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‘Effective’ Tests of the Standard Model

Adrian Signer

Paul Scherrer Institut

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setting the stage

- low energy:
  in this talk from atomic scale to scale beyond the reach of LHC, depending on context
- low energy $\simeq$ indirect $\simeq$ via effective theory
  consider the case where no new particles are produced in final state

- all particles of Standard Model (and only these) have been found
- up to electro-weak (EW) energies they behave as predicted by the SM
- further big step when LHC $\longrightarrow 13-14\ \mathrm{TeV}$
- long standing expectation: there is new physics at the TeV scale
  - NP real: some BSM particles explicitely produced
  - NP virtual: BSM effects through loops
- what if no deviations from SM are found at $14\ \mathrm{TeV}$ LHC

setting the stage

given phenomenal success of SM, why are we not happy with SM ??

- theoretical reasons
  - many parameters, no explanation for values of parameters ??
  - gauge coupling unification !?
  - not complete (gravity, dark energy not part of SM) !
  - hierarchy problem !!
- observational reasons
  - neutrino masses !! → can be acommodated in SM$^+$
  - dark matter !! → could be acommodated in SM^{++}
  - matter-antimatter asymmetry !!
  - strong CP problem ! → SM^{++}
  - “small” discrepancies ($g-2$ of muon, proton radius) ??

maybe we should take the SM more seriously ?
could it be the SM is valid to very high energies ?
only hierarchy problem points towards $\Lambda_{\rm NP} \sim \Lambda_{\rm EW}$

outline

theoretical considerations

- SM as an effective theory
- BSM as an effective theory
- limit of validity of SM

“random” examples of BSM effects

- non-collider searches
- collider searches
- mixed collider/non-collider searches

conclusions
with clear directions
how to proceed . . .

SM

the Standard Model

input: gauge group $SU(3) \times SU(2) \times U(1)$: $G^{\mu\nu}$, $W^{\mu\nu}$, $B^{\mu\nu}$

3 families of matter fields (in fundamental representation): ℓ_L, q_L, e_R, u_R, d_R

one scalar doublet for good measure: Φ

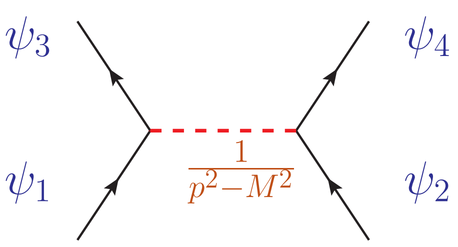
output: all renormalizable (Dim ≤ 4), gauge invariant operators

$$\mathcal{L}_{\text{SM}} = -\frac{1}{4} G^{\mu\nu} G_{\mu\nu} - \frac{1}{4} W^{\mu\nu} W_{\mu\nu} - \frac{1}{4} B^{\mu\nu} B_{\mu\nu} + \hat{\theta}\, G^{\mu\nu} \tilde{G}_{\mu\nu} + i \left(\bar{\ell} \not{D}\, \ell + \bar{e} \not{D}\, e + \ldots \right)$$
$$+ (D_\mu \Phi)^\dagger (D^\mu \Phi) + \Lambda_{\text{UV}}^2 \Phi^\dagger \Phi - \frac{\lambda}{2} (\Phi^\dagger \Phi)^2 - \left(Y_e\, \bar{\ell}\, e\, \Phi + \ldots + \text{h.c.} \right)$$

- (mass) dimensions: $[m] = [\partial^\mu] = [A^\mu] = 1$ and $[\ell] = 3/2$ and we must have $[\mathcal{L}] = 4$.
- all operators have Dim 4, except for $\Phi^\dagger \Phi$ which requires a dimensionfull coefficient $\Lambda_{\text{UV}}^2 \sim M_H^2 \quad \Longrightarrow$ hierarchy problem
- from experiment the (dimensionless) parameter θ is found to be extremely small (or 0?) $\Longrightarrow$ strong CP problem

beyond the Standard Model

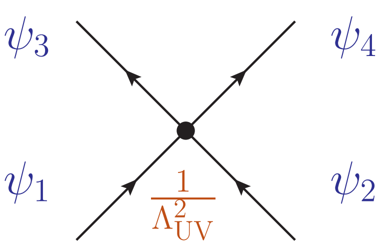
- standard option: new physics (particles) at a high scale $\Lambda_{\rm UV}$
- treat SM is an effective theory valid up to $\sim \Lambda_{\rm UV}$



$$\mathcal{O}^i = \frac{1}{\Lambda_{\rm UV}^2} (\bar\psi_3 \Gamma^a \psi_1)\, (\bar\psi_4 \Gamma^b \psi_2)$$

pseudoscalar: $\Gamma^a = \Gamma^b = \gamma^5$

coloured vector: $\Gamma^i = \gamma_\mu T^i$



$$\mathcal{L}_{\rm BSM}^{\rm ET} = \mathcal{L}_{\rm SM} + \sum \frac{c_i^{(5)}}{\Lambda_{\rm UV}}\, \mathcal{O}_i^{(5)} + \sum \frac{c_i^{(6)}}{\Lambda_{\rm UV}^2}\, \mathcal{O}_i^{(6)} + \ldots$$

