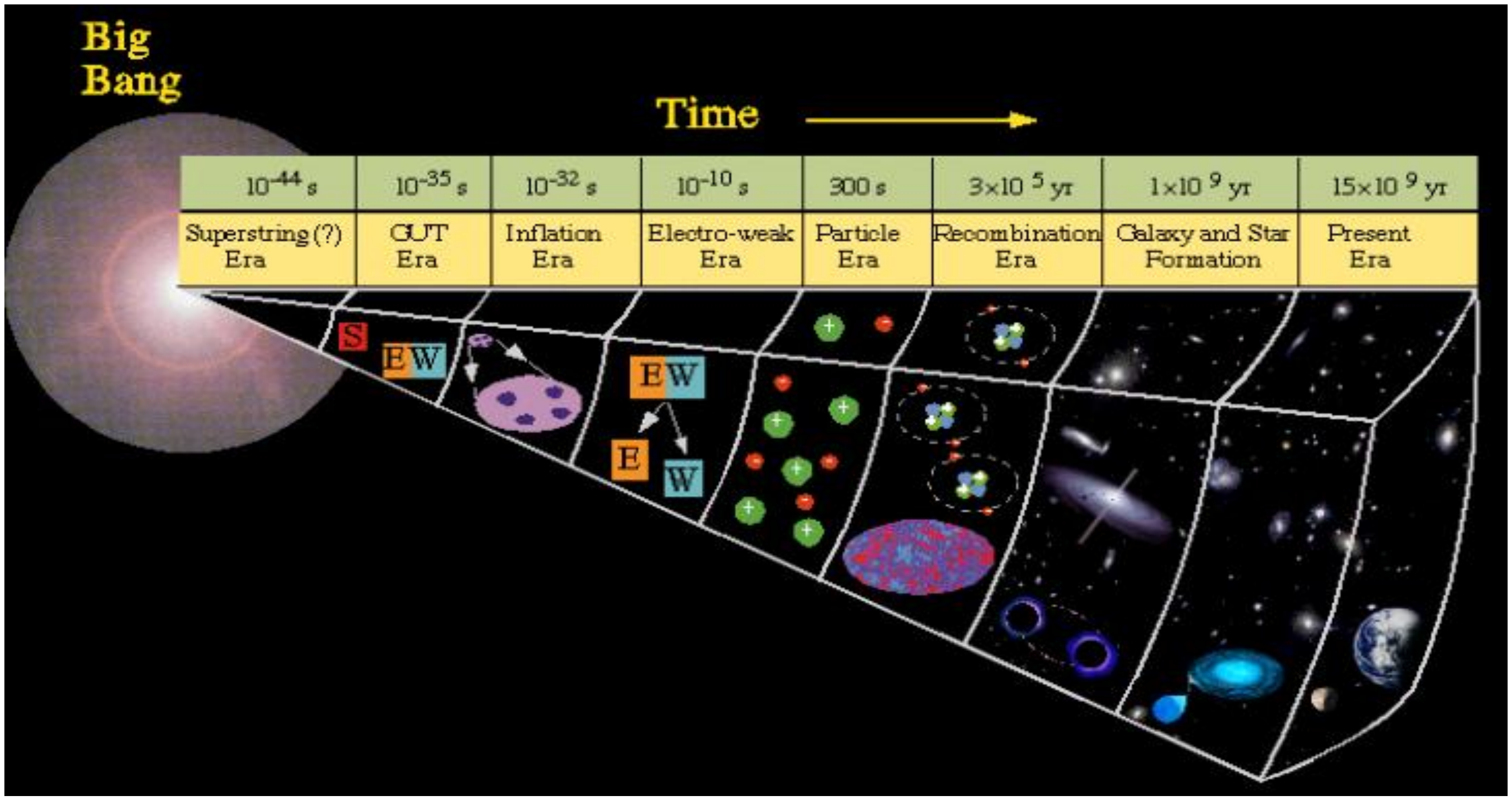
Introduction to the ILC

Lecture I-1



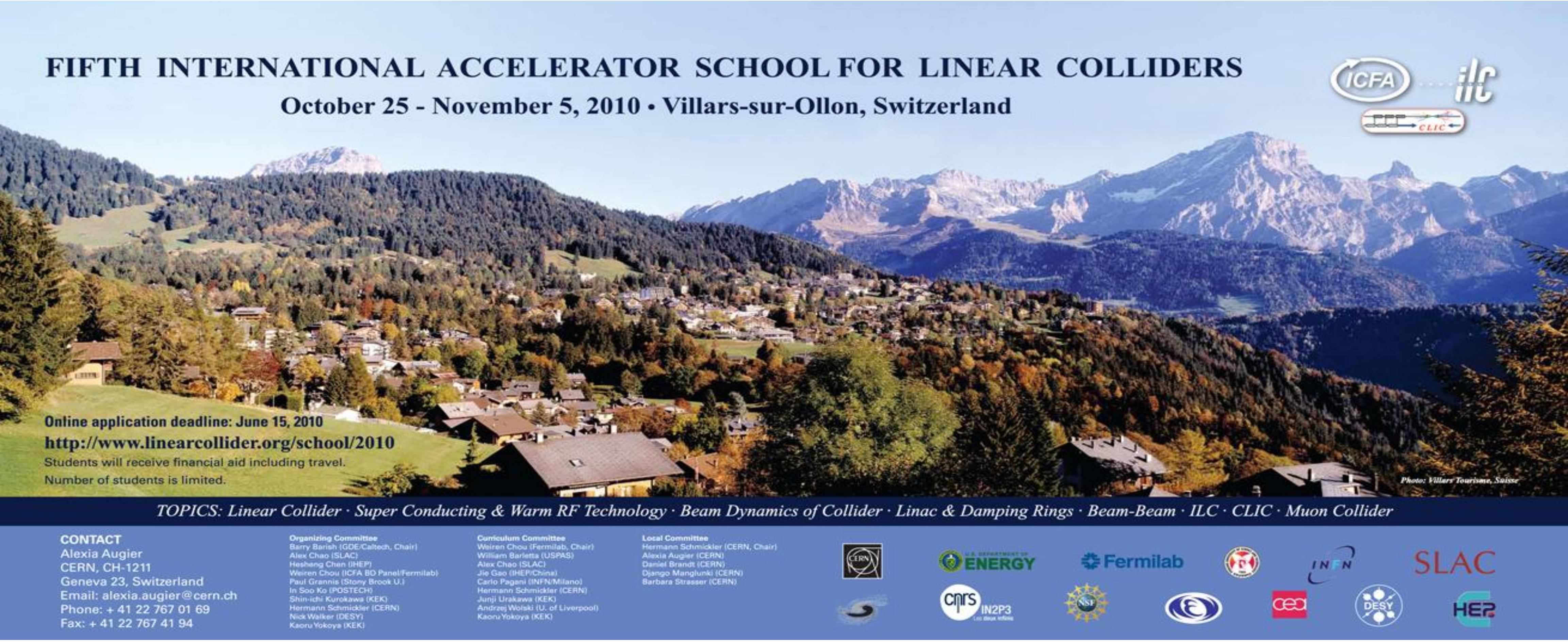
Barry Barish

Caltech / GDE

26-Oct-10

Lecture I-1

Fifth International LC Accelerator School



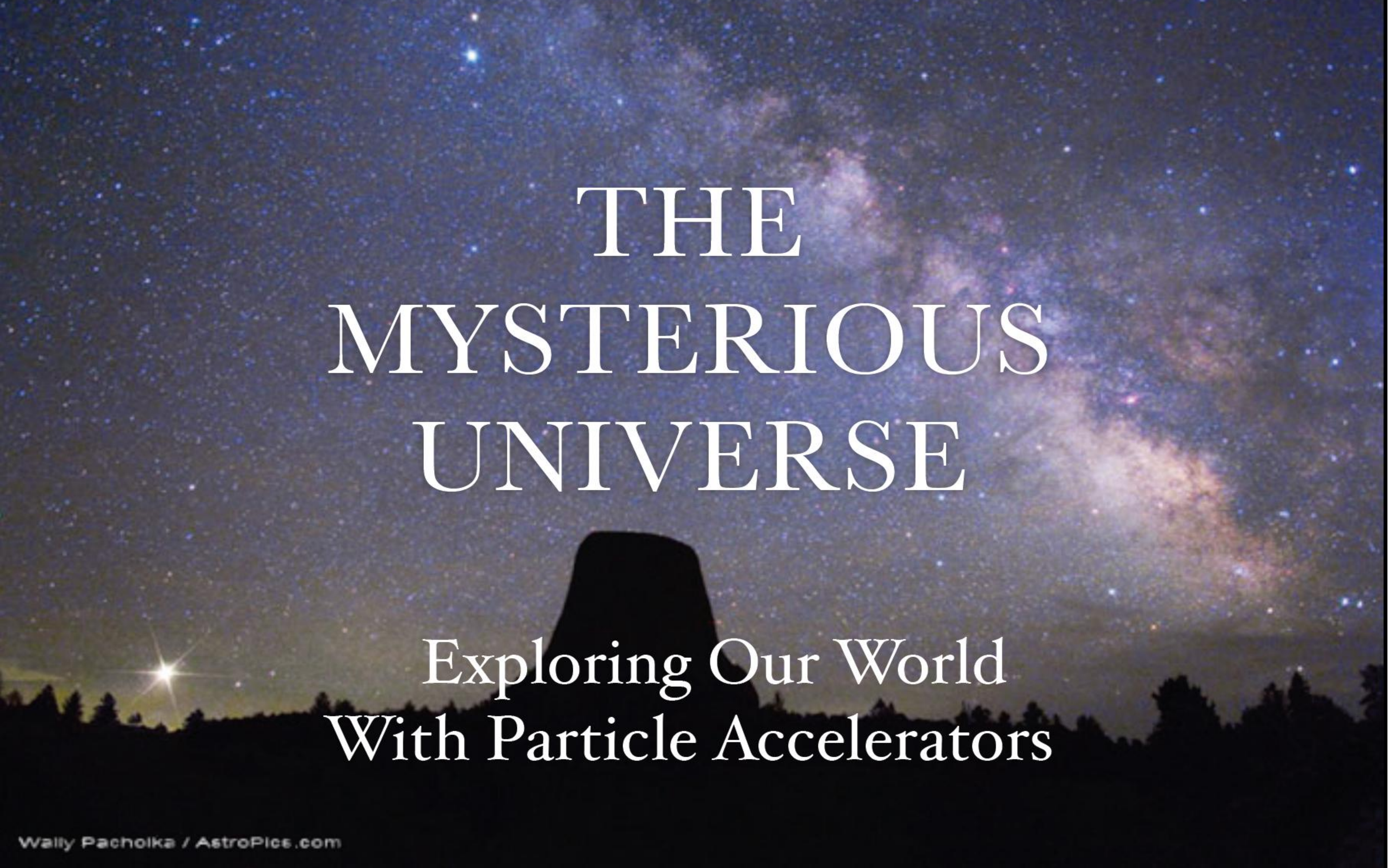
Lecture I-1

Science Motivation → Linear Collider

- Frontiers of Particle Physics
- The energy frontier
- The Large Hadron Collider
- Why a complementary lepton collider ?
- The ILC concept

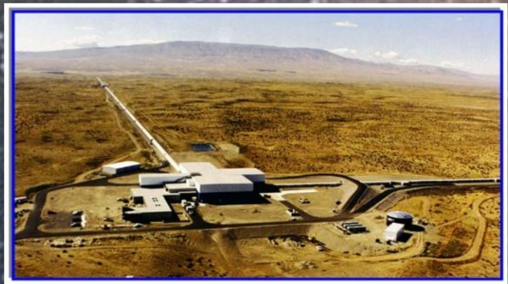
THE MYSTERIOUS UNIVERSE

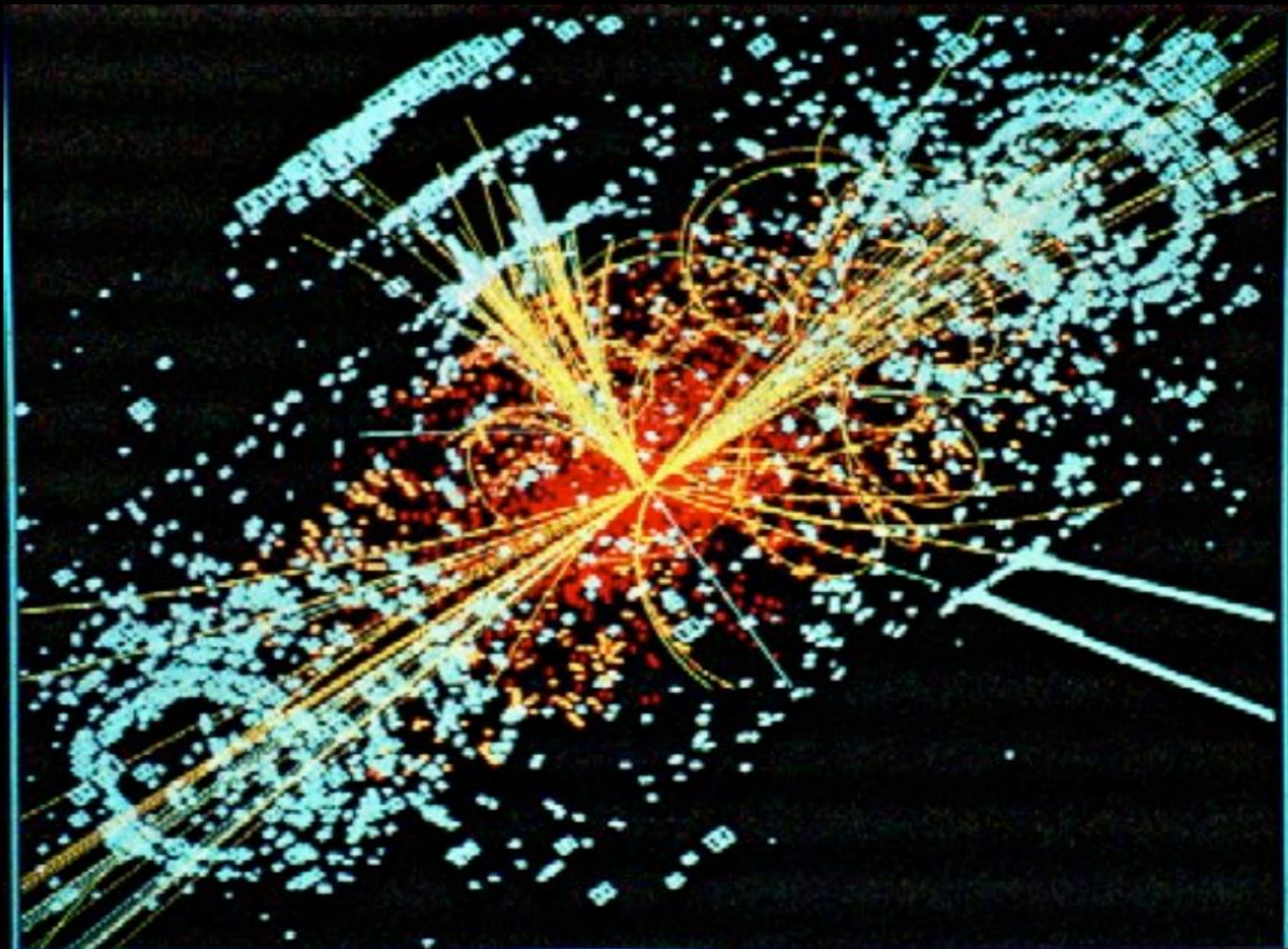
Exploring Our World With Particle Accelerators



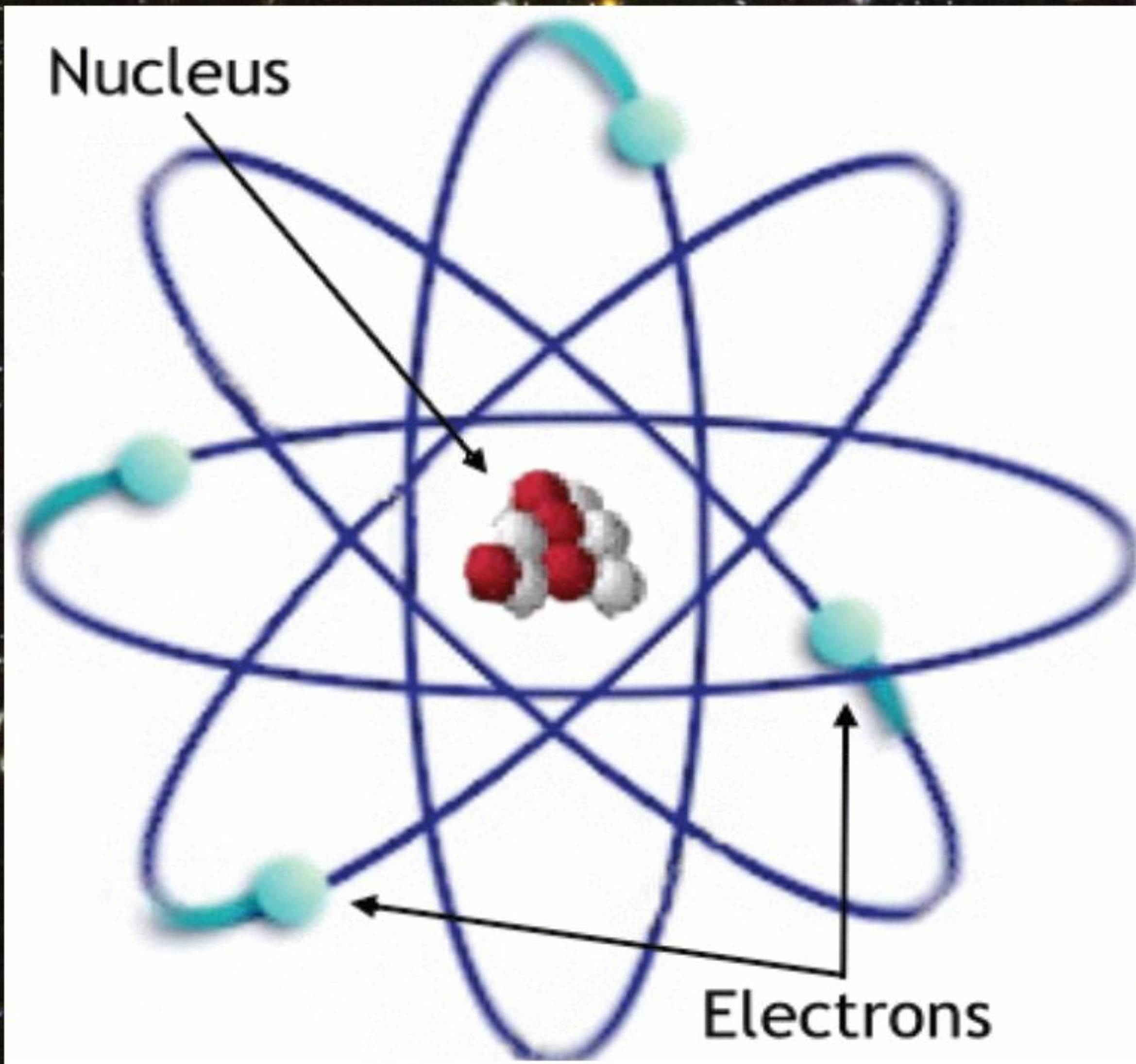
Tools: Astronomy and Astrophysics

Galileo to Hubble to LIGO



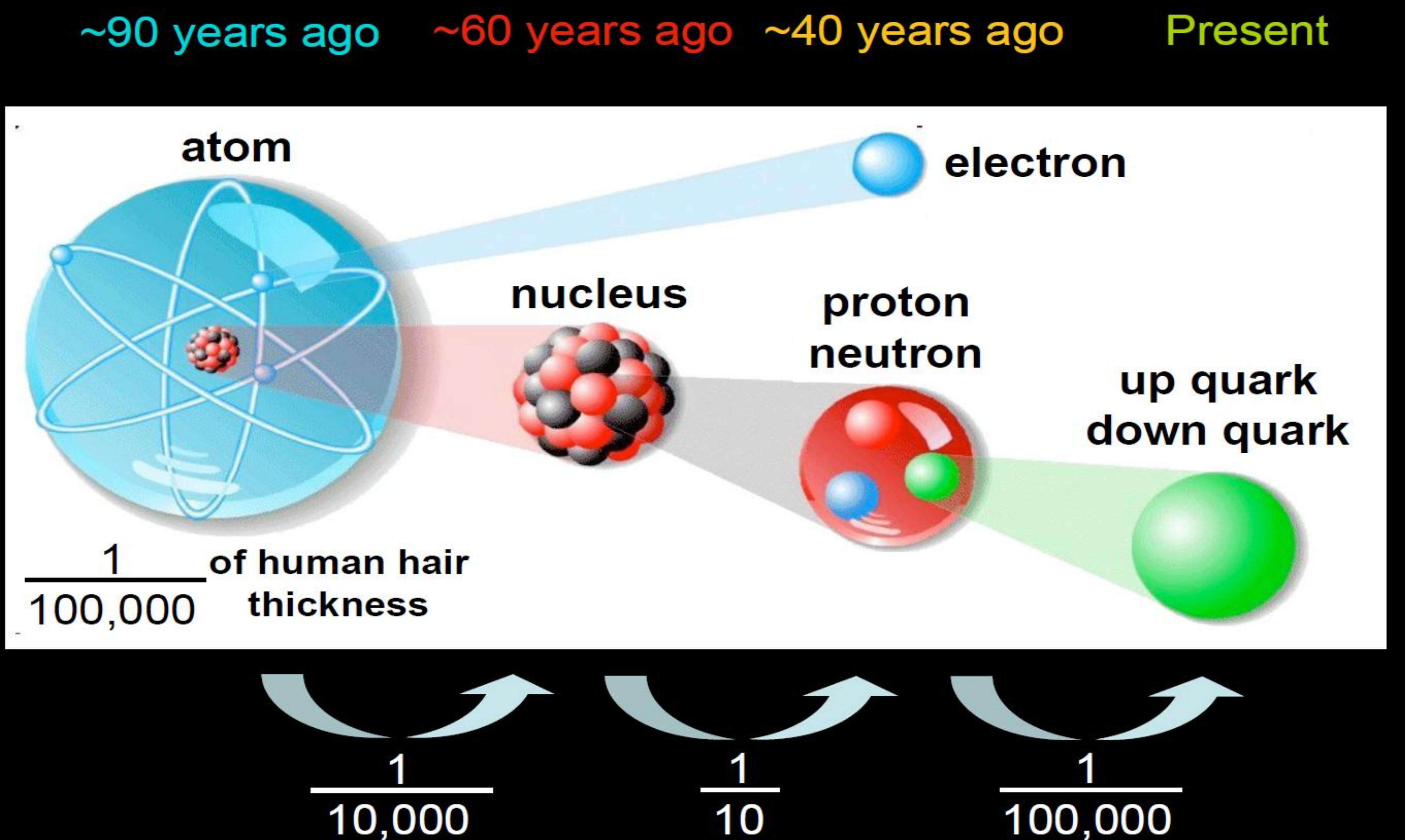


The Universe is Made of Particles



THE ATOM

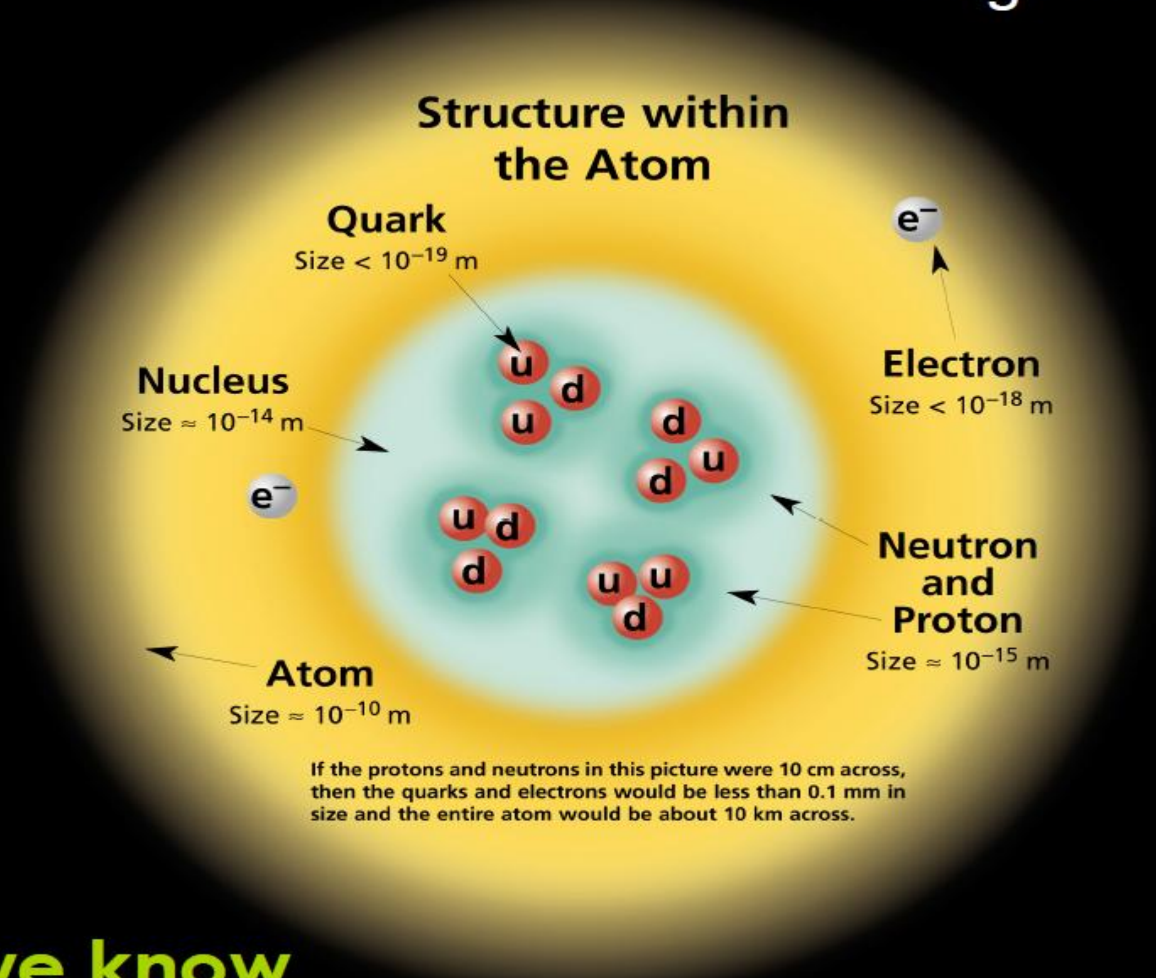
- Investigating the particles reveals the fundamental structure of the Universe and matter within it



~90 years ago
~60 years ago
~40 years ago
Present
atom
electron
nucleus
proton
neutron
up quark
down quark
$\frac{1}{100,000}$ of human hair thickness
$\frac{1}{10,000}$
$\frac{1}{10}$
$\frac{1}{100,000}$

The Nature of Matter

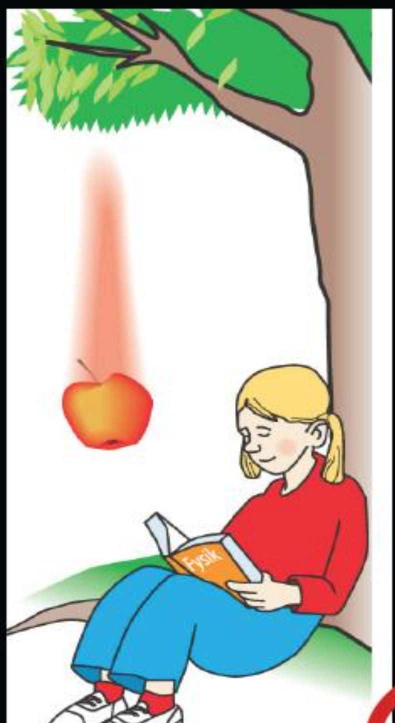
Could there be more quarks?
Or something smaller?



Atoms as we know them today

What Holds it all Together?

Gravitational Force

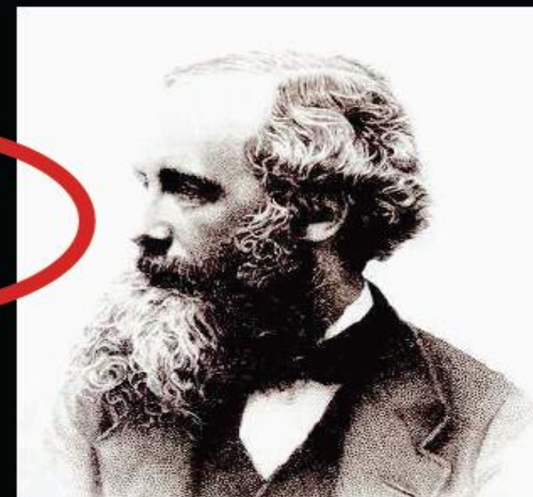


Issac Newton
(1642 - 1727)

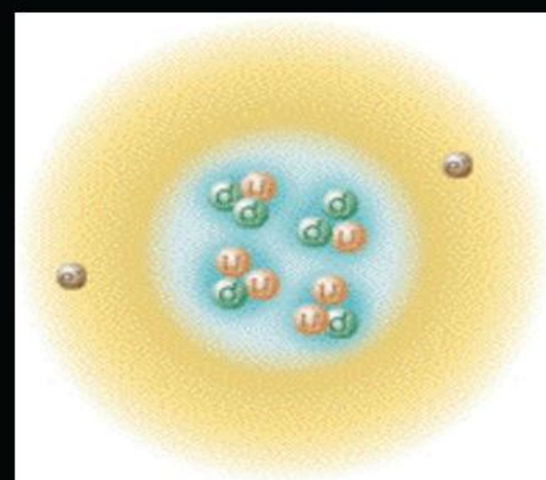
Graviton

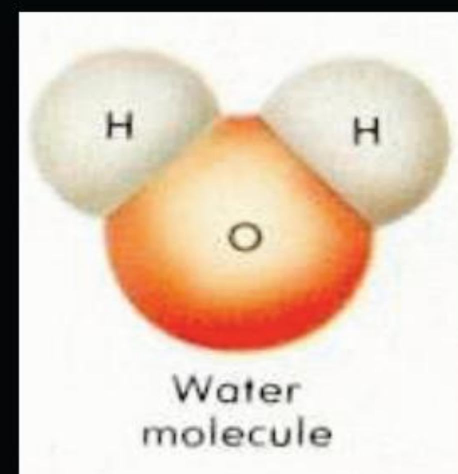
Electromagnetic Force

Photons
γ



James Clerk Maxwell
(1831 - 1879)

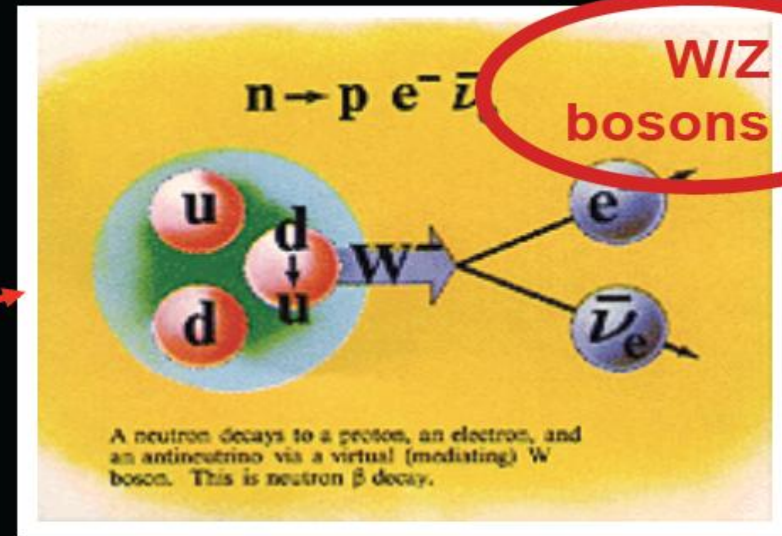


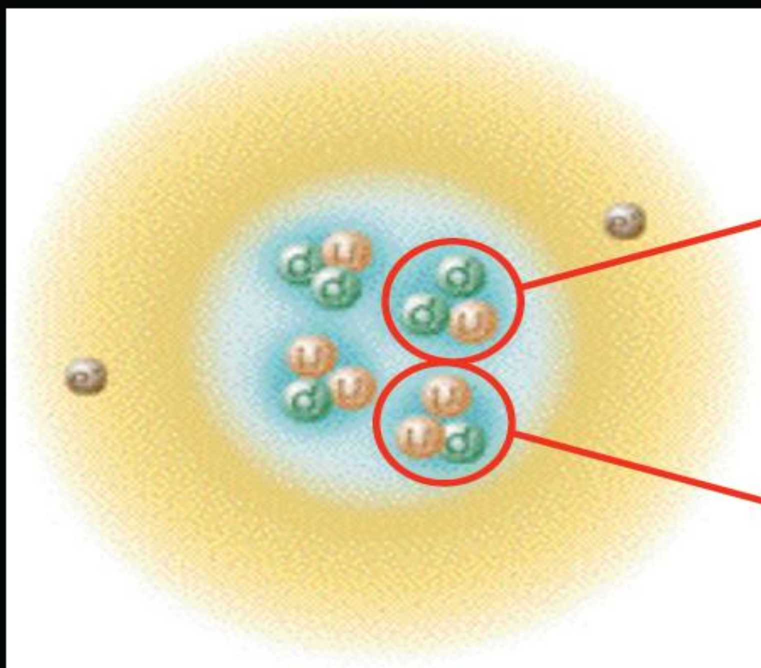


Weak Force

Enrico Fermi
(1901 - 1954)

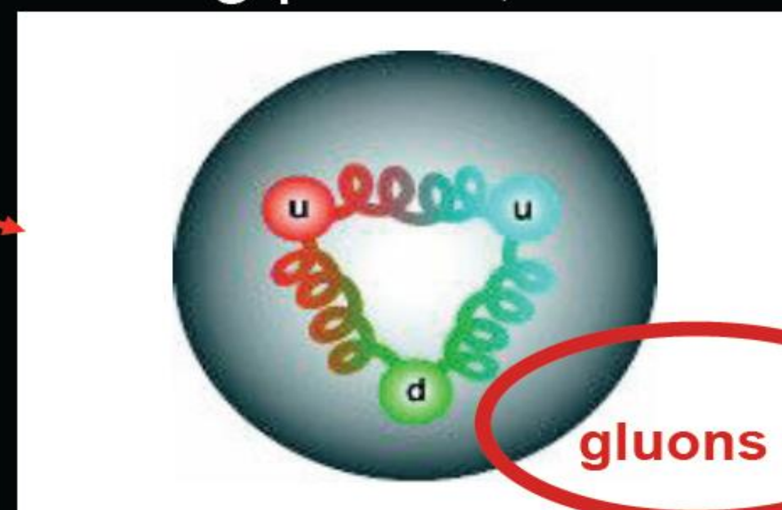
radioactive decays





neutron decay

holding proton, nucleus

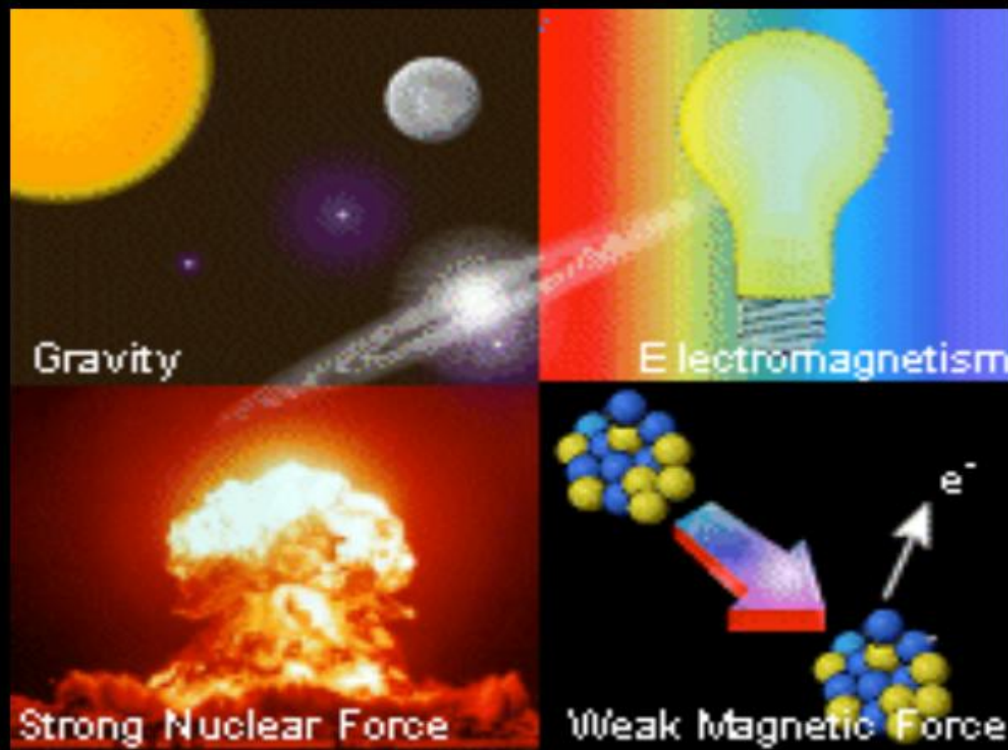


Strong Force

Four Fundamental Forces

graviton

Gamma ray,
Photon γ



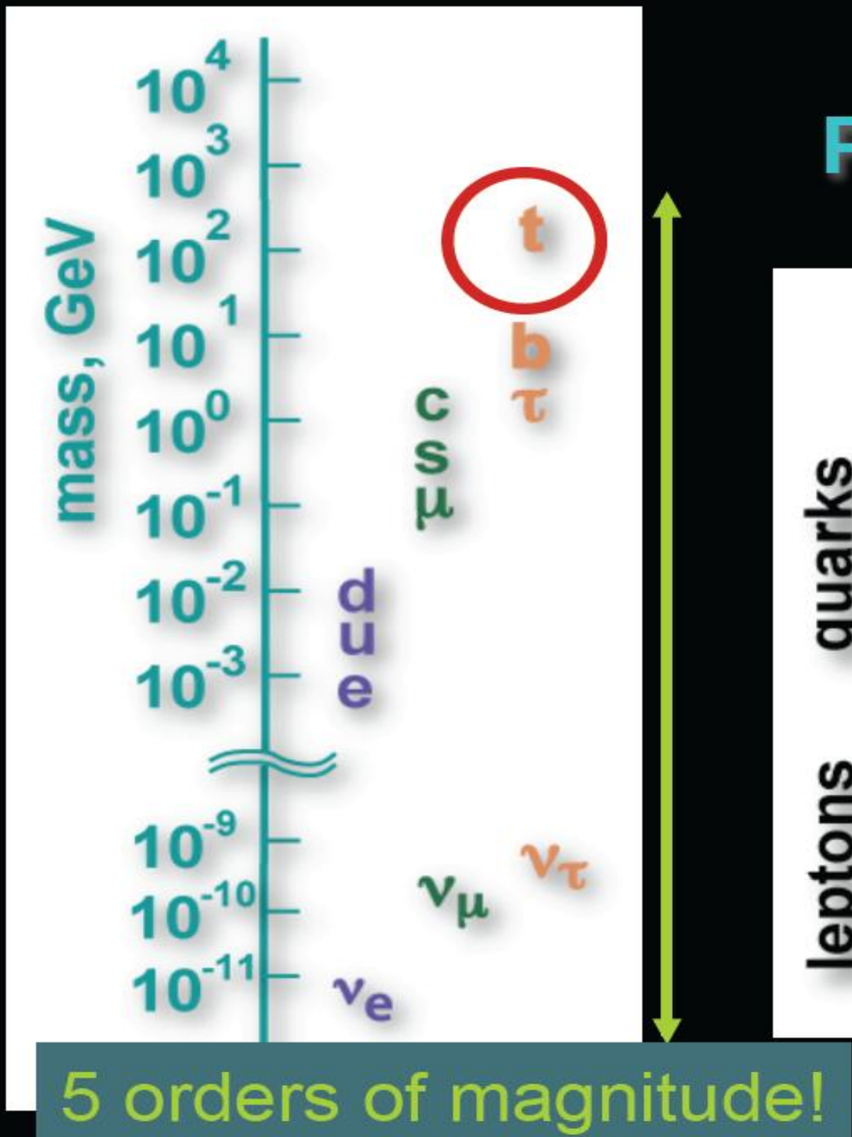
gluon

W, Z

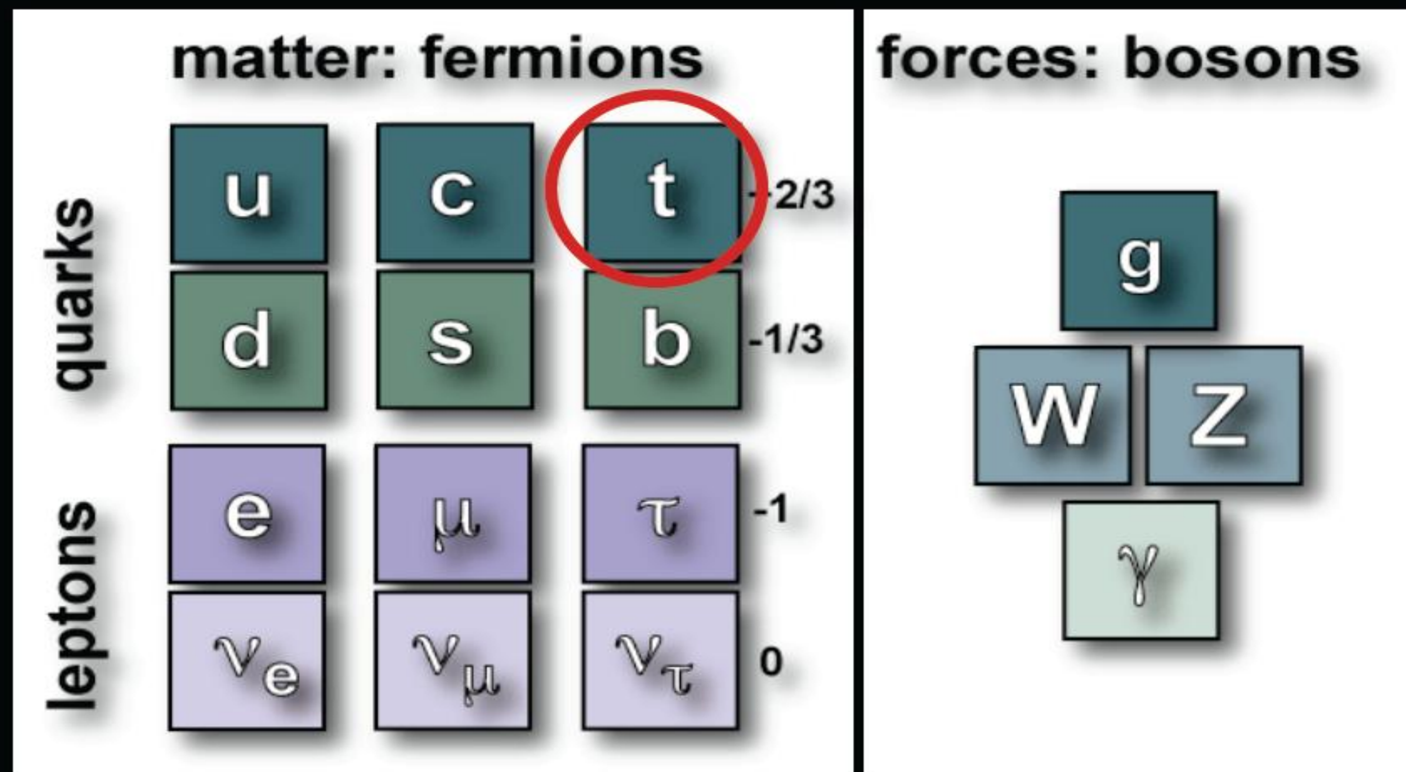
“Mediated” by particles called bosons!

* *Graviton not discovered yet.*

The Standard Model

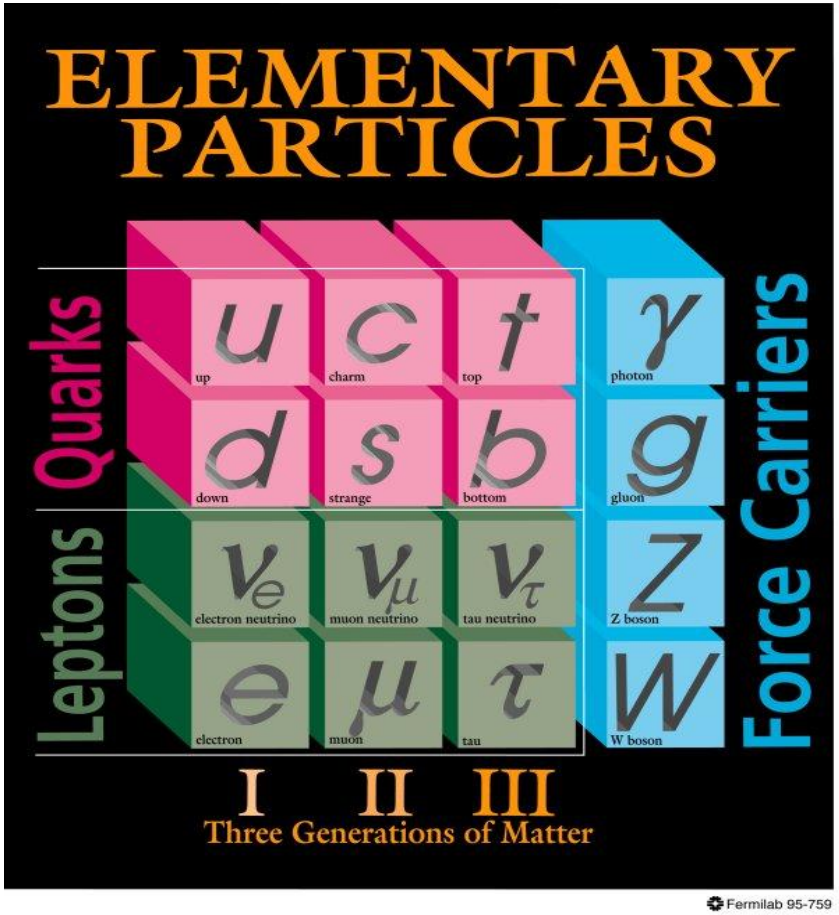


Periodic Table of the Particles

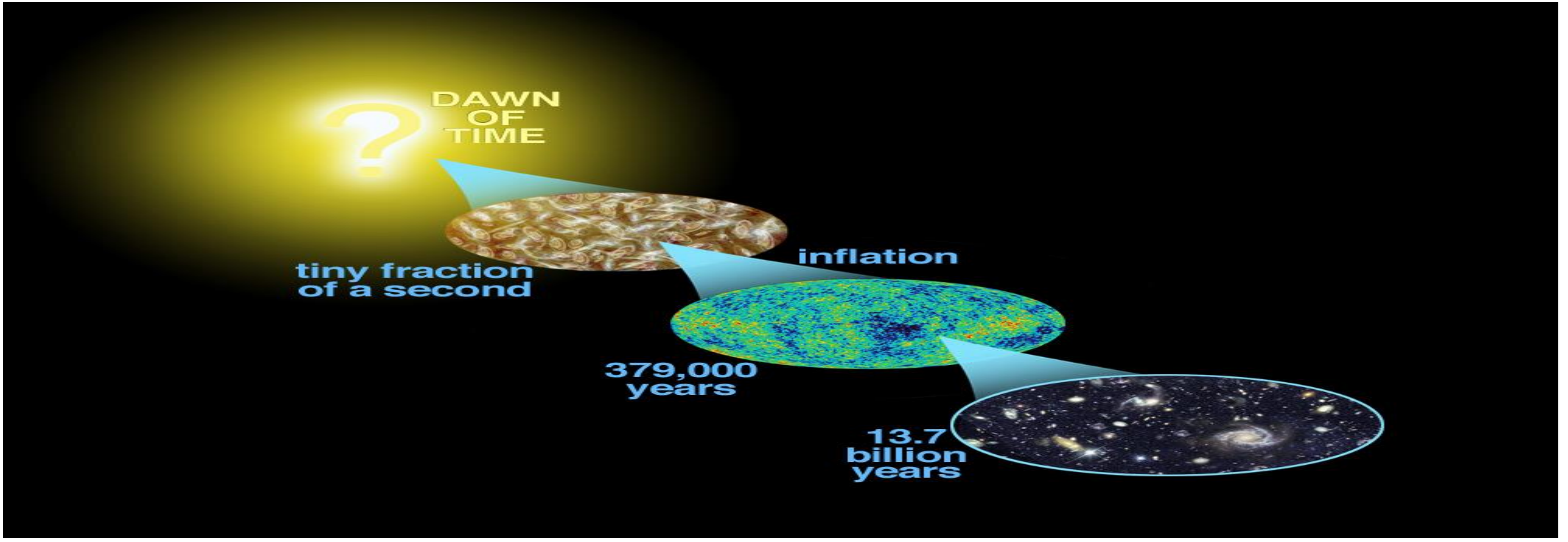


The fundamental questions

- What is the nature of the universe and what is it made of?
- What are matter, energy, space and time?
- How did we get here and where are we going?



