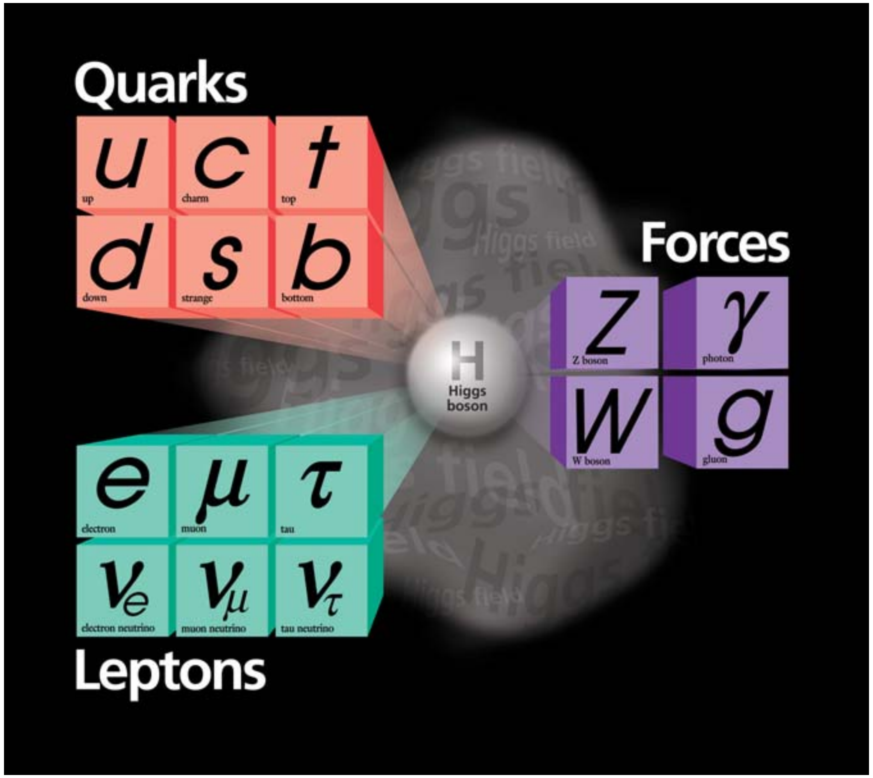
The Large Hadron Collider (LHC)

Tera-scale Frontier

- Increasing energy of particle collisions in accelerators corresponds to earlier times in the universe - exciting period:
  - Phase transitions from symmetry to asymmetry occurred
  - Structures like protons, nuclei and atoms formed.
- One Tera eV corresponds to 10^{-12} sec after the Big-Bang
- The ILC and Large Hadron Collider (LHC) are like telescopes that view the earliest moments of the universe.

The Standard Model



The Standard Model is a beautiful theory and arguably one that is most precisely tested

e.g. LEP and SM

Quantity	Value	Standard Model	Pull
m_t [GeV]	$172.7 \pm 2.9 \pm 0.6$	172.7 ± 2.8	0.0
M_W [GeV]	80.450 ± 0.058	80.376 ± 0.017	1.3
	80.392 ± 0.039		0.4
M_Z [GeV]	91.1876 ± 0.0021	91.1874 ± 0.0021	0.1
Γ_Z [GeV]	2.4952 ± 0.0023	2.4968 ± 0.0011	−0.7
$\Gamma(\text{had})$ [GeV]	1.7444 ± 0.0020	1.7434 ± 0.0010	—
$\Gamma(\text{inv})$ [MeV]	499.0 ± 1.5	501.65 ± 0.11	—
$\Gamma(\ell^+\ell^-)$ [MeV]	83.984 ± 0.086	83.996 ± 0.021	—
σ_{had} [nb]	41.541 ± 0.037	41.467 ± 0.009	2.0
R_e	20.804 ± 0.050	20.756 ± 0.011	1.0
R_μ	20.785 ± 0.033	20.756 ± 0.011	0.9
R_τ	20.764 ± 0.045	20.801 ± 0.011	−0.8
R_b	0.21629 ± 0.00066	0.21578 ± 0.00010	0.8
R_c	0.1721 ± 0.0030	0.17230 ± 0.00004	−0.1
$A_{FB}^{(0,e)}$	0.0145 ± 0.0025	0.01622 ± 0.00025	−0.7
	0.1439 ± 0.0043		−0.7
A_b	0.923 ± 0.020	0.9347 ± 0.0001	−0.6
A_c	0.670 ± 0.027	0.6678 ± 0.0005	0.1
A_s	0.895 ± 0.091	0.9356 ± 0.0001	−0.4
g_L^2	0.30005 ± 0.00137	0.30378 ± 0.00021	−2.7
g_R^2	0.03076 ± 0.00110	0.03006 ± 0.00003	0.6
$g_V^{\nu e}$	-0.040 ± 0.015	-0.0396 ± 0.0003	0.0
$g_A^{\nu e}$	-0.507 ± 0.014	-0.5064 ± 0.0001	0.0
A_{PV}	-1.31 ± 0.17	-1.53 ± 0.02	1.3
$Q_W(\text{Cs})$	-72.62 ± 0.46	-73.17 ± 0.03	1.2
$Q_W(\text{Tl})$	-116.6 ± 3.7	-116.78 ± 0.05	0.1
$\frac{\Gamma(b\to s\gamma)}{\Gamma(b\to Xe\nu)}$	$3.35^{+0.50}_{-0.44} \times 10^{-3}$	$(3.22 \pm 0.09) \times 10^{-3}$	0.3
$\frac{1}{2}(g_\mu - 2 - \frac{\alpha}{\pi})$	4511.07 ± 0.82	4509.82 ± 0.10	1.5
τ_τ [fs]	290.89 ± 0.58	291.87 ± 1.76	−0.4

$M_Z = 91.1876 \pm 0.0021$ (exp)

$M_Z = 91.1874 \pm 0.0021$ (SM)

$M_W = 80.392 \pm 0.039$ (exp)

$M_W = 80.376 \pm 0.017$ (SM)

Questions for the Standard Model and Beyond

LEP, SLC and the Tevatron: established that we really understand the physics at energies up to $\sqrt{s} \sim 100$ GeV

And any new particles have masses above 200 - 300 GeV – and in some cases TeV.

1. SM has an unproven element: the generation of mass

Higgs mechanism ? other physics ?

Answer will be found at $\sqrt{s} \sim 1$ TeV e.g. why $M_{\gamma} = 0$, $M_Z \sim 90$ GeV/c^2

2. SM without Higgs gives nonsense at LHC energies

At $\sqrt{s} > 1$ TeV probability of $W_L W_L$ scattering > 1 !!

The SM solution: Higgs exchange cancels bad high energy behavior.

Even if the Higgs exists, all is not 100% well with the SM alone: next question is "why is the (Higgs) mass so low"?

If SUSY is the answer, it must show up at O(TeV)

Recent: extra dimensions. Again, something must happen in the *O*(1-10) TeV scale if the above issues are to be addressed

Questions for the Standard Model and Beyond

3. SM is logically incomplete

Does not incorporate gravity.

Superstring theory → □□□□□□□□□□□□□□□□: supersymmetry, extra space-time dimensions ?

4. SM contains too many (arbitrary) parameters

Experimentally
□□□□□□□□□New particles/new symmetries/new forces?

Higgs boson(s), Supersymmetric particles, Z’, …
Extra space-time dimensions: gravitons, black holes etc. ?

The Cosmic Connection

Through the ‘Hot Big Bang’ model the laws of Elementary Particle Physics determine the early stages of cosmic evolution

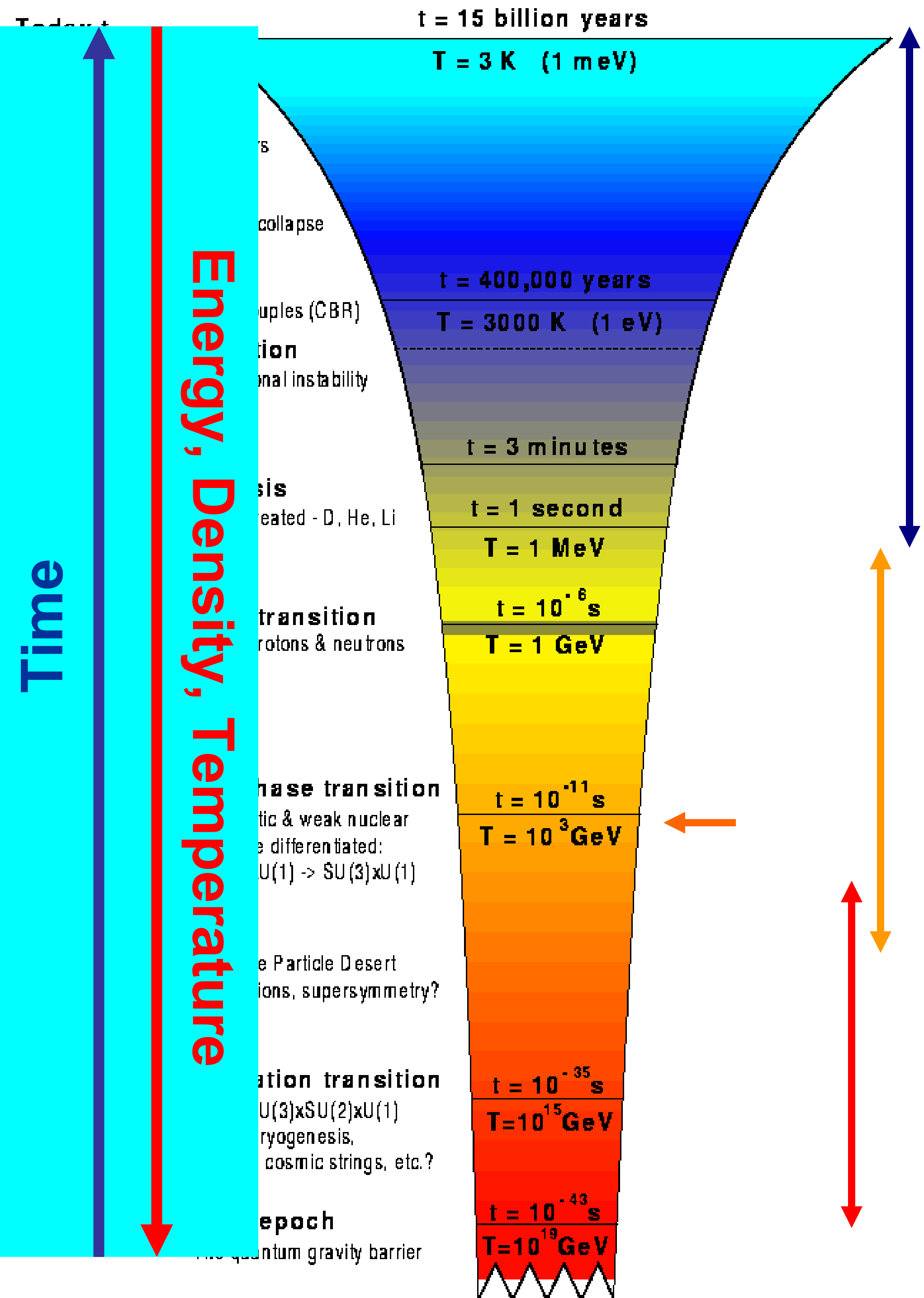
A next, crucial step in discovering these laws will be the exploration of phenomena around and above 1 TeV – electroweak symmetry breaking and more (super-symmetry?)

At high energies we effectively emulate, at an elementary level, the conditions that prevailed in the early universe

Cosmologists have a very good model for times > 0.01 sec
For earlier times (higher temperature, density) particle physics is relevant, but not all of it is known – we try to push back boundaries!

For the earliest times: energies become so high that gravity has to start playing a role in elementary particle interactions –
string theory?

Let us have a look at the following picture



Standard Cosmology

Supported by considerable observational evidence

Elementary Particle Physics

From the Standard Model into the unknown: towards energies of 1 TeV and beyond: the **Terascale**

Towards Quantum Gravity

From the unknown into the unknown...

The LHC

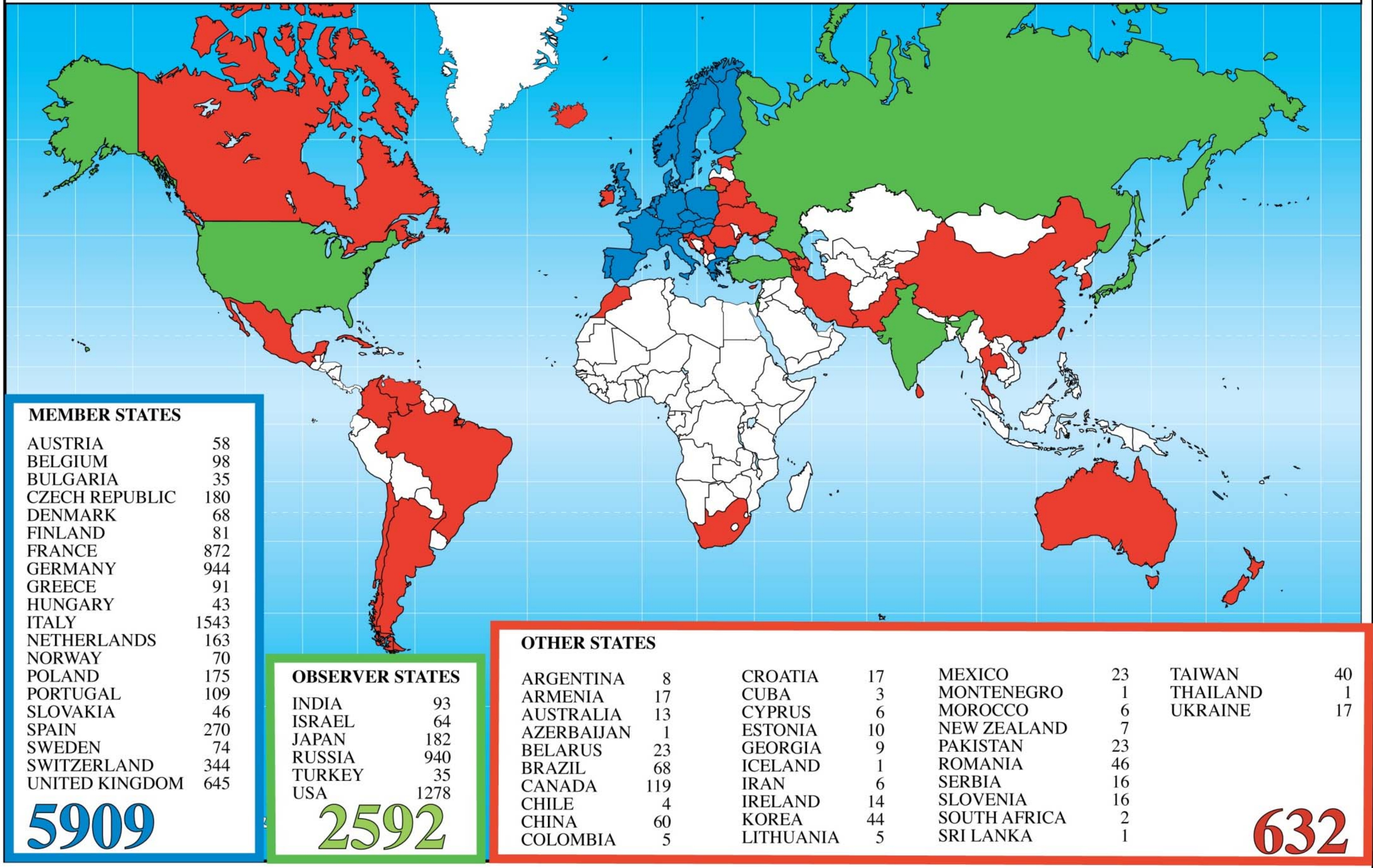
CERN in Numbers

- 2415 staff*
- 730 Fellows and Associates*
- 9133 users*
- Budget (2007) 982 MCHF (610M Euro)

*5 February 2008

- Member States: Austria, Belgium, Bulgaria, the Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Italy, Netherlands, Norway, Poland, Portugal, Slovakia, Spain, Sweden, Switzerland and the United Kingdom.
- Observers to Council: India, Israel, Japan, the Russian Federation, the United States of America, Turkey, the European Commission and Unesco

Distribution of All CERN Users by Nation of Institute on 5 February 2008



MEMBER STATES

AUSTRIA	58
BELGIUM	98
BULGARIA	35
CZECH REPUBLIC	180
DENMARK	68
FINLAND	81
FRANCE	872
GERMANY	944
GREECE	91
HUNGARY	43
ITALY	1543
NETHERLANDS	163
NORWAY	70
POLAND	175
PORTUGAL	109
SLOVAKIA	46
SPAIN	270
SWEDEN	74
SWITZERLAND	344
UNITED KINGDOM	645

5909

OBSERVER STATES

INDIA	93
ISRAEL	64
JAPAN	182
RUSSIA	940
TURKEY	35
USA	1278

2592

OTHER STATES

ARGENTINA	8
ARMENIA	17
AUSTRALIA	13
AZERBAIJAN	1
BELARUS	23
BRAZIL	68
CANADA	119
CHILE	4
CHINA	60
COLOMBIA	5
CROATIA	17
CUBA	3
CYPRUS	6
ESTONIA	10
GEORGIA	9
ICELAND	1
IRAN	6
IRELAND	14
KOREA	44
LITHUANIA	5
MEXICO	23
MONTENEGRO	1
MOROCCO	6
NEW ZEALAND	7
PAKISTAN	23
ROMANIA	46
SERBIA	16
SLOVENIA	16
SOUTH AFRICA	2
SRI LANKA	1
TAIWAN	40
THAILAND	1
UKRAINE	17

632

What Type of Accelerator ?

