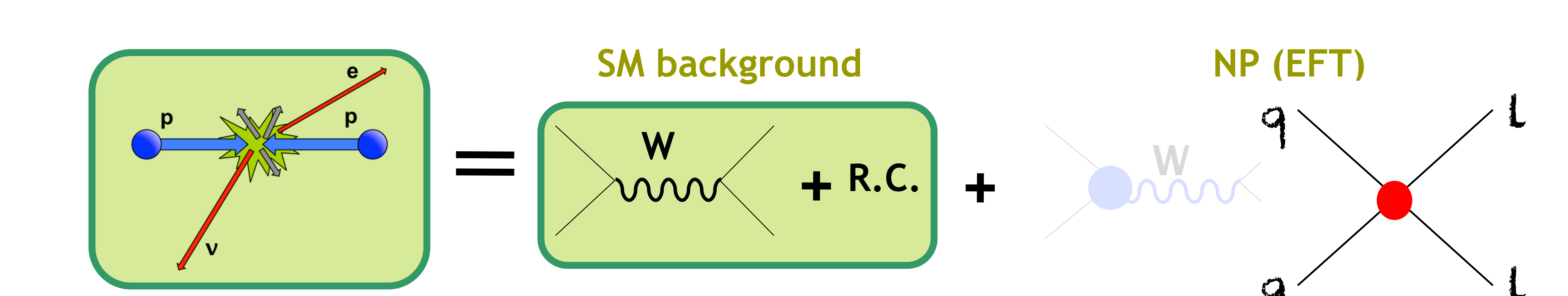
AA, Gonzalez-Alonso, Mimouni
1706.03783

Constraints on scale suppressing these dimension-6 operators between 250 GeV and tens of TeV

Global constraints on SMEFT

- 264 experimental inputs constraining simultaneously 61 combinations of SMEFT Wilson coefficients
- Flavor structure of Wilson coefficients assumed to be completely general. We are not assuming that some of the coefficients vanish (also those that we are not constraining in this analysis can be non-zero).
- The only assumptions are that SMEFT is valid up to O(200) GeV energy scale, and that tree-level contributions of dimension-6 operators to relevant observables dominate over loop-level contributions
- Marginalized constraints and the correlation matrix (thus global likelihood) is given -> can be used to constrain any BSM model that reduces to the SMEFT below 200 GeV energy scale
- Low-energy precision measurements often competitive or superior compared to the LEP electroweak precision measurements. In any case, they both are essential for lifting degeneracies in the SMEFT parameter space

Comparing LHC and low-energy bounds



Borrowed from Martin Gonzalez-Alonso

$(ee)(qq)$

	$[c^{(3)}_{\ell q}]_{1111}$	$[c_{\ell q}]_{1111}$	$[c_{\ell u}]_{1111}$	$[c_{\ell d}]_{1111}$	$[c_{eq}]_{1111}$	$[c_{eu}]_{1111}$	$[c_{ed}]_{1111}$
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

AA, Gonzalez-Alonso, Mimouni
1706.03783

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

ATLAS
1606.01736

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

Comparing LHC and low-energy bounds

Recent update (90% CL limits) of LHC constraints on 4-fermion SMEFT operators

	LO $\times 10^{-4}$		NLO $\times 10^{-4}$		Λ (TeV)	
$\lvert\Gamma^u_W\rvert$	< 480	< 710	< 460	< 640	1.1	0.9
$\lvert\Gamma^u_\gamma\rvert$	< 1200	< 1900	< 1200	< 1900	0.7	0.6
$\lvert\Gamma^d_W\rvert$	< 510	< 730	< 470	< 650	1.1	1.0
$\lvert\Gamma^d_\gamma\rvert$	< 1900	< 2700	< 1800	< 2600	0.6	0.5
$\lvert C_{LedQ}\rvert$	< 6.9	< 12	< 5.7	< 10	10	7.7
$\lvert C^{(1)}_{LeQu}\rvert$	< 4.6	< 10	< 3.9	< 8	12	8.7
$\lvert C^{(3)}_{LeQu}\rvert$	< 1.8	< 4.4	< 1.6	< 4	19	12
$C_{LQ,u}$	$[-7.4, 1.4]$	$[-16, 3.8]$	$[-6.9, 1.2]$	$[-14, 3.0]$	9.3	6.6
$C_{LQ,d}$	$[-7.1, 11]$	$[-14, 20]$	$[-6.9, 9.5]$	$[-13, 17]$	8.0	6.0
$C_{e,u}$	$[-6.9, 3.4]$	$[-16, 8.7]$	$[-6.4, 3.1]$	$[-14, 7.7]$	9.7	6.6
$C_{e,d}$	$[-8.9, 10]$	$[-17, 20]$	$[-8.1, 9.1]$	$[-15, 17]$	8.1	5.9
$C_{L,u}$	$[-6.0, 4.5]$	$[-14, 11]$	$[-5.5, 4.0]$	$[-12, 10]$	10	7.1
$C_{L,d}$	$[-9.0, 9.9]$	$[-18, 19]$	$[-8.4, 8.5]$	$[-15, 16]$	7.8	6.1
$C_{Q,e}$	$[-5.0, 4.0]$	$[-11, 10]$	$[-4.8, 3.4]$	$[-9.6, 8.6]$	11	8.2

