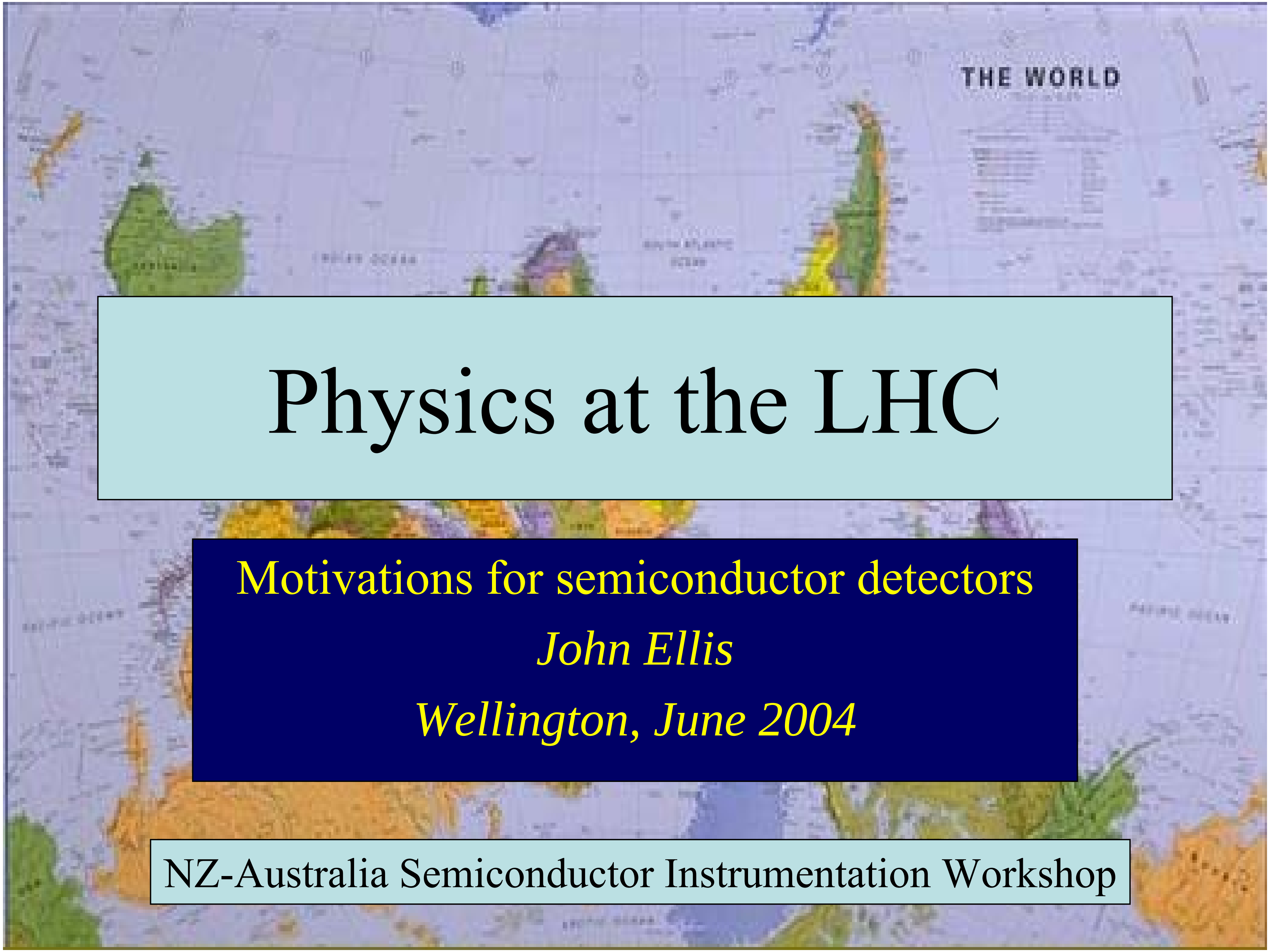


Physics at the LHC

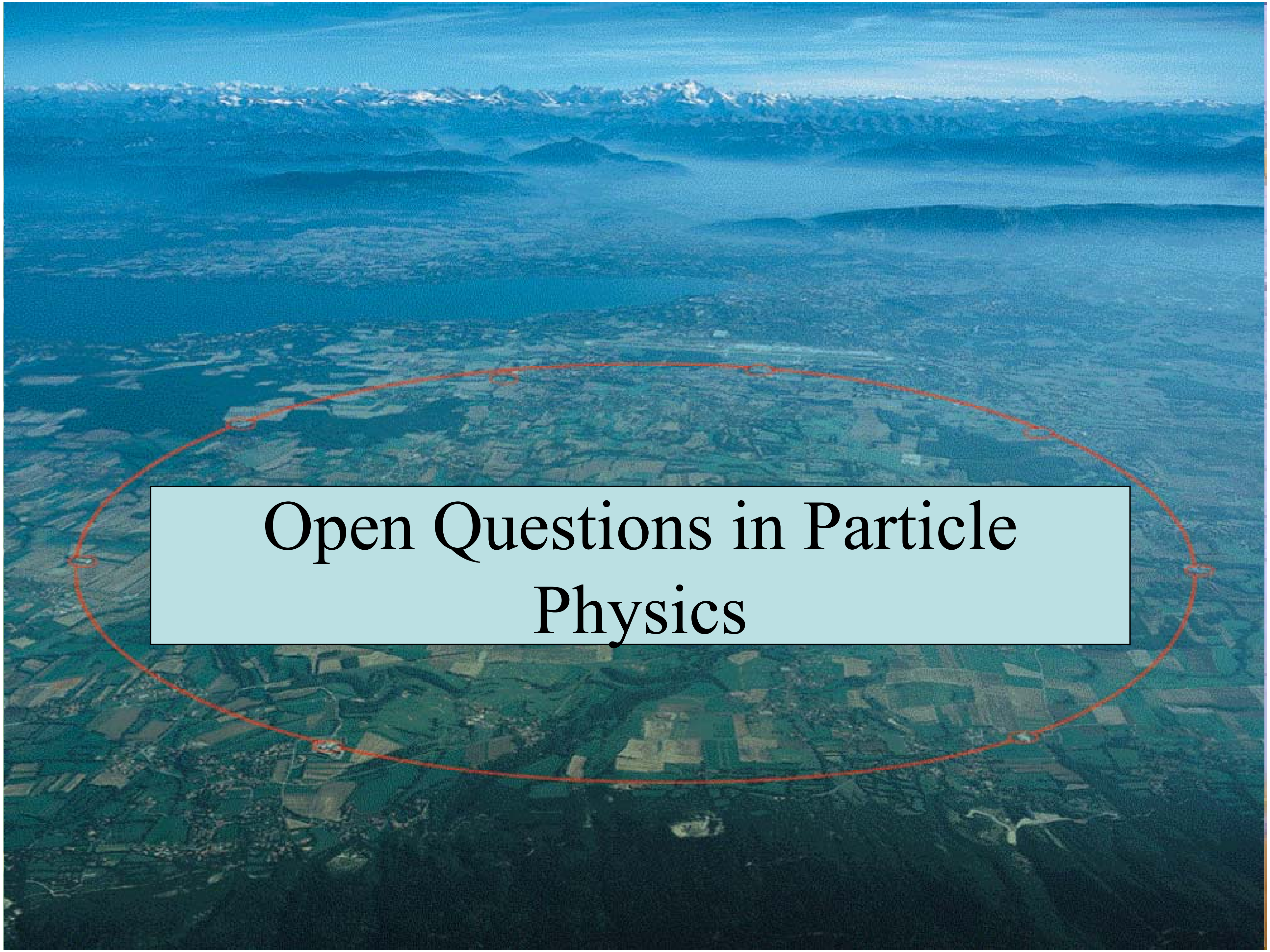
Motivations for semiconductor detectors

John Ellis

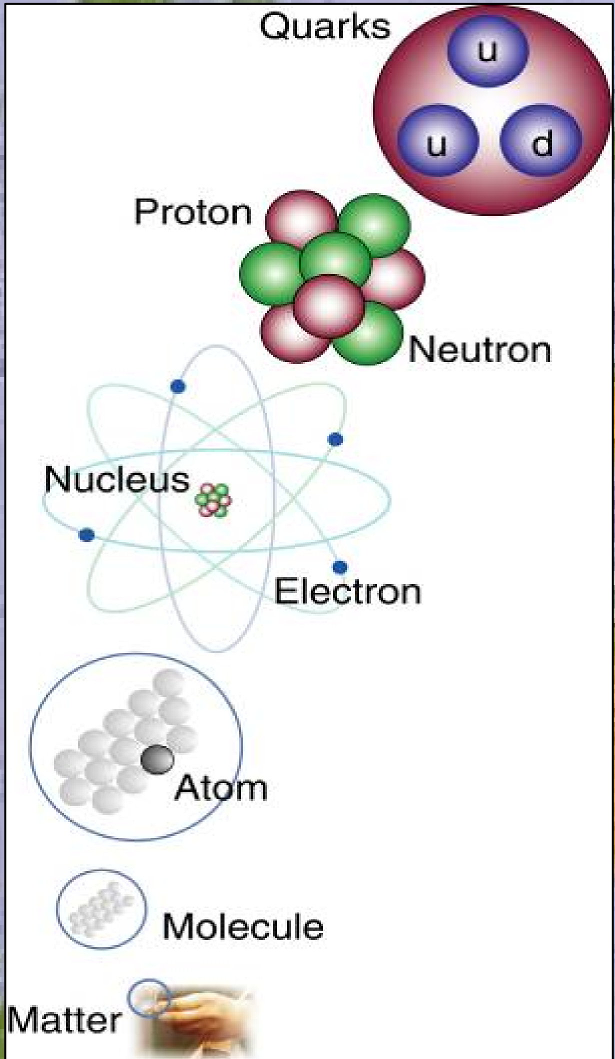
Wellington, June 2004

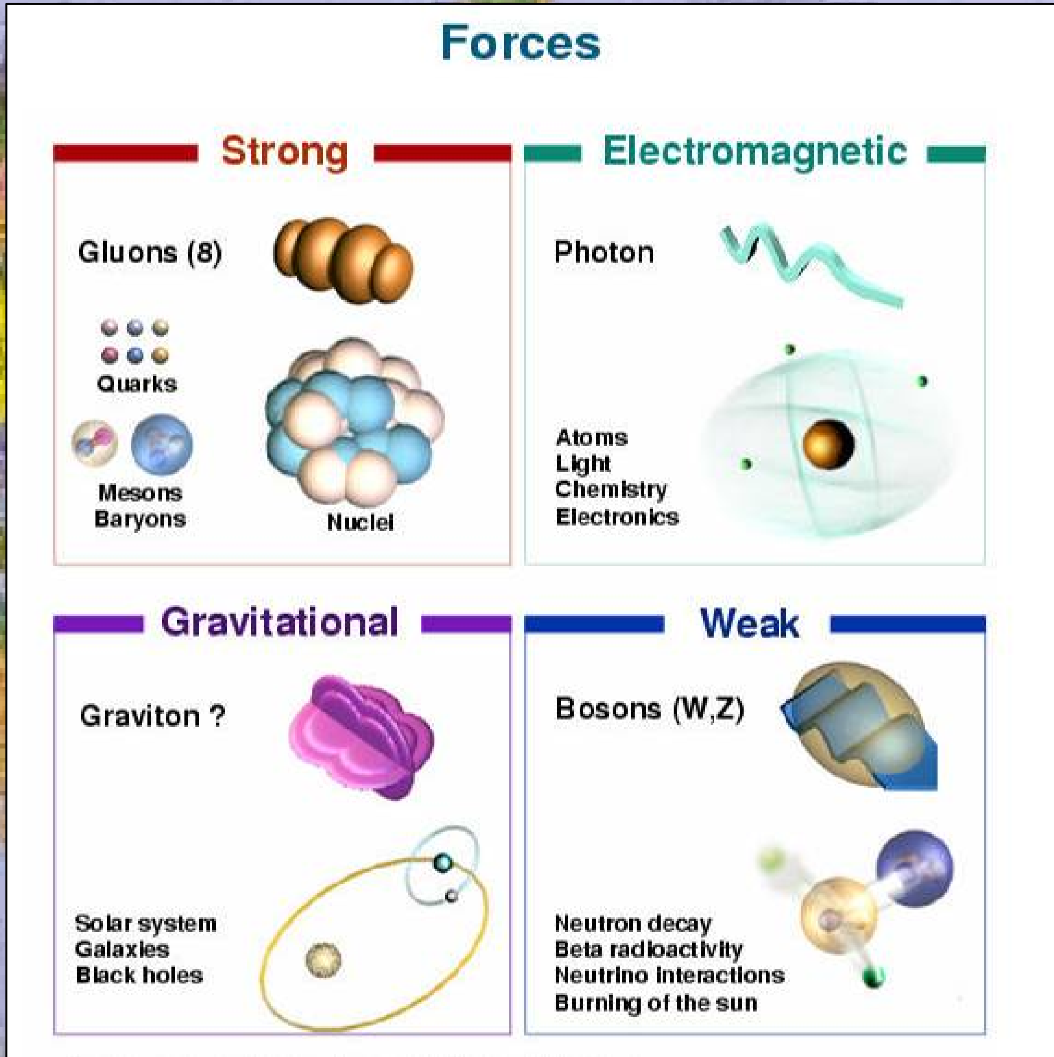
NZ-Australia Semiconductor Instrumentation Workshop

Open Questions in Particle Physics



Particles & Forces





Landmarks in Particle Physics

1897 : Electron discovered by Thomson

1910 : Nucleus discovered by Rutherford

1960's : Quarks proposed by Gell-Mann, Zweig

1970's : Experimental evidence for quarks at SLAC

1973: Neutral weak interactions discovered at CERN

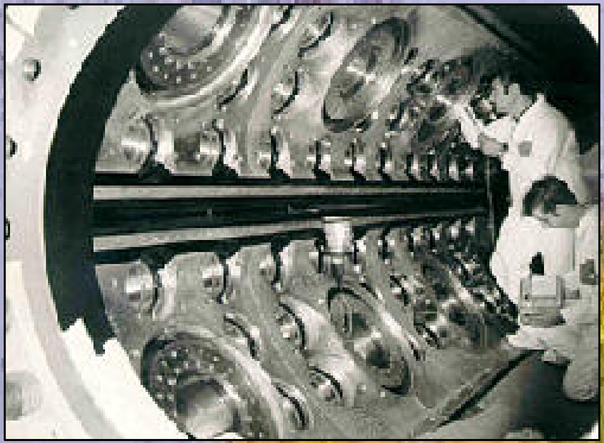
1983 : Carrier particles of the weak and electromagnetic forces discovered at CERN

1996 : Discovery of the last – top – quark at FNAL

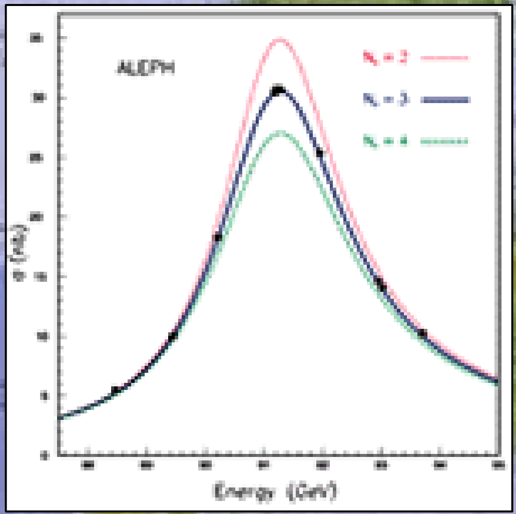
≥ 2007 : CERN will explore why particles weigh

The Standard Model of Particle Physics

Proposed by Abdus Salam, Glashow & Weinberg



Key tests in experiments at CERN



In perfect agreement with all laboratory experiments

Open Questions beyond the Standard Model

- What is the origin of particle masses?

  due to a Higgs boson? **ATLAS, CMS @ LHC**

  solution at energy < 1 TeV (1000 proton masses)
- Why so many types of matter particles?

  matter-antimatter difference? **LHCb @ LHC**
- Unification of the fundamental forces?

