BSM SEARCHES

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Their quantum numbers fit into an $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$ renormalizable, three-generation quantum gauge theory, with $SU(2)_L \otimes U(1)_Y \rightarrow U(1)_{em}$ spontaneous breakdown.
> Production x-sections follow the SM.
CMS tests: x-sections follow the SM

- Production x-sections follow the SM.

http://cern.ch/go/pNj7
No new colored particles in the TeV domain.
CMS tests: top pair production

- tt-bar production agrees with the SM.
Higgs couplings follow the SM.
CMS tests: anomalous gauge boson couplings

Anomalous gauge boson couplings (dim=6, 8, ...) are suppressed.
CMS tests: $B_{d,s} \rightarrow \mu^+ \mu^-$

$B_{d,s} \rightarrow \mu^+ \mu^-$, a powerful probe of the BSM, now agree with the SM.
despite experiment, the SM needs be extended!
electroweak stability: necessity of BSM

- Gravity makes SM’s UV boundary $\Lambda$ physical (it is not a regularization scale)

- Correction to Higgs boson mass:
  $$\delta m_h^2 = c_H \Lambda^2$$

- LHC Higgs mass measurement requires
  $$\Lambda \sim 550 \text{ GeV}$$

- Thus, TeV-scale BSM is a necessity!
electroweak stability: SUSY

Higgs mass is stabilized: \[ \delta m_h^2 = (c_H - \bar{c}_H) \Lambda^2 \equiv 0 \] (supersymmetry)
electroweak stability: SUSY (gluinos)

- No gluinos in the TeV domain.
electroweak stability: SUSY (squarks)

- No sub-TeV scalar quarks.
electroweak stability: SUSY (inos)

- No inos below Fermi scale.
electroweak stability: SUSY (long-lived sparticles)

Overview of CMS long-lived particle searches

Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included). The y-axis tick labels indicate the studied long-lived particle.

Long-lived TeV-mass sparticles seem to not exist.
electroweak stability: SUSY (heavy sparticle effects)

- CMS results suggest that “TeV-scale” SUSY, a mechanism of electroweak stability, seems to not exist at all.

- Superpartners, if any, seem to have at least multi-TeV masses. The problem is that their remnant log-contributions to the Higgs boson mass

\[ \delta m_h^2 \sim \left( \frac{\tilde{m}}{4\pi} \right)^2 \log \frac{\tilde{m}^2}{\Lambda^2} \]

violates the LHC result for multi-TeV $\tilde{m}$! Heavy SUSY is not allowed!
electroweak stability: extra dimensions

\[ M_{Pl} = \left( M_{Pl}^{4+n} R \right)^{\frac{n}{2}} M_{Pl}^{4+n} \]

\[ \approx \text{mm} \]

\[ \approx \text{TeV} \]

\[ \Lambda \approx \text{TeV} \Rightarrow \text{EW stability!} \]
CMS results suggest that “TeV-scale” extra dimensions, a mechanism of electroweak stability, seem to not exist at all.

In general, larger the $M_{Pl}^{(4+n)}$ larger the SM’s UV validity limit $\Lambda$ and larger the shift $\delta m_h^2$ in the Higgs boson mass!
electroweak stability: technicolor

SM Higgs boson is a techni-bound state!

The techni-QCD above the technicolor scale $\Lambda$ provides the requisite UV-completion!
CMS results suggest that “TeV-scale” technicolor (compositeness), a mechanism for electroweak stability, seems to not exist at all.

Larger the compositeness scale $\Lambda$ larger the Higgs boson mass

$$m_h \sim \frac{g_{TC}}{4\pi} \Lambda$$ and hence larger the violation of the LHC result!
electroweak stability: not understood at all!

- If the LHC experiments have taught us anything it is that the “TeV-scale new particles” theorized for stabilization of the EW scale do simply not exist!

- It seems that one needs a whole new intellecction for understanding the stability of the EW scale!

- The attempts below brought interesting novelties:

<table>
<thead>
<tr>
<th>Model</th>
<th>Its problems</th>
</tr>
</thead>
<tbody>
<tr>
<td>Twin Higgs (SM + twin SM with (Z_2) invariance)</td>
<td>(v_{SM}/v_{\text{twin SM}}) fine-tuning</td>
</tr>
<tr>
<td>Relaxation (driven by an axion-like field in inflationary era)</td>
<td>super-Planckian field swings, EDM bounds</td>
</tr>
<tr>
<td>Classical conformal invariance</td>
<td>quantum corrections</td>
</tr>
<tr>
<td>UV-IR mixing (trans-Planckian collisions produce BHs)</td>
<td>non-commutativity</td>
</tr>
</tbody>
</table>
The RH neutrinos $N_j (j = 1, 2, 3, \ldots)$ are pure SM singlets.

$$\mathcal{L} \ni \lambda_{ij} \bar{L}_i H N_j + \frac{1}{2} (M_N)_{jk} \bar{N}_j^c N_k + H.C.$$  

