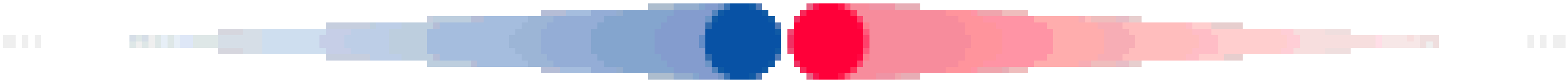
LHC

Overview of LHC Physics



Kingman Cheung

CUHK Lecture 1 Jan 2008

Outline of 4 Lectures

1. Overview
2. Basics in collider physics
3. Collider phenomenology on supersymmetry
4. Connection with cosmology

1. Overview

Particle Physics is entering an exciting era with the LHC

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Thousands of physicists' dream

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Hope that the LHC is NOT the last one

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- Neutrino experiments: MINOS, T2K, Gran Sasso, ICECUBE, Auger, ANTARES, Daya Bay.
- High energy accelerators: Tevatron, LHC, ILC, VLHC.

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1. 1995: Martin L. Perl: *for pioneering experimental contributions to lepton physics, specifically for the discovery of the tau lepton*;
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The earliest Accelerator

The earliest Accelerator

Galileo and the Leaning Tower of Pisa

Collider experiments in these three decades

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

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CERN: the LHC

The hope for high energy physics all seems rely on 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.

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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

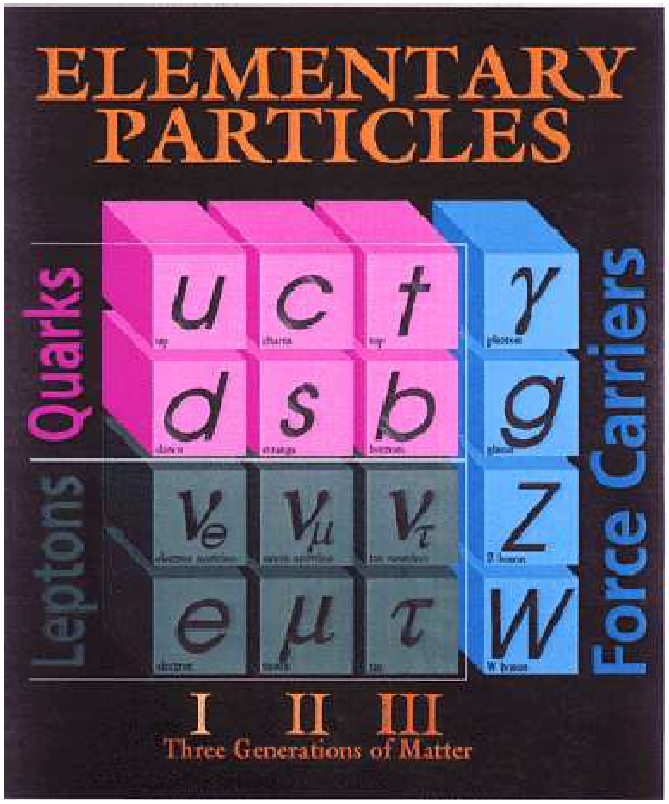
By accelerating and smashing particles, physicists can identify their components or create new particles, revealing the nature of the interactions between them.

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.

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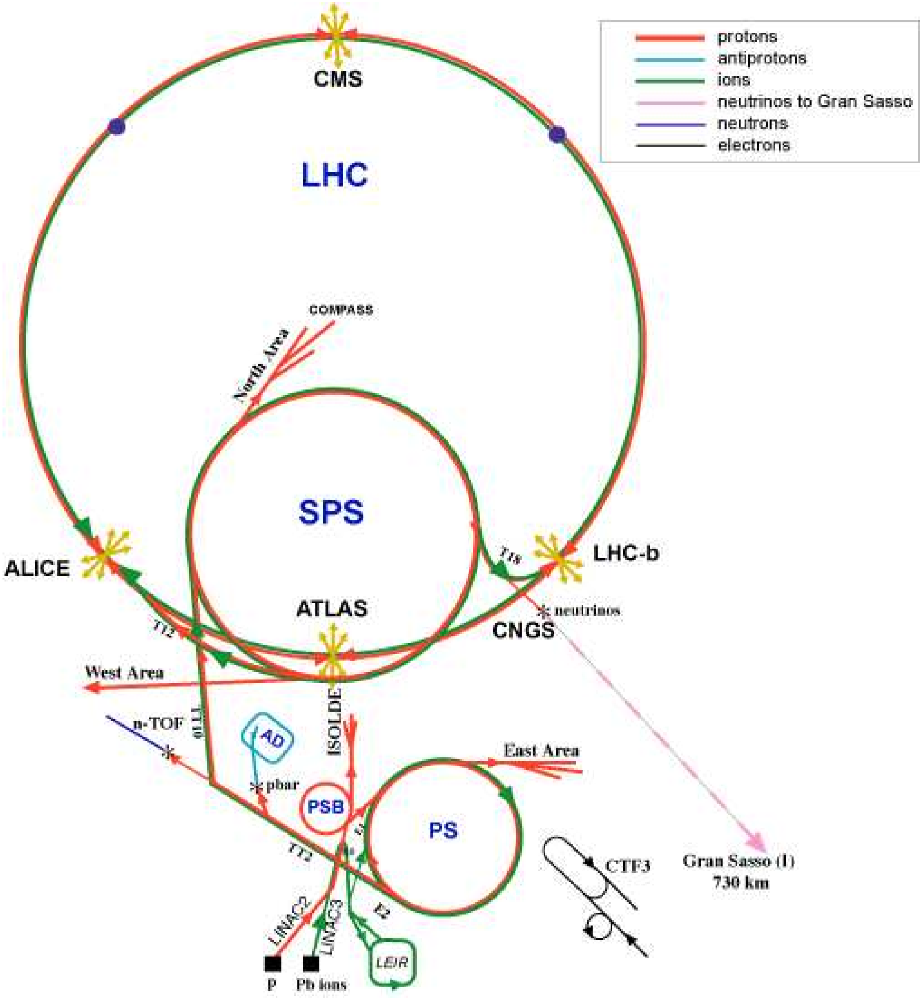
- **What is "Dark matter" made of?**

