Beyond the Standard Model

Theory Status

Kiwoon Choi

(ICHEP 2016, Chicago)

IBS Center for Theoretical Physics of the Universe
SM is simple enough to be summarized on a small coffee mug, yet it is amazingly successful!
Even with this great success, we have many reasons to speculate about physics beyond the SM (BSM):

* **BSM with observational evidence**
  
  Neutrino mass, Dark matter, 
  Matter-antimatter asymmetry, Inflation

* **BSM to explain the naturalness problems of the SM**
  
  Hierarchy problem: SUSY, Extra Dim, Composite Higgs, Relaxion, ..
  Strong CP problem: Axions, Spontaneously broken CP, ...

* **BSM for theoretical completeness**
  
  Quantum gravity, Unification, ...

* **Why not?**
  
  Z-prime, W-prime, extra Higgs, vector-like quarks/leptons, leptoquarks, ...
We have a long list of possible BSM physics, but we don’t know where they are.

After the discovery of the Higgs boson, we don’t have anymore a convincing argument to pinpoint the next scale.

Where is the next town beyond the horizon?
The scale of new physics is so ambiguous.

Dark matter mass & interaction strength

Baer et. al, 2014
Scales of new physics

- $10^{-10}$ GeV: neutrino mass
- $10^{-2}$ GeV: matter-antimatter asymmetry
  - inflation
  - SUSY
- $10^{-10}$ GeV: extra dim
- $10^{3}$ to $10^{9}$ GeV: grand unification

Hidden light world

LHC scale

Decoupled heavy world
This is why we need to explore BSM physics from all possible perspectives:

Dark matter, Neutrino mass, Inflation, Baryon asymmetry, Naturalness, Unification, Quantum gravity, ...

Anybody in this exciting adventure can be the hero of the next big discovery!
Although not convincing enough, we have had long-standing arguments suggesting BSM physics around the weak scale:

* Hierarchy problem: \( m_{\text{Higgs}}^2 \ll M_{\text{Planck}}^2 \)

* WIMP miracle: \( \Omega_{\text{WIMP}} \sim 0.2 \left( \frac{m_\chi}{200 \text{ GeV}} \right)^2 \left( \frac{0.1}{g^2} \right)^2 \)

These arguments are still alive as many talks in the BSM session are about the subjects motivated by those arguments.

**Topics discussed in the BSM session**

* SUSY, Composite Higgs, Extra Dim, Relaxion, Little conformal symmetry, ...
* Dark sector involving dark matter, dark gauge bosons, hidden valley ...
* 750 GeV diphoton excess (fluctuation)
* Others: W-prime, Z-prime, heavy Higgs, vector-like quarks, leptoquarks, GAMBIT, CheckMATE, ...
Subjects to be discussed in the rest of this talk:

* SUSY
  (most frequently discussed and still appealing)

* 750 GeV diphoton excess
  (hottest subject over the last 8 months)

* Relaxion
  (new approach to the hierarchy problem)

For other subjects of BSM physics related to neutrinos, Higgs boson, dark matter, flavor, see the talks by A. d. Gouvea, H. Logan, M. Nojiri, S. Khalil.
SUSY has been the prime candidate for BSM physics near the TeV scale.

Hierarchy problem

$\delta m_H^2 \sim M_{\text{Planck}}^2 \Rightarrow m_{\text{SUSY}}^2$

Dark matter

Gauge coupling unification
SUSY signatures at LHC:

Multi-jets (possibly with leptons or photons) + MET,
Displaced vertices, Long-lived particle (disappearing) tracks, ....

Details of SUSY signatures depend on

* What is the LSP?
  Higgsino, Bino/Wino, axino, gravitino, ...?

* SUSY spectrum: compressed or split?
  colored vs EW, squarks/sleptons vs Higgsino/gauginos, ...

* R-parity: conserved or broken?

* Extra singlet or U(1)?, .....
SUSY theory space is big & rich!

Theory of SUSY spectrum
= Mediation of SUSY breaking

Gravity, Gauge, Anomaly, Dilaton/Moduli, Mirage, Gaugino, D-term, Z-prime, ...
Mediations

Extra matters?
Extra gauge bosons?

Various types of LSP
Higgsino, Gaugino, Gravitino, Axino, ...

Various forms of SUSY spectrum
CMSSM, mSUGRA, NUHM, More-minimal, Natural, Split, Compressed, Stealth, Spread, ...

SUSY models possibly with extra matter/gauge bosons
MSSM, NMSSM, USSM, μνSSM, E6SSM, PQNMSSM, .....
Theorists are ready well to interpret any SUSY signature at LHC, but there is no sign of SUSY yet!
No sign of other BSM also!
• Significant improvement compared Run 1!

• ... but some excesses that will be interesting to follow as more data is recorded!

**LHC is performing amazingly well, stay tuned for more results by the end of the year!**
SUSY is either heavy or stealthy (compressed)!

