What’s Matter? Dark Matter!

SMP 2012

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http://faculty.physics.tamu.edu/kamon/research/talk/2012/120331_SMP2012/120331_SMP12_DarkParticleHunters_v2.pdf
Prologue

[Science]
- Curiosity-driven: Lots of Questions. Priceless!
- Fact-based: Interplay between theory and experiment
- Future investment: today's new idea can be a future application

[Todays Theme]
Thinking of the largest scale by studying the smallest object...

“What is the mysterious Dark Matter that dominates the mass in the Universe?”
Who Wanted “Dark Matter”?
While examining the Coma Galaxy Cluster (large cluster of galaxies - over 1,000 identified galaxies; mean distance from Earth is 99 Mpc or 321 million ly) in 1933, Zwicky was the first to use the Virial Theorem to infer the existence of unseen matter, what is now called Dark Matter. He was able to infer the average mass of galaxies within the cluster, and obtained a value about 160 times greater than expected from their luminosity, and proposed that most of the matter was dark. The same calculation today shows a smaller factor, based on greater values for the mass of luminous material; but it is still clear that the great majority of matter is dark.
Episode 1: Dark Matter in the Universe
Everything (that we can see) is made of electrons, up quarks and down quarks.
12 elementary particles are known fundamental building blocks of matter. 4 fundamental forces govern the transitions between particles. The Standard Model, a mathematical rule, includes 12 particles and 3 forces.

**Elementary Particles**

**ANIMAL MASSES SCALE WITH PARTICLE MASSES**

**Thirteen Generations of Matter**

**Quarks**
- Up
- Charm
- Top
- Down
- Strange
- Bottom

**Leptons**
- Electron
- Muon
- Tau
- Neutrino (masses: $< 3 \times 10^{-6}$ MeV, $< 0.19$ MeV, $< 18.2$ MeV)

**Masses in MeV**
- 2.75
- 1300
- 178000
- 6
- 110
- 4500
- 0.511
- 105.7
- 1777
- $< 3 \times 10^{-6}$
- $< 0.19$
- $< 18.2$
- Neutrino

**“Standard Model” Cube**

**Forces**
- Strong force
- Electromagnetic force
- Weak force
- Gravity

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Dark Matter!
However, the Universe is made of ...

3 Contents

- Ordinary matter (4%)
- Dark Matter (23%)
- Dark Energy (73%)
- 3.6% Intergalactic gas
- 0.4% Stars, etc.

Today’s focus

- Dark Matter (23%)
  - What is the dark matter?
  - An elementary particle?

Rotation curve of a typical spiral galaxy: predicted (A) and observed (B). The discrepancy between the curves is attributed to dark matter.
Dark Matter in the Universe
splitting normal matter and dark matter apart
– Another Clear Evidence of Dark Matter –
(8/21/06)

Ordinary Matter
(NASA’s Chandra X Observatory)

Dark Matter
(Gravitational Lensing)

Approximately the same size as the Milky Way

Learn how to determine distances throughout the whole universe. See Lecture 5 by Prof. Krisciunas on Mar. 3.
Properties of Cold Dark Matter

It Doesn’t Matter.
Right, it doesn’t shake hand with anyone easily. Two dark matter clusters (in blue) are just passing each other. It is a long-lived (stable) object.

It’s a Cold Matter.
Yes, it is a “relativistically” slowly moving (“cold”) object.

It’s an Invisible Matter.
Right, it doesn’t respond to your flash light. This means it is a neutral object.

So, It’s a Cold Dark Matter (CDM).

Can it be one of the known particles? Let’s check out!
[Q] Can be the dark matter a Standard Model particle?

[Recap: Dark matter particles]
(1) Weakly interacting
(2) Neutral
(3) Heavy ... *relativistically* slowly moving

[A] Quarks, electron, muon, and tau cannot be dark matter, because they are interacting via strong and/or electromagnetic forces. Neutrinos are too light.

[Q] What should we do?

[A] Expand the Standard Model framework based on a new symmetry, e.g., *Supersymmetry* or SUSY (next page)

→ New particles, including a dark matter candidate
Supersymmetry (SUSY)

Anti-Particles and SUSY

- Anti-particle Transformation
- SUSY Transformation

Spin (& charge) is a fundamental property and a powerful tool in information technology. See Lecture 1 by Prof. Sinova on Jan. 28.

