Experimental Opportunities
LHC Challenges for String Theory

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String Phenomenology:

Study of aspects of potential solutions of String Theory with features “similar” to those observed in our Universe
What are the “Broad Features” of Our Universe?

- $3 + 1$ “Large” dimensions ($R_{\text{extra}} < \sim 10^{-16}$ cm)

- Flat Universe with Dark Energy, Dark Matter & Ordinary * Matter -- $\Lambda$CDM cosmology

- Nearly scale invariant & adiabatic cosmological fluctuations
  -- CMB & Large-scale structure
Ordinary* Matter – Standard Model

* Elementary Matter (point-like)
* Force Carriers (gauge bosons)
* Scalar particle called the Higgs Boson

Broad Features

- Non-abelian gauge theory.
- Chiral fermions
  -- charged: hierarchical masses & small mixing.
  -- neutral (neutrinos): tiny, hierarchical masses & large mixing.
- Spontaneous symmetry breaking by the Higgs mechanism.
Recent Experimental Results

- **Energy Frontier**
  - Positive: Discovery of Higgs @ 125 GeV.
  - Null: Lack of Beyond SM physics so far

- **Intensity/Precision Frontier**
  - Positive: measured PMNS angle -- $\sin^2 \theta_{13}$
  - Null: No deviations from SM, more stringent constraints on new physics

- **Dark Frontier**
  - Null: LUX (direct detection), FERMI (indirect detection),...
  - Hints (?): X-ray line, Diffuse photons from GC, ...

- **Cosmic Frontier**
  - Null: No sign of non-gaussianity so far
  - Hint (?): Primordial Gravitational Waves (BICEP2)

*D. Marsh, M. Rummel*  
*Westphal, Burgess, Hebecker, Maharana, Takahashi, Sagnotti, Nilles, Grimm, Shiu, Kaloper, Uranga. Also many parallel talks ...*
Plan of Talk

• I) Higgs Discovery
  -- Summary of Results
  -- What kinds of New Physics models favored/disfavored by data?

• II) String motivated SUSY Models – Basic Features & Potential Signals

  "Imperfectly" Natural
  -- "Electroweak-Tuned"
  -- "Mostly" Un-natural

  -- "Electroweak-Natural" – briefly discuss one possibility
  -- R-parity or Not?

• III) Dark Matter – motivated from String Theory

  -- Status of LSP WIMP DM.
  -- Dark sectors.

• IV) Summary & concluding remarks

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I) Higgs Discovery

-- Summary of Results

-- Effect on BSM Models
• Discovery of a Higgs Particle @ 125 GeV

• Signal consistent with that of a SM-like Higgs
Effect on BSM Physics

• i) Technicolor Models
  – $v_{\text{EW}} = f$ (scale of New Strong Dynamics)
  -- All new resonances at $M \sim 4 \pi f = 4 \pi v_{\text{EW}}$

SM-like “Higgs” resonance at $M < \sim v_{\text{EW}}$

• ii) Composite Higgs Models

  -- Higgs pseudo-NGB of global symmetry (E.g. SO(5)/SO(4))
  -- Could be light compared to $4 \pi f$
  -- EW Precision observables under control, if $\xi = v_{\text{EW}}/f < 1.$

However, composite Higgs models in tension with data
Composite Higgs Models (contd.)

• Higgs couplings different from that in SM at tree-level
  -- The parameter $\xi = \frac{v_{EW}}{f}$ controls the deviation.

