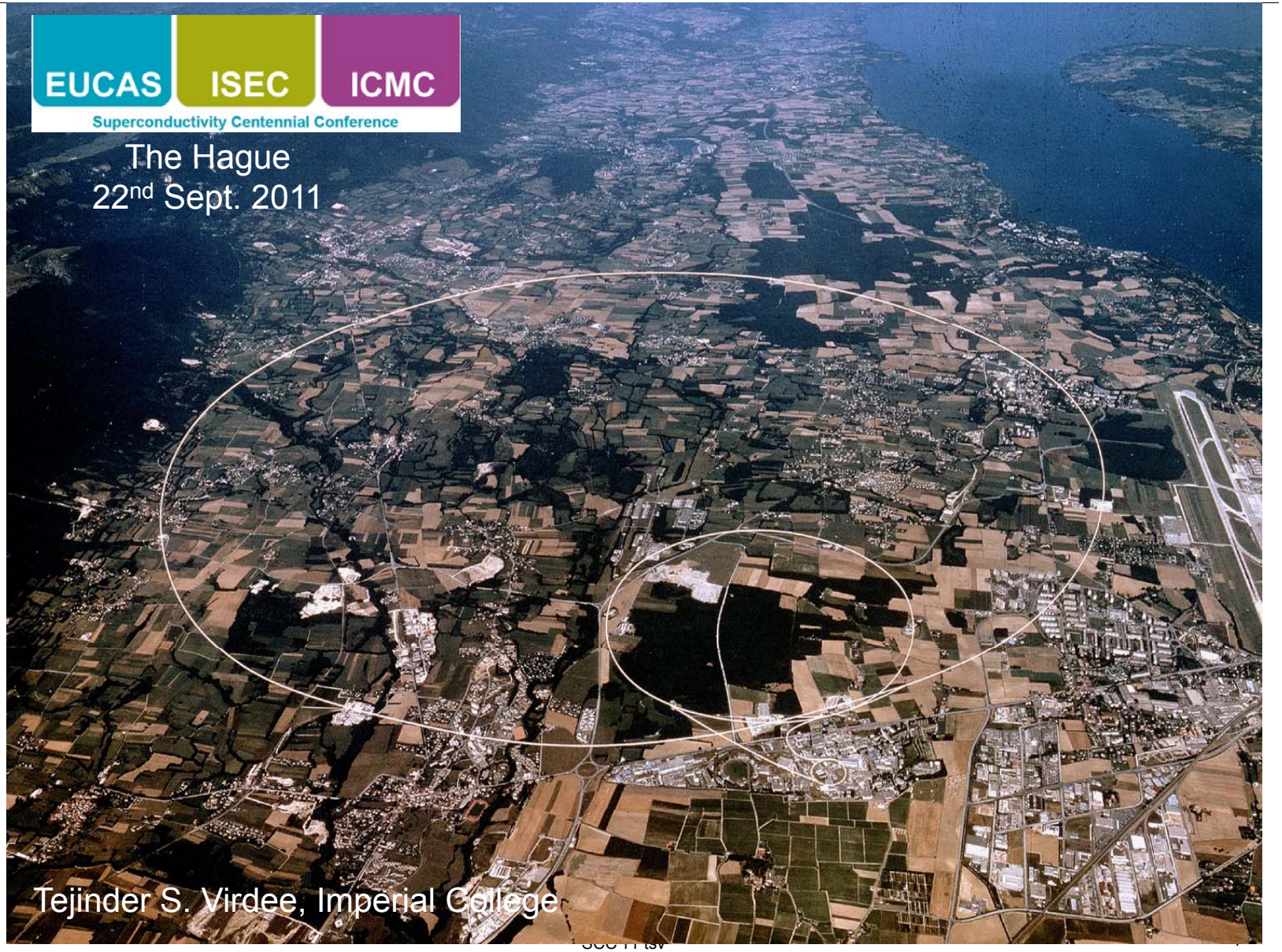
The Large Hadron Collider Project and Superconductivity



Particle Physics

Particle physics is a modern name for centuries old effort to understand the laws of nature.

E. Witten

Aims to answer the two following questions:

What are the elementary constituents of matter ?

What are the forces that control their behaviour at the most basic level?

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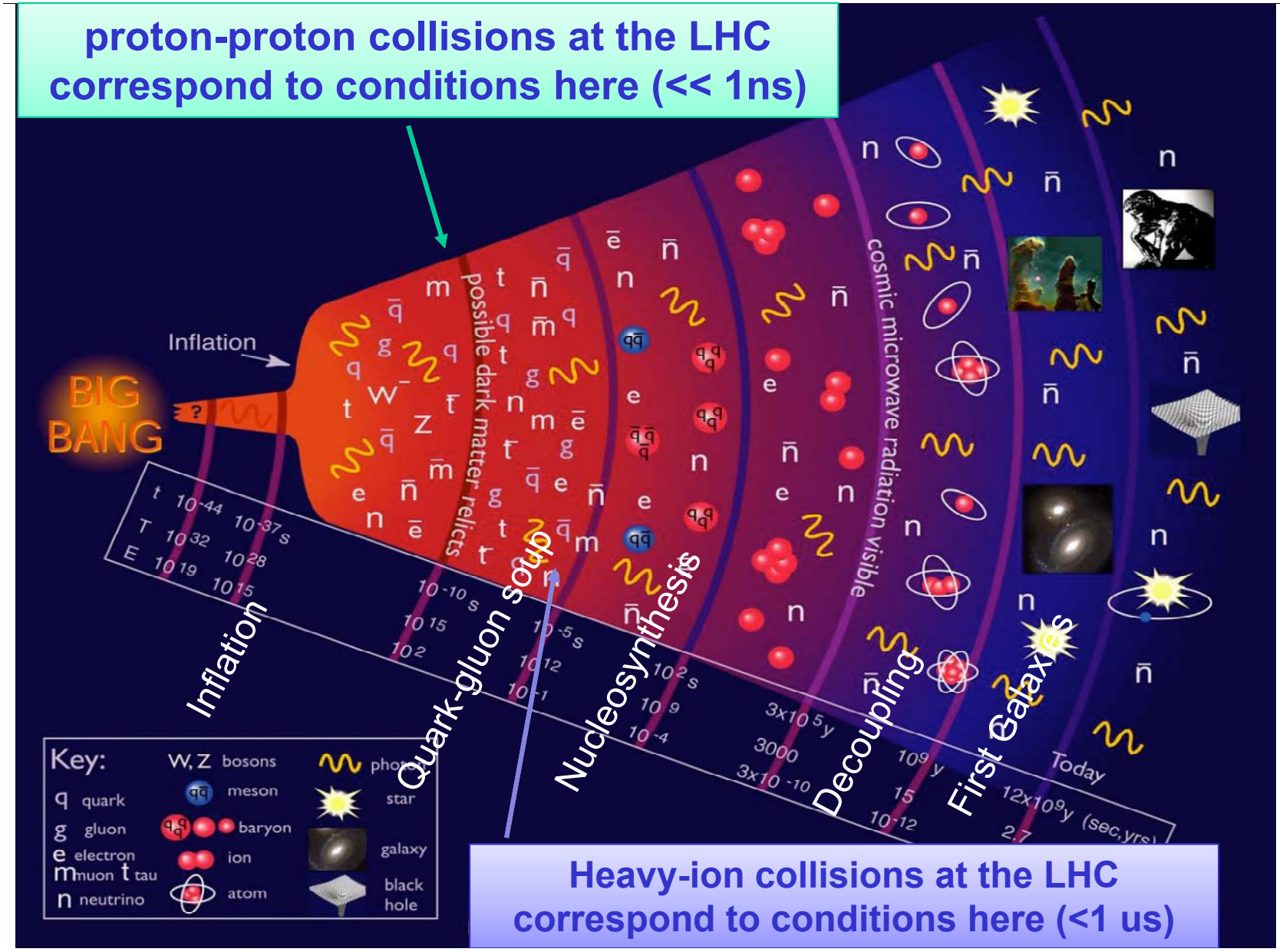
Brief History of Our Universe



Particle Accelerators

accelerate particles to extremely high energies.

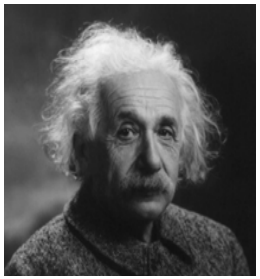
High energies allow us

i) To look deeper into Nature (E α 1/size), ("powerful microscopes")

ii) To discover new particles with high(er) mass ($E = mc^2$)

iii) Study the young universe (E= kT)

de Broglie



Einstein

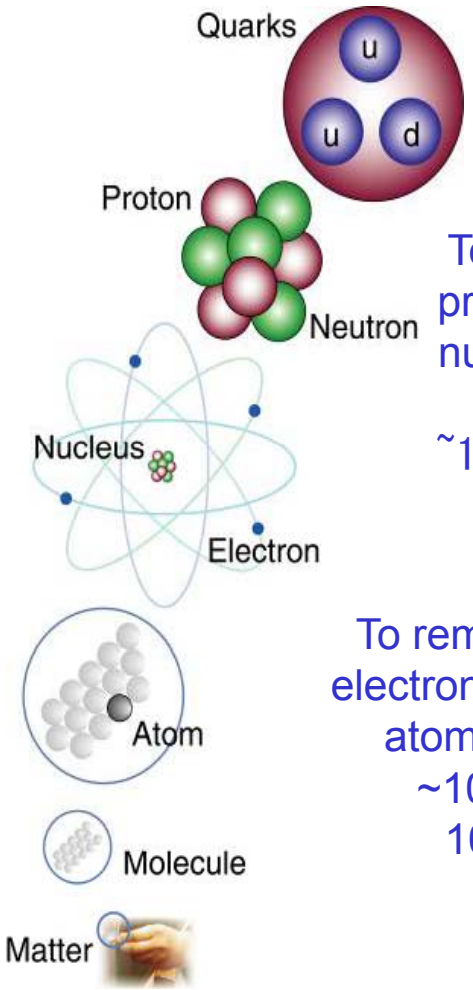
Boltzmann

Revisit the earlier moments of our ancestral universe ("powerful telescopes"),
to observe phenomena and particles normally no longer observable in our everyday experience.

All in a controlled way - "in the laboratory"

Matter and Forces

Matter



To remove a proton from a nucleus need ~10 MeV ~10 million ×

To remove an electron from an atom need ~10 eV 10 ×

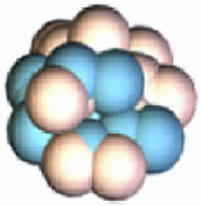
Forces

Strong

Gluons (8)

Quarks

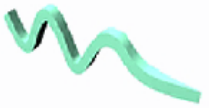
Mesons
Baryons

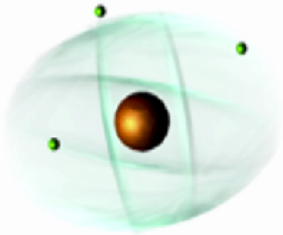


Nuclei

Electromagnetic

Photon





Atoms
Light
Chemistry
Electronics

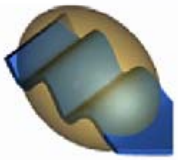
Gravitational

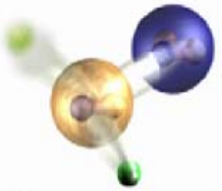
Graviton ?

Solar system
Galaxies
Black holes

Weak

Bosons (W,Z)





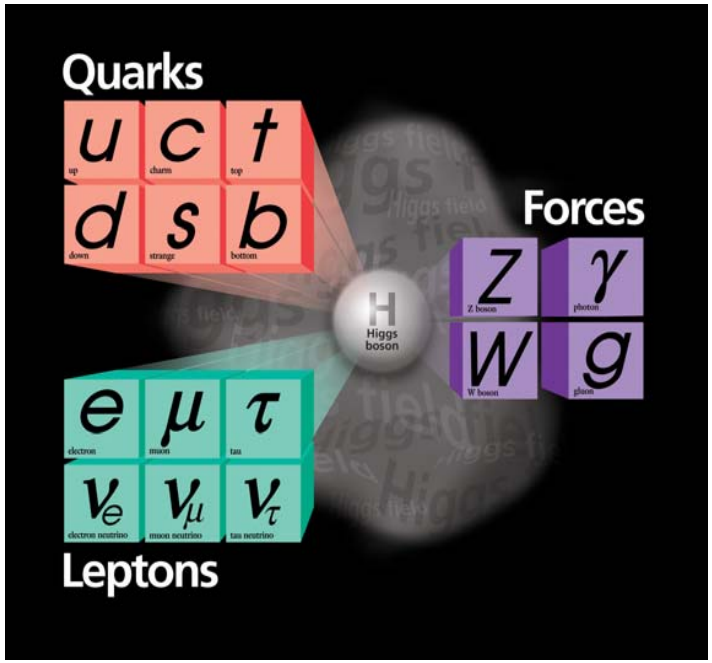
Neutron decay
Beta radioactivity
Neutrino interactions
Burning of the sun

All forces in the world can be attributed to these four interactions

The "Standard Model"

Over the last 100 years: combination of
Quantum Mechanics and Special Theory of relativity
along with all new particles discovered has led to the
Standard Model of Particle Physics.
The new (final?) "Periodic Table" of fundamental elements

Matter particles

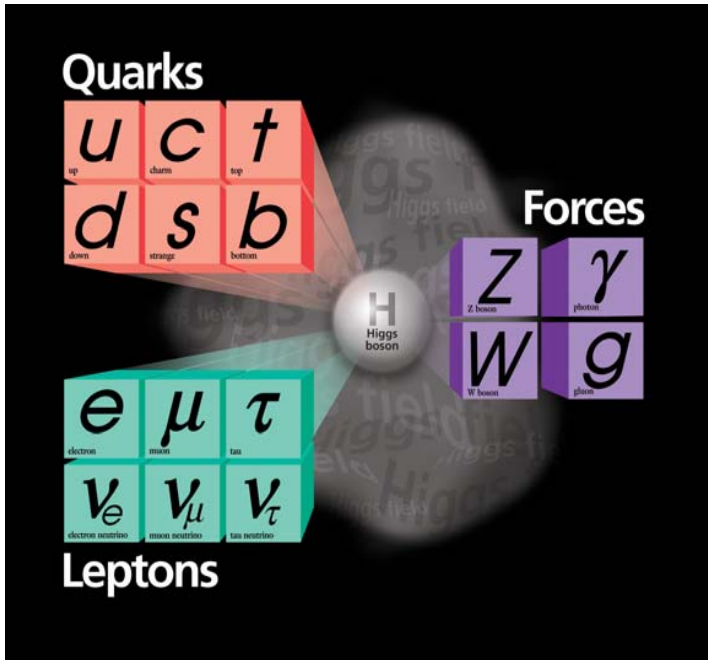


Force particles

- **Matter is composed of fermions (6 quarks and 6 leptons)**
- **Three families of fermions of increasing masses, « normal » matter is made of the first family**
- **Interactions (strong nuclear, electromagnetic, weak) are carried by exchange of bosons (gluons, photons, weak bosons)**
- **Very successful description of nature, good precision**

The "Standard Model"

Over the last 100 years: combination of
Quantum Mechanics and Special Theory of relativity
along with all new particles discovered has led to the
Standard Model of Particle Physics.
The new (final?) "Periodic Table" of fundamental elements



A crowning achievement of 20th Century Science

The SM has been tested thousands of times, to excellent precision. Yet, its most basic mechanism, that of granting mass to particles, the Higgs boson (?), is still missing!

And where is GRAVITY?

Physics at LHC

Why does anything have substance?

Following on from Newton... what is **mass**?

Hunting the Higgs boson

Are there more particles to find?

Are matter and force particles different?

Supersymmetry: uniting the forces

What is the universe really made of?

An enigma for science - the other 96%

Dark Secrets of the Universe

Do we really only live in 3D?

Messages from the **fifth dimension**

String theory and extra dimensions

What was the universe like just after the Big Bang?

Quark-gluon soup?

Colliding heavy ions

What and where is antimatter?

Nature's favouritism

Antimatter detectives

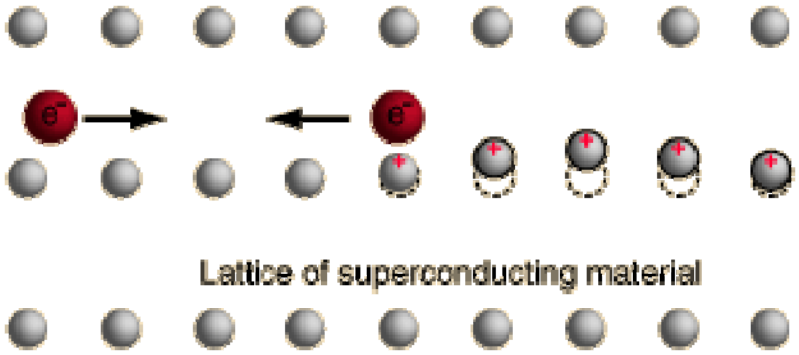
What happens if we don't find the Higgs boson or supersymmetry?

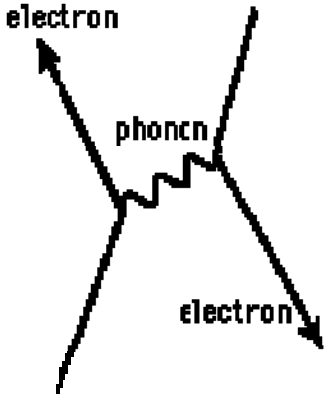
?

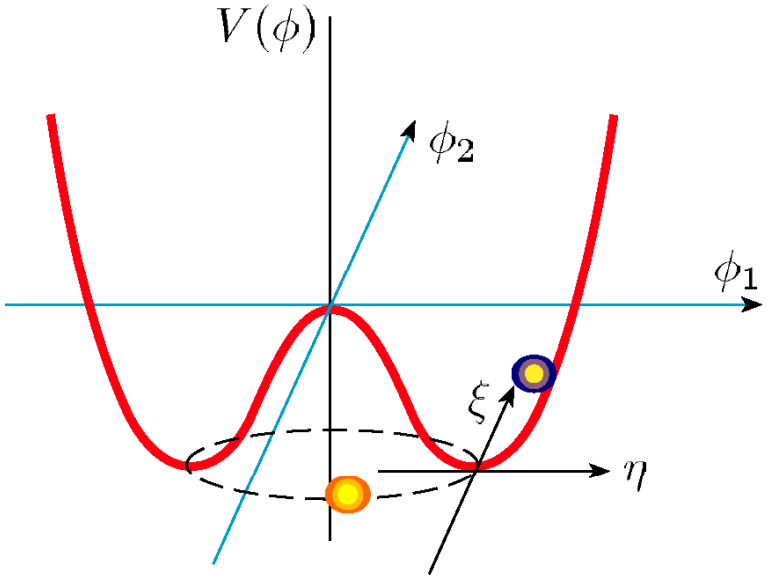
Re-writing physics

No superconductivity - no answers to these questions!

Superconductvity and the BEH Mechanism







Introduce two independent complex scalar fields

Three of the four degrees of freedom in the Higgs field mix with the W and Z bosons, while the one remaining degree of freedom becomes the Higgs boson – a new scalar particle.

Exploring the unknown:

the Large Hadron Collider (LHC)

Experimentally:

1. Make particles interact and study the products and properties of the result of the interaction
2. Measure the energy, direction and type of the products as accurately as possible
3. Reconstruct what happened during the collision

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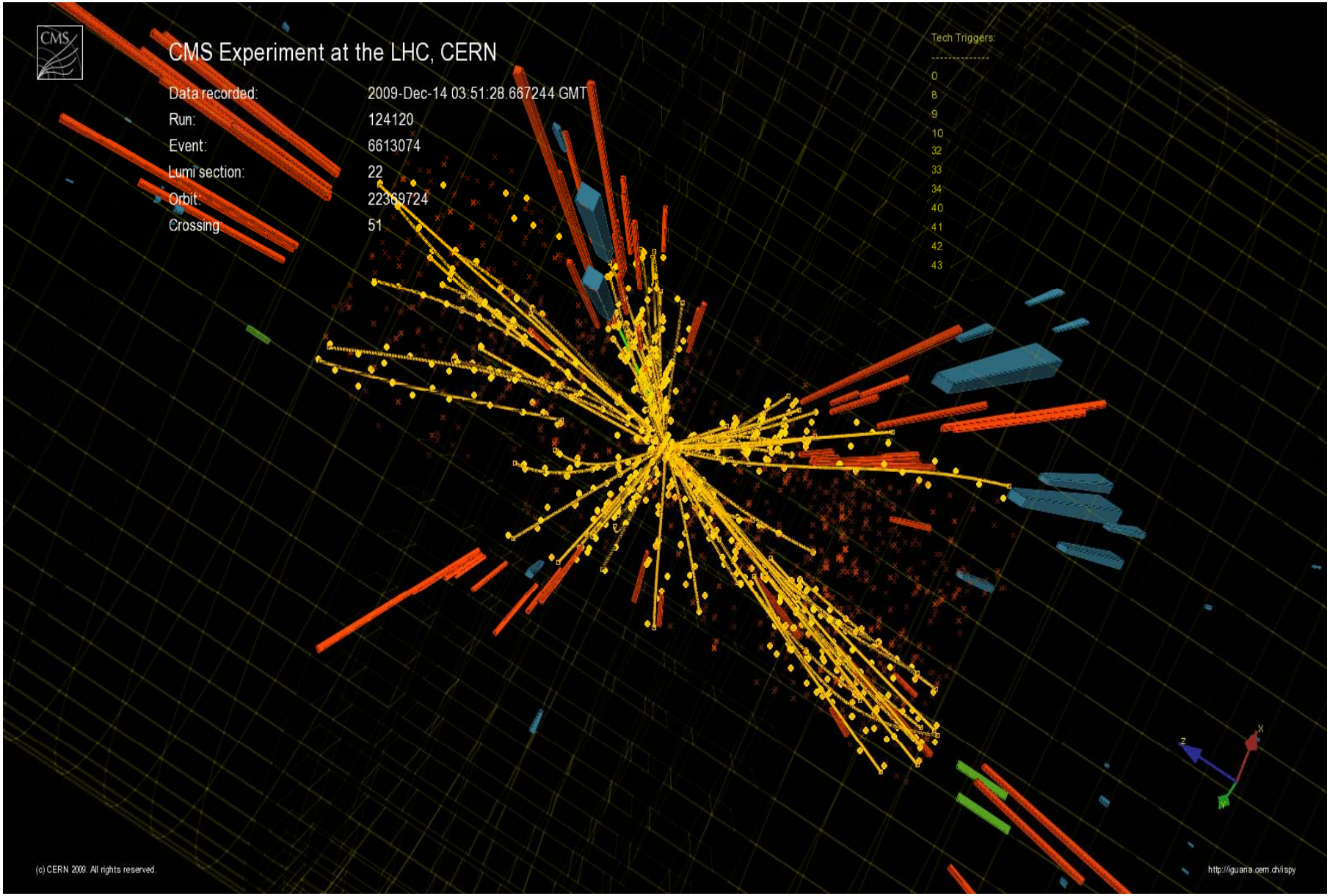
A Collision of Two Protons



This Study Requires…….

1. Accelerators : powerful machines that accelerate particles to extremely high energies and bring them into collision with other particles

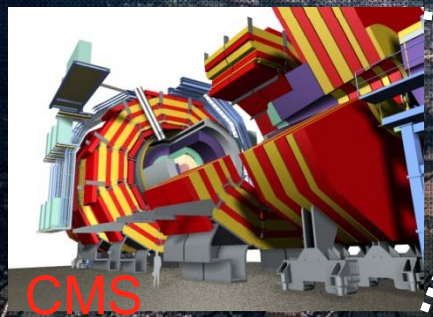
2. Detectors : gigantic instruments that record the resulting particles as they "stream" out from the point of collision.