+ very general and systematic approach

– limited information, $\mathcal{L}_{\rm BSM}^{\rm ET}$ only applicable at energies $\ll \Lambda_{\rm UV}$

– not all BSM scenarios can be covered, e.g. millicharged particles

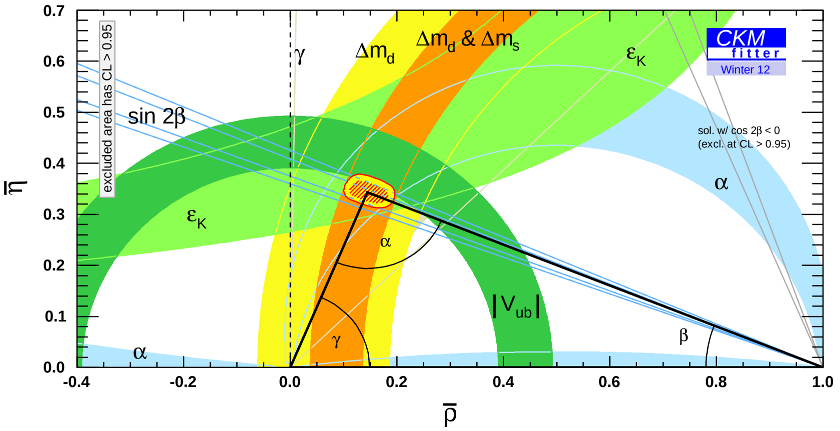
- alternative: find the explicit model out of the infinitely many possibilities

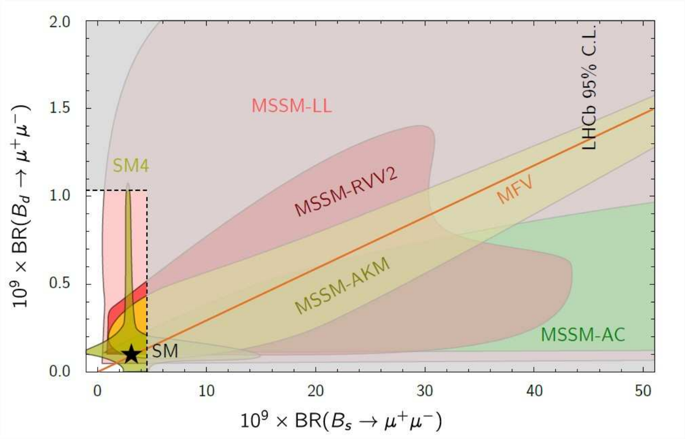
  – requires divine inspiration

  + more information, $\mathcal{L}_{\rm BSM}$ applicable at energies $\sim \Lambda_{\rm UV}$

constraints on $\Lambda_{\rm UV}$

- the SM is probably not completely wrong . . .





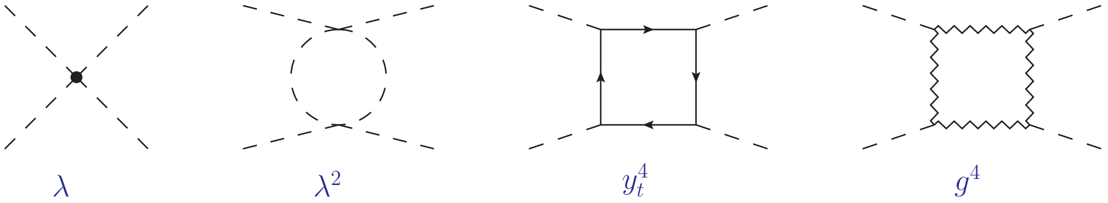
- make $\Lambda_{\rm UV} \gg \Lambda_{\rm EW}$ to minimize BSM effects
- this implies $M_H \gg \Lambda_{\rm EW}$ in contradiction to experiment (hierarchy problem)

	assume $\Lambda_{\rm UV} \sim \Lambda_{\rm EW}$	assume $\Lambda_{\rm UV} \gg \Lambda_{\rm EW}$
dilemma:	$+$ M_H as expected	$-$ why is $M_H \ll \Lambda_{\rm UV}$
	$-$ BSM physics seems to conspire	$+$ BSM effects naturally small
	many small problems	one big problem

