Prologue

It has been 13.8 B years since the LHC machine was set up. The LHC started taking data from proton-proton collisions at a center-of-mass energy of 7 TeV on March 30, 2010 and became the energy frontier machine to lead to discoveries such as 125-GeV Higgs boson in July 4, 2012. The Standard Model is currently well tested up to ~100 GeV, but is expected to break down in the TeV domain where new physics should occur. This is precisely the domain we will study at the LHC.

Hunt for Dark Matter

1) PHENO Projects
2) PPC Cube
3) Chasing DM Signals

Teruki Kamon

May 18, 2015

Teruki Kamon (1,2)
1) Mitchell Institute for Fundamental Physics and Astronomy, Texas A&M University
2) Kyungpook National University

Arnowitt Symposium
Our PHENO projects have begun with these simple questions:

(a) How well mSUGRA models can be tested experimentally;
(b) How cosmologically-consistent collider signals can be determined.

The choice of PHENO project topics has been evolving as

Upgrade to the Electroweak Theory for the Higgs boson and Supersymmetry. hep-ex/0905252 (unpublished)
(2) Fermilab Report, Future Electroweak Physics at the TeVatron. Fermilab-Pub-96-08 (unpublished)

Major scientific events occurred:

(iii) SSC was cancelled in 1993
(ii) WMAP results were out in 2002
(i) The Higgs boson was discovered in 2012.

This also helps us shaping up ideas of accelerator upgrades in the U.S.
PHENO projects continue…

1. SSC was cancelled in 1993
   - 2 preprints, 2 WG reports, 1 pre-print

2. WMAP results were out in 2002
   - 8 papers

3. The Higgs boson was discovered in 2012
   - 10 papers

4. 13-TeV LHC Run in 2015
   - Counting...

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Higgs boson

2012


He wanted to listen to the most recent results from both sides at the same conference. This is how we started the International Workshop on the Interconnection between Particle Physics and Cosmology (PPC).
Interconnection between Particle Physics and Cosmology

PPC 2011 at CERN, June 14-18
PPC 2012 at KIAS, Korea, Nov. 5-9
PPC 2013 at CETUP*, SD, USA, July 8-13
PPC 2014 at Univ. de Guanajuato, Mexico, June 23-27
PPC 2015 at CETUP*, SD, USA, June 28 - July 3
PPC 2016 at Brazil
PPC 2017 at ???

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

The poster was designed during lunch meetings with him...
He was always chasing the signals of models. The story began with the Tevatron. However, the LHC changed a landscape of how to search new physics. It is a BIG thinking machine.

My advisor, Kunitaka Kondo, was smiling and exciting by saying “Kamon-kun, there is an interesting theory.” It was “Supersymmetry”. But I didn’t pay attention much until 1990’s.

Even my daughter was influenced, and drawing “Texas-style SUSY hunting” in 2007.

Even if I was influenced by DM Signals & ET Collaboration Experimentalist-Theorist (ET) collaboration helps to solve the “dark matter” puzzle.

He was always chasing the signals of models.
Hunt for Dark Matter

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1983

Put Forward the Bold Idea to

...collide beams of protons and antiprotons...

1984

...Discovery of W’s

March 1995: Discovery of top quark

SSC was cancelled (75), Lett. B 560 (1999) 447.

1990’s

...possible indication of grand unification with MSSM based on LEP data:

R. Arnowitt and D. Nanopoulos suggested to search for large tan β scenarios.

H. Baer and X. Tata strongly suggested to look for large "tri-lepton" events as a SUSY signature at the Tevatron.

My first SUSY analysis (ν’s, GeV) at CDF for the Standard Model, PRD 50 (1994) 5676

December 1984: pp+14—420 (extrac.)

Teruki Kamon

Hunt for Dark Matter

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CERN Courier (July/August 2009)
Hunt for Dark Matter

Luminosity vs. Energy


(1) I. Arnowitt, B. Dutta suggested (i) Bs/g111/g111/g80/g80 search at the Tevatron (2002); (ii) stau-neutralino coannihilation search at the LHC (2004). WMAP results (2002) \( \Delta \omega_m = 23\% \)

Pheno papers (2002, 2006, …)
Hunt for Dark Matter

2002 \rightarrow 2013

A Story of Rare $B_s$ Meson Decay

Detection of $B_s \rightarrow \mu^+\mu^-$ at the Tevatron Run II and constraints on the SUSY parameter space

PLB 538 (2002) 121
Hunt for Dark Matter

No Hint of SUSY — I Cry.

Received 18 July 2013; published 9 September 2013

PRL 107 (2011) 191804

PRL 111 (2013) 101804

Hunt for Dark Matter

Cry for SUSY

Additional news on B^+ -> J/psi (LHCb and CDF)

PRL 107 (2011) 191801

LHCb will update their analysis at the end of this week.
Milestones in 2009-10

- No hints of SUSY. SUSY (gluino and 1st/2nd gen. squarks) seems to be heavier than ~1.5 TeV.

