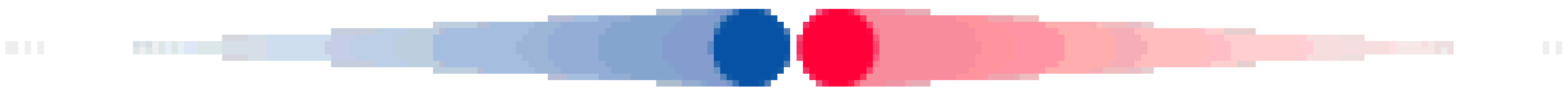
Lectures

on

Collider Physics



Kingman Cheung

NCTS 2007

Content of Lectures

1. Overview: collider physics enters an exciting era
2. Basics in collider physics
3. Collider phenomenology on supersymmetry
4. Connection with cosmology

Lecture 1

Overview

Particle Physics is entering an exciting era with the LHC?

Lecture 1

Overview

Particle Physics is entering an exciting era with the LHC?

YES: thousands of physicists' dream

Lecture 1

Overview

Particle Physics is entering an exciting era with the LHC?

YES: thousands of physicists' dream

May BE NOT: the LHC may be the last one

The Future of Particle Physics

There are going to be a number of particle physics experiments in this decade and the next:

The Future of Particle Physics

There are going to be a number of particle physics experiments in this decade and the next:

- More precision experiments: $g - 2$, EDM, Super-B.

The Future of Particle Physics

There are going to be a number of particle physics experiments in this decade and the next:

- More precision experiments: $g-2$, EDM, Super-B.
- Rarer decays: $\mu \to e\gamma, 3e$, $0\nu\beta\beta$

The Future of Particle Physics

There are going to be a number of particle physics experiments in this decade and the next:

- More precision experiments: $g-2$, EDM, Super-B.
- Rarer decays: $\mu \to e\gamma, 3e$, $0\nu\beta\beta$
- Neutrino experiments: MINOS, T2K, Gran Sasso, ICECUBE, Auger, ANTARES, Daya Bay.

The Future of Particle Physics

There are going to be a number of particle physics experiments in this decade and the next:

- More precision experiments: $g-2$, EDM, Super-B.
- Rarer decays: $\mu \to e\gamma, 3e$, $0\nu\beta\beta$
- Neutrino experiments: MINOS, T2K, Gran Sasso, ICECUBE, Auger, ANTARES, Daya Bay.
- High energy accelerators: Tevatron, LHC, ILC, VLHC.

Glorious moments of Collider experiments

Glorious moments of Collider experiments

5. 1976: Richter, Ting: *for their pioneering work in the discovery of a heavy elementary particle of a new kind*

Glorious moments of Collider experiments

4. 1984: Carlo Rubbia and Simon Van der Meer: *for their decisive contributions to the large project, which led to the discovery of the field particles W and Z, communicators of weak interaction*
5. 1976: Richter, Ting: *for their pioneering work in the discovery of a heavy elementary particle of a new kind*

Glorious moments of Collider experiments

3. 1988: Lederman, Schwartz, Steinberger: *for the neutrino beam method and the demonstration of the doublet structure of the leptons through the discovery of the muon-neutrino*
4. 1984: Carlo Rubbia and Simon Van der Meer: *for their decisive contributions to the large project, which led to the discovery of the field particles W and Z, communicators of weak interaction*
5. 1976: Richter, Ting: *for their pioneering work in the discovery of a heavy elementary particle of a new kind*

Glorious moments of Collider experiments

2. 1990: Friedman, Kendall, Taylor: *for their pioneering investigations concerning deep inelastic scattering of electrons on protons and bound neutrons, which have been of essential importance for the development of the quark model in particle physics*
3. 1988: Lederman, Schwartz, Steinberger: *for the neutrino beam method and the demonstration of the doublet structure of the leptons through the discovery of the muon-neutrino*
4. 1984: Carlo Rubbia and Simon Van der Meer: *for their decisive contributions to the large project, which led to the discovery of the field particles W and Z, communicators of weak interaction*
5. 1976: Richter, Ting: *for their pioneering work in the discovery of a heavy elementary particle of a new kind*