NLO QCD analysis of 13 TeV Drell-Yan data

Alioli et al 1804.07407

Comparing LHC and low-energy bounds

- In spite of poor O(10%) accuracy, currently LHC has similar sensitivity to chirality conserving eeqq 4-fermion operators as low-energy measurements with per-mille accuracy

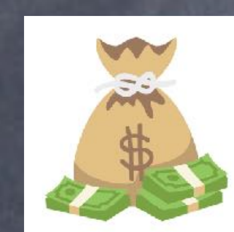
- This happens because effects of 4-fermion operators on scattering amplitudes are enhanced by E^2/v^2, where E is the center-of-mass energy of the parton collision. In this case, the superior energy reach of the LHC trumps the inferior accuracy

- Note that the same is not true for the vertex correction δg. These SMEFT deformations are not energy enhanced, and therefore it will be difficult to improve the constraints on δg at the LHC.

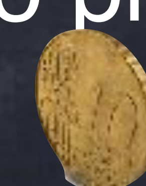
Gauging future precision measurements

- **Test #1:** Does your future experiment improve global constraints on wEFT Wilson coefficients?
- **Test #2:** Does your future experiment improve global constraints on SMEFT Wilson coefficients?

If Test #1 && Test #2

Excellent! 
You're exploring new territories!
Here is your cheque

If Test #1 && !(Test #2)

Your results may be useful to probe light new physics particles 

AA, Grilli Di Cortona, Tabrizi
1802.08296

AA, Gonzalez-Alonso
in progress

Near-future precision measurements

Measurement of atomic parity violation in radium ions:

Willmann et al.
CERN-INTC-2017-069

$$\Delta Q_W(^{225}\mathrm{Ra}) = 0.1376$$

Measurement of hydrogen and carbon weak charges in MESA P2:

Becker et al.
1802.04759

$$\Delta Q_W(^{1}\mathrm{H}) = 0.001207 \qquad \Delta \mathrm{Q_W}(^{12}\mathrm{C}) = 0.01655$$

Measurement of deep-inelastic PVES scattering in SoLID:

Zhao
1701.02780

$$2g_{AV}^{eu} - g_{AV}^{ed} = -0.7193 \pm 0.0276 \qquad 2g_{VA}^{eu} - g_{VA}^{ed} = -0.0949 \pm 0.0331 \qquad \rho = -0.9782$$

Measurement of parity violation in electron scattering in MOLLER:

Benesch et al.
1411.4088

$$\Delta g_{AV}^{ee} = 0.0006$$

Improved nuclear beta decays constraints
on charged current interactions

Gonzalez-Alonso, Naviliat-Cuncic, Severijns
1803.08732 Eq. (98)

Future wEFT constraints from APV and PVES

Current QWEAK, PVDIS, and APV cesium experiments:

$$\begin{pmatrix} \delta g_{AV}^{eu} \\ \delta g_{AV}^{ed} \\ 2\delta g_{VA}^{eu} - \delta g_{VA}^{ed} \end{pmatrix} = \begin{pmatrix} 0.74 \pm 2.2 \\ -2.1 \pm 2.5 \\ -39 \pm 54 \end{pmatrix} \times 10^{-3}$$

Projections from combined P2, SoLID, and APV radium experiments:

$$\begin{pmatrix} \delta g_{AV}^{eu} \\ \delta g_{AV}^{ed} \\ 2\delta g_{VA}^{eu} - \delta g_{VA}^{ed} \end{pmatrix} = \begin{pmatrix} 0 \pm 0.70 \\ 0 \pm 0.97 \\ 0 \pm 7.4 \end{pmatrix} \times 10^{-3}$$

