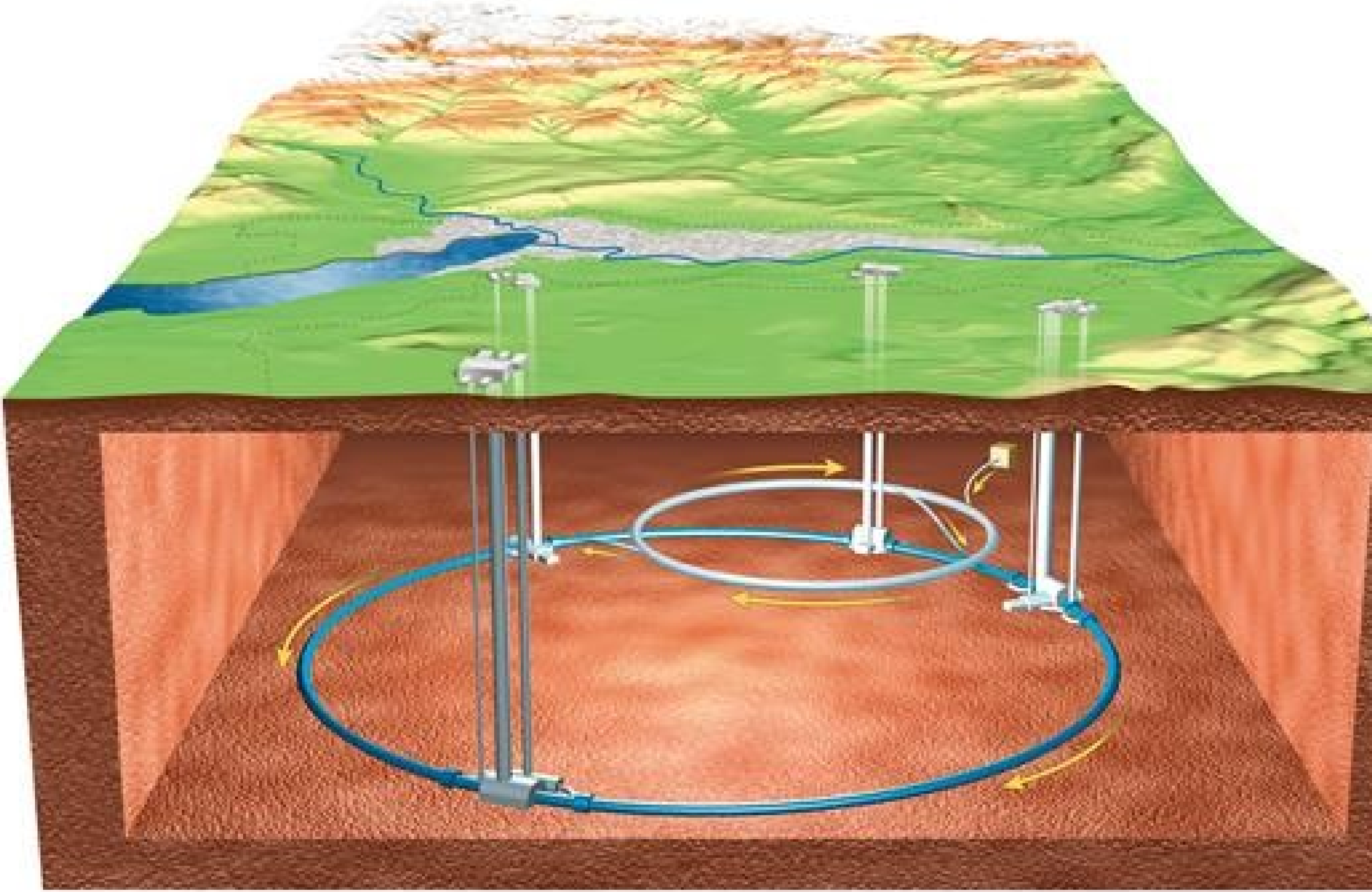
Computing for High Energy Physics Experiments

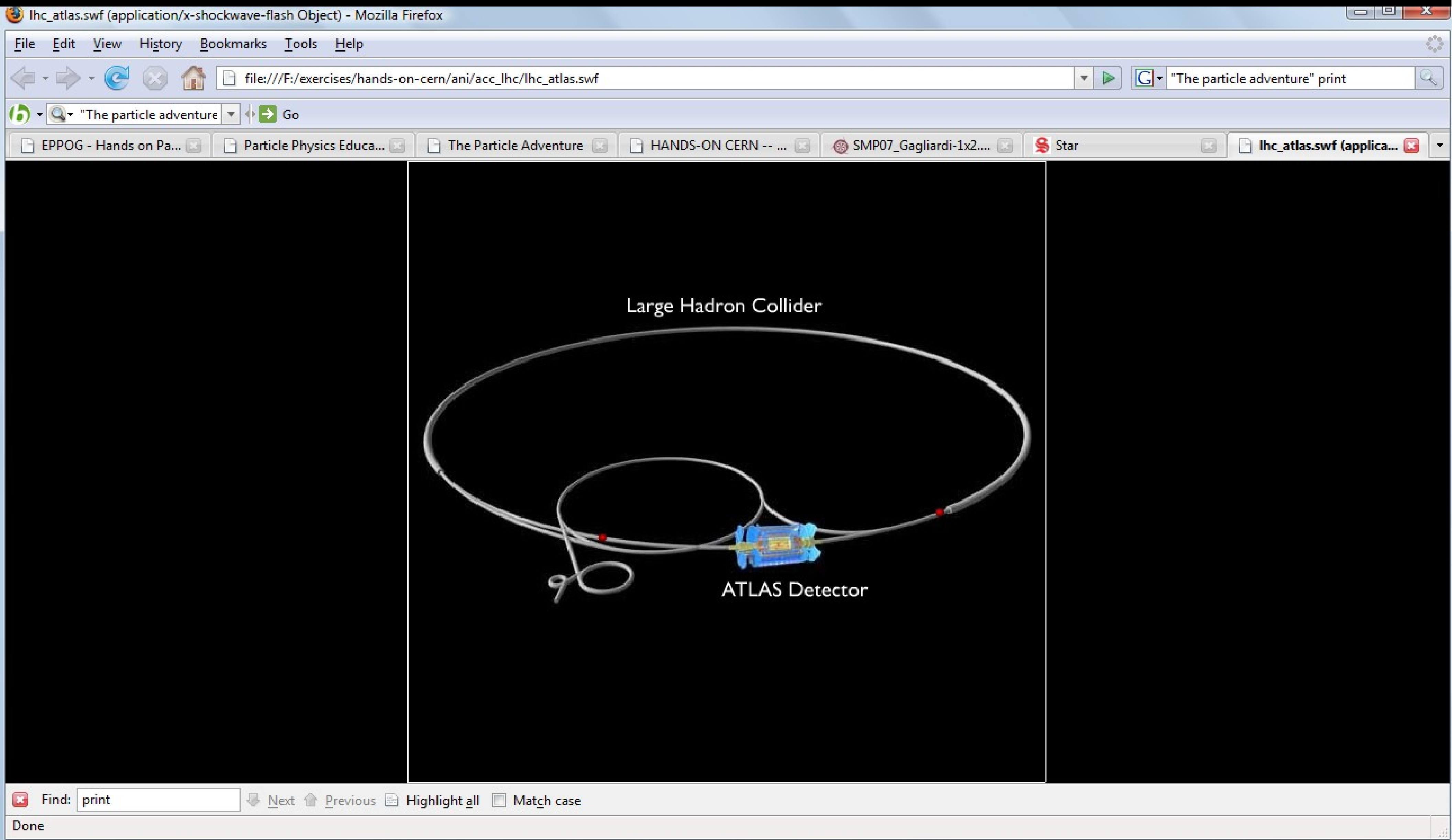
Simon Connell - UJ

- The Standard Model and beyond ?
- The LHC and ATLAS at CERN
- Data Processing

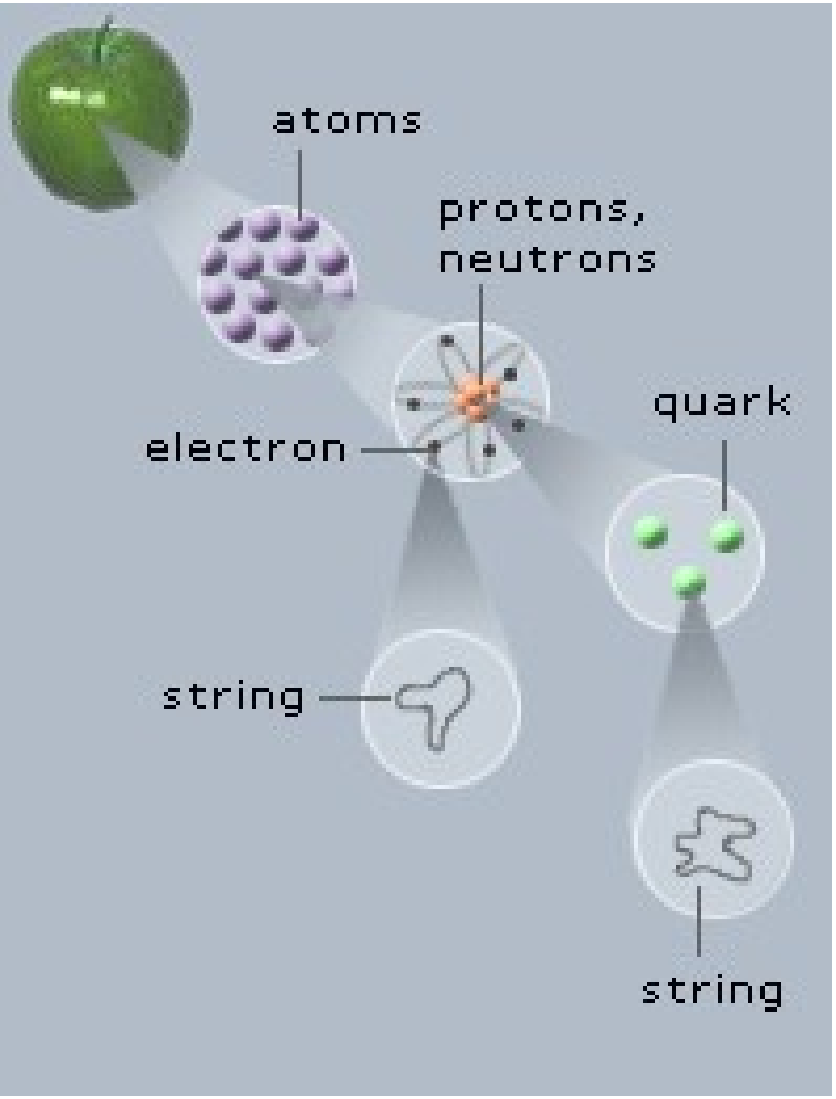
Credits
K Assamagan
CERN and ATLAS www-stes



Play accelerator animation (EPOG HEP Masterclasses)

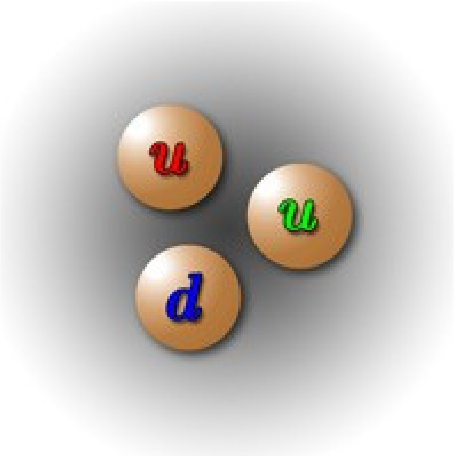


Particle Physics : The Standard Model

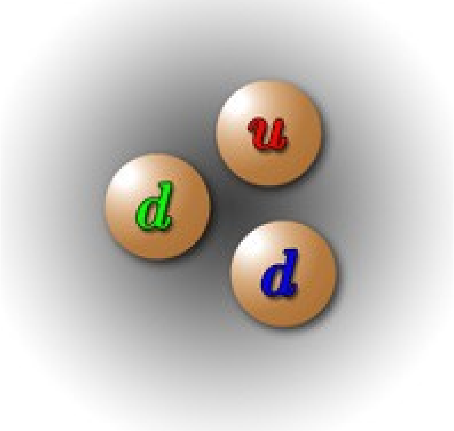


Matter particles

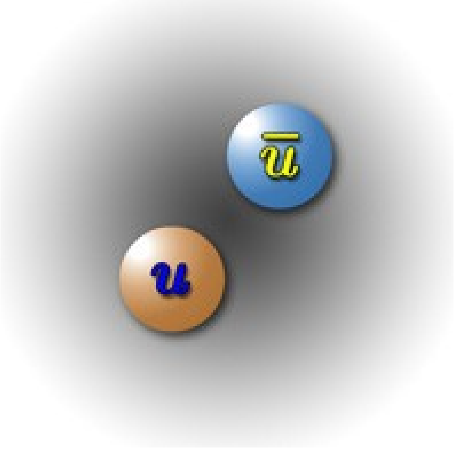
A proton consists of
three quarks
(up, up, down)

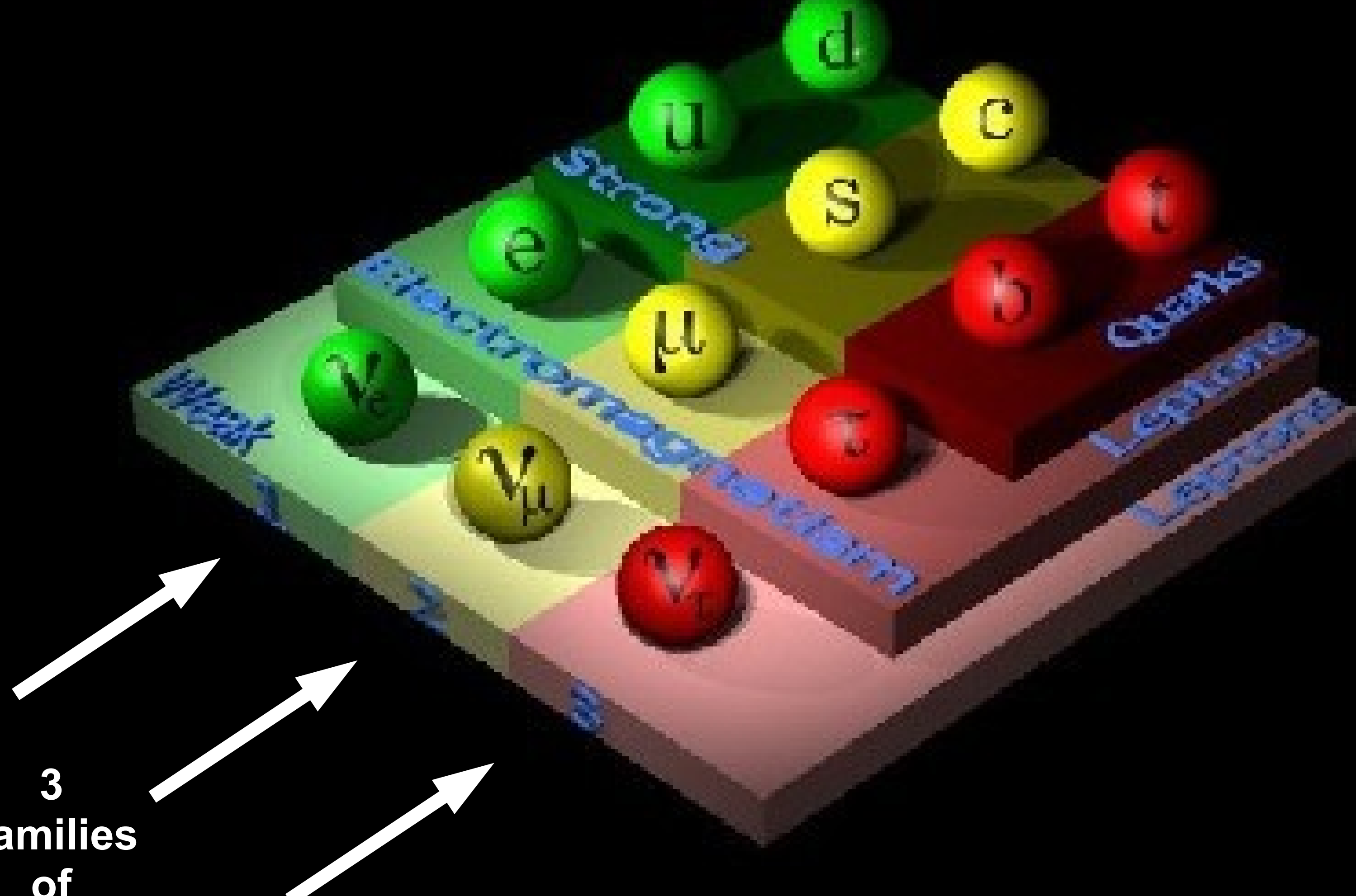


A proton consists of
three quarks
(up, up, down)