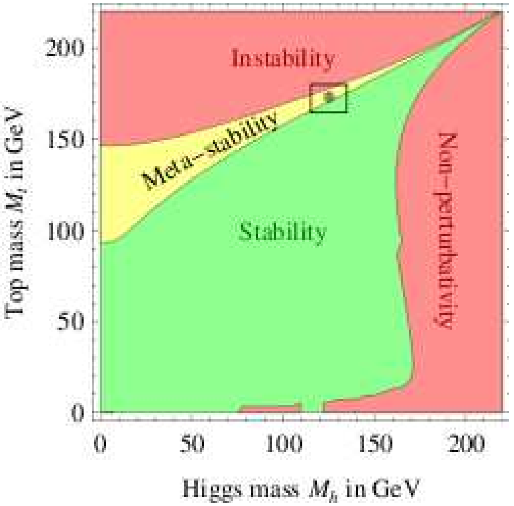
self-consistency of SM: the Higgs-Top miracle

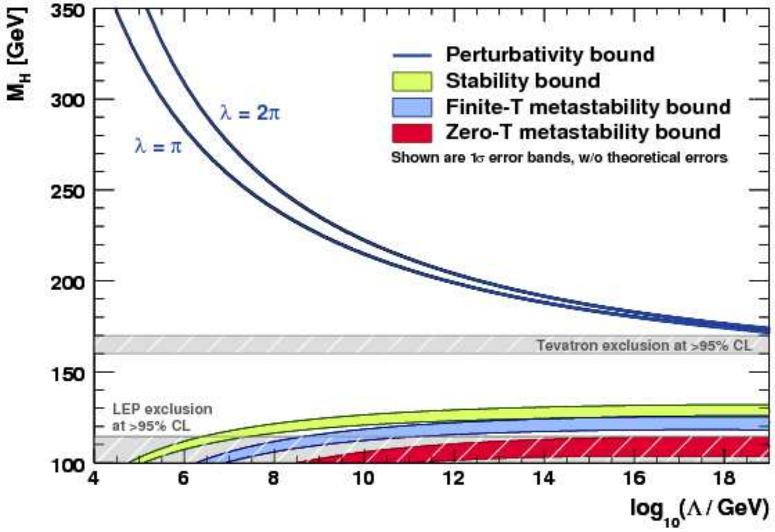
- consider self coupling of Higgs $\lambda(t)$ with $t = \ln \Lambda^2/Q_0^2$
- coupling runs:

$$\frac{4\pi^2}{3}\,\frac{d\lambda(t)}{dt} = \lambda^2 - y_t^2 + \ldots$$



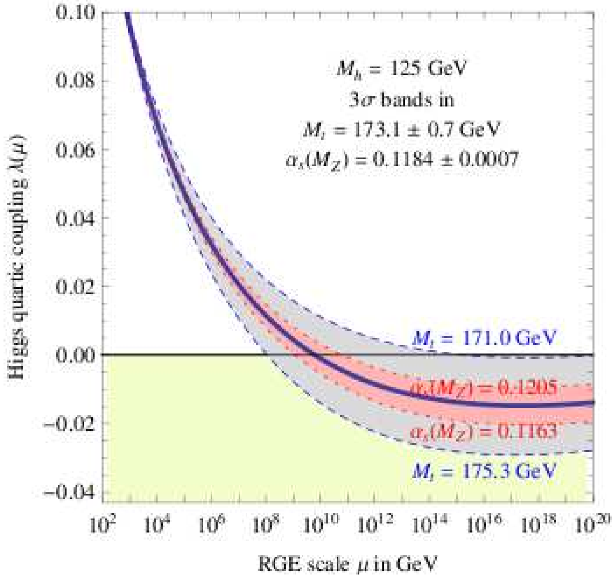
- triviality bound: $\lambda(\Lambda) = \dfrac{\lambda(Q_0)}{1 - 3/(4\pi^2)\,\lambda(Q_0)\,t} \implies 2\lambda(v)v^2 = M_H^2 < \dfrac{8\pi^2\,v^2}{3\ln(\Lambda^2/v^2)}$