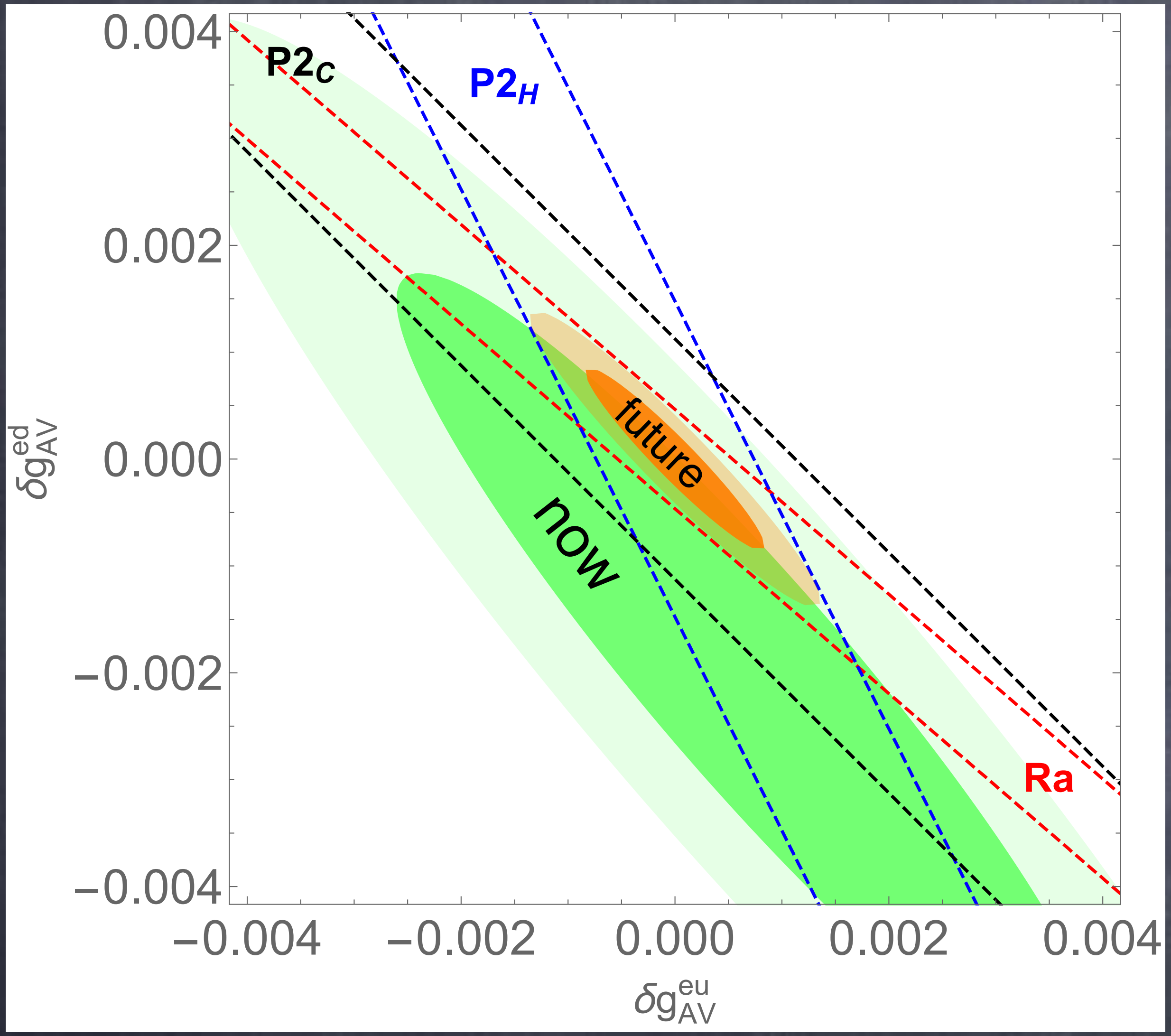
$$\mathcal{L}_{\mathrm{wEFT}} \supset -\frac{1}{2v^2} \sum_{q=u,d} g_{AV}^{eq} (\bar{e}\,\bar{\sigma}_\rho e - e^c \sigma_\rho \bar{e}^c)(\bar{q}\,\bar{\sigma}^\rho q + q^c \sigma^\rho \bar{q}^c)$$
$$- \frac{1}{2v^2} \sum_{q=u,d} g_{VA}^{eq} (\bar{e}\,\bar{\sigma}_\rho e + e^c \sigma_\rho \bar{e}^c)(\bar{q}\,\bar{\sigma}^\rho q - q^c \sigma^\rho \bar{q}^c)$$

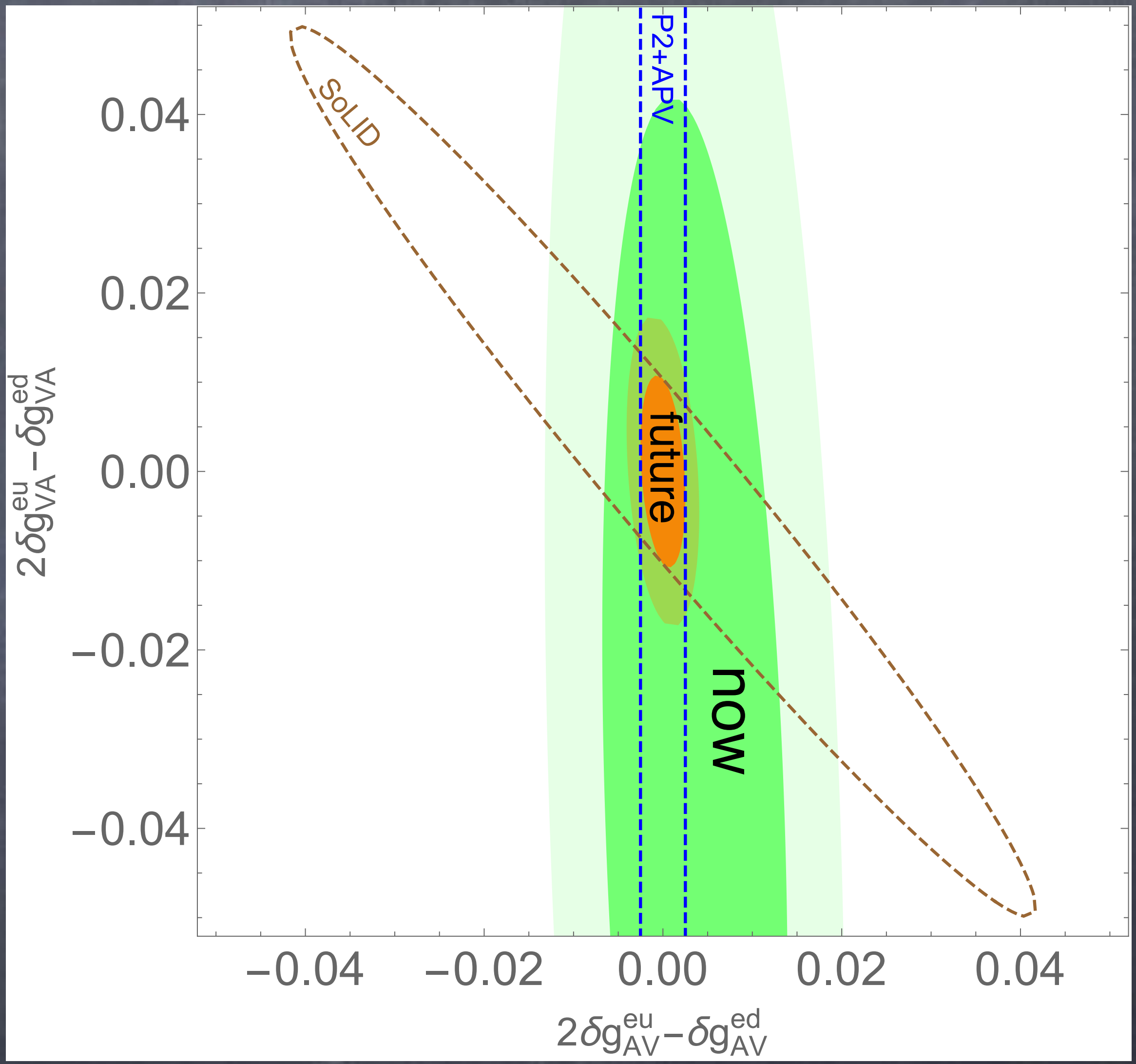
AA, Grilli Di Cortona, Tabrizi
1802.08296