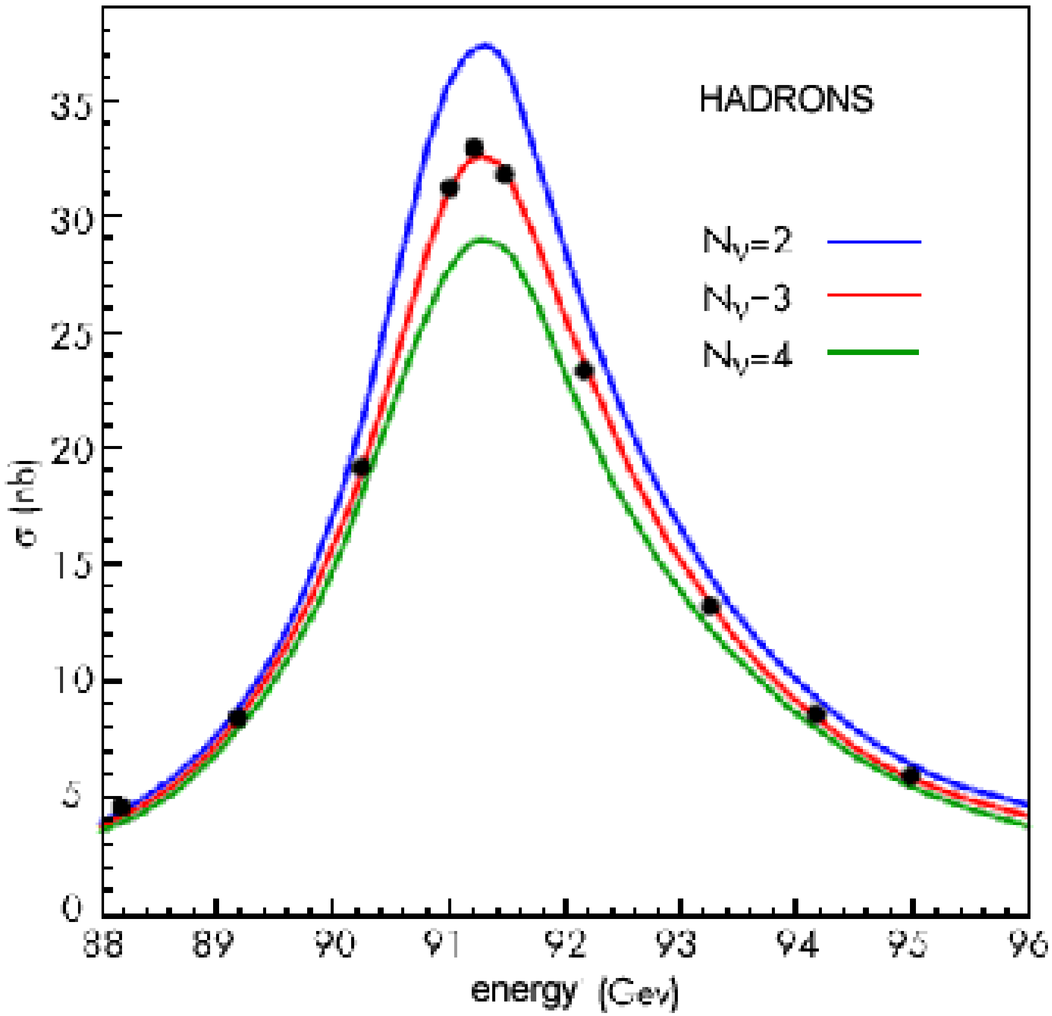


A pion consists of
two quarks
(up, anti-up)

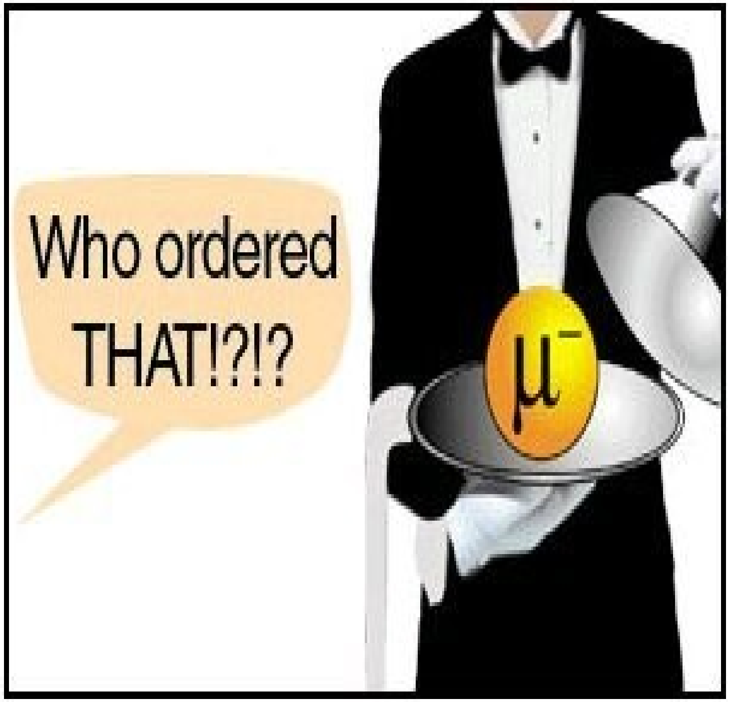




3
Families
of
Matter
Particles

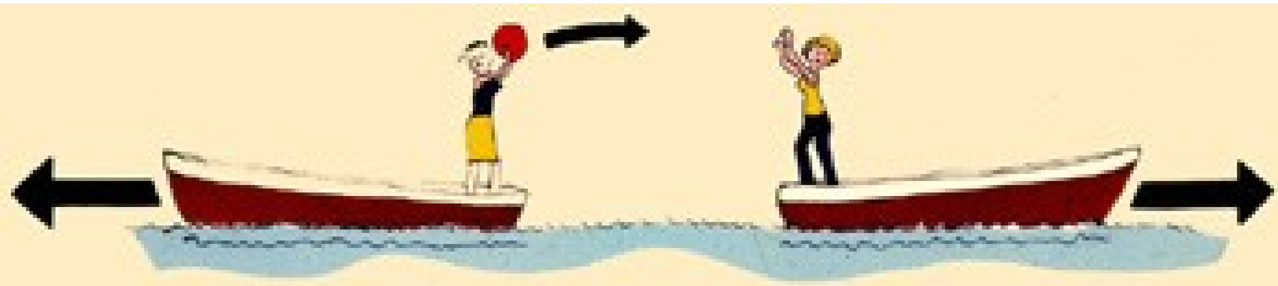


Previous experiments at LEP (fore-runner of the LHC) have shown there are three families of particles.

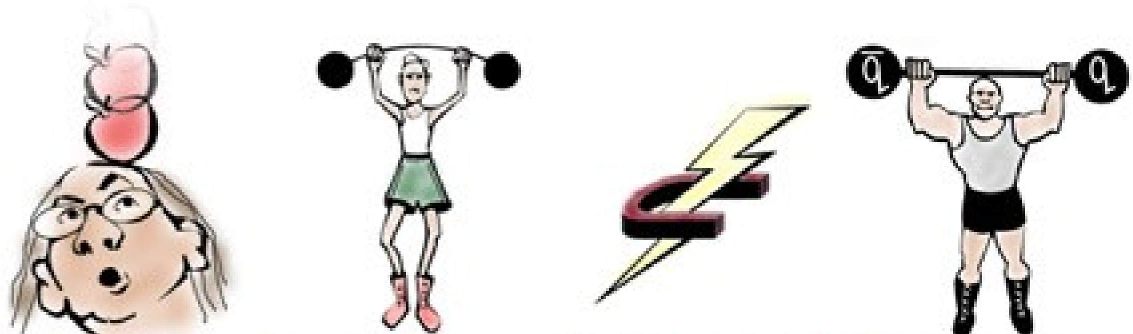


Rabi's famous comment on being given a telegram about the discovery of the muon (second family) while being served his dinner in a hotel.

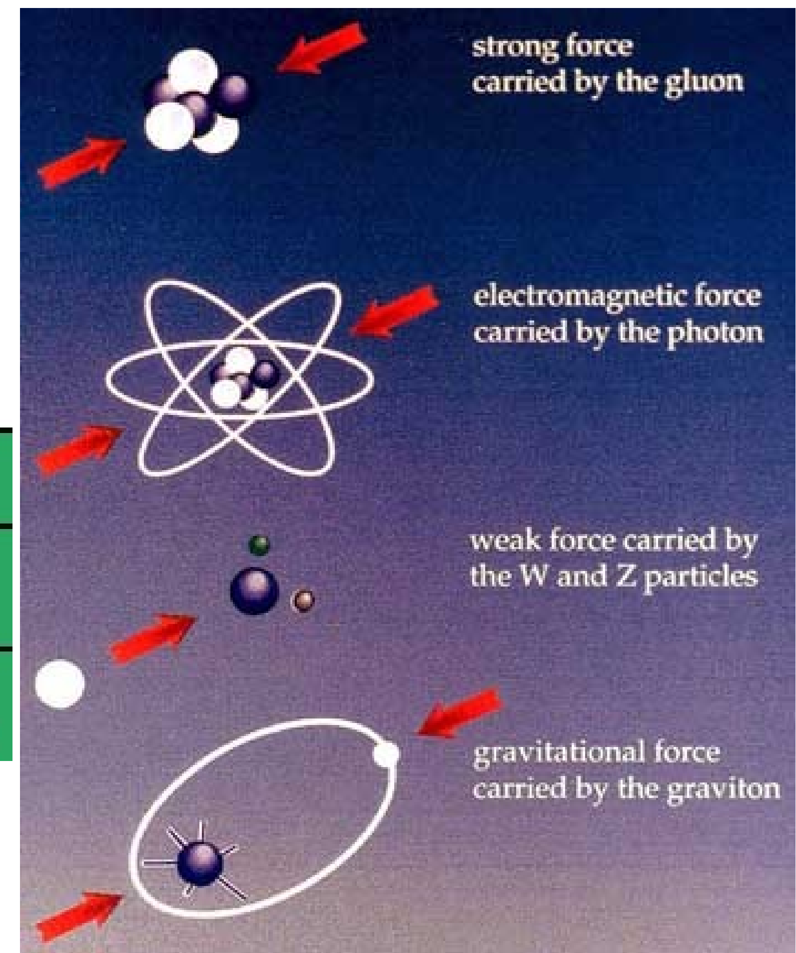
Force particles



In Quantum Field Theory, forces are represented by "force particles" which are exchanged between the "matter particles"

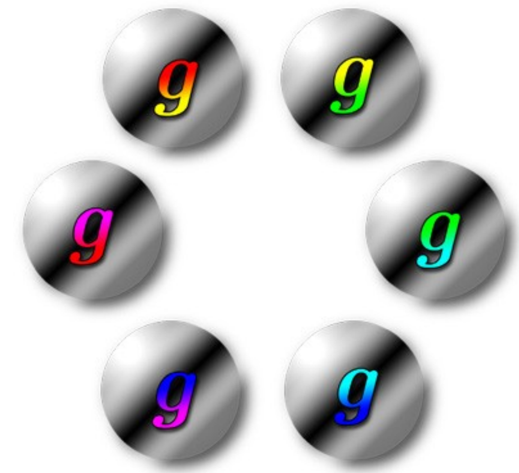


	Gravity	Weak (Electroweak)	Electromagnetic (Electroweak)	Strong
Carried By	Graviton (not yet observed)	W^+ W^- Z^0	Photon	Gluon
Acts on	All	Quarks and Leptons	Quarks and Charged Leptons and W^+ W^-	Quarks and Gluons



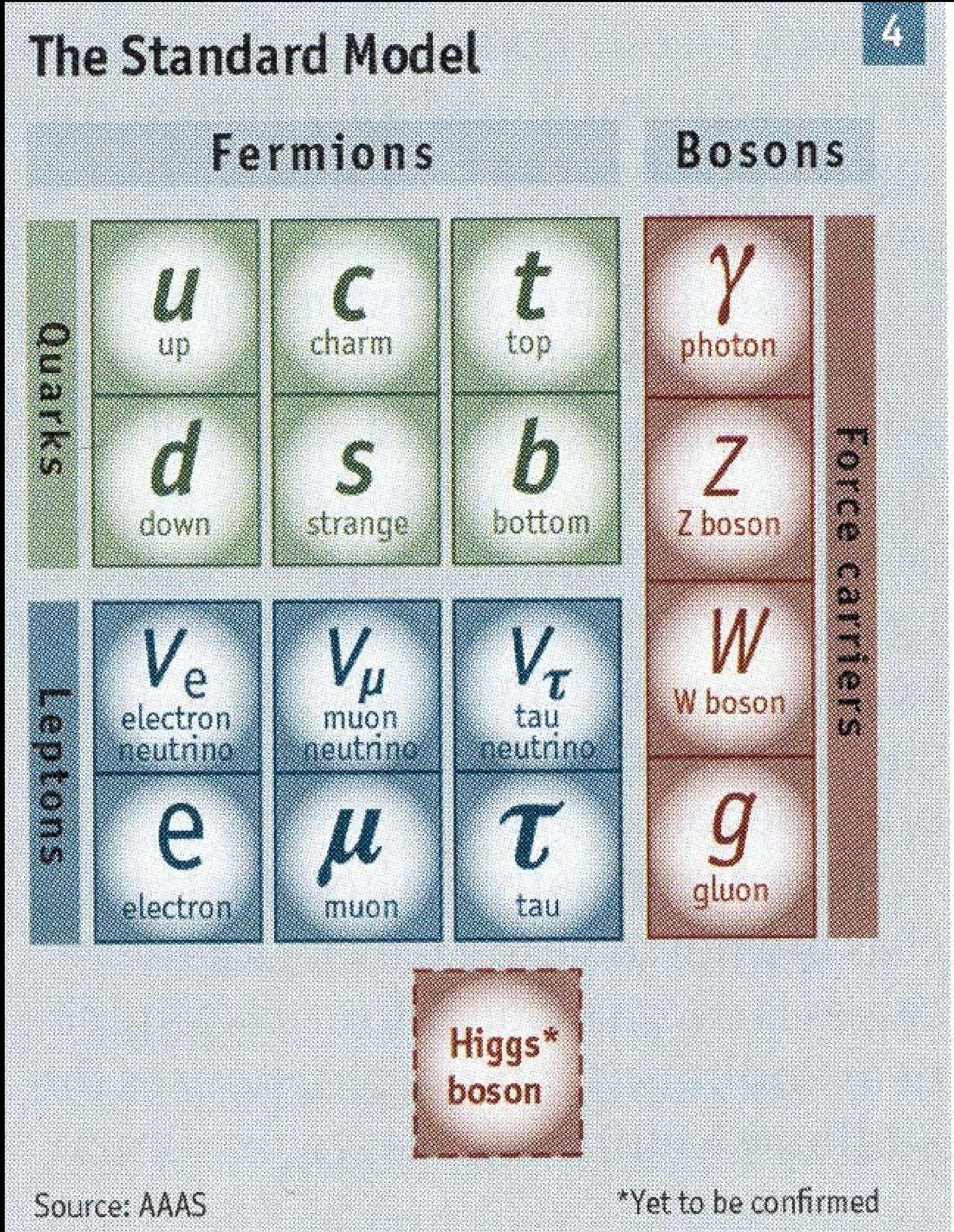
The 8 quarks are carriers of the strong force (binding nucleons in a nucleus, or quarks in a hadron)

6 of the gluons are shown, each exhibiting a colour:anti-color combination



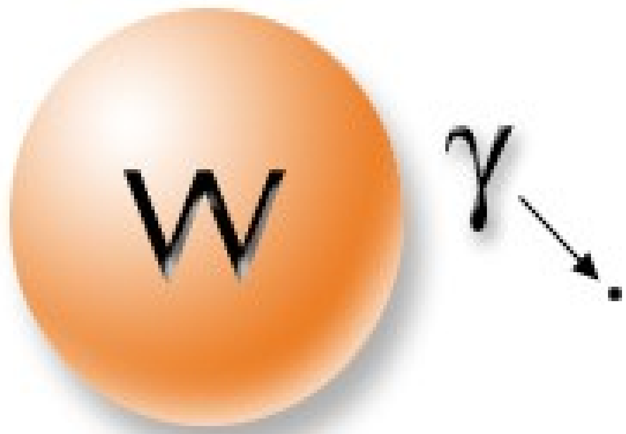
The Z and W particles are carriers of the weak force (involved for example, in beta decay radioactivity)

A neutron decays to a proton via the change of a don quark to an up quark, emitting a W^-, which decays to an electron and a anti-neutrino.