There is something “magic” about the 1 TeV energy scale to be studied at the LHC

New Energy Domain

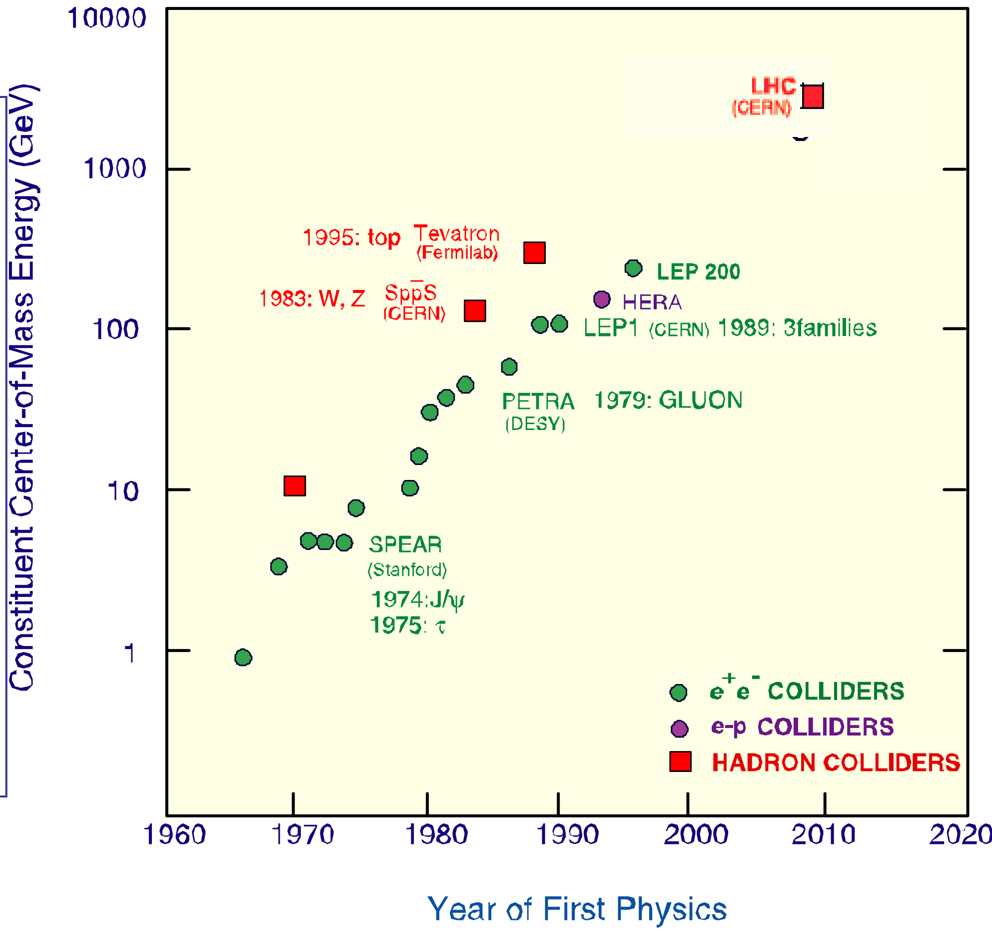
Search for the unexpected in an energy domain √s > 1 TeV

Exploratory machine required

- ⇨ **“Broadband”**
- ⇨ **hadron-hadron collider with:**

Largest possible primary energy

Largest possible luminosity

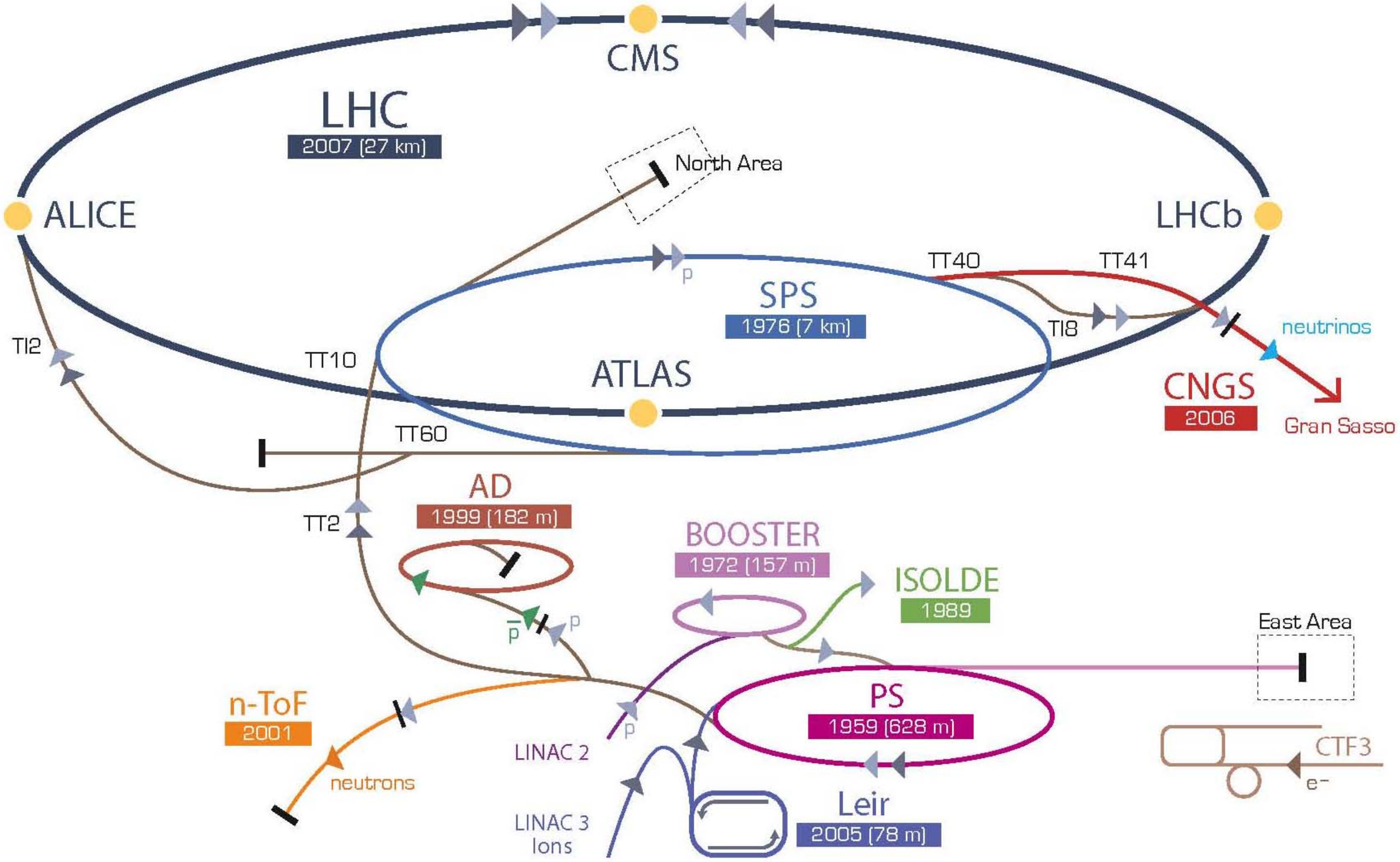


LHC Timeline

1984	Workshop on a Large Hadron Collider in the LEP tunnel, Lausanne
1987	Rubbia "Long-Range Planning Committee" recommends Large Hadron Collider as the right choice for CERN's future
1990	ECFA LHC Workshop, Aachen
1992	General Meeting on LHC Physics and Detectors, Evian les Bains
1993	Letters of Intent (ATLAS and CMS selected by LHCC)
1994	Technical Proposals Approved
1996	Approval to move to Construction (ceiling of 475 MCHF)
1998	Memorandum of Understanding for Construction Signed
1998	Construction Begins (after approval of Technical Design Reports)
2000	CMS assembly begins above ground. LEP closes
2004	CMS Underground Caverns completed
2008	CMS ready for First proton-proton Collisions

The CERN Accelerator Complex

(not to scale)



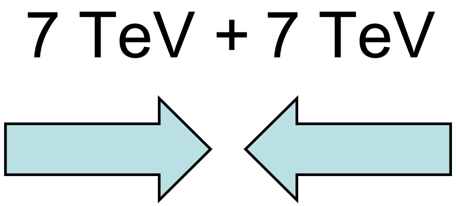
▸ p (proton) ▸ ion ▸ neutrons ▸ p̄ (antiproton) →+→ proton/antiproton conversion ▸ neutrinos ▸ electron

LHC Large Hadron Collider SPS Super Proton Synchrotron PS Proton Synchrotron

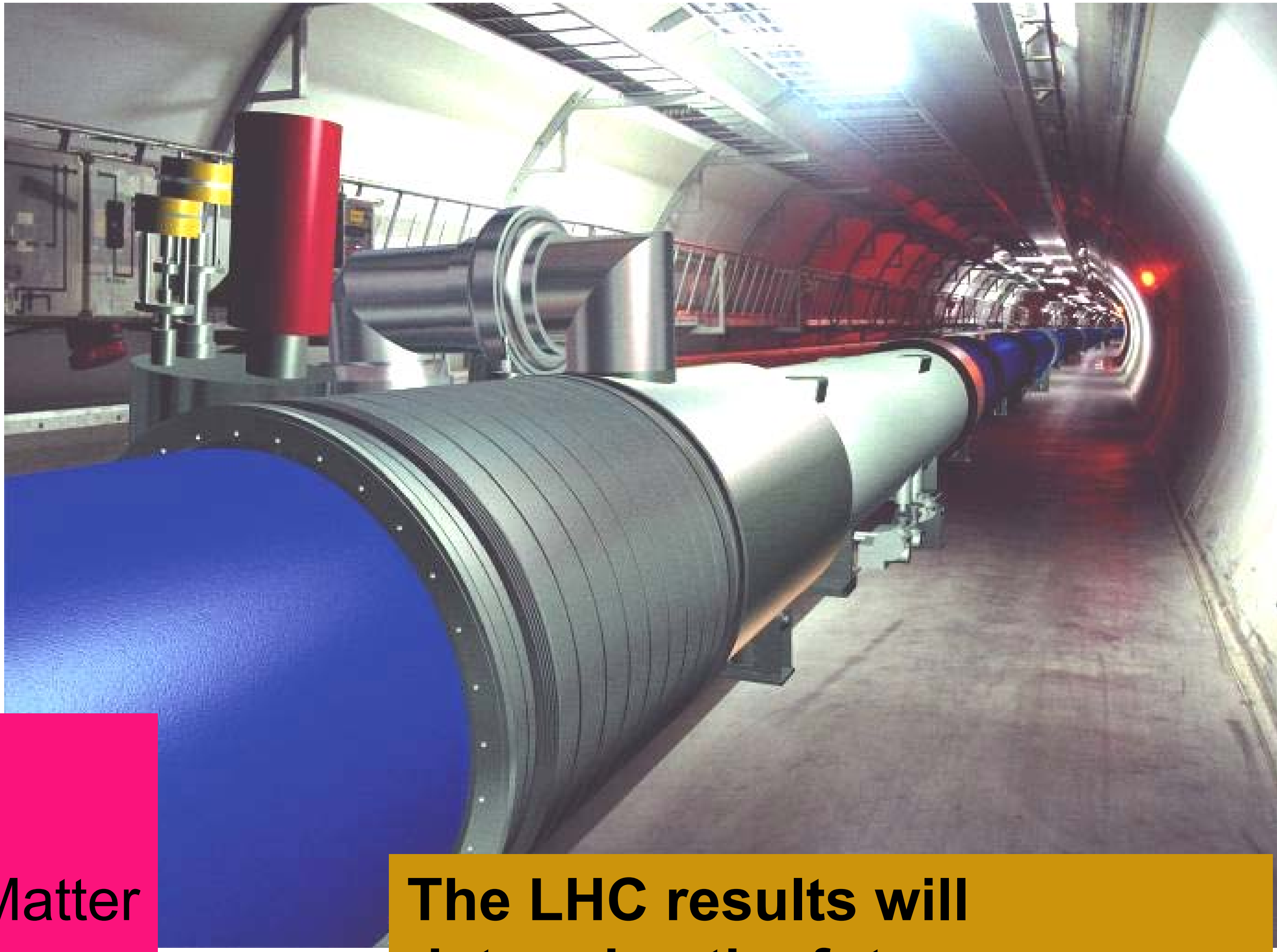
AD Antiproton Decelerator CTF3 Clic Test Facility CNGS Cern Neutrinos to Gran Sasso ISOLDE Isotope Separator OnLine DEvice

LEIR Low Energy Ion Ring LINAC LINear ACcelerator n-ToF Neutrons Time Of Flight

The LHC = Proton - Proton Collider


7 TeV + 7 TeV

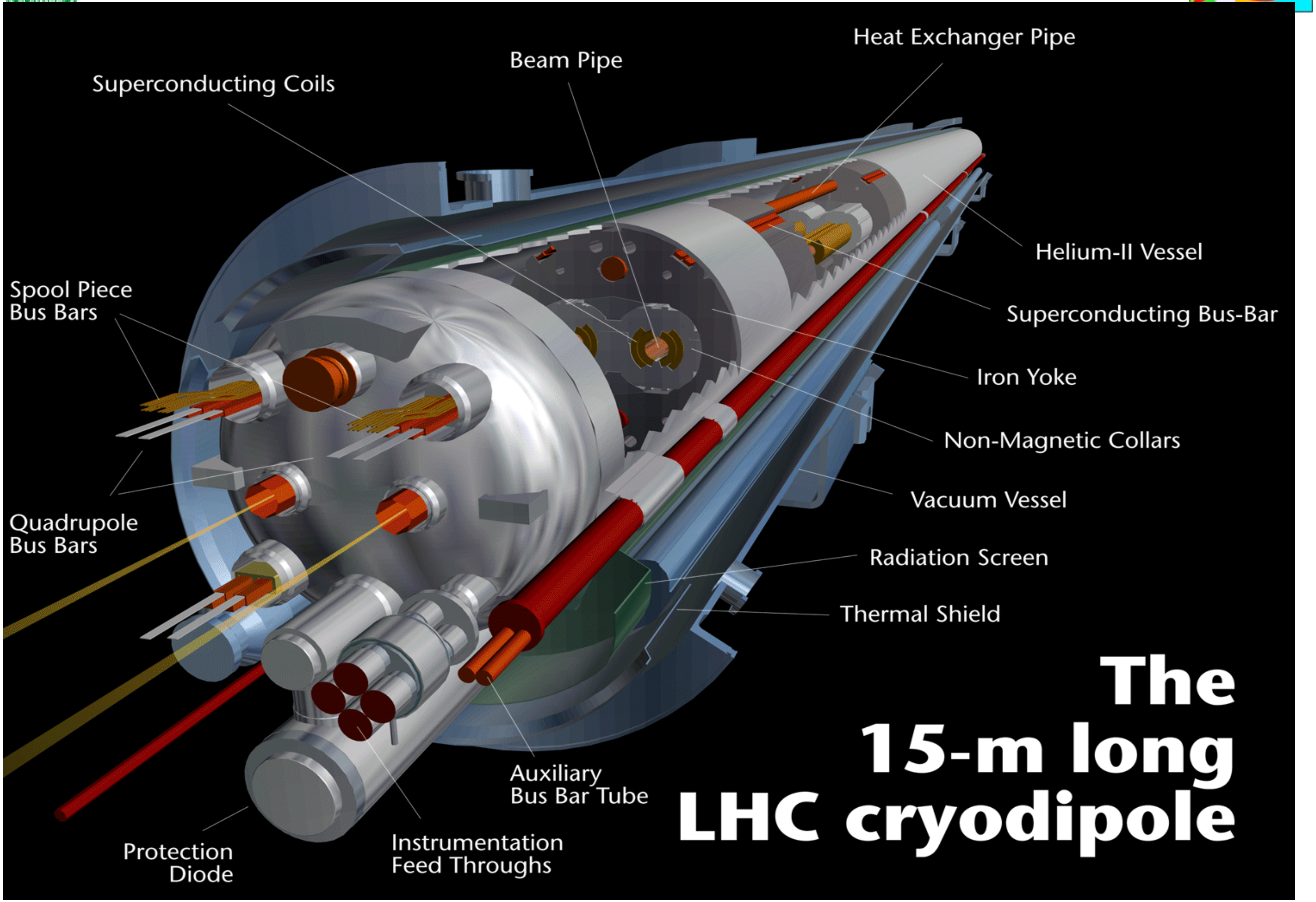
Luminosity = 10^{34}cm^{-2}sec^{-1}



Primary targets:
- Origin of mass
- Nature of Dark Matter
- Primordial Plasma
- Matter vs Antimatter

The LHC results will determine the future course of High Energy Physics

The LHC Cryodipole



The Design of CMS

Experimental Challenge

LHC Detectors (especially ATLAS, CMS) are radically different from the ones from the previous generations

High Interaction Rate

pp interaction rate **1 billion interactions/s**

Data can be recorded for only ~10^2 out of 40 million crossings/sec

Level-1 trigger decision takes ~2-3 μs

⇨ **electronics need to store data locally (pipelining)**

Large Particle Multiplicity

~ <20> superposed events in each crossing

~ 1000 tracks stream into the detector every 25 ns

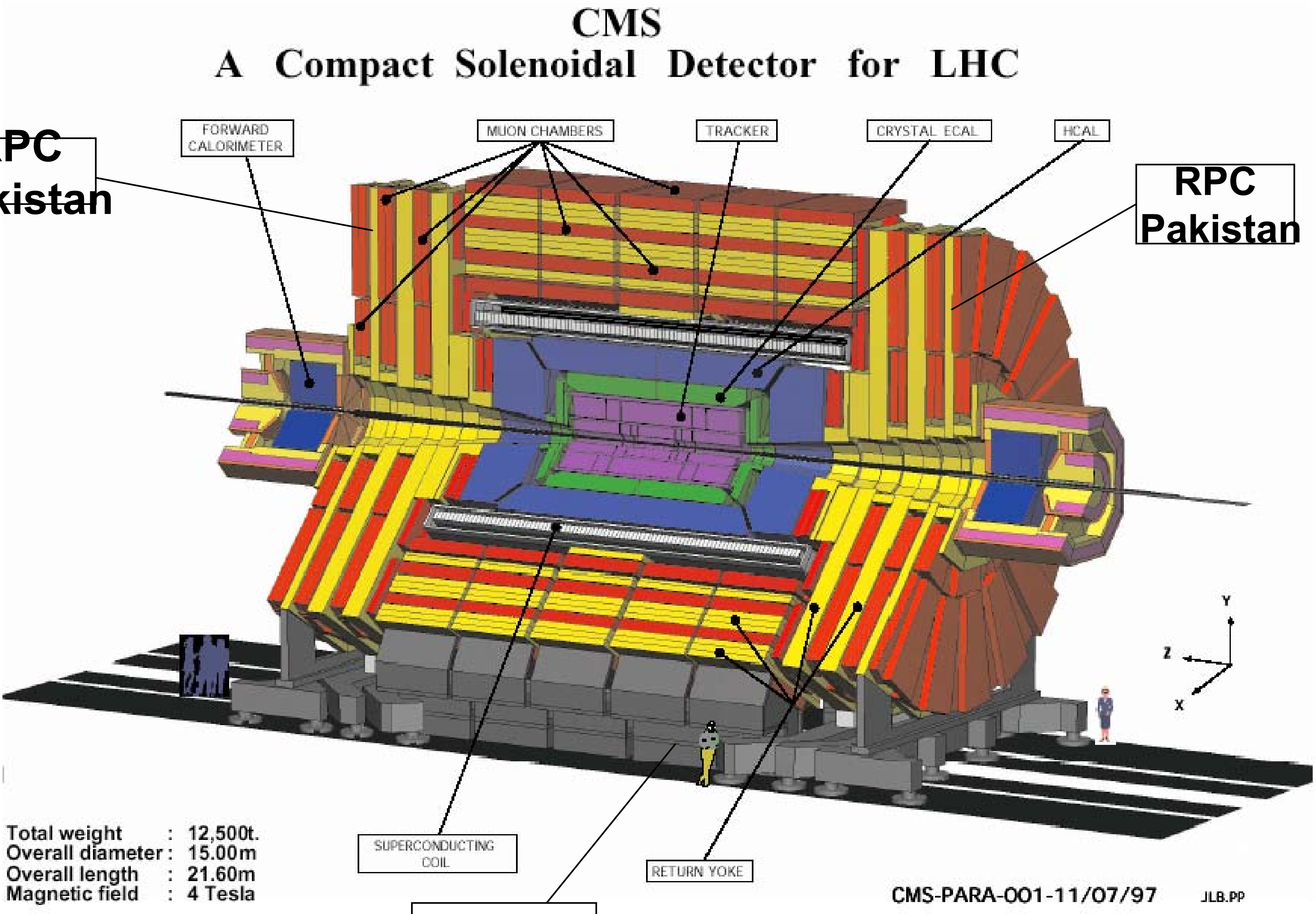
need highly granular detectors with good time resolution for low occupancy

⇨ **large number of channels (~ 100 M ch)**

High Radiation Levels

⇨ **radiation hard (tolerant) detectors and electronics**

The CMS Detector



Total weight : 12,500t.
Overall diameter : 15.00m
Overall length : 21.60m
Magnetic field : 4 Tesla

RPC Pakistan

RPC Pakistan

Base Pakistan

CMS Detector

- Several hundred million channels are used for read-out.
- Each channel is one data bit.
- For a given event, detector occupancy (number of channels hit) is typically **5-10%.**
- Average event size is **1 MB**.
- Event rate is **100 Hz**.
- 10^6 x 100 x 10^7 = 10^{15} B/year
  - **Total data in a year is 1 PB**

How Big Is A PetaByte?