AA, Gonzalez-Alonso
in progress

Future wEFT constraints from APV and PVES

Test #1: all passed





$$\mathcal{L}_{\rm wEFT} \supset -\frac{1}{2v^2} \sum_{q=u,d} g_{AV}^{eq} (\bar{e}\,\bar{\sigma}_\rho e - e^c \sigma_\rho \bar{e}^c)(\bar{q}\,\bar{\sigma}^\rho q + q^c \sigma^\rho \bar{q}^c)$$
$$- \frac{1}{2v^2} \sum_{q=u,d} g_{VA}^{eq} (\bar{e}\,\bar{\sigma}_\rho e + e^c \sigma_\rho \bar{e}^c)(\bar{q}\,\bar{\sigma}^\rho q - q^c \sigma^\rho \bar{q}^c)$$

Project global SMEFT constraints

Test #2: failed?

APV+PVES

Current and projected 1σ error in units of 0.01

Coefficient	Now	Future
$[\hat{c}_{eu}]_{1111}$	11	9.7
$[\hat{c}_{ed}]_{1111}$	20	19
$[c_{\ell\ell}]_{1111}$	0.38	0.27
$[c_{ee}]_{1111}$	0.38	0.27

MOLLER

Displaying Wilson coefficients for which projected global constraints are improved by at least 1%