• Also expect “Top-partners” below $\sim 1$ TeV (None observed)

$k_F \sim$ Coupling to Fermions

$k_V \sim$ Coupling to Gauge bosons

Stringent upper bound on $\xi$

Still possible, but increasingly disfavored

Same with Randall-Sundrum Models, since these are “duals” of composite Higgs
iii) TeV-scale Strings

*Well-known that String scale can be made very small ($>\sim$ TeV) at the expense of making extra dimensions very large (relative to $M_s$)*

$$M_P^2 = \frac{1}{g_s^2} M_s^{2+n} R^n,$$

Arkani-Hamed, Dvali, Dimopoulos hep-ph/9803315
Antoniadis et al hep-ph/9804398

*Experimental Signals*

-- Kaluza-Klein Excitations
-- String Resonances with Regge behavior : $M_n^2 = nM^2$, $j = j_0 + \alpha' M_n^2$
-- Production of Black-Holes

$M_{BH} \sim M_s/g_s^2$, so threshold higher than that for string resonances.

-- $Z'$ bosons with mass $M_{Z'} \sim g M_s$ generic in isotropic compactifications. receive mass by Green-Schwarz mechanism : Stuckelberg U(1)
Constraints & Interpretation

- String resonances produced in $gg \rightarrow gg$, $gg \rightarrow gg$ scattering
  -- universal amplitude:
  Anchordoqui, Goldberg, Lüst, Nawata, Steiberger, Taylor 0808.0497
  -- current bound $M_s > \sim 5$ TeV
  Also see Lüst, Taylor 1308.1619

- FCNCs impose stronger bounds generically
- Also, bounds on $Z'$ (for isotropic)

$M_{Z'} > \sim 2$ TeV if $Z'$ couples the same as $Z$
Effect of Higgs Discovery @ $M_H$ near 125 GeV

- EWSB can occur with $M_H$ suppressed relative to $M_s$ by loop factor
  
  Antoniadis, Benakli, Quiros NPB 583 (2000) 35
  Antoniadis, Dimopoulos, Pomarol, Quiros NPB 544 (1999)503

  $\Rightarrow$ 5 TeV

* So, $M_H$ in the correct range, however at tree-level: $M_H = M_Z$

* Need large corrections to Higgs Quartic $\lambda$ to raise $M_H$ to 125 GeV, from KK and string modes (not clear if fully computable)

Prospect: Does not seem likely, but may still be a possibility
II) (String-motivated) SUSY Models

(with a high $M_s$)
SUSY Models

• Favored by current Experimental Data over other approaches.

Reasons:

a) contain a Higgs-like boson with mass $M_h < \sim v_{EW}$

b) possess a “decoupling limit”:

$\text{when } M_{\text{soft}} \gg v_{EW}, \text{Higgs SM-like \& superpartners heavy}$

• Of course, string theory $\rightarrow$ SUSY at microscopic level

• However, nature of favored SUSY models different from naïve expectations ....
At Crossroads.....

- Electroweak-Tuned but “minimal”
- Electroweak-Natural but “elaborate”

- Seems more likely
- Talk more about it
- Possible, but challenging
- Briefly mention one possibility

Higgs @ ~125 GeV
No superpartners so far

More Data will Decide!
Electroweak-Tuned

- Higgs Mass @ 125 GeV points roughly to two sub-classes

A) “Imperfectly” Natural

* Scalar superpartners $M_{\text{soft}} \sim O(10-100)$ TeV
* Gauginos may be naturally suppressed by (moduli) dynamics
* Can explain most of the Hierarchy
* An unexplained Little Hierarchy remains

B) “Mostly” Un-natural

* $\lambda_H = 0$ at $M_{\text{soft}} \sim O(10^{10})$ GeV
* Gauginos may or may not be suppressed relative to $M_{\text{soft}}$
* Most of the Hierarchy is NOT explained – invoke fine-tuning

Talk about both:

a) Basic characteristics b) Potential Experimental Signals

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A) “Imperfectly” Natural

- Question: What sets the mass-scale of the scalar superpartners?

**Elegant Solution**: Moduli Dynamics

For “Generic” Kahler potential for Moduli & Matter Fields,

\[ M_{\text{modulus}} \sim M_{\text{soft}} \sim M^{3/2} \]

Denef, Douglas hep-th/0411183; Gomez-Reino, Scrucca hep-th/0602246; Acharya, Kane, Kuflik 1006.3272

* Can be obtained from Theory for O(1) choices of microscopic constants

Acharya, Bobkov, Kane, PK, Shao PRD 76 2007, 126010

\[ M^{3/2} = O(10-100) \text{ TeV} \]

* Moduli heavy enough to decay before BBN.

