The Large Hadron Collider: Experiments at the Big Bang Machine

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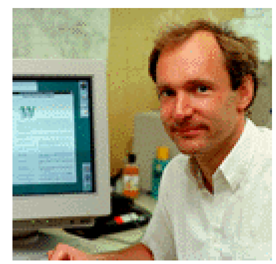
12 August 2010

AFRICAN SCHOOL ON FUNDAMENTAL PHYSICS AND ITS APPLICATIONS

Stellenbosch, South Africa

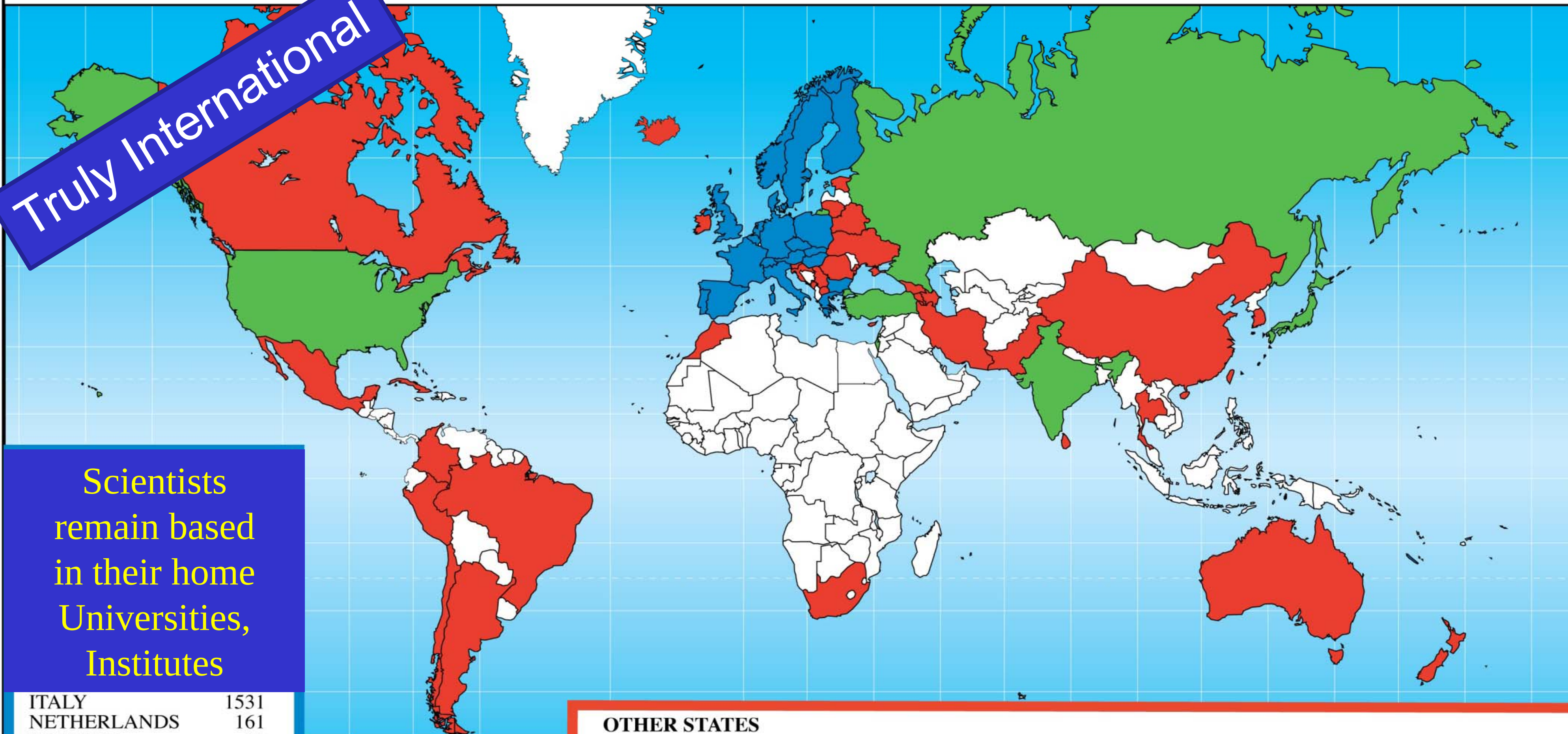
CERN
The European Laboratory for Particle Physics

CERN is the European Organization for Nuclear Research, the world's largest Particle Physics Centre, near Geneva, Switzerland
It is now commonly referred to as European Laboratory for Particle Physics
It was founded in 1954 and has 20 member states + several observer states
CERN employes >3000 people + hosts 9000 visitors from >500 universities.
Annual budget ~ 1100 MCHF/year (2009)



CERN: the place where the World Wide Web was born

Distribution of All CERN Users by Nation of Institute on 17 July 2007



Scientists remain based in their home Universities, Institutes

ITALY	1531
NETHERLANDS	161
NORWAY	66
POLAND	179
PORTUGAL	100
SLOVAKIA	35
SPAIN	268
SWEDEN	69
SWITZERLAND	337
UNITED KINGDOM	602

5695

OBSERVER STATES

INDIA	87
ISRAEL	49
JAPAN	153
RUSSIA	959
TURKEY	38
USA	1269

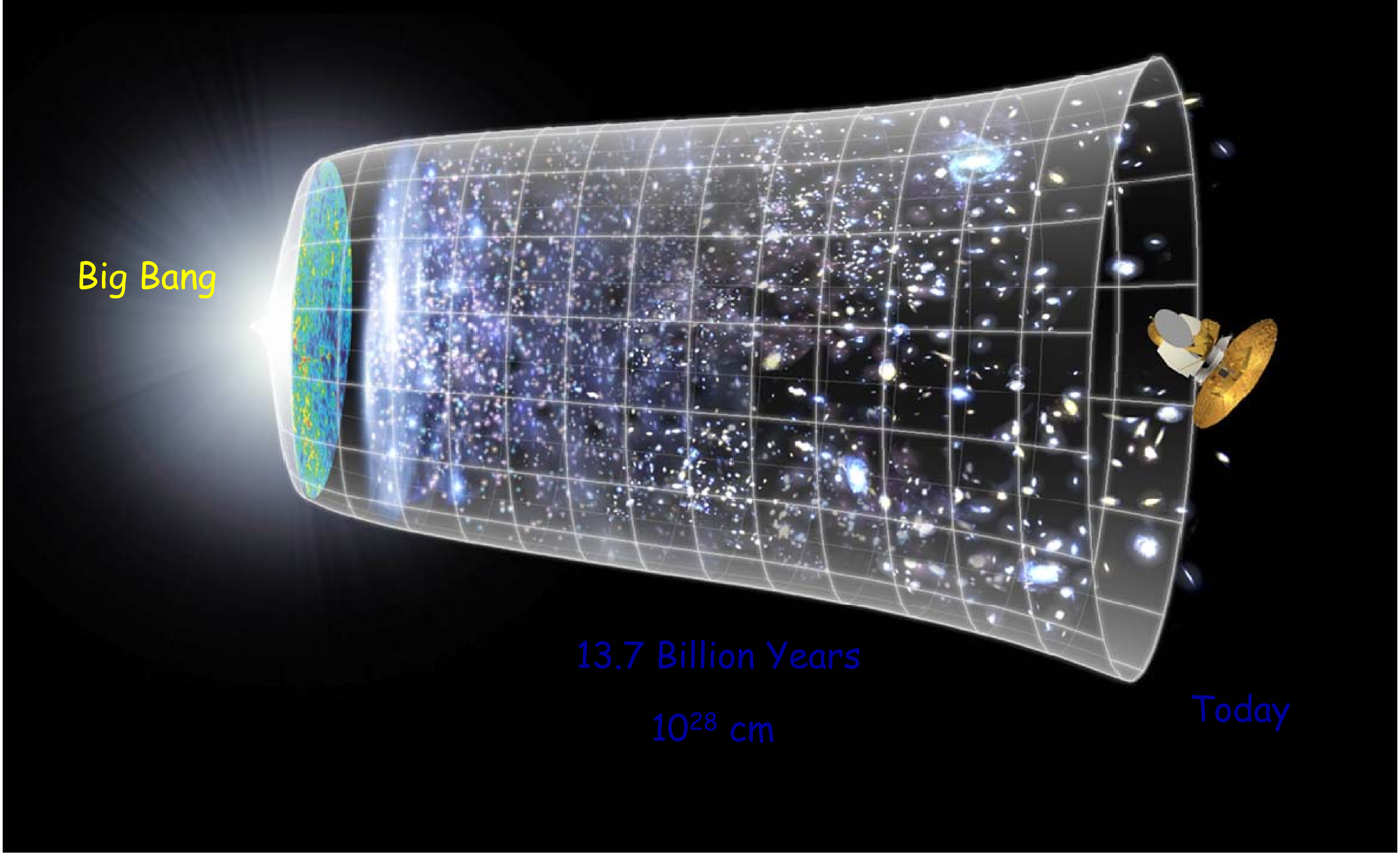
2555

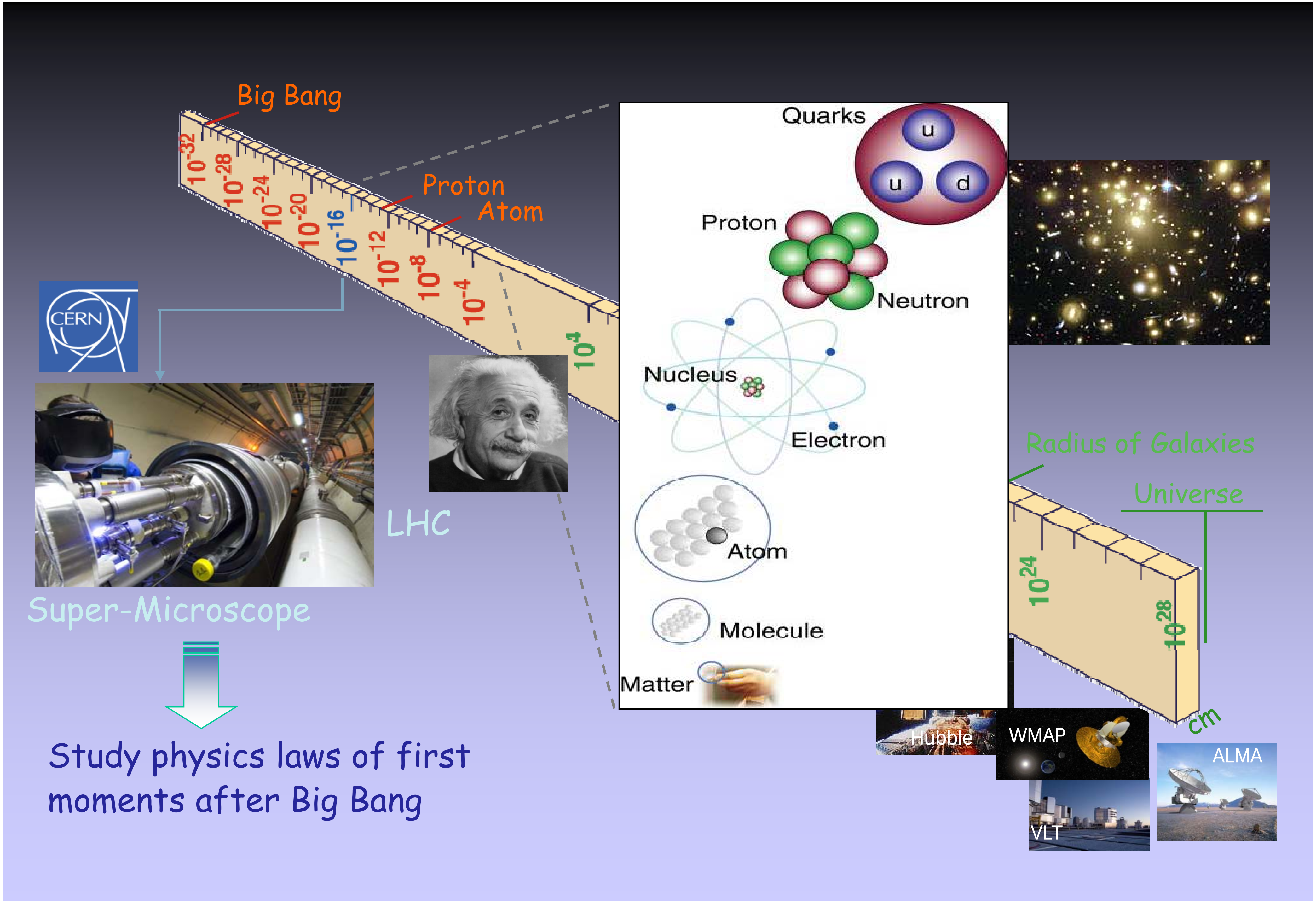
OTHER STATES

ARGENTINA	6
ARMENIA	17
AUSTRALIA	13
AZERBAIJAN	1
BELARUS	19
BRAZIL	55
CANADA	110
CHILE	4
CHINA	62
COLOMBIA	7
CROATIA	21
CUBA	2
CYPRUS	8
ESTONIA	14
GEORGIA	8
ICELAND	4
IRAN	6
IRELAND	11
KOREA	30
LITHUANIA	5
MACEDONIA, F.Y.R.	1
MADAGASCAR	1
MALTA	2
MEXICO	26
MONTENEGRO	1
MOROCCO	5
NEW ZEALAND	10
PAKISTAN	26
ROMANIA	39
SERBIA	13
SLOVENIA	15
SOUTH AFRICA	3
SRI LANKA	2
TAIWAN	34
THAILAND	1
UKRAINE	16
U.A.E.	3
VIETNAM	2

605

Evolution of the Universe

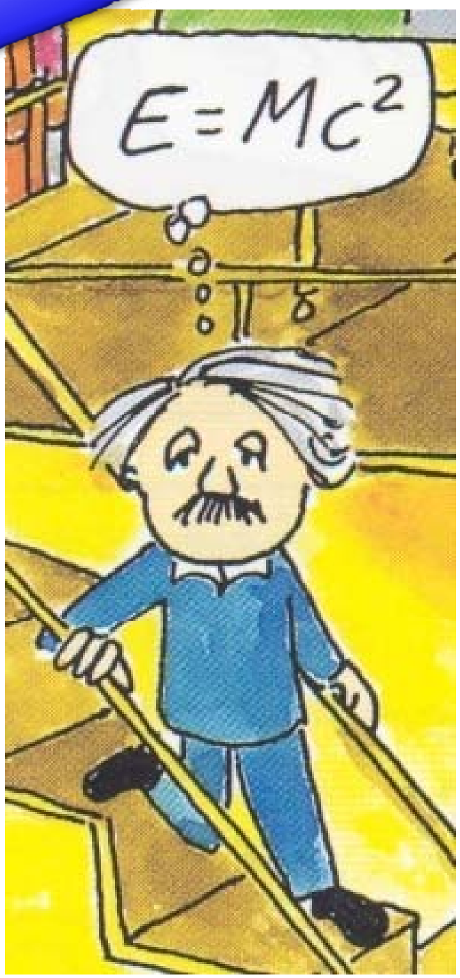


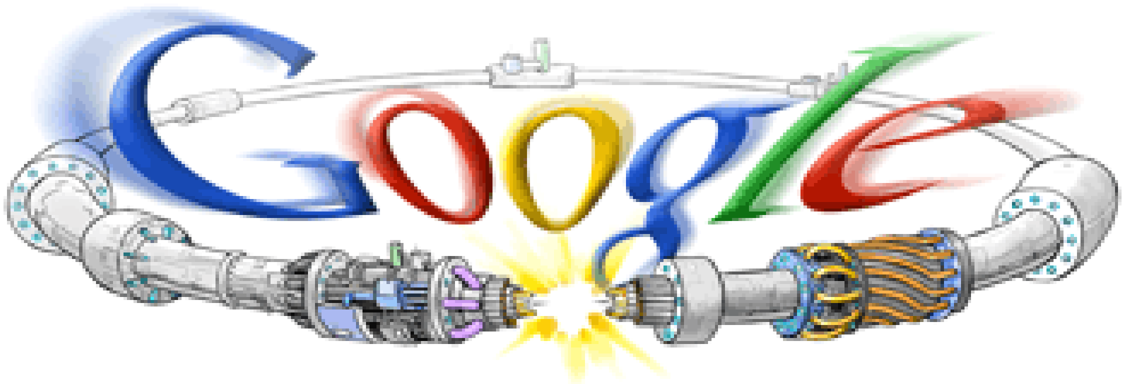

Big Bang
Proton
Atom
10^{-32}
10^{-28}
10^{-24}
10^{-20}
10^{-16}
10^{-12}
10^{-8}
10^{-4}
10^{4}
CERN
LHC
Super-Microscope
Quarks
u
u
d
Proton
Neutron
Nucleus
Electron
Atom
Molecule
Matter
Radius of Galaxies
Universe
10^{24}
10^{28}
cm
Hubble
WMAP
VLT
ALMA
Study physics laws of first moments after Big Bang

CERN
Provides
Particle Beams
&
Research Infrastructure

Why do we need particle accelerators?

We can create particles from energy

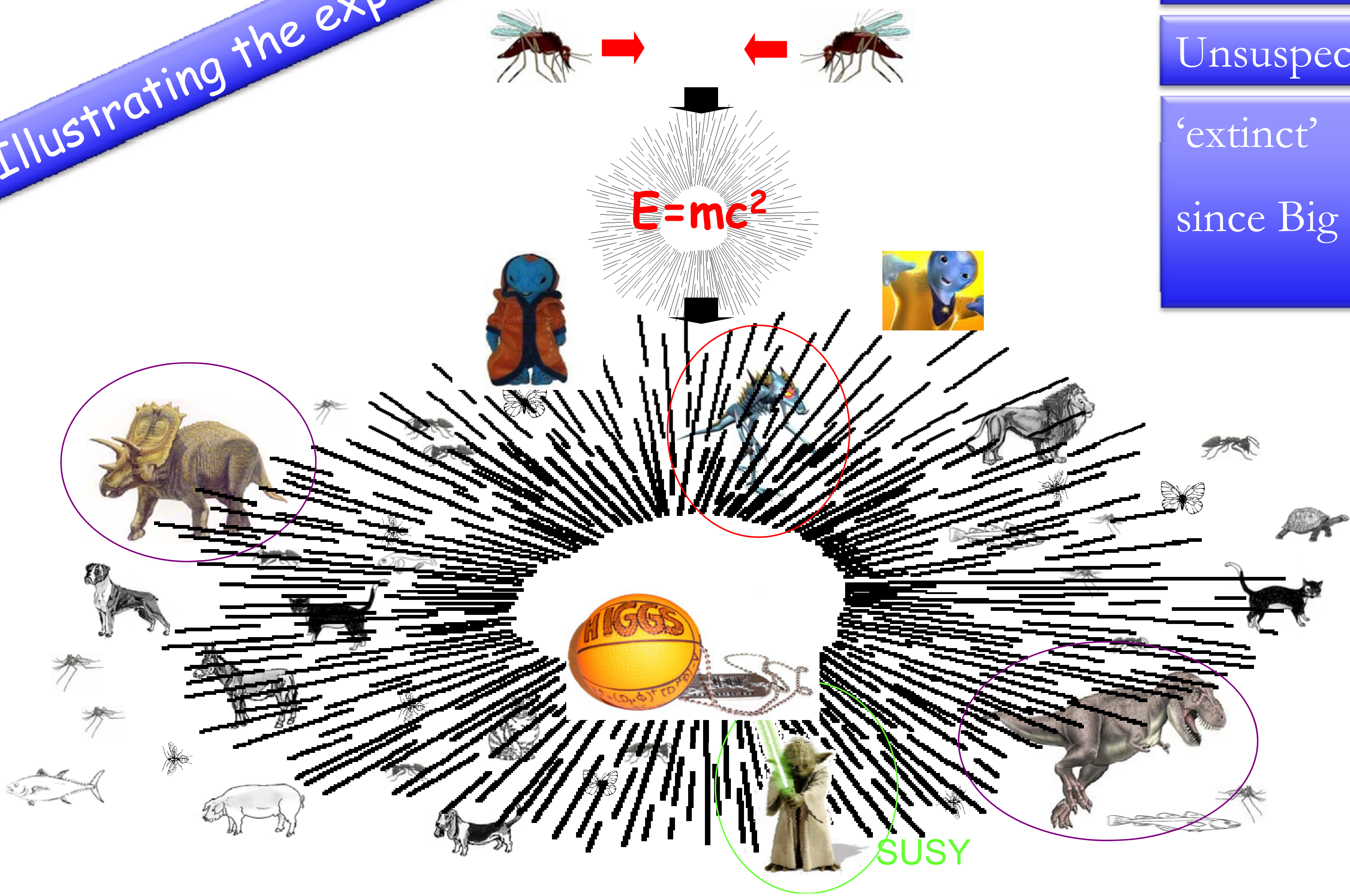




Two beams of protons collide and generate, in a very tiny space, temperatures over a billion times higher than those prevailing at the center of the Sun.

Illustrating the experiment

- Highly Expected
- Hypothetical
- Unsuspected ?
- 'extinct' since Big Bang



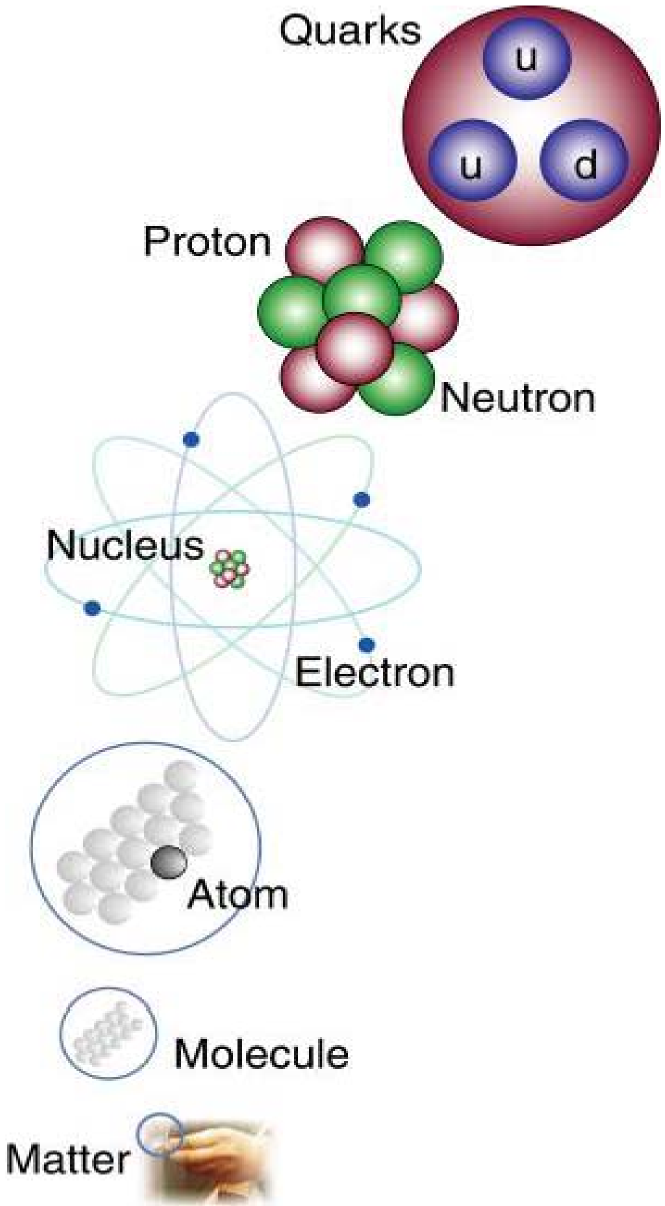
Important Questions in Particle Physics

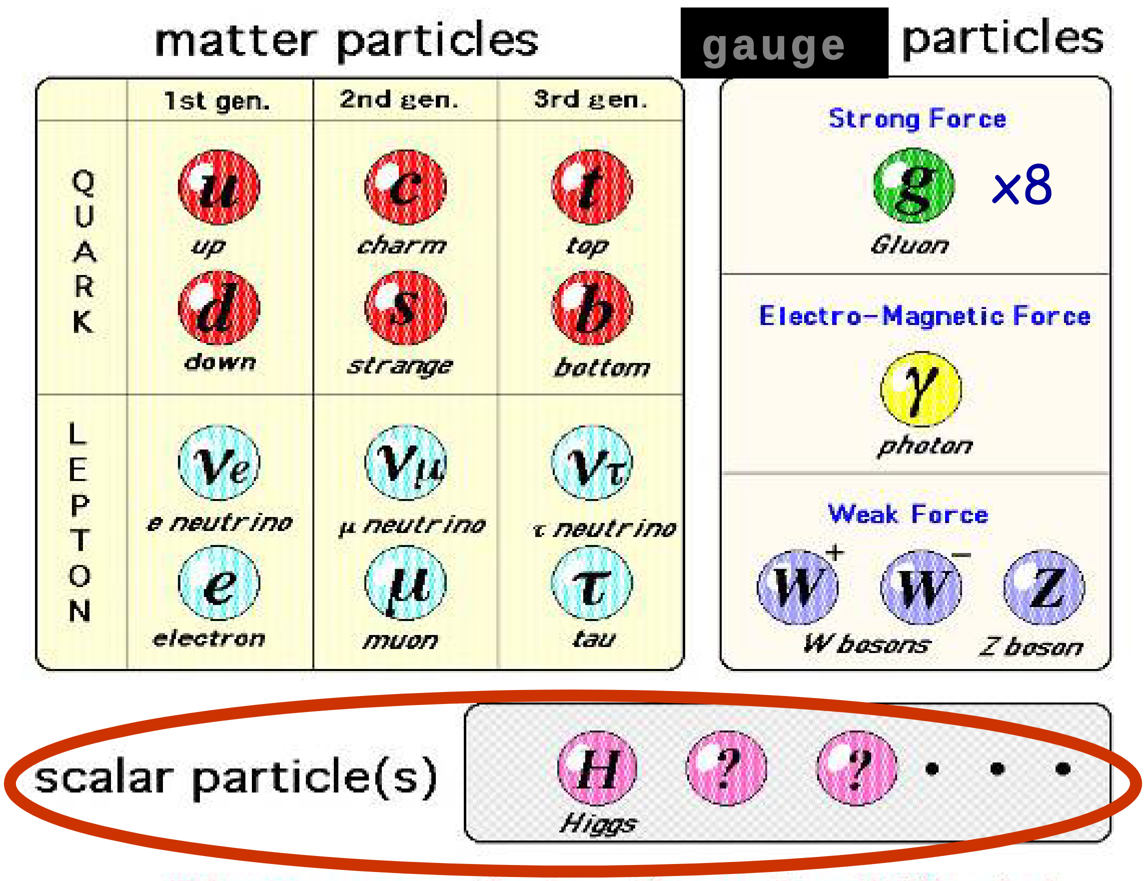
- What is the origin of particle masses?
- Why are there so many types of matter particles?
- What is the cause of matter-antimatter asymmetry?
- What are the properties of the primordial plasma?
- What is the nature of the invisible dark matter?
- Can all fundamental particles be unified?
- Is there a quantum theory of gravity

"Quantum Universe" and
"Discovering the Quantum Universe"

The physics programmes at CERN will address these questions and may well provide definite answers.

The Study of Particles and their Interactions





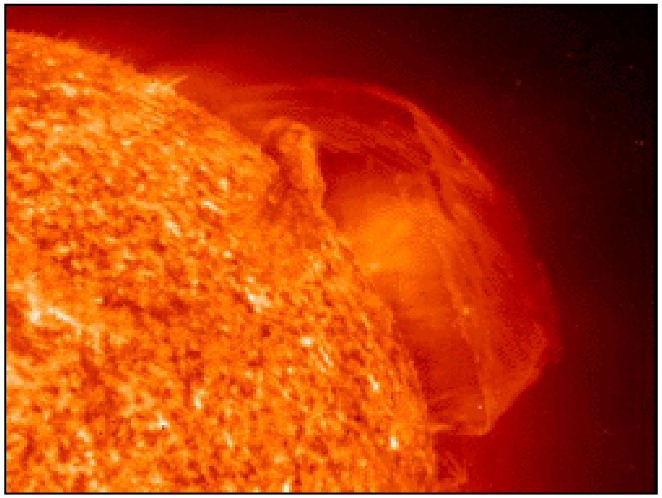
Elements of the Standard Model

The Fundamental Forces of Nature

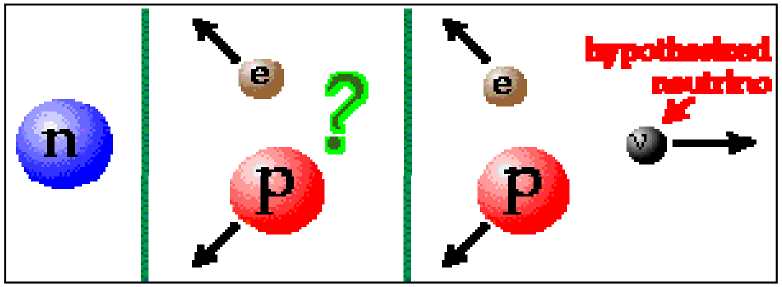
Electromagnetism:
gives light, radio, holds atoms together

Strong Nuclear Force:
holds nuclei together

Weak Nuclear Force:
gives radioactivity



together they make the Sun shine



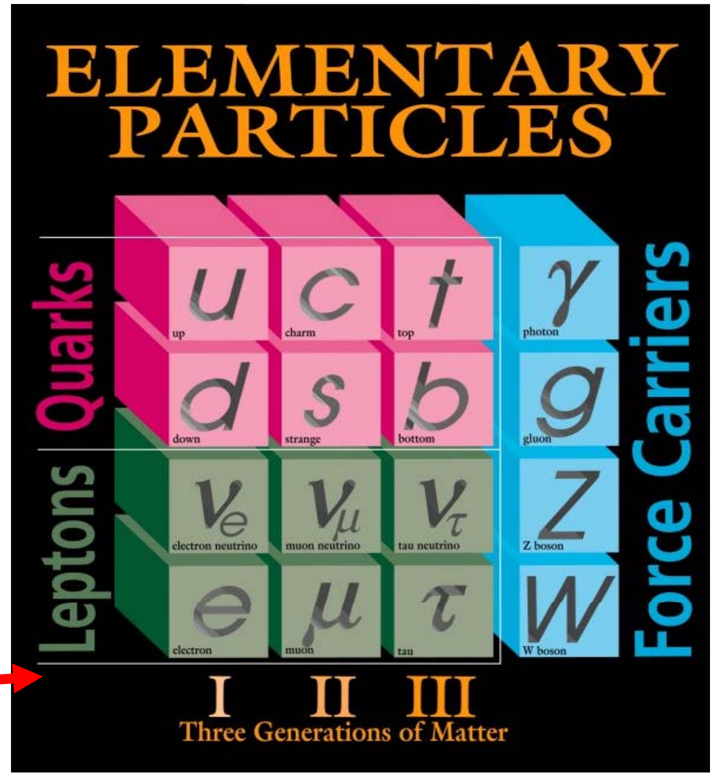
Gravity:
holds planets and stars together

The Standard Model in Particle Physics

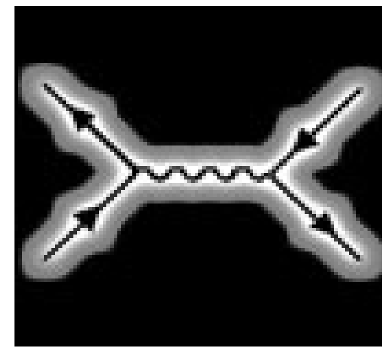
But not all questions solved:

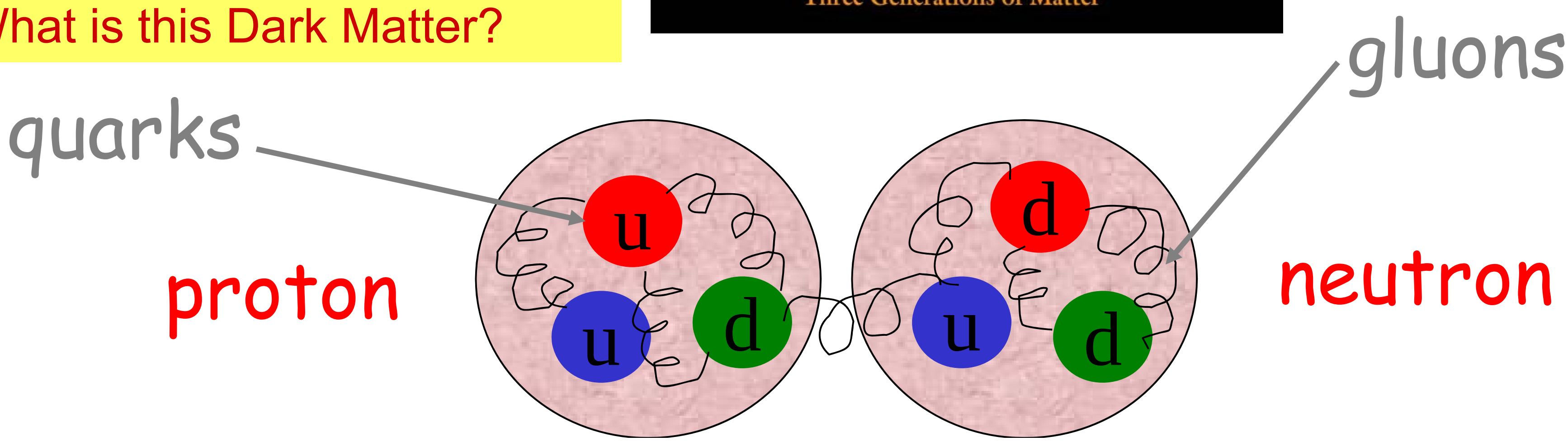
Why is the top quark much more heavy than the quarks
⇒Mass(top) = gold nucleus
What is the origin of mass?

Astrophysics/cosmological measurements show that most matter in the universe is NOT in this table
What is this Dark Matter?



Four known forces
- Gravity
- Electro-magnetisme
- Strong nuclear force
- Weak force



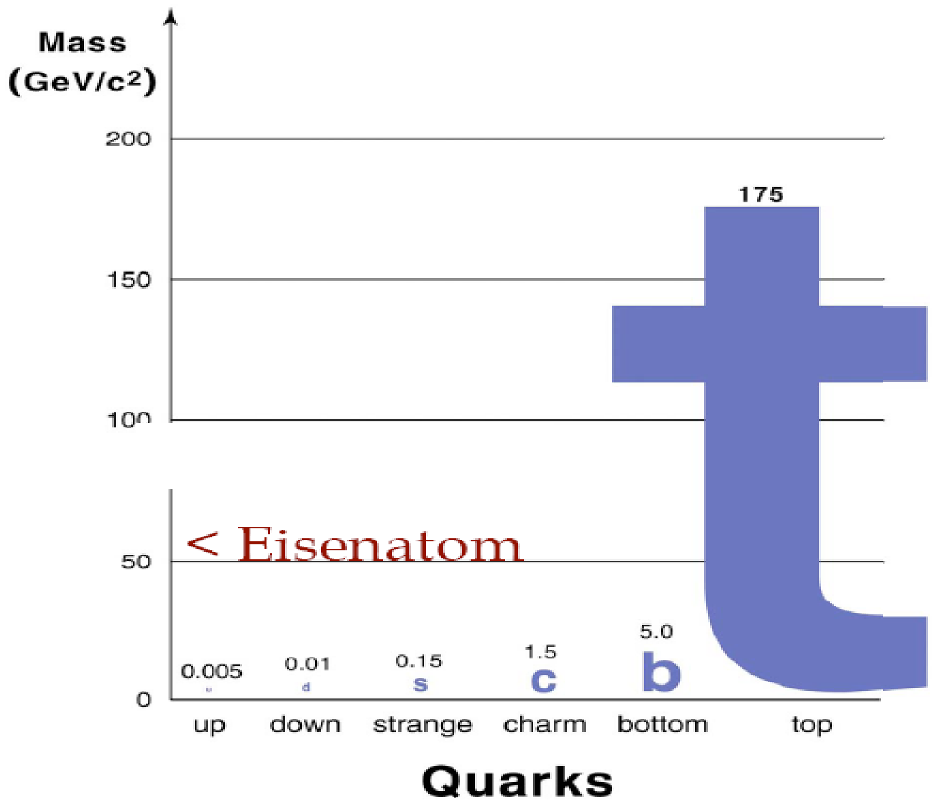


The Origin of Mass

A most basic question is why particles (and matter) have masses (and so different masses)

The mass mystery could be solved with the 'Higgs mechanism' which predicts the existence of a new elementary particle, the 'Higgs' particle (theory 1964, P. Higgs, R. Brout and F. Englert)

Peter Higgs



The Higgs (H) particle has been searched for since decades at accelerators, but not yet found…

The LHC will have sufficient energy to produce it for sure, if it exists

Francois Englert

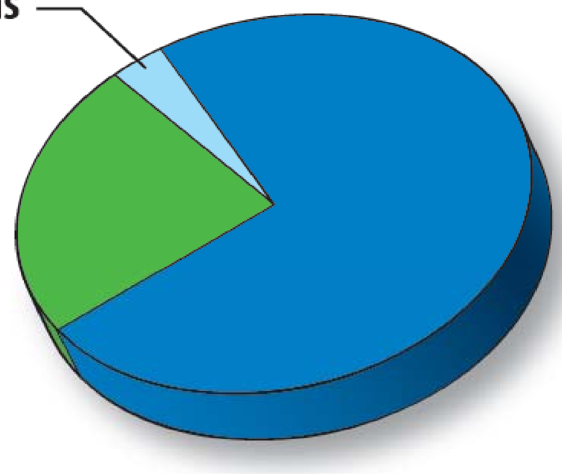
Dark Matter in the Universe

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

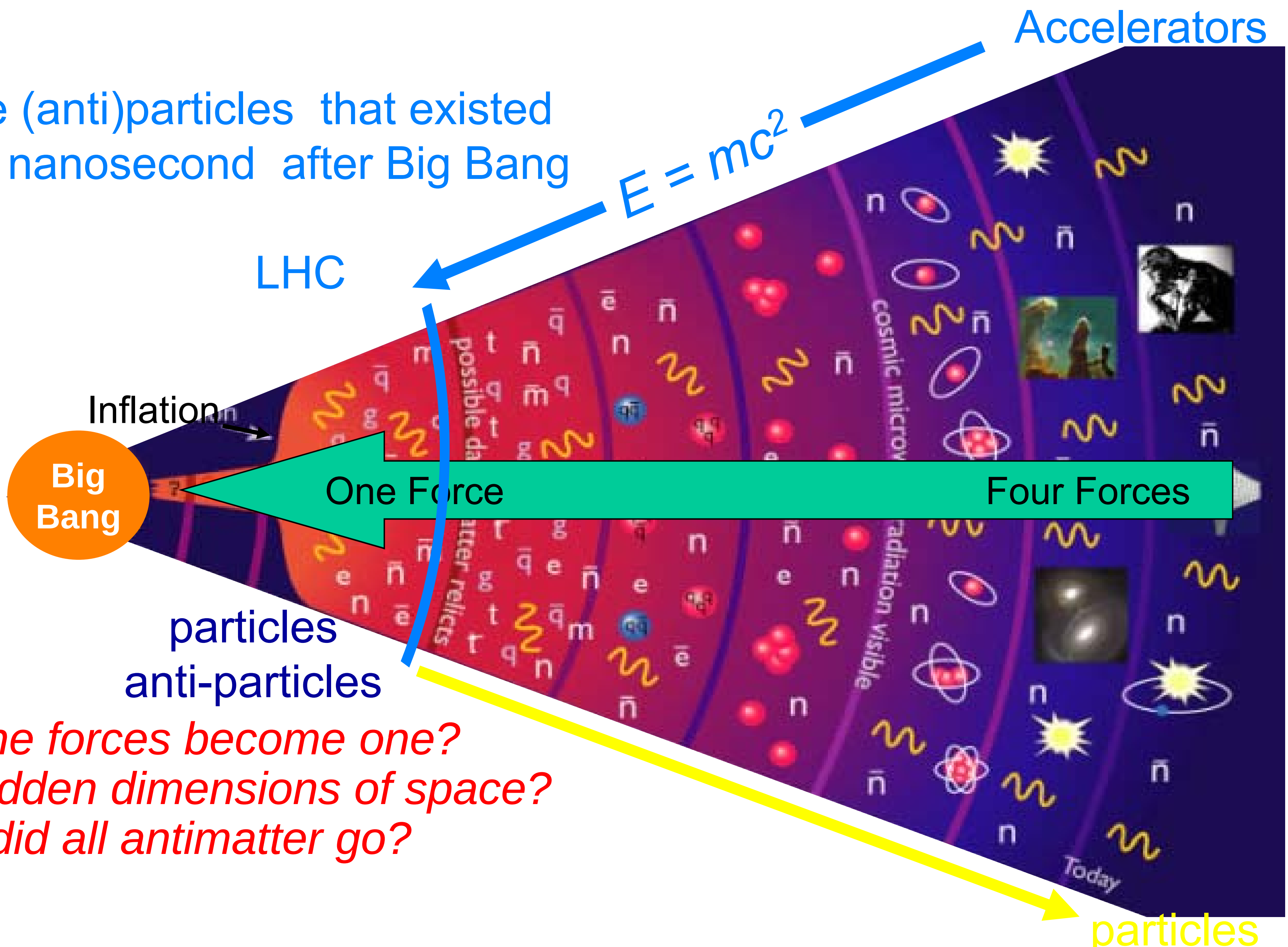
'Supersymmetric' particles ?