The Meaning
Of It ALL
56

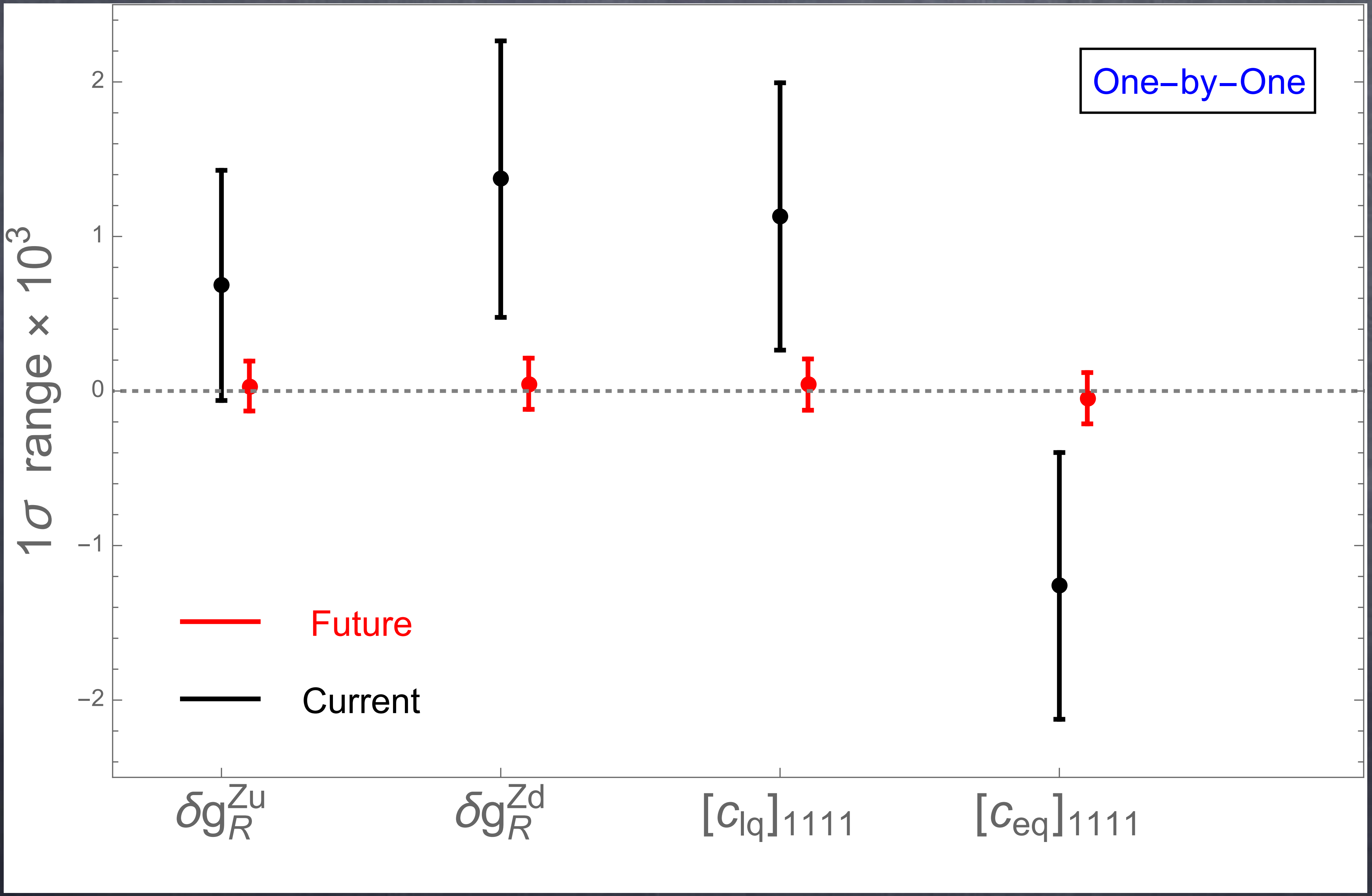
Projected 1-by-1 SMEFT constraints

Current and projected 1σ errors in units of 0.0001

	Now	MOLLER	APV-Ra	P2-H	P2-C	All
δg_R^{Zu}	7.4	$\times$	2.1	2.8	4.1	1.6
δg_R^{Zd}	8.9	$\times$	1.9	5.0	4.2	1.7
$[c_{\ell q}]_{1111}$	8.6	$\times$	2.0	3.7	4.2	1.7
$[c_{\ell u}]_{1111}$	16	$\times$	4.3	5.8	8.4	3.3
$[c_{\ell d}]_{1111}$	18	$\times$	3.7	10	8.3	3.3
$[c_{eq}]_{1111}$	8.6	$\times$	2.0	3.7	4.2	1.7
$[c_{eu}]_{1111}$	15	$\times$	4.3	5.8	8.3	3.2
$[c_{ed}]_{1111}$	18	$\times$	3.7	10	8.3	3.3
$[c_{\ell\ell}]_{1111}$	28	11	$\times$	$\times$	$\times$	11
$[c_{ee}]_{1111}$	28	11	$\times$	$\times$	$\times$	11

Displaying Wilson coefficients for which projected
1-by-1 constraints are improved by at least a factor of two

Projected 1-by-1 SMEFT constraints



Projected 1-by-1 SMEFT constraints from LHC

Current and projected 2σ errors

C_i	ATLAS 36.1 fb^{-1}	3000 fb^{-1}
$C^{(1)}_{Q^1L^1}$	$[-0.0, 1.75] \times 10^{-3}$	$[-1.01, 1.13] \times 10^{-4}$
$C^{(3)}_{Q^1L^1}$	$[-8.92, -0.54] \times 10^{-4}$	$[-3.99, 3.93] \times 10^{-5}$
$C_{u_R L^1}$	$[-0.19, 1.92] \times 10^{-3}$	$[-1.56, 1.92] \times 10^{-4}$
$C_{u_R e_R}$	$[0.15, 2.06] \times 10^{-3}$	$[-7.89, 8.23] \times 10^{-5}$
$C_{Q^1 e_R}$	$[-0.40, 1.37] \times 10^{-3}$	$[-1.8, 2.85] \times 10^{-4}$
$C_{d_R L^1}$	$[-2.1, 1.04] \times 10^{-3}$	$[-7.59, 4.23] \times 10^{-4}$
$C_{d_R e_R}$	$[-2.55, 0.46] \times 10^{-3}$	$[-3.37, 2.59] \times 10^{-4}$

Greljo, Marzocca
1704.09015

After high-luminosity phase, LHC sensitivity to 4-fermion qqee operators should be somewhat superior, compared to that of future PVES and APV experiments