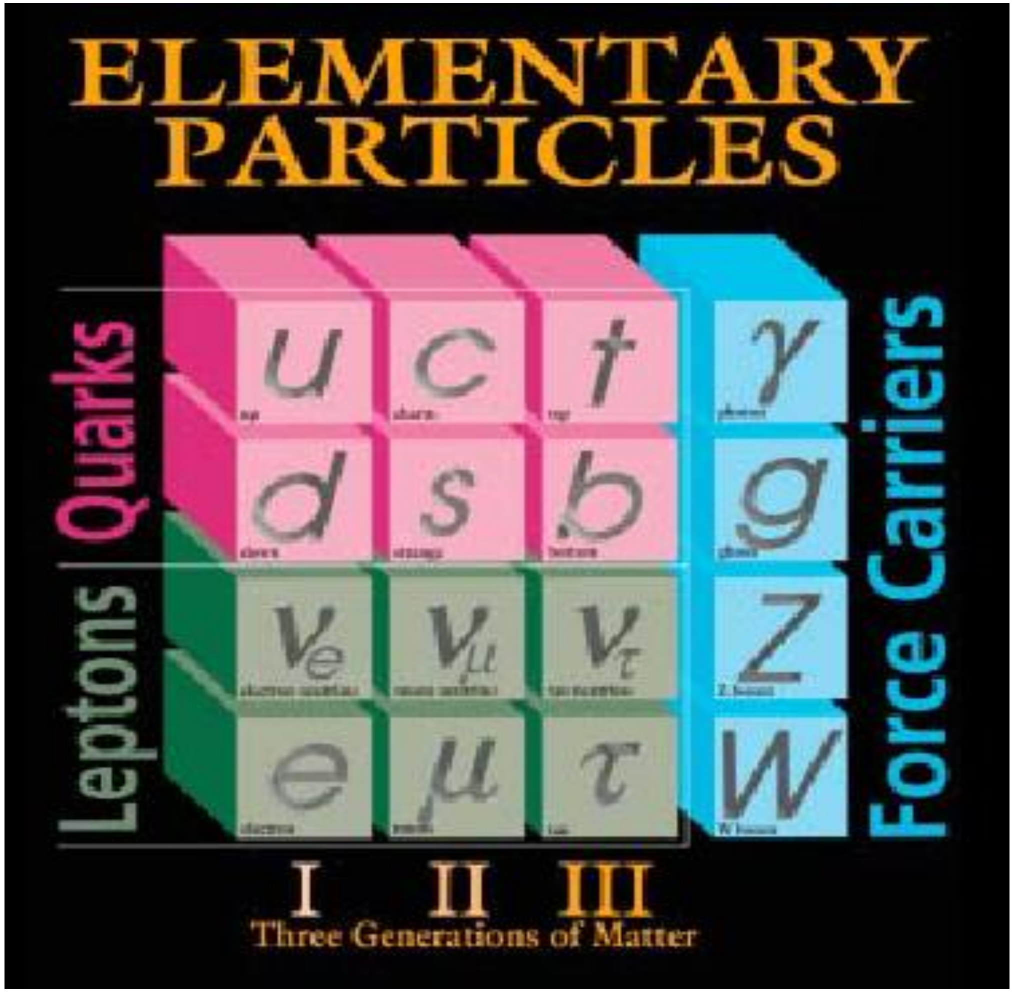
How did we get where we are?



"There are more things in heaven and earth, Horatio, than are dreamt of in your philosophy" *(Hamlet, I.5)*

The Physical World -- Matter

The physical world is composed of Quarks and Leptons interacting via force carriers (Gauge Bosons)



Last discovered quark & lepton

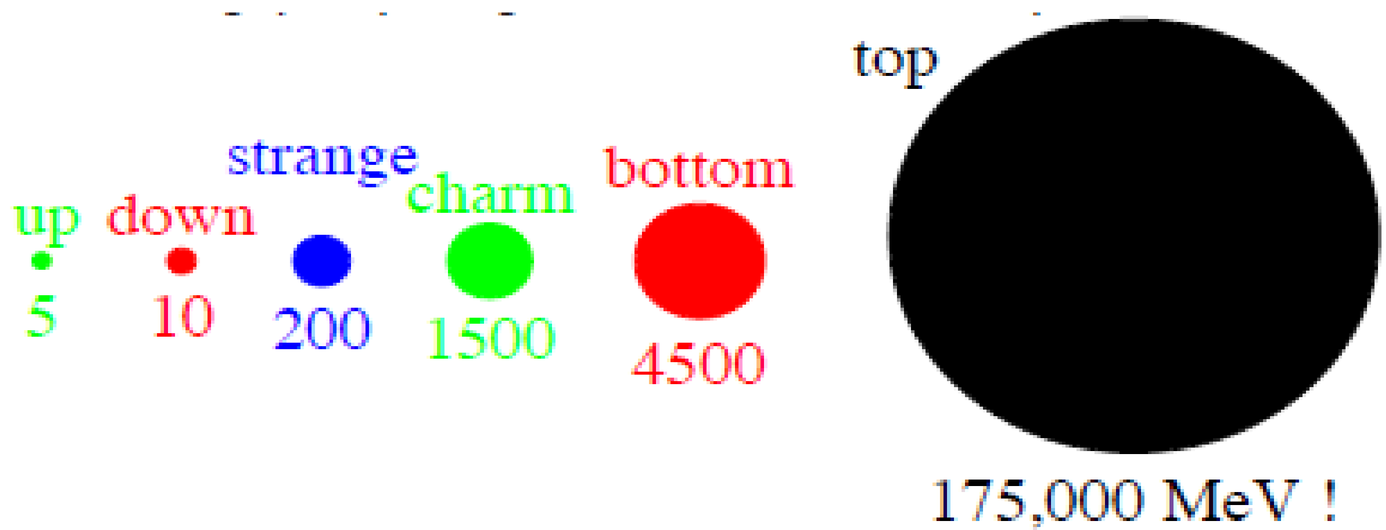
top-quark 1995

tau-neutrino 2000

Relations between the constituents

Ordinary matter is made up of up and down quarks and electrons.

What are the rest? The distinguishing feature is the mass.



The Three families only connected via weak interaction

Matter

- Three families of *Quarks* and *Leptons, but m*atter around us made up of only first of the three families

- At high energies, particles produced democratically, that is all three families are produced equally.

- This was the how particles were made in the early universe, near the time of the big bang, BUT .....

- We live in a world of particles. Where are the antiparticles? Answer: There was apparently a near cancellation where slightly more particles than antiparticles produced. The reasons are unknown, but leading ideas connect to CP violation and baryon instability.

The Forces in Nature

type	rel.strength	force carriers	acts on/in
Strong Force	**1**	**Gluons g** **m = 0**	**Quarks** **Atomic Nucleus**
Electro-magnet Force	**~ 1/1000**	**Photon γ** **m = 0**	**Electric Charge** **Atoms, Chemistry**
Weak Force	**~ 10^{-5}**	**W, Z Bosons** **m = 80 , 91 GeV**	**Leptons, Quarks** **Radioactive Decays** **ecay)**

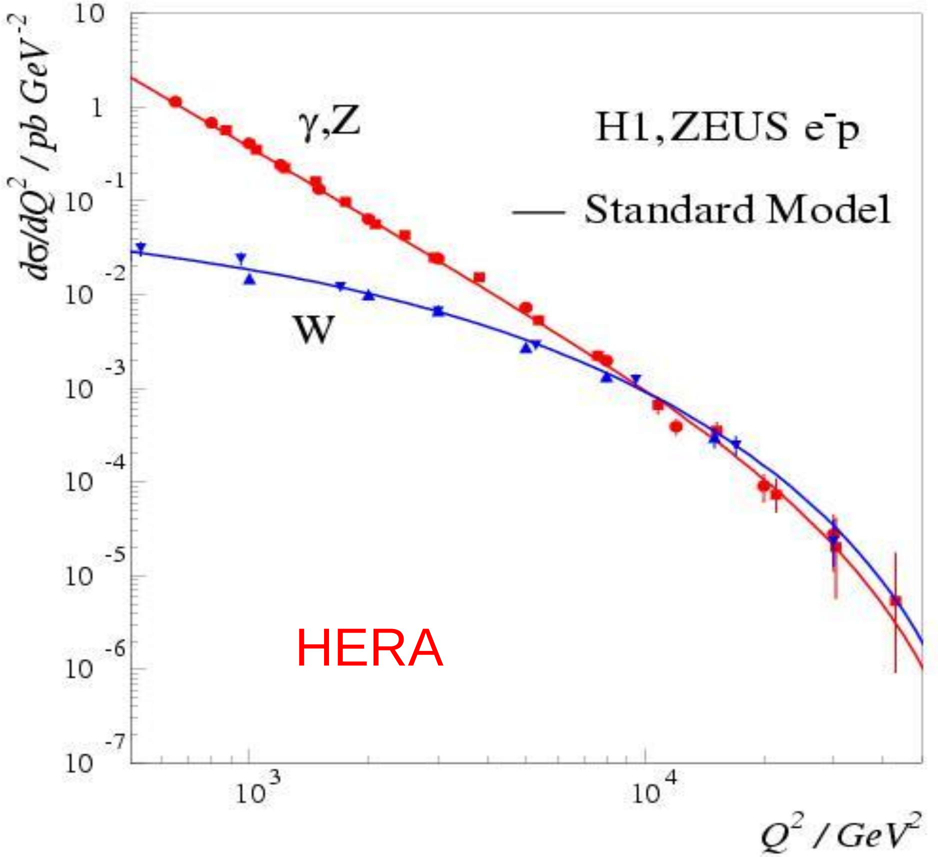
Force Carriers (Bosons) exchange interactions

Carriers of Force

Four fundamental *Forces* act between *Matter Particles* through *Force Carriers* (Gluons, $W^{\pm}$ und Z^0, γ, Graviton)

Forces in our energy regime:
different strengths
Forces at high energies:
democratic……..UNIFICATION

>Situation immediately after creation of the Universe



Unification

Electricity and Magnetism

Maxwell (1873) Unification of Electricity and Magnetism

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$

$$\nabla \bullet \vec{D} = \rho$$

$$\nabla \times \vec{H} = \frac{\partial \vec{D}}{\partial t} + \vec{J}$$

$$\nabla \bullet \vec{B} = 0$$

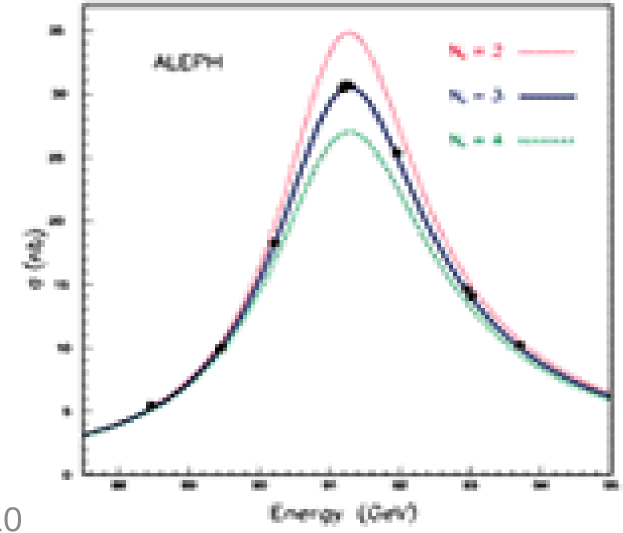
Triumph of the 19th century. Led to understanding of E&M form electromagnets to motors to modern devices like lasers

Further Unification
--- *Electroweak* ---

Proposed by Abdus Salam, Glashow & Weinberg

Key tests at LEP

In good agreement with all laboratory experiments

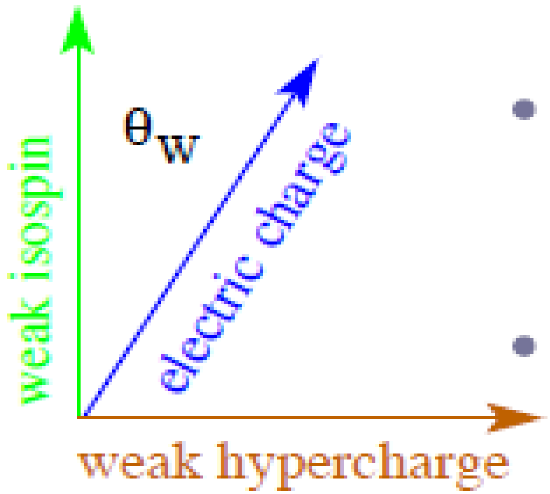


Electroweak Unification

"The standard model" of electroweak interactions
(Glashow, Weinberg, Salam)

Unification of Weak and Electromagnetic Forces

- SU(2) group: "weak isospin" ⇒ isotriplet of gauge bosons
- U(1) group: "weak hypercharge" ⇒ single gauge boson



- Weak isospin is quantum charge associated with Fermi's charge-carrying weak interaction
- Combination of weak isospin and weak hypercharge gives electro-magnetic interaction

Electroweak Unification

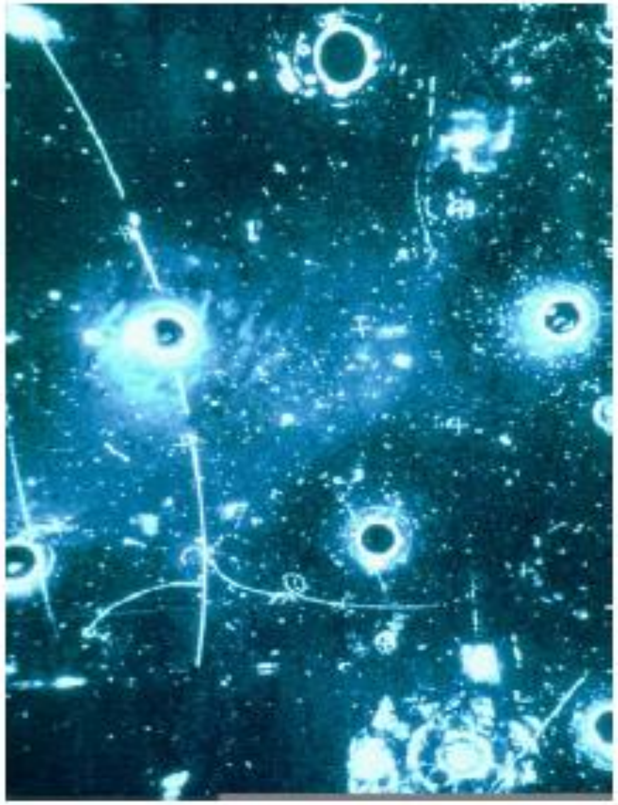
Parameters of unified theory (g, M_W, g') can be related to low energy parameters (e, G_F)

Let $g' \equiv g \tan\theta_W$; then:

$$
\begin{aligned}
e &= g \sin\theta_W, \\
G_F &= \frac{g^2\sqrt{2}}{8{M_W}^2}, \\
\frac{M_W}{M_Z} &= \cos\theta_W
\end{aligned}
$$

- Theory not only predicts a new weak interaction. . .
- But all of its properties follow from a single parameter, one of M_W, M_Z or θ_W

Experimental Proof

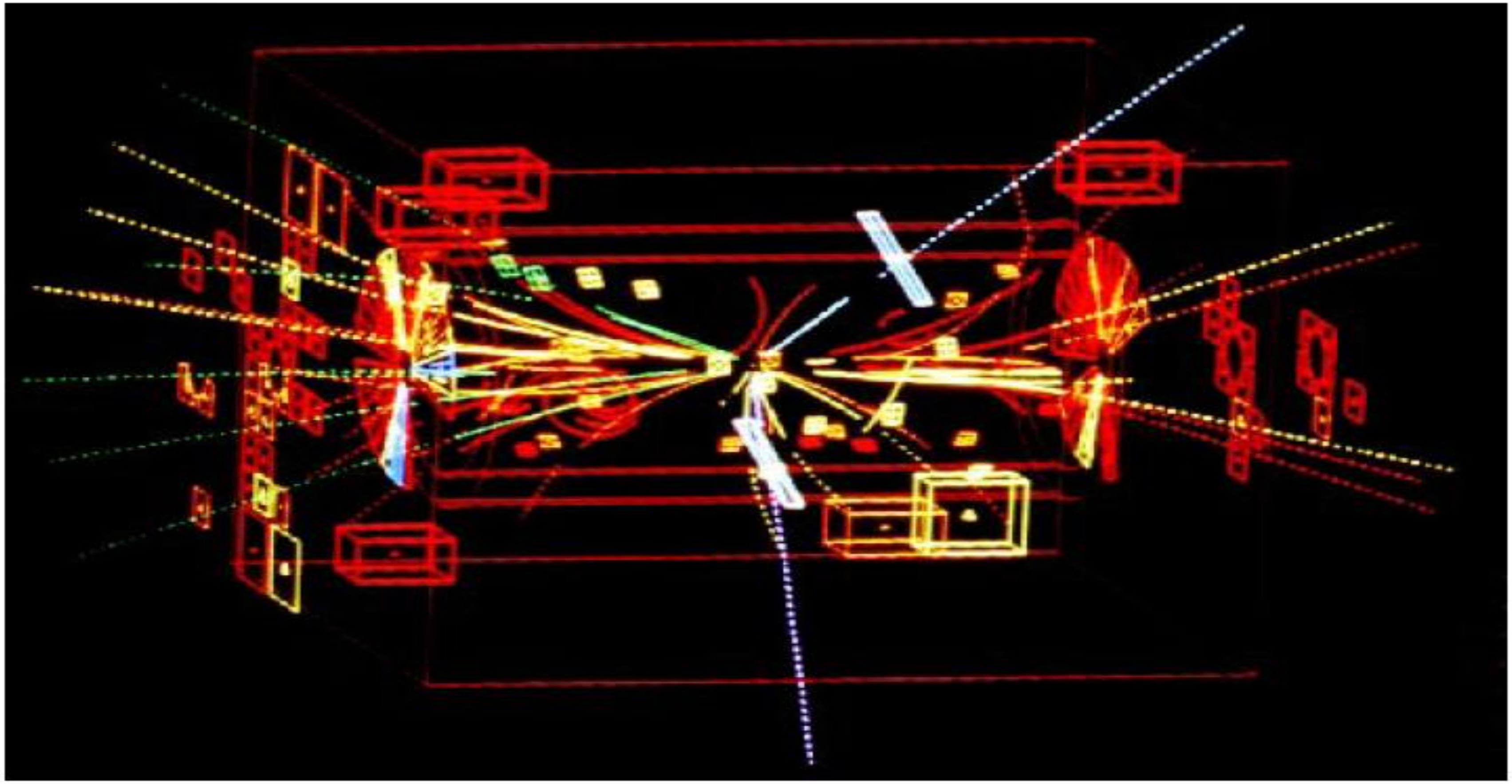


Discovery of the weak neutral current (1974)

ν + N → ν + Hadrons

Direct Confirmation

UA1 experiment at CERN $Sp\overline{p}S$ collider ($\sqrt{s} = 540$ GeV)



$M_W \approx 81$ GeV, $M_Z \approx 91$ GeV

Prediction of the Standard Model

$e^+e^- \longrightarrow Z^0 \longrightarrow f\ \bar{f}$

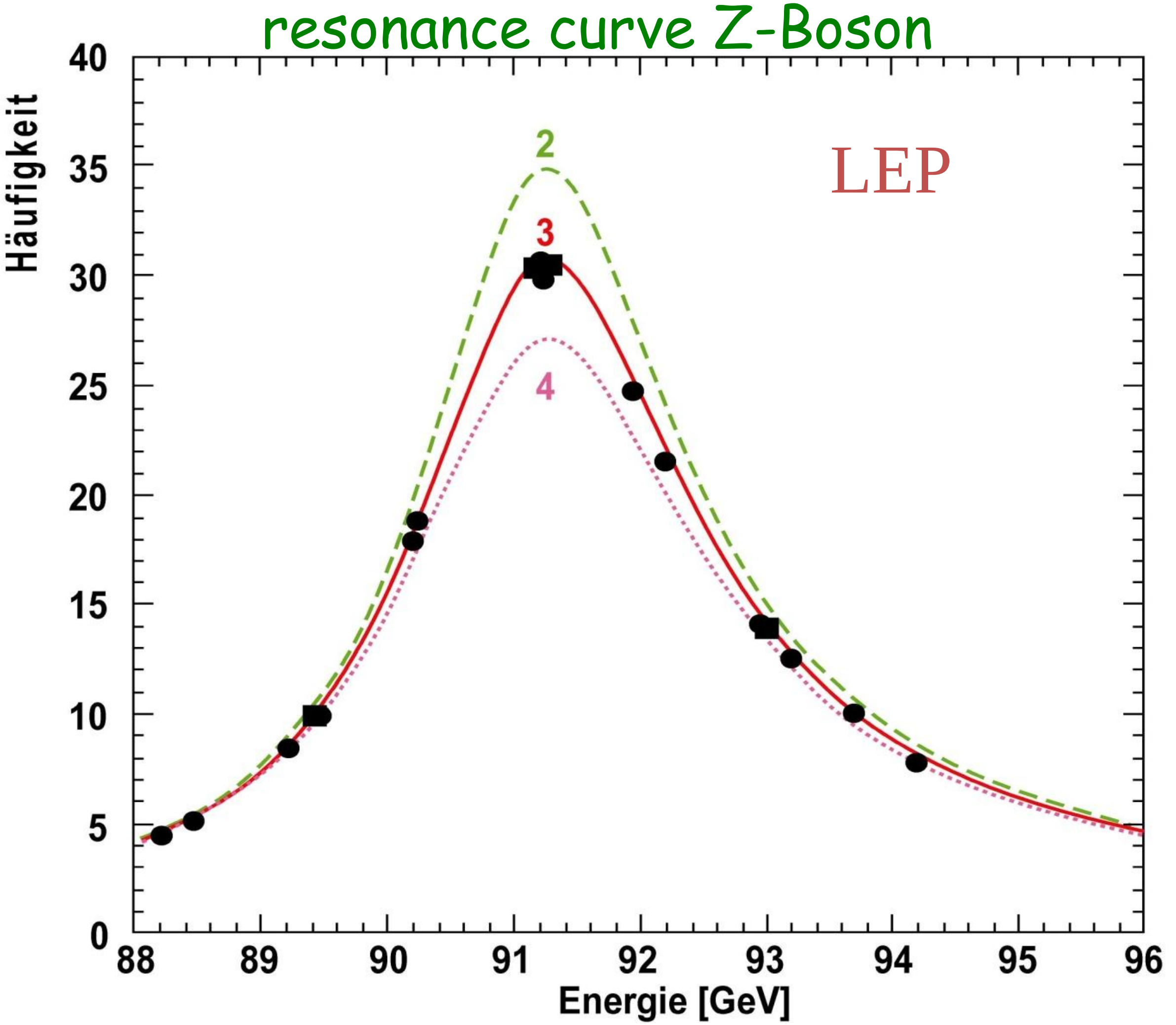
where $f=q,l,\nu$

σ_Z and Γ_Z depend on number of (light) neutrinos

Number of families:

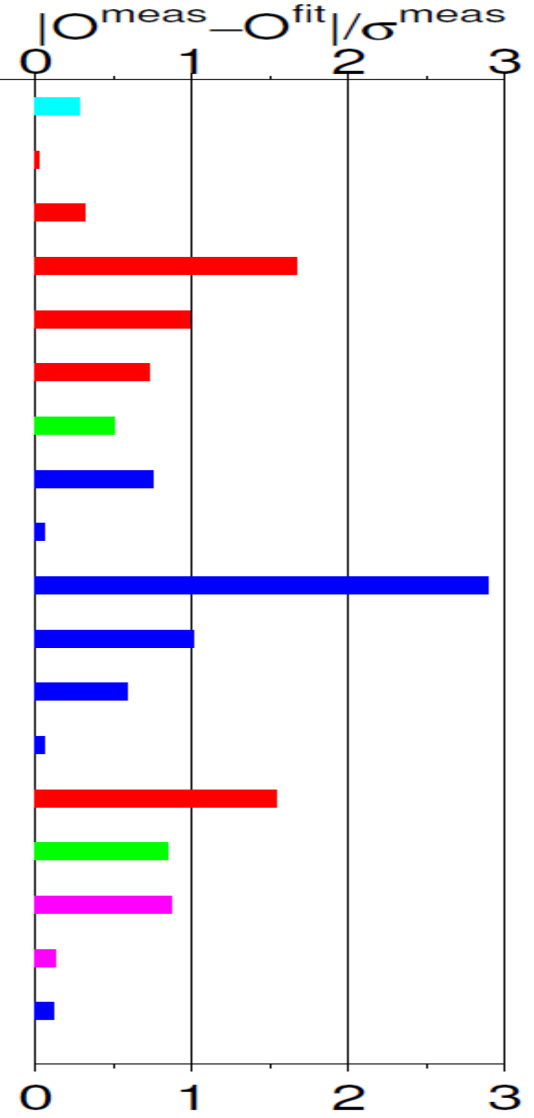
N = 2.984 +– 0.008

Nobel Prize 2008: Kobayashi-Maskawa)

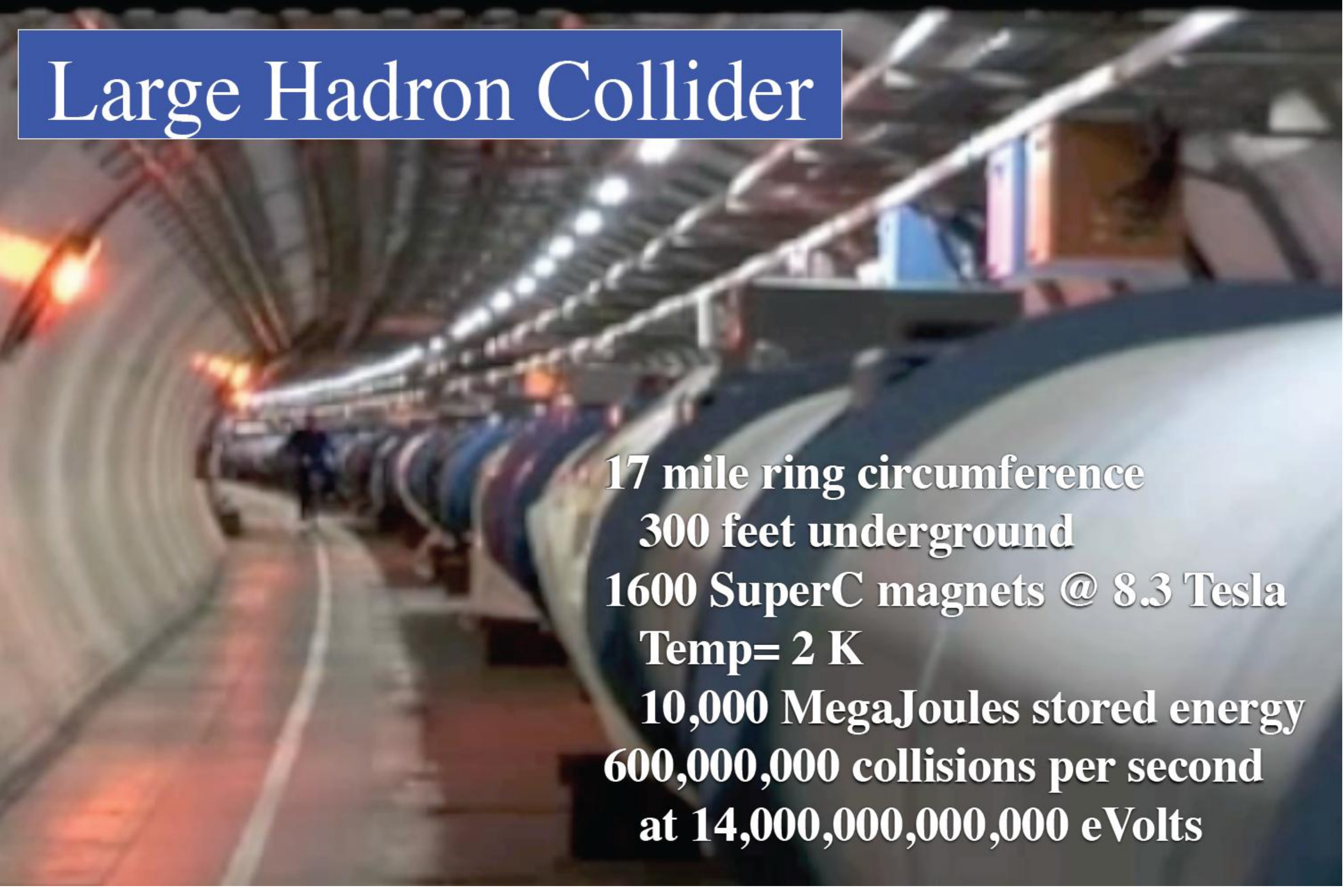


LEP – Precision Tests of EW Model

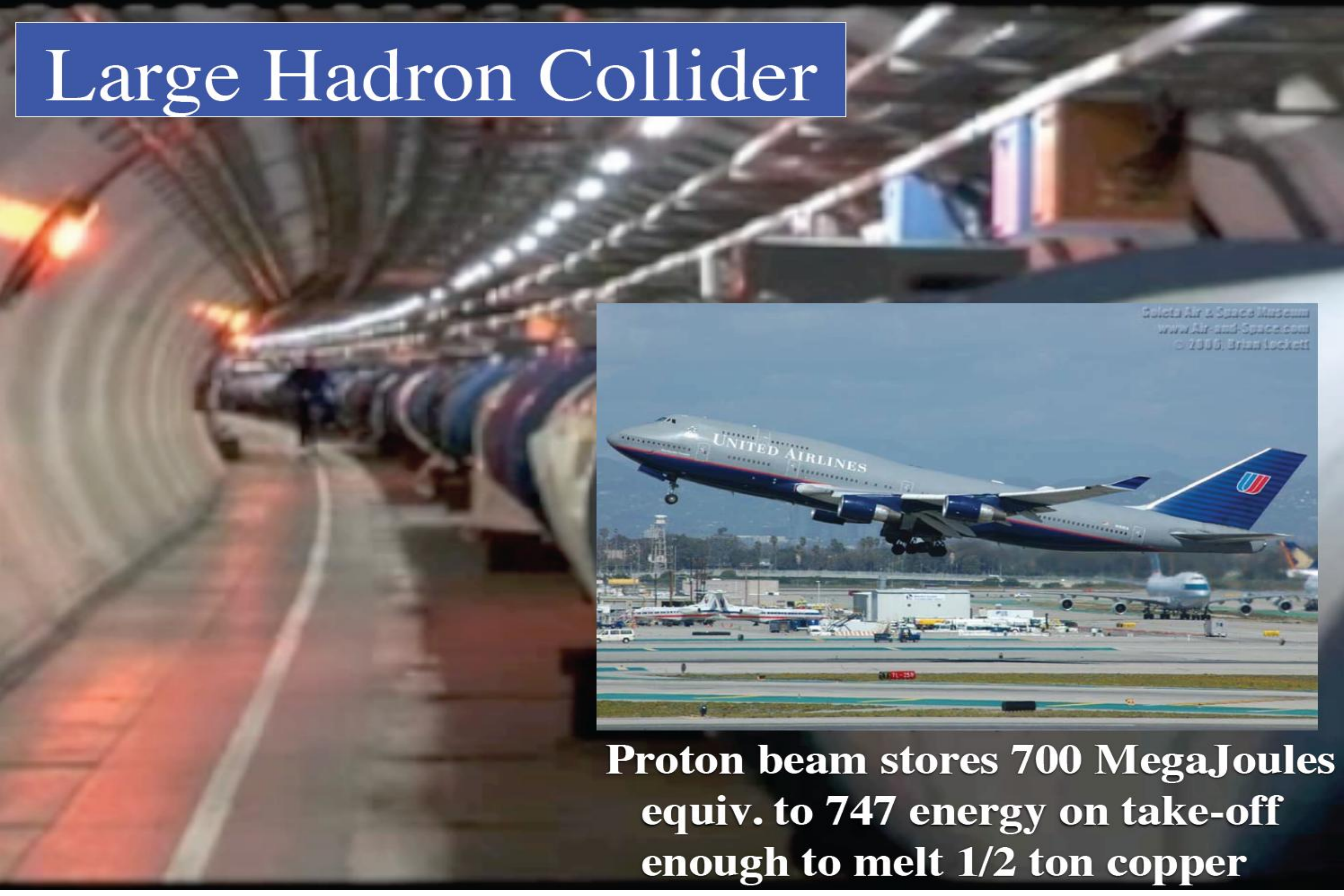
	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02758 ± 0.00035	0.02768
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959
σ_{had}^0 [nb]	41.540 ± 0.037	41.478
R_l	20.767 ± 0.025	20.742
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01645
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481
R_b	0.21629 ± 0.00066	0.21579
R_c	0.1721 ± 0.0030	0.1723
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1038
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1481
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.399 ± 0.023	80.379
Γ_W [GeV]	2.098 ± 0.048	2.092
m_t [GeV]	173.1 ± 1.3	173.2



August 2009

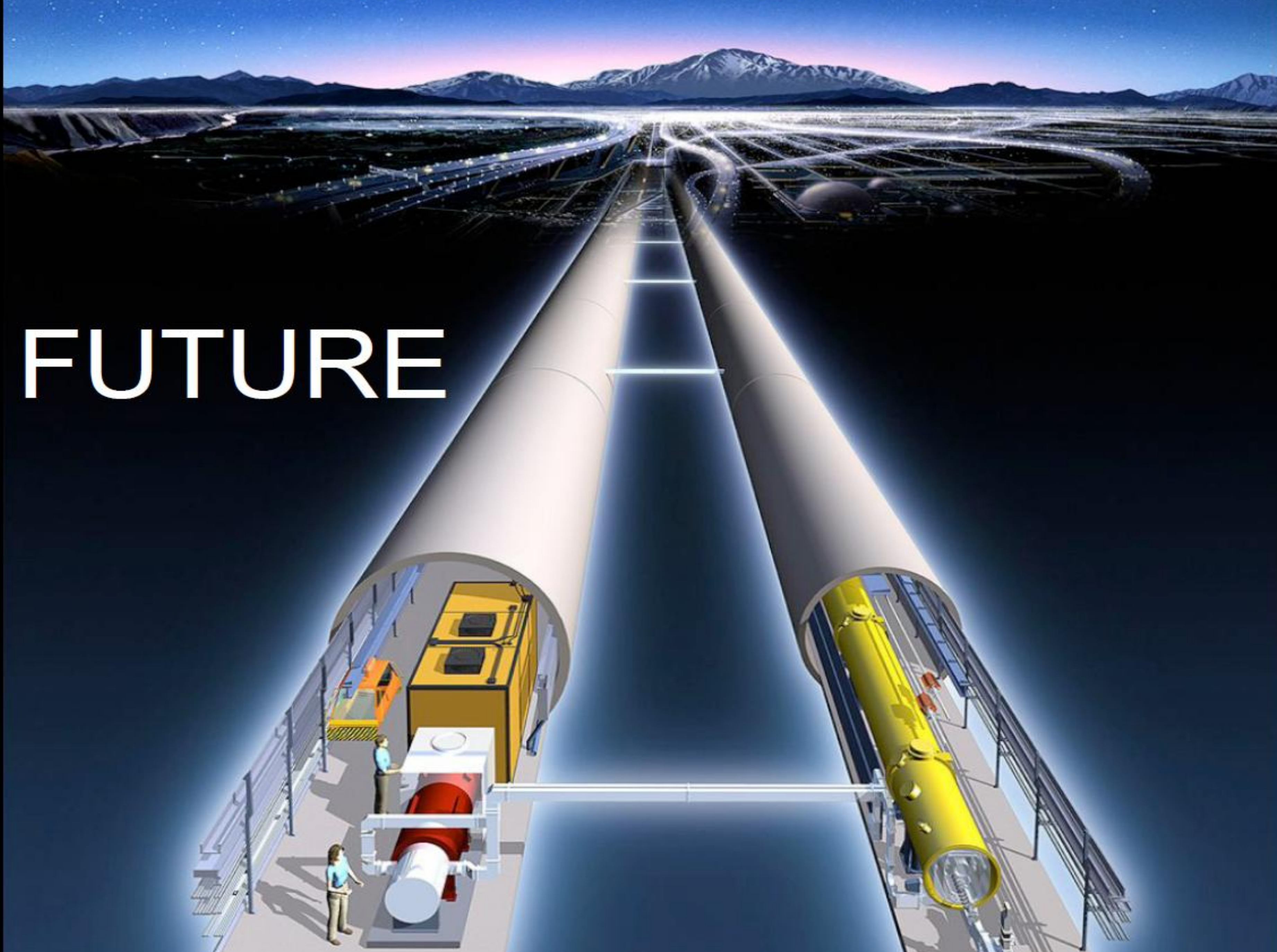

Large Hadron Collider
17 mile ring circumference
300 feet underground
1600 SuperC magnets @ 8.3 Tesla
Temp= 2 K
10,000 MegaJoules stored energy
600,000,000 collisions per second
at 14,000,000,000,000 eVolts

Large Hadron Collider



Proton beam stores 700 MegaJoules
equiv. to 747 energy on take-off
enough to melt 1/2 ton copper

Linear Collider



- Exploring deep mysteries of the fundamental substance of the Universe
- Expect revolutionary discoveries to come soon
  - impact to human knowledge akin to quantum revolution of early 20th Century
  - Dark Matter, Dark Energy, Higgs Boson, Extra Dimensions, Other New Particles or Forces ...

Today's biggest question

What's beyond the Standard Model?

1. Are there undiscovered principles of nature:
   New symmetries, new physical laws?
2. How can we solve the mystery of dark energy?
3. Are there extra dimensions of space?
4. Do all the forces become one?
5. Why are there so many kinds of particles?
6. What is dark matter?
   How can we make it in the laboratory?
7. What are neutrinos telling us?
8. How did the universe come to be?
9. What happened to the antimatter?

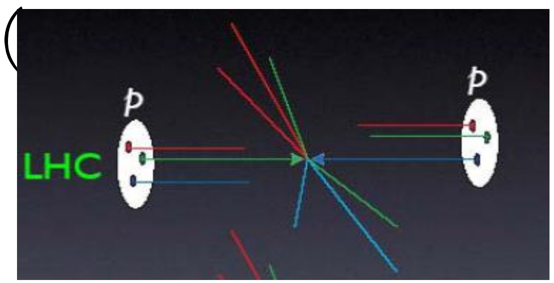
from the Quantum Universe

Addressing the Questions

- Neutrinos
  - Particle physics and astrophysics using a weakly interacting probe

- Particle Astrophysics/Cosmology
  - Dark Matter; Cosmic Microwave, etc

- High Energy pp Colliders
  - Opening up a new energy frontier (1 TeV scale)



- High Energy e^+e^- Colliders
  - Precision Physics at the new energy frontier

Answering the Questions
Three Complementary Probes

- Neutrinos as a Probe
  - Particle physics and astrophysics using a weakly interacting probe
- High Energy Proton Proton Colliders
  - Opening up new energy frontier (~ 1 TeV scale)
- High Energy Electron Positron Colliders
  - Precision Physics at the new energy frontier

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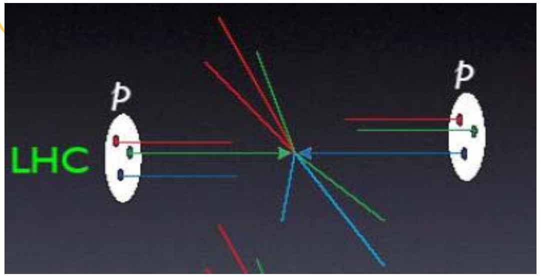

- High Energy e^+e^- Colliders
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Neutrinos – Many Questions

- Why are neutrino masses so small ?
- Are the neutrinos their own antiparticles?
- What is the separation and ordering of the masses of the neutrinos?
- Neutrinos contribution to the dark matter?

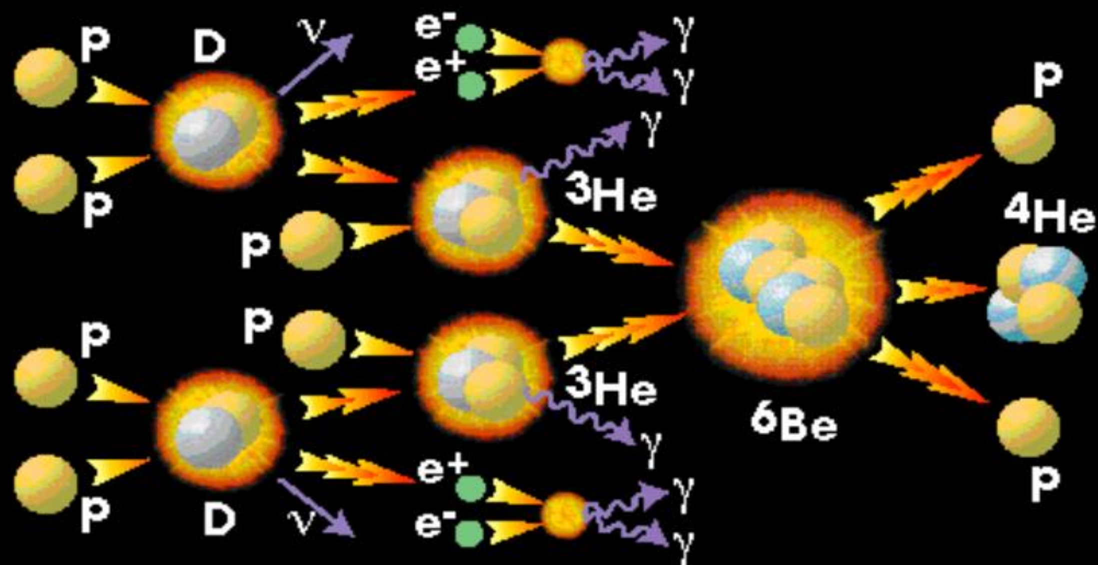
- CP violation in neutrinos, leptogenesis, possible role in the early universe and in understanding the particle antiparticle asymmetry in nature?

Solar Energy

- What is the Sun's source of energy?
  - 19th Century - Chemical reactions? (burning)
    - Predicted solar lifetime too short - only 20,000 years
    - Evidence on Earth for much longer duration
  - 20th Century
    - Einstein's relativity $E=mc^2$
    - discovery of atomic nucleus and nuclear reactions

Solar Energy

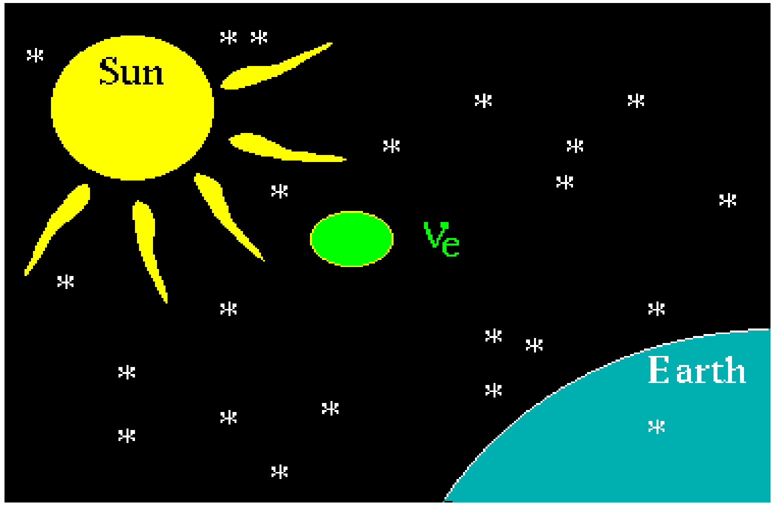
- What is the Sun’s source of energy?



Enough energy
for the Sun to shine
for ten billion years

Neutrinos from the Sun

<u>Discovery:</u> Neutrinos coming from the Sun were detected, demonstrating the solar fusion burning process. (Davis / Koshiba Nobel Prize)



<u>Problem:</u> The rate of neutrinos were measured to be <u>only about half the predicted rate</u>. Conclusion: either the sun works differently than theory or half the neutrinos disappear on their journey to the earth.