* Higgs mass can be successfully computed

Kane, PK, Lu, Zheng PRD 85 2012, 075026
• If \( H_{\text{inf}} > M_{3/2} \), then Moduli dominated Universe before BBN.

- Potentially important implications for Cosmology/Astrophysics,
  E.g. growth of substructure at small scales *Erickcek, Sigurdson 1106.0536*
  *Fan, Ozsoy, Watson 1405.7373*

- Crucial implications for Dark Matter in terms of candidates, abundance, interactions

  **One example**: “Non-thermal WIMP Miracle”
  *Moroi, Randall hep-ph/9906527; Acharya, Kane, PK, Watson 0908.2430, Many follow-up works in the literature*

• **What about gaugino masses?**

Gaugino masses naturally suppressed relative to scalars in many string frameworks:

*Choi, Falkowski, Nilles, Olechowski, Pokorski hep-th/0411066; hep-th/0503216
Conlon, Quevedo hep-th/0605141; Acharya, Bobkov, Kane, PK, Shao hep-th/0701034*
A i) Collider Phenomenology of Framework with

“Heavy” scalars & “Light” Gauginos

- Broad features applicable to all models in this framework.
- Precise constraints & signals depend on particular models.
Constraints & Prospects @ LHC

• Since light(er) particles – chargino, neutralino, gluino

-- Main Production Processes at the LHC:

\[ pp \rightarrow \tilde{g}\tilde{g} \quad \chi_2^0\chi_1^\pm \quad \chi_1^\pm\chi_1^\pm \]

Strong Electroweak

Other channels, such as \( \chi_1^0\chi_2^0, \chi_1^0\chi_1^0, \chi_2^0\chi_2^0 \) more model dependent

-- Decays at the LHC:

\( \text{gluino} \quad \rightarrow \quad \chi_1^0t\bar{t}, \quad \chi_2^0t\bar{t}, \quad \chi_1^\pm b\bar{t}, \quad t\bar{b} \quad \chi_2^0b\bar{b}, \quad \chi_1^0b\bar{b} \)

\( \chi_2^0 \quad \rightarrow \quad \chi_1^0 Z; \quad \chi_1^0 h, \ldots \)

\( \chi_1^+ \quad \rightarrow \quad \chi_1^0 W^+; \ldots \)

Again, precise BR’s model-dependent

**Typical Final State:** High \( p_T \) multi-jets, \( >= 3 \) b jets + 0 or 1 lepton + \( E_T \)
Constraints and Future Prospects

• Analysis of LHC data presented in terms of “simplified models”
  -- assume 100% BR of $\tilde{g}$ to one channel, for e.g. $\tilde{g} \rightarrow \chi_1^0 t\bar{t}$
  -- Real Models BR’s to many channels can be non-trivial.
  -- Should compute bound on masses for each model.

E.g. 1: **String-Motivated SO(10) Yukawa Unification Models**

**Bounds on Gluino Masses**: Raby 1309.3247
Anandakrishnan, Bryant, Raby 1404.5628, 1303.5125

E.g. 2: **M-theory motivated G$_2$-MSSM**
S. Ellis, Kane: To be published

**Similar technique**: $M_{\text{gluino}} > 0.9-1$ TeV
Implicit Assumption: Gluino reasonably heavier than the LSP jets, leptons “hard”, i.e. have large $p_T$.

• However, if Gluino and LSP close in mass, then
  -- spectra “compressed”
  -- jets & leptons “soft”, many do not pass cuts.