  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

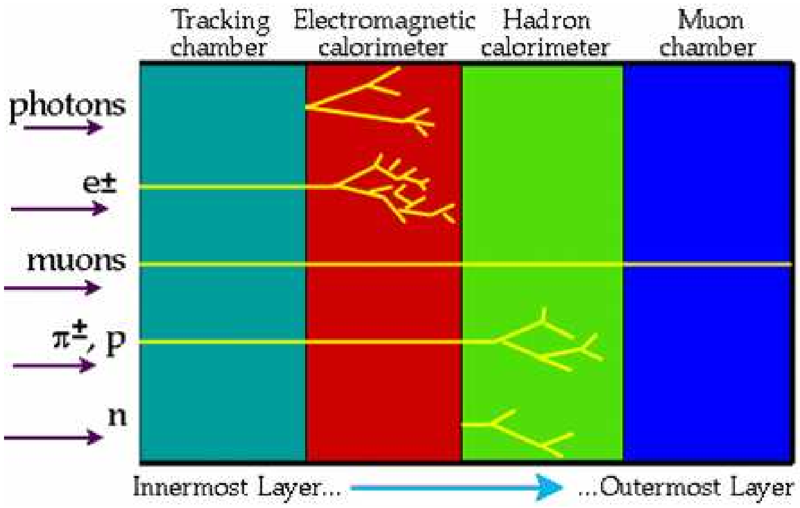


Collider experiments: ATLAS and CMS

Physicists smash particles into each other with two main objectives:

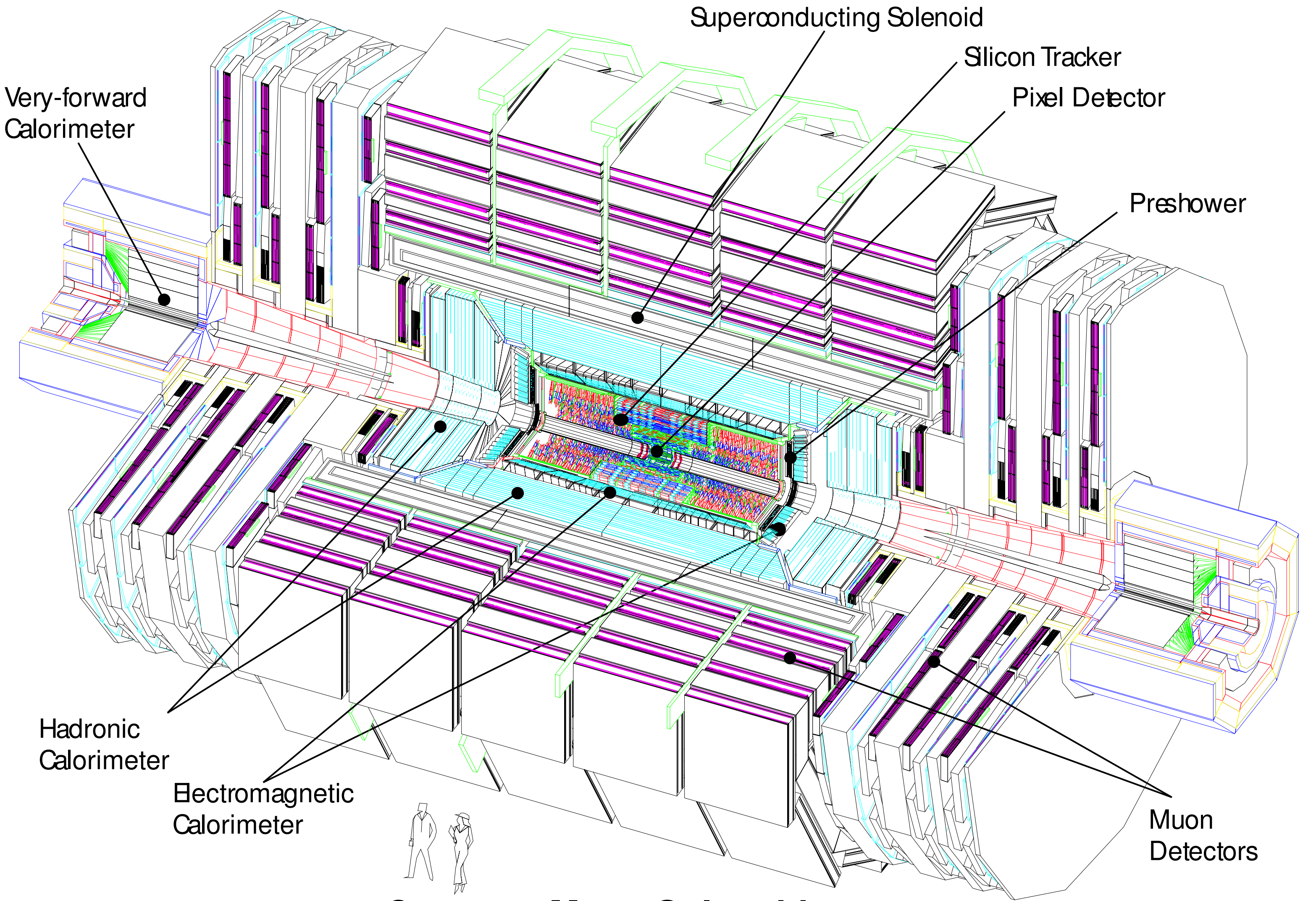
- to find out what is inside them
- to use the energy available in the collision to “create” new particles.

Physicists need “particle detectors” to see new particles.



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

CMS detector



Compact Muon Solenoid

Detection of the particles

Most particles will decay right after they are produced, e.g., W, Z, H, t, Z', RS graviton, ... We do not see them directly.

Colored particles (q, g) will hadronize into hadrons, such as $\pi, K, p, n, \ldots$

The distance that a particle travels in the detector

$$d = \gamma c \tau = (300\ \mu\mathrm{m}) \left(\frac{\tau}{10^{-12}\ \mathrm{s}} \right) \gamma$$

- Short-lived particles decay instantaneously into other particles, such as π^0, ρ.
- Particles with displaced vertex has a $\tau \sim 10^{-12}$ s, such as B, D, $\tau^\pm$.
- Quasi-stable particles with $\tau \gtrsim 10^{-10}$ s will interact with the detector before decay.
- Particles that do not interact with the detector at all, leading to missing transverse energy.

So at the end, the detector will only "see" γ, $e^\pm$, $\mu^\pm$, $\pi^\pm$, K, p, n.

2. Collider Physics 101

In a collider experiment one measures the number of events for the signal

$$N_{\rm observed} = \sigma_{\rm process} \times \epsilon_{\rm detection} \times \int \mathcal{L} dt \;+\; N_{\rm bkgd}$$

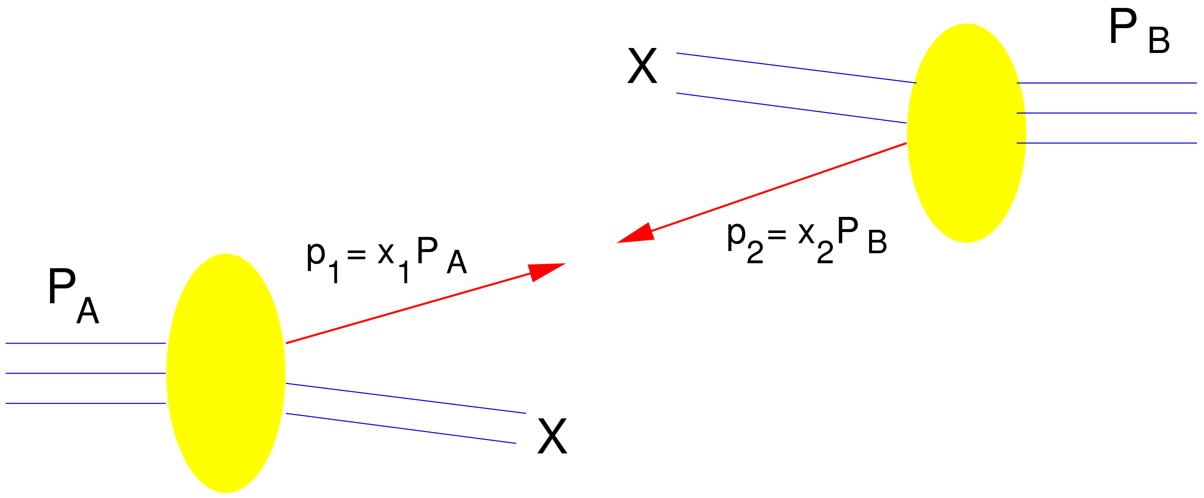
$\sigma_{\rm process} \equiv$ cross section of the signal process, e.g. the Higgs boson, extra dimension signal that one wants to look at.