- Kilobyte (1,000)
  - 2 Kilobytes : A Typewritten Page.
- Megabyte (1,000,000)
  - 2 Megabytes : A High Resolution Photograph
  - 5 Megabytes : The Complete work of Shakespeare
- Gigabyte (1,000,000,000)
  - 1 Gigabyte : A pickup Truck filled with books

How Big Is A PetaByte?

- Terabyte (1,000,000,000,000)
  - **1 Terabyte : 50,000 Trees made into paper and printed**
  - **10 Terabyte :The print collection of the U.S Library of congress**
- Petabyte (1,000,000,000,000,000)
  - **2 Petabyte : All U.S academic research libraries**
- Exabyte (1,000,000,000,000,000,000)
  - **2 Exabyte : Total Volume of information generated in 1999**

Computing Challenge

• Event Rate	10^9 events/sec
• Amount of Data	10^{15} B or 1 PB *(per year per experiment)*
• Number of Users	Two thousand *(distributed geographically)*
• Life-time	25 years
• Processing Power	10 TIPS *(17,000 PC)*

1 TIPS = 25 kSI2K
PC (2003) = 15 SI2K

How “big” are particles

- This table summarizes typical size scales we discuss

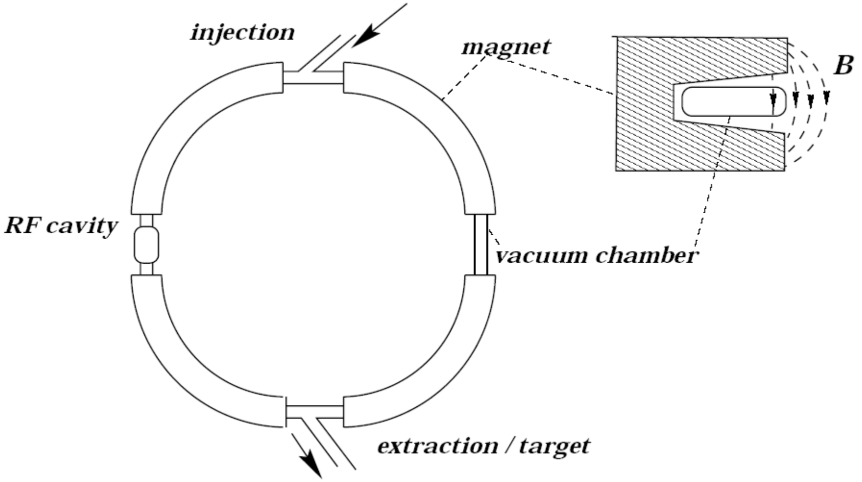
Scale	Abbreviation	Size	Radius (fm)	Energy (GeV)	Objects
Barn	b	10^-28 m^2	5.64E+00	3.54E-02	Nuclei
Millibarn	mb	10^-3 b	1.78E-01	1.12E+00	Nucleons
Microbarn	ub	10^-6 b	5.64E-03	3.54E+01	Charm/Bottom
Nanobarn	nb	10^-9 b	1.78E-04	1.12E+03	Electroweak
Picobarn	pb	10^-12 b	5.64E-06	3.54E+04	Top
Femtobarn	fb	10^-15 b	1.78E-07	1.12E+06	Supersymmetry

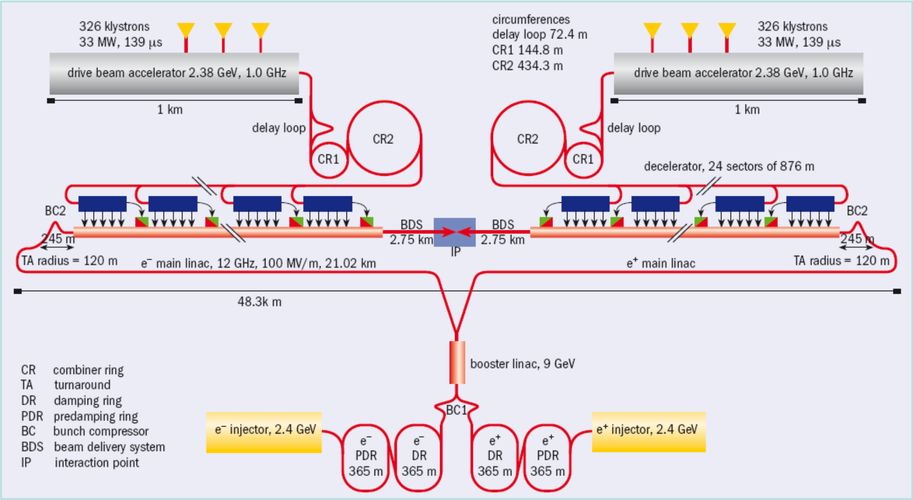
  - Radius
  - Momentum scale
  - Typical phenomena probed at this scale
    - More “exotic” things are “smaller”!

$$r = \sqrt{\sigma / \pi}$$

$$\hbar c / r = (200\ MeV \cdot fm) / r(fm)$$

Accelerators Circular/Liner



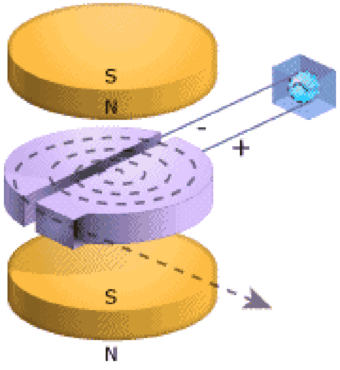


- Modern accelerators fall into two basic categories:

  - Linear Accelerators

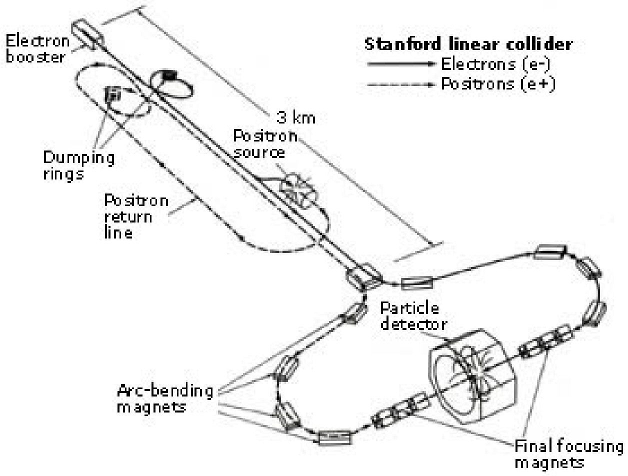
  - Circular Accelerators

Accelerators

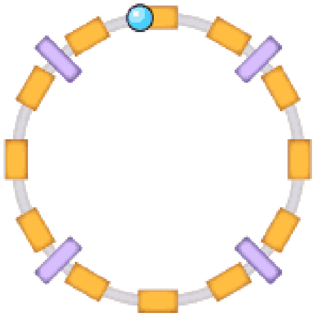


Ernest Orlando Lawrence
Berkeley National Laboratory

Cyclotron



Linear Accelerator

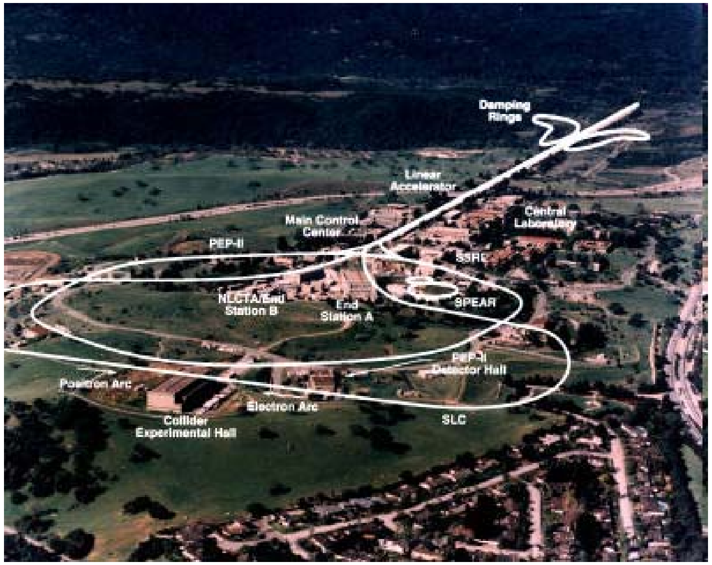


Synchrotron

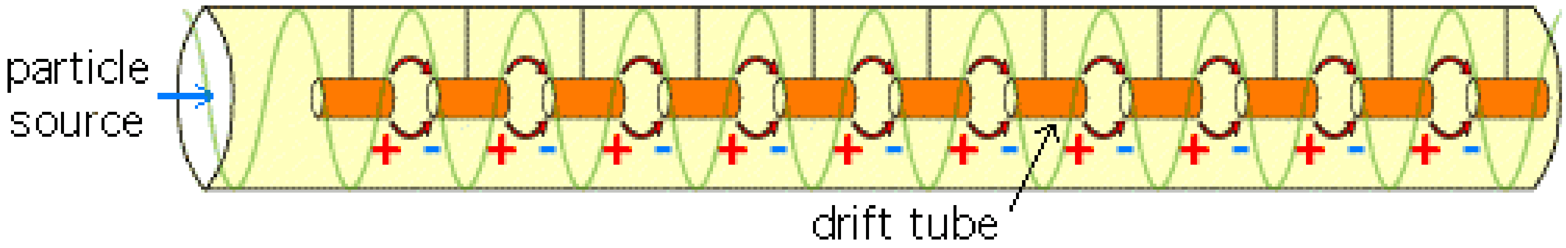
Linear Accelerators

❑ In linear accelerators, particles are accelerated in a straight line, often with a target at one to create a collision

❑ The size of linear accelerators varies greatly

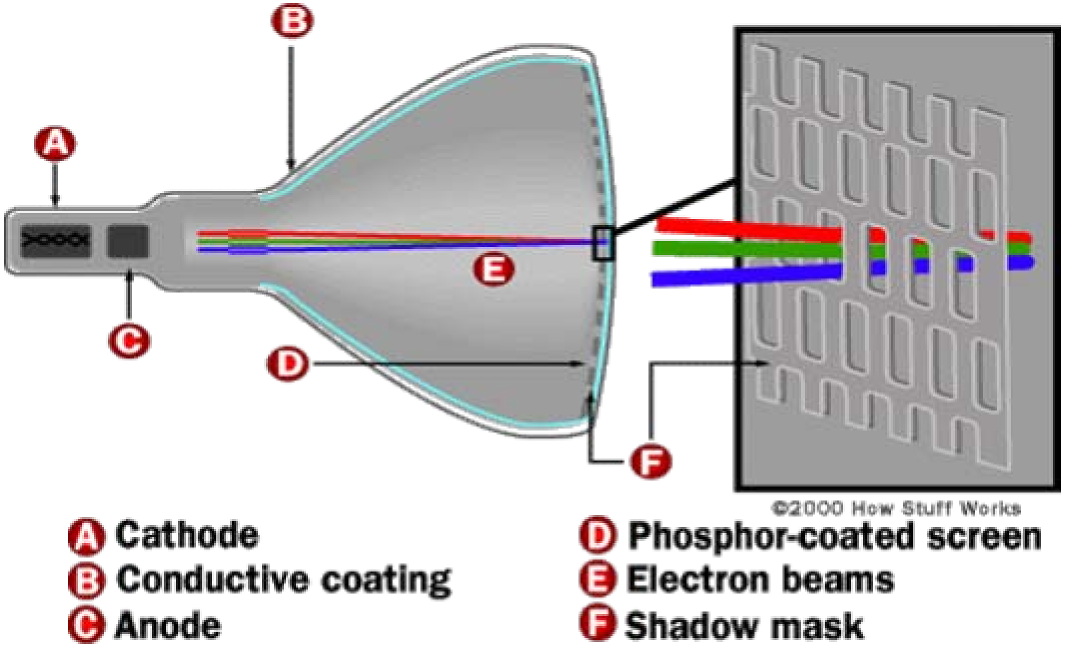


❑Cathode Ray Tube - CRT
❑Stanford's Linear Accelerator - SLAC



Linear Accelerator – CRT

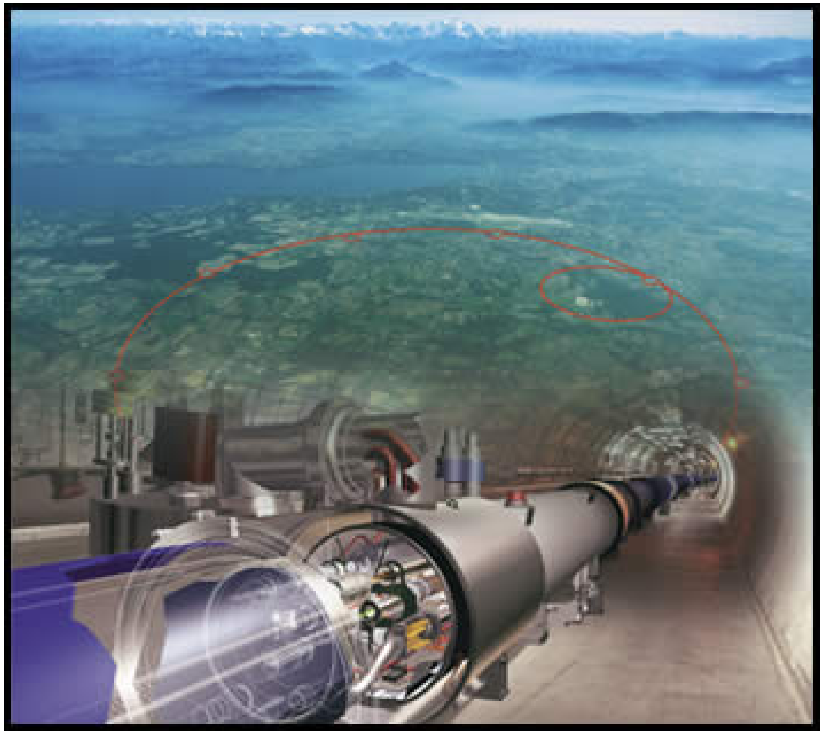
CRT is an example of linear accelerator found in TV and computer monitors



Linear Accelerator - SLAC

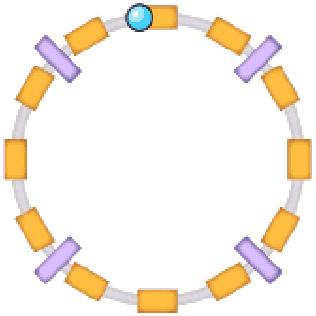
THE UNDERGROUND
TWO MILE STANFORD
HIGH ENERGY PARTICLE
ACCELERATOR

Circular Accelerators

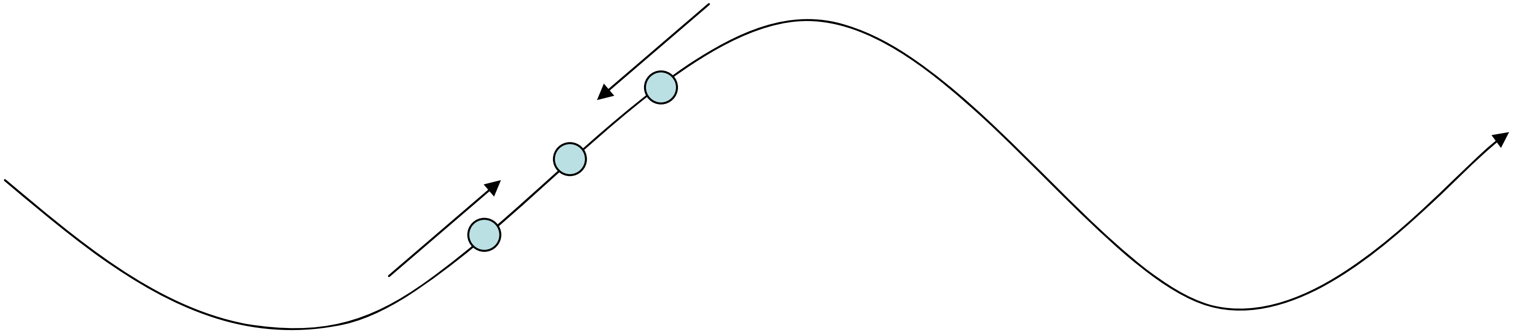


- Circular accelerators use RF cavities and bending magnets.
- Particles are accelerated in one direction, while anti-particles are accelerated in the opposite direction.

Synchrotrons



- Particles “ride” an RF wave
  - Slower particles get pushed
  - Faster get slowed
  - Leads to synchrotron oscillations
    - However, “bunches” are formed
  - Transverse instabilities lead to “betatron” oscaillations
- Magnets are used to steer the beams during acceleration and during “fill”



Circular Accelerators, cont.