Eg: “Mirage Mediation Models” with Precision Gauge Unification

* Choi, Jeong, Kobayashi, Okumura hep-ph/0508029
* Krippendorf, Nilles, Ratz, Winkler 1306.0574

Also see Pheno. Papers on ‘compressed SUSY’

• Gluino bounds considerably relaxed.
• Gluino may be long-lived (10µm – 1 mm)
• Co-annihilation effects important for LSP annihilation in early Universe.
Prospects @ ~100 TeV Collider

- LHC sensitive to gluino masses $\lesssim 2-2.5$ TeV.
- A larger CM-Energy Collider will increase the reach.
- Studies quite preliminary. Lot to do.
- Some work done for “simplified models”

E.g. Gluino-Neutralino Simplified Model

Final State: Multi-jets + No Leptons + $E_T$

Dominant Background: $t\bar{t}$ + jets
(in contrast to $W/Z+$jets @ LHC)

I. Antoniadis’ Talk

Cohen et al 1311.6480
• Significant improvement compared to the LHC Cohen et al 1311.6480

• What about stops & heavier electroweak-inos?
  -- No detailed studies yet. Acharya, Bozek, Pongkitivanichkul,Sakurai: To appear
  -- May be possible to detect these for \( M_{3/2} < \sim 30 \) TeV

* LHC has a good chance of discovering “Imperfect-Naturalness”

* 100 TeV collider would be a wonderful development
  - would greatly help in confirming/ruling out the above and also other ideas
B) “Mostly” Un-natural

* Basic Motivation:

SM -- well-known that certain values of Higgs Mass can be tied to vanishing of Higgs quartic $\lambda$ at some High scale.

Higgs near $125 \text{ GeV} - \lambda$ vanishes at $M \sim 10^{10} \text{ GeV}$

(uncertain due to $M_{\text{top}}$ uncertainty)

Elias-Miro et al 1112.3022; Holthausen et al 1112.2415; Wetterich 1112.2910,…

• Proposal:

SUSY @ High scale $M_{\text{soft}}$ such that $\lambda(M_{\text{soft}}) \rightarrow 0$ at $M_{\text{soft}}$

But

$\lambda(m_S) = \frac{g^2(m_S) + g'^2(m_S)}{8} \cos^2 2\beta \rightarrow \tan \beta = 1$ at $M_{\text{soft}}$

Most of the Hierarchy NOT explained, just fine-tuned

Can be motivated from theoretical approaches:

Hebecker, Knochel, Weigand 1204.2551; 1304.2567
Ibanez, Marchesano, Regalado, Valenzuela 1206.2655; Ibanez, Valenzuela 1301.5167

L. Ibanez’s Talk
SUSY at $M \sim 10^{10}$ GeV can be combined with Gauge Unification in F-Theory: Both scales can be related

$$M_{SS} = \left(\frac{(2g_s)^{1/2}}{\alpha_G^{1/2}}\right)\frac{M_e^2}{M_p}$$

Unification @ $M_c \sim 10^{14}$ GeV with threshold corrections.

Ibanez, Marchesano, Regalado, Valenzuela 1206.2655
Camara, Ibanez, Valenzuela 1404.0817

• Can give rise to QCD Axion with decay constant $F_a \sim 10^{12}$ GeV

• However, proton decay with a low Unification scale a challenge
Hebecker, Unwin 1405.2930

“Fake Split-SUSY” – Goodsell’s talk.

Experimental Probes (if no light fermions)

• Precise Measurements of Higgs & Top Mass & couplings.
• Possible discovery of QCD Axion DM in ADMX with $F_a \sim 10^{12}$ GeV.
• Observation of Proton Decay.
“Electroweak-Natural”
• As mentioned earlier, current data makes it challenging to realize this possibility.

• However, Nature may still work this way. Within SUSY, have to go beyond the MSSM:
  -- Additional contributions to Physical Higgs Mass
  -- New contributions to the Higgs potential
  * may improve naturalness of EWSB
  -- No Beyond-the-SM physics so far models more “elaborate”

• Fully explicit and viable models hard to construct. Nevertheless many attempts in literature.

