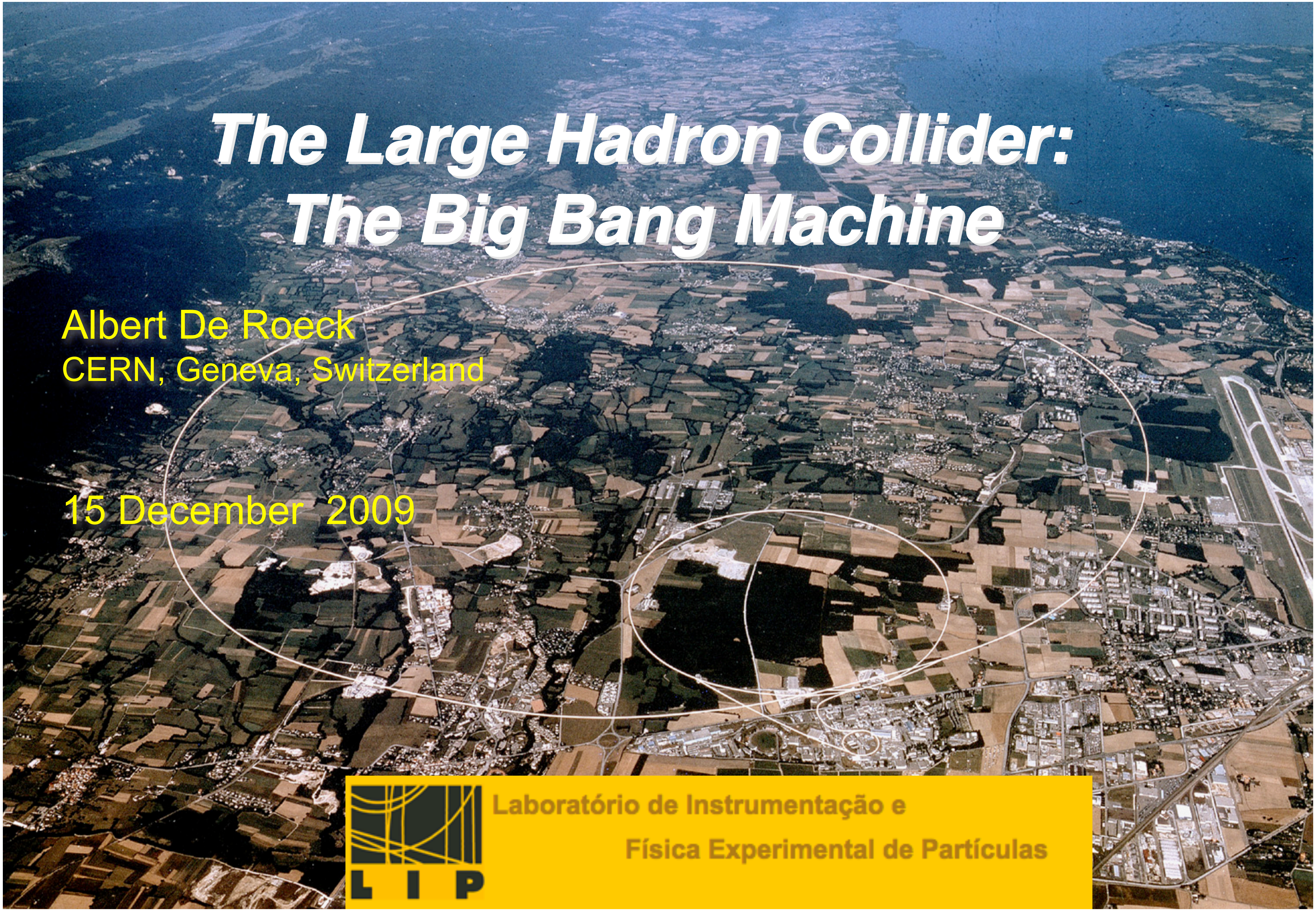


The Large Hadron Collider: The Big Bang Machine

Albert De Roeck

CERN, Geneva, Switzerland

15 December 2009

Laboratório de Instrumentação e Física Experimental de Partículas

LIP

Contents

In this talk I will present and discuss the most complex, most challenging and at the same time one of the most anticipated scientific instruments so far built by mankind:

The Large Hadron Collider (LHC), built at CERN, Switzerland

- What are the fundamental questions in particle physics?
- What is the Large Hadron Collider?
- What are the challenges of the collider and experiments?
- What is the science of the Large Hadron Collider?