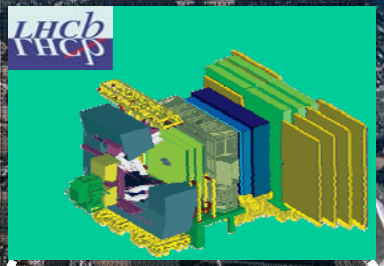
3. Computing : to collect, store, distribute and analyse the vast amount of data produced by these detectors

4. Collaborative Science on Worldwide scale : thousands of scientists, engineers, technicians and support staff to design, build and operate these complex "machines".

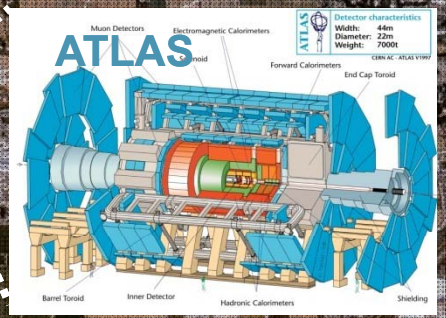
A New Era in Fundamental Science was Launched in March 2010

Start-up of the Large Hadron Collider (LHC), one of the largest and truly global scientific projects ever, is the most exciting turning point in particle physics.





Exploration of a new energy frontier
Proton-proton collisions at E_{CM} = 7-14 TeV



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(click for video)

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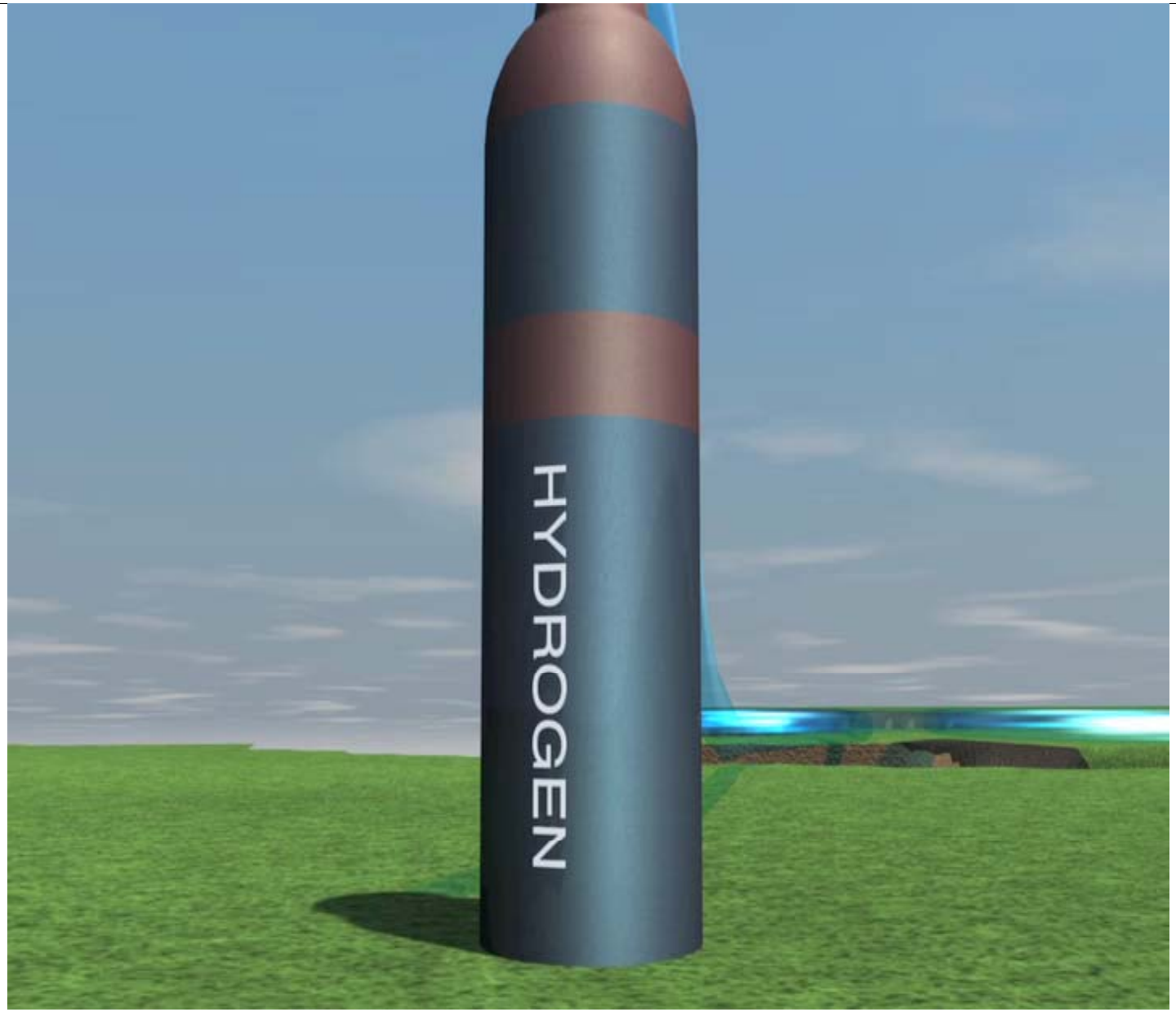
“Bangs From a Bottle”



The LHC Accelerator

Protons are accelerated by powerful electric fields to very (very) close to the speed of light **(superconducting r.f. cavities)**

And are guided around their circular orbits by powerful **superconducting dipole magnets**.

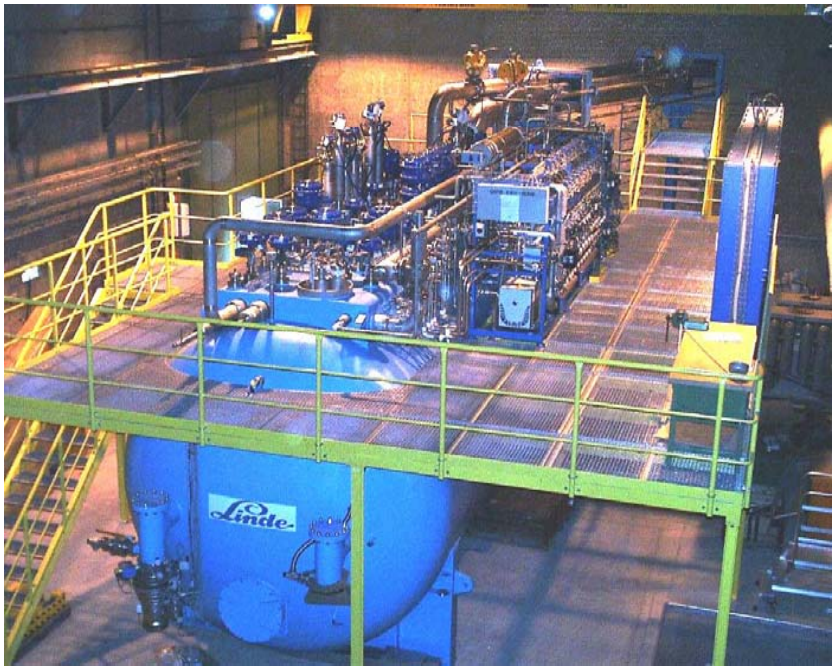
The dipole magnets operate at 8.3 Tesla (200'000 x Earth's magnetic field) & 1.9K (-271° C) in **superfluid helium**.

Protons travel in a tube which is under a better vacuum, and at a lower temperature, than that found in inter-planetary space.

Technology: 100 Years of Superconductivity

Liquid helium displays two phenomena which are both pillars in the design of LHC:
superconductivity and superfluidity

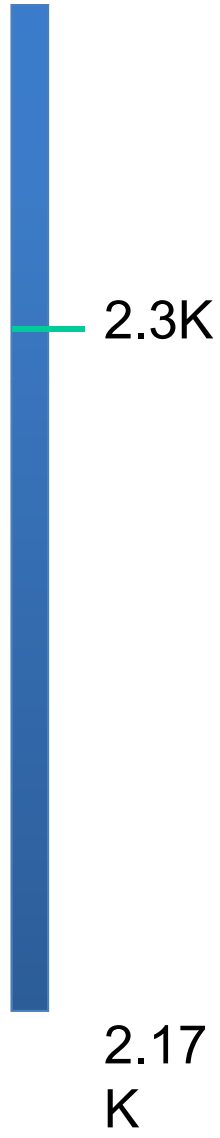
1908: Kamerlingh Onnes first **liquefied** Helium in Leiden (60 ml in 1 hr)
and in 1911 he discovered **superconductivity**



LHC today: 32000 liters of He liquefied per hour by eight big cryogenic plants - the largest refrigerator in the world.

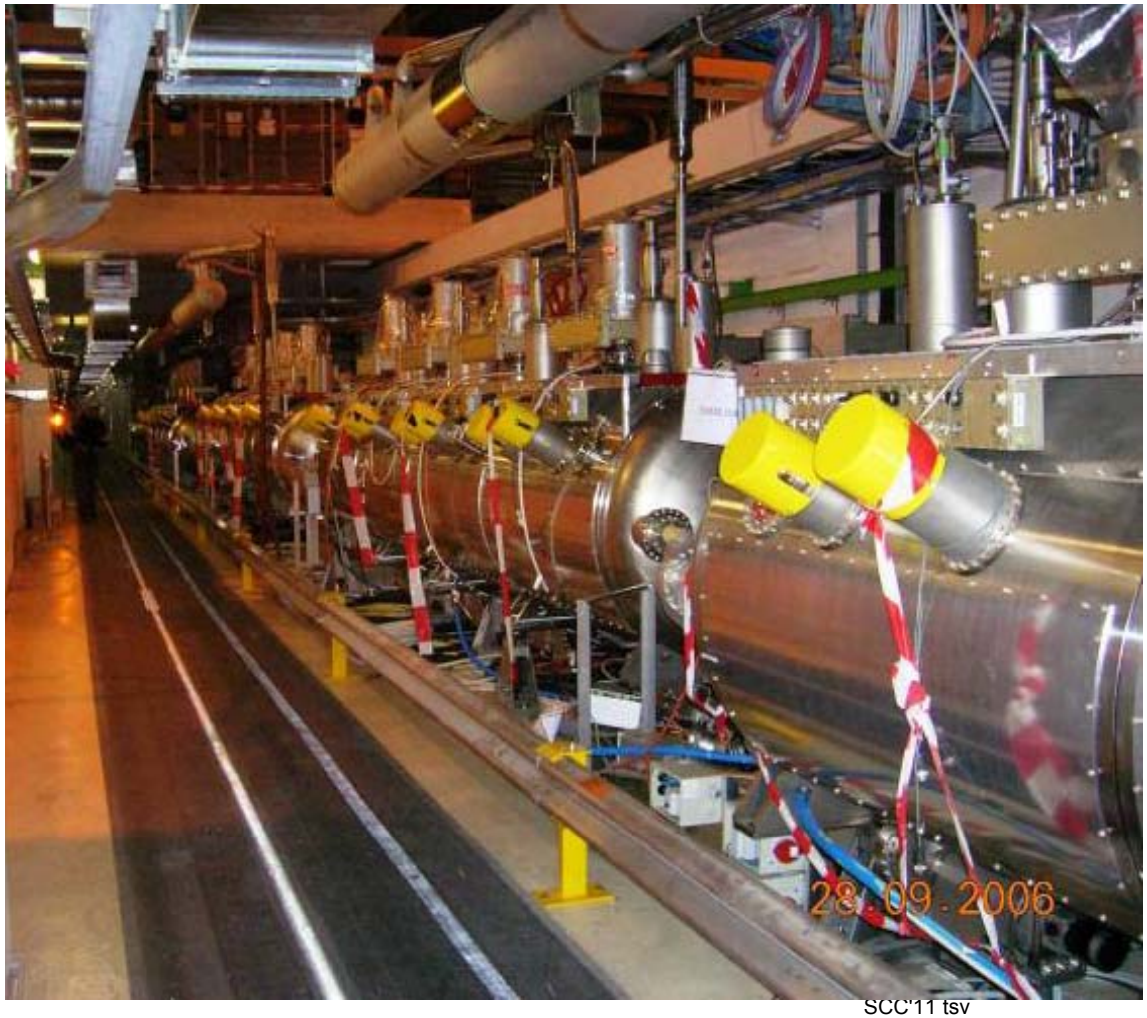
(click for video)

Properties of Superfluid Helium



Kicks

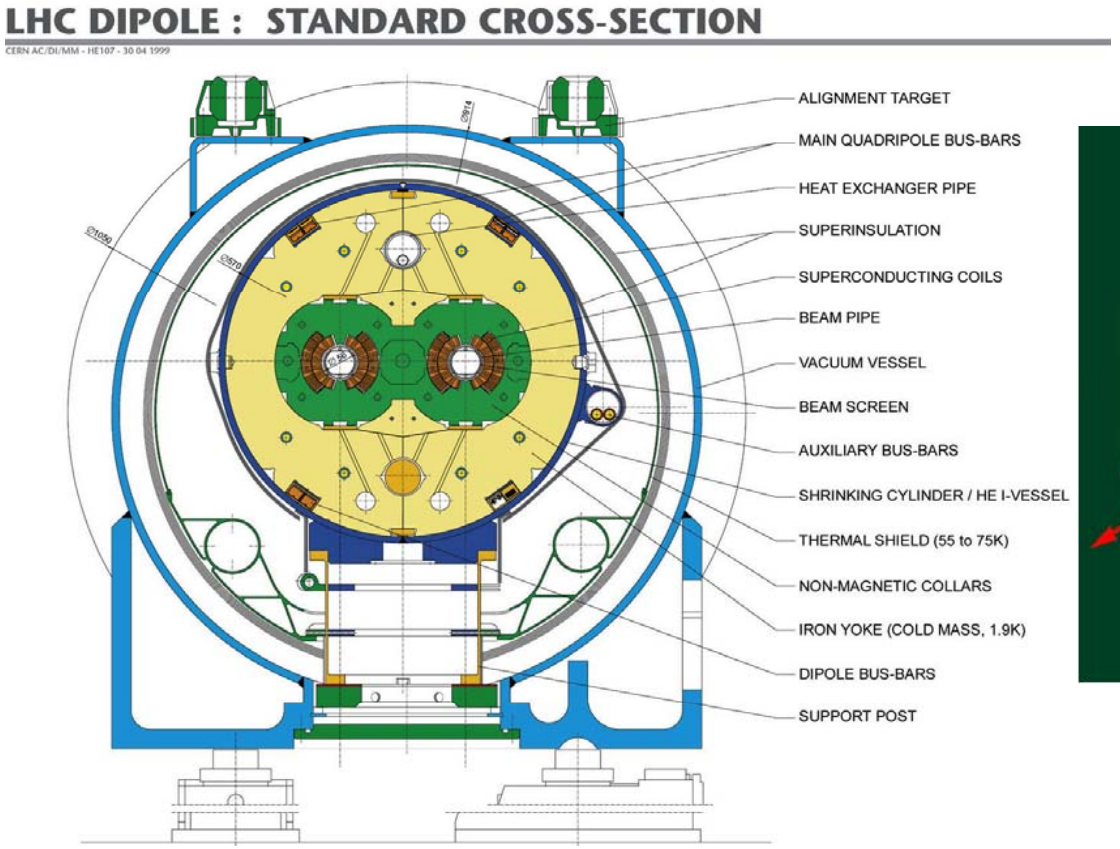
Superconducting radio-frequency cavities
Protons "surf" the electromagnetic waves! And are accelerated.

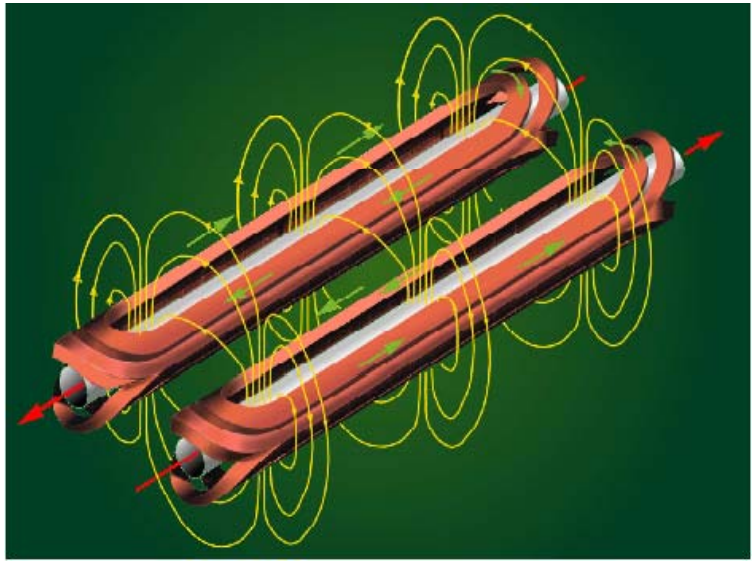


The LHC Dipole Superconducting Magnet

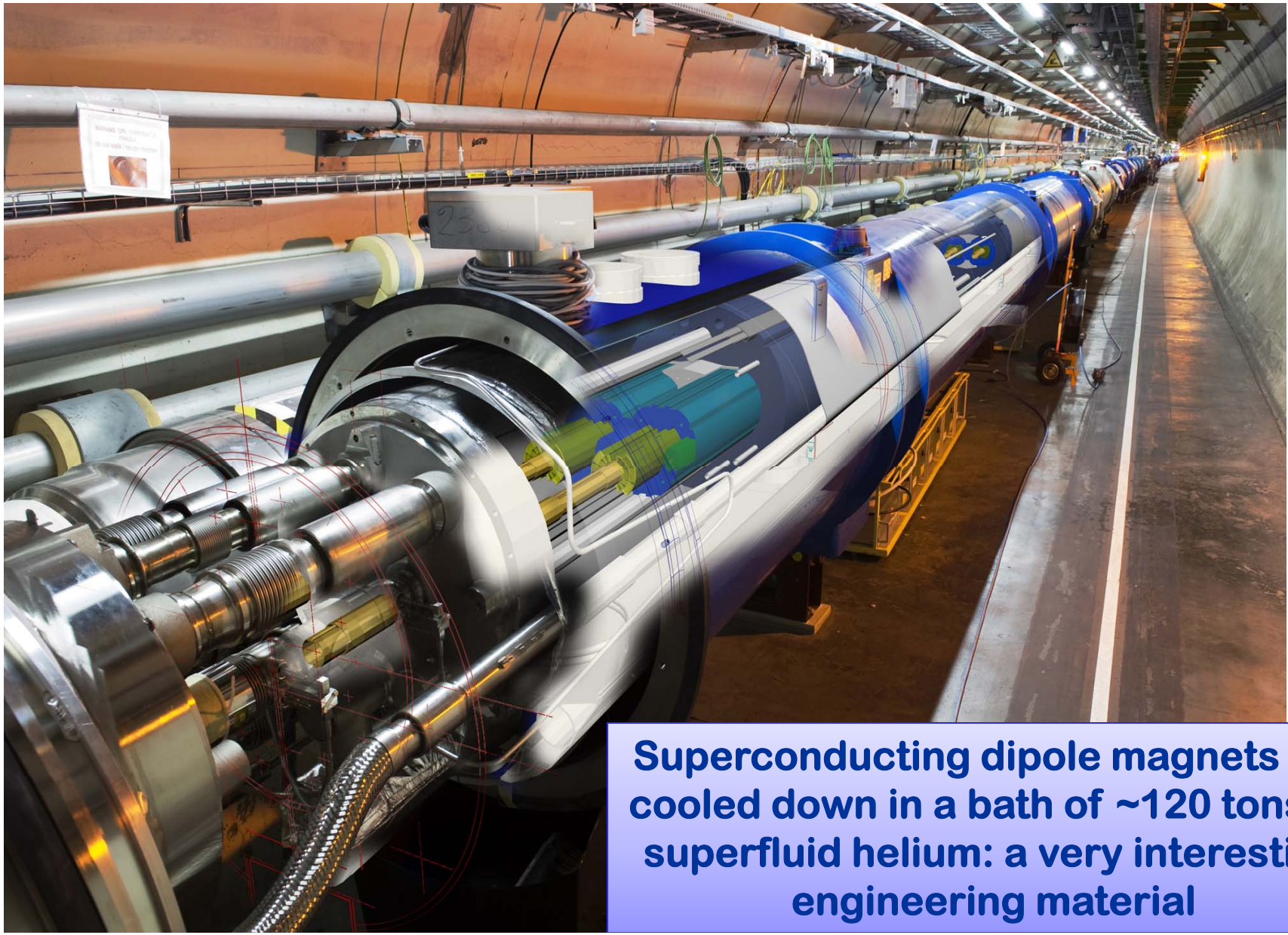
Magnetic Field Needed
p (TeV) = 0.3 B(T) R(km)
For p= 7 TeV, R= 4.3 km
⇨ B = 8.4 T

Superconductivity is Needed!





The LHC Dipole Superconducting Magnet



Superconducting dipole magnets are cooled down in a bath of ~120 tons of superfluid helium: a very interesting engineering material

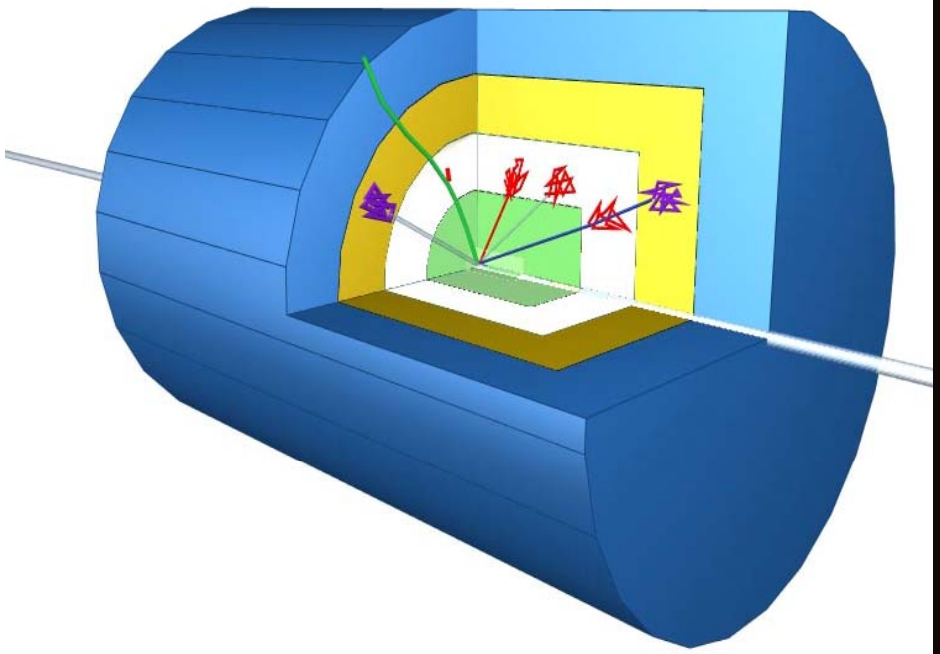
The Detectors

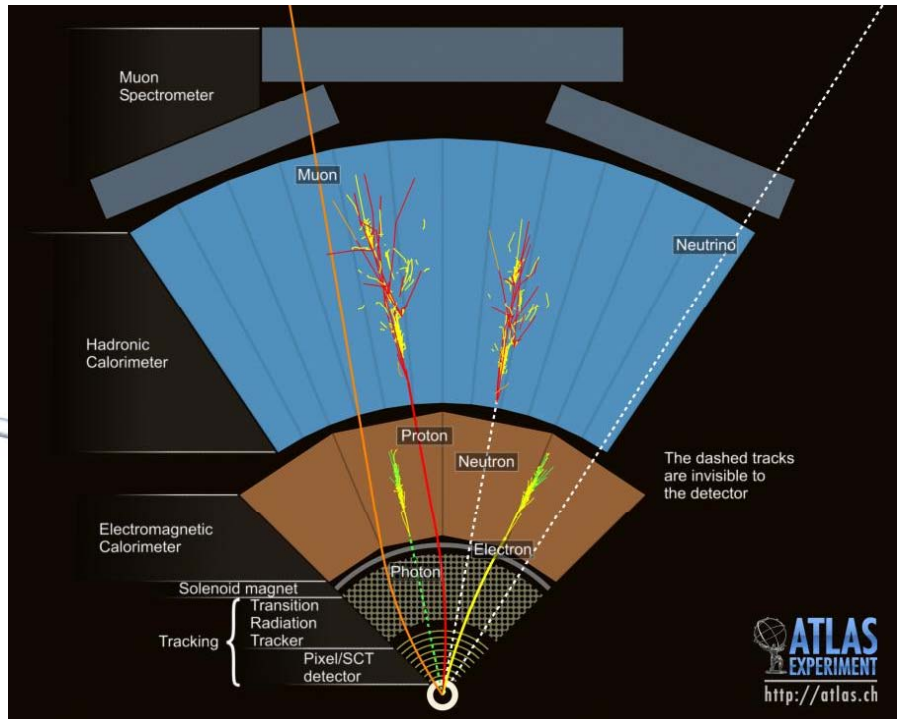
Schematic of an HEP Detector

Physics requirements drive the design: Analogy with a cylindrical onion:

Technologically advanced detectors comprising many layers, each designed to perform a specific task.
Together these layers allow us to identify and precisely measure the energies and directions of all the particles produced in collisions.