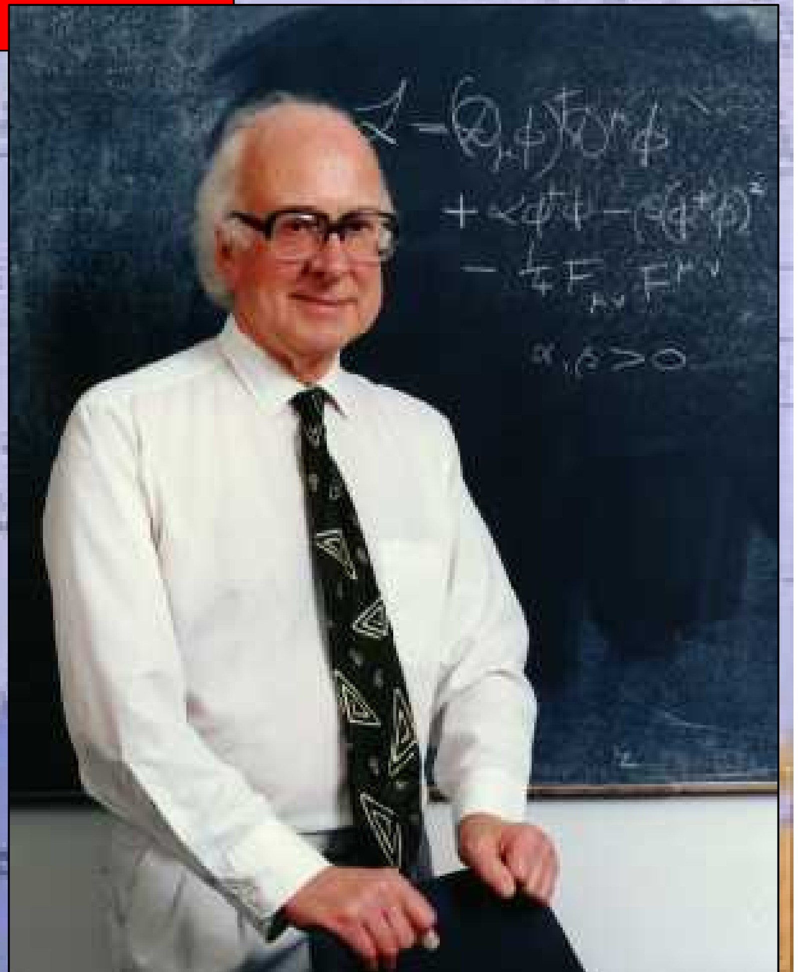
  at very high energy ~ 10^{16} GeV

  indirect @ accelerators, source of dark matter **ATLAS, CMS**
- Quantum theory of gravity? **ATLAS, CMS**

  additional dimensions of space?

Some particles have mass, some do not

Where do the masses come from?



Newton:

Weight proportional to Mass

Einstein:

Energy related to Mass

Neither explained origin of Mass

Are masses due to Higgs boson?

Illustration of the Higgs Idea

The excitation crosses the room = the Higgs boson

And Supersymmetry (Susy)?

- Unifies matter and force particles
- Links fermions and bosons

Exclusion principle vs laser coherence

- Relates particles of different spins

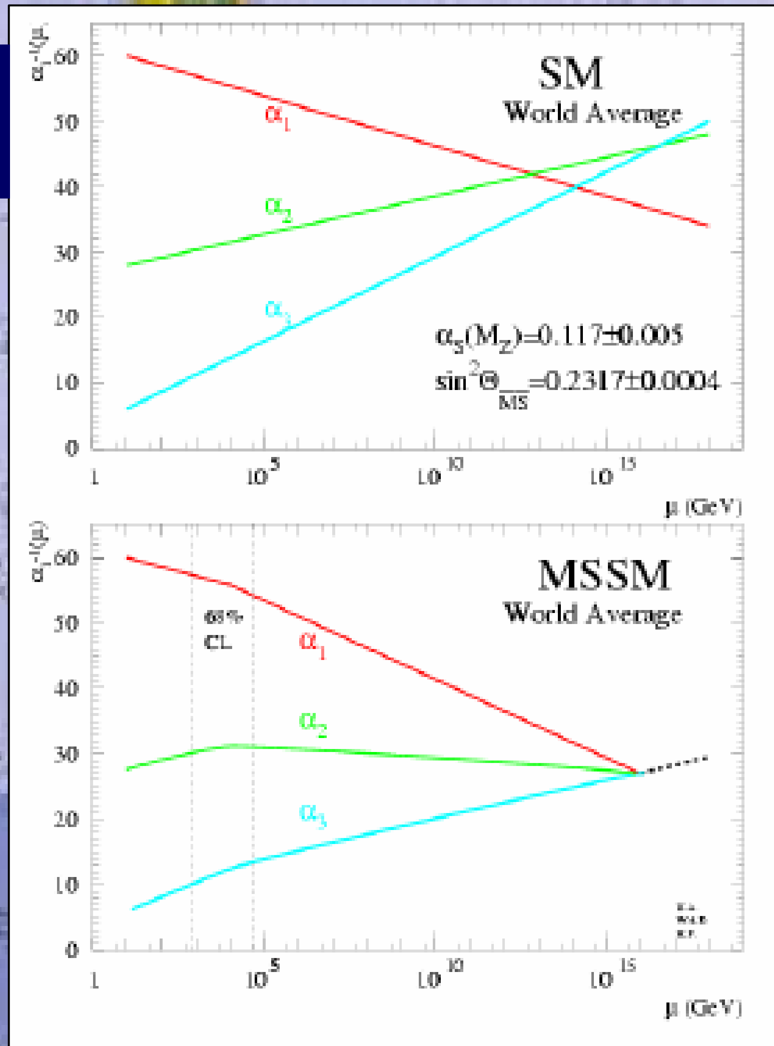
0 - ½ - 1 - 3/2 - 2

Higgs - Electron - Photon - Gravitino - Graviton

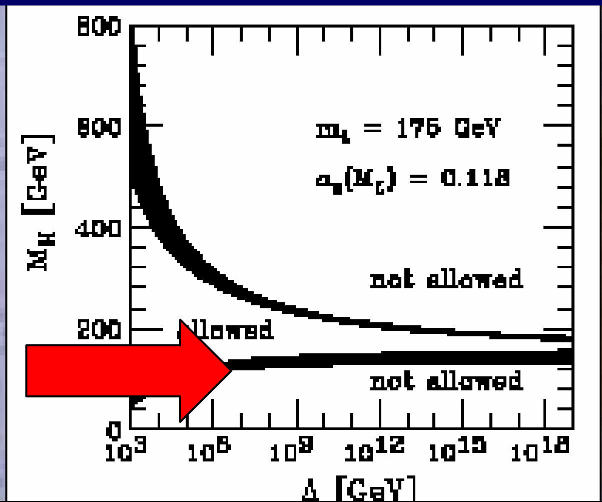
- Helps fix masses, unify fundamental forces
- Could provide astrophysical dark matter

Other Reasons to like Susy

It enables the gauge couplings to unify



It stabilizes the Higgs potential for low masses



Approved by Fabiola Gianotti

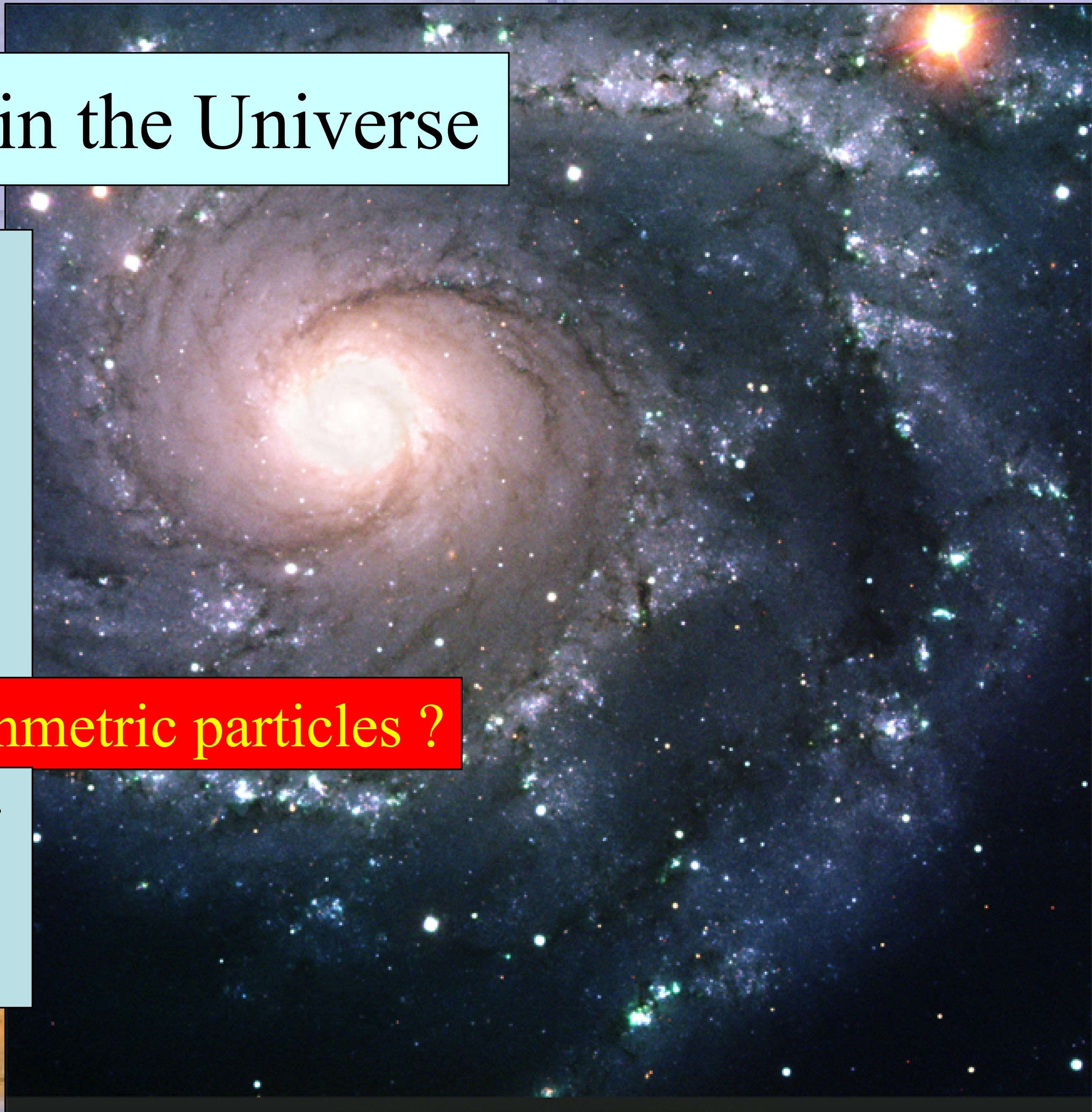
Dark Matter in the Universe

Astronomers say that most of the matter in the Universe is invisible

Dark Matter

Lightest Supersymmetric particles ?

We shall look for them with the LHC



Constraints on Supersymmetry

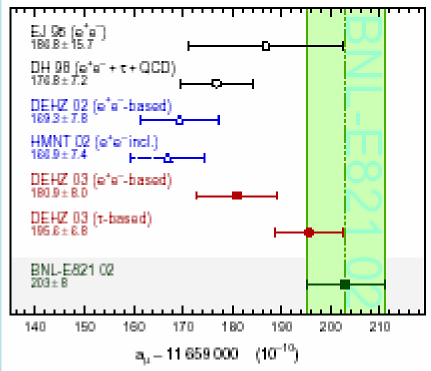
- Absence of sparticles at LEP, Tevatron

  selectron, chargino > 100 GeV

  squarks, gluino > 250 GeV

- Indirect constraints

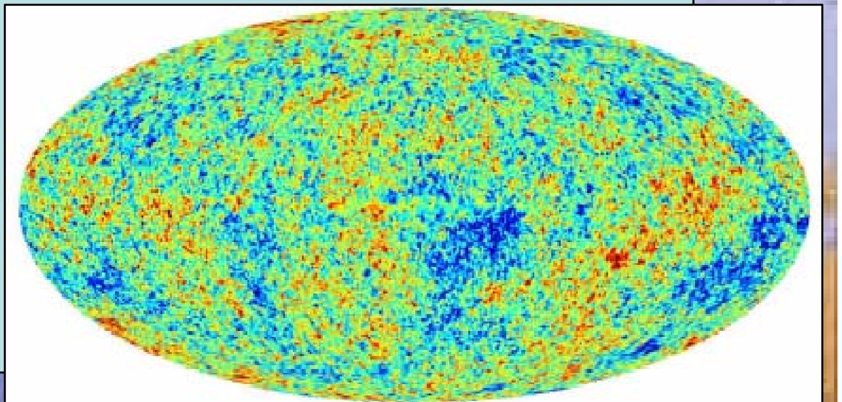
  Higgs > 114 GeV, b -> s γ $\qquad$ g_μ - 2



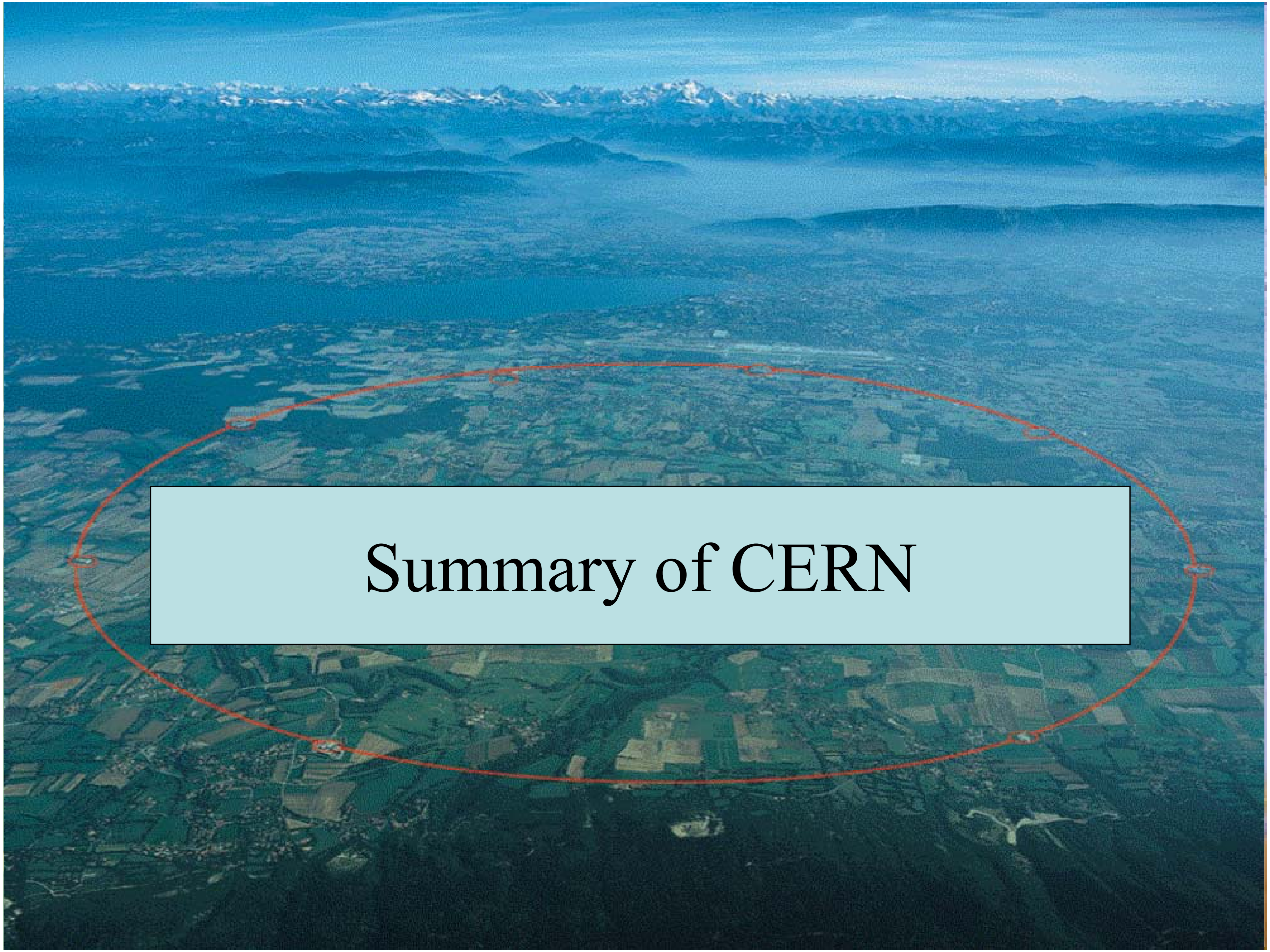
- Density of dark matter

  lightest sparticle χ:

WMAP: $0.094 < \Omega_\chi h^2 < 0.124$



Summary of CERN



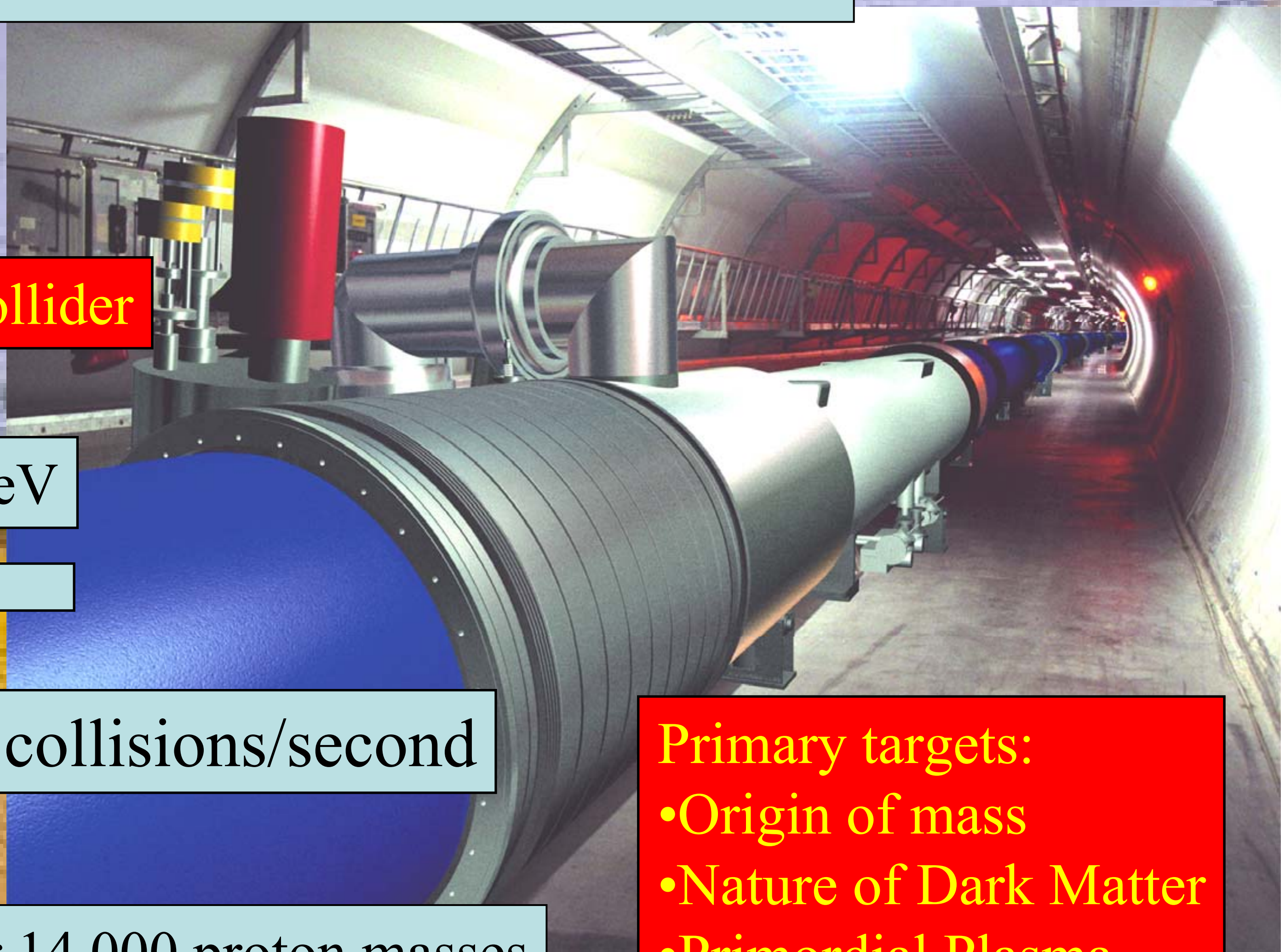
Member States of CERN

Scientists using CERN in 2003

- Research
- Technology
- Training
- International Collaboration

The LHC & its Experimental Programme

The Large Hadron Collider (LHC)



Proton- Proton Collider

7 TeV + 7 TeV

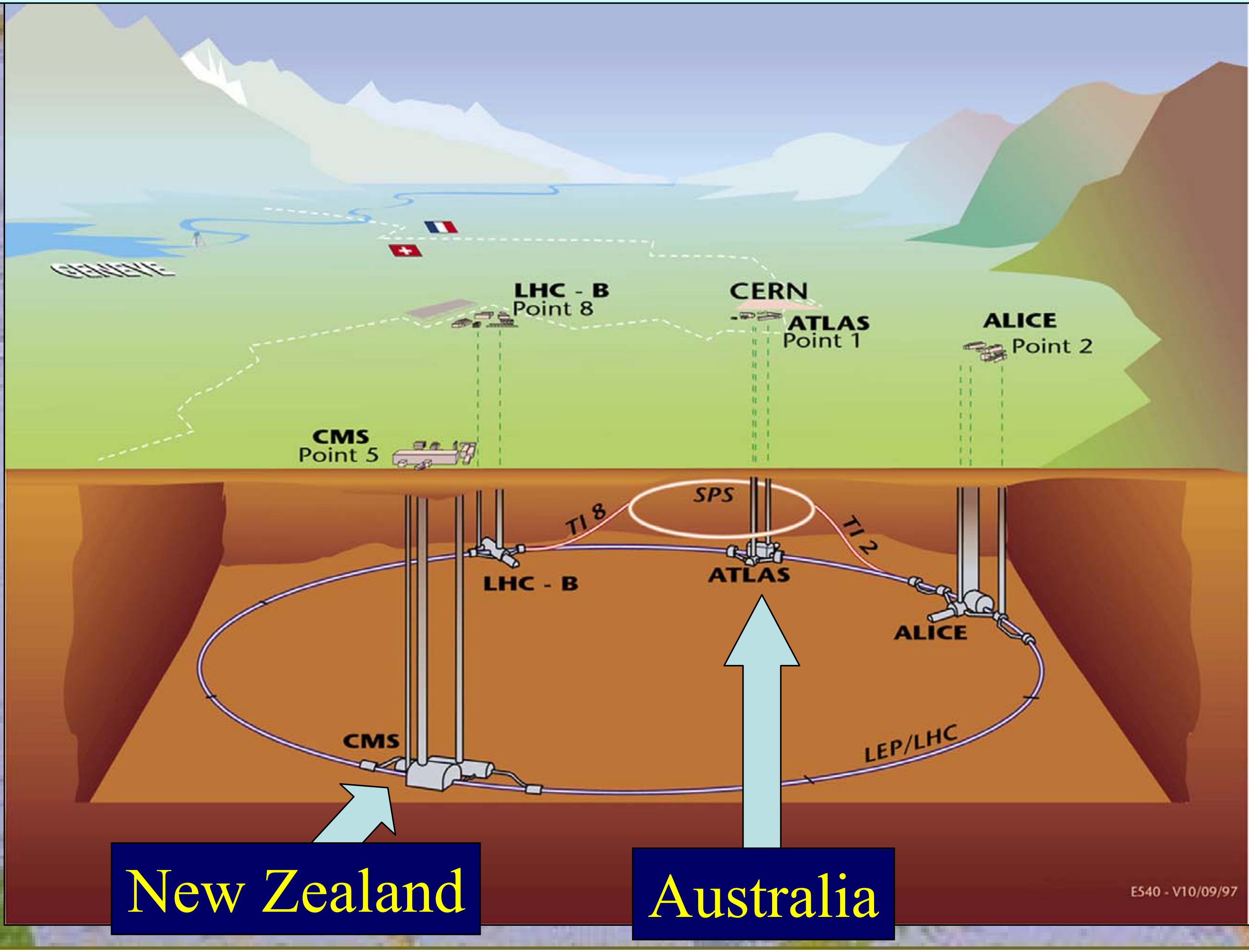
1,000,000,000 collisions/second

Total energy over 14,000 proton masses

Primary targets:

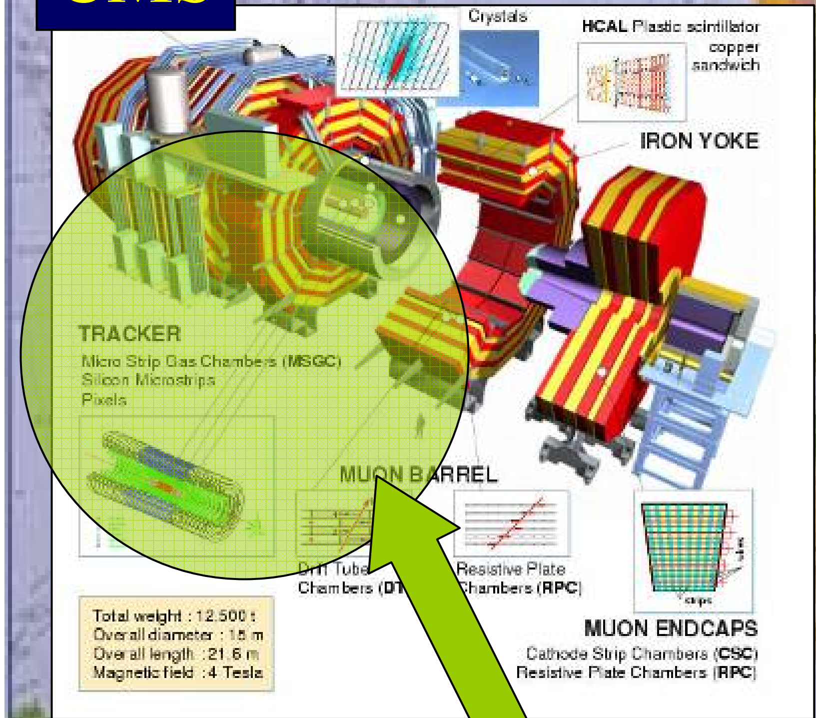
- Origin of mass
- Nature of Dark Matter
- Primordial Plasma
- Matter vs Antimatter

Overall View of the Large Hadron Collider (LHC)

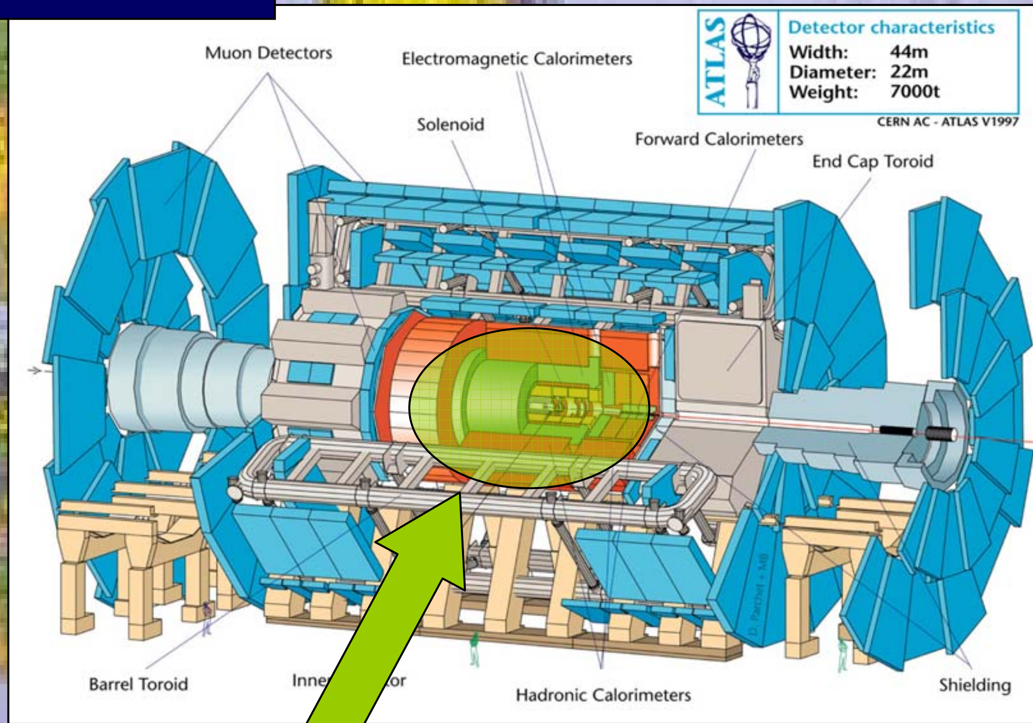


The General-Purpose LHC Detectors

CMS



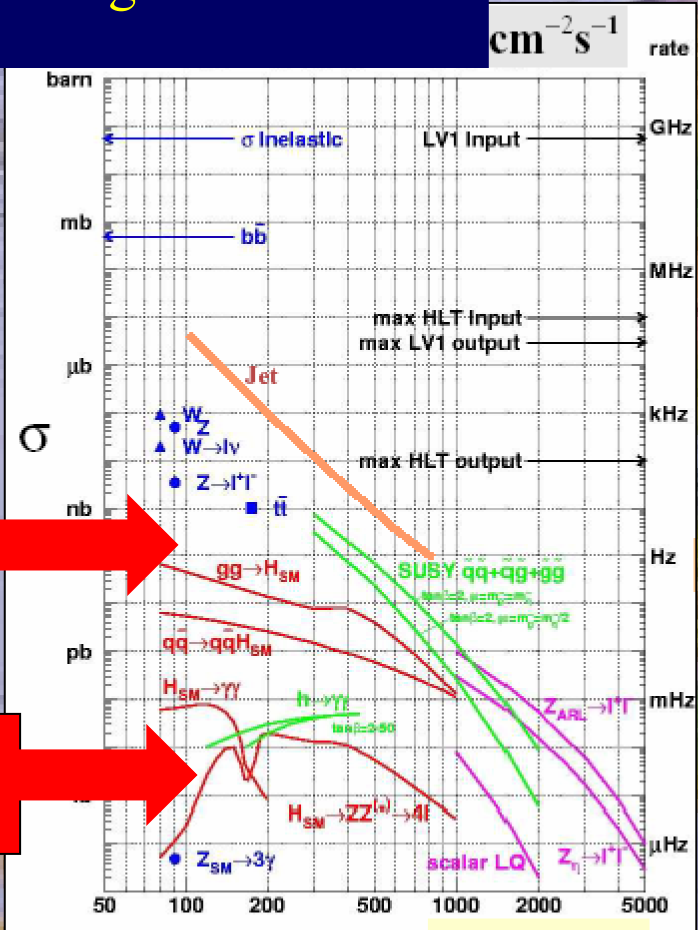
ATLAS



Semiconductor Trackers

The LHC Physics Haystack(s)

Interesting cross sections



Susy

Higgs

- Cross sections for heavy particles
  - $\sim 1/(1\ \text{TeV})^2$
- Most have small couplings $\sim \alpha^2$
- Compare with total cross section
  - $\sim 1/(100\ \text{MeV})^2$
- Fraction ~ 1/1,000,000,000,000
- Need ~ 1,000 events for signal
- Compare needle
  - $\sim 1/100{,}000{,}000\ \text{m}^3$
- Haystack ~ 100 m^3
- Must look in ~ 100,000 haystacks