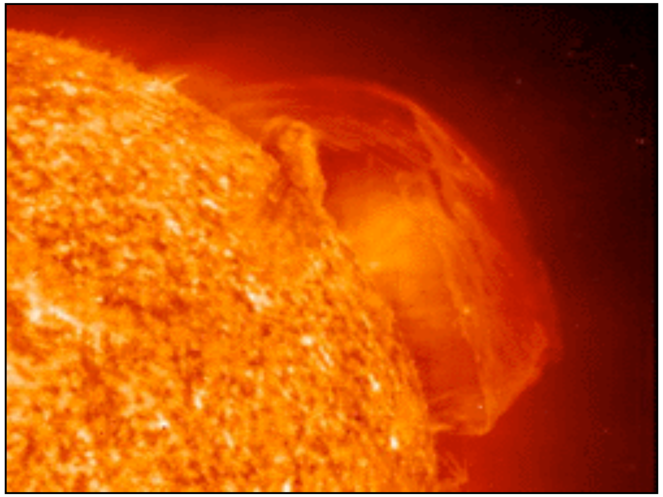

What is the world made of?
What holds the world together?
Where did we come from?

The Fundamental Forces of Nature

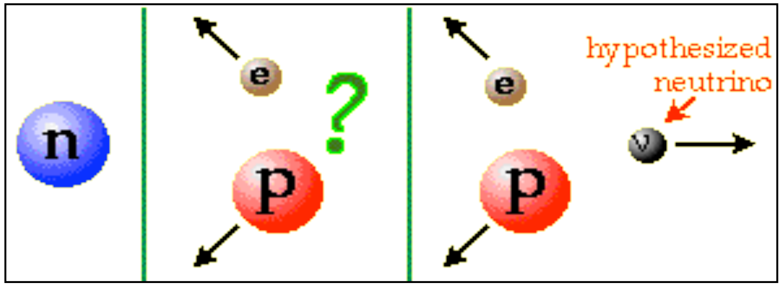
Electromagnetism:
gives light, radio, holds atoms together

Strong Nuclear Force:
holds nuclei together

Weak Nuclear Force:
gives radioactivity



together they make the Sun shine



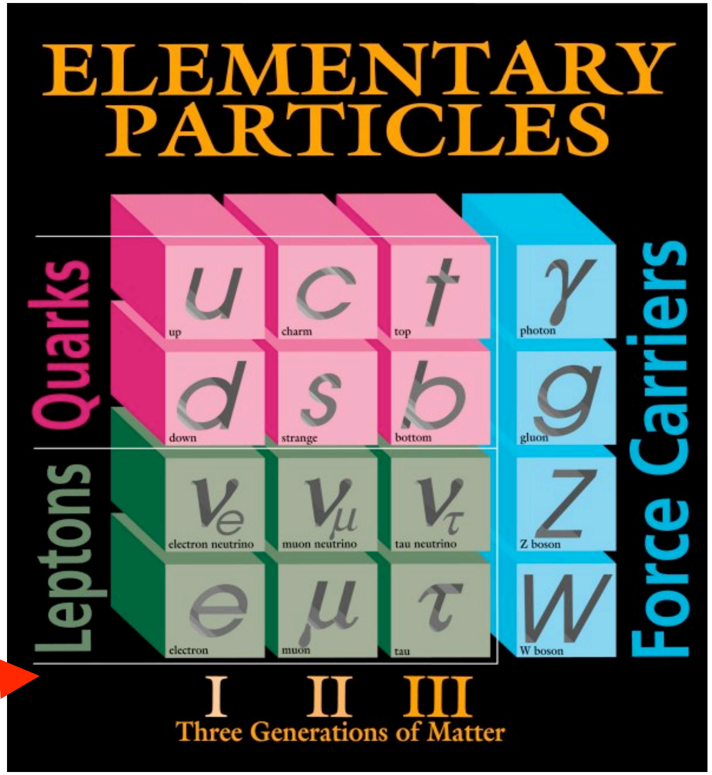
Gravity:
holds planets and stars together