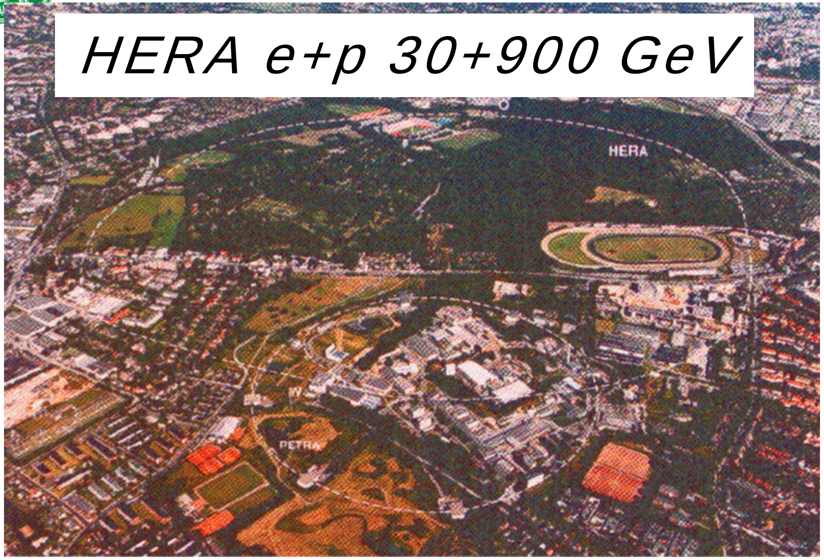
- Circular accelerators are able to bring particles up to very high energies
- The size - circumference of a circular accelerator can be quite large

  Fermilab's Tevatron - USA - 4 miles (6.44 km)

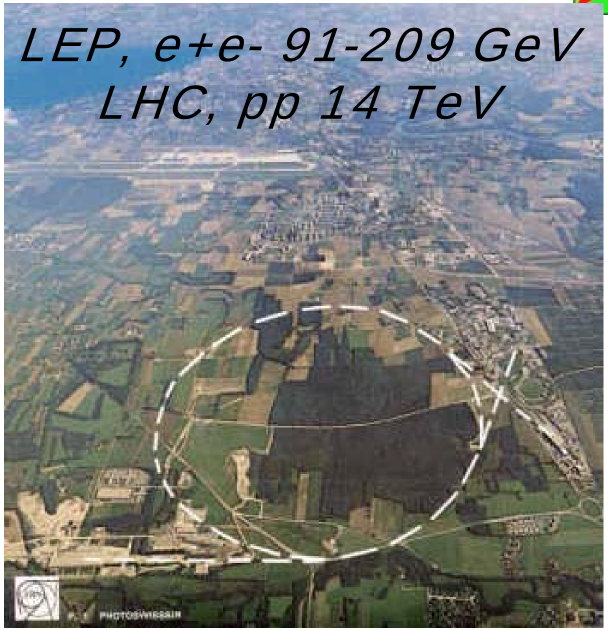
  CERN's LHC - Switzerland – 16.8 miles (27 km)

- The particle and anti-particle beams are focused and directed at particular points around the ring in order to collide with one another.

Colliders in Use

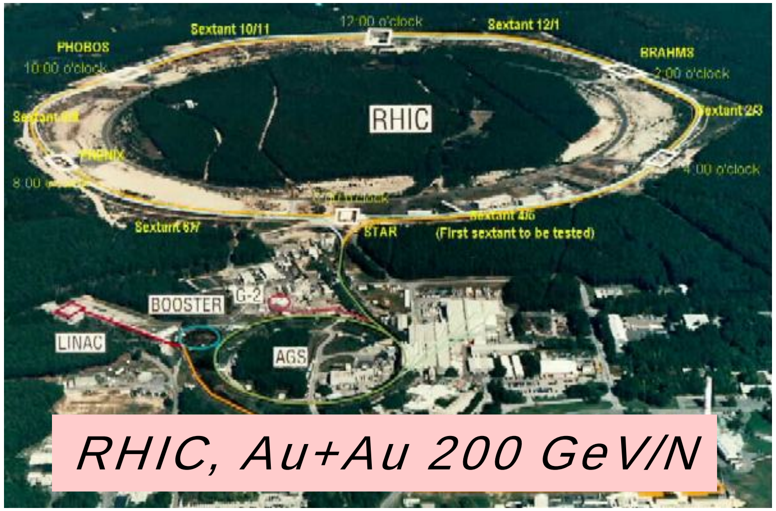


HERA e+p 30+900 GeV



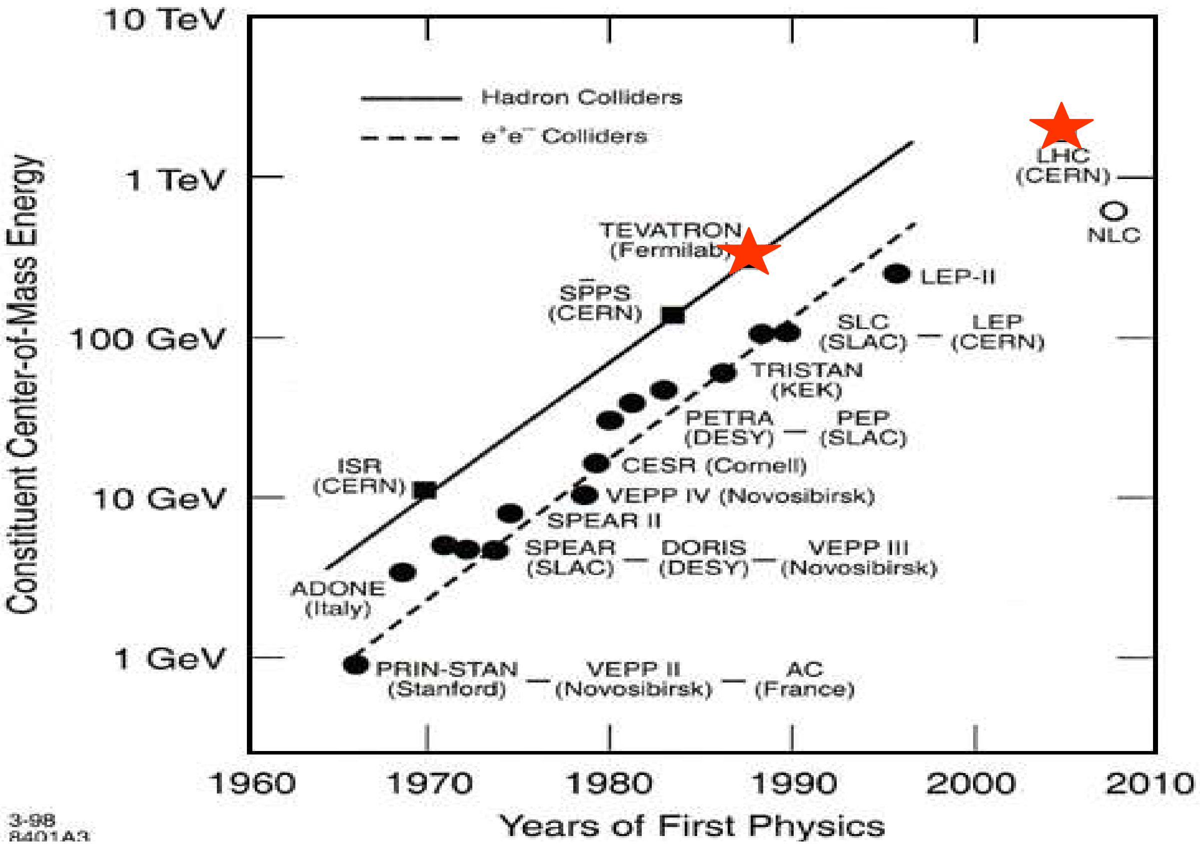
LEP, e+e- 91-209 GeV
LHC, pp 14 TeV

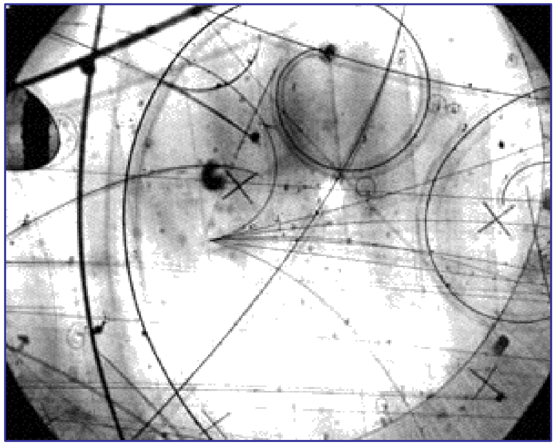
Tevatron, p+p 2 TeV



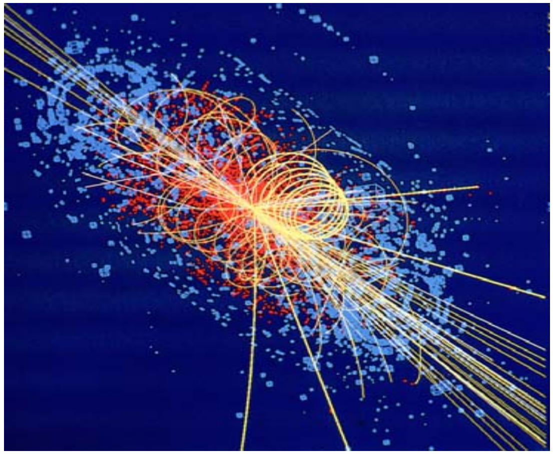
RHIC, Au+Au 200 GeV/N

Historical Development of Colliders





Fixed Target Colliders



Colliding Beams

Acceleration Issues

- Circular accelerators are subject to synchrotron radiation, if the particles are light

$$\Delta E = \frac{4\pi}{3}\left(\frac{e^2\beta^3\gamma^4}{R}\right) = \frac{4\pi}{3}\left(\left(\frac{p}{m}\right)^3 \frac{E}{m}\frac{e^2}{R}\right) \sim \frac{1}{m^4}$$

- Easier to accelerate protons to very high energies than electrons

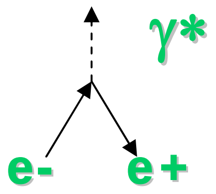
Why Hadron Colliders (I)?

- **Before Colliders:** There were “fixed-target experiments” – a beam of particles hits a block of matter.
  - Modern era of accelerators started in 1931.
  - Relativistic disadvantage: E_{CM} increases slowly as $\sqrt{E_{beam}}$

- **Colliders:** counter-rotating beams within a vacuum pipe.
  - Advantage: $E_{CM} = 2*E_{beam}$ increases faster
  - Developed around 1970.
  - Need pretty intense beams for a worthwhile rate of interactions.

Why Hadron Colliders (II)?

Electron-positron (e^+e^-) colliders (>1970) are excellent!



- The Feynman diagrams are simple.
- Positrons circulate in the same set of magnets as the electrons.
- The initial state energy and momentum (zero) precisely by the magnetic field and the radius of the electron path.

Many great things were discovered with e^+e^-, but…

Why Hadron Colliders (III)?

- Electrons are by far the lightest particles.
- Acceleration of charges results in electromagnetic “synchrotron” radiation.
- For highly relativistic particles, this radiation depends on the relativistic $\gamma = E/mc^2$ factor as:

$$P = \frac{2Ke^2\gamma^4 c}{3r^2}$$

How much SR?

- For highly relativistic e:

$W = 8.85 \times 10^{-5} E^4/\rho$ MeV per turn

E = Energy (GeV), ρ = radius (km)

- At **LEP**: W ~ 2 GeV per turn (E = 100 GeV)
- For relativistic protons:

$W = 7.8 \times 10^{-3} E^4/\rho$ keV per turn

E = Energy (TeV), ρ = radius (km)

- At **LHC**: W ~ 18.7 keV per turn (E = 7 TeV)

Why Hadron Colliders (IV)?

- Electrons, having the lowest mass, radiate large amount of synchrotron radiation alike if E (hence γ) is high.
- Circular e^+e^- machines topped out with the LEP accelerator,
- LEP reached about 200 GeV energy, which required massive amounts of power to keep the electrons going around.
- So if one wants more center-of-mass energy then, use heavy particles such as protons,
- SR power goes like $1/m^4$ - for protons which are 2000 times more massive than the electron, the emitted power is reduced by a large factor.

Hadron vs. Lepton Collisions

- The Tevatron is currently running at E_{CM} = 1.96TeV colliding protons and antiprotons.

- The LHC will start again in Nov. 2009 and run for about 15 years colliding protons at 14 TeV.
- People are working hard on the design of electron-positron *Linear* Colliders for the future.
  - No synchrotron radiation
  - But have to accelerate the particles *very forcefully* to reach high energy in one pass (linear accelerator already many km long)

The Long-Term Future of Colliders

- A future linear collider (ILC for International Linear Collider) operating between 500 GeV and 1 TeV will hopefully be built to start data taking some time after LHC start-up.

- A second generation linear collider operating at energies of up to 5 TeV could then be built to explore higher energies (e.g. the CLIC research project at CERN).

- These machines will measure the properties in more detail.
- There are other proposals to build a neutrino factory as the first step towards a muon collider. This would be on the same sort of timescale as a second generation linear collider.

Tricks of the trade

- Particles of opposite charge will feel the accelerator components “backwards”
  - RF will accelerate e+ oppositely to e-
  - Magnets will steer them oppositely
- Thus, you only need one ring to make a collider for oppositely charged particles
  - This was how the SPS (Super Proton Synchrotron) was turned into the SppS (a proton-antiproton collider)
  - This is how you get a nobel prize…

Collider parameters

- **The total event rate:**

$$R = \sigma L$$

- The cross sections depend on what you are looking for
- **The luminosity:**

Number of particles in each beam

$$L = fn\frac{N_1 N_2}{A}$$

frequency

Number of bunches

Cross-sectional area

Typical values

- For **e^+e^-** colliders $L \sim 10^{31} cm^{-2}s^{-2}$
- For **antiproton-proton** machines 10^{31}
- For **proton-proton** machines 10^{33}
- A **fixed target experiment** can have 10^{13} protons/sec traversing liquid hydrogen target 1m long:
  - **Effective $L=10^{38}$!!**

Kinematics

- Theory of relativity (x, y, z, t) are treated on equal footings:

$$p = p_x i + p_x j + p_z k$$

$$p_1 = p_x, p_2 = p_y, p_3 = p_z, p_4 = iE$$

- Energy-momentum 4-vector p_μ is

$$p_\mu \equiv (p, iE)$$

$$p^2 = \sum p_\mu p_\mu = p_1^2 + p_2^2 + p_3^2 + p_4^2 = |p|^2 - E^2 = -m^2$$

Kinematics

- Theory of relativity (x, y, z, t) are treated as same:

$$\beta = \nu / c, \qquad \gamma = \frac{1}{\sqrt{1-\frac{\upsilon^2}{c^2}}} = \frac{1}{\sqrt{1-\beta}}$$

- Transformation from reference frame ‘S’ to ‘S`’ are connected through Lorentz transformations:

$$p_{\upsilon}^{'} = \sum_{\upsilon=1}^{4} \alpha_{\mu\nu} p_{\nu}$$

Kinematics

$$\alpha_{\mu\nu} = \begin{bmatrix} \gamma & 0 & 0 & i\beta\gamma \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ -i\beta\gamma & 0 & 0 & \gamma \end{bmatrix}$$

$$p_1' = \gamma p_1 + i\beta\gamma p_4$$
$$p_2' = p_2$$
$$p_3' = p_3$$
$$p_4' = -i\beta\gamma p_1 + \gamma p_4$$

$$p_x' = \gamma(p_x - \beta E) \qquad E' = \gamma(E - \beta p_x)$$

$$|p'|^2 - E'^2 = -m^2$$
$$\Rightarrow \sum_\mu p_\mu p^\nu = \sum_\nu p_\nu' p^{\nu'} = -m^2$$

- It implies that the 4-momentum squared is a Lorentz invariant.

Kinematics

Use of 4-vectors

- Two particles “A” and “B” with m_A, p_A ,E_A and m_B, p_B , E_B. All quantities are measured in Lab frame.

$$p^2 = (p_A + p_B)^2 - (E_A + E_B)^2$$

$$= |p_A|^2 + |p_B|^2 + 2p_A.p_B - E_A^2 - E_B^2 - 2E_A E_B$$

$$= -m_A^2 - m_B^2 + 2p_A.p_B - 2E_A E_B$$

The center of Mass frame is defined as where total 3-momentum is zero.

$$p^2 = -E^2$$

E^2 is the total energy measured in CM Frame.

Kinematics

- Let us assume ‘A’ is incident particle on a stationary target ‘B’.

$$E_B = m_B \quad \& \quad p_B = 0$$

$$p^2 = -m_A^2 - m_B^2 - 2m_B^2 E_A$$

$$E^{*2} = -p^2 = m_A^2 + m_B^2 + 2m_B^2 E_A$$

E* is the total energy available for the creation of particle with total mass m*.

$$m^{*2} = m_A^2 + m_B^2 + 2m_B^2 E_A$$

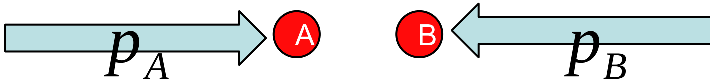
$$E_A = \frac{m^{*2} - m_A^2 - m_B^2}{2m_B}$$

$$m^* \rangle\rangle m_A, m_B$$

Kinematics

$$E_A \cong \frac{m^{*2}}{2m_B} \qquad E^* \cong \sqrt{2m_B E_A}$$

If the two particles ‘A’ and ‘B’ travel in opposite direction:



$$p^2 = (p_A + p_B)^2 - (E_A + E_B)^2$$

$$p^2 = -(E_A + E_B)^2 = -E_A^2 - E_B^2 - 2E_A E_B \qquad \textit{if} \quad p_A = -p_B$$

If ‘A’ and ‘B’ are identical $E_A = E_B$:

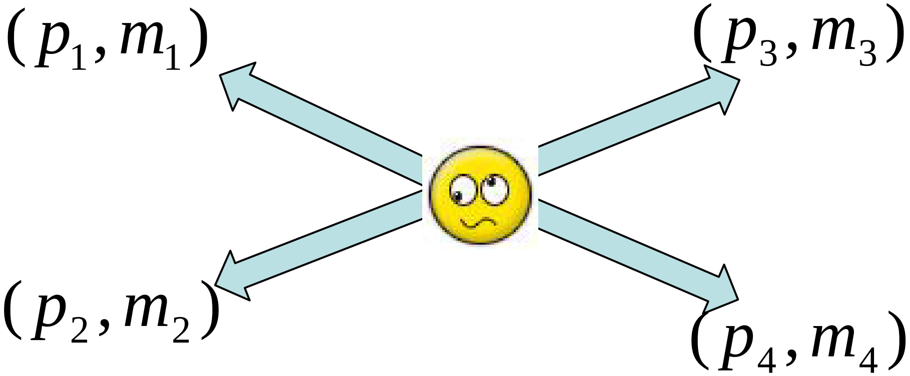
$$E^{*2} = 4E_A{}^2 \Rightarrow E^* = 2E$$

Fixed target experiment $E^* \propto (E_A)^{\frac{1}{2}}$

Colliding beam experiment $E^* \propto E_A$

Kinematics

Two-body reactions



(p_1, m_1)

(p_3, m_3)

(p_2, m_2)