Neutrinos from the Sun

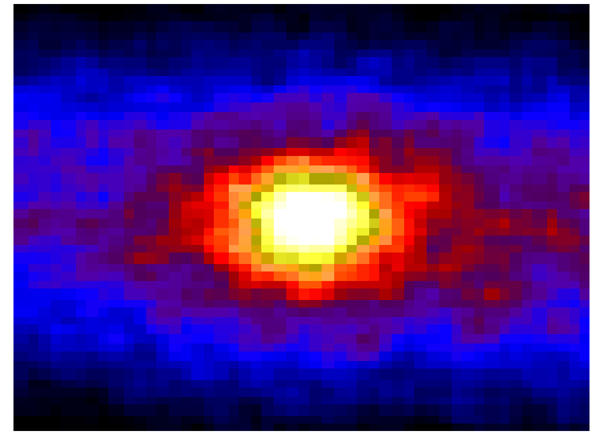
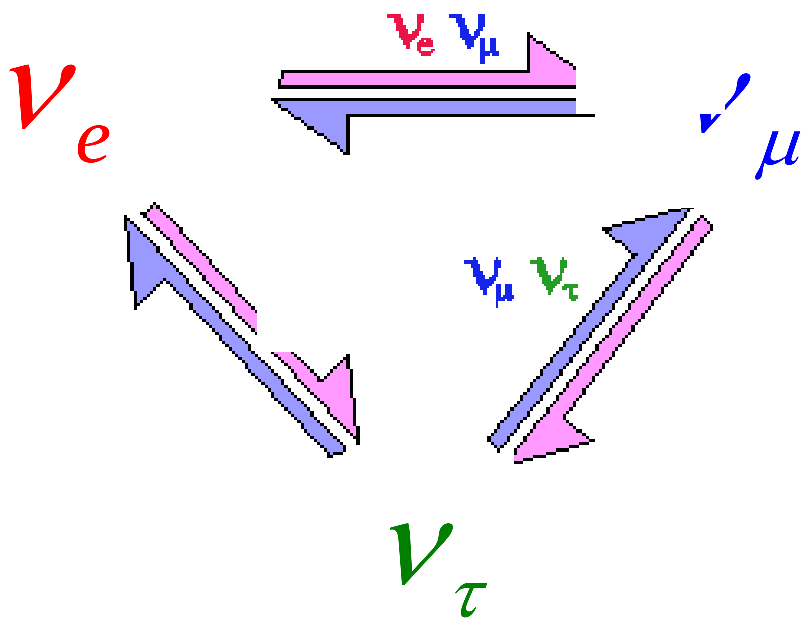
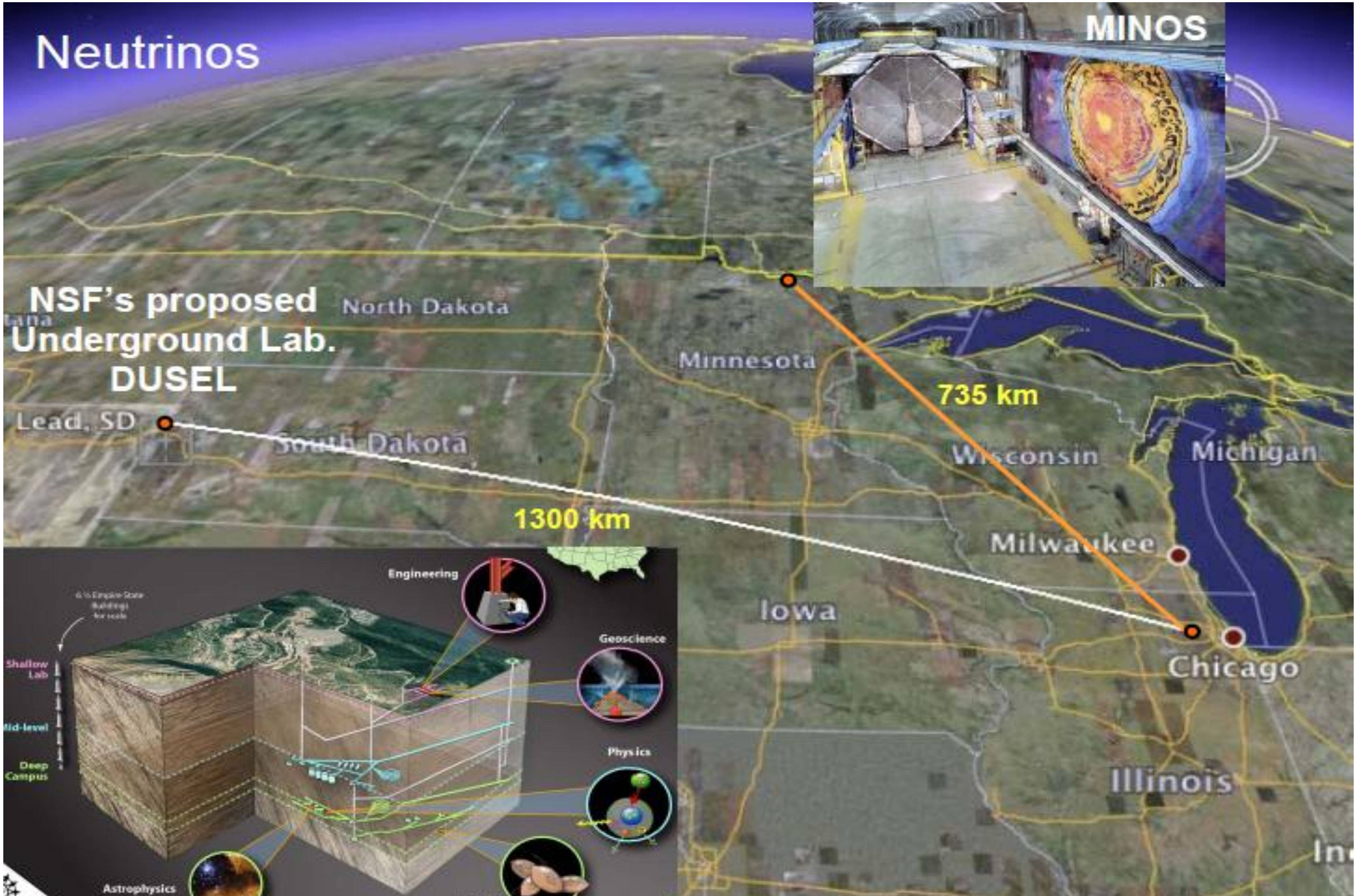


Photo of Sun taken underground using neutrinos



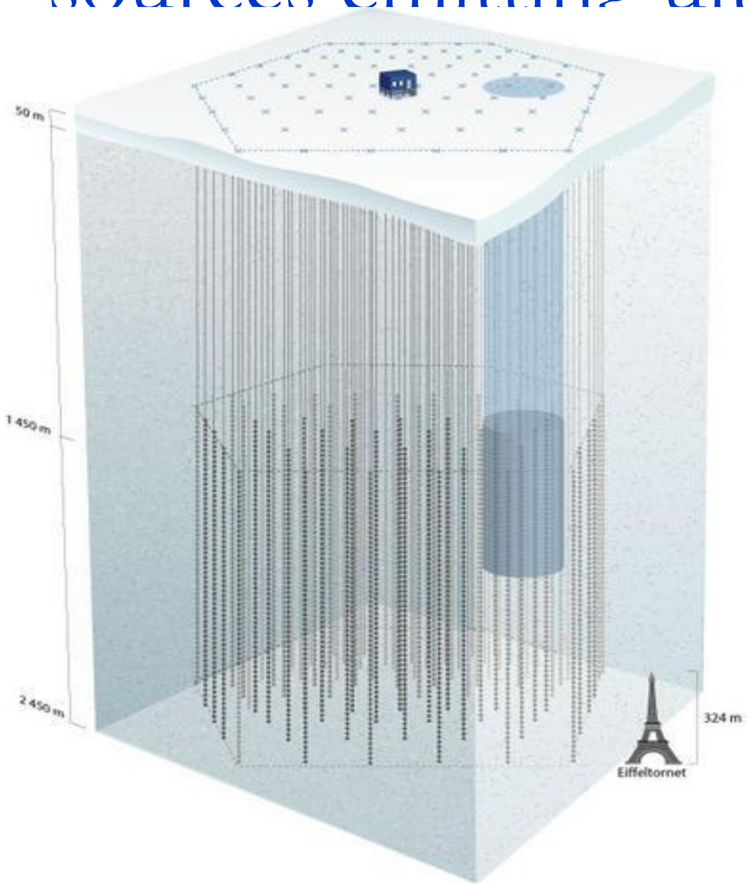
Subsequent experiments at Kamioka mine in Japan and Sudbury mine in Canada demonstrated the reduced rate was due to neutrino oscillations

Neutrino Oscillations in the Lab

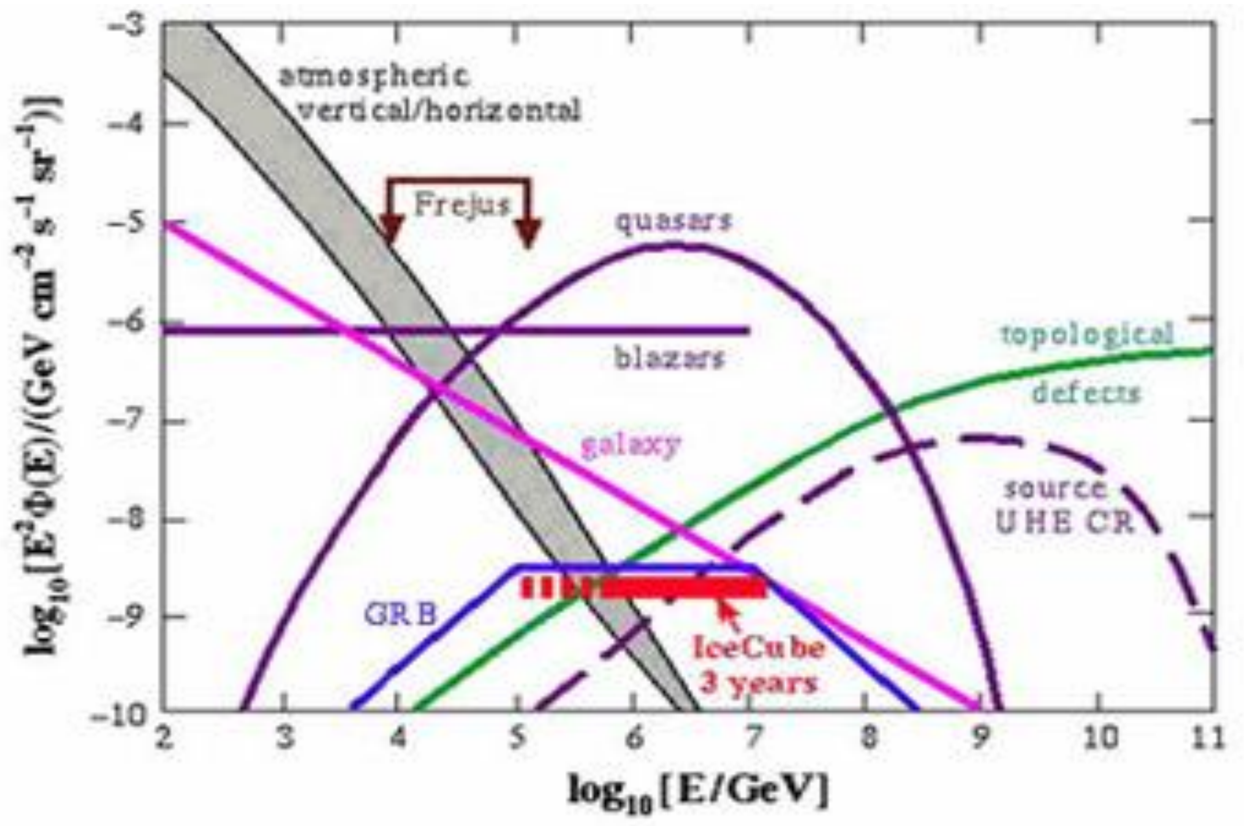


Ice Cube Project

- Neutrino Astrophysics – Investigating astrophysical sources emitting ultra high energy neutrinos



South Pole



Neutrinos – Many Questions

Neutrino oscillations, due to mixing of mass eigenstates, have been observed in atmospheric and solar neutrino experiments such as Super-K and SNO, as well as in KamLAND and K2K using prepared neutrino sources.

- In the mixing matrix of three neutrino generations, two parameters have yet to be determined: the smallest mixing angle, θ_{13}, and the CP violating phase, δ_{CP} . Knowing the size of θ_{13} will define the future direction of investigating neutrino oscillation.

Accelerators and Neutrinos

- Long baseline neutrino experiments – Create neutrinos at an accelerator or reactor and study at long distance when they have oscillated from one type to another.

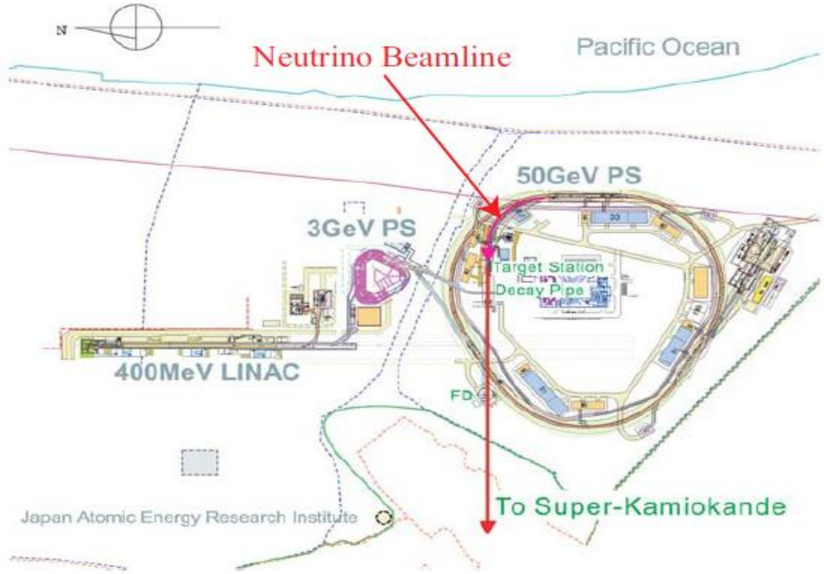
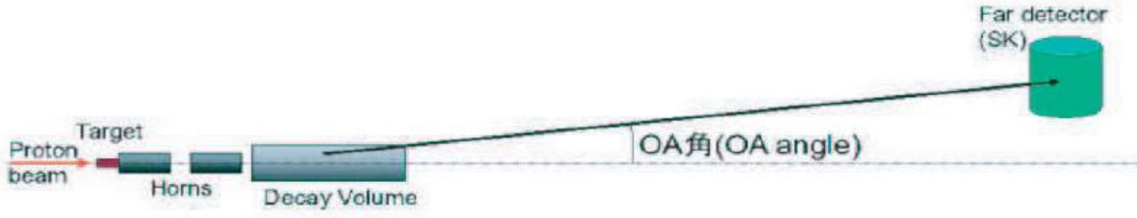


Figure 2.2: Accelerator of J-PARC.

Accelerators and Neutrinos

PPARC

$$E_\nu = \frac{m_\pi^2 - m_\mu^2}{2(E_\pi - p_\pi \cos\theta)} \qquad (2.1)$$



- Kinematics off-axis give a Eν that is almost independent of Eπ.
- Therefore intense very narrow band beam

	K2K	J-PARC
Kinetic Energy	12 GeV	50 GeV
Beam Intensity	6.0×10^{12} ppp.	3.3×10^{14} ppp.
Repetition Rate	1pulse/2.2sec	1pulse/3.5sec
Beam Power	0.0052MW	0.75MW
Spill Width	1.1 μsec. (9 bunches/pulse)	$\sim$ 5μsec. (8bunches/pulse)

Addressing the Questions

- Neutrinos
  - Particle physics and astrophysics using a weakly interacting probe

- Particle Astrophysics/Cosmology
  - Dark Matter; Cosmic Microwave, etc

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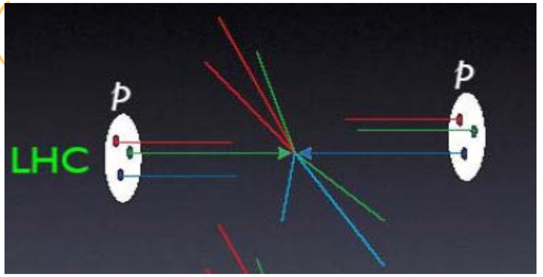
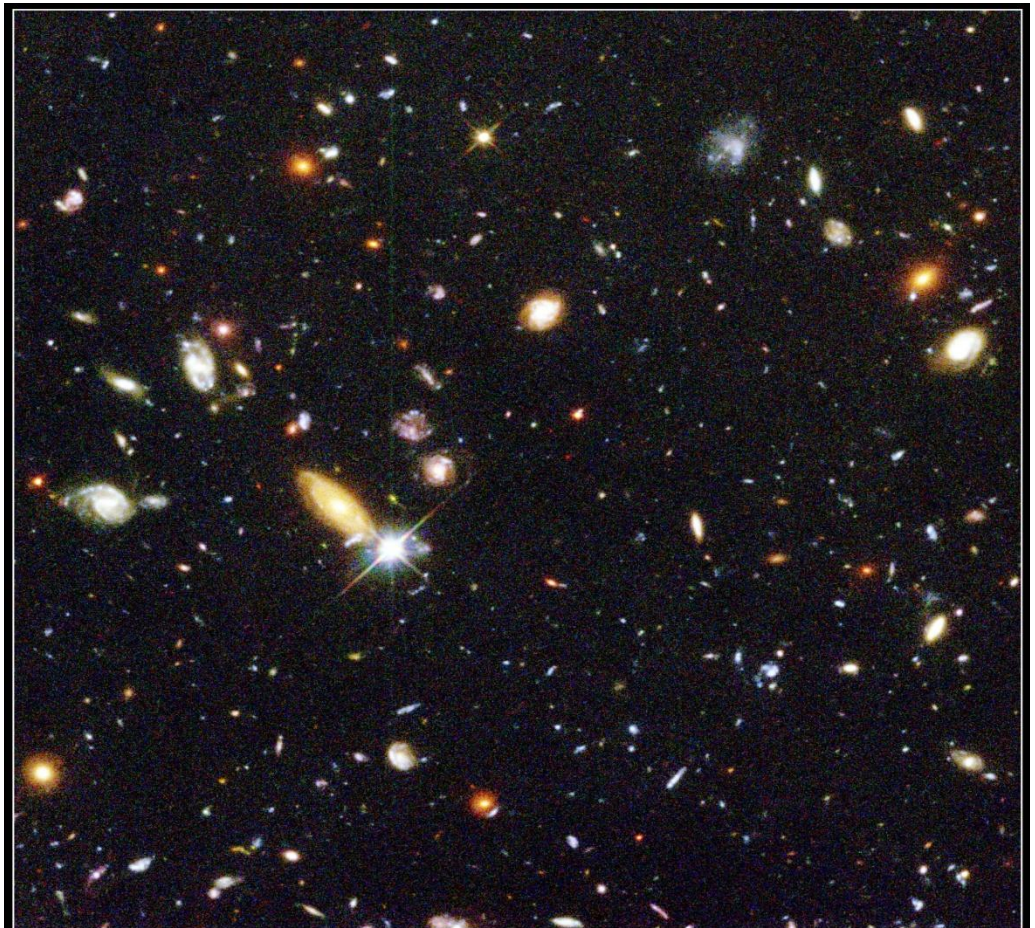
  - Opening up a new energy frontier (1 TeV scale)



- High Energy e^+e^- Colliders
  - Precision Physics at the new energy frontier

Dark Matter



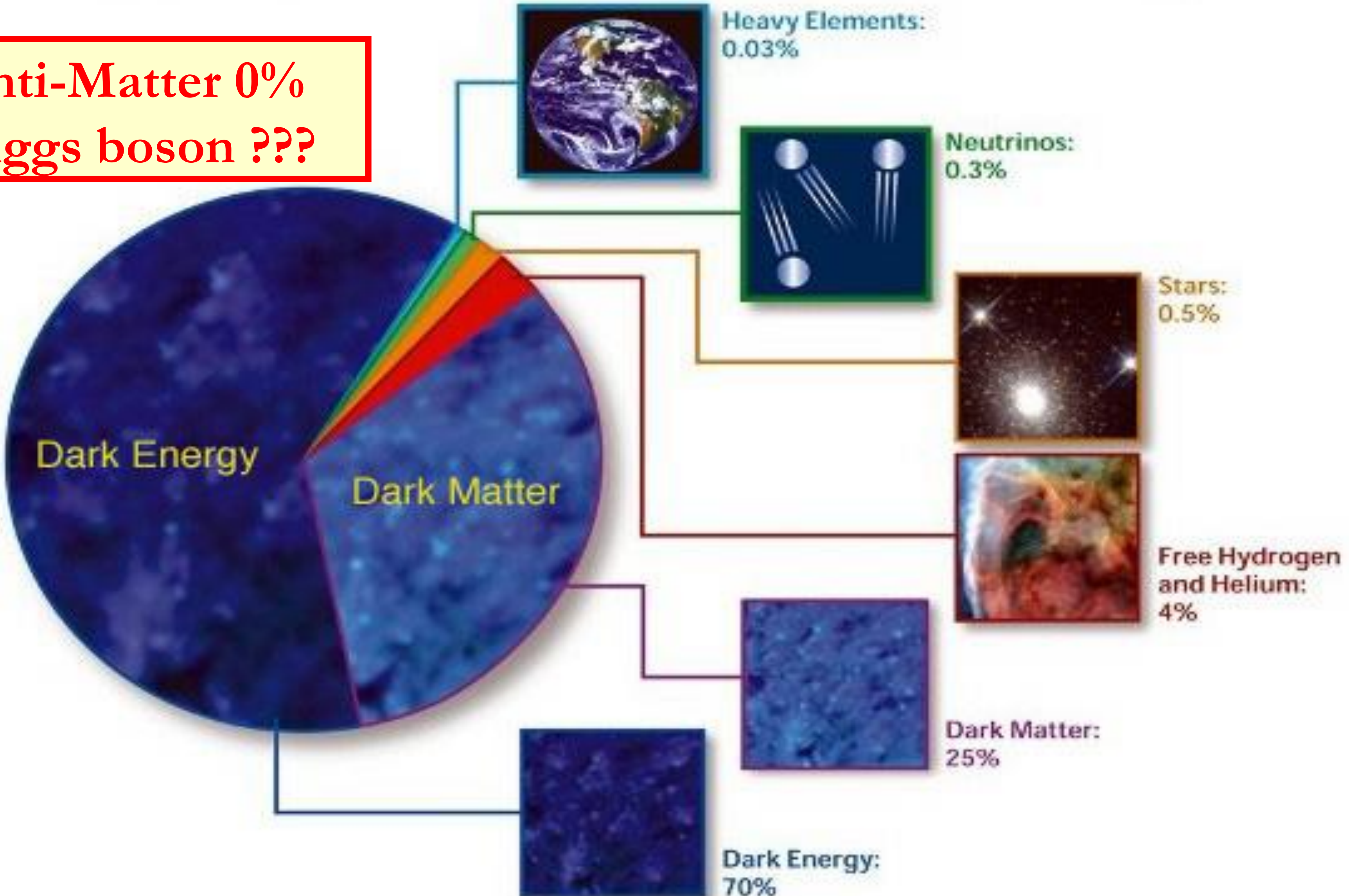
Hubble Deep Field
Hubble Space Telescope · WFPC2

What don't we see?

Dark Matter
Neutrinos
Dark Energy
…
Higgs Bosons !
Antimatter !!

The Energy Budget of the Universe

Anti-Matter 0%
Higgs boson ???



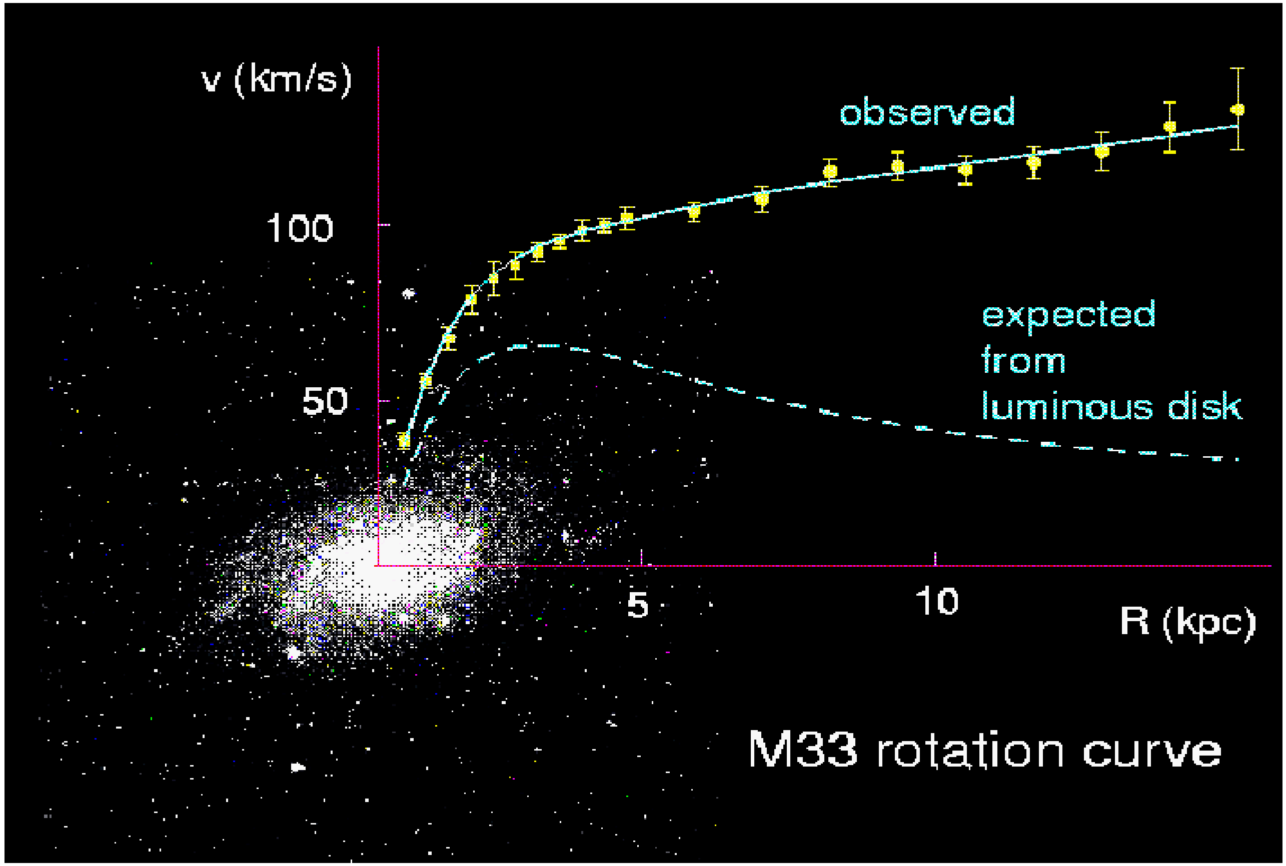
Dark Matter
the evidence

From the Kepler's law, $v_{circ} = \sqrt{\frac{GM(r)}{r}}$ for r much larger than the luminous terms, you should have v α r $^{-1/2}$ However, Instead, it is flat or rises slightly.

This is the most direct evidence for dark matter.

There are many complementary measurements at all scales

Corbelli & Salucci (2000);
Bergstrom (2000)



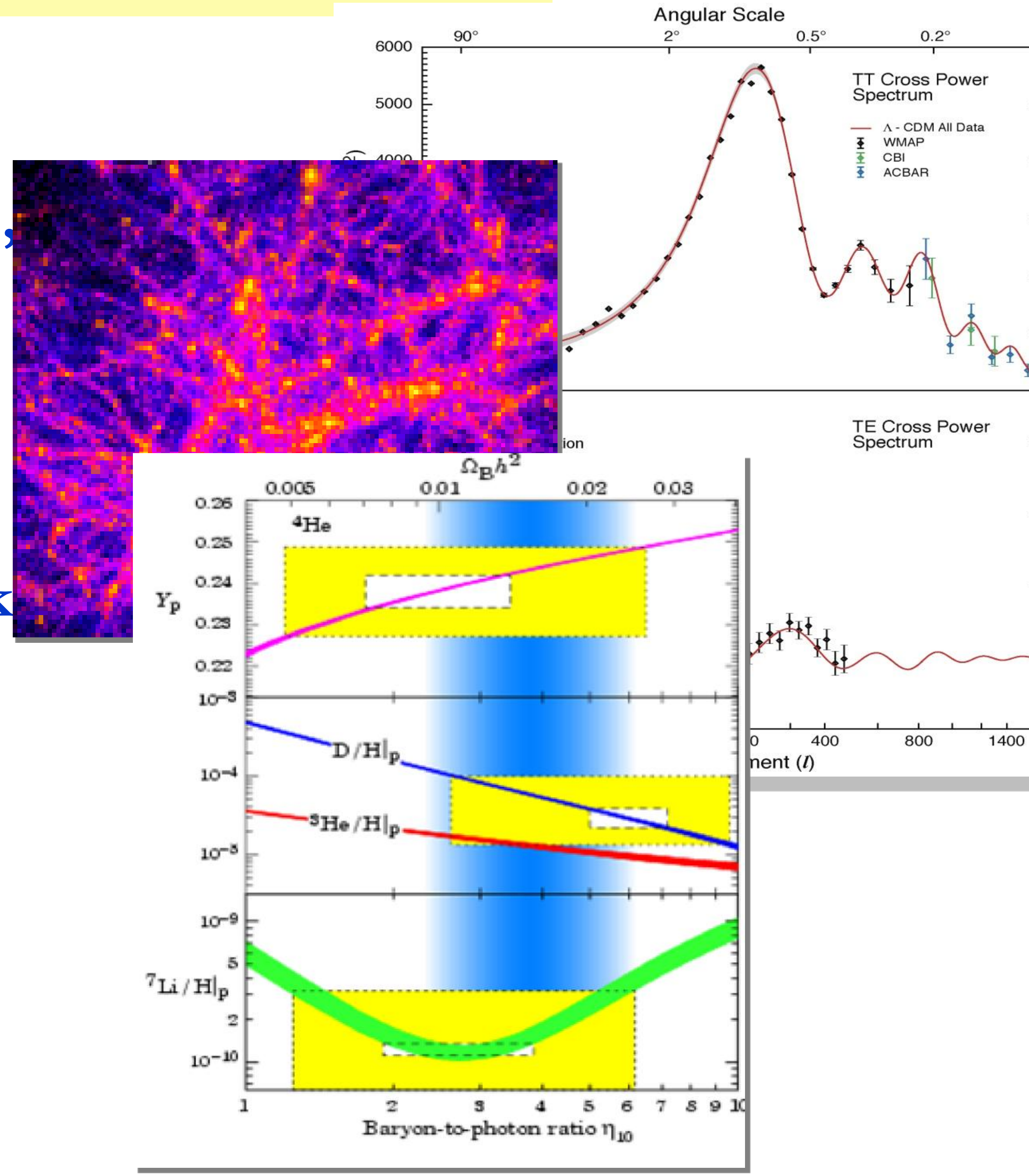
Other Dark Matter Evidence

- Evidence from a wide range of astrophysical observations including rotation curves, CMB, lensing, clusters, BBN, SN1a, large scale structure

- Each observes dark matter through its gravitational influence

- Still no (reliable) observations of dark matter's electroweak interactions (or other non-gravitational interactions)

- Still no (reliable) indications of dark matter's particle nature



Dark Matter Particle Candidates

Axions, Neutralinos, Gravitinos, Axinos, Kaluza-Klein Photons, Kaluza-Klein Neutrinos, Heavy Fourth Generation Neutrinos, Mirror Photons, Mirror Nuclei, Stable States in Little Higgs Theories, WIMPzillas, Cryptons, Sterile Neutrinos, Sneutrinos, Light Scalars, Q-Balls, D-Matter, Brane World Dark Matter, Primordial Black Holes, …

EVIDENCE STRONGLY FAVORS NON-BARYONIC COLD DARK MATTER

Leading Dark Matter Candidate

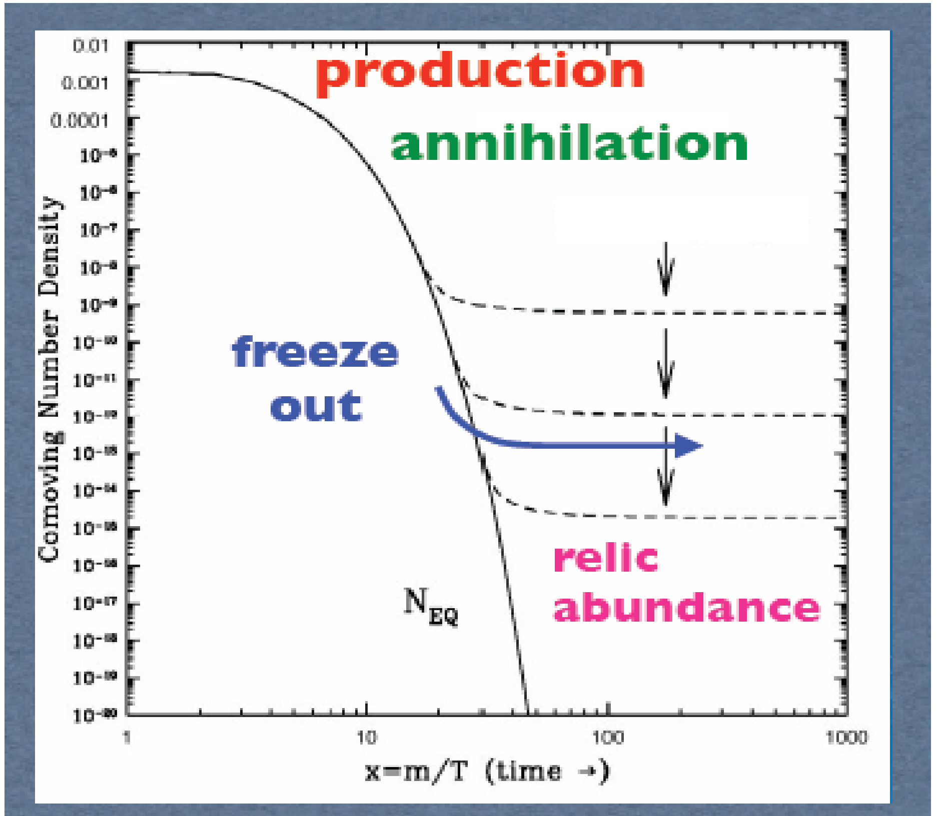
Weakly Interacting Massive Particles (WIMPs)

Weakly interacting particles produced thermally in the early universe

Large mass compared to standard particles.

Due to their large mass, they are relatively slow moving and therefore "cold dark matter."

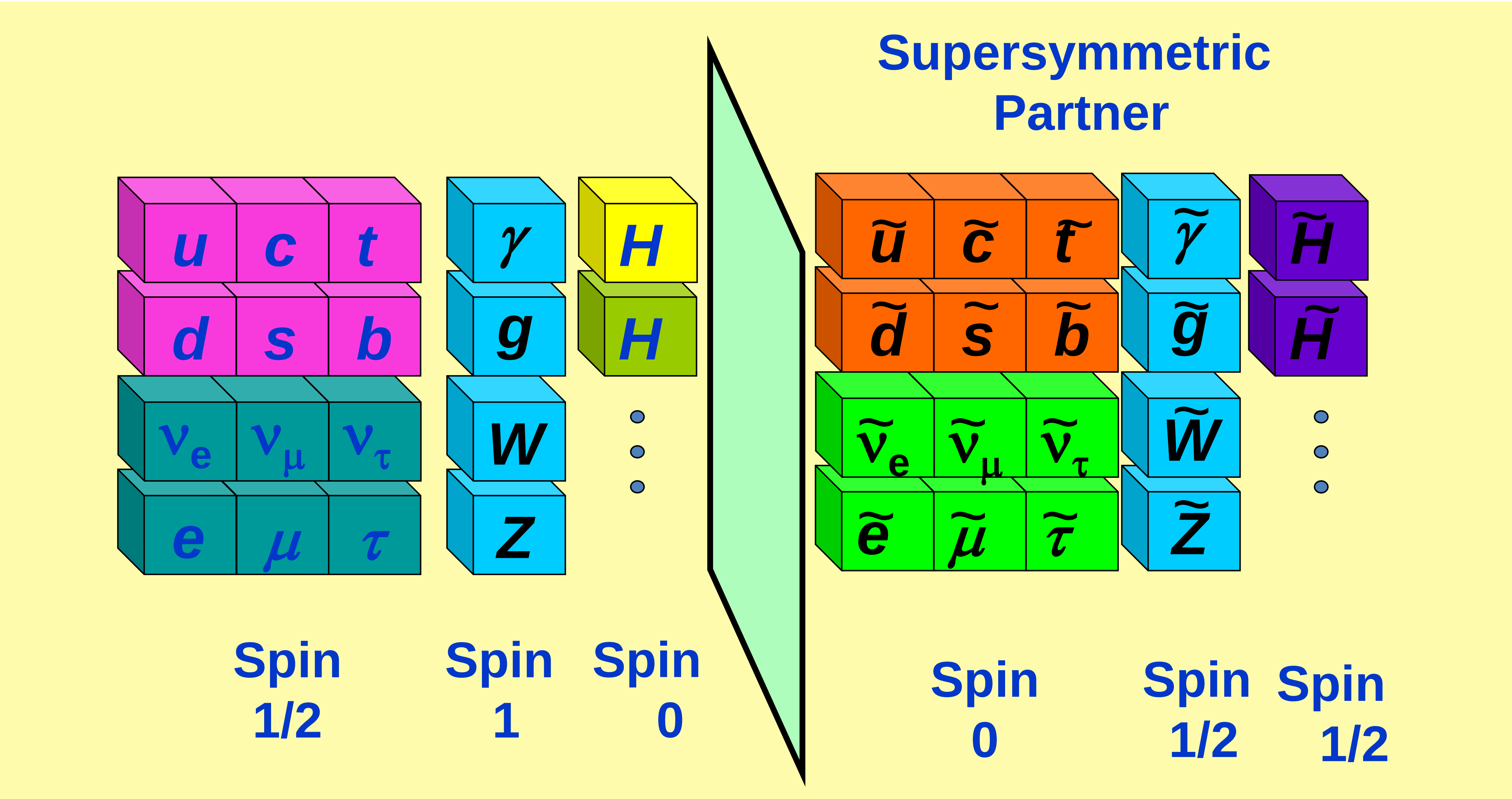
Leading candidate – "Supersymmetric Particles"



$$\Omega_\chi h^2 \approx \frac{3 \times 10^{-27}}{< \sigma_\chi v >}$$

Supersymmetric dark matter would solve one of biggest problems in astrophysics and particle physics at the same time !

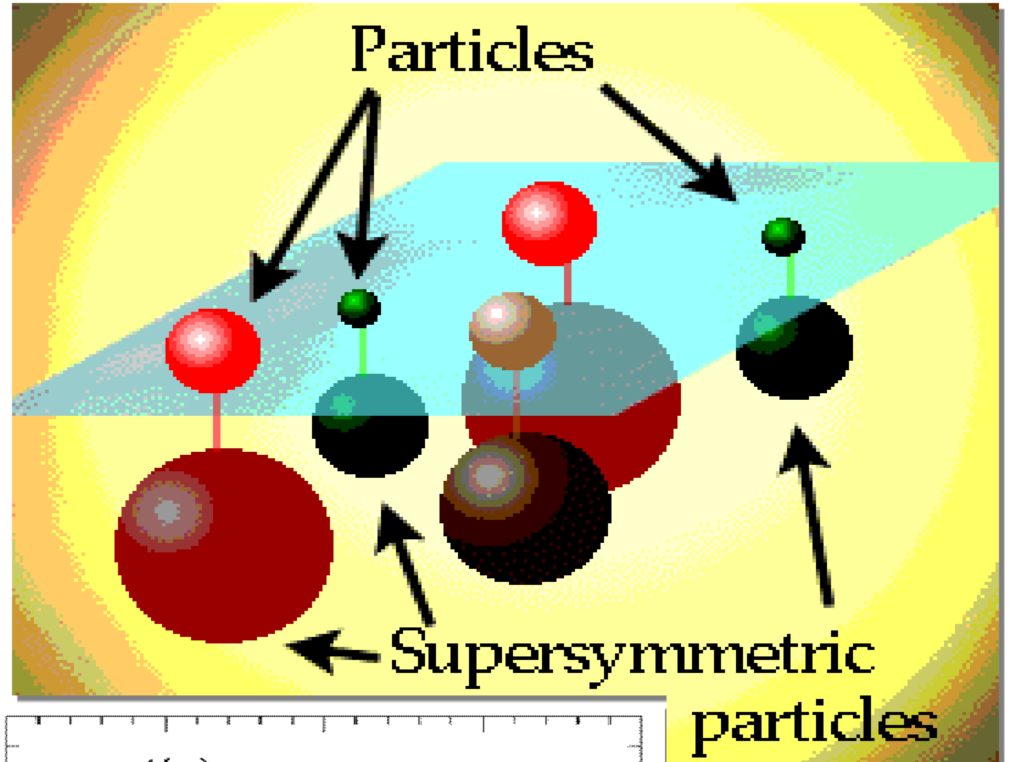
What is Supersymmetry?

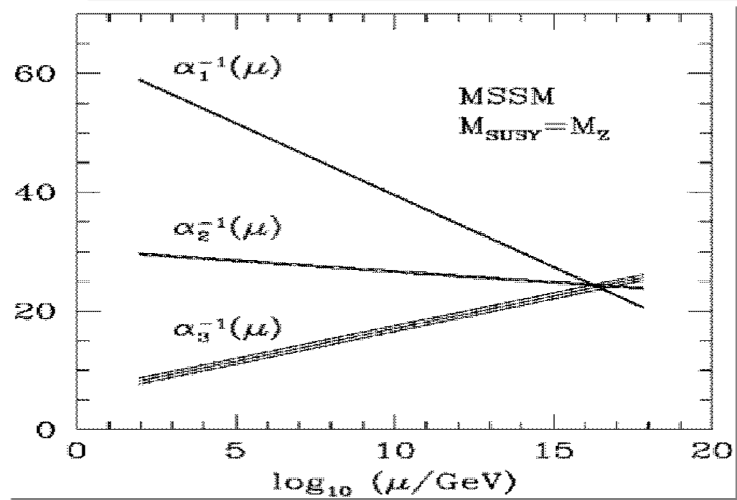


Supersymmetry

- The most theoretically appealing extension of the Standard Model
- Natural solution to hierarchy problem (stabilizes quadradic divergences to Higgs mass)
- Restores unification of couplings
- Vital ingredient of string theory
- Naturally provides a compelling candidate for dark matter

$$\tilde{\gamma}, \tilde{Z}, \tilde{h}, \tilde{H}$$



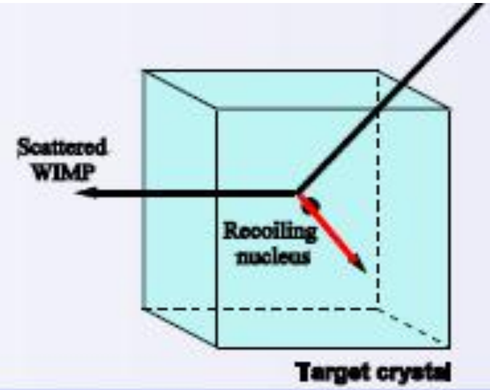


Searching for Dark Matter

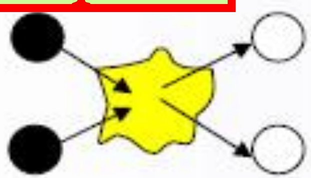
Underground

- Direct Detection:

Look for the elastic scattering of dark matter with nuclei



In Space



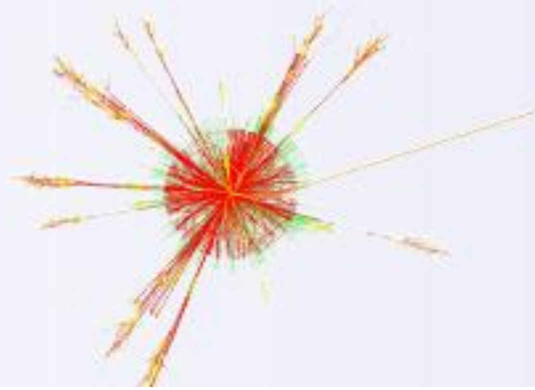
- Neutrinos
- Photons
- Electron-Positron, Antimatter

- Indirect Detection:

Look for the annihilation products

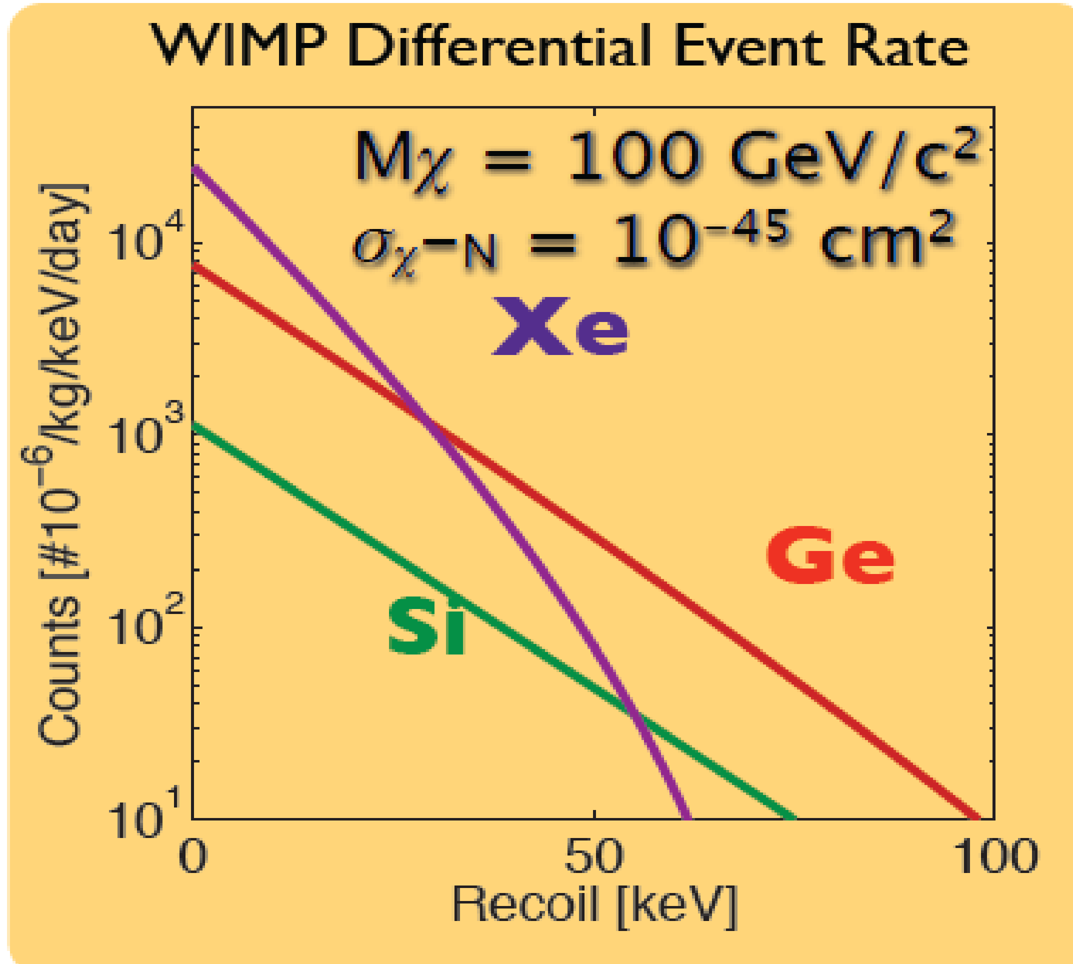
On Accelerators

Look for signals of new physics

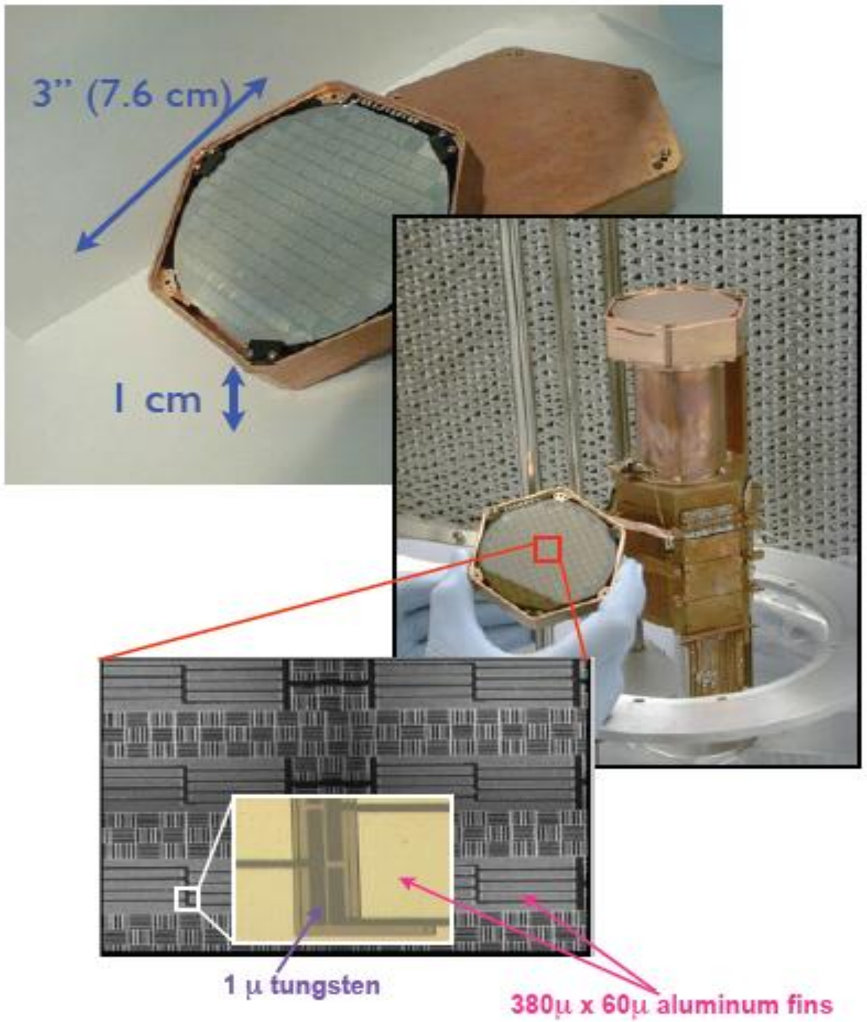


Direct Detection of Relic WIMPS

- Elastic scattering of a WIMP deposits small amounts of energy into recoiling nucleus (~ few 10s of keV)
- Featureless exponential spectrum
- **Expected rate: < 0.01/kg-d**
- Radioactive background of most materials higher than this rate.



