Research Plan of A02 (theory): Beyond SM and Spacetime

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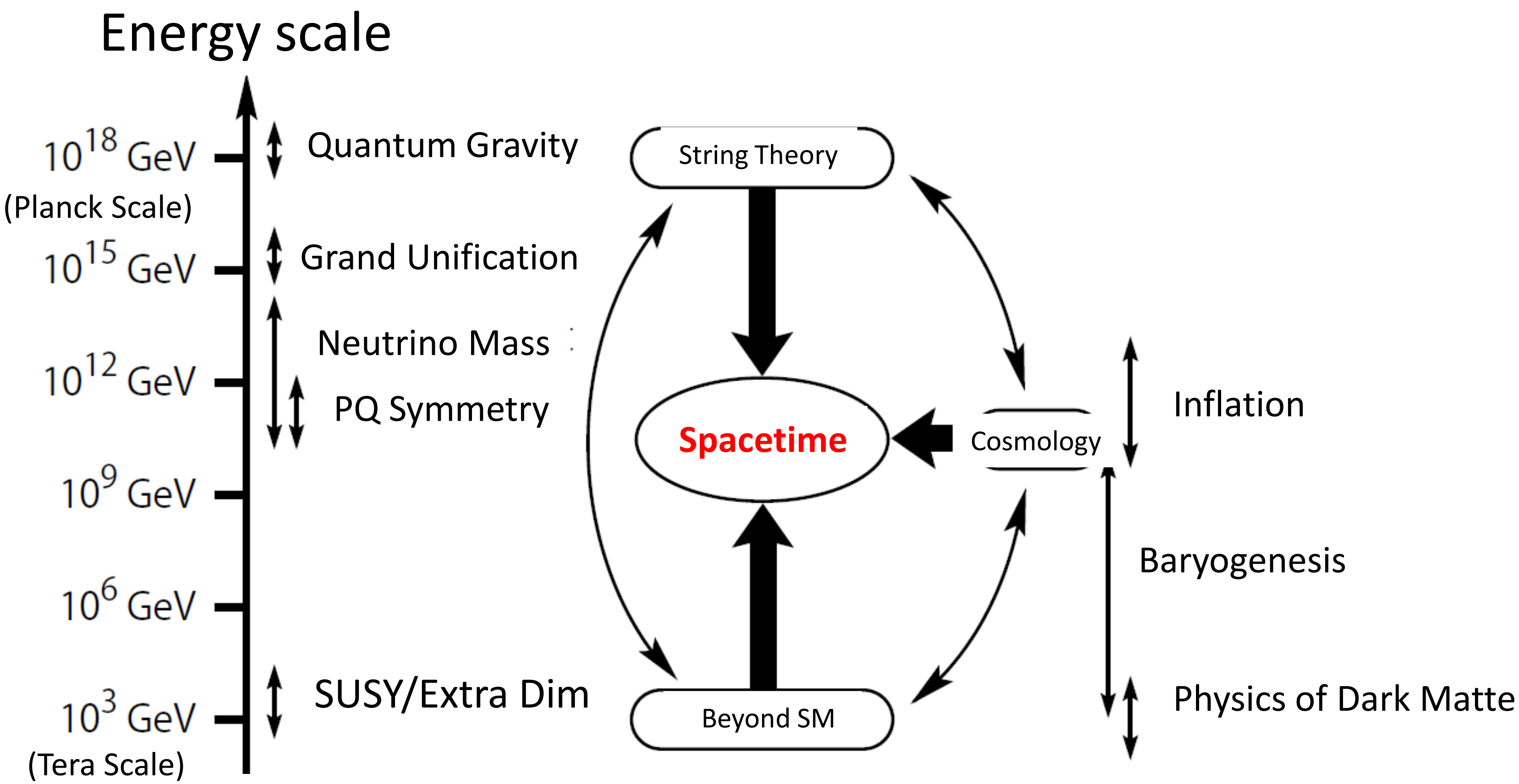
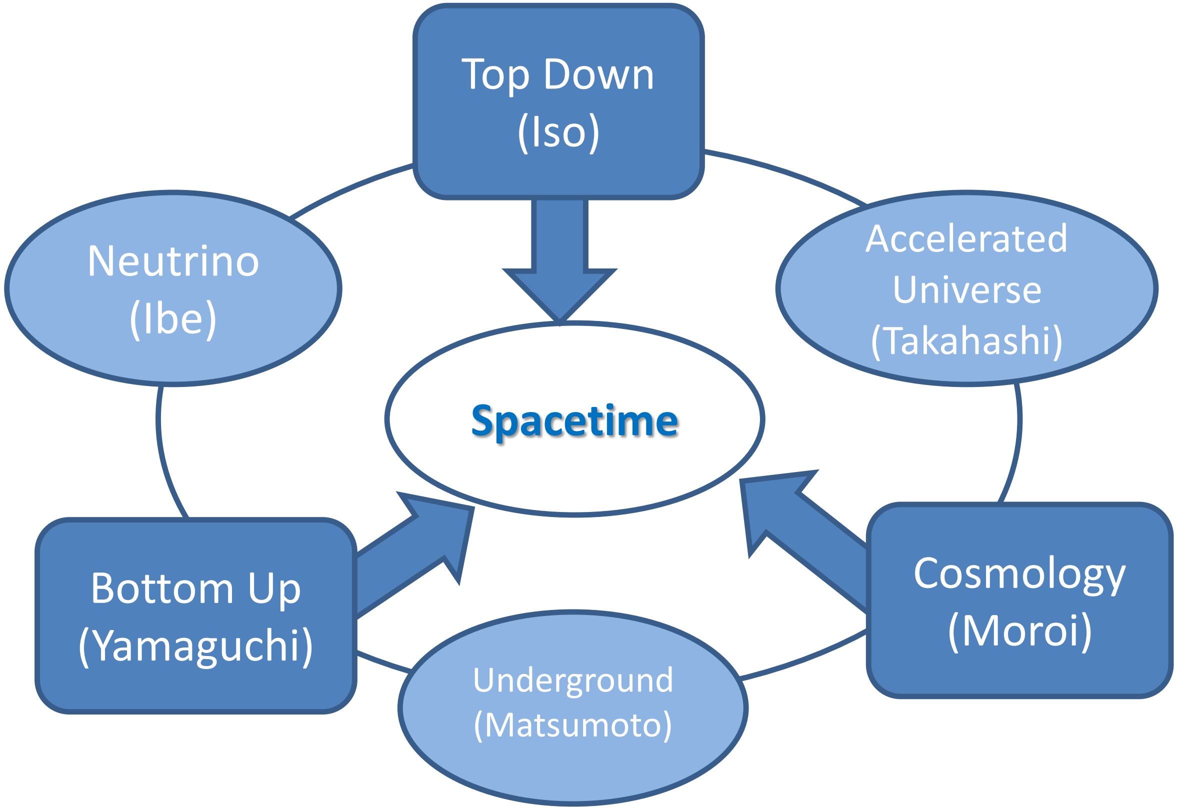
Research Target of A02:
Explore New Spacetime Concept