Overall design pf LHC general-purpose detectors was driven the choice of the (superconducting) magnetic field configuration.





Particles that are detected in an HEP Detector

Any new particles will manifest themselves through known particles

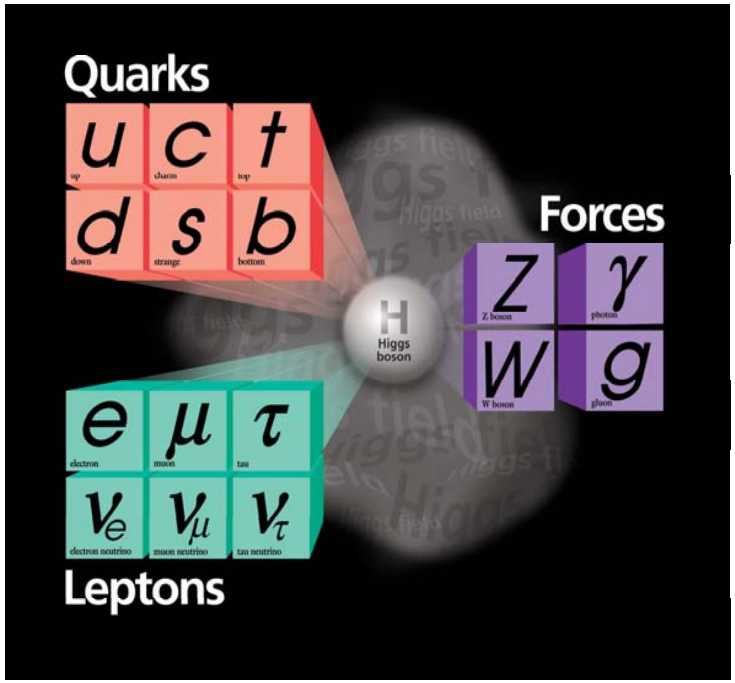
Photons
Electrons
Muons

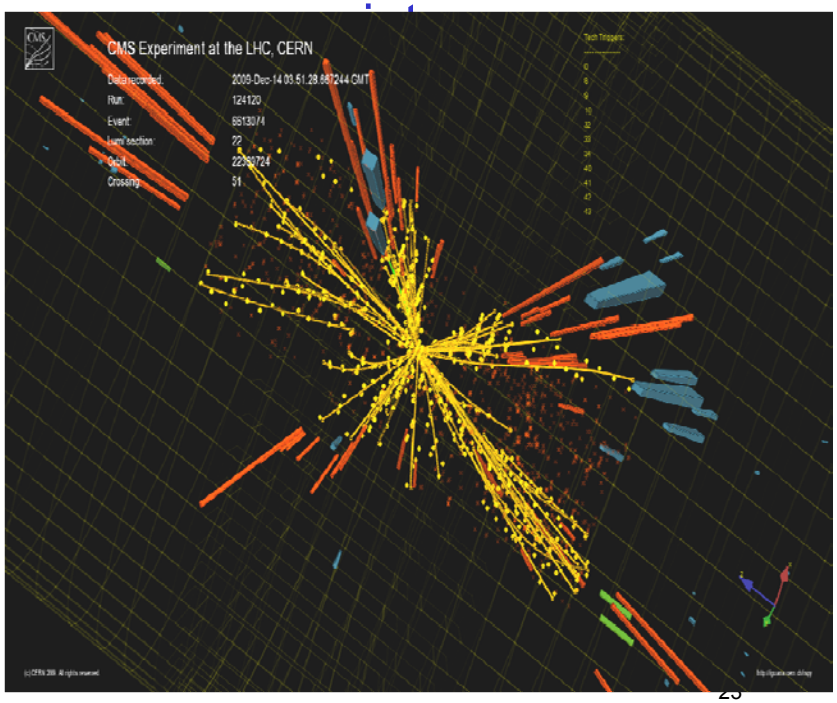
Quarks and gluons

collimated bunches of long-lived or stable particles labeled “jets”

Taus

Highly collimated low multiplicity

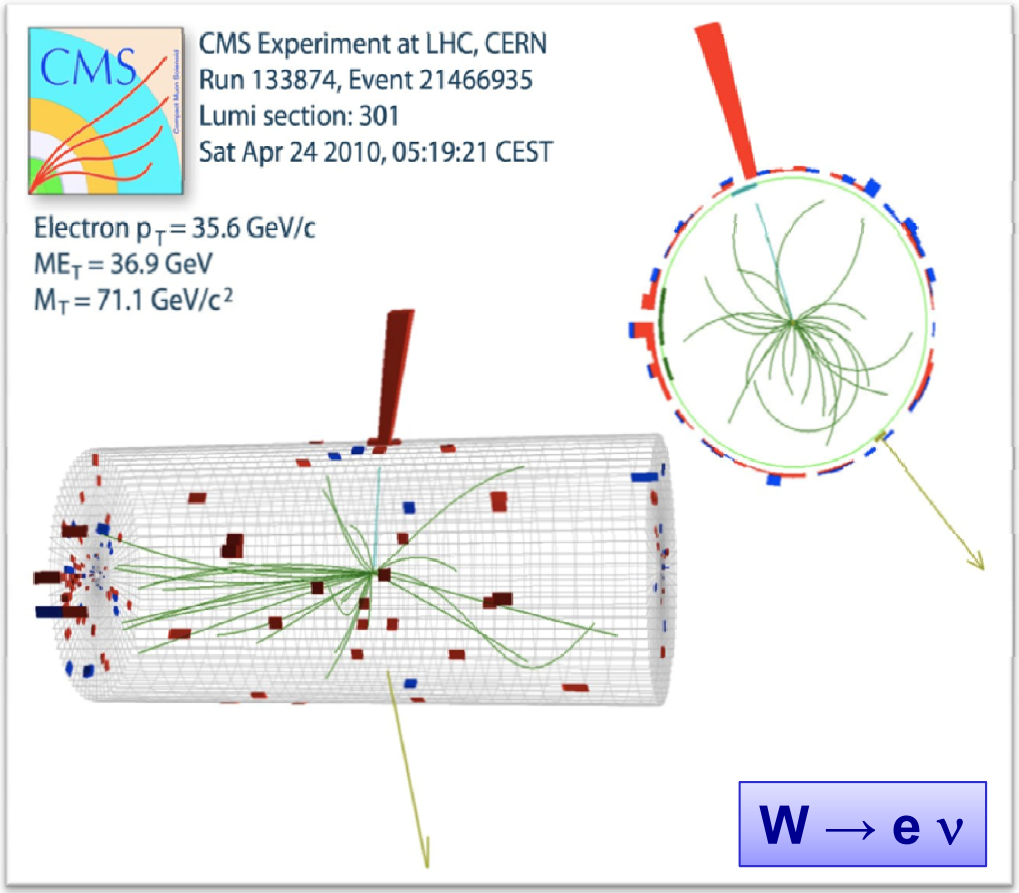




Particles that are detected in an HEP Detector

Any new particles will manifest themselves as known particles

And Neutrinos !

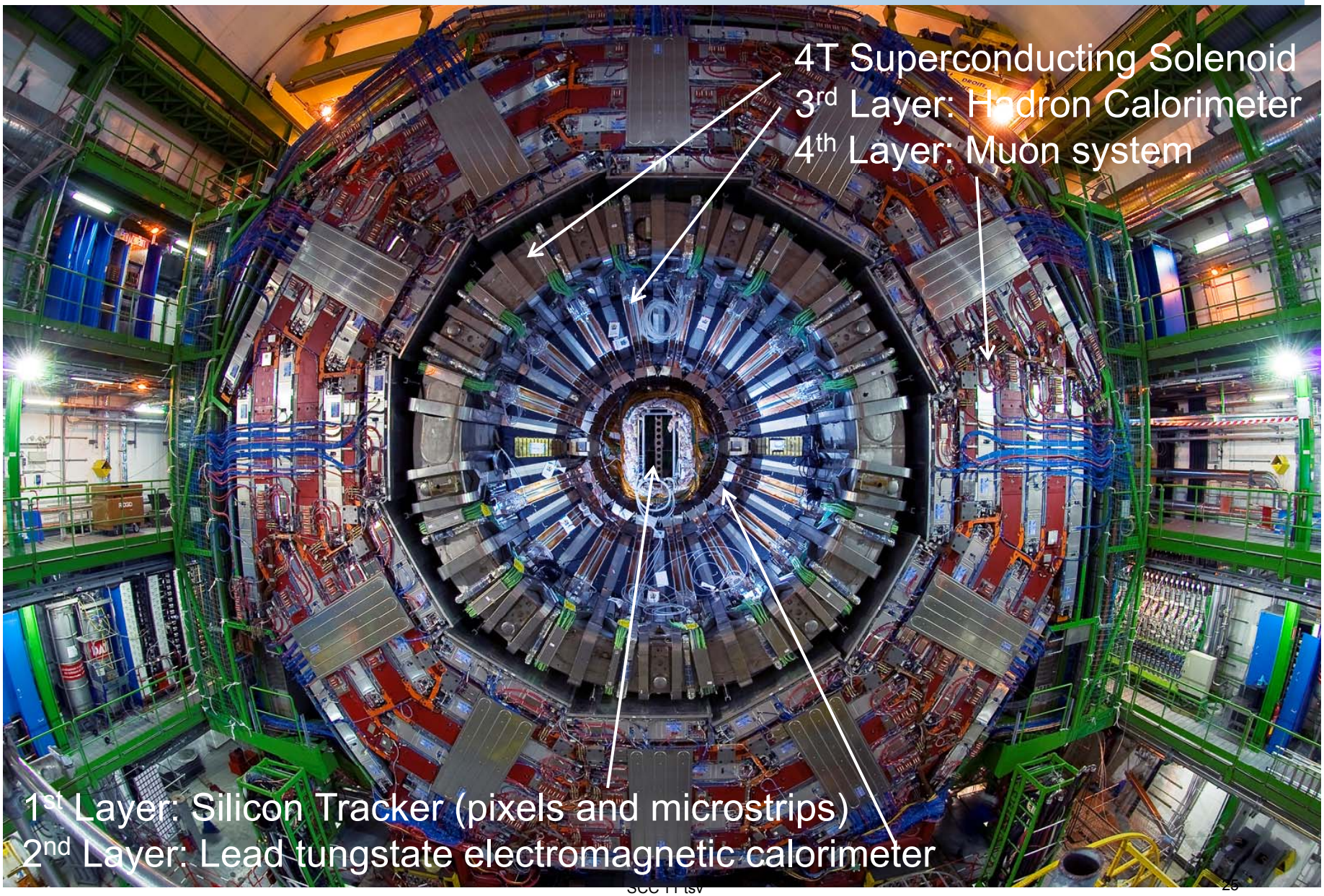


In hadron colliders the initial momentum of colliding partons is not known. However the momentum transverse to the beam is ZERO.

Any net momentum transverse to the beam indicates "missing transverse energy" (masses << energy)

Significant missing transverse energy is indicative of "non-interacting" particles such as neutrinos or LSP.

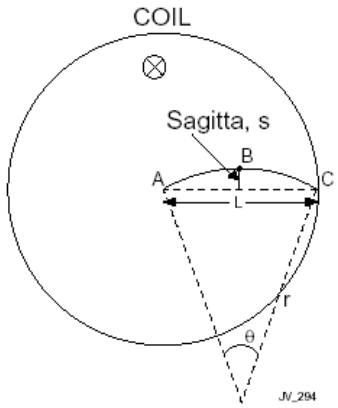
Transverse View of the CMS Detector



ATLAS Superconducting TOROID

Design goal: measure 1 TeV muons with 10% resolution

ATLAS: <B>~0.6T over 4.5 m → s=0.5mm → need σ_s=50μm



- **Ampere's theorem:**

$2\pi RB=\mu_0 nI \rightarrow nI=2x10^7$ At

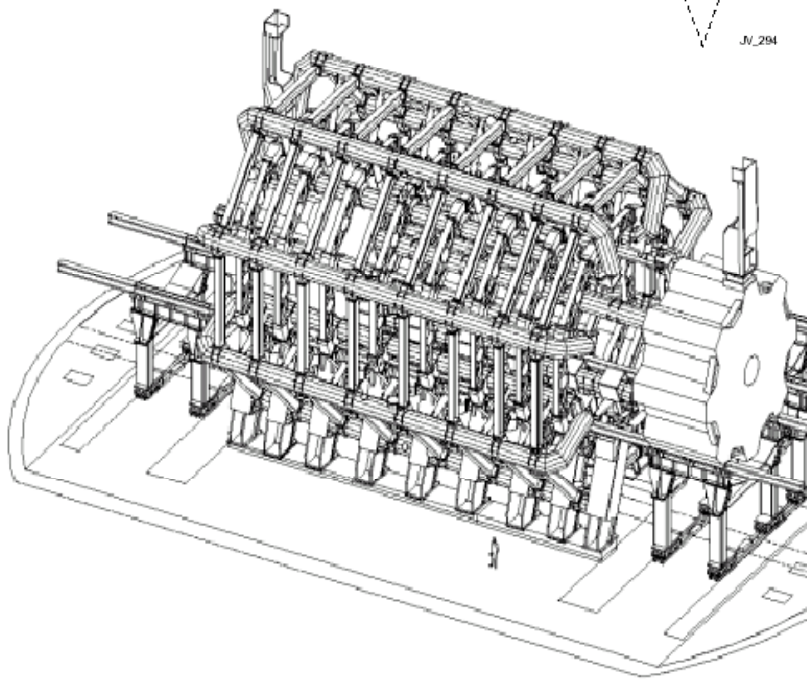
- With 8 coils, 2x2x30 turns: **I=20kA** (superconducting)

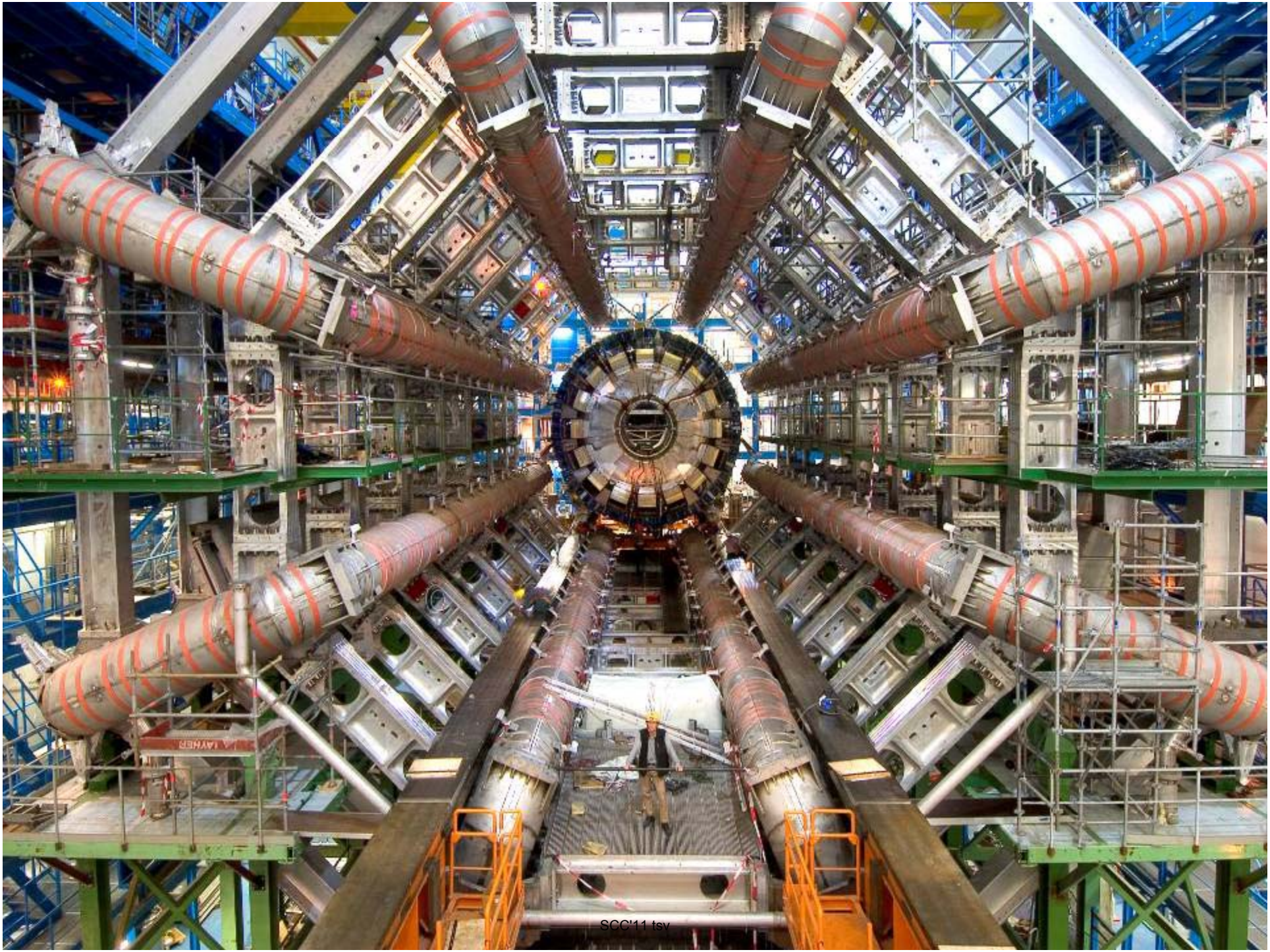
- **Challenges:**

Design of structure capable of holding the magnetic forces

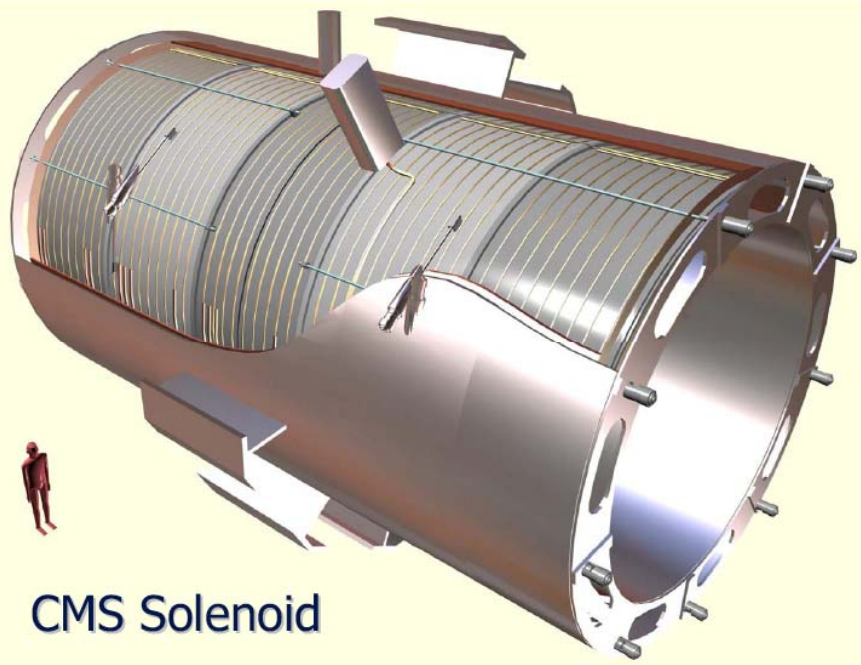
High stored energy 1.5GJ,

Spatial & alignment precision over large surface area





CMS Solenoid



CMS: B=4T (E=2.7 GJ!)