(p_4, m_4)

$$s = (p_1 + p_2)^2 = (p_3 + p_4)^2$$
$$= p_1{}^2 + p_2{}^2 + 2E_1E_2 - 2p_1.p_2$$
$$= m_1{}^2 + m_2{}^2 + 2E_1E_2 - 2p_1.p_2$$

$$t = (p_1 - p_3)^2 = (p_2 - p_4)^2$$
$$= m_1{}^2 + m_3{}^2 - 2E_1E_3 + 2p_1.p_3$$

$$u = (p_1 - p_4)^2 = (p_2 - p_3)^2$$
$$= m_1{}^2 + m_4{}^2 - 2E_1E_4 + 2p_1.p_4$$

$$s + t + u = p_1{}^2 + p_2{}^2 + p_3{}^2 + p_4{}^2 + 2p_1{}^2 + 2p_1p_2 - 2p_1p_3 - 2p_1p_4$$
$$= m_1{}^2 + m_2{}^2 + m_3{}^2 + m_4{}^2 + 2p_1{}^2 + 2p_1(p_2 - p_3 - p_4)$$

Kinematics

$$p_1 + p_2 = p_3 + p_4 \Rightarrow -p_1 = p_2 - p_3 - p_4$$

$$s + t + u = m_1^{\ 2} + m_2^{\ 2} + m_3^{\ 2} + m_4^{\ 2} + \cancel{2p_1}^{\ 2} - \cancel{2p_2}^{\ 2}$$

In the scattering process

AB ⟶ CD

Possible Lorentz invariants are:

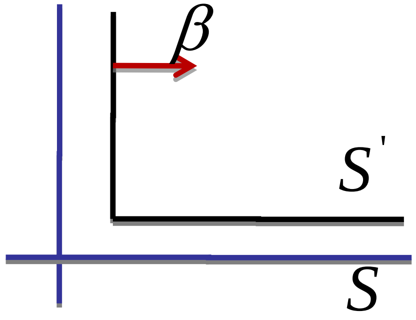
$$p_1 \cdot p_2 \qquad p_1 \cdot p_3 \qquad p_1 \cdot p_4 \qquad p_2 \cdot p_3 \qquad p_2 \cdot p_4 \qquad p_3 \cdot p_4$$

For a given reaction we have:

$$\textit{phase factor} = d^3 p = dp_x dp_y dp_z$$

$$p_x^{'} = \gamma\left(p_x - \beta E\right) \qquad p_y^{'} = p_y \qquad p_z^{'} = p_z \qquad E^{'} = \gamma\left(E - \beta p_x\right)$$

Kinematics



$$dp'_x = \frac{\partial p'_x}{\partial p_x} dp_x + \frac{\partial p'_x}{\partial E} dE$$

as $\frac{\partial p'_x}{\partial p_x} = \gamma$ *and* $\frac{\partial p'_x}{\partial E} = -\beta\gamma$

$$\Rightarrow dp'_x = \gamma dp_x - \beta\gamma dE = \gamma\left(dp_x - \beta dE\right)$$

Notice that $p_x^{\ 2} + p_y^{\ 2} + p_z^{\ 2} - E^2 = -m^2$

p_y & p_z are fixed so:

$$2p_x dp_x = 2EdE \Rightarrow p_x dp_x = EdE$$

$$dp'_x = \gamma\left(1 - \beta p_x / E\right)$$

Kinematics

$$\frac{dp_x'}{E'} = \frac{\gamma\left(1-\cancel{\beta p_x / E}\right)dp_x}{\gamma E\left(1-\cancel{\beta p_x / E}\right)} = \frac{dp_x}{E}$$

$$\frac{d^3 p_x'}{E'} = \frac{dp_x' dp_y' dp_z'}{E'} = \frac{dp_x dp_y dp_z}{E} = \frac{d^3 p_x}{E}$$

So the phase factor is Lorentz invariant.

The differential cross section for producing a particle of momentum p and energy E can be written in the form

$$E\frac{d^3\sigma}{dp^3}$$

and is Lorentz invariant.

THE ROLE OF PAKISTAN IN CERN PROGRAM

History

1994	Protocol Agreement was signed.
1995	QAU joined CMS Collaboration.
1997	Contract for 8 magnet-supports was signed.
1998	Memorandum of Understanding signed.
1998	CERN-CTC Computer Centre.
1999	National Centre for Physics was established.
2000	The 432 Resistive Plate Chambers (RPC)
2000	NCP became a full member institute of CMS

History

2000	LoI signed for the Regional Computer Center.
2001	LoI signed for further contribution towards LHC
2001	Agreement between NCP and CERN
2003	Protocol signed for an additional contribution of US $ 10 million to LHC Project.
2004	Addendum to 2003 Protocol signed between ATLAS and SES
2006	**LoI for further contribution to LHC and future CERN projects.**
2006	**MoU for Shielding door of LHC**
2006	**MoU for Grid Computing**

Joint CERN-Pakistan Committee (JCPC)

- The committee was constituted under article 10.1 of July 2003 Protocol.
- To monitor the execution of CERN – Pakistan Cooperation.
- The committee meets once a year or when considered appropriate by the parties.
- So far six meetings have been held.

MEMBERS

- PAEC
  - Dr. Shoaib Ahmad, Member Physical Science
  - Mr. Mohammad Naeem, Director, PWI
- NCP - QAU
  - Dr. Hafeez Hoorani
- CERN
  - Dr. Jean Pierre Revol - Detectors
  - Dr. Philip Bryant - Accelerator
  - Dr. David Jacobs - Computing

Present Areas of Involvement

- Manufacturing of mechanical components & Engineering Services
  - (PAEC)
- Detector Assembly and Testing
  - (PAEC, NCP - QAU)
- HRD for Physics Analysis
  - (NCP - QAU)
- Grid Computing
  - (NCP - QAU, PAEC)

Magnet Support for CMS Detector

RAISERS

Extended Barrel Support

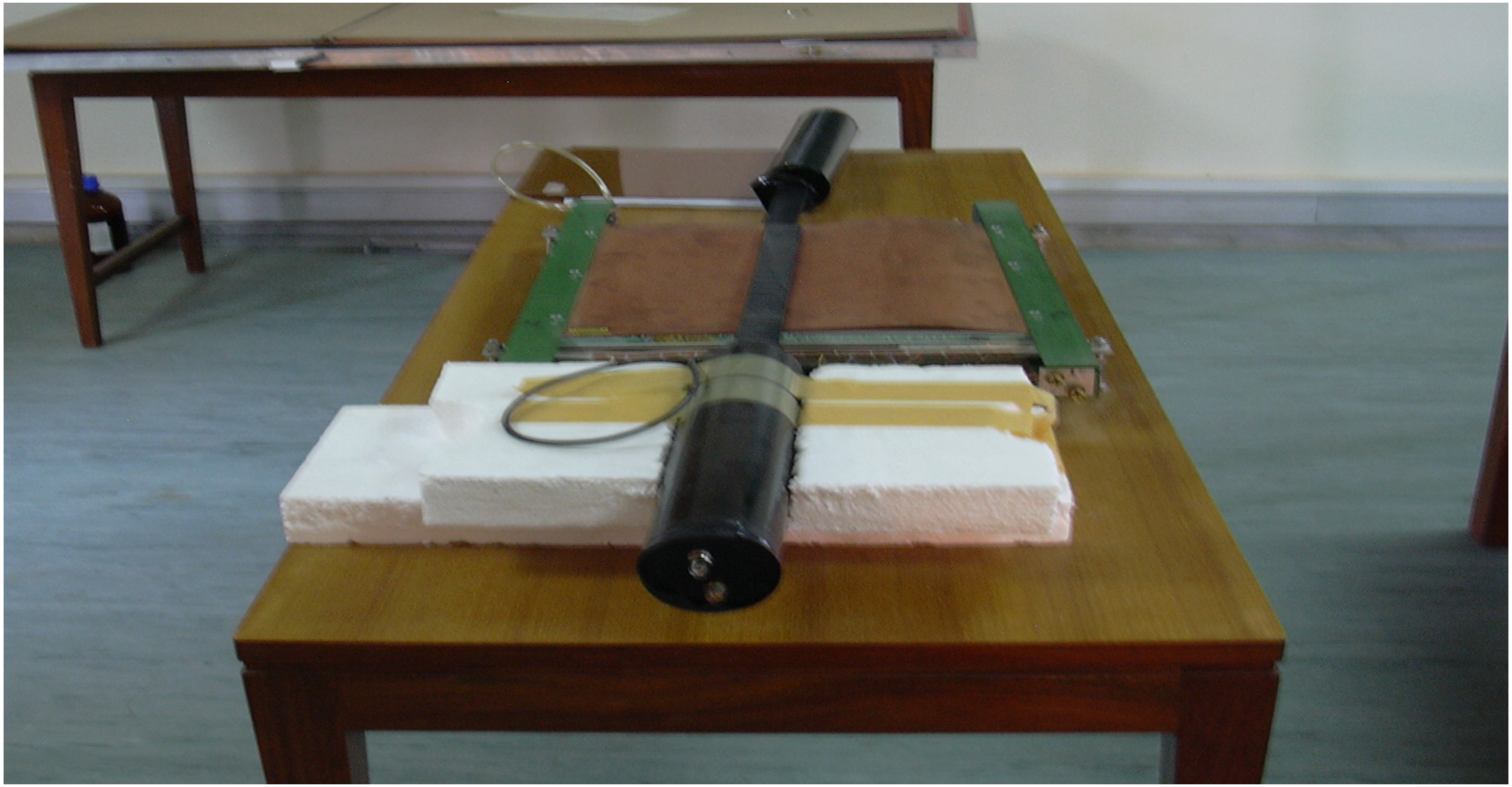
RPC Project

- Resistive Plate Chambers:
  - Assembly and Testing of 288 chambers.
    - Gas gaps are provided by Korea
  - Mechanical Design + Integration
  - Front-End Electronics (50,000 channels)
    - ASIC provided by CMS Collaboration.
  - Slow Control, Monitoring, Gas and Cooling System.
  - On-site installation of 10 deg.

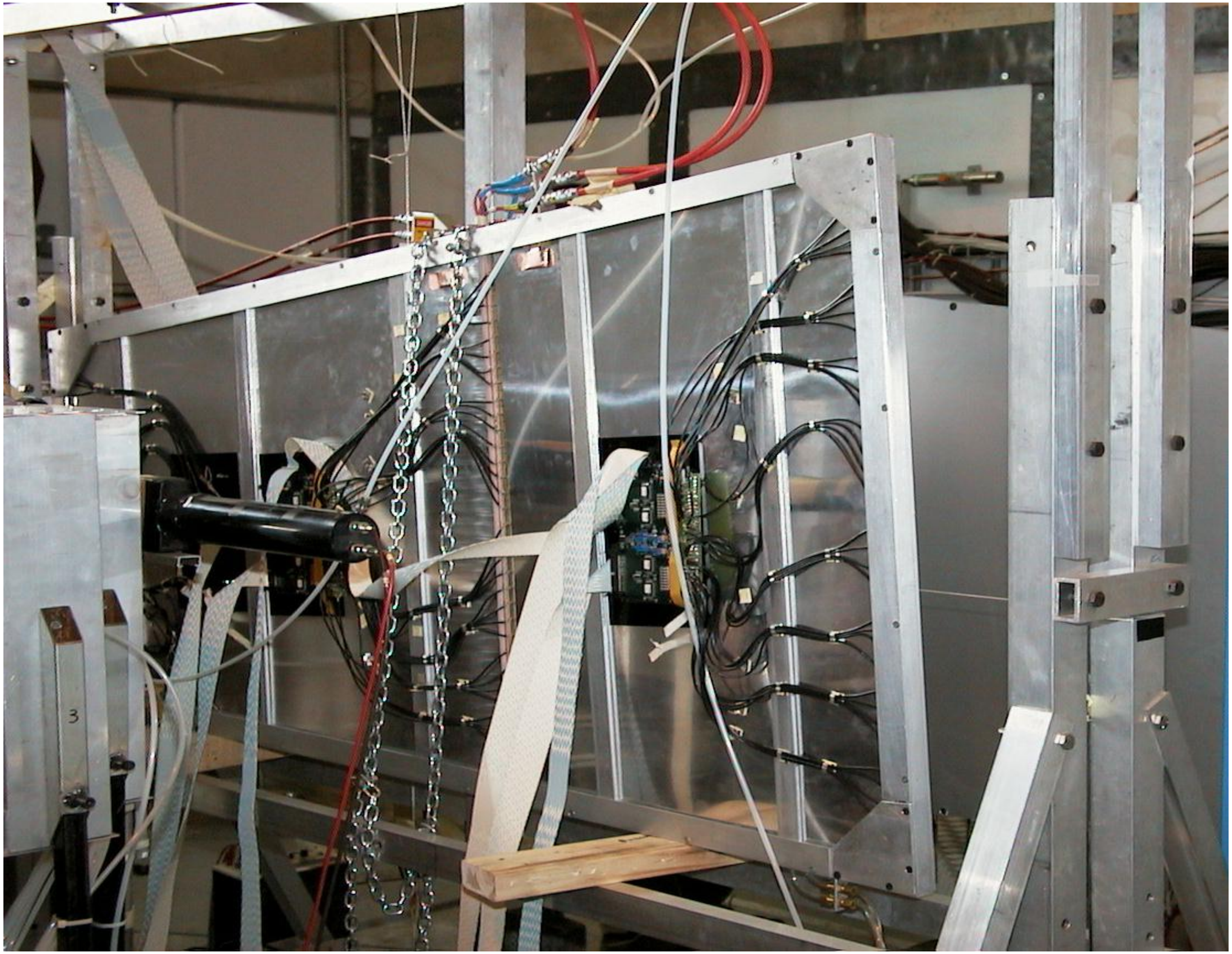
Detector Assembly & Testing

- Resistive Plate Chambers:
  - First small-scale prototype was build in 1999.
  - Full-scale prototypes were built in 2001 - 03
    - Tested successfully in X5 beam line 200 GeV muons.
    - Gamma Irradiation Facility (GIF)
  - Engineering Design Review (EDR) was presented and approved in 10/02.
  - Group from Pakistan has contributed into:
    - Mechanical Design
    - Integration
    - Installation
    - Commissioning