We shall look for them with the LHC

F. Zwicky 1898-1974

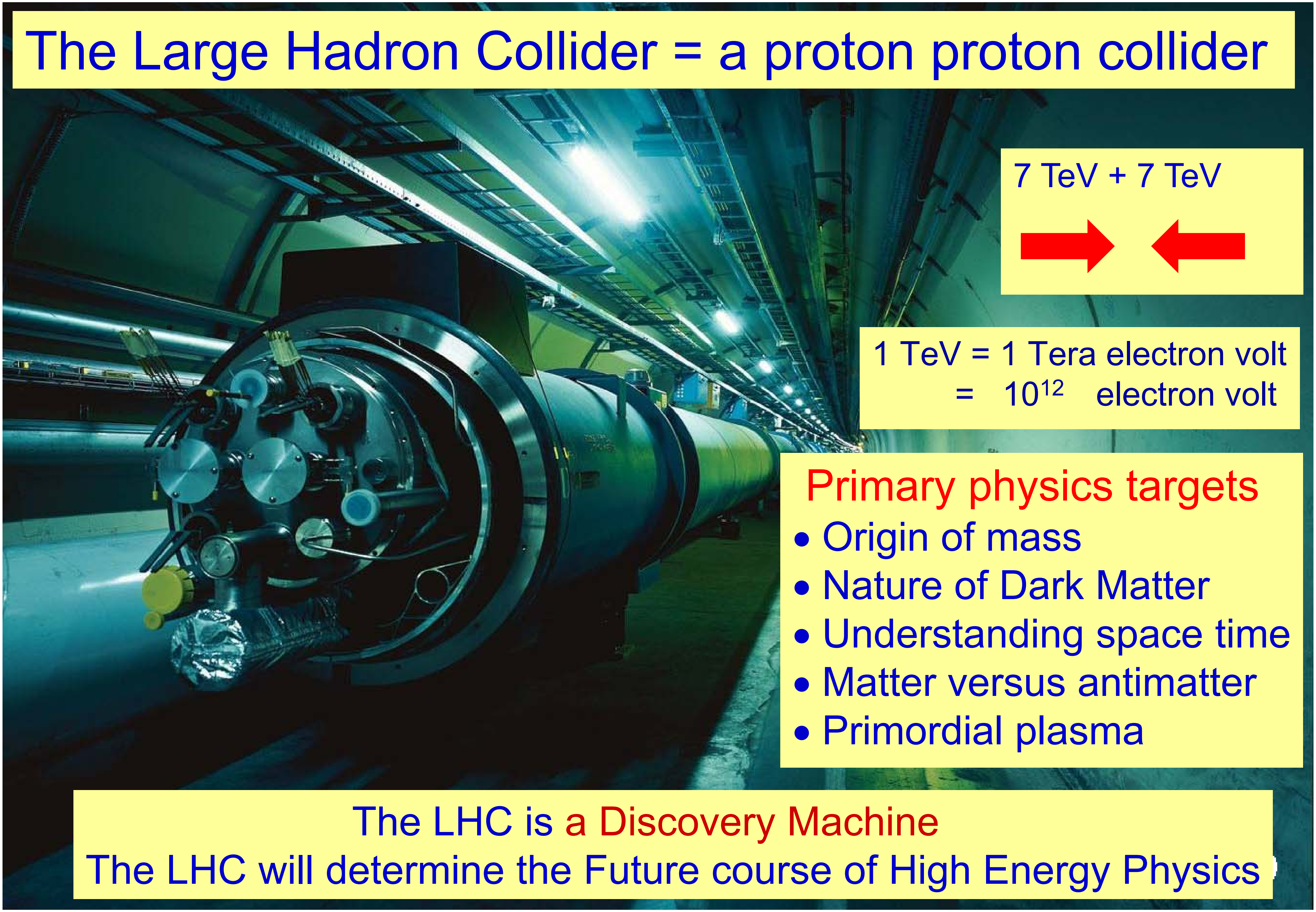


Create (anti)particles that existed
~0.001 nanosecond after Big Bang



Do all the forces become one?
Extra hidden dimensions of space?
Where did all antimatter go?

The Large Hadron Collider = a proton proton collider



7 TeV + 7 TeV

1 TeV = 1 Tera electron volt
= 10^{12} electron volt

Primary physics targets

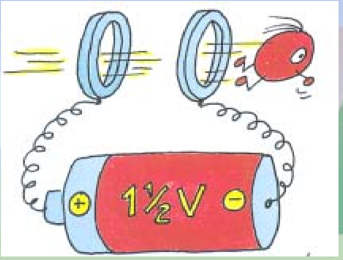
- Origin of mass
- Nature of Dark Matter
- Understanding space time
- Matter versus antimatter
- Primordial plasma

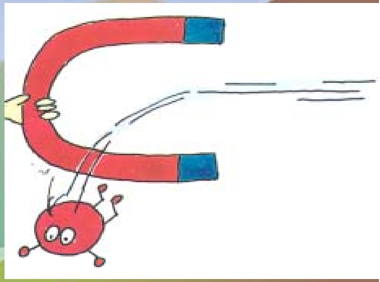
The LHC is a Discovery Machine

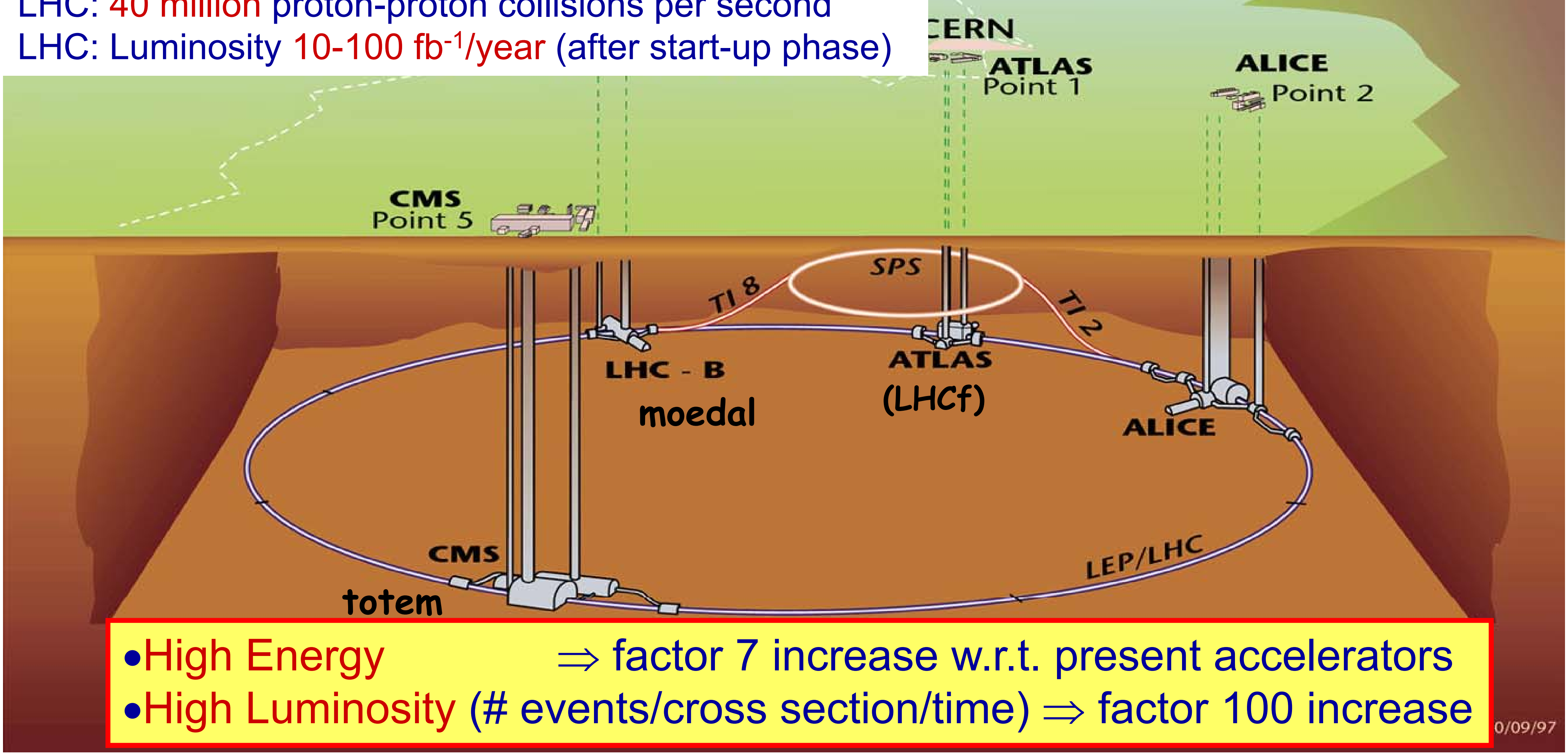
The LHC will determine the Future course of High Energy Physics

The LHC Machine and Experiments

LHC is 100m underground
LHC is 27 km long
Magnet Temperature is 1.9 Kelvin = -271 Celsius
LHC has ~ 9000 magnets
LHC: 40 million proton-proton collisions per second
LHC: Luminosity 10-100 fb^{-1}/year (after start-up phase)



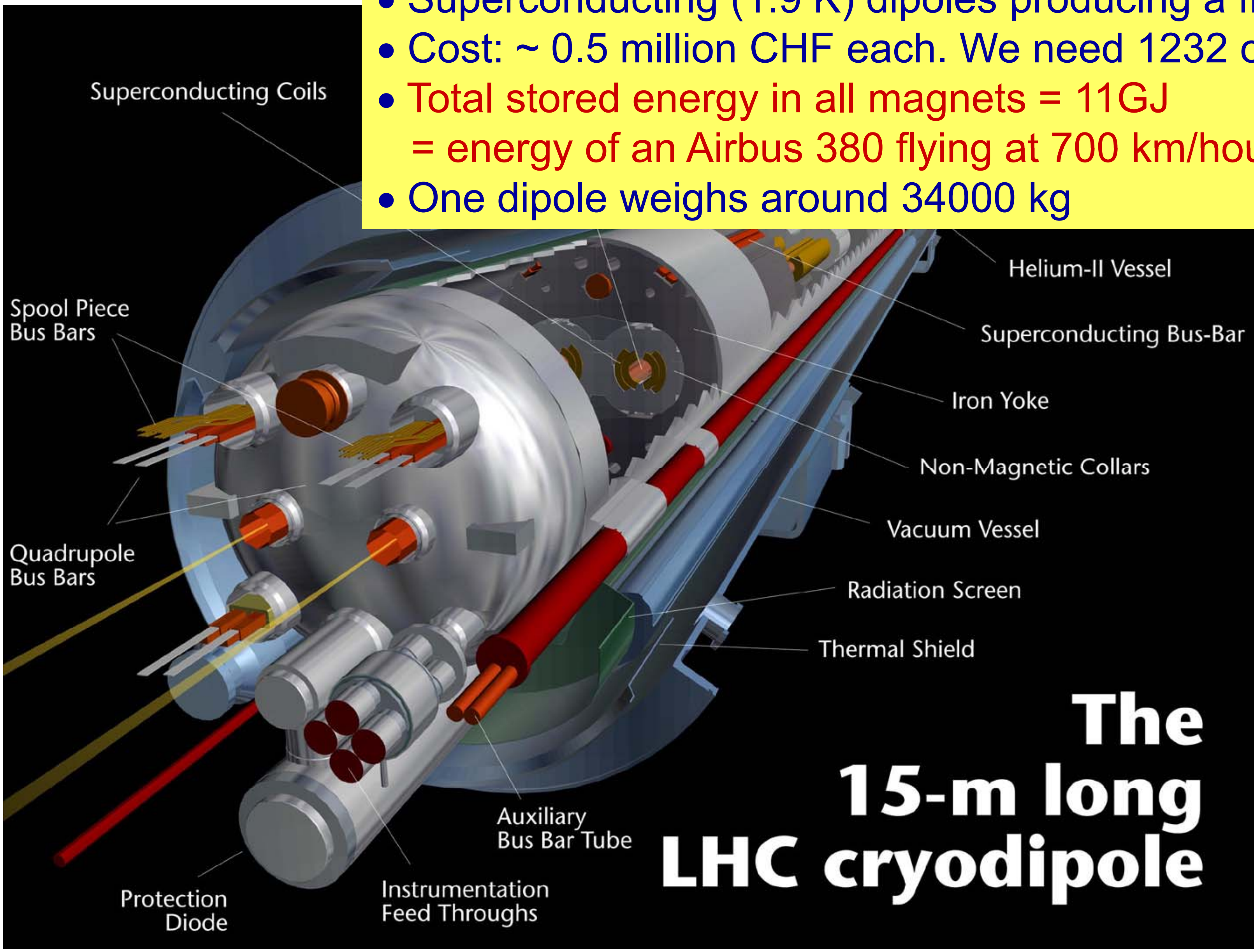




•High Energy ⇒ factor 7 increase w.r.t. present accelerators
•High Luminosity (# events/cross section/time) ⇒ factor 100 increase

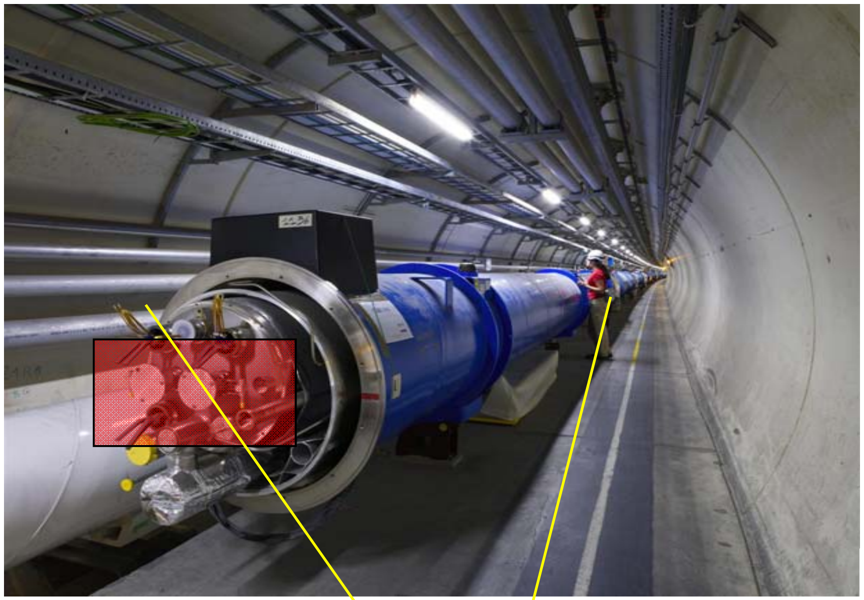
The Cryodipole Magnets

- Superconducting (1.9 K) dipoles producing a field of 8.4 T
- Cost: ~ 0.5 million CHF each. We need 1232 of them
- Total stored energy in all magnets = 11GJ
  = energy of an Airbus 380 flying at 700 km/hour
- One dipole weighs around 34000 kg



LHC facts

The **emptiest** space in the solar system…



To accelerate protons to almost the speed of light, we need a vacuum similar to interplanetary space. The pressure in the beam-pipes of the LHC will be about ten times lower than on the moon.

LHC facts

One of the coldest places in the Universe…

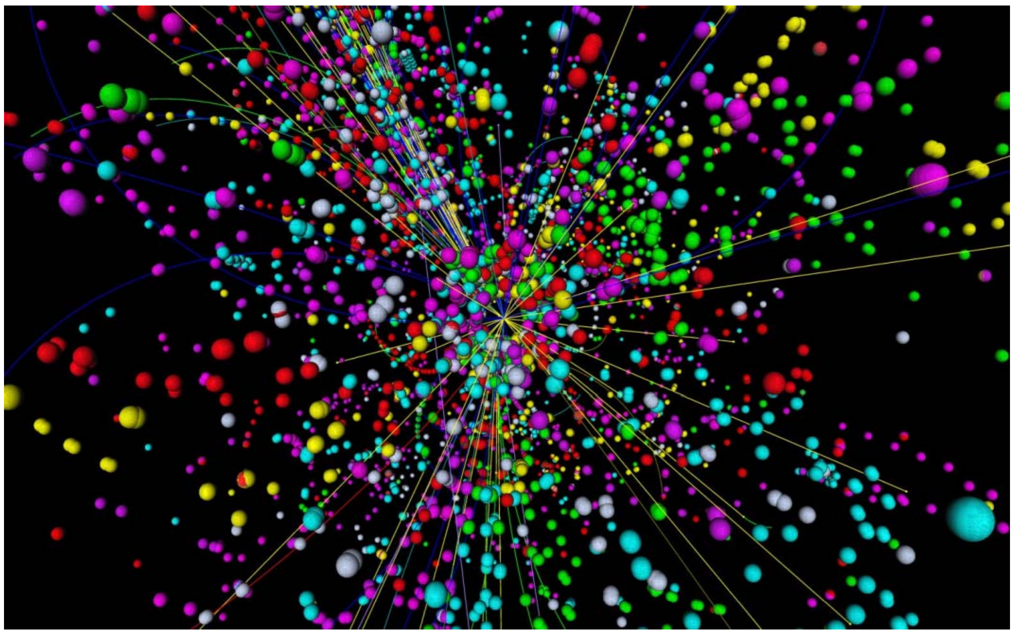
the largest cryogenic system ever built

54 km fridge!

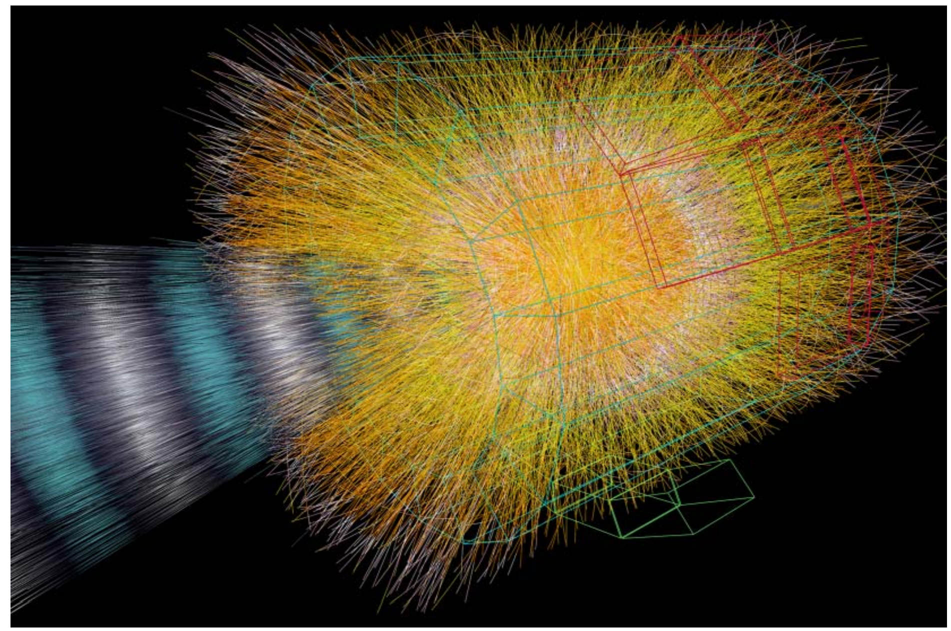
With a temperature of around -271 degrees Celsius, or 1.9 degrees above absolute zero, the LHC is colder than interstellar space.

LHC facts

One of the hottest places in the Galaxy…



Simulation of a collision in the CMS experiment

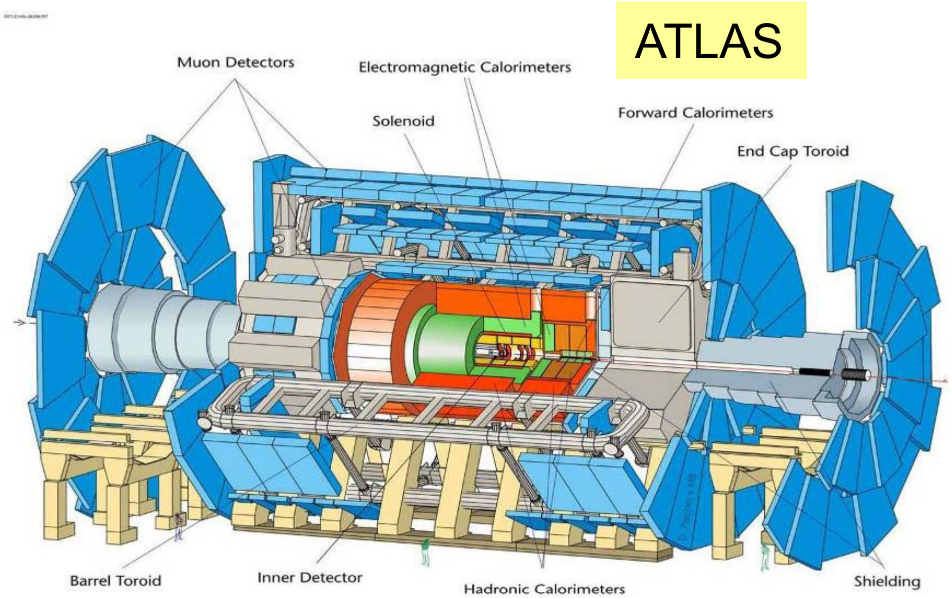


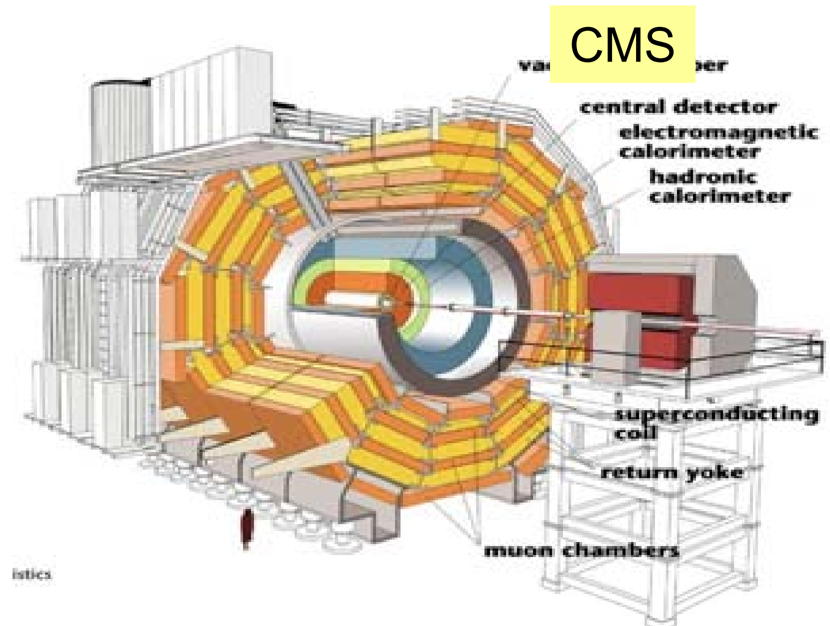
Simulation of a collision in the ALICE experiment

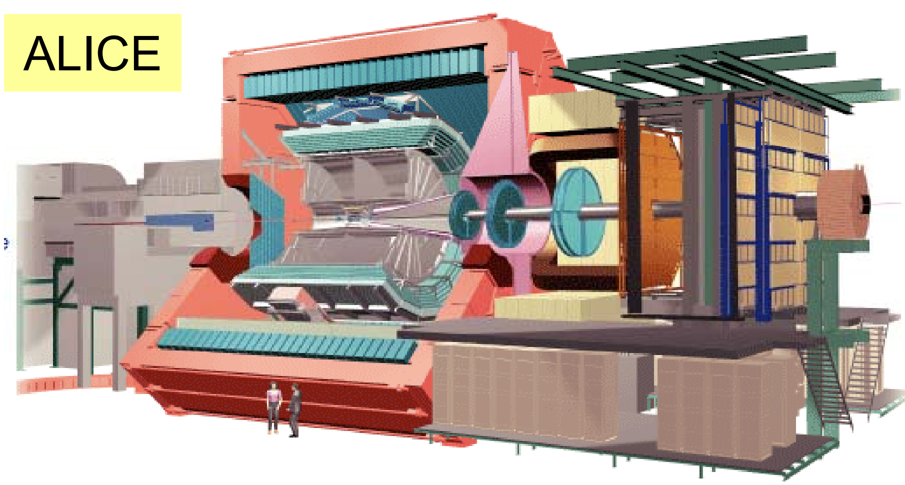
When two beams of protons collide, they generate within a tiny volume, temperatures more than a billion times those in the very heart of the Sun.

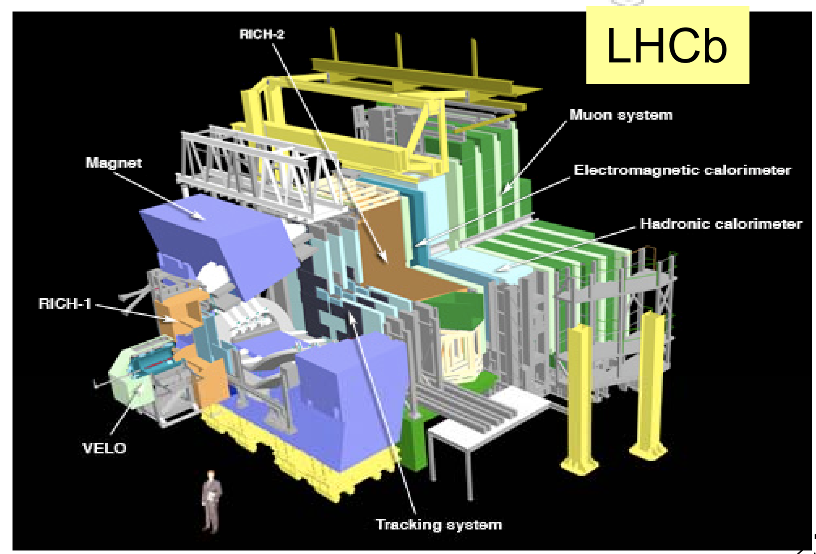
22

The Four Main LHC Experiments





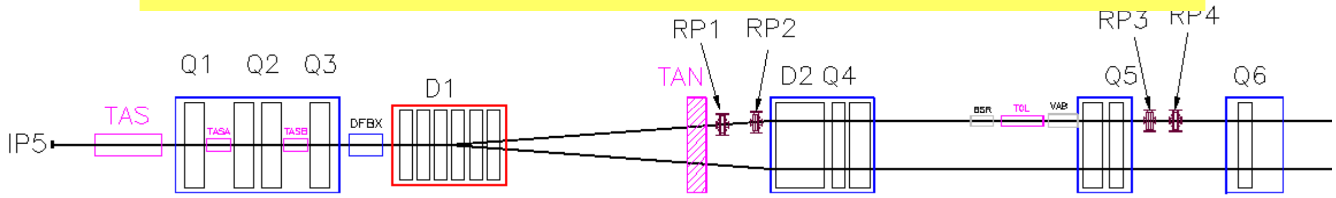


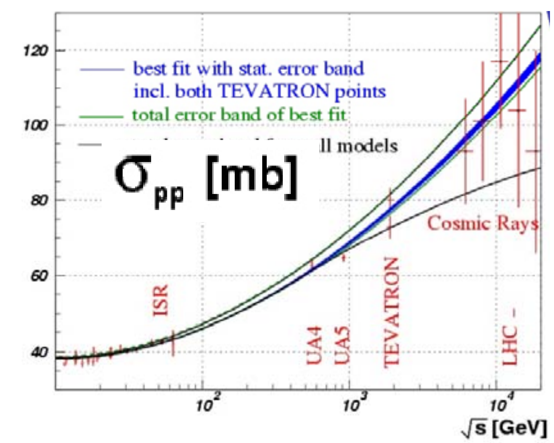


A Few Smaller Experiments: TOTEM & LHCf

TOTEM: measuring the total, elastic and diffractive cross sections
Add Roman pots (and inelastic telescope) to CMS interaction regions (200 m from IP)
Common runs with CMS planned

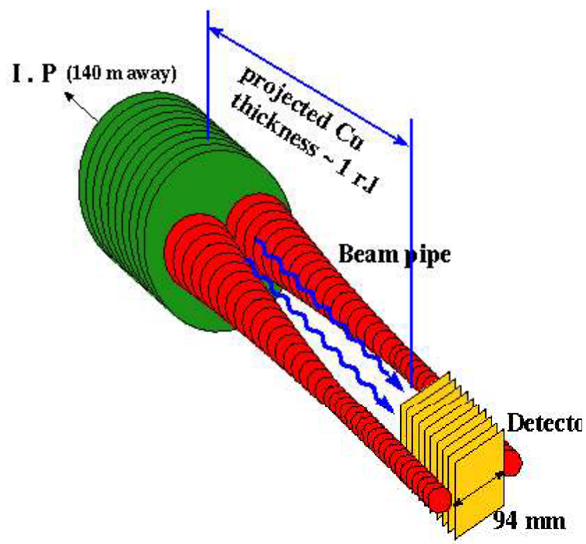
TOTal and Elastic cross section Measurement

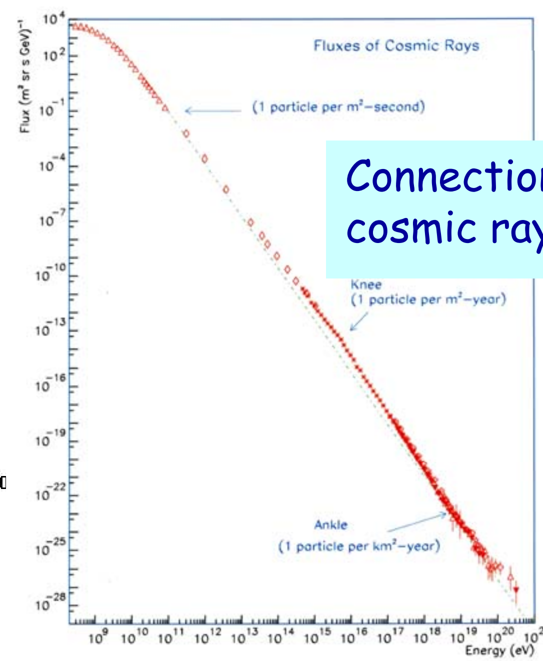




LHCf: measurement of photons and neutral pions in the very forward region of LHC

Add a EM calorimeter at 140 m from the Interaction Point (of ATLAS)

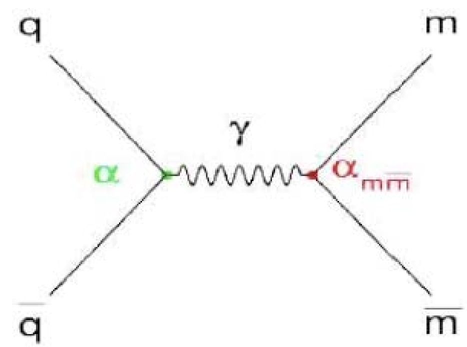




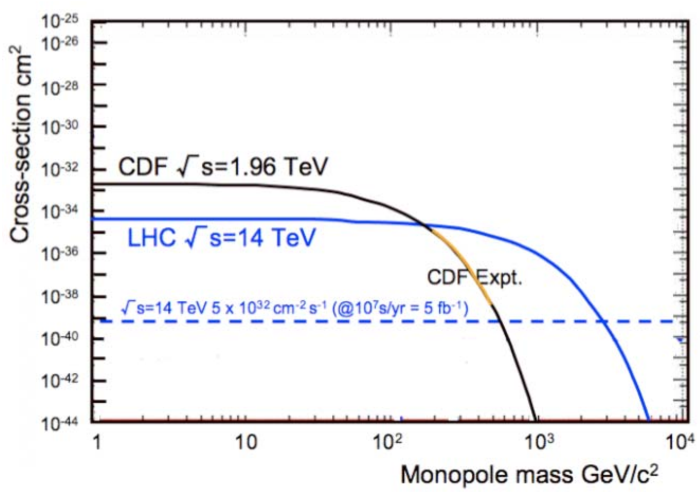
Connection with cosmic rays

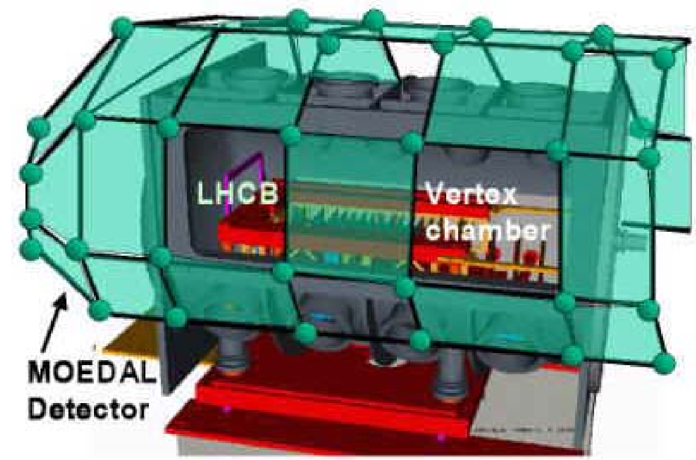
Moedal: MOnopole and Exotics Detector at the LHC

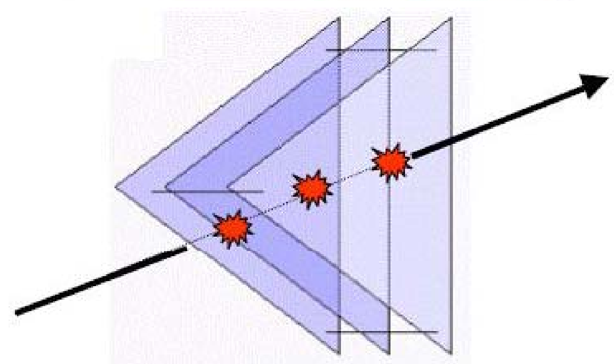
Heavy particles which carry "magnetic charge"
Could eg explain why particles have "integer electric charge"



Direct Monopole production

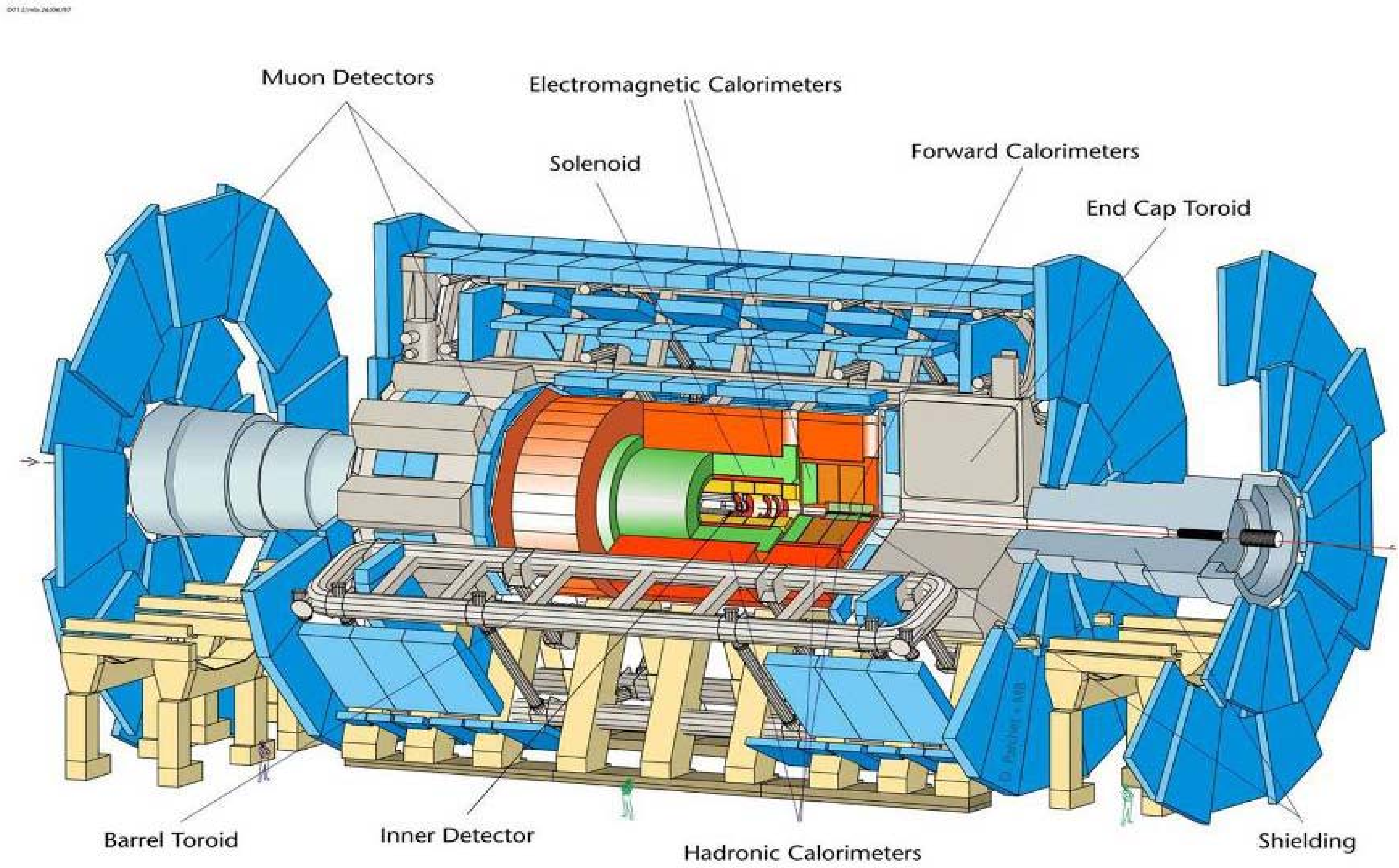






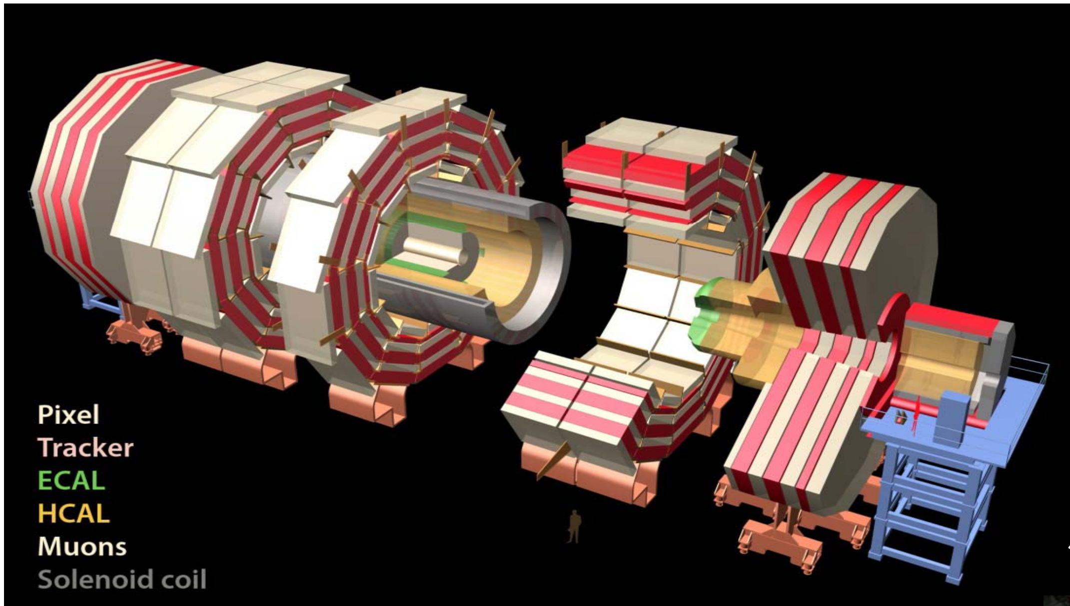
Remove the sheets after some running time and inspect for 'holes'

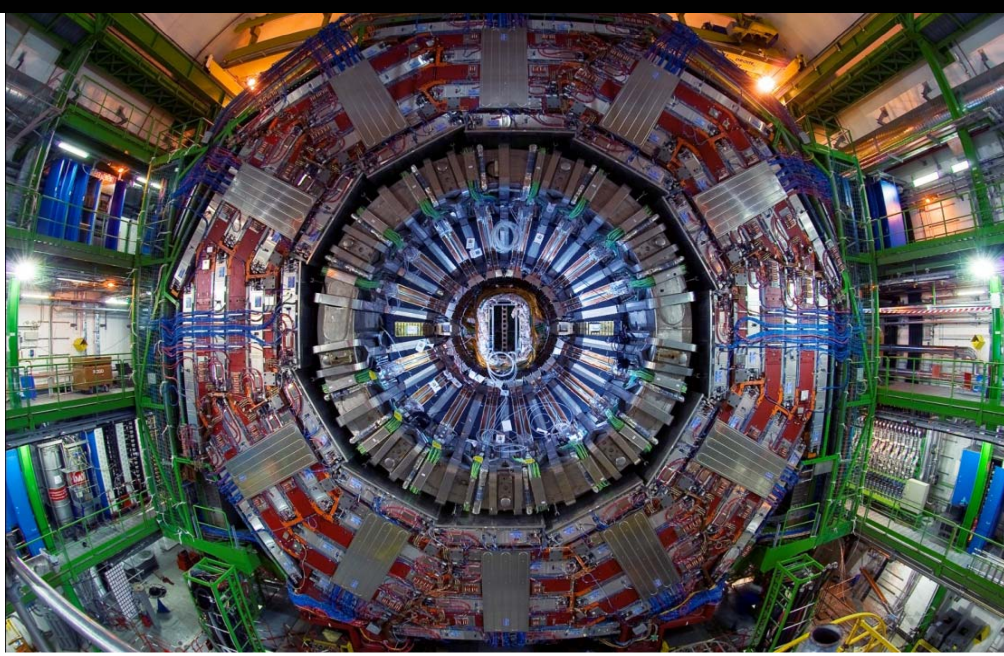
[redacted]



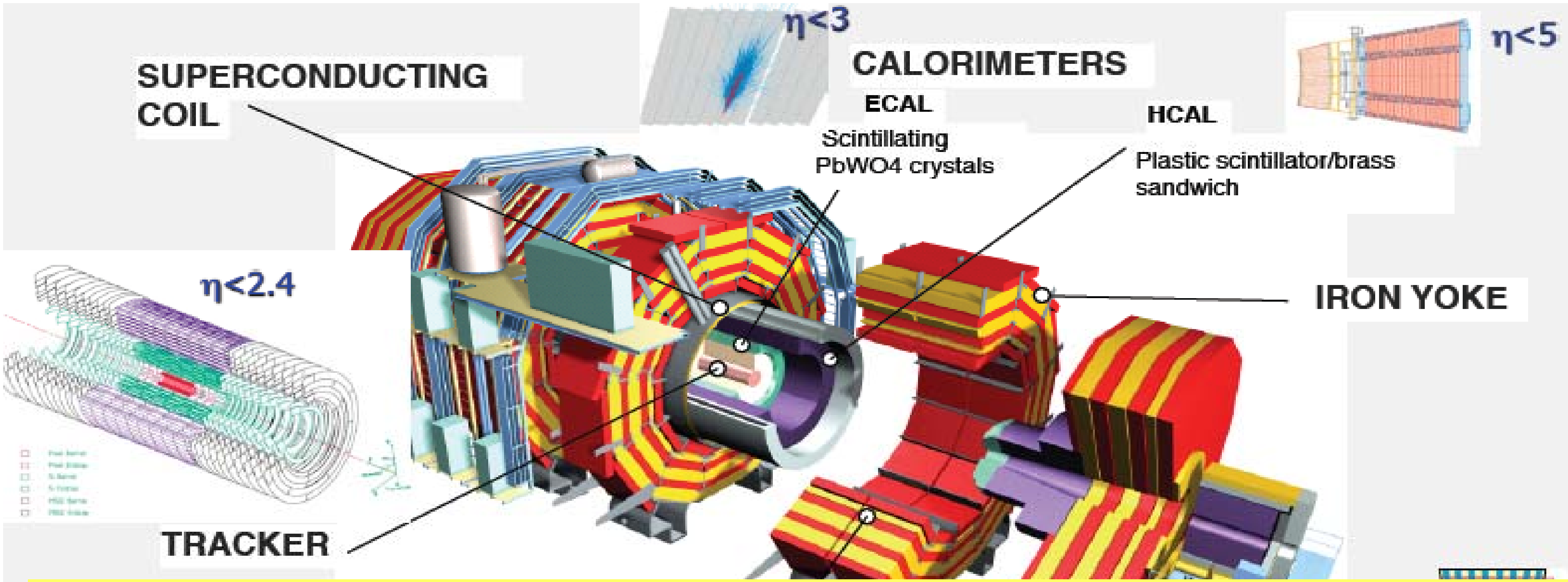
Length = 55 m   Width = 32 m   Height = 35 m   but spatial precision ~ 100 μm

The CMS Collaboration: >3000 scientists and engineers, >700 students from 182 Institutions in 39 countries .