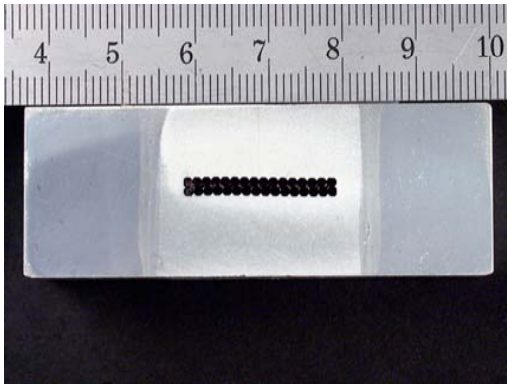
- $dp_T/p_T \ \alpha \ (1/BL^2) \ (\sigma_x/\sqrt{N_{points}}) \ p_T$
- **$B=\mu_0 nI$;**

2168 turns/m$\rightarrow$ I=20kA (Superconducting)

- **Challenges:**

4-layer winding to carry enough current,

Design of reinforced superconducting cable

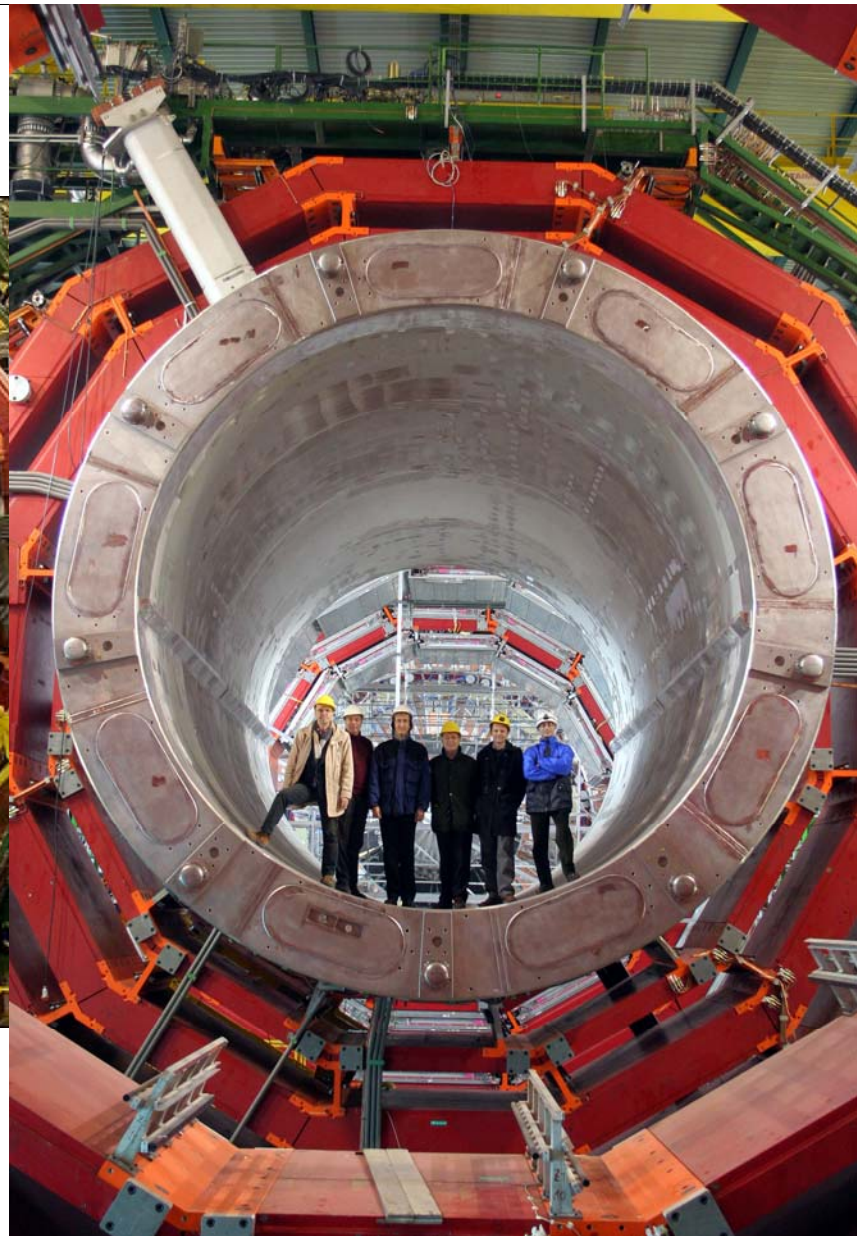


The CMS Superconducting Magnet

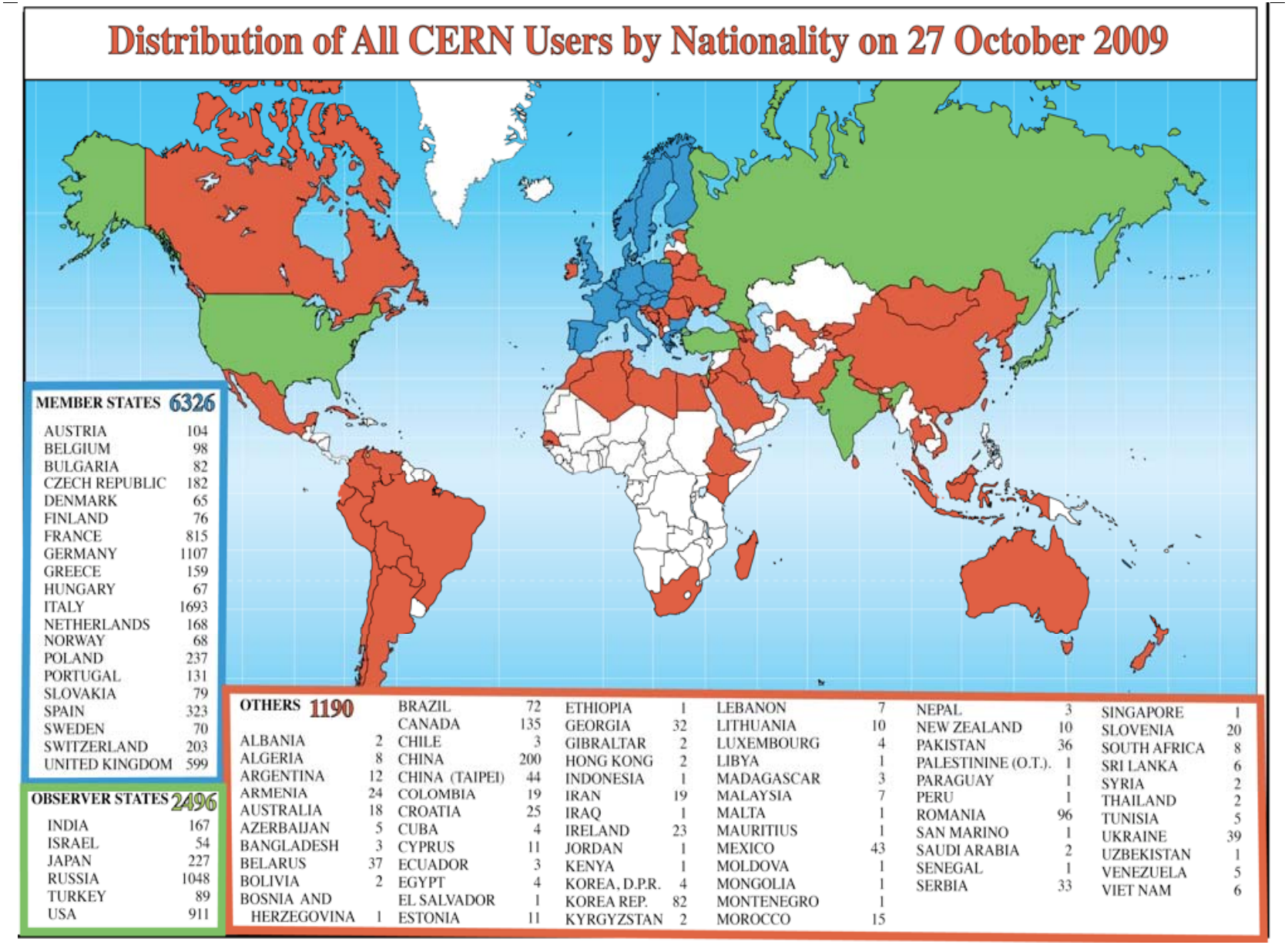
CMS Conductor Production

Total 20 + 1 (prototype) conductor units, each of 2550 m length

Completion of CMS Solenoid

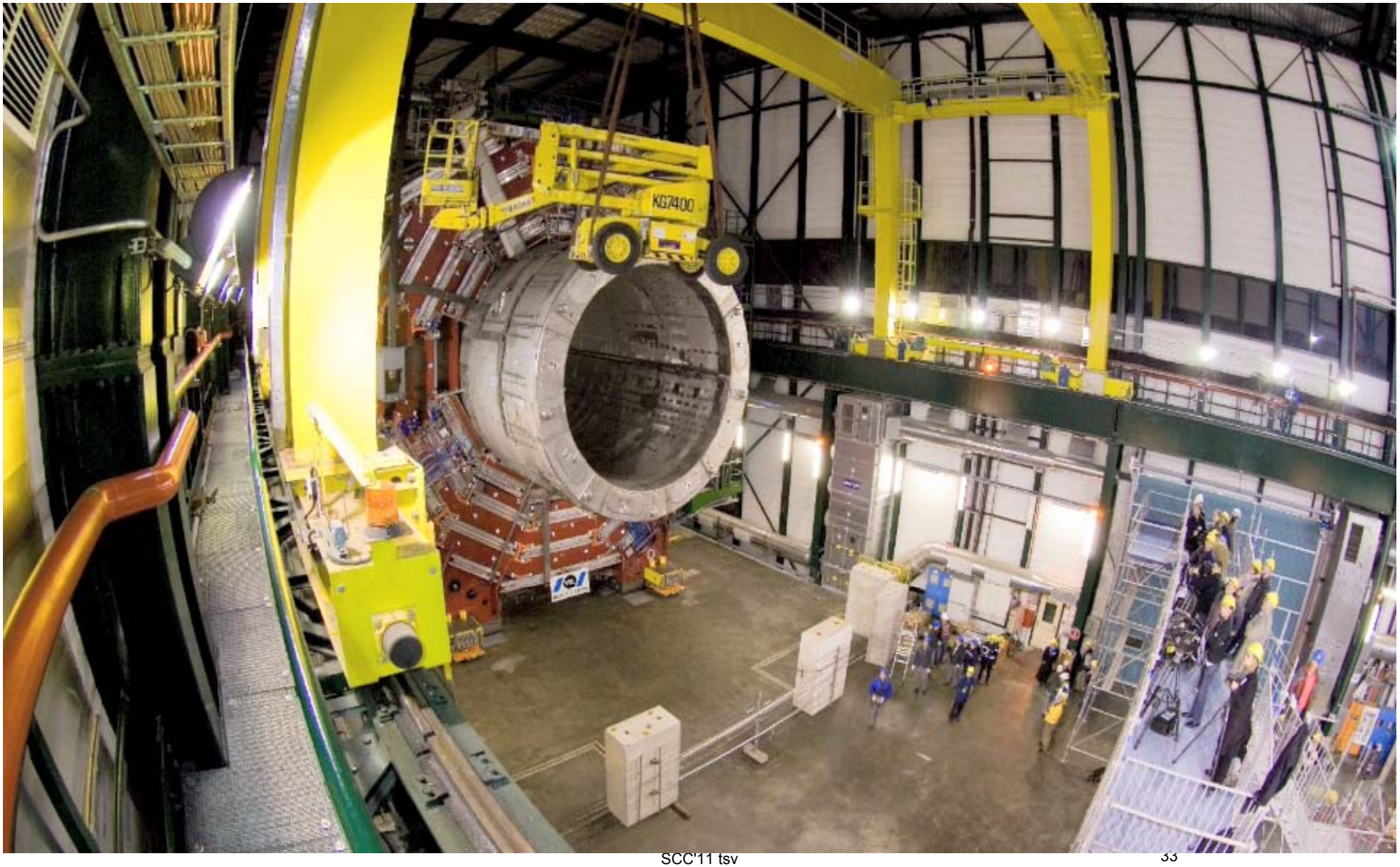


CERN: Founded in 1954



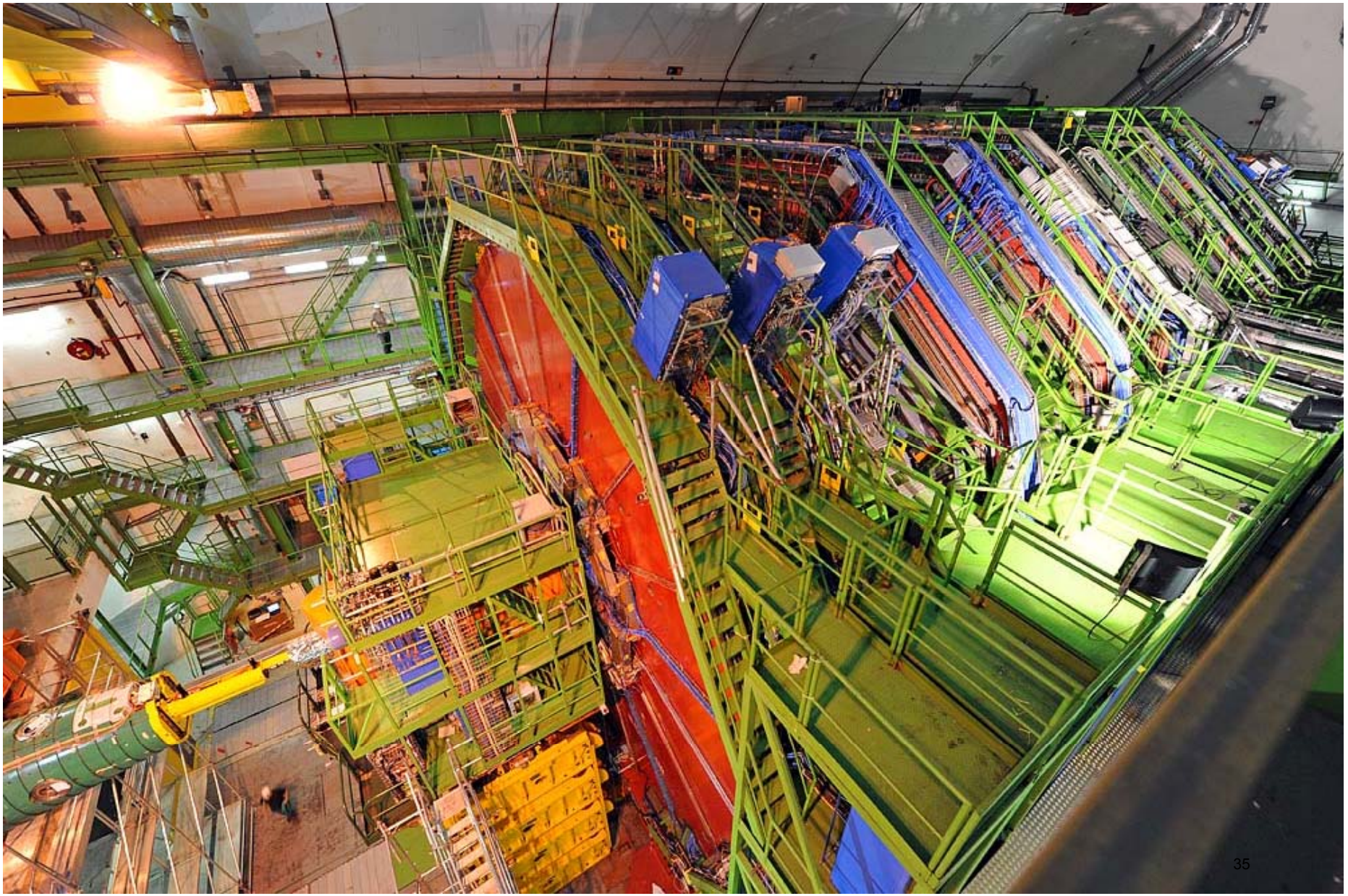
The Construction of the LHC Detectors (primarily CMS)

Spectacular Operations (Feb. 2007)



Cables, Pipes and Optical Fibres !

CMS Detector Closed



Experimental and Technological Challenge

1 billion proton-proton interactions per second

Bunches, each containing 100 billion protons, cross 40 million times a second in the centre of each experiment

Large Particle Fluxes

~ thousands of particles stream into the detector every 25 ns

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

⇨ ~ 1 MB/25ns i.e**. 40 TB generated per second !**

High Radiation Levels

⇨ radiation hard (tolerant) detectors and electronics

Extreme requirements in several domains

“If it doesn’t exist and we need it, we will invent it”

Limited budgets!

Look at what exists, innovate and automate to drive costs down

Pathway of an Innovation

Dirac's Equation
a most beautiful equation of physics

$$i\frac{\partial\psi}{\partial t} = (-i\alpha.\nabla + \beta m)\psi$$

1928: description of electrons consistent with Einstein's special theory of relativity and quantum mechanics
Predicted existence of anti-particles (**e.g. positron - basis of Positron Emission Tomography (PET)**)
and explained spin (**- basis of Magnetic Resonance Imaging (MRI)**)

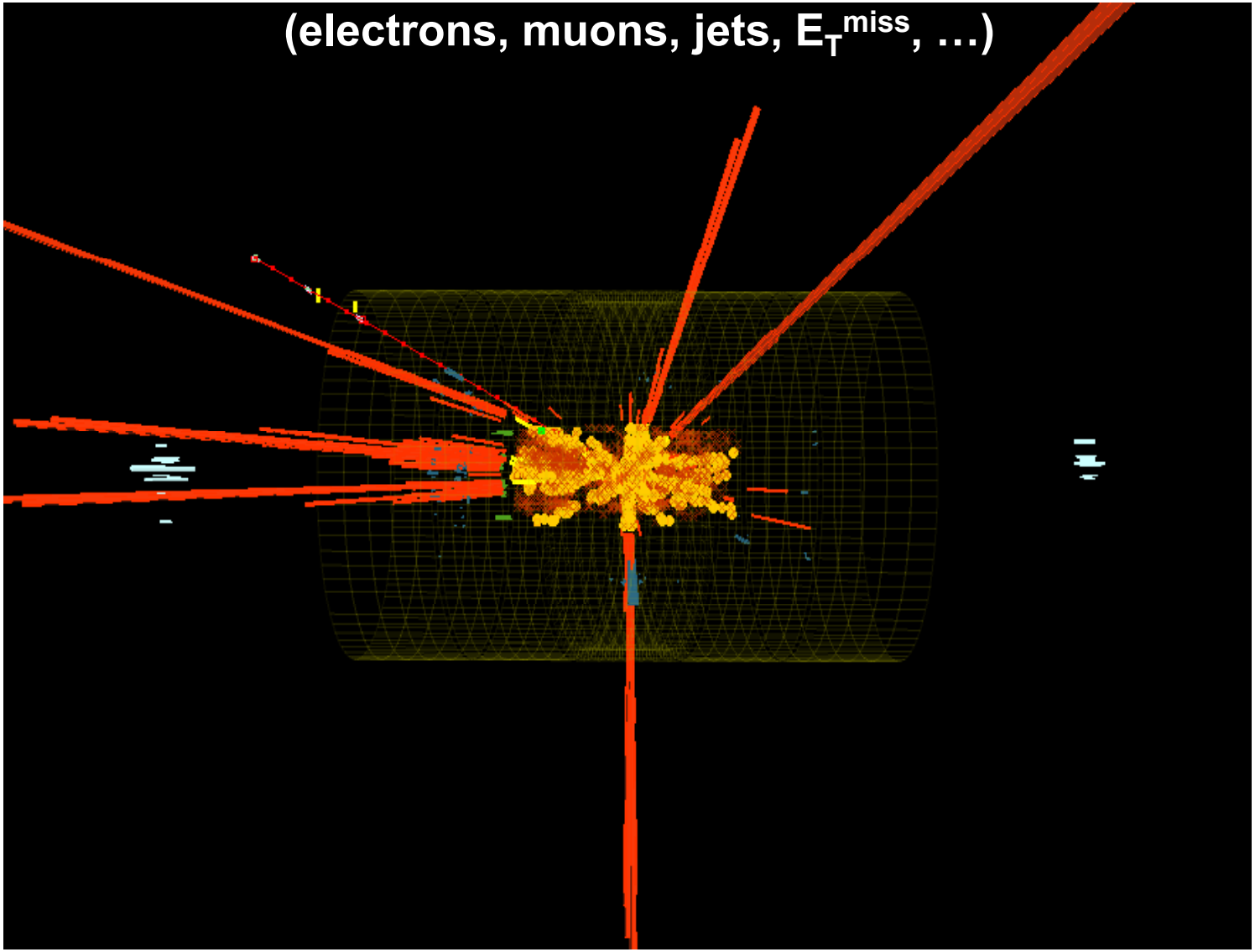
1932: Operation of first cyclotron , the anti-electron (positron) discovered

Radionuclides used in PET scanning are produced by cyclotrons in hospitals – glucose labeled with positron emitters e.g. Fluorine 18.
PET cameras today use APDs (and Si PMs) and heavy scintillating crystals and starting to be combined with MRI scanner (s.c. magnets).

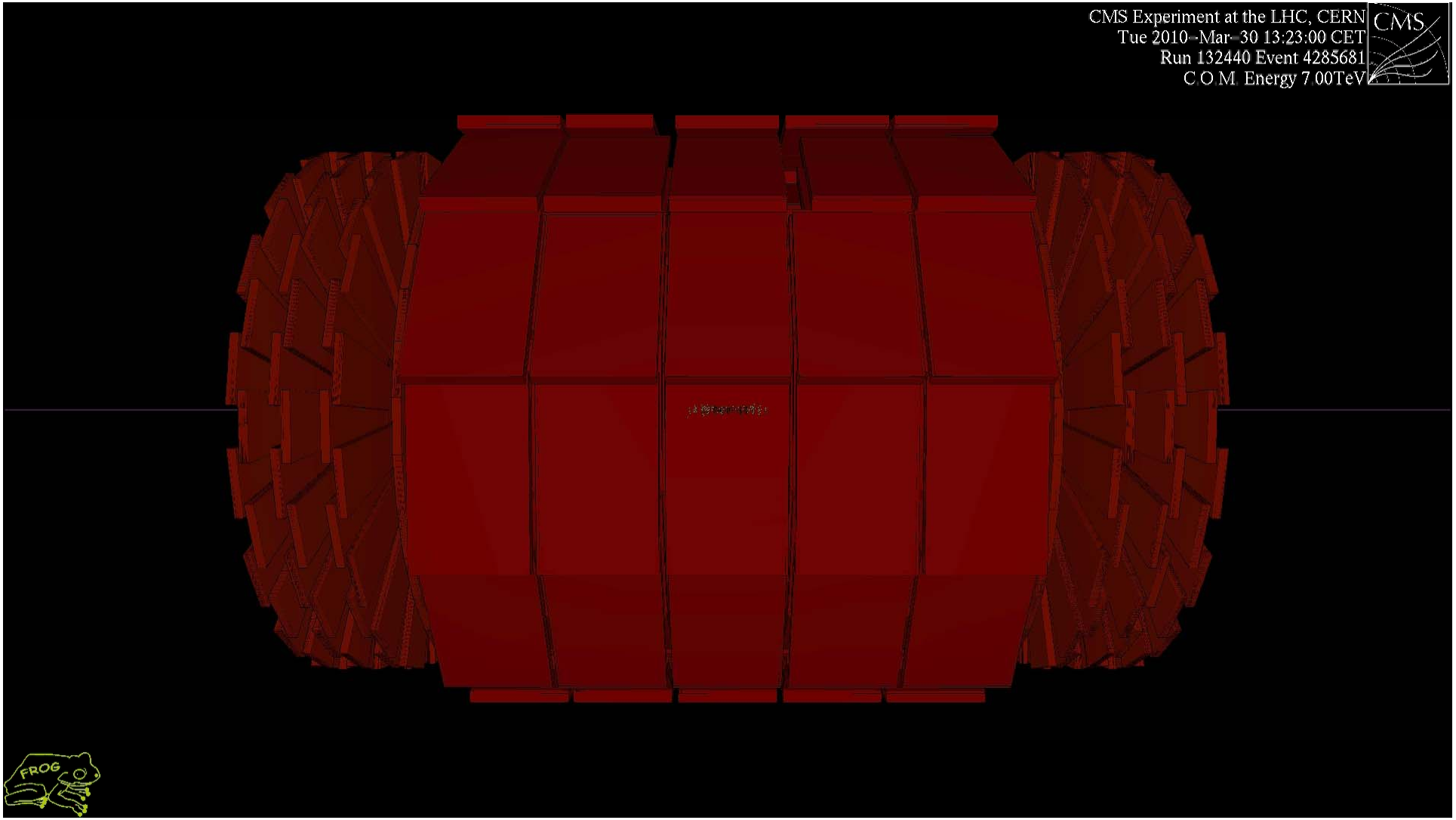
The scientific basis for all medical imaging (functional & physiological) are steeped in nuclear/particle physics

