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Low-energy precision frontier

Arles, 7 November 2018

Goals

- Overview of current and future searches for heavy new physics using low-energy precision measurements
- Advertisement of EFT and global likelihood approach
- Possibly, some new directions to entertain within the GdR-InF

Status report

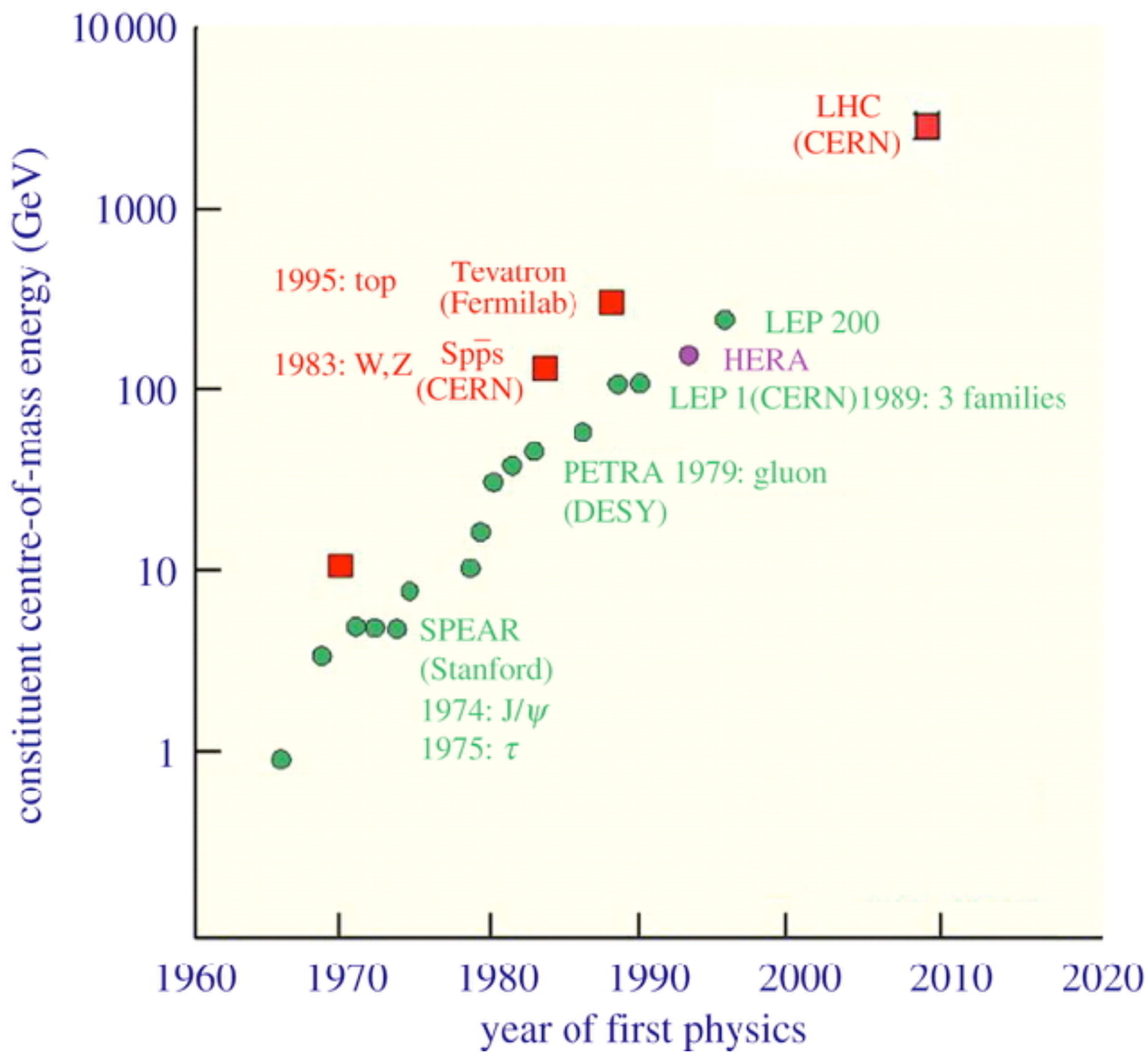
- The SM has been excessively successful in describing (almost) all collider and low-energy experiments. The discovery of the 125 GeV Higgs boson was the last piece of the puzzle that nicely fell into place. No more free parameters in the SM

- But 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 unifications, naturalness problem)

- At the same, certainly one cannot point to one specific model or a class of models that is strongly preferred theoretically. In particular, the naturalness paradigm seems to be a dead end, which means that BSM physics can be at any mass scale, from sub-eV to Planck scales

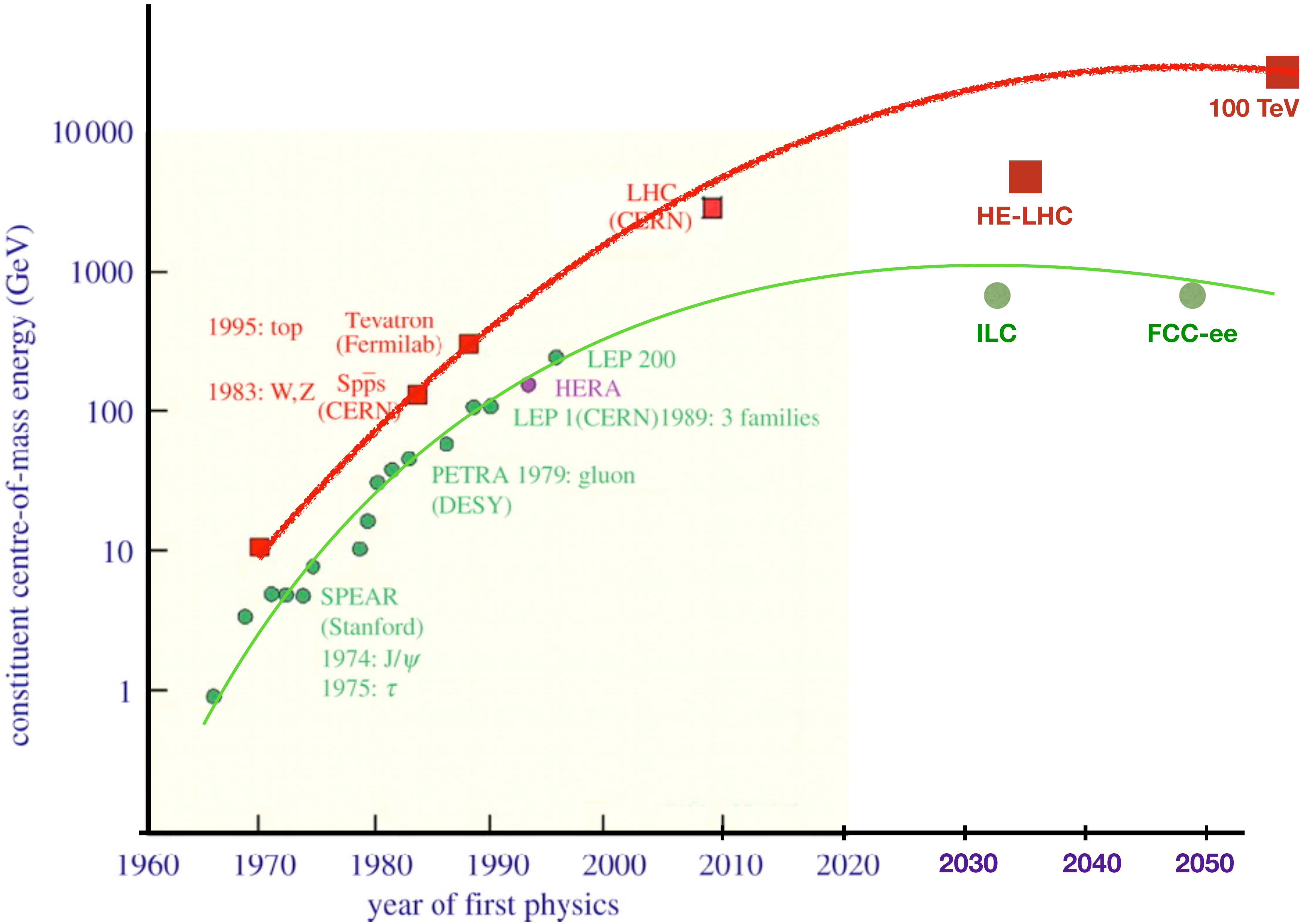
- To make further progress we need a hint from experiment