Research Organization



Current Status for BSM

- Discovery of Higgs Boson with 125 GeV mass

$$m_h = 125.36 \pm 0.37(\text{stat.}) \pm 0.18(\text{syst.})\ \text{GeV}\ (\text{ATLAS})$$
$$m_h = 125.03^{+0.26}_{-0.27}(\text{stat.})^{+0.13}_{-0.15}(\text{syst.})\ \text{GeV}\ (\text{CMS}).$$

- Non-discovery of Beyond-Standard-Model (BSM)

Motivations for Supersymmetry

- Unnaturalness of Higgs Sector:
  - gauge hierarchy problem/naturalness problem

- Unification of forces: Grand unification

- Muon g-2: possible deviation from SM

- Call for Beyond SM
  - Neutrino masses and mixings
  - Cosmology Connection
    - Dark Matter, Baryogenesis, Dark Energy, Inflation

Higgs Mass in MSSM

In MSSM

SUSY → Higgs Self Coupling = gauge coupling

$m_h < m_Z$ @tree level (SUSY relation)

Inoue et al '85

Large SUSY breaking loop effect can raise the Higgs mass

stop-top loops

1) large log m_{stop}/m_{top}

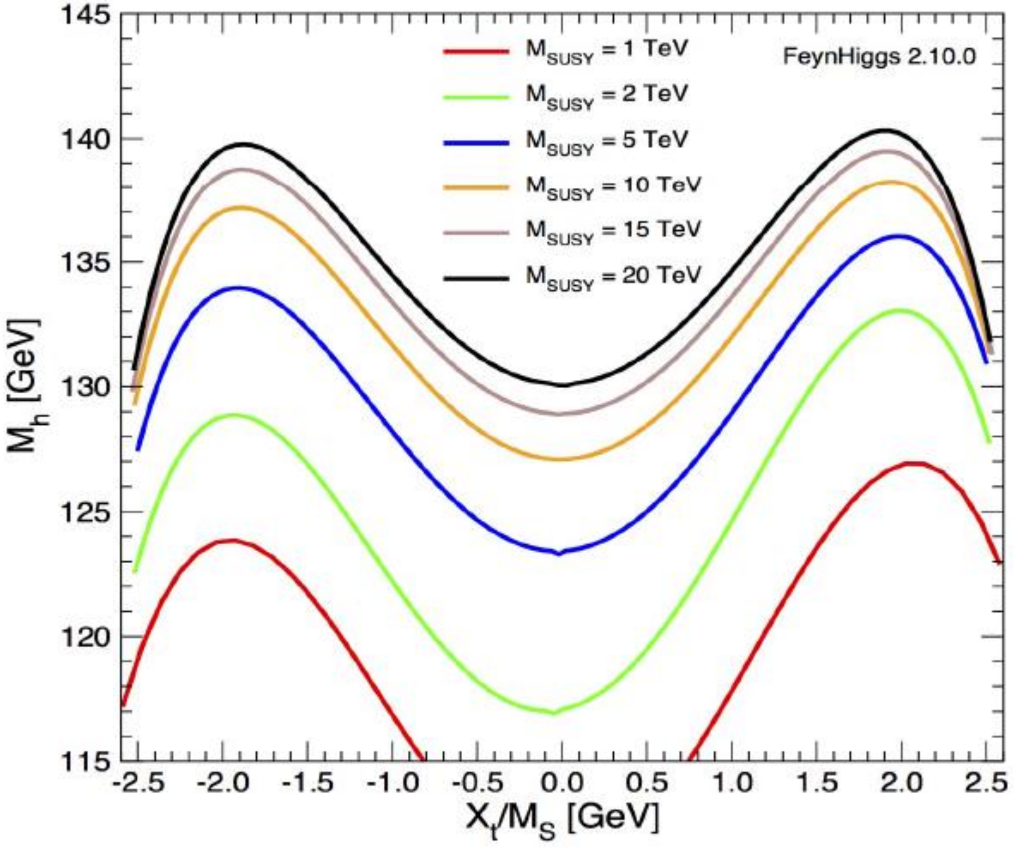
2) finite A-term(stop-stop-Higgs coupling) contribution

Okada, MY, Yanagida '91
Haber, Hempfling
Ellis, Ridolfi, Zwirner

$$m_0^2 = m_Z^2 + \frac{3m_t^4}{4\pi^2 v^2} \ln\left(\frac{m_{\tilde{t}}^2}{m_t^2}\right) + \frac{3m_t^4}{4\pi^2 v^2}\left(X_t^2 - \frac{1}{12}X_t^4\right) + \cdots$$

$$X_t = (A_t - \mu \cot\beta)/m_{\tilde{t}}$$

Higgs Mass @3-loop



Hahn, Heinemeyer, Hollik, Rzehak, Weiglein, 2014

$$m_A = M_2 = \mu = 1000\,\mathrm{GeV},\ m_{\tilde{g}} = 1600\ \mathrm{GeV}\ \text{and}\ \tan\beta = 10$$

Implications to SUSY Standard Model

To achieve the observed Higgs mass (125 GeV), we need either

1) Heavy stop (～7TeV) and/or large stop mixing

or

2) Addition of new source of Higgs mass at TeV scale

e.g. Vector-like Generation (T+Tbar)
Additional Gauge Sym. (eg. $U(1)_{B-L}$sym.)
Singlet Extension

Singlet Extensions

Jeong, Shoji & MY '11, '12, '14
Choi, Im, Jeong & MY '12

Superpotential

$$W = \lambda S H_u H_d + f(S) + (\text{MSSM Yukawa terms})$$

New Sources to increase Higgs Mass

1) tree-level coupling λ (significant only for small tan β)

   $+ \lambda^2 |H_u H_d|^2$: new contribution to the Higgs potential

2) Higgs/Higgsino loop (>0, for heavy singlet boson)

   New coupling: Higgs-Higgsino-Singlino

1) Doublet-Singlet Mixing (>0, for light singlet boson)

   If singlet boson is light, mixing increases doublet Higgs mass.