Selection of Interesting Events

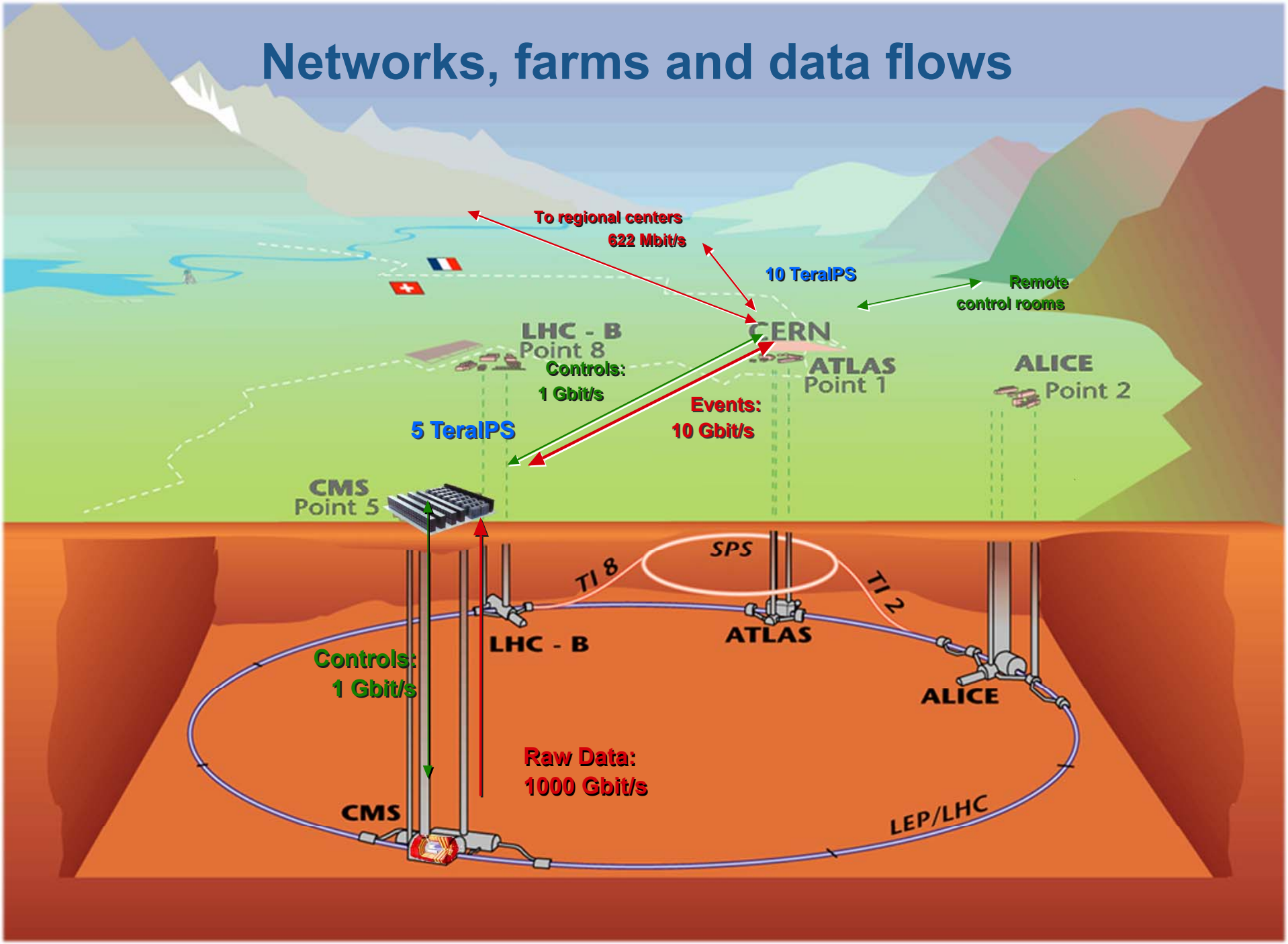
A collision is considered interesting if it contains high p_T objects (electrons, muons, jets, E_T^{miss}, …)



Collisions


CMS Experiment at the LHC, CERN
Tue 2010-Mar-30 13:23:00 CET
Run 132440 Event 4285681
C O M Energy 7 00TeV
CMS
FROG

Networks, farms and data flows



The Worldwide LHC Computing Grid

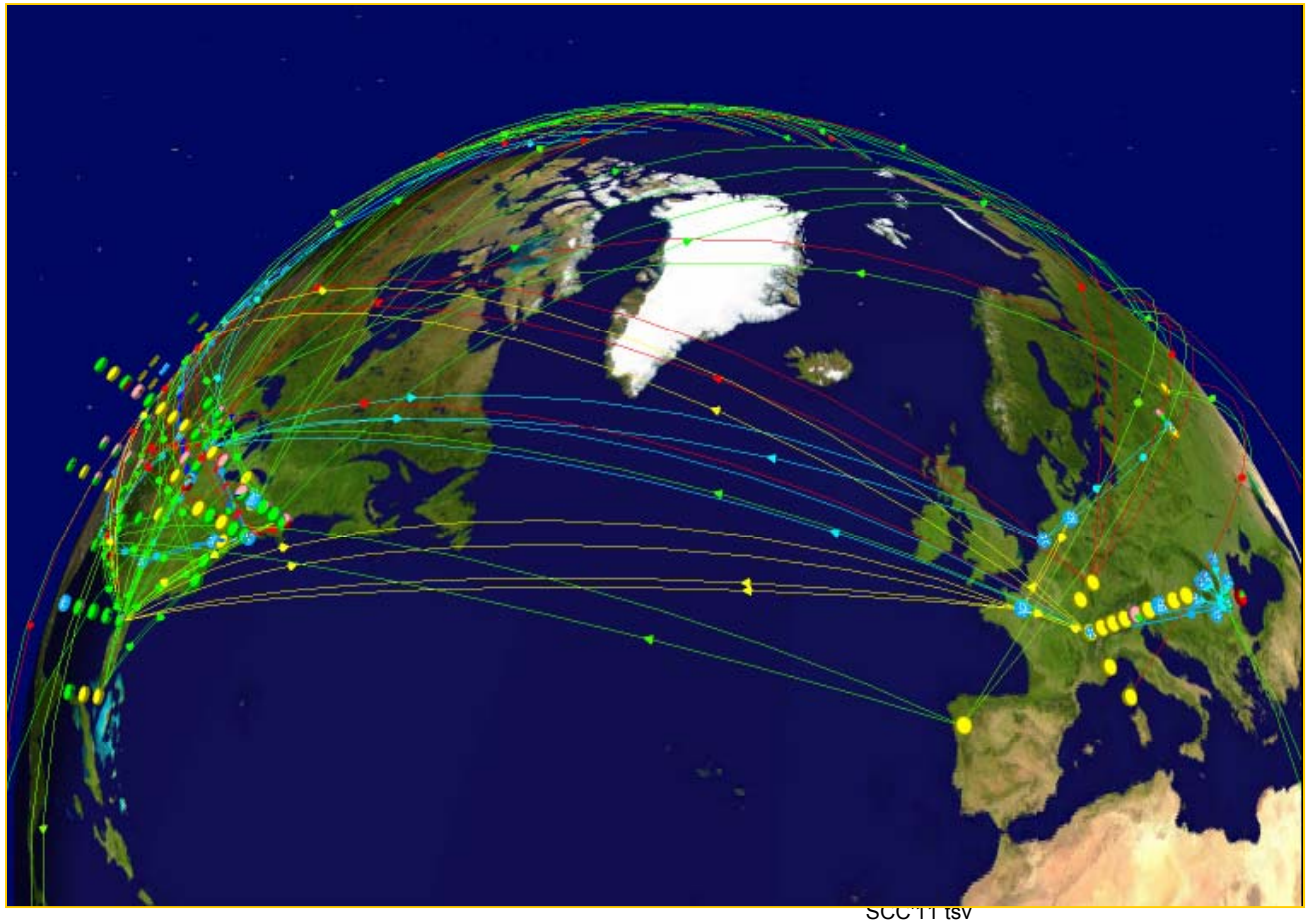
The Grid unites computing resources of particle physics institutions around the world

The **World Wide Web** (invented at CERN) provides seamless access to information that is stored in many millions of different geographical locations

The **Grid** is an infrastructure that provides seamless access to computing power and data storage capacity distributed over the globe

The Grid at Work

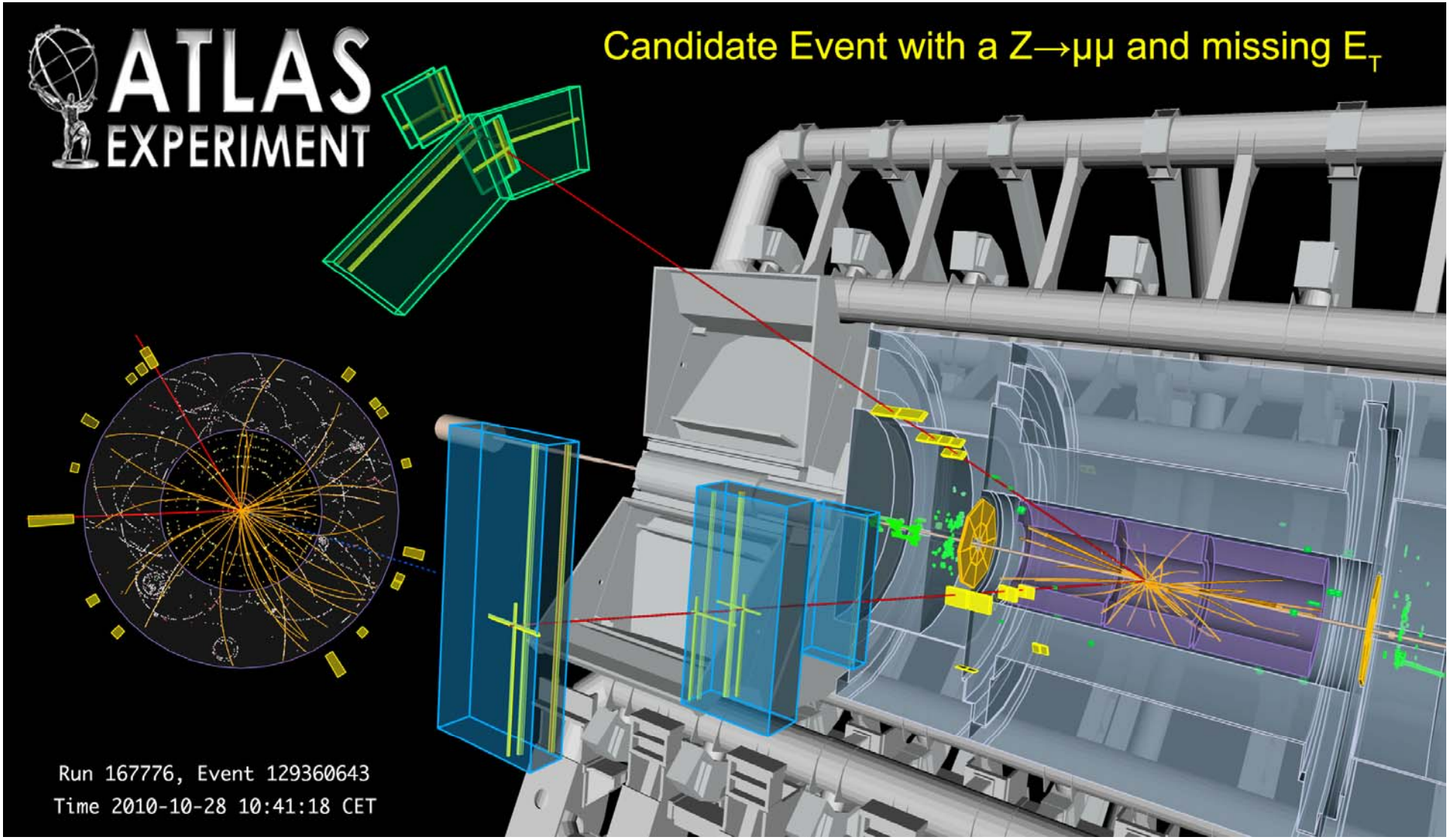
Worldwide LHC Computing Grid connects
100,000 processors in 34 countries
with ultra-high-speed data transfers



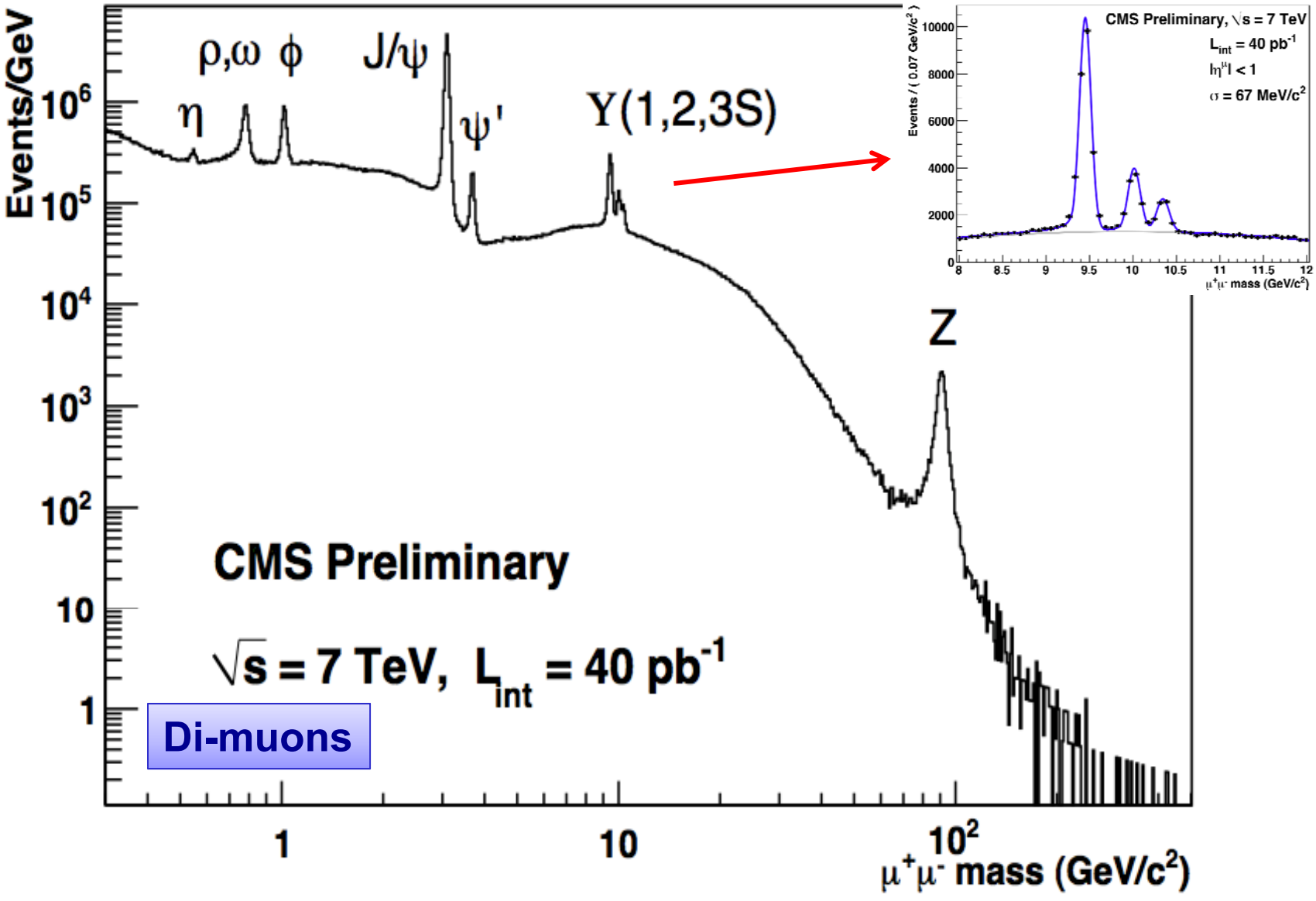
***Millions of Gigabytes* of data each year.**

Going on to the Science

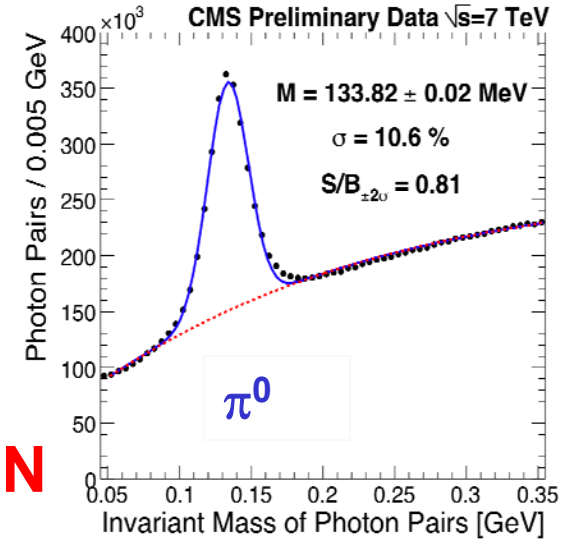
An ATLAS Z and MET Candidate Event



CMS Performance: Tracking and Muons



CMS - 50 Years of Particle Physics



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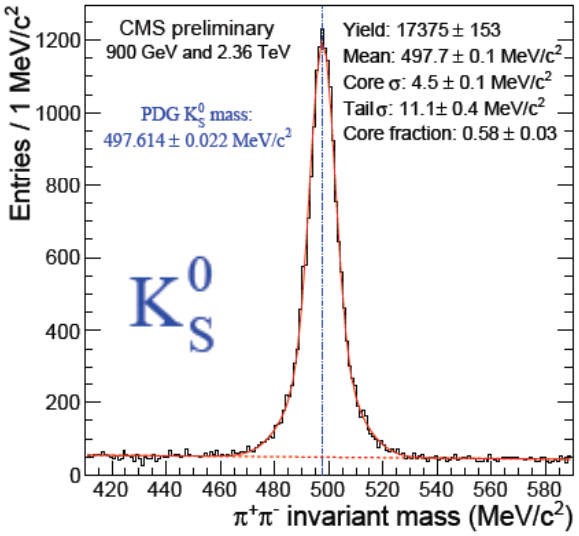

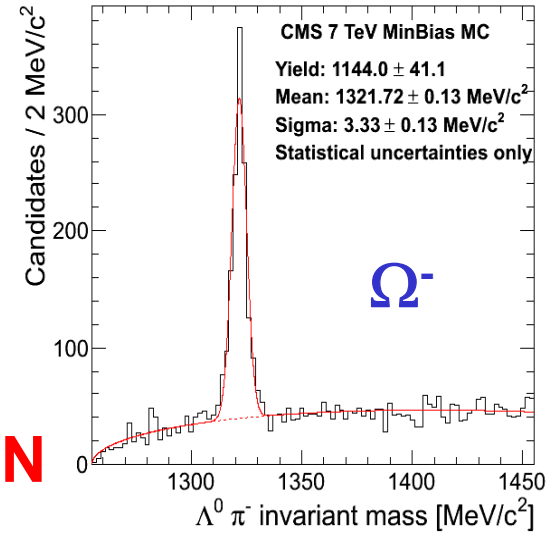

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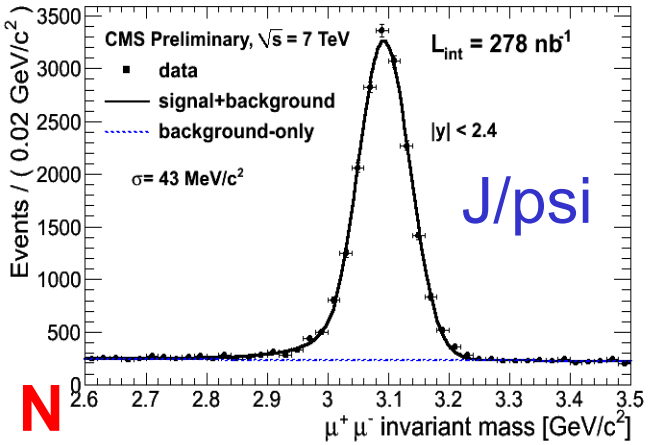

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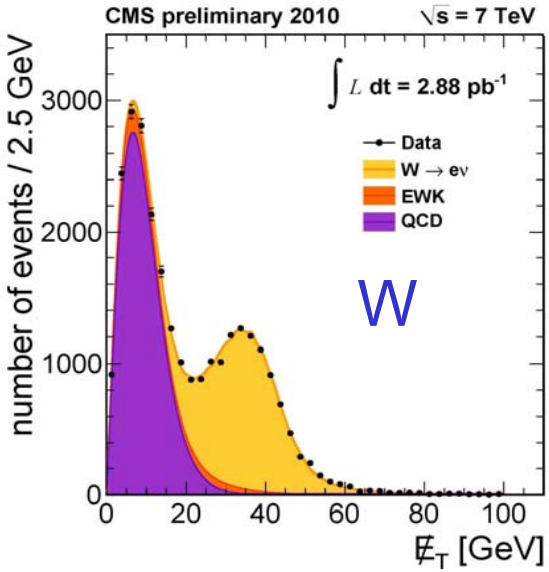

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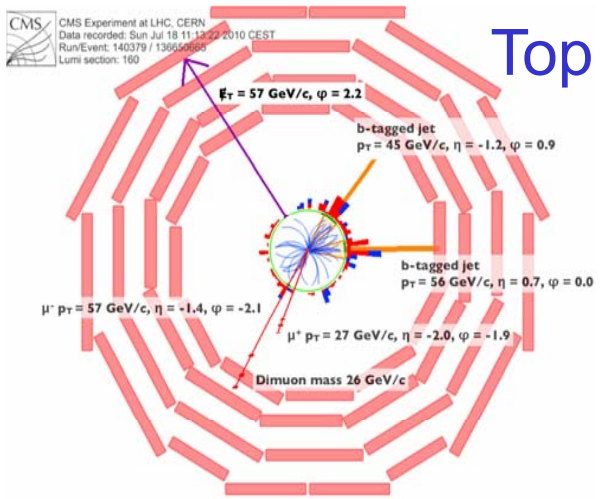

The Physics Programme

- **Looking for signals of new physics.**
  - Waiting for Higgs: the origin of mass
  - Seeking SUSY: Could dark matter be revealed?
  - Extra dimensions: do we live in more dimensions than 4?
  - Compositeness: is there further sub-structure?
  - Unknown!