The Standard Model in Particle Physics

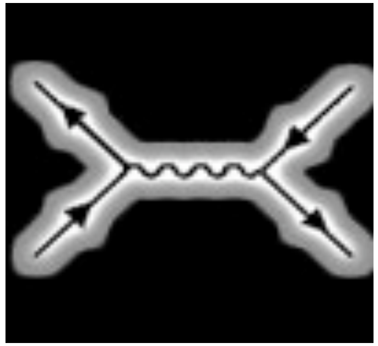
But not all questions solved:

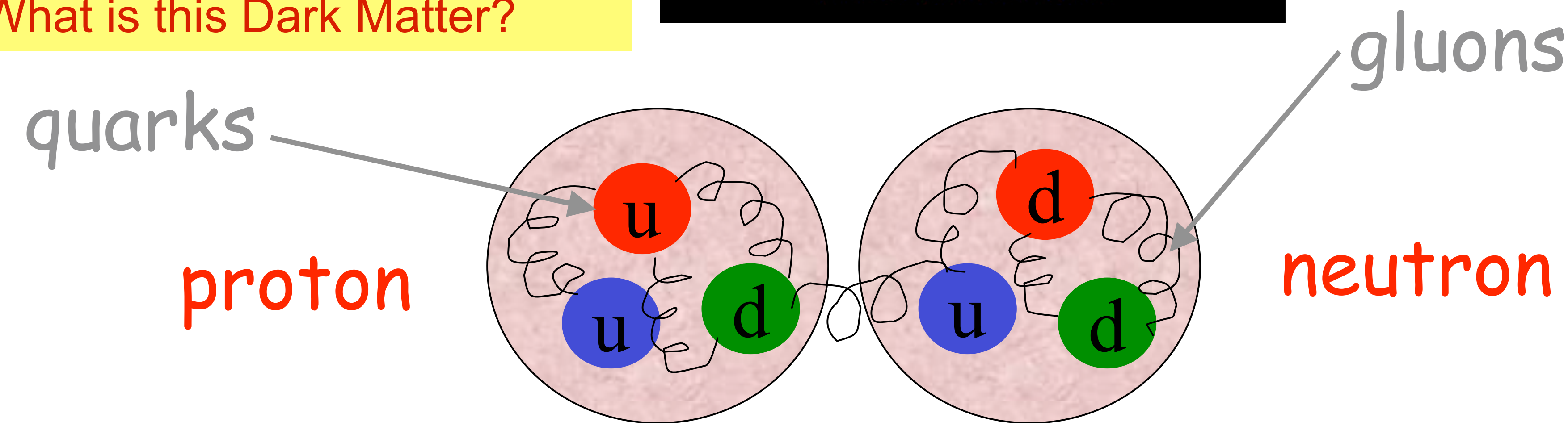
Why is the top quark much more heavy than the quarks
⇒Mass(top) = gold nucleus
What is the origin of mass?