First Prototype RPC
1999

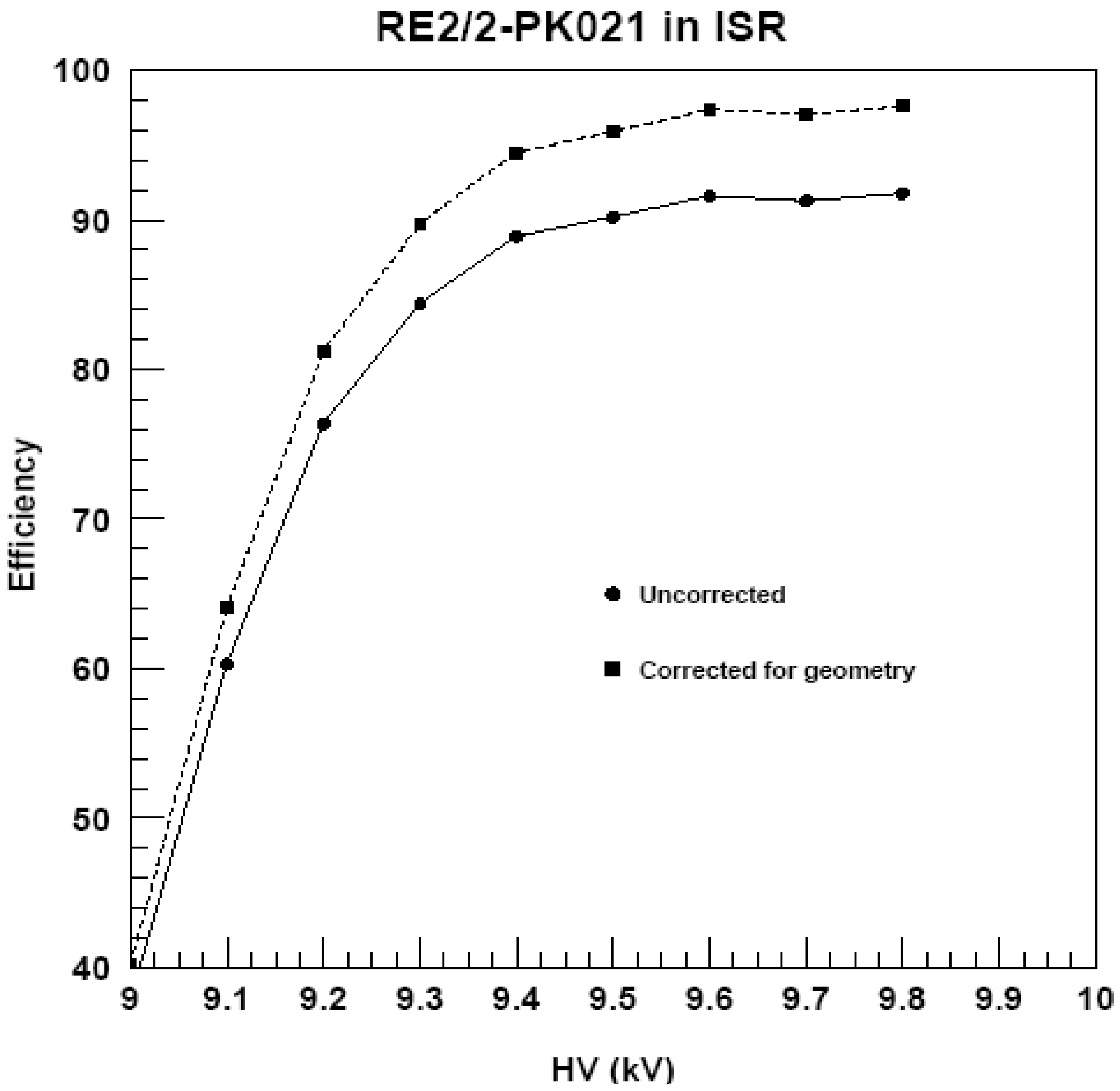


RPC Prototype in 2002

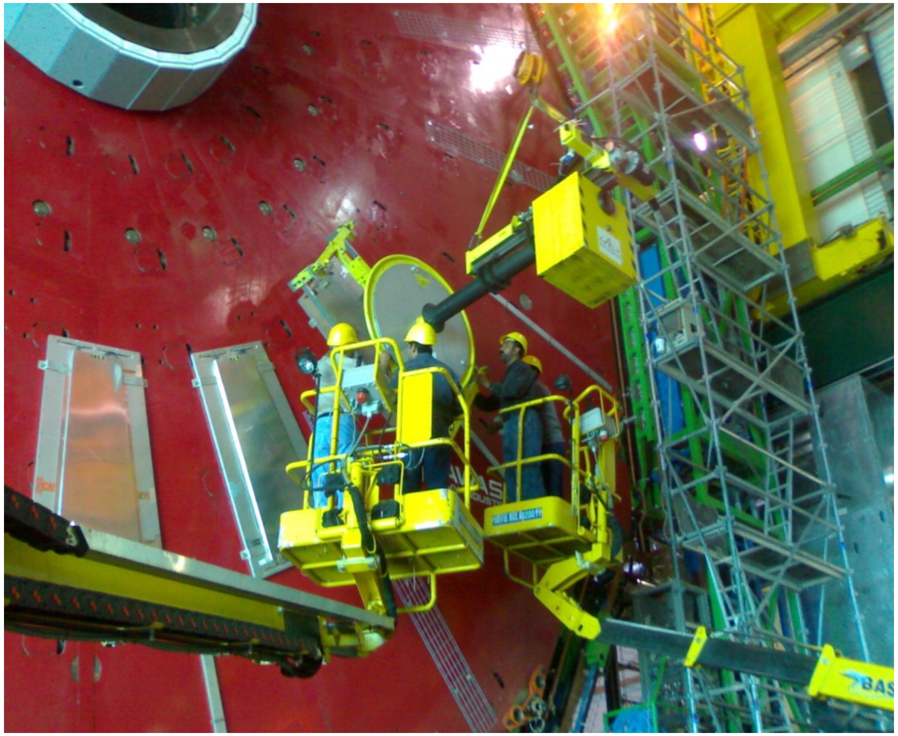



COSMIC
RAY MUON
TELESCOPE

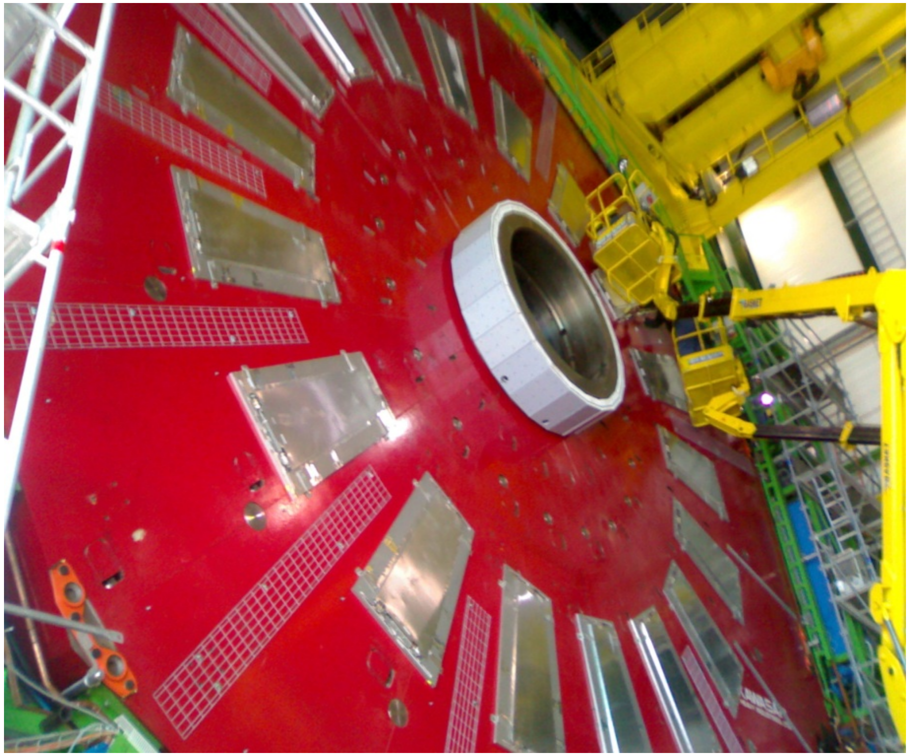
Efficiency of RPC



Installation Procedure



2 cherry pickers 4 persons



18 On Yoke */2 RPCs

Disk Completion

36

54

72

HRD for Physics Analysis

HRD for Physics Analysis

- Following are the topics of interest:
  - Analysis of RPC testbeam data
  - Study of Standard Model Physics and Parameters.
  - Study of heavy quark flavor (b, t)
  - Detailed studies of RPC trigger
  - $e/\gamma/\pi^0$ separation.
  - $H \rightarrow \gamma\gamma$ & $H \rightarrow ZZ \rightarrow 4\mu$

HRD for Physics Analysis

- Group of physicists:
  - 6 faculty members
    - Theory + Experiment
  - 7 Ph. D. students
  - 6 SO (Physics)
    - Physics Analysis, RPC Commissioning
  - 3 M. Phil students
- 10 M.Phil & 2 Ph.Ds already completed.

HRD Activities

- **Annual Particle Physics Workshop.**
- **Regular courses for training:**
  - Scientific Computing
  - Instrumentation
  - Data Analysis (Statistics, Error Analysis)
  - C++
- Three Ph.D. student at CERN for last 08 months. Another will go in April 2009.
- For students, we use the funds generated by commercial work done for mechanical

Grid Computing

LHC Computing Grid (LCG)

- It is common computing facility for all LHC experiments.
- As of April 14, 2008:
  - **Countries: 42**
  - **Number of Nodes: 181**
  - **Number of CPUs: 46,836**
  - **Total Storage: 5.23 PB**

LHC will produce **15 PB** of data per year.

LHC Computing Grid Node at NCP

- NCP has a network connectivity of 14 Mbps, used for:
  - Last month using LCG Node (1.5 TB downloaded) and CMS Data Production (280 GB produced and uploaded)
  - Sending/receiving emails and web surfing
- LCG Node, Web and Mail Servers are maintained by NCP staff
- Increased hardware resources recently for the LCG Node

LHC Computing Grid Node at NCP

- Linux based PC Cluster, CERN certified version.
- All user accounts (NIS), files (NFS) and software (CVS) is centralized
- Job scheduling done using open PBS.
- CERN Libraries and CMS software

LHC Computing Grid Node at NCP

Servers: Intel Xeon 3.2 GHz, Dual Processor, Hot pluggable SCSI Drives, Redundant Power Supplies

Clients: 90 P-IV, 3.2 GHz + *20 P-IV 3.4 GHz*

Mass Storage: 5 TB with hot pluggable SCSI (RAID – 5) Magnetic Tape Storage: 5 TB with 40/80 GB tapes

Network: 14 Mbps


pcncp21.ncp.edu.pk
202.83.169.238
UI
RB
CE
DELL


PK-GRID-CA
SIGNING SERVER
PK-GRID-CA
SIGNING SERVER
PHILIPS


WORKER NODES
UI
RB
CE
WORKER NODES


APC
APC

Summary I

- The LHC project was conceived & designed to probe the physics of the Terascale.
- Everything from the accelerator (its cryogenic systems, superconducting magnets,…), and the experiments (their detectors, electronics, data handling, selection of a precious few events,..) has to operate at unprecedented scales and complexity in an unprecedented environment.
- Their construction has required a long and painstaking effort on a global scale. They will be unparalleled scientific instruments.
- The LHC at CERN will open a window on the “magic” 1 TeV energy scale.
- If indeed new physics is at the TeV-scale, CMS (and ATLAS) should find it.

Summary II

- Construction and Commissioning of the CMS experiment is almost completed.
- Commissioning work already carried out gives confidence that CMS will operate with the expected performance.
- Commissioning using cosmic is going on since June 2008.
- Computing, Software & Analysis: 24/7 Challenges @ 50% of LHC running already conducted.
- Preparations for the rapid extraction of physics being made.

Summary III

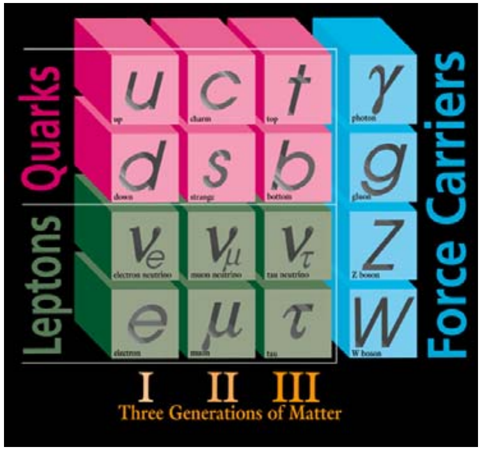
We are poised to tackle some of the most profound questions in physics.

The data collected by the LHC detectors could change our perception of how nature operates at a fundamental level.

It is time to find out what Nature has in store for us at the TeV scale.

LHC Physics Potential

The Standard Model



Over 30 years, the SM has been assembled and tested with 1000's of precision measurements. No significant departures.

3 weak isospin doublets of quarks and leptons. Strong and unified EM and Weak forces transmitted by carriers – gluons, photon and W/Z.

A complex Higgs boson doublet (4 fields) is included to fix unitarity violation, break the EW symmetry into distinct EM and Weak forces with massless photon and W/Z bosons at ~100 GeV, & give masses to quarks and leptons. One remains as a particle to be discovered.

The Higgs couplings to W,Z, top quark etc. gives them mass; direct Higgs search and mass measurements now tell us the SM Higgs mass is 115 – 200 GeV.

The Standard Model is flawed

The SM can’t be the whole story:

- Quantum corrections to Higgs mass (& W/Z) would naturally drive them to the Planck (or grand unification) scale. Keeping Higgs/W/Z to ~ 10^{-13} of Planck mass requires extreme fine tuning (hierarchy problem) – or new physics at TeV scale.

- Strong and EW are just pasted together in SM, but are not unified. New Terascale physics could fix this.

- 26 bizarre and arbitrary SM parameters are unexplained (e.g. why are **n** masses ~10^{-12} times top quark mass, but not zero?)

- SM provides CP violation, but not enough to explain asymmetry of baryons and antibaryons in the universe.

- Gravity remains outside the SM

The Terascale terrain

There is non-SM physics in the universe at large:

Dark Matter is seen in galaxies and seems needed to cluster galaxies in the early universe. It appears to be a heavy particle (or particles) left over from the Big Bang, whose mass is in the Teravolt range. Physics beyond the SM gives natural candidates.

Dark Energy is driving the universe apart; it may be due to a spin zero field, so study of the Higgs boson (the only other suspected scalar field) may help understand it.

New physics is needed at the Terascale to solve or make progress on these puzzle. There are many theoretical alternatives, so experiment is needed to show us the way. And we now have the tools to enable them!

The Quantum Universe Questions

The “Quantum Universe” report gives nine key questions in three major areas.

I. Einstein’s dream

1. Undiscovered principles, new symmetries?
2. What is dark energy?
3. Extra space dimensions?
4. Do all forces become the same?

II. The particle world

5. New particles?
6. What is dark matter?
7. What do neutrinos tell us?

III. Birth of universe

8. How did the universe start?
9. Where is the antimatter?

The LHC and ILC will address at least eight of these. The LHC should show us there is new physics at the Terascale; the ILC should tell us what it really is. The LHC and ILC are highly synergistic – each benefits from the other.

Revealing the Higgs

The Higgs field pervades all of space, interacting with quarks, electrons W, Z etc. These interactions slow down the particles, giving them mass.

The Higgs field causes the EM and Weak forces to differ at low energy. Three of the four higgs fields give the longitudinal polarization states required for massive $W^{\pm}$ and Z. The fourth provides one new particle (the Higgs boson).

The Higgs boson is somewhat like the Bunraku puppeteers, dressed in black to be ‘invisible’, manipulating the players in the drama.

Higgs Search Strategy at the LHC

Resonances - narrow width approximation:

$$d\hat{\sigma} \sim \pi^2 (2J+1)(\Gamma / M)\delta(\hat{s} - M^2)$$

$$\hat{\sigma} \sim \pi^2 (2J+1)\Gamma / M^3$$

e.g.

$$(2J+1)\pi^2 \Gamma / M^3 \sim 47\, nb$$

$$for\ W\ \ production$$

$$2\ Body\ Scattering:$$

$$\Delta\hat{\sigma} \sim \pi\alpha_1\alpha_2 /(2M_o)^2$$

$$e.g.\, \Delta\hat{\sigma}_{WW} \sim 50\ pb$$

LHC Cross Sections:

$$\sigma_I \sim 50 mb$$

$$\sigma_{b\bar{b}} \sim 0.1 mb$$

$$\sigma_W \sim 100 nb$$

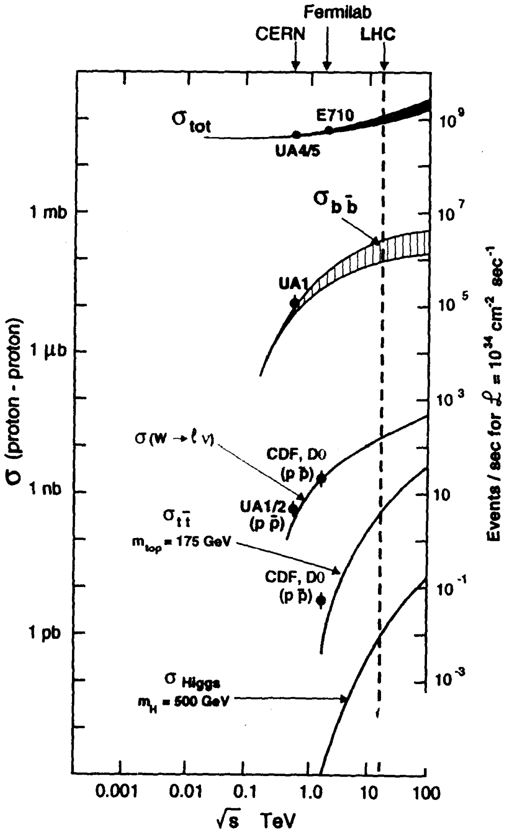
$$\sigma_{WW} \sim 100\, pb$$

$$\sigma_{ZZ} \sim 10\, pb$$

$$\sigma_H (120\ \ GeV) \sim 2\, pb$$

There is a factor > 10^{10} between the Higgs cross section and the total inelastic cross section. There is also the final state branching fraction to consider. This is why the LHC design luminosity is so high.

Higgs Cross section VS Energy



CDF and D0 successfully found the top quark, which has a cross section ~ 10^{-10} the total cross section. A 500 GeV Higgs has a cross section 1000 times smaller at the Tevatron

A 500 GeV Higgs has a cross section ratio of ~ 10^{-11}, which requires great rejection power against backgrounds and a high luminosity. Multiple redundant measurements of the SM particles are needed.

For one year of running we put in an efficiency of ~ 1/3 or a data taking time of 10^7 sec. This means a sensitivity of $10^{41}/cm^2 yr$ or 100 fb^{-1}/yr. In one year at design luminosity 100,000 (1,000,000) Higgs particles of 500 GeV (100 GeV) mass will be produced.

LHC Rates at $10^{33}/(\text{cm}^2\text{sec})$

Process			
W → $e\nu$			

Higgs Decay Rates

Direct:

Quarks and Leptons

$$\Gamma(H \rightarrow q\overline{q}) = 3\Gamma(H \rightarrow l\overline{l}), \textit{ due to color}$$

$$\Gamma(H \rightarrow q\overline{q}) = \left[\alpha_W / 8(m_q / M_W)^2\right] M_H$$

Gauge Bosons

$$\Gamma(H \rightarrow ZZ) = \Gamma(H \rightarrow WW) / 2$$

$$\Gamma(H \rightarrow WW) = \left[\alpha_W / 16(M_H / M_W)^2\right] M_H, \textit{ recall top width}$$

Loop Decays - Gauge Bosons:

$$\Gamma(H \rightarrow gg) \sim \left[\alpha_W / 9(M_H / M_W)^2\right] \quad \left[(\alpha_s / \pi)^2 |I|^2 / 8\right] M_H$$

$$\Gamma(H \rightarrow \gamma\gamma) \sim \left[\alpha_W / 9(M_H / M_W)^2\right] \left[(\alpha \ / \pi)^2 |I|^2 / 8\right] M_H$$

Higgs couples to mass, with no direct Hγγ or Hgg coupling

Higgs - Production via gg Fusion

- The formation cross section is,

$$\boxed{d\sigma/dy \sim \pi^2\Gamma(H \rightarrow gg)/(M_H^3)[xg(x)]_{x1}[xg(x)]_{x2}}$$

- Using the expression for Γ(H-->gg) and normalizing the gluon distribution with a = 6,

$$\boxed{d\sigma/dy \sim 49\pi^2[\Gamma(H \rightarrow gg)/(4M_H^3)][(1 - M_H/\sqrt{s})^{12}] \sim 49\pi^2\Gamma(H \rightarrow gg)/(4M_H^3)}$$

$$\boxed{d\sigma/dy \sim 49|I|^2\alpha_s^2\alpha_W/[288M_W^2].}$$

- Note that the M_H^3 behavior of Γ cancels the $1/M_H^3$ behavior of $d\sigma/dy$, leaving a roughly constant cross section,

Higgs Event Rate Estimate

$\Gamma(H \to gg) \sim 0.59 GeV$

$(d\sigma / dy)_{y=0} \sim 3.5 pb$

$\Delta y \sim 5, \ \Delta\sigma \sim 17 pb$

$1 yr \sim 10^7 \sec, \ L \sim 10^{34} /(cm^2 \sec)$

$1,600,000 \ \ H \ \ produced$

$B(H \to ZZ) \sim 1/3$

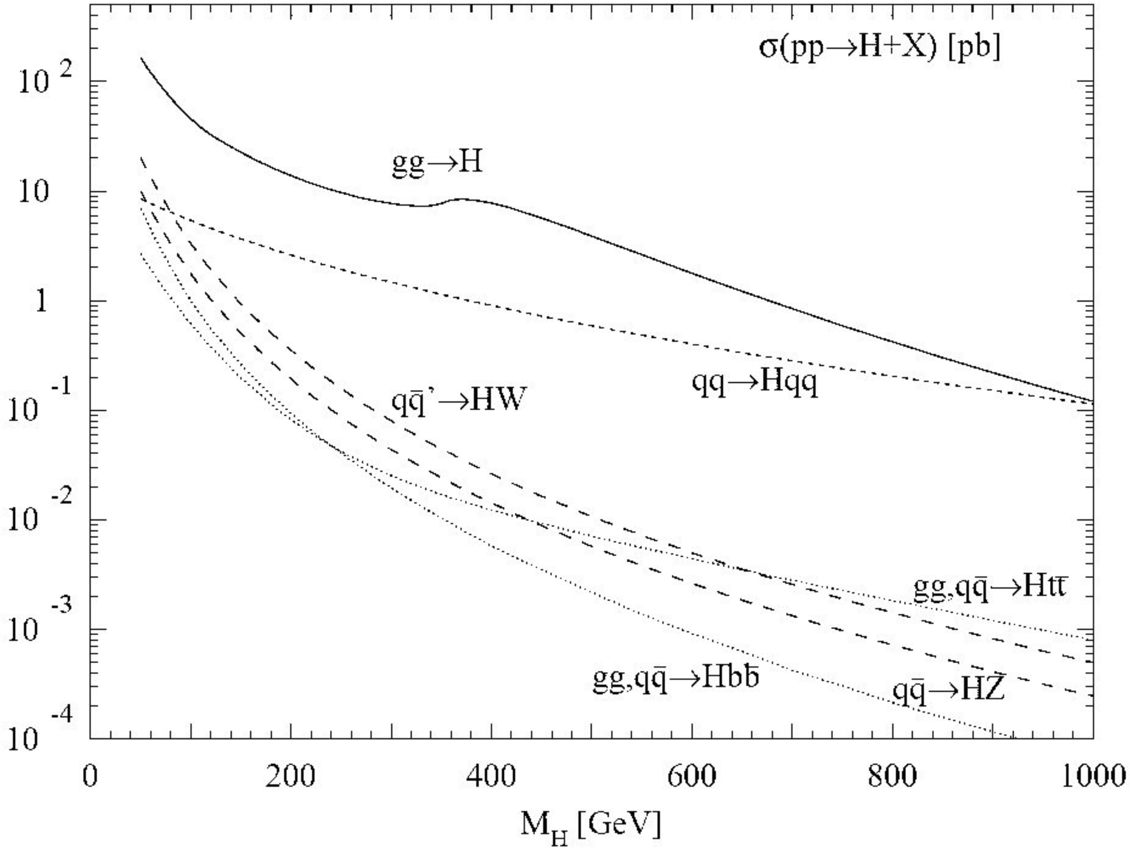
$B(Z \to e\overline{e} + \mu\overline{\mu}) \sim 0.07$