Good tracking essential: need to tag b quarks and τ leptons

Huge Statistics thanks to High Energy and Luminosity

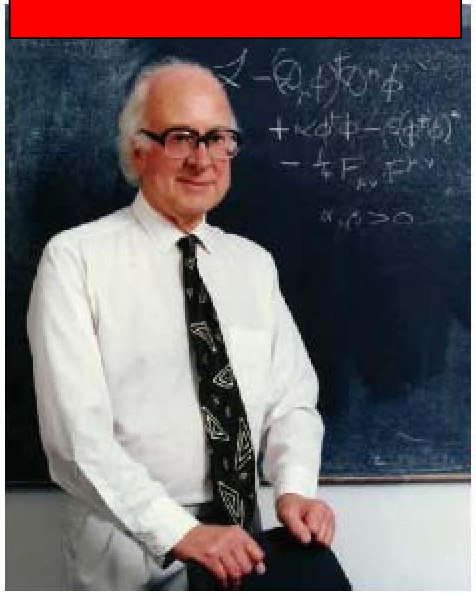
Event rates in ATLAS or CMS at L = 10^{33} cm^{-2} s^{-1}

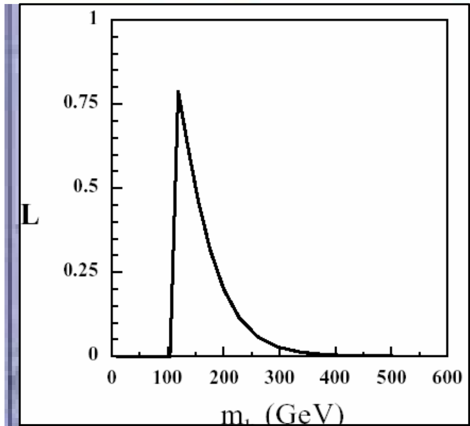
Process	Events/s	Events per year	Total statistics collected at previous machines by 2007
$W \to e\nu$	15	10^8	10^4 LEP / 10^7 Tevatron
$Z \to ee$	1.5	10^7	10^7 LEP
$t\bar{t}$	1	10^7	10^4 Tevatron
$b\bar{b}$	10^6	10^{12} – 10^{13}	10^9 Belle/BaBar ?
H m=130 GeV	0.02	10^5	?
$\tilde{g}\tilde{g}$ m= 1 TeV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

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

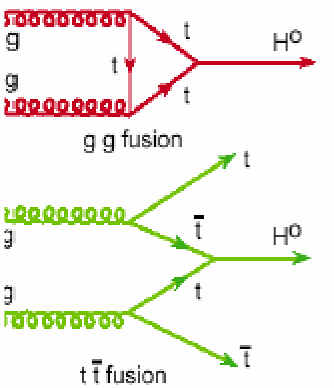
A la recherche du
Higgs perdu …

Higgs Production at the LHC

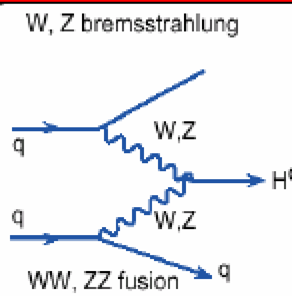


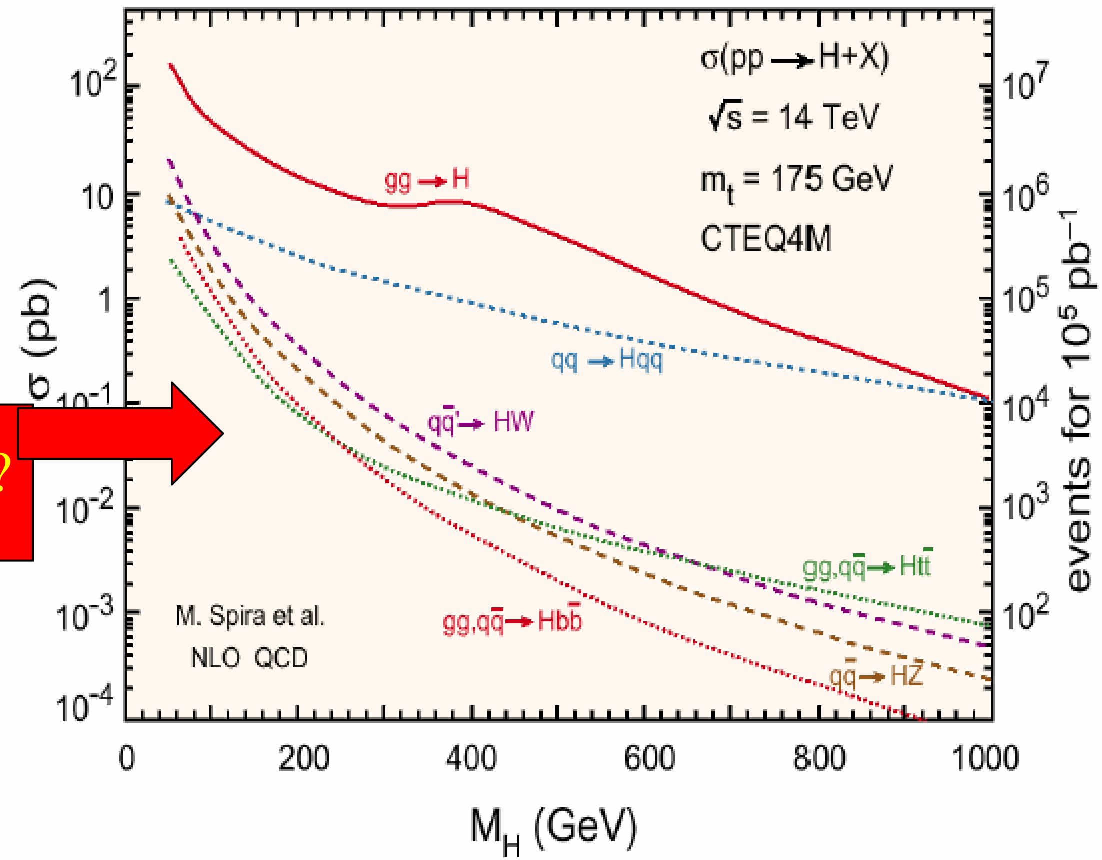


Combining direct,
Indirect information

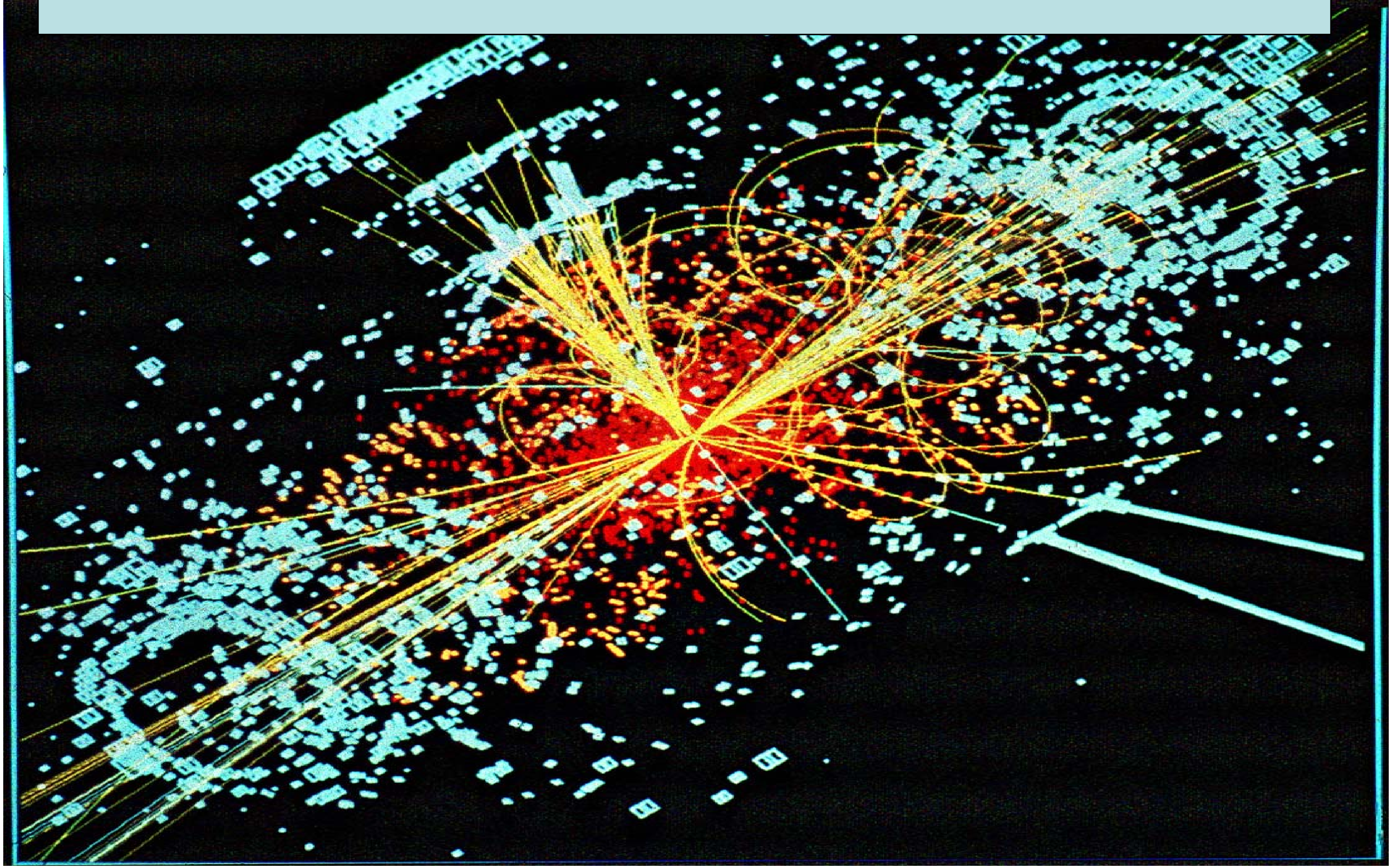


… not far away?