The "Cryogenic Dark Matter Search" (CDMS)



The CDMS experiments measures the recoil energy imparted to detector nuclei through WIMP-nucleon collisions by employing sensitive phonon detection equipment coupled to arrays of cryogenic germanium and silicon crystals.

WIMP Direct Searches

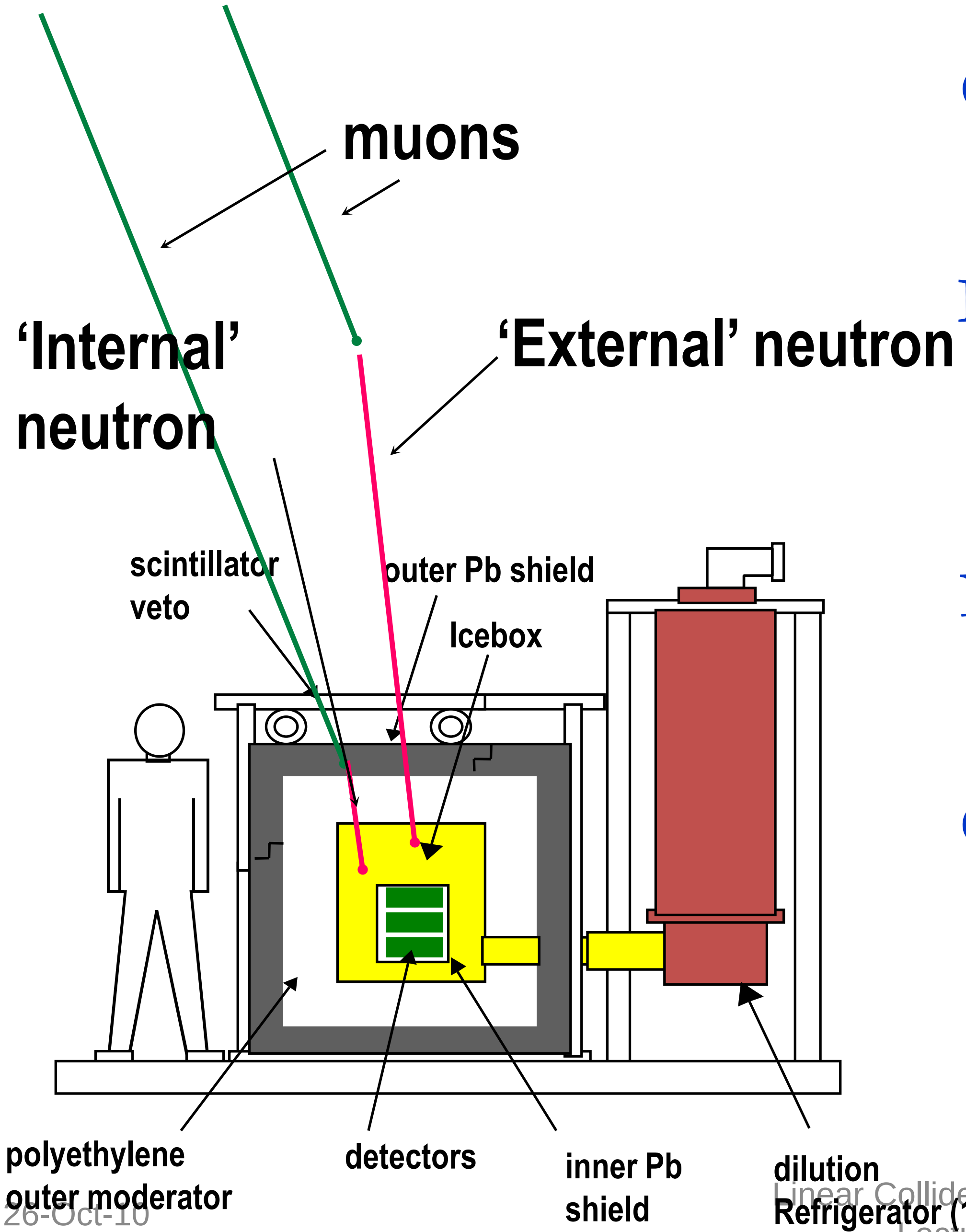
• **Located at the Soudan mine in sunny Minnesota**

• **CDMS II is 2341 feet below the surface (2090 mwe)**

CDMS

Cryogenic
Dark Matter Search

Sources of Background



Gammas / X-Rays

- Reject using additional shielding

Electrons

- Produced in the detector – rejected via analysis

Neutrons

- Reject by additonal scintillator veto

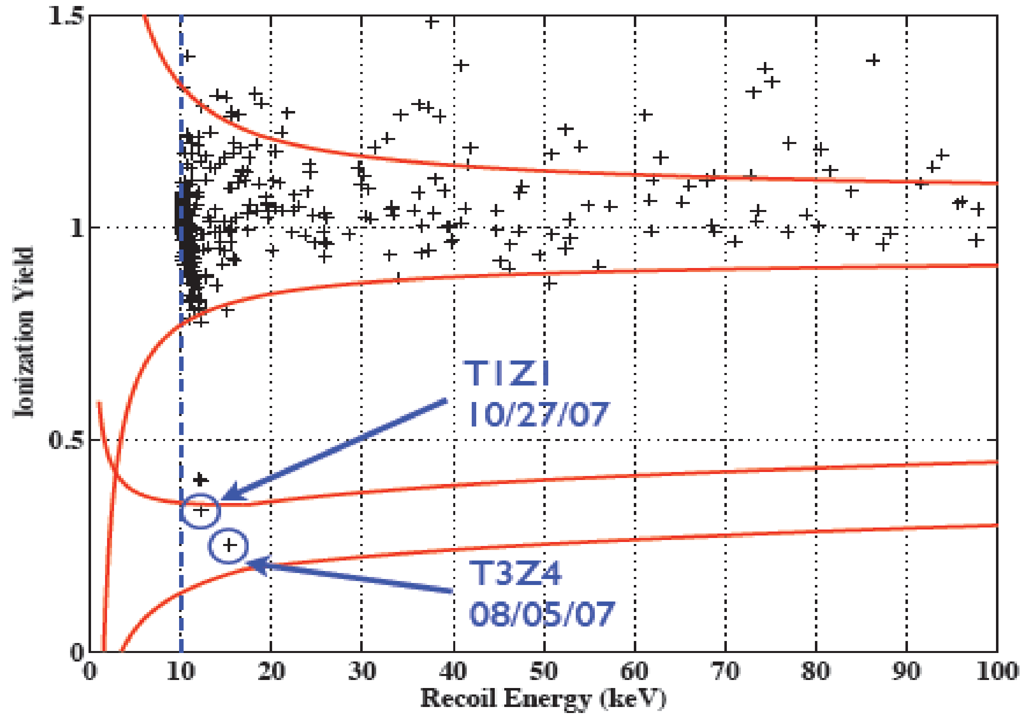
Cosmic Ray Muons

- Depth (2090mwe) reduces muon flux by a factor of ~50,000

Recent CDMS Result

"The final exposure of our low-temperature Ge particle detectors at the Soudan Underground Laboratory yielded two candidate events, with an expected background of 0.9 ± 0.2 events."

"The combined CDMS II data place the strongest constraints on the WIMP-nucleon spin-independent scattering cross section for a wide range of WIMP masses and exclude new parameter space in inelastic dark matter models."

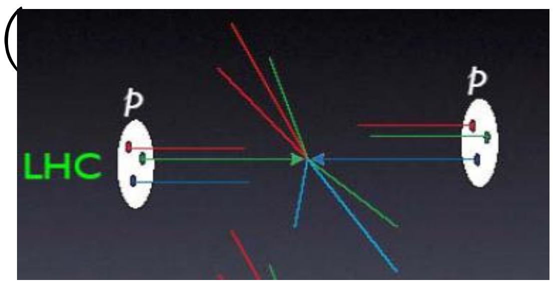


Published Online February 11, 2010
Science DOI: 10.1126/science.1186112

Addressing the Questions

- Neutrinos
  - Particle physics and astrophysics using a weakly interacting probe

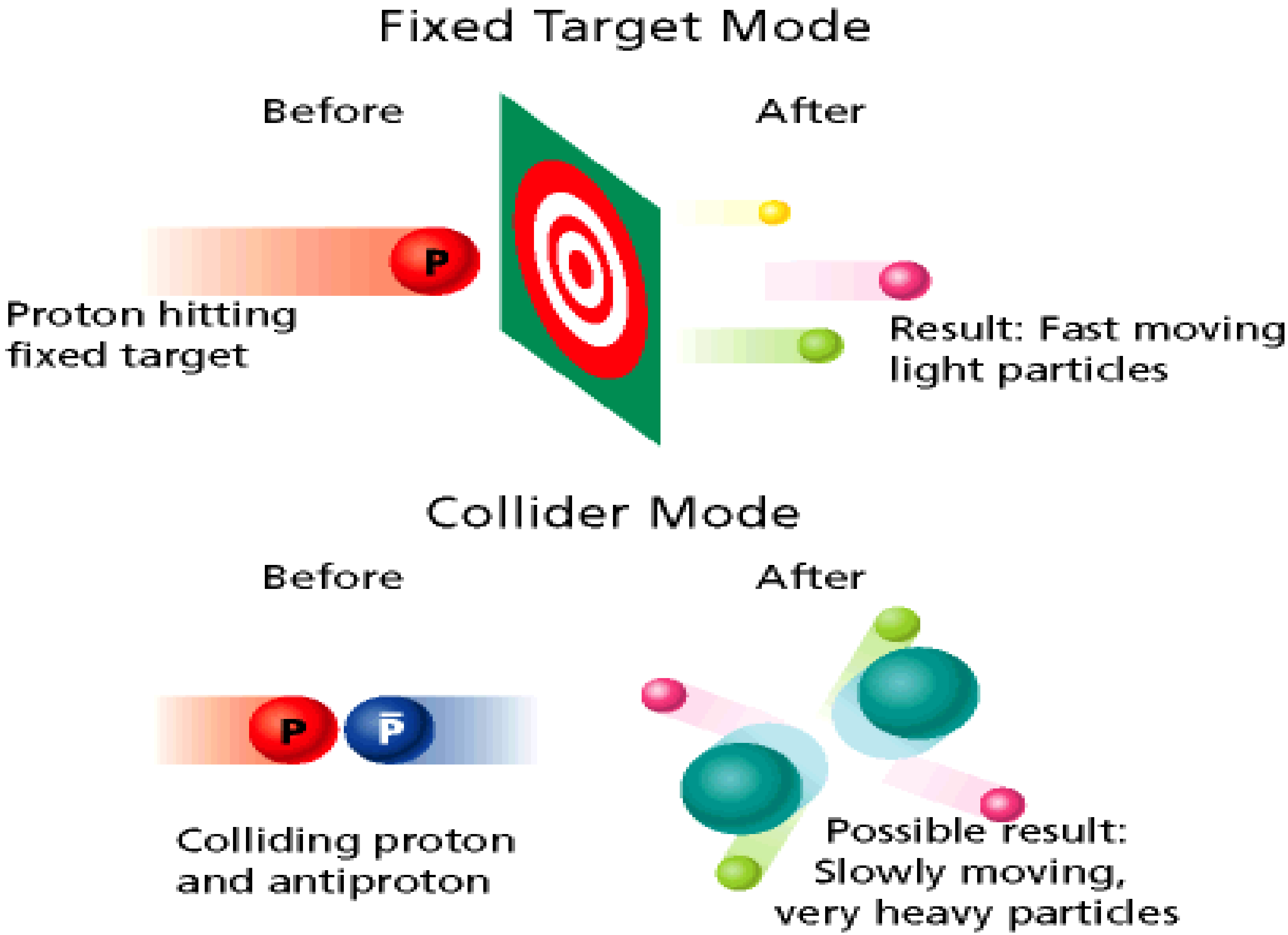
- Particle Astrophysics/Cosmology
  - Dark Matter; Cosmic Microwave, etc
- High Energy pp Colliders
  - Opening up a new energy frontier (1 TeV scale)



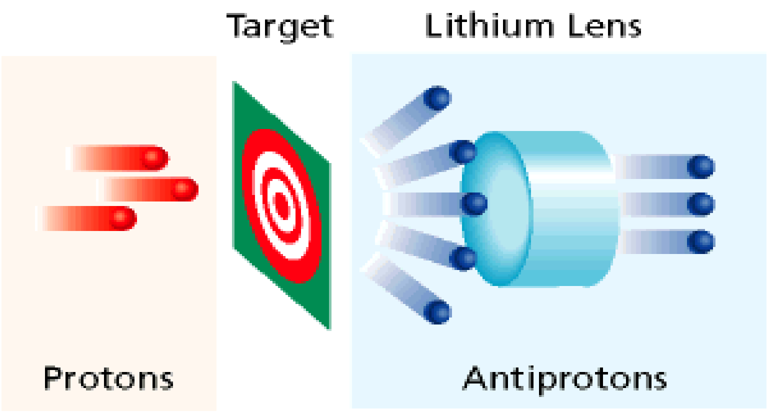
- High Energy e^+e^- Colliders
  - Precision Physics at the new energy frontier

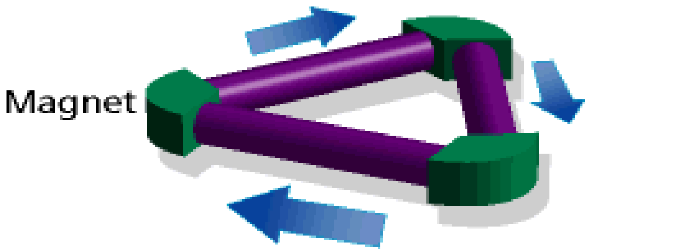
Break

Particle Colliders

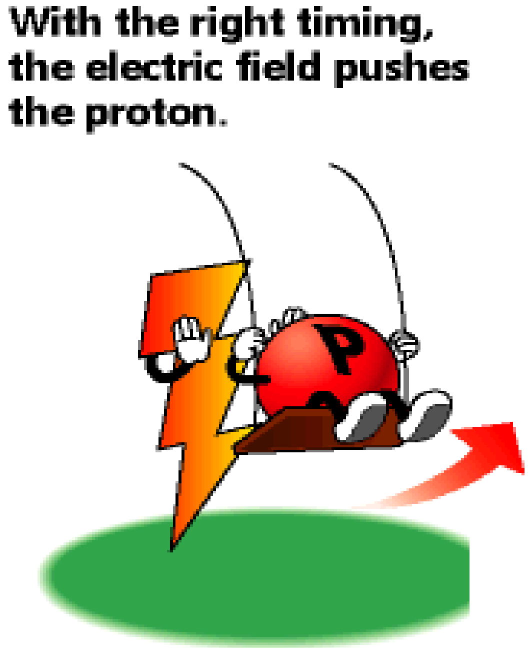


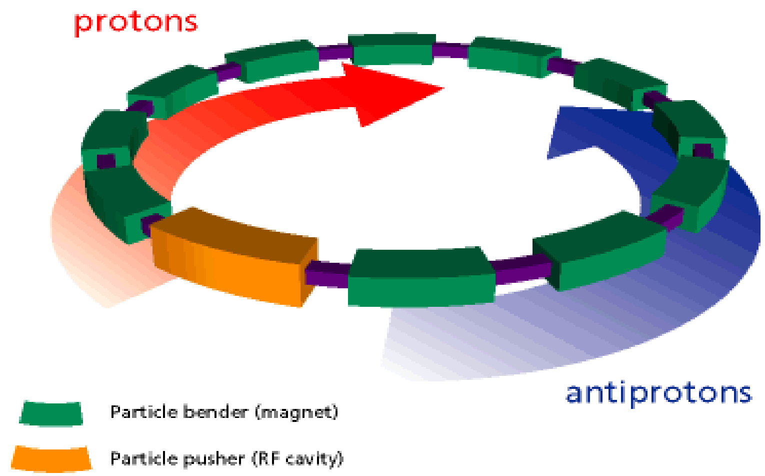
Particle Colliders

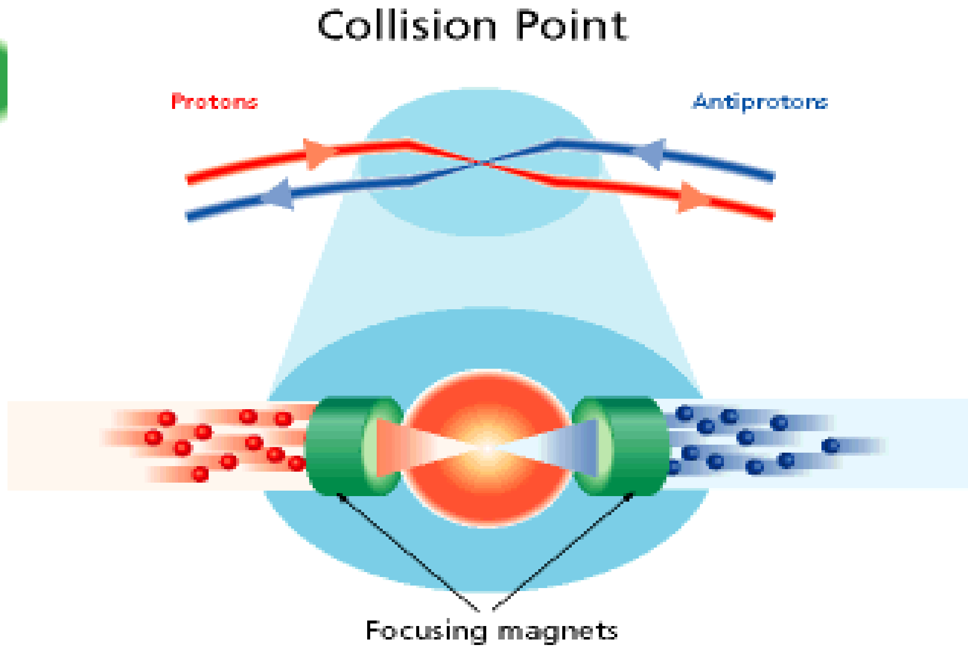




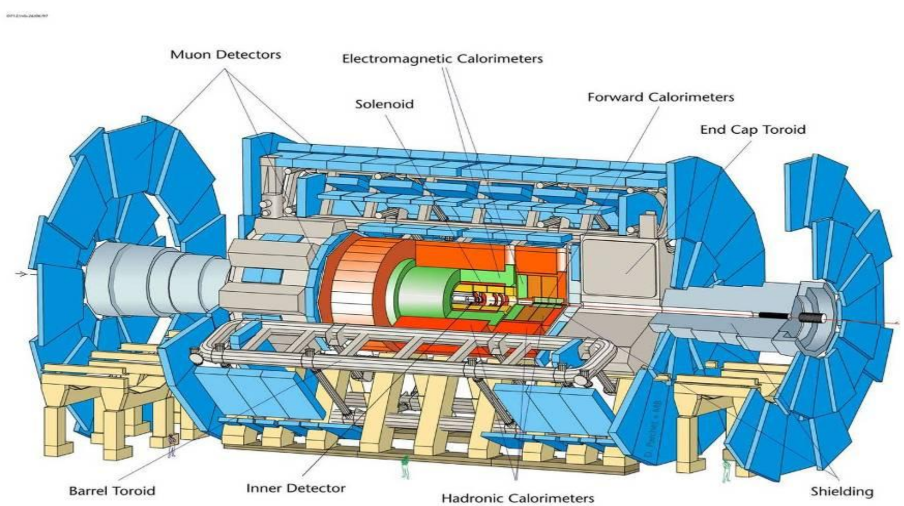
Antiproton Accumulator

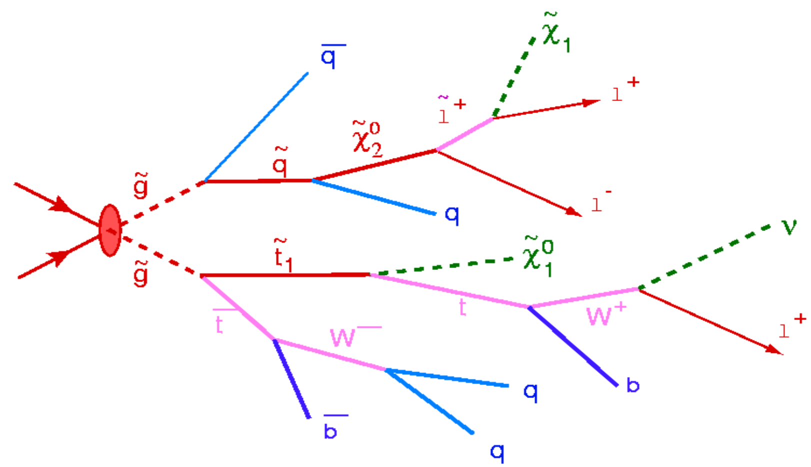






Megascience project --- LHC





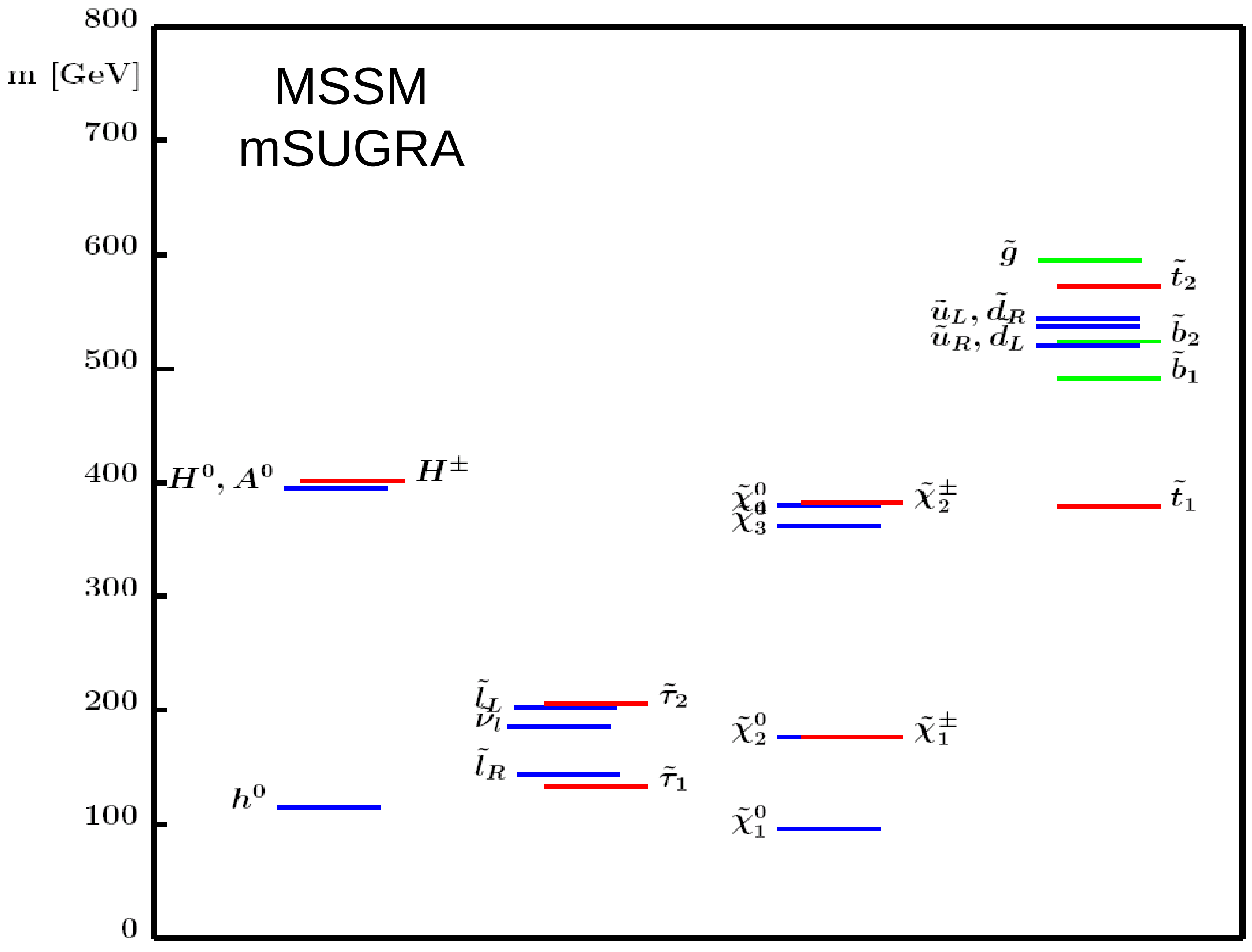
3 isolated leptons
+ 2 b-jets
+ 4 jets
+ E_t^{miss}

Exploring the Terascale

the tools

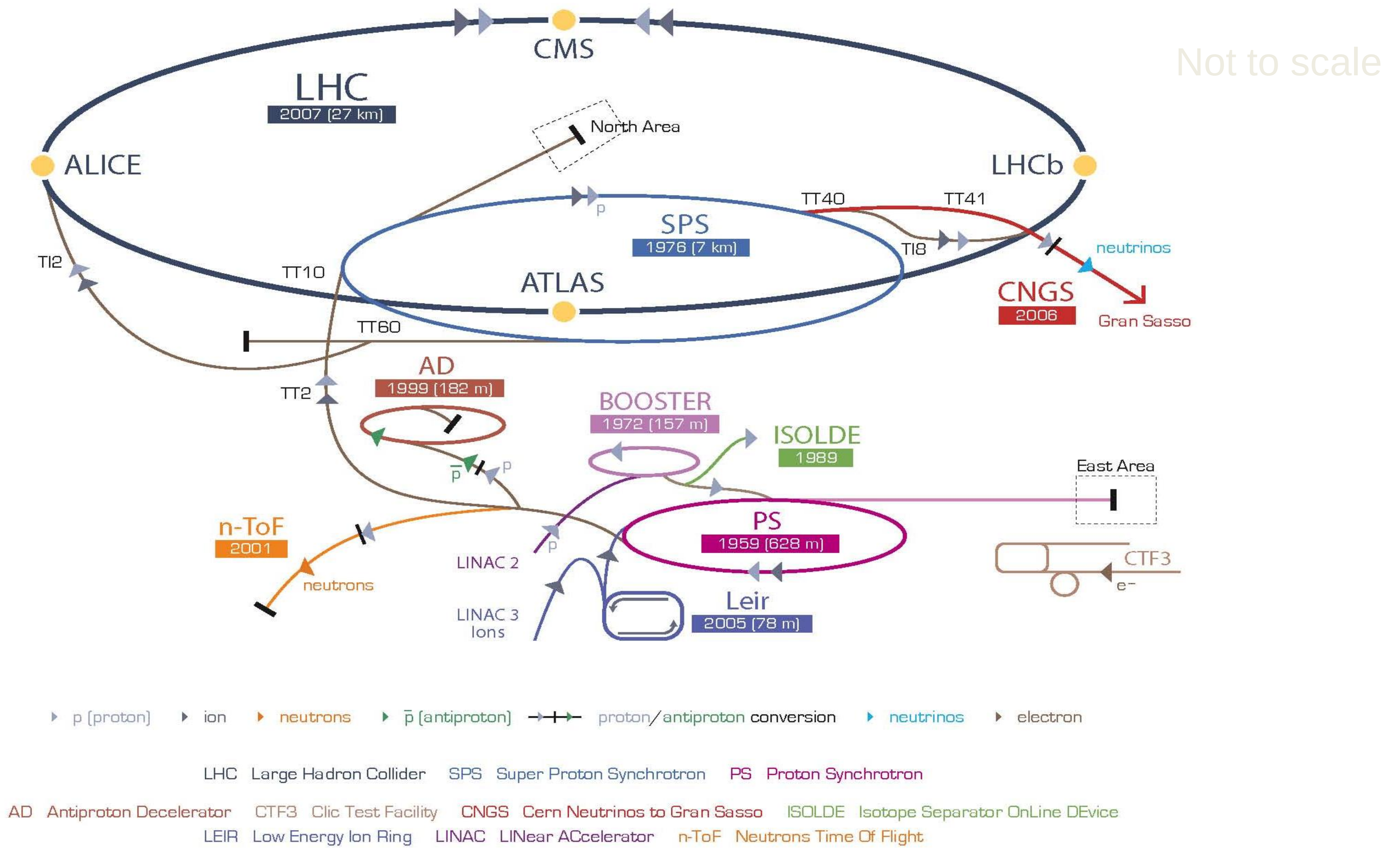
- The LHC
  - It will lead the way and has large reach
  - Quark-quark, quark-gluon and gluon-gluon collisions at 0.5 - 5 TeV
  - Broadband initial state
- The ILC
  - A second view with high precision
  - Electron-positron collisions with fixed energies, adjustable between 0.1 and 1.0 TeV
  - Well defined initial state
- Together, these are our tools for the terascale

Spectrum of Supersymmetric Particles

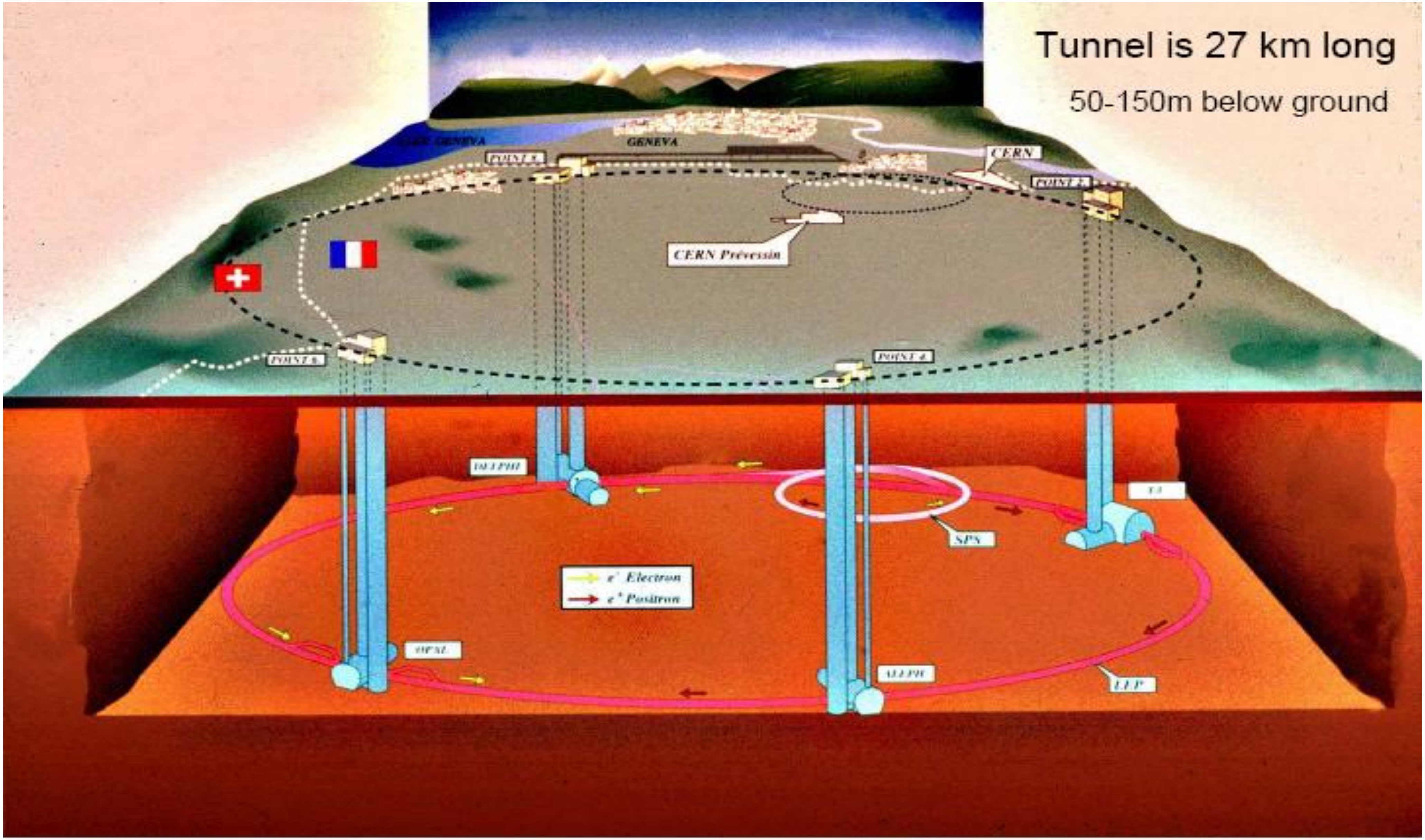


squarks and sgluons heavy yielding long decay chains ending with LSP neutrilino

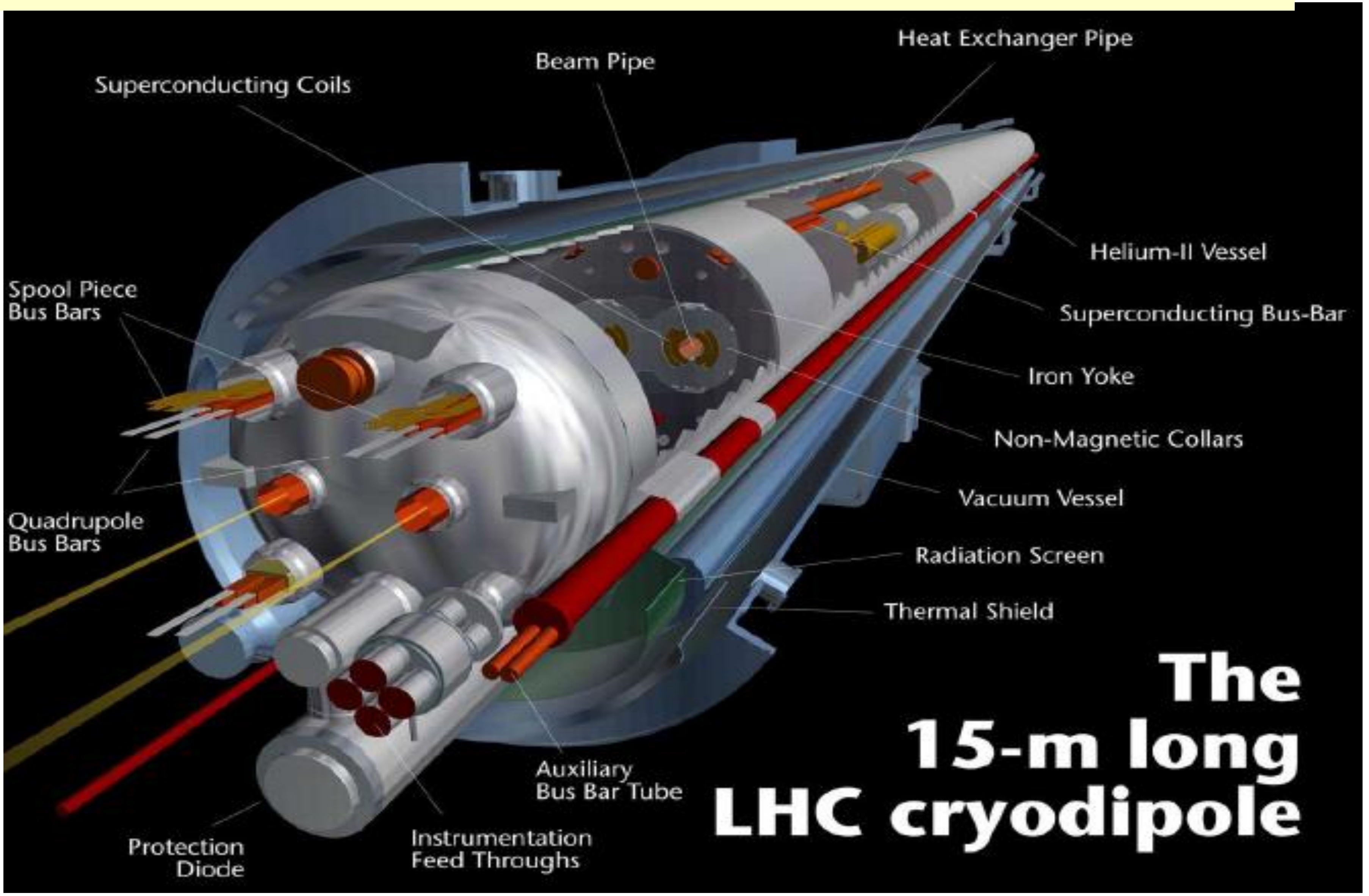
LHC – CERN Accelerator Complex



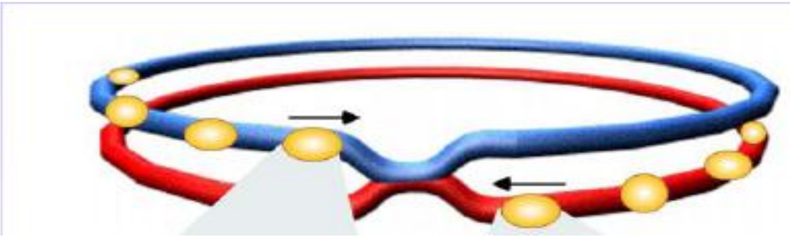
LHC is deep underground

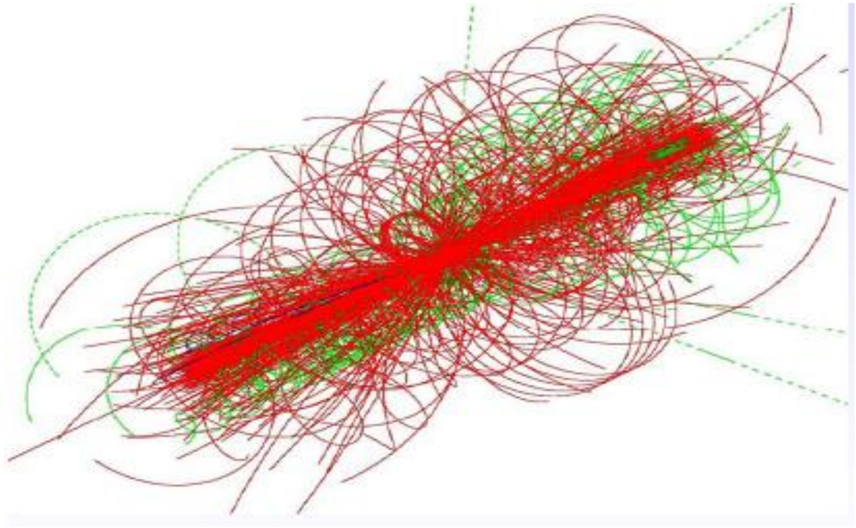


LHC --- **Superconducting** Magnet



Proton-Proton Collisions at the LHC





- 2835 + 2835 proton bunches separated by 7.5 m

→ collisions every 25 ns
= 40 MHz crossing rate

- 10^{11} protons per bunch

- at 10^{34}/cm^2/s
≈ 35 pp interactions per crossing
<u>pile-up</u>

→ ≈ 10^9 pp interactions per second !!!