• Talk about one possibility.
“Holomorphic” Higgs Portal

Visible Sector
(MSSM)

Higgs

Extra Sector

\[ W = \lambda_u H_u O_u + \lambda_d H_d O_d. \]

Higgs couples to operators in the Extra sector (in the superpotential).

\[ O_u, O_d \] -- part of SUSY breaking sector or part of messenger sector which couples to another SUSY sector -- extension of Gauge Mediation to Higgs sector.

Such terms considered in various field-theoretic contexts ...

Azatov et al 1106.3646,1106.4815; Kitano et al 1206.4053; Stancato et al 0807.3961; Gherghetta, Pomarol 1107.4697; Komargodski, Seiberg 0812.3900; Craig et al 1302.2642; Knapen et al 1311.7107, Schafer-Nameki et al 1005.0841, ....
Setup could arise naturally in a class of string frameworks

“F-Theory” --- 7-brane probed by a D3-brane

Visible Sector

Extra Sector

Heckman, Vafa 1006.5459
Follow-ups with collaborators

Visible Sector

Extra Sector

D3-brane – Theory strongly coupled in general

M6

M4

R3,1

7-brane

Local Model -- study region in which D3-brane is close to the 7-brane
Phenomenologically interesting Features

-- Higgs Potential could change relative to the MSSM

\textit{Heckman, PK, Vafa, Wecht JHEP 1201 (2012)}

-- Consistent with gauge coupling unification in the MSSM.

\textit{Heckman, Vafa, Wecht 1103.3287}

-- Possible to compute Higgs couplings: \textit{(Using SUSY, Holomorphy & Gauge invariance)}

\textit{Heckman, PK, Wecht 1204.3640; Heckman, PK, Wecht 1212.2979}

MSSM coupled to sector which is superconformal in the UV:

-- Imagine conformal symmetry broken with a “mass-gap” $M$ and SUSY at scale $(F)^{1/2}$.

-- very interesting to understand this dynamically.

Possible Collider Signal:

\begin{itemize}
  \item Many soft $O_{\text{neut}}$'s
  \item Soft jets
\end{itemize}
III) To be, or not to be, that is the question...
• Until now, implicitly assumed R-parity conservation.

• However, possibility of R-parity violation quite interesting:
  -- LSP no-longer stable.
  -- Significant reduction in missing $E_T$ @ LHC
  --> constraints on superpartners weakened.
  -- Viable RPV models can be constructed phenomenologically

• What about R-parity violation from top-down point of view?

Talk about: i) SU(5) GUT models, ii) SO(10) GUT models.

Any RPV disfavored
Spontaneous RPV a possibility

B. Ovrut’s Talk
SU(5) GUTs: appealing due to simplicity

-- GUT breaking to $G_{SM}$ and doublet-triplet splitting.
   employ some global symmetry $H'$ arising in string theory
-- To solve $\mu/B\mu$ problem, either by KN/CM or GM mechanism.


$H'$ forbids $\mu$ parameter at High scale, but $H'$ must be broken to $H \subset H'$

True in both Heterotic orbifolds & M-theory constructions
Kappl, Nilles, Ramos-Sanchez, Ratz, Schmidt-Hoberg 0812.2120;
Lee, Raby, Ratz, Ross, Schieren 1009.0905; 1102.3595;
Chen, Ratz, Staudt, Vaudrevange 1206.5375; Witten hep-ph/0201018;
Acharya, Kane, Kuflik, Lu 1102.0556

Then, can show that bilinear RPV coefficient $\kappa$ in $\int d^2 \theta \kappa LH_u$ is such that

either a) $\kappa/\mu = O(1)$ (H is trivial), or b) $\kappa/\mu = 0$ (H equivalent to R-parity)
Acharya, Kane, PK, Lu, Zheng 1403.4948

But stringent constraints on bilinear RPV from neutrino masses: $\kappa/\mu < \sim 10^{-3}$