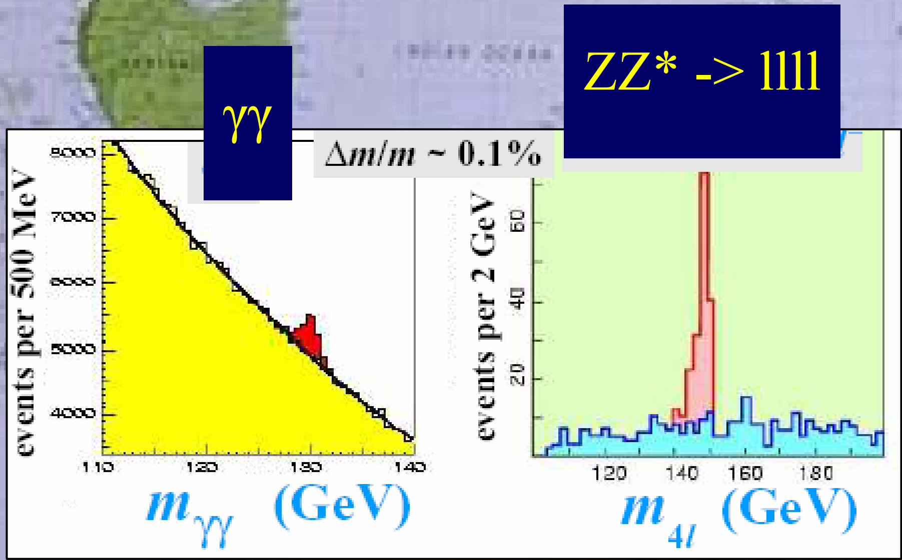


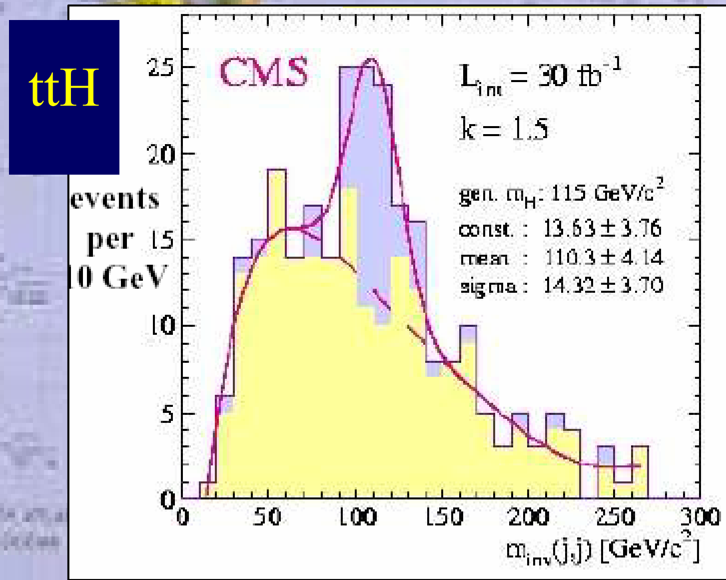


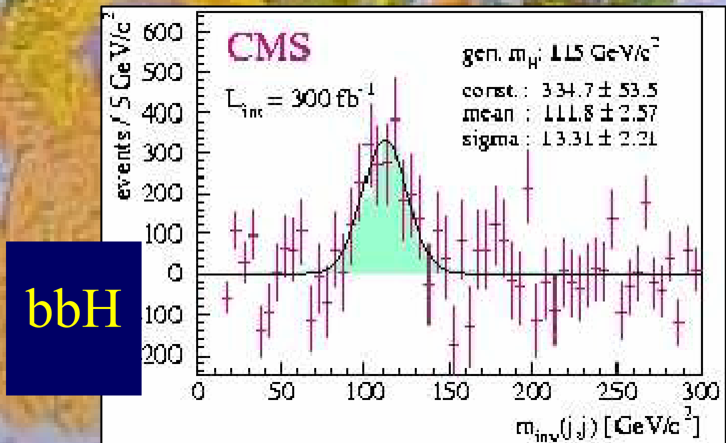
A Simulated Higgs Event in CMS



Some Sample Higgs Signals



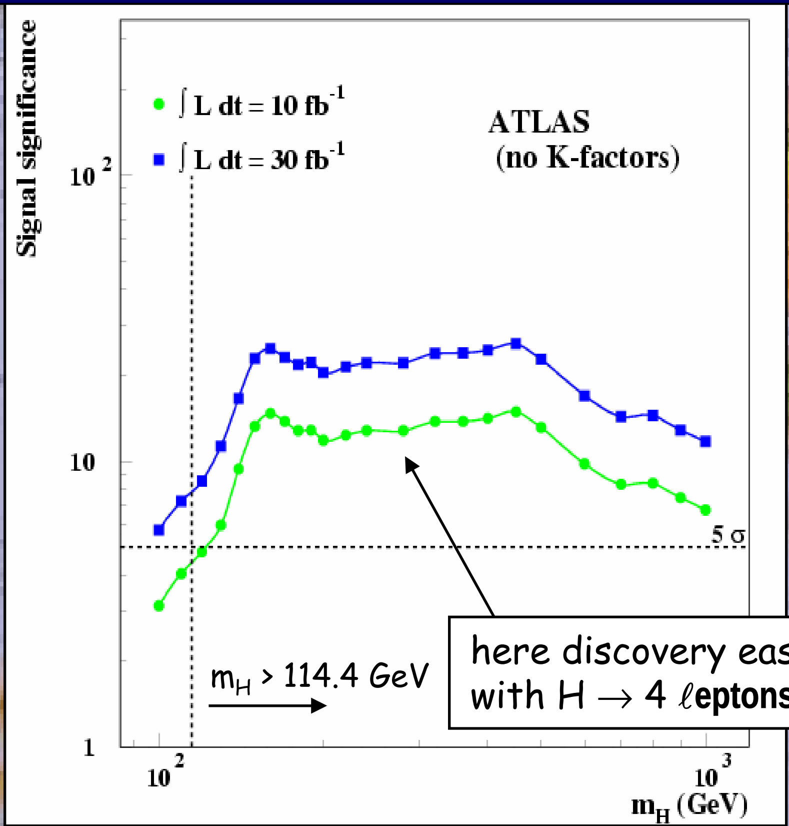




Essential role
for Silicon tracking

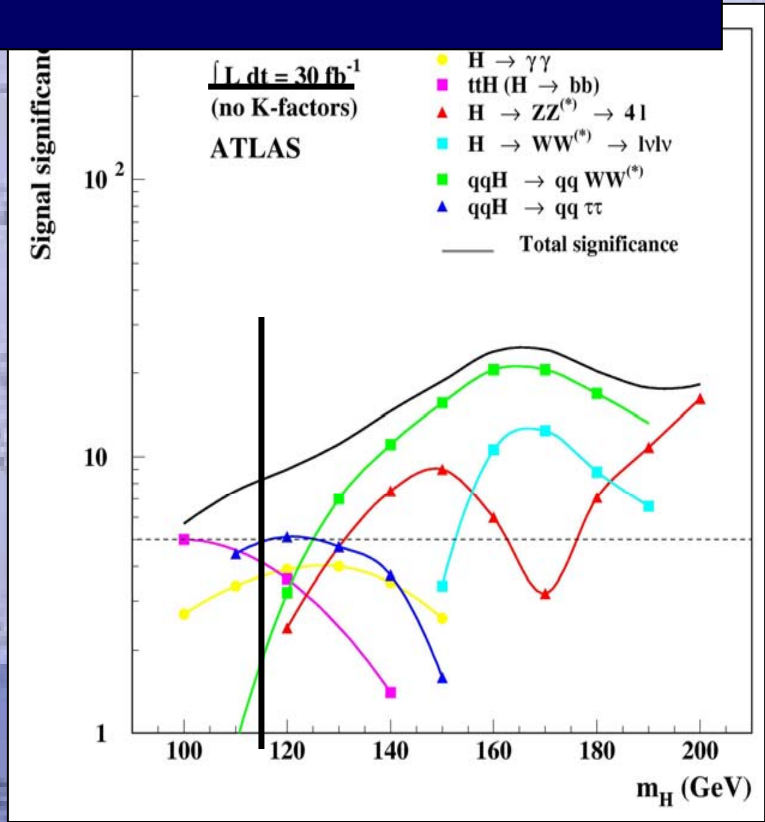
Higgs Detection at the LHC

The Higgs may be found quite quickly …



here discovery easier with H → 4 ℓeptons

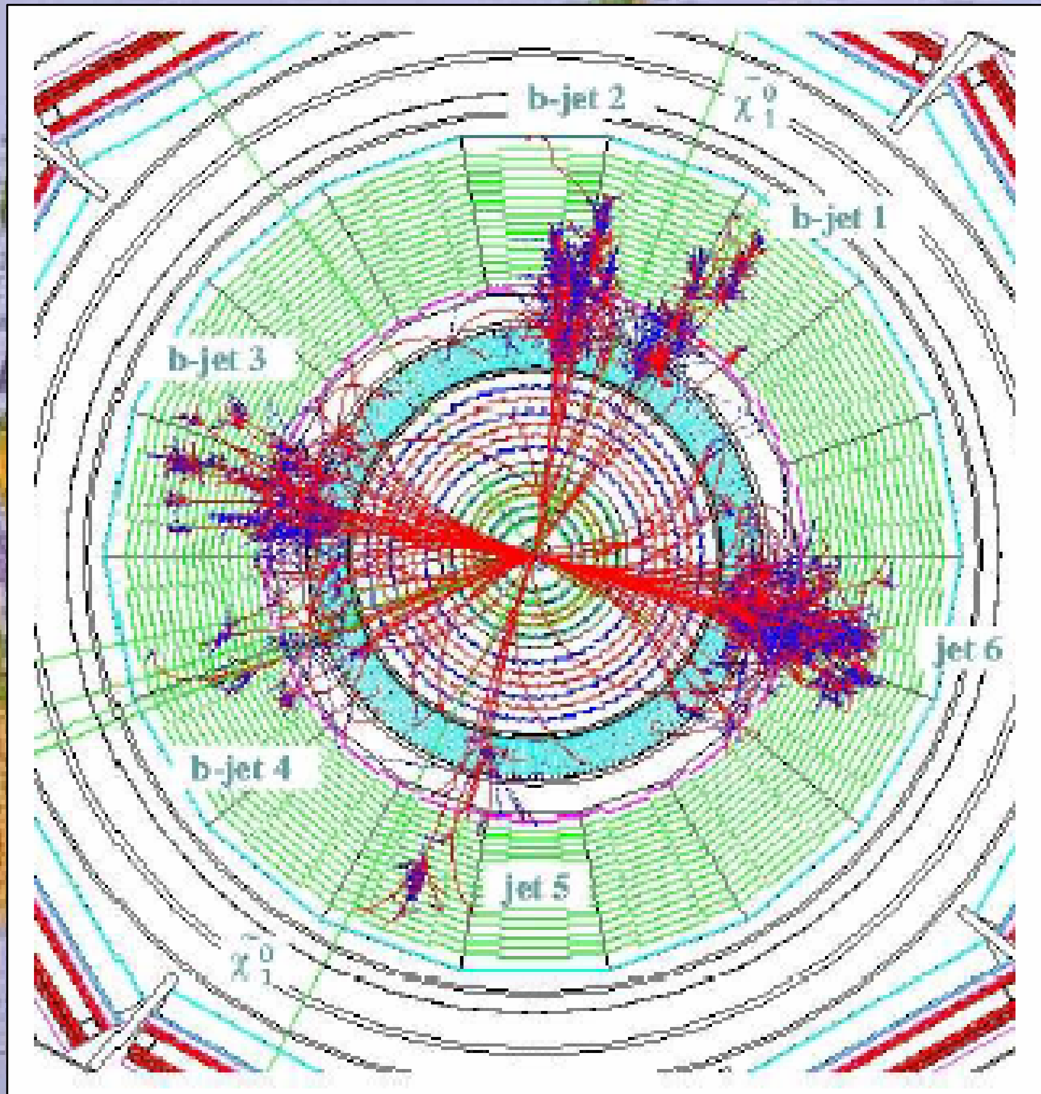
… in several different channels



Supersymmetry Searches at LHC

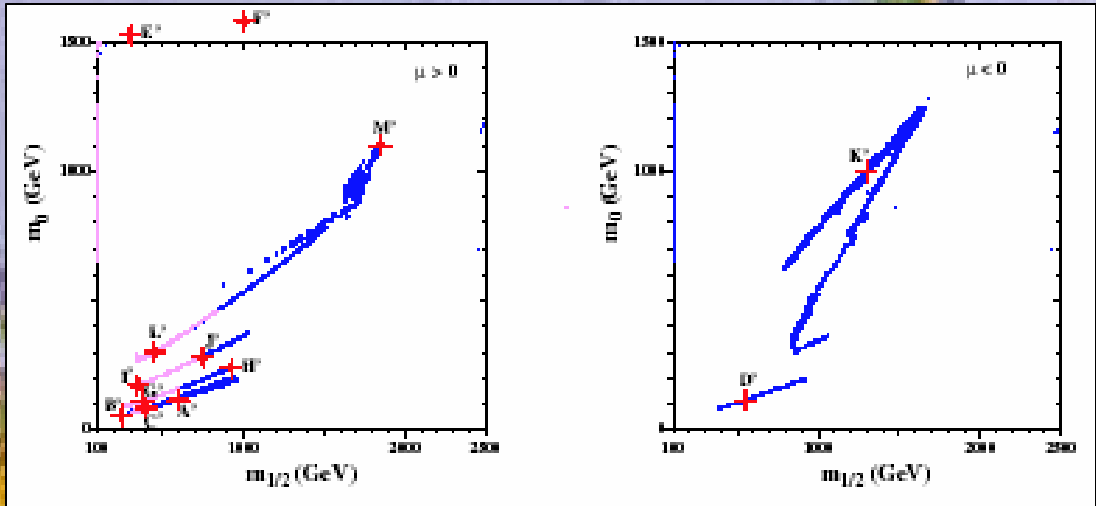
`Typical' supersymmetric Event at the LHC

Can cover most possibilities for astrophysical dark matter



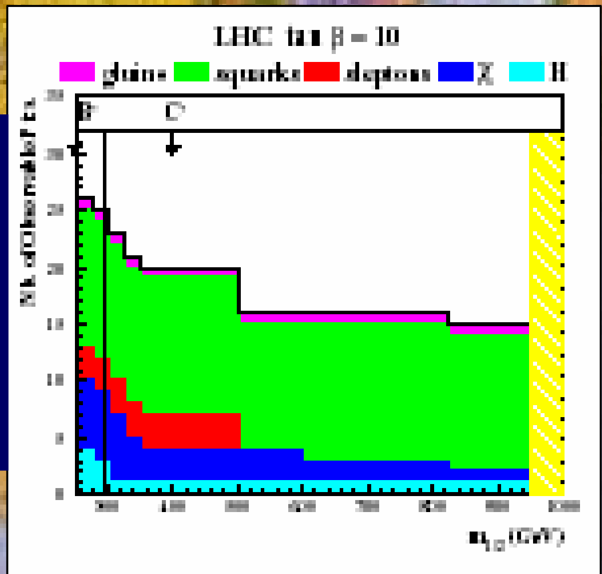
Supersymmetric Benchmark Studies

Lines in susy space allowed by accelerators, WMAP data

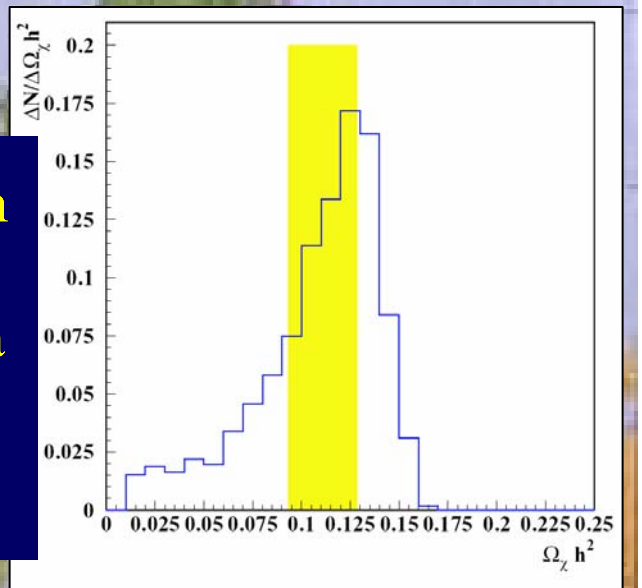


Specific benchmark Points along WMAP lines

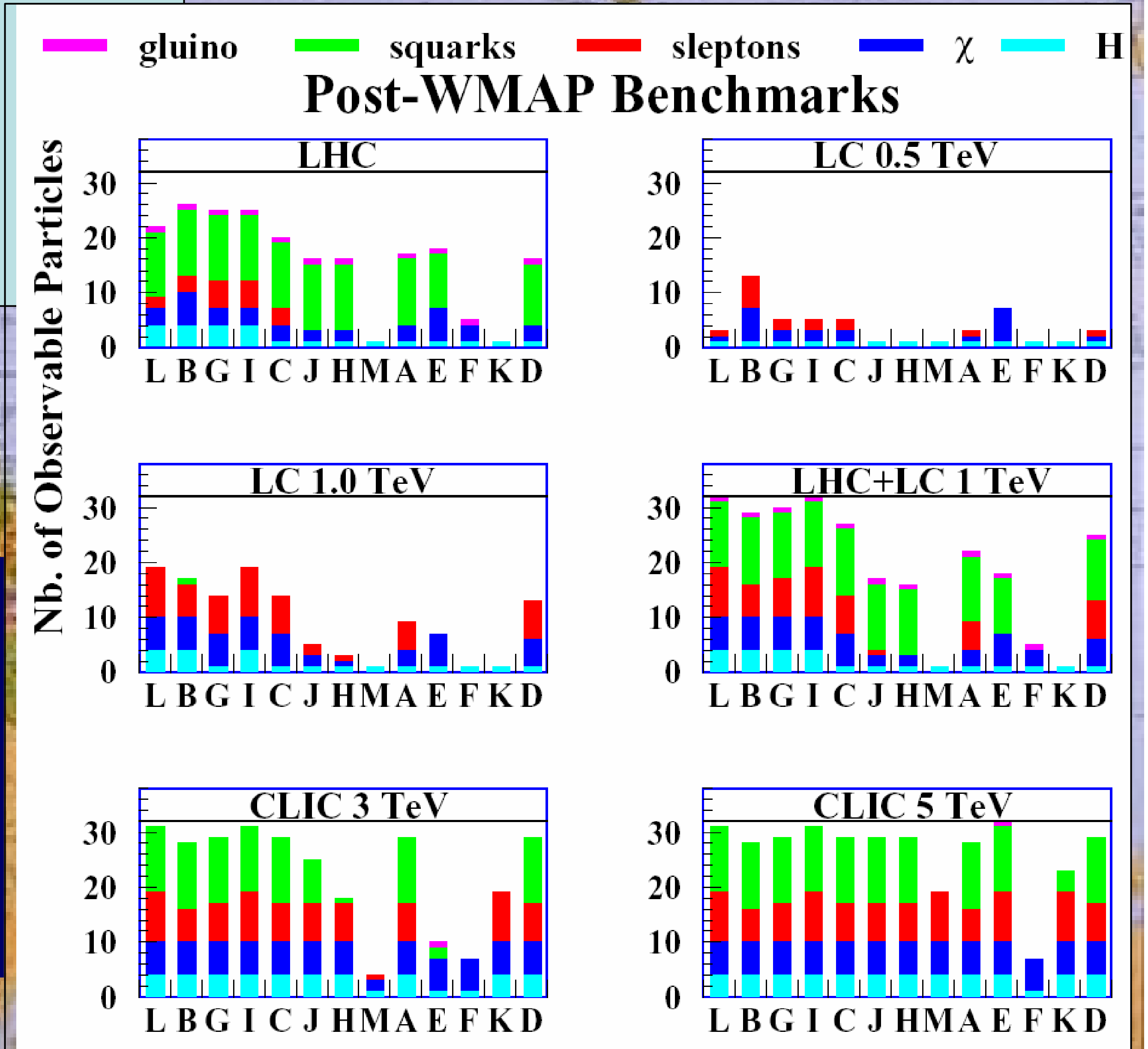
Sparticle detectability Along one WMAP line



Calculation of relic density at a benchmark point



Summary of LHC Scapabilities … and Other Accelerators



LHC almost
`guaranteed'
to discover
supersymmetry
if it is relevant
to the mass problem

How do Matter and Antimatter Differ?