High-energy frontier



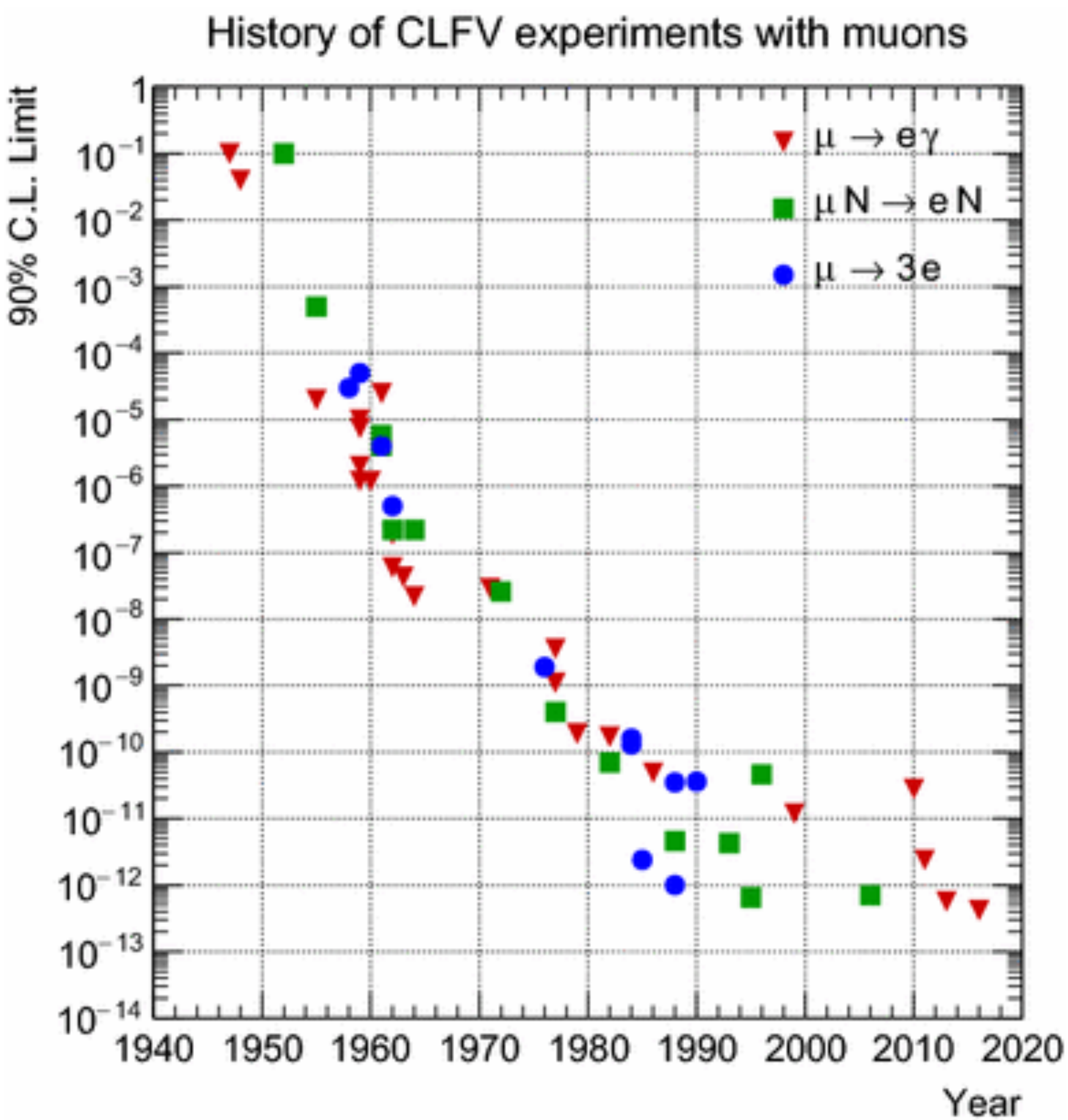
Most of what we know about fundamental interactions we learned on the high-energy frontier

High-energy frontier



Initially, impressive progress of order of magnitude per decade, which is however flatlining in this century

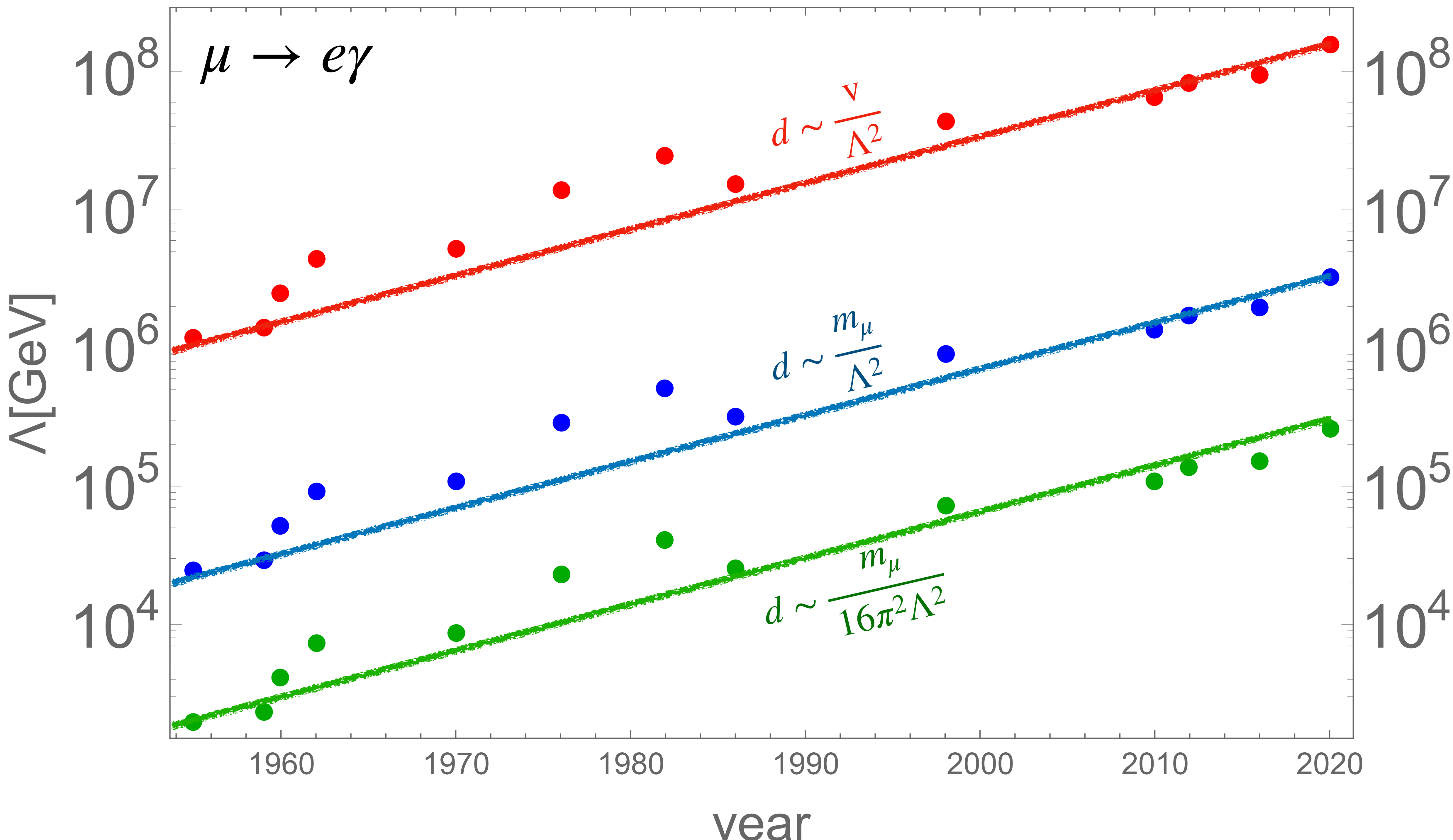
Low-energy frontier



A host precision measurements is providing complementary information about fundamental interactions

Low-energy frontier

$$\mathscr{L} = d\,\bar{e}\sigma_{\mu\nu}\mu F^{\mu\nu} \quad \Rightarrow \quad \Gamma(\mu \to e\gamma) \approx \frac{m_\mu^3}{4\pi} d^2$$



Precision frontier has had a slower pace of progress compared to high-energy colliders, order of magnitude/30 years, however higher scales reached and no sign of flatlining

Low-energy frontier

- Low-energy measurements can, indirectly, probe heavy new physics, sometimes far above the reach of present or near-future high-energy colliders
- Mostly small- or moderate-scale experiments
- Good prospects for progress at many fronts and for pushing the reach to higher mass scales

Low-energy frontier

Rare or forbidden processes

E.g.
proton decay,
neutron and electron EDM
CLFV: μ->eγ, τ->lγ, B_s->μe …

Zero or negligible SM background
Simple interpretation: any signal is unambiguous evidence of new physics

$$\text{Precision} \sim \frac{1}{\Lambda^4}$$

Precision measurements

E.g.
electron or muon MDM,
atomic parity violation,
basically entire flavor physics:
neutral meson mixing, kaon ε'/ε
π->lν, B_s->μμ, K-> πνν, …

Signal appears as a small correction on top of the SM prediction
More difficult interpretation: evidence from new physics requires good understanding of backgrounds (often non-perturbative)

$$\text{Precision} \sim \frac{1}{\Lambda^2}$$

Sensitive to new physics scale as

Low-energy precision frontier

- The rest of this talk focuses on the precision frontier, with the focus on observables involving first generation quarks
- A huge amount of observables
- Convenient and systematic model-independent language to describe this wealth of information is that of effective field theory (EFT)

EFT Formalism

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

In the following, assume no new very light degrees of freedom other than the SM ones

EFT ladder

Energy Scale	Theory	Particles	Expansion Parameter
1 TeV	SMEFT		$\frac{E}{\Lambda}$
100 GeV 10 GeV	WEFT (aka Fermi theory, LEFT, WET)	γ,g,ν,e,μ,τ + N_f q	$\frac{E}{m_W}$
1 GeV	χPT	γ,ν,e,p,n,μ,π,K	$\frac{E}{4\pi f_\pi}$
100 MeV			
10 MeV	eQED+NEFT	γ,ν,e,N	$\frac{E}{m_\mu}, \frac{E_k}{m_p}$
1 MeV	Euler-Heisenberg	γ,ν	$\frac{E}{m_e}$

WEFT: EFT below the weak scale

- For most low-energy precision observables, the characteristic energy scale is much smaller than the W and Z boson mass

- Below m_W, the only SM degrees of freedom available are leptons, photon, gluons, and 3,4,or 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 the 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/m_W, $m_W \approx 80$ GeV.