$2600 \ \ \det ectable, \ 1/\sqrt{2600} = 1/51$

$51 \ \ \sigma \ \ if \ \ no \ \ background$

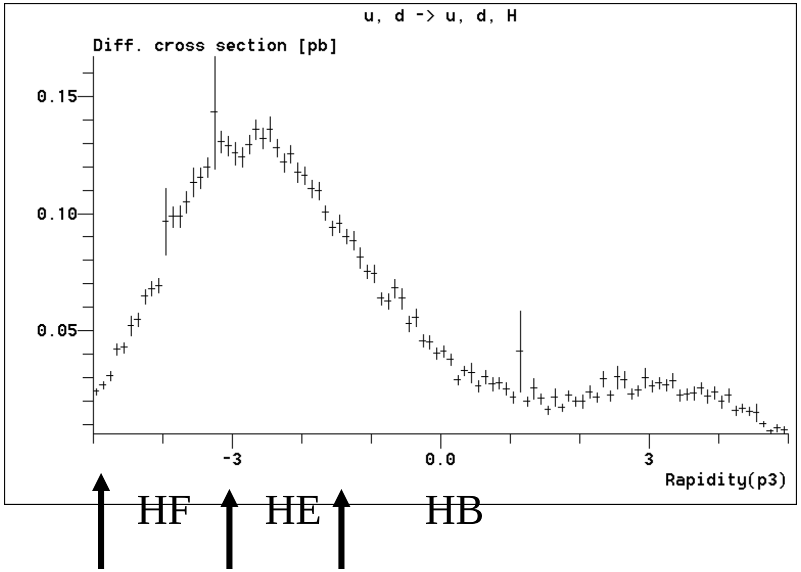
Ignore |I| dependence on Higgs mass (n.b. peak at ~ twice the top mass). If M_H= 500 GeV then the gluon source factor $(1-M_H/\sqrt{s})^{12}$ is ~ 0.65. The falloff of the cross section with source function at the LHC is small for low mass Higgs.

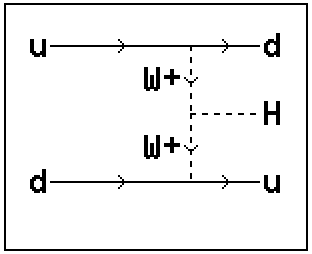
Higgs Production Modes



The Higgs cross section has as largest contribution g+g with an internal top loop. Note that qqH is quite large, followed by associated production modes including DY production of W, Z with H bremmstrahlung and H with top pairs

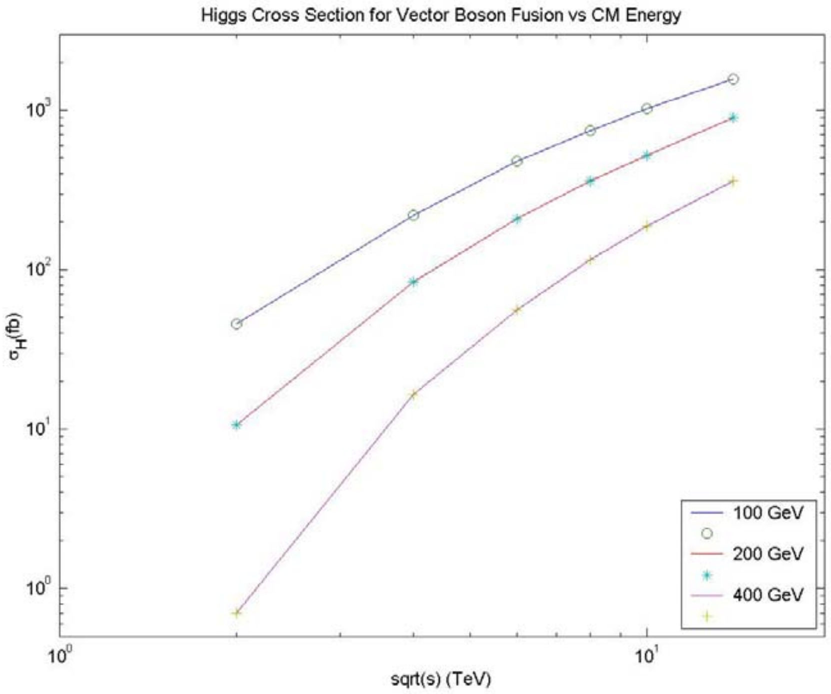
H Production from W+W





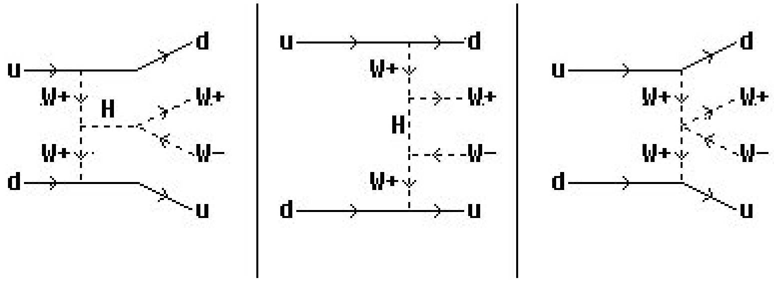
Use the EW radiation of a W by a quark. The “effective W approximation” analogous to the WW approximation. Need good jet coverage to low P_T and small angles. Cross section depends only on the Higgs coupling to W, Z – isolate g_{HWW}.

VBF at Tevatron and LHC

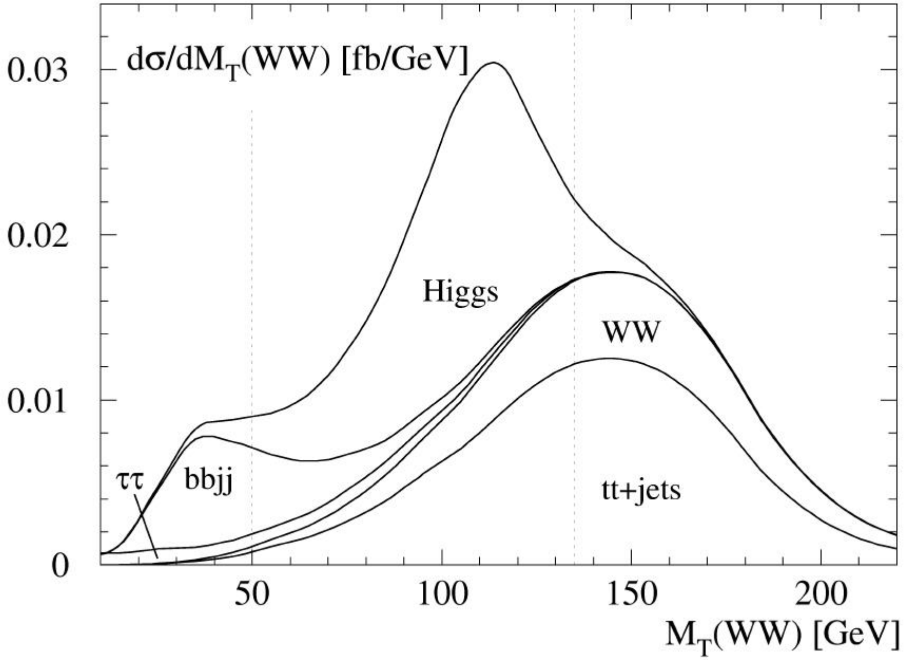


Over the Higgs mass range (100,1000) GeV VBF is a substantial fraction of the Higgs production rate and it offers a good signature – 2 tag jets. The tevatron cross section is down by > 10 x. In addition the rapidity plateau is wider at the LHC which makes the tag jets, with <η>~ 3 more distinct there than at the Tevatron.

VBF is a ‘Discovery” Mode at the LHC



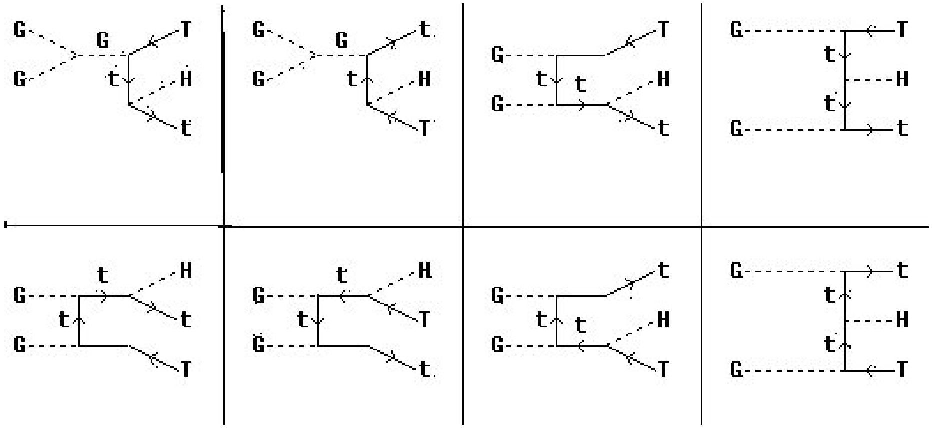
The “continuum” WW cross section is small w.r.t. the Higgs contribution.



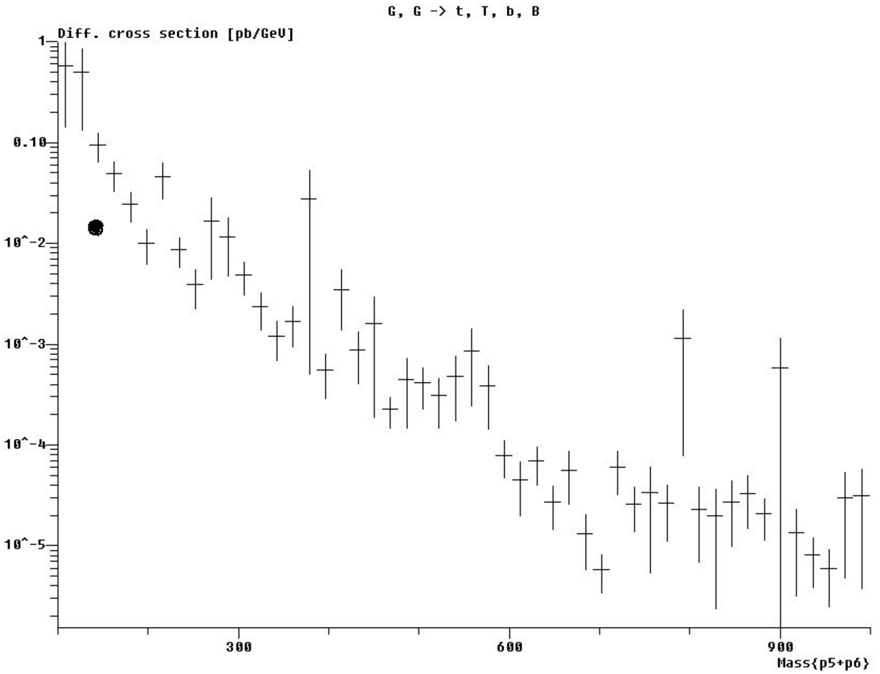
In a full study the main background is from top pairs and WWJJ radiative DY background.

Higgs + Top Pairs at the LHC

Top pair QCD production with a radiated accompanying H.

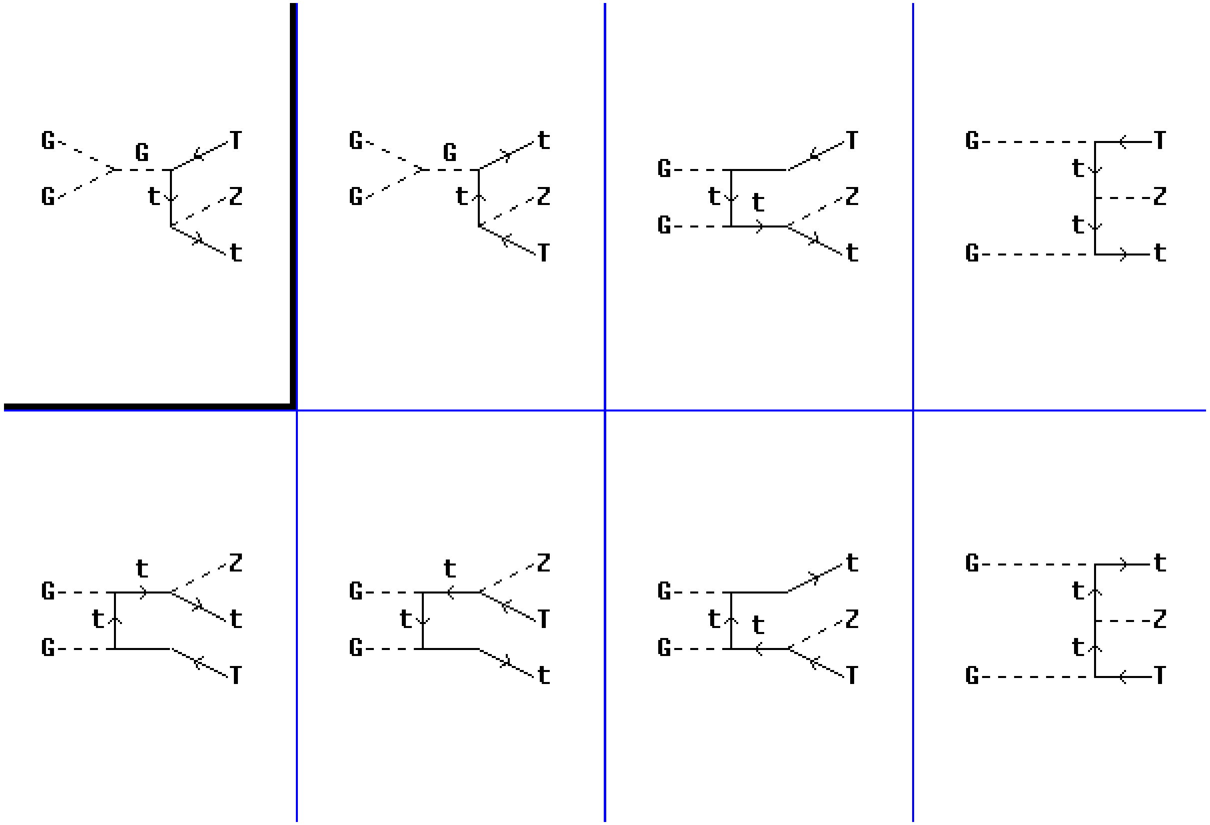


A top pair is ~ 0.35 TeV. This is too heavy for the Tevatron to make a useful rate. It is a useful mode at LHC for low mass Higgs with a good ratio of $S/\sqrt{B}$



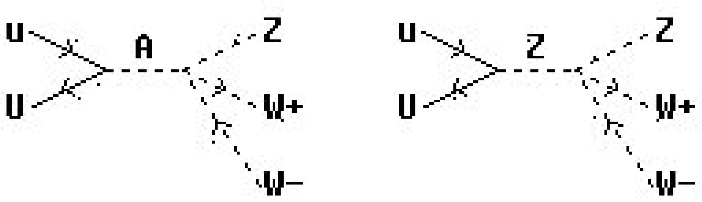
Take Higgs cross section and divide by +-2 sigma in the mass resolution ~ 20 GeV (recall Z) to get $d\sigma / dM$

Z “Control” Sample



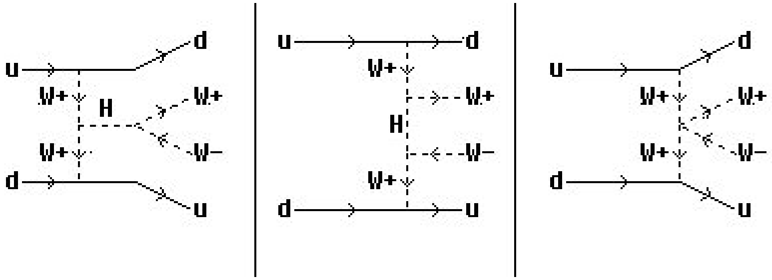
In many cases the H can be replaced by a Z and the process will have a similar cross section and other dynamics. Then the dilepton decays of the Z can be used as a clean signature and the process can be validated prior to looking for the H itself.

Quartic gauge Couplings – D-Y, VBF



Beyond the range of Run II at present. Seen at LEP -II

Therefore, at the LHC the SM prediction for quartic couplings can be confronted very directly. For example for *WWZ* with both *W* decaying into leptons and *Z* decaying also into electrons or muon pairs $(\ell^+ + \nu_\ell + \ell^- + \bar{\nu}_\ell + \ell^+ + \ell^-)$, in one year there are ~ 1000 events assuming full efficiency for triggering and reconstruction. Note also that the gauge boson pairs from WW fusion (see Fig.5.6) at high *WW* mass probe the strength of the quartic coupling predicted in the SM.



High WW or ZZ mass VBF processes will let us explore quartic couplings at the LHC.