Dirac predicted the existence of antimatter:

- same mass
- opposite internal properties:
  - electric charge, …

Discovered in cosmic rays

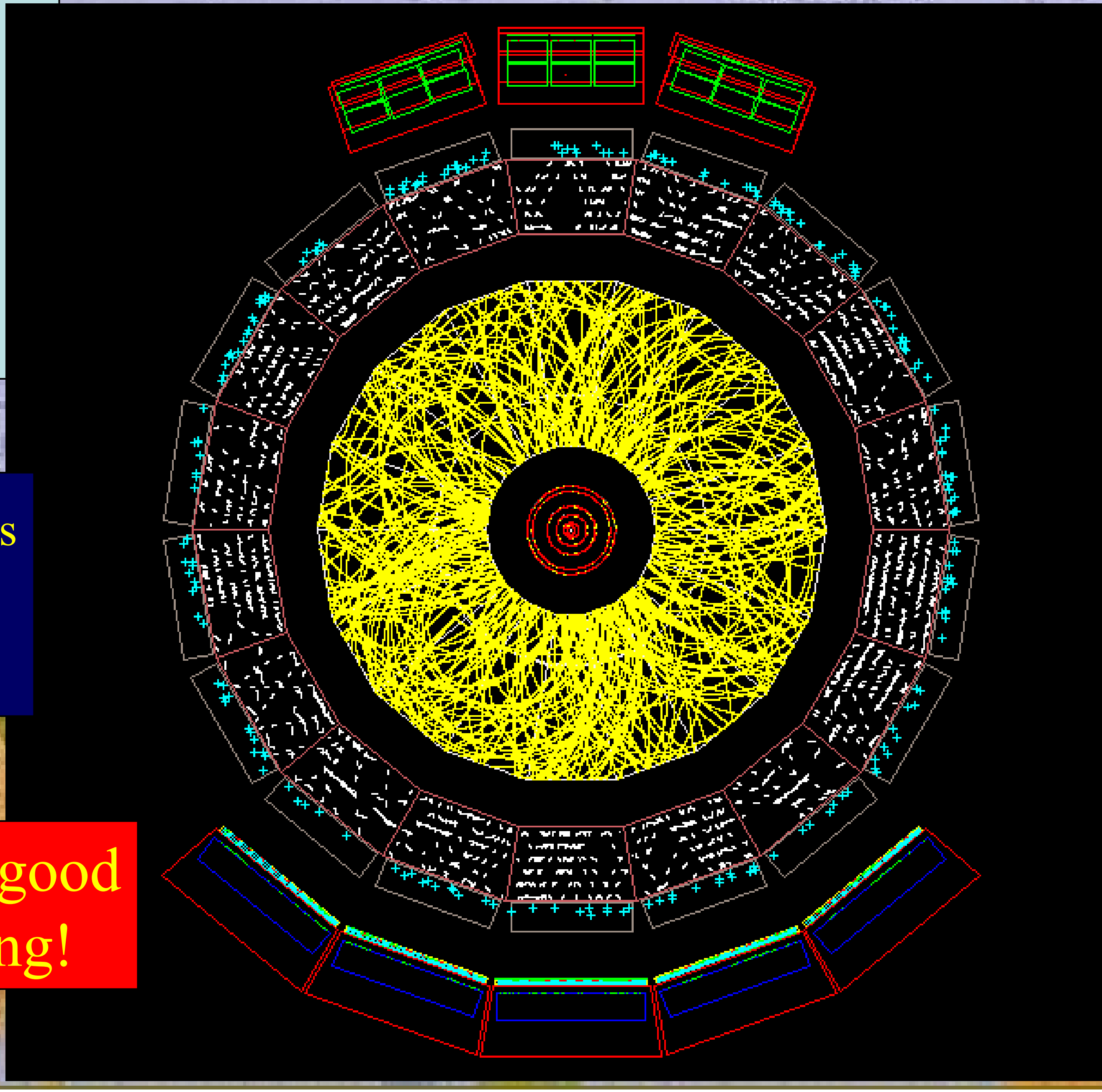
Studied using accelerators

Matter and antimatter not quite equal and opposite: WHY?

Why does the Universe mainly contain matter, not antimatter?

Experiments on B particles at LHC will look for answers

‘Typical’ Heavy-Ion collision at the LHC

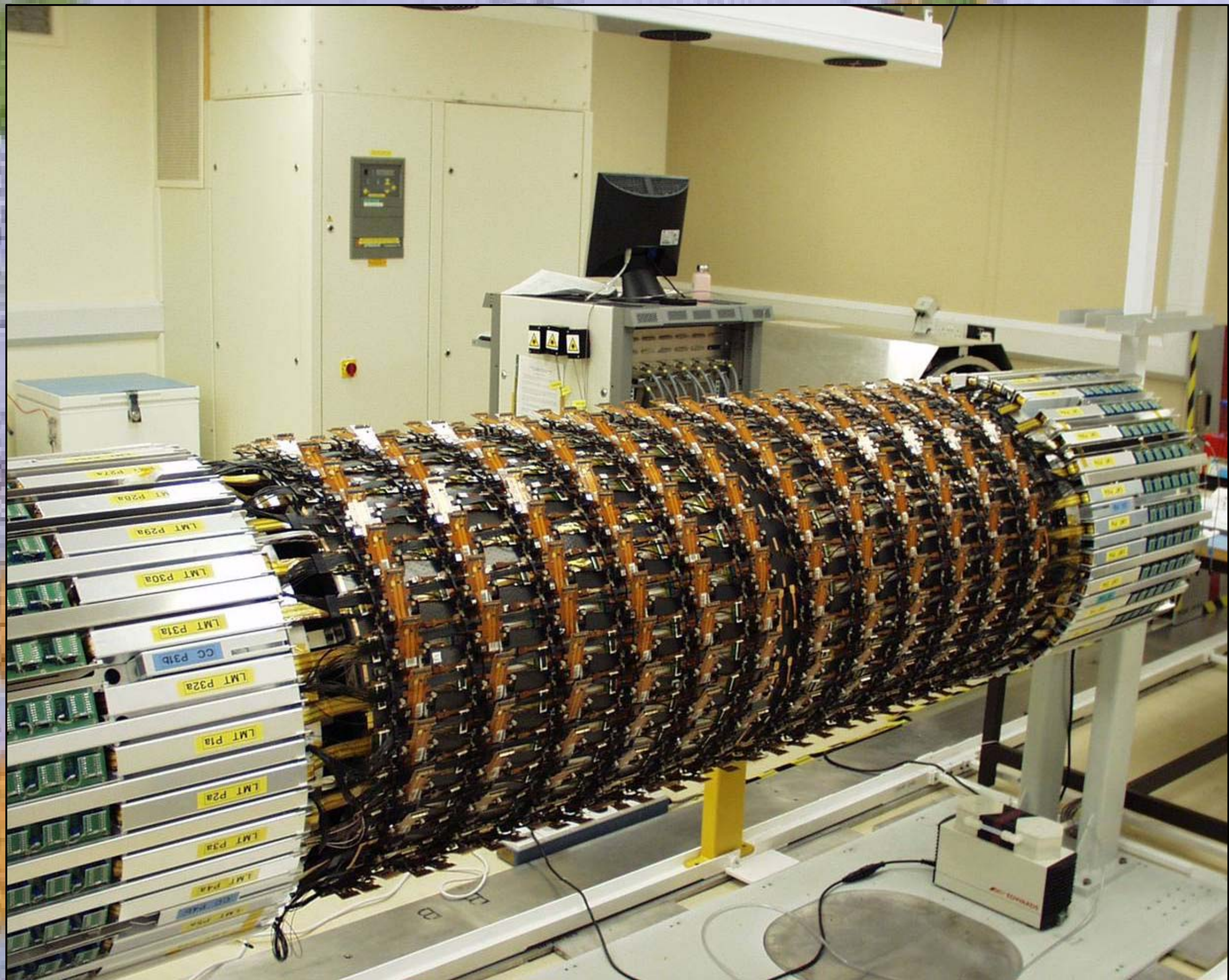


8000 particles in the central detector ?

Need good tracking!

The Role of Semiconductor Detectors

ATLAS Barrel Silicon Tracker

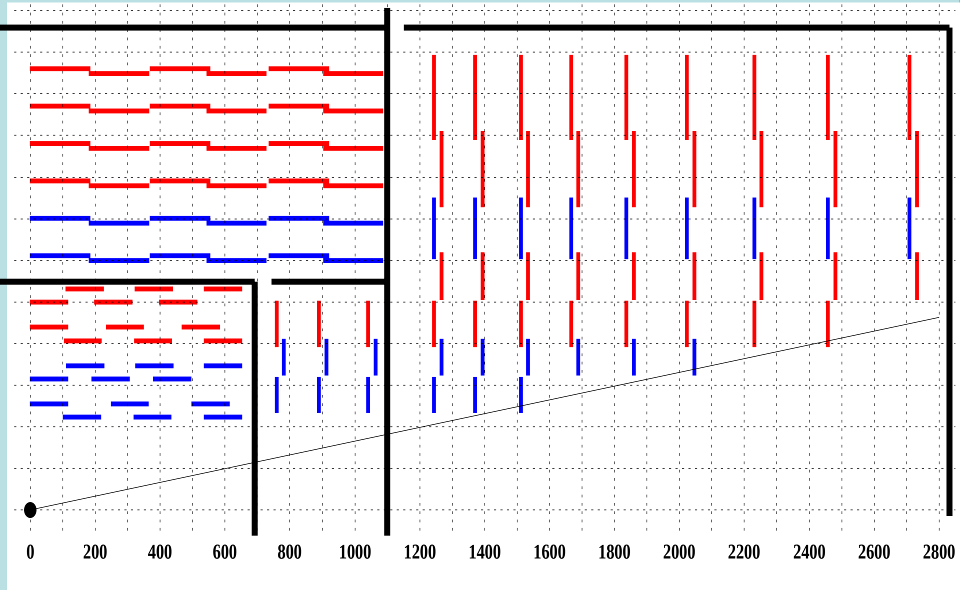


CMS Silicon Tracker

Radius ~ 110cm, Length/2 ~ 270cm

6 layers TOB

4 layers TIB



3 disks TID

9 disks TEC

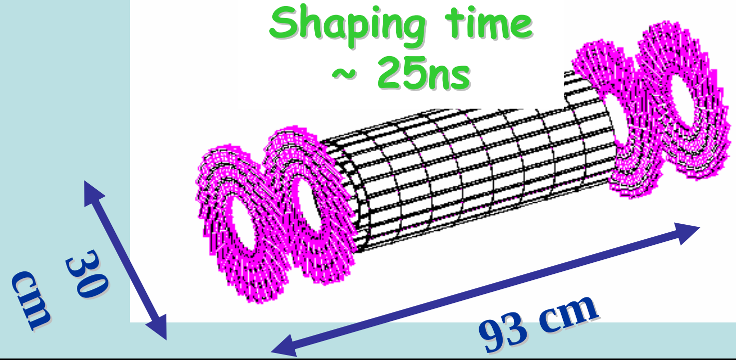
Central role of pixel detectors:

Vertex location
B physics
τ tagging

The region below 20 cm is instrumented with Silicon Pixel Vertex systems

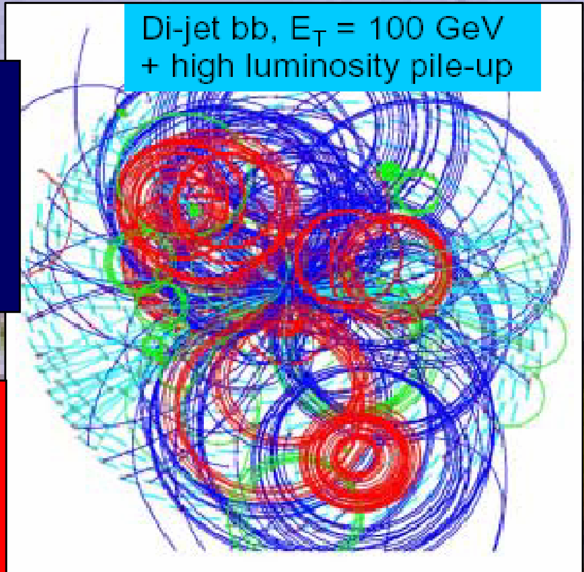
4 10^7 pixels

Shaping time ~ 25ns



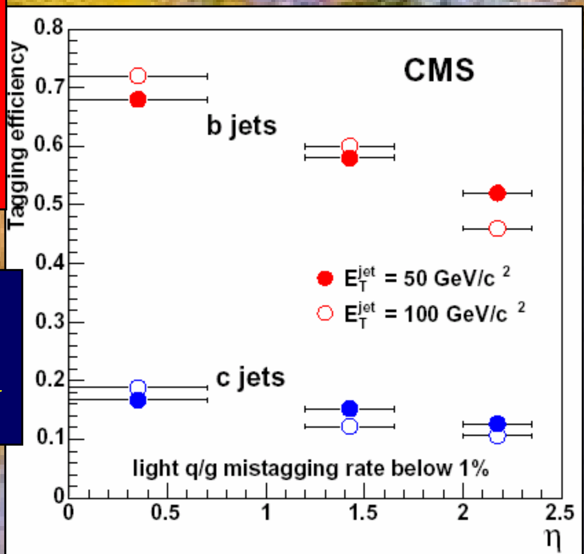
B & τ Tagging

Typical B production event

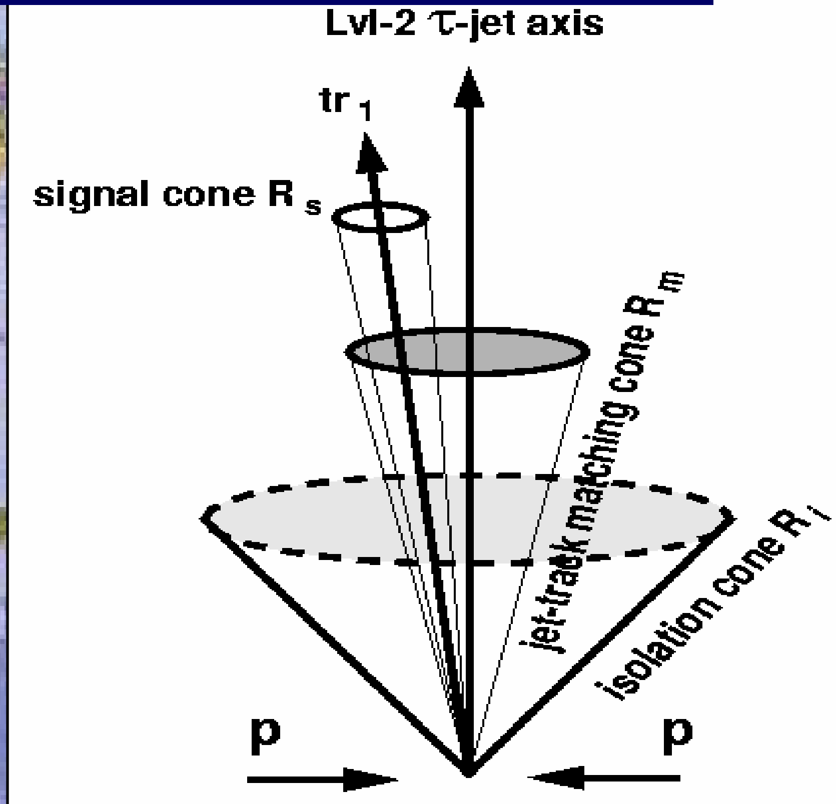


Use the pixels to identify primary vertices

B tagging efficiency



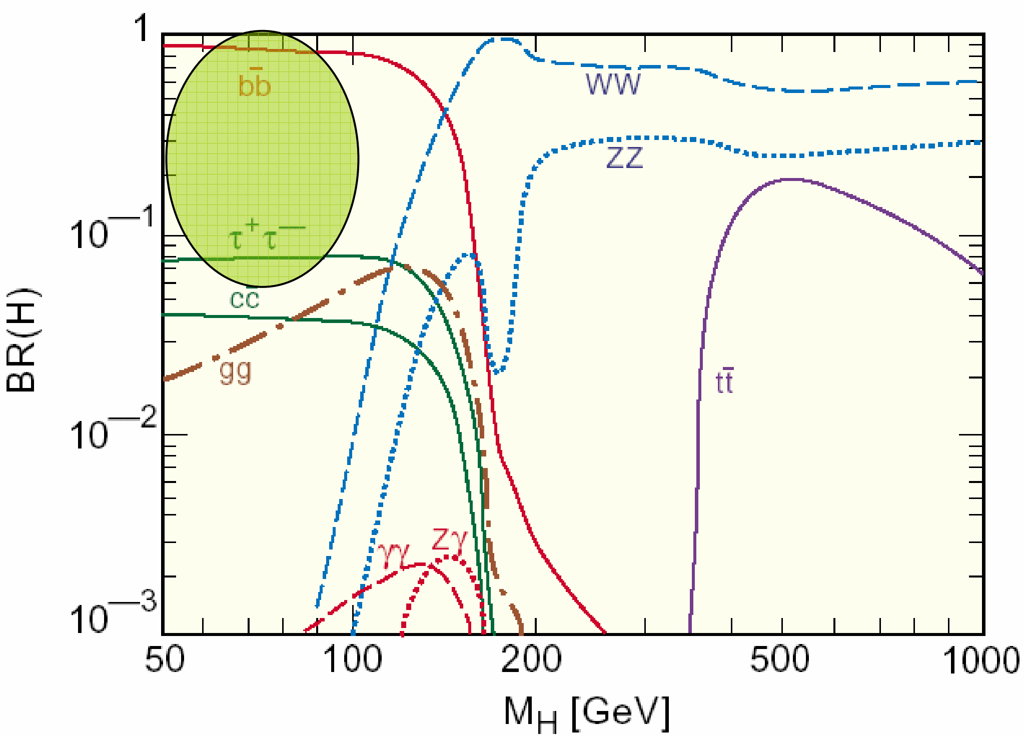
Define τ by track isolation



Importance of B tagging for New Physics

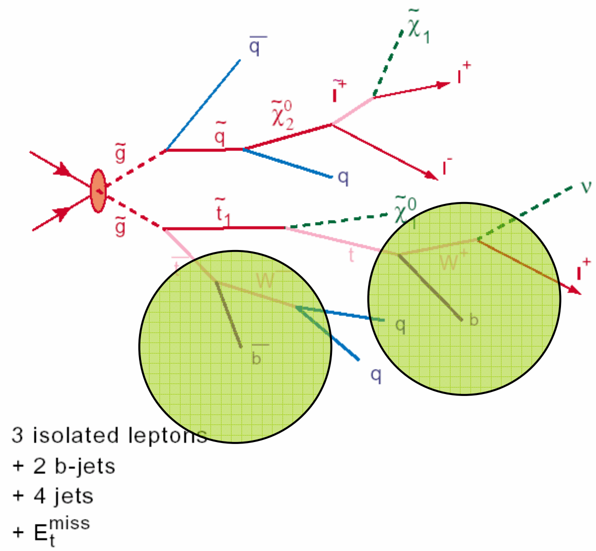
Higgs → bb, ττ decays

SM Higgs
Branching ratios and total decay width



Sparticle cascade decays

Gluino/squark production event topology allowing sparticle mass reconstruction



Such cascade decays allow to reconstruct sleptons, neutralinos, squarks, gluinos... in favorable cases with %level mass resolutions