- There are 70 dimension-5 and 3631 dimension-6 operators preserving baryon and lepton number

Jenkins et al
1711.05270

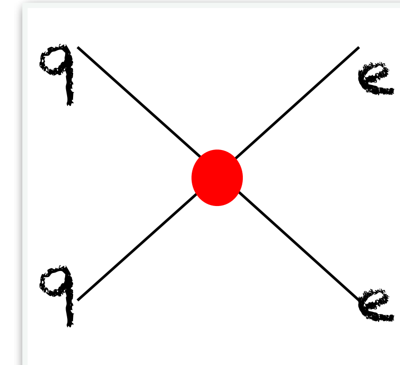
In a way, apply a similar approach as that familiar from model-independent treatment of B-meson anomalies, however more generally and more globally

Example #1: atomic parity violation

Subset of WEFT: parity-violating neutral current interactions of 2 electron and 2 light quarks

$$\mathscr{L}_{\rm WEFT} \supset \frac{G_F}{\sqrt{2}} \sum_{q=u,d} g_{AV}^{eq} (\bar{e}\gamma_\rho\gamma_5 e)(\bar{q}\gamma^\rho q)$$

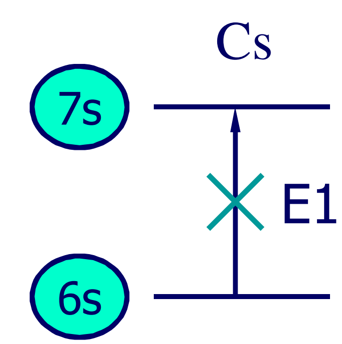
Closely following PDG notation



There are 2-independent couplings here, which are probed by atomic parity violation, and parity violating electron scattering

Weak charge of a nucleus:

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



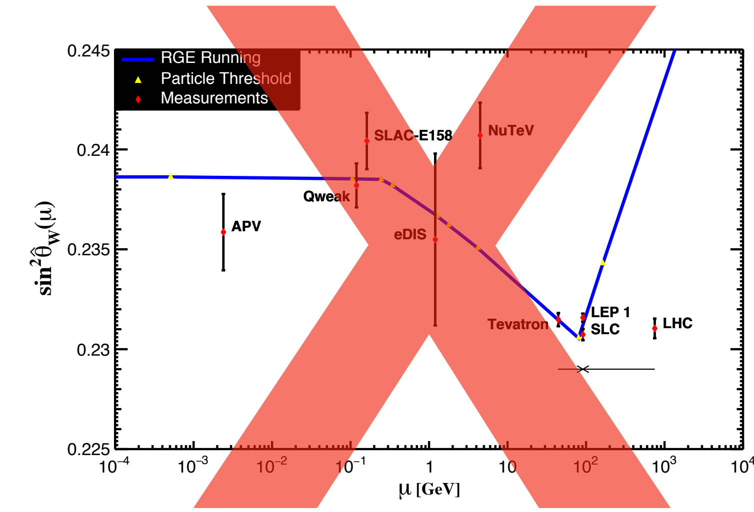
Wood et al (1997)

$$Q_W(\mathrm{Cs}) = -72.62 \pm 0.43, \qquad Q_W^{\rm SM}(\mathrm{Cs}) = -73.25 \pm 0.02$$

QWEAK Nature 557 (2018)

$$Q_W(p) = 0.0719 \pm 0.0045, \qquad Q_W^{\rm SM}(p) = 0.0708 \pm 0.0003$$

Example #1: atomic parity violation



These data often interpreted as constraints on the Weinberg angle but that is a waste…

Instead, more useful information if they are interpreted as constraint on WEFT Wilson coefficients

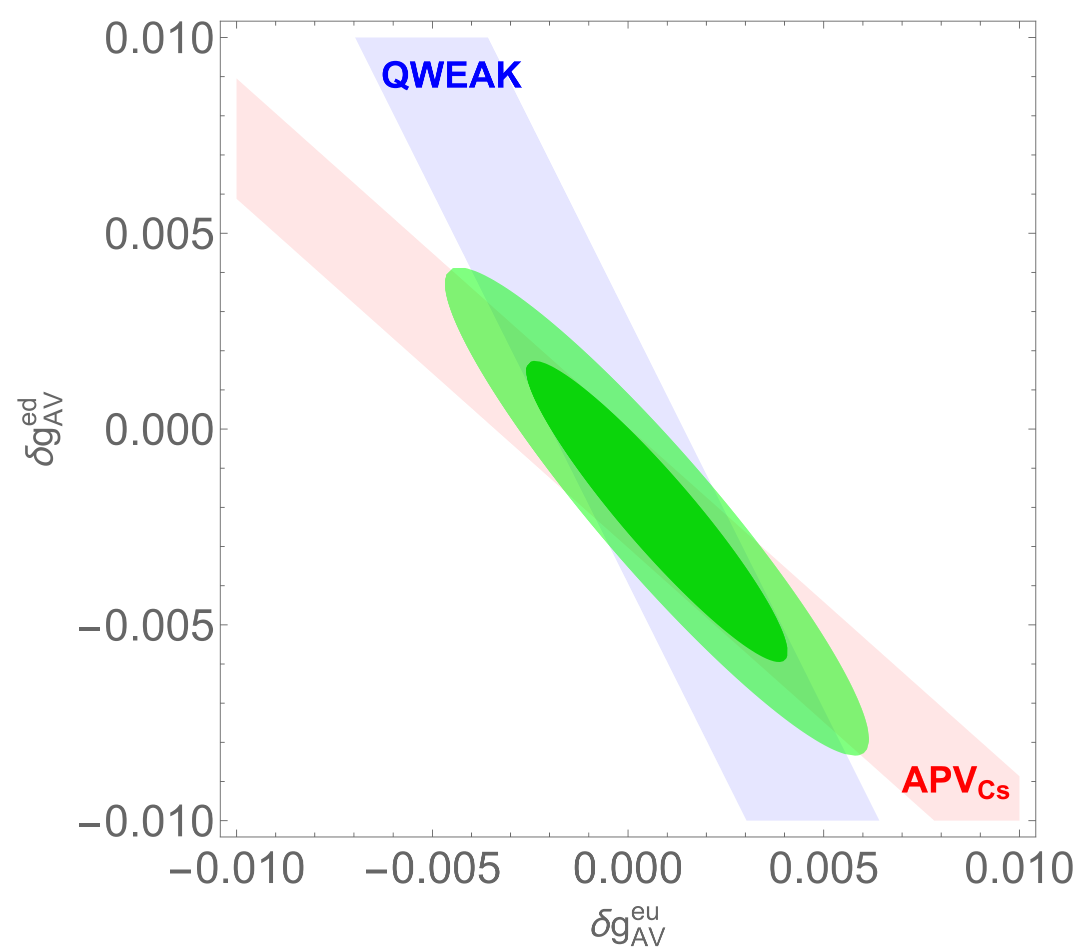
$$g_{AV}^{eq} = g_{AV,\mathrm{SM}}^{eq} + \delta g_{AV}^{eq}, \qquad g_{AV,\mathrm{SM}}^{eu} = -0.1888, \qquad g_{AV,\mathrm{SM}}^{ed} = 0.3419$$

Combined fit:
per-mille level constraints!

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

$$\rho = \begin{pmatrix} 1 & -0.88 \\ -0.88 & 1 \end{pmatrix}$$

Important for interpretations in specific models!



Example #2: hadronic tau decays

Cirigliano et al
1809.01161

Subset of WEFT: charged current interactions of tau with 2 light quarks

$$\mathscr{L}_{\text{WEFT}} \supset -\frac{G_F V_{ud}}{\sqrt{2}} \Bigg[\left(1 + \epsilon_L^\tau\right) \bar{\tau}\gamma_\mu(1-\gamma_5)\nu_\tau \cdot \bar{u}\gamma^\mu(1-\gamma_5)d$$
$$+\epsilon_R^\tau\, \bar{\tau}\gamma_\mu(1-\gamma_5)\nu_\tau \cdot \bar{u}\gamma^\mu(1+\gamma_5)d$$
$$+\, \bar{\tau}(1-\gamma_5)\nu_\tau \cdot \bar{u}\left[\epsilon_S^\tau - \epsilon_P^\tau\gamma_5\right]d$$
$$+\epsilon_T^\tau\, \bar{\tau}\sigma_{\mu\nu}(1-\gamma_5)\nu_\tau \cdot \bar{u}\sigma^{\mu\nu}(1-\gamma_5)d \Bigg] + \text{h.c.}$$

At leading order, 5 independent coefficients ε_X,
corresponding to different Lorentz structures of the hadronic and leptonic currents

Multiple observables needed to disentangle them,
and constrain all Wilson coefficients independently

Example #2: hadronic tau decays

$\tau \to \pi \nu$:

$$\Gamma(\tau \to \pi\nu) = \frac{V_{ud}^2 f_{\pi^\pm}^2 (m_\tau^2 - m_{\pi^\pm}^2)^2}{32\pi m_\tau v^4}\left[1 + 2\epsilon_L^\tau - 2\epsilon_L^e - 2\epsilon_R^\tau - 2\epsilon_R^e - \frac{2m_{\pi^\pm}^2}{m_\tau(m_u+m_d)}\epsilon_P^\tau\right]$$

Lattice error dominates total uncertainty

$$\epsilon_L^\tau - \epsilon_L^e - \epsilon_R^\tau - \epsilon_R^e - \frac{B_0}{m_\tau}\epsilon_P^\tau = (-1.5 \pm 6.7)\cdot 10^{-3} \qquad B_0 \equiv \frac{m_\pi^2}{m_u+m_d} \approx 11 m_\tau$$

Chiral enhancement makes it a perfect probe of pseudo-scalar interactions, but dependence on axial interaction should not be neglected either

$\tau \to \pi\,\eta\,\nu$:

$$\epsilon_S^\tau = (-6 \pm 15)\times 10^{-3}$$

Decays to η provide a complementary probe, as they are sensitive to scalar interactions

$\tau \to \pi\,\pi\,\nu$: **Depends on vector and tensor interactions, but form factors poorly known**

Can be related by e+e- → π π via isospin rotation

$a_\mu^{\rm had}[\pi\pi]$ →

hadronic vacuum polarization contribution to muon g-2

$$\frac{a_\mu^\tau - a_\mu^{ee}}{2\,a_\mu^{ee}} = \epsilon_L^\tau - \epsilon_L^e + \epsilon_R^\tau - \epsilon_R^e + 1.7\,\epsilon_T^\tau = (8.9 \pm 4.4)\cdot 10^{-3},$$

Example #2: hadronic tau decays

The last ingredient is inclusive vector and axial spectral functions

$$\int_{4m_\pi^2}^{s_0} \frac{ds}{s_0}\omega\left(\frac{s}{s_0}\right)\rho^{\rm exp}_{V\pm A}(s) \approx (1+2\epsilon_V)\,X_{VV}$$

$$\pm\,(1+2\epsilon_A)\left(X_{AA} - \frac{f_\pi^2}{s_0}\omega\left(\frac{m_\pi^2}{s_0}\right)\right) + \epsilon_T^\tau\,X_{VT}$$