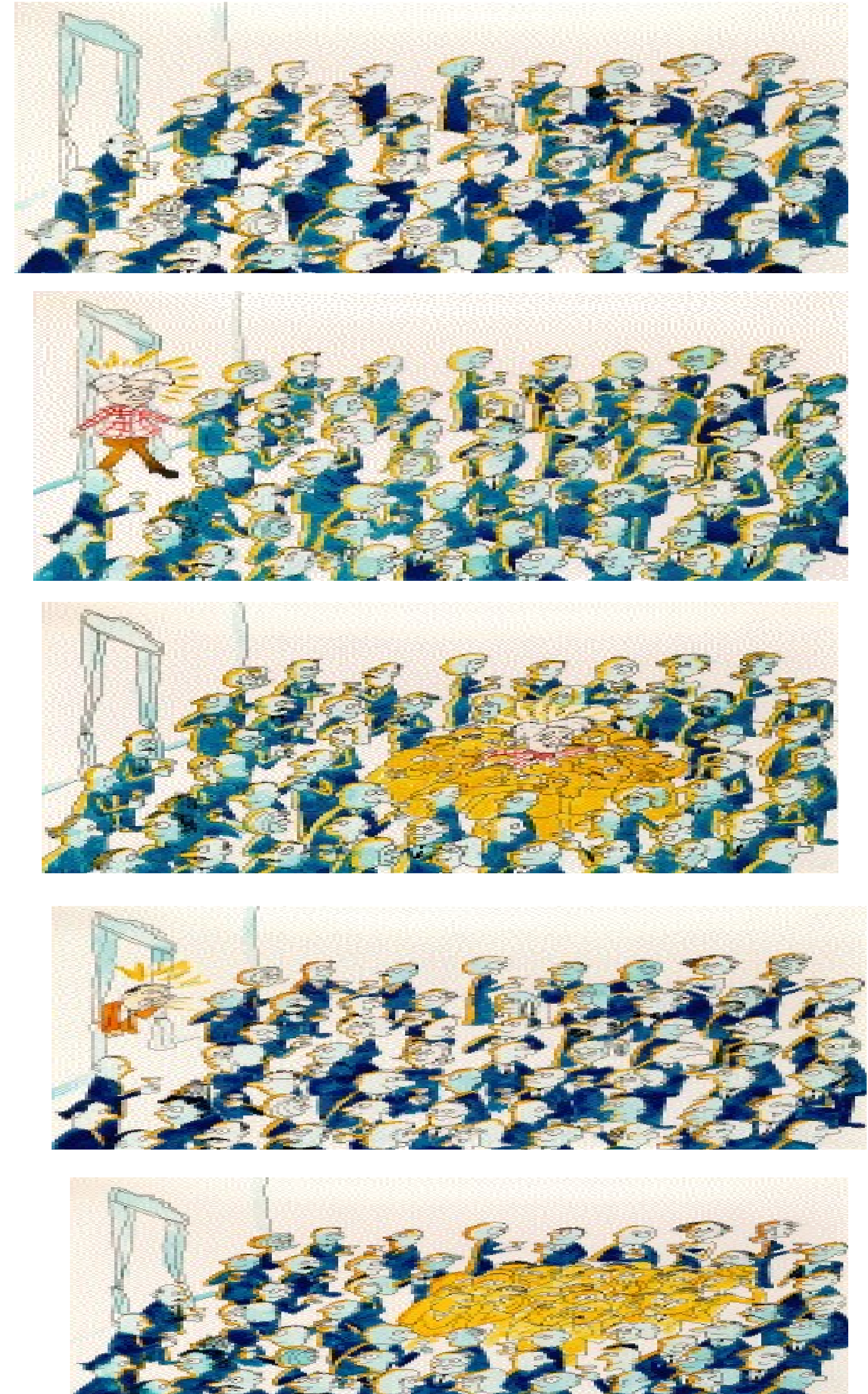
The Standard Model
4
Fermions
Bosons
Quarks
u up
c charm
t top
d down
s strange
b bottom
Leptons
ν_e electron neutrino
ν_μ muon neutrino
ν_τ tau neutrino
e electron
μ muon
τ tau
γ photon
Z Z boson
W W boson
g gluon
Force carriers
Higgs* boson
Source: AAAS
*Yet to be confirmed

The Higgs Particle



Why do some particles have large masses while the photon and neutrinos have puny masses?

The Higgs Mechanism



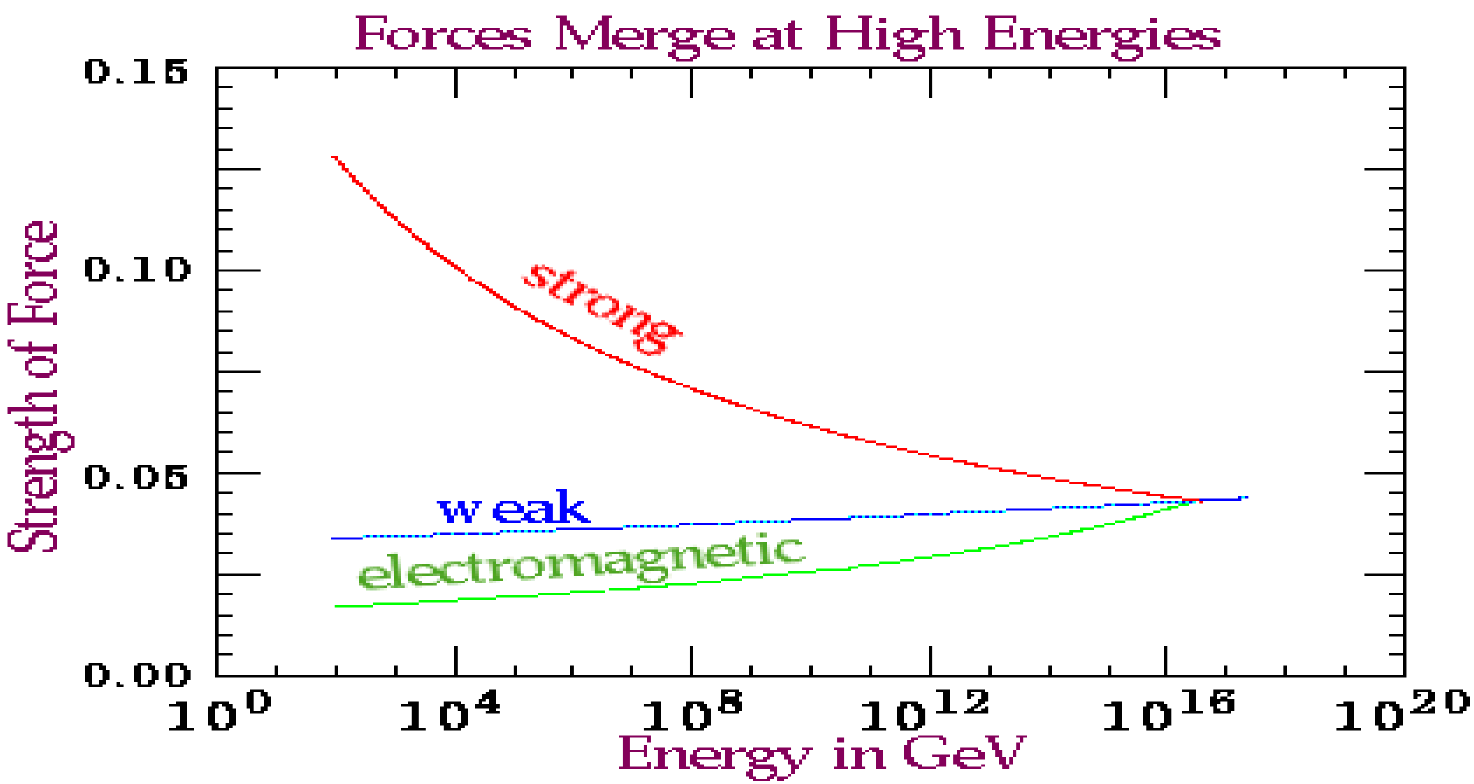
The SM proposes the existence of
Of another particle, the Higgs Field.
Particles acquire mass by interacting with
This field. The particle associated with
This field is the Higgs Particle

Beyond the Standard Model

- The Standard Model has given a very successful description of
  - The strong force, the electro-magnetic force and the weak force
  - The elementary particles and force carriers
  - Just like Maxwell united the Electric force and the magnetic in the Electro-magnetic force, the Electromagnetic force and the weak force have united into the Electroweak force
- However, there are still problems
  - The Higgs boson has not been discovered - there may be more than one Higgs bosons. Higher order corrections to the Higgs mass diverge; you have to finely tweak parameters to cancel this divergence: the fine-tuning or naturalness problem
  - Gravity is not "a part" of the SM
  - Why is gravity so week compared all the other forces (the hierarchy problem)
  - Are there super-particles? Are there extra dimensions (large)?
  - Why are there only 3 generations of leptons?
  - Neutrinos are not massless: neutrino oscillations
  - Grand Unified Theory (GUT)- to unify the strong force and the Electroweak force. The inclusion of Gravity would require String Theory ...

Grand Unified Theories

The theory which (we hope!) will unify the strong, weak, and electromagnetic interactions is called the **"Grand Unified Theory."** Physicists can write such theories today, but more data is needed to tell which of the many versions, if any, describes nature.

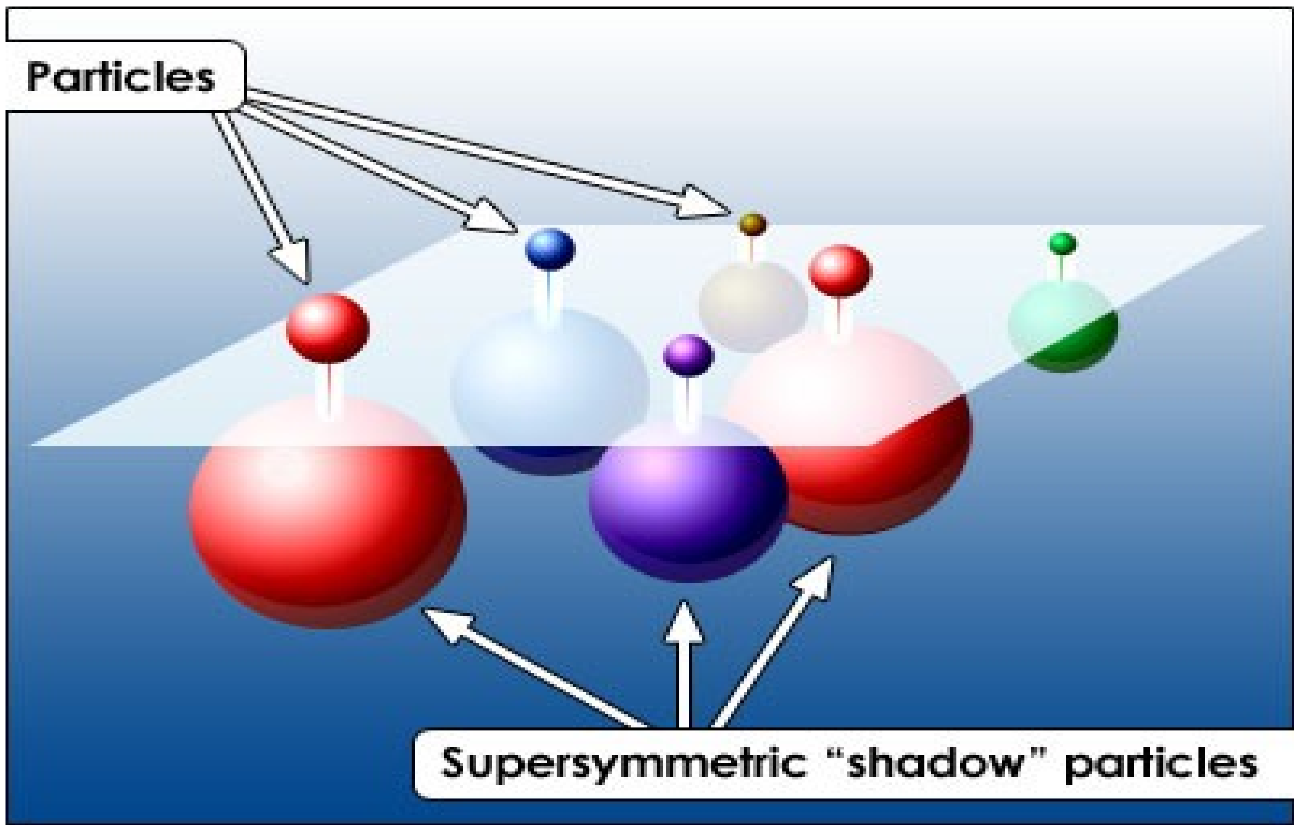


Still GUT must protect against rapid proton decay,
Otherwise the world would exist today!

Data: Proton lifetime > 10^{32} years

Super Symmetry (SUSY)

Many physicists have developed theories of **supersymmetry**, particularly in the context of Grand Unified Theories. The supersymmetric theories postulate that every particle we observe has a massive "shadow" particle partner. For example, for every quark there may be a so-called "squark" tagging along.



No SUSY particles have been discovered. To be searched At the CERN Large Hadron Collider

Dark Matter

that the majority of the universe is not made of the same type of matter as the Earth. From gravitational effects, we can infer the existence of this "dark matter," a type of matter that we cannot see. There is extensive circumstantial evidence that much of this is not made up of protons, neutrons, and electrons, as we are.

INVISIBLE

Dark Matter

What **is** dark matter? We don't know. Possibly dark matter is composed of neutrinos, or even more exotic forms of matter hypothesized by theorists

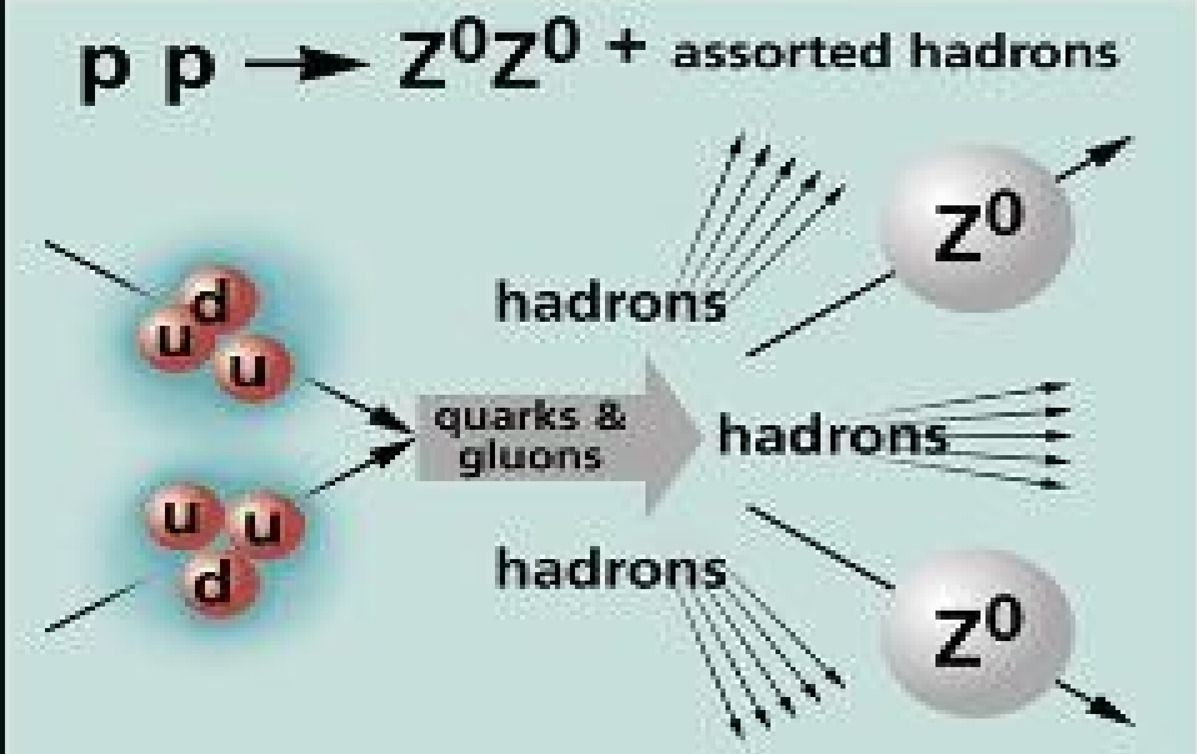
The Neutralino particle from Supersymmetry could be a Dark Matter candidate (WIMP).