A Novel Approach to Fine-tuned SUSY

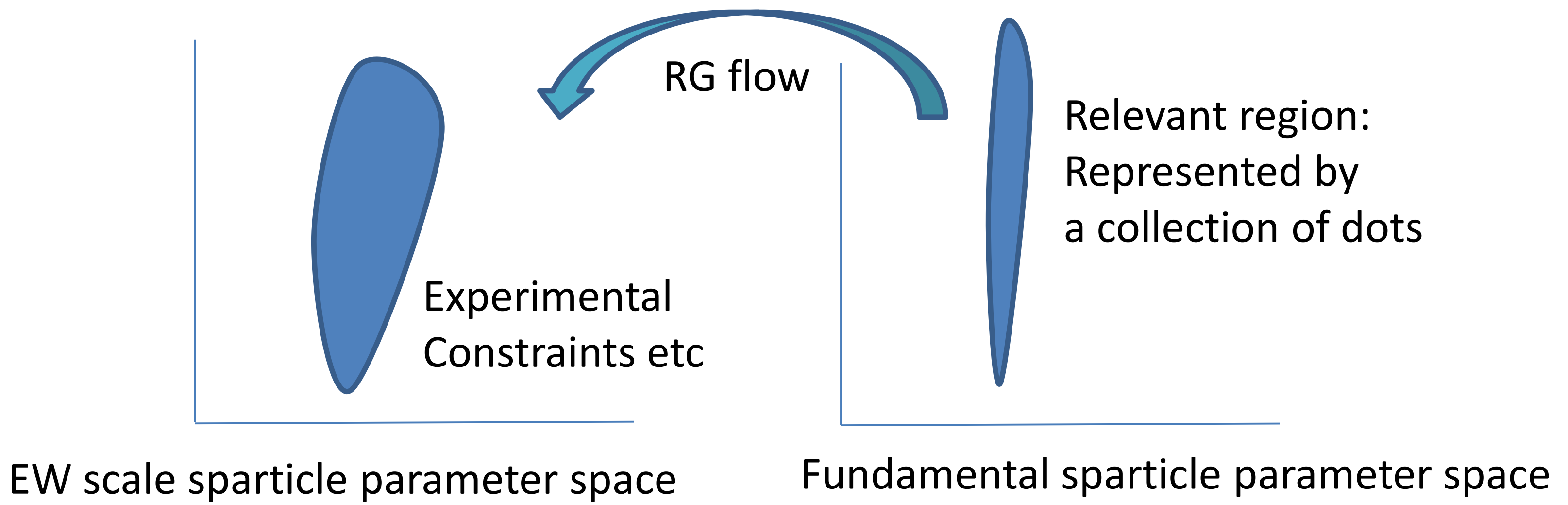
MY &Wen Yin (1606.04953)

- Within MSSM, sparticles seem to be heavy (e.g. stop mass around 7 TeV)
- Some fine-tuning is required to obtain EW scale.

- Don't give up SUSY
- Throw out the prejudices of the amount of fine tuning and the pattern of sparticle masses
- Nature may be described by fine-tuned SUSY.
- New complication to explore wider range of parameter space