Calculated using OPE

$$\epsilon^\tau_{L+R} - \epsilon^e_{L+R} - 0.78\epsilon^\tau_R + 1.71\epsilon^\tau_T = (4\pm16)\cdot10^{-3}$$

$$\epsilon^\tau_{L+R} - \epsilon^e_{L+R} - 0.89\epsilon^\tau_R + 0.90\epsilon^\tau_T = (8.5\pm8.5)\cdot10^{-3}$$

$$\epsilon^\tau_{L+R} - \epsilon^e_{L+R} + 3.1\epsilon^\tau_R + 8.1\epsilon^\tau_T = (5.0\pm50)\cdot10^{-3}$$

$$\epsilon^\tau_{L+R} - \epsilon^e_{L+R} + 1.9\epsilon^\tau_R + 8.0\epsilon^\tau_T = (10\pm10)\cdot10^{-3}\,.$$

Example #2: hadronic tau decays

Putting it all together

$$\begin{pmatrix} \epsilon_L^\tau - \epsilon_L^e + \epsilon_R^\tau - \epsilon_R^e \\ \epsilon_R^\tau \\ \epsilon_S^\tau \\ \epsilon_P^\tau \\ \epsilon_T^\tau \end{pmatrix} = \begin{pmatrix} 1.0 \pm 1.1 \\ 0.2 \pm 1.3 \\ -0.6 \pm 1.5 \\ 0.5 \pm 1.2 \\ -0.04 \pm 0.46 \end{pmatrix} \cdot 10^{-2}, \qquad \rho = \begin{pmatrix} 1 & 0.88 & 0 & -0.57 & -0.94 \\ & 1 & 0 & -0.86 & -0.94 \\ & & 1 & 0 & 0 \\ & & & 1 & 0.66 \\ & & & & 1 \end{pmatrix}$$

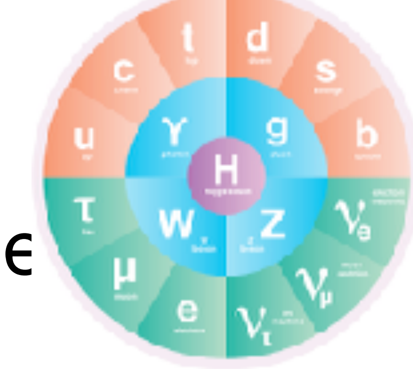
Percent level constraints on all 5 independent Lorentz structures in tau-hadronic charged currents !

$$\begin{aligned} \mathscr{L}_{\rm WEFT} \supset -\frac{G_F V_{ud}}{\sqrt{2}} \Bigg[& \Big(1+\epsilon_L^\tau\Big) \bar\tau \gamma_\mu (1-\gamma_5) \nu_\tau \cdot \bar u \gamma^\mu (1-\gamma_5) d \\ & + \epsilon_R^\tau \, \bar\tau \gamma_\mu (1-\gamma_5) \nu_\tau \cdot \bar u \gamma^\mu (1+\gamma_5) d \\ & + \, \bar\tau (1-\gamma_5) \nu_\tau \cdot \bar u \Big[\epsilon_S^\tau - \epsilon_P^\tau \gamma_5 \Big] d \\ & + \epsilon_T^\tau \, \bar\tau \sigma_{\mu\nu} (1-\gamma_5) \nu_\tau \cdot \bar u \sigma^{\mu\nu} (1-\gamma_5) d \Bigg] + {\rm h.c.} \end{aligned}$$

Low-energy precision measurements

- APV and PVES, including deep inelastic PV scattering
- Pion decays
- Nuclear beta decays
- Leptonic tau and muon decays
- Moller scattering of electrons
- Neutrino scattering on electron and nucleon targets
- Trident muon production
- Soon: coherent neutrino scattering, kaon decays, strange hadronic tau decays

WEFT vs SMEFT



- WEFT should be directly matched to BSM models if new particle fairly light, at or below the weak scale

- However, most likely new particles are much heavier than that, more than a few TeV masses

- Then at the weak scale WEFT has to be matched to another EFT, which has the same particle spectrum as the SM, and the full SU(3)xSU(2)xU(1) local symmetry broken only by the Higgs VEV

- This goes under the name of the SMEFT

- SMEFT can be matched to specific BSM models (like Z', or leptoquarks) at the scale Λ where new particles appear. Automated tools for this purpose are already on the market.

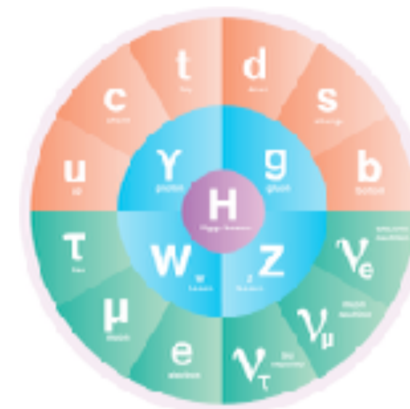
- Global likelihood for the SMEFT Wilson coefficients can be readily translated into constraints on masses and couplings in specific models

SMEFT

$$\mathscr{L}_{\mathrm{SMEFT}} = \mathscr{L}_{\mathrm{SM}} + \frac{1}{\Lambda_L}\mathscr{L}_{D=5} + \frac{1}{\Lambda^2}\mathscr{L}_{D=6} + \frac{1}{\Lambda_L^3}\mathscr{L}_{D=7} + \frac{1}{\Lambda^4}\mathscr{L}_{D=8} + \ldots$$

Known SM Lagrangian

Higher-dimensional $SU(3)_C \times SU(2)_L \times U(1)_Y$ invariant interactions added to the SM



Dimensionful expansion parameter interpreted as the mass scale of new physics

$$1\ \mathrm{TeV} \lesssim \Lambda \lesssim\ ?$$

Dimensionful expansion parameter for B-L violating interactions

$$\Lambda_L \sim 10^{15}\ \mathrm{GeV}$$

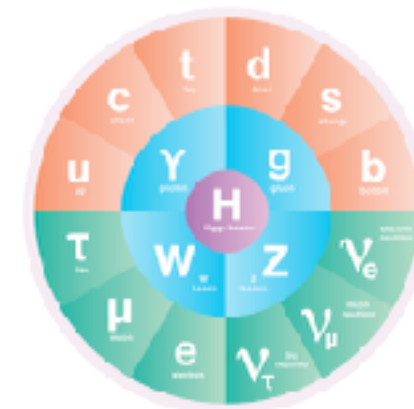
SMEFT

Buchmuller,Wyler (1986)

$$\mathscr{L}_{\text{SMEFT}} = \mathscr{L}_{\text{SM}} \qquad + \frac{1}{\Lambda^2}\mathscr{L}_{D=6} \qquad + \frac{1}{\Lambda^4}\mathscr{L}_{D=8} + \dots$$

Known SM Lagrangian

Higher-dimensional $SU(3)_C \times SU(2)_L \times U(1)_Y$ invariant interactions added to the SM



Dimensionful expansion parameter interpreted as mass scale of new physics

$$1 \text{ TeV} \lesssim \Lambda \lesssim \, ?$$

In the following for simplicity we set $\Lambda_L \to \infty$
(so that all odd-dimension lepton-number violating operators vanish)

and moreover we ignore operators of dimension-8 and higher

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}	$\left\|H^\dagger D_\mu H\right\|^2$		
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.

$(\bar R R)(\bar R R)$	
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}	$(u^c\sigma_\mu T^a\bar u^c)(d^c\sigma_\mu T^a\bar d^c)$

$(\bar L L)(\bar R R)$	
$O_{\ell e}$	$(\bar\ell\bar\sigma_\mu\ell)(e^c\sigma_\mu\bar e^c)$
$O_{\ell u}$	$(\bar\ell\bar\sigma_\mu\ell)(u^c\sigma_\mu\bar u^c)$
$O_{\ell d}$	$(\bar\ell\bar\sigma_\mu\ell)(d^c\sigma_\mu\bar d^c)$
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}	$(\bar q\bar\sigma_\mu T^a q)(d^c\sigma_\mu T^a\bar d^c)$

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

$(\bar L R)(\bar L R)$	
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

Alonso et al 1312.2014, Henning et al 1512.03433

Enough fun for everyone :)

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 $c \to c\, \Lambda^2/v^2$,

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

Matching WEFT to SMEFT

At the scale μ=m$_Z$, WEFT and SMEFT Wilson coefficients can be related, e.g. :

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

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

SM contribution from Z exchange

Effect of shifted Z couplings

Trivial matching of 4-fermion operators

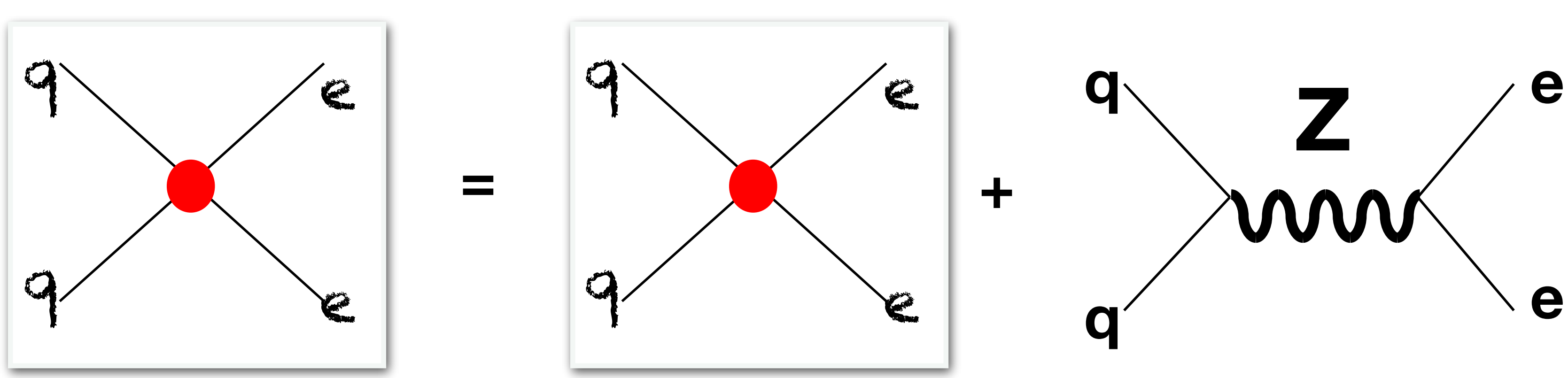
$$\mathscr{L}_{\rm WEFT} \supset \frac{G_F}{\sqrt{2}} \sum_{q=u,d} g_{AV}^{eq} (\bar{e}\gamma_\rho\gamma_5 e)(\bar{q}\gamma^\rho q)$$