Glorious moments of Collider experiments

1. 1995: Martin L. Perl: *for pioneering experimental contributions to lepton physics, specifically for the discovery of the tau lepton*;
   Frederick Reines: *for pioneering experimental contributions to lepton physics, specifically for the detection of the neutrino.*
2. 1990: Friedman, Kendall, Taylor: *for their pioneering investigations concerning deep inelastic scattering of electrons on protons and bound neutrons, which have been of essential importance for the development of the quark model in particle physics*
3. 1988: Lederman, Schwartz, Steinberger: *for the neutrino beam method and the demonstration of the doublet structure of the leptons through the discovery of the muon-neutrino*
4. 1984: Carlo Rubbia and Simon Van der Meer: *for their decisive contributions to the large project, which led to the discovery of the field particles W and Z, communicators of weak interaction*
5. 1976: Richter, Ting: *for their pioneering work in the discovery of a heavy elementary particle of a new kind*

The earliest Accelerator

The earliest Accelerator

Galileo and the Leaning Tower of Pisa

Collider experiments in these three decades

Accelerator	Location	$E_{\rm CM}$	expts	Major results
SPEAR	SLAC	e^+e^-	Mark I	Charm
	(72-90)	$3-6$ GeV	Crystal Ball	τ,jets
Petra	DESY	e^+e^-	JADE	gluon jets
	(78-86)	$14-46$ GeV	Tasso, Argus	b mixing
PEP	SLAC	e^+e^-	Mark II, TPC,	b lifetime
	(80-90)	29 GeV	MAC, ASP	
$Sp\bar{p}S$	CERN	$p\bar{p}$	UA1, UA2,	W, Z
	(81-90)	540 GeV	UA5	
Tristan	KEK	e^+e^-	Amy, Topaz,	top is heavy
	(87-95)	$50-64$ GeV	Venus	
SLC	SLAC	e^+e^-	SLC	polarized Z properties
	(90's)	91 GeV		
LEP	CERN	e^+e^-	Aleph, Opal,	precision EW
	(89-96)	91 GeV	L3, Delphi	

Accelerator	Location	$E_{\rm CM}$	expts	Major results
HERA	DESY	ep	ZEUS, H1,	PDF, diffraction
	(92-now)	30×900 GeV	Hermes, HeraB	
Tevatron I	Fermilab	$p\bar{p}$	CDF,	top and
	(87-96)	1.8 TeV	DØ	W mass
LEP II	CERN	e^+e^-	Aleph, Opal,	WW, ZZ
	(96-00)	$91 - 209$ GeV	L3, Delphi	production
Tevatron II	Fermilab	$p\bar{p}$	CDF,	Higgs,
	(01-now)	1.96 TeV	DØ	EWSB, SUSY?
LHC	CERN	pp	Atlas,	Higgs, EWSB,
	(07-?)	14 TeV	CMS, LHCb	DM, SUSY?
ILC	Fermilab?	e^+e^-		
	(??)	$0.5 - 1$ TeV		

The Next High Energy Frontier: LHC

The next high energy accelerator is only the LHC. The LHC has 5 experiments, with more than 10,000 physicists from more than 40 countries. They work together to search for new discovery.

The Next High Energy Frontier: LHC

The next high energy accelerator is only the LHC. The LHC has 5 experiments, with more than 10,000 physicists from more than 40 countries. They work together to search for new discovery.

Paradise: everyone has a hope

The Next High Energy Frontier: LHC

The next high energy accelerator is only the LHC. The LHC has 5 experiments, with more than 10,000 physicists from more than 40 countries. They work together to search for new discovery.

Paradise: everyone has a hope

The high energy frontier beyond the LHC is uncertain. The future of high energy physics depends critically on the outcome of the LHC.

The Next High Energy Frontier: LHC

The next high energy accelerator is only the LHC. The LHC has 5 experiments, with more than 10,000 physicists from more than 40 countries. They work together to search for new discovery.

Paradise: everyone has a hope

The high energy frontier beyond the LHC is uncertain. The future of high energy physics depends critically on the outcome of the LHC.

If nothing is found, there is no legitimate reason to build the next accelerator.

The Next High Energy Frontier: LHC

The next high energy accelerator is only the LHC. The LHC has 5 experiments, with more than 10,000 physicists from more than 40 countries. They work together to search for new discovery.

Paradise: everyone has a hope

The high energy frontier beyond the LHC is uncertain. The future of high energy physics depends critically on the outcome of the LHC.