- **Of course, all these signals can only be claimed after understanding Standard Model channels (known physics as backgrounds)**
  - **QCD jets**, prompt γ's, J/ψ, y, ….
  - b-quark production
  - Drell-Yan, **W+Z production** (plus jets); multi-IVB (WW,WZ,ZZ)
  - Top quark
  - **Very large number of measurements indicate that the LHC experiments are "physics commissioned".**

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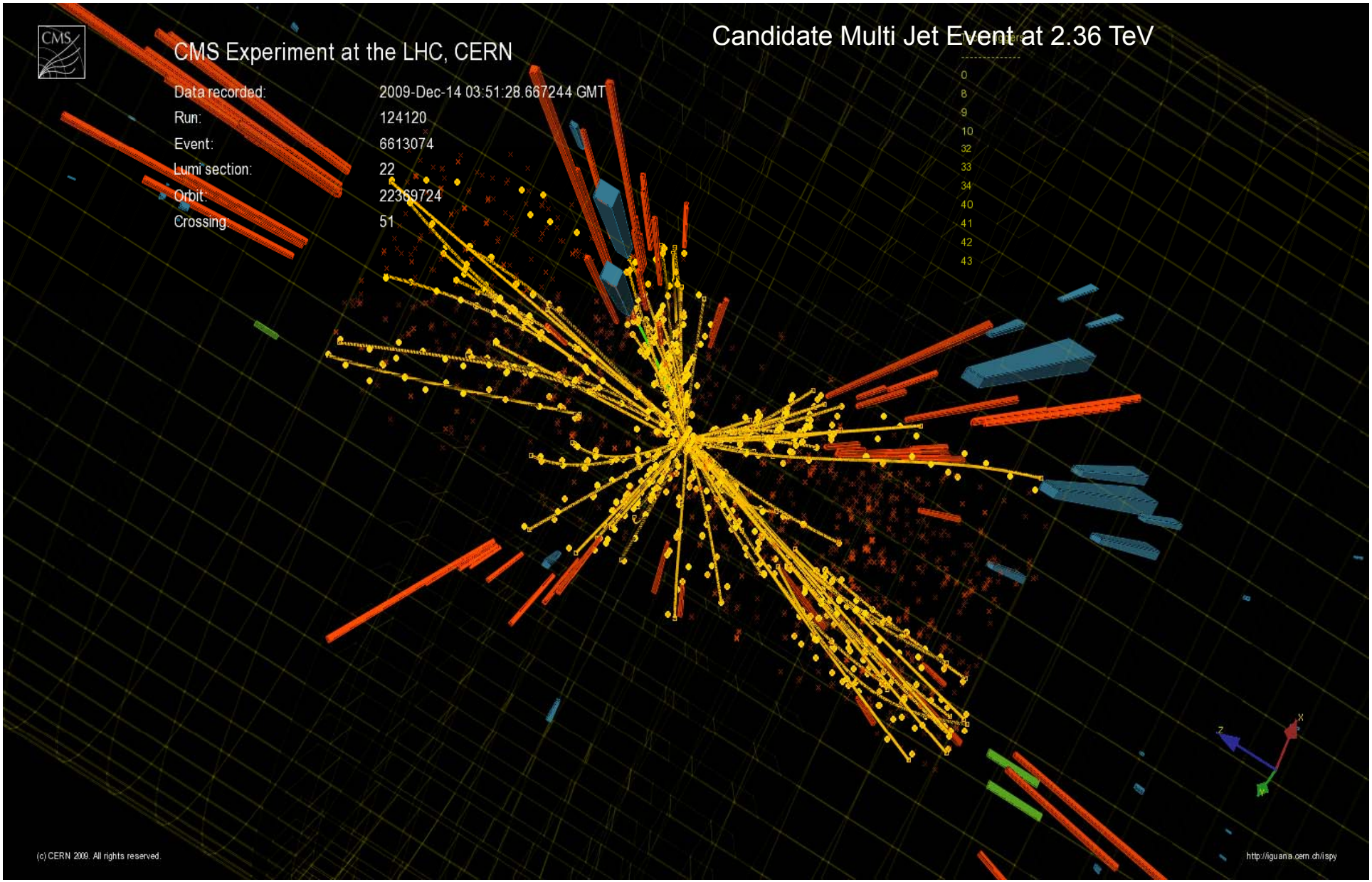
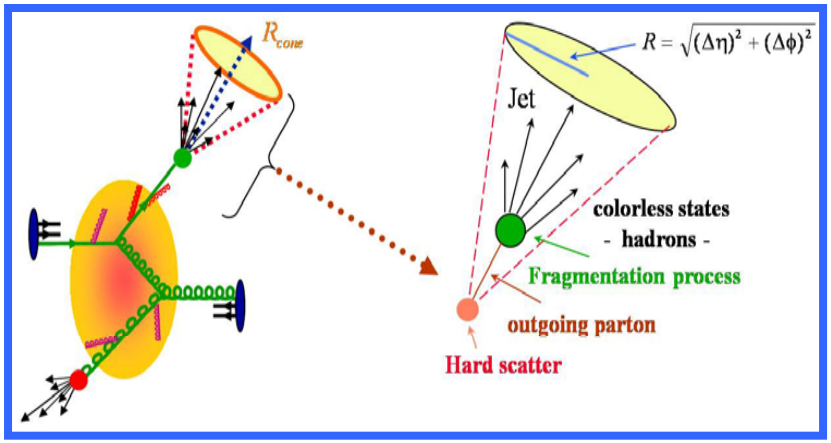
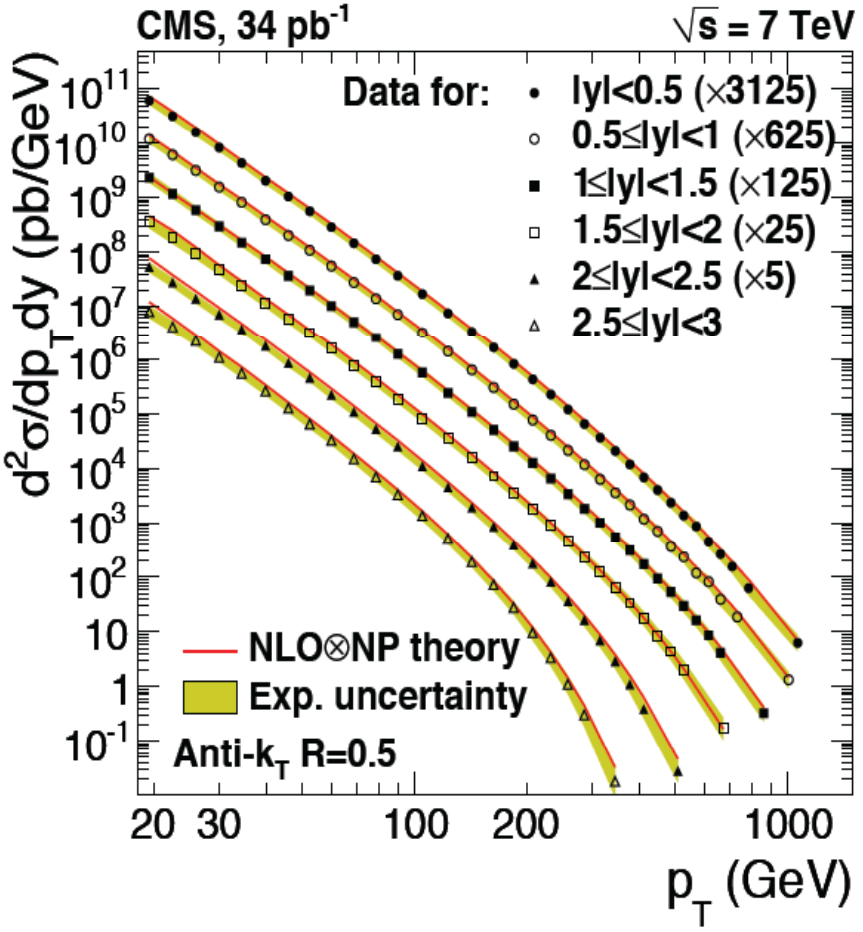
Measuring the Production of Quarks & Gluons



Inclusive jet (quarks/gluons) production

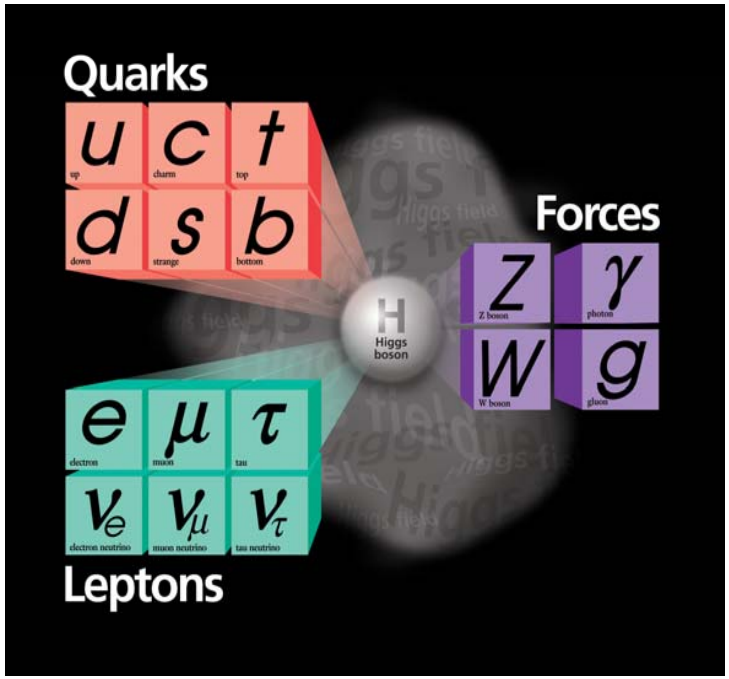
The measured jet production rate is in good agreement with theoretical predictions- NLO QCD (within errors)

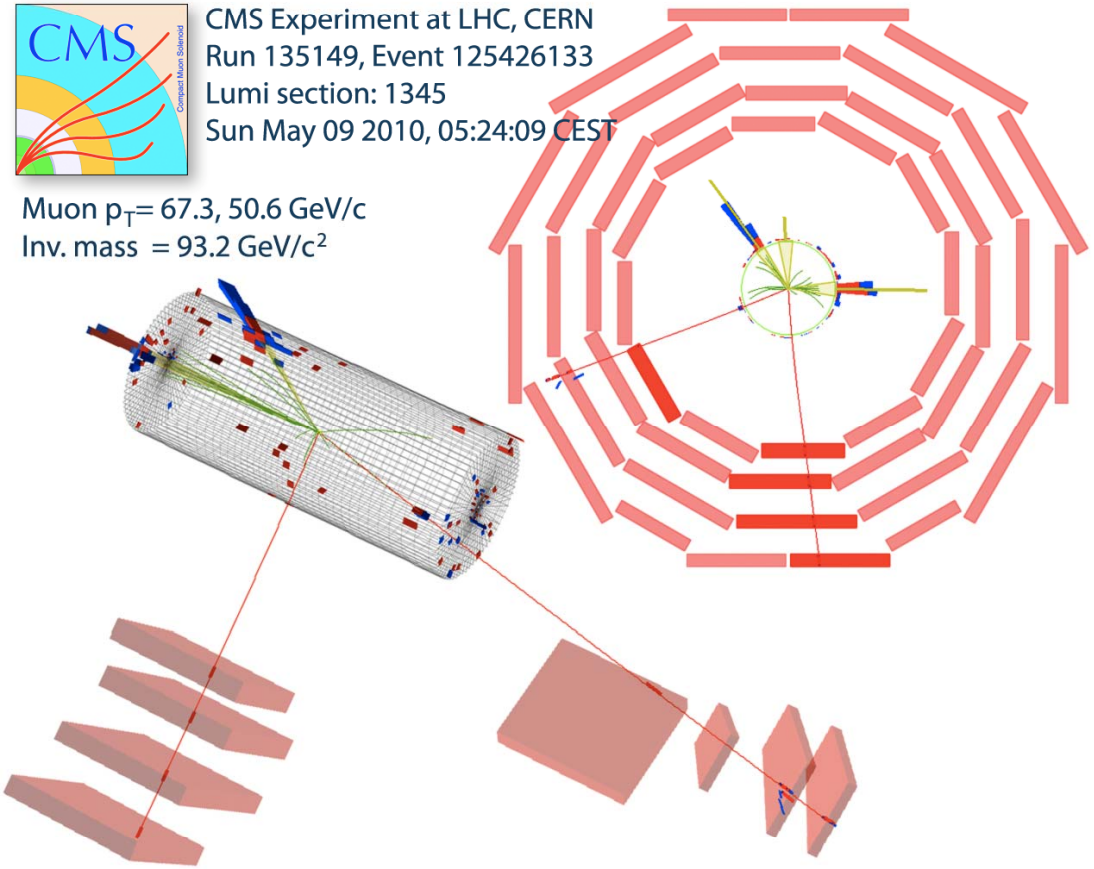




Detecting Z Bosons!

$Z \rightarrow \mu\,\mu$

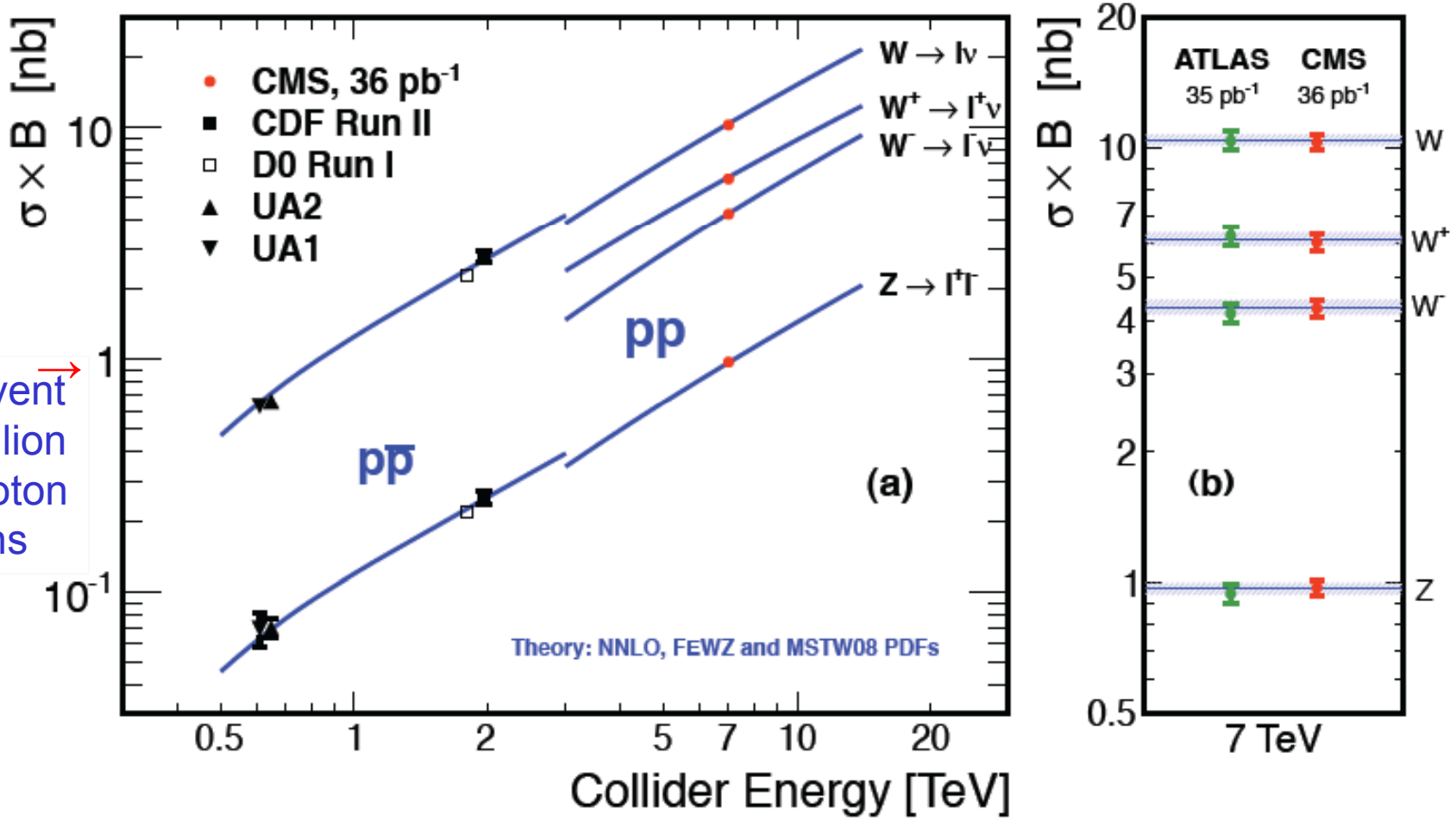


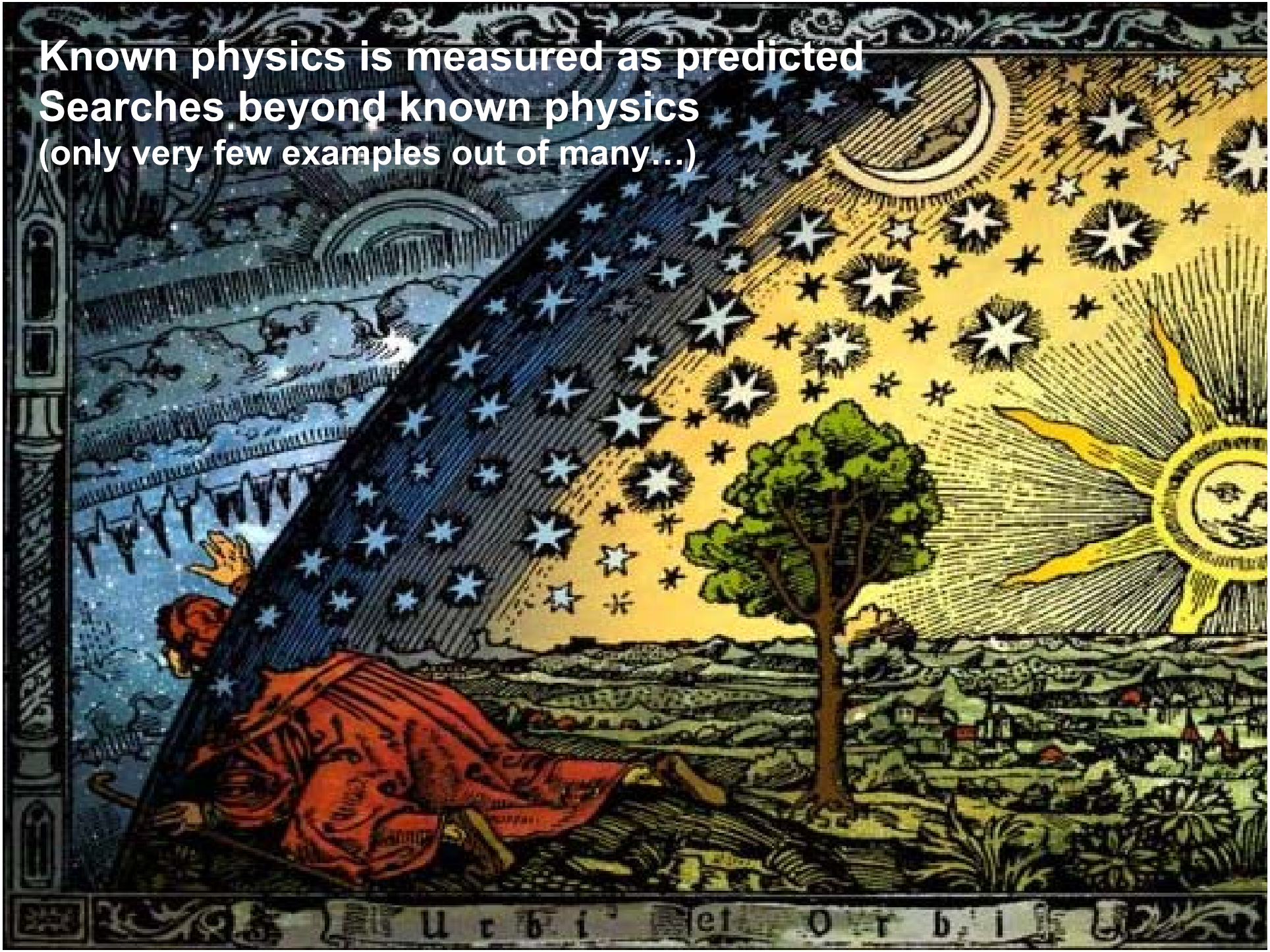


W, Z production: Confronting Predictions

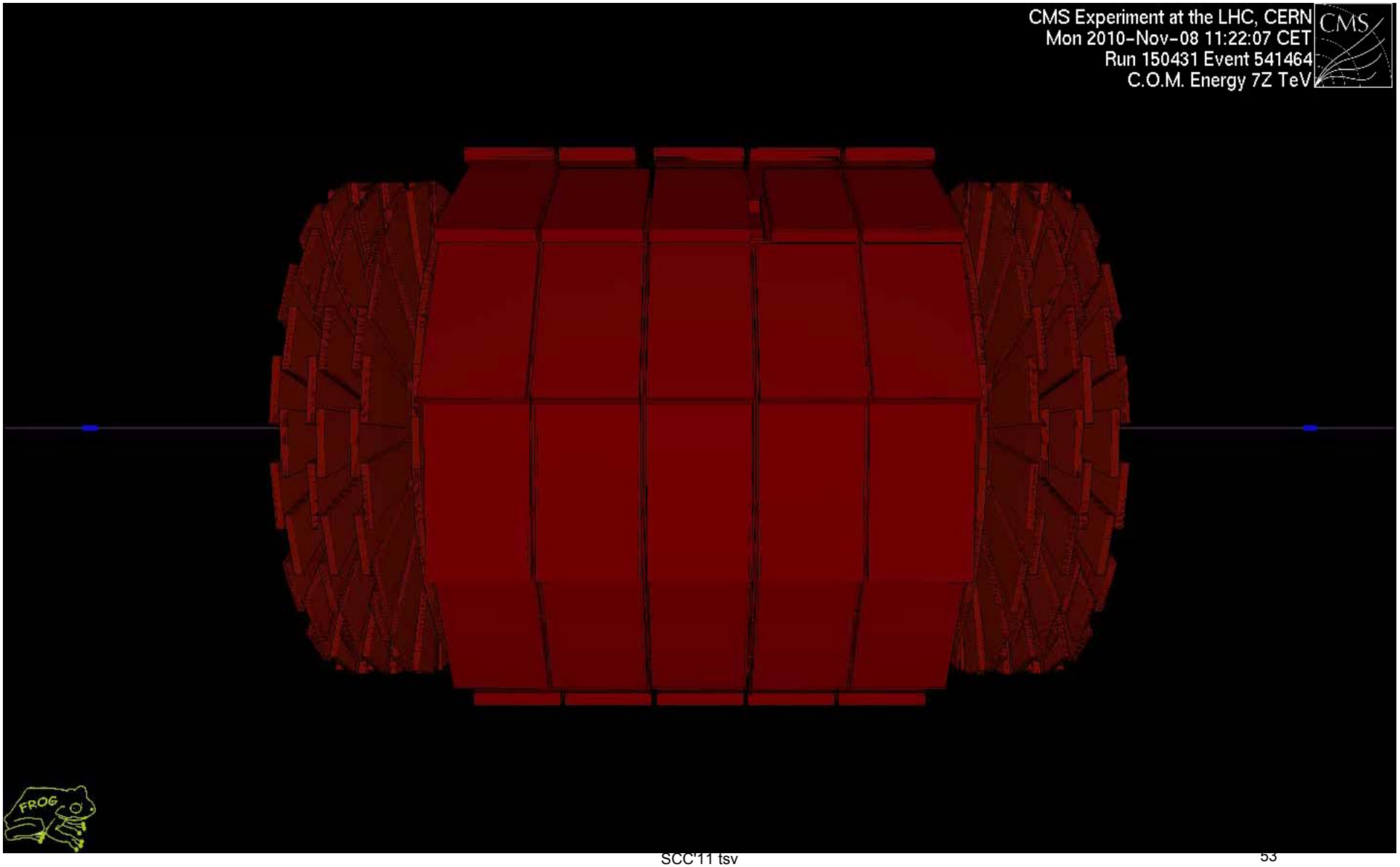
Data correspond to an examination of ~ 3 trillion pp collisions

1 Z →ll event per 70 million proton-proton collisions




Known physics is measured as predicted
Searches beyond known physics
(only very few examples out of many…)
Urbi et Orbi

Central Heavy Ion Event



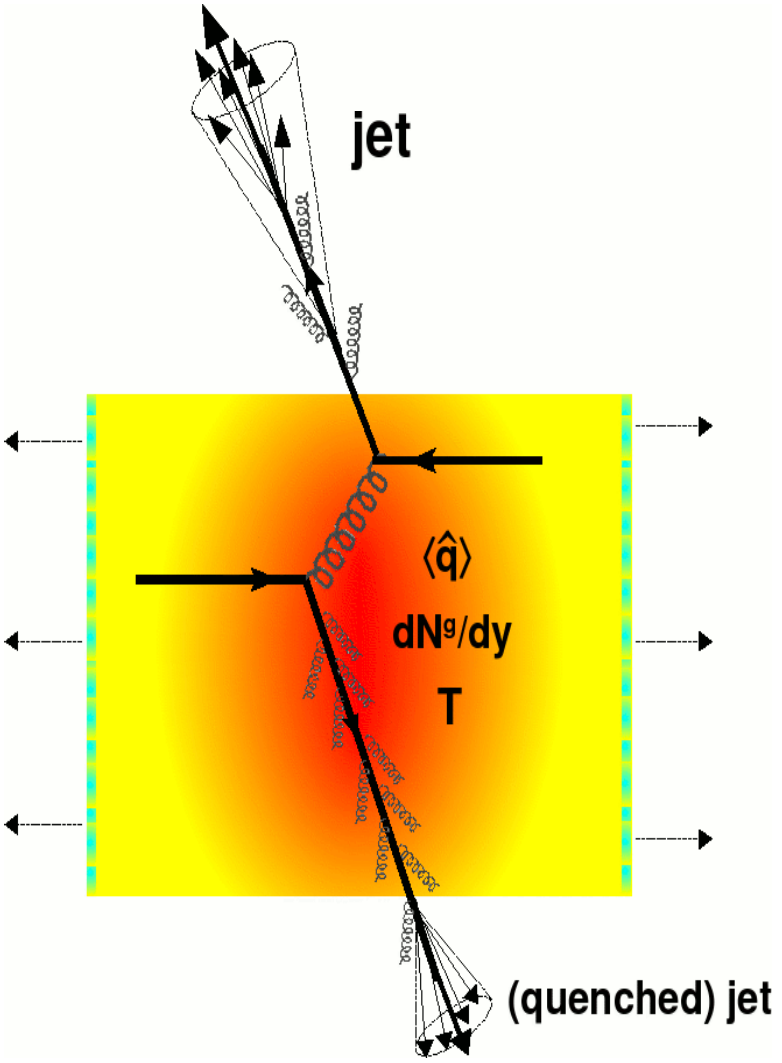
Quarks and Gluons in a Dense Medium

• Fragmentation of quarks and gluons into jets is strongly modified as they traverse the qu**ark-gluon medium created** in head-on (central) high energy Pb-Pb collisions - labeled **"jet quenching"**.