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

$$\mathscr{L}_{\rm SMEFT} \supset$$

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

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



Matching WEFT to SMEFT

At the scale μ=mZ, WEFT and SMEFT Wilson coefficients can be related, e.g. :

$$\epsilon_L^\tau - \epsilon_L^e = \delta g_L^{W\tau} - \delta g_L^{We} - [c_{\ell q}^{(3)}]_{\tau\tau 11} + [c_{\ell q}^{(3)}]_{ee11}$$

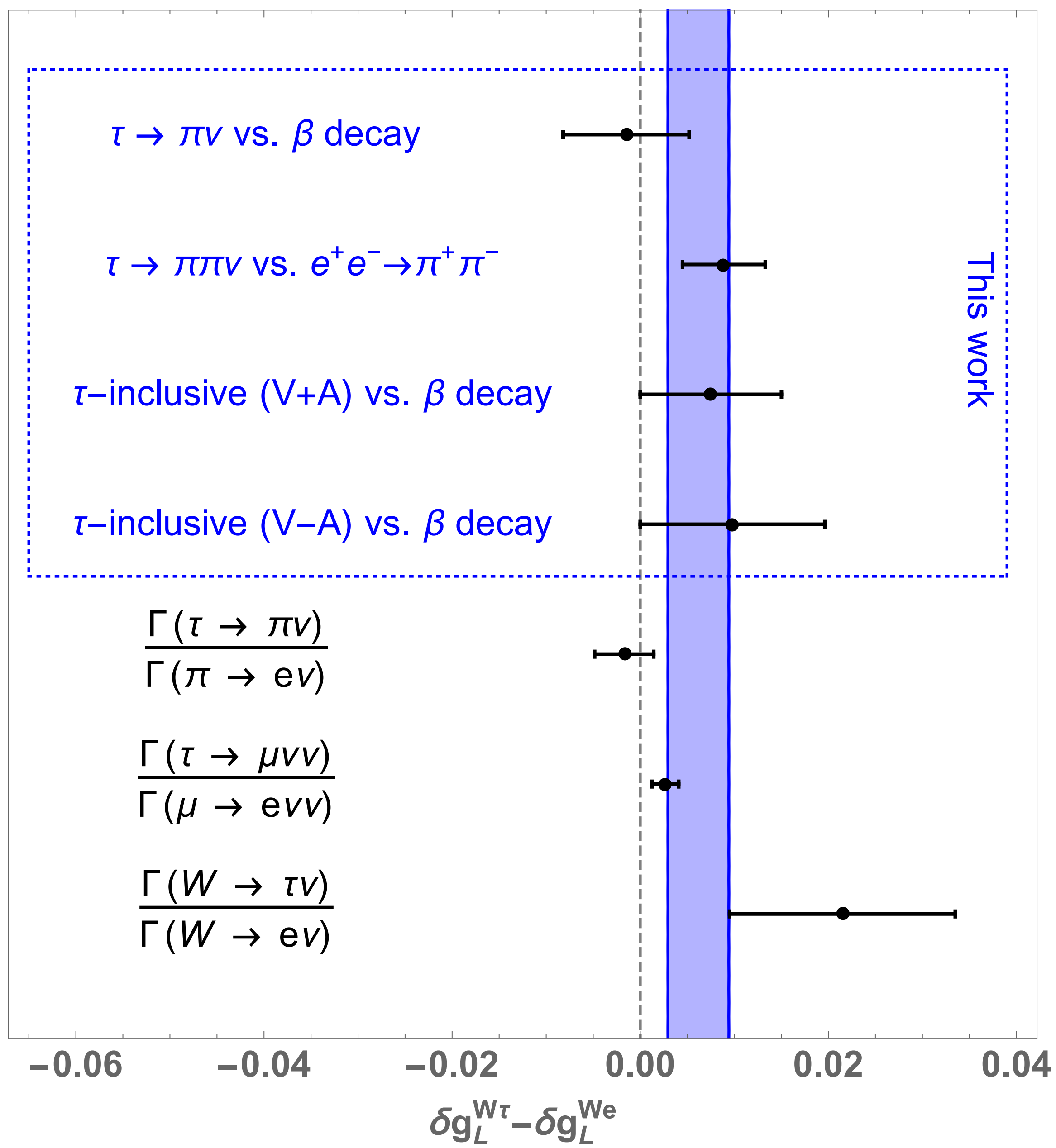
$$\epsilon_R^\tau = \delta g_R^{Wq_1},$$

Right-handed currents are flavor universal in SMEFT-D=6

$$\epsilon_{S,P}^\tau = -\frac{1}{2}[c_{lequ} \pm c_{ledq}]^*_{\tau\tau 11},$$

$$\epsilon_T^\tau = -\frac{1}{2}[c_{lequ}^{(3)}]^*_{\tau\tau 11},$$

Left-handed currents related to lepton-flavor non-universality



Weighing in on lepton-flavor universality violation!

Cirigliano et al 1809.01161

Matching WEFT to SMEFT

Running can be important in some case:

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

Scalar and pseudoscalar coefficient evolve by almost a factor of two between low and high energy

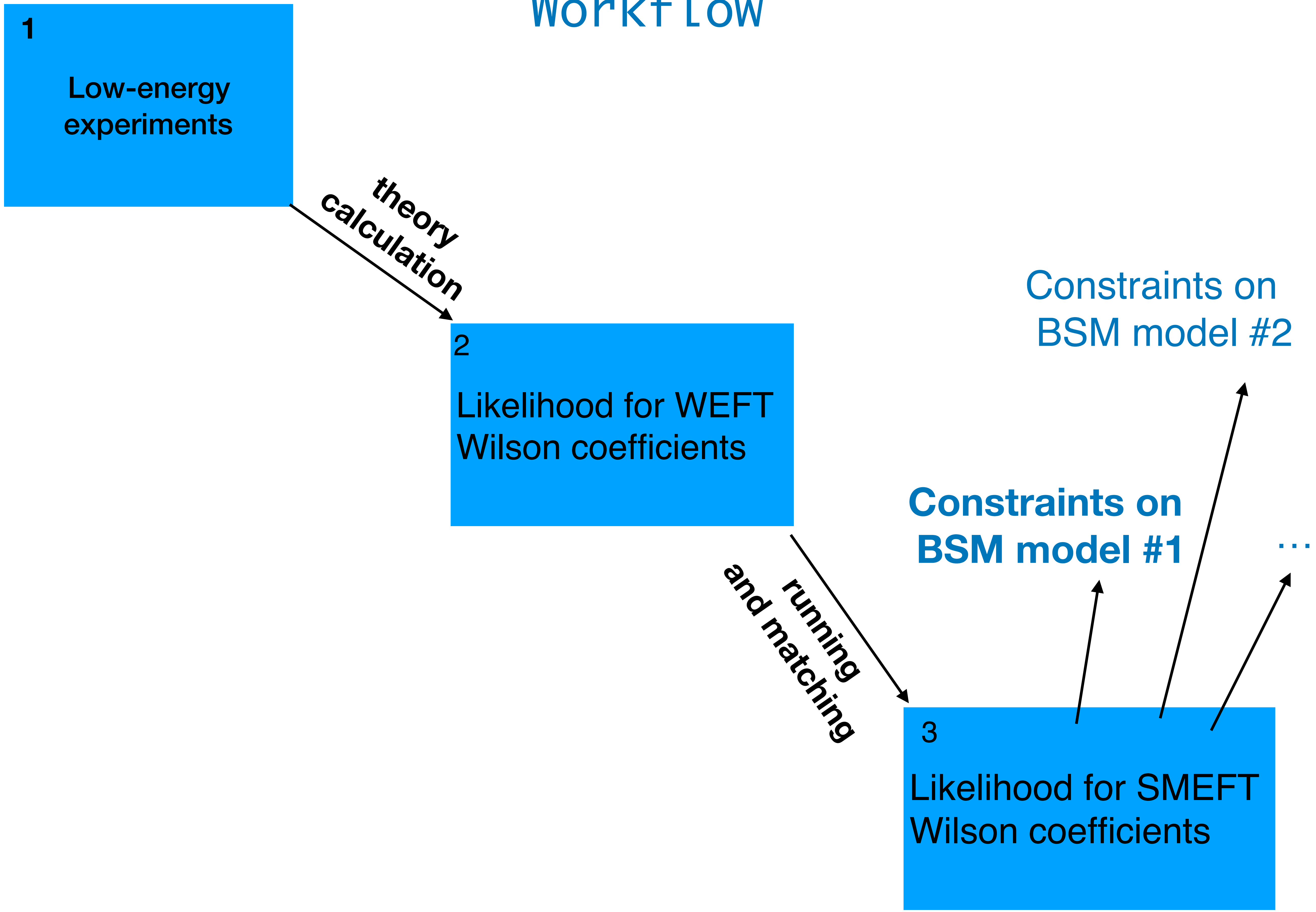
Electromagnetic effects mix (pseudo)scalar couplings, which are often strongly constrained by experiment, with the tensor ones, which are often less constrained