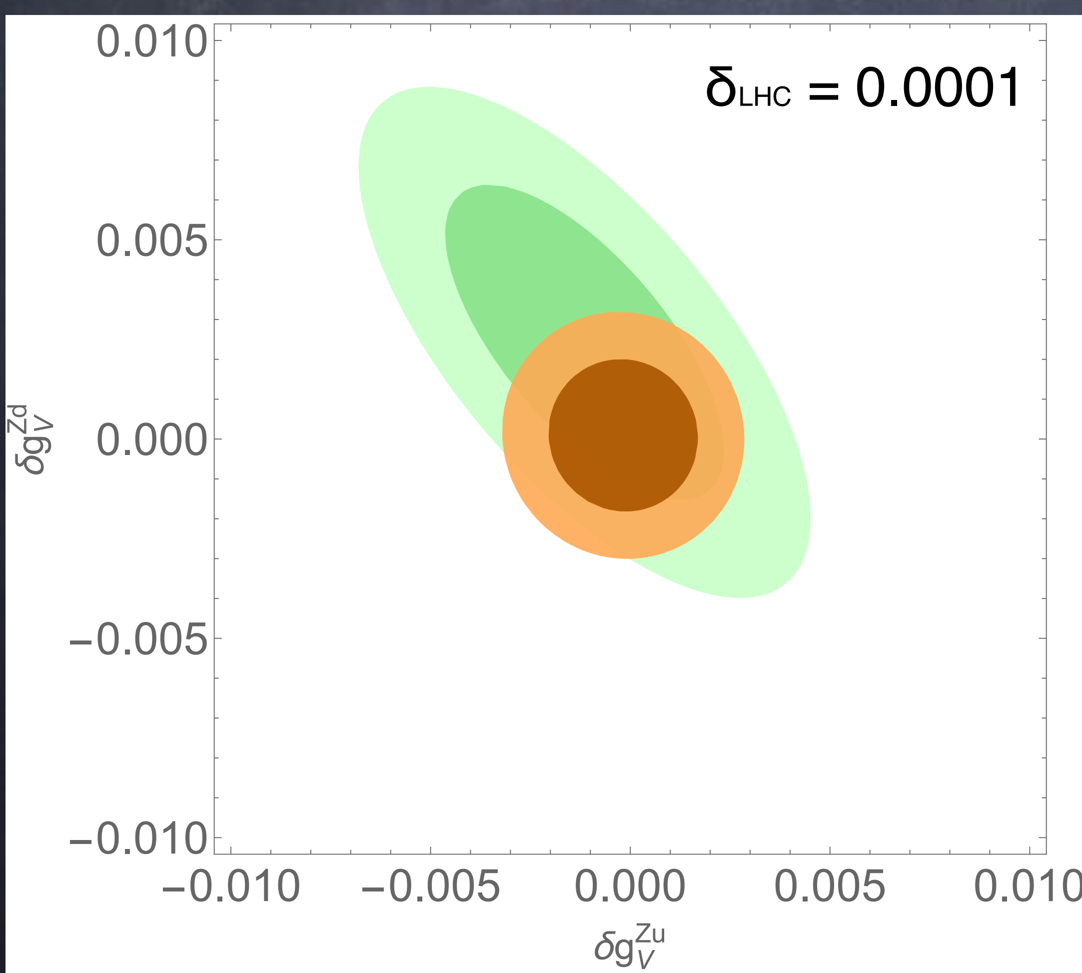
However, future PVES and APV experiments should be greatly superior in constraining certain 4-electron operators, and Zqq vertex corrections!

Projected global constraints

“Every disadvantage has its advantage”

One can estimate project SMEFT constraints from future PVES and APV experiments, taking into account strong constraints on qqee operators from the LHC

