INVITATION: DM AT THE LHC

DM@LHC 2017
University of California, Irvine

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3 April 2017
INTRODUCTION

Motivations for new physics

- Gauge hierarchy problem
- Dark matter
- Dark energy
- Baryon asymmetry
- Inflation
- Flavor problem
- Neutrino masses and mixings
- ...

In the last few years, the cosmic questions have risen in importance, and among these, dark matter has become the dominant motivation to expect new particles and forces.
DARK MATTER AT THE LHC

1997
LHC
Standard Model
Higgs Boson
Gauge Hierarchy

2007
LHC
Dark Matter
Higgs Boson
Gauge Hierarchy

2017
LHC
Dark Matter
Higgs Boson
Gauge Hierarchy

• Why has dark matter become so important?

WARNING Ancient history ahead!
• ~1984: LHC Conception

• 1993: SSC Canceled, future hadron colliders = LHC. LHC program:
  – Discover and study the Higgs boson
  – Precisely study SM particles, e.g., the top quark
  – Discover and study new particles that solve the gauge hierarchy problem

• 1993: SLAC demonstrates highly polarized beams, linear collider efforts in Asia, Europe, and America start becoming the ILC. ILC program:
  – Precisely study the Higgs boson
  – Precisely study SM particles, e.g., the top quark
  – Discover and precisely study new particles that solve the gauge hierarchy problem with mass up to $E_{\text{beam}}$

• Why build the ILC? What does precision study of new particles buy you?
THE ANSWER: DARK MATTER

• 1998: Accelerating universe discovered
• 2001-: rapid rise in precision cosmology from CMB experiments, etc.
• Late 1990’s-: a new boom in DM candidates begins (Q balls, WIMPzillas, inelastic DM, KK dark matter, T-odd dark matter, superWIMPs, etc.)
• New collider goals
  – What can colliders tell us about cosmology?
  – How well can dark matter properties be determined?
  – For example, how precisely can $m_X$ and $\Omega_X$ be determined?
• A shift in thinking
  – old: lightest neutralino = cascade endpoint, missing $E_T$ signature
  – new: lightest neutralino = dark matter, critically importance
• Most LHC physicists were too busy doing real work, and so this largely fell to ILC study groups to investigate
ILC COSMOLOGY GROUP 2004-05

ALCPG COSMOLOGY SUBGROUP

- Goals (Brau, Oreglia):
  - Identify cosmological questions most likely to be addressed by the ILC
  - Determine the role cosmology plays in highlighting specific scenarios for new physics at the ILC
  - Identify what insights the ILC can provide beyond those gained with other experiments and observatories

- Editors: Marco Battaglia, Jonathan Feng*, Norman Graf, Michael Peskin, Mark Trodden*

  *co-conveners

- 30-50 contributors, international participation
  Preliminary results presented here
THE WIMP MIRACLE

• “Determine the role cosmology plays in highlighting specific scenarios for new physics”

• The WIMP miracle: Continuous (relic density) and Discrete (stability)

• Irrespective of the gauge hierarchy problem, cosmology $\rightarrow$ weak scale, and the LHC is ideally suited to probing this scale definitively

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PRECISION CONSTRAINTS

• Problem: Large Electron Positron Collider, 1989-2000, provided precision constraints on new particles

- 14 Gyr later, Martha Stewart sells ImClone stock – the next day, stock plummets

- Final $N$ determined by $\sigma_A$

- $\Omega_{DM} \sim 0.1 \times \sigma_{weak}/\sigma_A$

- Remarkable!

- Coincidences? Maybe, but worth serious investigation!

• Solution: discrete parity $\rightarrow$ new particles interact in pairs. Lightest new particle is then stable

- Cheng, Low (2003); Wudka (2003)

• Dark Matter is easier to explain than no dark matter
COMPLEMENTARITY

“Identify what insights the ILC can provide beyond those gained with other experiments and observations”

essentially required understanding what the LHC, direct detection, and indirect detection could do: complementarity

The LHC is an integral part of any comprehensive program to understand dark matter
RELIC DENSITY AND COMPLETE MODELS

- A crowning achievement: given a complete model, determine the relic density to % level, compare with cosmological measurements
  - Baltz, Battaglia, Peskin, Wizansky (2006)

- Addressed many now famous slogans: “colliders can’t discover dark matter”, “dark matter might be multi-component”, “the dark sector could be complicated”

- The LHC can determine if missing particles are all of the DM, probe the Universe’s history back to $t \sim 1$ ps (cf. BBN and 1 s)
COMPLETE MODELS

• How is the WIMP paradigm doing now?