$\epsilon_{\rm detection} \equiv$ prob. that the signal to be observed in the detector, including detector coverage, cut efficiencies, detector efficiencies.

$\int \mathcal{L} dt \equiv$ integrated luminosity.

$N_{\rm bkgd} \equiv$ no. of bkgd events that will go into the detector under the same selection cuts.

Calculation of σ: Parton Model



- Proton is a composite particle made up of point-like partons $(q, \bar{q}, g)$. The partons are directly involved in the collision.
- The probability distribution of finding a parton with the momentum fraction x is given by $f_{q/p}(x, Q^2)$.
- The subprocess cross section is calculated by perturbation, then convulated with the parton distribution functions:

$$\sigma(p_A p_B \to X) = \int dx_1 \, dx_2 \, f_{i/p_A}(x_1) \, f_{j/p_B}(x_2) \, \hat{\sigma}(ij \to X)$$

Separation of Signal from the backgrounds

We need to use some kinematic variables to identify the dynamics of the signal.

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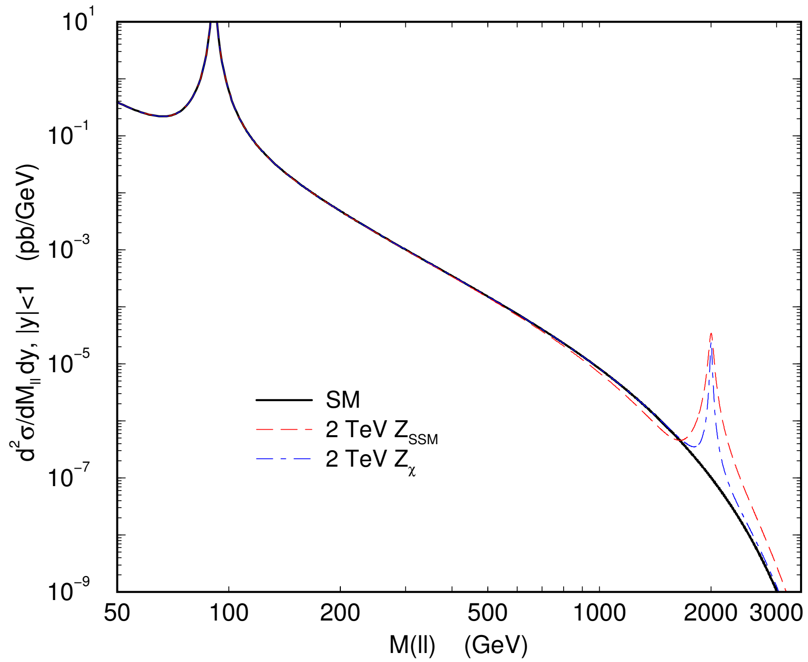
For example, in search of new resonances one can use the invariant mass of the final state particles:



It is obvious that $M_{\ell\ell}$ can reveal new resonances.

Physics Beyond the Standard Model

The coverage of physics models at the LHC is very broad. Popular ones include

- EWSB: Higgs bosons.
- Supersymmetry: SUSY particles.
- Extra dimension models: Kaluza-Klein states.
- GUT models: Z', leptoquarks.

3. Collider phenomenology on Supersymmetry

Motivations:

- Provide an elegant solution to hierarchy problem
- Gauge coupling unification
- Dynamical electroweak symmetry breaking
- Provide a natural dark matter candidate

A few SUSY breaking models:

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

Current limits

Minimal Supersymmetric Standard model (MSSM)

Standard Model

$$Q = \begin{pmatrix} u_L \\ d_L \end{pmatrix} \qquad \Longleftrightarrow$$

$$L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \qquad \Longleftrightarrow$$

$$u^c,\ d^c,\ e^c \qquad \Longleftrightarrow$$

$$H_u = \begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix} \qquad \Longleftrightarrow$$

$$H_d = \begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix} \qquad \Longleftrightarrow$$

$$g \qquad \Longleftrightarrow$$

$$W^\pm,\ W^0 \qquad \Longleftrightarrow$$

$$B \qquad \Longleftrightarrow$$

Minimal Supersymmetric Standard model (MSSM)