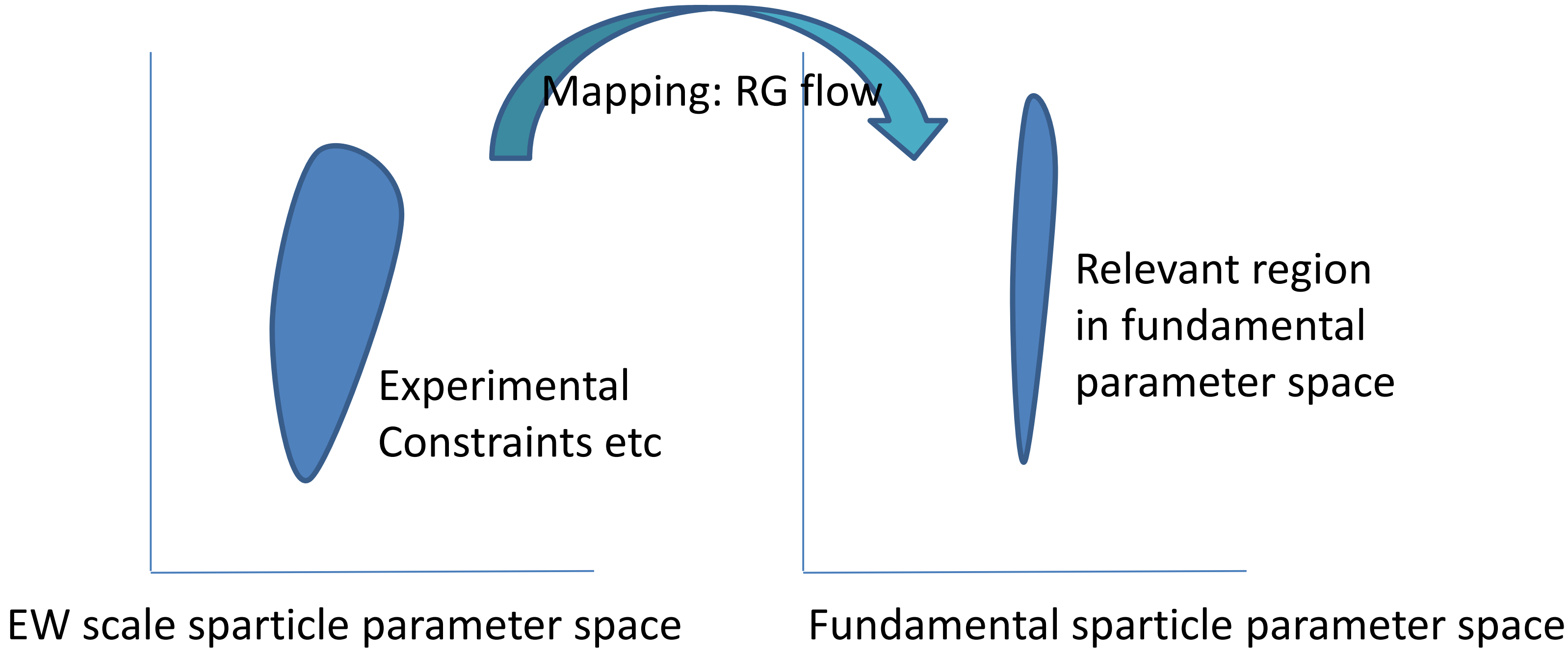
How to analyze fine-tuned SUSY?

- Scatter plot method:
  - Represents a relevant region of the parameter space as a collection of dots
  - In fine-tuned SUSY, the relevant region might be too tiny to be explored in this way
  - Time consuming (by computer), inefficient and maybe misleading (wrong conclusion)

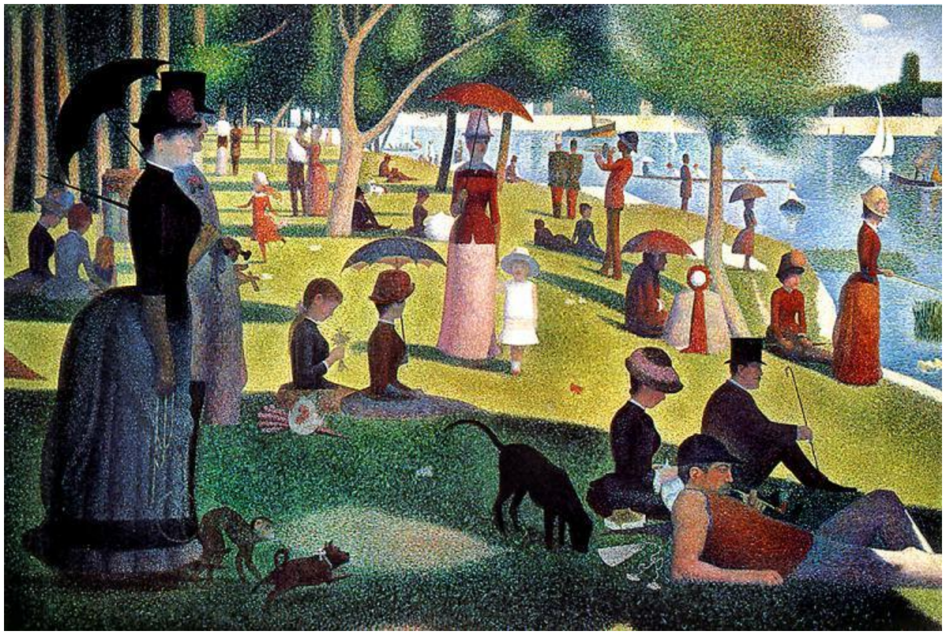


- An alternative approach:

mapping into the fundamental parameter space



Pointillism vs Ukiyoe



Pointillism vs Ukiyoe

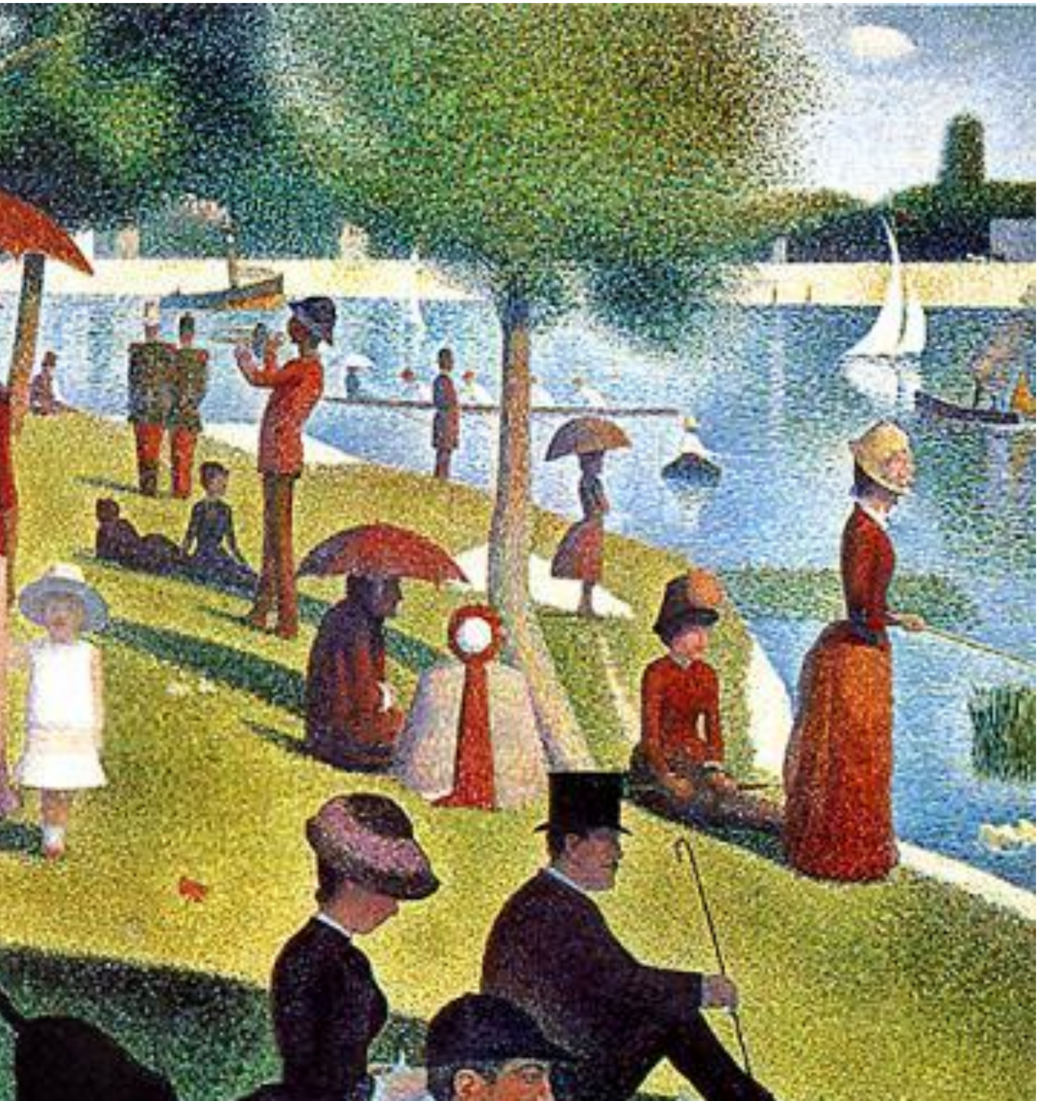


Illustration in Non-Universal Higgs Masses model

Set of the parameters: next simplest to CMSSM

$$\mathrm{m}^2_{\tilde{\mathrm{Q}}} = \mathrm{m}^2_{\tilde{\mathrm{u}}} = \mathrm{m}^2_{\tilde{\mathrm{d}}} = \mathrm{m}^2_{\tilde{\mathrm{L}}} = \mathrm{m}^2_{\tilde{\mathrm{e}}} = m_0^2 \mathbf{1}$$

$$M_1 = M_2 = M_3 = M_0$$

$$\mathbf{A}_u = \mathbf{A}_d = \mathbf{A}_e = A_0 \mathbf{1}$$

$$m^2_{\mathrm{Hu}} = m^2_{\mathrm{Hu0}},\ m^2_{\mathrm{Hd}} = m^2_{\mathrm{Hd0}}$$