Gonzalez-Alonso et al
1706.00410

for full set of anomalous dimensions see
Jenkins et al 1711.05270

for automated tool, see e.g.
DsixTools 1704.04504

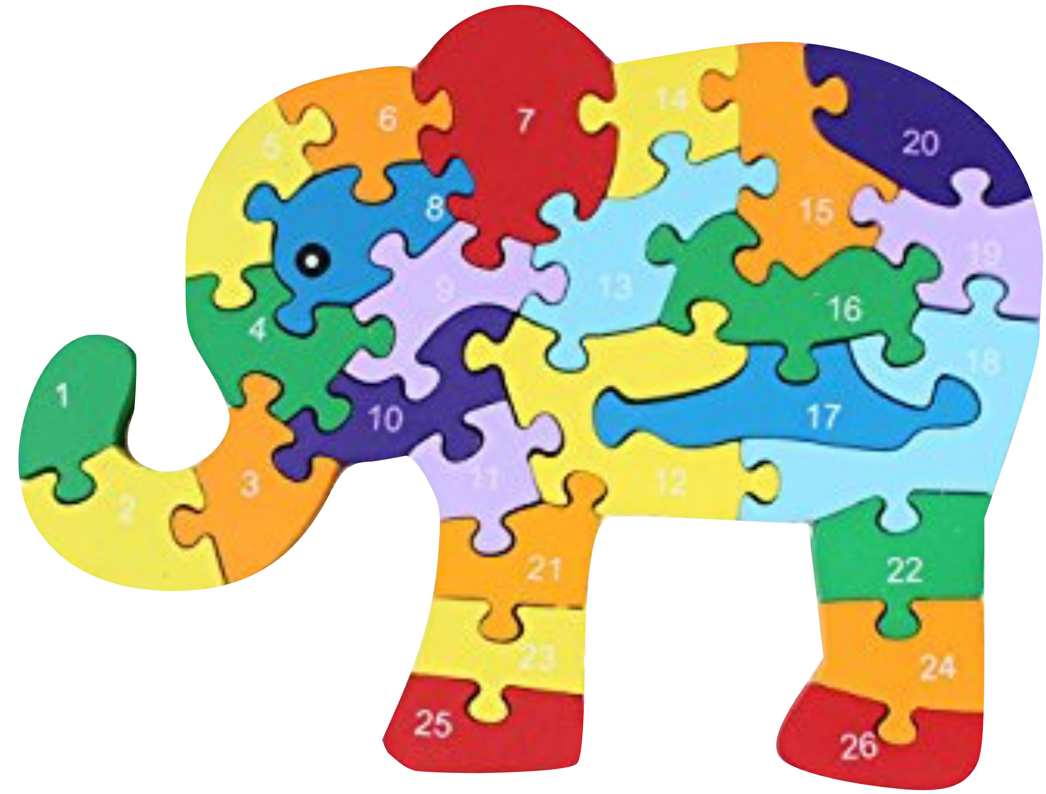
Workflow


1
Low-energy experiments
theory calculation
2
Likelihood for WEFT Wilson coefficients
running and matching
3
Likelihood for 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

Global likelihood SMEFT

- The SMEFT fit also includes weak scale observables: W mass, W and Z decays, and electron-positron scattering at LEP, LEP-2 and TRISTAN. Higgs data can be easily added.



- Global likelihood currently includes more than 300 experimental inputs, simultaneously constraining 77 linear combination of SMEFT Wilson coefficients

- Completely general flavor structure allowed

- Currently targets flavor conserving vertex corrections δg and 4-lepton operators, as well as QQLL operators involving first generation quarks

- Others: for SMEFT fits to lepton-flavor violating observables see 1702.03020

Crivellin et al.
1702.03020

- Others: for SMEFT fits involving flavor changing operators with b-quarks see 1810.07698

Aebischer et al.
1810.07698

Global constraints on SMEFT

AA, Gonzalez-Alonso, Mimouni
1706.03783

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

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

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

Future

Future of low-energy precision measurements

- Ongoing flavor physics program (nothing to add here)
- Tau program in BELLE-II in conjunction with lattice progress

Chang et al 1805.12130

Seng et al 1807.10197

- Progress in nuclear beta decays, both on the experimental front, as well as on the theory side (g_A, radiative corrections). New observables (e.g. forbidden decays)

Gonzalez-Alonso, 1803.08732

- MOLLER experiment for Moller scattering

Benesch et al. 1411.4088

- Coherent neutrino scattering just starting
- Astrophysical neutrinos as precision probes?

Canas et al 1806.01310

- Rich neutrino beam program, which could also be diverted into a precision program
- New experiments in atomic parity violation, and for parity-violating electron scattering planned in the near future

Willmann et al. CERN-INTC-2017-069

Becker et al. 1802.04759

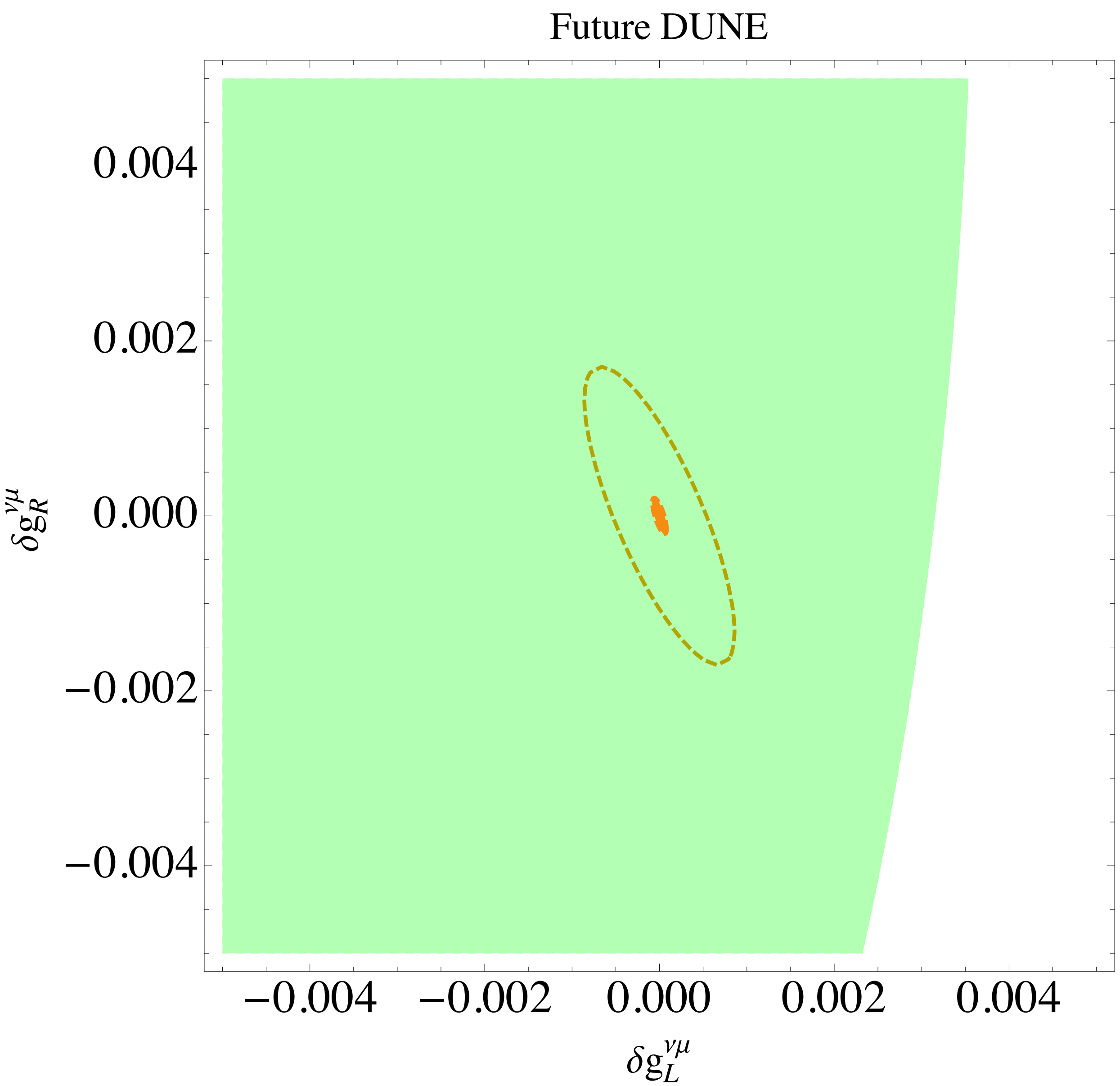
Example: DUNE potential for WEFT constraints

Well-known that DUNE should improve all important constraints on trident events

$$R_\mu \equiv \frac{\sigma(\nu_\mu \to \nu_\mu \mu^- \mu^+) + \sigma(\overline{\nu}_\mu \to \overline{\nu}_\mu \mu^- \mu^+)}{\sigma(\nu_\mu \to \nu_\mu \mu^- \mu^+)_{\rm SM} + \sigma(\overline{\nu}_\mu \to \overline{\nu}_\mu \mu^- \mu^+)_{\rm SM}}$$

forecast: $R_\mu = 1 \pm 0.039,$

However, huge statistics collected in DUNE should allow one to improve constraints on other WEFT couplings, e.g. on neutrino couplings to electrons and to quarks



AA, Grilli Di Cortona, Tabrizi
1802.08296

Example: future of atomic parity violation

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:

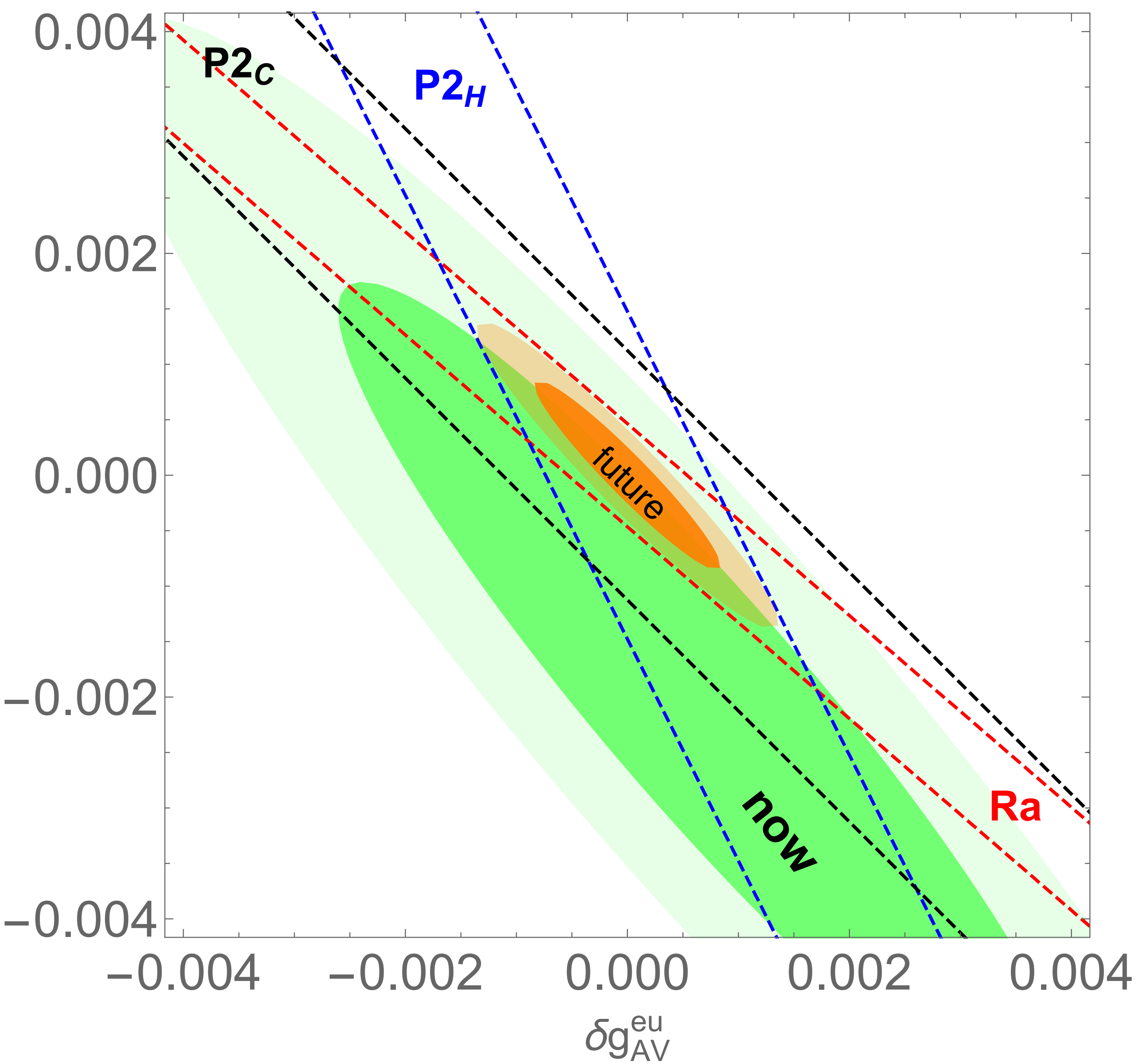
Benesch et al.
1411.4088

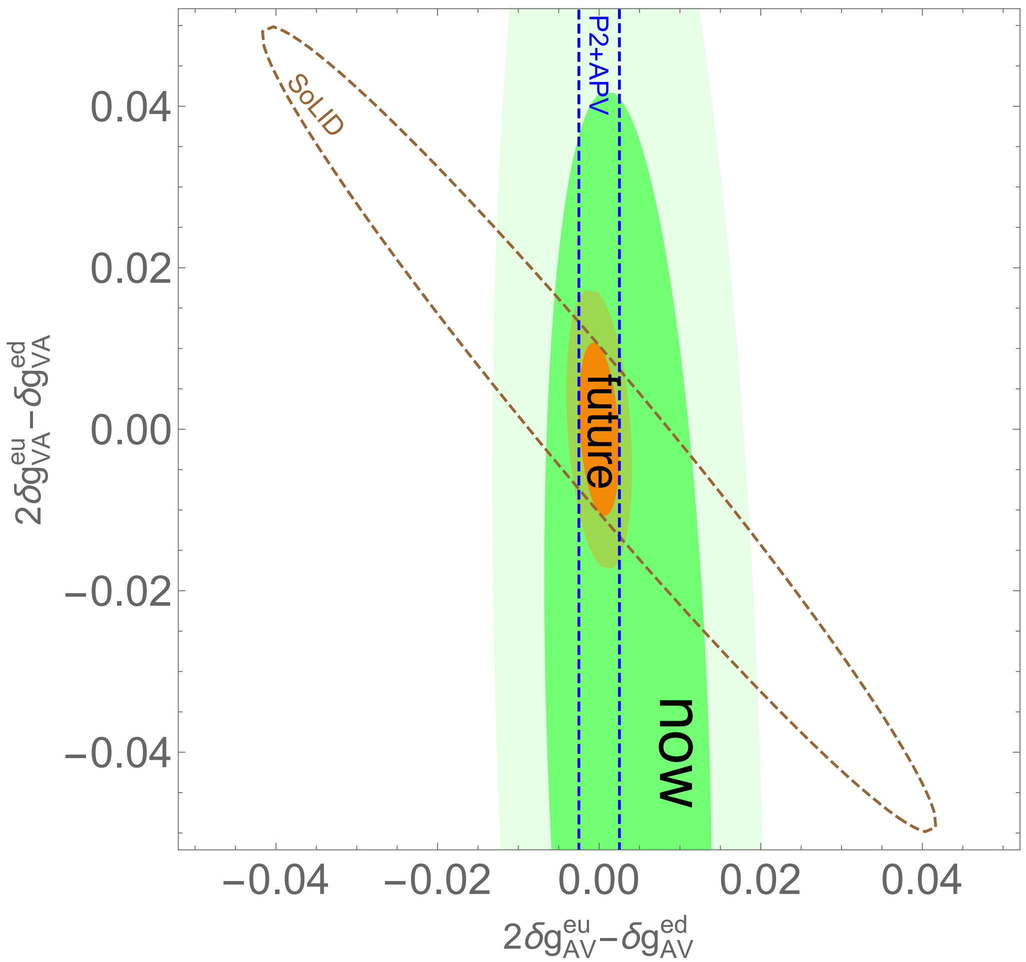
$$\Delta g_{AV}^{ee} = 0.0006$$

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





AA, Gonzalez-Alonso
in progress

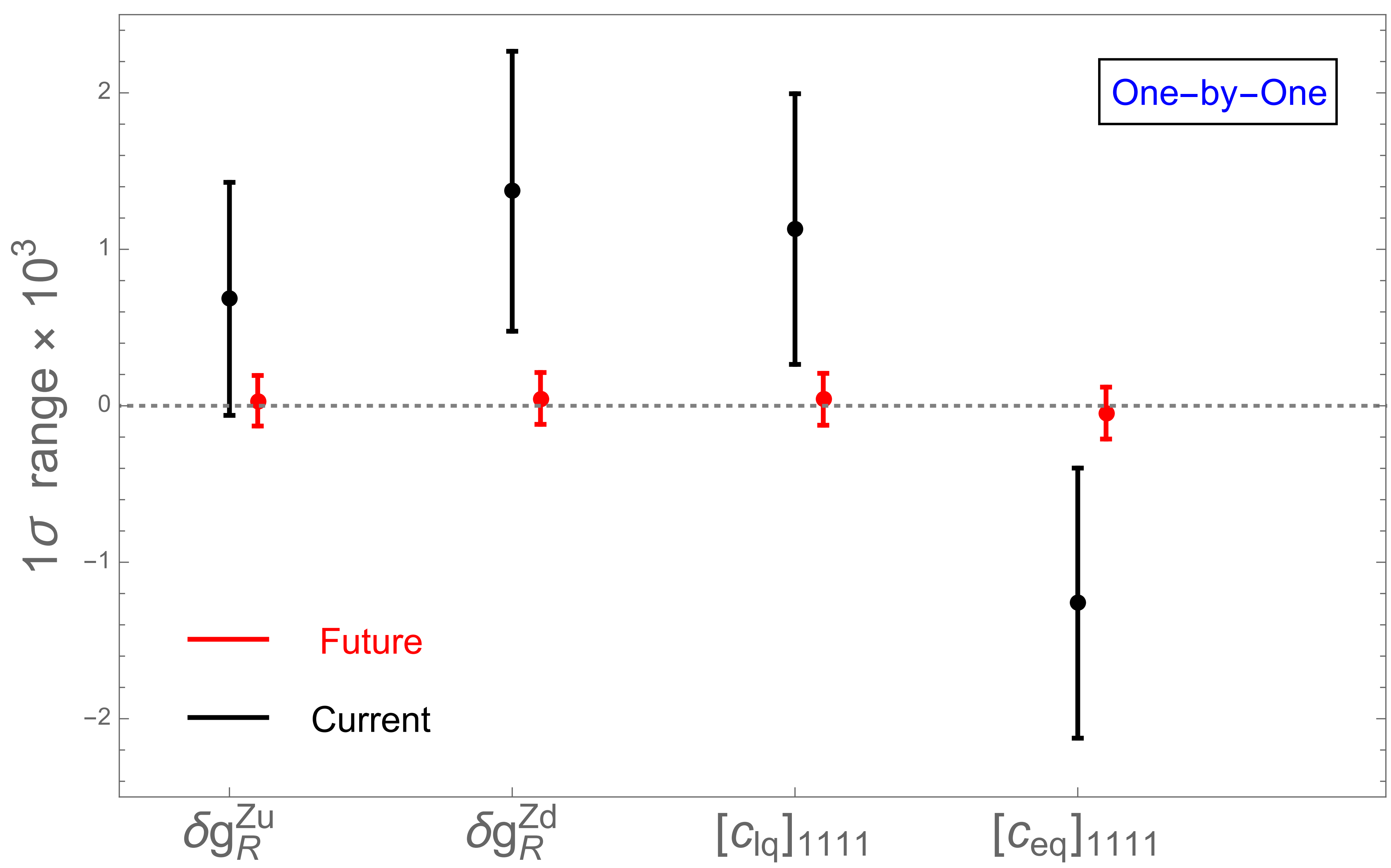
Projected 1-by-1 SMEFT constraints

Current and projected 1σ errors in units of 0.0001

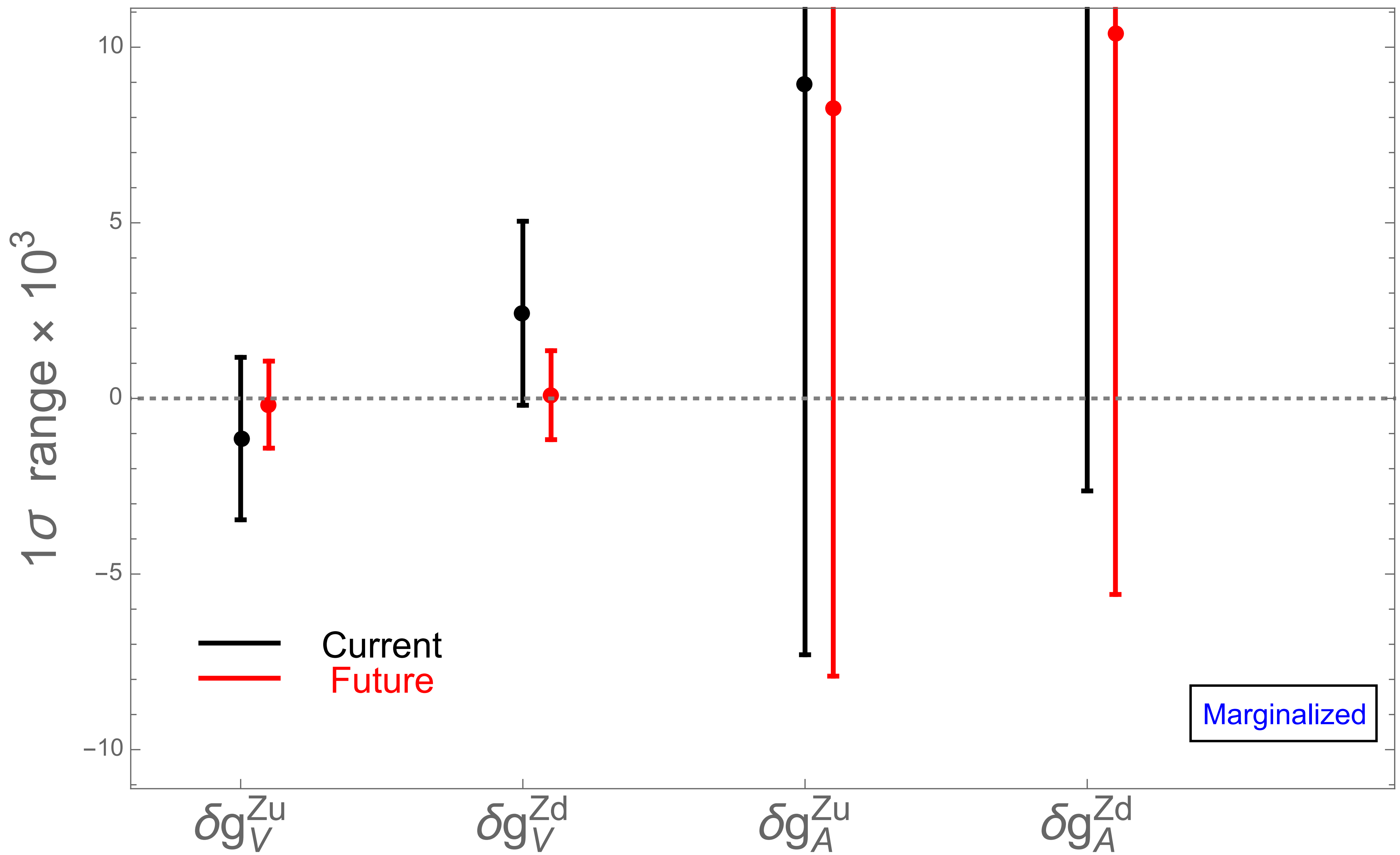
	Now	MOLLER	APV-Ra	P2-H	P2-C	All
δg_R^{Zu}	7.4	$\times$	2.1	2.8	4.1	1.6
δg_R^{Zd}	8.9	$\times$	1.9	5.0	4.2	1.7
$[c_{\ell q}]_{1111}$	8.6	$\times$	2.0	3.7	4.2	1.7
$[c_{\ell u}]_{1111}$	16	$\times$	4.3	5.8	8.4	3.3
$[c_{\ell d}]_{1111}$	18	$\times$	3.7	10	8.3	3.3
$[c_{eq}]_{1111}$	8.6	$\times$	2.0	3.7	4.2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



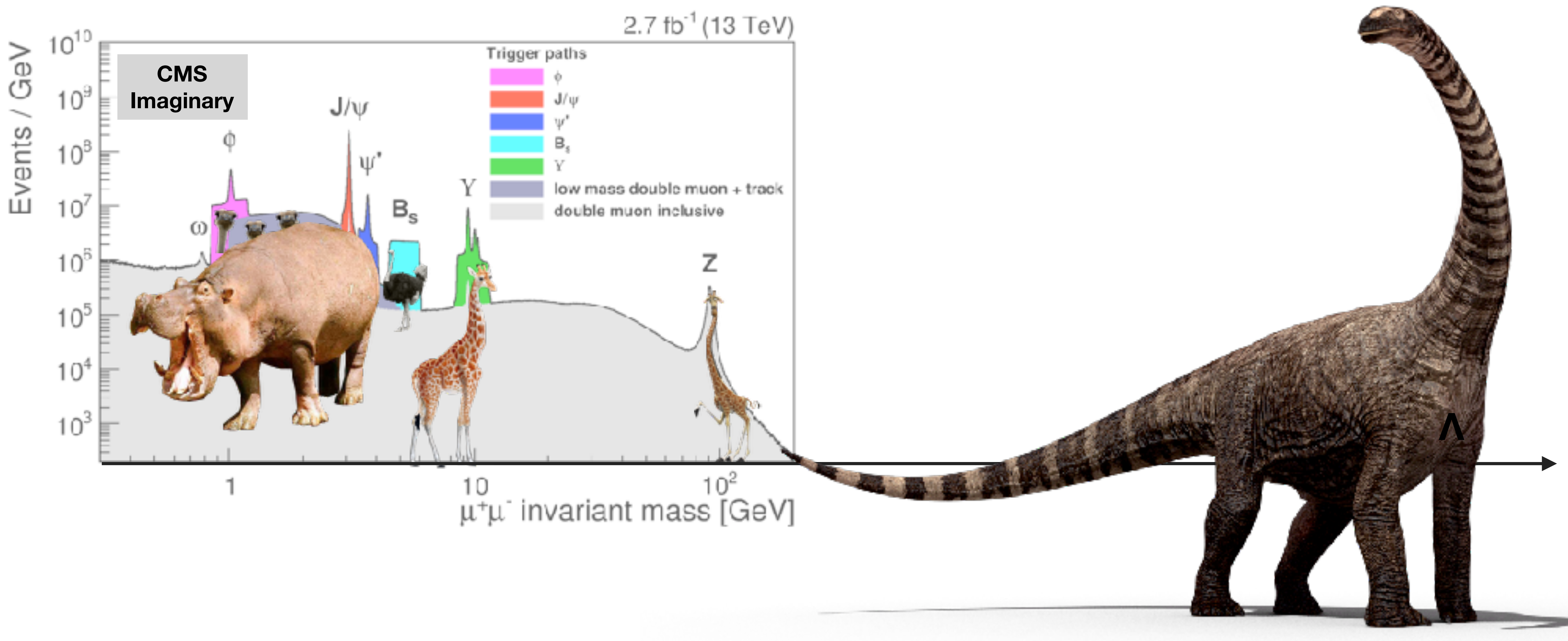
Projected global constraints



Take-away

- Both rare decays and low-energy precision measurements will enjoy tremendous progress in the coming years
- The latter explores heavy new physics at the rate $\Lambda \sim (\text{Precision})^{-1/2}$.
- Conveniently described in the model-independent language of WEFT, which can be matched to the SU(3)xSU(2)xU(1) invariant SMEFT, and then to specific BSM models