Standard Model		Supersymmetrize
$Q = \begin{pmatrix} u_L \\ d_L \end{pmatrix}$	$\Longleftrightarrow$	$\begin{pmatrix} \tilde{u}_L \\ \tilde{d}_L \end{pmatrix}$
$L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$	$\Longleftrightarrow$	$\begin{pmatrix} \tilde{\nu}_L \\ \tilde{l}_L \end{pmatrix}$
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Minimal Supersymmetric Standard model (MSSM)

Standard Model		Supersymmetrize	
$Q = \begin{pmatrix} u_L \\ d_L \end{pmatrix}$	$\Longleftrightarrow$	$\begin{pmatrix} \tilde{u}_L \\ \tilde{d}_L \end{pmatrix}$	squarks
$L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$	$\Longleftrightarrow$	$\begin{pmatrix} \tilde{\nu}_L \\ \tilde{l}_L \end{pmatrix}$	sleptons
$u^c,\ d^c,\ e^c$	$\Longleftrightarrow$	$\tilde{u}^c,\ \tilde{d}^c,\ \tilde{e}^c$	
$H_u = \begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix}$	$\Longleftrightarrow$	$\begin{pmatrix} \tilde{H}_u^+ \\ \tilde{H}_u^0 \end{pmatrix}$	higgsinos
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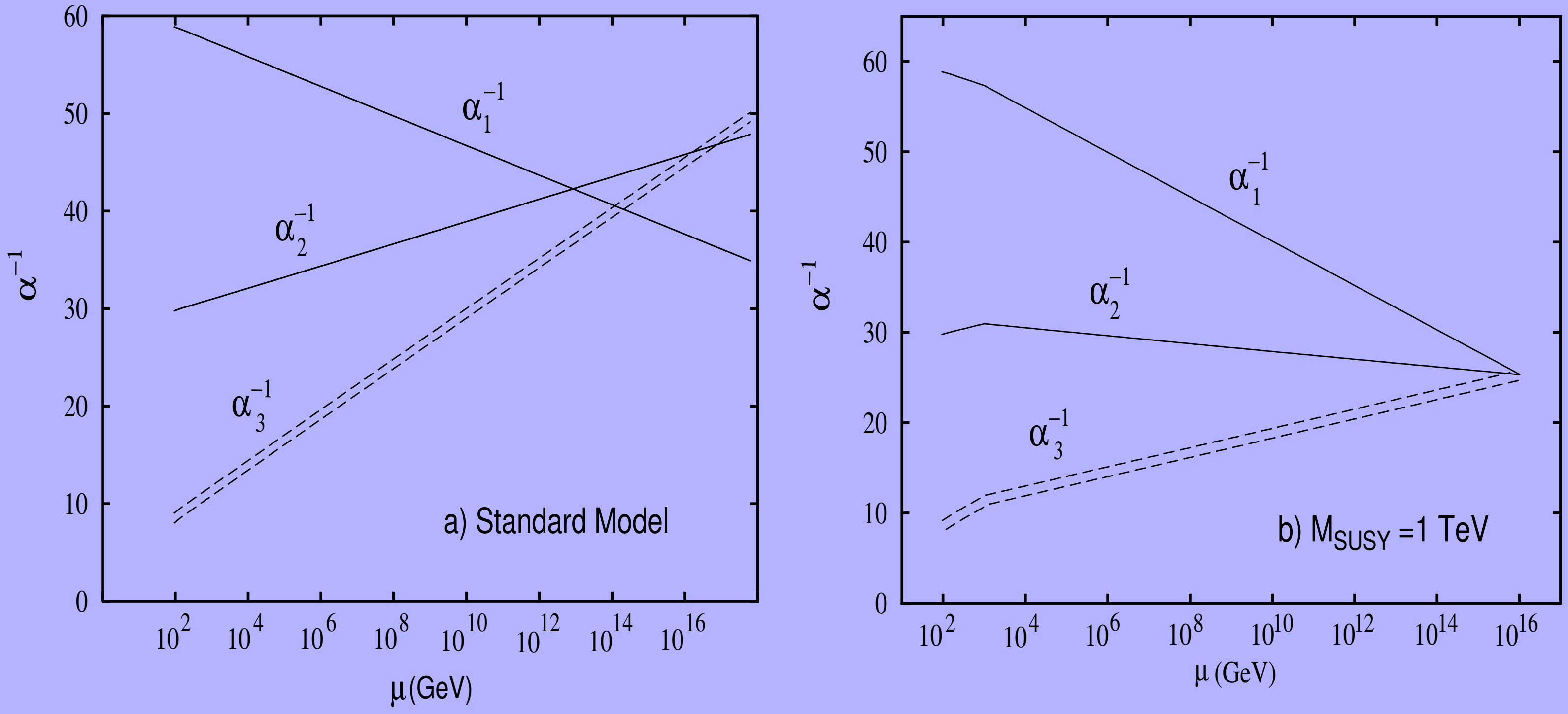
g	$\Longleftrightarrow$	$\tilde{g}$	gluino
$W^\pm,\ W^0$	$\Longleftrightarrow$	$\tilde{W}^\pm,\ \tilde{W}^0$	winos
B	$\Longleftrightarrow$	$\tilde{B}$	bino