The Compact Muon Solenoid Experiment



In total about

~100 000 000 electronic channels

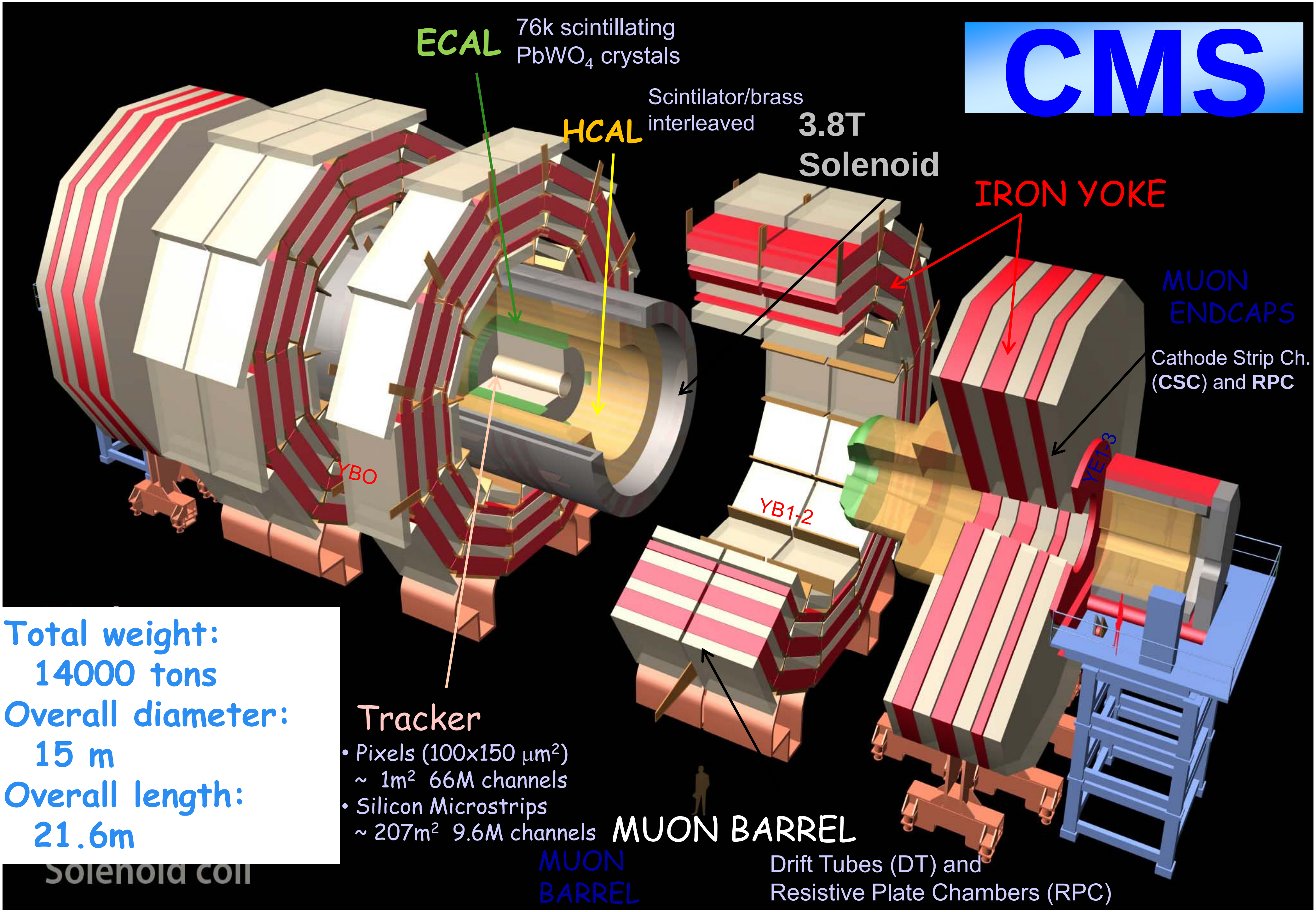
Each channel checked

40 000 000 times per second (collision rate is 40 MHz)

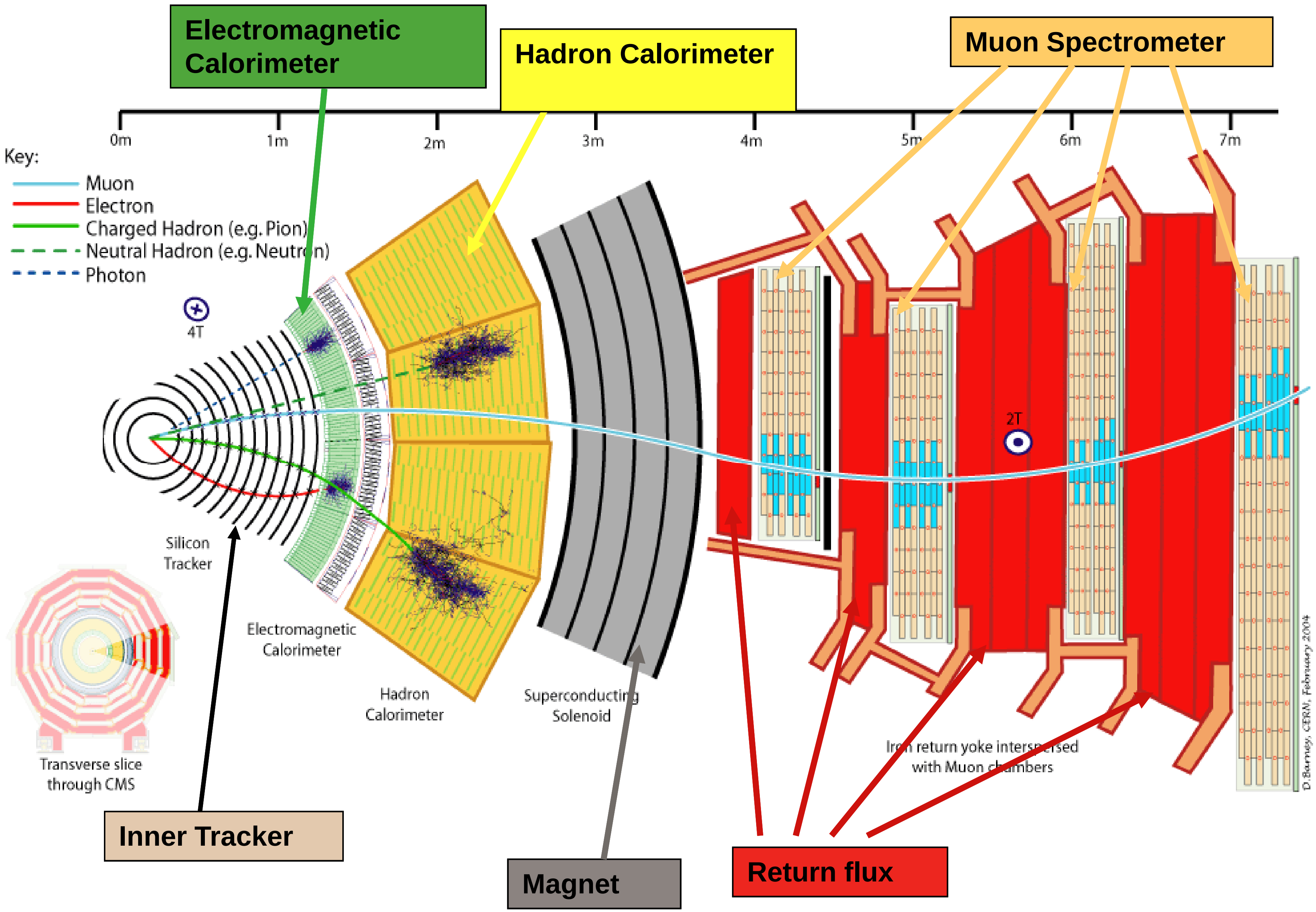
An on-line trigger selects events and reduces the rate from 40MHz to ~200 Hz

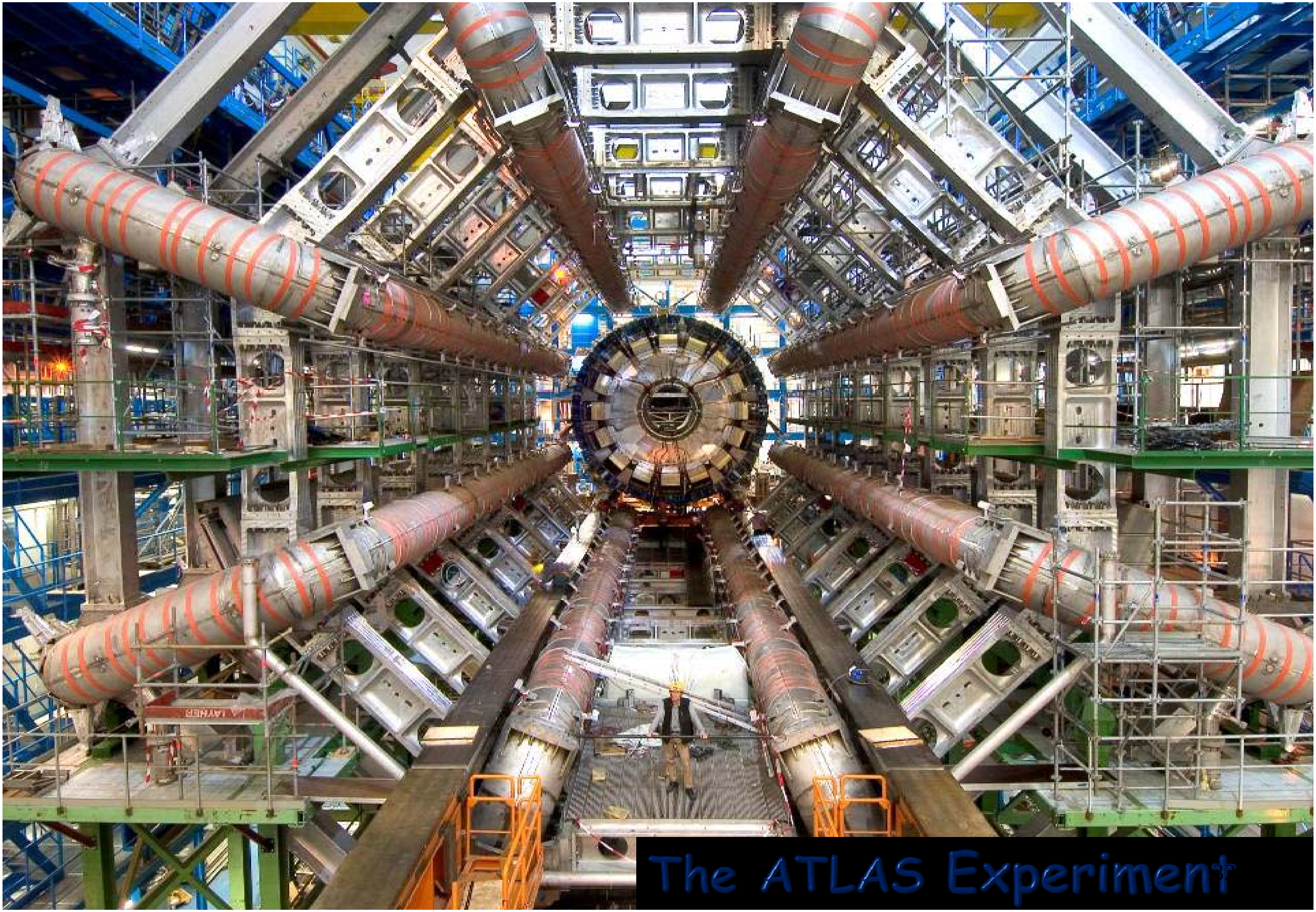
Amount of data of just one collisions

>1 500 000 Bytes


CMS
ECAL
76k scintillating
$PbWO_4$ crystals
HCAL
Scintilator/brass
interleaved
3.8T
Solenoid
IRON YOKE
MUON
ENDCAPS
Cathode Strip Ch.
(**CSC**) and **RPC**
YE1-3
YBO
YB1-2
Total weight:
14000 tons
Overall diameter:
15 m
Overall length:
21.6m
Solenoid coil
Tracker
• Pixels (100x150 μm^2)
~ $1m^2$ 66M channels
• Silicon Microstrips
~ $207m^2$ 9.6M channels
MUON BARREL
MUON
BARREL
Drift Tubes (DT) and
Resistive Plate Chambers (RPC)

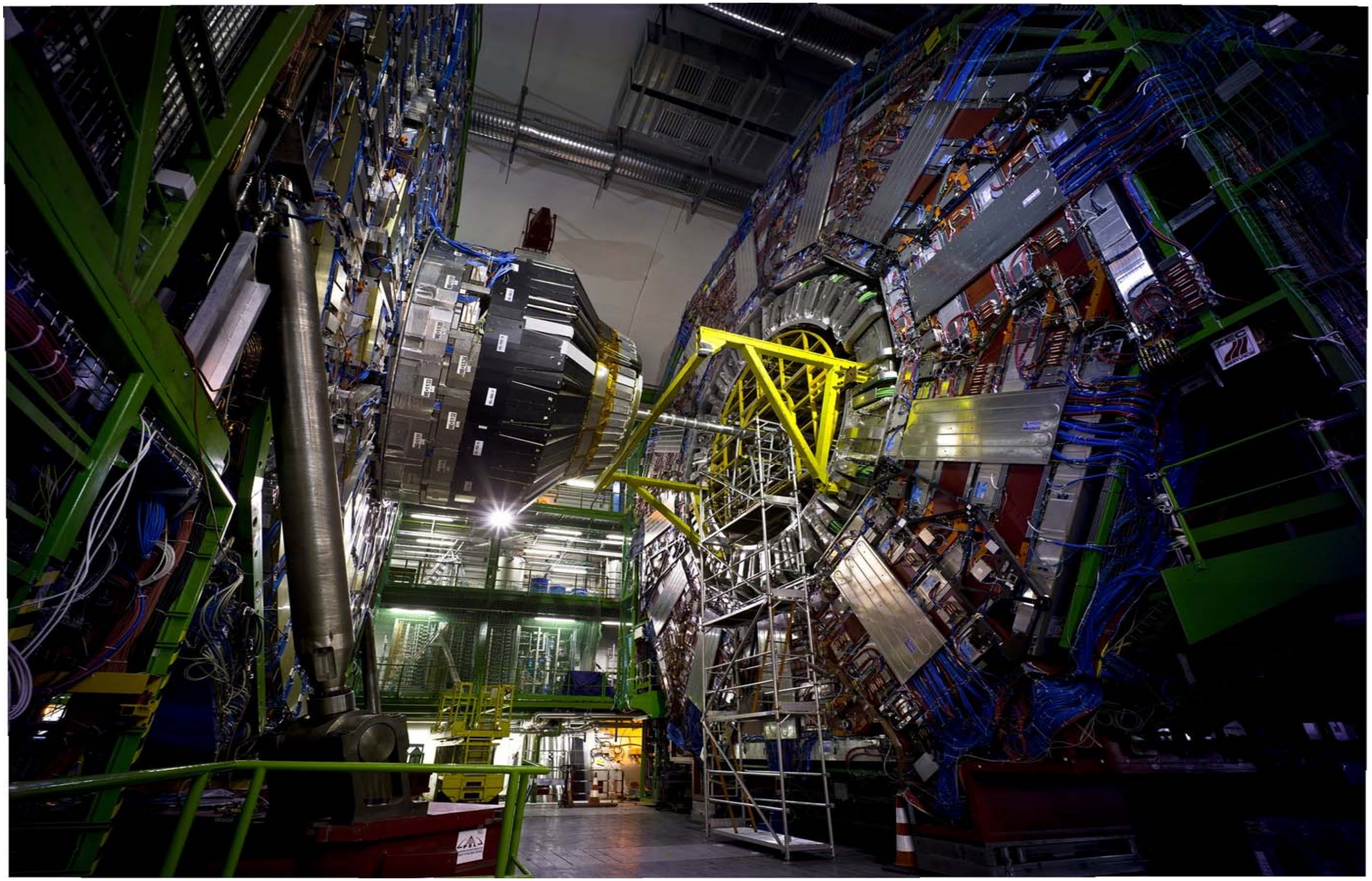
Particles in the detector




The ATLAS Experiment


CMS before closure
HE-RBX 03
HE-RBX 02
HE-RBX 01
ME-1/1/06
ME-1/1/05
ME-1/1/04
ME-1/1/03
ME-1/1/02
ME-1/1/01
ME-1/1/36
ME-1/1/35
LIFTLUX

The CMS Experiment



CMS Ready for Collisions

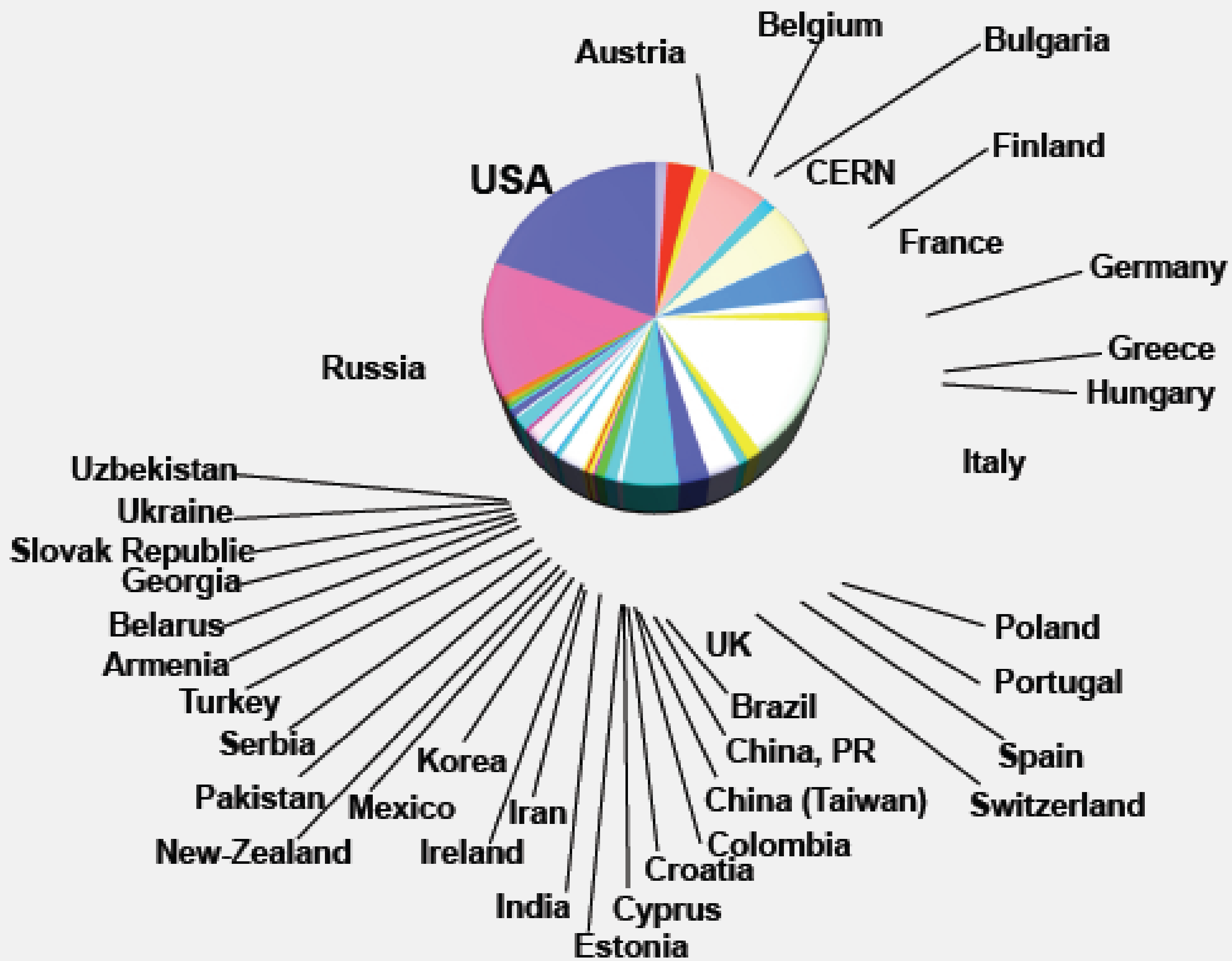
The CMS Collaboration

2006

	Institutions
Member States	61
Non-Mem. States	64
USA	49
Total	174

	Scientists
Member States	1055
Non-Mem. States	428
USA	547
Total	2030

Associated Institutes	
Number of Scientists	46
Number of Laboratories	8



Now: 2900 Physicists 184 Institutions 38 countries

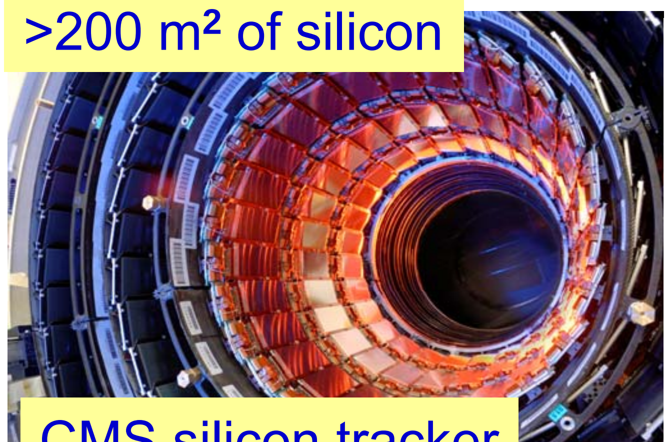
May, 04 2006/gm
http://cmsdoc.cern.ch/pictures/cmsorg/overview.html

The LHC Detectors are Major Challenges

- CMS/ATLAS detectors have about 100 million read-out channels
- Collisions in the detectors happen every 25 nanoseconds
- ATLAS uses over 3000 km of cables in the experiment
- The data volume recorded at the front-end in CMS is 1 TB/second which is equivalent to the world wide communication network traffic
- Data recorded during the 10-20 years of LHC life will be about all the words spoken by mankind since its appearance on earth
- A worry for the detectors: the kinetic energy of the beam is that of a small aircraft carrier of 10^4 tons going 20 miles/ hour

ATLAS pixel detector

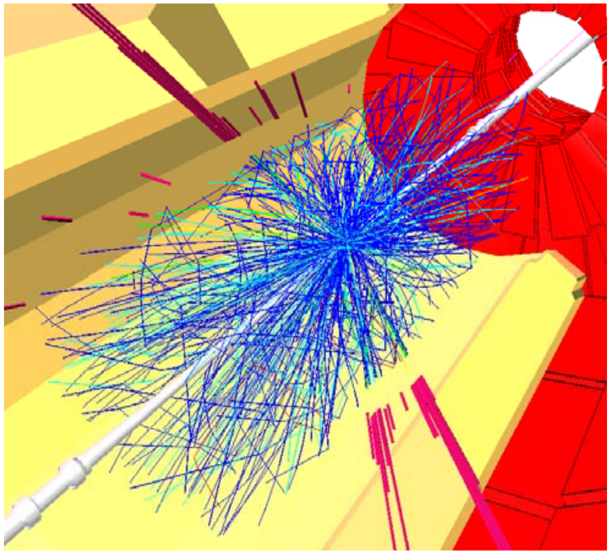
>200 m^2 of silicon



CMS silicon tracker

Object	Weight (tons)
Boeing 747 [fully loaded]	200
Endeavor space shuttle	368
ATLAS	7,000
Eiffel Tower	7,300
USS John McCain	8,300
CMS	12,500

Worldwide LHC Computing Grid (wLCG)



WLCG is a worldwide collaborative effort on an unprecedented scale in terms of storage and CPU requirements, as well as the software project's size

GRID computing developed to solve problem of data storage and analysis

LHC data volume per year:
10-15 Petabytes

One CD has ~ 600 Megabytes
1 Petabyte = 10^9 MB = 10^{15} Byte

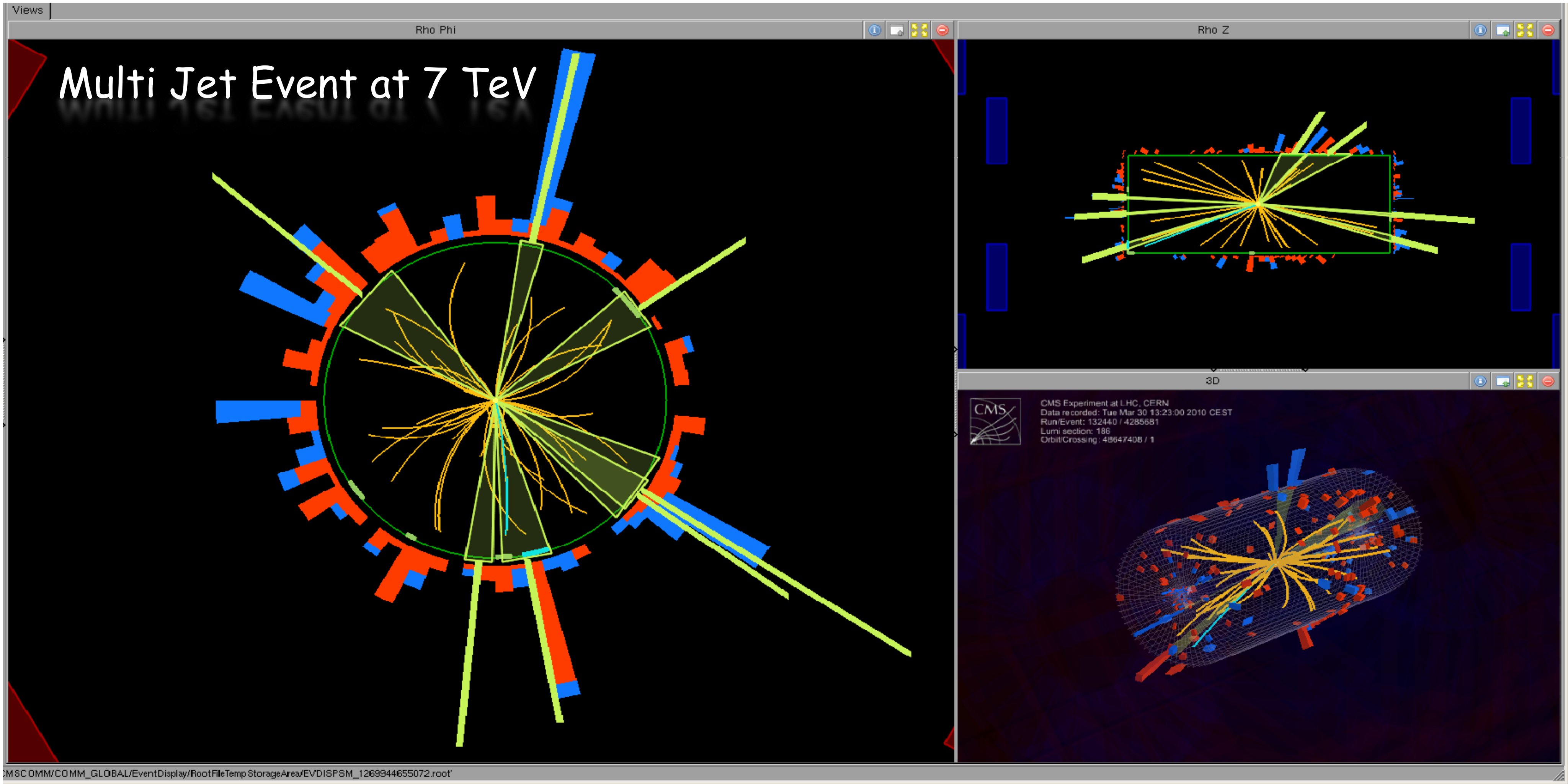
(Note: the WWW is from CERN...)

30/3/2010: High Energy Collision Day…

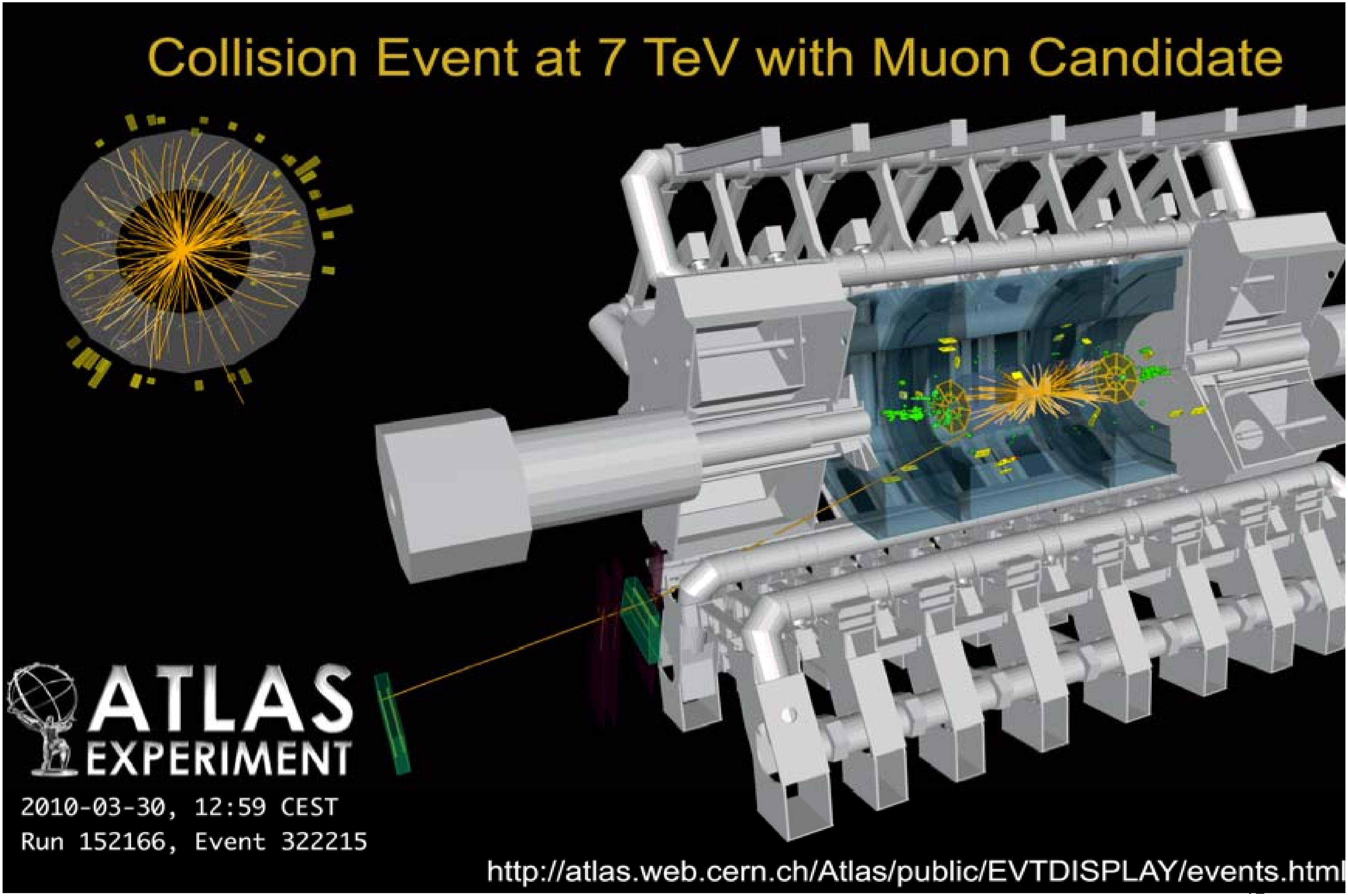
Waiting for collisions (since 4:00 AM!!)

12:58
7 TeV collisions!!!

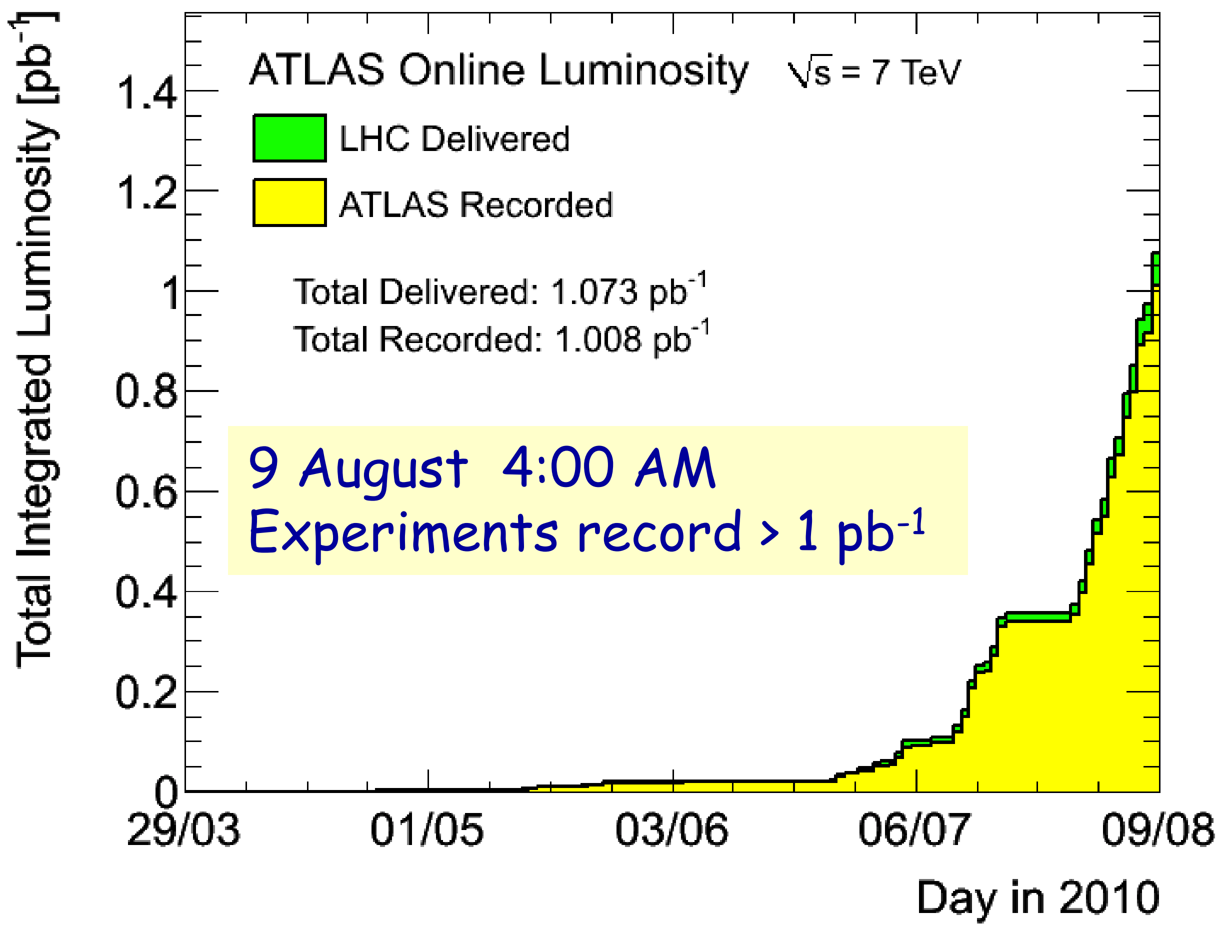
First Collisions at 7 TeV



Very interesting events are coming!!