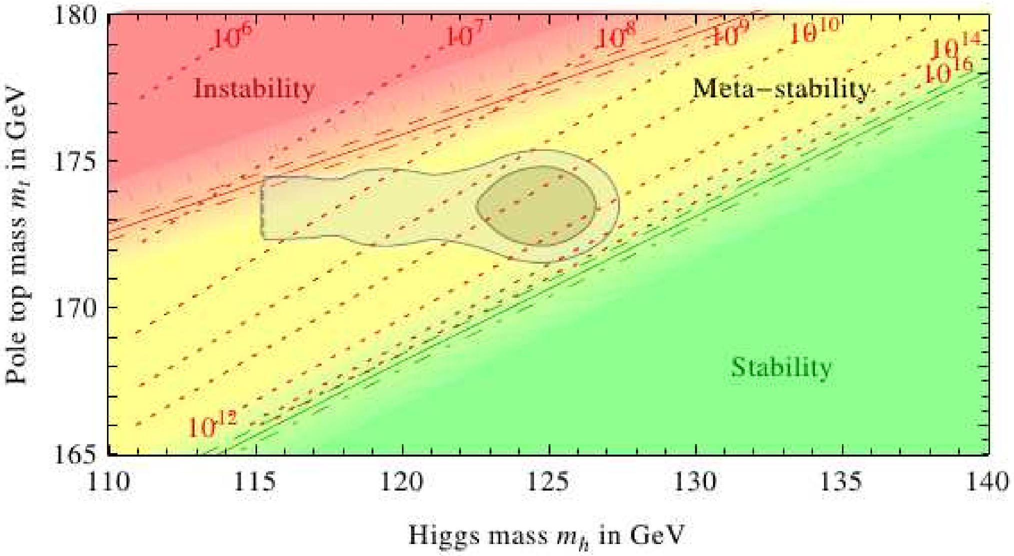




self-consistency of SM: the Higgs-Top miracle plots: [Degrassi et al. 1205.6497]

- vacuum stability: $\lambda(\Lambda) = \lambda(Q_0) - \frac{3}{4\pi^2}\, y_t^4\, t \overset{!}{>} 0 \quad \Longrightarrow \quad M_H^2 > \frac{3\, v^4\, y_t^4}{2\pi^2 v^2} \ln \frac{\Lambda^2}{v^2}$



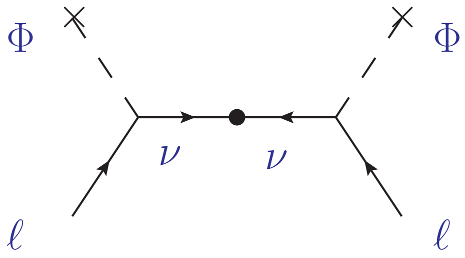


- for $M_H \sim 125\ \mathrm{GeV}$ and $M_t \sim 173\ \mathrm{GeV}$ the SM seems to be consistent up to very high energies $\Lambda_{\mathrm{UV}} \sim 10^9 - 10^{14}\ \mathrm{GeV}$
- is this a coincidence ?? (small M_H is not only a triumph for SUSY, but also for SM) M_t larger than expected, M_H smaller than expected, $\lambda(\Lambda_{\mathrm{UV}}) = \dot{\lambda}(\Lambda_{\mathrm{UV}}) = 0$

SM$^+$

neutrino masses

- add right handed singlet $\nu \equiv \nu_R$ to SM: $\mathcal{L}_{\text{SM}+} = \mathcal{L}_{\text{SM}} + \Big(Y_\nu \, \bar\ell \, \nu_R \, \tilde\Phi + M \bar\nu \, \nu + \text{h.c.} \Big)$
- Dirac mass term (as for all other fermions) $m \sim Y_\nu \, v$

  Majorana mass term (only for right-handed neutrino) $M \sim \Lambda_{\text{UV}} \gg \Lambda_{\text{EW}}$
- mass matrix $(\nu_L, \nu_R) \begin{pmatrix} 0 & m \\ m & M \end{pmatrix} \begin{pmatrix} \nu_L \\ \nu_R \end{pmatrix}$ eigenvalues $m_1 \sim \frac{m^2}{M}$ and $m_2 \sim M$
- view this as  and integrate out heavy ν field
- $\Longrightarrow$ Dim 5 (Weinberg) operator: $\mathcal{L}^{\text{ET}}_{\text{SM}+} = \mathcal{L}^{\text{ET}}_{\text{SM}} + \frac{c^{(5)}}{M} (\bar\ell \, \tilde\Phi)(\bar\ell \, \tilde\Phi)$
- $M \sim \Lambda_{\text{UV}} \sim 10^{11}$ GeV to generate masses consistent with experiment
- Weinberg operator is the only possible Dim 5 operator

BSM in SM$^+$

- absence of large BSM effects “explained” by requiring $\Lambda_{\text{UV}} \gg \Lambda_{\text{EW}}$
- classify Dim 6 operators (~ 60) [Buchmüller, Wyler; Grzadkowski et al.]

$$\mathcal{L}^{\text{ET}}_{\text{SM+}} = \mathcal{L}^{\text{ET}}_{\text{SM}} + \frac{c^{(5)}}{\Lambda_{\text{UV}}} (\bar\ell\,\tilde\Phi)(\bar\ell\,\tilde\Phi)$$

$$+ \frac{c^{(6)}_{0F}}{\Lambda^2_{\text{UV}}}\, f\, G_\mu^{\ \nu} G_\nu^{\ \rho} G_\rho^{\ \mu} + \frac{c^{(6)}_{2F}}{\Lambda^2_{\text{UV}}}\, \bar q \sigma^{\mu\nu} u\, \Phi G_{\mu\nu} + \frac{c^{(6)}_{4F}}{\Lambda^2_{\text{UV}}}\, \bar q \Gamma q\; \bar e \Gamma e + \dots$$