R-parity violation disfavored
Any observation of R-parity violation disfavor above class of Models
• **SO(10) GUTs**:  
  -- appealing, since 16 of SO(10) contains all SM particles + RH neutrino.  
  Eg : $E_8 \rightarrow SO(10) \rightarrow G_{SM} \times U(1)_{B-L}$

Heterotic M-theory: “Exact” MSSM spectrum -- Minimal
  * Braun, He, Ovrut, Pantev hep-th/0501070; hep-th/0512177; hep-th/0602173

• $U(1)_{B-L}$ must be broken to make $Z_{B-L}$ sufficiently massive.

• Since only candidate $\langle \tilde{\nu}^c \rangle$ has odd B-L,

  \[ \rightarrow \text{R-parity, a } Z_2 \text{- even subgroup of B-L, is spontaneously broken} \]

For $\langle \tilde{\nu}^c \rangle$ to obtain a pheno. viable vev, need:

-- large flavor-dependent non-universality in the sneutrino soft masses relative to that for sleptons & selectrons
  * Amboroso, Ovrut, 0910.1129; Acharya, Kane, PK, Lu, Zheng 1403.4948

Option: Have extra 10’s, 16’s of SO(10)

Acharya et al : To appear
Broad Experimental Signals

- $Z_{B-L}$ gauge boson with mass $>\sim$ few TeV
- Existence of two light RH neutrinos.
- Leptonic RPV through the $L H_u$ operator

“LSP” can decay. Also, “LSP” can be charged or colored.

- Neutrino-Neutralino Mixing
  -- generate majorana neutrino masses at tree level.

- Can also have correlation between LSP decays & Neutrino Hierarchy!
  Marshall, Ovrut, Purves, Spinner 1401.7989, 1402.5434

More details/signals should be explored....
III) Dark Matter

(motivated from String Theory)

* B. Dutta’s Talk
The Dark Matter Zoo

Just an illustration – many more candidates possible ...

Most popular candidates –

WIMPs & Axions

- String Axions – many talks

-- could be important during inflation.

-- could also naturally comprise Dark Matter.

Arvanitaki et al 0905.4720
Acharya, Bobkov, PK 1004.5138
Cicoli et al 1206.0819; Arias et al 1201.5902
Allahverdi et al 1401.4364; Honecker et al 1312.4517, Sik Jeong et al 1310.1774; Many others..

Proposal to detect QCD axion with GUT scale $F_a$
Graham, Rajendran 1306.6088

Finally, Axions can be Dark Radiation
Talks by D. Marsh, Angus, Pongkitvanichkul
(SUSY) WIMPs – minimal, since part of BSM Model.

**Direct Detection**

- Many hints in the past few years
- All of them killed by LUX
- A large chunk of SUSY WIMP parameter space ruled out, and large chunks still left..

Example of SUSY WIMP not ruled out by direct detection – **Wino LSP**,  

-- Winos do not interact via Z-exchange or Higgs-exchange at tree level.  
-- Winos can also give rise to the correct abundance via the “non-thermal WIMP miracle”

However, …
Indirect detection

Fan et al 1307.4400

Latest bounds disfavor Wino DM.
E.g. FERMI diffuse $\gamma$ from Galactic Center

Also, recent hints for WIMP indirect detection less convincing now
* 130 GeV “$\gamma$-line” from GC
* PAMELA Antipositron fraction from nearby region of Milky way.

Although LSP-WIMPs still viable,

-- Constraints more & more stringent.
-- In some sense, “Lamp-post” Physics.

Worth considering other approaches

“I’m looking for DM”
Dark Sectors

Motivation:

• Additional sectors in String Theory very common/natural.
  -- UV completion of SM has additional gauge/matter spectra in most cases.
  -- String-consistency conditions “demand” it.
    E.g. Hidden E_8 in Heterotic, RR-Tadpole cancellation in Type II.