- In each collision
≈ 1600 charged particles produced

Enormous challenge for the detectors

The LHC Accelerator

Tests of superconducting magnets
(3 years, 24 hours per day)

Teams from India at the CERN test facility

The LHC Accelerator

Transfer line magnets from SPS to LHC (~5km)

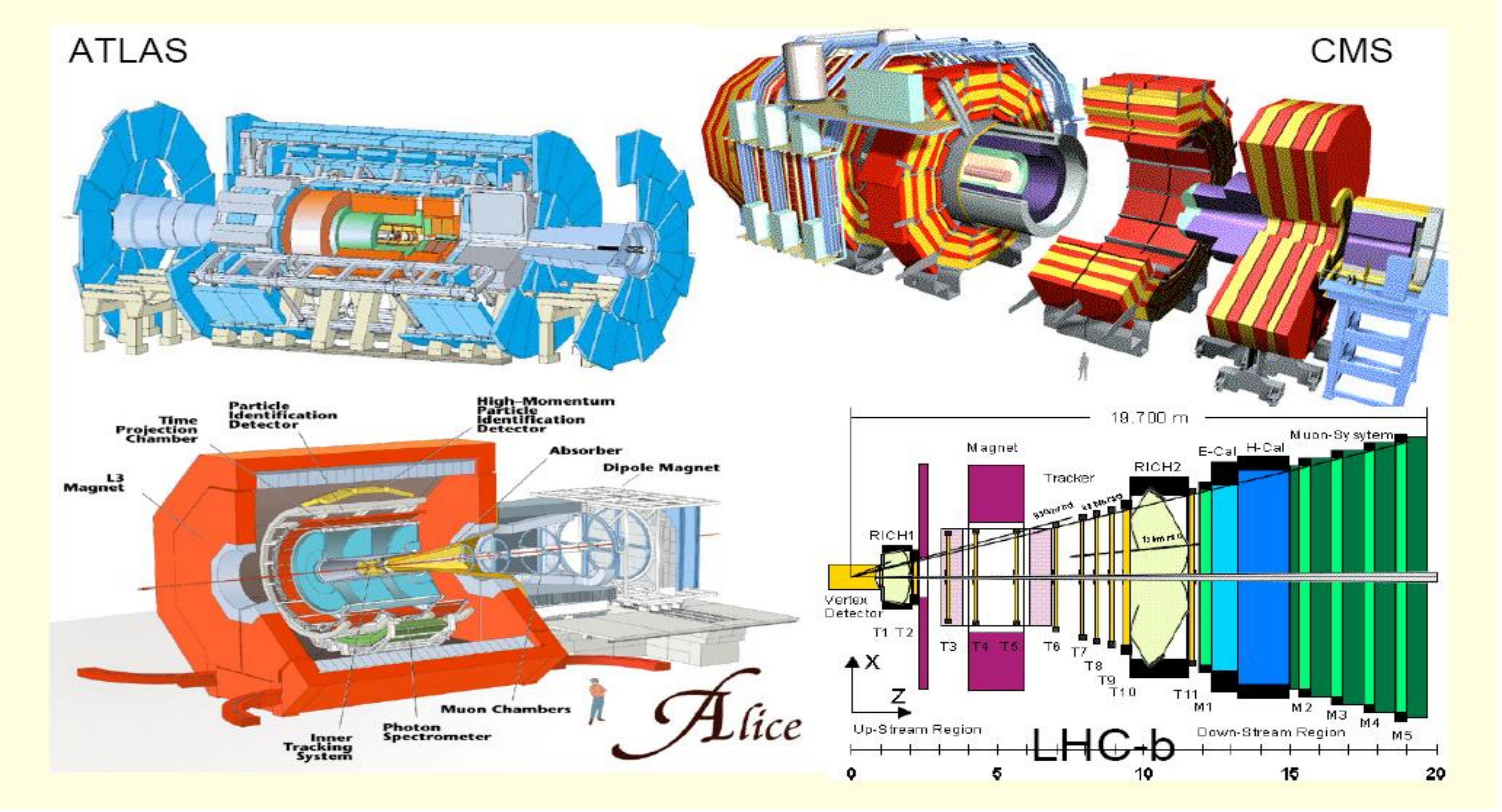
Transfer Line: main quadrupole (blue), followed by a corrector (green) and a series of main dipoles (red). All built by Budker Institute for Nuclear Physics (BINP) in Novosibirsk, Russia

The LHC Accelerator

Inner triplet magnets from US and Japan
focusing the LHC beams towards the collision points

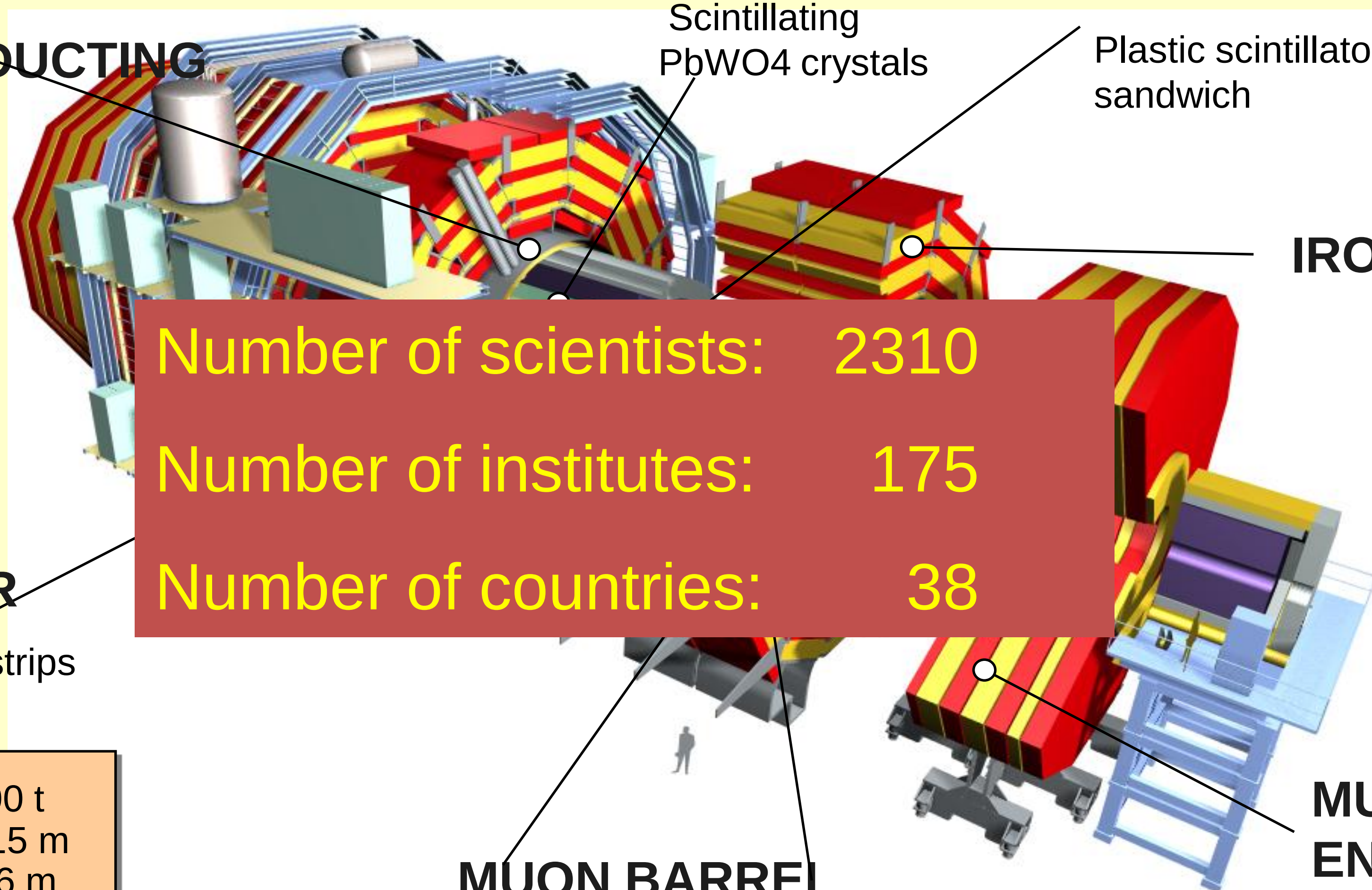
The LHC Experiments

- Each experiment has its own independent management and governance structure



LHC Experiments

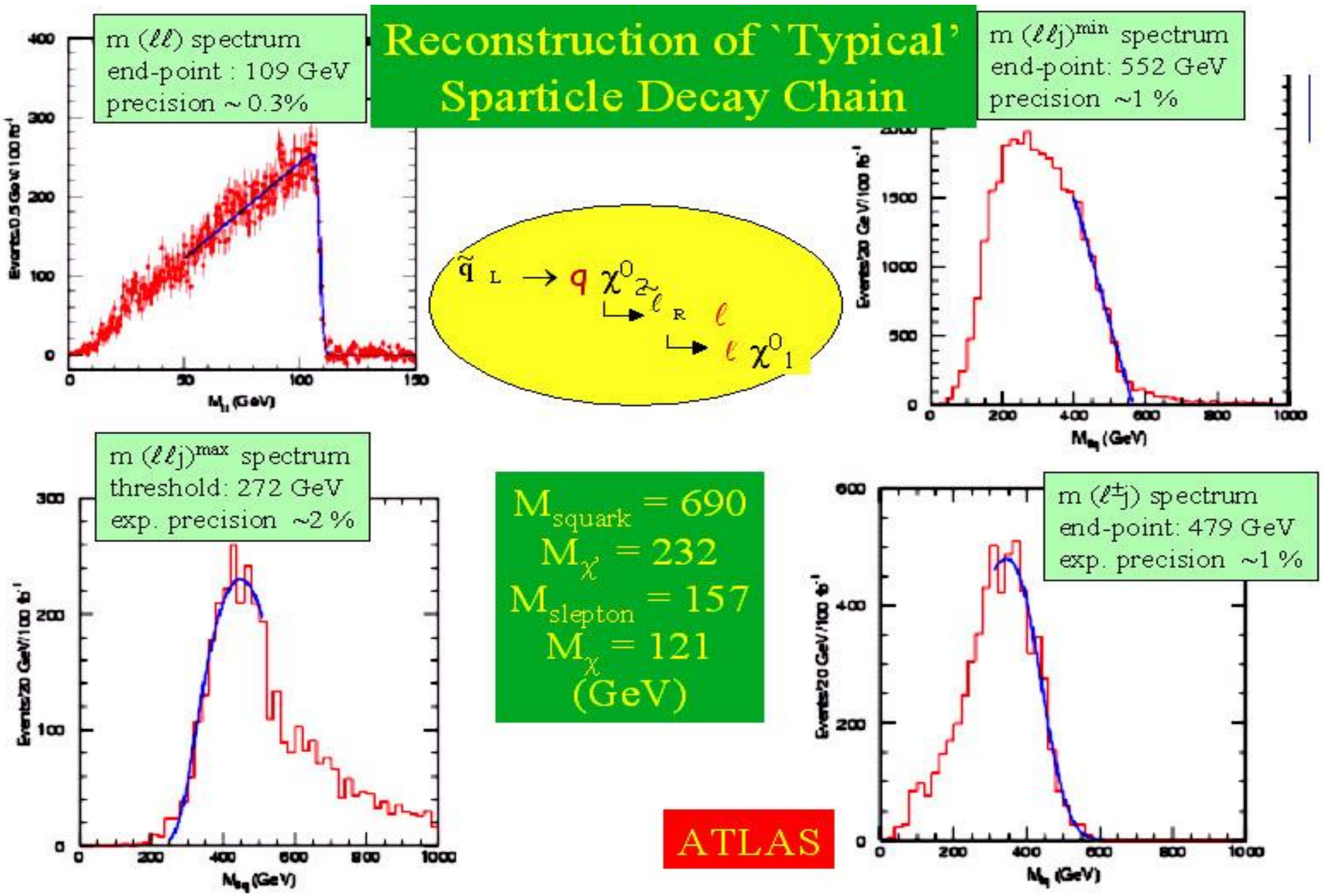
Compact Muon Solenoid - CMS



Number of scientists:	2310
Number of institutes:	175
Number of countries:	38

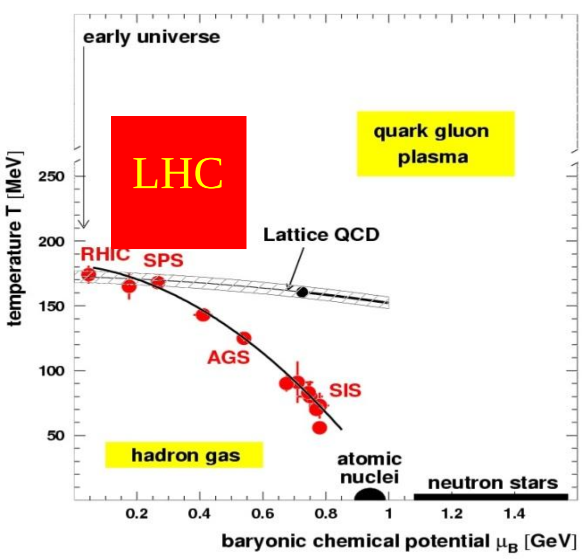
Total weight : 12,500 t
Overall diameter : 15 m
Overall length : 21.6 m
Magnetic field : 4 Tesla

Supersymmetric Detection at LHC



Broad Physics Probe

- Dense hadronic matter
  - relativistic heavy-ion collisions
  - quark-gluon plasma?
- Matter-antimatter asymmetry
  - CP violation in B system



- Connections with cosmology
  - Inflation and dark matter
  - early Universe and the origin of matter

Statistics at High Energy and Luminosity

Event rates in ATLAS or CMS at $L = 10^{33}\ cm^{-2}\ s^{-1}$

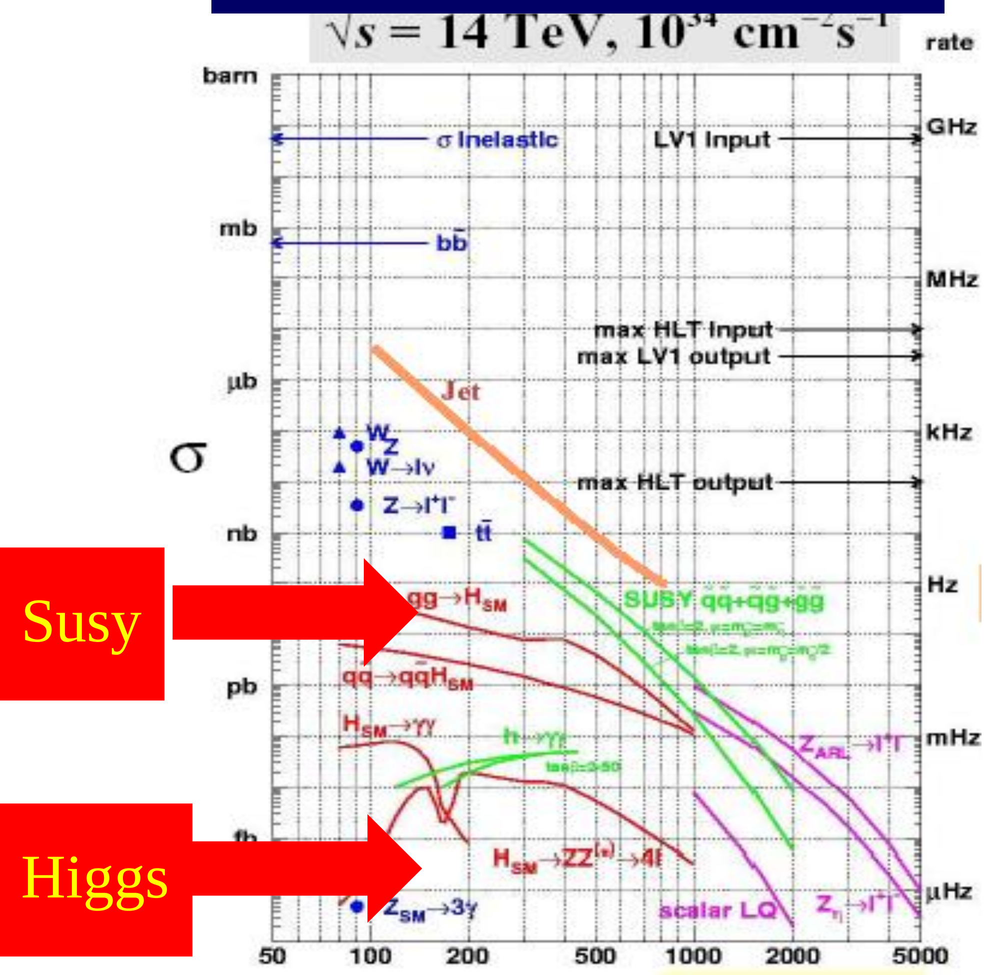
Process	Events/s	Events per year	Total statistics collected at previous machines by 2007
$W \to e\nu$	15	10^8	10^4 LEP / 10^7 Tevatron
$Z \to ee$	1.5	10^7	10^7 LEP
$t\bar{t}$	1	10^7	10^4 Tevatron
$b\bar{b}$ **LHC-b**	10^6	$10^{12} - 10^{13}$	10^9 Belle/BaBar ?
H m=130 GeV	0.02	10^5	?
$\tilde{g}\tilde{g}$ m= 1 TeV	0.001	10^4	---
Black holes m > 3 TeV (M_D=3 TeV, n=4)	0.0001	10^3	---

+ Ion Collisions

LHC is a factory for anything: top, W/Z, Higgs, SUSY, etc….
mass reach for discovery of new particles up to m ~ 5 TeV

LHC Physics

Interesting cross sections



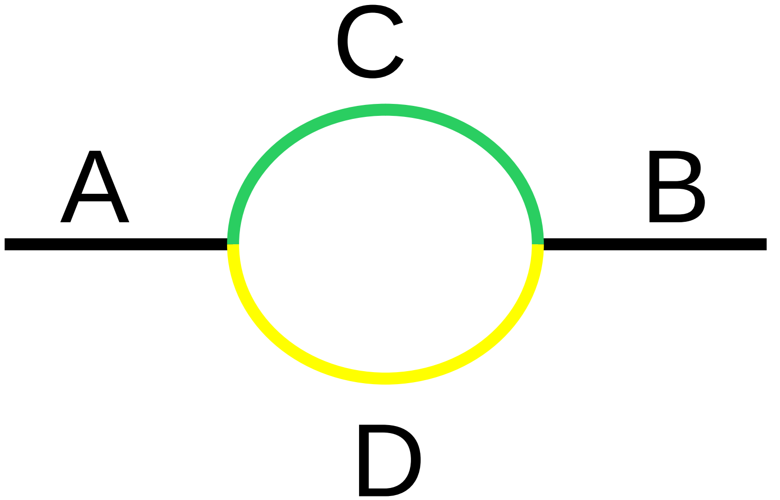
- **Small couplings ~ α^2**
- **Fraction ~ 1/1,000,000,000,000**
- **Need to pull out rare events**
- **Need ~ 1,000 events for signal**

Mass Range of the Higgs

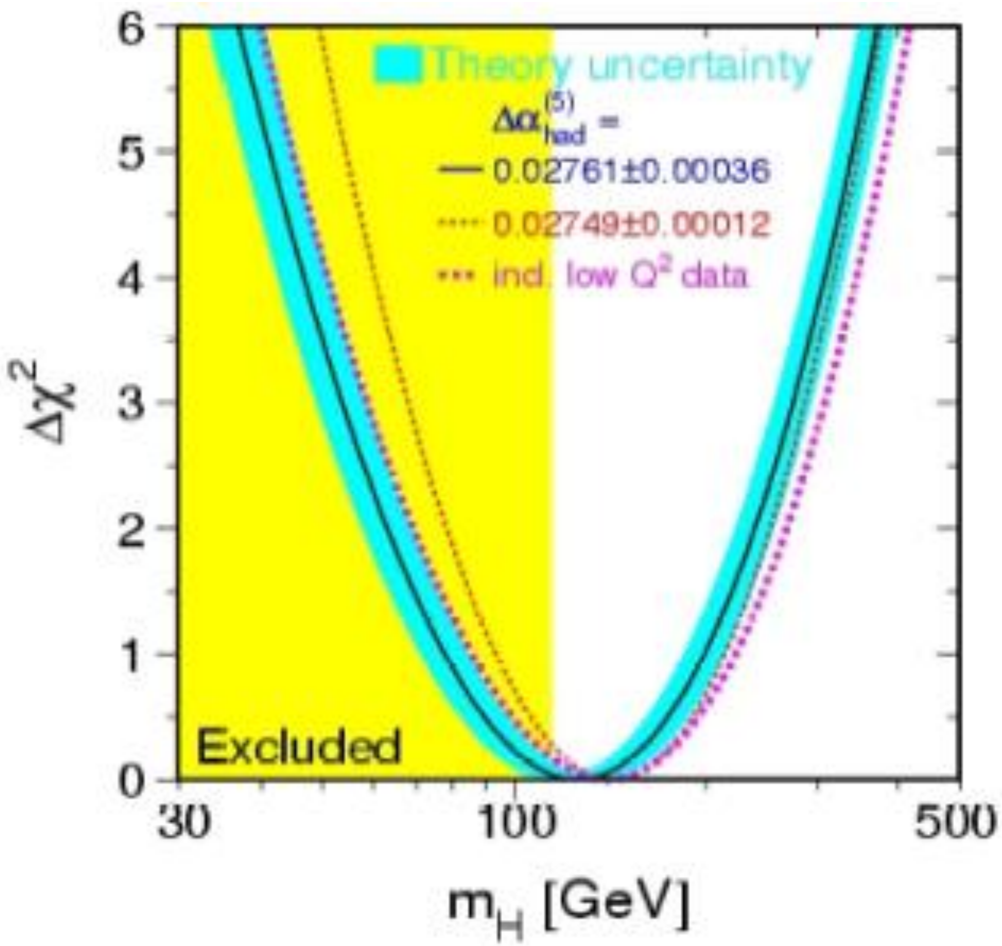
The current knowledge of Mass Range of The Higgs comes from the examination of very precise experimental data collected in the last decades incorporating the "Higher Order effects" of the interactions.

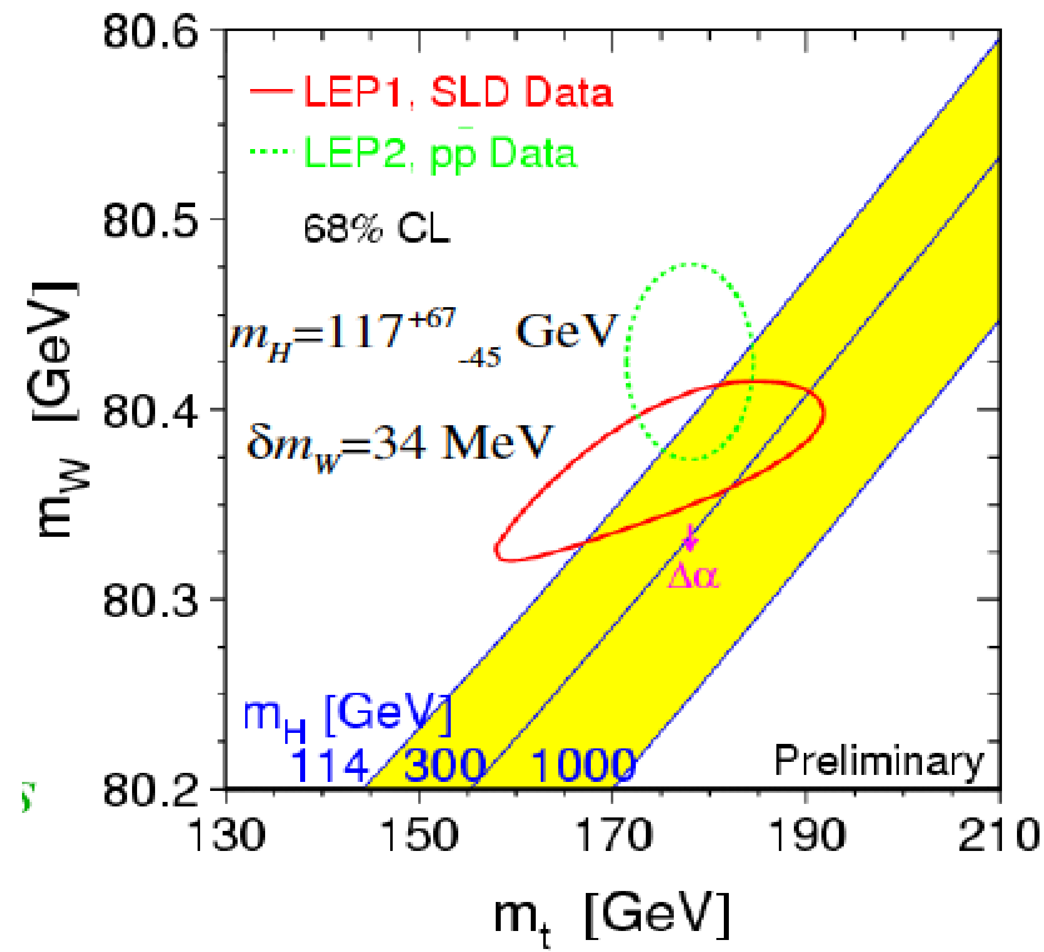
$$m_W^2 = \frac{\pi\alpha_{EM}}{\sqrt{2}G_F \sin^2\theta_W(1 - \Delta r)}$$

Higher Order Correction



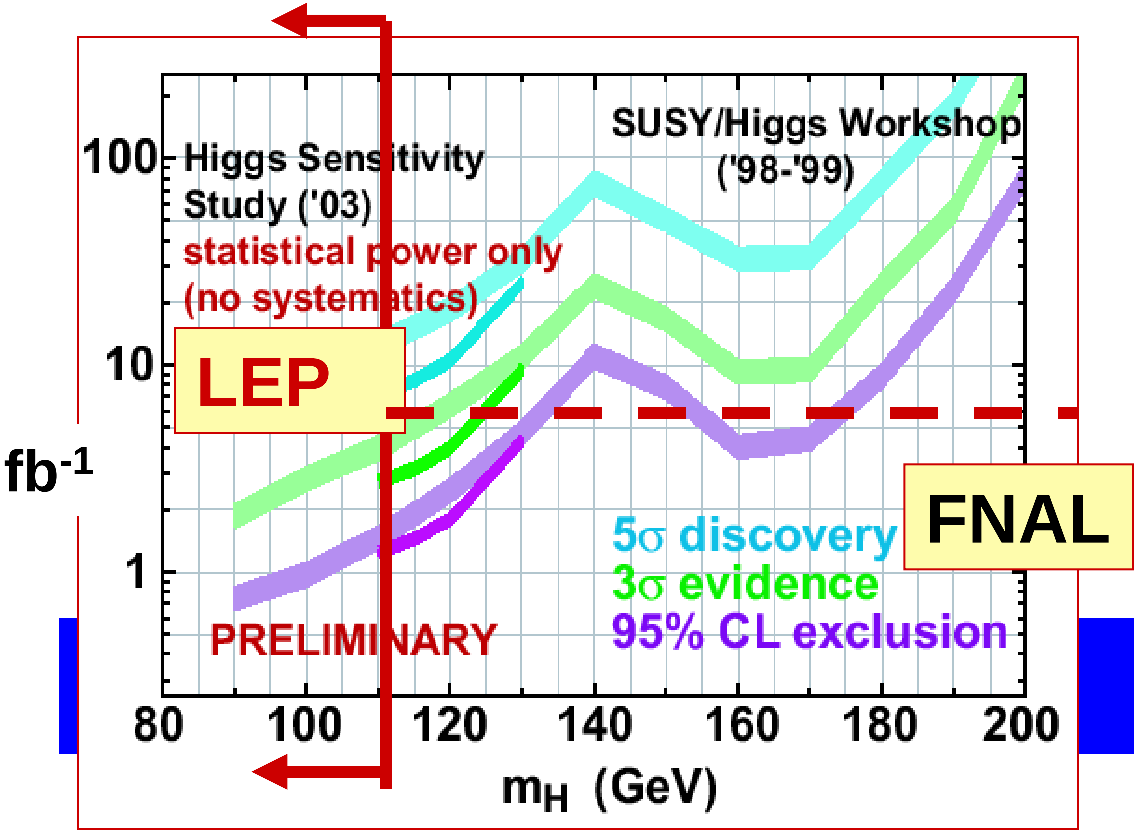
Estimation of the Higgs mass range



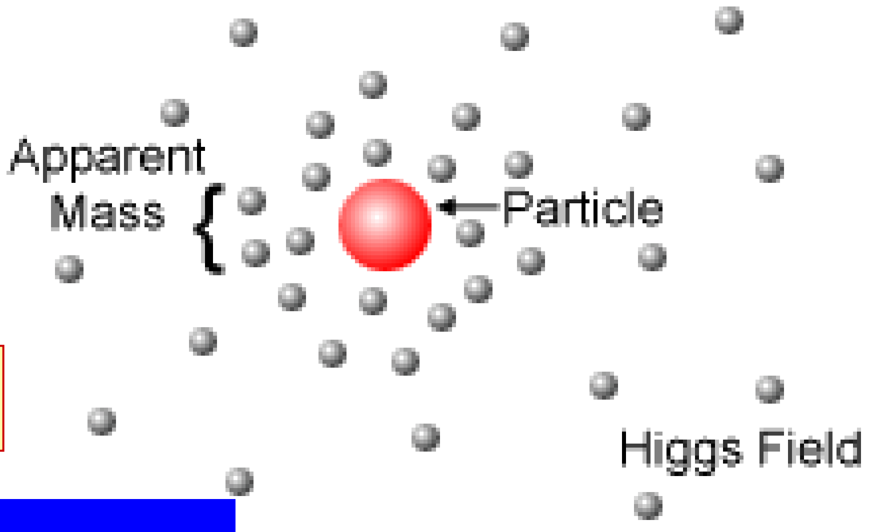


LHC and the Energy Frontier
Source of Particle Mass

Discover the Higgs



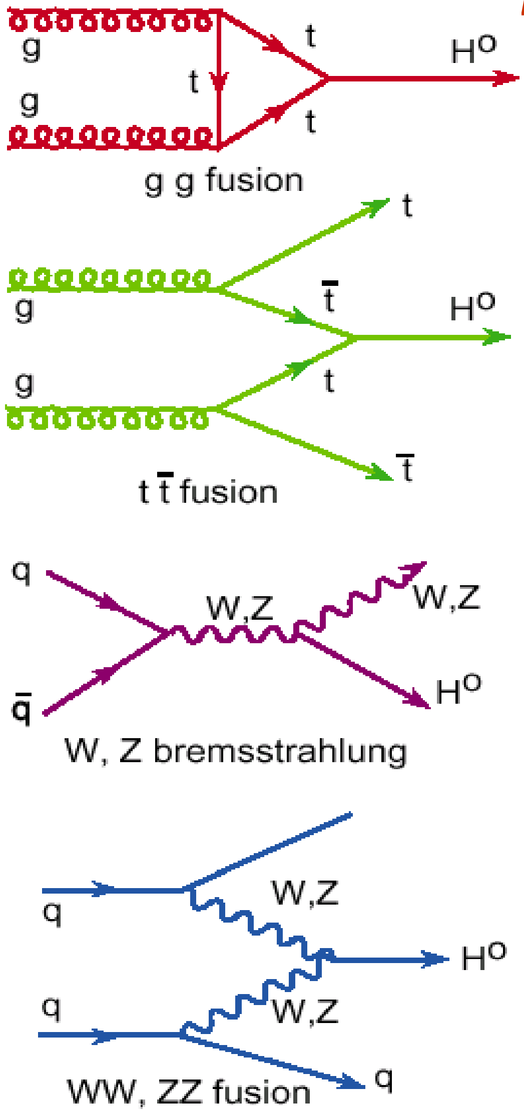
The Higgs Field

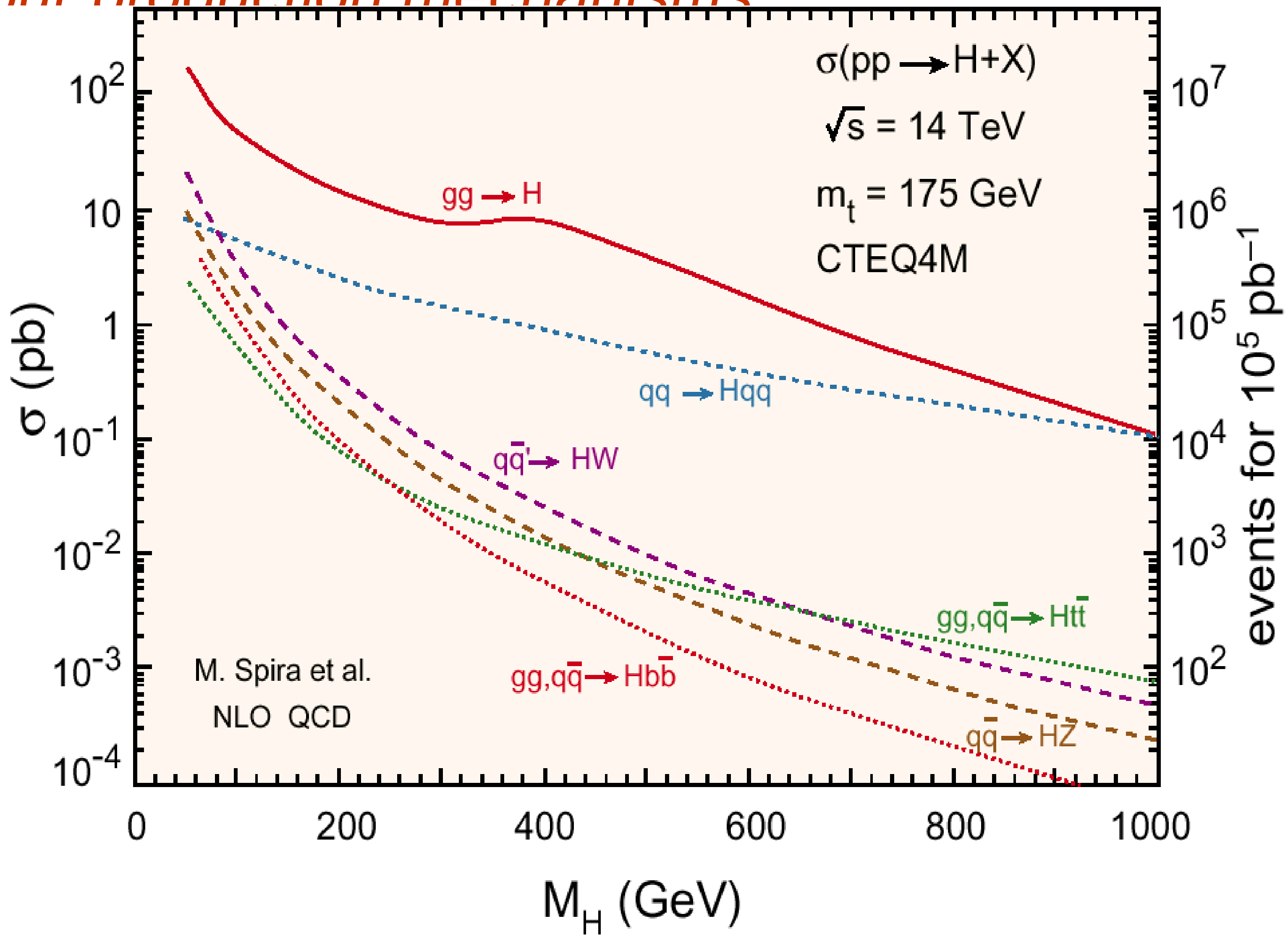


or variants or ???

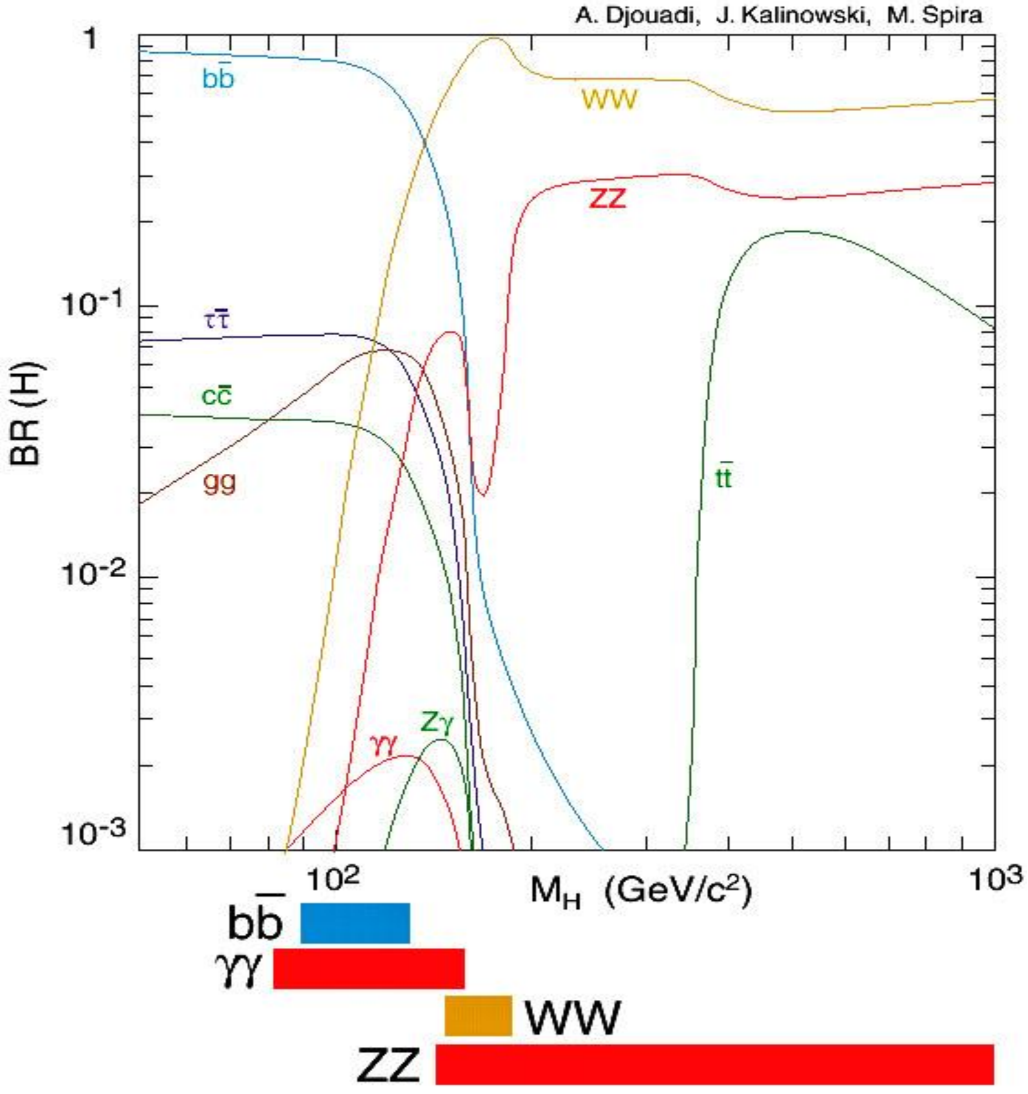
LHC - Higgs Production and Cross Section

four production mechanisms





LHC - Higgs Discovery Channels



Higgs coupling proportional to $m_{f,}$ therefore b-quark dominates until reach WW, ZZ thresholds

Large QCD backgrounds:

σ ($H \to bb$) $\approx$ 20 pb
(for M_H =120 GeV)

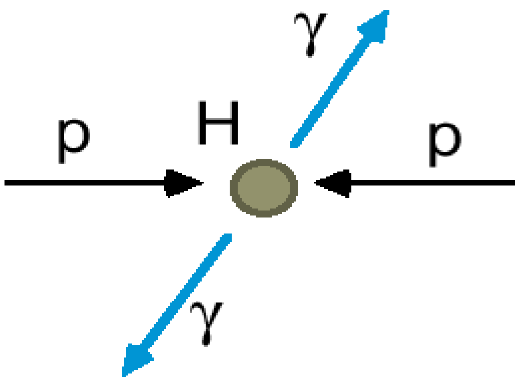
σ (bb) $\approx$ 500 mb

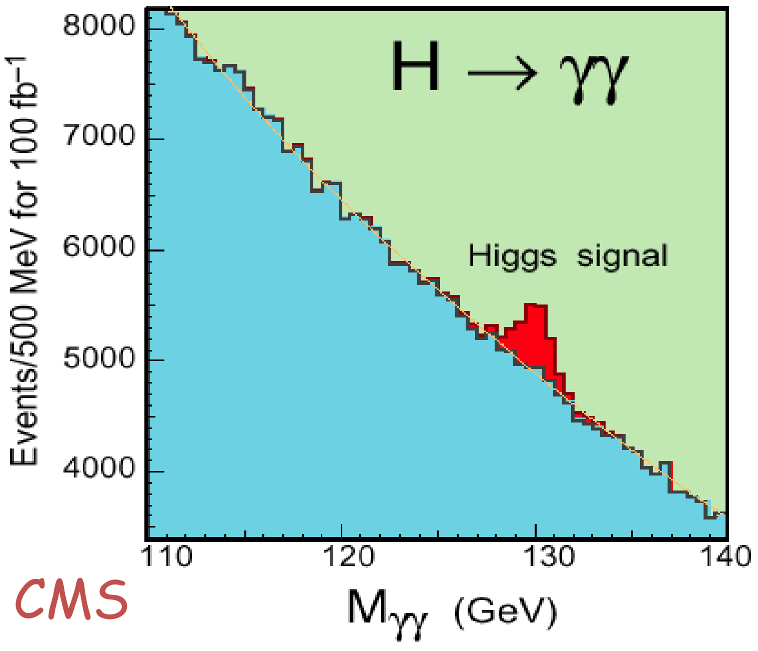
Search for ℓ, γ final states

LHC: Low mass Higgs: $H \to \gamma\gamma$

$M_H < 150$ GeV/c^2

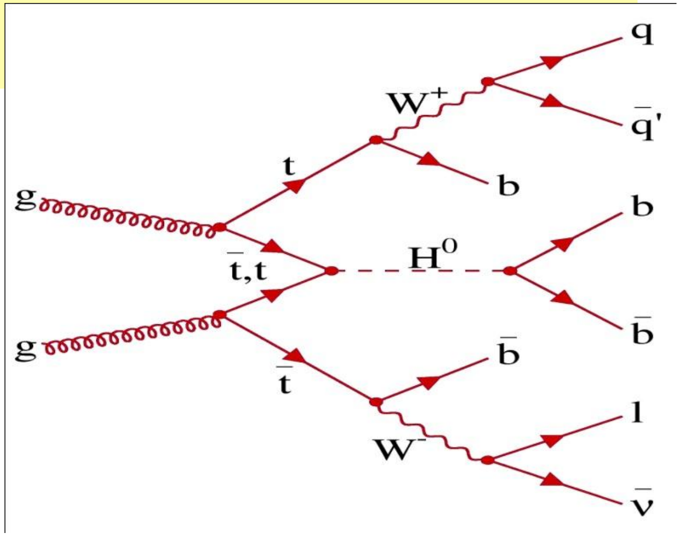
- Rare decay channel: BR~10^{-3}
- Requires excellent electromagnetic calorimeter performance
  - acceptance, energy and angle resolution,
  - γ/jet and γ/π^0 separation
  - Motivation for LAr/$PbWO_4$ calorimeters for CMS
- Resolution at 100 GeV: $\sigma \approx 1$ GeV
- Background large: S/B ≈ 1:20, but can estimate from non signal areas



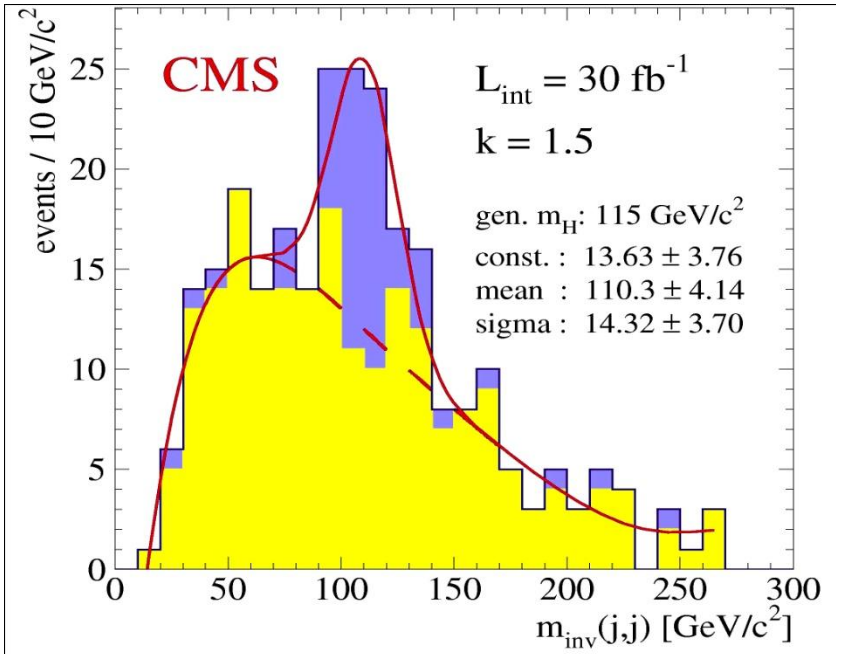


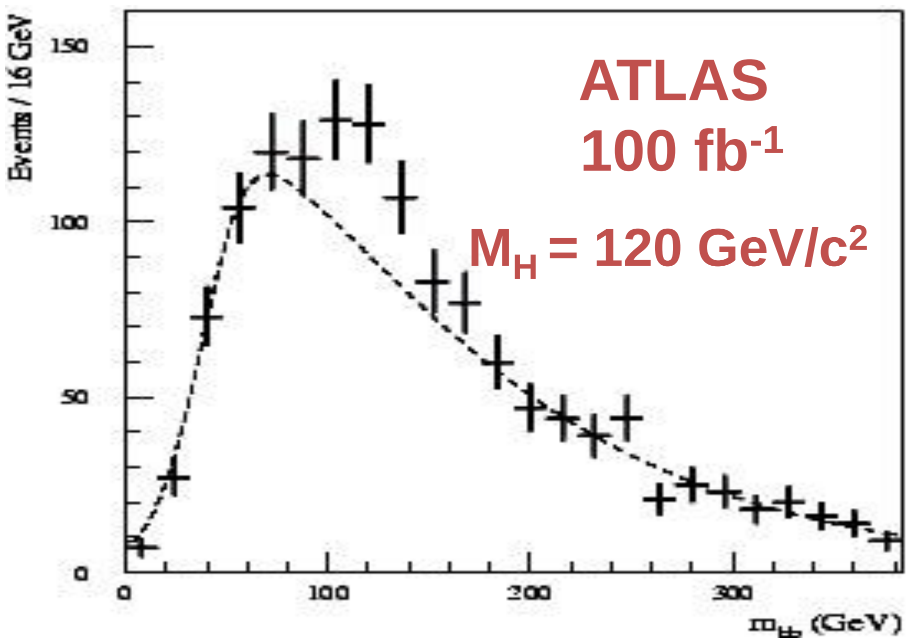
Low mass Higgs: *ttH* $\rightarrow$ *ttbb* channel

M_H < 130 GeV/c²



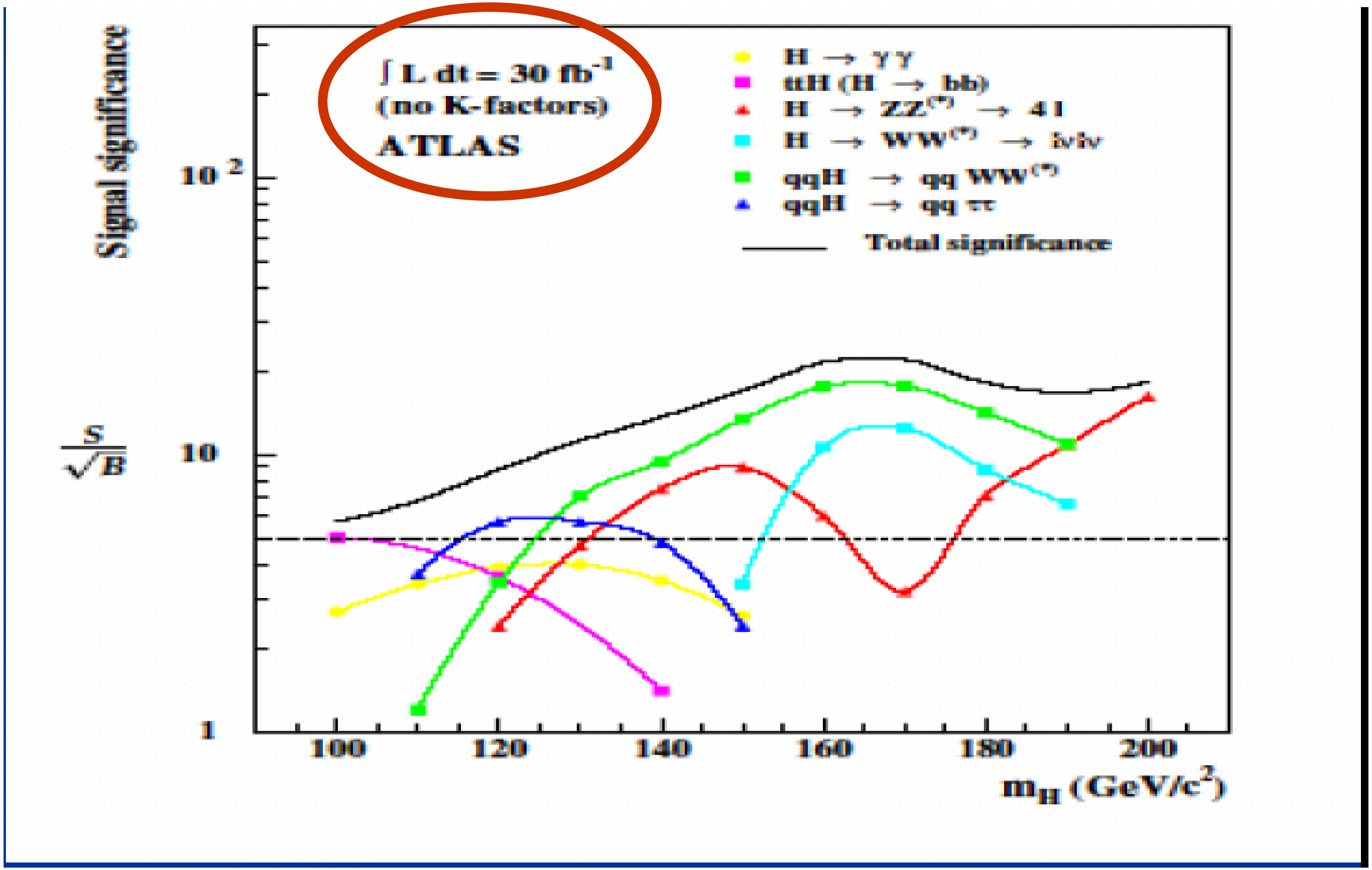
- **Trigger - one lepton + 4 b-jets + 2 jets**
- **Sophisticated background reduction**





LHC: Higgs Discovery

a few years away?

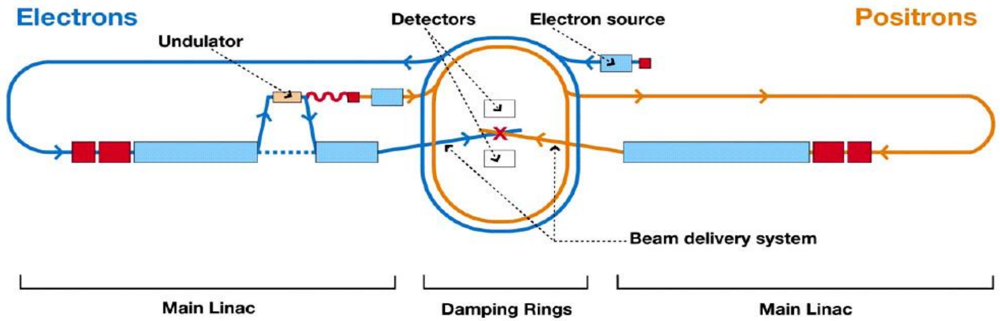


Why a TeV Scale e^+e^- Accelerator?

- Two parallel developments over the past few years (**the science** & the technology)
  - The precision information from LEP and other data have pointed to a low mass Higgs; Understanding electroweak symmetry breaking, whether supersymmetry or an alternative, will require precision measurements.
  - There are strong arguments for the complementarity between a ~0.5-1.0 TeV ILC and the LHC science.