- can always link an explicit (large-scale) BSM model to ET, by calculating coefficients $c^{(6)}_{nF}$ of operators in ET
- within ET, the coefficients are independent $\Longrightarrow$ tests like $\mu \to e\gamma$ and $\mu \to e\,e\,e$ are independent
- coefficients of SM operators are also free to deviate from SM values $\Longrightarrow$ tested e.g. in search for anomalous triple-gauge couplings

axion and strong CP problem

- $\mathcal{L}_{\rm SM} \supset \dfrac{\alpha_s}{8\pi}\bar\theta\, G^{\mu\nu}\tilde{G}_{\mu\nu}$ CP-violating term in QCD (and EW)
- no effect in perturbation theory, but cannot be ignored
- bounds from experiment (neutron EDM) $\bar\theta \lesssim 10^{-10}$, why so small ??
- drastic measure: add new field, axion a (dynamical θ parameter)

$$\begin{aligned}\mathcal{L}_{\rm SM++} \supset\ & \frac{1}{2}\partial_\mu a\, \partial^\mu a - \frac{\alpha_s}{8\pi}\left(\bar\theta + \frac{a}{f_a}\right) G^{\mu\nu}\tilde{G}_{\mu\nu} \\ & - \frac{\alpha_s}{8\pi}\, C_{a\gamma}\, \frac{a}{f_a}\, F^{\mu\nu}\tilde{F}_{\mu\nu} + \sum C_{a\psi}\, (\bar\psi\gamma^\mu\psi)\, \frac{\partial_\mu a}{f_a}\end{aligned}$$

- nontrivial potential s.t. $\langle\bar a\rangle \equiv \langle\theta + \dfrac{a}{f_a}\rangle = 0$, i.e. $V(0) < V(a)$

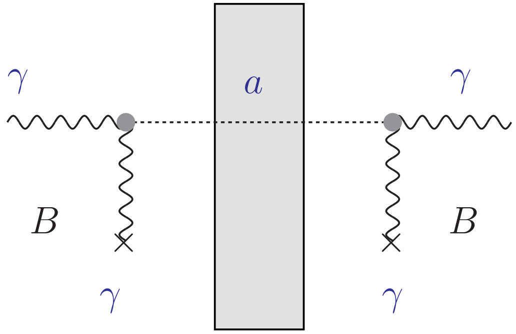
  excitations about minimum correspond to particle axion
- axion is pseudo-Goldstone boson, with global Peccei-Quinn $U(1)$ symmetry broken at high scale f_a $\Longrightarrow$ axion has very small mass $m_a \simeq m_\pi^2/f_a$ and slim interactions

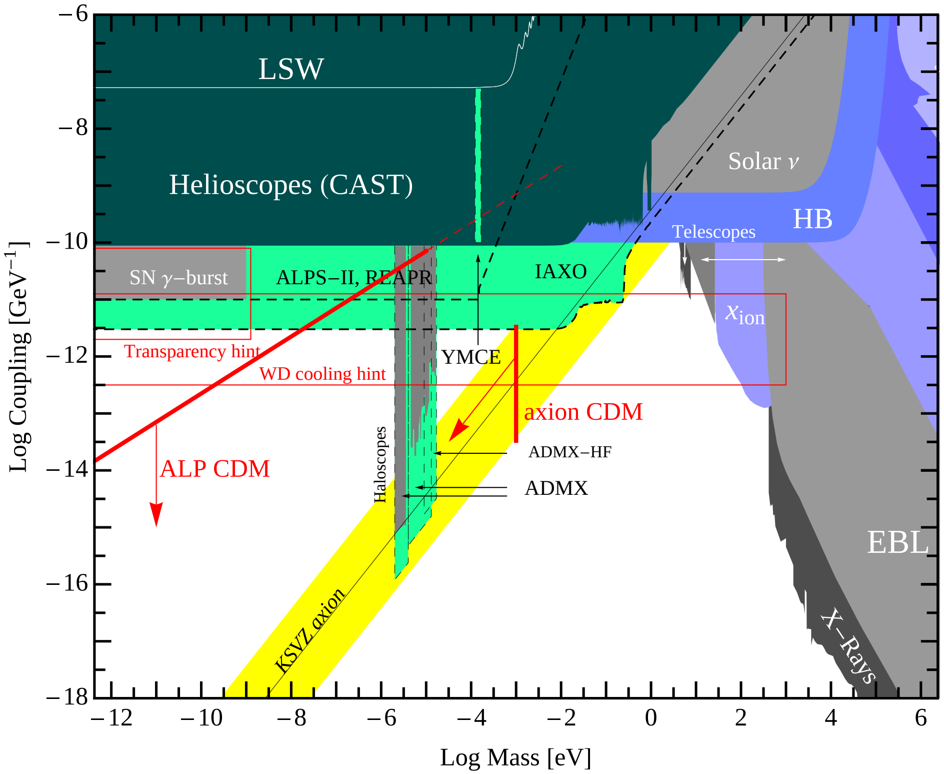
search for axion

axion and dark matter

- axion is a very good dark matter candidate for $f_a \simeq 10^{10}\ \mathrm{GeV} \Longrightarrow m_a \simeq 10^{-3}\ \mathrm{eV}$
- also searches e.g. via shining light-through-wall experiments