![Diagram showing SUSY mass limits](image_url)
Hints on SUSY scales:

* Naturalness:

\[
\delta m_{H_u}^2 = m_{higgsino}^2 - \frac{3y_t^2}{4\pi^2} \left( m_{stop}^2 + \frac{g_s^2}{3\pi^2} m_{gluino}^2 \ln \left( \frac{\Lambda_{mess}}{m_{gluino}} \right) \right) \ln \left( \frac{\Lambda_{mess}}{m_{stop}} \right) + \ldots
\]

⇒ Higgsino, stop and gluino are around the weak scale (Natural SUSY).

(cf: Radiatively-driven naturalness with stop and gluino around 1-4 TeV)

However there are some alternatives to the naturalness, which allow SUSY to be well above the weak scale:

\[ m_{SUSY} >> m_{Higgs} \]

with anthropic selection or relaxion?

G. Villadoro
Even when we abandon the naturalness, still there are some indications that SUSY may not be too far away from the weak scale.

* Higgs mass = 125 GeV: \[ m_h^2 = M_Z^2 \cos^2 2\beta + \frac{3y_t^2m_t^2}{4\pi^2} \ln \left( \frac{m_{\text{stop}}}{m_t} \right) + \ldots \]

\[ \Rightarrow \text{squark and slepton masses: } m_0 < 1000 \text{ TeV } \text{ for } \tan\beta > 2 \]

* Gauge coupling unification:

\[ \Rightarrow \text{Higgsino and gaugino masses: } m_{1/2} < 10 \text{ TeV} \]
SUSY is certainly a compelling candidates of BSM physics, so we should keep searching for her without leaving any stone unturned.

* Taking the gauge coupling unification seriously, SUSY may have some chance to be seen at LHC, and a good chance at the FCC:

![Graphs showing high luminosity LHC and 100 TeV collider results](image)
* An interesting possibility for relatively light SUSY:

Stealth SUSY

Stealth sector

MSSM

axino/gravitino LSP

J. Fan et al '11

* EW SUSY may be much lighter than colored SUSY: (cf: \((g-2)_{\mu}\), DM, ...)

EWKinos or sleptons (or generic WIMP) search @ High luminosity LHC
(also @ ILC (Talks by Berggren, Habermehl, List/Baer), @ CLIC (Talk by Simonnielo))
SUSY can leave an observable imprint in **flavor mixing** or **EDM** even when she is well above the weak scale: (Talk by S. Khalil)

Altmannshofer et. al. ‘13

Giudice, Romanino ‘05

**Flavor mixing**

squarks/sleptons $\gg 10^3$ TeV, EWKinos $< 10^3$ TeV

$\Rightarrow$ Hadronic EDMs $> 10^{-30}$ e-cm

Storage-ring EDM experiment

Y. Semertzidis
750 GeV diphoton excess


What is it?

New resonance to revise the Particle Data Book?
New data @ ICHEP 2016:

Signals are fading away, so does the excitement.
What have we learned?

750 GeV flood!  
https://jsfiddle.net/adavid/bk2tmc2m/show/

Theorists have been so hungry for experimental discovery, a lot more than what we have thought.
It was indeed a big rush, even the theory of ambulance chasing does not work in this case:

M. Backovic, 1603.01204 [physics.soc-ph]
Most straightforward explanation for the diphoton excess:

\[ \mathcal{L}_{\text{eff}} = \frac{S}{M_2} \left( G^{a\mu\nu} G_{a\mu\nu} \text{ or } G^{a\mu\nu} \tilde{G}_{a\mu\nu} \right) + \frac{S}{M_1} \left( F^{\mu\nu} F_{\mu\nu} \text{ or } F^{\mu\nu} \tilde{F}_{\mu\nu} \right) \]

New physics communicating with the SM dominantly through the SM gauge bosons:

Elementary or composite?

Different decay topologies?

Alternative production?
Models for 750 GeV excess discussed in the Higgs-BSM joint session:

- Composite meson in relaxion model, M. Fedderke
- Dark sector Higgs boson, P. Ko
- NMSSM singlet decaying into light diaxions, K. Rolbiecki
- Singlet in SUSY model with extra U(1) and vector-like quarks, Q. Shafi
- Anomalous quartic photon coupling (induced by new resonance) in forward pp -> ppyγγ, C. Royon

Some speakers changed the content of the talk, and one speaker even didn’t show up.
Many different explanations:

- Composite Pseudo-Nambu-Goldstone boson,
- Quarkonium-like bound state, Sgoldstino, Heavy axion (axizilla),...

**Interpreting the 750 GeV digamma excess: a review**

ALESSANDRO STRUMIA

*CERN, INFN and Dipartimento di Fisica, Università di Pisa*

References

This was not an waste of time!