A set of new particles, including a dark matter candidate

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Dark Matter!
Connection to Early Universe

We want to understand mysterious dark matter.

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Dark Matter!
Episode 2: Where and how?

“Interconnection” between particles and dark matter
Possible Dark Matter Interactions

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Dark Matter!
Interconnection at TAMU

<table>
<thead>
<tr>
<th>CMS</th>
<th>SuperCDMS</th>
<th>AMS-2</th>
<th>GMT</th>
</tr>
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<tbody>
<tr>
<td>2009</td>
<td>2012</td>
<td>2011</td>
<td>2018?</td>
</tr>
<tr>
<td>Geneva, Switzerland</td>
<td>North America</td>
<td>ISS</td>
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<td>Dark matter in pp collisions at the CERN’s LHC</td>
<td>DM-proton elastic collisions in Ge detector at SNOLAB</td>
<td>DM annihilation</td>
<td>Dark matter &amp; Dark energy, Black hole, Galaxy formation</td>
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7 trillion electron-Volts (TeV) → 14 TeV

Today’s focus

Dark Matter!

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AMS-2

Alpha Magnetic Spectrometer

Giant Magellan Telescope

Cryogenic Dark Matter Search

Large Hadron Collider

Dark matter in pp collisions at the CERN’s LHC

DM-proton elastic collisions in Ge detector at SNOLAB

Dark matter & Dark energy, Black hole, Galaxy formation

24.5-meter primary mirror

Geneva, Switzerland

North America

ISS

Chile

2011

2012

2009

2018?
Conseil Européen pour la Recherche Nucléaire (European Organization for Nuclear Research)

Large Hadron Collider

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Dark Matter!
LHC : Proton-Proton Collider

27 km ring

27km-long ultra high vacuum tubes with about one thousand 14.3m-long dipole magnets and 8000 other types of magnets, accelerating protons to 99.999999% of speed of light. You would have to connect 600,000,000,000 (0.6 trillion) 12V batteries. 

Magnets are used everywhere and can be explored at nano-scale. See Lecture 3 by Prof. Roshchin on Feb. 11.
Irradiation of nasopharyngeal carcinoma (a cancer originating in the nasopharynx) by photon (X-ray) therapy (left) and proton therapy (right).

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Pretty Big & Heavy Detector

21 m x 15 m x 15 m, 12,500 tons

“Particle” Telescope at CERN vs. Hubble Space Telescope in outer space

The CMS is one of two super-fast & super-sensitive detectors, consisting of 15 heavy elements, collecting debris from the collision and converting a visual image for us.
Proton and (anti)proton collision can produce the Standard Model particles like heavy top quarks (~180 times heavier than a proton!) as well as dark matter particles.
Possible?

Yes! Possible to create heavier new particles in the “elementary particle” world.

New particle will be seen as a Peaking Signal …
Mass of System

When a top quark is created, followed by a break-up ("decay"; \( t \rightarrow W + b; \ W \rightarrow e \ \nu \)), its signal is detected at a specific amount of energy (e.g., "mass" of the "e", "\( \nu \)" and "b" system).

Complete the decay diagram.

\( t \rightarrow W^+ + b \)

\( W^+ \rightarrow e^+ \ \nu \)
What is “Peaking” Signal?

When a new particle (e.g., top quark) is created, followed by a break-up (“decay”; \( t \rightarrow W + b; \ W \rightarrow e + \nu \)), its signal is detected at a specific amount of energy (“mass”). We plot the frequency of total energy of “e”, “\( \nu \)” and “b”.

Complete the decay diagram.

\[
t \rightarrow W^+ + b \\
W^+ \rightarrow e^+ \nu
\]
What is “Peaking” Signal?

When a new particle (e.g., top quark) is created, followed by a break-up ("decay"); $t \rightarrow W + b$; $W \rightarrow e \nu$), its signal is detected at a specific amount of energy ("mass"). We plot the frequency of total energy of "e", "\nu" and "b".

Complete the decay diagram.