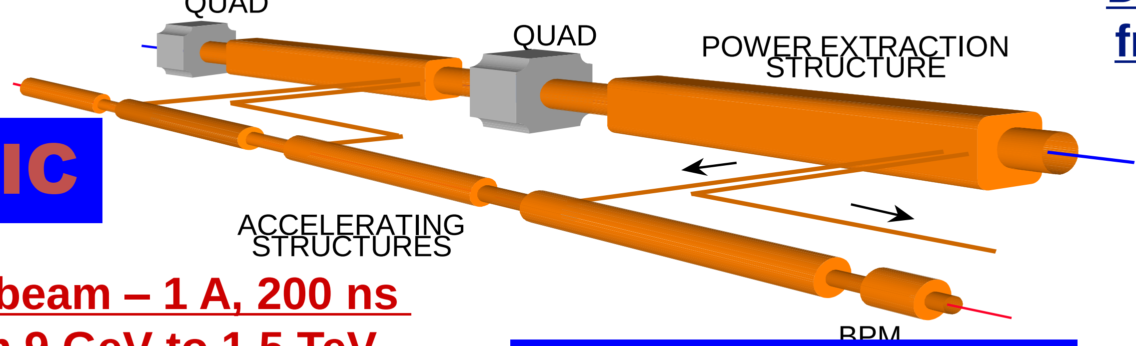
Possible TeV Scale Lepton Colliders

ILC



ILC < 1 TeV
Technically possible
~ 2019

CLIC

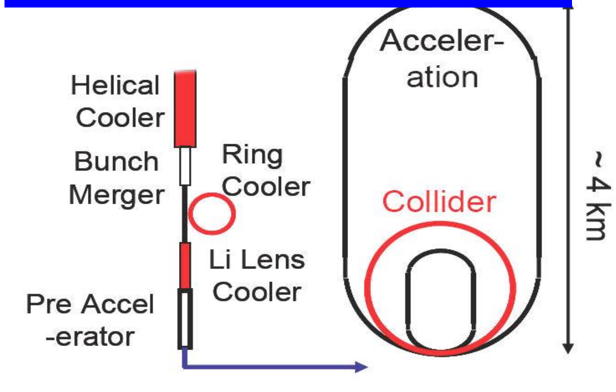


Drive beam - 95 A, 300 ns
from 2.4 GeV to 240 MeV

Main beam – 1 A, 200 ns
from 9 GeV to 1.5 TeV

CLIC < 3 TeV
Feasibility?
ILC + 5-10 yrs

Muon Collider



Much R&D Needed
- Neutrino Factory R&D +
- bunch merging
- much more cooling
- etc

Muon Collider
< 4 TeV
FEASIBILITY??
ILC + 15 yrs?

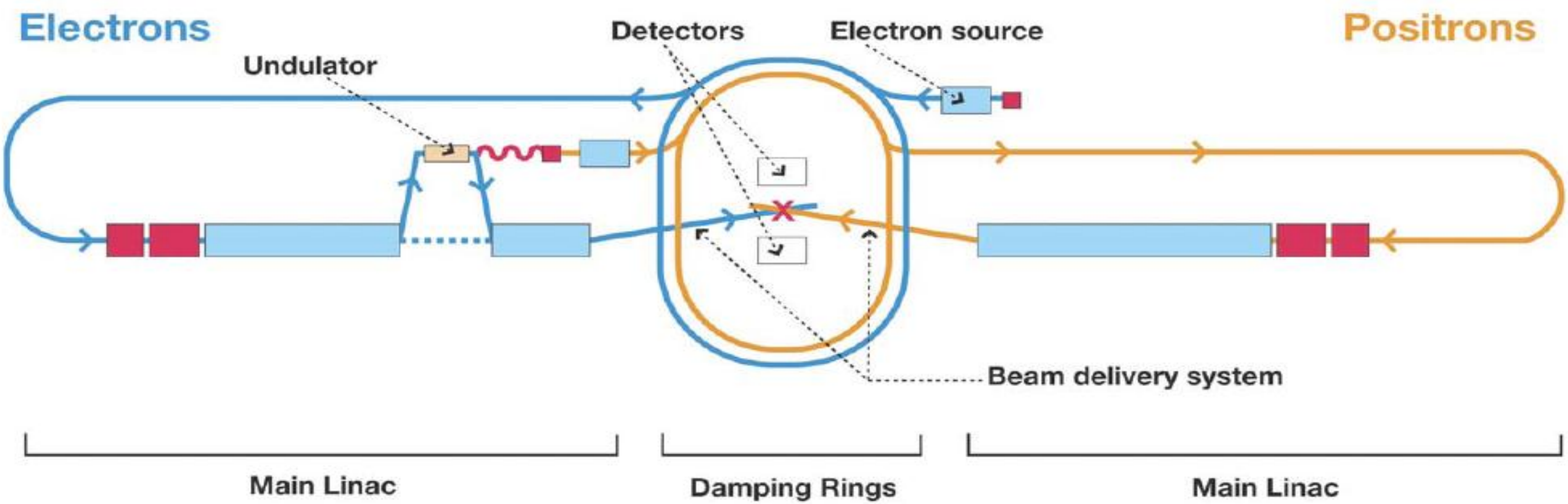
ILC- CLIC Collaboration

- CLIC – ILC Collaboration has two basic purposes:
  1. allow a more efficient use of resources, especially engineers
     - CFS / CES
     - Beamline components (magnets, instrumentation…)
  2. promote communication between the two project teams.
     - Comparative discussions and presentations will occur
     - Good understanding of each other's technical issues is necessary
     - Communication network – at several levels – supports it
- Seven working groups which are led by conveners from both projects

Collaboration Working Groups

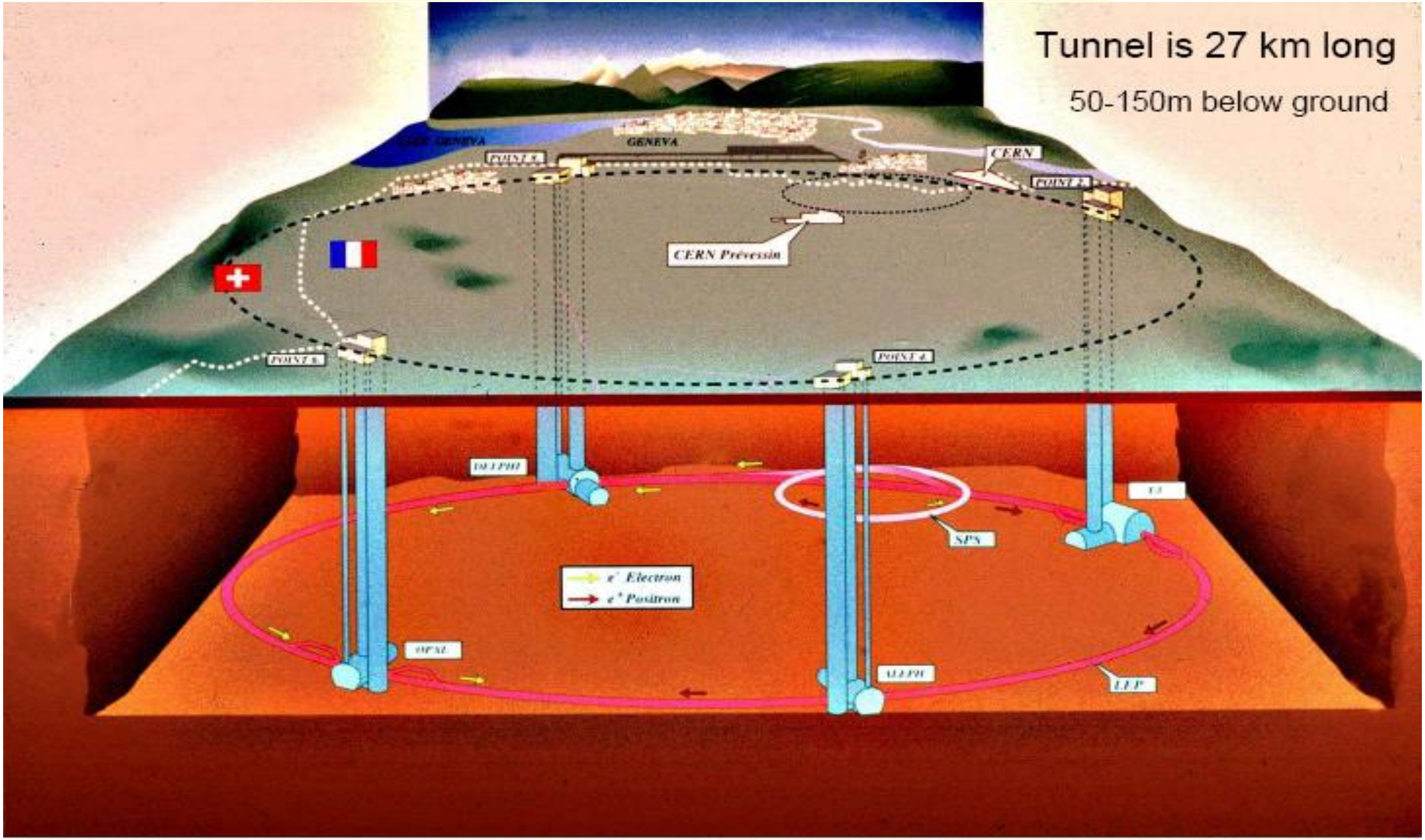
	CLIC	ILC
Physics & Detectors	**L.Linssen, D.Schlatter**	**F.Richard, S.Yamada**
Beam Delivery System (BDS) & Machine Detector Interface (MDI)	**L.Gatignon D.Schulte, R.Tomas Garcia**	**B.Parker, A.Seriy**
Civil Engineering & Conventional Facilities	**C.Hauviller, J.Osborne.**	**J.Osborne, V.Kuchler**
Positron Generation	**L.Rinolfi**	**J.Clarke**

The ILC

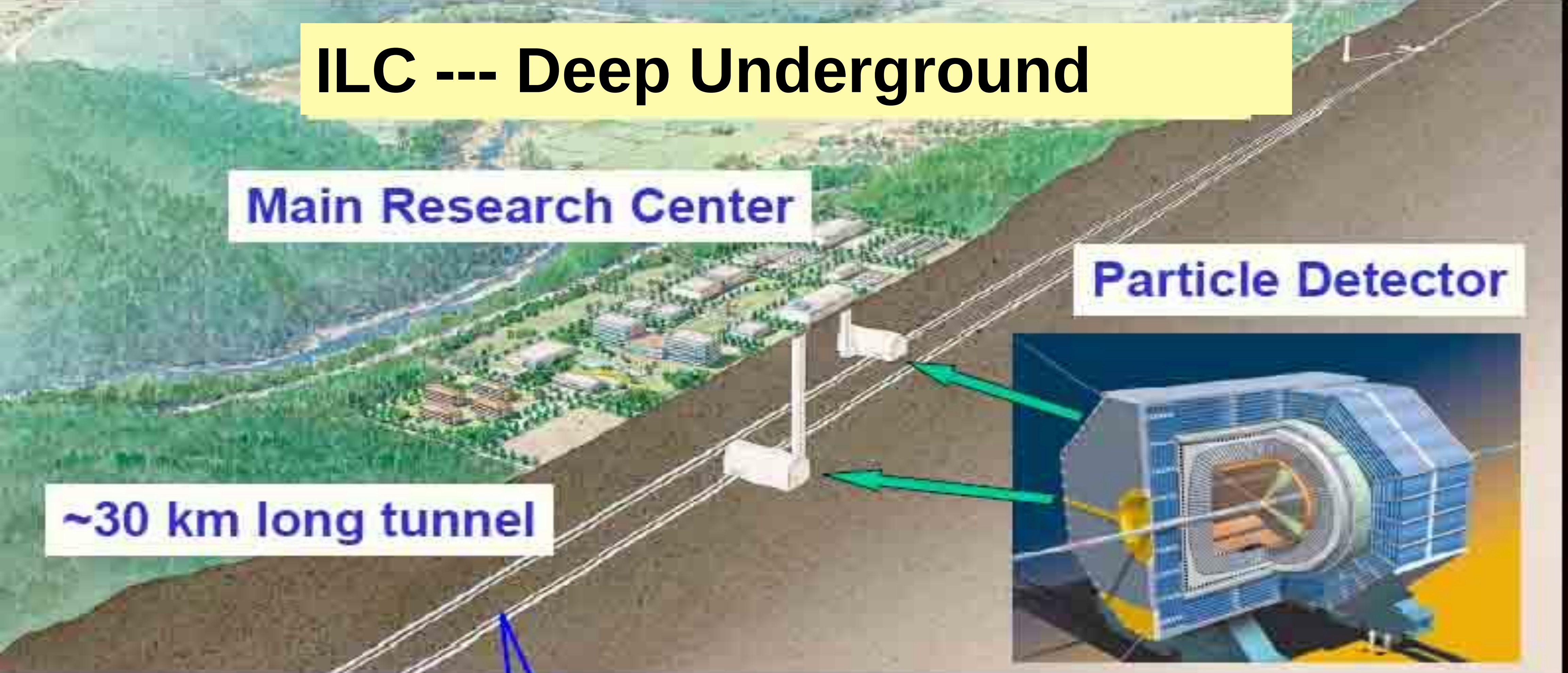


- Two linear accelerators, with tiny intense beams of electrons and positrons colliding head-on-head
- Total length ~ 30 km long (comparable scale to LHC)
- COM energy = 500 GeV, upgradeable to 1 TeV

LHC --- Deep Underground



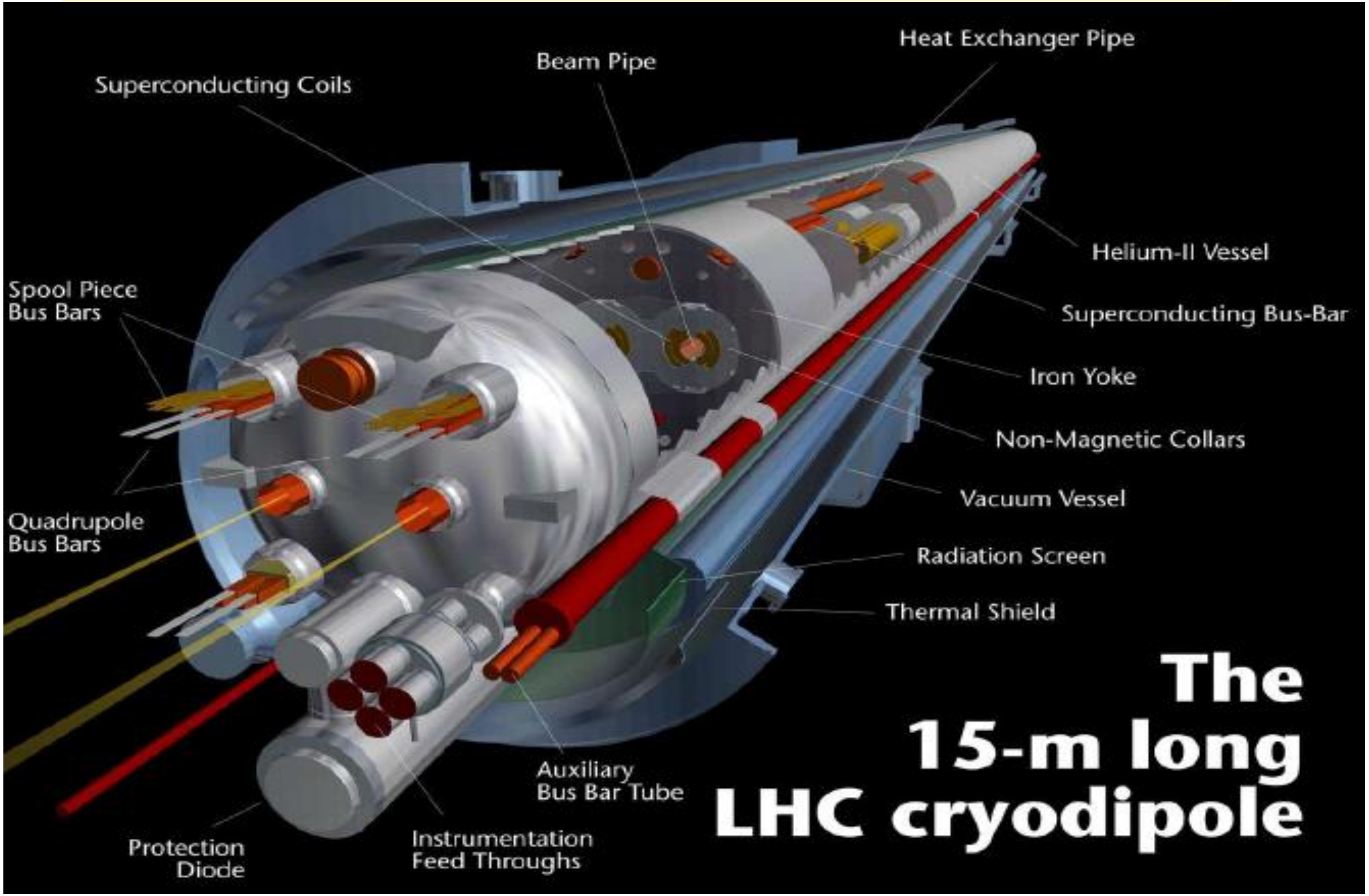
ILC --- Deep Underground



<u>Two tunnels</u>

- accelerator units
- other for services - RF power

LHC --- Superconducting Magnet



ILC - Superconducting RF Cryomodule

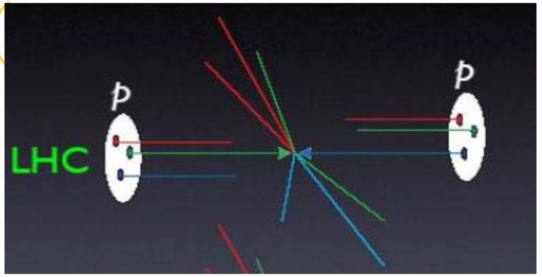
LHC --- Magnets Installed

Addressing the Questions

- Neutrinos
  - Particle physics and astrophysics using a weakly interacting probe

- Particle Astrophysics/Cosmology
  - Dark Matter; Cosmic Microwave, etc

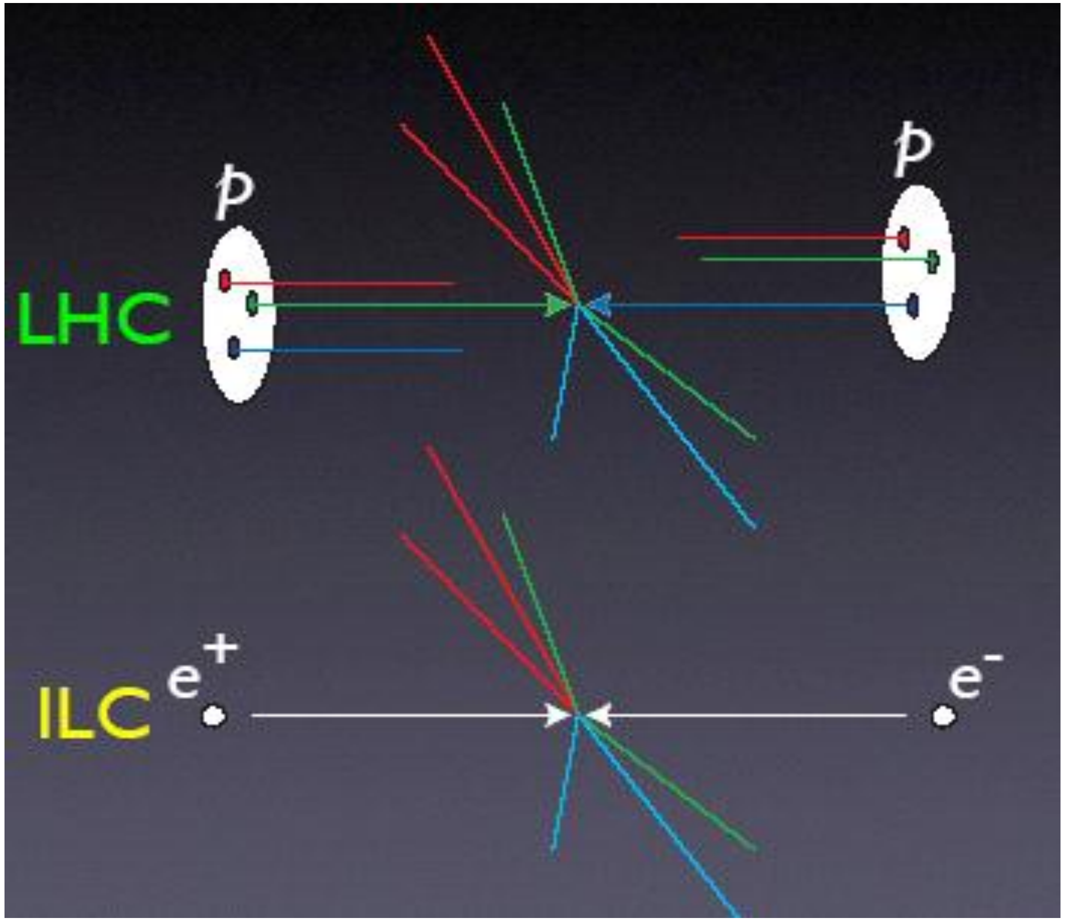
- High Energy pp Colliders
  - Opening up a new energy frontier (1 TeV scale)



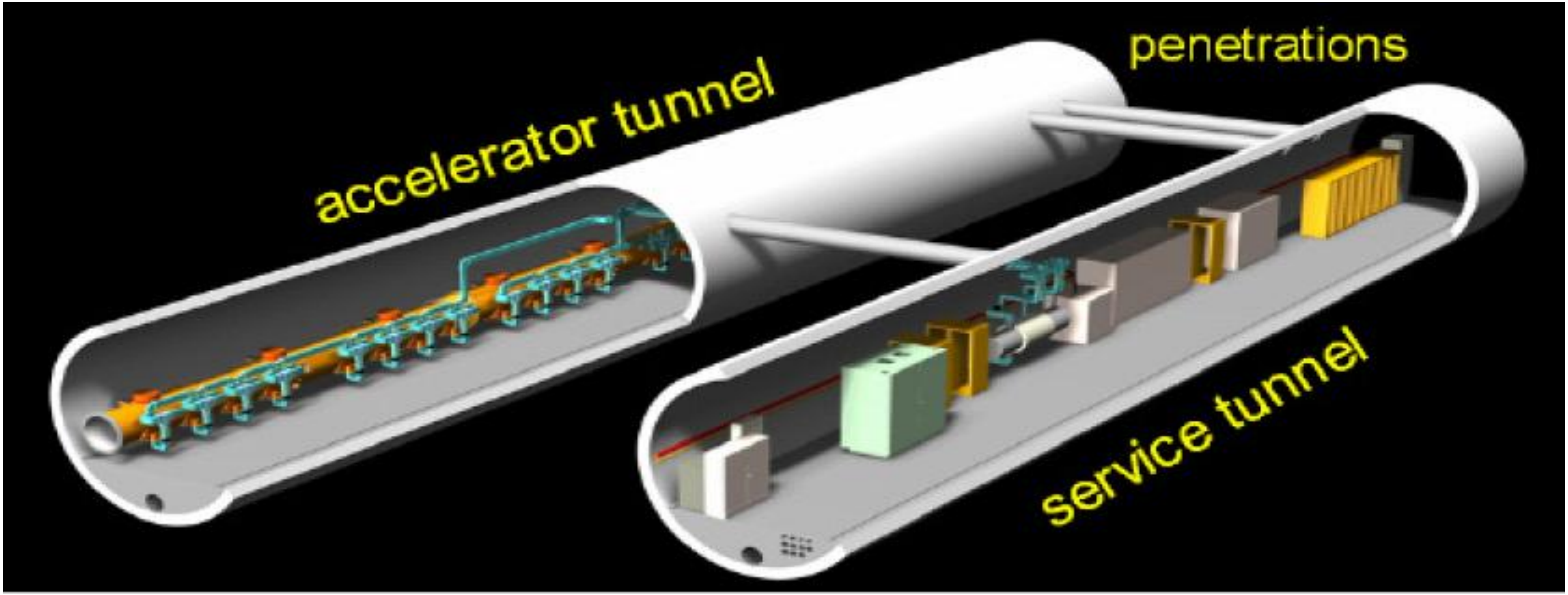
- High Energy e^+e^- Colliders
  - Precision Physics at the new energy frontier

What will e^+e^- Collisions Contribute?

- elementary particles
- well-defined
  - energy,
  - angular momentum
- uses full COM energy
- produces particles democratically
- can mostly fully reconstruct events



Main Linac Double Tunnel

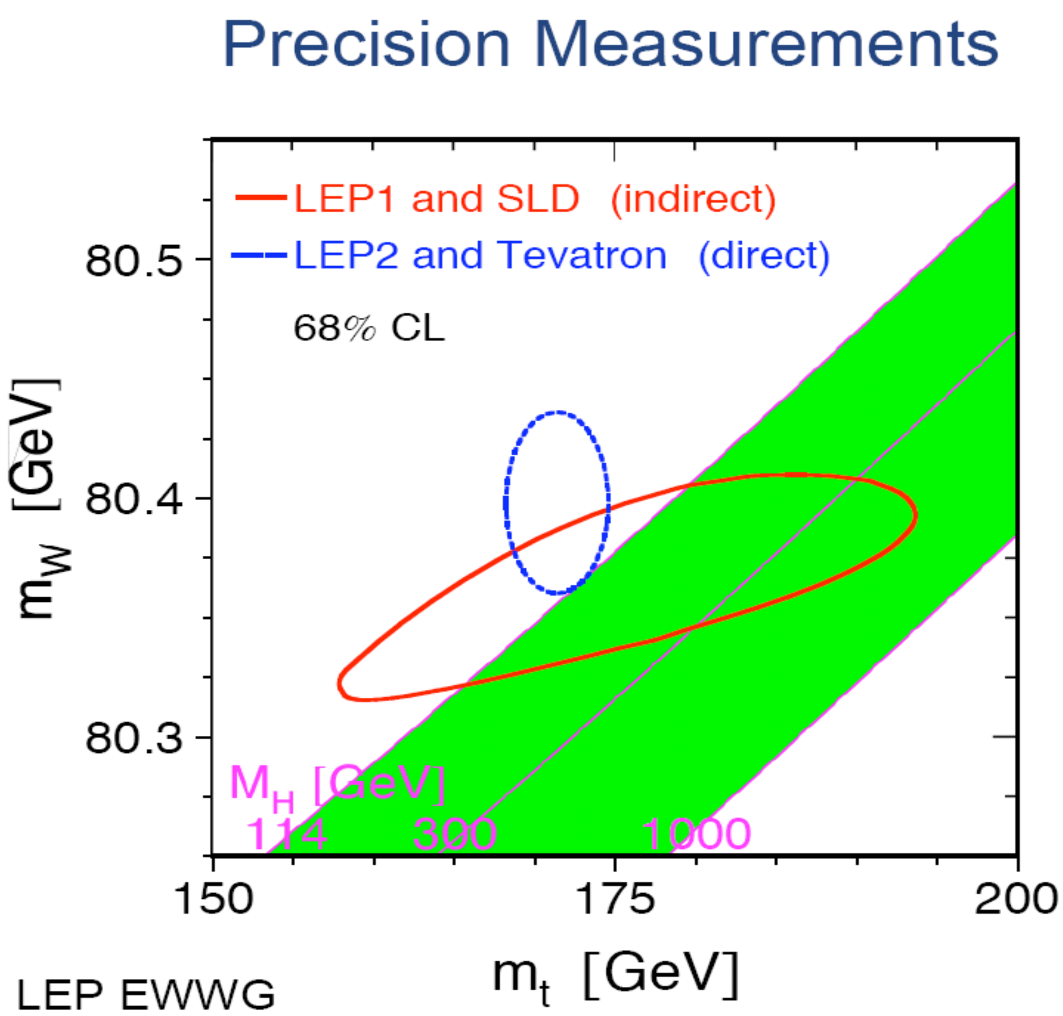


- Three RF/cable penetrations every rf unit
- Safety crossovers every 500 m
- 34 kV power distribution

Comparison: ILC and LHC

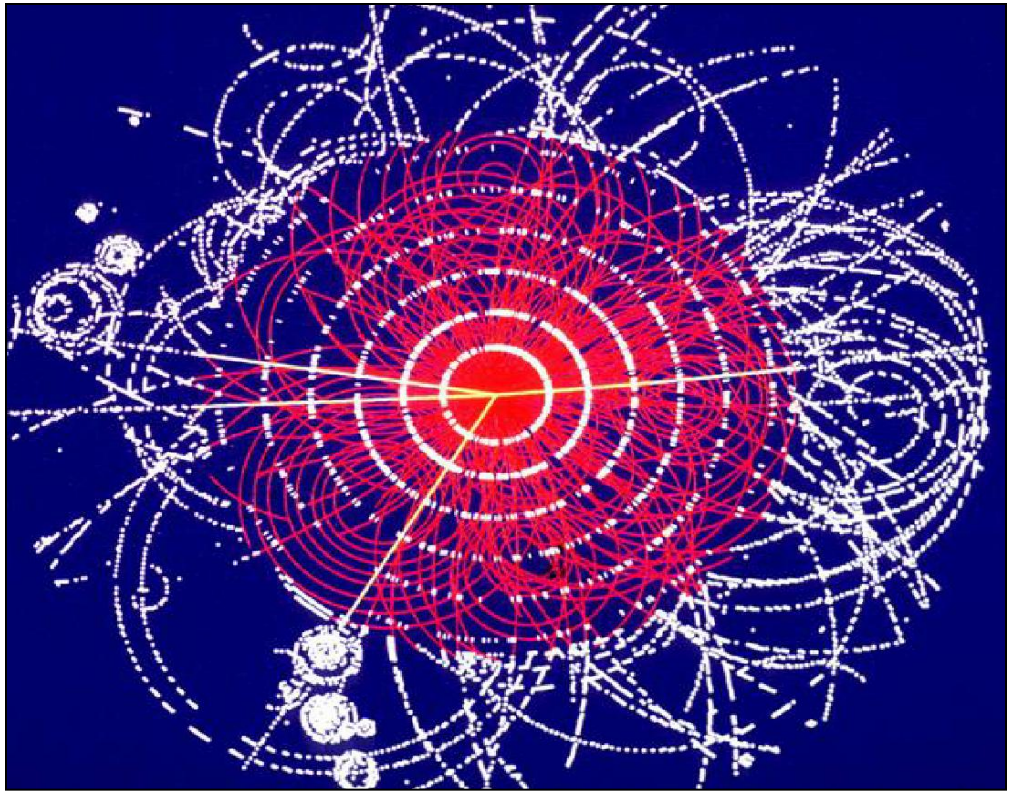
	ILC	LHC
Beam Particle :	Electron x Positron	Proton x Proton
CMS Energy :	0.5 – 1 TeV	14 TeV
Luminosity Goal :	2 x 10^{34} /cm^2/sec	1 x10^{34} /cm^2/sec
Accelerator Type :	Linear	Circular Storage Rings
Technology :	Supercond. RF	Supercond. Magnet

The Higgs and the ILC

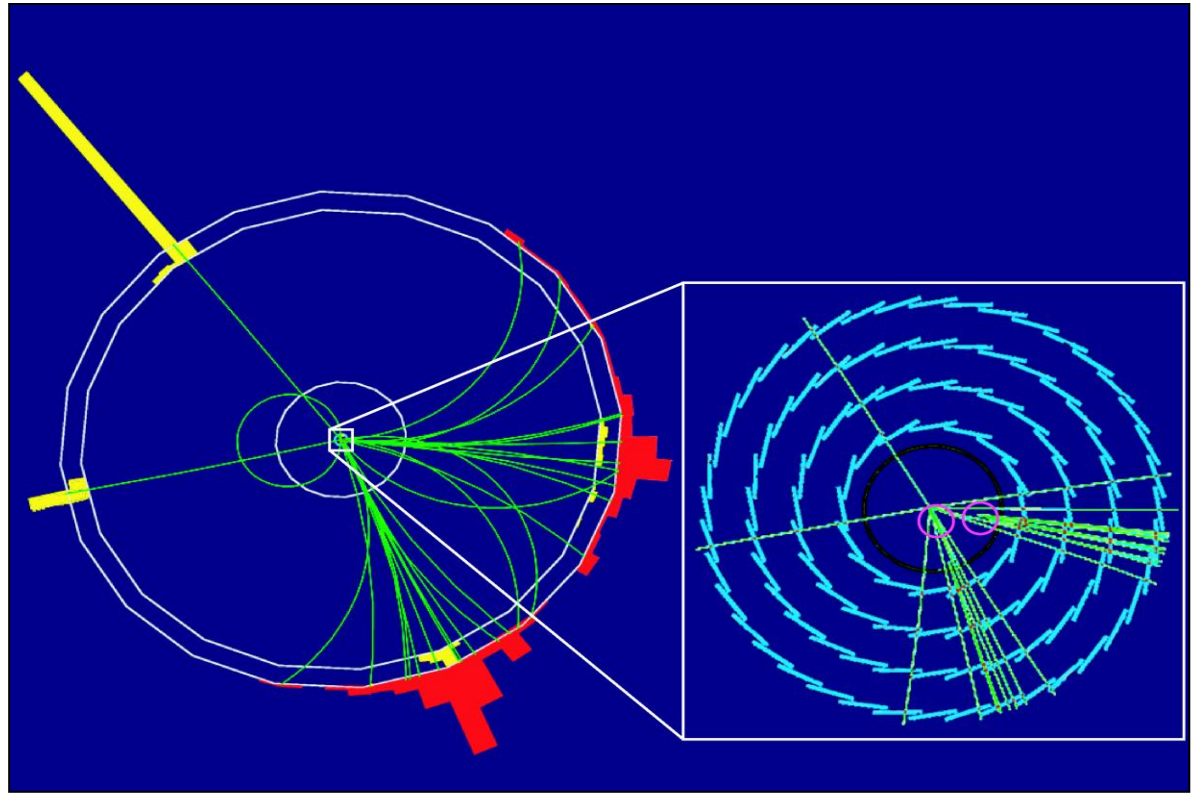


- The Higgs discovery appears around the corner (at the LHC)
- The mass appears below 200 GeV, well within the range of a 500 GeV linear collider
- Is the Higgs the Higgs? Are there more? Is it a variant?

Higgs event Simulation Comparison



LHC

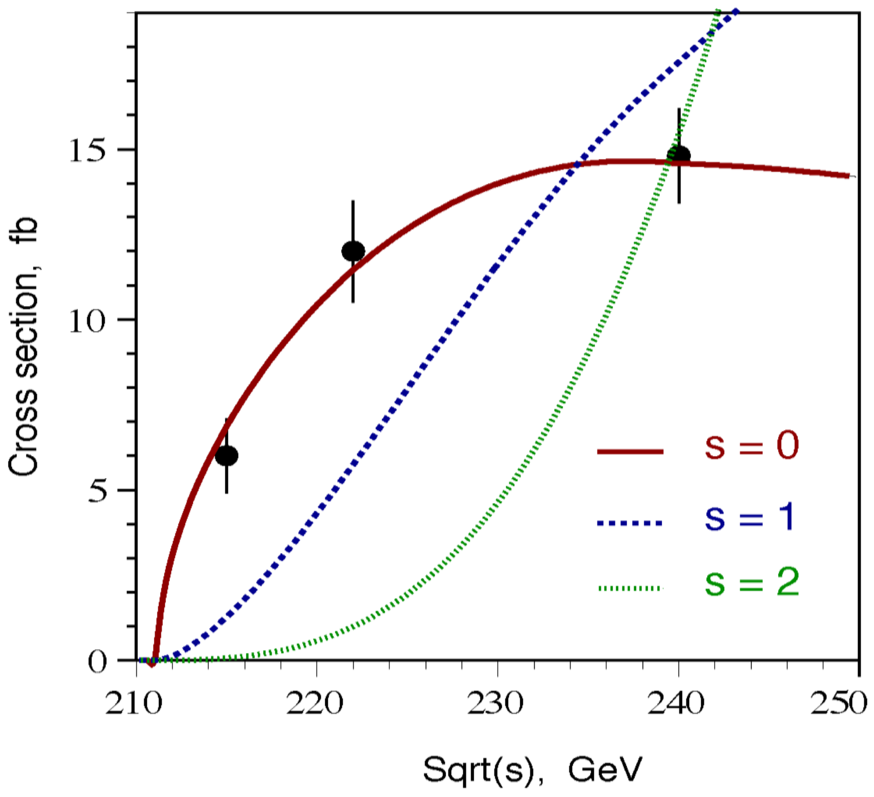


ILC

$e^+ e^- \rightarrow Z\,H$

$Z \rightarrow e^+ e^-$, $H \rightarrow b$ …

ILC: Is it really the Higgs ?



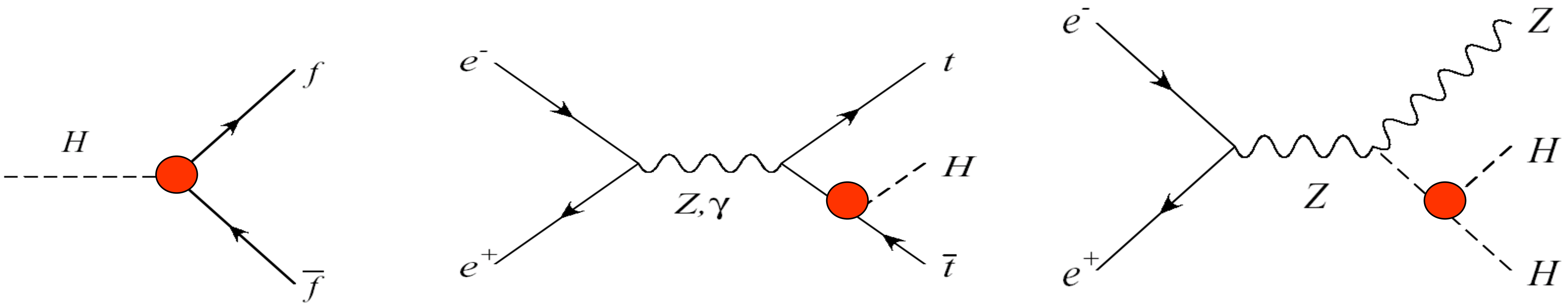
Measure the quantum numbers. The Higgs must have spin zero !

The linear collider will measure the spin of any Higgs it can produce by measuring the energy dependence from threshold

Remember - the Higgs is a Different!

- It is a zero spin particle that fills the vacuum

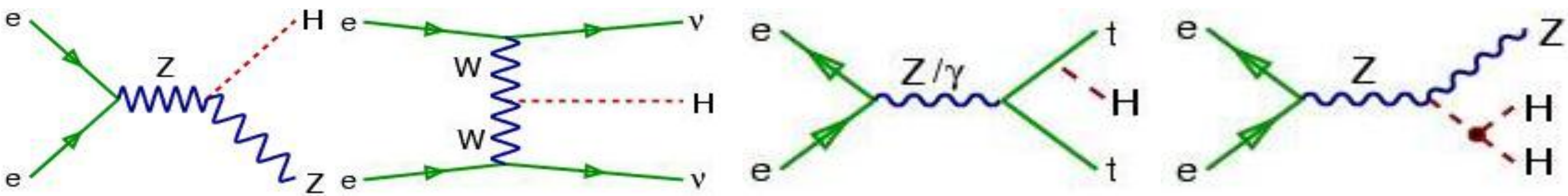
- It couples to mass; masses and decay rates are related

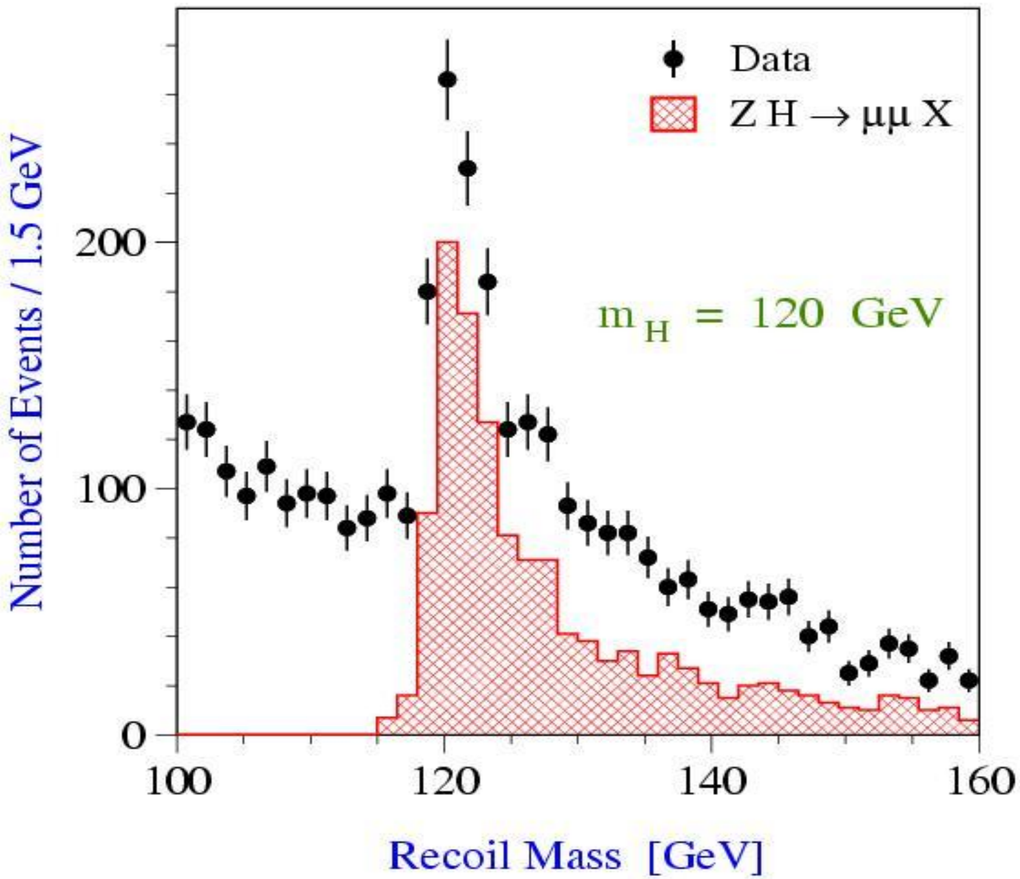


Higgs Coupling-mass relation

$$\mathrm{m_i} = \mathrm{v} \times \kappa_{\mathrm{i}}$$

Precision Higgs physics

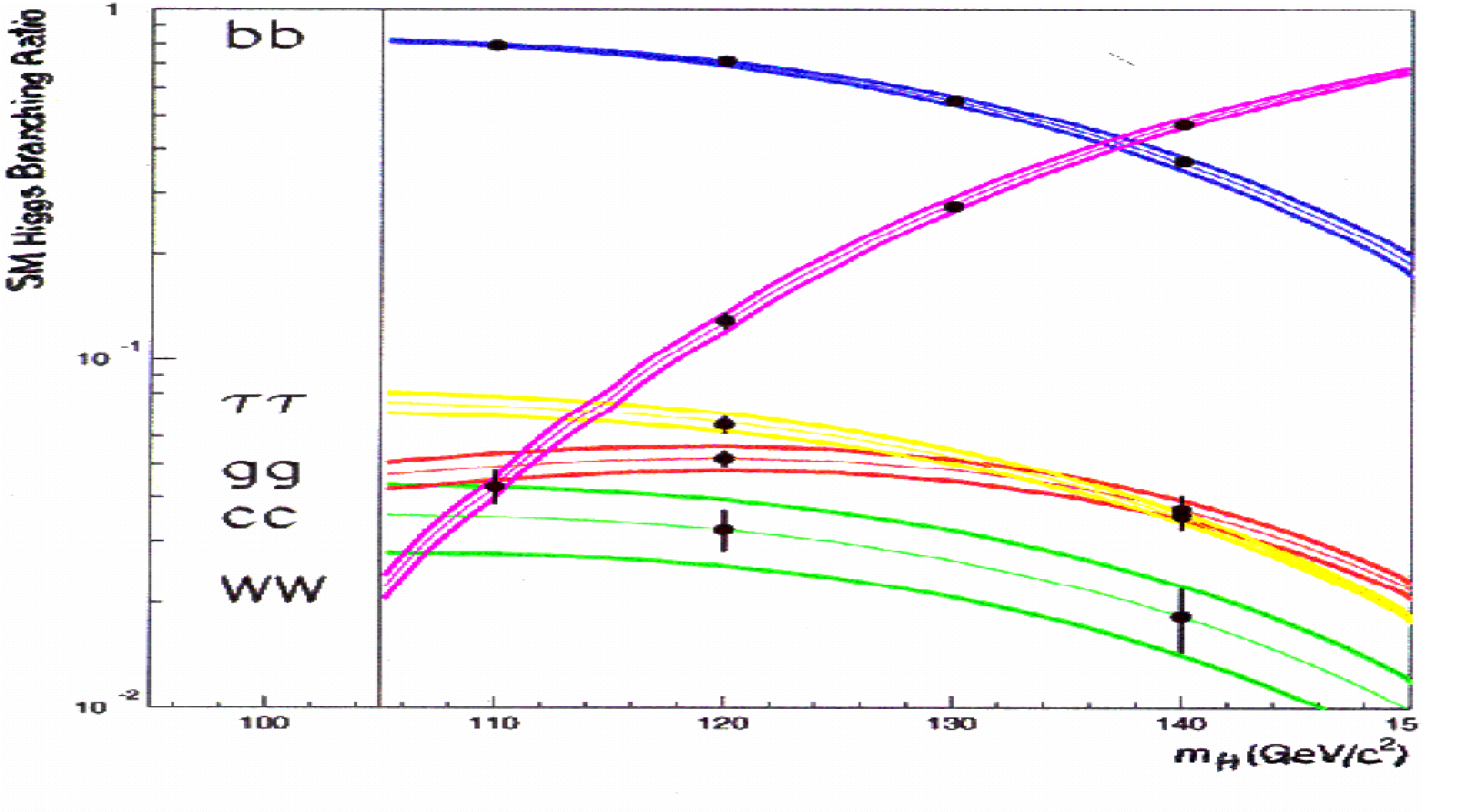




Garcia-Abia et al

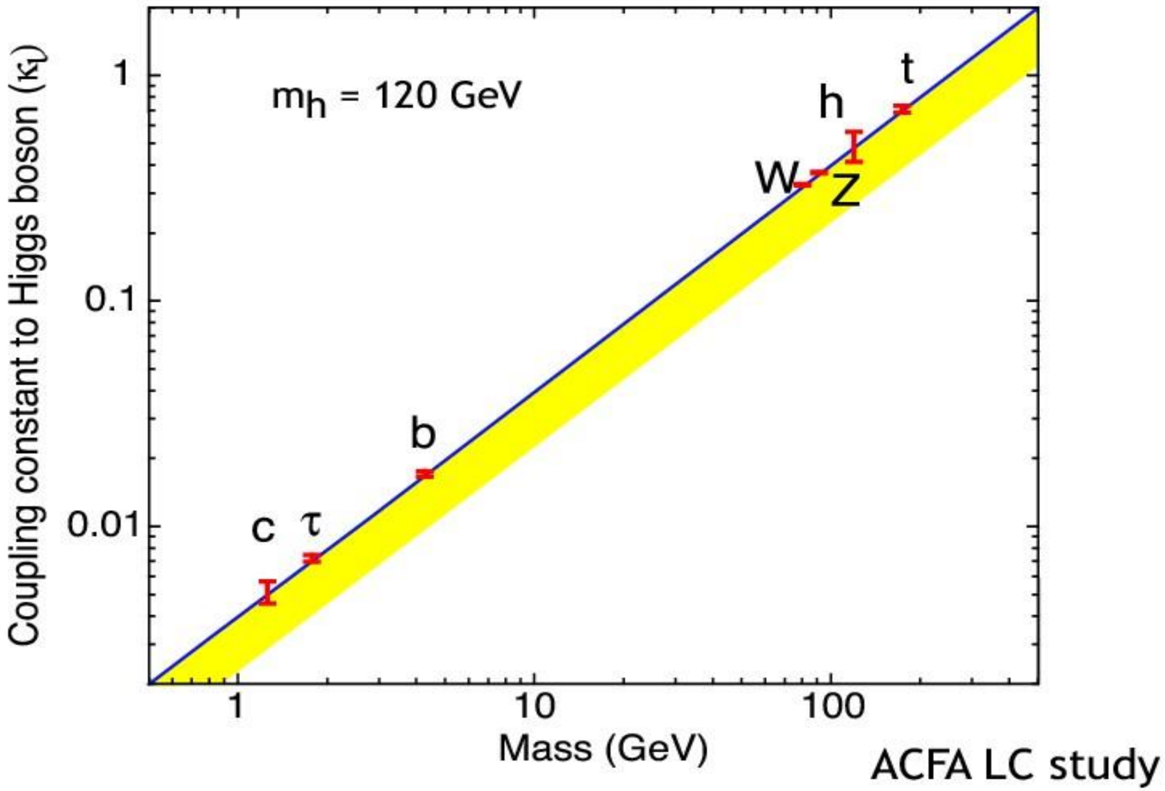
- **Model-independent Studies**
  - mass
  - absolute branching ratios
  - total width
  - spin
  - top Yukawa coupling
  - self coupling
- **Precision Measurements**

Higgs Branching Ratios



What can we learn from the Higgs?