If nothing is found, there is no legitimate reason to build the next accelerator.

We still have 10–20 years of good physics to do

Large Hadron Collider (LHC)

The LHC is a particle accelerator which will probe deeper into matter than ever before. Due to switch on in 2007, it will ultimately collide beams of protons at an energy of 14 TeV

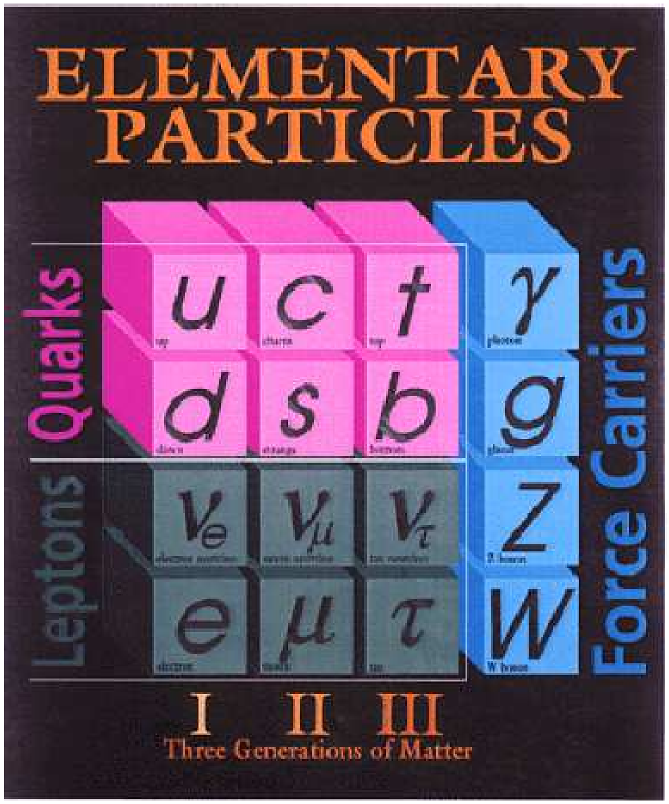
By accelerating and smashing particles, physicists can identify their components or create new particles, revealing the nature of the interactions between them.

The LHC is the next step in a voyage of discovery which began a century ago. Back then, scientists had just discovered all kinds of mysterious rays, X-rays, cathode rays, alpha and beta rays.

Because our current understanding of the Universe is incomplete! We have seen that the theory we use, the Standard Model, leaves many unsolved questions.

Questions that the LHC wants to address

- What's the origin of the mass of particles?



The answer may lie within the Standard Model, in an idea called the Higgs mechanism. The Higgs field has at least one new particle associated with it, the Higgs boson. If such particle exists, the LHC will be able to make it detectable.

- **Can the electroweak and the strong forces be unified?**

  Two forces, the electromagnetic force and the weak force were "unified" into a single theory in the 1970s. The weakest and the strongest forces, however, gravity and the strong force, remain apart.