Gauge Coupling Unification

$$\frac{dg_i}{dt} = \frac{g_i}{16\pi^2}\left[b_i g_i^2 + \frac{1}{16\pi^2}\left(\sum_{j=1}^{3} b_{ij} g_i^2 g_j^2 - \sum_{j=1}^{3} a_{ij} g_i^2 \lambda_j^2 \right)\right]$$



Ellis, Kelly, Nanopoulos; Amaldi, de Hoer, Furstenau; Langacker, Luo (1991).

The lightest SUSY particle (LSP)

is a **Dark Matter** candidate.

Imposing the R-parity conservation

- $R = 1$ for the SM particles
- $R = -1$ for SUSY particles

SUSY particles must be pair produced. E.g.

$$p\, p \;\rightarrow\; q\, \bar{q}\, \tilde{g}\, \tilde{g}$$

The LSP is stable:

$$\tilde{\chi}_1^0 \not\rightarrow \text{SM particles}$$

LSP remains since freeze-out in the early universe

Some problems of SUSY

- Too many soft parameters, more than 100.
- μ problem
- Proton decay operators
- Too many sources for FCNC and CP violation

No SUSY Particles (NSP) Found So Far

Various SUSY scenarios
and
Associated Phenomenology

Gravity mediated SUSY breaking

Arnowitt, Chamseddine, Nath

MSSM
visible sector

Mediation
Sector

SUSY
Breaking
hidden sector

SUSY breaking theory origin is in the hidden sector, and the SUSY breaking effect is transmitted by a mediation sector.

Historically, the most popular one is the gravity. Gravitation, suppressed by $M_{\rm Pl}$ couples the hidden sector to the visible. By dimension:

$$M_{\rm soft} \sim \frac{\langle F \rangle}{M_{\rm Pl}}$$

Naturalness requires $M_{\rm soft} \sim O(0.1-1)$ TeV, implying

$$\sqrt{\langle F \rangle} \sim 10^{11-12}\ {\rm GeV}$$

Gravitino mass is $\sim F/M_{\rm Pl}$.

Gauge mediated SUSY breaking

Dine, Nelson, Shirman; Dimopoulos, Dine, Raby, Thomas

This is a very simple idea to use the gauge interactions to communicate the SUSY breaking from the hidden sector to the visible sector. It is flavor-blind. It could just be the $SU(3)_C \times SU(2)_L \times U(1)_Y$ symmetry.

Typical soft masses are of order

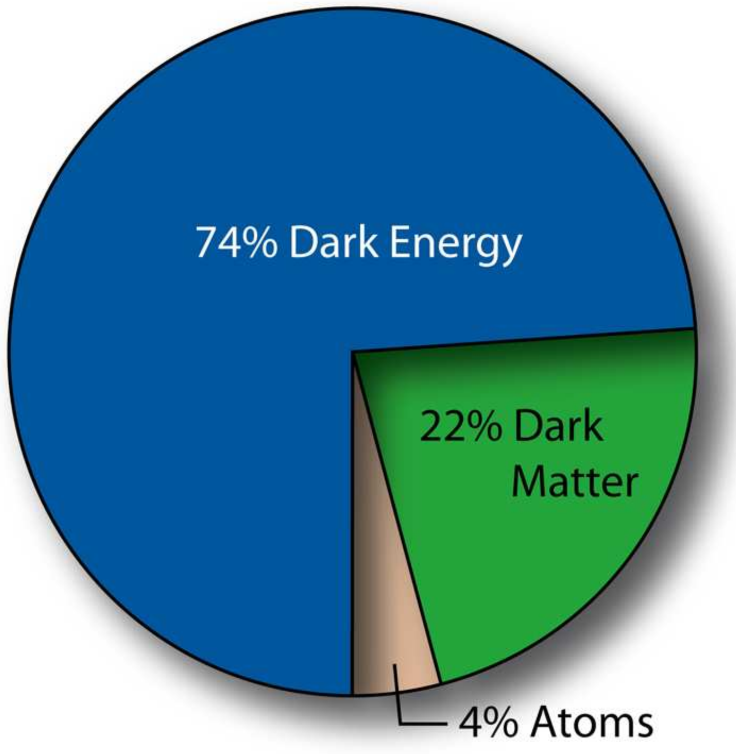
$$M_{\rm soft} \sim \frac{\alpha}{4\pi} \frac{\langle F_X \rangle}{M_{\rm mess}}$$