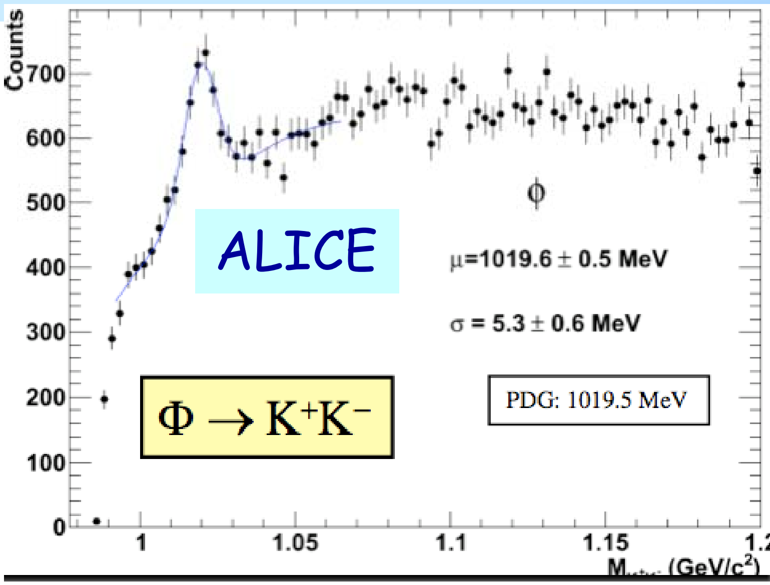

Collision Event at 7 TeV with Muon Candidate
ATLAS
EXPERIMENT
2010-03-30, 12:59 CEST
Run 152166, Event 322215
http://atlas.web.cern.ch/Atlas/public/EVTDISPLAY/events.html

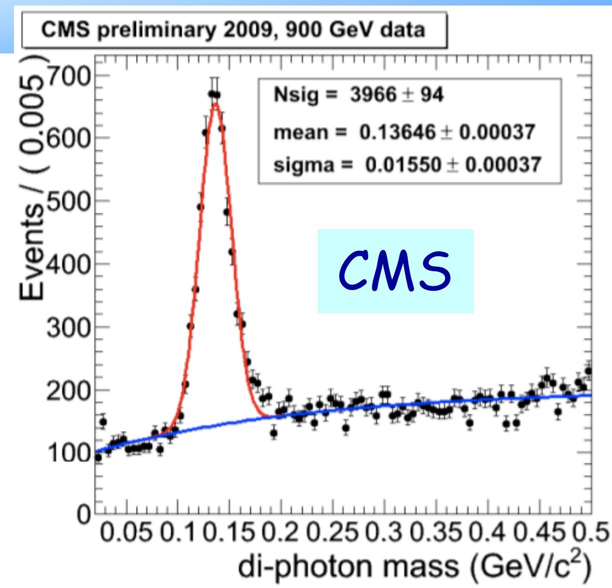
Data Collected Since March 30th

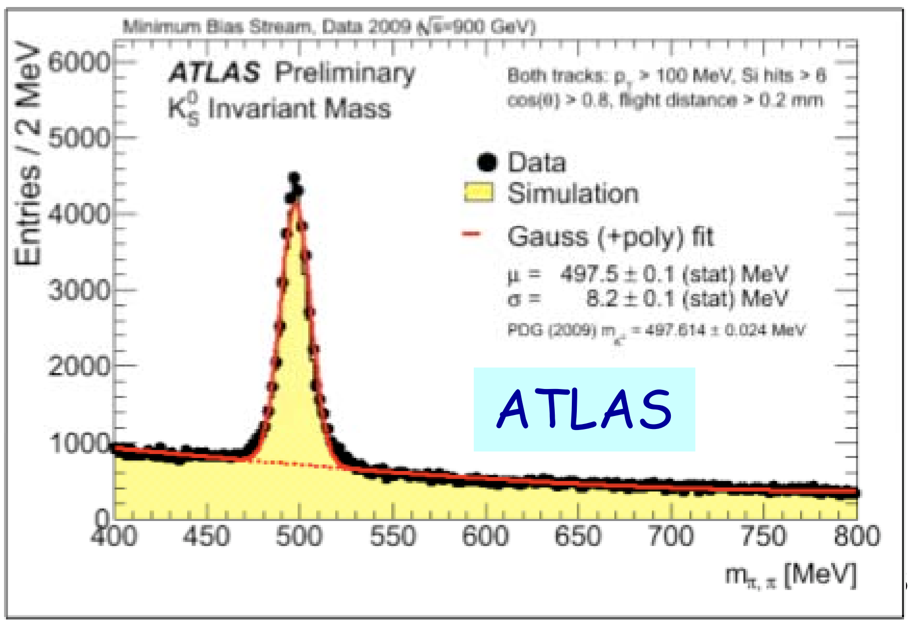


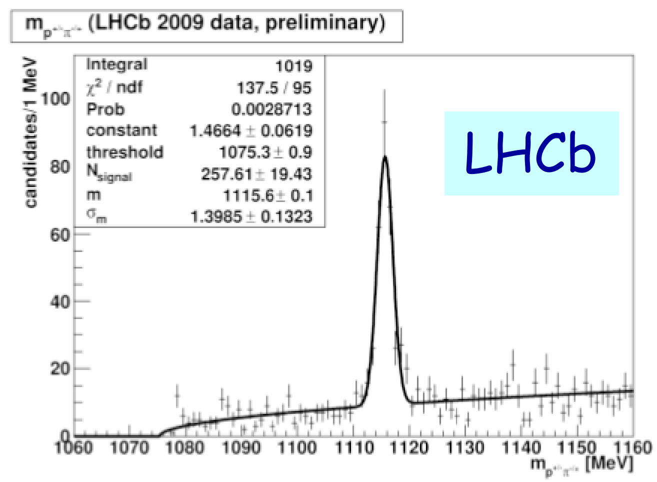
Another luminosity increase by factor 100 in the next 2 months

"Standard Model" Particles









$M(\Lambda)$ = 1115.6 ± 0.1 MeV/c^2
σ= 1.4 ± 0.1 MeV/c^2

$M(\Lambda^{PDG})$ =1115.7 MeV/c^2

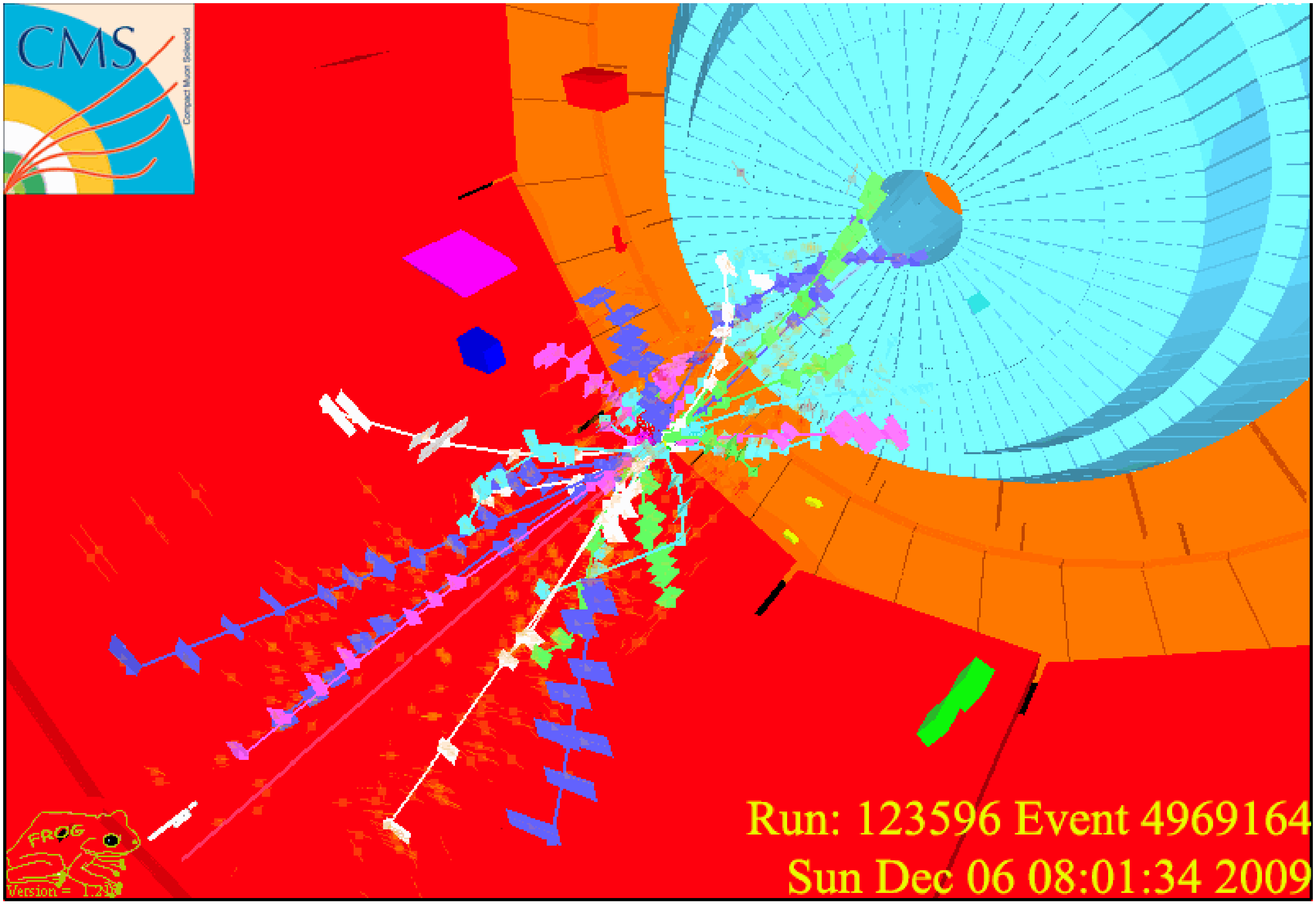
The Science of the LHC

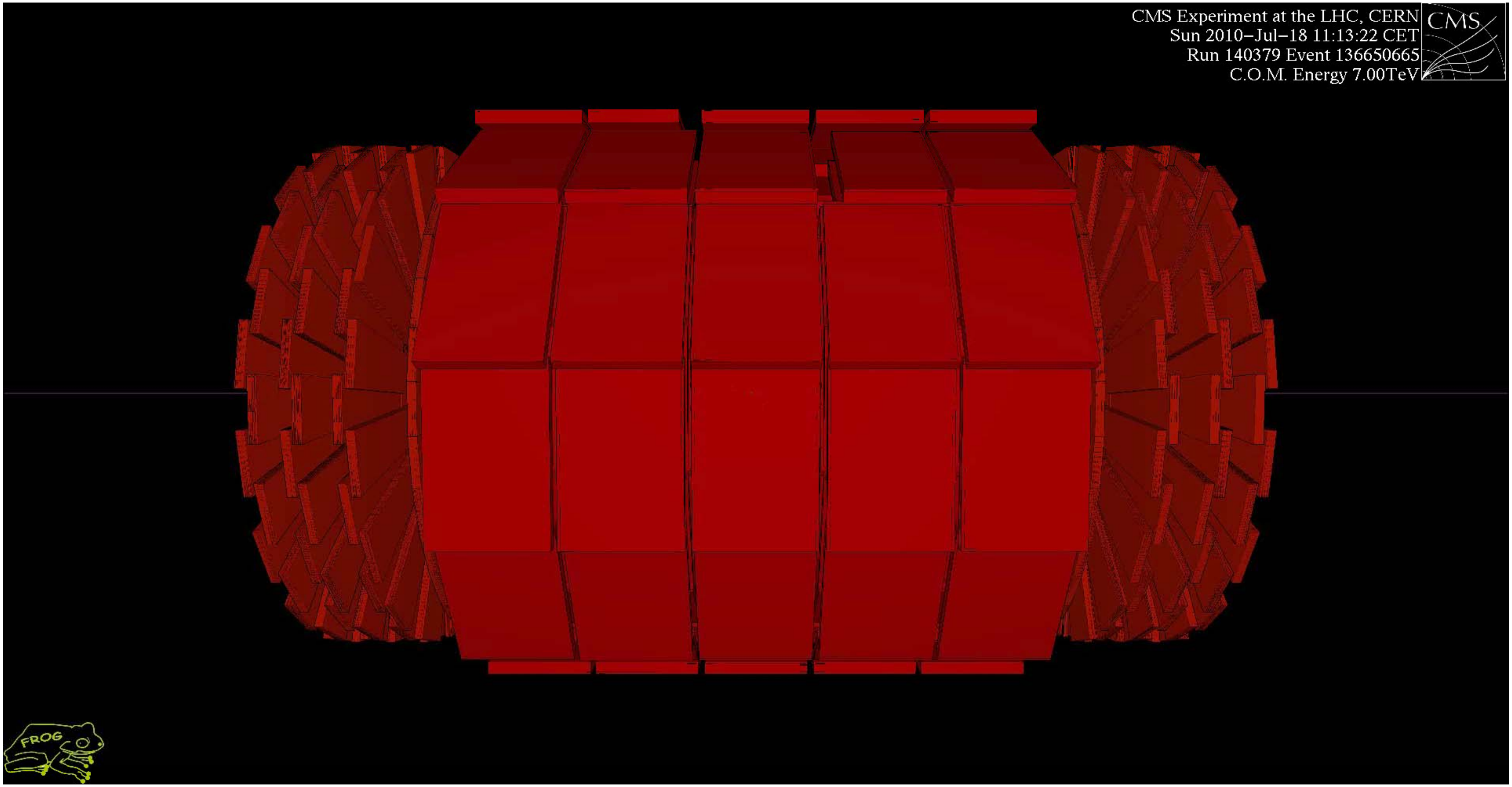
$\Rightarrow$ Explore the new high energy regime: The Terascale

LHC Physics Program

- Discover or exclude the Higgs in the mass region up to 1 TeV. Measure Higgs properties
- Discover Supersymmetric particles (if exist) up to 2-3 TeV
- Discover Extra Space Dimensions, if these are on the TeV scale, and black holes?
- Search other new phenomena (e.g. strong EWSB, new gauge bosons, Little Higgs model, Split Supersymmetry…)
- Study CP violation in the B sector,B physics, new physics in B-decays
- Precision measurements on top, W, anomalous couplings…
- Heavy ion collisions and search for quark gluon plasma
- QCD and diffractive (forward) physics in a new regime
- …

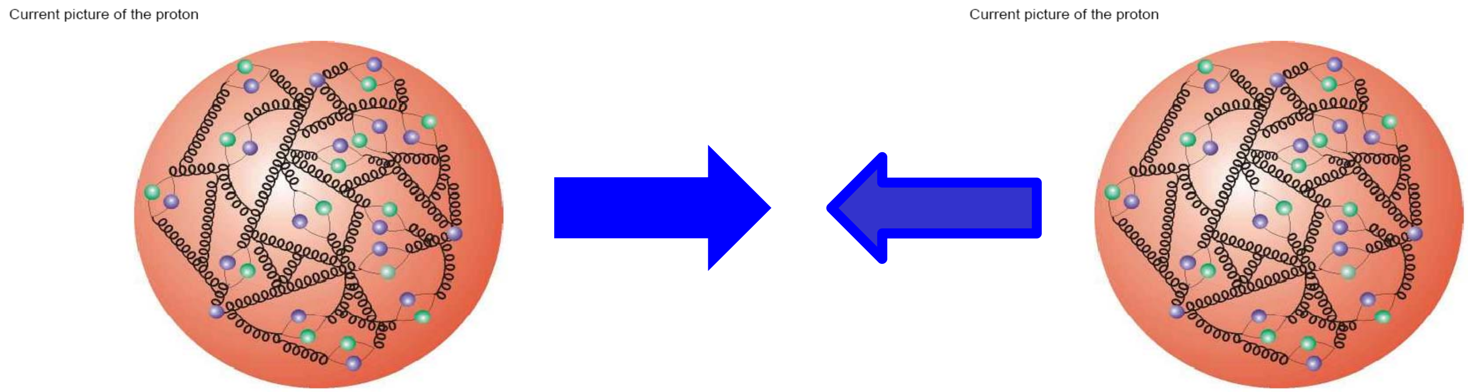
Looking at Events



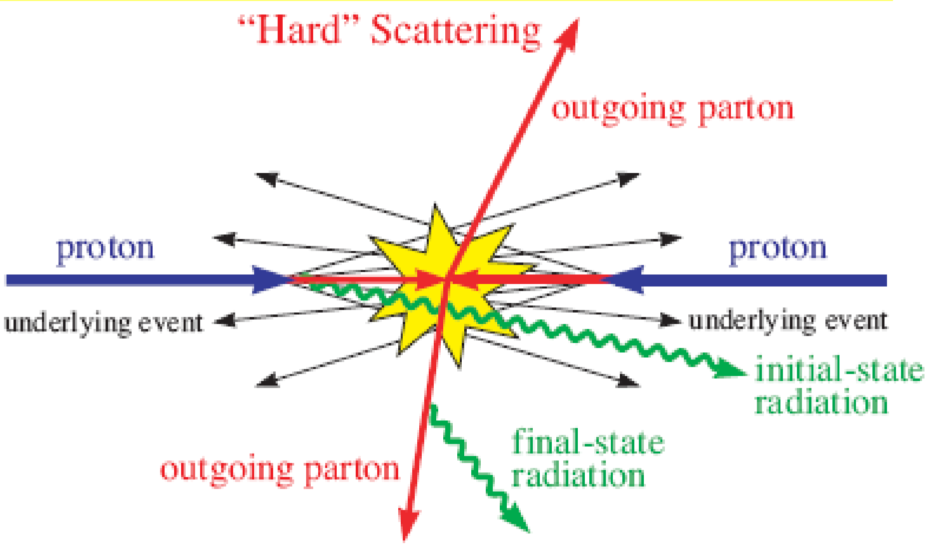

CMS Experiment at the LHC, CERN
Sun 2010–Jul–18 11:13:22 CET
Run 140379 Event 136650665
C.O.M. Energy 7.00TeV
CMS
FROG

pp collisons : complications...

Protons are composed objects

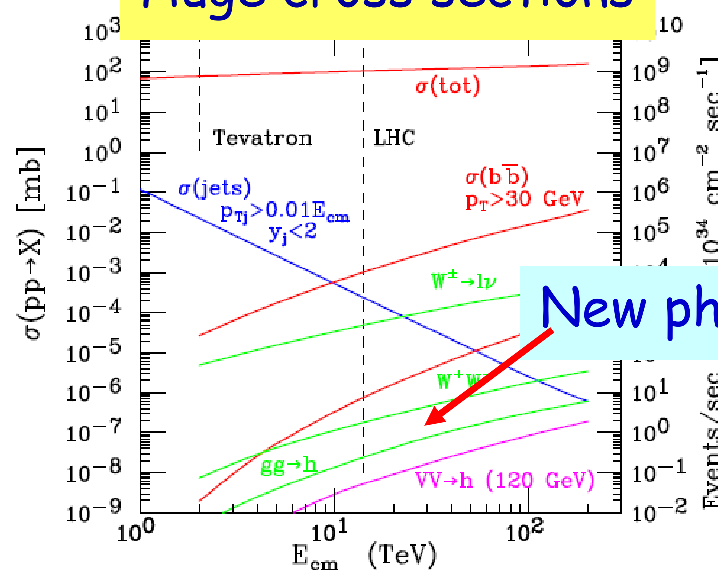


quark/gluon on quark/gluon scattering



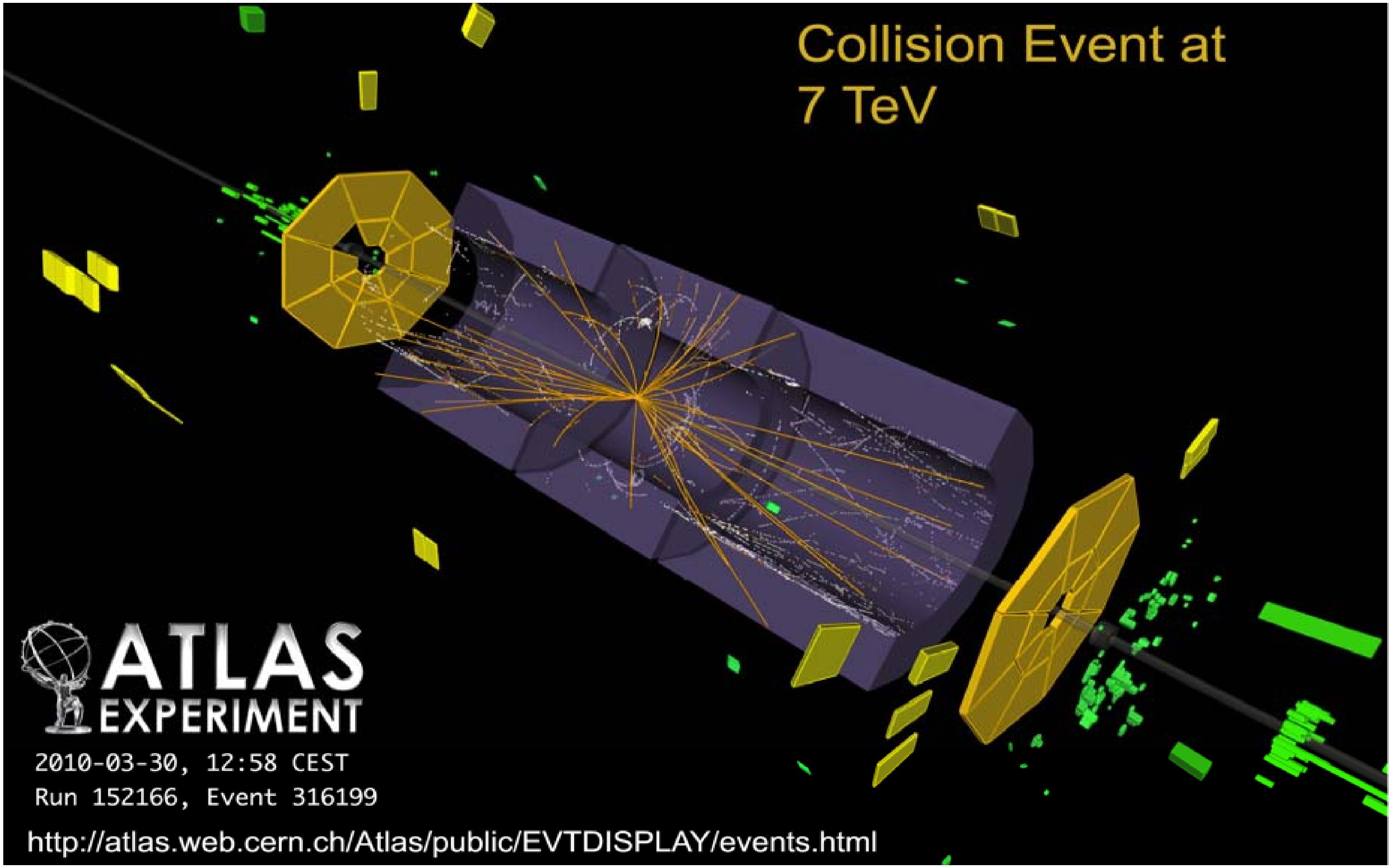
Scattering cross sections for various SM processes:

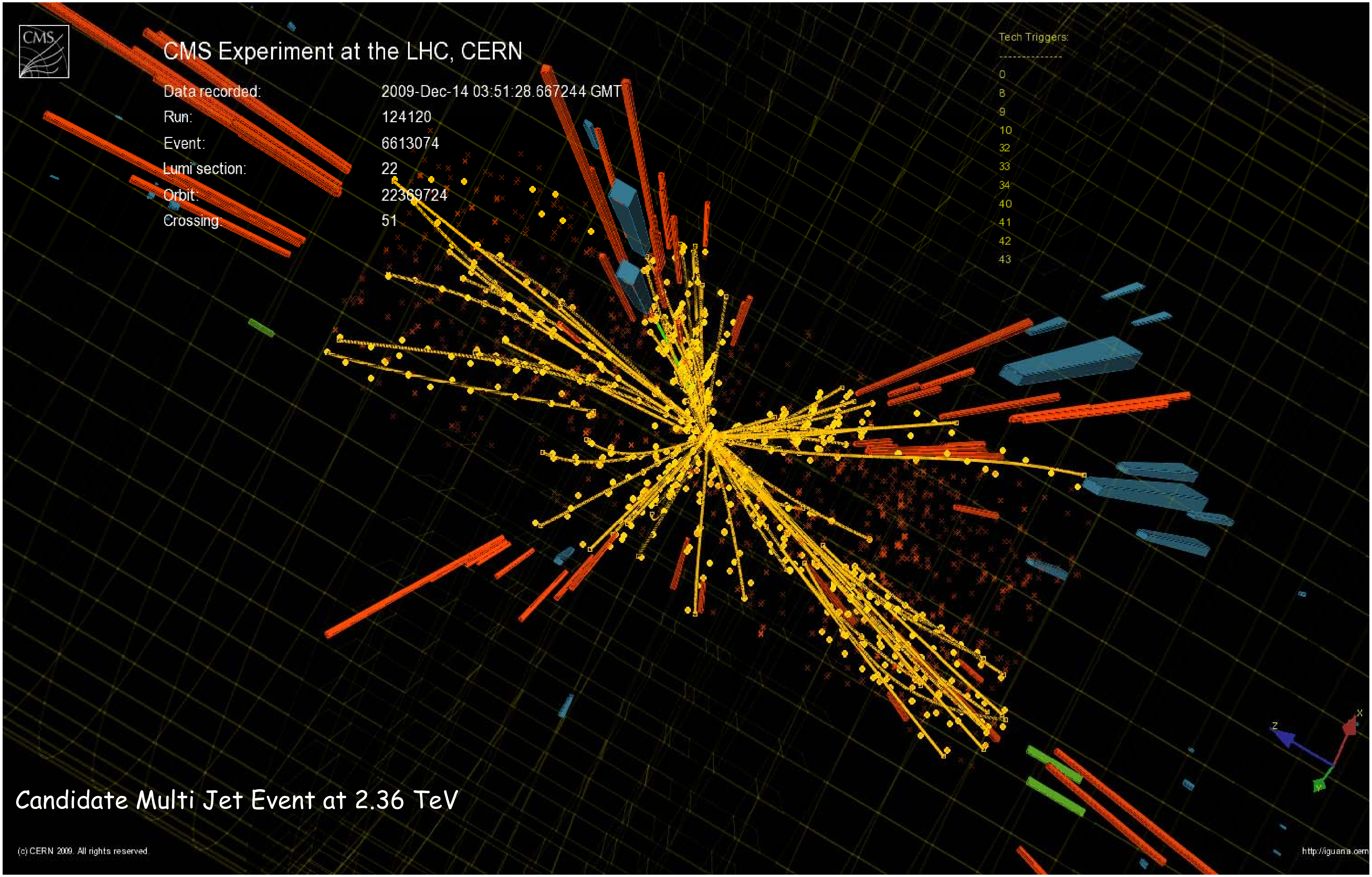
Huge cross sections



New physics ?

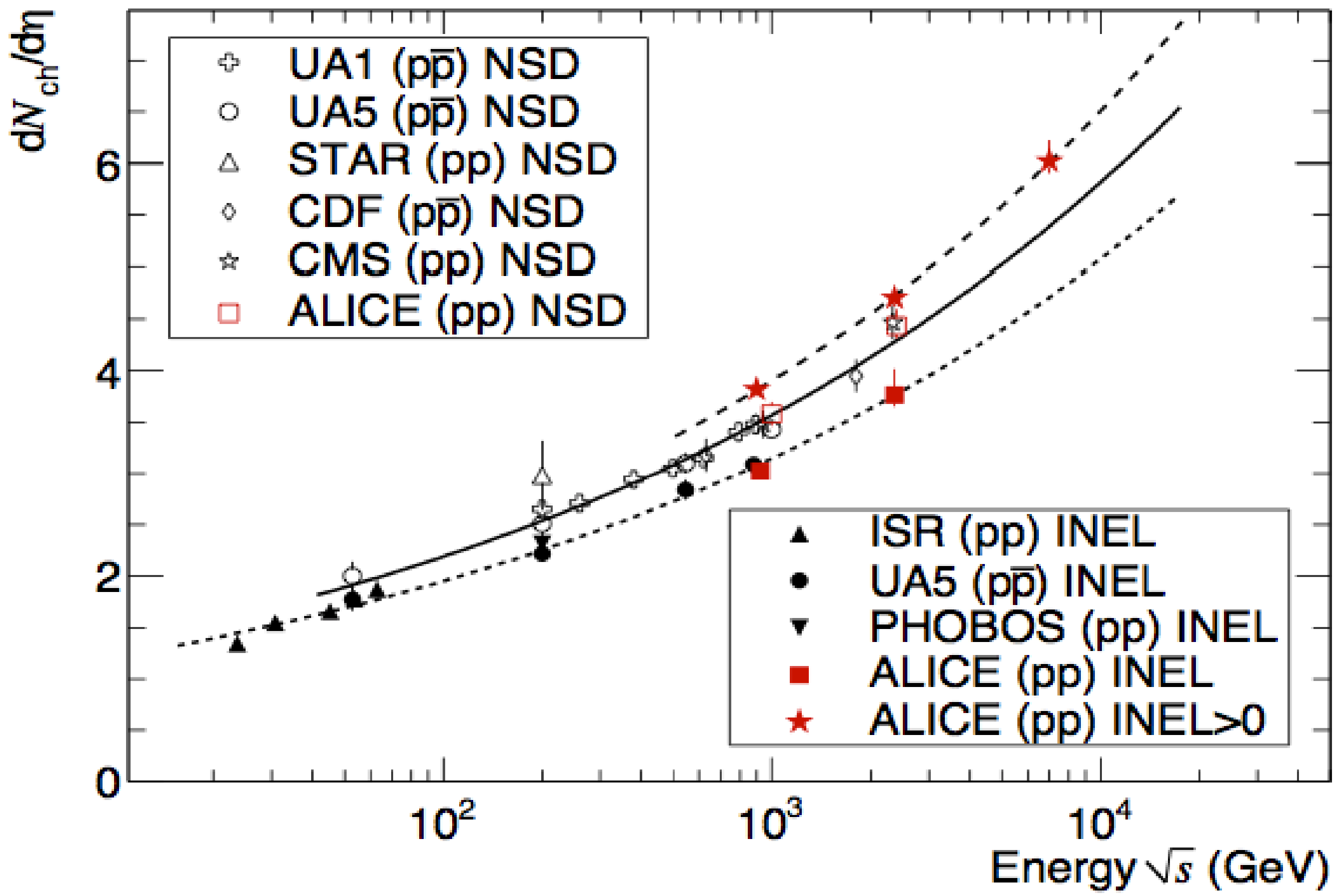
First Collisions at 7 TeV




CMS Experiment at the LHC, CERN
Data recorded: 2009-Dec-14 03:51:28.667244 GMT
Run: 124120
Event: 6613074
Lumi section: 22
Orbit: 22369724
Crossing: 51
Tech Triggers:
0
8
9
10
32
33
34
40
41
42
43
Candidate Multi Jet Event at 2.36 TeV
(c) CERN 2009. All rights reserved.
http://iguana.cern

7 TeV Early Analysis

Measurement of the charged particle density in proton proton collisions at 7 TeV

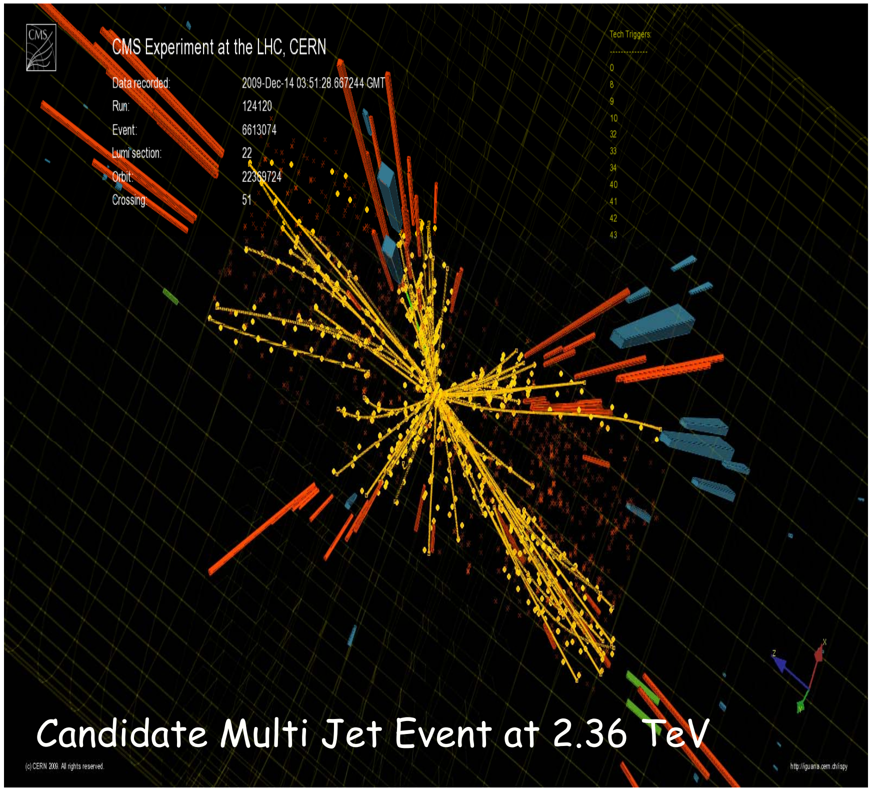


First physics papers of the experiments

Strong rise of the central particle density with energy

In the beginning "there will be QCD"

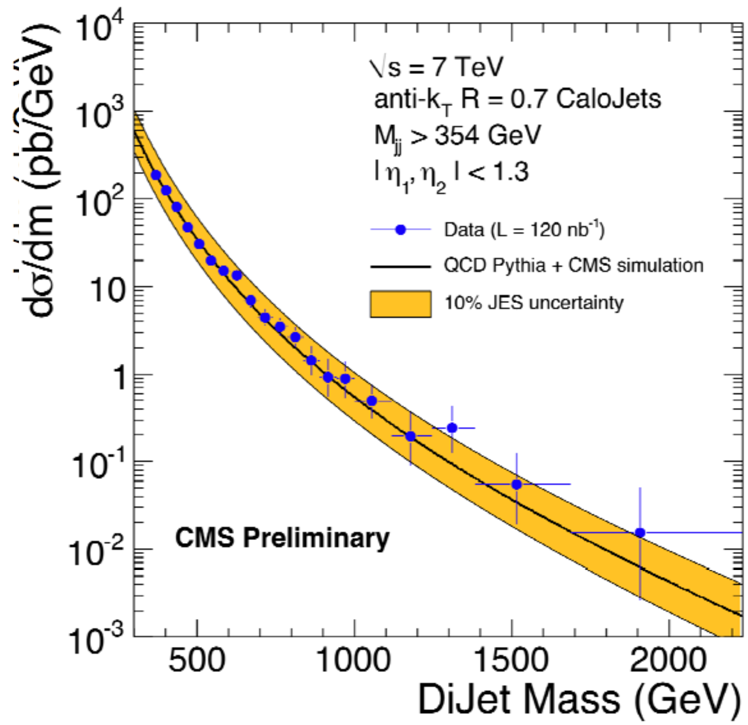
E.g. Jet Physics



Study of the strong force

Huge cross sections:

Eg for 100 pb^{-1} ~ 500 events with E_T> 1 TeV

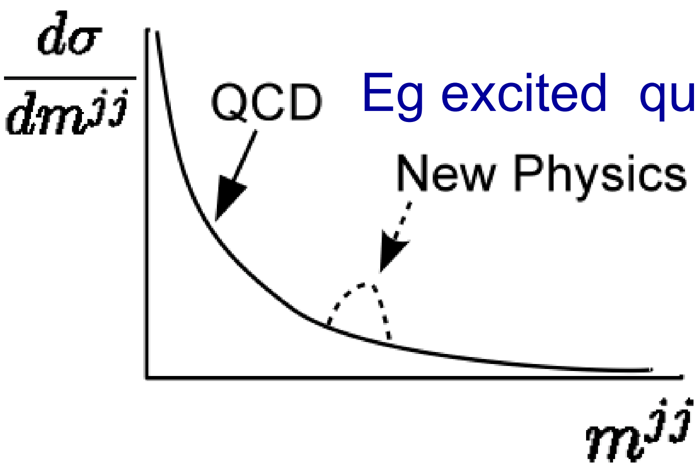


Precision measurements of the strong force QCD, New physics…

Understanding QCD at 10/14 TeV will be one of the first topics at the LHC

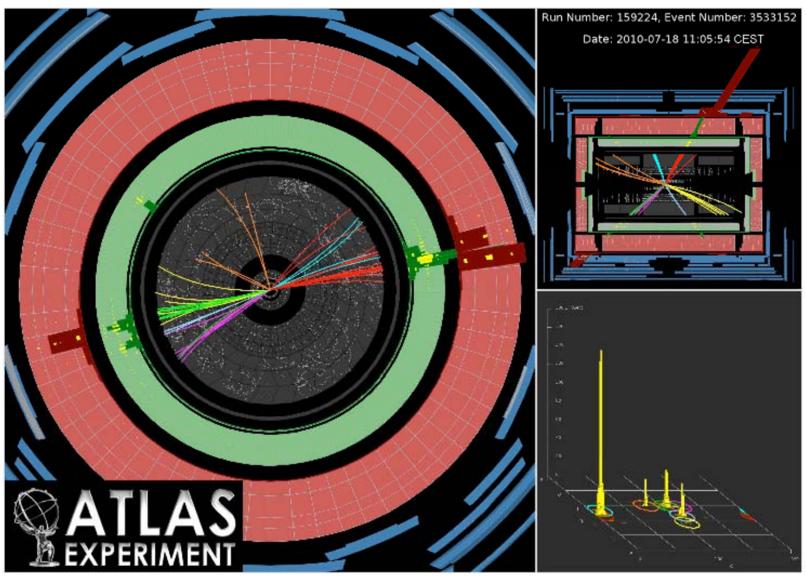
Di-jets: one of the first channels for LHC

Eg excited quarks q*

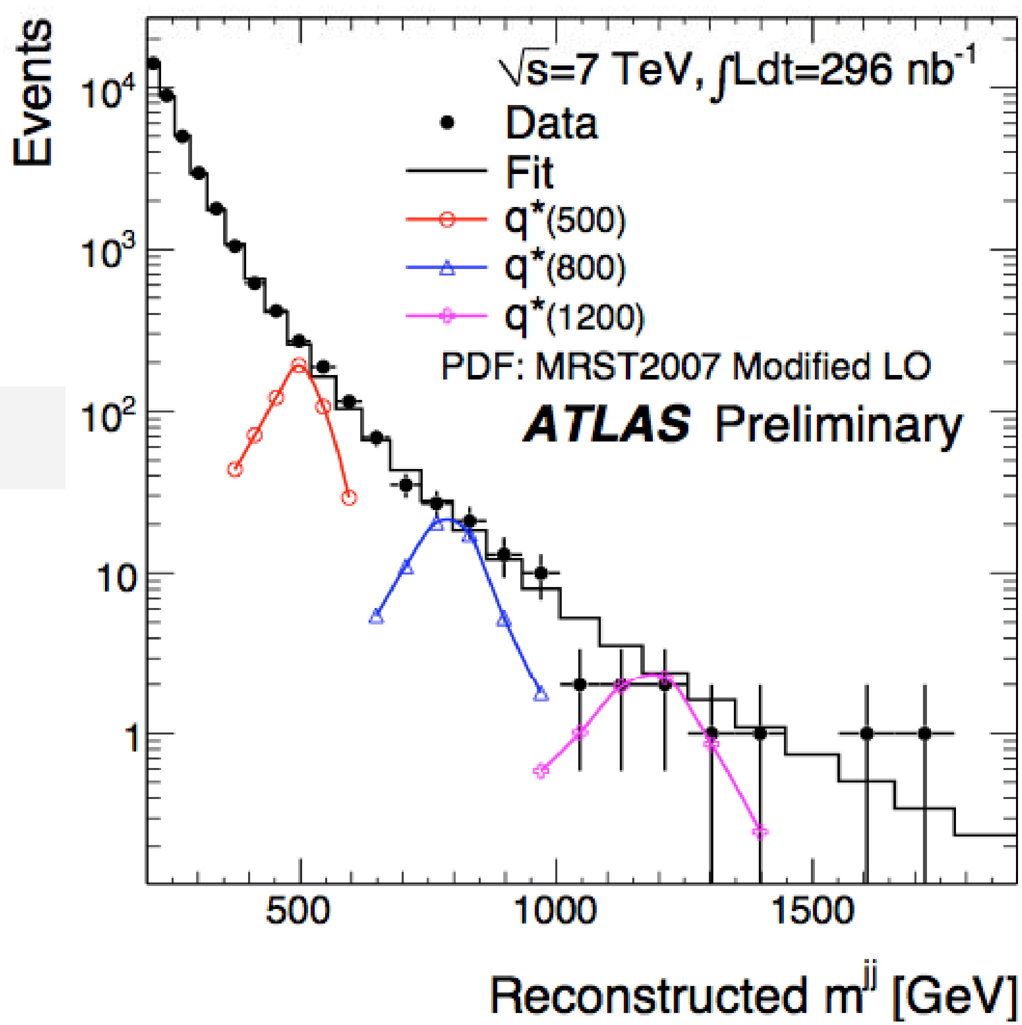


The highest-m^{jj} central event observed

$m^{jj} = 1.77$ TeV. $p_T^{j1} = 1.1$ TeV. $p_T^{j2} = 480$ GeV, partly in calorimeter gap.