The Theory of Everything …

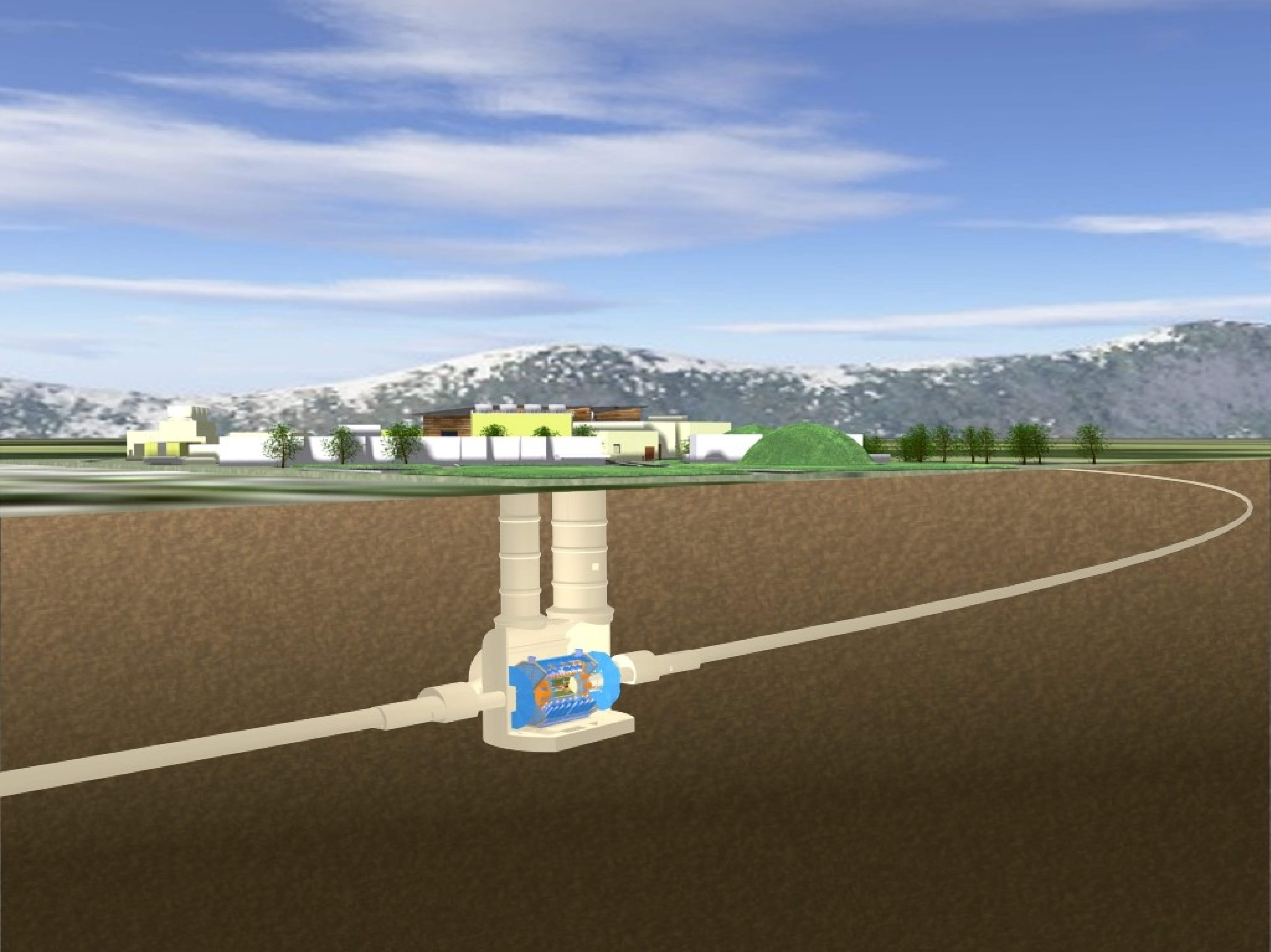
To unify Gravity with GUT (Strong Force+Electroweak Force)

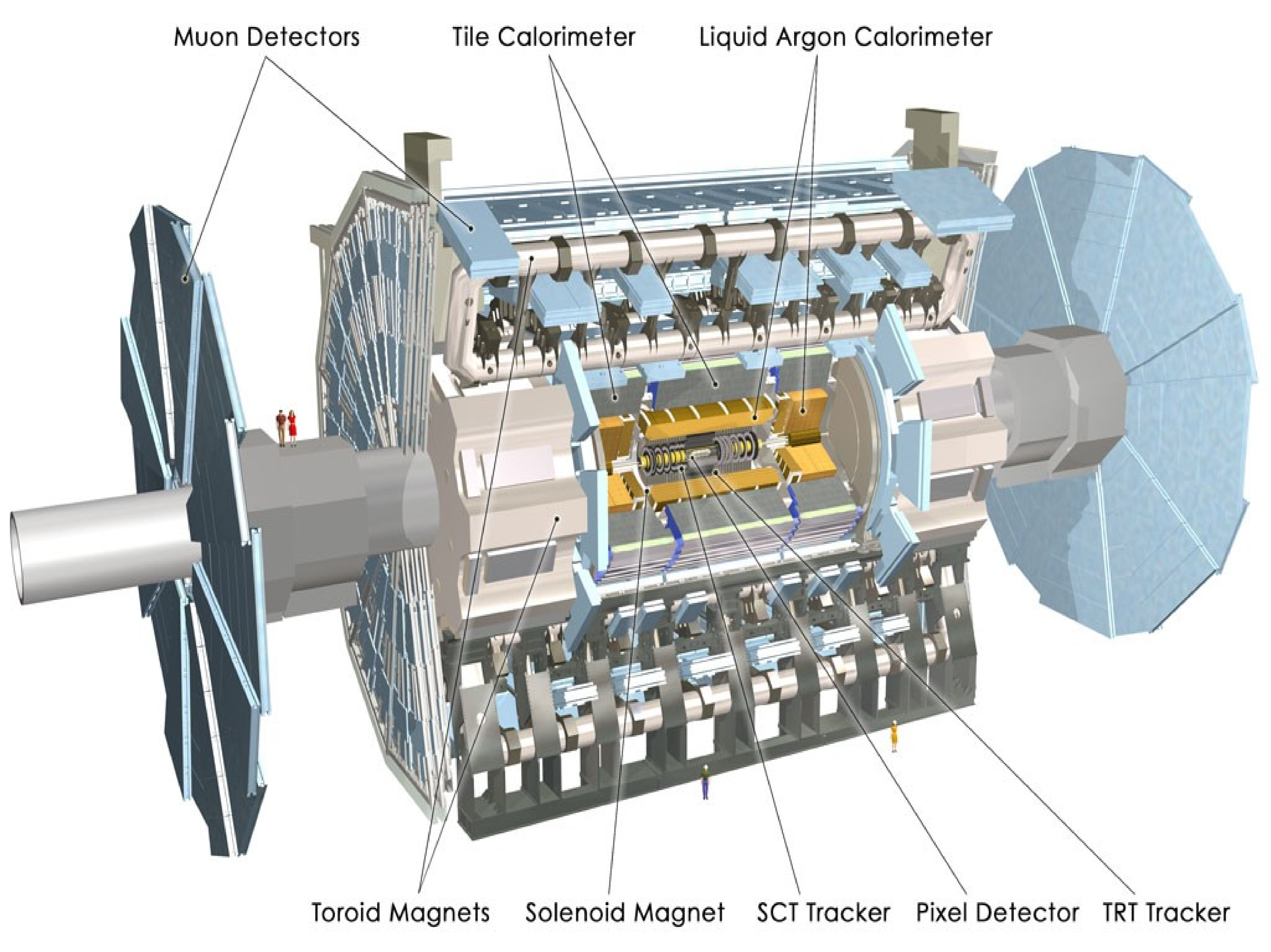
Gravity is due to Curvature of space-time. Need Quantum Gravity where the force carrier would be the Graviton. Not easy to quantize space-time.
Maybe Super String Theories have the answer but must be verified by experiments (at the LHC)

Proton-Proton Collisions inside the LHC at CERN



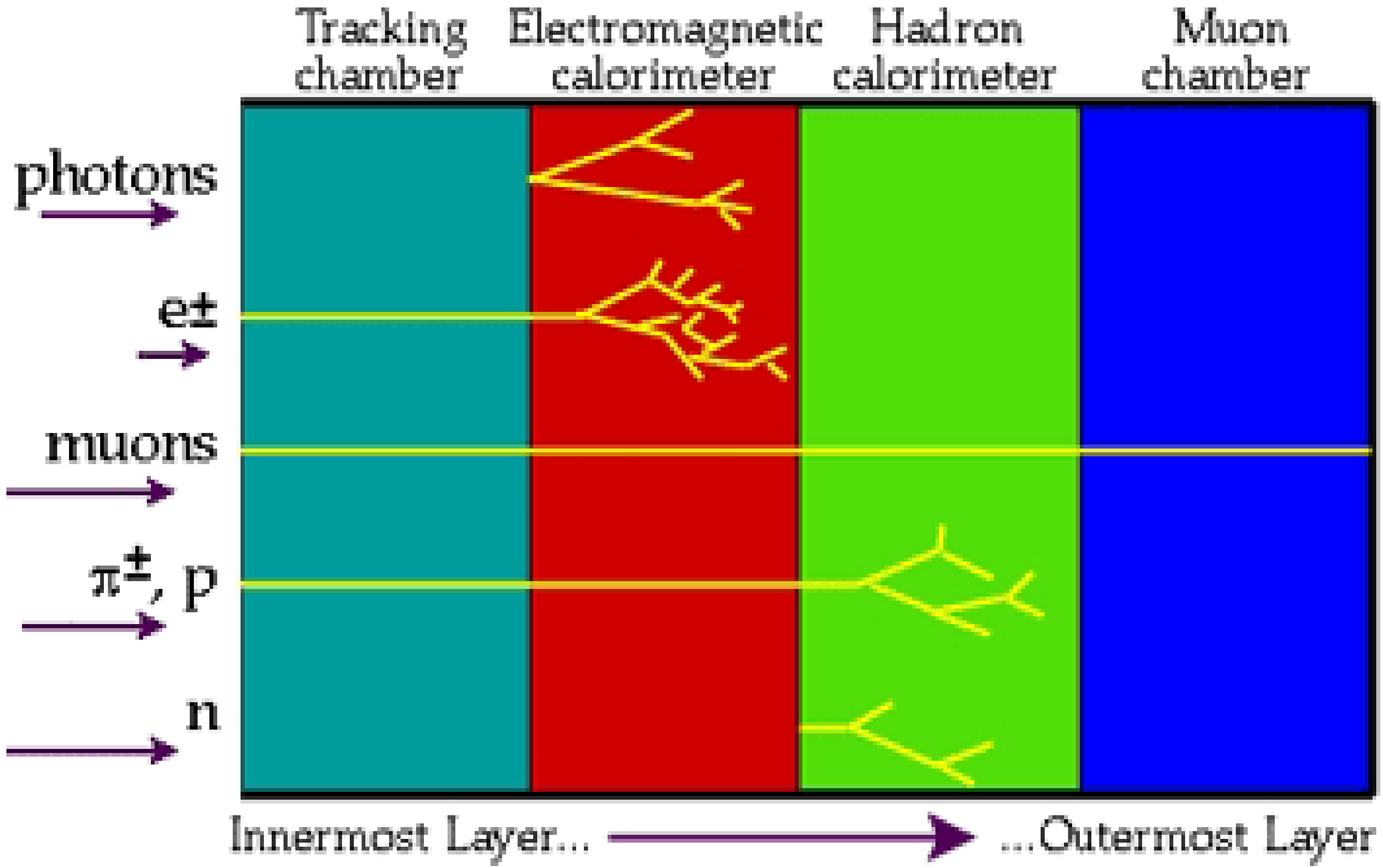
Two protons colliding at high energy can produce various hadrons plus very high mass particles such as Z bosons. Events such as this one are rare but can yield vital clues to the structure of matter.



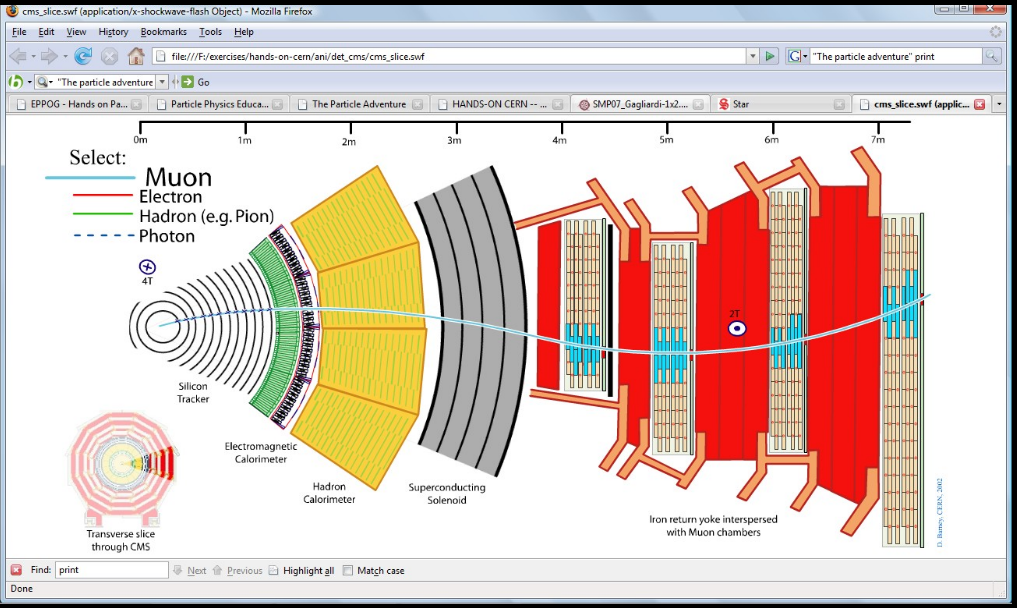

Muon Detectors
Tile Calorimeter
Liquid Argon Calorimeter
Toroid Magnets
Solenoid Magnet
SCT Tracker
Pixel Detector
TRT Tracker

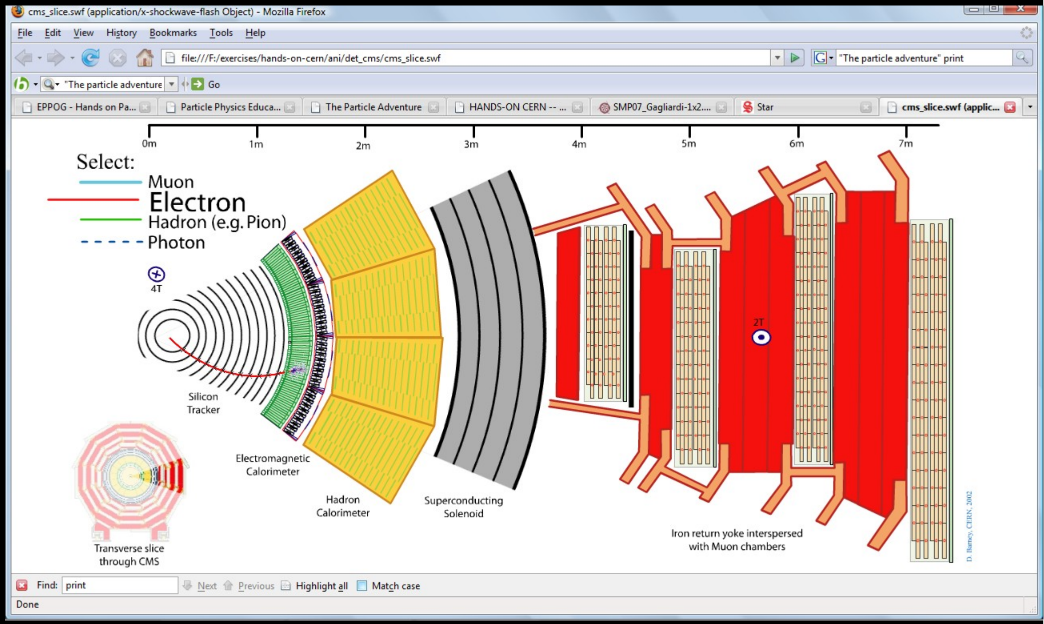
	ATLAS	CMS
INNER TRACKER	• Silicon pixels + strips • TRT with particle identification • B = 2T • $\sigma(p_T)$ ~ 3.8% (at 100 GeV, η = 0)	• Silicon pixels + strips • No dedicated particle identification • B = 4T • $\sigma(p_T)$ ~ 1.5% (at 100 GeV, η = 0)
MAGNETS	• Solonoid + Air-core muon toroids • Calorimeters outside field • 4 magnets	• Solenoid • Calorimeters inside field • 1 magnet
EM CALORIMETER	• Pb / Liquid argon accordion • $\sigma(E)$ ~ 10–12% / $\sqrt{E}$ $\oplus$ 0.2–0.35% • Uniform longitudinal segmentation • Saturation at ~ 3 TeV	• $PbWO_4$ scintillation crystals • $\sigma(E)$ ~ 3–5.5% / $\sqrt{E}$ $\oplus$ 0.5% • No longitudinal segmentation • Saturation at 1.7 TeV
HAD CALORIMETER	• Fe / Scint. & Cu-liquid argon • $\sigma(E)$ ~ 45% / $\sqrt{E}$ $\oplus$ 1.3% (Barrel)	• Brass / scint. • $\sigma(E)$ ~ 100% / $\sqrt{E}$ $\oplus$ 8% (Barrel)
MUON	• Monitored drift tubes + CSC (fwd) • $\sigma(p_T)$ ~ 10.5 / 10.4% (1 TeV, η = 0) (standalone / combined with tracker)	• Drift tubes + CSC (fwd) • $\sigma(p_T)$ ~ 13 / 4.5% (1 TeV, η = 0) (standalone / combined with tracker)