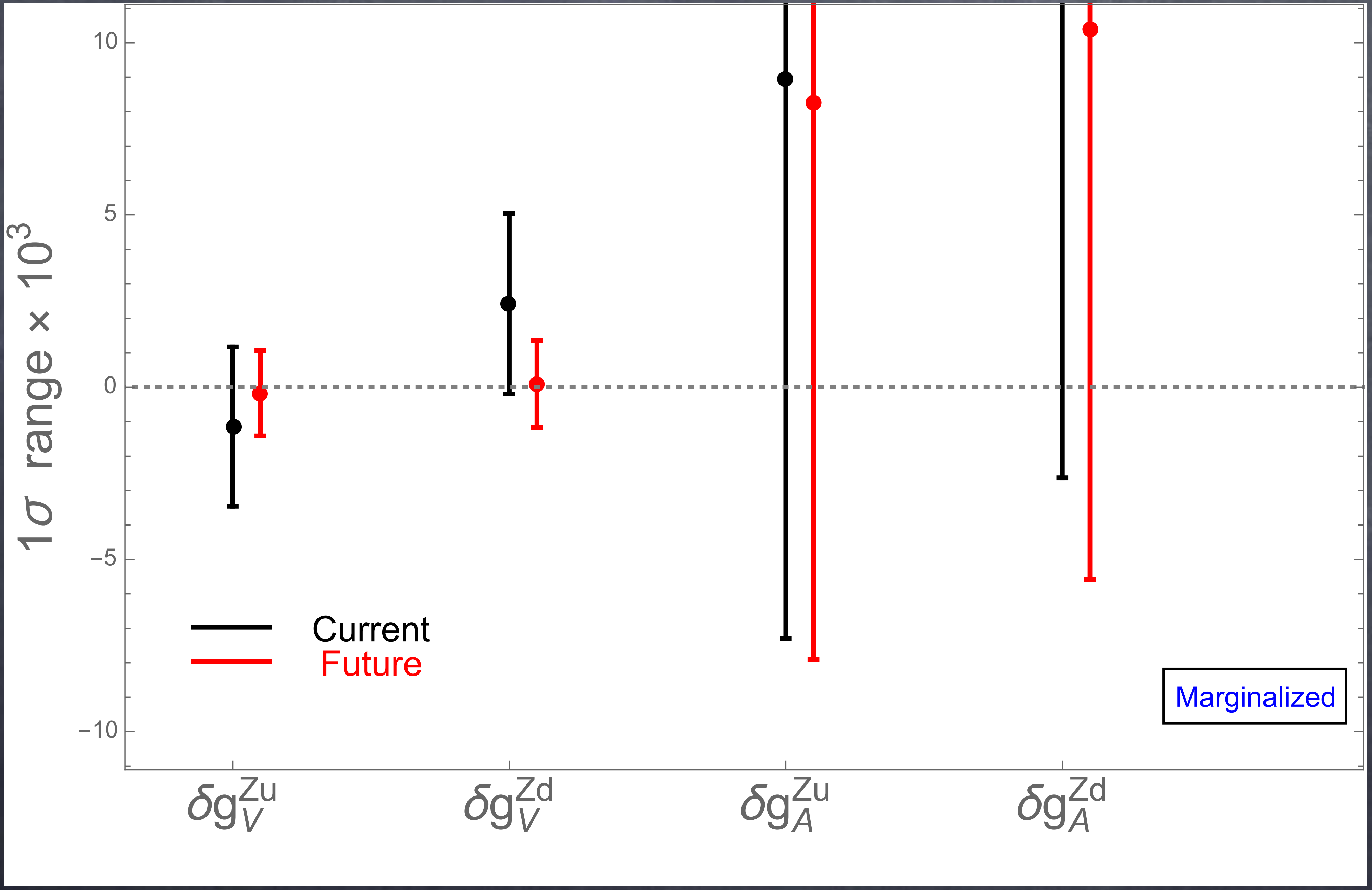
Coefficient	Now ($\delta_{\rm LHC} = 10^{-3}$)	Future ($\delta_{\rm LHC} = 10^{-3}$)	Future ($\delta_{\rm LHC} = 10^{-4}$)
δg_V^{Zu}	2.3	1.2	0.55
δg_V^{Zd}	2.6	1.3	0.59
δg_A^{Zu}	16	16	16
δg_A^{Zd}	17	16	16



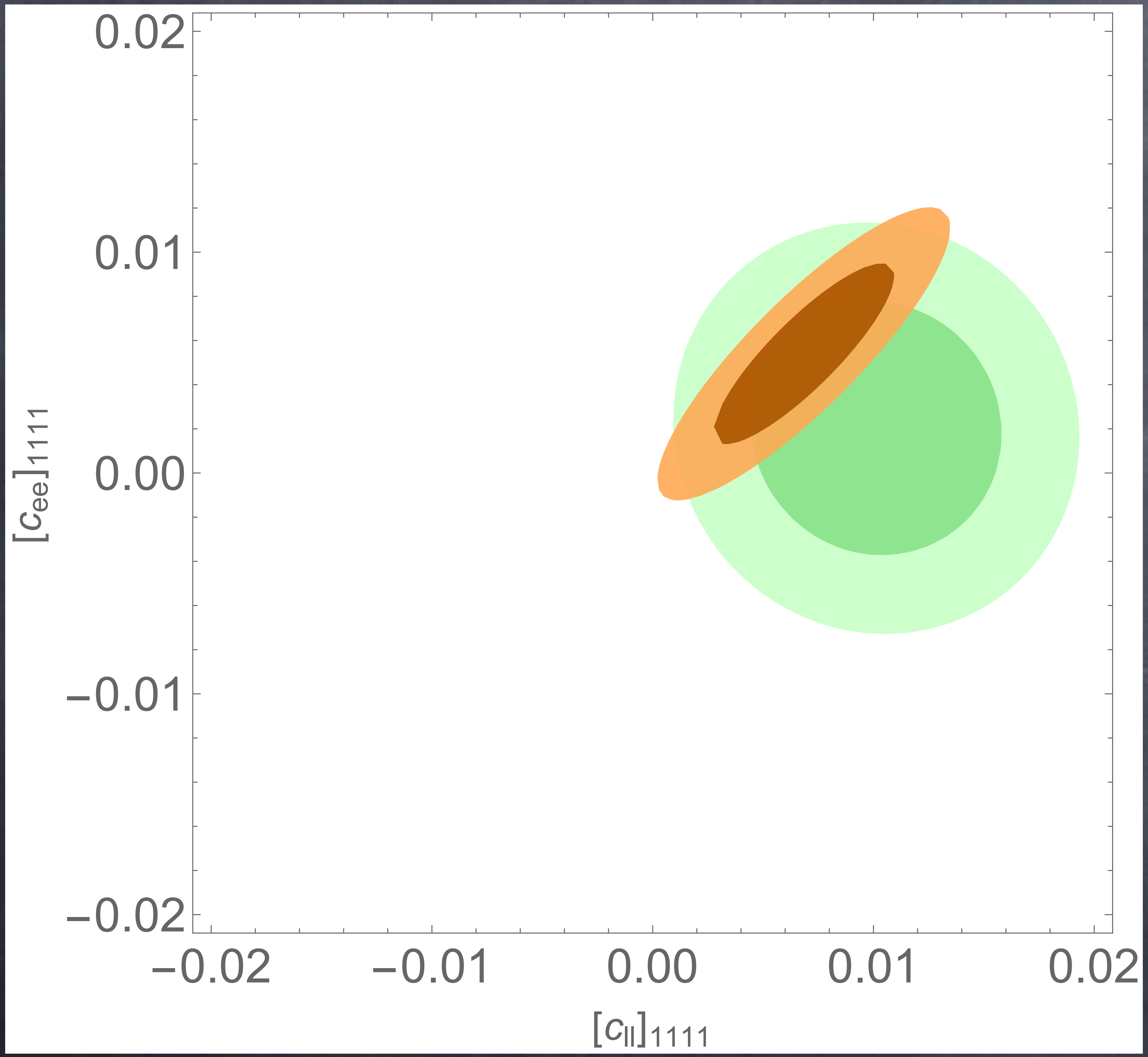
LHC and low-energy measurements are complementary. Together, they are expected to lead to factor of 4 improvement of the uncertainty on Z couplings to light quarks