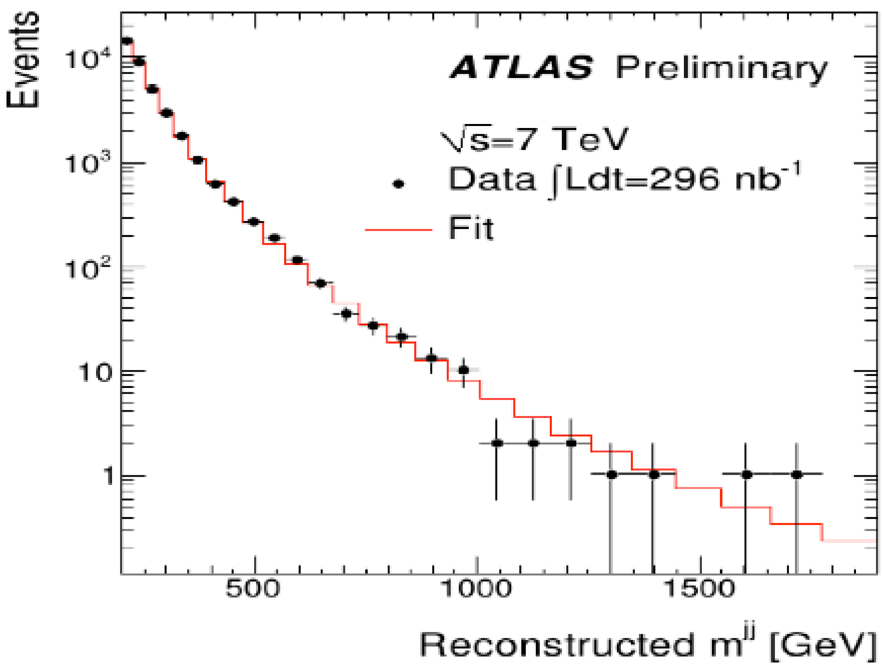


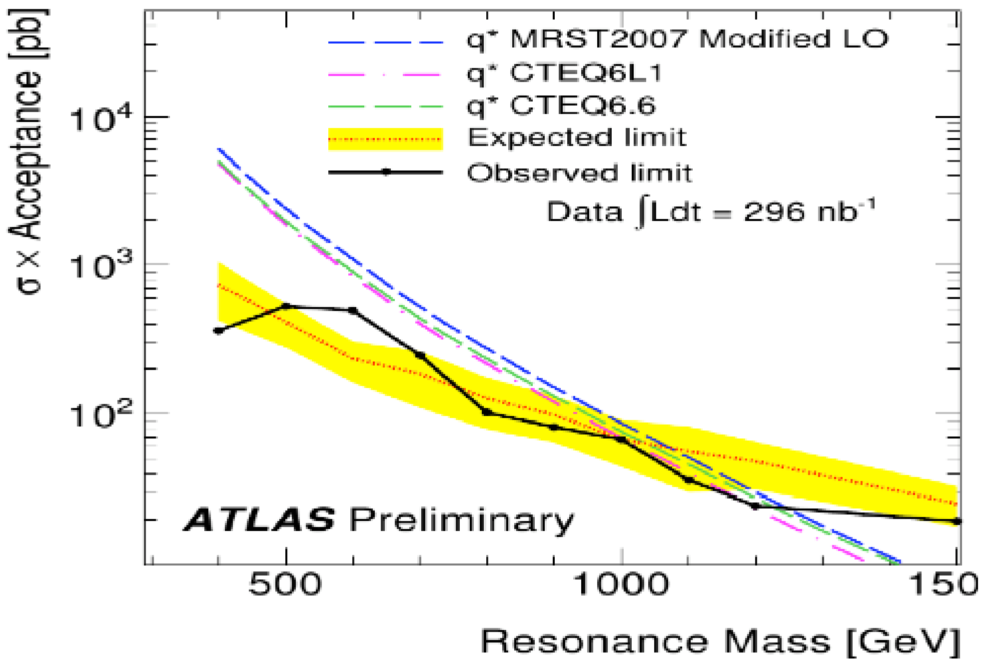
Find two jets and construct the invariant mass of the jet pair



Search using di-jet events

- select event with 2 or more jets
- require $|\Delta\eta_{12}| < 1.3$ to improve sensitivity to the high-mass signal



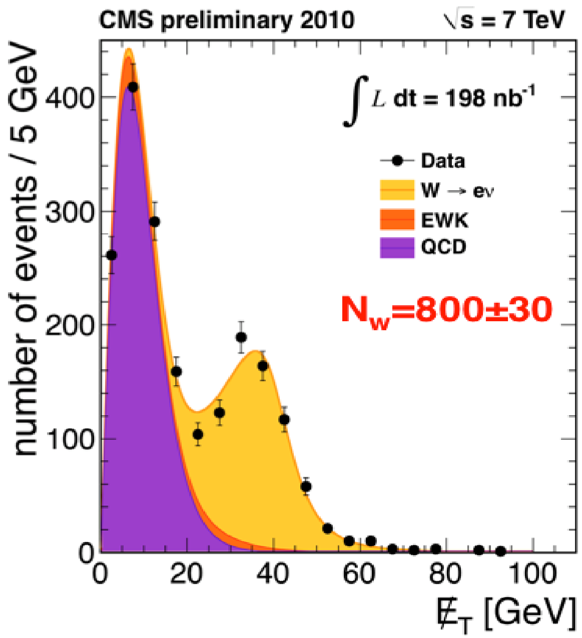


- ATLAS'2010 excluded @ 95% CL
  - M_{Q*} in [400 GeV, 1180 GeV] with CTEQ6 L1 PDF's
  - M_{Q*} in [400 GeV, 1290 GeV] with MRST'2007 PDF's

improving best published limit $M_{Q*} > 870 GeV$ (CDF,1.1 fb^{-1}, PRD79(2009)112002)

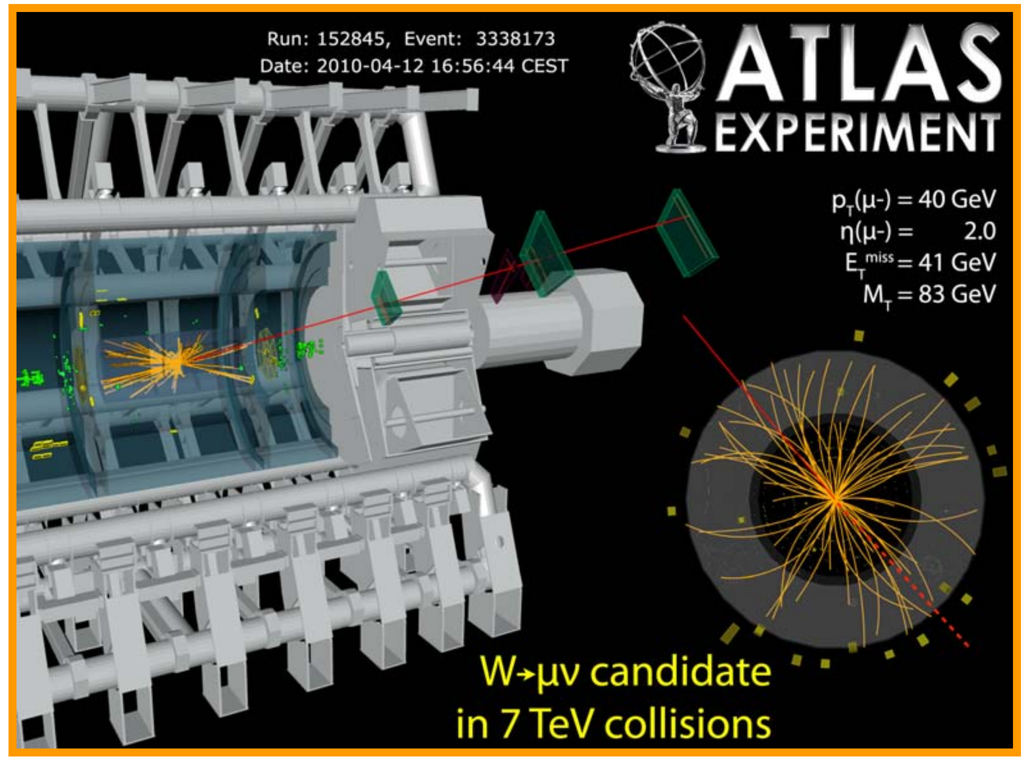
Reach into a new regime, beyond the Tevatron

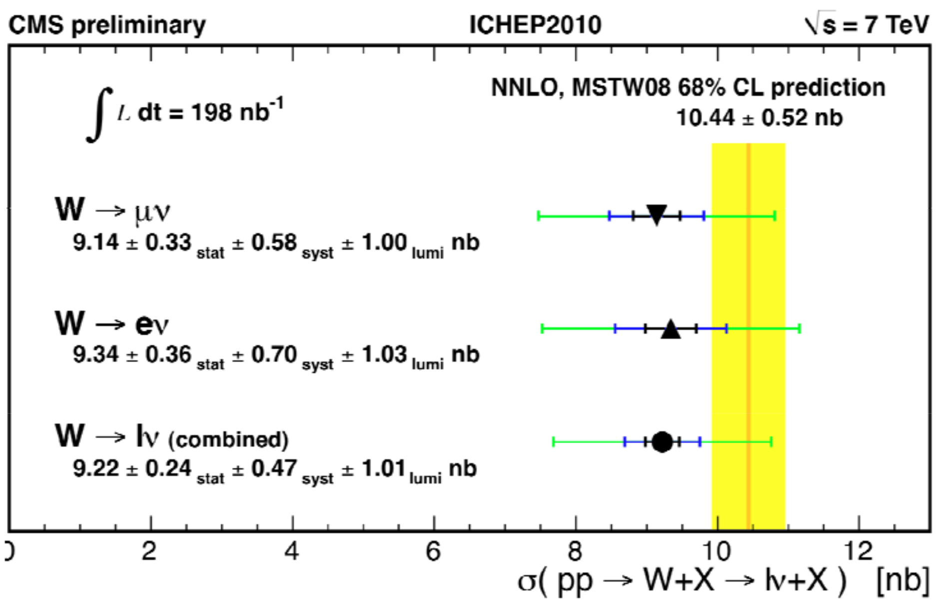
Heavy W Particles



Directly observed for the first time at CERN in 1983

Massof W = 80.4 GeV

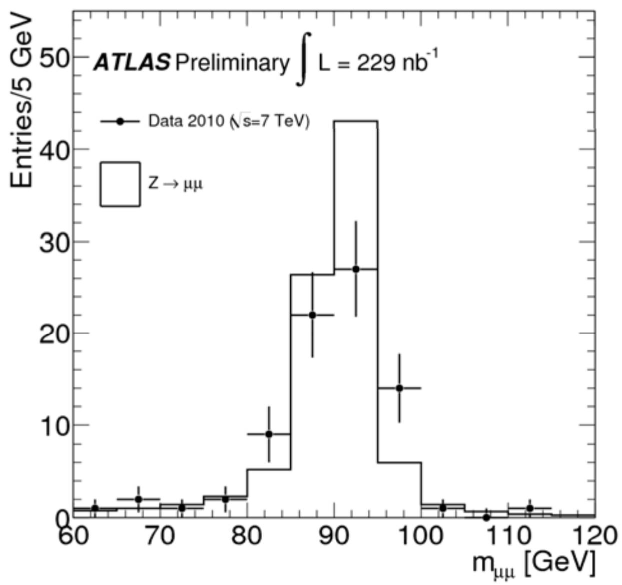


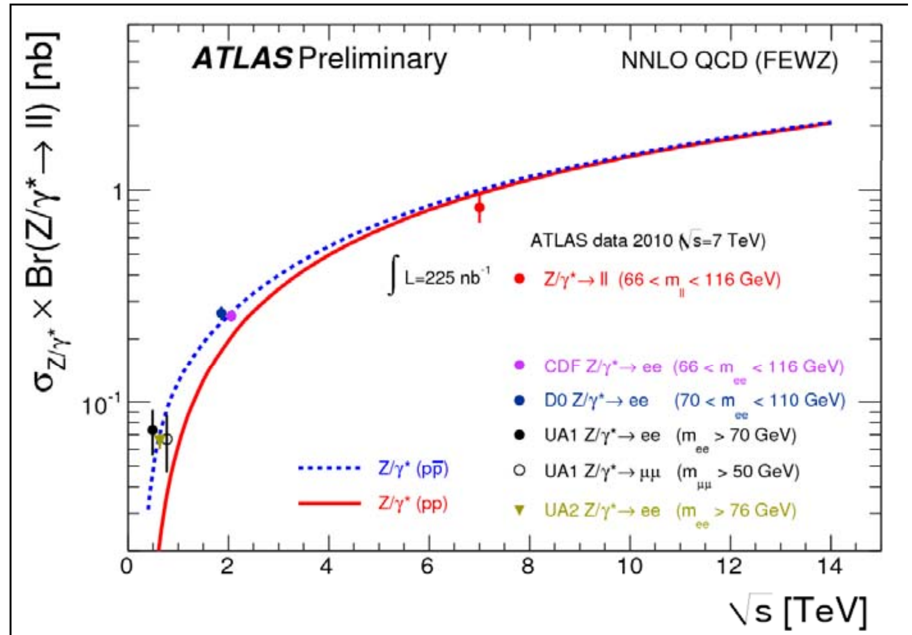


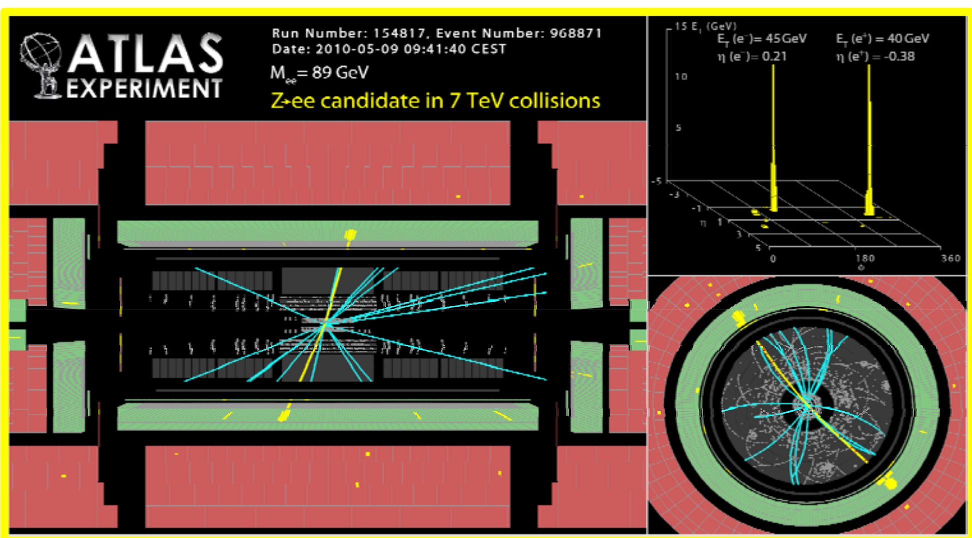
W's are back in town!!!

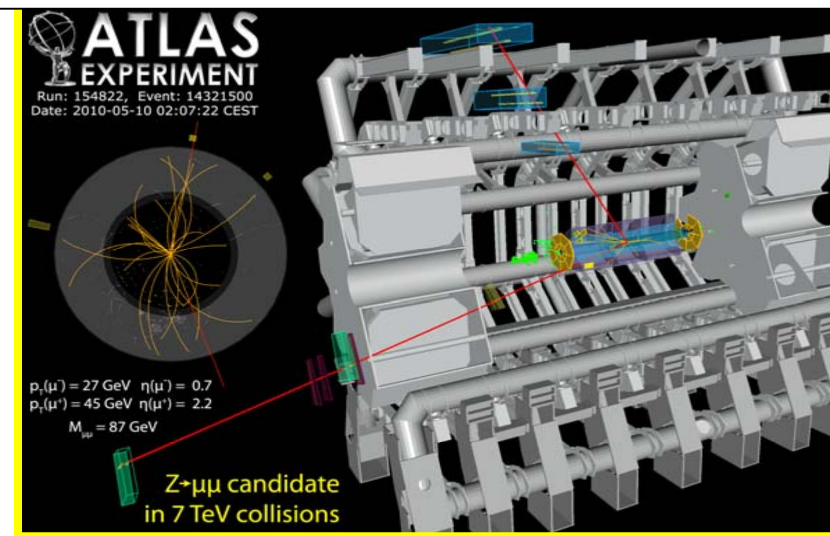
Heavy Z Particles

Studied in detail at CERN in the 90's (LEP) Mass of Z = 91.2 GeV



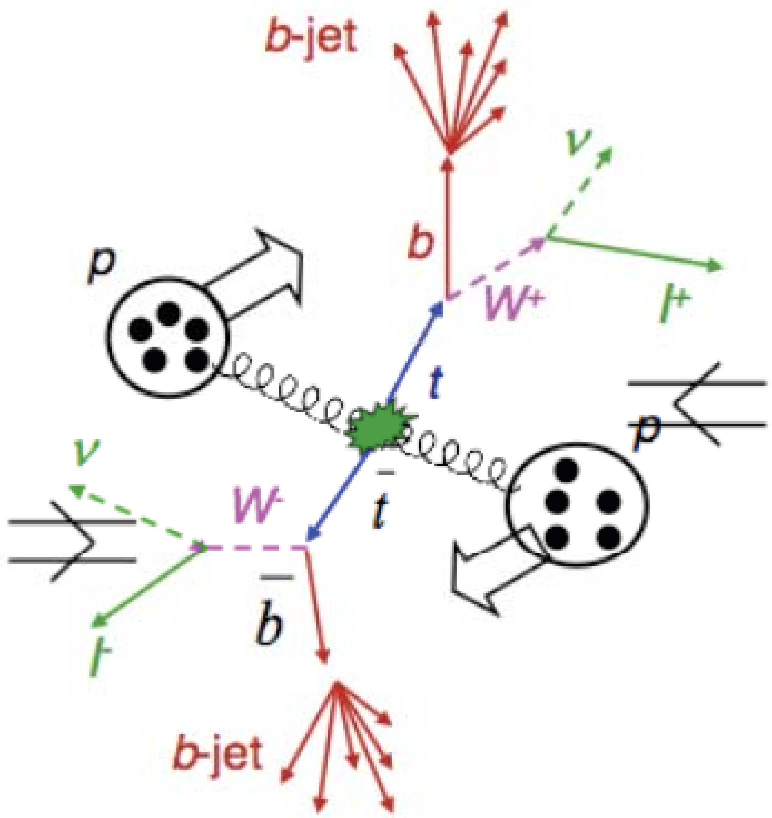


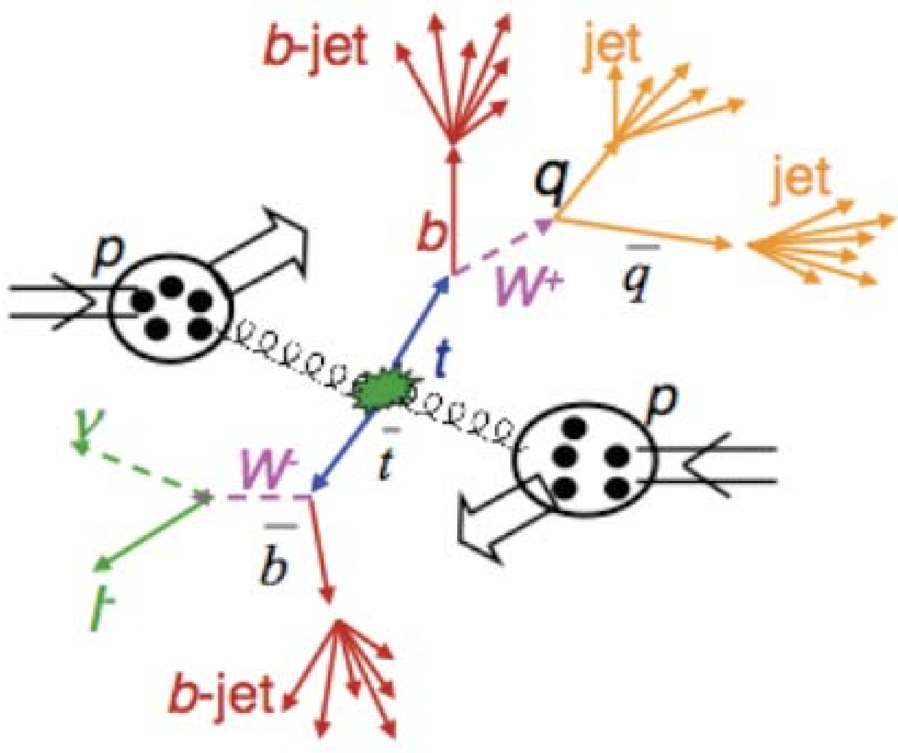




Top Quark Search at LHC

On the road to searched for new physics: next stop, the top quark
The heaviest elementary particle known to us

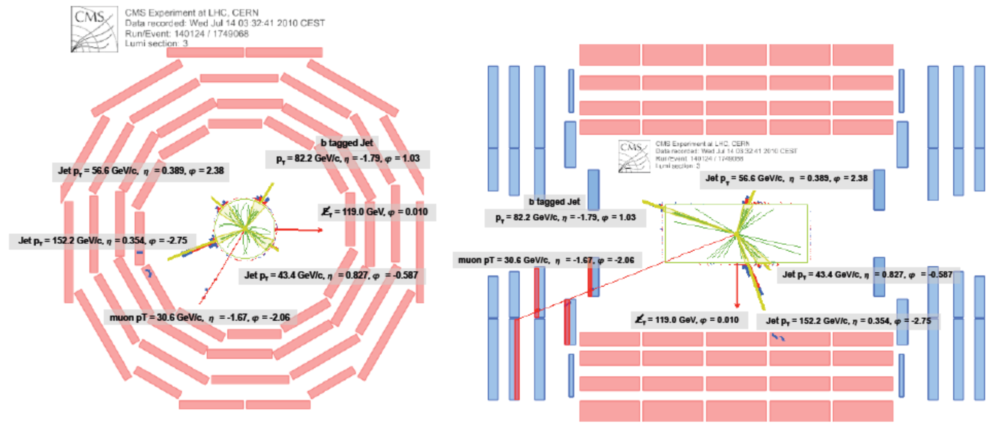




2 Leptons + jet+ Missing ET channel

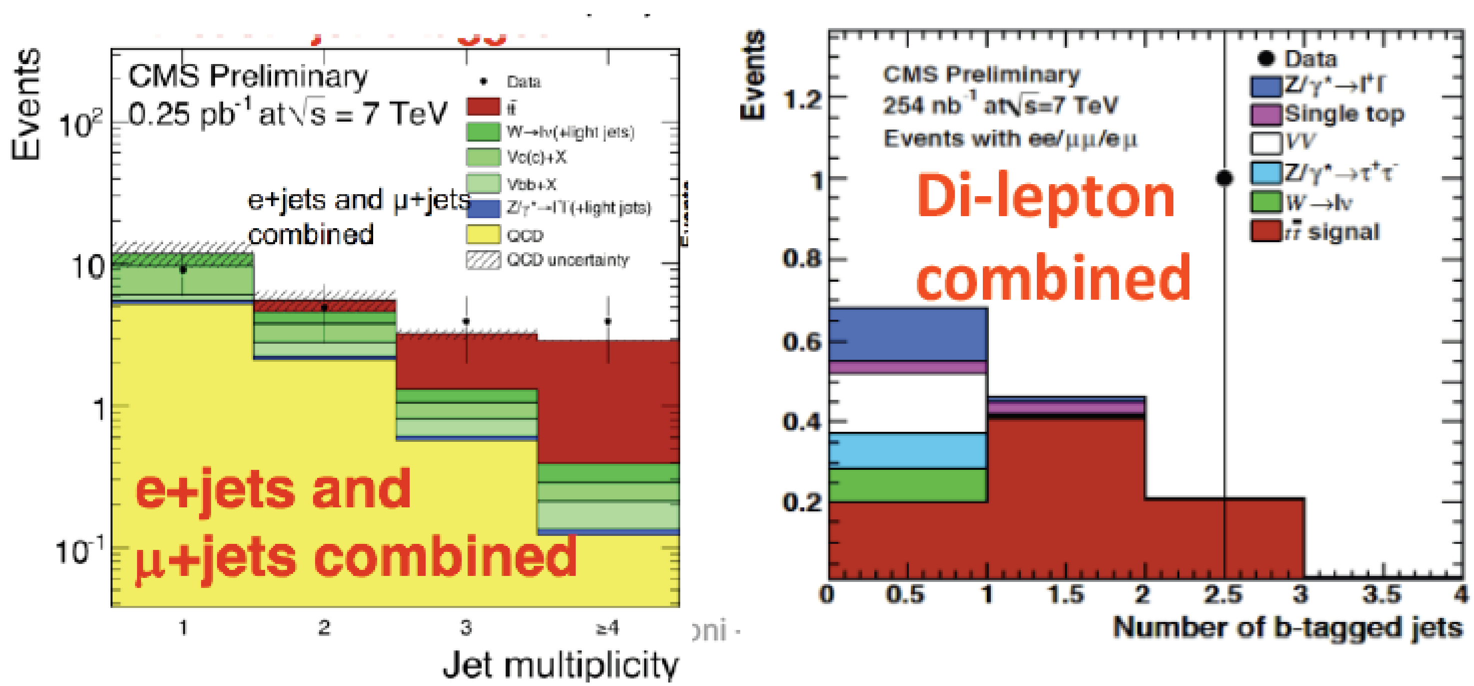
Leptons + jet+ MET channel

Top Quark Search at LHC



Four high P_T Jets, one with tight b-tagging
Di-jet mass (untagged jets): 104,105,151 GeV/c^2

One high P_T Muon
Top mass~210GeV
$M_T(W)$ = 104GeV/c2
MET>100GeV

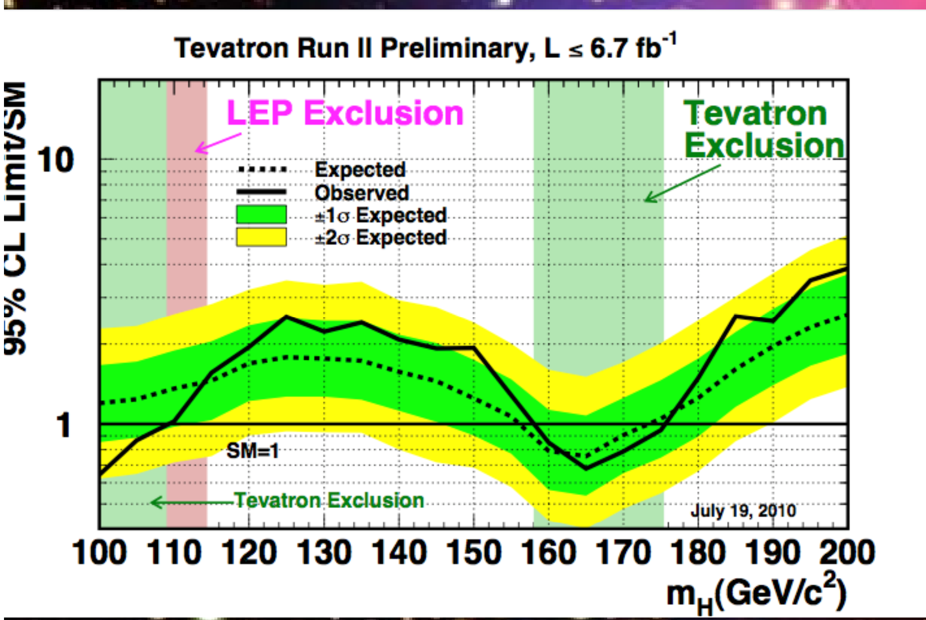


The Origin of Mass

Some particles have mass, some do not

Where do the masses come from ?

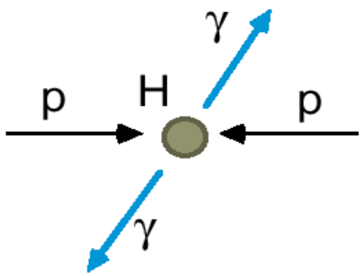
Explanation of Profs P. Higgs R. Brout en F. Englert
⇒ A new field and particle

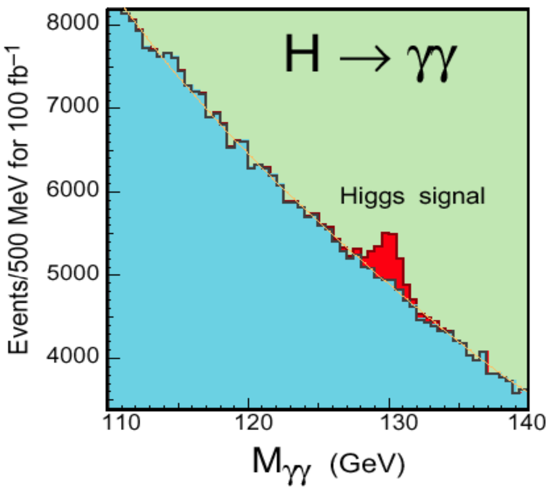


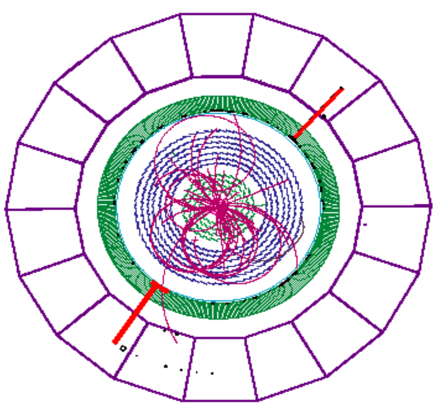
The key question:
Where is the Higgs?

Higgs Boson Searches

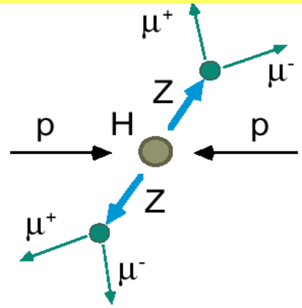
Low M_H < 140 GeV/c^2

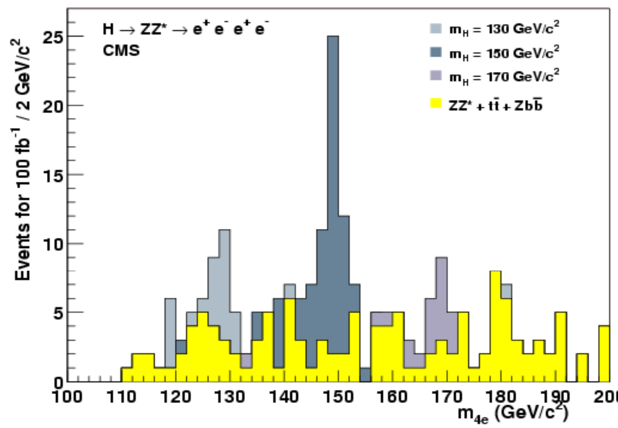


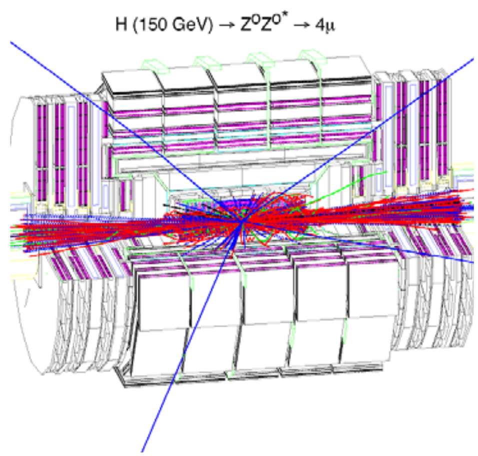




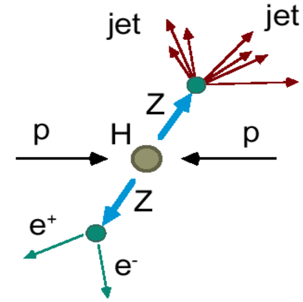
Medium 130<M_H<500 GeV/c^2

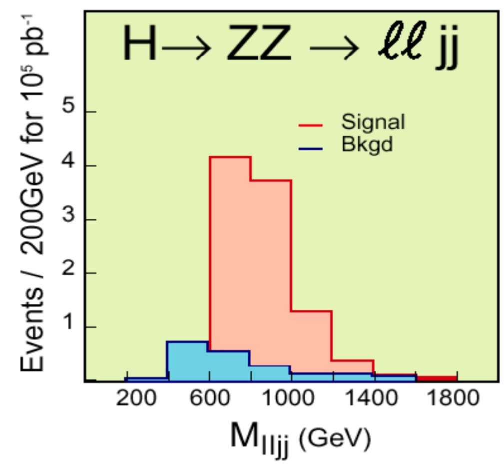


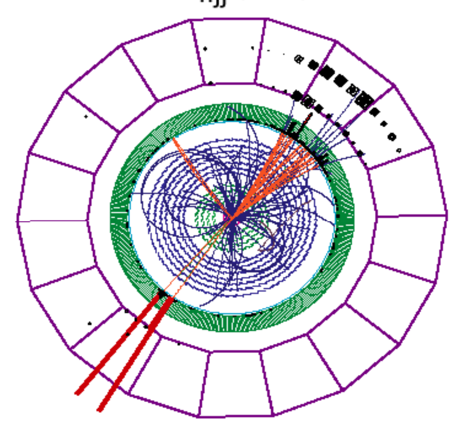




High M_H > ~500 GeV/c^2



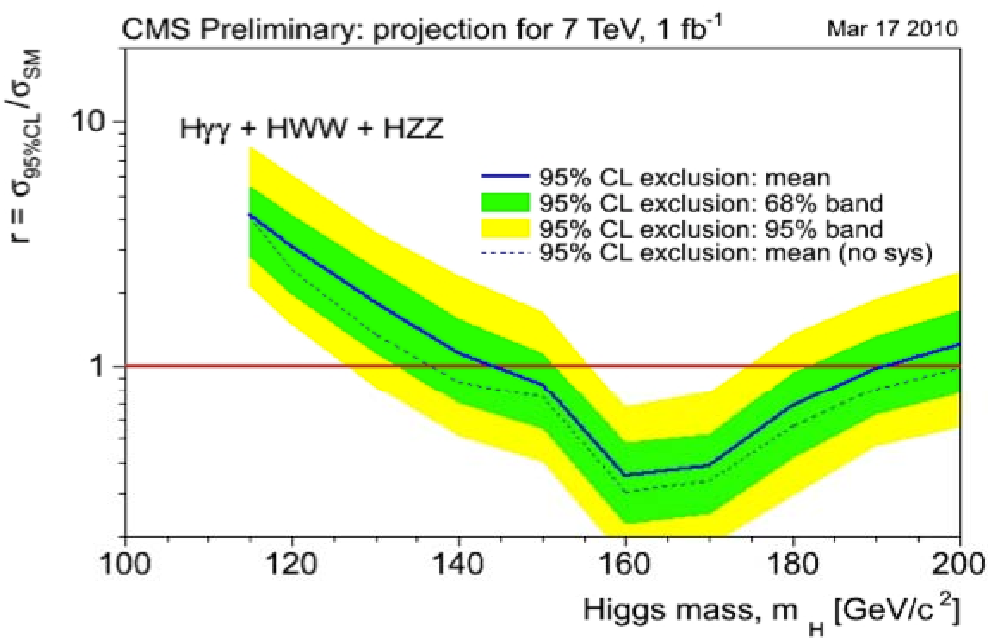




Search for Higgs (Simulation)

- Sizeable integrated luminosity is needed before significant insights can be made in SM Higgs search.
- However, even with moderate luminosity per experiment, Higgs boson discovery is possible in particular mass regions.

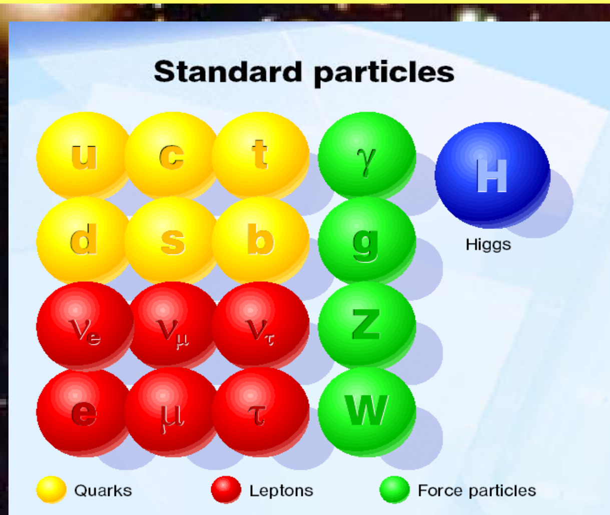
Example Reach by end of 2011

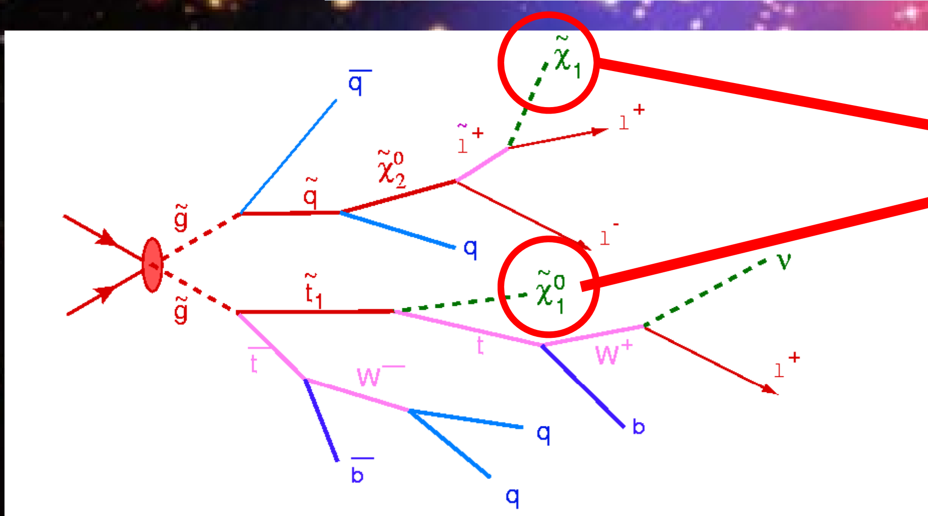


- If the Higgs exist: LHC will discover it after 3-4 years of operation
- If the Higgs does not exist: LHC should see other spectacular new effects

Beyond the Higgs Particle

Supersymmetry: a new symmetry in Nature

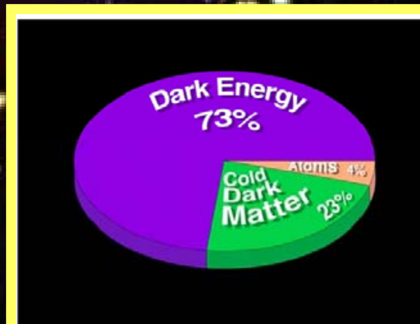




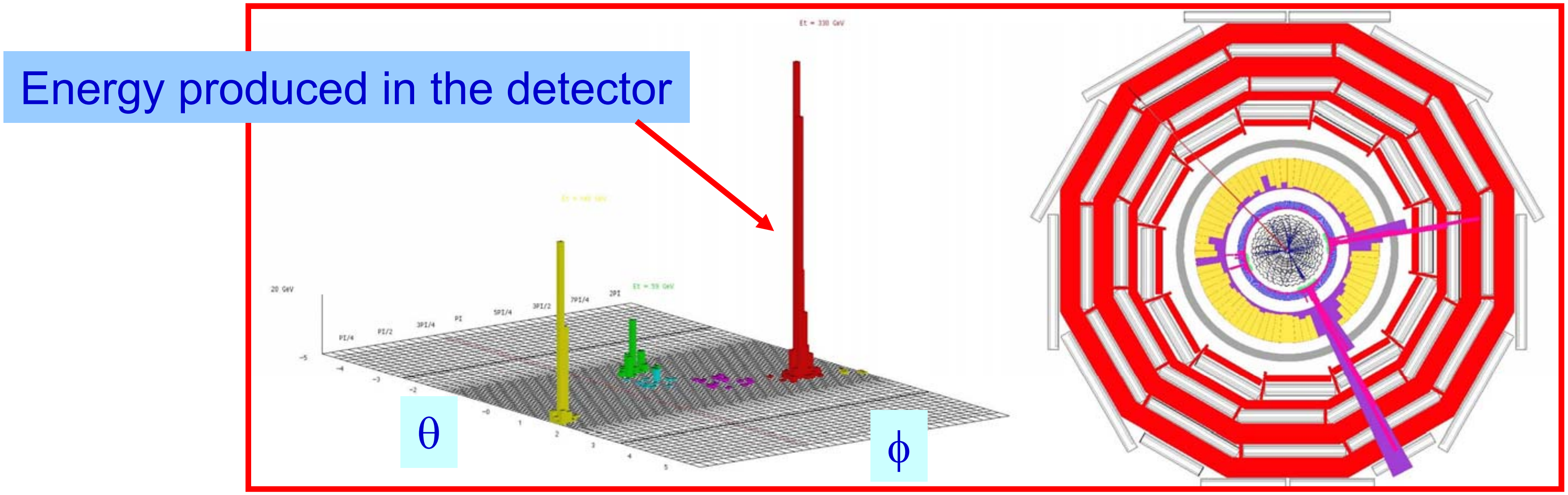
SUSY particle production at the LHC

Candidate particles for Dark Matter

⇒ Produce Dark Matter in the lab



Detecting Supersymmetric Particles



Supersymmetric particles decay and produce a cascade of jets, leptons and missing (transverse) energy due to escaping 'dark matter' particles

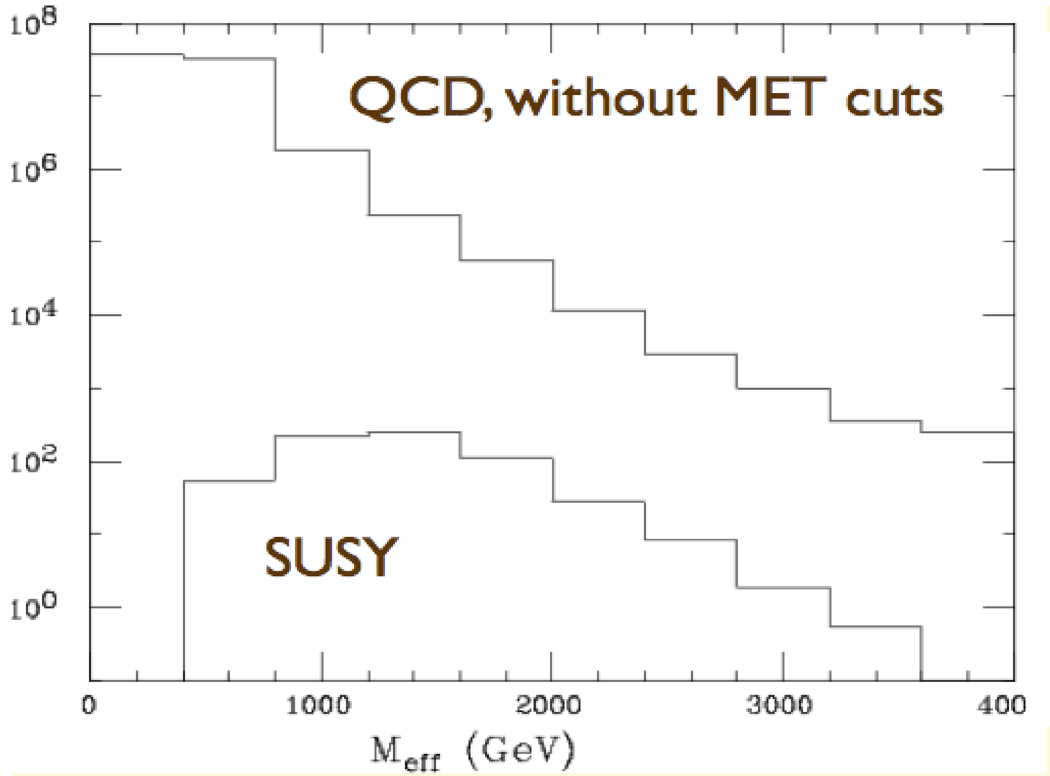
➡ Very clear signatures in CMS and ATLAS