$$B = B_0, \mu = \mu_0.$$

Two interesting cases found

Case 1) Inverted light squark

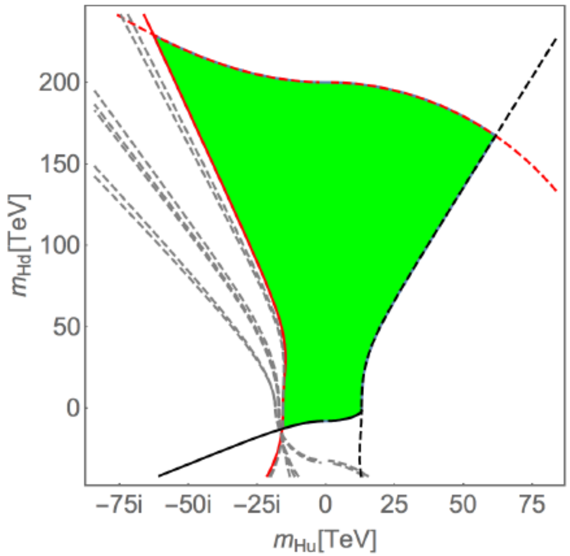
- Heavy 3rd generation squark → Higgs mass
- Light 1st &2nd generation squarks → within reach of LHC

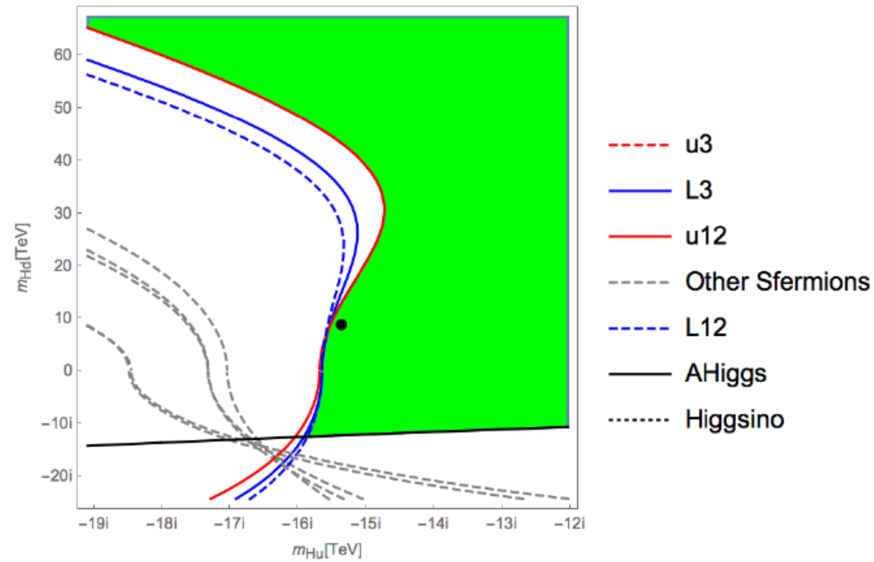
Case 2) Region explaining the muon g-2 anomaly

- Very very tiny region in the parameter space can explain the muon g-2 anomaly

Case 1) Inverted light squark region

In the region close to the red line, the first two generation squarks are light (close to the experimental bound).





Sparticle masses in the sample point (represented by the black dot)

EW scale	$m_{\mathrm{H_u}}$	$m_{\mathrm{H_d}}$	$m_{\tilde{\mathrm{Q}}3}$	$m_{\tilde{\mathrm{u}}3}$	$m_{\tilde{\mathrm{d}}3}$	$m_{\tilde{\mathrm{L}}3}$	$m_{\tilde{\mathrm{e}}3}$	$m_{\tilde{\mathrm{Q}}12}$
TeV	$-12.1i$	8.3	6.6	7.5	4.3	1.3	5.1	4.1
$m_{\tilde{\mathrm{u}}12}$	$m_{\tilde{\mathrm{d}}12}$	$m_{\tilde{\mathrm{L}}12}$	$m_{\tilde{\mathrm{e}}12}$	M_1	M_2	M_3	μ	m_A
1.6	4.4	1.4	5.2	0.31	0.62	2.2	12.2	14.9