• “Rumors of its death have been greatly exaggerated.” -- Dark Twain

• Naturalness is highly subjective. Within the considerable variation of what constitutes a good definition of naturalness, there are natural, viable models. For example, in SUSY:
  – Effective SUSY
  – Focus point SUSY
  – Compressed SUSY
  – R-parity violating SUSY
  – Dirac gaugino SUSY
  – ...

• A new personal favorite: 4th generation SUSY
MSSM4G

- Naturalness suggests light stops and sbottoms, $m_h = 125$ GeV suggests heavy stops and sbottoms

- A resolution: introduce a 4\textsuperscript{th} generation of particles to raise the Higgs mass

- Chiral 4\textsuperscript{th} generation particles are possible, but highly constrained. Instead, add vector-like 4\textsuperscript{th} generation particles

- Remarkably, requiring gauge coupling unification, there are only two options: the QUE and QDEE models. E.g., QUE:
  
  \begin{align*}
  &\text{Dirac fermions: } T_4, B_4, t_4, \tau_4 \\
  &\text{Complex scalars: } \tilde{T}_{4L}, \tilde{T}_{4R}, \tilde{B}_{4L}, \tilde{B}_{4R}, \tilde{t}_{4L}, \tilde{t}_{4R}, \tilde{\tau}_{4L}, \tilde{\tau}_{4R}
  \end{align*}

Moroi, Okada (1992)
MSSM4G COSMOLOGY

Abdullah, Feng (2015); Abdullah, Feng, Iwamoto, Lillard (2016)

• The introduction of a heavy 4\textsuperscript{th} generation completely changes the cosmology

• The single process $\chi\chi \rightarrow \tau_4\tau_4$ dominates all SM processes combined

• The resulting DM is a Bino-like neutralino, but heavier

• Direct detection cross sections are Higgs-mediated and Higgsino-fraction suppressed, naturally fall between current bounds and the neutrino floor
MSSM4G AT THE LHC

see Mo Abdullah and Ben Lillard’s poster

• A broad range of interesting LHC signals. 4th generation particles must decay, but can decay to any of the 1st three generations with a variety of lifetimes

• Quarks and squarks in the 1-2 TeV range

• $\tilde{\tau}_4 \tilde{\tau}_4$ Drell-Yan production, leading to long-lived charged particles, displaced vertices, etc.

• $\tilde{\tau}_4 \tilde{\tau}_4$ Drell-Yan production, followed by decays $\tilde{\tau}_4 \rightarrow e \chi, \mu \chi, \tau \chi$

• $\tau_4 \tau_4$ Drell-Yan production, followed by decays $\tau_4 \rightarrow \tau Z, \nu W, \tau h$, etc.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>QUE (GeV)</th>
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<tbody>
<tr>
<td>$M_{\tilde{B}}$</td>
<td>$200 - 540$</td>
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<tr>
<td>$m_{\tilde{q}_4}$</td>
<td>$1000 - 4000$</td>
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<tr>
<td>$m_{\tilde{\ell}_4}$</td>
<td>$350 - 550$</td>
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<tr>
<td>$m_{q_4}$</td>
<td>$1000 - 2000$</td>
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<td>$m_{\ell_4}$</td>
<td>$170 - 450$</td>
</tr>
<tr>
<td>$m_{\tilde{\tau}}$</td>
<td>$1000 - 4000$</td>
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OTHER COMPLETE MODELS

Theories of Dark Matter?

Other Complete Models

- MSSM
- R-parity violating
- NMSSM
- Supersymmetry
- Extra Dimensions
- Warped Extra Dimensions
- Little Higgs
- T-odd DM
- Axion-like Particles
- Littlest Higgs
- QCD Axions
- Axion DM
- UED DM
- Solitonic DM
- Quark Nuggets
- Dynamic DM
- WIMPless DM
- Hidden Sector DM
- Self-Interacting DM
- Dirac DM
- R-parity Conserving
- Gravitino DM
- Q-balls
- Dark Photon
- Light Force Carriers
- Sterile Neutrinos
Complete Models

Produce other particles, which decay to DM

Effective Theories

Produce DM directly
PROTO-EFFECTIVE THEORIES AT THE ILC

• Thermal relic WIMPs annihilate to SM particles, and so should be produced directly at colliders