We could learn more on many things related to BSM physics which communicate with the SM mainly through the SM gauge bosons:

- Vector-like fermions,
- EW symmetry preserving new strong forces,
- Axion-like-particles,
- Near threshold behavior of heavy particle loops,
- Resonance-continuum interference,
- Single photon vs diphoton-jet,

.....
**Relaxion:** New approach to the weak scale hierarchy problem

An axion-like field (\(\phi\)) is introduced, which scans the Higgs mass.

\[ m_H^2(\phi) \]

\[ \langle H \rangle = v = 246 \text{ GeV} \]

\[ -(90 \text{ GeV})^2 \]

\[ \Lambda^4 \]

\[ \Lambda = \text{Higgs mass cutoff} \gg v \]

Relaxion potential to trigger the necessary relaxion motion

Barrier potential to stop the relaxion

\[ V_b = -\mu_b^4(H) \cos \left( \frac{\phi}{f} \right) \]

\[ \mu_b^4(H = v) \lesssim v^4 \]

Graham, Kaplan, Rajendran, 1504.07551
Possible origin of the barrier potential:

\[ V_b = -\mu_b^4(H) \cos \left( \frac{\phi}{f} \right) \]

* QCD: \[ \frac{1}{32\pi^2} \frac{\phi}{f} \left( G\tilde{G} \right)_{\text{QCD}} \]

\[ \Rightarrow \quad \mu_b^4(H = v) \sim m_u \Lambda_{\text{QCD}}^3 \sim \left( 0.1 \text{ GeV} \right)^4 \]

* QCD-like hidden-color dynamics confining around TeV:

\[ \Rightarrow \quad \mu_b^4(H = v) \sim \left( 200 \text{ GeV} \right)^4 \]

(* Perturbative shift symmetry breaking yielding \[ \mu_b^4(H = v) \sim \left( 200 \text{ GeV} \right)^4 \])

Gupta et al, 1509.0047
Price to pay: (expensive?)

- Long time of energy dissipation and long field excursion

\[ \mu_b^4(H = v) \lesssim v^4 \]

\[ \Lambda^4 \gg v^4 \]

\( v = 246 \text{ GeV} \)
How long excursion?

Barrier slope \( \sim \) Sliding slope

\[
\frac{\mu_b^4}{f} \sim \frac{\Lambda^4}{\Delta \phi}
\]

\[\Rightarrow\]
Relaxion excursion (in angle unit)

\[
\frac{\Delta \phi}{f} \gtrsim \left( \frac{\Lambda^2}{v^2} \right)^2
\]

Technically unnatural
weak scale hierarchy

\( \Lambda^2 \gg v^2 = (246 \text{ GeV})^2 \)

Technically natural, but even bigger relaxation scale hierarchy

\[
\frac{\Delta \phi}{f} \gtrsim \left( \frac{\Lambda^2}{v^2} \right)^2
\]
Mechanism to generate long relaxation excursion:

(= big hierarchy in relaxation scales)

Clockwork mechanism with multiple axions

(=rotation angle of multiple wheels)

Relaxion identified as the rotation angle of the last wheel:

\[ \frac{\Delta \phi}{f} \sim n_1 n_2 n_3 \ldots n_{N-1} \sim e^N \quad (N = \text{Number of axions}) \]

( Exponentially long relaxation excursion)

KC, Im, 1511.00132; Kaplan, Rattazzi, 1511.01827
Observable consequences?

QCD-like hidden-color with vector-like fermions: L, L^c, N, N^c

Graham et al, 1504.07551; Antipin & Redi, 1508.01112; KC & Im, in preparation

$$\Delta \mathcal{L} = y_1 H L N + y_2 H^* L^c N^c + m_L e^{i\phi/f} L L^c + m_N N N^c$$

$$\Delta \mathcal{L}_{\text{eff}} = \mu_1^4 \cos \left( \frac{\eta H}{f_H} \right) + \mu_2^2 |H|^2 \cos \left( \frac{\eta H}{f_H} + \frac{\phi}{f} \right) + \frac{1}{16\pi^2} \left( \frac{\eta H}{f_H} + \frac{\phi}{f} \right) F \tilde{F}$$

TeV scale composite mesons with a variety of observable consequences which may be probed at LHC & future collider

Axion-like relaxion with mass and couplings in the range probed by SHiP

EDMs from the relaxion-Higgs mixing

Talk by Fedderke
Relaxion is a new baby in town, so deserves more attention:

* UV completion? Talk by Evans

  **Supersymmetric UV completion:**
  Batell et al, 1509.00834; KC and Im, 1511.00132; Evans et al, 1602.04812

* Coincidence problem?
  Espinosa et al, 1506.09217

* Relaxion energy dissipation other than the Hubble friction?
  Hook & Marques-Tavares, 1607.01786

* Further collider signature and/or low energy observable?
Conclusion

* Long list of candidates for BSM physics, but scales are uncertain.  

  BSM physics should be explored from all possible perspectives.

* Dark matter and hierarchy problem are yet the major driving engine of our search for BSM physics, and hopefully SUSY or WIMP DM may be just around the corner.

* From 750 GeV diphoton excess, we learned more on many things related to BSM physics communicating with the SM mainly through the SM gauge bosons.

* Relaxion is a new baby in town, so deserves further attention.
* To make a further progress, definitely we need a guide from experiments.

Let’s hope big discoveries come soon from some of the on-going (or planned) efforts to search for BSM physics:

Thank you for your attention!