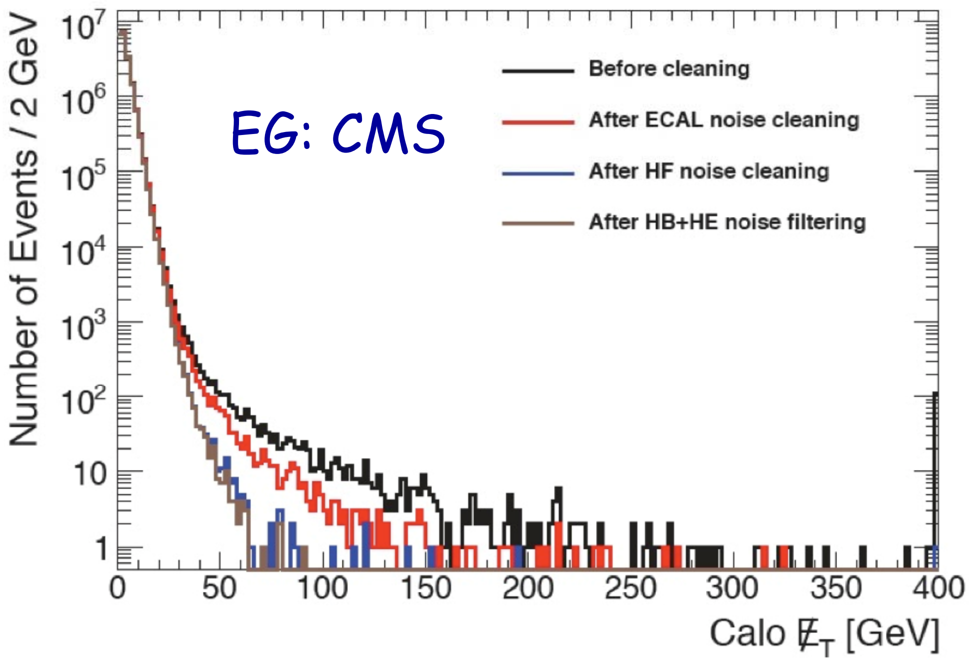
LHC can discover supersymmetric partners of the quarks and gluons as heavy as 2 to 3 TeV

The expected cross sections are huge!! ⇒ 10,000 to 100,000 particles per year

Missing Transverse Energy

A challenging quantity to measure!
Need to control detector and background effects





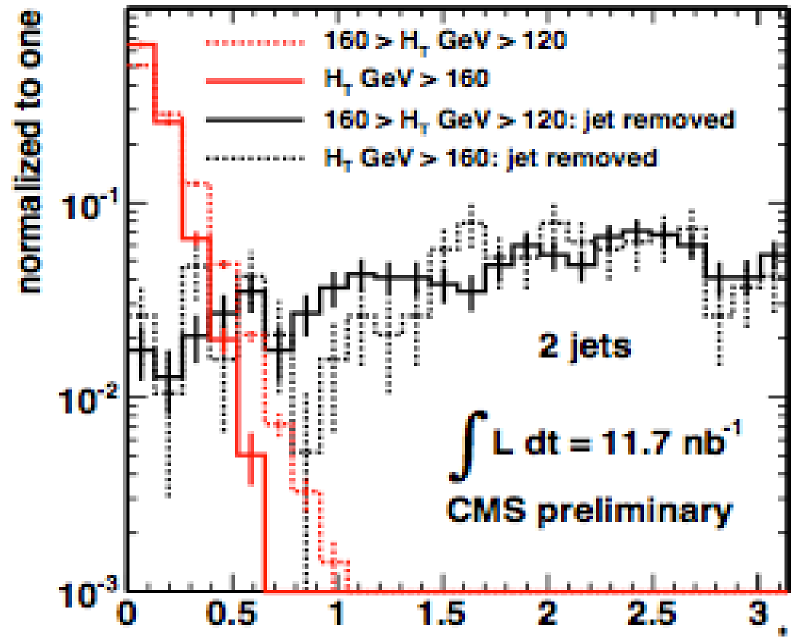
First data experience at the LHC:
Clean up cuts: cosmics, beam halo, dead channels, noise

Preparing for SUSY Searches

Use LHC data itself to control the background
I.e. «driven methods» eg for QCD multi-jet backgrounds

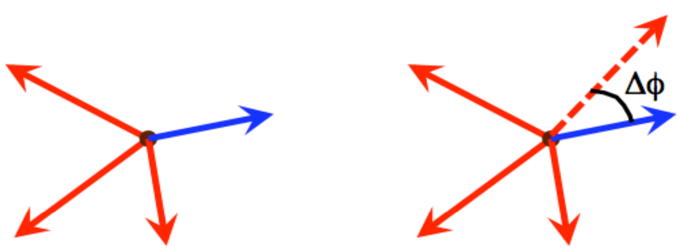
- A complementary observable, $\Delta\phi^*$, to diagnose background events where one jet mis-measured.
- Test each jet to see if it is responsible for the MHT (vectorial sum of the jet p_T)

$$\Delta\phi^* \equiv \min_{\text{jets } k}\left(|\Delta\phi(\vec{p}_k, -\sum_{\text{jets } i\neq k}\vec{p}_i)|\right)$$



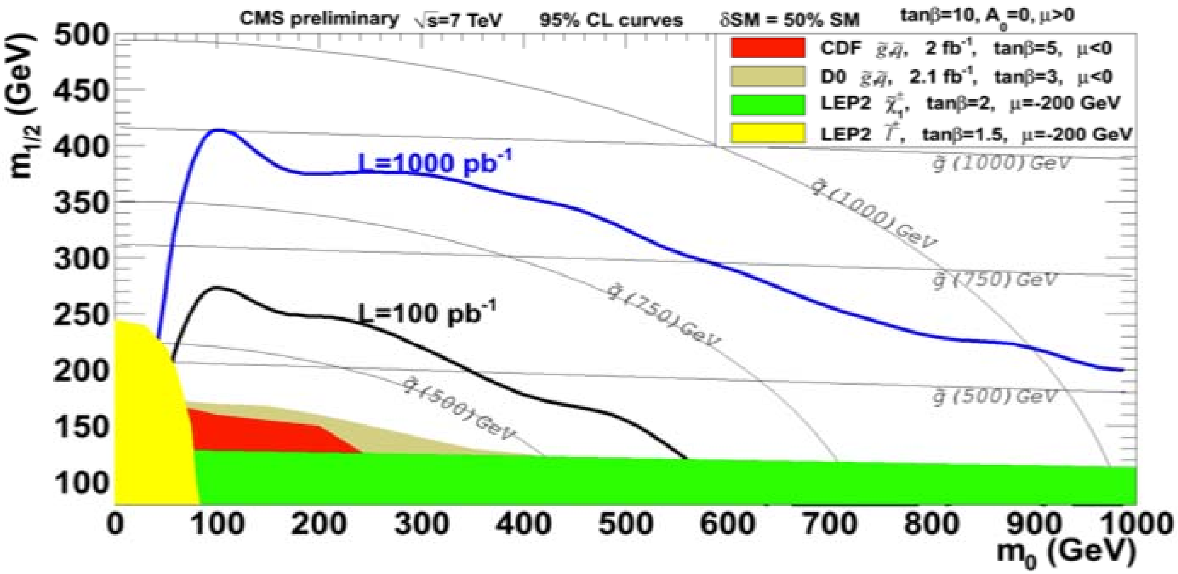
- expect small $\Delta\phi^*$ for QCD
- more uniform for real MET (emulated by removing one jet)

$\Delta\phi^*$ is min over all jet partitions



Early SUSY Reach

Sensitivity to SUSY will come soon at the LHC



minimal Supergravity (mSUGRA)

$m_{1/2}$: universal gaugino mass at GUT scale
m_0: universal scalar mass at GUT scale
$\tan\beta$: vev ratio for 2 Higgs doublets
sign(μ): sign of Higgs mixing parameter
A_0: trilinear coupling

100 pb^{-1} = end of 2010
1000 pb^{-1} = end of 2011

Low mass SUSY(m_{gluino}~500 GeV) will show an excess for O(100) pb^{-1}
⇒ Time for discovery will be determined by:

- Time needed to understand the detector performance, Etmiss tails,
- Time needed collect SM control samples such as W+jets, Z+jets, top..

Where do we expect SUSY?

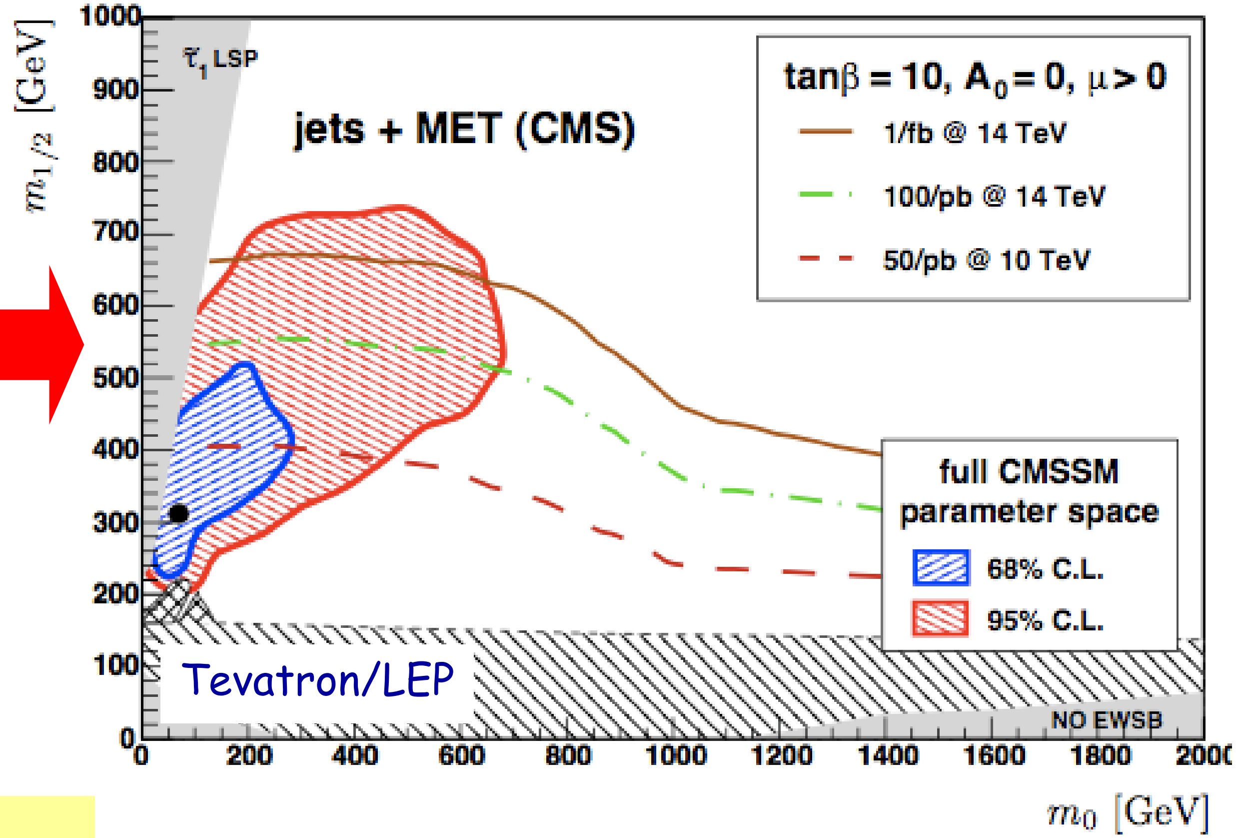
O. Buchmuller et al
arXiv:0808.4128

OB, R.Cavanaugh, A.De Roeck,
J.R.Ellis, H.~Flaecher, S.~Heineme
G.Isidor, K.A.Olive, P.Paradisi,
F.J.Ronga, G.Weiglein

Precision measurements
Heavy flavour observables

Simultaneous fit of CMSSM parameters m_0, $m_{1/2}$, A_0, tan (μ>0) to more than 30 collide and cosmology data (e.g. M_W, M_{top}, g-2, BR(B→Xγ), relic density)

"LHC Weather Forecast"

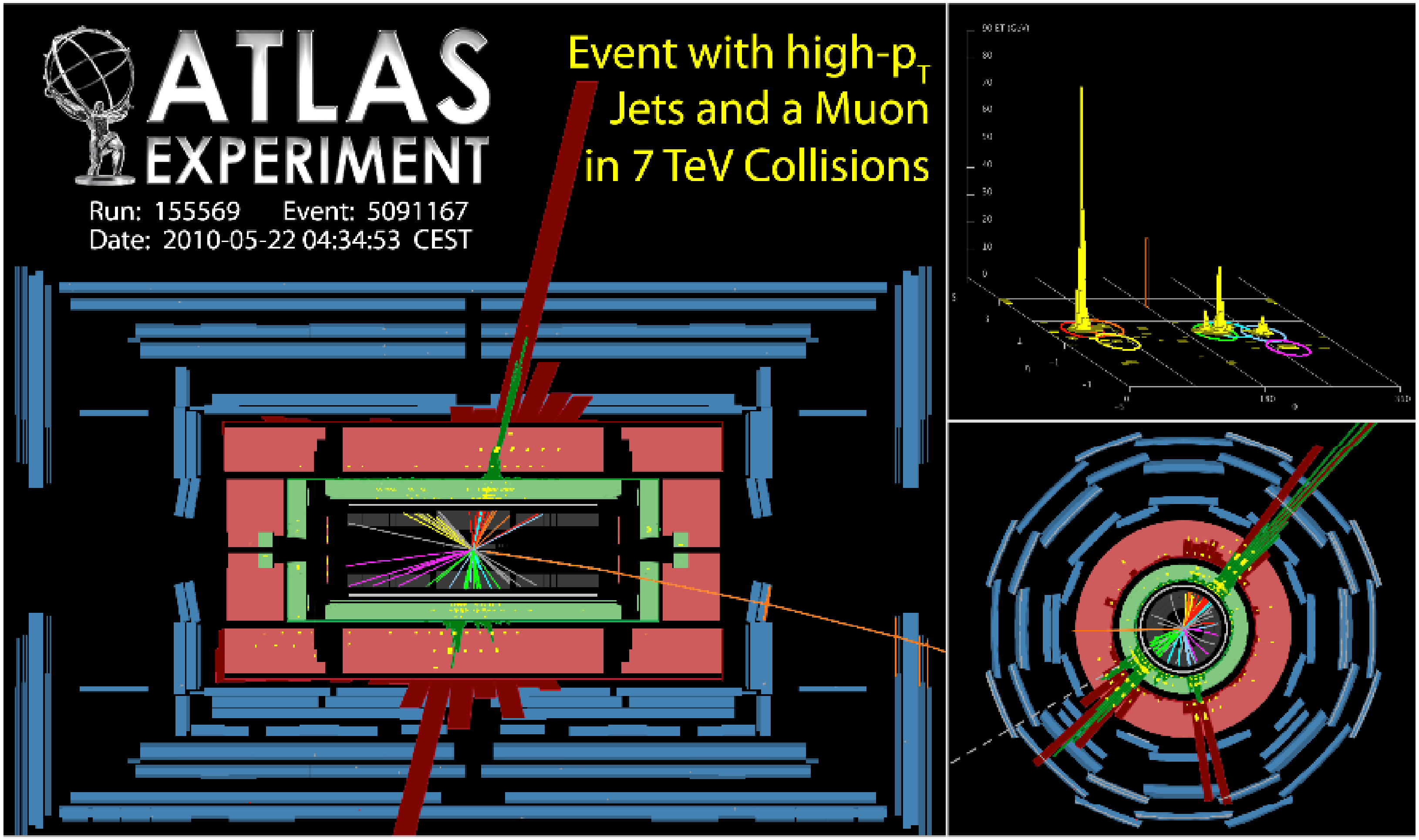


"CMSSM fit clearly favors low-mass SUSY - Evidence that a signal might show up very early?!"

"Predict" on the basis of present data what the preferred region for SUSY is (in constrained MSSM SUSY)

Many other groups attempt to make similar predictions

An Interesting Event…



Hot News as of Last Week

It's On: Early Interpretations of ATLAS Results in Jets and Missing Energy Searches

Daniele S. M. Alves,[1,2] Eder Izaguirre,[1,2] and Jay G. Wacker[1]

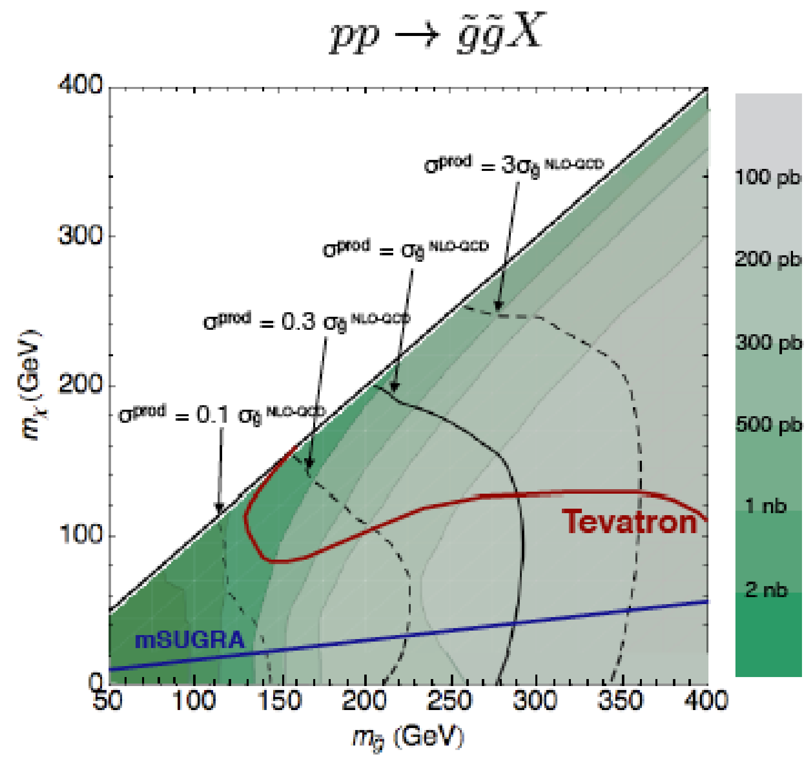
[1] *Theory Group, SLAC National Accelerator Laboratory, Menlo Park, CA 94025*
[2] *Physics Department, Stanford University, Stanford, CA 94305*

4/8/2010

The first search for supersymmetry from ATLAS with 70 nb^{-1} of integrated luminosity sets new limits on colored particles that decay into jets plus missing transverse energy. For gluinos that decay directly or through a one step cascade into the LSP and two jets, these limits translate into a bound of $m_{\tilde{g}} \geq 205$ GeV, regardless of the mass of the LSP. In some cases the limits extend up to $m_{\tilde{g}} \simeq 295$ GeV, already surpassing the Tevatron's reach for compressed supersymmetry spectra.

ATLAS Data for the summer conference

Cut	Topology	$1j + \not{E}_T$	$2^+j + \not{E}_T$	$3^+j + \not{E}_T$	$4^+j + \not{E}_T$
1	p_{T1}	$> 70\,\mathrm{GeV}$	$> 70\,\mathrm{GeV}$	$> 70\,\mathrm{GeV}$	$> 70\,\mathrm{GeV}$
2	p_{Tn}	$\leq 30\,\mathrm{GeV}$	$> 30\,\mathrm{GeV}\,(n=2)$	$> 30\,\mathrm{GeV}\,(n=2,3)$	$> 30\,\mathrm{GeV}\,(n=2-4)$
3	$\not{E}_{T\,\mathrm{EM}}$	$> 40\,\mathrm{GeV}$	$> 40\,\mathrm{GeV}$	$> 40\,\mathrm{GeV}$	$> 40\,\mathrm{GeV}$
4	$\Delta\phi(j_n, \not{E}_{T\,\mathrm{EM}})$	none	$[> 0.2, > 0.2]$	$[> 0.2, > 0.2, > 0.2]$	$[> 0.2, > 0.2, > 0.2, \mathrm{none}]$
5	$\not{E}_{T\,\mathrm{EM}}/M_{\mathrm{eff}}$	none	> 0.3	> 0.25	> 0.2
	N_{Pred}	46^{+22}_{-14}	6.6 ± 3.0	1.9 ± 0.9	1.0 ± 0.6
	N_{Obs}	73	4	0	1
	$\sigma(pp \to \tilde{g}\tilde{g}X)\epsilon\vert_{95\%\ \mathrm{C.L.}}$	663 pb	46.4 pb	20.0 pb	56.9 pb



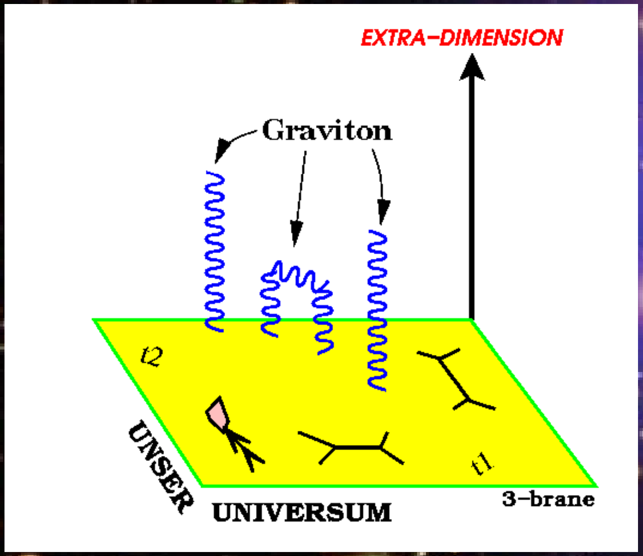
70 nb^{-1} only!!

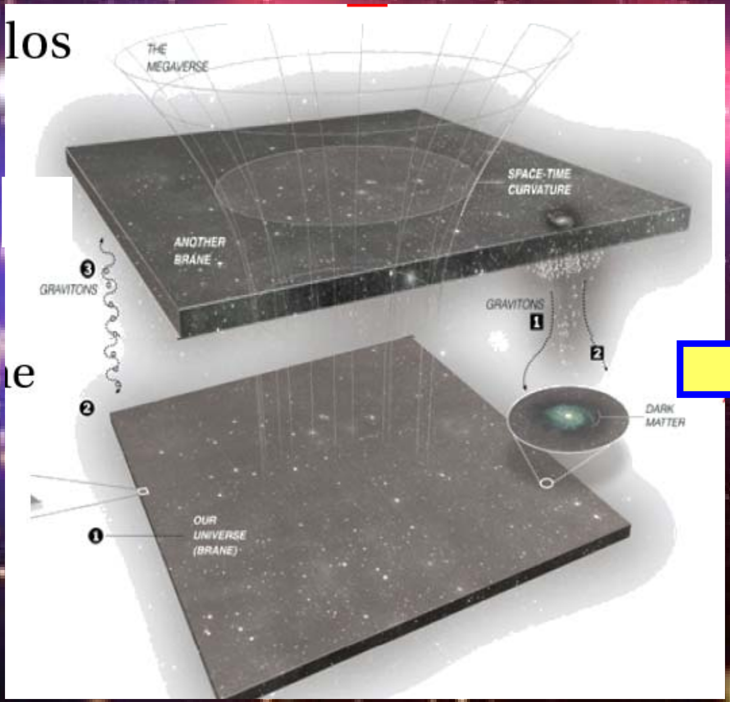
Low luminosity but can already exclude some special SUSY regions with LHC

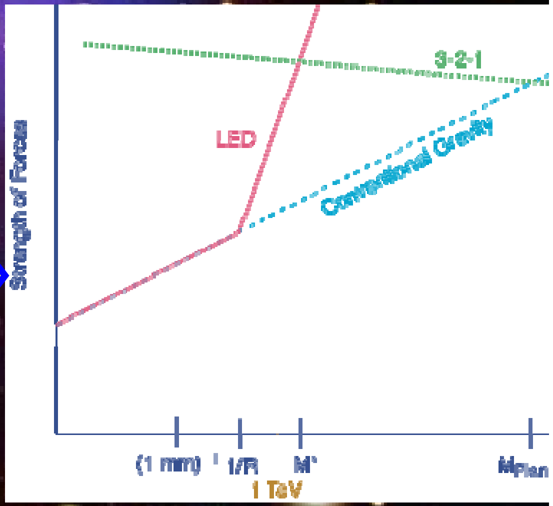
Extra Space Dimensions

Problem:

$$m_{EW} = \frac{1}{(G_F \cdot \sqrt{2})^{\frac{1}{2}}} = 246 \text{ GeV} \quad \Longleftrightarrow \quad M_{Pl} = \frac{1}{\sqrt{G_N}} = 1.2 \cdot 10^{19} \text{ GeV}$$





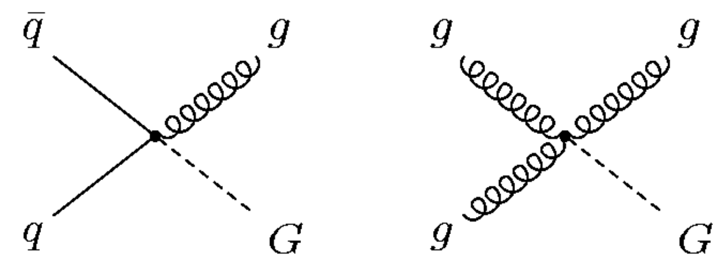


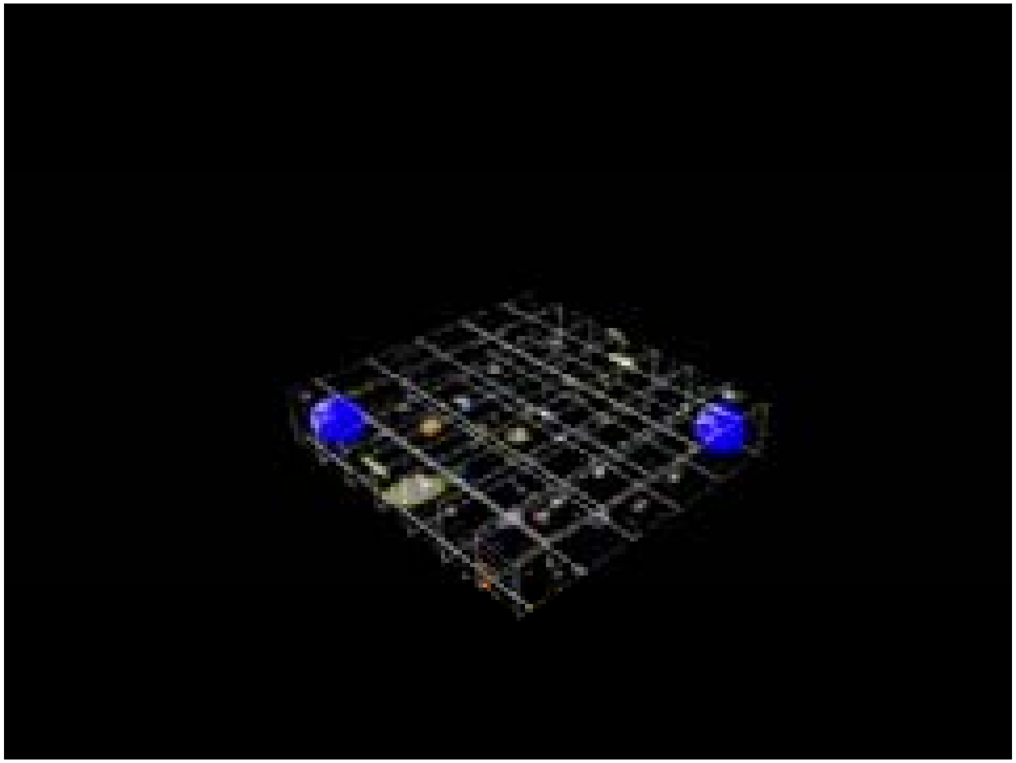
The Gravity force becomes strong!

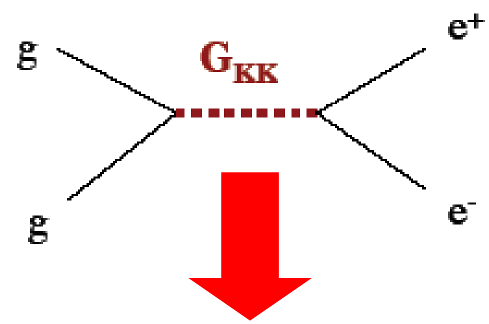
Detecting Extra Dimensions at the LHC

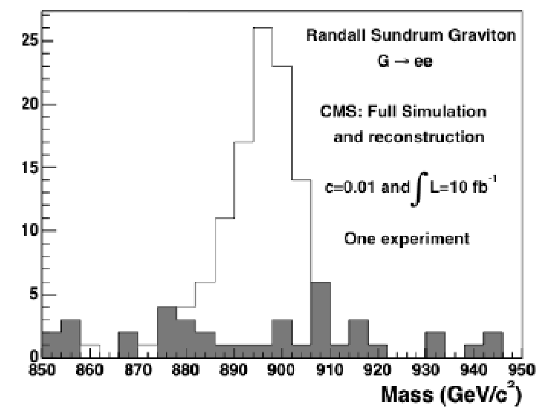
Main detection modes at the experiments

- Large missing (transverse) energy
- Resonance production







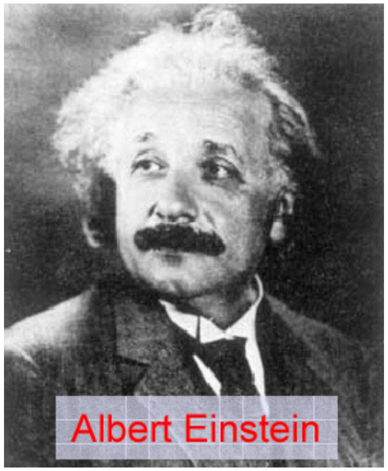


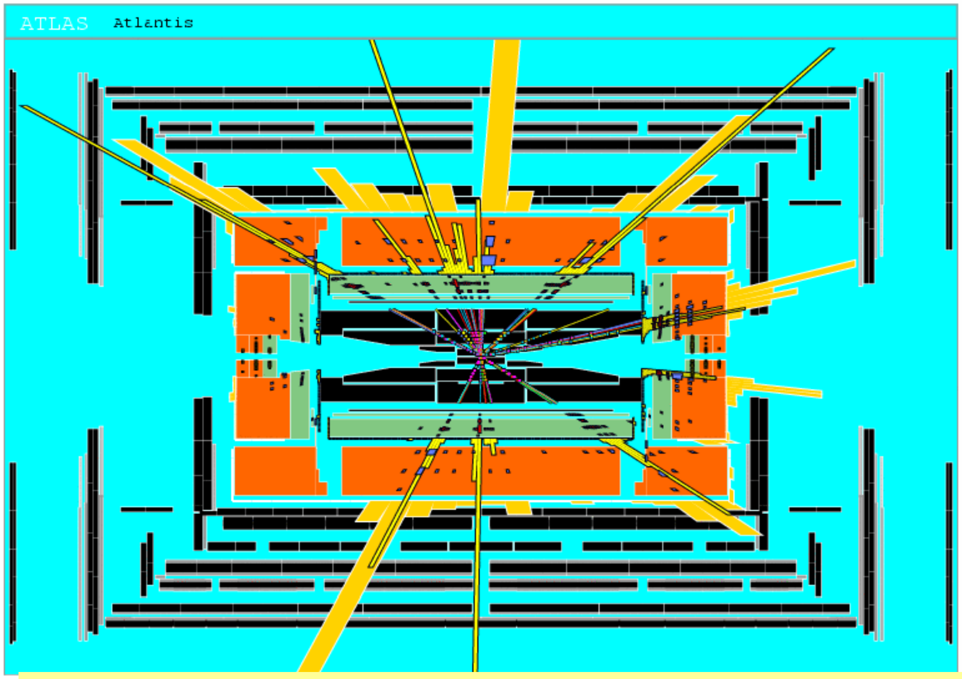
LHC can detect extra dimensions for scales up to 5 to 9 TeV

Quantum Black Holes at the LHC?

Black Holes are a direct prediction of Einstein's general theory on relativity

If the Planck scale is in ~TeV region:
can expect Quantum Black Hole production





Simulation of a Quantum Black Hole event

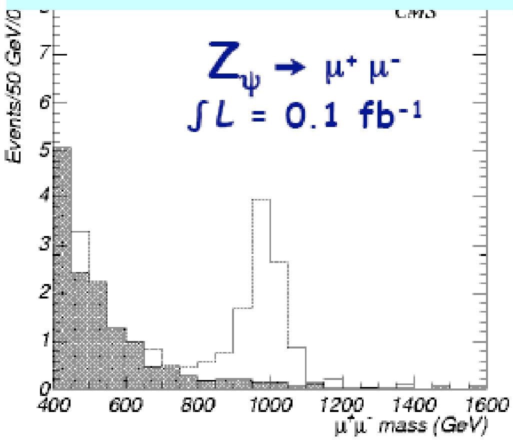
Quantum Black Holes are harmless for the environment: they will decay within less than 10^{-27} seconds ⇒ SAFE!

Quantum Black Holes open the exciting perspective to study Quantum Gravity in the lab!

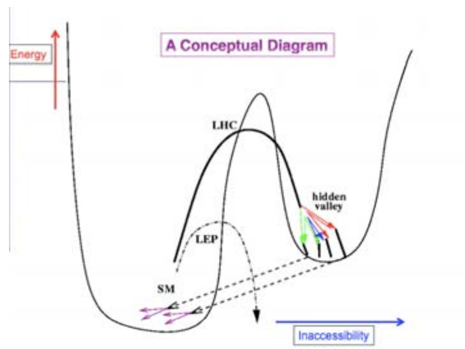
Black Holes Hunters at the LHC…

Other New Physics Scenarios at the LHC

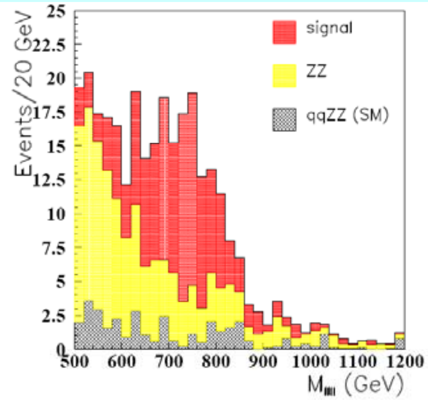
New Gauge Bosons?



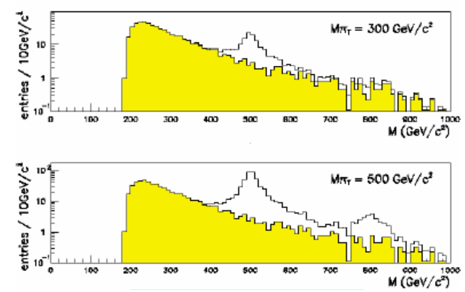
Hidden Valleys?



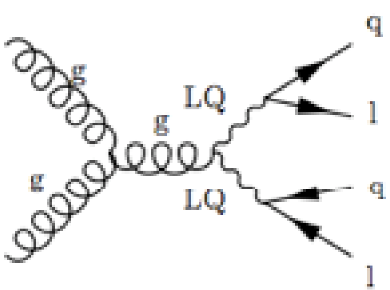
ZZ/WW resonances?



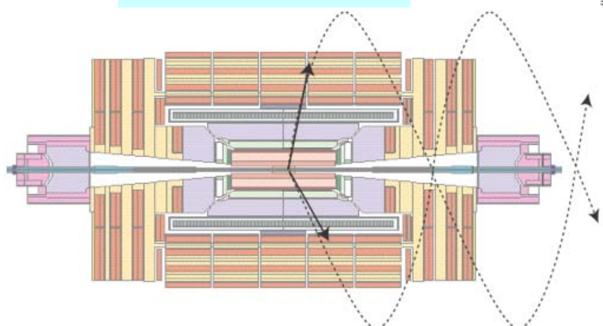
Technicolor?



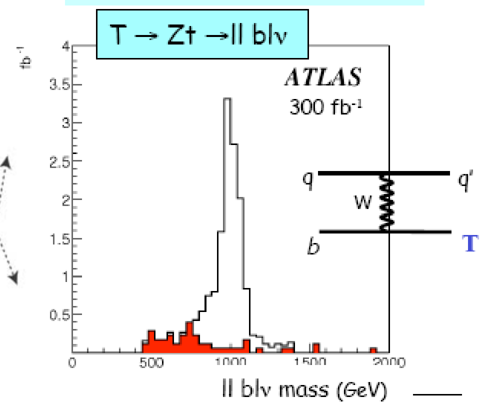
Leptoquarks?



Quirks???

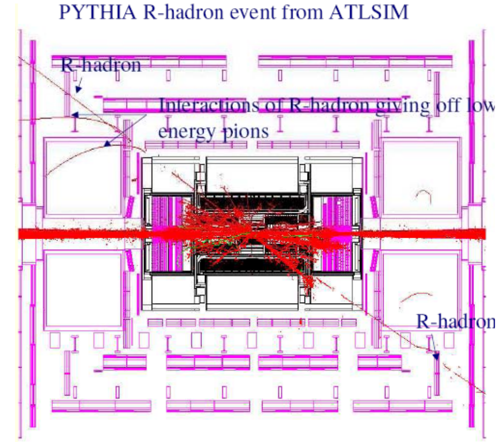


Little Higgs?



Split Susy?

PYTHIA R-hadron event from ATLSIM



We do not know what is out there waiting for us…

Long Lived Particles in Supersymmetry

Split Supersymmetry

- Assumes nature is fine tuned and SUSY is broken at some high scale
- The only light particles are the Higgs and the gauginos

- Gluino can live long: sec, min, years!

- R-hadron formation (eg: gluino+ gluon): slow, heavy particles containing a heavy gluino.

Unusual interactions with material

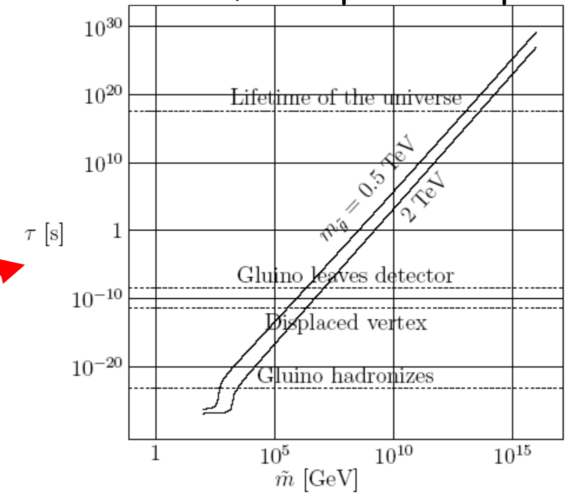
eg. with the calorimeters of the experiments!

Gravitino Dark Matter and GMSB

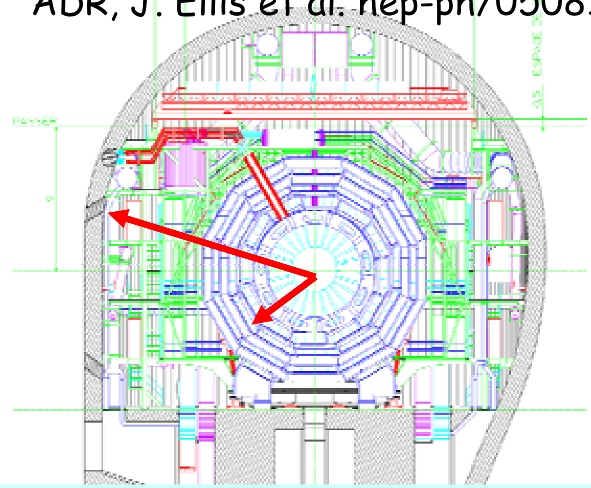
- In some models/phase space the gravitino is the Lightest supersymetric particle (LSP)
- ⇒ NLSP (neutralino, stau lepton) can live 'long'
- ⇒ non-pointing photons

⇒Challenge to the experiments!