$t \rightarrow W^+ + b$
$W^+ \rightarrow e^+ \nu$

No particular structure

Normal -like distribution

"Signal"

"Background"
We establish the existence of the top quark using a $67 \text{ pb}^{-1}$ data sample of $\bar{p}p$ collisions at $\sqrt{s} = 1.8 \text{ TeV}$ collected with the Collider Detector at Fermilab (CDF). Employing techniques similar to those we previously published, we observe a signal consistent with $t\bar{t}$ decay to $WWbb$, but inconsistent with the background prediction by 4.8$\sigma$. Additional evidence for the top quark is provided by a peak in the reconstructed mass distribution. We measure the top quark mass to be $176 \pm 8(\text{stat}) \pm 10(\text{syst}) \text{ GeV}/c^2$, and the $t\bar{t}$ production cross section to be $6.8^{+3.6}_{-2.3} \text{ pb}$. 

PACS numbers: 14.65.Ha, 13.85.Qk, 13.85.Ni

**FIG. 3.** Reconstructed mass distribution for the $b$-tagged $W^+ \pm 4$-jet events (solid). Also shown are the background shape (dotted) and the sum of background plus $t\bar{t}$ Monte Carlo simulations for $M_{\text{top}} = 175 \text{ GeV}/c^2$ (dashed), with the background constrained to the calculated value, $6.9^{+2.5}_{-1.9}$ events. The inset shows the likelihood fit used to determine the top mass.
More Peaking Signals (II)

Aug. 9, 2010

LHC is powerful enough to re-discover those particles in 4 months.

We expect an evidence of dark matter to appear as “Peaking Signal” in complex final states.
Where will the spin-0 Higgs Bosons be discovered?
How about the dark matter particles?
Discovery Path at the LHC

14 TeV (~14,000 x proton mass) = Collision Energy
Protons fly at 99.999999% of speed of light

??? = Bunches/Beam
??? = Protons/Bunch

14 TeV Proton-Proton Collisions

Bunch Crossing ??? Hz

Proton Collisions ??? Hz

Parton Collisions

New Particles 1 Hz to 10 micro (10^{-5}) Hz
(Higgs, SUSY, ....)

We want to see many “discovery” events.

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Dark Matter!
14 TeV (~14,000 x proton mass) = Collision Energy
Protons fly at 99.999999% of speed of light
2808 = Bunches/Beam
100 billion (10^{11}) = Protons/Bunch

Why do we need so many collisions?

Fabrication of nanometer devices is the key for modern telecommunication to read massive data super fast. See Lecture 4 by Prof. Belyanin on Feb. 25.
Supposed that you have a black box of a “die” system (you don’t know the number of dices and its shape), but you know the total number.

How do you know the probability of seeing “1”?

What do you do to report it accurately?

If the nature were a complex die system, how can we probe?

We need many trials !!!
Quiz: How Many Giraffes?

Shot #1

One!
Two!!

Still, one!

No! It is two!!

Yes, definitely!!

We need more than one snap-shot!!!
Experimental Method

We analyze “debris” after each proton-proton collision using super-fast and super-sensitive detector and extract evidence (“peaking signal”) of new and rare phenomena.
Episode 3: Brief History of “Peaking Signal” Hunters At Hadron Colliders
Big Bang, Back to the Future

History of the Universe

Accelerators: CERN-LHC

BNL-RHIC

CERN-LEP

SLAC-SELC

Inflation

Key:

- $w, z$ bosons
- $\nu, \bar{\nu}$ photon
- $q$ quark
- $g$ gluon
- $e$ electron
- $m$ muon
- $\nu$ neutrino

Particle Data Group, LBNL, © 2000
13.8 Billion Years Ago

13.8 BILLION YEARS AGO, A FEW SECONDS BEFORE THE CREATION OF OUR UNIVERSE...

All set. Let's fire up this Large Hadron Particle Collider and see what happens!
1983

There was jubilation at CERN following the announcement on 17 October that Carlo Rubbia and Simon van der Meer had been nominated for the 1984 Nobel prize in physics “for their decisive contributions to the large project which led to the discovery of the field particles W and Z, communicators of the weak interaction”. Rubbia, together with David Cline and Peter McIntyre, put forward the bold idea to collide beams of protons and antiprotons in existing machines. Stochastic cooling [invented by van der Meer in 1968] was the key in making antiproton beams sufficiently intense for the scheme to work.

- December 1984 pp419–420 (extract).