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

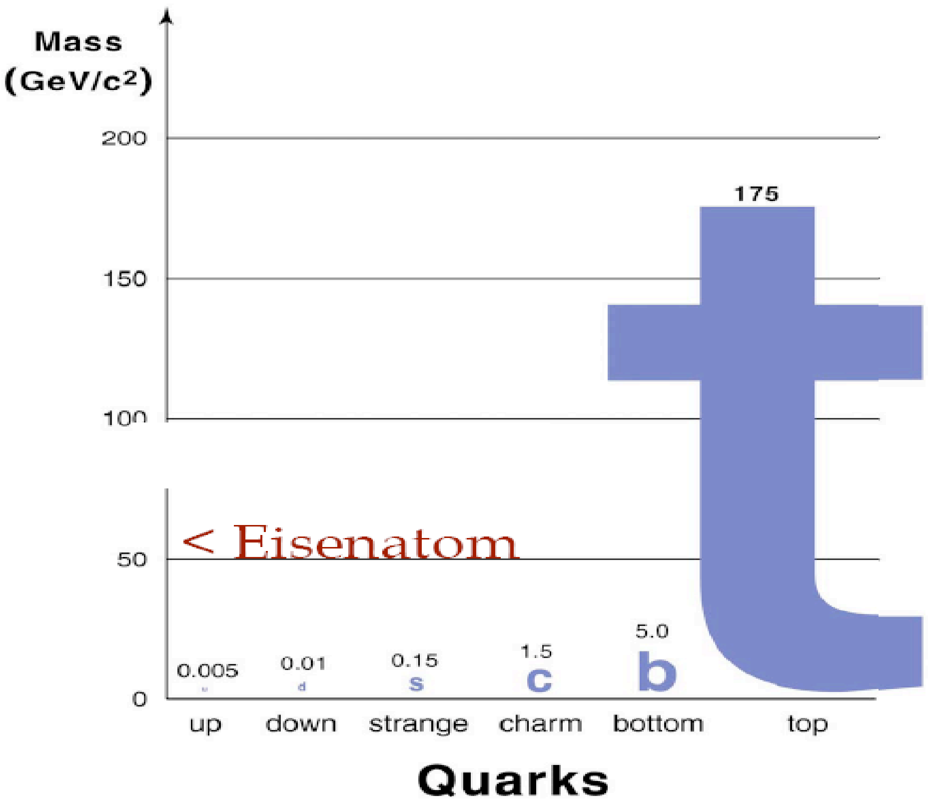




The Origin of Mass

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)



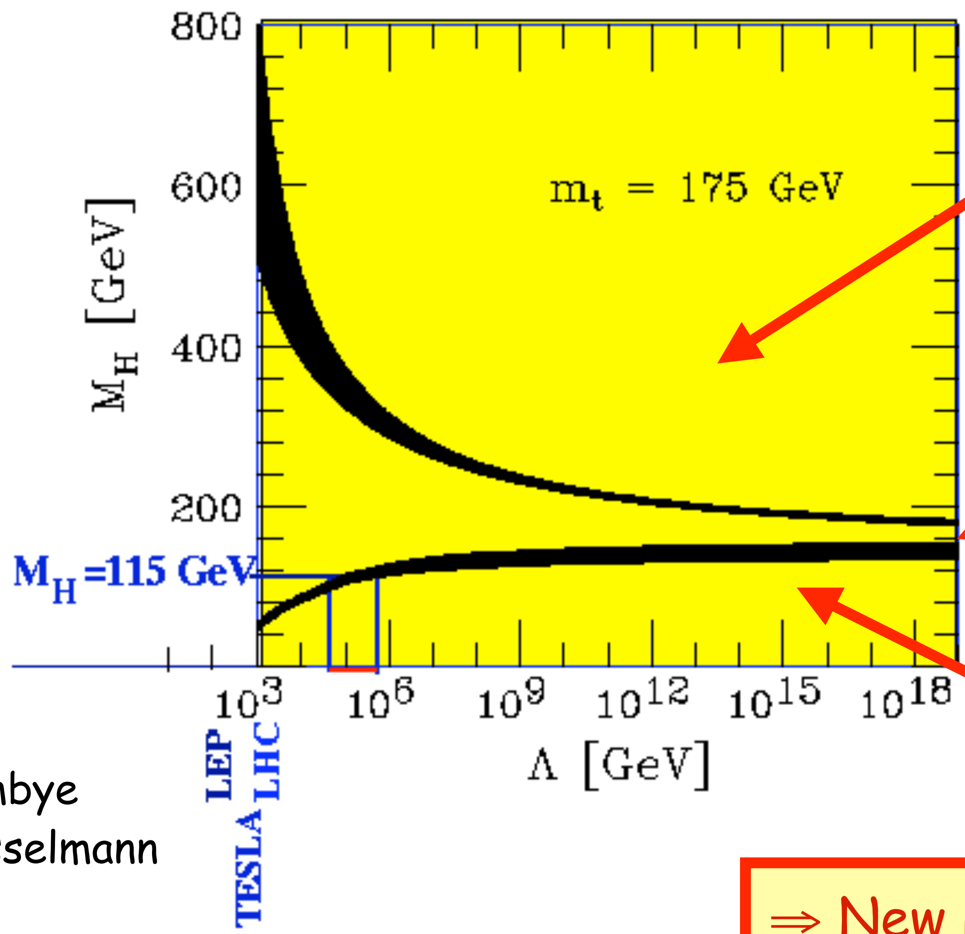
The Higgs (H) particle has been searched for since decades at accelerators, but not yet found…

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

Francois Englert

Higgs Mass?