Higgs Particle Production at the LHC

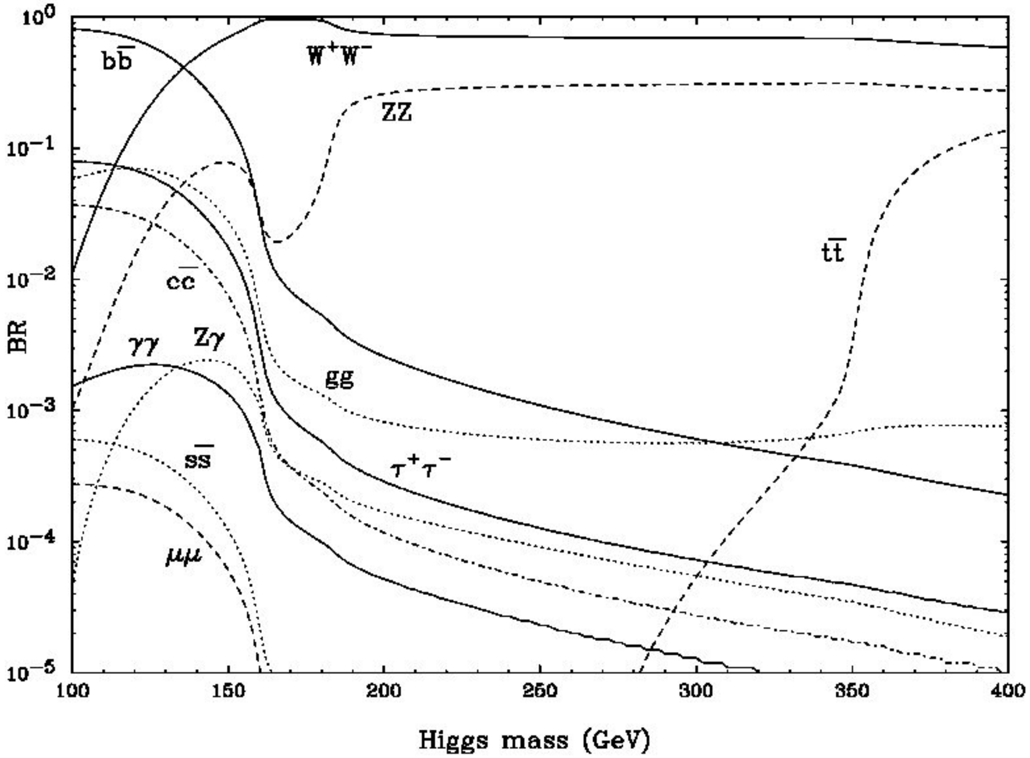
- The coupling of the Higgs field to the fermions is proportional to the fermion mass. Thus the Higgs field couples only weakly to ordinary matter, u,d quarks and gluons. Therefore, production cross sections are rather small, making discovery difficult.

- The Higgs mass is unknown. For low masses bb and $\tau\tau$ modes are favored. When energetically allowed , WW and ZZ modes dominate.

- The large top mass makes the tt mode substantial, > 10%. The backgrounds are overwhelming, however.

- The CMS detector is designed to discover the Higgs for all masses < 1 TeV in 1 year of full luminosity operation.

Higgs Branching ratios



Note that q,l width ~ M while W,Z width ~ M^3. Hence bb dominates below WW "threshold". ττ is down by ~ 9 due to coupling to mass, and 1/3 color factor.

below *ZZ* "threshold" there is a Zl^+l^- mode with an "off shell *Z*", conventionally called *ZZ**. The decay width, Γ_Z~ 2.5 GeV and the Breit-Wigner resonant mass distribution, $d\sigma/dM \sim (\Gamma/2)^2/[(M-M_o)^2+(\Gamma/2)^2]$ means that the *ZZ** decay rate is suppressed by a factor of $\sim[(\Gamma_Z/2)/(M-M_Z)]^2$ with respect to *ZZ* decays

Similarly for *WW**

Low Mass Higgs

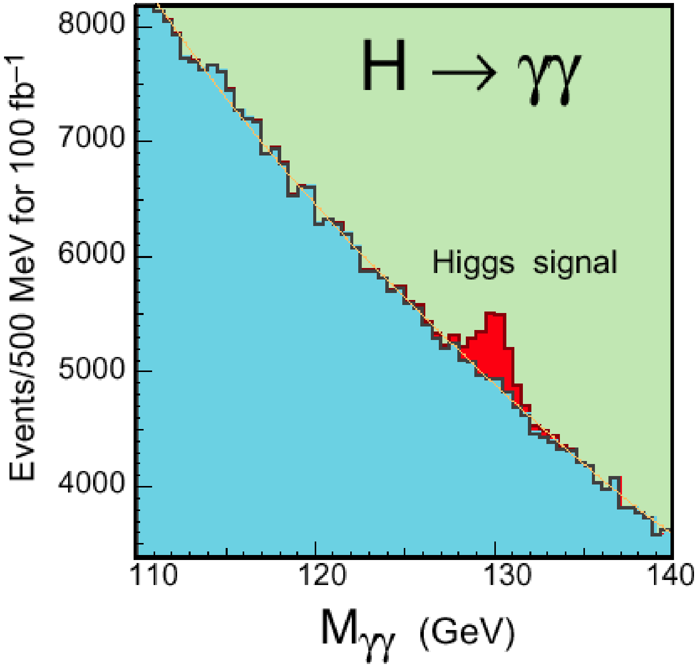
$H \to \gamma\gamma$: decay is rare ($B \sim 10^{-3}$)

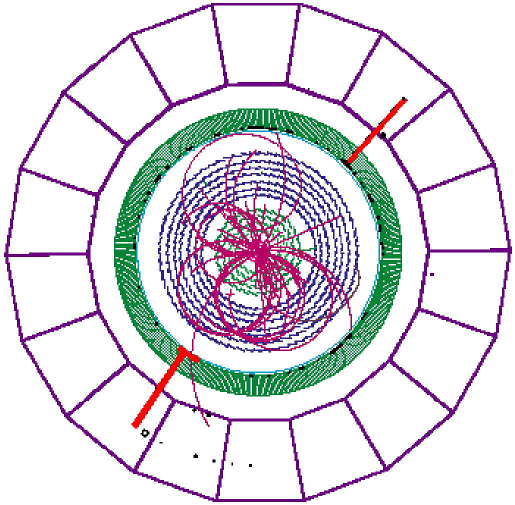
But with good resolution, one gets a mass peak

Motivation for $PbWO_4$ calorimeter

CMS: at 100 GeV, $\sigma \approx$ 1GeV

S/B ≈ 1:20





Higgs Mass - Upper Limit

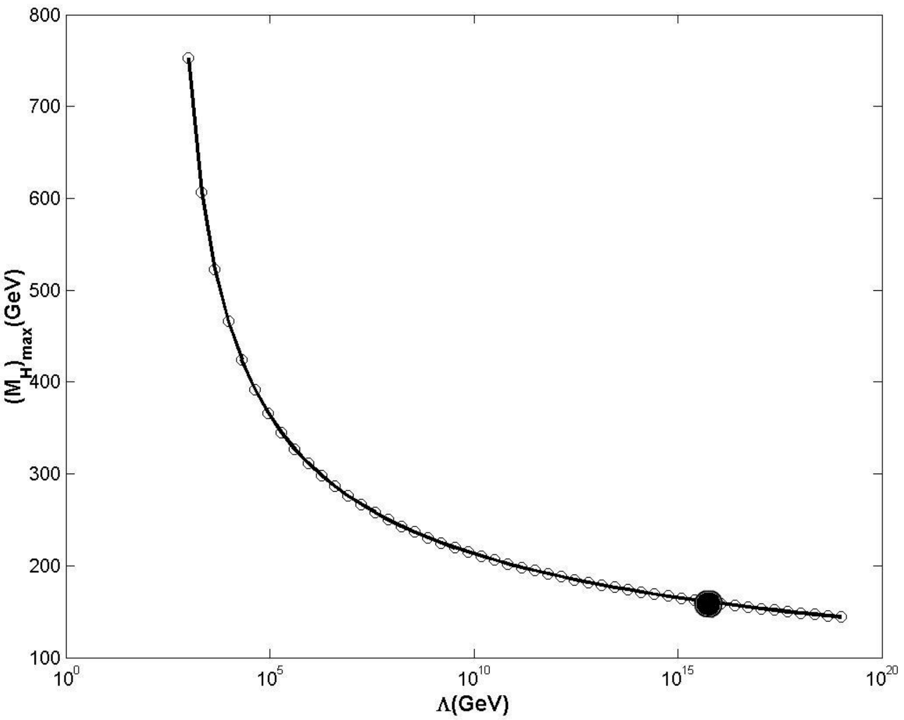
- The couplings are a function of the mass scale at which they are probed. We require that λ(Q) is well behaved from $<\phi>$ = 174 GeV up to a scale Λ, with 1/ λ(Λ) = 0 (strong coupling at Λ), the running of λ includes loops with H and t - with opposite sign.

$$\lambda(Q^2) = \lambda(<\phi>^2)/[1 - (3\lambda(<\phi>^2)/8\pi^2)\ln(Q^2/2<\phi>^2)]$$

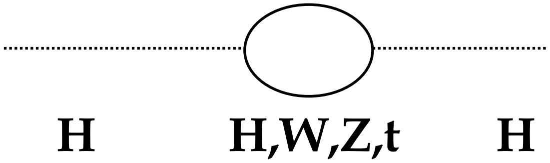
$$1/\lambda(Q^2) = 1/\lambda(<\phi>^2) - (3/8\pi^2)[\ln(Q^2/2<\phi>^2)]$$

$$M_H = \sqrt{2\lambda} <\phi>$$

Higgs Mass - Upper Limit



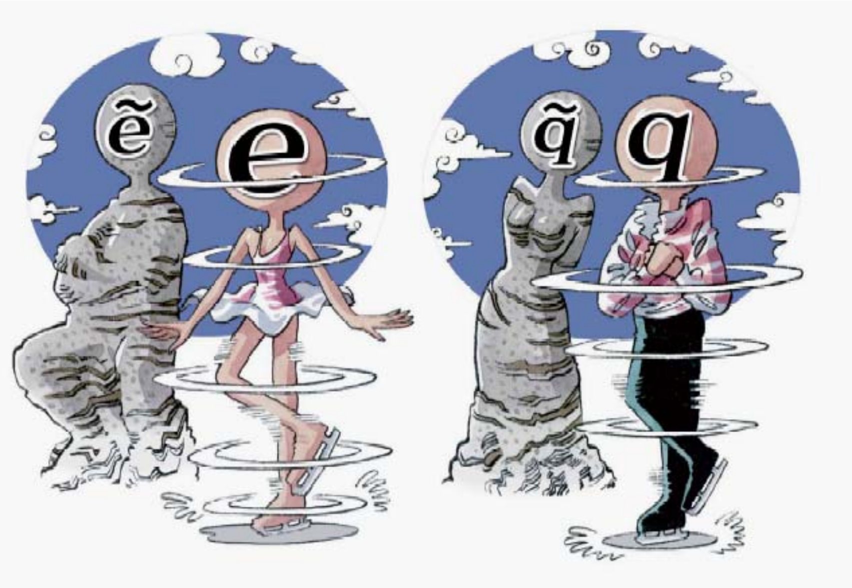
If there is no new physics up to the GUT scale, then the Higgs mass must be < 160 GeV. Again a low mass Higgs is favored.



$$(M_H)_{\max} \sim 4\pi < \phi > / \sqrt{3\ln(\Lambda^2 / 2 < \phi >^2)}$$

Decoding Super symmetry

Super symmetry overcomes inconsistencies in the standard model by introducing new fermionic space-time coordinates.It requires that every known particle has a super symmetric counterpart at the terascale. These particles stabilize the EW scale to the Terascale solving the hierarchy problem.



The partner of the spin ½ electron is a spinless ‘selectron’.

All quarks also have their partners, as do the W and Z bosons, etc.

Decoding Super symmetry

The LHC is guaranteed to see the effects of supersymmetry, if it has relevance for fixing the standard model. The counterparts of quarks and gluons will be produced copiously, but the LHC will not be sensitive to the partners of leptons, the photon, or of the W/Z bosons.

The ILC can produce the lepton, photon, and W/Z partners, and determine their masses and quantum properties.

If the matter-antimatter asymmetry in the universe arises from supersymmetry, the ILC can show this to be the case.

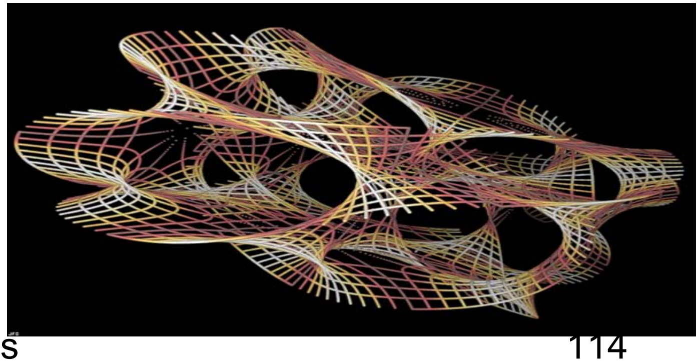
Understanding dark matter

Our own and other galaxies are gravitationally bound by unseen dark matter, predominating over ordinary matter by a factor of five. Its nature is unclear, but it is likely to be due to very massive new particles created in the early universe.

Supersymmetry provides a very attractive candidate particle, called the neutralino. All supersymmetric particles decay eventually to a neutralino. At the LHC the neutralino cannot be directly observed, but can be 'seen' at the ILC.

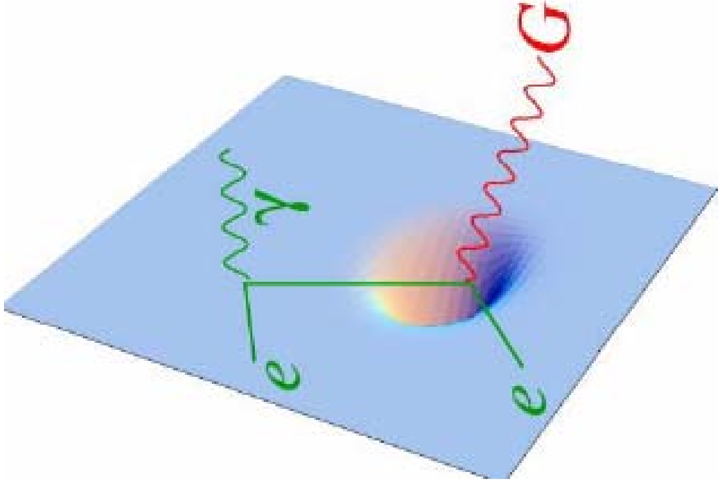
Finding extra spatial dimensions

String theory requires at least 6 extra spatial dimensions (beyond the 3 we already know). The extra dimensions are curled up like spirals on a mailing tube. If their radius is ‘large’ (~1 atto meter = billionth of an atomic diameter) or larger, they could unify all forces (including gravity) at lower energy than the Planck mass.

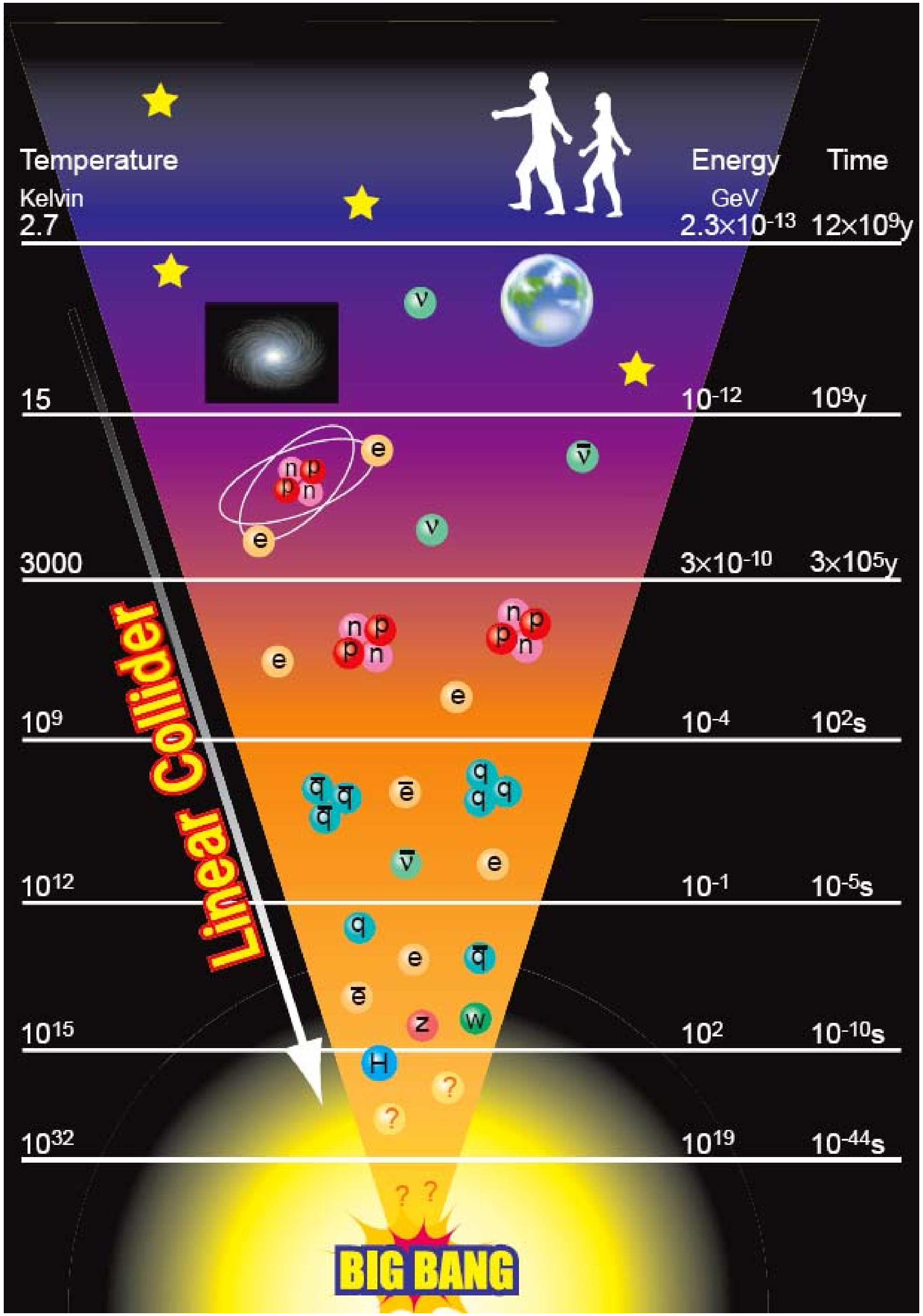


Finding extra spatial dimensions

If a particle created in an energetic collision goes off into the extra dimensions, it becomes invisible in our world and the event shows missing energy and total momentum imbalance.



There are many possibilities for the number of large extra dimensions, their size and metric, and which particles can move in them. LHC and ILC see complementary processes that will help pin down these attributes.


Temperature
Kelvin
Energy
GeV
Time
2.7
2.3×10^{-13}
12×10^{9}y
15
10^{-12}
10^{9}y
3000
3×10^{-10}
3×10^{5}y
10^{9}
10^{-4}
10^{2}s
10^{12}
10^{-1}
10^{-5}s
10^{15}
10^{2}
10^{-10}s
10^{32}
10^{19}
10^{-44}s
Linear Collider
BIG BANG