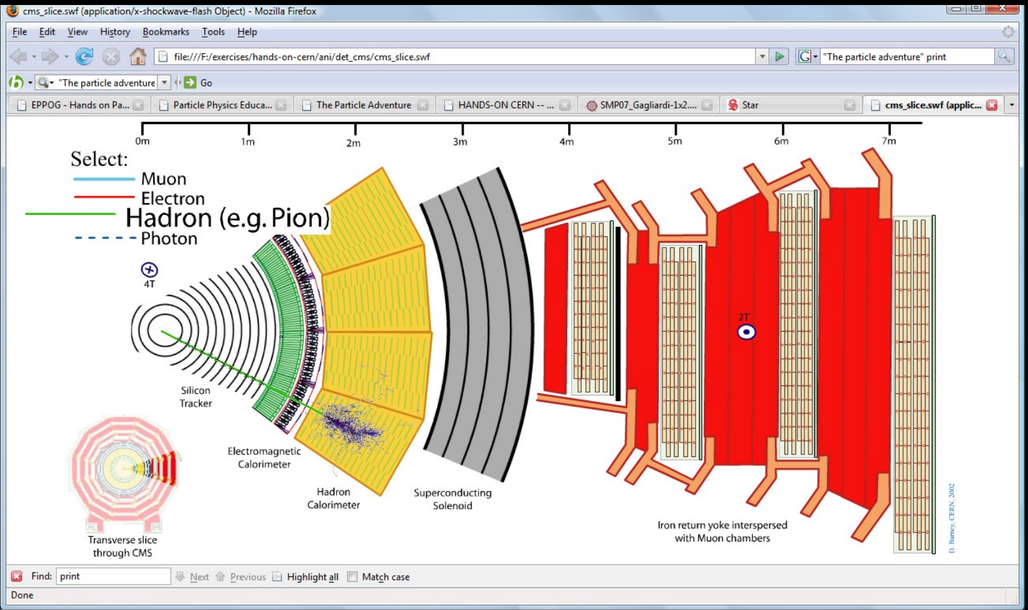
Source: Froidevaux-Sphicas, Ann Rev 56, 375 (2006)

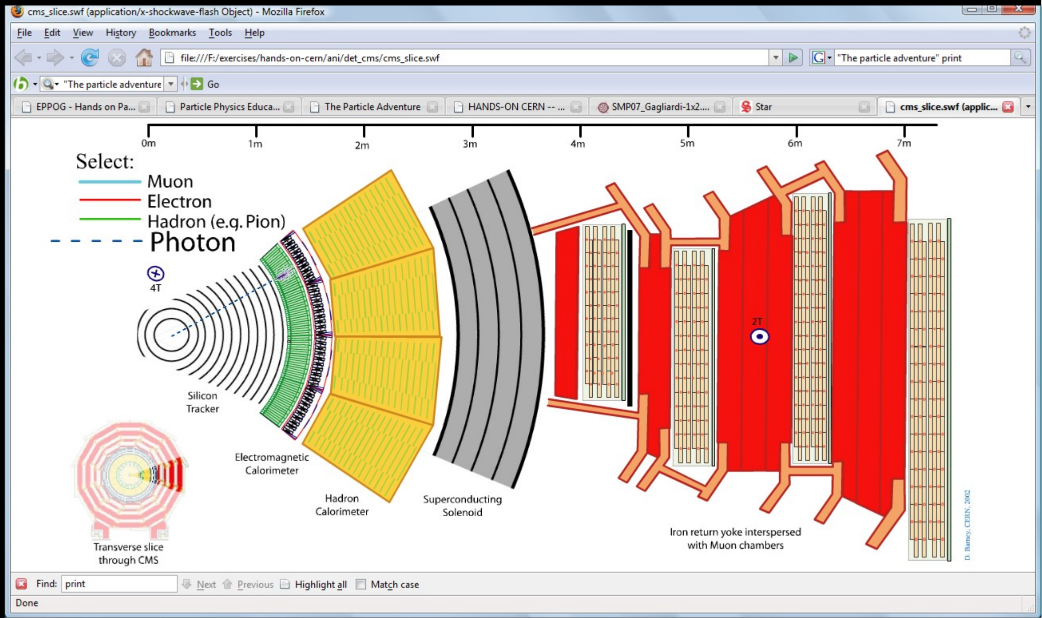

Tracking chamber
Electromagnetic calorimeter
Hadron calorimeter
Muon chamber
photons
e±
muons
π±, p
n
Innermost Layer...
...Outermost Layer

Play CMS detector animation (EPOG HEP Masterclasses)





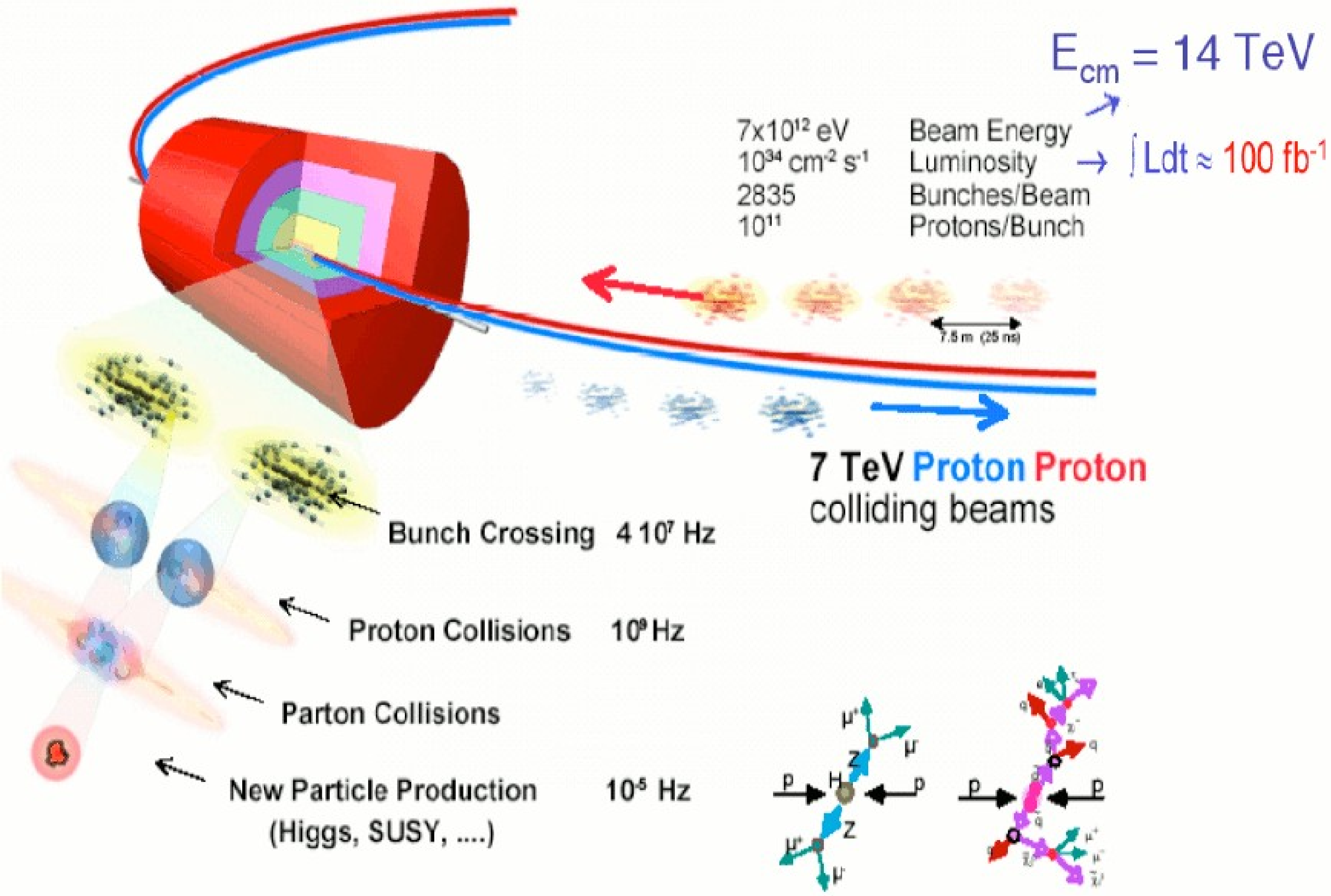




Sub-detector	Number of Channels	% of non-working channels
Pixels	$80.0\ 10^6$	0.2
Silicon Strips (SCT)	$6.0\ 10^6$	0.3
Transition Radiation Tracker	$3.5\ 10^5$	1.0
Electromagnetic Calorimeter	$1.7\ 10^5$	0.04
Scintillator Tile Calorimeter	9800	0.8
Liquid Argon Had. End-cap Calorimeter	5600	0.09
Liquid Argon Forward Calorimeter	3500	0.2
Barrel Muon Spectrometer	$7.0\ 10^5$	0.5
End-cap Muon Spectrometer	$3.2\ 10^5$	0.02

About 100 million channels of information

The LHC



$E_{cm} = 14$ TeV
7x10¹² eV Beam Energy
10³⁴ cm⁻² s⁻¹ Luminosity → ∫Ldt ≈ 100 fb⁻¹
2835 Bunches/Beam
10¹¹ Protons/Bunch
7.5 m (25 ns)
7 TeV Proton Proton
colliding beams
Bunch Crossing 4 10⁷ Hz
Proton Collisions 10⁹ Hz
Parton Collisions
New Particle Production 10⁻⁵ Hz
(Higgs, SUSY, ...)
p
H
Z
μ⁺
μ⁻

ATLAS Data pipeline

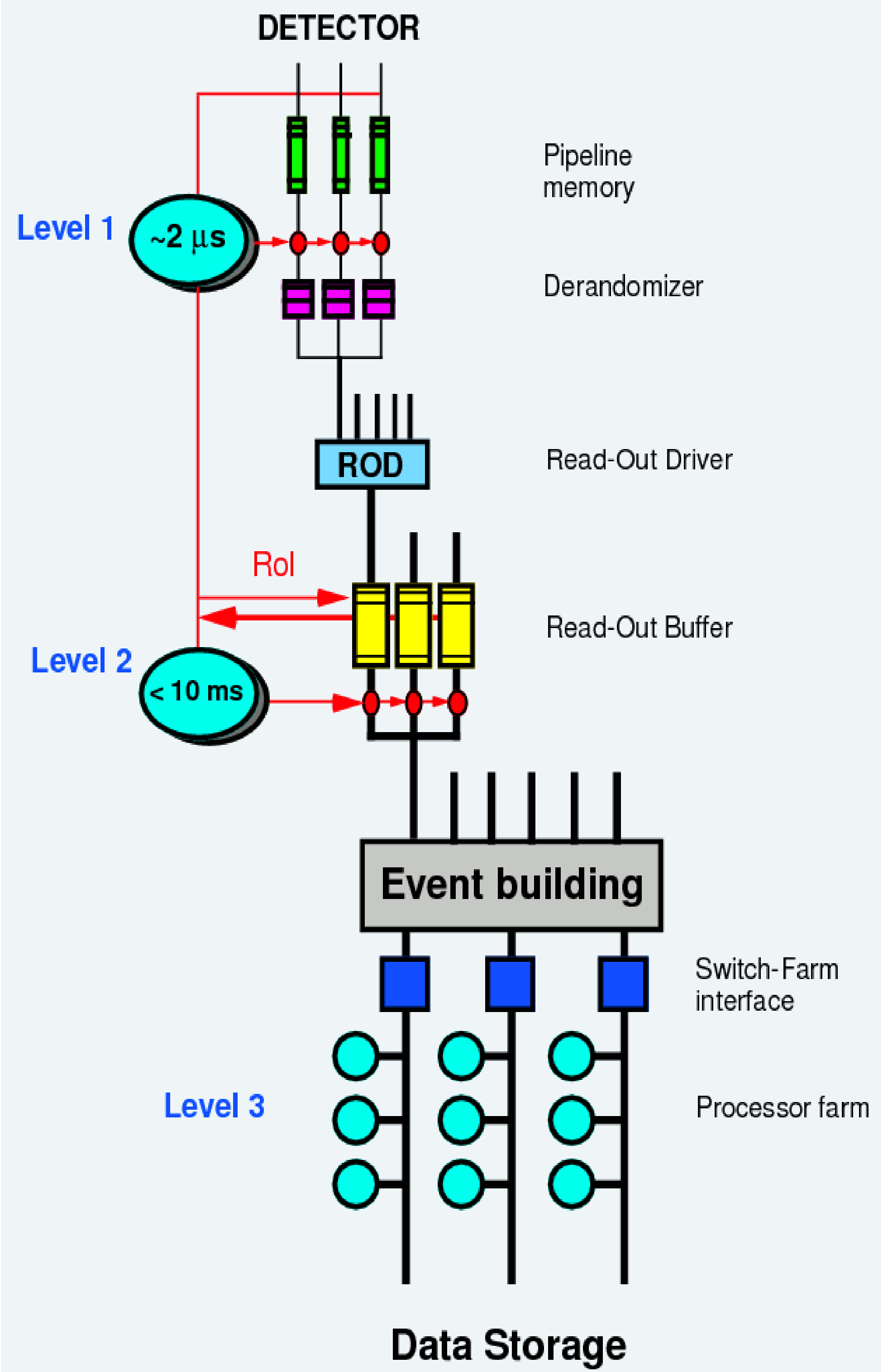
Data rates
The bunch crossing rate is 40MHz
There are 25 interactions per crossing.
This gives an interaction rate of 1GHz.

Each interaction leads to an event of 1MB

The data rate must be reduced to 1kHz.

Trigger System
There are three Levels of Trigger, the first is hardware processing, and the next two are via Linux farms.

DAQ System
The Level three trigger is part of the DAQ which selects events for permanent storage.