A light Higgs implies that the Standard Model cannot be stable up to the GUT (= Grand Unified Theory) or Planck scale (10^{19} GeV)



Hambye
Riesselmann

The effective potential blows up, due to heavy top quark mass

Allowed corridor but needs strong fine-tuning...

The electroweak vacuum is unstable to corrections from scales $\Lambda \gg v = 246$ GeV

$\Rightarrow$ New Physics expected in O(TeV) range

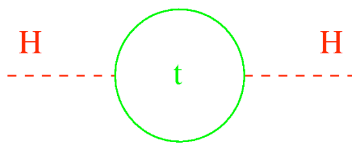
Why we believe the Standard Model is NOT the Ultimate Theory?

SM predictions confirmed by experiments (at LEP, Tevatron, SLAC, etc.) with precision $\approx 10^{-3}$ or better

Reasons for our scepticism :

- About 20 free parameters (masses of fermions and bosons, couplings
- Higgs: mass $m_H \approx 115$ GeV? Then New Physics for $\Lambda < 10^6$ GeV
- "Naturalness" problem :

  radiative corrections



  $\delta m_H^2 \sim \Lambda^2$ $\Rightarrow$ diverge for large Λ

  $\Rightarrow$ fine tuning!!

- "Hierarchy" problem: why $M_{EW}/M_{Planck} \sim 10^{-17}$?

+ contribution of EW vacuum to cosmological constant ($\sim v^4$) is ~ 55 orders of magnitudes too large !

+ flavour/family question, coupling unification, gravity incorporation, ν masses/oscillations, … Dark Matter. Dark Energy?

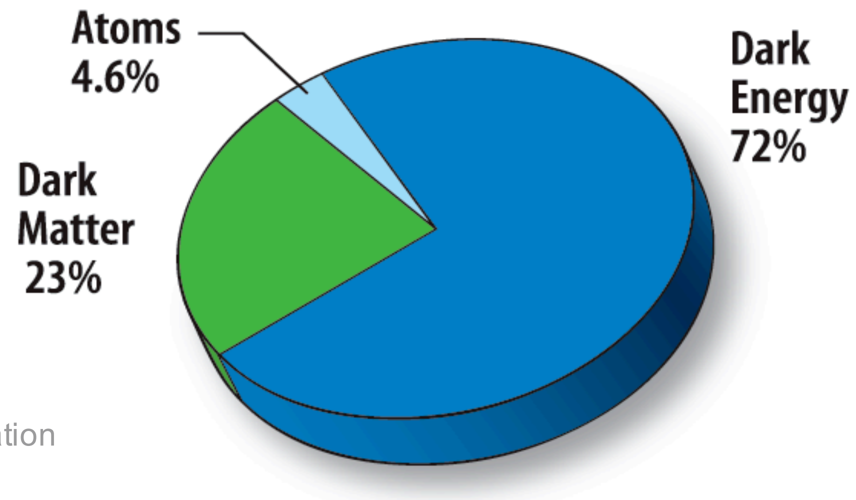
Dark Matter in the Universe

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

'Supersymmetric' particles ?