Test #2: passed,
at least for P2 and APV radium

Projected global constraints



Projected global constraints

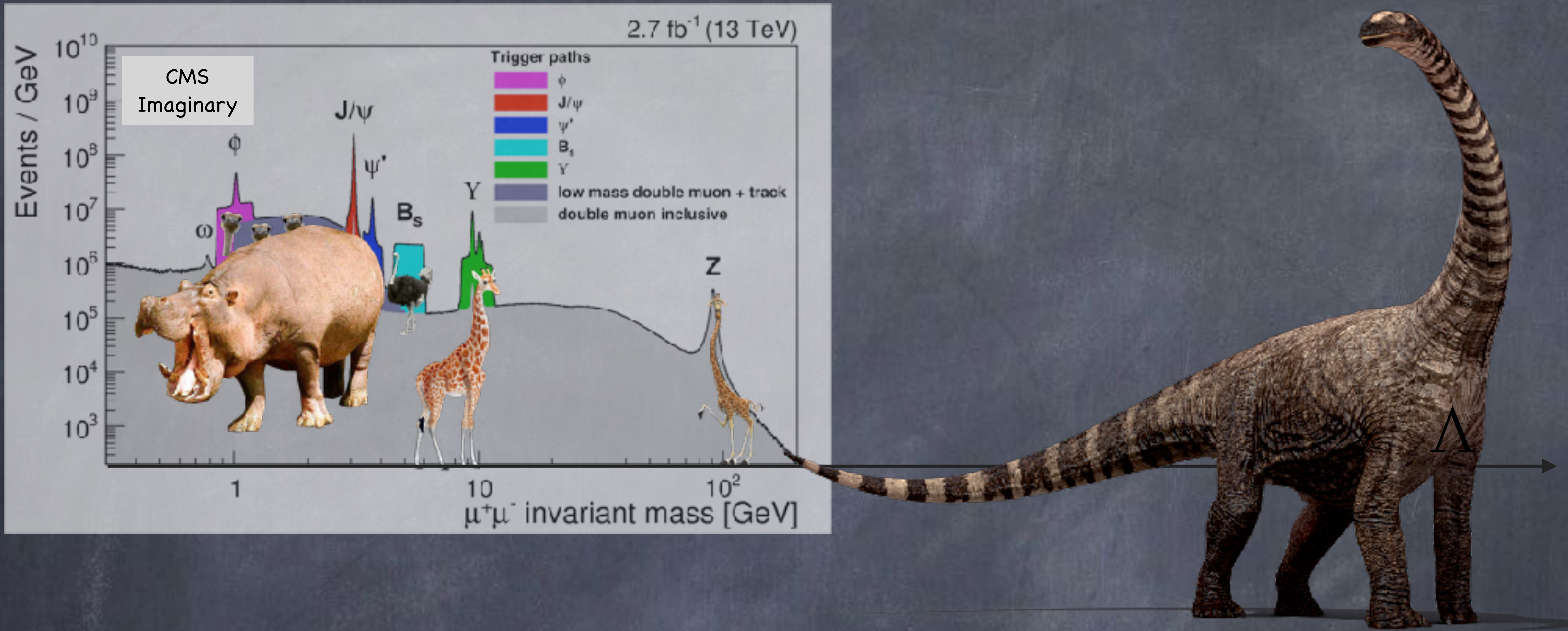


The impact of MOLLER will be to improve constraints on one linear combination of 4-lepton operators (electron vertex corrections better measured by LEP)

Take-away

- EFT approach has numerous advantages
- It is a tool to combine, within a consistent framework, results of different precision experiments at different energy scales
- It offers a global view of the new physics landscape, and helps highlighting poorly or strongly constrained directions in the BSM model space
- It allows one to understand what kind of BSM theories can be probed by future P2, SoLID, and APV radium experiments
- P2 and APV radium will significantly improve constraints on the Z boson couplings to up and down quarks
- MOLLER will significantly improve constraints on new parity-violating forces coupled to electrons

Fantastic Beasts and Where To Find Them



THANK YOU