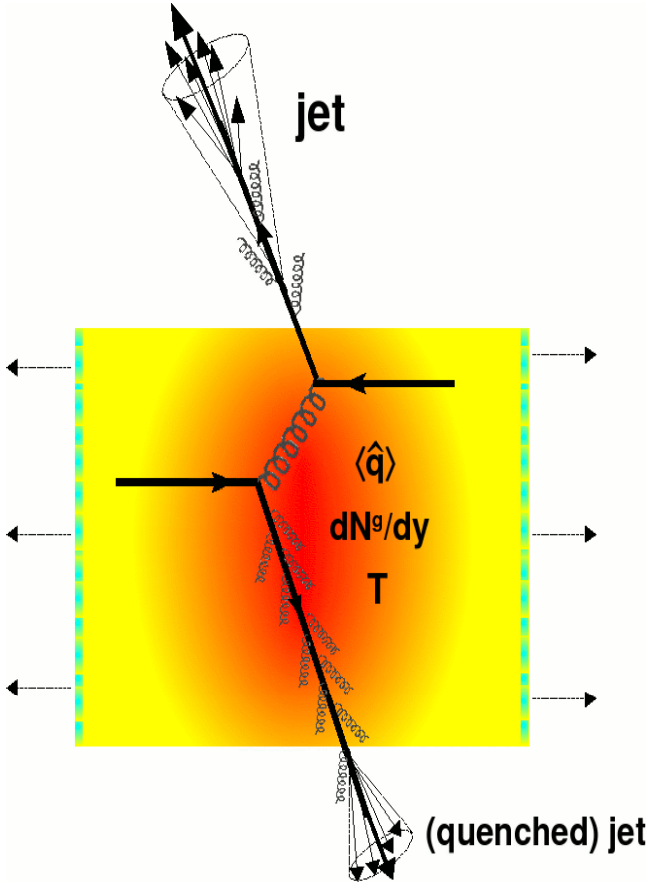
•

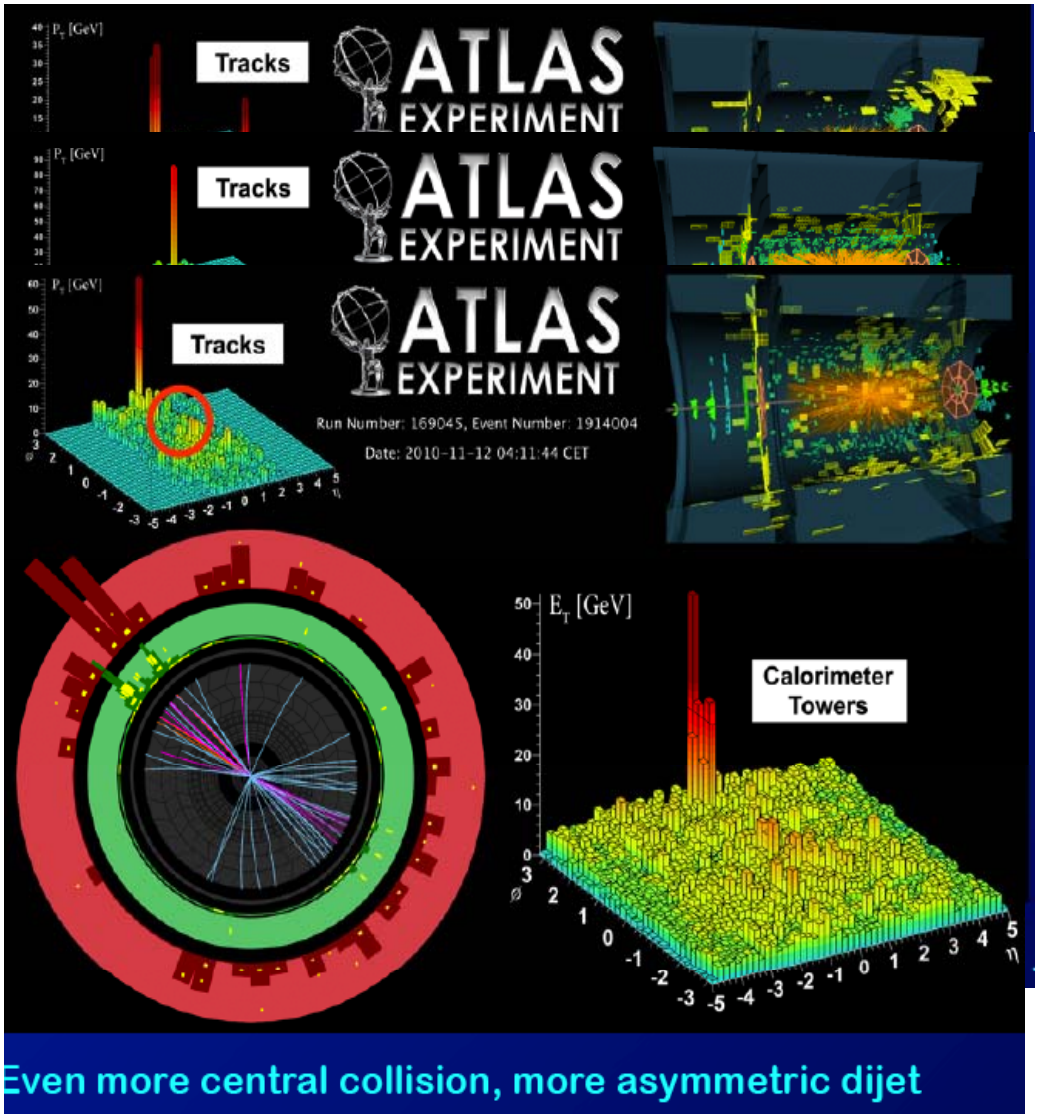
• Such effects were observed in at RHIC for single particle spectra and particle correlations.

• **At the LHC one can fully reconstruct the jets!**



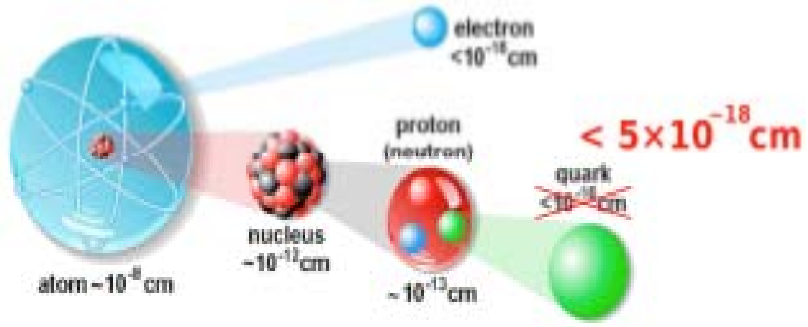
Formation of Quark-Gluon Fluid "Jet Quenching": ATLAS





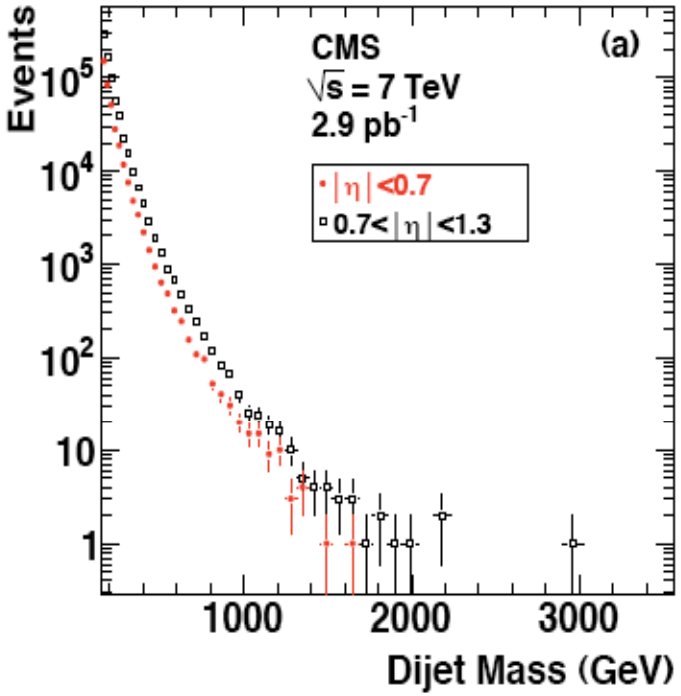
Compositeness: do quarks have sub-structure?

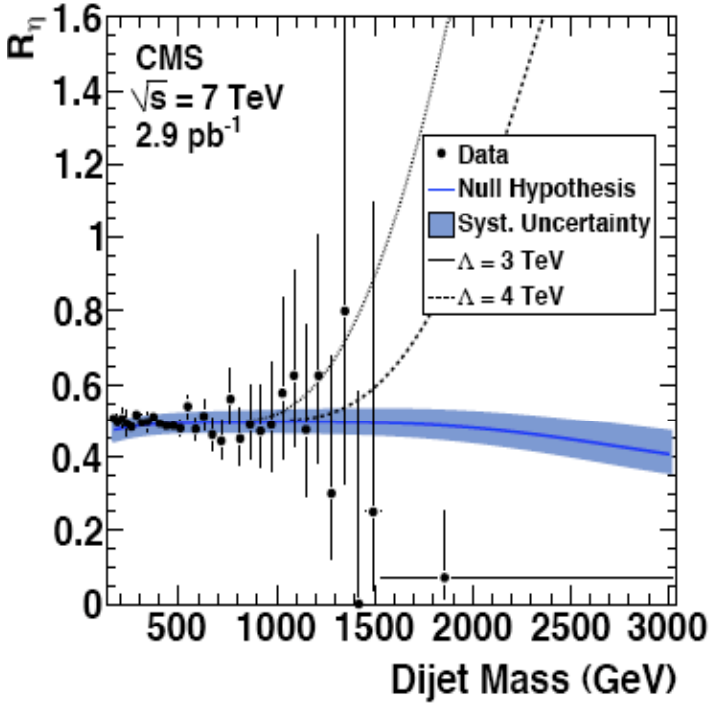
An experiment similar to the one carried out by Rutherford exactly 100 years earlier



Search based on ratio of jet pairs (leading dijets)

$$R_\eta = \frac{\sum Dijets}{\sum_{0.7<|\eta|<1.3} Dijets}$$





The observed limit is Λ < 4.0 TeV at the 95% CL

Probing sizes < 5 10^{-18} cm

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Is there a difference between matter and force particles?

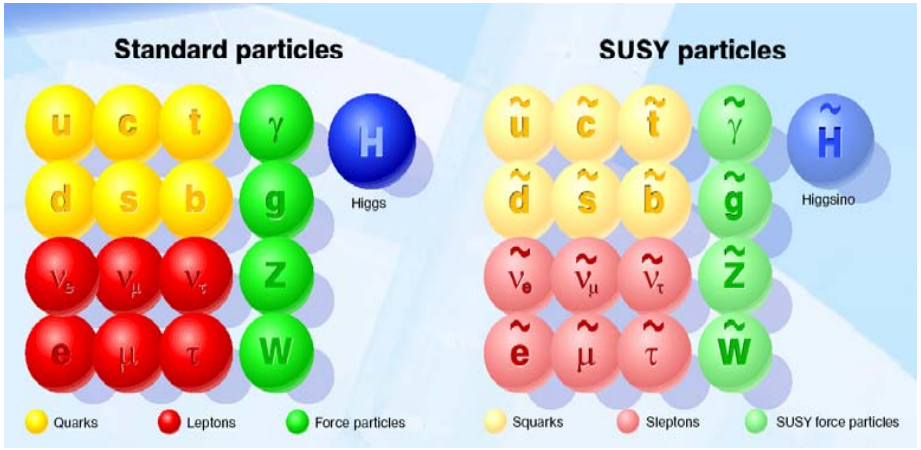
The difference between matter particles and force particles is what we label "spin". How profound is this difference?

Nature may indeed have put the two on the same footing!

Could be the "ultimate symmetry" thus labeled "supersymmetry"

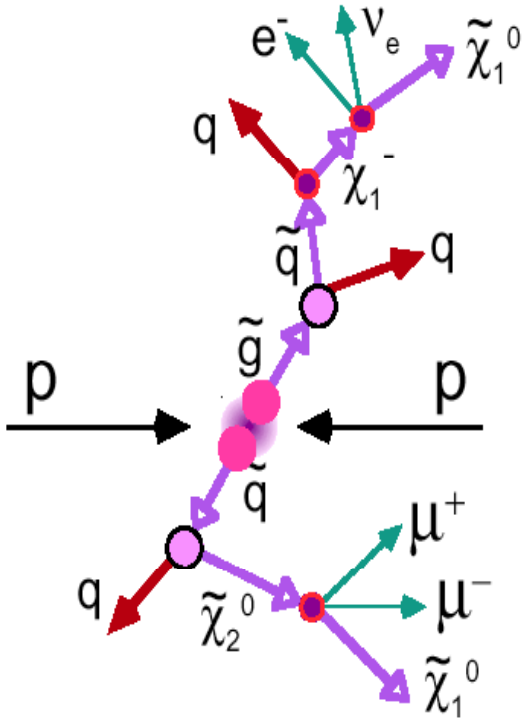
And it is the last remaining symmetry that we do not quite know how and where Nature has used it

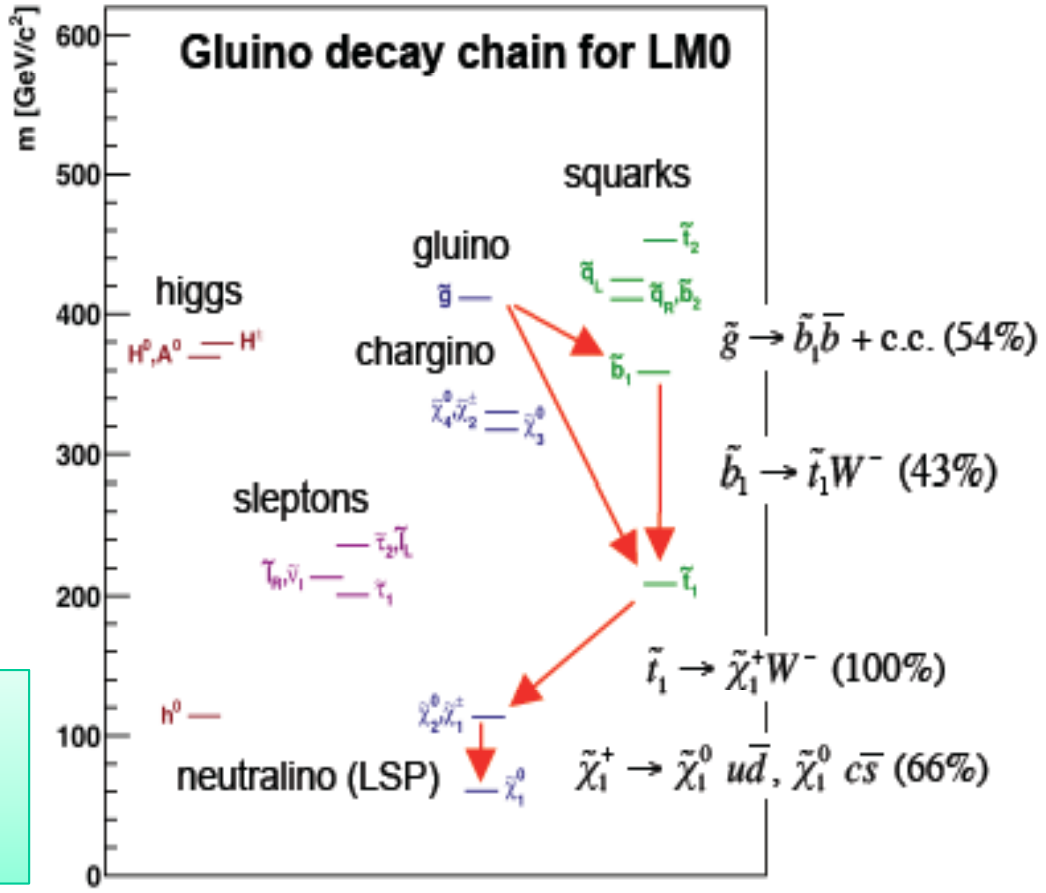
Predicts a doubling of all known fundamental particles !!!



Circumstantial evidence points to supersymmetry being relevant at the LHC! AND the lightest particle of this new species may explain "dark matter"

Supersymmetry: a New Zoology of Particles?





Searches require several (high-P_T) jets + (high) ME_T and charged leptons.

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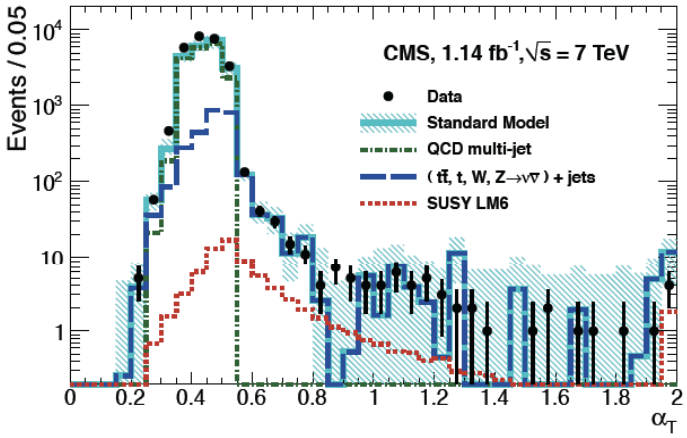
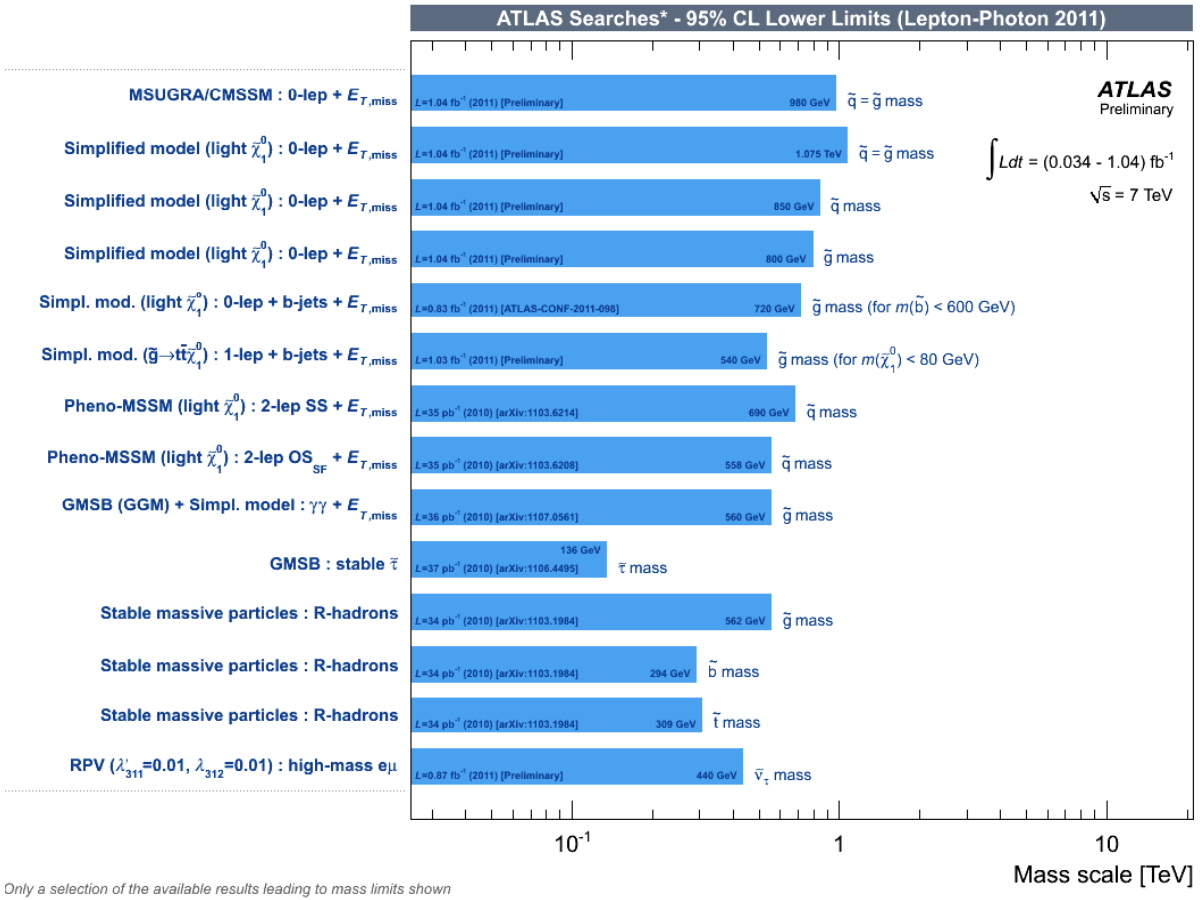
CMS:Search for Supersymmetry - Update



H_T>350 GeV,
2 Leading jets
E_T>100GeV
(| η | <2.5)
Other jets E_T>50 GeV
(| η | <3