Arkani-Hamed, Dimopoulos hep-th/0405159



K. Hamaguchi,M Nijori,ADR hep-ph/0612060
ADR, J. Ellis et al. hep-ph/0508198

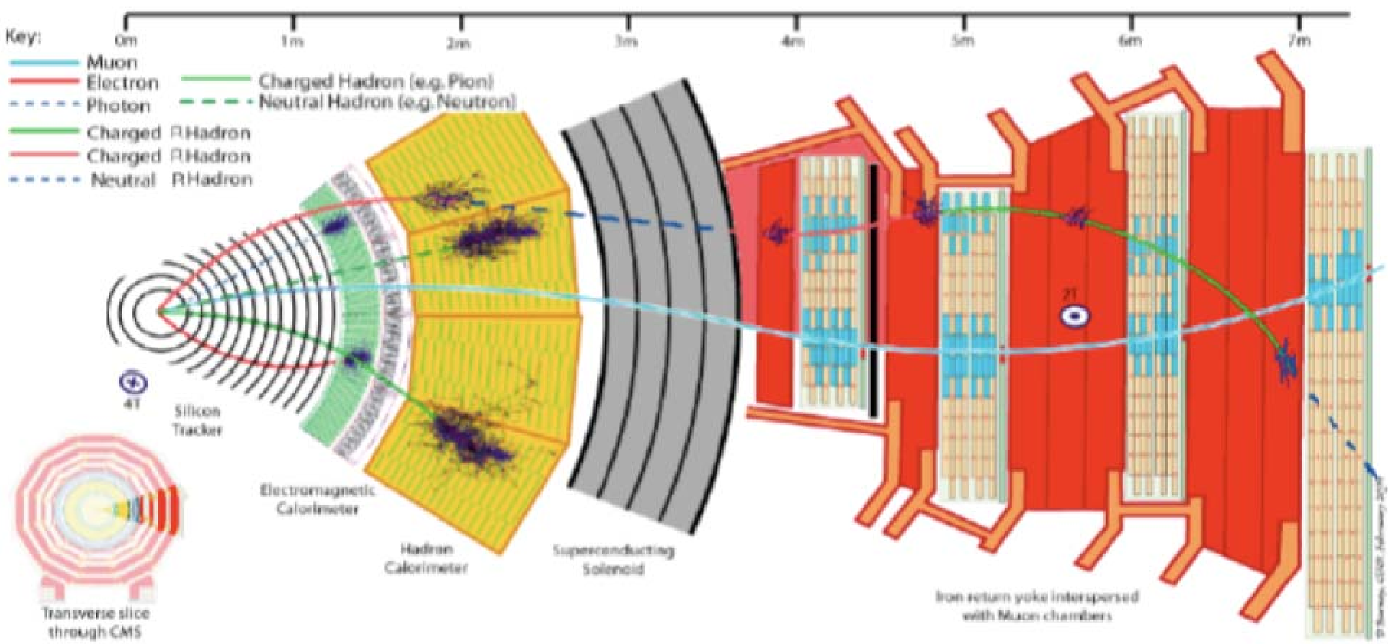


Sparticles stopped in the detector,walls of the cavern, or dense 'stopper' detector. They decay after hours---months…

R-Hadrons Passing Through the Detector

R-hadrons would have a mass of at least a few 100 GeV

- They 'sail' through the detector like a 'heavy muon'
- In certain (hadronization) models they may change charge on the way
- They also loose a lot of energy when passing the detector (dE/dx)

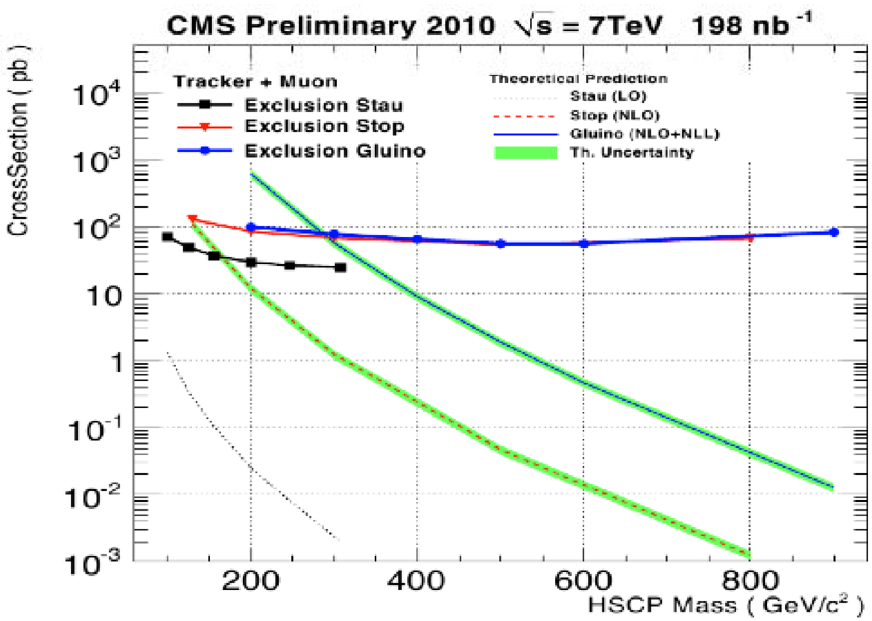


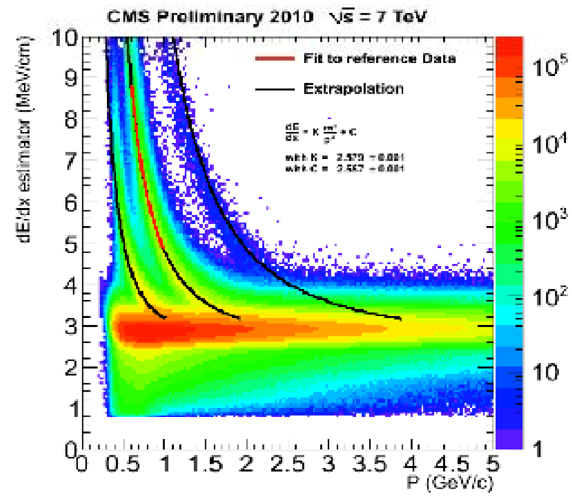
Weird signature!!

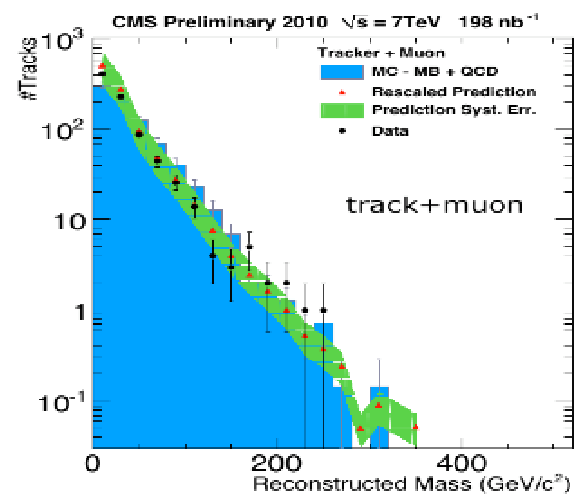
Heavy Stable Charged Particles

New for the summer conferences (~200 nb^{-1})

Search for Heavy Stable Charged Particles (HSCP) by CMS







- seach for heavy gluino, hadronizing into a charged R-hadron
- reconstruct R-hadron mass based on measured dE/dX
- CMS'2010 95% CL exclusion:
  - $M_{\tilde{g}} < 271(284)\ GeV/c^2$ for track (muon)

Stopped R-hadrons or Gluinos!

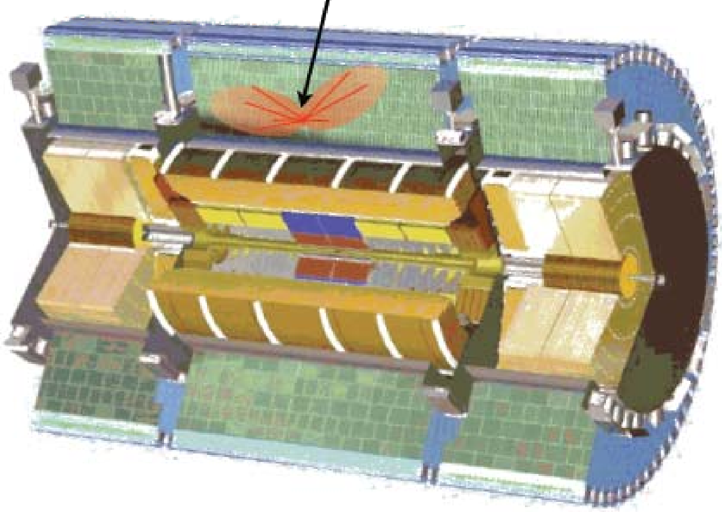
The R-hadrons may loose so much energy that they simply stop in the detector

Long Lived Gluinos

$\tau_{\tilde{g}} > 100$ ns

looking for stopped gluinos that later decay

100s GeV Unbalanced $= \not{E}_T$



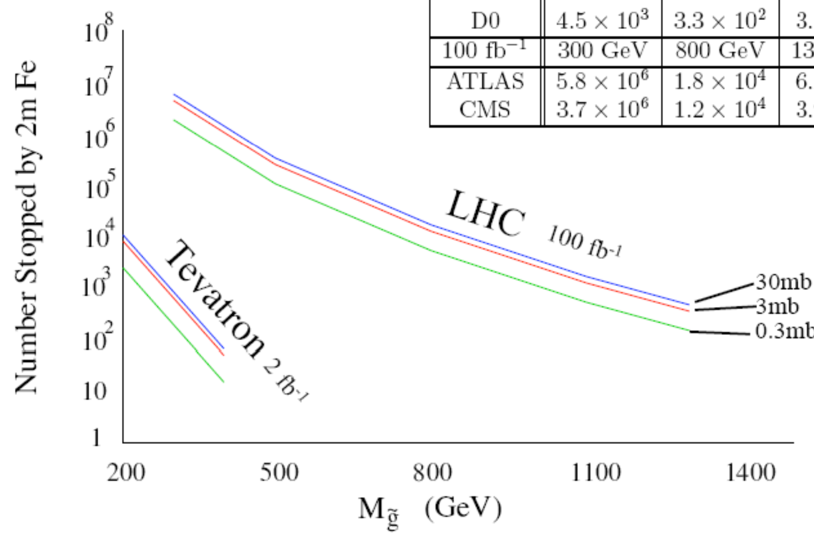
Uncorrelated with any beam crossing

No tracks going to or from activity

Total Number of Stopped Gluinos

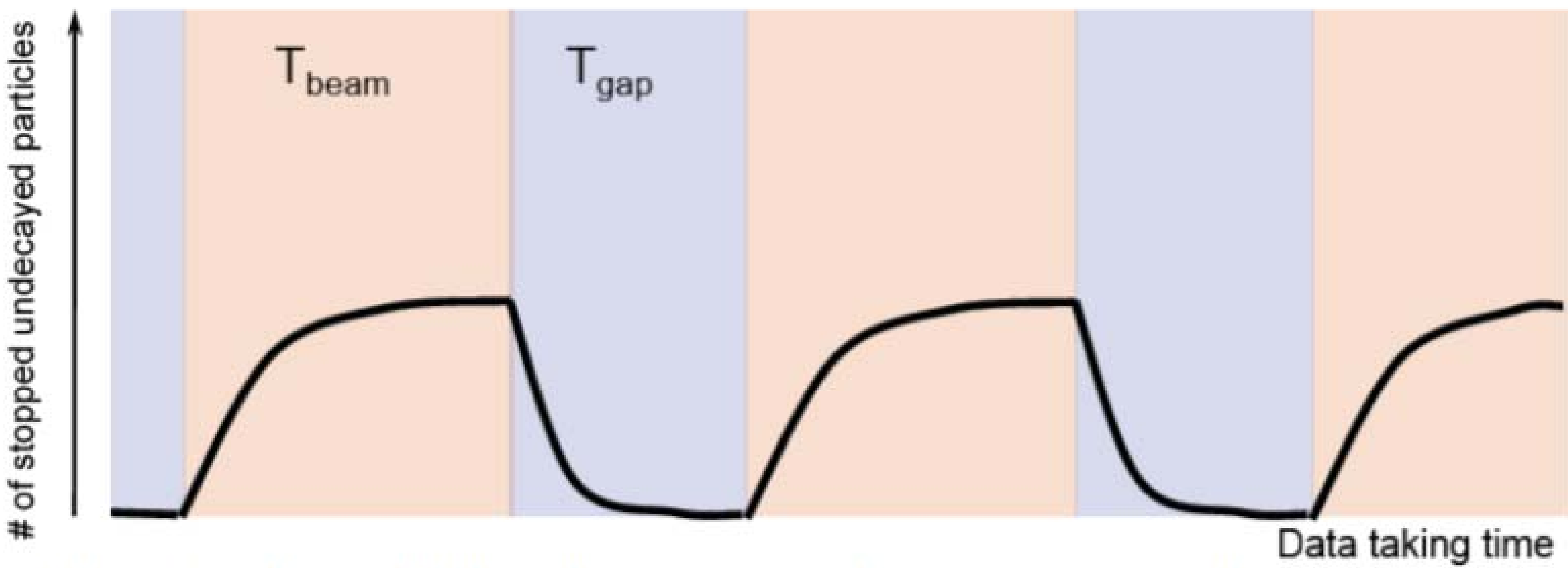
Arvanitaki, Dimopoulos, Pierce, Rajendran, JW hep-ph/0506242

$2\ fb^{-1}$	200 GeV	300 GeV	400 GeV
CDF	4.1×10^3	3.1×10^2	3.3×10^1
D0	4.5×10^3	3.3×10^2	3.4×10^1
$100\ fb^{-1}$	300 GeV	800 GeV	1300 GeV
ATLAS	5.8×10^6	1.8×10^4	6.2×10^2
CMS	3.7×10^6	1.2×10^4	3.9×10^2



⇒ Special triggers needed, asynchronous with the bunch crossing

Stopped gluinos



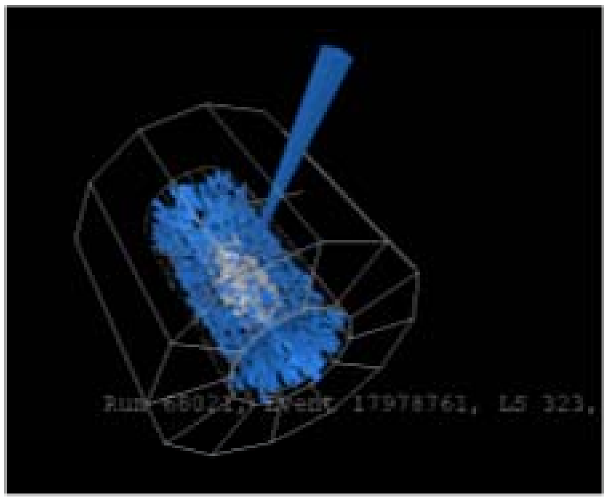
- Basic idea: R-hadrons can loose enough energy in the detector to stop somewhere inside (usually calorimeters)
- Sooner or later they must decay   Eg when there is no beam!
- Trigger: (jet) && !(beam)
- Only possible backgrounds: cosmics and noise

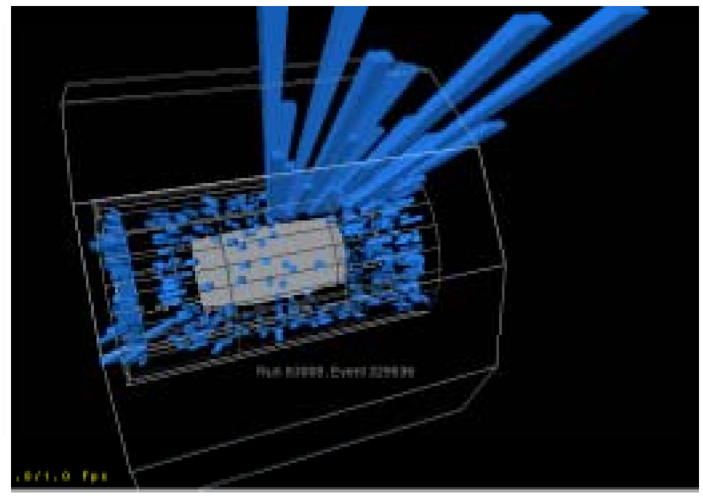
Can be studied in the experiments with cosmic data

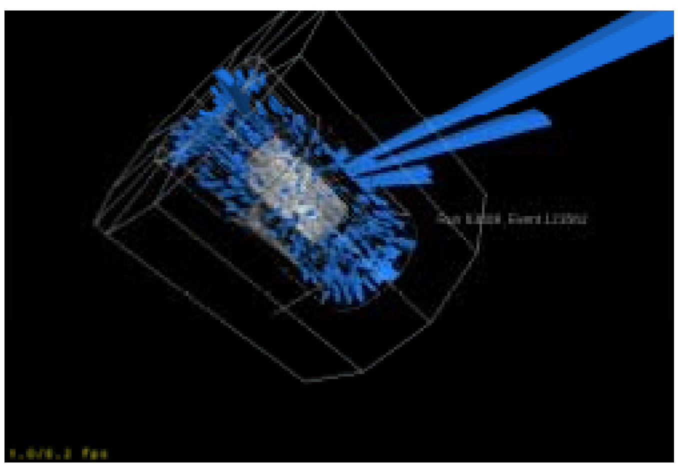
Heavy Particles: Stopped Gluinos

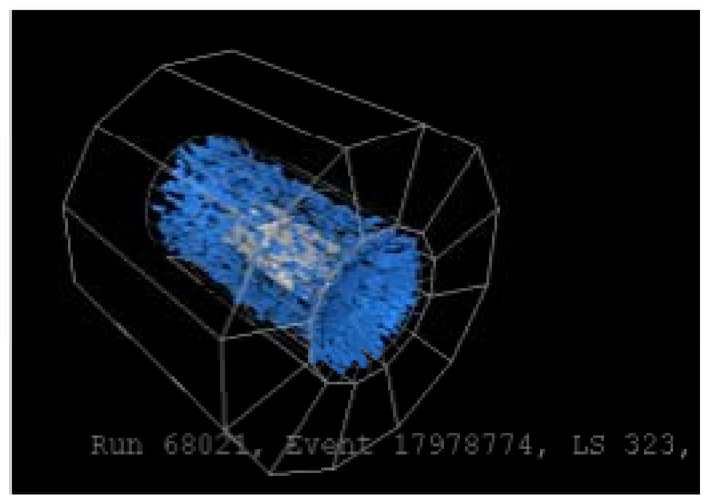
Studies in CMS with the 2008/2009 cosmic data:
All events we find now are background and we can learn how to cut on them!

Find energy splashes with certain topology





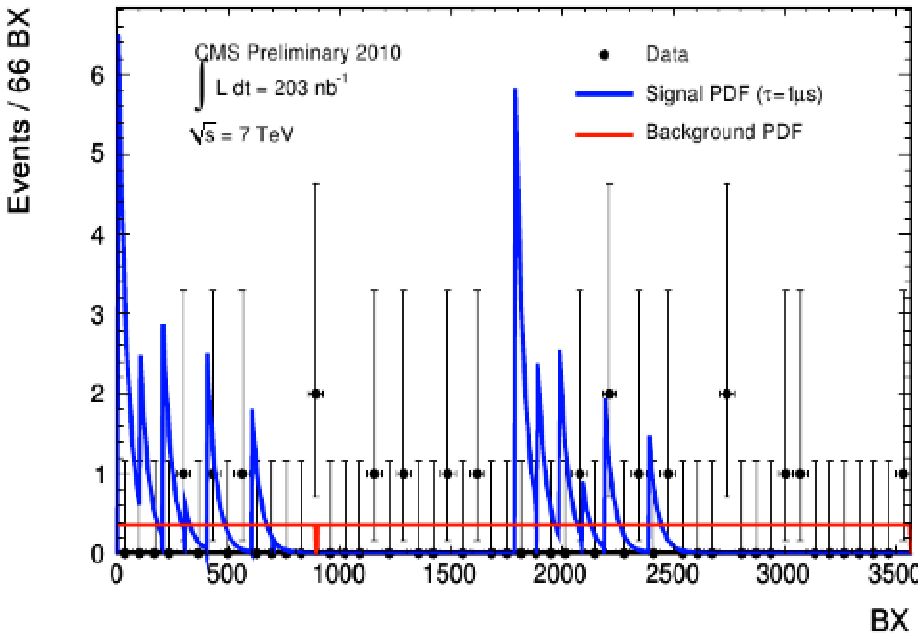


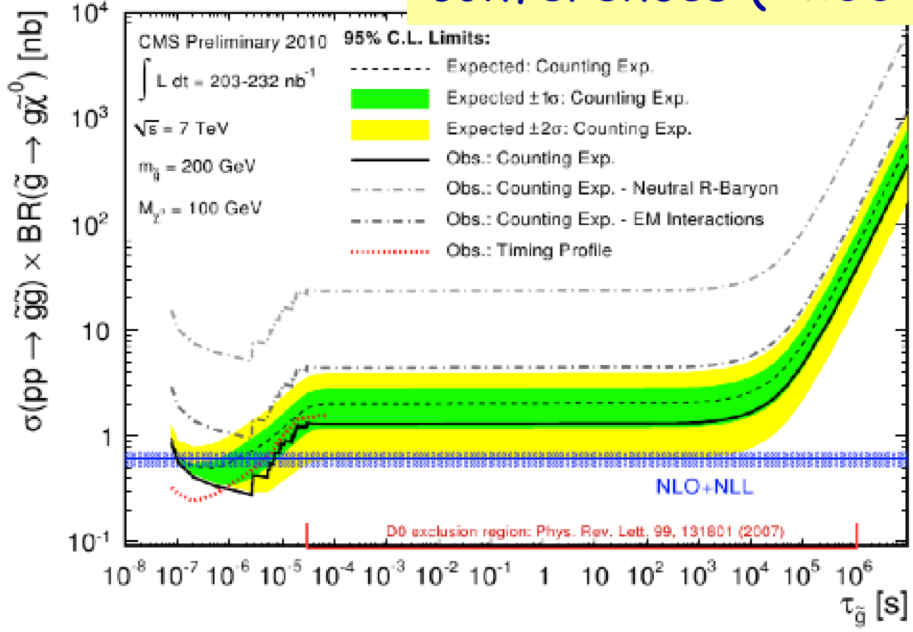


Heavy Partciles: Stopped Gluinos

New for the summer conferences (~200 nb^{-1})

Searches for Stopped Gluino

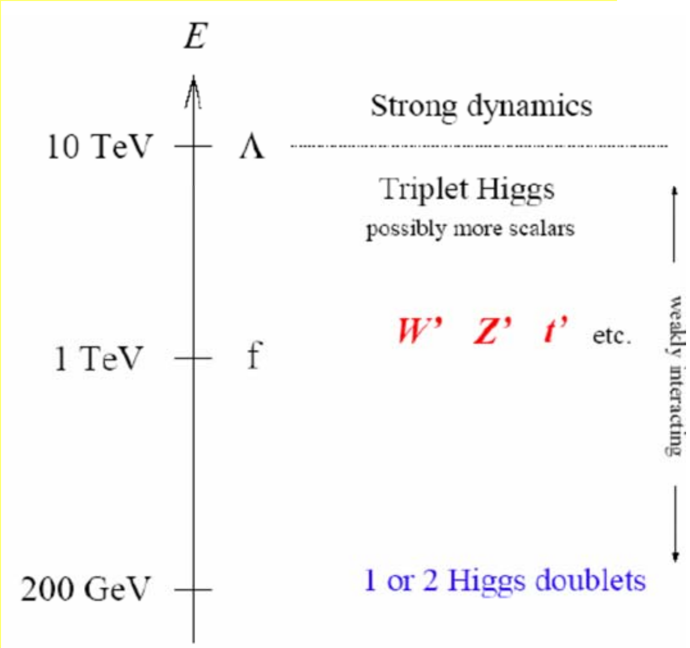




- gluino, hadronized into a charged R-hadron, can stop and decay in the calorimeter
- trigger on large “out-of-collision” energy depositions
- sensitive to the large lifetimes
- assume $BR(\tilde{g} \to g\tilde{\chi}^0) = 100\%$, $M_{\tilde{g}} - M_{\tilde{\chi}^0} > 100\ GeV$
- CMS’2010 95% CL limits on gluino lifetime $\tau_{\tilde{g}}$:
  - counting experiment excludes $\tau_{\tilde{g}}$ within [120ns, 6μs]
  - time profile analysis improves low limit down to 75ns

Other New Physics Ideas…

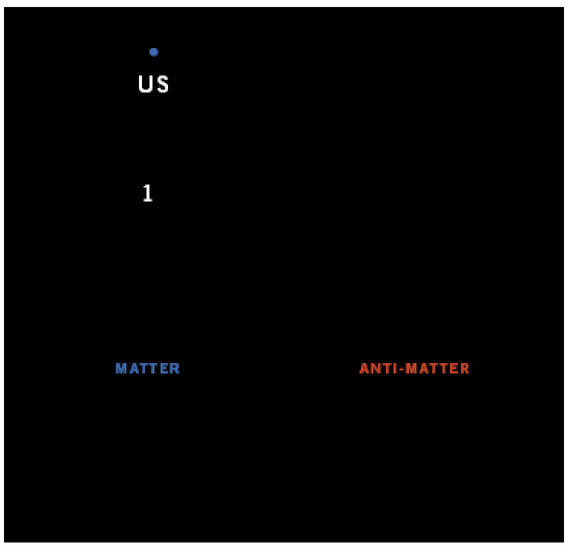
- Plenty!
  - Compositeness/excited quarks & leptons
  - Little Higgs Models
  - String balls/T balls
  - Bi-leptons
  - RP-Violating SUSY
  - SUSY+ Extra dimensions
  - Heavy Majorana Neutrinos
  - WW,WZ resonances
  - Unparticles
  - …

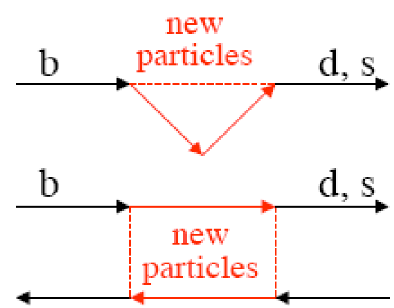


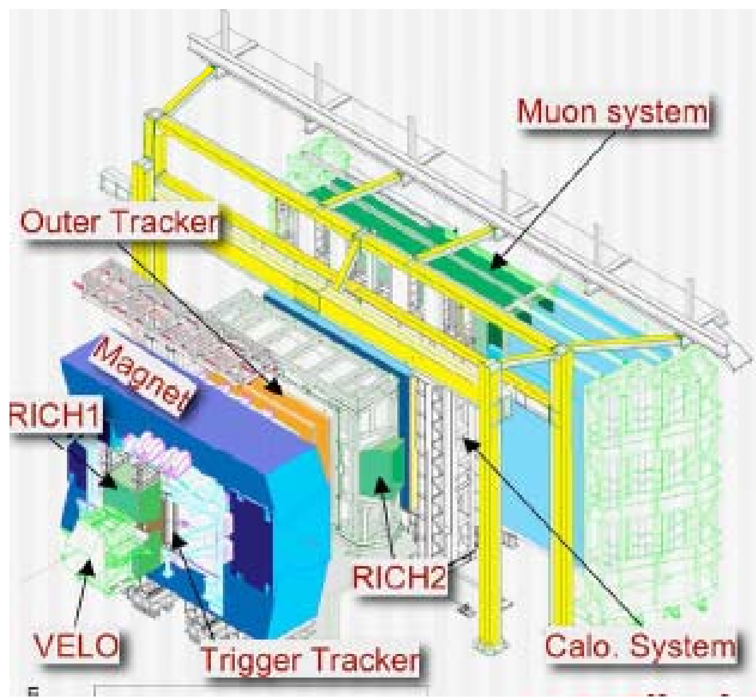
Have to keep our eyes open for all possibilities:
Food for many PhD theses!!

Matter-Antimatter

The properties and subtle differences of matter and anti-matter using mesons containing the beauty quark, will be studied further in the LHCb experiment

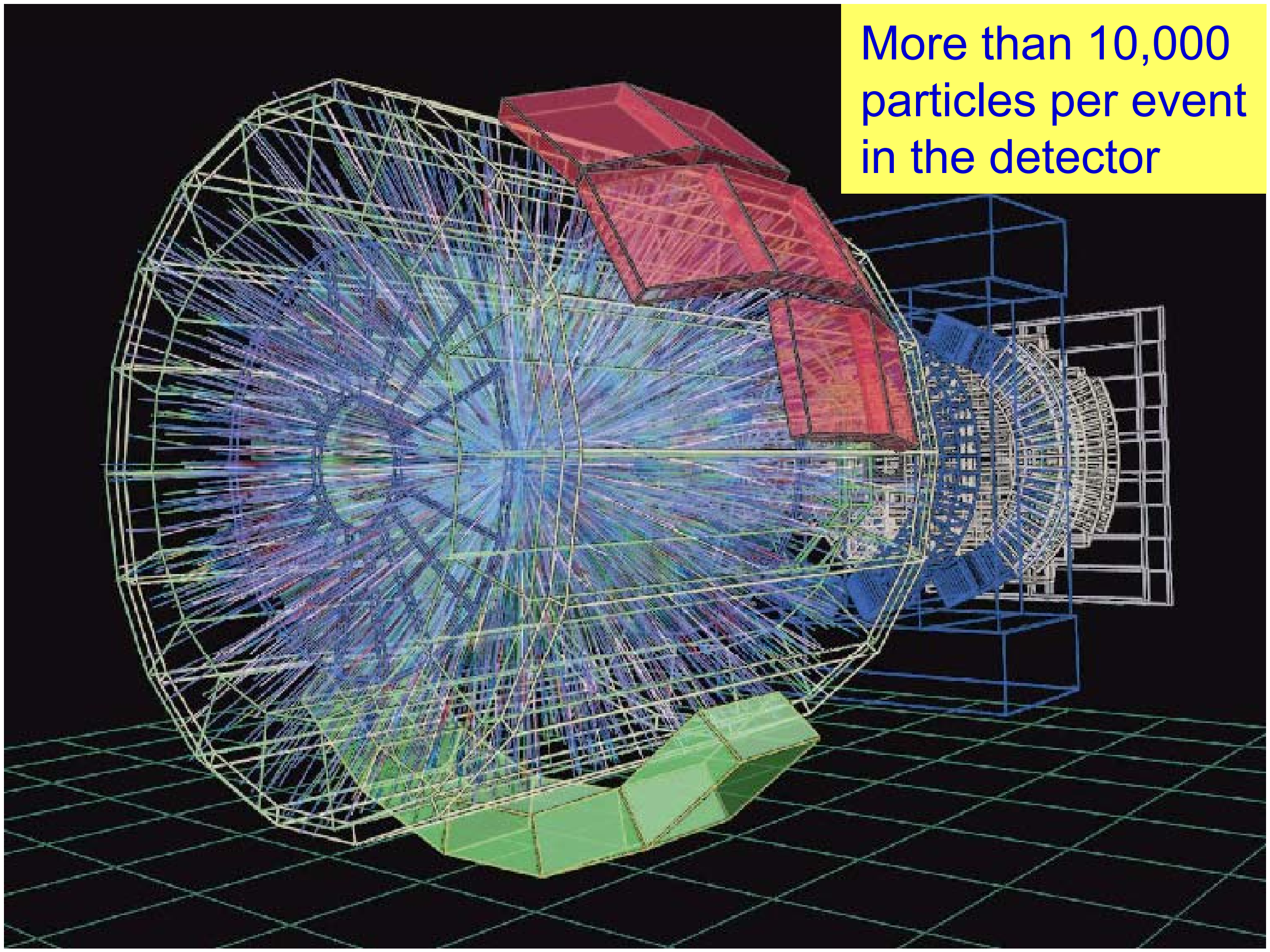




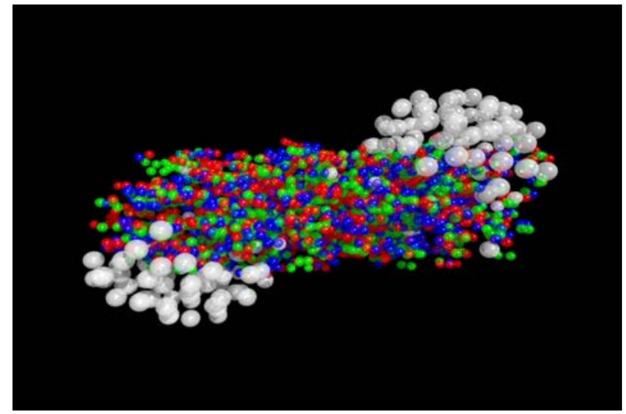


Primordial Plasma

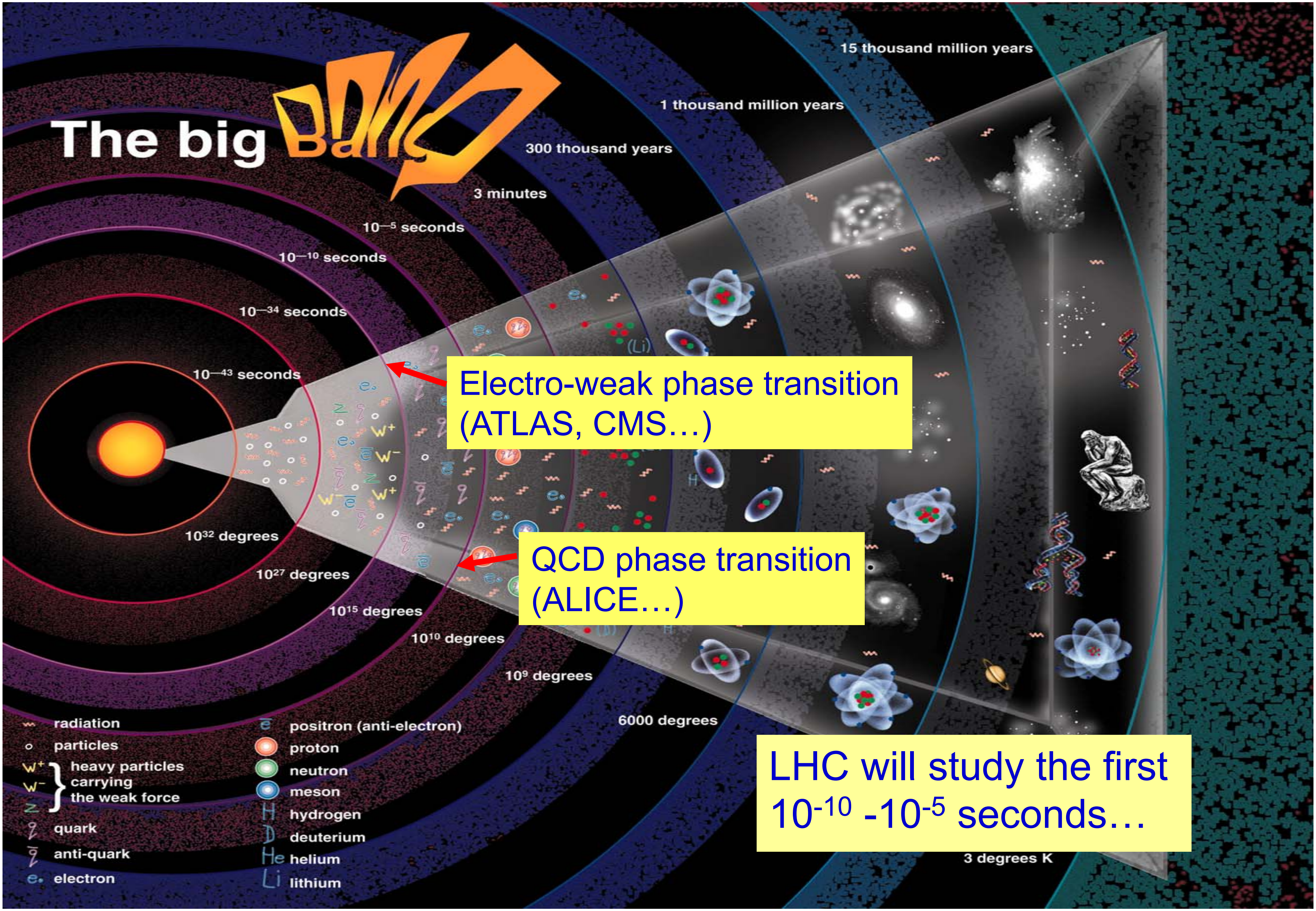
Lead-lead collisions at the LHC to study the primordial plasma, a state of matter in the early moments of the Universe



A lead lead collision simulated in the ALICE detector



Study the phase transition of a state of quark gluon plasma created at the time of the early Universe to the baryonic matter we observe today



Electro-weak phase transition (ATLAS, CMS…)

QCD phase transition (ALICE…)

LHC will study the first 10^{-10} - 10^{-5} seconds…

The LHC will reveal the origin of mass of particles

It will very likely reveal much more ….
There is mounting evidence, from neutrino mass to dark matter and dark energy observations, that there is something profound that we do not yet understand
Is it supersymmetry, extra dimensions, other…?

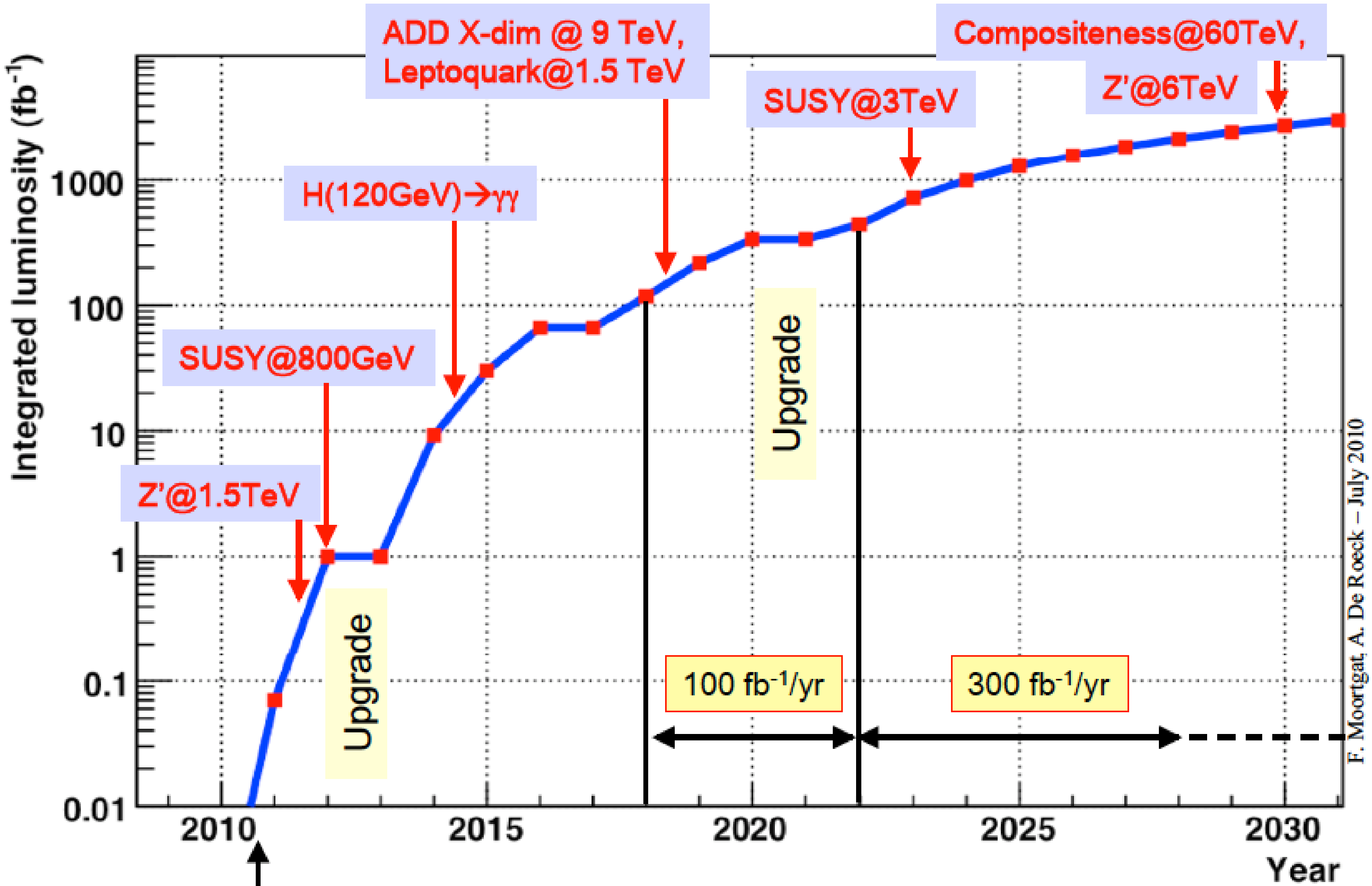
The LHC operates at an energy and precision that will take us far beyond our current understanding, into a new regime

Machine and detectors are of an unprecedented scale and complexity. The LHC has started for a first physics run in 2010 -2011.