- 2010-2014
  - Few shifts. Target first physics measurements if possible.
  - Week of Nov. 30.
  - Week of Nov. 16.
  - Nov. 7-8. Hopefully order 50 jets on first collisions for Bs signal.

- March 2010: First 7-TeV pp collisions
- December 2011: 3-sigma evidence for Higgs boson; no hint of SUSY
- July 2012: 5-sigma observation; still no Higgs boson: no hint of SUSY
- Sep. 2013: Strong evidence for Bs signal

- Connection to the dark matter
- SU(2) Higgs bosons
- Lightest (7) scalar top quark (stop)
- Compressed chargino/neutralino mass spectra

- Milestones in 2009-10
  - Nov 17 (Sat)
  - Nov 20 (Fri)
  - Dec 14 (Sun)

- LHC restarts in the middle Feb 2010.
- Ready for 7 TeV collisions
- LHC operation ends on Dec 16.
- WR: 1.18 TeV beam
- Dec 14 (Sun)
- 00:44 am
- Nov 30 (Mon)
- Dec 14 (Sun)
- Nov 20 (Fri)
- Nov 17 (Sat)
- Start of the long run!
He asked me one thing in 2006: “Teruki, how soon ATLAS and CMS can publish their first papers after the LHC turns on?”.

I answered: “It will take 2 years”. I was damn wrong.
Rise of the particle density at $\sqrt{s} = 7$ TeV steeper than in model predictions. Careful tuning effort of the MC generators is ongoing.

"Transverse Momentum and Pseudorapidity Distributions of Charged Hadrons in pp Collisions at $\sqrt{s} = 7$ TeV"
Hunt for Dark Matter

March 2004: When the ILC coannihilation "2tau" analysis was near complete, we (R. Arnowitt, B. Dutta, T. Kamon) started thinking of a possibility of detecting the coannihilation signal in the LHC. The idea was to capture two $\tau^0$ in the final state. This has come about due to both theoretical and experimental developments. On the other hand, the standard model of cosmology has become deeply interconnected with theoretical physics and particle physics and our understanding of nature.

No Hint of SUSY. I cry. But...

PHENO papers:

PLB 649 (2007) 73;
PLB 639 (2006) 46;
PLB 639 (2006) 46;
2011.12.13: Preliminary Results

Delivered by LHC: 5.72 fb

Recorded by CMS: 5.20 fb

High quality data: 4.7 fb

(about 92%)

(~350 trillion collisions)

Keep in mind they are preliminary results;
Keep in mind they are small numbers;
Keep in mind we will run in the next year.

Hunt for Dark Matter Teruki Kamon

2012.07.04: After 48 Years of...

After 48 years of postulate, ...

Hunt for Dark Matter

2011.12.13: Preliminary Results
Where will more new particles be discovered?  

I hope we see any sign of SUSY before my retirement...

How about the dark matter particles?

World "Discovery" Map
Energy Frontier Challenge

Teruki Kamon

Hunt for Dark Matter

Peter has been putting forward ideas of energy upgrade of the accelerator.

Dick was always enjoying with physics discussion:

- [1994] 4 TeV p-pbar Collider
- [2001] 6 TeV p-pbar Collider
- [2014] The history repeated. He is now proposing 100-300 TeV pp Collider.

Understanding the limitations at LHC14 will be an important step for FCC100pp.

A 100-TeV collider is powerful in producing heavy objects.

(*) just use a naïve scaling

<table>
<thead>
<tr>
<th>Collider</th>
<th>Gluino/Squark (GeV)</th>
<th>Mass Reach (M)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FCC (100 TeV)</td>
<td>~20.2 *</td>
<td></td>
</tr>
<tr>
<td>LHC (14 TeV)</td>
<td>~2.8 TeV</td>
<td></td>
</tr>
<tr>
<td>LHC (8 TeV)</td>
<td>~1.7 TeV</td>
<td></td>
</tr>
<tr>
<td>Tevatron (2 TeV)</td>
<td>~400 GeV</td>
<td></td>
</tr>
</tbody>
</table>

330 km x $3000/m = $810M

http://arxiv.org/abs/1402.5973

Peter originally proposed 100-km collider and seek inputs from B. Dutta, R. Eusebi, TK, and A. Safonov. We simply responded “What is the difference?” Peter replied “Hmm, I was not thinking big enough.”
Superstring: Beware!

I can't tell you what's in the dark matter.

Hunt for Dark Matter

No, Sir. But with neutralinos?

I am hungry. Can you make the DM sandwich with any Standard Model particle?

---

J. Ellis, SUSY07

Hunt for Dark Matter in 20??

*Dark Matter Sandwich*...

- All elements in one...$5
- Neutral, long-lived...$27
- Chef's choice...
- Dark Energy Power Drink...$68

~SPECIALS~

(Standard Model Particles)

Experimental Observation of Events with Large Missing Transverse Energy Accompanied By a Jet or Photon(s) in ppbar Collisions at $\sqrt{s} = 540$ GeV

29 March 1984

CERN-EP/84-42