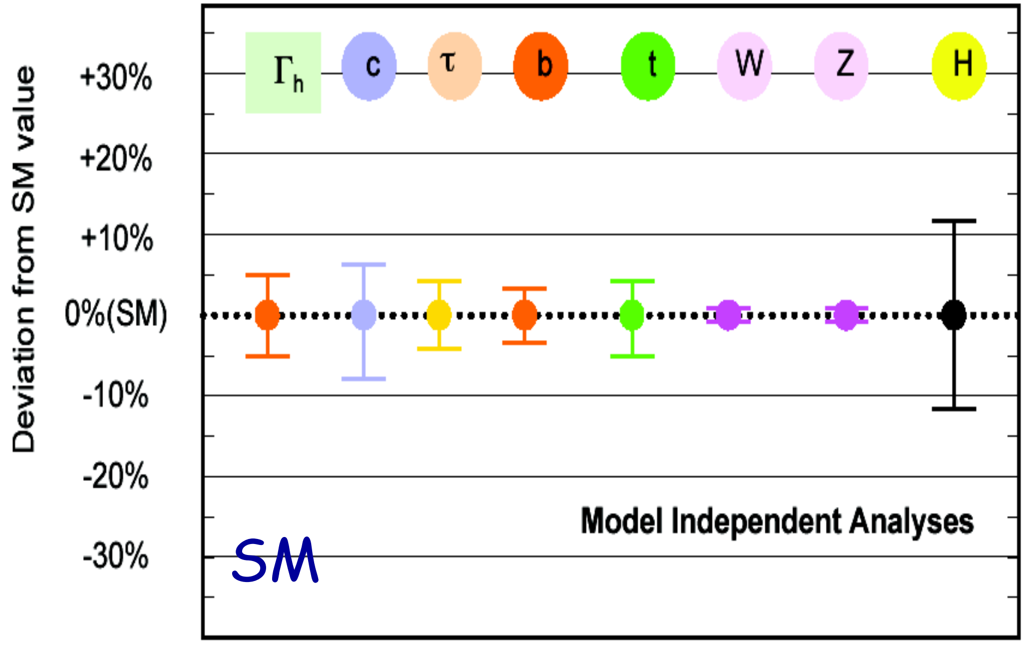
Precision measurements of Higgs coupling



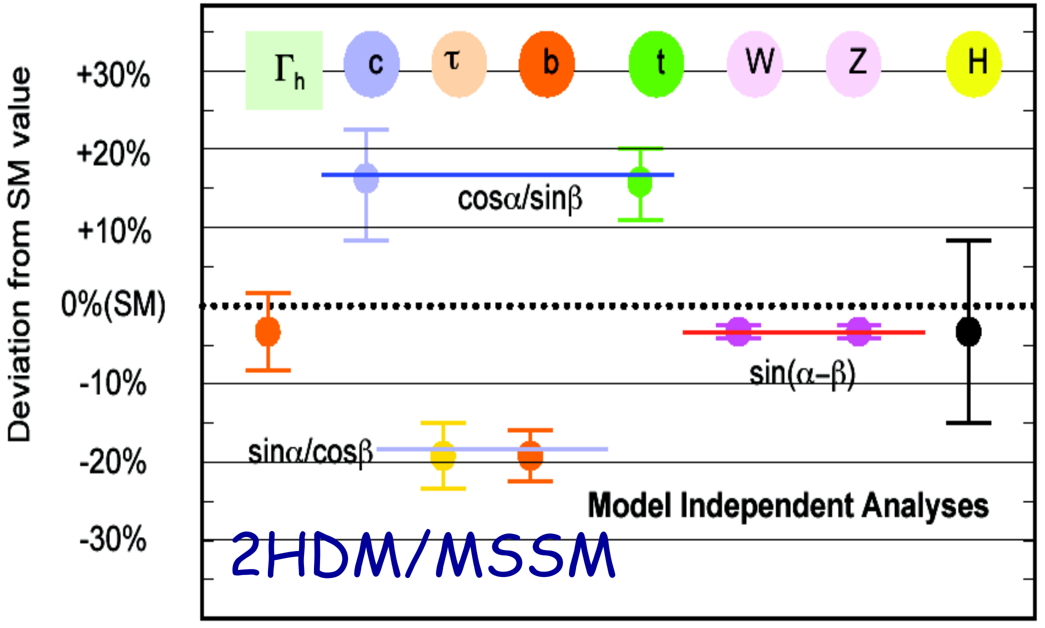
Higgs Coupling strength is proportional to Mass

e^+e^- : Studying the Higgs

determine the underlying model

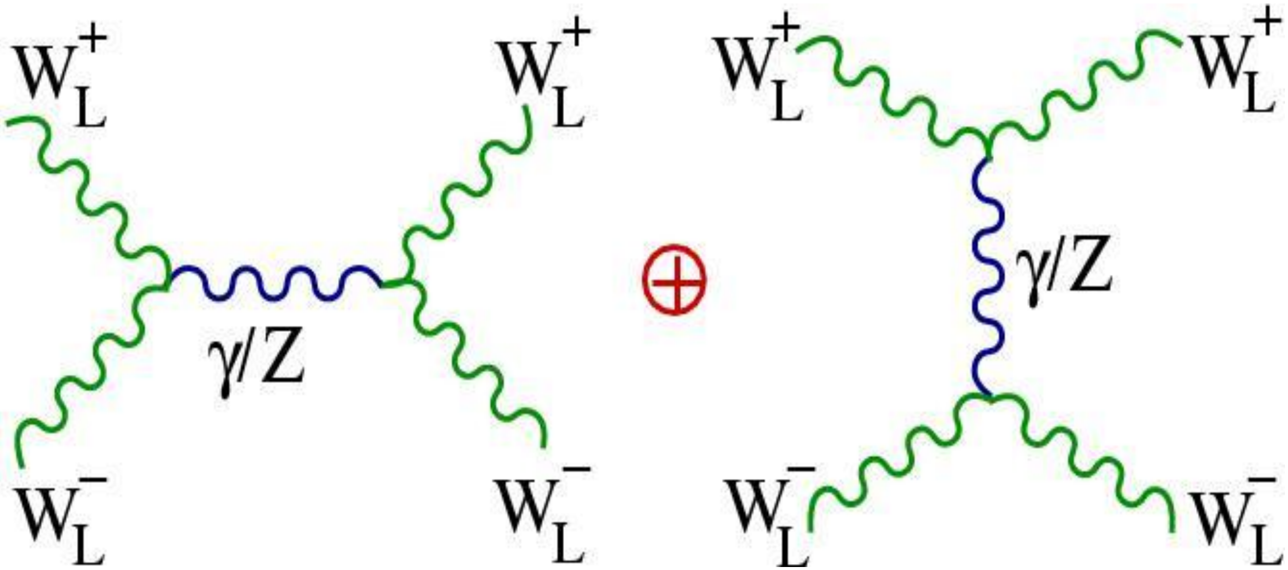


Yamashita et al



Zivkovic et al

If the Higgs is not found?



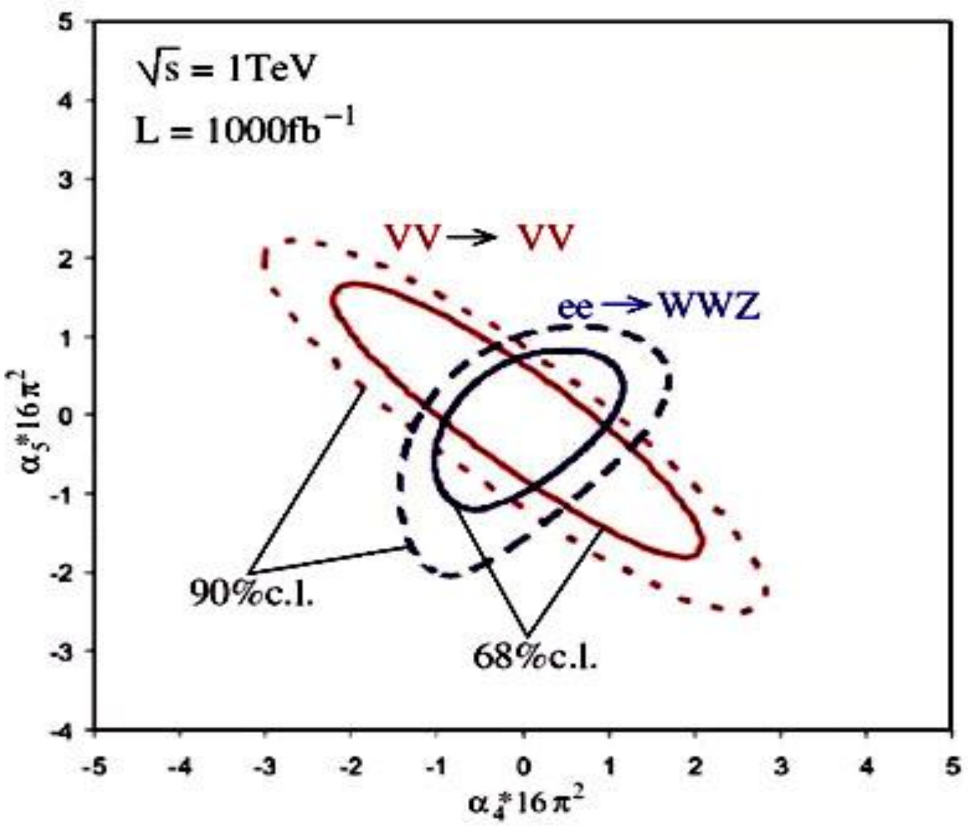
Cross section for WW scattering violates unitarity at ~1.2 TeV, unless there are new resonances

ILC has sensitivity into multi-TeV region

Krstonosic et al.

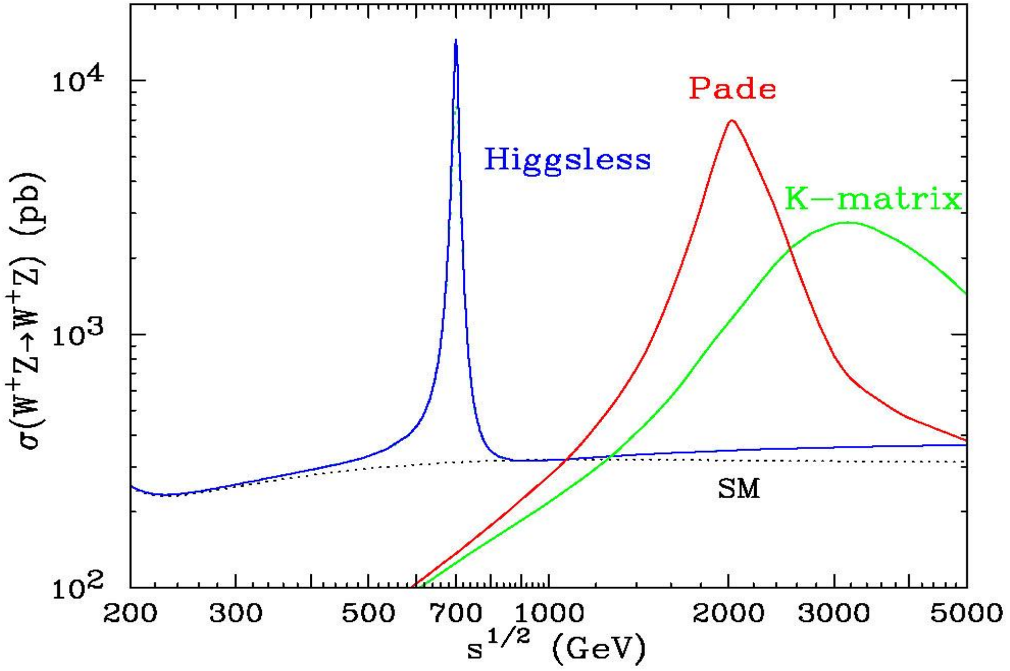
Higgs not found

Effective Lagrangian
Strong EWSB:



Krstonosic et al.

New resonance in WZ→WZ



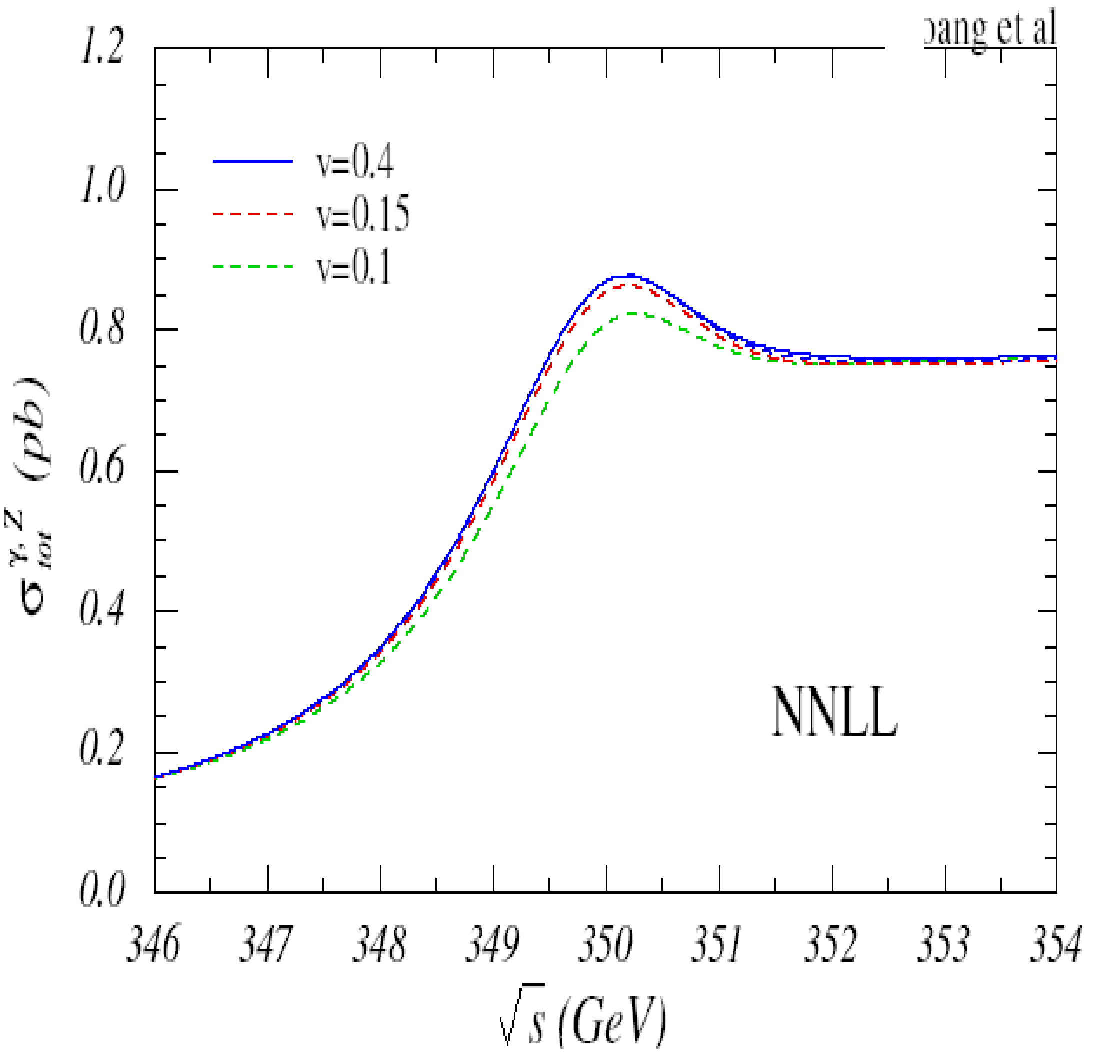
Birkedal et al.

Coupling structure can be determined at ILC if resonance seen by LHC

Top Quark Measurements

Threshold scan provides mass measurement

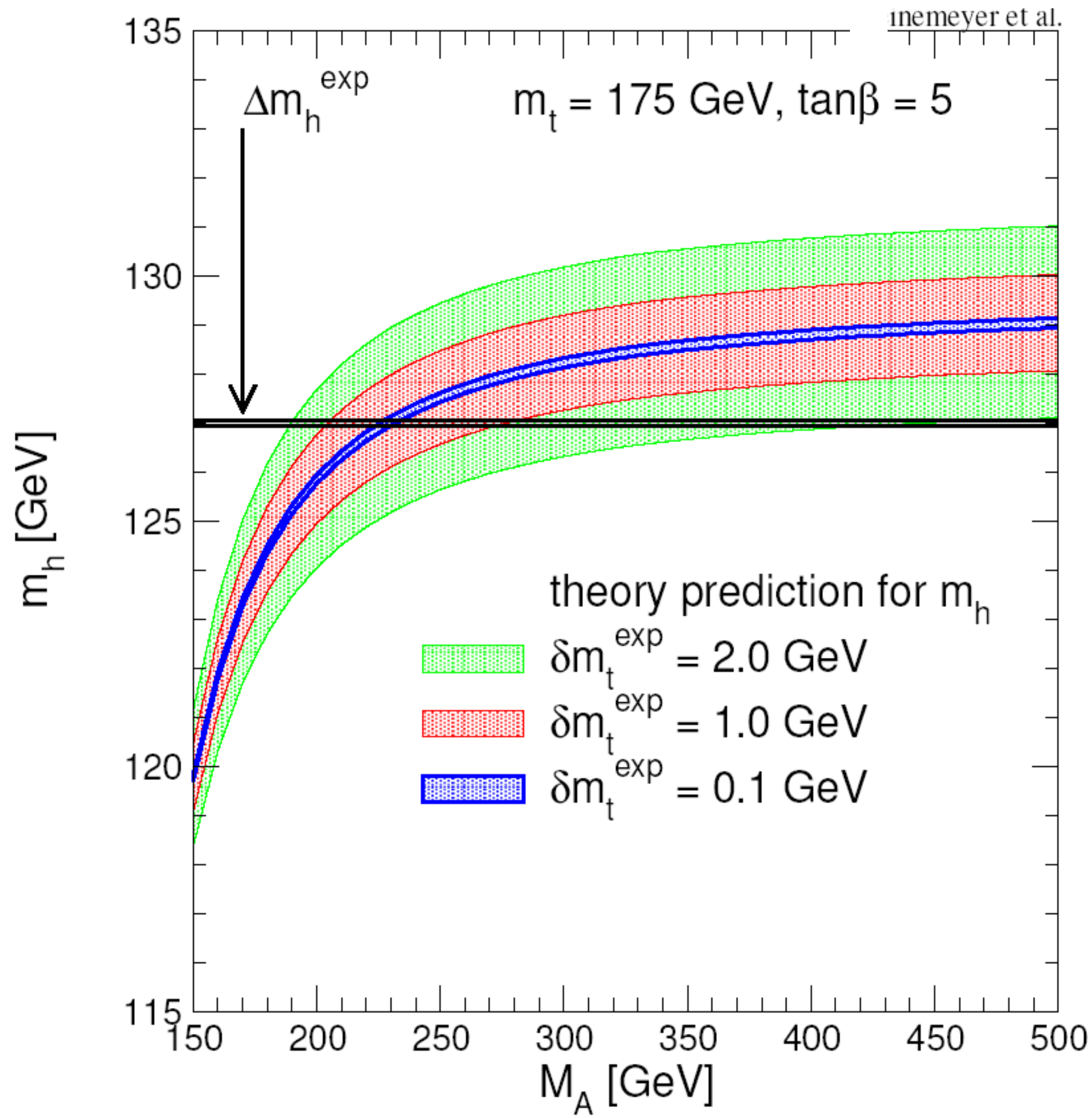
Theory (NNLL) controls m_t(MS) to 100 MeV



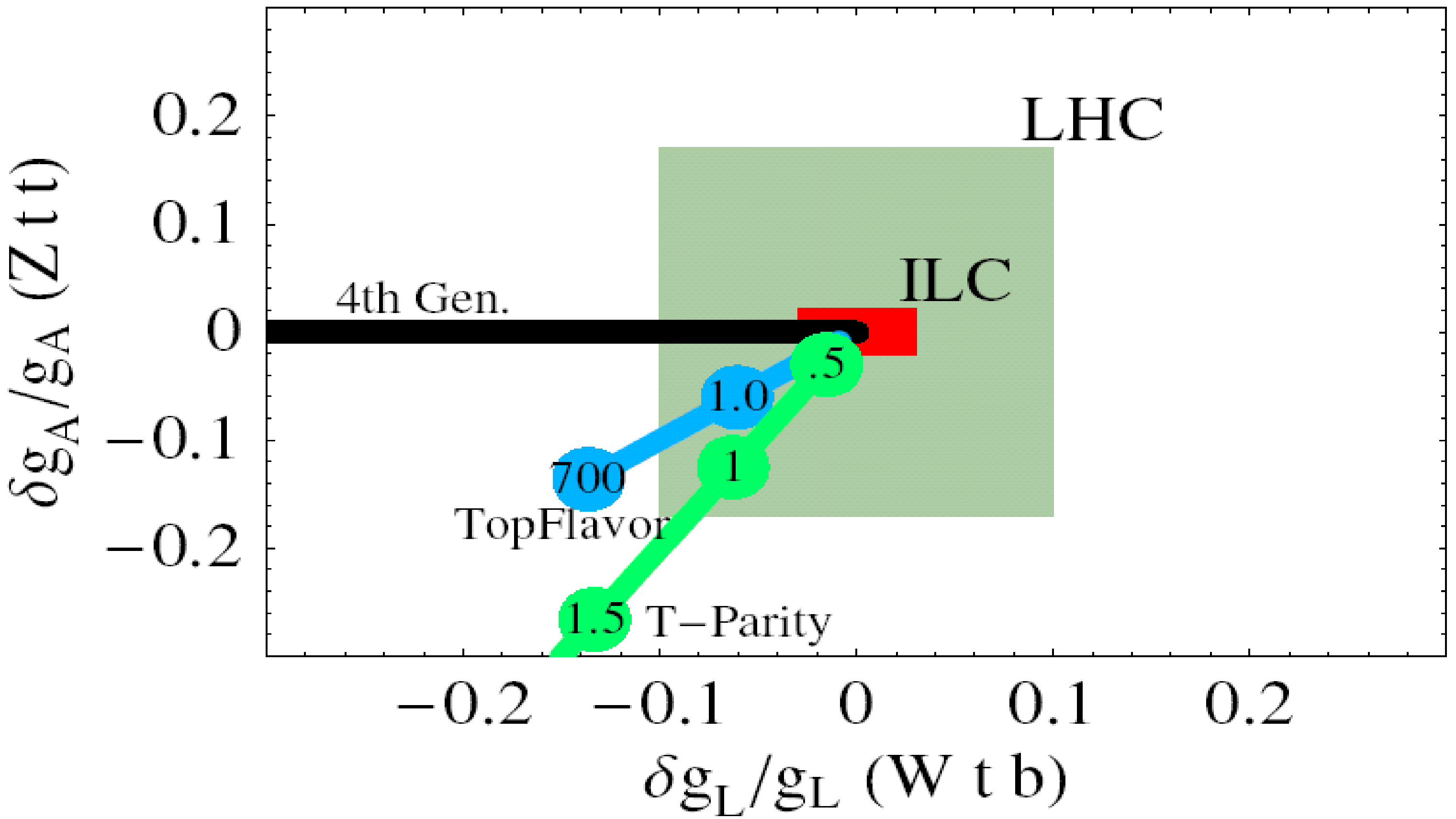
Top Quark Measurements

Precision top mass

- Improved Standard Model fits
- MSSM (m_h prediction)
- ...

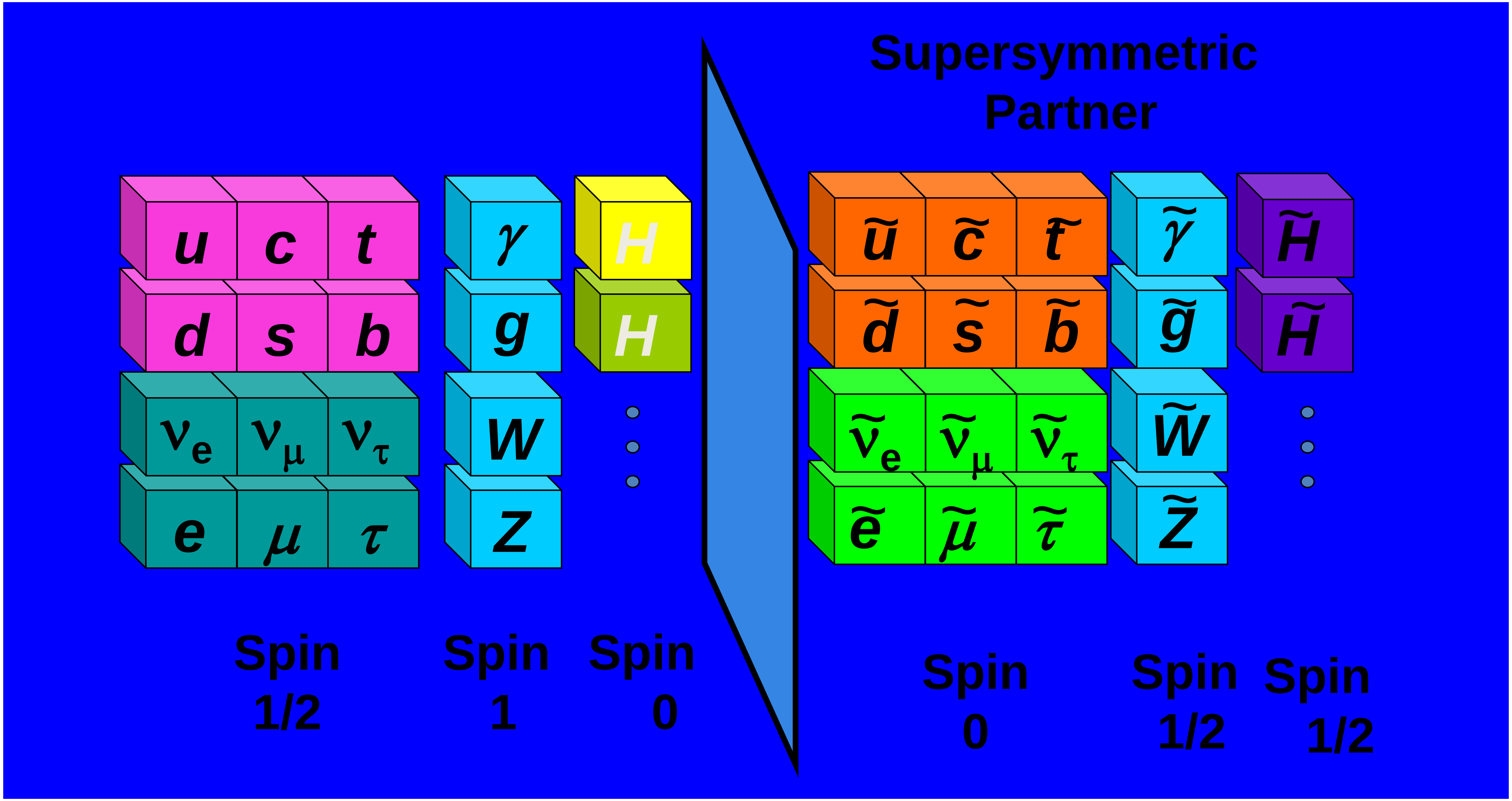


Top Quark Measurements



Bounds on axial ttbarZ and left handed tbW for LHC and ILC compared to deviations in various models

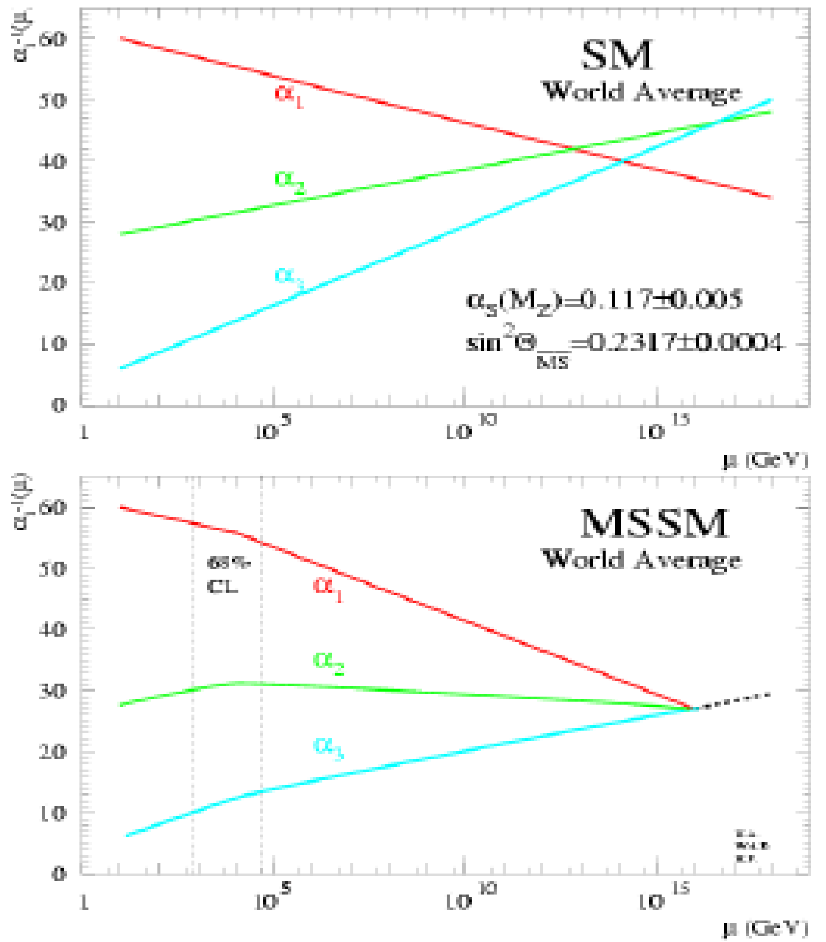
Supersymmetry



Is there a New Symmetry in Nature?

Bosons
Integer Spin: 0, 1,..

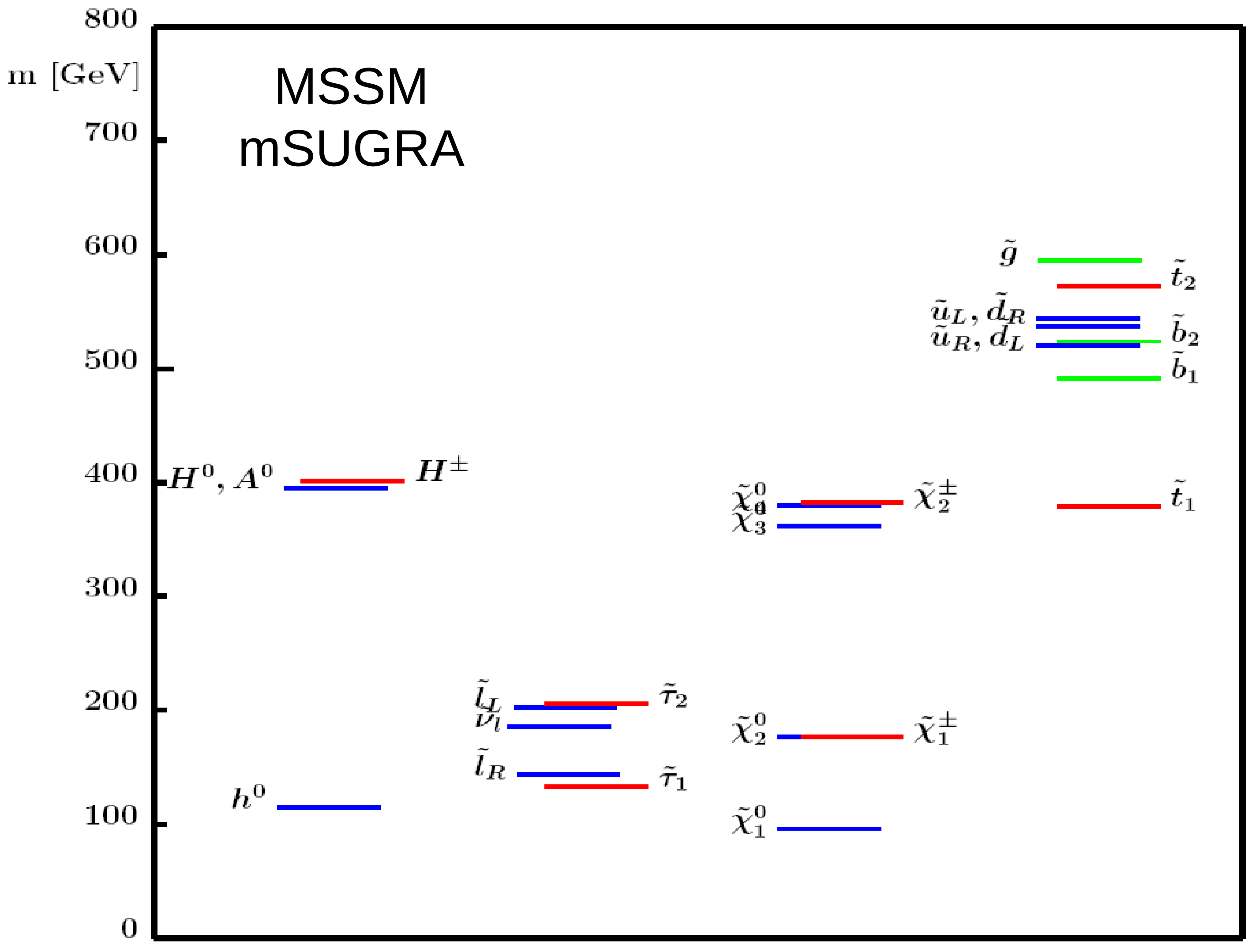
Fermions
Half integer Spin: 1/2, 3/2,..



The virtues of Super-symmetry:

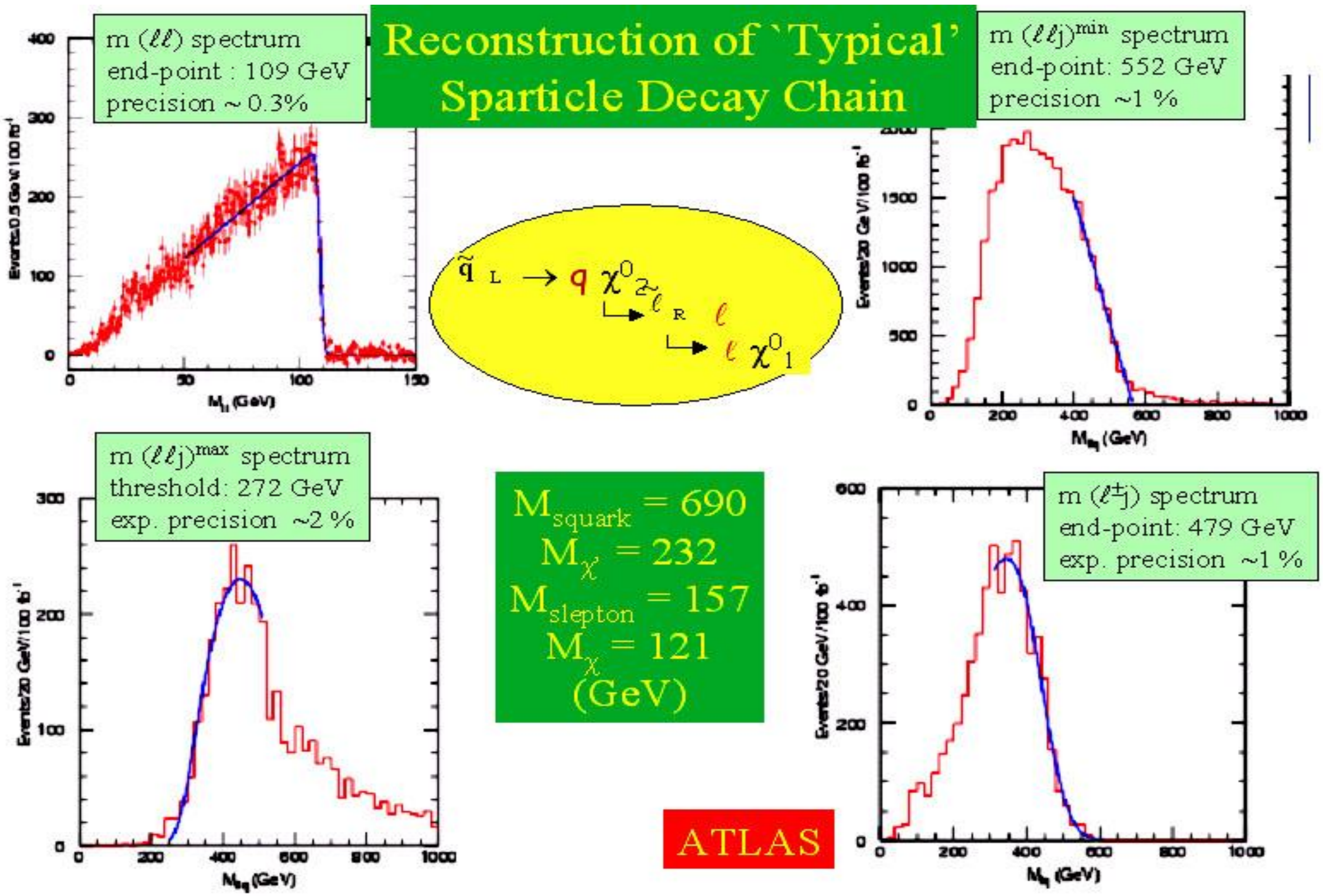
- **Unification of Forces**
- **The Hierarchy Problem**
- **Candidate for the Dark Matter**
  - **…**

Spectrum of Supersymmetric Particles

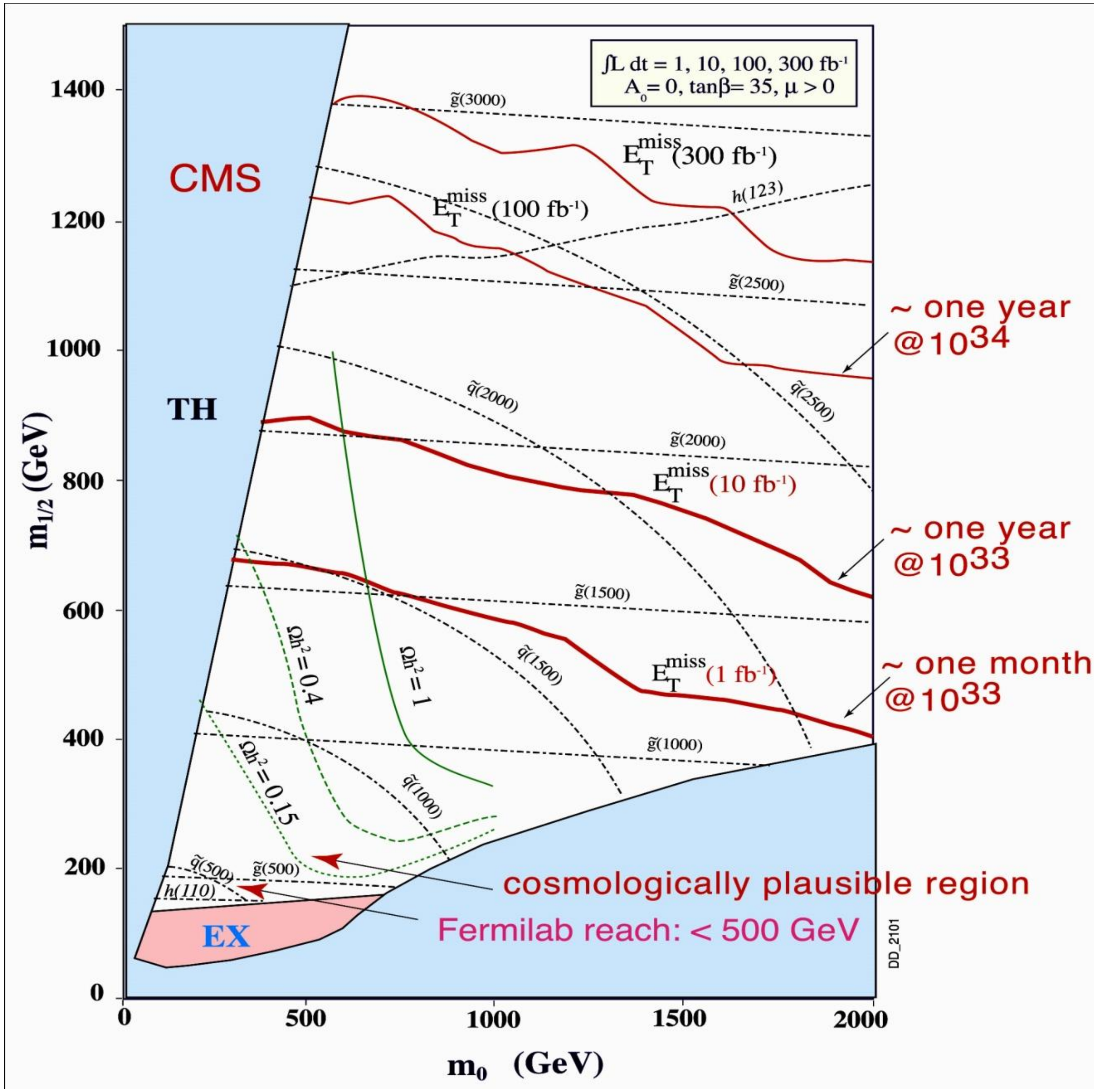


squarks and sgluons heavy yielding long decay chains ending with LSP neutrilino

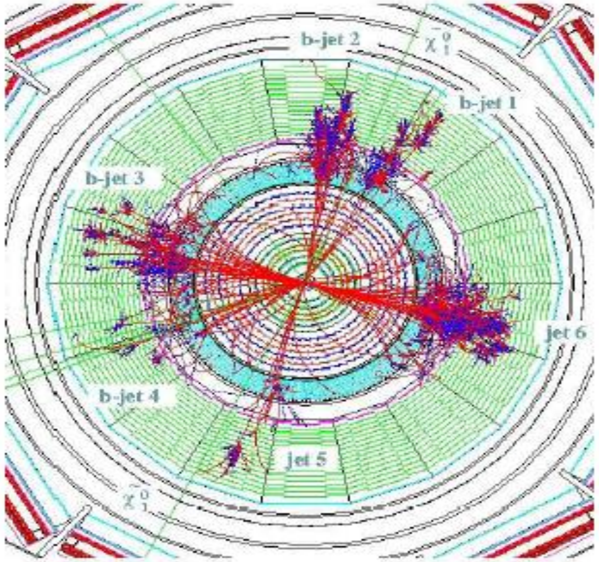
Supersymmetric Detection at LHC



Supersymmetry Reach at LHC

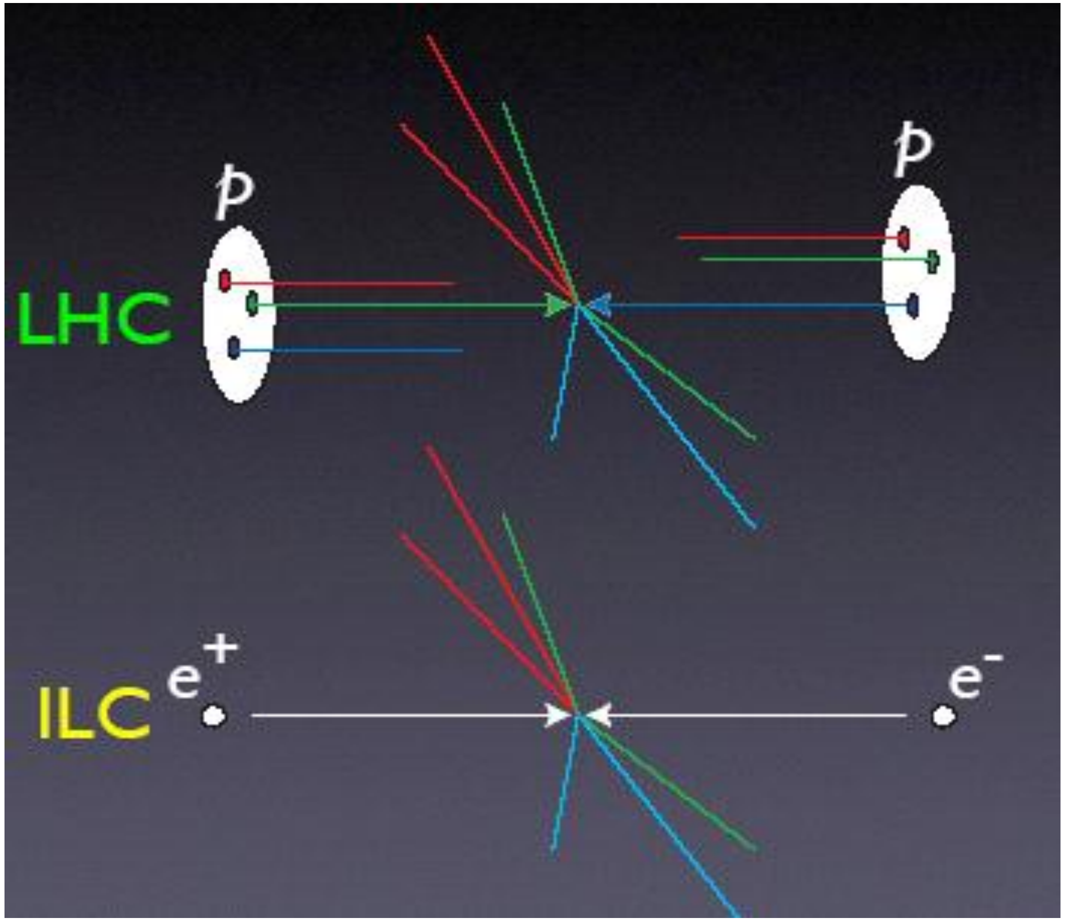


Supersymmetric Parameter Space



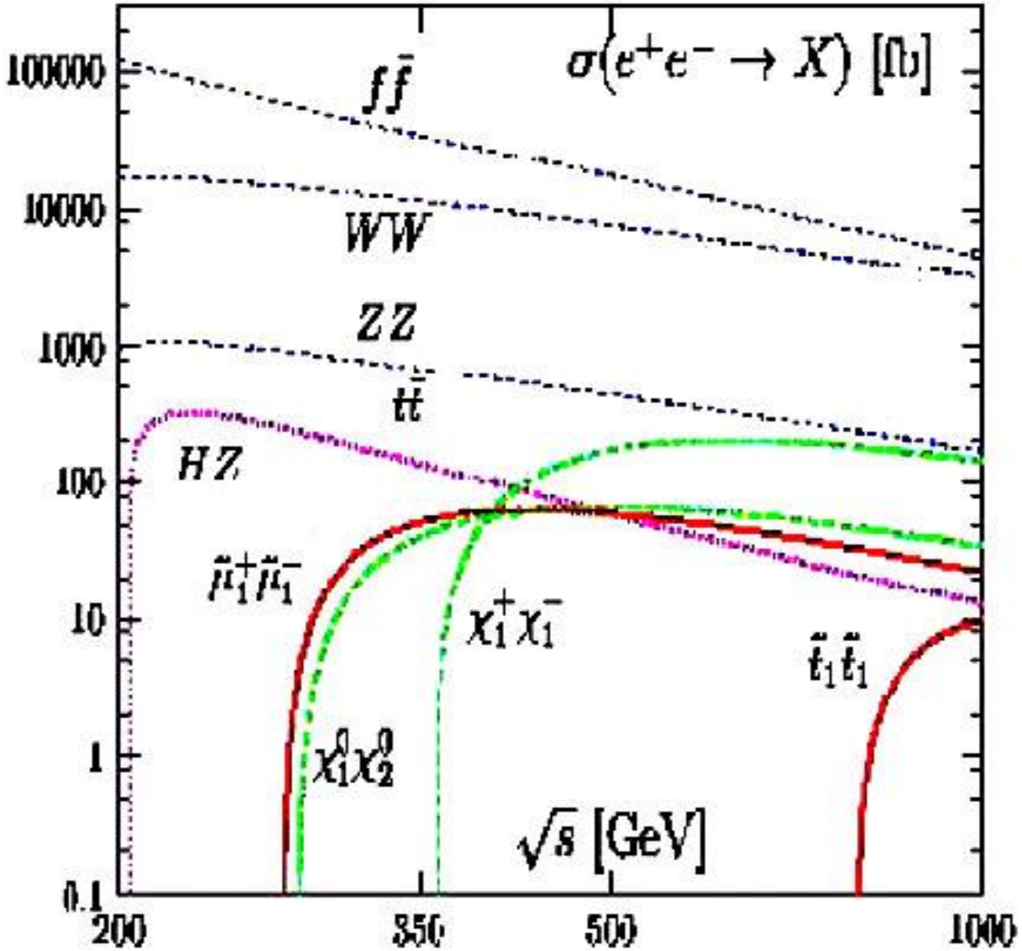
Why e^+e^- Collisions ?