Dark Matter could naturally be part of these additional sectors.

• Some “common” observations:
  Many talks on massive U(1)s in string theory
  -- Extra U(1) gauge bosons -- Z' (massive), γ' (massless)
    a) Z' – Stuckelberg; b) Z’ – Higgs; c) γ’ - massless
  -- Hidden sector DM or “Light” Messenger DM
    Cvetic, Halverson, Piragua 1210.5245; Feng, Shiu, Soler, Ye 1401.5880, 1401.5890;
    Halverson, Orlofsky, Pierce 1403.1592; Many others....
Kinetic Mixing:

- **Marginal coupling** → If generated, will persist to low energies
- **Phenomenology depends on** \( \{M_{A'}, \varepsilon\} \) & \( \{M_X\} \)
  
  - a) \( M_{A'} = 0 \), Hidden sector fields acquire milli-charge \( \sim \varepsilon \).

*Holdom PLB 166 (1986); Banks, Seiberg 1011.5120; Abel, Schofield hep-th/0311051, Marchesano et al 1406.27*
b) $M_{A'} \neq 0$. Variety of $\{M_{A'}, \varepsilon\}$ can be generated.

*Abel et al hep-ph/0608248, 0803.1449; Goodsell et al 0909.0515; 11110.6901; Cicoli et al 1103.3705*

**Dark Gauge boson will have small coupling $\sim \varepsilon$ to visible sector & vice-versa**

**Interesting Consequence:**

“LSP” will decay to Dark Sector before BBN even with R-parity conservation.

E.g. Bounds on Winos can be evaded

**Mass Mixing:**

-- **Physical $Z'$ eigenstates:** generically couple with $O(1)$ strength to SM fermions
*Feng, Shiu, Soler, Ye 1401.5880, 1401.5890*

-- $M_{Z'}$ can only be suppressed by a few orders of magnitude relative to $M_{\text{string}}$.

-- Phenomenologically relevant only for low string scale.

-- Bound on $M_{Z'} > \sim \text{few TeV}$

--- Piyush Kumar ---
Only the tip of the DM Iceberg...

- Until now, only talked about $U(1)_{\text{dark}}$
- Many other possibilities: $G_{\text{dark}}$; $G_{\text{dark}} \ast U(1)_{\text{dark}}$; $G_{\text{dark}} \ast G_{\text{flavor}}$; ....
- Important and useful to have well-motivated theoretical guide

Theory Framework

DM Candidates

DM Couplings

Cosmology

Abundance

Signals

Tons to explore ...
Summary & Concluding Remarks

• **We are living in a data-rich era.**
  -- Data, even if “Null”, can provide important insights.

• **Talked about some aspects of recent data in High-energy physics, and the insights it provides for string-motivated frameworks vis-à-vis:**
  -- Higgs and Beyond-SM physics.
  -- Dark Matter Physics.

• **SUSY still the most probable framework for Beyond-SM physics.**
  -- However, SUSY models different from what naively expected.
  -- Most “simple” models appear to be “electroweak-tuned”

-- Studied potential signals of each

--- Imperfectly Natural

--- Mostly Un-natural
• **R-parity violation** – interesting implications for string-GUT models.

  * Observation of RPV will disfavor SU(5) GUT models. (with mild assumptions)
  * SO(10) models compatible with *spontaneous* RPV in principle -- can give rise to interesting signals.

• **Dark Matter** -- Variety of possibilities

  * Status of LSP WIMP DM -- still viable but under increasing strain.

  * Worth looking at other frameworks:

    E.g. Dark Sectors very well motivated

    -- incredible array of possibilities, just scratched the tip ...
    -- very important to have an underlying theoretical framework for understanding different aspects in a coherent manner.
“Electroweak-Natural” Models seem rather challenging.

-- Should not give up hope, however. May still be possible...

Think outside the Box!

Hope that Nature is kind to us and provides us with opportunities to make String Theory an experimental science.