1976 ... A bold idea of proton-antiproton collider by Cline, McIntyre and Rubbia
1983 ... Discovery of W and Z
1984 ... Nobel prize to Carlo Rubbia and Simon van der Meer
Twenty-three years ago an event at CERN changed the world forever. Tim Berners-Lee handed a document to his supervisor Mike Sendall entitled “Information Management : a Proposal”. “Vague, but exciting” is how Mike described it, and he approved it to go forward. The following year, the World Wide Web was born.

“We’ve learned Earth’s languages through the WWW.”

“Faster” internet! See Lecture 4 by Prof. Belyanin on Feb 25.
1985.10.13: First pp$^-$ Collisions

43 candidates from $3.4 \times 10^{12}$ collisions

In this artist’s representation of a particle collision, a proton and antiproton collide at high energy to produce top and antitop quarks.

Discovery of Top
2007-2008

International Workshop on
The Interconnection Between
Particle Physics and Cosmology

Scientific Topics
- Dark Matter & Dark Energy
- CMB Measurements
- Supernovae, Weak Lensing, & Large Scale Structure
- Future Telescopes
- Space Programs
- Particle Cosmology
- String Cosmology
- Dark Matter Searches
- Collider Searches
- Future Accelerators

http://ppc07.physics.tamu.edu

Program Advisory Committee

Organizing Committee

Cambridge-Mitchell (TAMU) Collaboration in Cosmology
Texas A&M University, College Station, TX, USA
May 14-18, 2007

Credit and Copyright [Left to Right]: CERN Photo (CMS), Richard Massey/Nature, NASA/Chandra X-ray Center

CBS comedy “Big Bang Theory”
(Season 1 Episode 15)

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2010.03.30: First 7000-GeV pp Collisions

2.5 x $10^{12}$ Collisions
2011 ...

350 x 10^{12} Collisions

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Dark Matter!
2012 ...

>1000 x 10^{12} Collisions

Dark Matter!
Interconnection between Particle Physics and Cosmology

Program Advisory Committee
- Program Chair: Dr. John Doe
- Program Co-Chair: Dr. Jane Smith

Organizing Committee
- Chair: Dr. Bob Johnson
- Co-Chair: Prof. Jane Smith

Cambridge-Mitchell (TAMU) Collaboration in Cosmology
Texas A&M University, College Station, TX, USA

Scientific Topics
- Dark Matter & Dark Energy
- CMB Measurements
- Supernovae
- Weak Lensing & Large Scale Structure
- Future Telescopes & Space-based
- Particle Cosmology
- Search for Dark Matter
- Collider Searches
- Future Accelerators

2nd International Workshop on the Interconnection between Particle Physics and Cosmology
PPC 2009
University of Oklahoma, Norman, OK, USA
May 18-22, 2009

PPC 2011 at CERN, June 14-18
PPC 2012 in Korea
PPC 2013 in TAMU??

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Dark Matter!
Discovery of Dark Matter?
Epilogue

Still huge puzzle

23% DARK MATTER

73% DARK ENERGY

New particle?
Expected to be discovered at the LHC.

3.6% INTERGALACTIC GAS
0.4% STARS, ETC.

Explained by known particles.

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Dark Matter!
Congratulations for finishing 7th lecture!

Episode 4: Here are some fun examples of Particle Physics!
Particle-Physics in Movie

Dark Matter!
Particle-Physics in Movie [2]

Universal Pictures presents The Hulk, directed by Ang Lee, opening June 20, 2003.
Credit: ILM/Universal

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Dark Matter!
New Movies

**TERMINATOR**
*MODEL T-1999*

~DIRECTED BY STEVEN WEINBERG
~PRODUCED BY LEON LEDERMAN
~STARRING BHASKAR DUTTA RICHARD ARNOWITT ADAM G. RIESS TERUKI KAMON

**MISSION POSSIBLE**

**MISSION LEADER**
SUSY RA2tau

**HISTORY**
Achieved fame after finding THE HIGGS BOSON, wrote the national bestseller "Dark Matter Hunters"

**STATUS**
Currently working under cover for the World Physics Agency at TAMU, CERN, FNAL, DESY, and KNU

**GOAL**
Find dark matter in the remote corners of the universe and also prove string theory

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Dark Matter!
New Movie: Dark of the “Cube”

“Cube”
“Standard Model” Cube
“Dark Matter” Cube