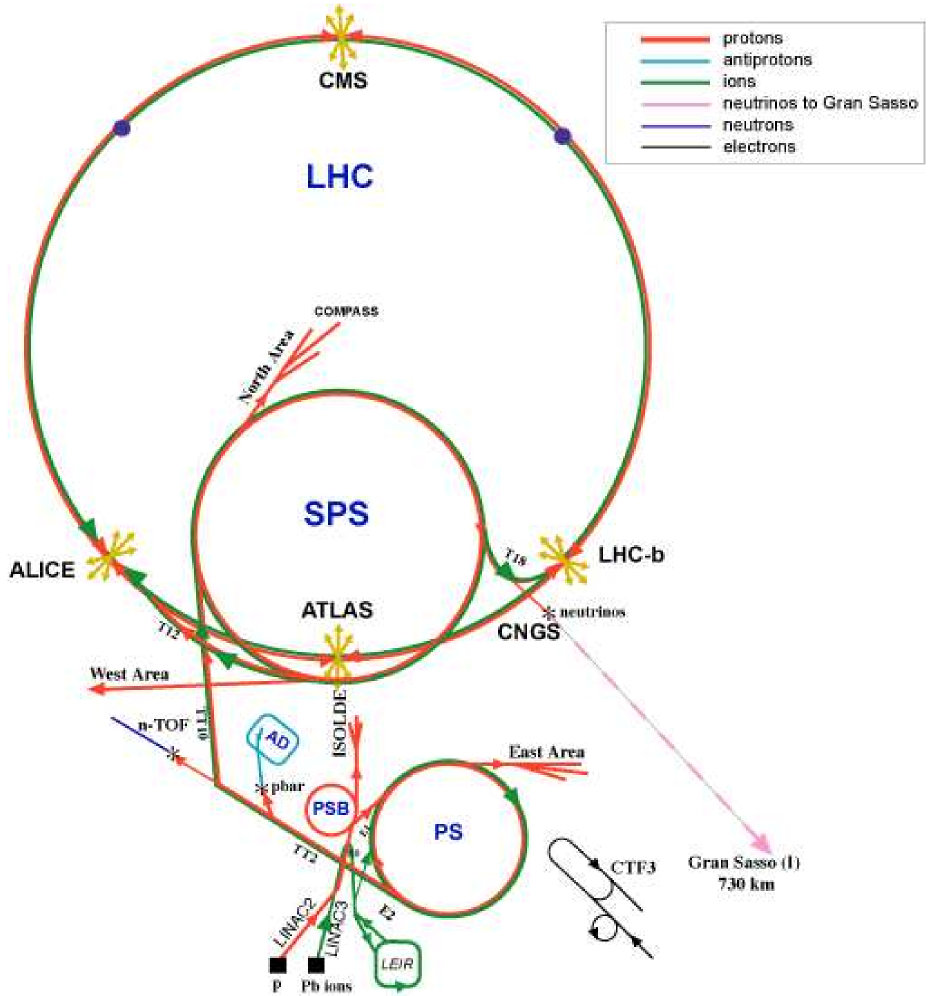
  Some attempts, grand unified theories, have success in unifying strong force too. GUT also have consequences at lower energies and can thus be tested with present day experiments. They require, for instance, a deep symmetry in the laws of nature, which in turn require the existence of special "superparticles". Some of these could be seen at the LHC.

- **Can the electroweak and the strong forces be unified?**
  Two forces, the electromagnetic force and the weak force were “unified” into a single theory in the 1970s. The weakest and the strongest forces, however, gravity and the strong force, remain apart.

  Some attempts, grand unified theories, have success in unifying strong force too. GUT also have consequences at lower energies and can thus be tested with present day experiments. They require, for instance, a deep symmetry in the laws of nature, which in turn require the existence of special ”superparticles”. Some of these could be seen at the LHC.

- **What is “Dark matter” made of?**
  Measurements in astronomy imply that up to 90% or more of the Universe is not visible, called dark energy and dark matter. Models predicting dark matter, e.g., the LSP in supersymmetry, also predict testable consequence at colliders.

Inside the LHC

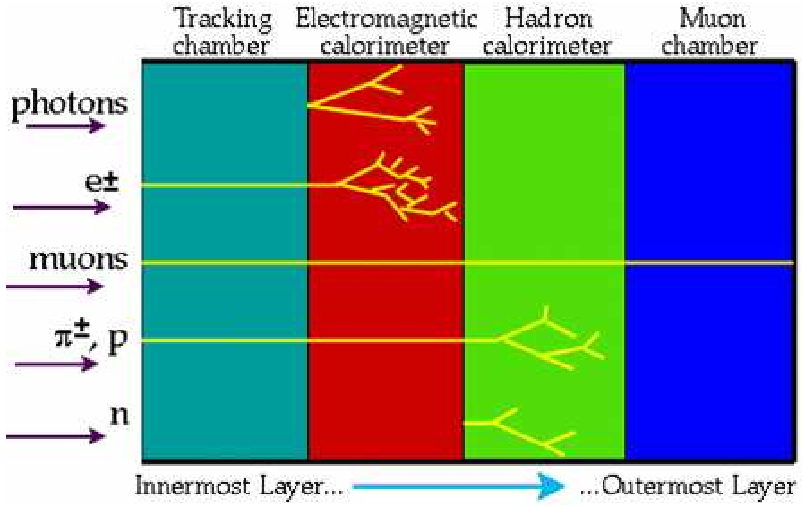


Collider experiments: ATLAS and CMS

Physicists smash particles into each other with two main objectives:

- to find out what is inside them
- to use the energy available in the collision to "create" new particles.