- The EFT approach offers a good diagnostics for the utility of new observables and new experiments
- Low-energy precision measurements may soon improve LEP-era bounds on the Z couplings to matter, well before new Z-pole facilities become available

Fantastic Beasts and Where To Find Them



THANK YOU

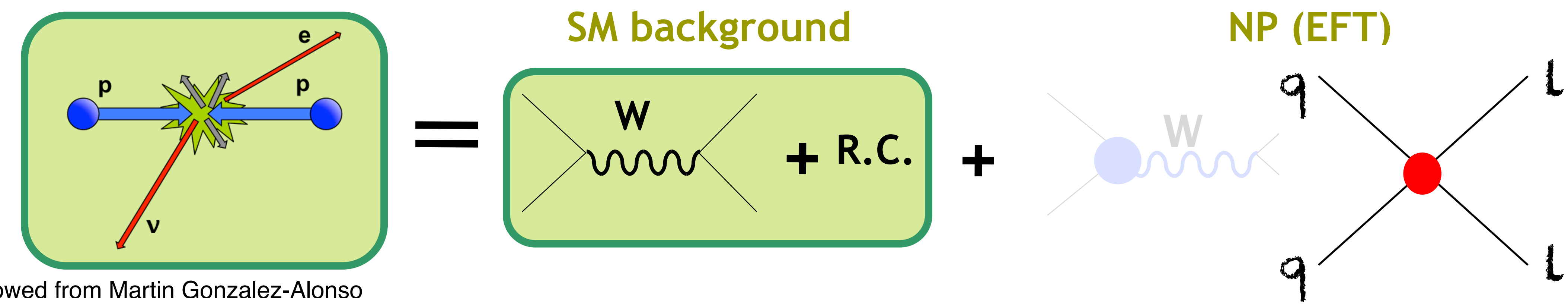
Comparing LHC and low-energy bounds

- 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.

Comparing LHC and low-energy bounds



Borrowed from Martin Gonzalez-Alonso

$(ee)(qq)$

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

AA, Gonzalez-Alonso, Mimouni
1706.03783

$(\mu\mu)(qq)$

	$[c_{\ell q}^{(3)}]_{2211}$	$[c_{\ell q}]_{2211}$	$[c_{\ell u}]_{2211}$	$[c_{\ell d}]_{2211}$	$[c_{eq}]_{2211}$	$[c_{eu}]_{2211}$	$[c_{ed}]_{2211}$
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)

	$[c_{\ell equ}]_{1111}$	$[c_{\ell edq}]_{1111}$	$[c_{\ell equ}^{(3)}]_{1111}$	$[c_{\ell equ}]_{2211}$	$[c_{\ell edq}]_{2211}$	$[c_{\ell equ}^{(3)}]_{2211}$
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

ATLAS
1606.01736