  ($\gamma \to a \to \gamma$ via $C_{a\gamma}\, a\, \vec{E}\cdot\vec{B}$ interaction)





[Ringwald 1210.5081]

charged current LFV

indirect tests @ LHC vs neutron/pion decay tests

- neutrino oscillation $\Longrightarrow$ lepton flavour violation
- test LFV also in charged sector
- Dim 6 operators in effective theory

$$\mathcal{L}_{\rm SM} + \frac{\alpha_{qde}}{\Lambda^2}(\bar\ell\, e)(\bar d q) + \frac{\alpha^t_{lq}}{\Lambda^2}(\bar\ell\sigma^{\mu\nu}\, e)(\bar q\sigma_{\mu\nu}u) + \ldots$$

- these operators feed into anomalous charged current interactions $\alpha_i \longrightarrow \epsilon_j$

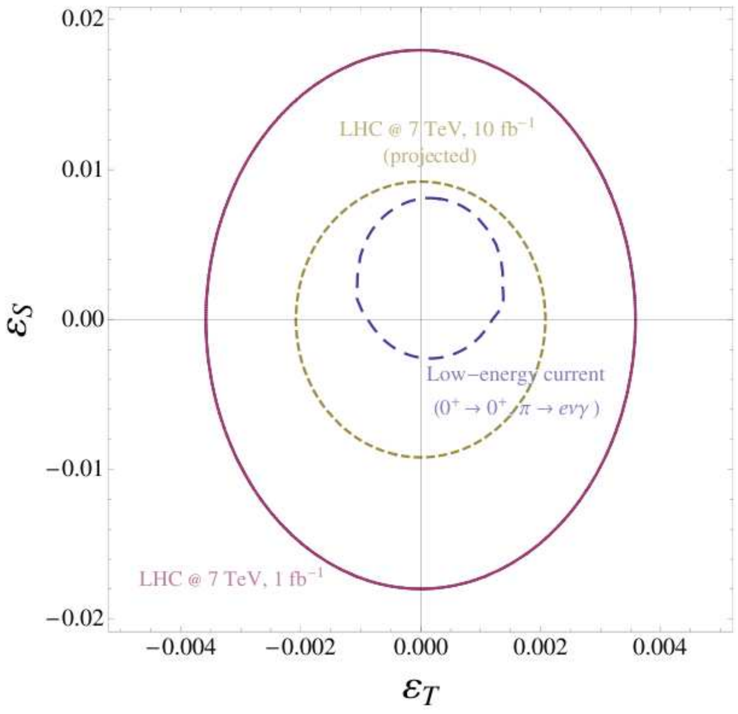
$$\mathcal{L}_{\rm cc} = -\frac{G_F V_{ud}}{\sqrt{2}}\Big[(1+\epsilon_L)\,\bar e\gamma_\mu P_L\nu\cdot\bar u\gamma^\mu P_l d$$

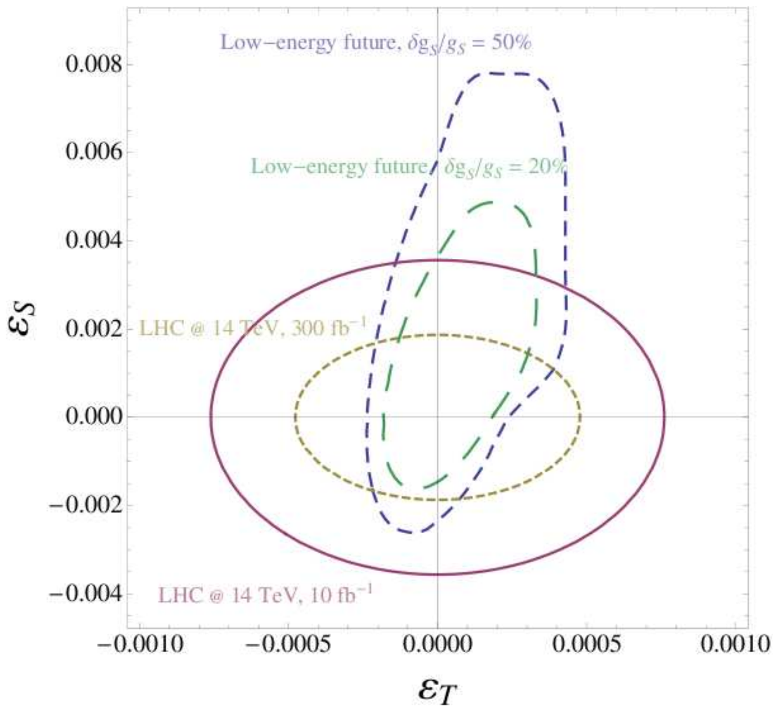
$$+\,\epsilon_S\,\bar e\gamma_\mu P_L\nu\cdot\bar u d + \epsilon_T\,\bar e\sigma_{\mu\nu}P_L\nu\cdot\bar u\sigma^{\mu\nu}P_L d + \ldots\Big]$$