Physicists need "particle detectors" to see new particles.



A detector consists of tracking systems, calorimeters, muon systems to identify various particles.

In the other lectures, I will discuss

1. Collider Physics 101
2. Physics beyond the SM, current limits and expectations of
   - SUSY scenarios
   - Extra dimension models (not enough time)
3. Connection with Cosmology

1. Collider Physics 101

- Basics.
- Overview of a collider detector, using CMS as illustration.
- Details of a sample calculation of cross section (Z' production)
- Kinematics, e.g., in the Higgs search.

2. Supersymmetry

Perhaps, the minimal supersymmetric standard model (MSSM) is the most studied model beyond the SM. I remember some peoples in the field regard MSSM as “the SM”.

Motivations:

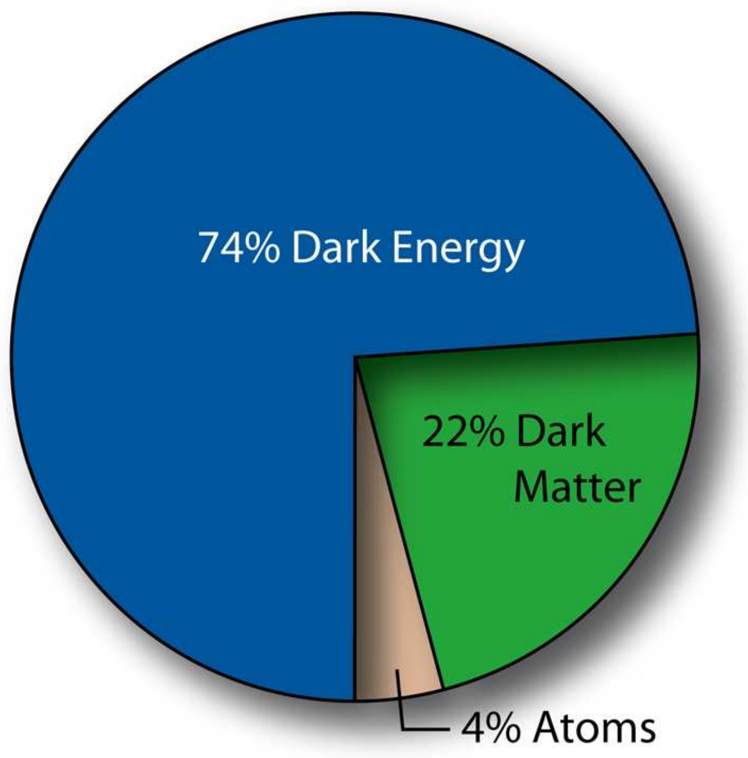
- Dynamical electroweak symmetry breaking
- Provide a natural dark matter candidate

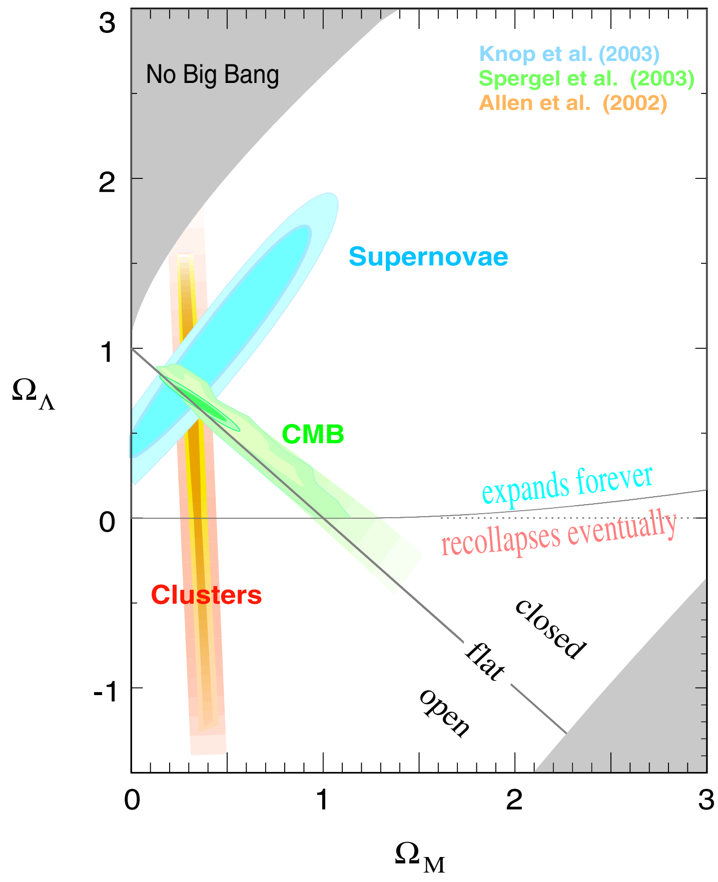
A few SUSY breaking models or scenarios:

- Gravity-mediated SUSY breaking (SUGRA).
- Gauge-mediated SUSY breaking (GMSB).
- Anomaly-mediated SUSY breaking (AMSB).
- Split supersymmetry.

Current limits

3. Cosmological Connections





Cosmology Connection with Particle Physics

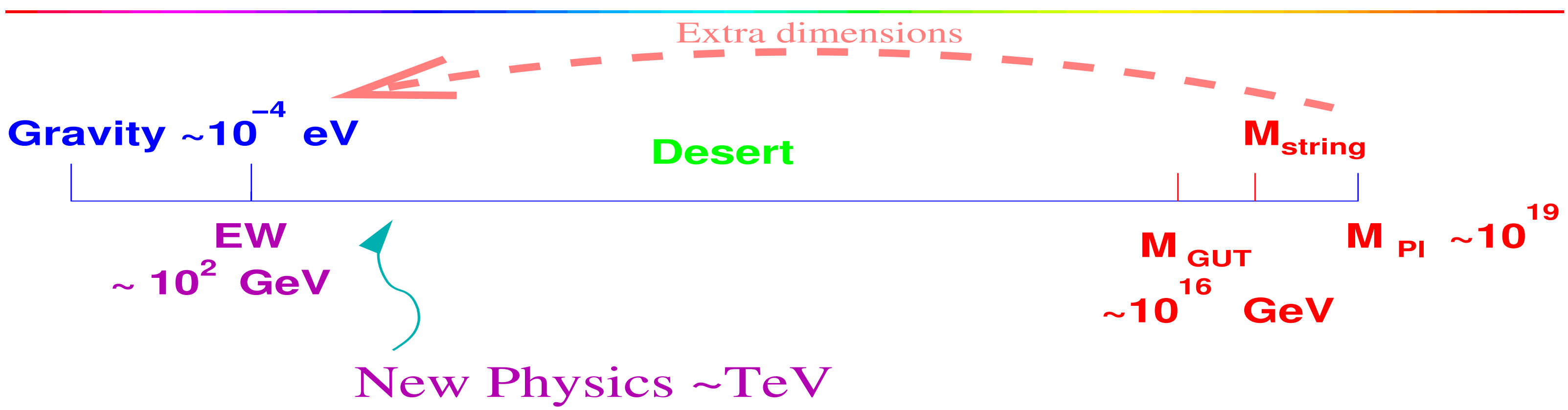
Cosmology needs new physics beyond the standard model (BSM):

- Dark energy.
- Dark matter.
- Baryon asymmetry.

To understand the above problems in the astronomical scales require the fundamental understanding of the micro-physics – Synergy between the studies of the Universe on the smallest and the largest scales.

The LHC will commence in 2007, which targets at TeV scale physics.

4. Extra Dimension models (if time permitted)



New ideas using extra dimensions can bring $M_{\rm Pl}$ down to TeV.

- Large extra dimension
- Warped extra dimension
- TeV^{-1} sized extra dimension
- Universal extra dimension
- A 5D SU(5) Supersymmetric GUT in an AdS slice
- A string resonance model

2007

2007

- The start of the LHC is a beginning of a very rich program. Many new ideas will be tested.

2007

- The start of the LHC is a beginning of a very rich program. Many new ideas will be tested.
- The ultimate mechanism for EWSB should be revealed.

2007

- The start of the LHC is a beginning of a very rich program. Many new ideas will be tested.
- The ultimate mechanism for EWSB should be revealed.
- Deep interplay between cosmology and collider studies.

2007

- The start of the LHC is a beginning of a very rich program. Many new ideas will be tested.
- The ultimate mechanism for EWSB should be revealed.
- Deep interplay between cosmology and collider studies.

We are looking forward to the LHC.