We shall look for them with the LHC

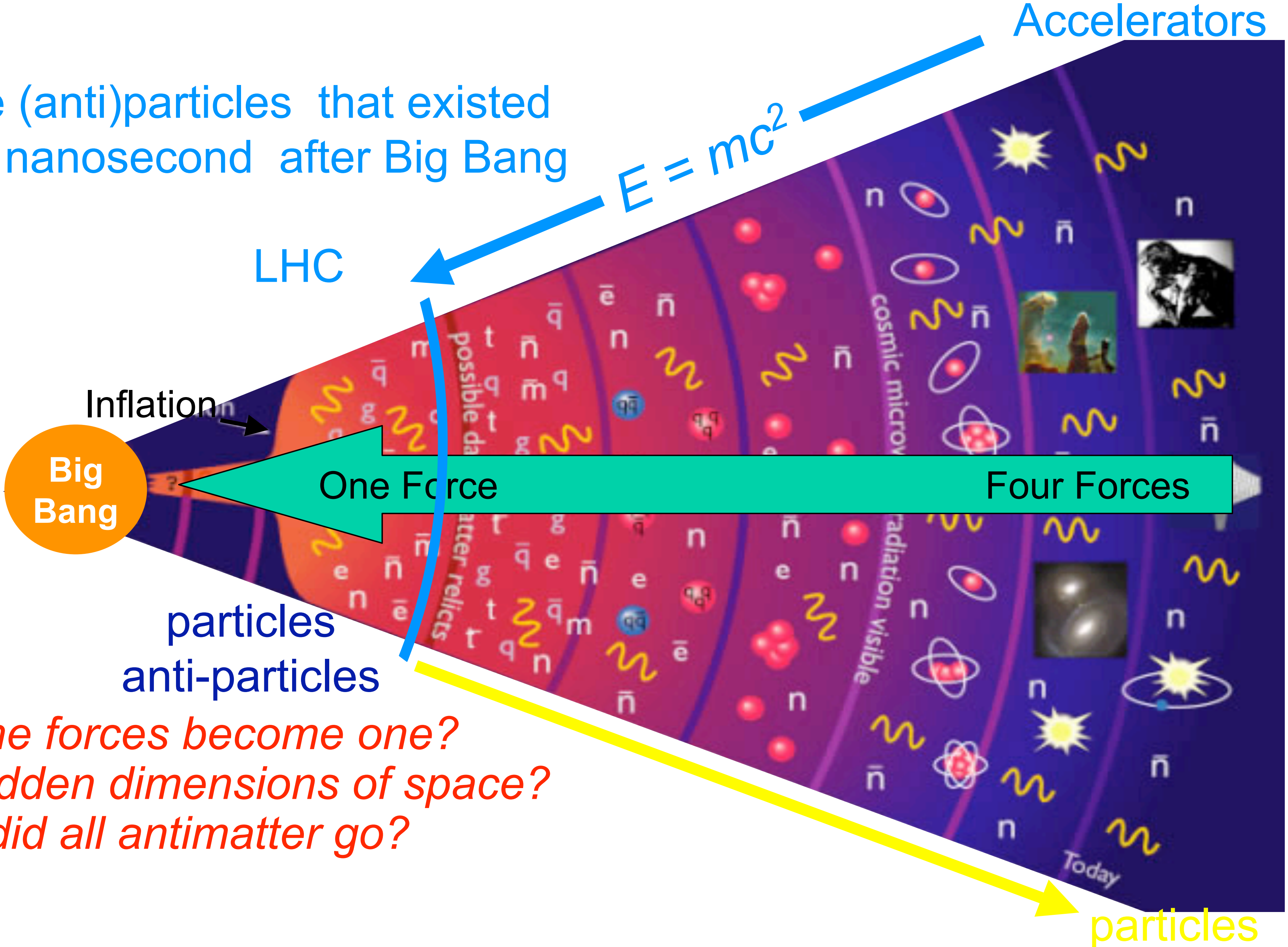
F. Zwicky 1898-1974



What can we expect?
Ask an (un)baised theorist:

Murayama LP03

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

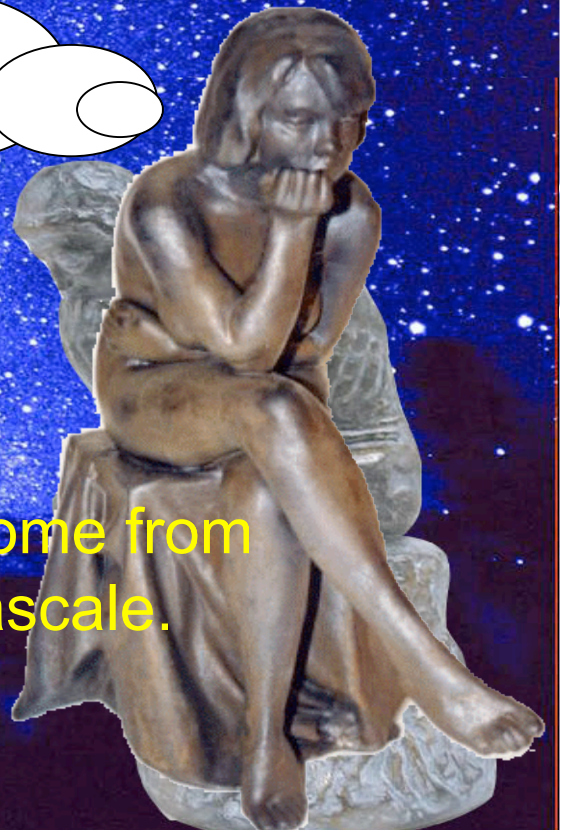


Do all the forces become one?
Extra hidden dimensions of space?
Where did all antimatter go?