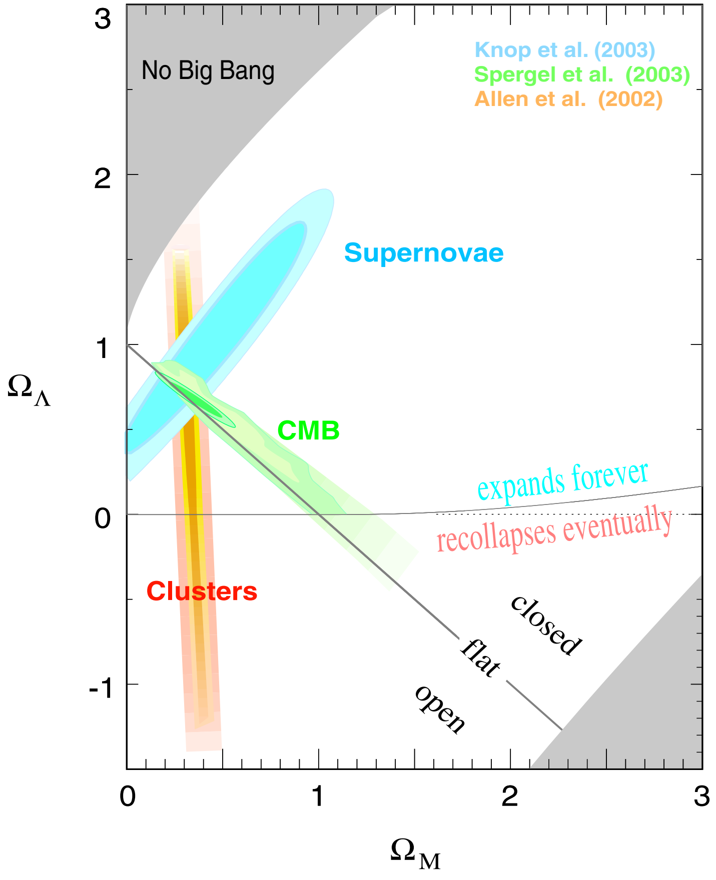
where F_X is the auxillary field of a chiral superfield in the hidden sector, $M_{\rm mess}$ is the mass scale of the messenger sector.

Both $\langle F_X \rangle$ and $M_{\rm mess}$ can be as low as 10 TeV.

The gravition mass $M_{3/2} \sim \langle F_X \rangle / M_{\rm Pl} \ll M_{\rm soft}$ can be as low as sub-eV.

4. Cosmological Connections





Cosmology Connection with Particle Physics

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

- Often a scalar field is used as the inflaton, and to generate primordial fluctuations.
- Nature of the dark energy. Models for dark energy, such as quintessence, requires scalar fields.
- Dark matter is non-baryonic and requires physics BSM.
- Baryon asymmetry also requires physics BSM.

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

- Atomic physics is needed to understand the CMB signal at 379,000 years from Big Bang.
- Nuclear physics successfully predicts the BBN at $t \sim 1$ s.
- EW and TeV scale physics help us to understand the time before $t \sim 10^{-8}$ s.

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

Dark matter and Collider studies

It is a coincidence that the required annihilation for weak scale dark matter is right at the weak scale interaction. Weakly-interacting massive particles (WIMP) is the leading candidate for the dark matter.

Most studied WIMPs are

- Lightest supersymmetric particle (LSP) of SUSY models.
- Lightest Kaluza-Klein (LKP) in universal extra dimenion models.
- Lightest T-odd particle (LTP) in little Higgs models with T parity.
- Branons in large extra dimension models.