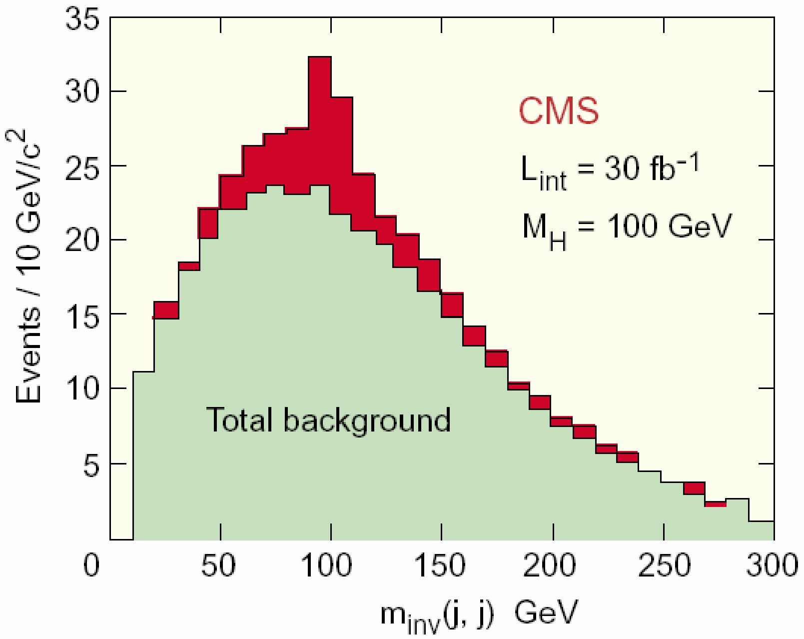
Examples of Physics with B Tagging

Higgs discovery

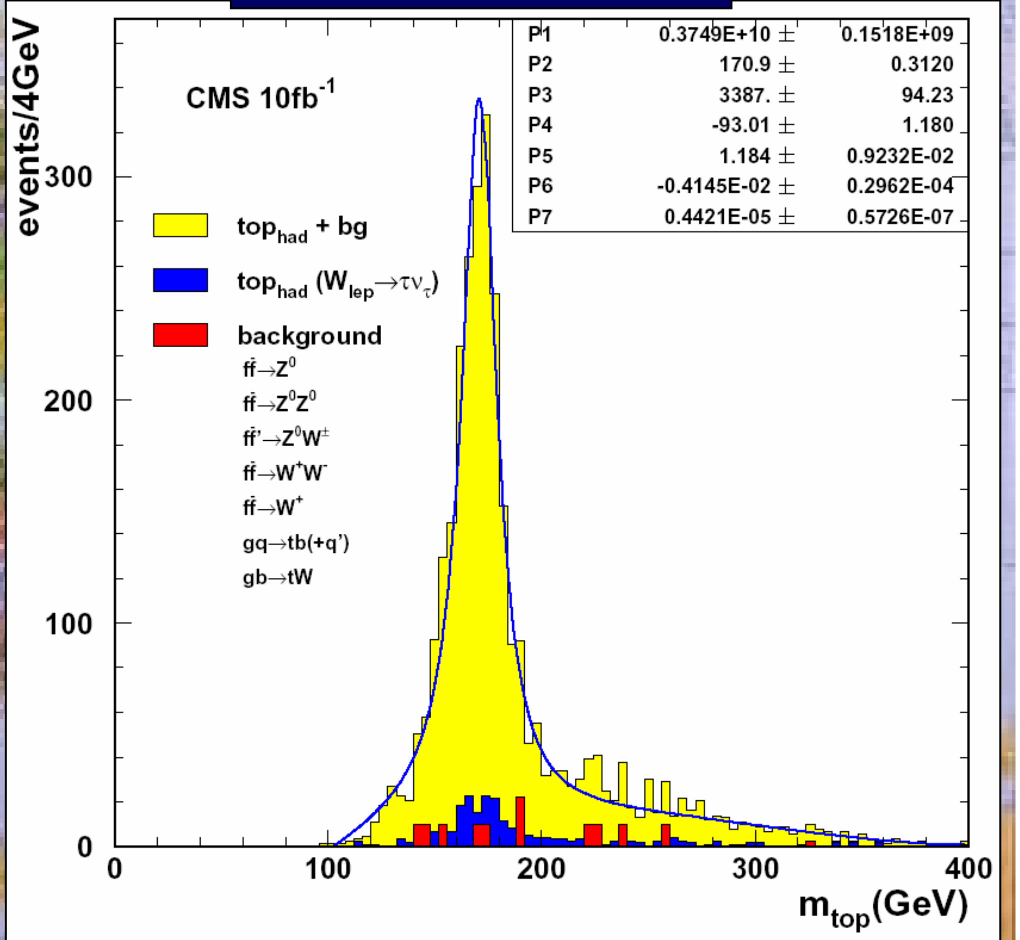
$H^0 \rightarrow b\bar{b}$ in $t\bar{t}H$