We are on the verge of a revolution in our understanding of the Universe and our place within it

The End

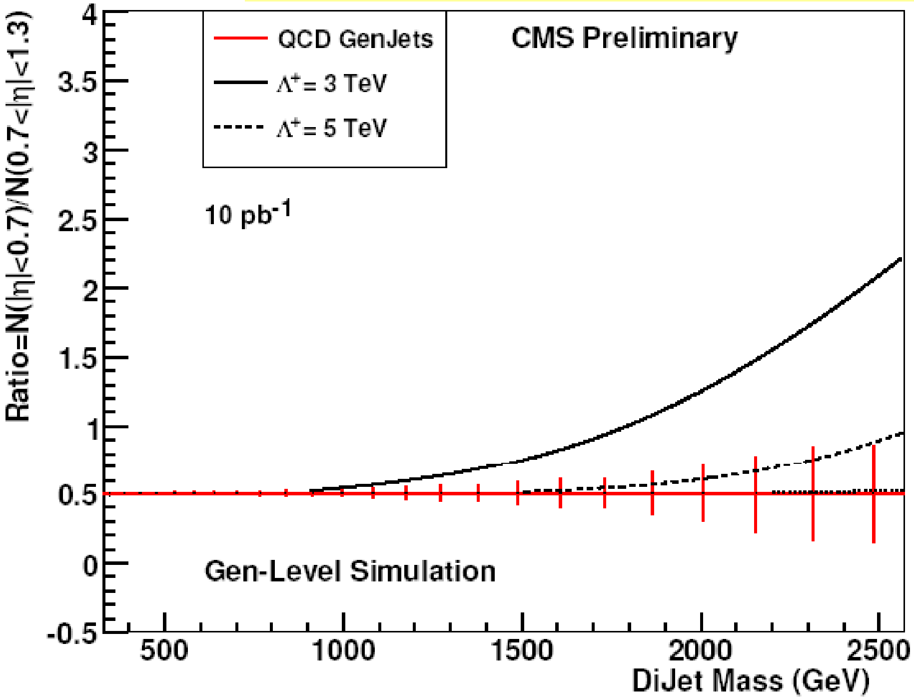
The LHC Outlook

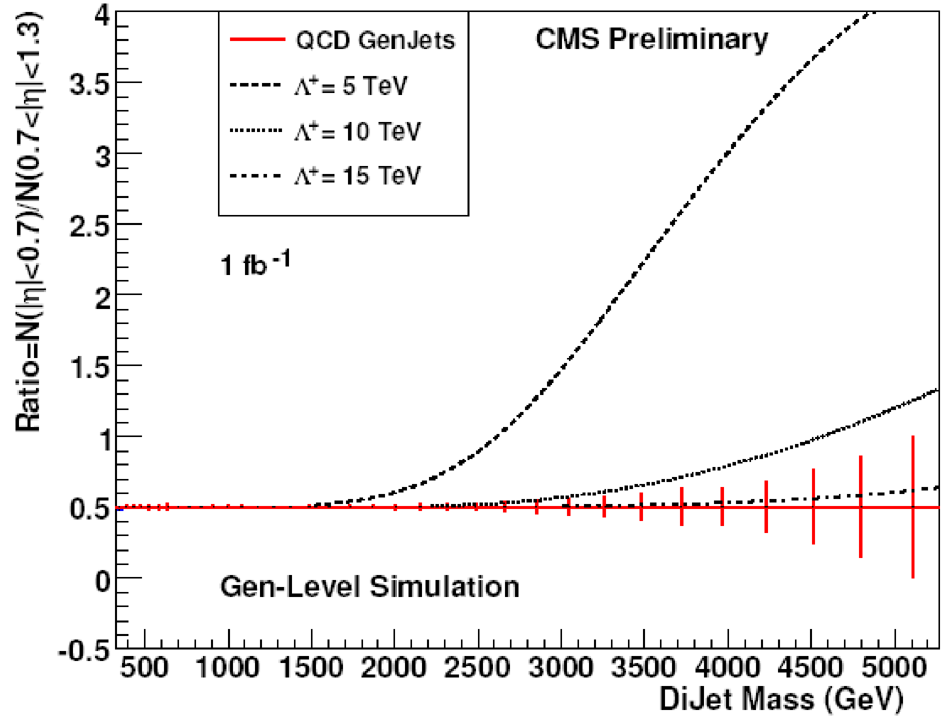


First physics run in 2010-2011: 1 fb^{-1} @ 7 TeV

New Physics with Jets

Eg Contact Interactions
⇒ Using dijet event ratios in pseudorapidity η bins





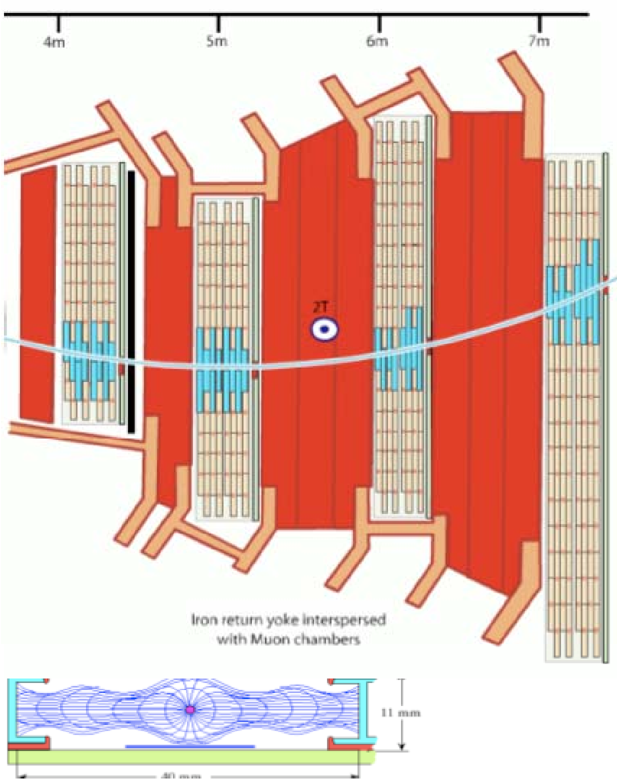
	Excluded Λ (TeV)			Discovered Λ (TeV)		
	$10\ pb^{-1}$	$100\ pb^{-1}$	$1\ fb^{-1}$	$10\ pb^{-1}$	$100\ pb^{-1}$	$1\ fb^{-1}$
DØ and PTDR η cuts	< 3.8	< 6.8	< 12.2	< 2.8	< 4.9	< 9.1
Optimized η cuts	< 5.3	< 8.3	< 12.5	< 4.1	< 6.8	< 9.9

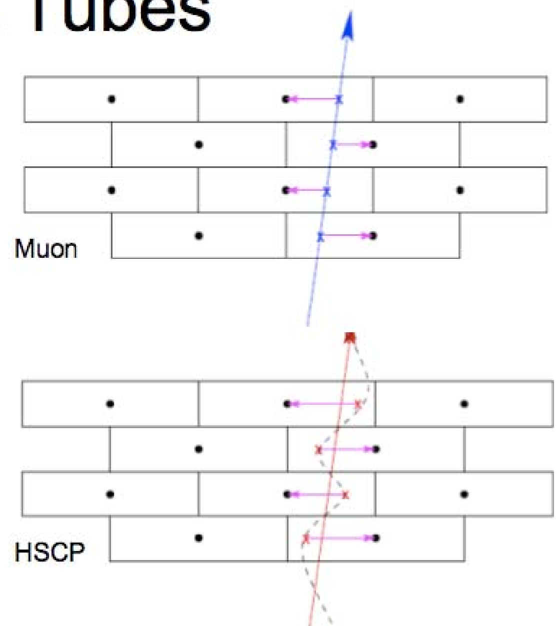
Already sensitivity with 10 pb^{-1}

Heavy Stable Charged Particles

The heavy particles are moving with less the speed of light, ie. $\beta < 1$
A particle with $\beta = 1$ reaches the muon detectors in CMS after 13 ns
A particle with $\beta < 1$ reaches the muon detectors later than 13 ns

TOF in Drift Tubes





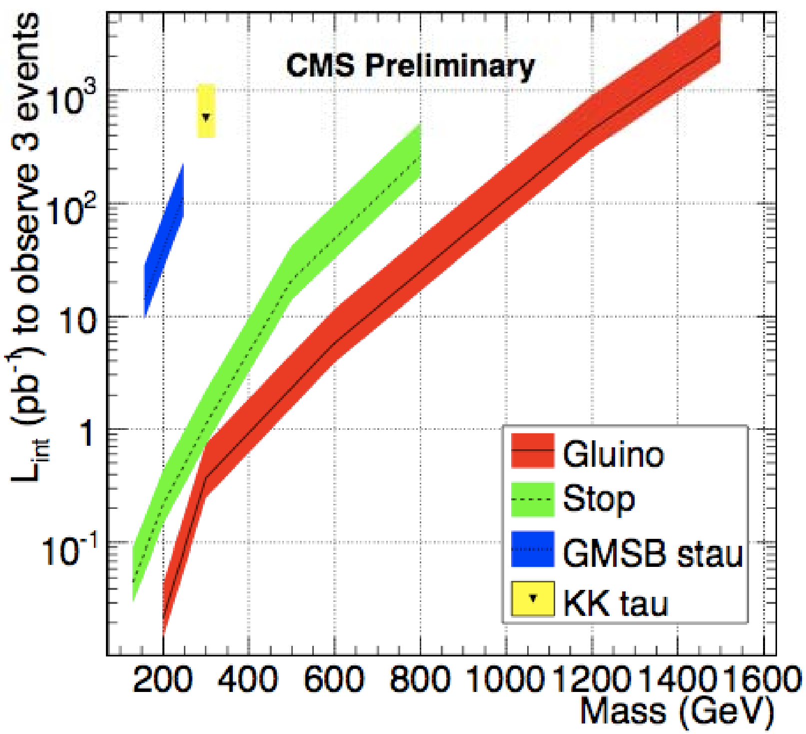
Normally the fit assumes $\beta=1$; here δt is left as a free parameter in the fit
=> TOF measurement
(see extra slides)

8

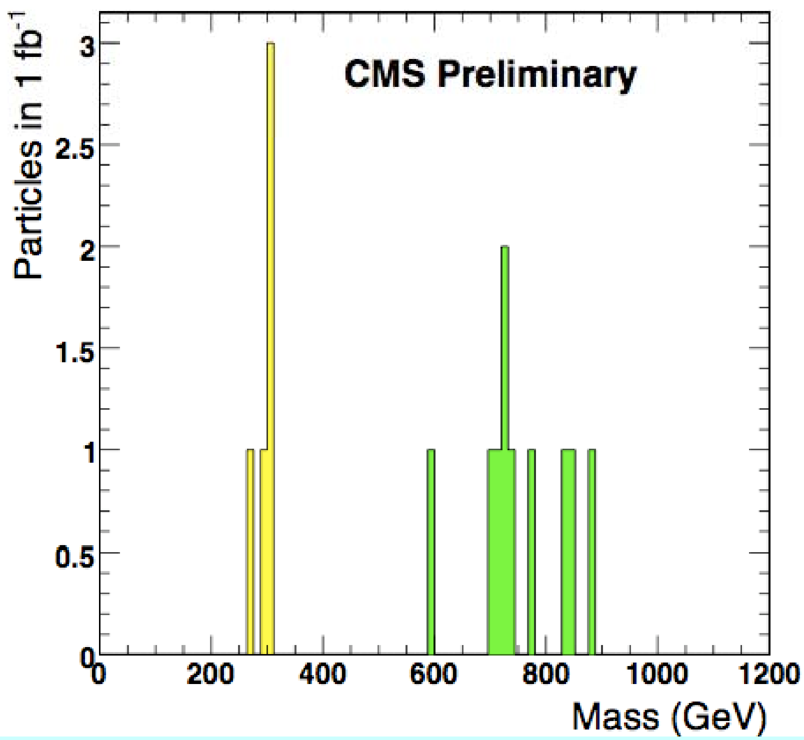
Derive the Time-of-flight from hit pattern in the muon chambers
$\Rightarrow$ Measure β of the particle from the time-of-flight!!

Heavy Stable Charged Particles

Sensitivity for different models:
⇒ Gluinos, stop, stau and KKtau production

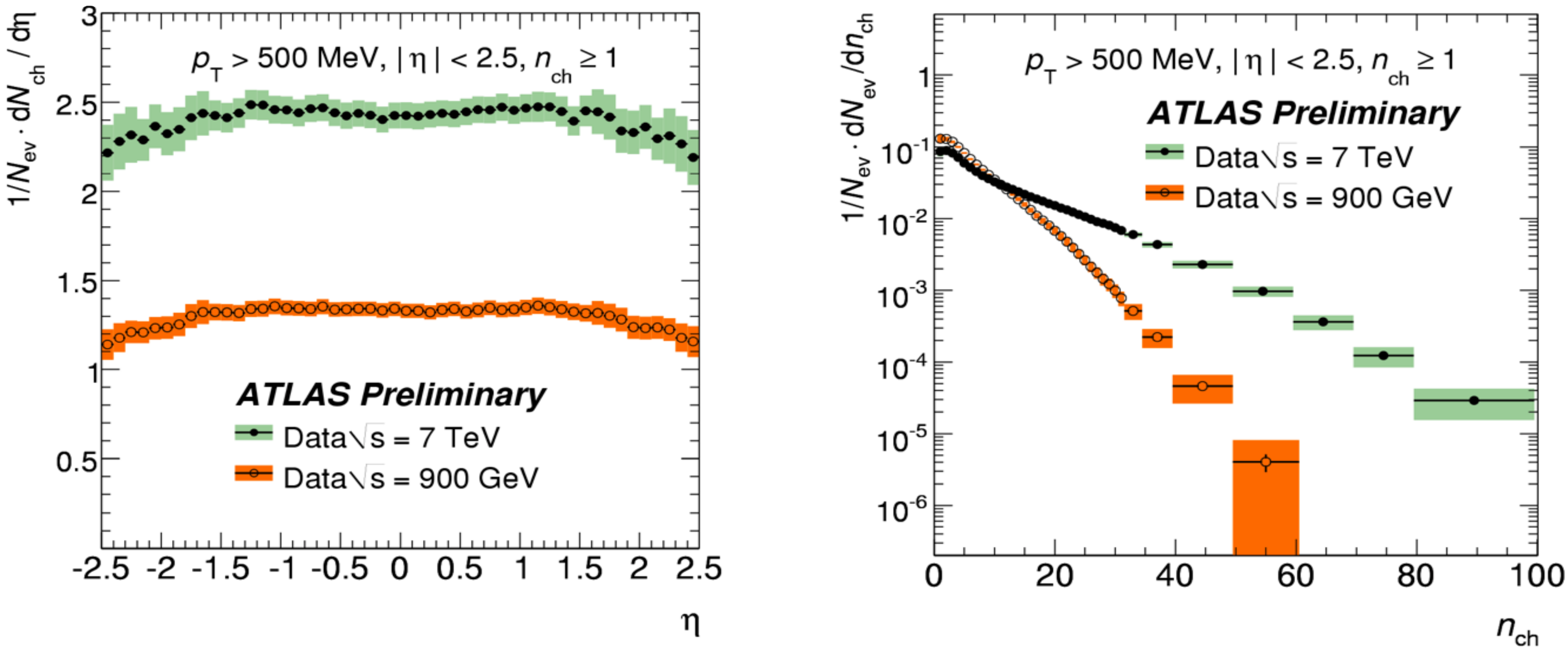


Luminosity needed for a discovery



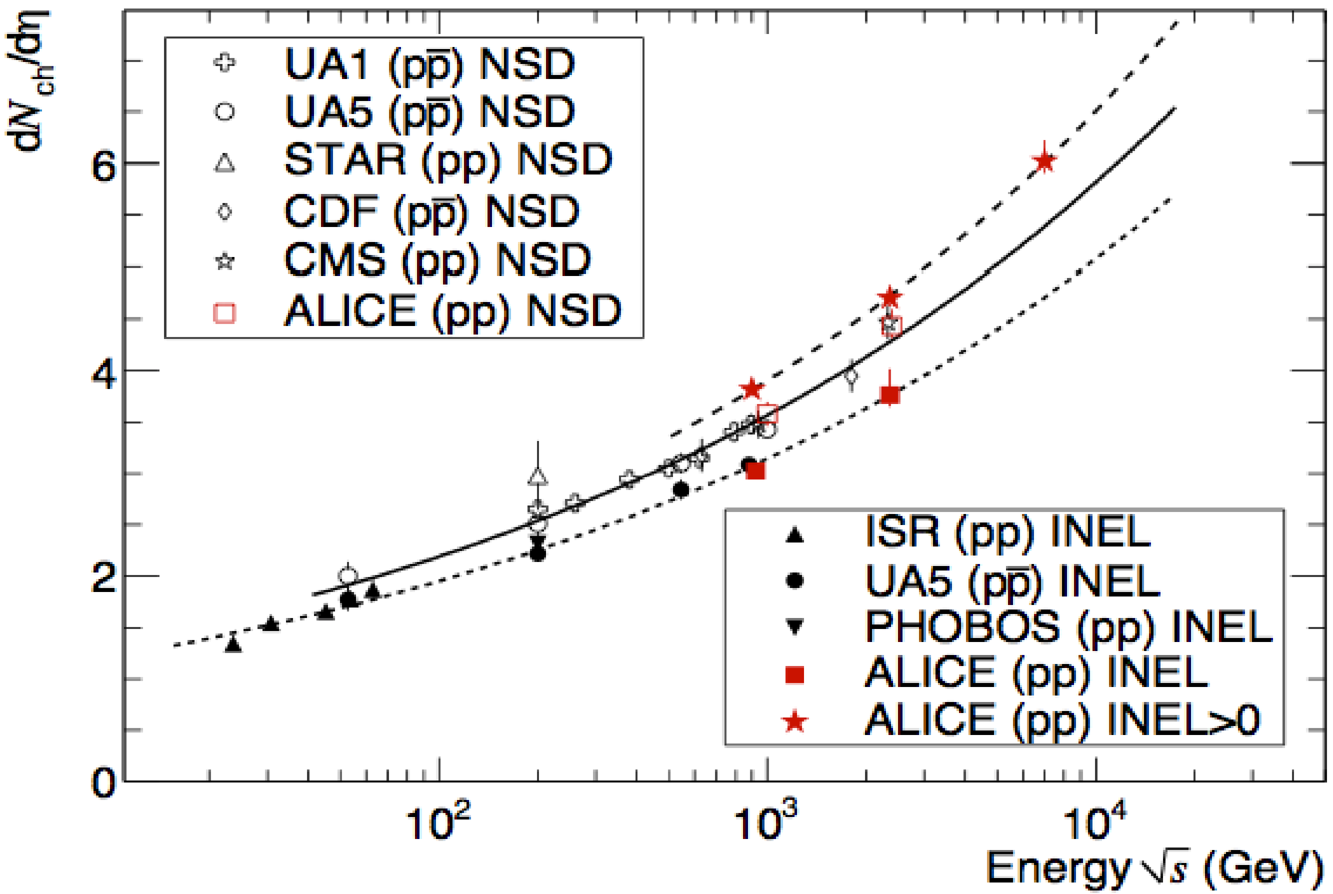
Mass reconstruction for a 200 GeV KKtau and a 800 GeV stop particle

7 Data Early Analysis



Strong rise of the central particle density

7 TeV Early Analysis



Strong rise of the central particle density

Event Rates for pp at $\sqrt{s}$=14 TeV

Process	Events/s	Events/
$W\rightarrow e\nu$	15	10^8
$Z\rightarrow ee$	1.5	10^7
$t\bar{t}$	0.8	10^7
$b\bar{b}$	10^5	10^{12}
$\tilde{g}\tilde{g}$ (m=1 TeV)	0.001	10^4
H (m=0.8 TeV)	0.001	10^4
Black Holes M_D=3 TeV n=4	0.0001	10^3

In the first 3 minutes at $10^{33}cm^{-2}s^{-1}$ LHC will produce per experiment:

- ~5000 $W\rightarrow\mu\nu,e\nu$ decays
- ~ 500 $Z\rightarrow\mu\nu,e\nu$ decays
- >2.10^7 bottom quark pairs
- ~150 top quark pairs
- ~10 Higgs particles (M_H=120 GeV)
- ~20 gluino pairs with mass 500 GeV
- A quantum black hole (M_D = 2TeV)
- ….

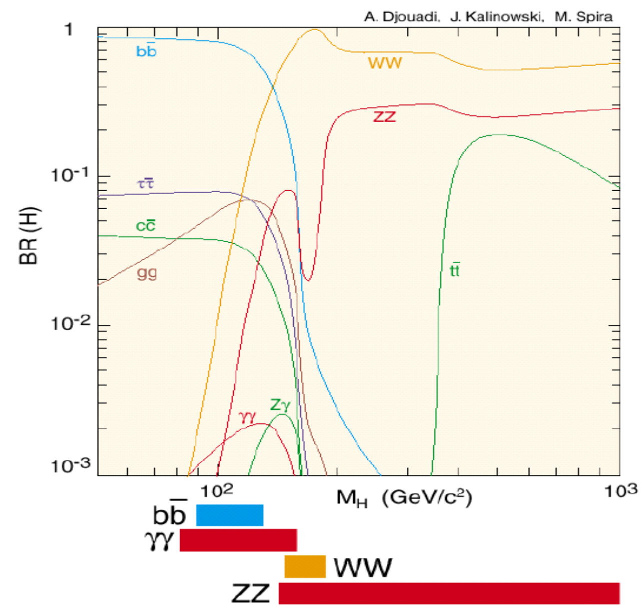
Startup luminosity at 10 TeV will be much lower, perhaps like 10^{31}-10^{32} $cm^{-2}s^{-1}$ (less bunches/current)

3 minutes: Record ~ 20K events/30Gbyte

Higgs Boson Search Channels

Low mass M_H ❒ 200 GeV

Production / DECAY	Inclusive	VBF	WH/ZH	ttH
$H \to \gamma\gamma$	YES	YES	YES	YES
$H \to bb$			YES	YES
$H \to \tau\tau$		YES		
$H \to WW^*$	YES	YES	YES	
$H \to ZZ^*$, $Z \to \ell^+\ell^-$, ℓ=e,μ	YES			
$H \to Z\gamma$, $Z \to \ell^+\ell^-$, ℓ=e,μ	very low σ			



Intermediate mass
(200 GeV ❒ M_H ❒700 GeV)

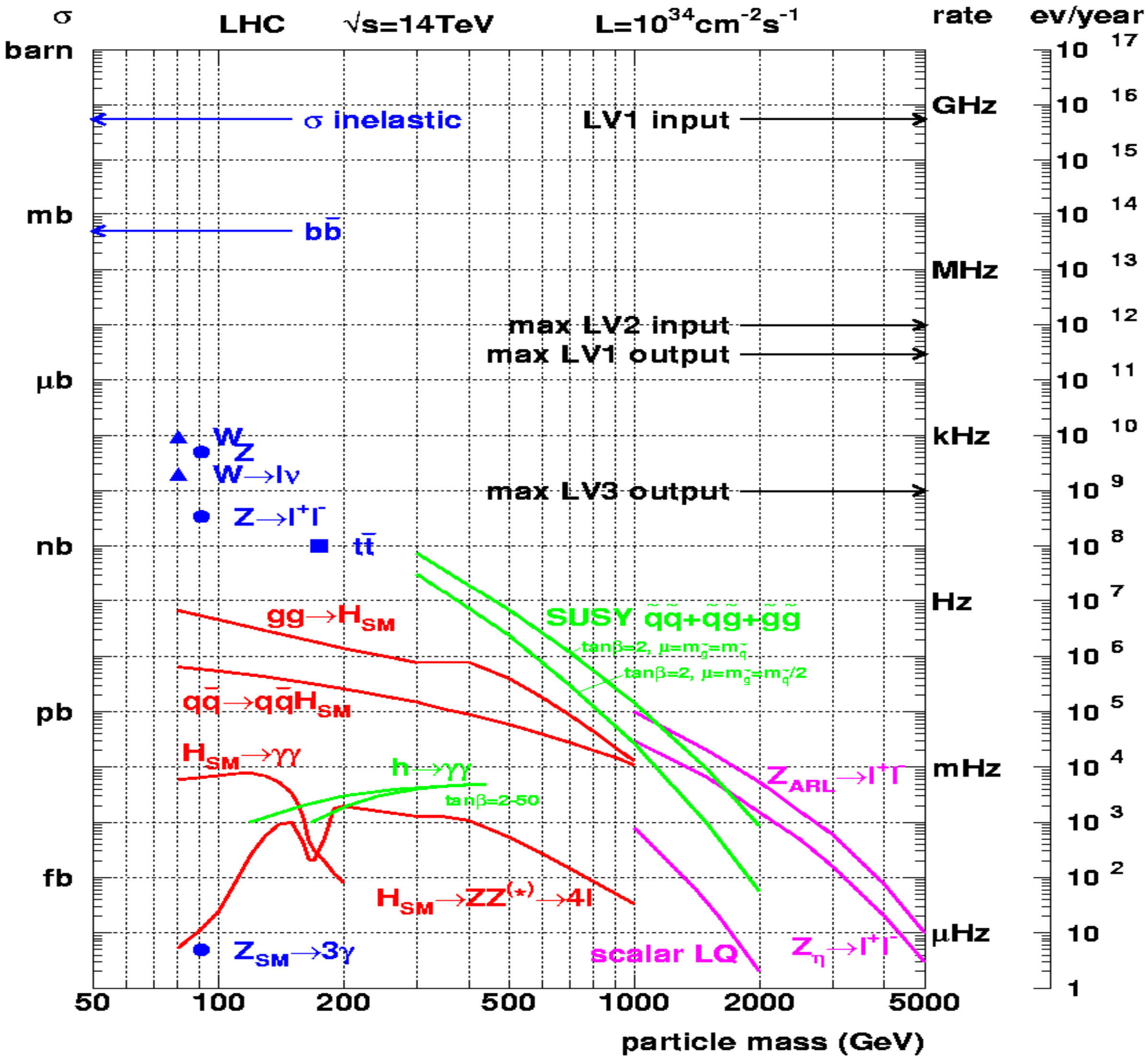
inclusive $H \to WW$
inclusive $H \to ZZ$

High mass (M_H ♦ 700 GeV)

VBF $qqH \to ZZ \to \ell\ell\nu\nu$
VBF $qqH \to WW \to \ell\nu jj$

$H \to \gamma\gamma$ and $H \to ZZ^* \to 4\ell$ are the only channels with a very good mass resolution ~1%

Cross Sections at the LHC



"Well known" processes, don't need to keep all of them …

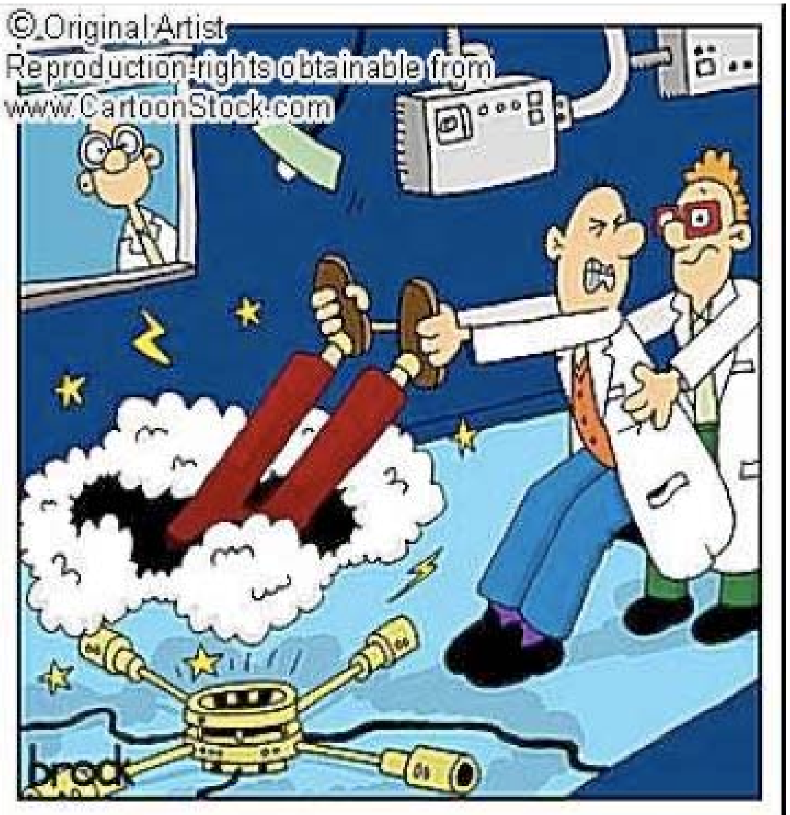
New Physics!!
This we want to keep!!

Quatum Black Holes

- Can LHC destroy the planet?

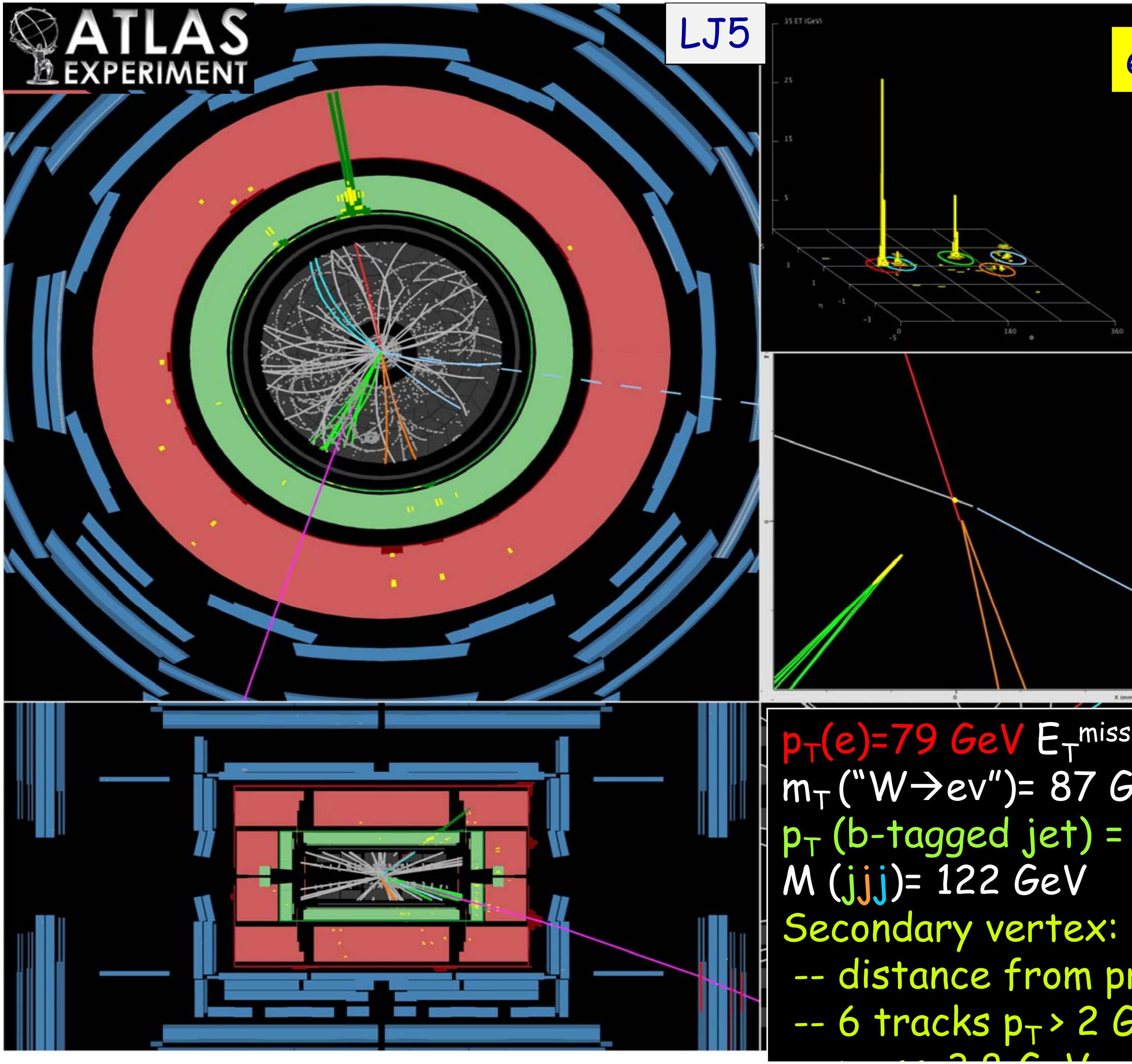
  $\Rightarrow$ No!

- See the report of the LHC Safety assesment group (LSAG) *http://arXiv.org/pdf/0806.3414*
- More information on
  - S.B. Giddings and M. Mangano, *http://arXiv.org/pdf/0806.3381*



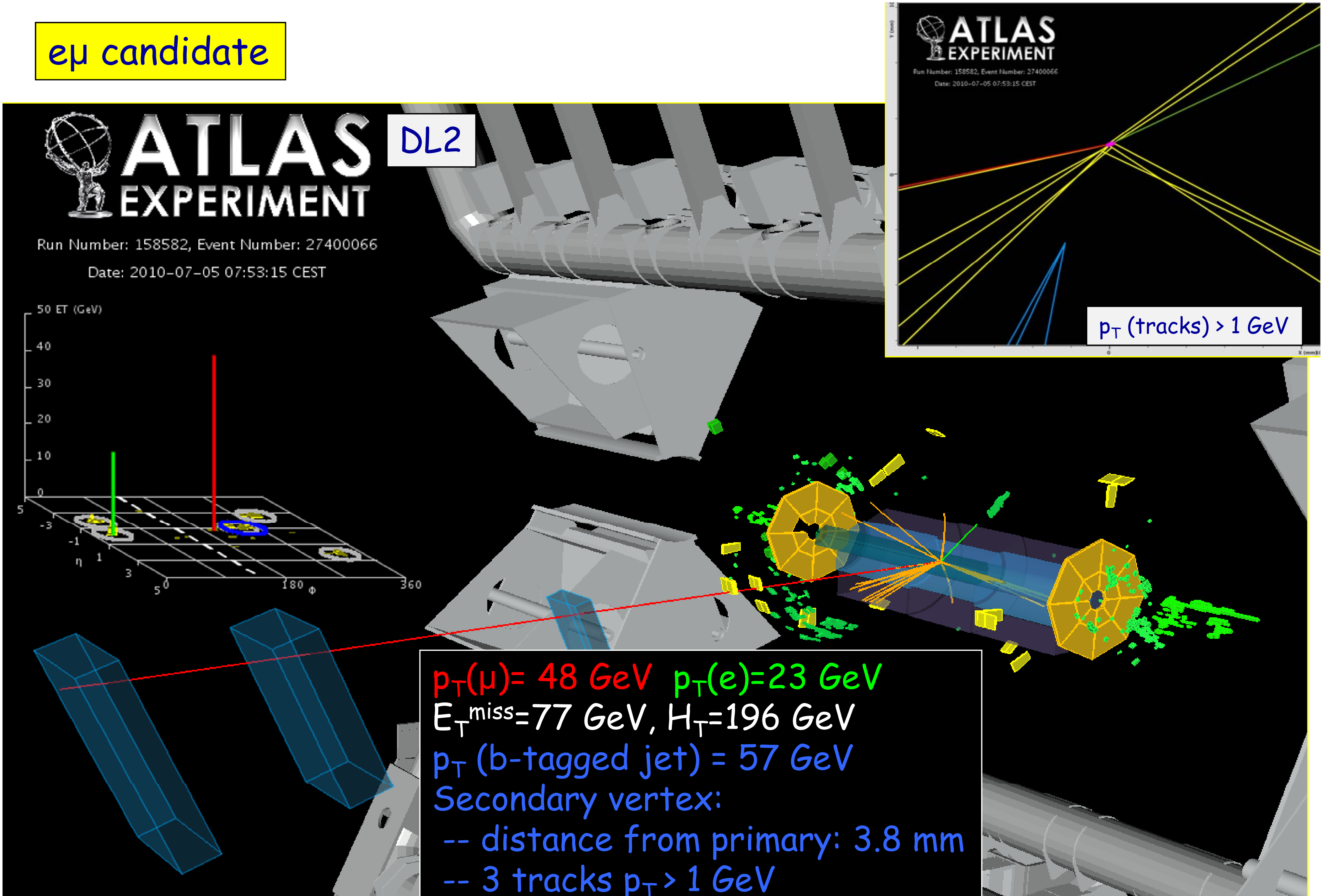
Professor Landsberg was fast regretting becoming the first man to successfully create a mini black hole in the laboratory.

e+jets candidate



$p_T(e)$=79 GeV E_T^{miss} = 43 GeV
m_T("W→eν")= 87 GeV
p_T (b-tagged jet) = 91 GeV
M (jjj)= 122 GeV
Secondary vertex:
-- distance from primary: 5 mm
-- 6 tracks p_T > 2 GeV

eμ candidate



$p_T(\mu)$= 48 GeV $p_T(e)$=23 GeV

E_T^{miss}=77 GeV, H_T=196 GeV

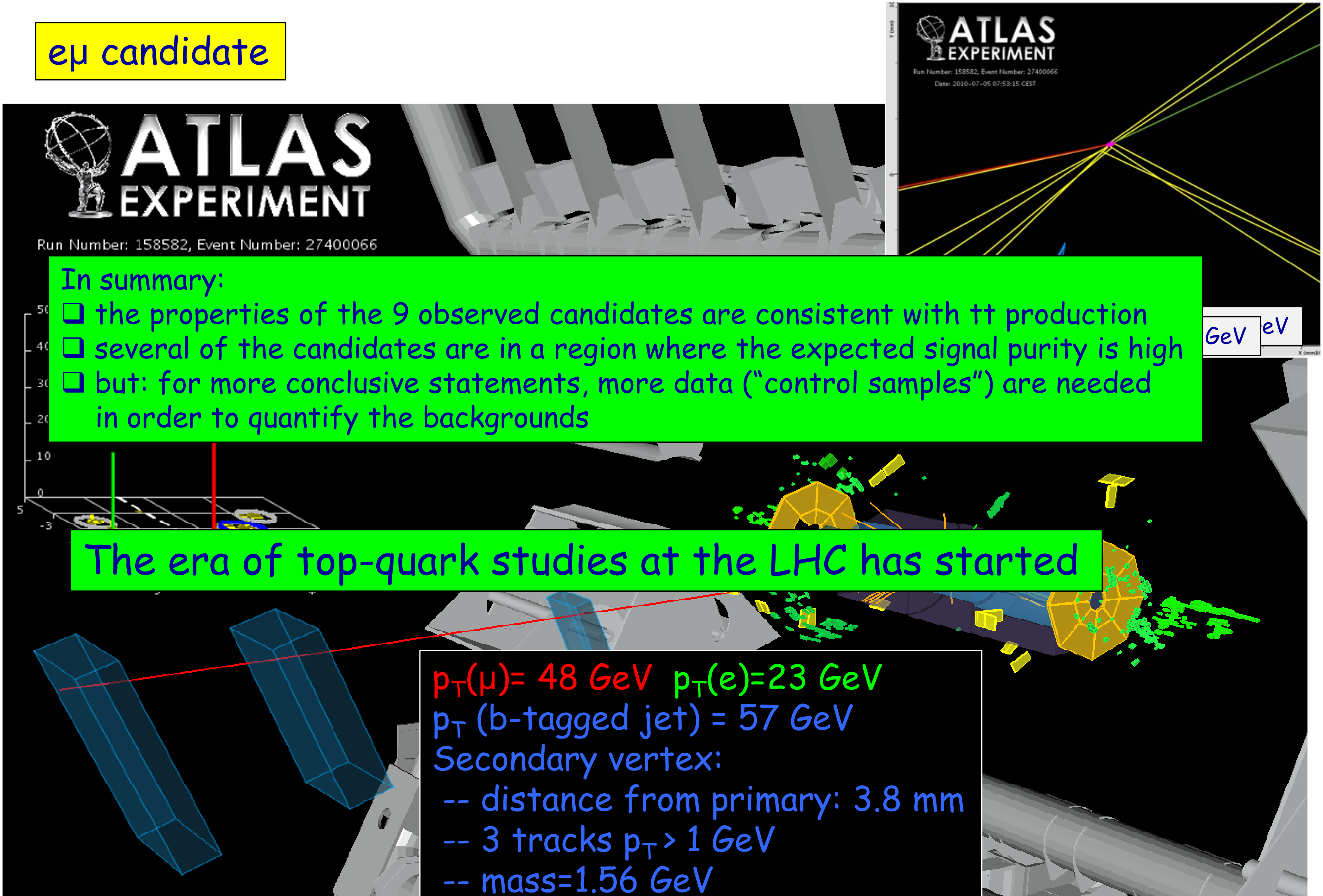
p_T (b-tagged jet) = 57 GeV

Secondary vertex:

-- distance from primary: 3.8 mm

-- 3 tracks p_T > 1 GeV

eμ candidate



In summary:

- the properties of the 9 observed candidates are consistent with tt production
- several of the candidates are in a region where the expected signal purity is high
- but: for more conclusive statements, more data ("control samples") are needed in order to quantify the backgrounds

The era of top-quark studies at the LHC has started

$p_T(\mu)$= 48 GeV $p_T(e)$=23 GeV
p_T (b-tagged jet) = 57 GeV
Secondary vertex:
-- distance from primary: 3.8 mm
-- 3 tracks p_T > 1 GeV
-- mass=1.56 GeV