• First considered at the ILC: pair production is invisible, so consider photon radiation

\[
\Omega_{\text{dm}} \Rightarrow e^- e^+ \Rightarrow e^- e^+ \Rightarrow e^- e^+ \Rightarrow \text{ILC } \sigma(\gamma + \bar{\nu})
\]

Birkedal, Matchev, Perelstein (2004)

• Also (less successfully) mono-jets and mono-photons at the Tevatron and LHC

Feng, Su, Takayama (2005)
DM EFFECTIVE THEORY

• This approach received a huge boost when hints of light DM motivated a hierarchy between the DM and mediator masses
  Beltran, Hooper, Kolb, Krusberg, Tait (2006)
  Goodman, Ibe, Rajaraman, Shepherd, Tait, Yu (2010)
  Bai, Fox, Harnik (2010)

• These have motivated a plethora of mono-$\gamma$, j, b, t, W, Z, h searches, probing dark matter at the LHC one operator at a time

• DM effective theory allows comparison to indirect, direct search results; LHC does very well for some operators, low DM masses

<table>
<thead>
<tr>
<th>Name</th>
<th>Operator</th>
<th>Coefficient</th>
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<tr>
<td>D1</td>
<td>$\bar{\chi}\chi\bar{q}q$</td>
<td>$m_q/M_*^3$</td>
</tr>
<tr>
<td>D2</td>
<td>$\bar{\chi}\gamma^5\chi\bar{q}q$</td>
<td>$i m_q/M_*^3$</td>
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<tr>
<td>D3</td>
<td>$\bar{\chi}\chi\gamma^5q$</td>
<td>$i m_q/M_*^3$</td>
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<td>D4</td>
<td>$\bar{\chi}\gamma^5\chi\bar{q}\gamma^5q$</td>
<td>$m_q/M_*^3$</td>
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<tr>
<td>D5</td>
<td>$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma^\mu q$</td>
<td>$1/M_*^2$</td>
</tr>
<tr>
<td>D6</td>
<td>$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma^\mu q$</td>
<td>$1/M_*^2$</td>
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</tbody>
</table>

...
• Extends coverage to include explicit dark mediators/forces, signatures include dijets, etc.
• Provides simple framework to interpret searches in terms of
  - Discrete choices of couplings: vector, axial, scalar, pseudoscalar
  - Continuous choices of a small set of parameters: $g_q$, $g_\chi$, $m_\chi$, $m_{\text{MED}}$
**RECENT LHC RESULTS**

### List of CMS/ATLAS DM searches

#### K. Hahn Aspen 2017 talk

<table>
<thead>
<tr>
<th>X</th>
<th>Dataset</th>
<th>Documentation</th>
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<td>EXO-16-039</td>
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<td>Higgs (yy)</td>
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<td>Higgs (bb), with yy combo</td>
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<td>EXO-16-012</td>
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<td>tt (hadronic, semileptonic)</td>
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<td>EXO-16-005</td>
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<td>tt (dileptonic + tt combination)</td>
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<td>EXO-16-028</td>
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<td>t hadronic</td>
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<td>bb</td>
<td>2015, 2.2 fb-1</td>
<td>B2G-15-007</td>
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#### S. Schramm 2016 Moriond talk

**Analysis summary table**

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<tr>
<th>Analysis</th>
<th>Dataset</th>
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<tr>
<td><strong>Production search:</strong></td>
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<td>$E_{T}^{miss} + V$</td>
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<td>$E_{T}^{miss} + V / Z \rightarrow qq$</td>
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<td>2015</td>
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<td>Dijet + ISR</td>
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<td>Mediator searches</td>
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<td>Search combination</td>
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<td>Plot: Summary plot page</td>
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**Trofato, Cosmic Visions talk (2017)**
CONCLUSIONS

- Dark matter has long been one of the great scientific problems of our time, but it has become leading evidence for new particles and forces. Much of BSM physics is now also DM physics.

- Irrespective of the gauge hierarchy problem, cosmology $\rightarrow$ weak scale, and the LHC is ideally suited to probing this scale definitively.

- The LHC is an integral part of any comprehensive program to understand dark matter and may probe the Universe’s history back to $t \approx 1$ ps (cf. BBN and 1 s).

- Recent progress continues to make the DM/LHC interface an incredibly fertile area for creative ideas connecting theory/experiment and astrophysics/particle physics, with dark matter motivating many interesting scenarios that the LHC is ideally suited to probe. Lots of fascinating work ahead!