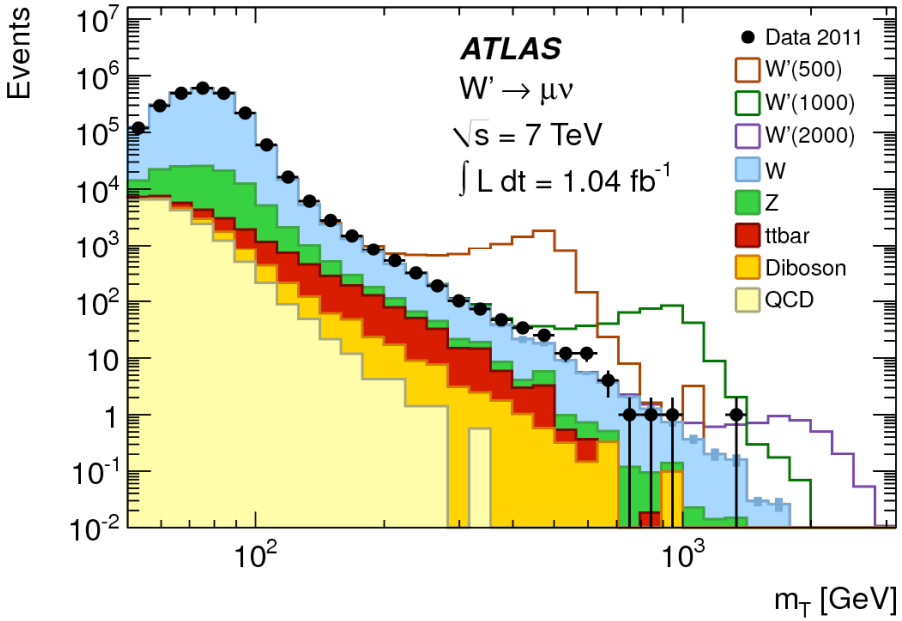


Only a selection of the available results leading to mass limits shown

Search for Heavy Vector Bosons W'/Z' SSM

Heavy vector bosons could arise from e.g.
- grand unified theories
- models with extra dimensions

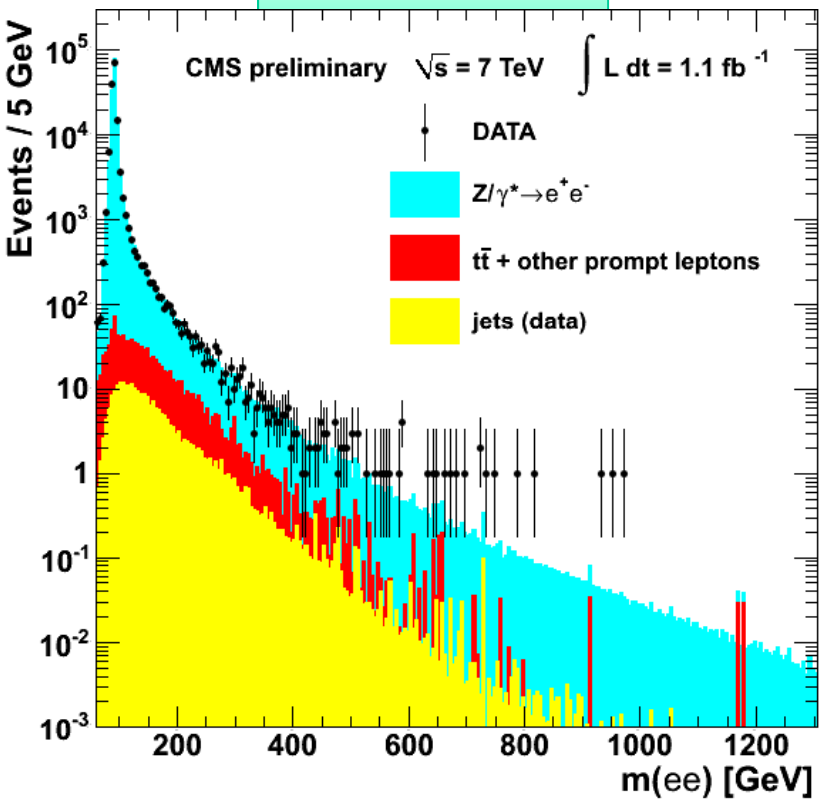
Muons + missing E_T



ATLAS: W' → l ν

$M_{W'}$ > 2.15 TeV 95% CL

Di-electrons



CMS: ee and μμ

$M_{Z'}$ > 1.94 TeV 95% CL

Microscopic Evaporating Black Holes

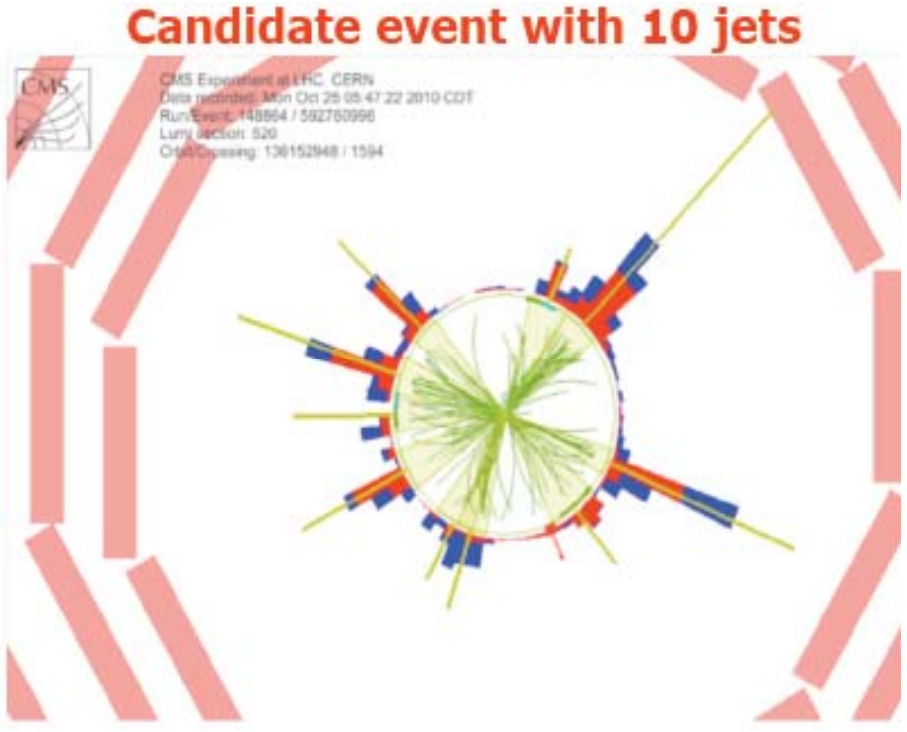
THE signature of low-scale quantum gravity ($M_D << M_{Pl}$)

BH formation when the two colliding partons have distance smaller than R_S,, the Schwarzschild radius corresponding to their invariant mass

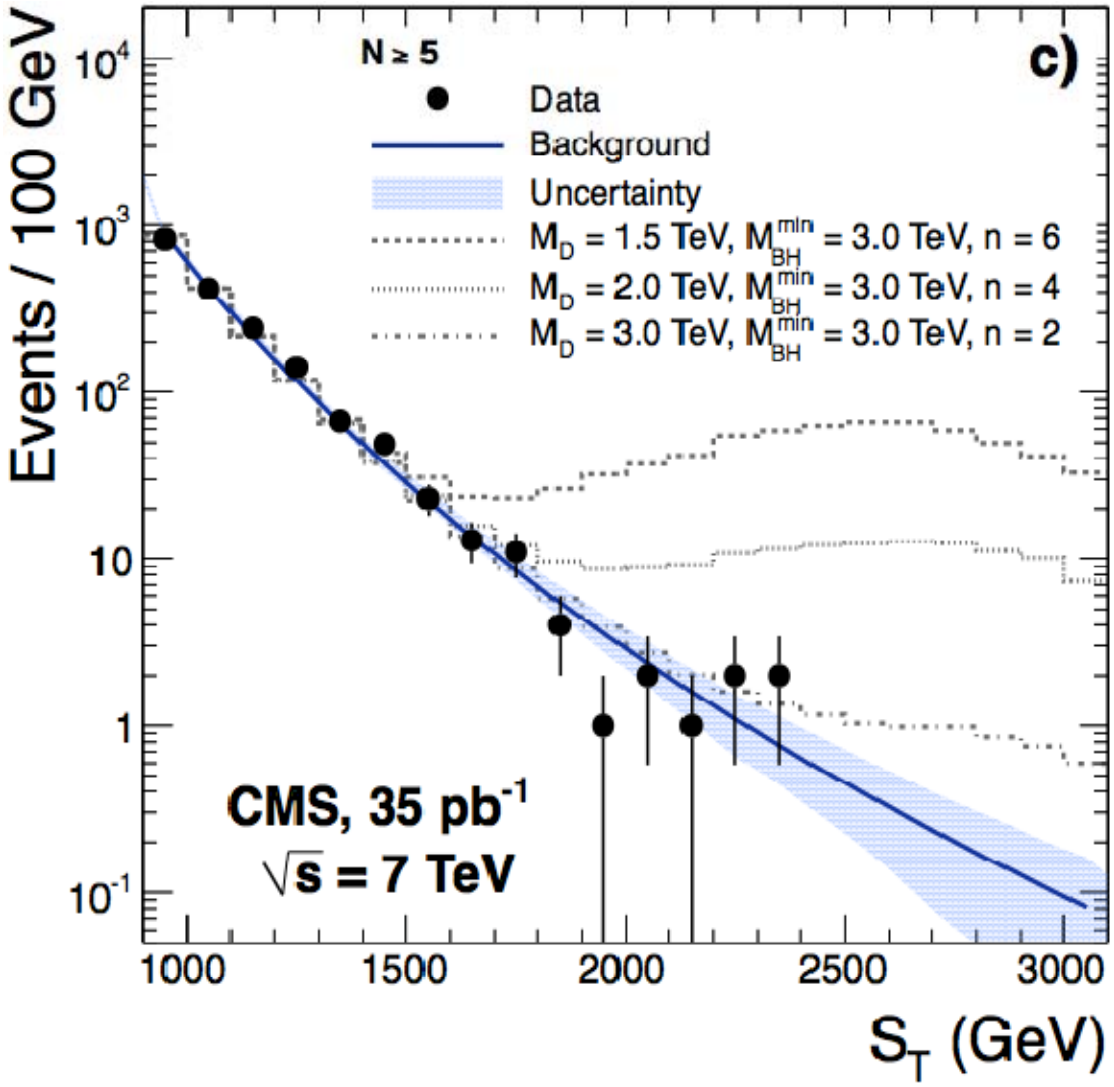
Large cross section from geometry: $\sigma = \pi R_S^2 \sim TeV^{-2}$ (up to ~100 pb!)

Microscopic BHs decay instantaneously via Hawking evaporation emitting "democratically" a large number of energetic quarks, gluons, leptons, photons, W/Z, h, etc.

Expect lots of activity in the event, so Use S_T = Sum E_T of all objects (including ME_T) with E_T>50 GeV



Search for Microscopic BHs



No excess, so set limits
M_{BH} > 3.5-4.5 TeV

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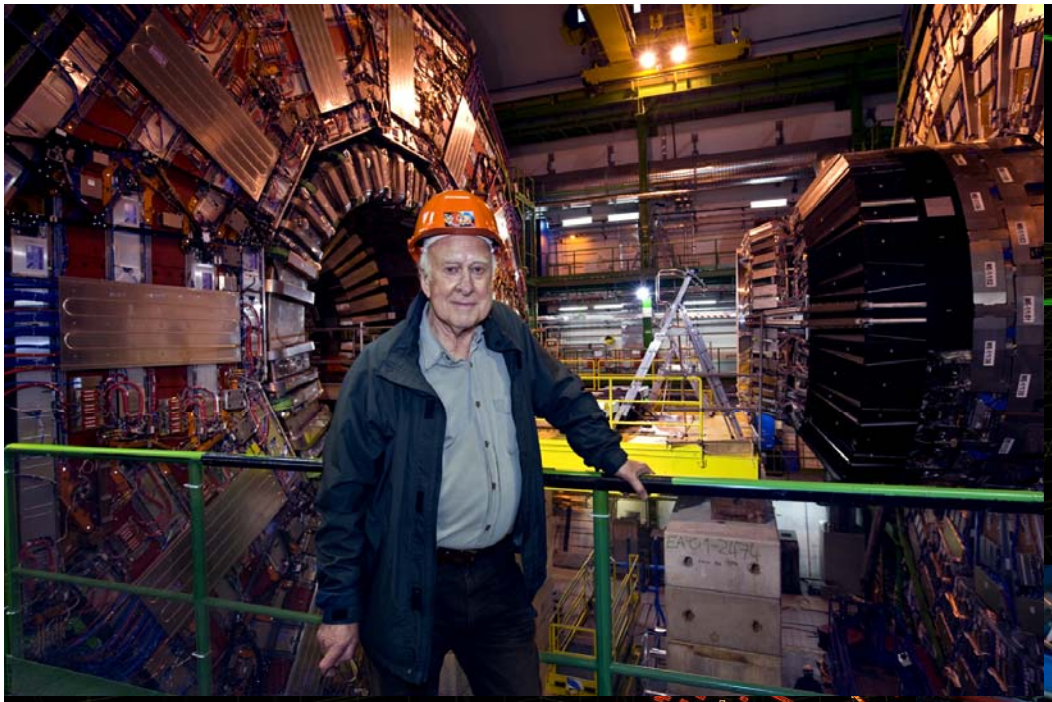
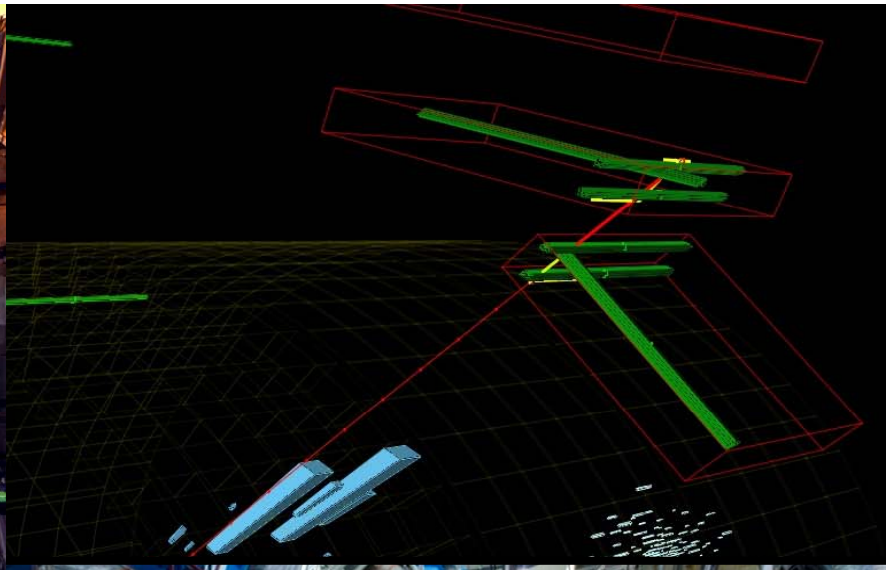
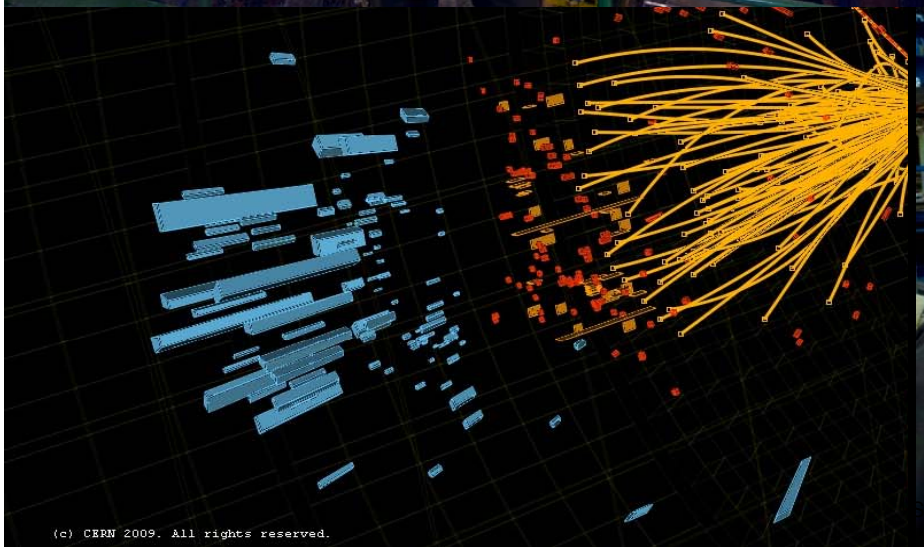
Search for the Higgs Bososn







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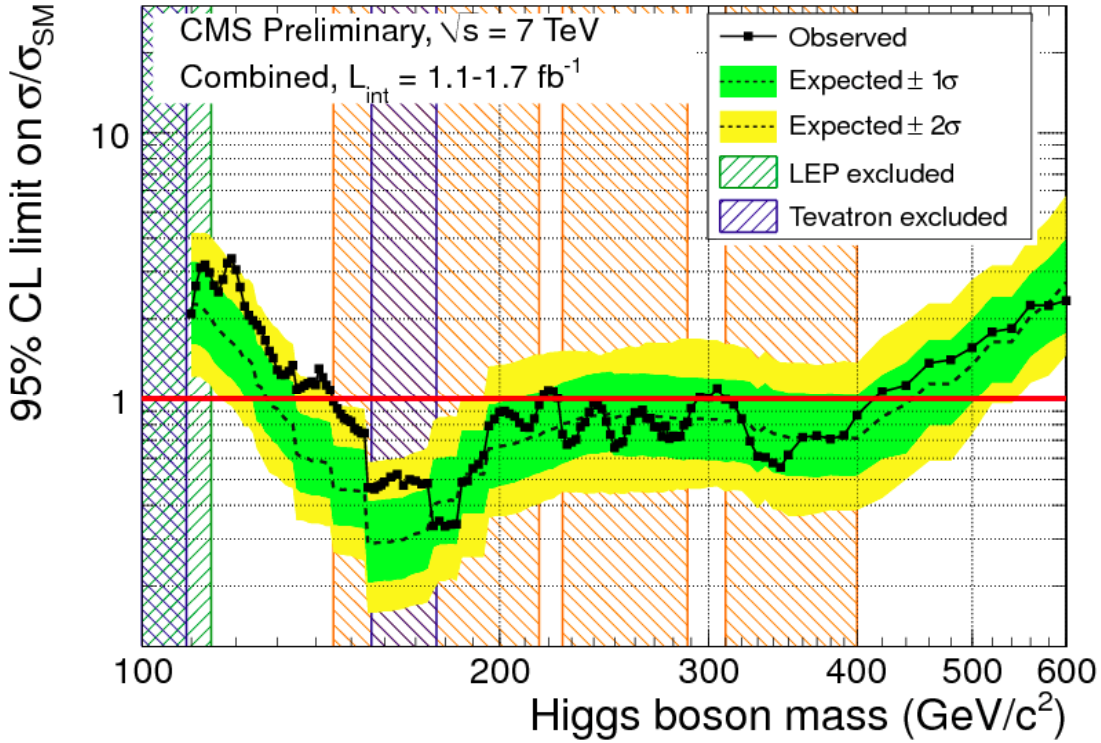
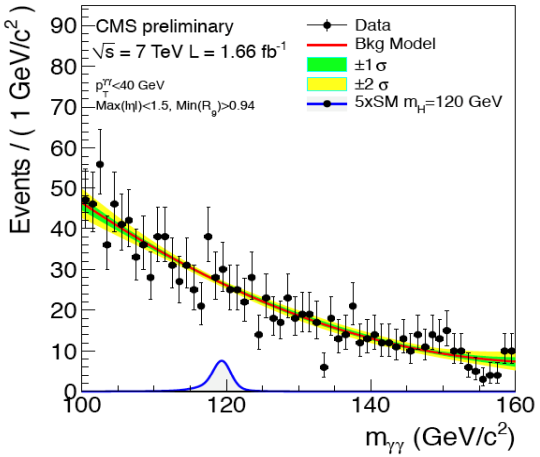
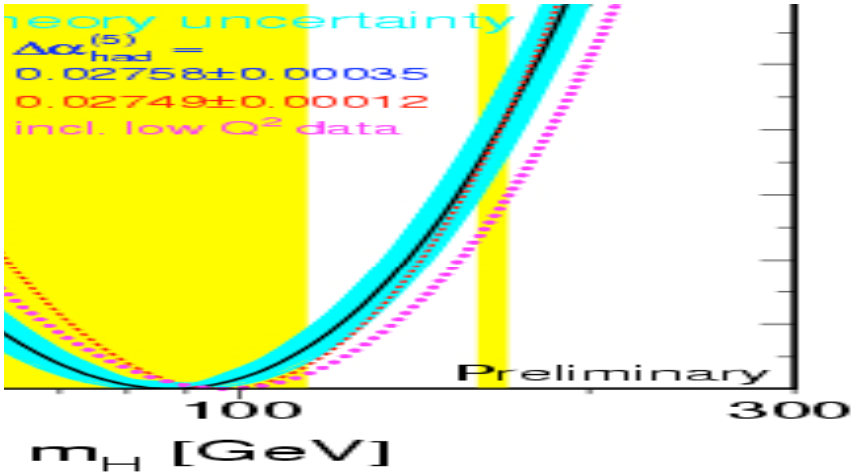
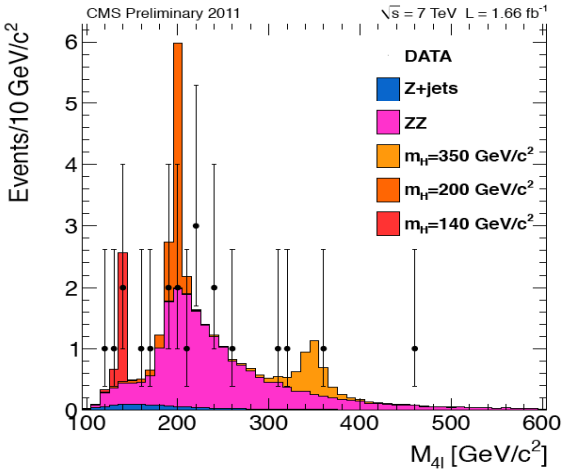
Standard Model (like) Higgs: LHC at 7 TeV









Hatched ranges are disfavoured at 95% CL

SCC'11 tsv

Outlook 2011-2012

Physics with
> 1 thousand trillion proton-proton interactions

Make more precise SM measurements – confront theory

Search for the Higgs Boson

Search for Supersymmetry

Search for conjectured new physics

Look and be prepared for the unexpected

Conclusions: The LHC Project

• The LHC project (the accelerator and experiments) was conceived & designed to attack fundamental questions in science:

about the origin, evolution and composition of our universe.

In particular, what is the origin of mass, what constitutes dark matter, do we live in more than 3 space dimensions, why is the universe composed of matter, and not antimatter.

•Unprecedented instruments in scale and complexity operating in an unprecedented & hostile environment.

• Driven by the science many technologies pushed to their limits.

• The Project has required a long and painstaking effort on a global scale – a tribute to human ingenuity and collaboration.

• The accelerator and the experiments are unparalleled scientific instrument(s) - powerful "microscopes" as well as powerful "telescopes".

Outlook

After twenty years of design, construction the 2nd half of the journey of extraction of physics has started in earnest. A new era in modern physics has been launched. The accelerator and the experiments are now operating very well.

The LHC experiments have become physics producing engines! They have observed all particles of the standard model (save for neutrinos directly) and are already exploring new territory.

It is just the beginning - but tremendous encouragement for the future. A long and interesting journey lies ahead.

All expectations are that what we find at the LHC will reform our understanding of nature at the most fundamental level.

Only experiments reveal/confirm Nature's inner secrets.