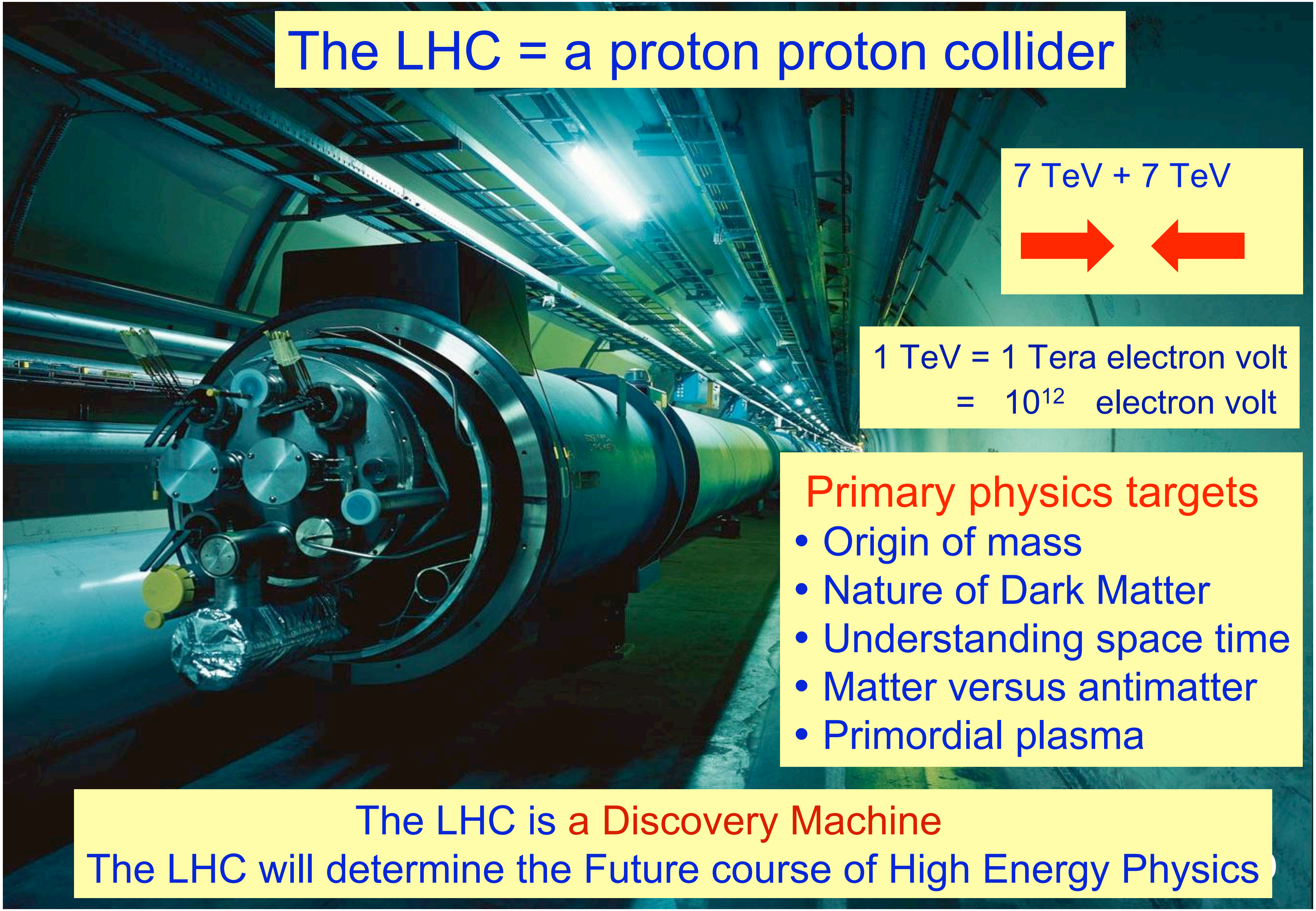
1. Are there undiscovered principles of nature: New symmetries, new physical laws?
2. How can we solve the mystery of dark energy?
3. Are there extra dimensions of space?
4. Do all the forces become one?
5. Why are there so many kinds of particles?
6. What is dark matter? How can we make it in the laboratory?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