$t\bar{t}H \rightarrow \ell\nu\, b\, jj\, \bar{b}\, b\bar{b}$

E_t (jet) > 15 GeV



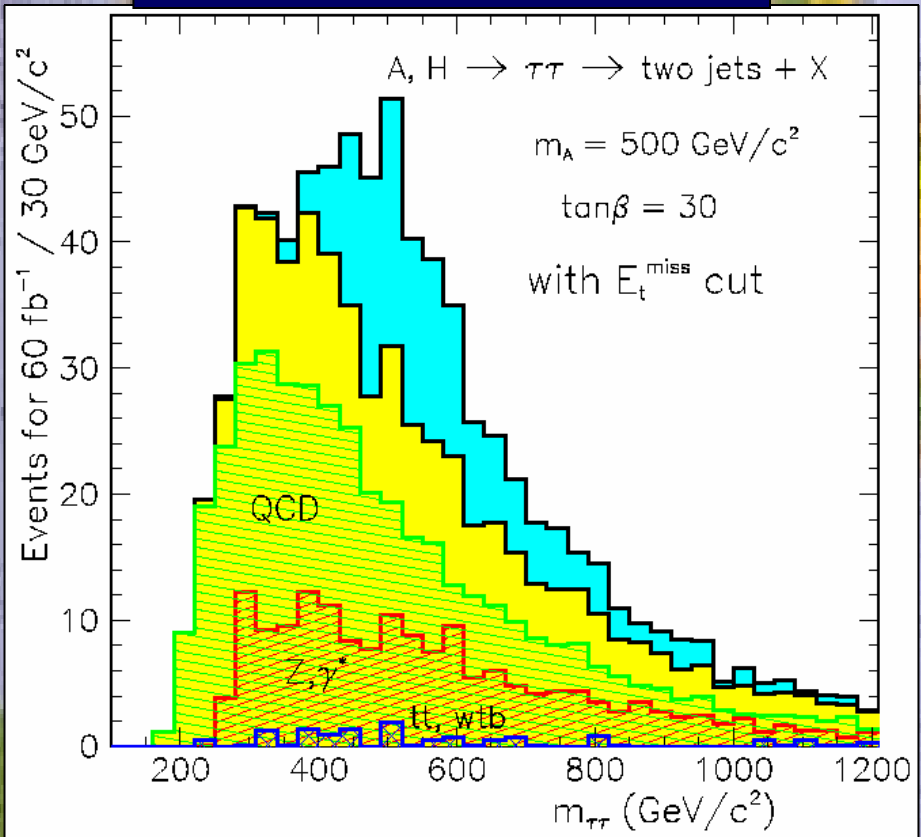
Top measurement



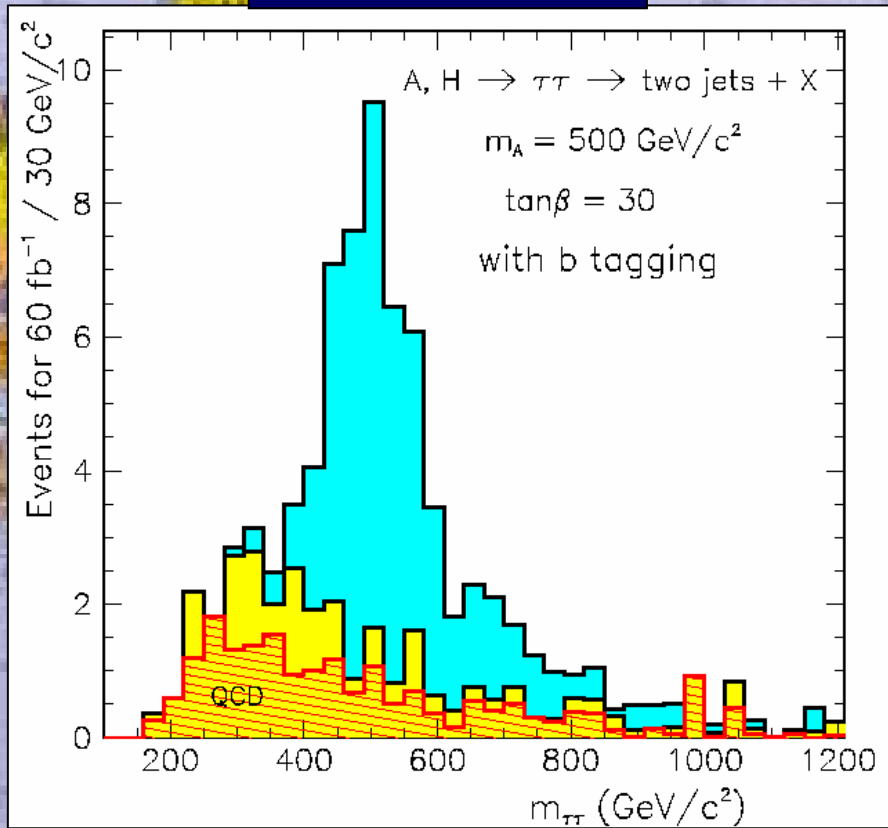
Example of Physics with τ & B Tagging

Heavier supersymmetric neutral Higgs bosons

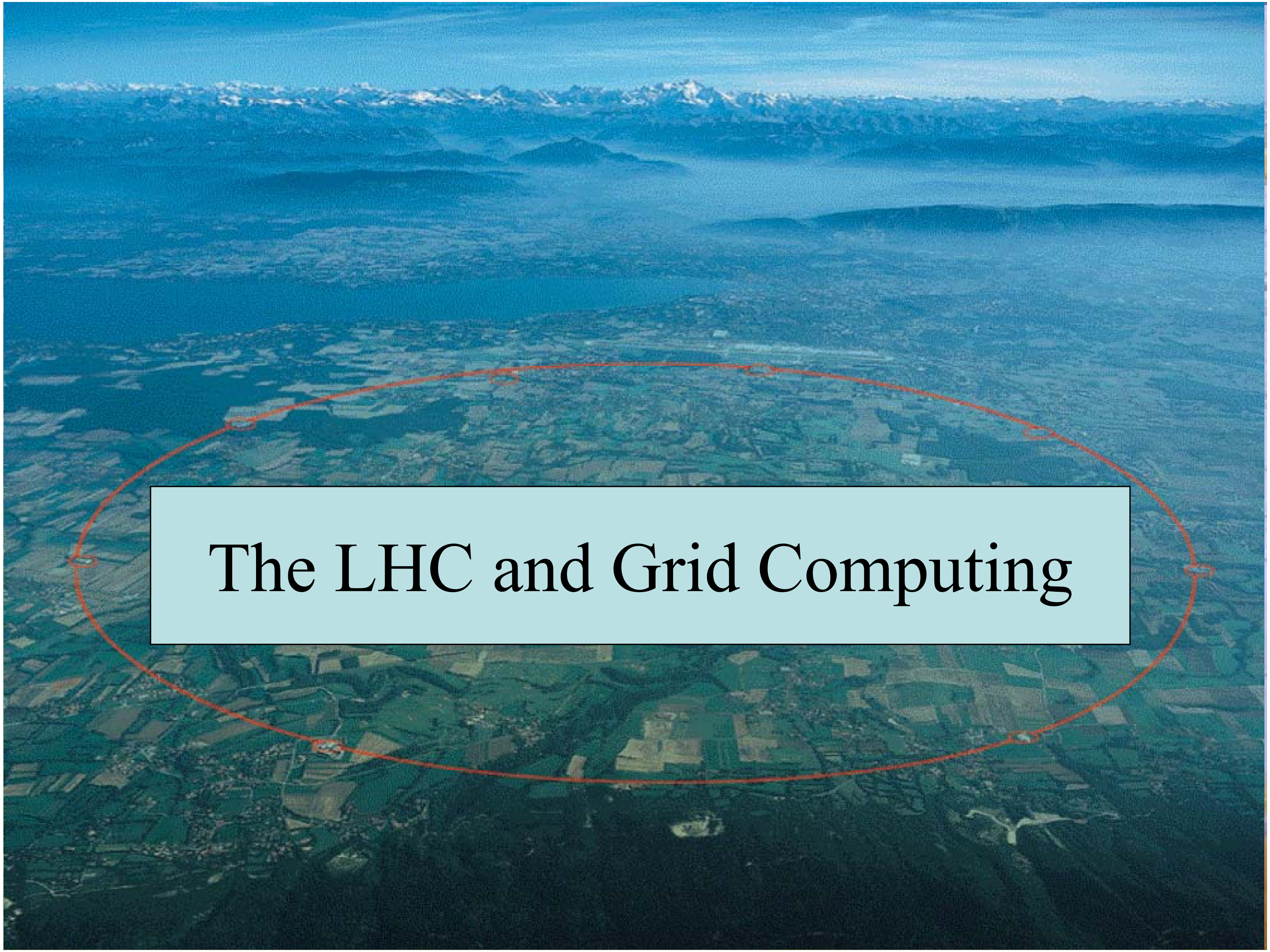
τ tagging, no B tagging



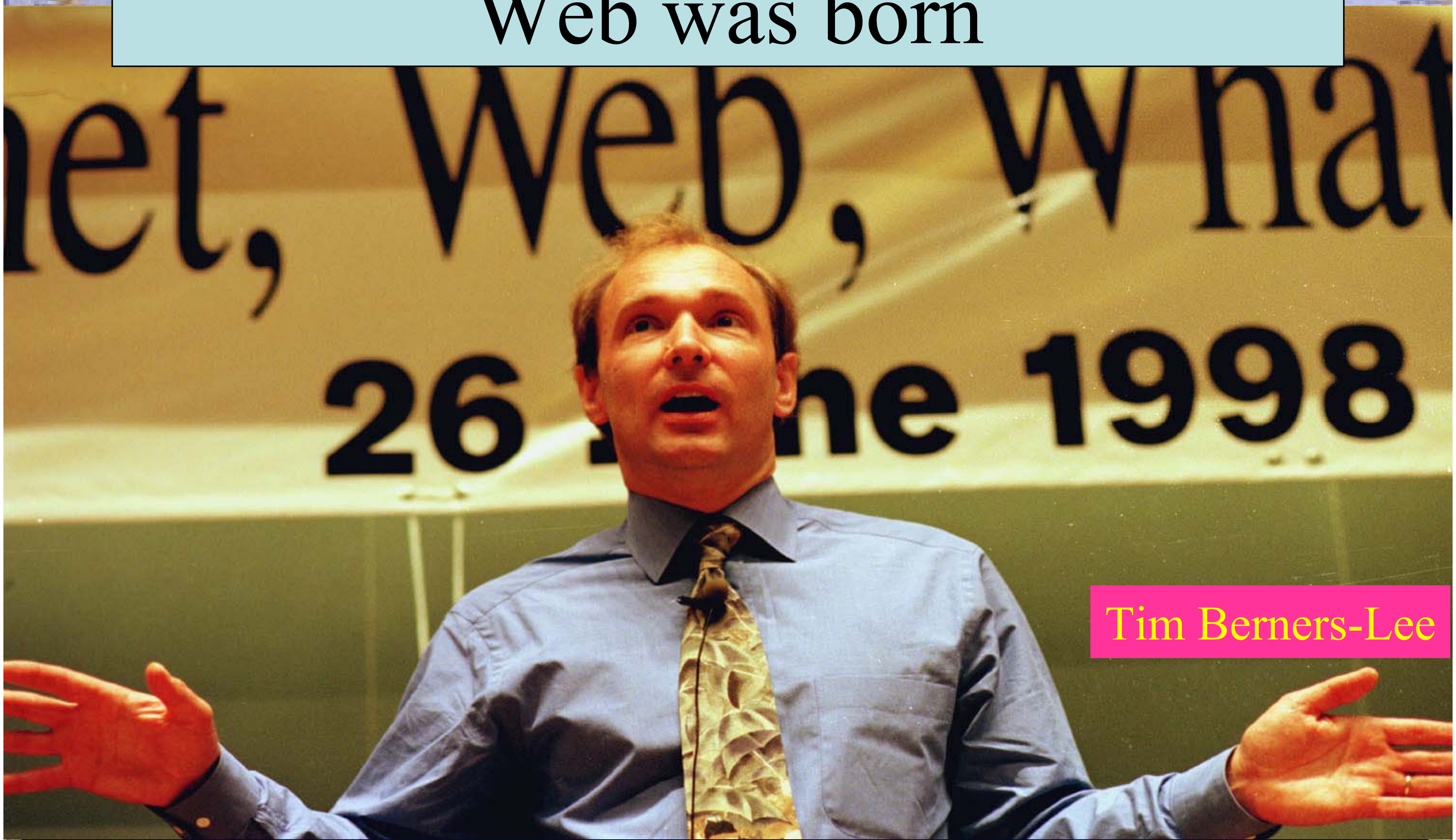
τ & B tagging



The LHC and Grid Computing



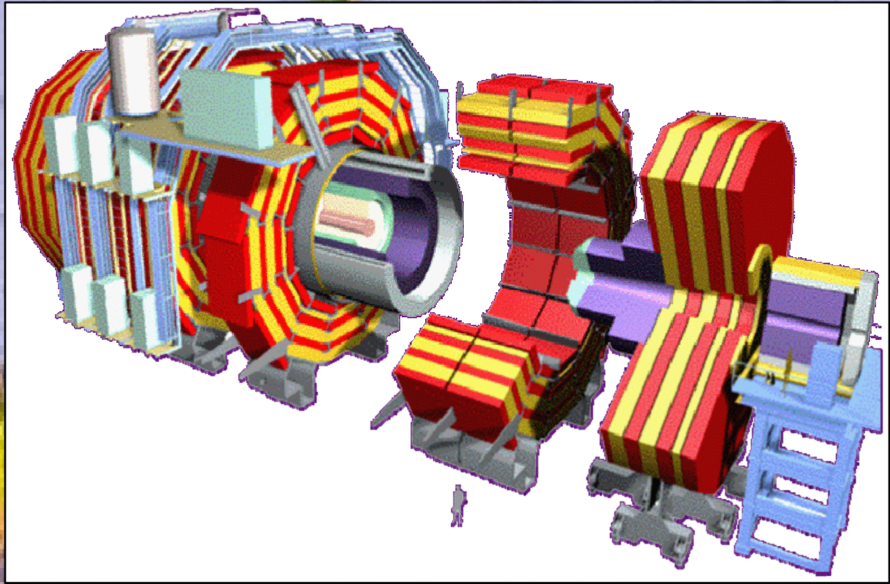
CERN: where the World-Wide Web was born



Tim Berners-Lee

Invented to enable physicists around world to share data: next, the Grid

CERN's World-Wide Web becomes the GRID



The Problem:

- Data-taking rate:

1 Petabyte = Million GigaBytes/second
= Billion people surfing Web
simultaneously
= Trillion digital phone calls
@1-2 kiloBytes/sec

- Data storage:

12 Petabytes/yr = 100,000 desktop PCs

The Strategy: transparent user access to data, programs and computing power anywhere in the world

Other applications: Environmental science, human genome, …

LHC Computing Grid (LCG)

Mission:

• Grid deployment project aimed at installing a functioning Grid to help the LHC experiments collect and analyse the data coming from the detectors

Strategy:

• Integrate thousands of computers at dozens of participating institutes worldwide into a global computing resource

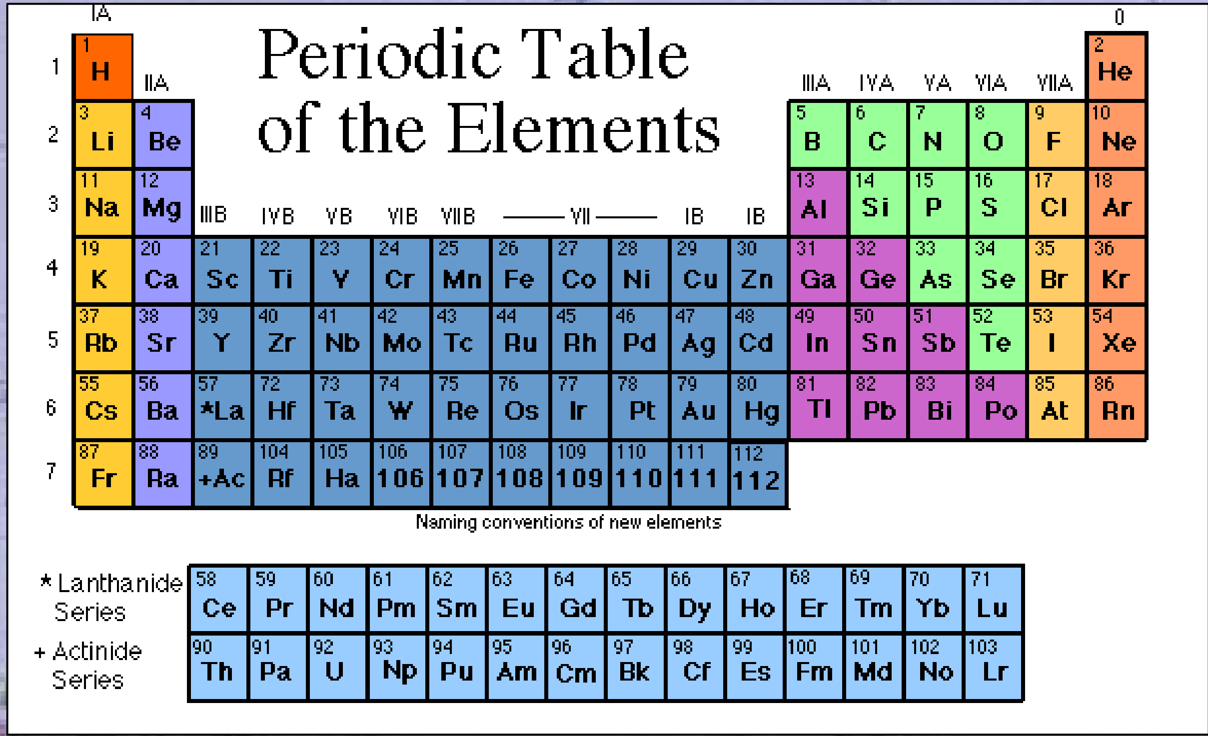
• Rely on software being developed in advanced grid technology projects, in Europe and elsewhere

The LHC will Probe New Dimensions of Physics

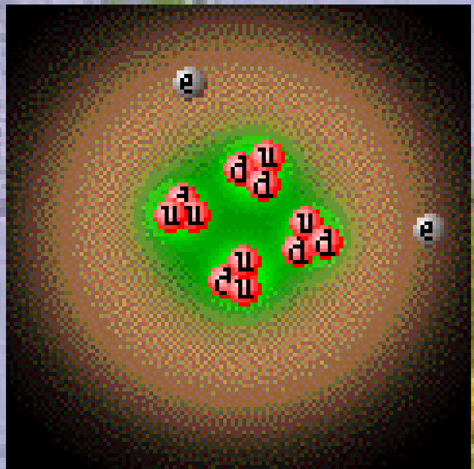
- A new dimension in energy: ~ TeV
  - Origin of mass ?
- New dimensions of space ?
  - More familiar 'bosonic' dimensions ?
  - Supersymmetric 'quantum' dimensions ?
- New dimension of time
  ~ 10^{-12} sec after Big Bang
  - Primordial soup ?
  - Dark matter ?
  - Origin of matter ?

… and semiconductor detectors will play an essential role

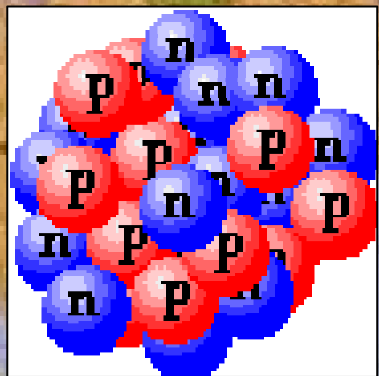
All the different Elements …



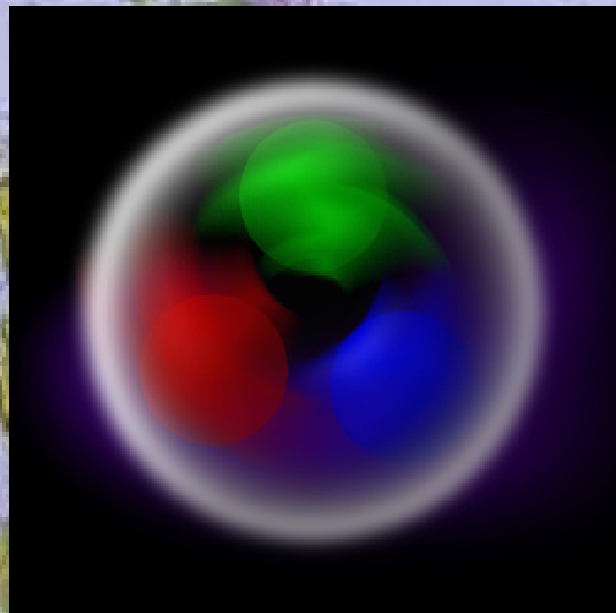
… are made of atoms …



… whose nuclei contain Protons & Neutrons …



… whose structure we study at CERN

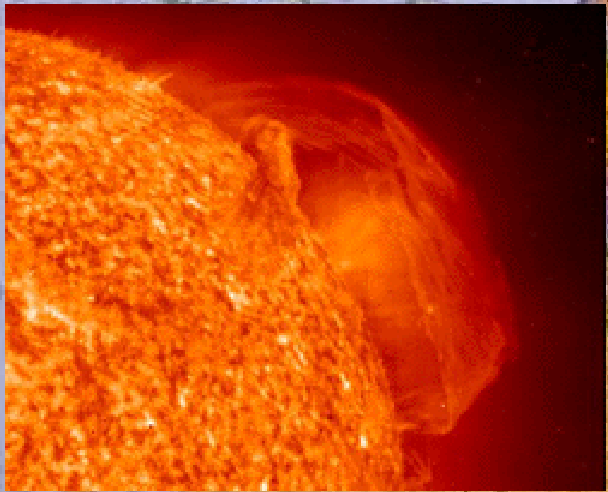


The Fundamental Forces of Nature

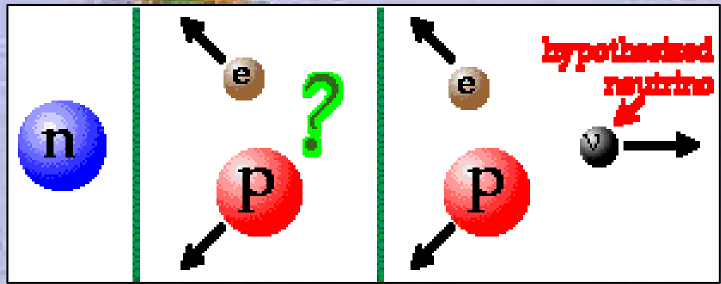
Electromagnetism:
gives light, radio, holds atoms together

Strong Nuclear Force:
holds nuclei together

Weak Nuclear Force:
gives radioactivity

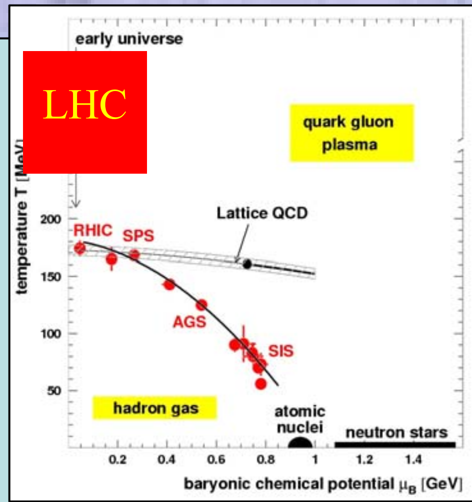


together they make the Sun shine

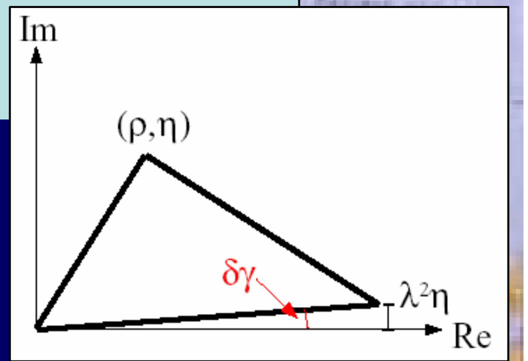


Gravity:
holds planets and stars together

… and New Opportunities for other Explorations



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



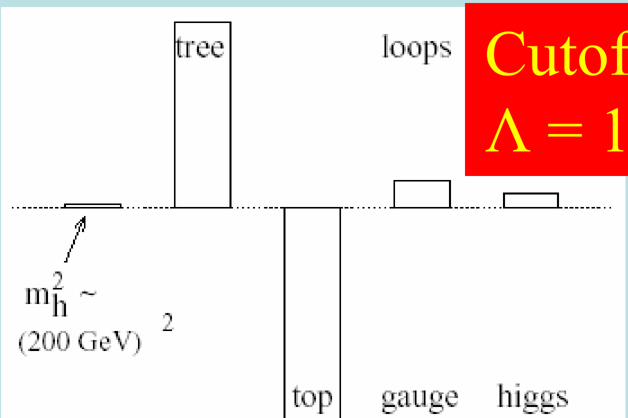
- Connections with cosmology
  - Inflation and dark matter
  - early Universe and the origin of matter

Elementary Higgs or Composite?

- Higgs field:

  <0|H|0> =/= 0

- Quantum loop problems



Cutoff
Λ = 10 TeV

- Cut-off Λ ~ 1 TeV with

  Supersymmetry?

- Fermion-antifermion condensate
- Just like QCD, BCS superconductivity
- Top-antitop condensate? needed m_t > 200 GeV

- New technicolour force? inconsistent with precision electroweak data?