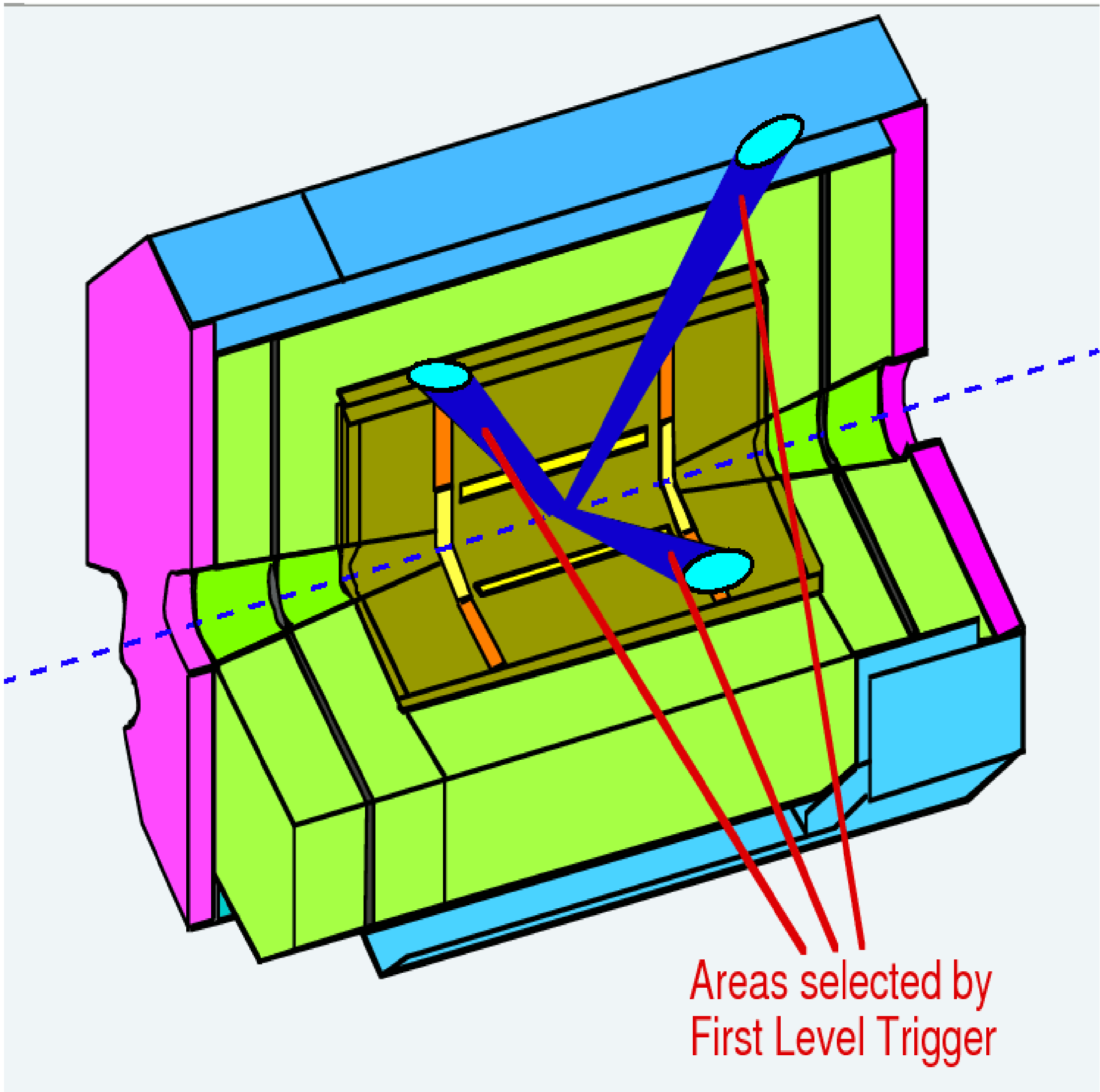
Trigger System

Level 1 Trigger

The LVL1 trigger works on a subset of information from the calorimeter and muon detectors. It looks for clusters of tracks called **Regions of Interest** (RoI)

It requires about 2 us to reach its decision.

All of the information from the detector must be stored in pipeline memories until the LVL1 decision is available.



Level 2 Trigger

The data are transferred to readout buffers where they remain until the LVL2 decision is available. Many events are analysed concurrently by the LVL2 trigger system using processor farms. The selection of events is refined using full-granularity information from all detectors, including the inner tracker (not used at LVL1).

The final rate can be reduced to ~1kHz.

LVL1 Hardware Trigger

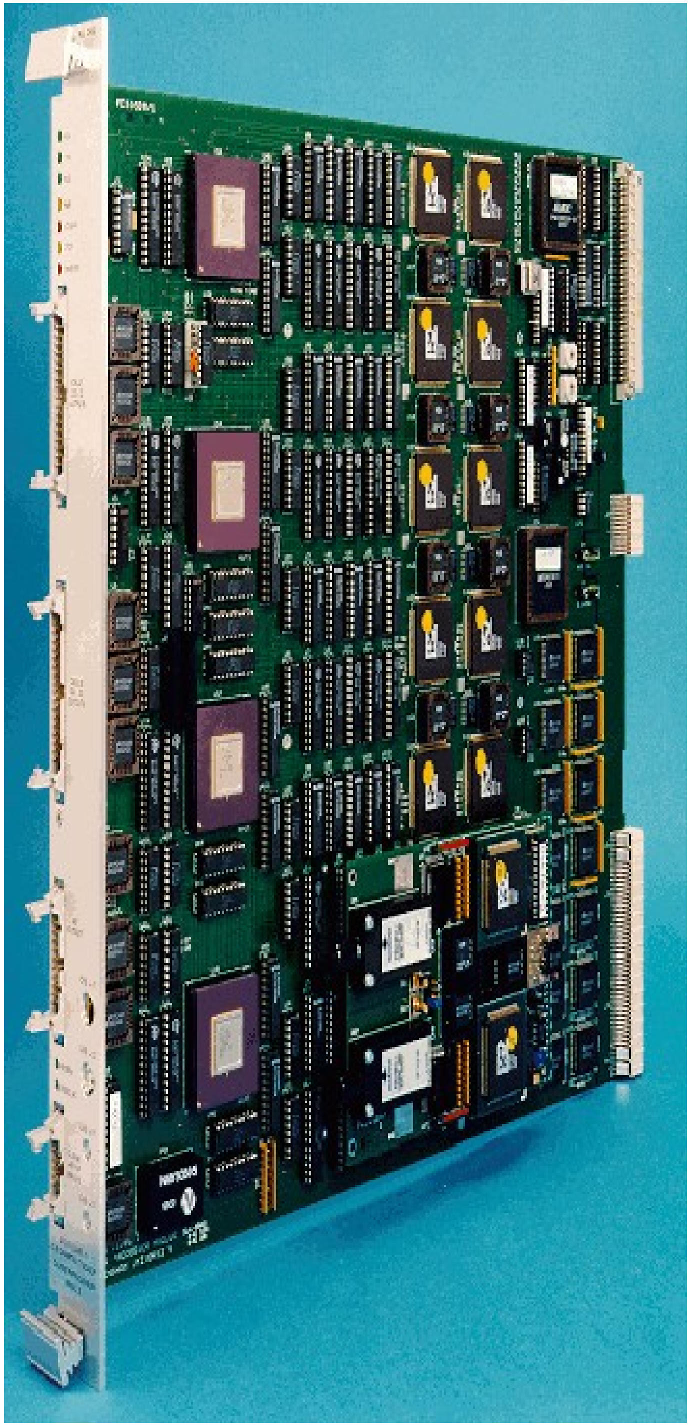
1 GHZ in

2 us for decision

The LVL1 trigger works using Application Specific Integrated Circuits which operate in digital mode on each channel of digitised raw data directly from each granulated detector element.

It is a direct streaming pipeline mode, with no latency. Only LVL1 filtered data makes it through to the buffered transient storage.

100 kHZ out



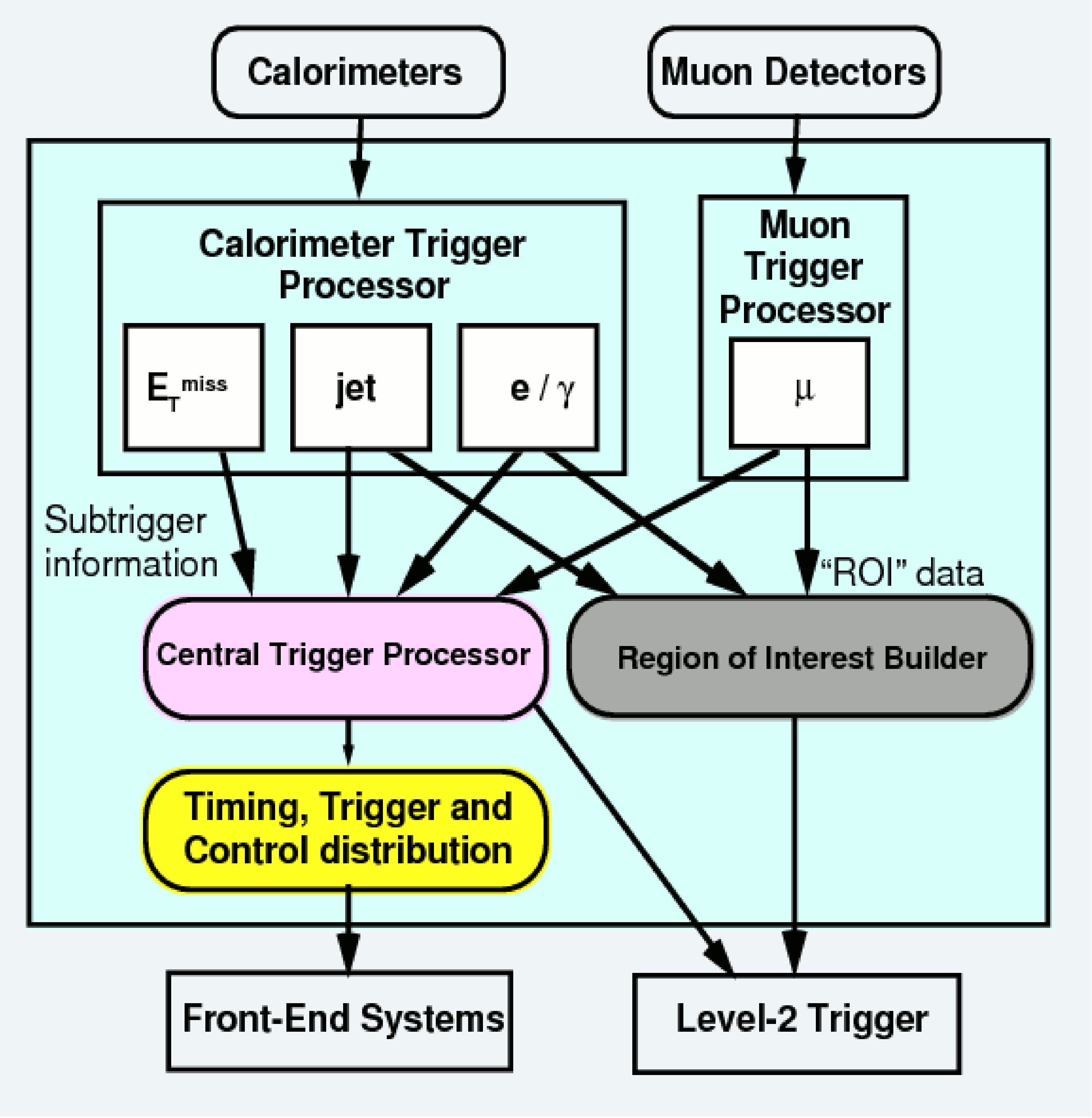
LVL1 Trigger

The LVL1 trigger searches specific event classes.

There is a high data rate.

Eg. in just the Calo

3000 GB/s



LVL2 Software Trigger

100 kHZ in

10 ms latency

The LVL2 trigger uses full granularity of the detector, as well as the Inner Tracker, using the RoI concept to deal only with a small subset of the detector volume, accessing the data via the readout buffer of LVL1, spreading the events over the farm.

The decision of LVL 1 is refined

1 kHZ out

An intersting event, like

$H \rightarrow 4$ leptons

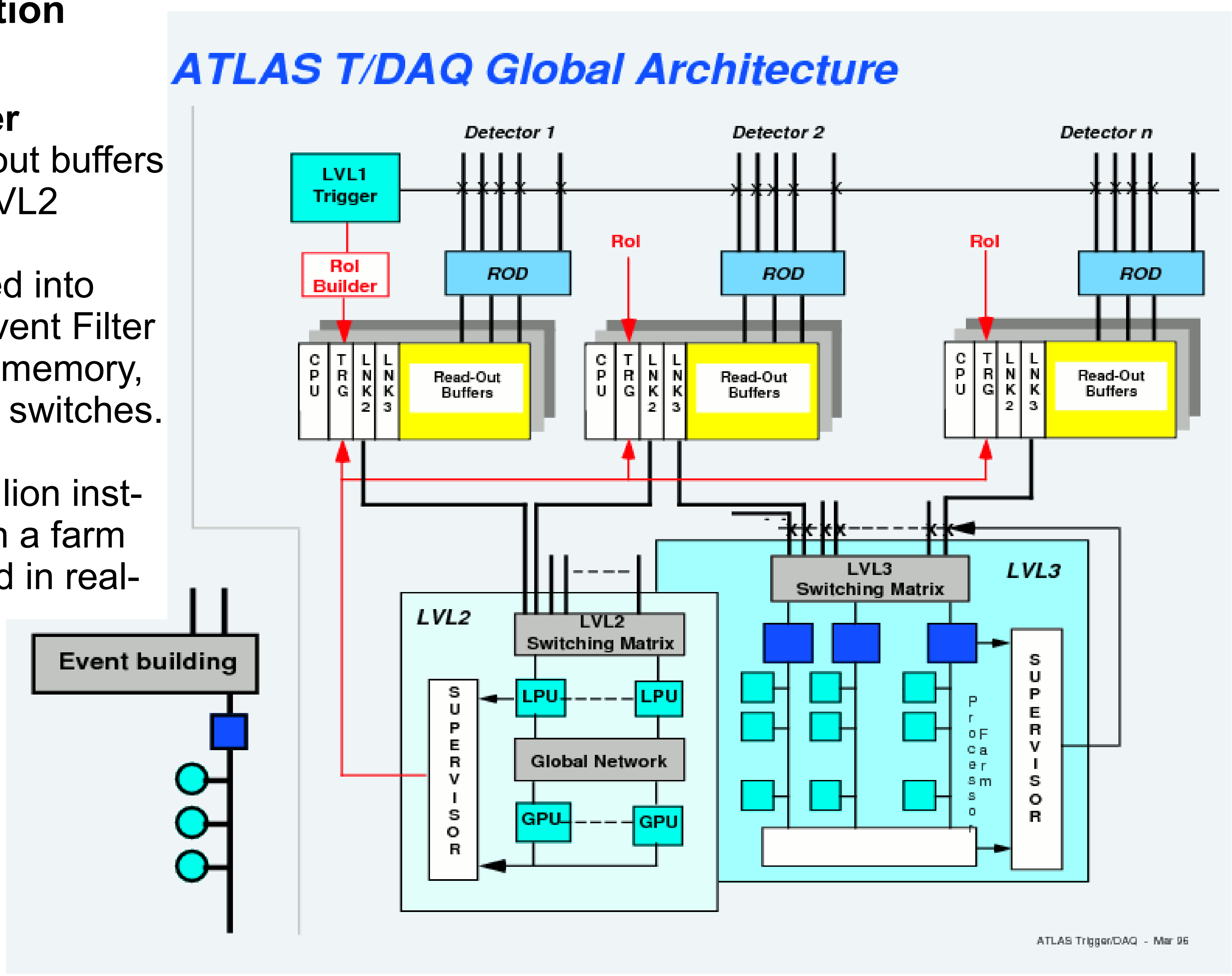
happens at a low rate, like 1 out of every 10^{13} interactions

There needs to be a rather high event rejection rate.

The Data Acquisition System

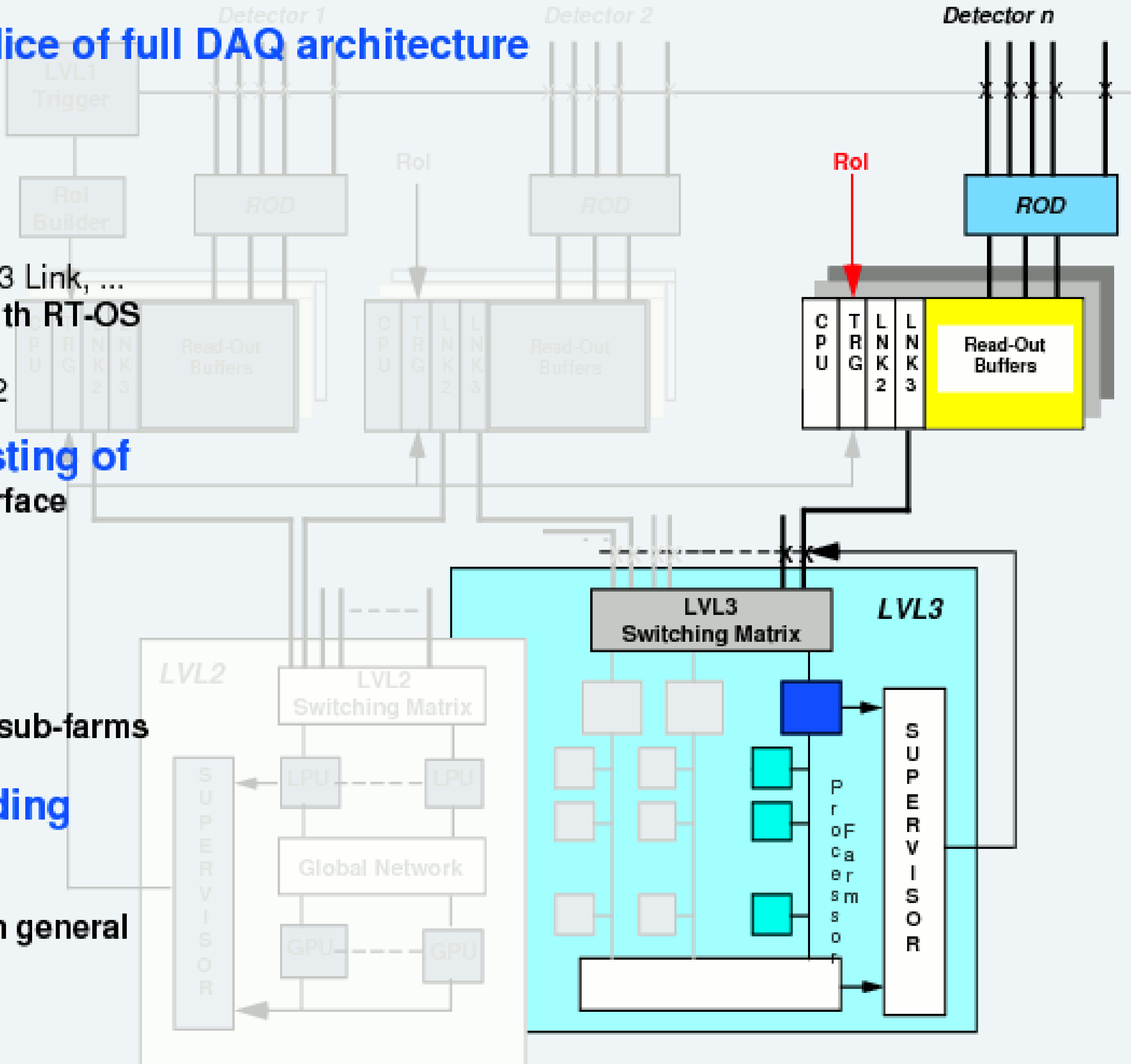
Event filter
The read-out buffers from the LVL2 trigger are synthesised into a single Event Filter processor memory, using data switches.