- this is a “standard procedure”, also used for tests on anomalous TGC, top couplings, Higgs couplings etc.

charged current LFV

- “low energy” beta decay $n \longrightarrow p\, e\, \nu$, requires non-perturbative input (form factors, from Lattice or measurements)
- “high energy” LHC $pp \longrightarrow e + \mathrm{MET}$, requires non-perturbative input (parton distribution functions, from measurements)
- compare constraints [Cirigliano et al.] true complementarity



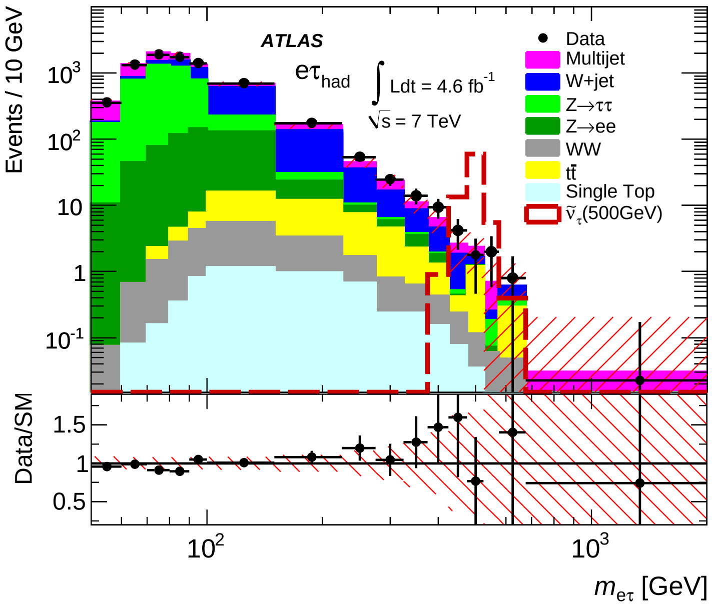


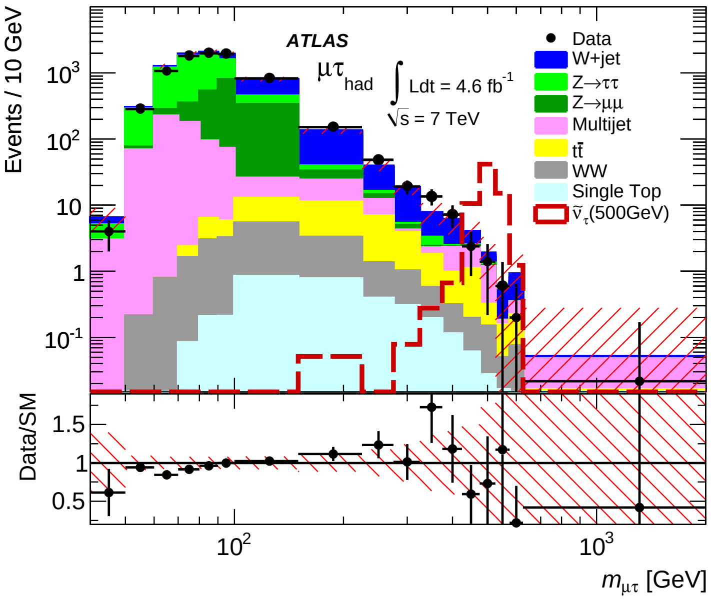
[Bhattacharya et al. 1110.6448]

charged current LFV

indirect tests vs direct tests

- “virtual”/indirect tests as above or $\mu \to e\gamma$ and $\mu \to e\,e\,e$ extremely powerfull
- also done as “real”/direct test at LHC
- e.g. ATLAS search for narrow resonances decaying to $e\mu$, $e\tau$ or $\mu\tau$
- compare observation with SM and signal simulation $m_{\ell\ell'} = 500~\mathrm{GeV}$ in R-parity violating $\tilde{\nu} \to \ell\,\ell'$ [1212.1272]