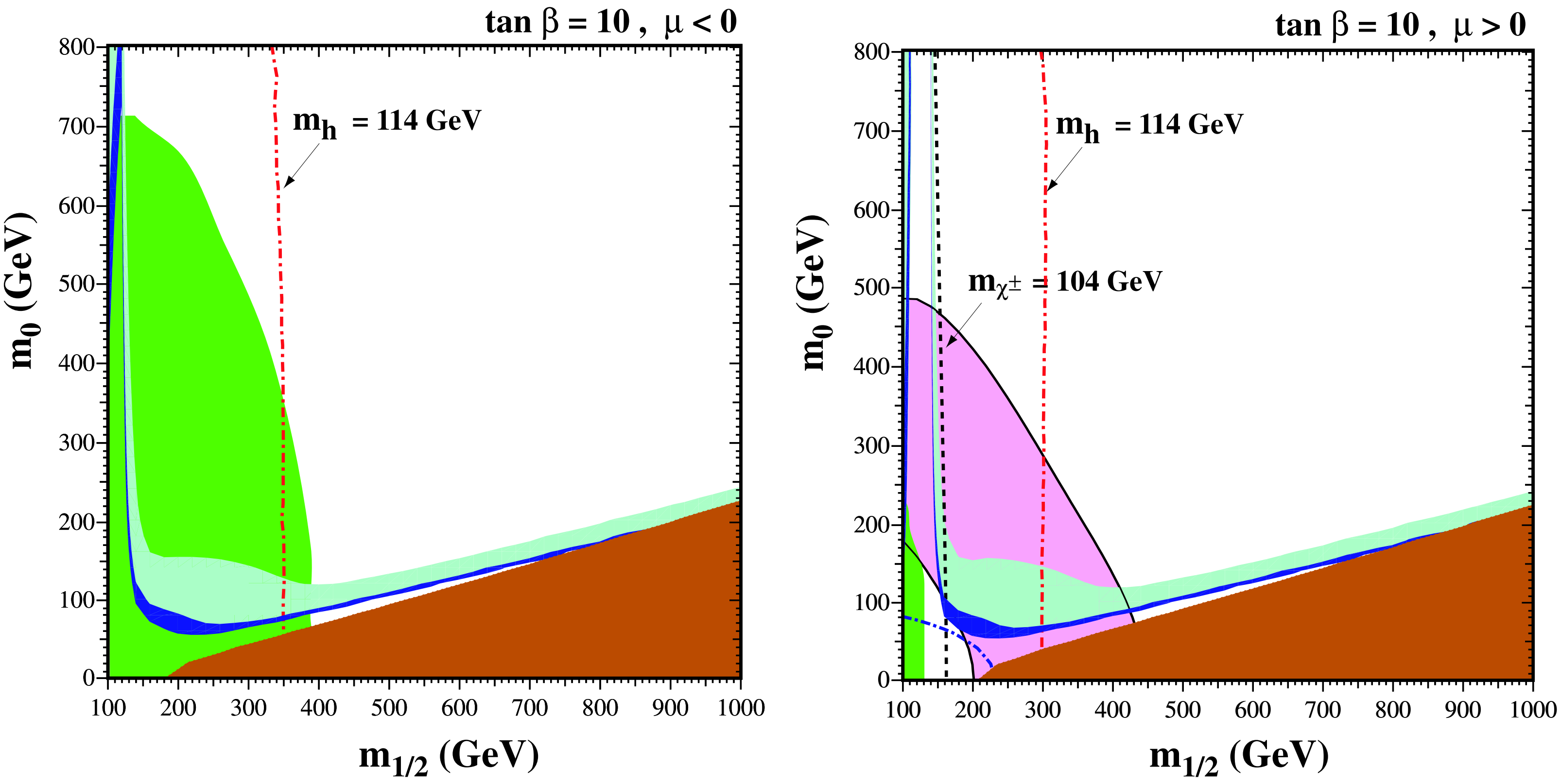
These candidates offer immediate tests that can be readily carried out at colliders.

mSUGRA: neutralino

There are 3 regions still consistent with WMAP data in mSUGRA ($m_{1/2}$, m_0, A_0, $\tan\beta$, and sign(μ).)

- Stau-neutralino coannihilation region.
- Higgs-funnel region where $m_{A,H} \simeq 2m_{\widetilde{\chi}_1^0}$.
- Focus point region where $\widetilde{\chi}_1^0$ has a large higgsino component.

Stau-neutralino coannihilation region



(Ellis, Olive, Santoso, Spanos 2003)

Universal Extra Dimension (UED) and the LKP

All SM particles are free to move in the extra dimensions. It is natural in the sense why some are confined and some are not.

Translational invariance

$\Rightarrow$ Conservation of KK numbers (momentum)

Boundary breaks the momentum conservation down to a Z_2 parity,

Conservation of KK parity

Radiation corrections and the boundart terms lift the mass degeneracy of KK states.

B^1, the first KK state of the hypercharge gauge boson, is the lightest KK particle (LKP)

The LKP with weak scale interaction could be a natural DM candidate.

Appelquist, Cheng, Dobrescu hep-ph/0012100

Little Higgs model with T parity

(Cheng, Low hep-ph/0308199, 0405243, 0409025)

The original "little Higgs" models propose the existence of TeV scale particles:

$$Z_H\,, W_H\,, A_H\,, \Phi, T_H\,, Q_H\,, L_H$$

which are the heavy partners of Z, W, A, t, q, ℓ, resp. They are introduced in a special way such that they cancel the loop correction to the Higgs boson mass. However, the early versions of LH models suffer from the constraints of precision measurements.

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T-parity was introduced

SM particles	$T = +$ parity
Heavy partners	$T = -$ parity

By doing that the vertex involving the heavy partners must occur in pairs, thus relieving the precision constraints.

The T parity also implies the lightest T-odd partner (LTP) is stable, thus can be a dark matter candidate. In general, the γ_H (B_H) is the LTP.

Conclusions

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We are looking forward to the LHC.