- Nonzero masses of active neutrinos necessitate RH neutrinos (heavy or light).
- Baryogenesis, clearly not electroweak, can result from leptogenesis (or AD mech.)
N_j can be heavy (good for leptogenesis and neutrino Majorana masses).
strong CP problem

\[ \mathcal{L} \ni \frac{\alpha_s}{4\pi} \left( \theta - \arg[\text{Det}[m_f]] \right) G_{\mu\nu}^{r} \tilde{G}_{\mu\nu}^{r} \]

\[ \theta_{\text{eff}} \]

neutron EDM: \( \theta_{\text{eff}} \lesssim 10^{-10} \)

axion \( \frac{a(x)}{f_a} \)

\[ \mathcal{L} \ni \frac{1}{2} \partial_{\mu} a \partial^{\mu} a - \frac{1}{2} m_a a^2 + \frac{\alpha_s}{4\pi} \frac{a}{f_a} G_{\mu\nu}^{r} \tilde{G}_{\mu\nu}^{r} + \frac{\alpha}{4\pi} \frac{a}{f_a} F_{\mu\nu} \tilde{F}_{\mu\nu} \]

**B. Yoom et al., 1712.08557**
strong CP problem: axion searches

- Experiment seems to favor high PQ scales.
Stars at the skirts of galaxies exhibit not Keplerian \( (v^2 \propto 1/R) \) but flat \( (v^2 \approx \text{const.}) \) rotation curves.

This might be taken as breakdown of Newton’s 2nd law (MOND).

Or, less radically, as evidence for non-shining matter (dark matter).
**dark matter**

DM must be massive  
(for it to take part in structure formation)

DM must be stable  
(for it to affect galactic dynamics today)

DM must be neutral and weakly-interacting  
(for it to not disrupt cosmology)
There exist various DM candidates (excluding non-particle ones like Q-balls)
dark matter: CMS searches

- CMS seems to have excluded WIMPs!
- CMS shows sensitivity even to GeV-DM via $H \rightarrow$ invisible!

Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included).

> CMS seems to have excluded WIMPs!

> CMS shows sensitivity even to GeV-DM via $H \rightarrow$ invisible!
Direct detection experiments have found so far no evidence for DM (experiments started hitting the neutrino floor).

“Undetectable DM” implies that the SM-BSM couplings must be rather small!
Sterile neutrino DM seems possible at small mixings in 10-30 keV region.
DM as axion (yellow band) and as dark photon (ADMX is searching)
flavor

- Flavor mixings need be understood

- With a flavon $S$ (at a scale $\Lambda_F$ with some discrete symmetry or U(1) symmetry)

$$\mathcal{L} \supset \lambda^u \left( \frac{S}{\Lambda_F} \right)^{n^u_{i,j}} \bar{Q}_{Li} H u_{Rj} + \lambda^\ell \left( \frac{S}{\Lambda_F} \right)^{n^\ell_{i,j}} \bar{L}_{Li} H^c e_{Rj} + \cdots$$

Quark and lepton flavor mixings are generated by $n^f_{i,j}$ with $\langle S \rangle \neq 0$!

- CMS found yet no such signals:

![Graph showing Flavon VEV vs BR for Higgs decay]

K. Huitu et al., 1603.0614
- something must have flattened the Universe
- something must have broken causal contact
- something must have wiped out monopoles (of GUTs)
CMB measurements are able to differentiate among inflationary models:

- Planck prefers the Starobinsky model (with $M \approx 10^{-5} M_{Pl}$)

\[ S \supset \int d^4x \sqrt{-g} \left\{ \frac{M^2_{Pl}}{2} R + \frac{M^2_{Pl}}{6M^2} R^2 \right\} \]

which is just the higher-curvature gravity (not a true BSM)!
Conclusion

- The SM needs be extended in various channels, most pressing being the stability of the EW scale!

- There is, however, no discernible signal of any BSM physics!

- It seems that we have to make sense of the problems of the SM in a way admitting a feebly-coupled BSM physics! Isn’t gravity itself also a BSM?
thank you!
each problem necessitates a certain BSM!
Global fit: W mass agrees with SM

68% and 95% CL contours
- Direct $M_W$ and $\sin^2(\theta^l_{\text{eff}})$ measurements
- Fit w/o $M_W$, $\sin^2(\theta^l_{\text{eff}})$ and Z widths measurements
- Fit w/o $M_W$, $\sin^2(\theta^l_{\text{eff}})$ and $M_H$ measurements
- Fit w/o $M_W$, $\sin^2(\theta^l_{\text{eff}})$, $M_H$ and Z widths measurements

$M_W = 80.379 \pm 0.013$ GeV

$\sin^2(\theta^l_{\text{eff}}) = 0.23153 \pm 0.00016$
Global fit: top mass agrees with SM

68% and 95% CL contours

- Fit w/o $M_W$ and $m_t$ measurements
- Fit w/o $M_W$, $m_t$ and $M_H$ measurements
- Direct $M_W$ and $m_t$ measurements

$m_t$ comb. ± 1σ

- $m_t = 172.47$ GeV
- $\sigma = 0.46$ GeV
- $\sigma = 0.46 \pm 0.50_{\text{theo}}$ GeV

$M_W$ comb. ± 1σ

$M_W = 80.379 \pm 0.013$ GeV