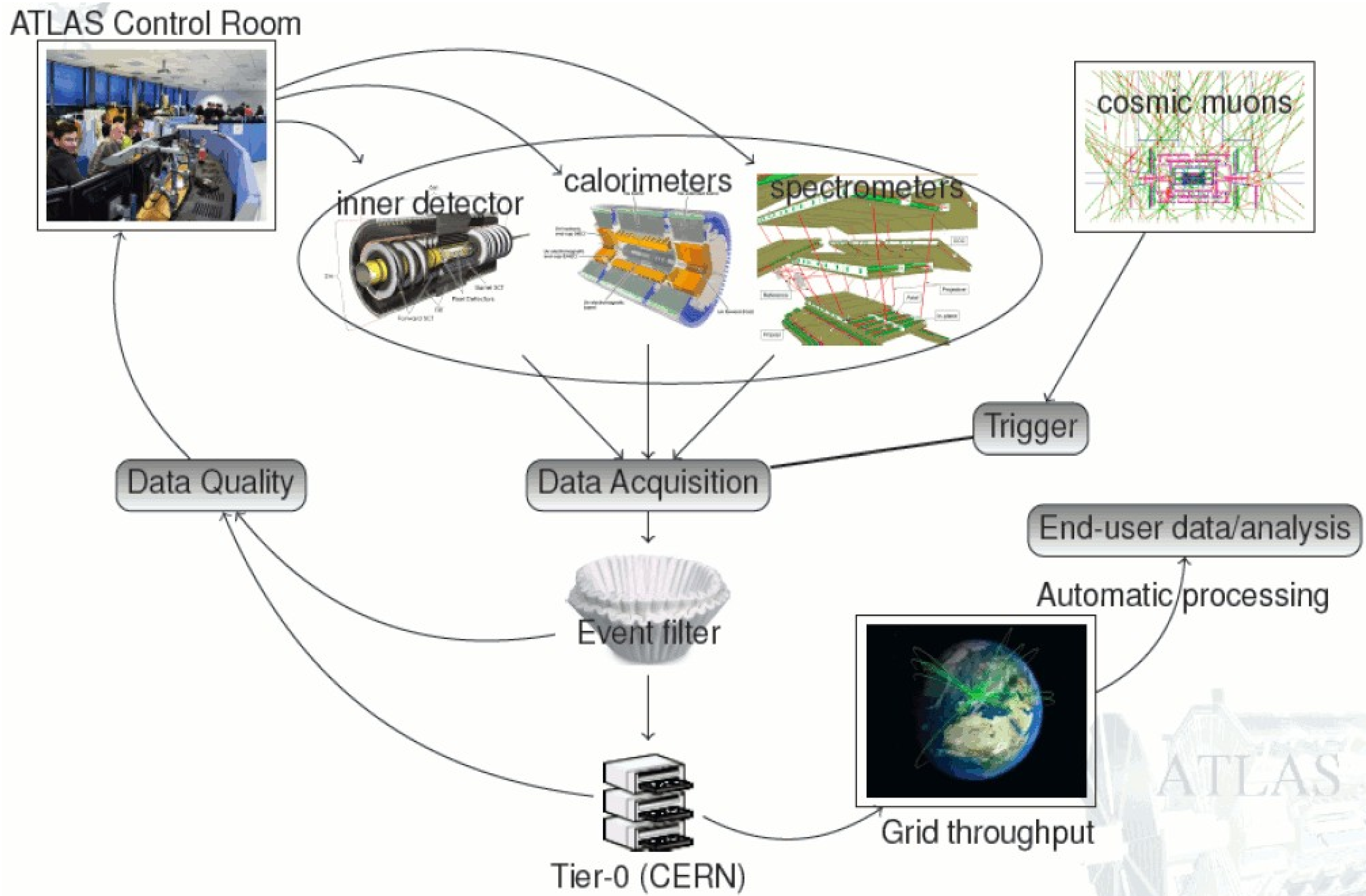
About 1 billion instructions on a farm are needed in real-time in 1s.

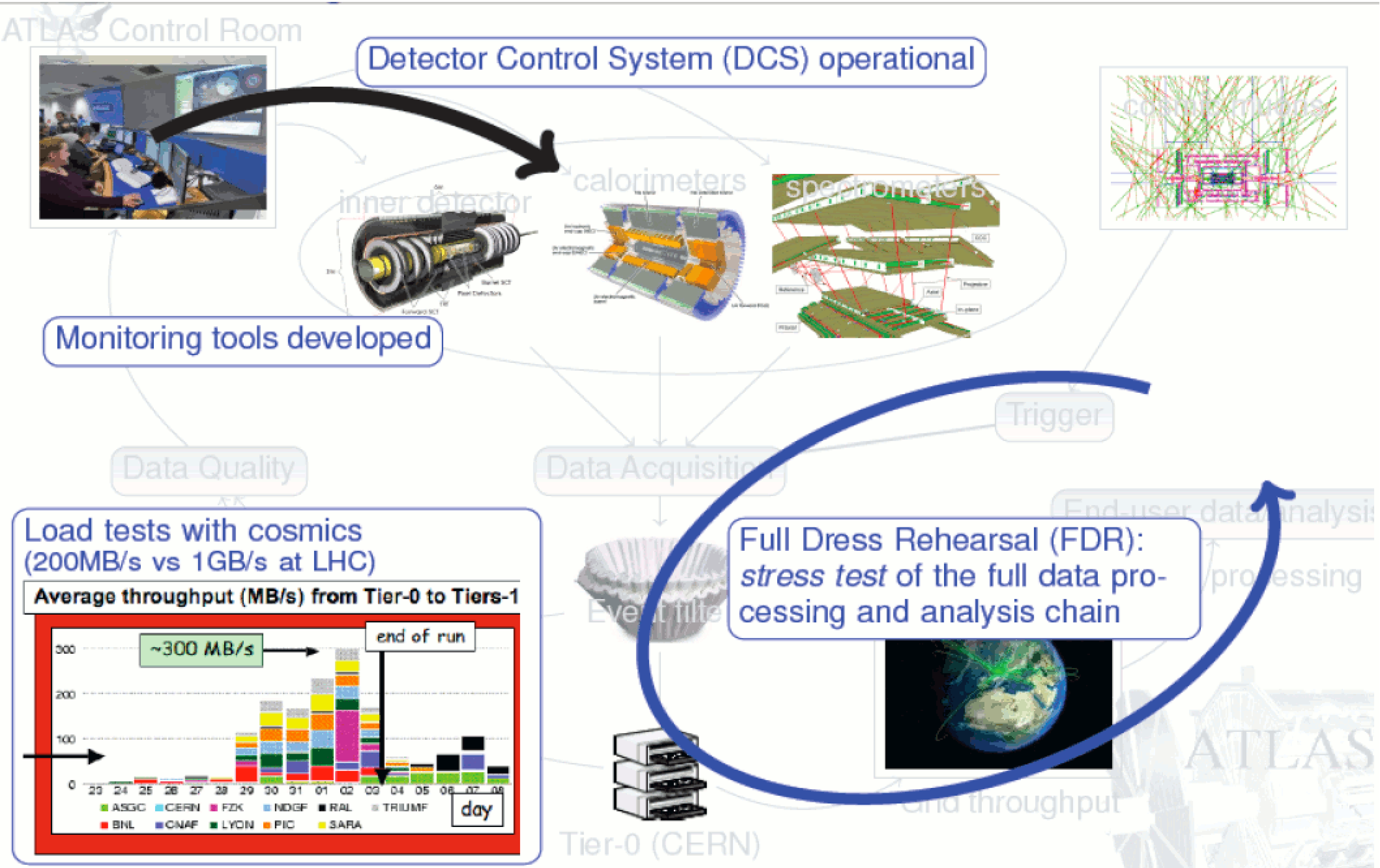


LVL3/DAQ Prototype "-1"

- **Essentially a vertical slice of full DAQ architecture including**
- **1- FrontEnd DAQ with**
  - Intelligent I/O module
    - ReadOut Buffer, Lvl3 Link, ...
  - DAQ CPU (controller) with RT-OS
  - Trigger Interfaces
    - Link to Lvl1 and Lvl2
- **2- Event Builder consisting of**
  - Source/Destination Interface
  - Switching system
  - Data Flow Manager
- **3- Lvl3 System with**
  - Switch-Farm-Interfaces
  - A number of processor sub-farms
- **4- BackEnd DAQ including**
  - Run Control
  - DataBases
  - Software environment in general



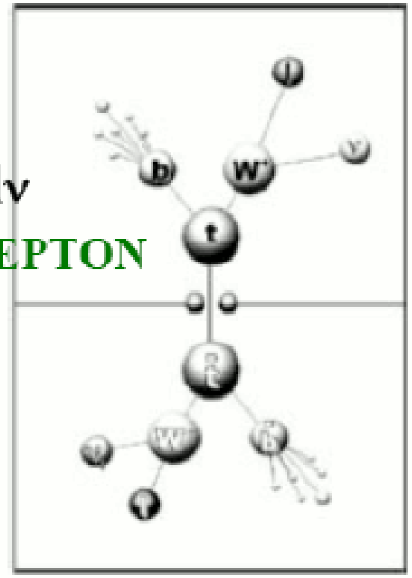

ATLAS Control Room
inner detector
calorimeters
spectrometers
cosmic muons
Trigger
Data Quality
Data Acquisition
End-user data/analysis
Automatic processing
Event filter
Grid throughput
Tier-0 (CERN)
ATLAS


ATLAS Control Room
Detector Control System (DCS) operational
inner detector
calorimeters
spectrometers
Monitoring tools developed
Trigger
Data Quality
Load tests with cosmics
(200MB/s vs 1GB/s at LHC)
Average throughput (MB/s) from Tier-0 to Tiers-1
~300 MB/s
end of run
300
200
100
0
23 24 25 26 27 28 29 30 31 01 02 03 04 05 06 07 08
day
ASGC CERN FZK NDGF RAL TRIUMF
BNL CNAF LYON PIC SARA
Full Dress Rehearsal (FDR):
stress test of the full data processing and analysis chain
Grid throughput
Tier-0 (CERN)
ATLAS

top-quark decays

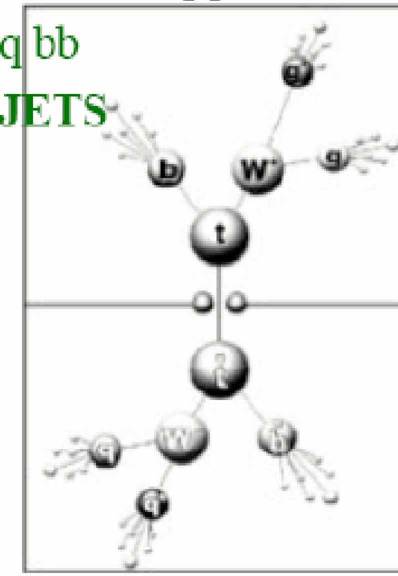
Top quark decay modes

- BR(t → Wb) @ 100 %
  - – Both W's decay via W → lν
    - final state: lνlν bb - **DILEPTON**

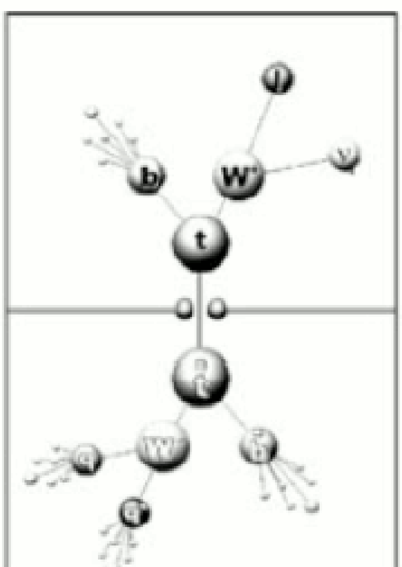


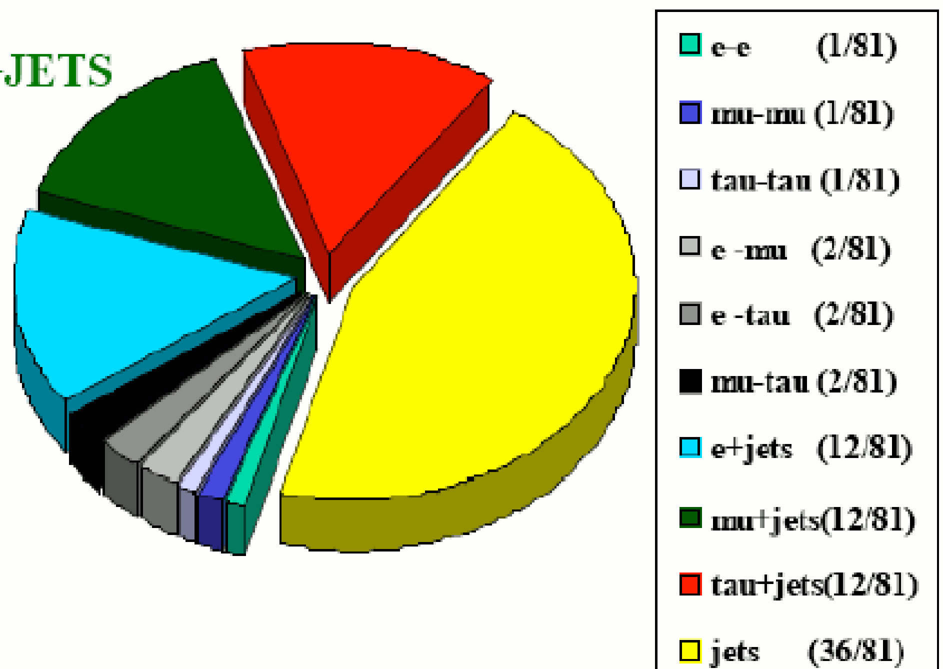
- – Both W's decay via W → qq
  - final state: qq qq bb

ALL JETS



- – One W decays via W → lν
  - final state: lν qq bb - **LEPTON+JETS**

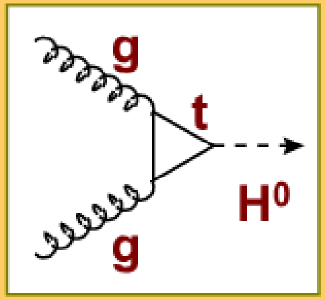




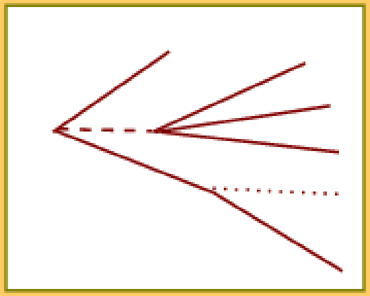
The ATLAS DAQ Control room,
nerve centre to interact with the experiment (farms for LVL2 Trigger, Event Builder, etc)