- elementary particles
- well-defined
  - energy,
  - angular momentum
- uses full COM energy
- produces particles democratically
- can mostly fully reconstruct events



Supersymmetry at ILC

e^+e^- production crosssections



- **Measure quantum numbers**
- **Is it MSSM, NMSSM, …?**
- **How is it broken?**

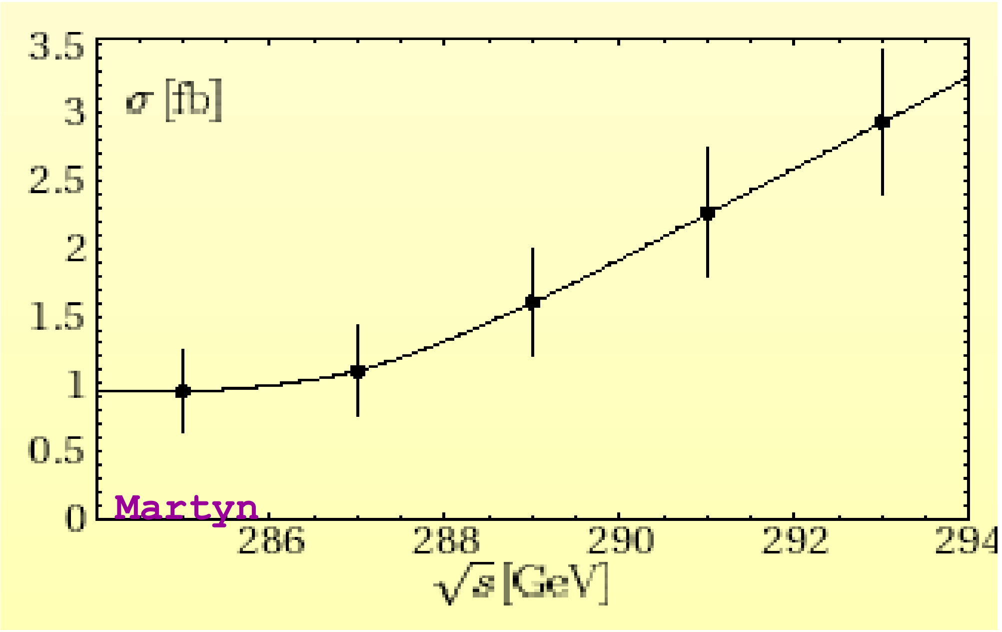
ILC can answer these questions!

- **tunable energy**
- **polarized beams**

ILC Supersymmetry

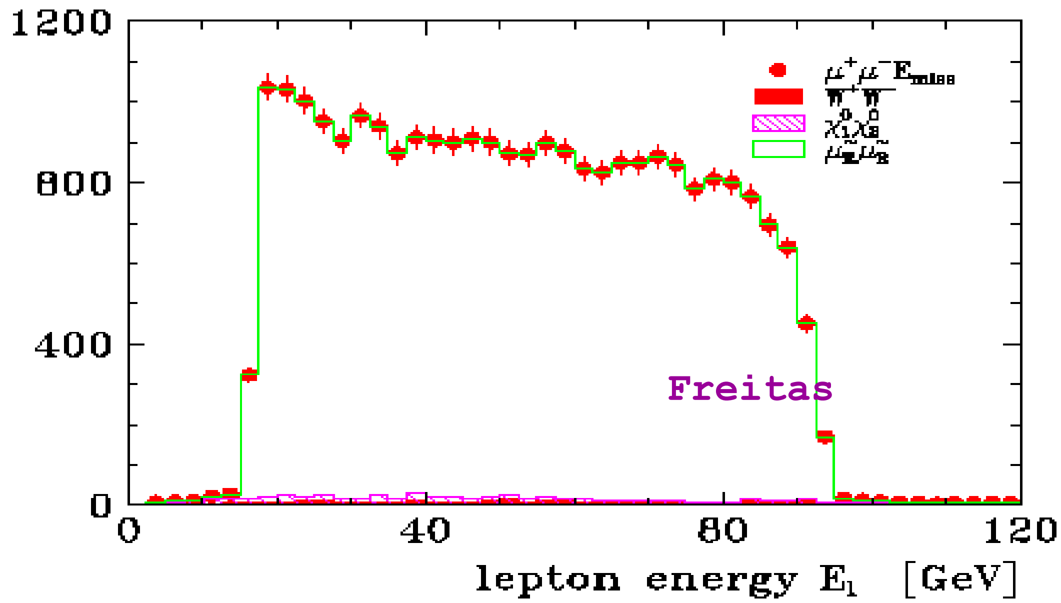
Two methods to obtain absolute sparticle masses:

Kinematic Threshold:



Determine SUSY parameters without model assumptions

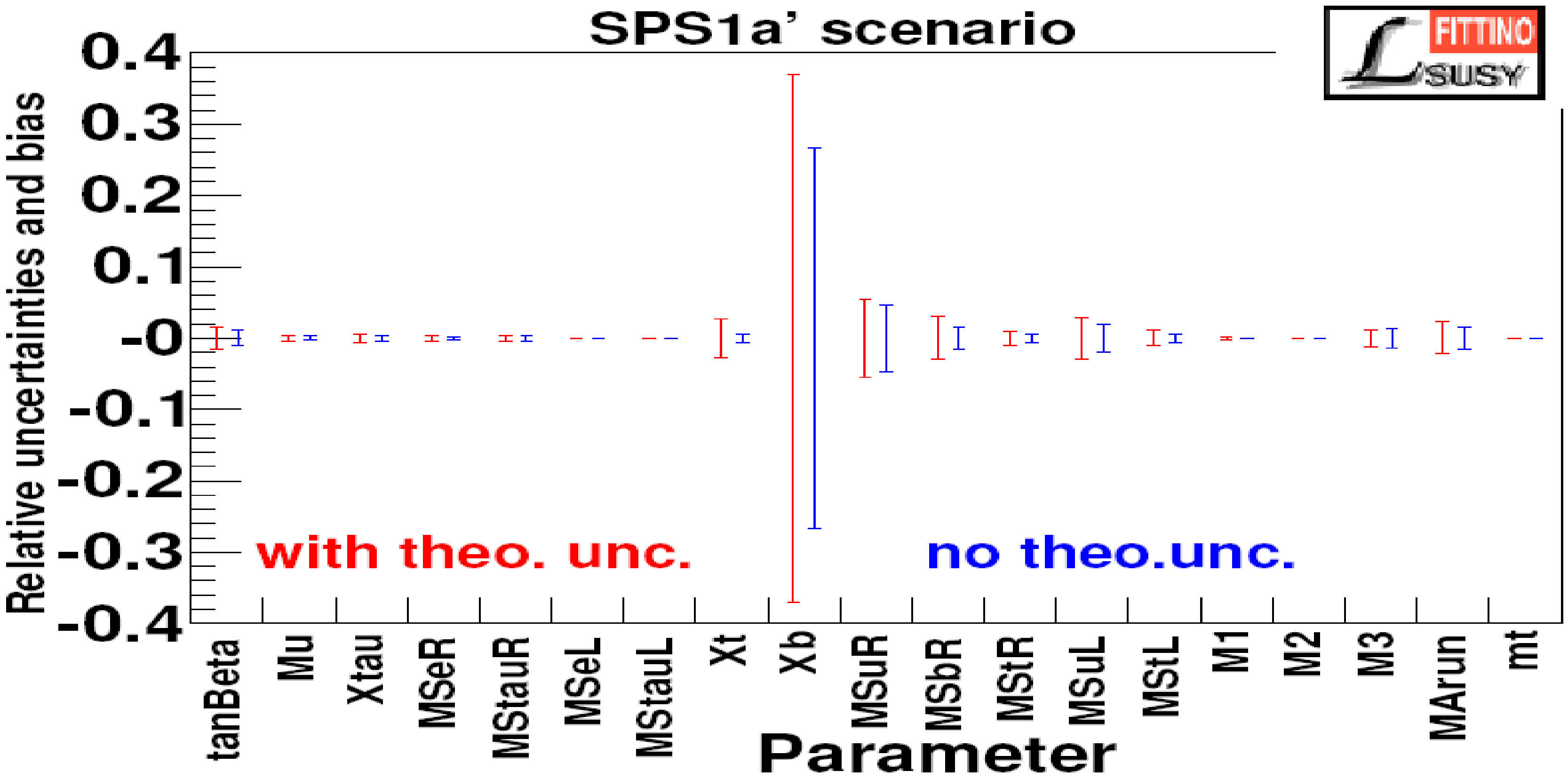
In the continuum



Minimum and maximum determines masses of primary slepton and secondary neutralino/chargino

LHC + ILC Supersymmetry

ILC precision + LHC mass reach for squarks/gluinos

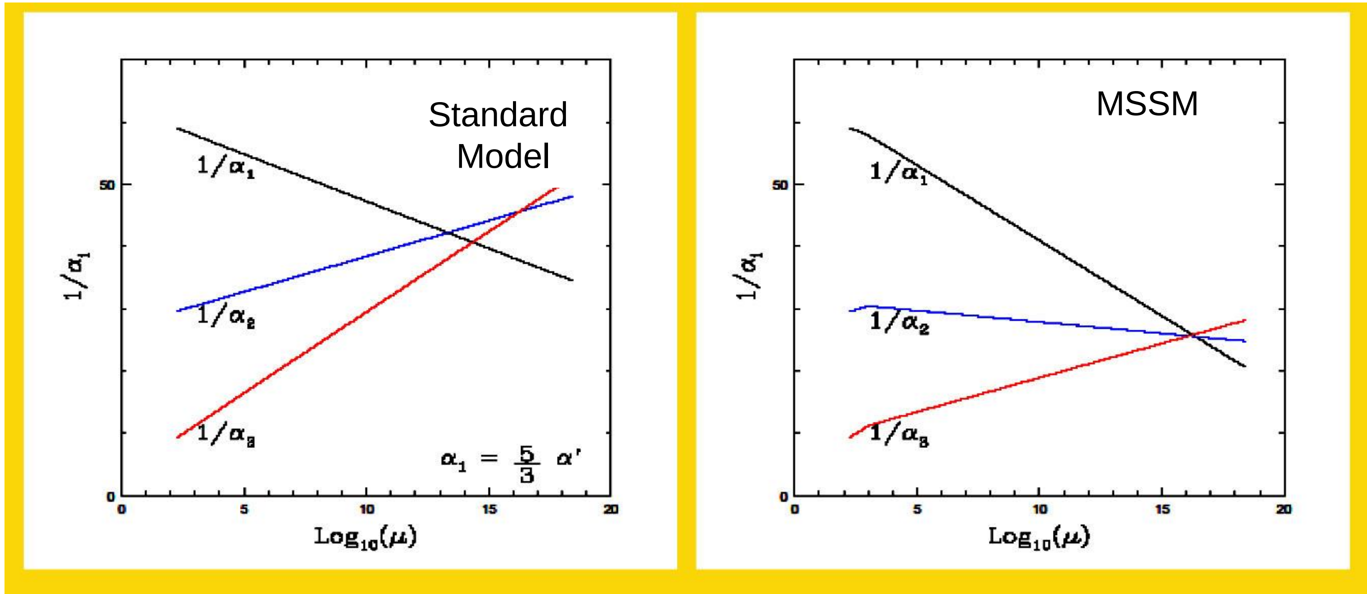


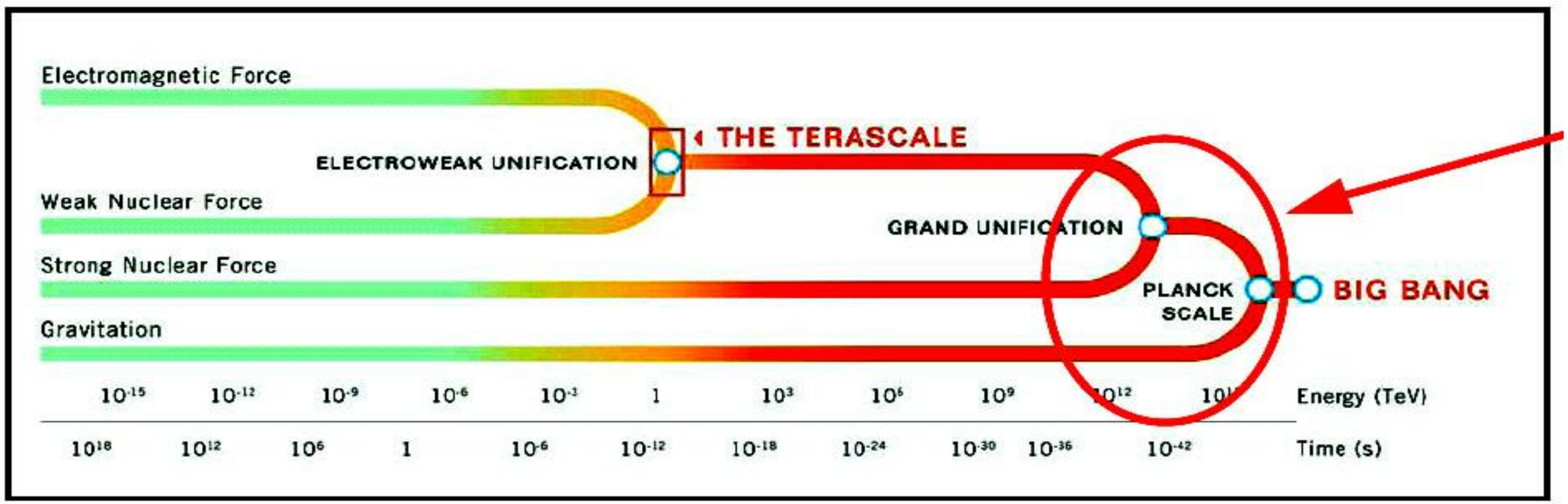
Errors

19-parameter fit using ILC+LHC:

Only possible with both LHC and ILC data

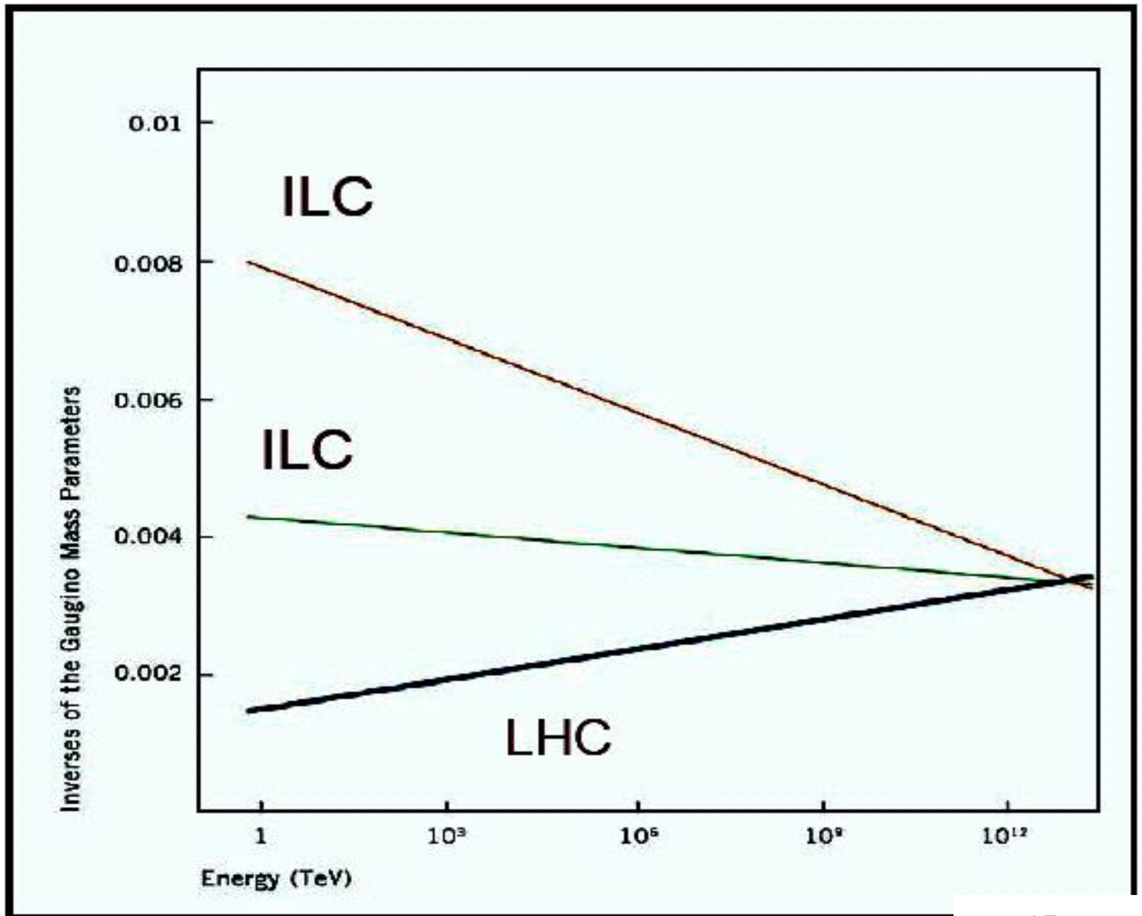
The Ultimate Unification





Supersymmetry

Model-independent investigation of GUT/Planck scale features of the theory



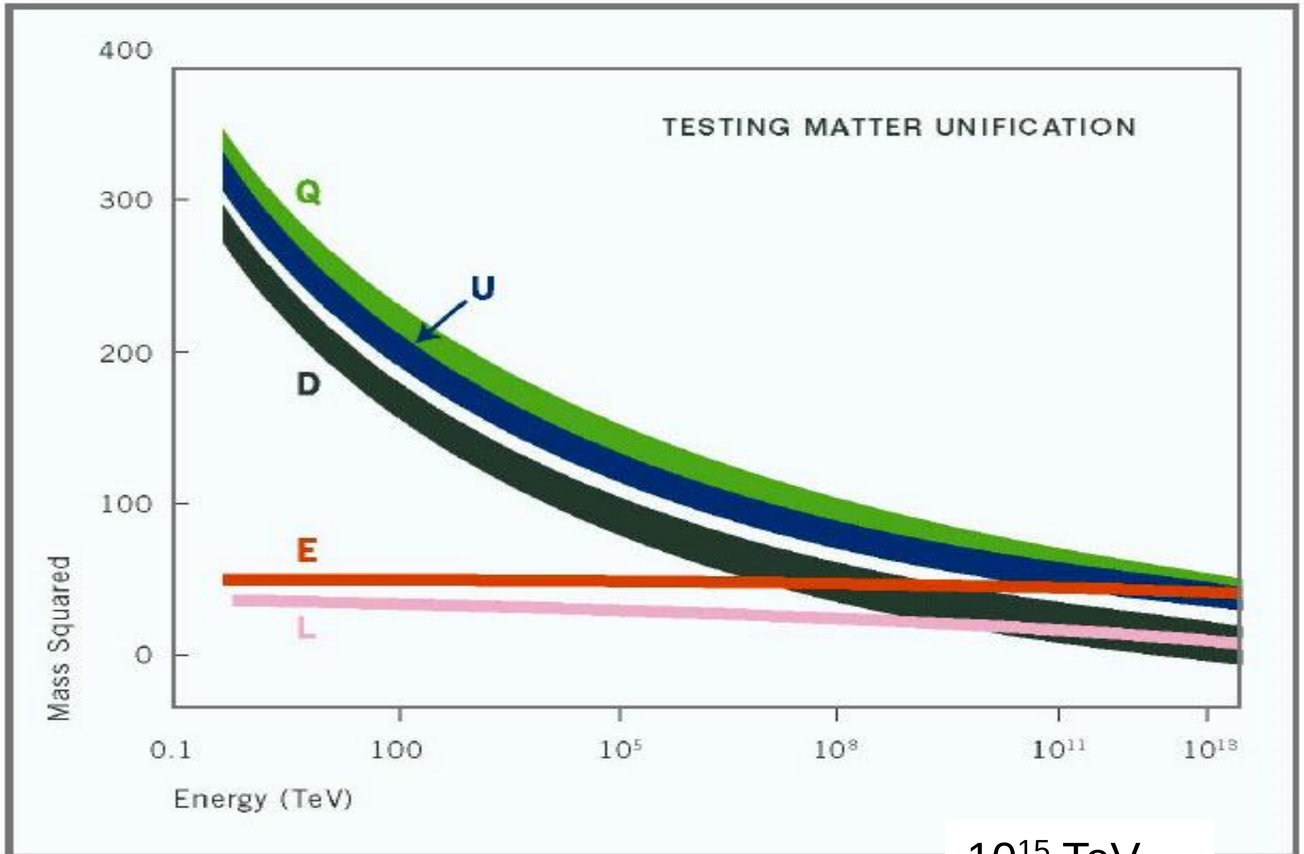
10^{15} TeV

Evolution from low to high scales of gauginos and scalar mass parameters

- **LHC → gluino**
- **ILC → wino, zino, photino**

Supersymmetry

quark and lepton unification



10^{15} TeV

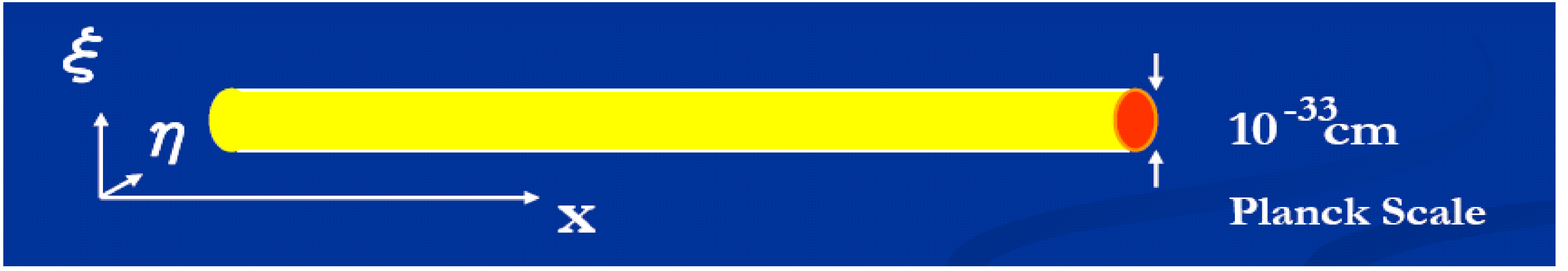
Do Quarks and Leptons also Unify?

- **Predicted in most models**
- **Can be tested at the ILC**

Superstring Theory

extra dimensions

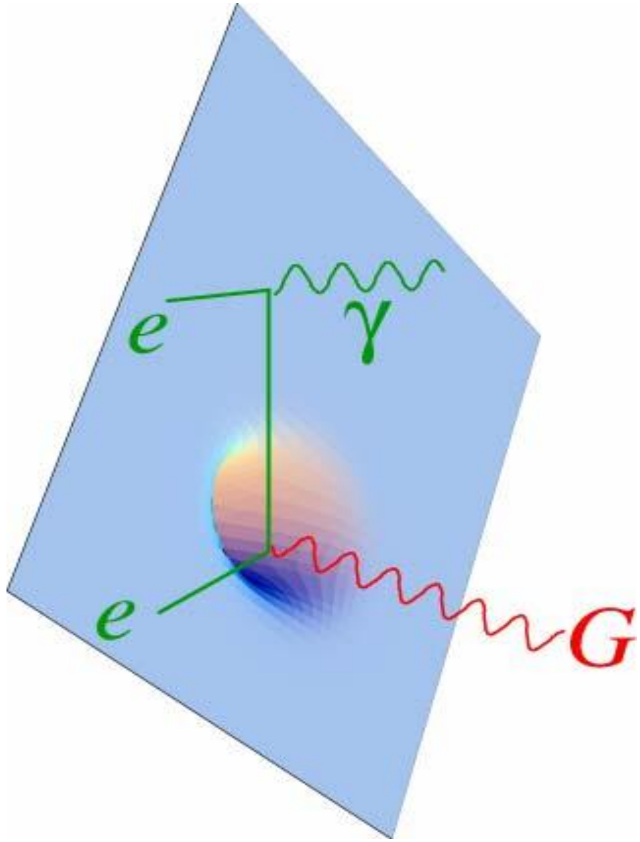
- In addition to the 3+1 dimensional space-time, extra space-dimensions exist, presumably curled into a small space size.

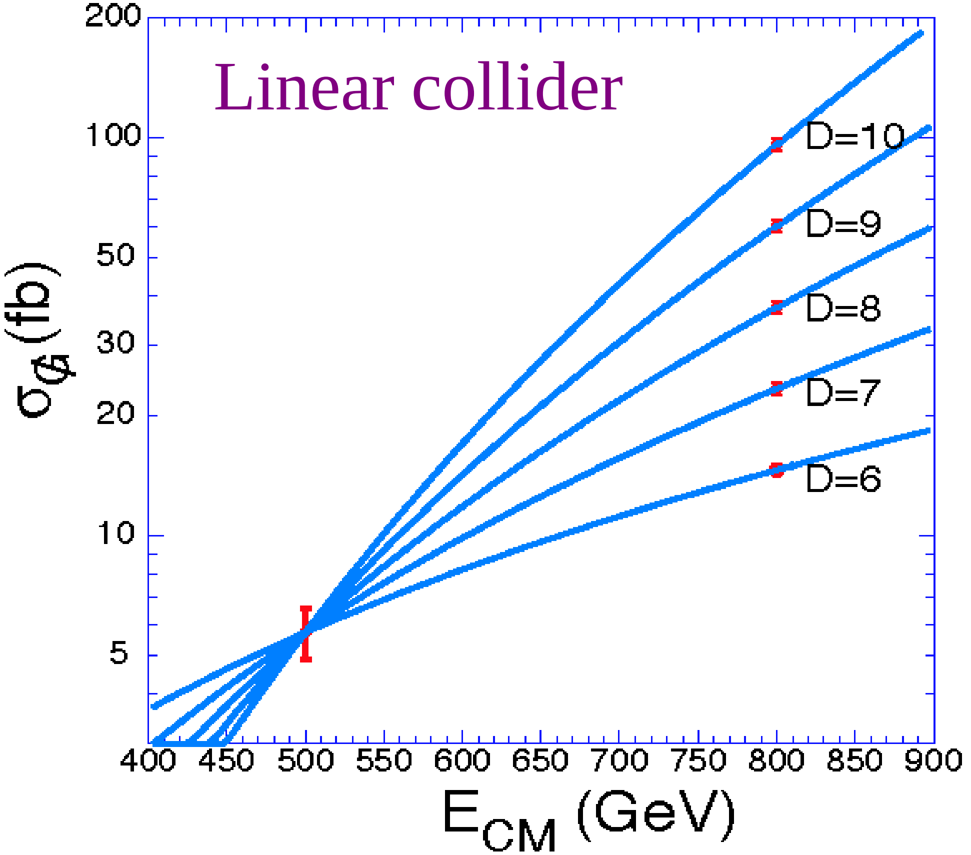


Internal quantum numbers of elementary particles are determined by the geometrical structure of the extra dimensions

Kaluza-Klein - Bosonic partners

Direct production from extra dimensions ?

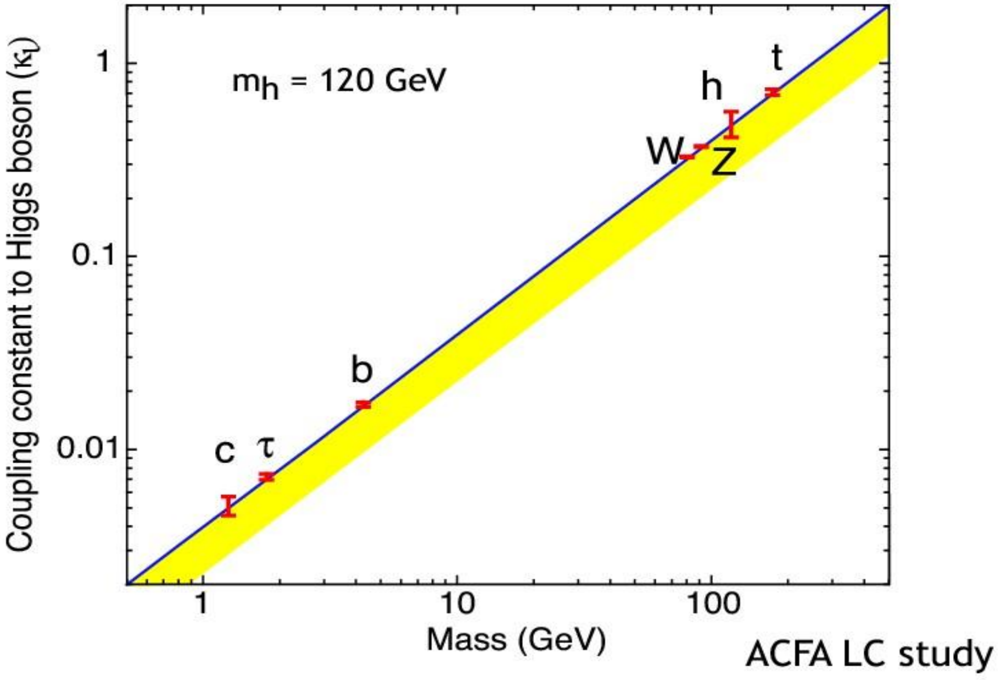




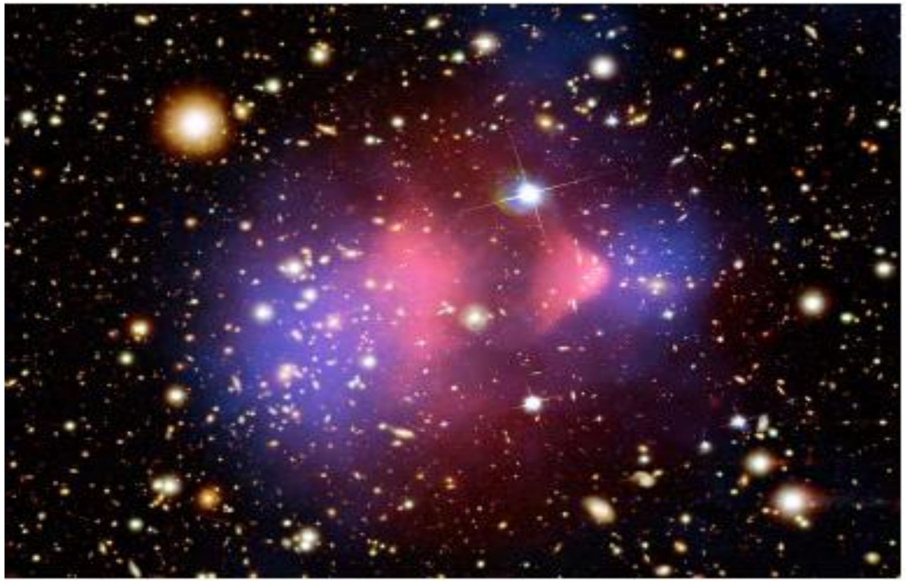
New space-time dimensions can be mapped by studying the emission of gravitons into the extra dimensions, together with a photon or jets emitted into the normal dimensions.

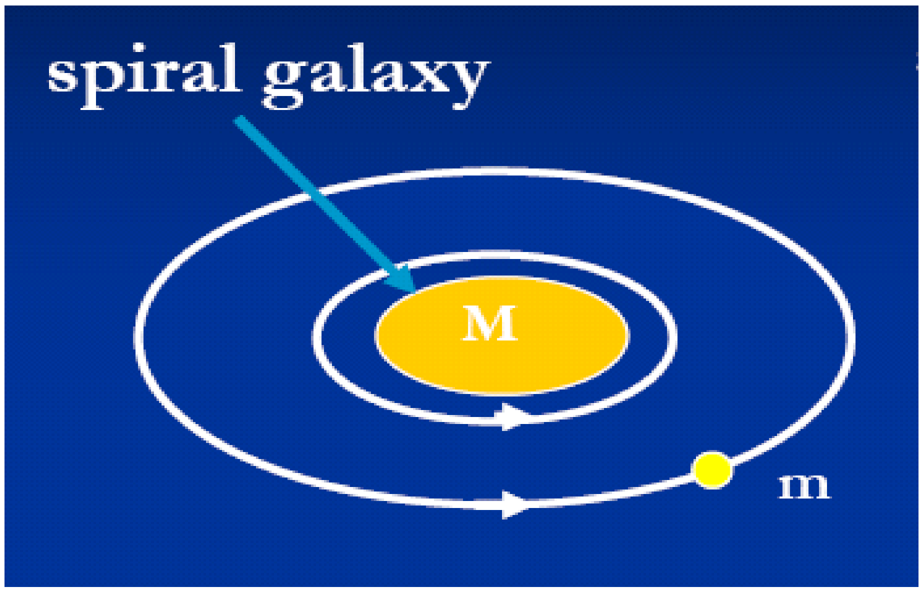
Extra dimensions and the Higgs?

Precision measurements of Higgs coupling can reveal extra dimensions in nature



- **Straight blue line gives the standard model predictions.**
- **Range of predictions in models with extra dimensions -- yellow band, (at most 30% below the Standard Model**
- **The red error bars indicate the level of precision attainable at the ILC for each particle**





Dark Matter

- gravity = centrifugal

  $GMm/r^2 = mv/r^2$

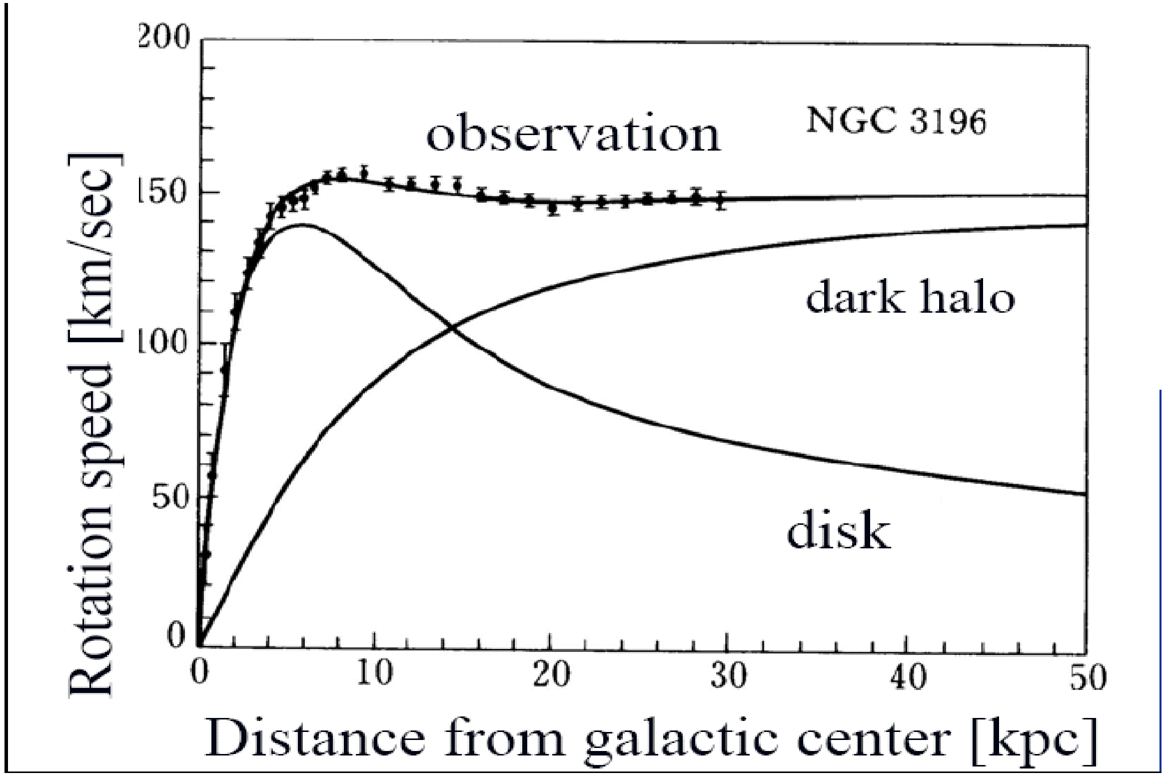
- outside of galaxy

  $v = \sqrt{GM/r}$

- inside of galaxy

  $v = \sqrt{4\pi G\rho/3}\ r$

Dark Matter in our Galaxy



- Rotation speed of the spiral is almost constant over wide distance from the center

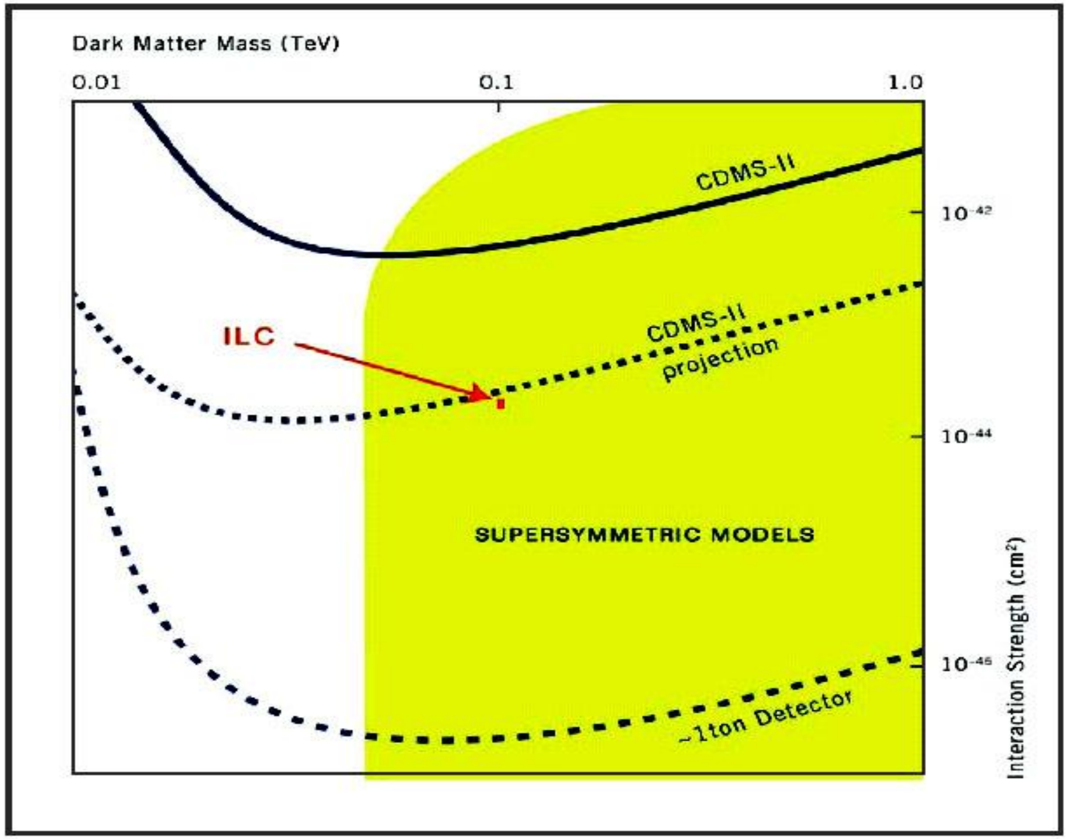
  ⇒ 0.3 GeV/cm of Dark Matter exists in our Galaxy

Dark Matter Candidates

LSP

The most attractive candidate for the dark matter is the lightest SUSY particle

- The abundance of the LSP as dark matter can be precisely calculated, if the mass and particle species are given.
- ILC can precisely measure the mass and the coupling of the LSP
- The Dark Matter density in the universe and in our Galaxy can be calculated.

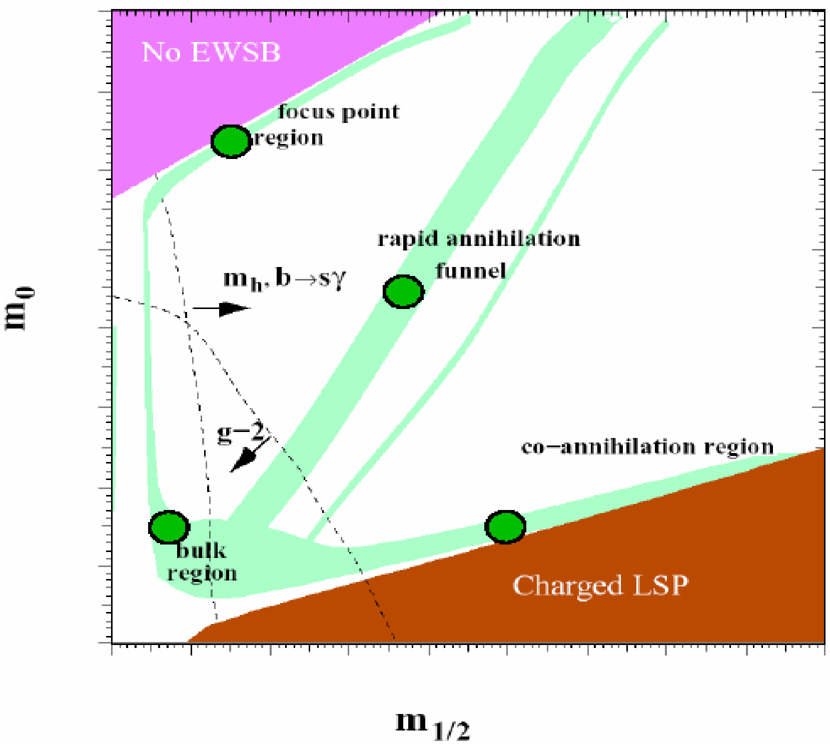


The Cosmic Connection

SUSY provides excellent candidate for dark matter (LSP)

Other models also provide TeV-scale WIMPs

How well can the properties of the DM-candidates (to be found at accelerators) be compared to the properties of the real DM (inferred from astrophysical measurements) ?



	$\Delta\Omega_{DM}/\Omega_{DM}$	main sensitivity
bulk	3.5%	$\tilde{\chi}_1^0, \tilde{e}_R, \tilde{\mu}_R, \tilde{\tau}_1$
focus	1.9%	$\tilde{\chi}_1^0, \tilde{\chi}_2^0 - \tilde{\chi}_1^0, \tilde{\chi}_3^0 - \tilde{\chi}_1^0, \tilde{\chi}_1^+ - \tilde{\chi}_1^0, \sigma(\tilde{\chi}_1^+\tilde{\chi}_1^-)$
co-ann.	6.5%	$\tilde{\chi}_1^0, \tilde{\chi}_1^0 - \tilde{\tau}_1$
funnel	3.1%	$A^0, \tilde{\chi}_1^0, \tilde{\tau}_1$

Matches precision of future CMB exp.

How the physics defines the ILC

Parameters for the Linear Collider

September 30, 2003

Asia: Sachio Komamiya, Dongchul Son
Europe : Rolf Heuer (chair), Francois Richard
North America: Paul Grannis, Mark Oreglia

How the physics defines the ILC

charge

The group comprises two members each from Asia, Europe and North America. It shall produce a set of parameters for the future Linear Collider and their corresponding values needed to achieve the anticipated physics program. This list and the values have to be specific enough to form the basis of an eventual cost estimate and a design for the collider and to serve as a standard of comparison in the technology recommendation process. The parameters should be derived on the basis of the world consensus document "Understanding Matter, Energy, Space and Time: The case for the e+e- Linear Collider" using additional input from the regional studies. The final report will be forwarded to the ILCSC for its acceptance or modification by end of September, 2003.

The parameter set should describe the desired baseline (*phase 1*) collider as well as possible subsequent phases that introduce new options and/or upgrades.

How the physics defines the ILC?

charge (continued)

The parameter set should describe the desired baseline (*phase 1*) collider as well as possible subsequent phases that introduce new options and/or upgrades.

For all phases and options/upgrades priorities should be discussed wherever possible and appropriate, and the description should include at least the following parameters:

- Operational energy range
- Minimum top energy
- Integrated luminosity and desired time spent to accumulate it, for selected energy values
  (e.g. at the top energy, at the Z-pole, at various energy thresholds…)
- Polarisation and particle type for each beam
- Number and type of interaction regions

The committee may include any other parameter that it considers important for reaching the physics goals of a particular phase, or useful for the comparison of technologies, subject to the approval of the ILCSC.

Parameters for the ILC

- E_{cm} adjustable from 200 – 500 GeV
- Luminosity → $\int L dt$ = 500 fb^{-1} in 4 years
- Ability to scan between 200 and 500 GeV
- Energy stability and precision below 0.1%
- Electron polarization of at least 80%

- The machine must be upgradeable to 1 TeV

Lecture I-2
this afternoon

OVERVIEW of the ILC

- History and Concept
- Technologies and technical challenges
- Designing the ILC
- Detectors for the ILC