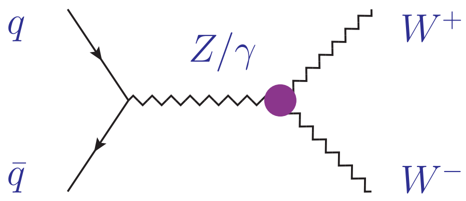
anomalous gauge couplings

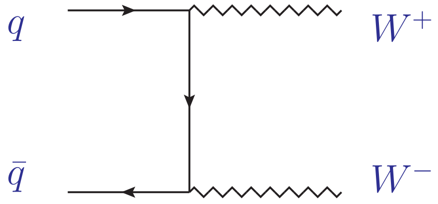
tests of triple gauge couplings (TGC) at LEP/Tevatron/LHC

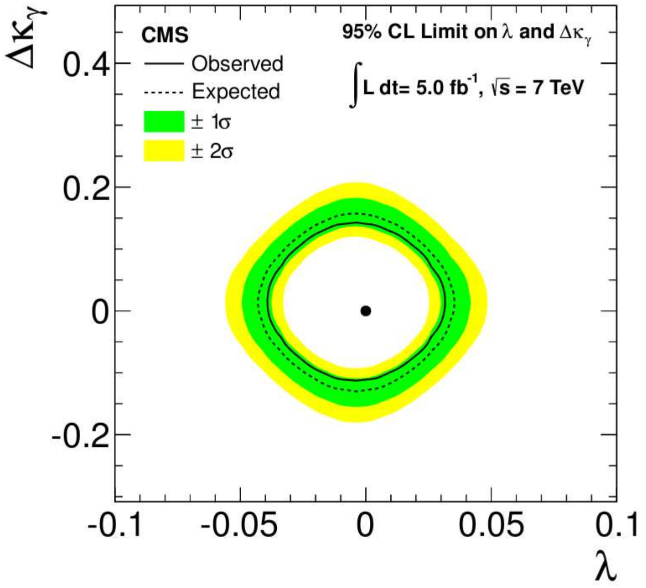
- consider subset of $\mathcal{L}_{\rm SM}^{\rm ET}$, $\qquad V \in \{\gamma, Z\}$

$$\mathcal{L} \simeq (1+\Delta g_v) W_{\mu\nu} W^{\mu} V^{\nu} + (1+\Delta\kappa_v) W_{\mu} W_{\nu} V^{\mu\nu} + \frac{\lambda_V}{\Lambda^2} W_{\mu\nu} W^{\nu}_{\rho} V^{\rho\nu}$$

- ET: insist on $SU(2)\times U(1)$ gauge invariance $\Longrightarrow$ constraints $\Delta g_\gamma = 0$ and $\lambda_\gamma = \lambda_Z$
- measure WW,WZ, $W\gamma\ldots$ cross section and obtain limits on (or find) anomalous couplings Δg_v, $\Delta\kappa_v$, λ_V (but form factors needed)
- recent example for $\sigma_{WW} + \sigma_{WZ}$ [CMS, 1210.7544]







SME

Lorentz and CPT violation via effective theory

- assume spontaneous Lorentz breaking in underlying fundamental theory at very high scale $\Lambda \sim M_{\rm P}$ [Colladay, Kostelecky]
- SM/QED Lagrangian modified: $\mathcal{L}^{\rm eff}_{\rm QED} = i\,\bar\psi\gamma^{\rm eff}_\mu D^\mu\psi - \bar\psi m^{\rm eff}\psi$

$$\gamma^{\rm eff}_\mu = \gamma_\mu + c_{\mu\nu}\gamma^\nu + d_{\mu\nu}\gamma_5\gamma^\nu + e_\mu + \ldots$$

$$m^{\rm eff} = m + a^\nu\gamma_\nu + b^\nu\gamma_\nu\gamma_5 + \ldots$$

- induced parameters $c_{\mu\nu}$, $d_{\mu\nu}$, a^ν etc $\Longrightarrow$ (particle) Lorentz-violating and CPT-violating extension of SM
- theory still invariant under observer Lorentz transformations
- can test Lorentz and CPT invariance without having to understand Planck-scale physics !
- tests/limits on all energy scales: from study of hydrogen spectrum to effects in top quark (e.g. m_t vs $m_{\bar t}$)

conclusions

conclusions

- maybe the SM is even better than we think, $\Lambda_{\mathrm{NP}} \gg \Lambda_{\mathrm{EW}}$ is a possibility!
- if we can directly access BSM physics
  - with an explicit model coefficients of ET-operators can be computed
  - consistency checks between various observables (high-energy vs low energy)
- if we cannot directly access BSM physics
  - ET approaches offer a method to study large classes of BSM effects
  - ET applied at different levels, depending on what is integrated out and what is kept dynamical
- not everything can be covered by ET approach

  NP at low scales, but hidden by small couplings (e.g millicharged particles)
- recently a move towards using ET-framework in many different areas

$\Longrightarrow$ good news for combining cosmology, high-energy and high-precision frontier

conclusions

directions how to proceed

$\Longrightarrow$ dig deep