From physics to raw data

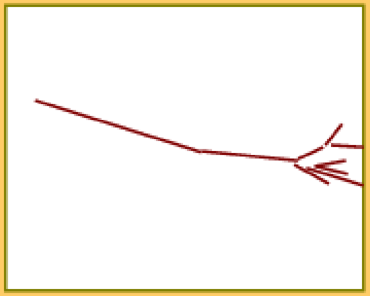
Simulation (Monte Carlo)



Basic physics

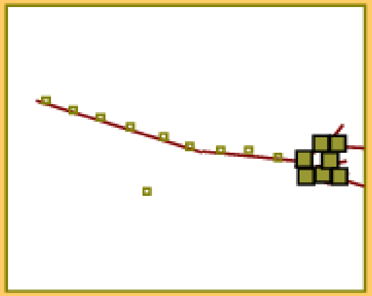


Fragmentation, Decay



Interaction with detector material

Multiple scattering, interactions



Detector response

Noise, pile-up, cross-talk, inefficiency, ambiguity, resolution, response function, alignment

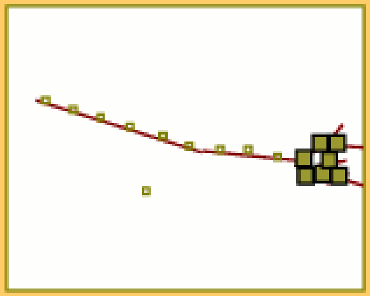
2037	2446	1733	1699
4003	3611	952	1328
2132	1870	2093	3271
4732	1102	2491	3216
2421	1211	2319	2133
3451	1942	1121	3429
3742	1288	2343	7142

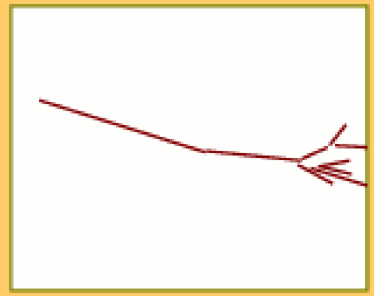
Raw data

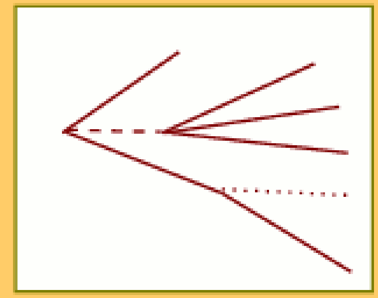
Read-out addresses, ADC, TDC values, Bit patterns

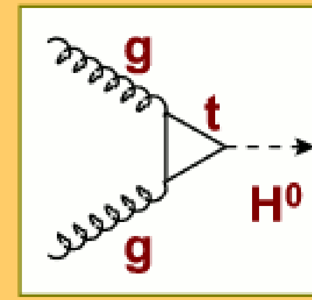
From raw data to physics

```
2037 2446 1733 1699
4003 3611  952 1328
2132 1870 2093 3271
4732 1102 2491 3216
2421 1211 2319 2133
3451 1942 1121 3429
3742 1288 2343 7142
```









Raw data

Convert to physics quantities

Detector response

apply calibration, alignment

Interaction with detector material

Pattern, recognition, Particle identification

Fragmentation Decay

Physics analysis

Basic physics

Results

Reconstruction

Analysis

Simulation (Monte-Carlo)

Hardware

Requirements

The ATLAS **data** will be delivered at a rate of 100 events per second to the offline system. Each event will consist of about 1 Mbyte of raw data. The data produced in one second correspond to the information content of the phone-books of Switzerland.

The amount of data produced per year will amount to 1 Peta-Byte (10^{15} Bytes) - filling 2 Million of today's CD-ROMs.

In order to extract the physics out of these data, an enormous **computing power** of 250,000 SPECint95 will be needed. Today, this would require 50,000 of the most powerful PCs.

A large number of the 1600 physicists in ATLAS will participate in the physics analysis. As they all need to access the data, performing **networks** are essential elements in the ATLAS computing model.

Monte-Carlo production sites

Currently, simulated ATLAS events for detector optimisation and reconstruction studies are produced in many institutes of the collaboration, in particular: LBL Berkeley (USA), RAL Chilton (UK), Milano (Italy), Pavia (Italy), Lyon (France), Innsbruck (Austria) and CERN.

ATLAS Computing - Analysis

Must process 10^{15} bytes of raw data

Raw Data → **AOD Analysis Object Data** → **DPD Derived Physics Data**

1000 kb/event | **100 kb/event** | **10 kb/event**

Tier 0 | **Tier 1** | **Tier 2**

ATLAS software comes in a kit. Is partially installed on the Wits-UJ cluster

Analysis Object Data (AOD) has a summary of information, and is stripped of some physics, eg, a version with no jets..
Can be ROOT accessible.

Begin in SA by producing the AOD both locally and on the external GRID.
Download a small event set. Develop analysis algorithms locally.
Eventually run full physics analysis over the GRID with the full data set.

ATLAS Computing – QCD Phenomenology

Simulate effect in detector of possible new physics versus backgrounds

New Physics → **Event Generator** → **Add known QCD / QED Fast MC of detector response**

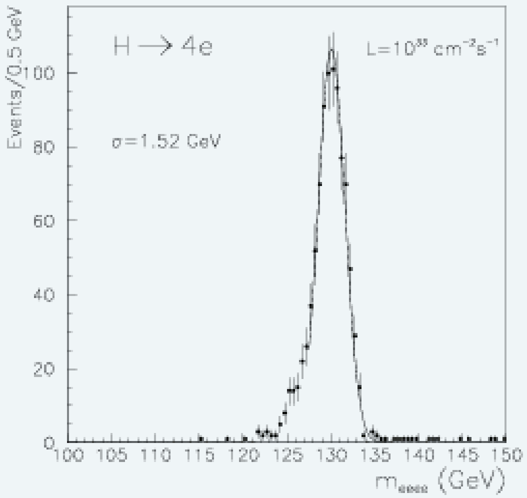
1000 kb/event | **100 kb/event** | **10 kb/event**

Requires a cluster with ATLAS software installed

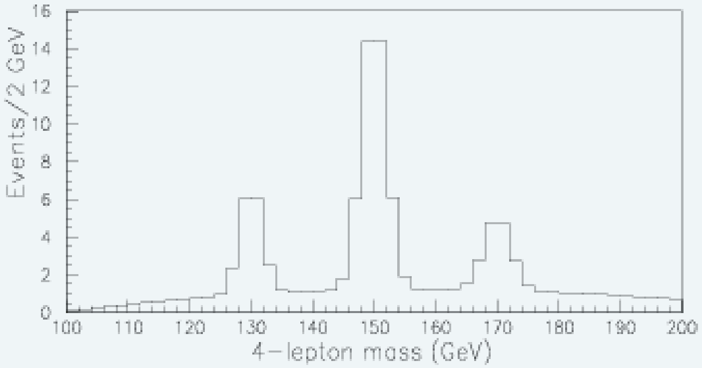
Examples are shown below

$H \rightarrow ZZ^{(*)} \rightarrow 4$ leptons

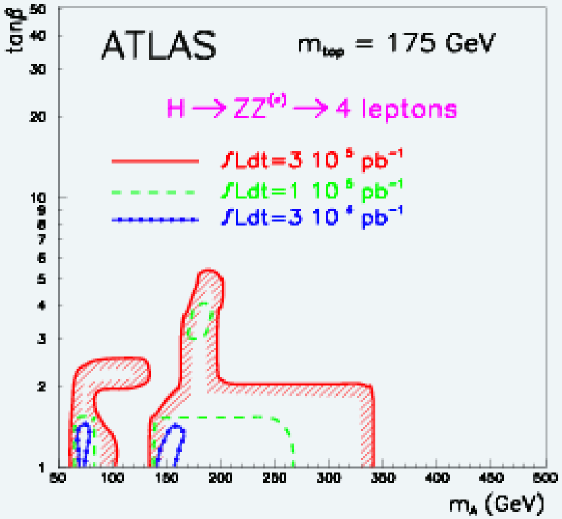
This decay channel into electrons and muons is the most promising one to observe the Standard Model Higgs boson in the mass-range 130 < m_H < 700 GeV. This requires excellent charged-lepton momentum/energy resolution and very good electron and muon identification capabilities (rejection of QCD jets, impact-parameter measurements, etc).



For m_H = 130 GeV, reconstructed 4-electron mass-spectrum from a full simulation of the ATLAS electromagnetic calorimeter.



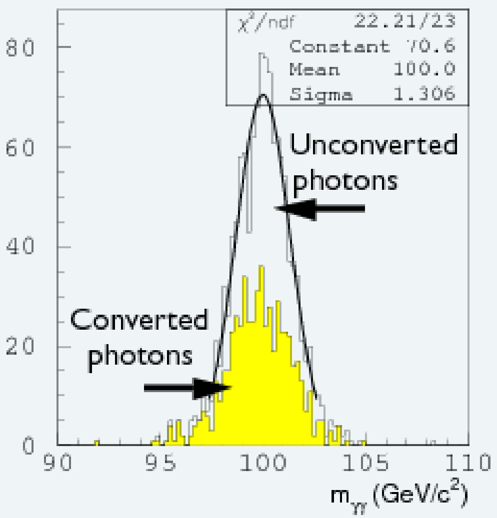
For three different Higgs-boson masses, expected signal from $H \rightarrow ZZ^* \rightarrow 4$ lepton decays above the residual background after three years of operation at low luminosity.



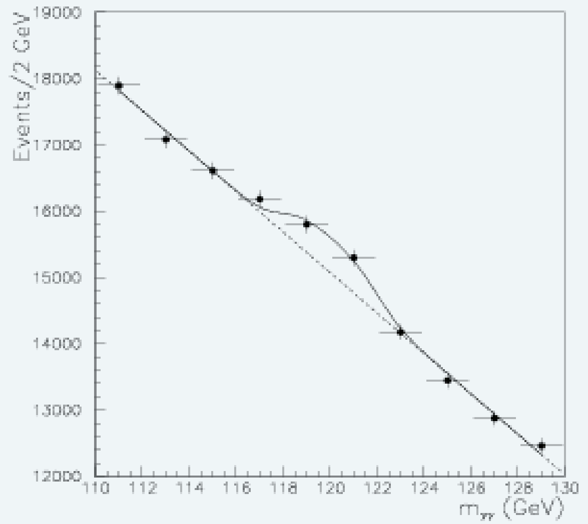
Discovery region of the MSSM parameter space covered by the search for $H \rightarrow ZZ^{(*)} \rightarrow 4$ lepton decays.

$h \rightarrow \gamma\gamma$ and $H \rightarrow \gamma\gamma$

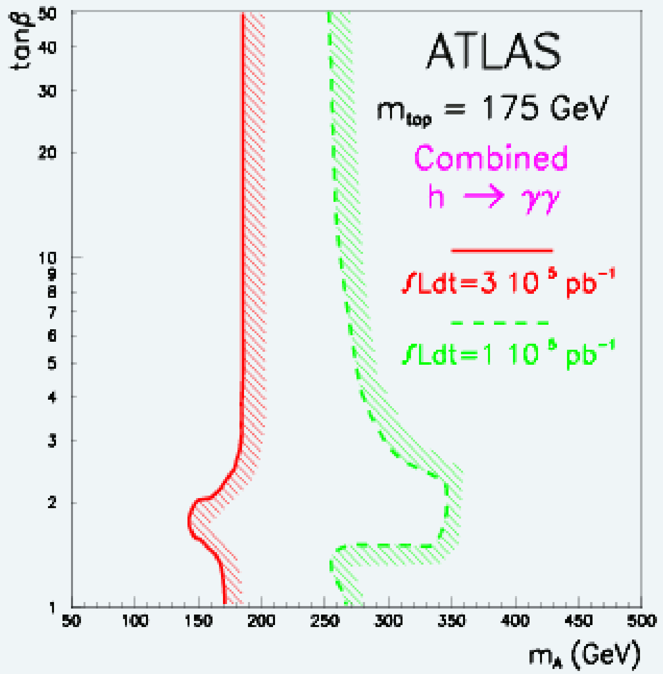
This decay channel is the most promising one to observe the Standard Model Higgs boson in the mass-range $95 < m_H < 130$ GeV. This requires excellent energy and angular resolution in the electromagnetic calorimeter and a rejection against jets faking photons of about 500



For $m_H = 100$ GeV, $H \rightarrow \gamma\gamma$ mass spectrum reconstructed in the ATLAS EM calorimeter with full simulation at high luminosity.



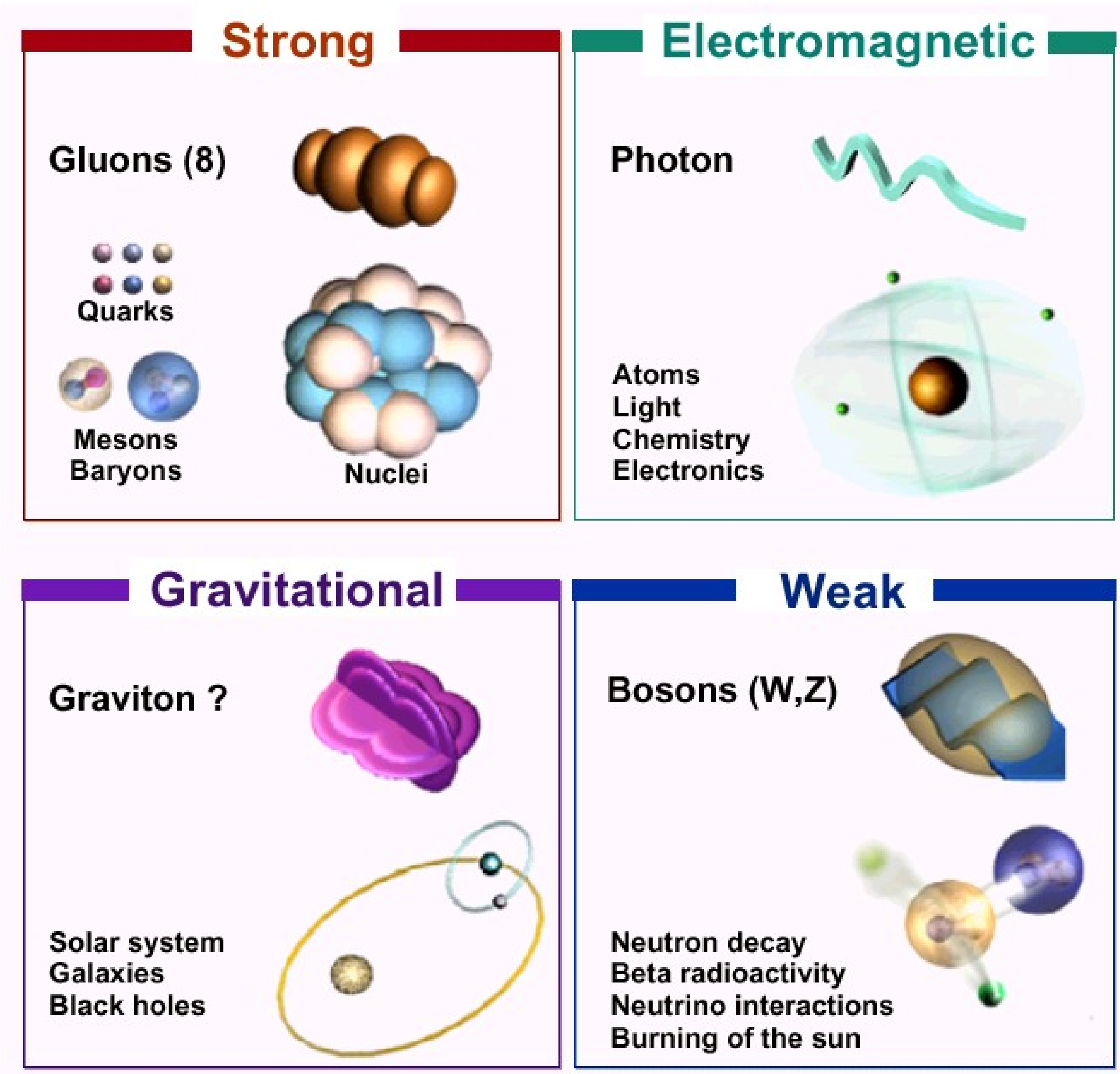
Expected signal from $H \rightarrow \gamma\gamma$ decays with $m_H = 120$ GeV over the $\gamma\gamma$ continuum background after one year of operation at high luminosity.



Discovery region of the MSSM parameter space covered by the search for $h \rightarrow \gamma\gamma$ decays.

SA participation in ATLAS

UJ group joined ATLAS
as an affiliate of Brookhaven (July 2008)
working with K Assamagan



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