Mechanism for Inverted light squark

RGEs

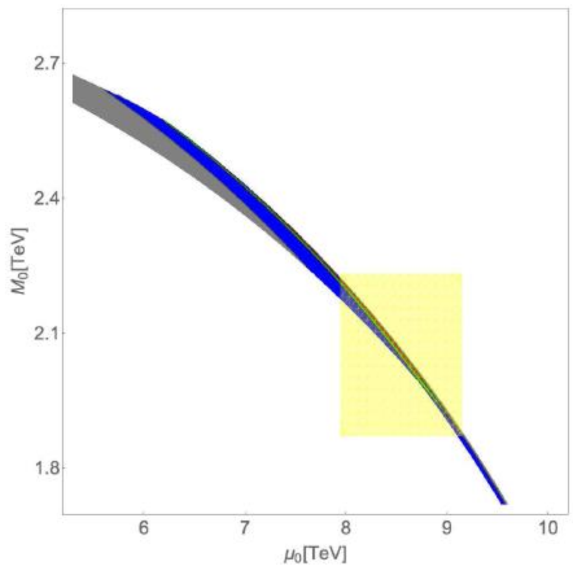
$$\frac{d}{dt} m_{\tilde{\mathrm{u}}\mathrm{i}}^2 \sim \frac{2}{16\pi^2} \left\{ 2y_{\mathrm{t}}^2 X_{\mathrm{t}} \delta_{i3} + Y g'^2 S - \frac{16}{3} g_3^2 M_3^2 - 4g'^2 Y^2 M_1^2 \right\},$$

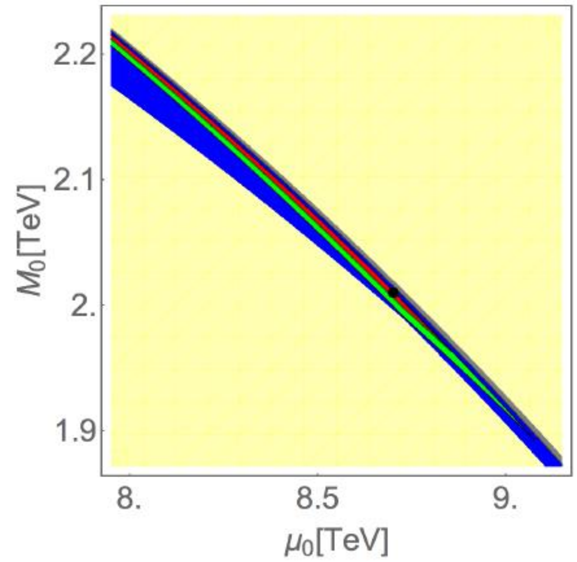
$$S \equiv \left(m_{\mathrm{H_u}}^2 - m_{\mathrm{H_d}}^2 + \mathrm{Tr}[m_{\tilde{\mathrm{Q}}}^2 - m_{\tilde{\mathrm{L}}}^2 - 2m_{\tilde{\mathrm{u}}}^2 + m_{\tilde{\mathrm{d}}}^2 + m_{\tilde{\mathrm{e}}}^2] \right),$$

$$X_{\mathrm{t}} \equiv m_{\mathrm{H_u}}^2 + m_{\tilde{\mathrm{Q}}_3}^2 + m_{\tilde{\mathrm{u}}3}^2 + |A_{\mathrm{t}}|^2,$$

Large and negative X_t makes the third generation squark heavier.

Case 2) Region explaining muon g-2





Sample point represented by black dot

EW scale	m_{H_u}	m_{H_d}	$m_{\tilde{Q}3}$	$m_{\tilde{u}3}$	$m_{\tilde{d}3}$	$m_{\tilde{L}3}$	$m_{\tilde{e}3}$	$m_{\tilde{Q}12}$
GeV	$8044i$	$7992i$	5834	6161	5089	1637	2275	5168
$m_{\tilde{u}12}$	$m_{\tilde{d}12}$	$m_{\tilde{L}12}$	$m_{\tilde{e}12}$	M_1	M_2	M_3	A_{u3}	A_{d3}
4920	4999	429	429	839	1659	5770	−4497	−6749
A_{e3}	A_{u12}	A_{d12}	A_{e12}	μ	m_A	FeynHiggs	m_h by FH	$\delta\alpha_\mu$ by FH
−1011	−7891	−7820	−1372	8043	907	(2.11.2) [4]	126(1.4)GeV	2.5×10^{-9}

Conclusions

- Quest for new physics beyond Standard Model is underway.
- Hope to emerge a new concept of spacetime such as SUSY/Extra dimensions
- Should explore it from various directions

  (top-down/bottom-up/Cosmology connection)

Stay Tuned!   Thank you very much