"Quantum Universe" and
"Discovering the Quantum Universe"

Evolved Thinker

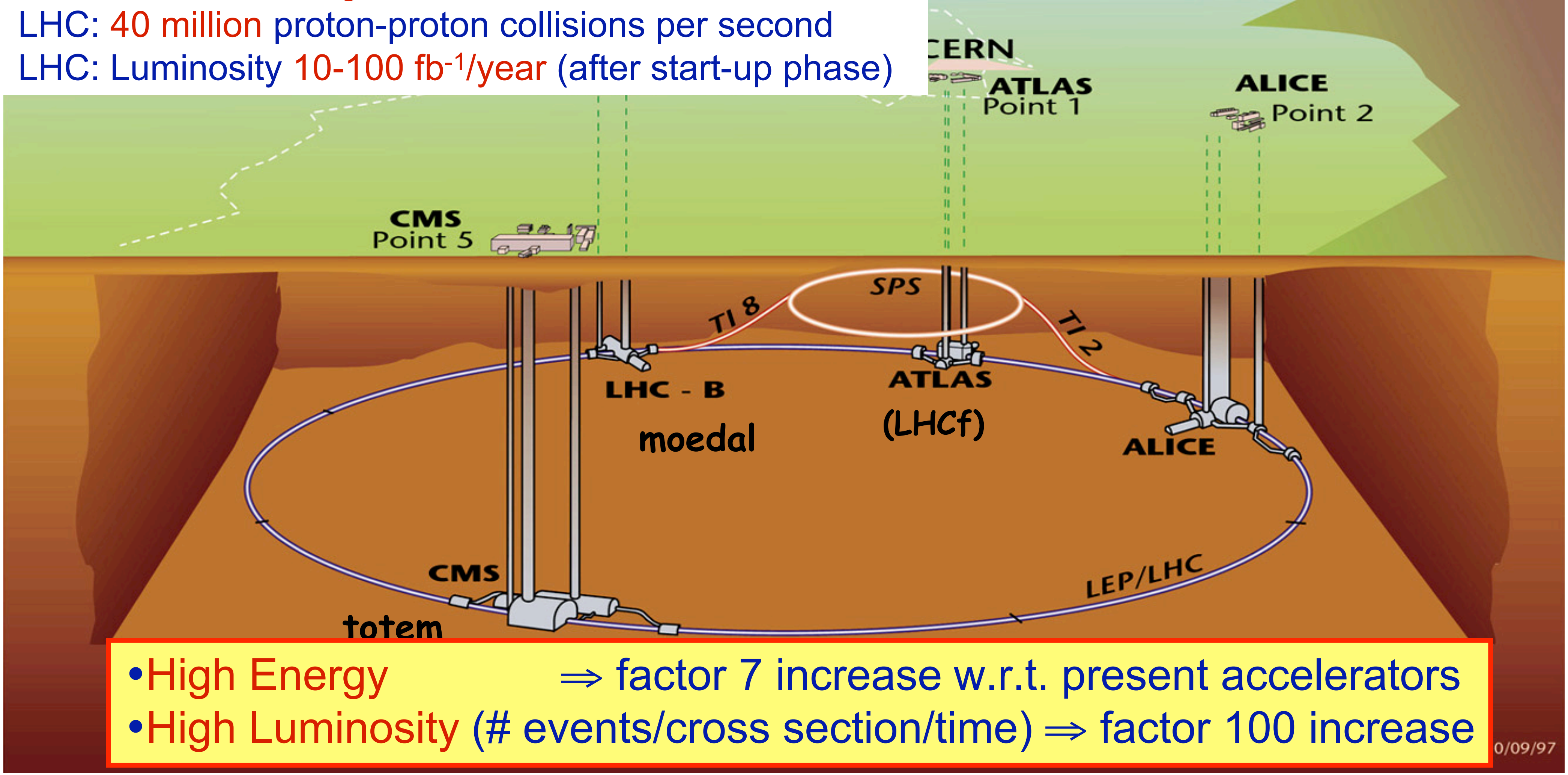


Discoveries and breakthroughs will likely come from Energy Frontier Accelerators at the Terascale.


The LHC = 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

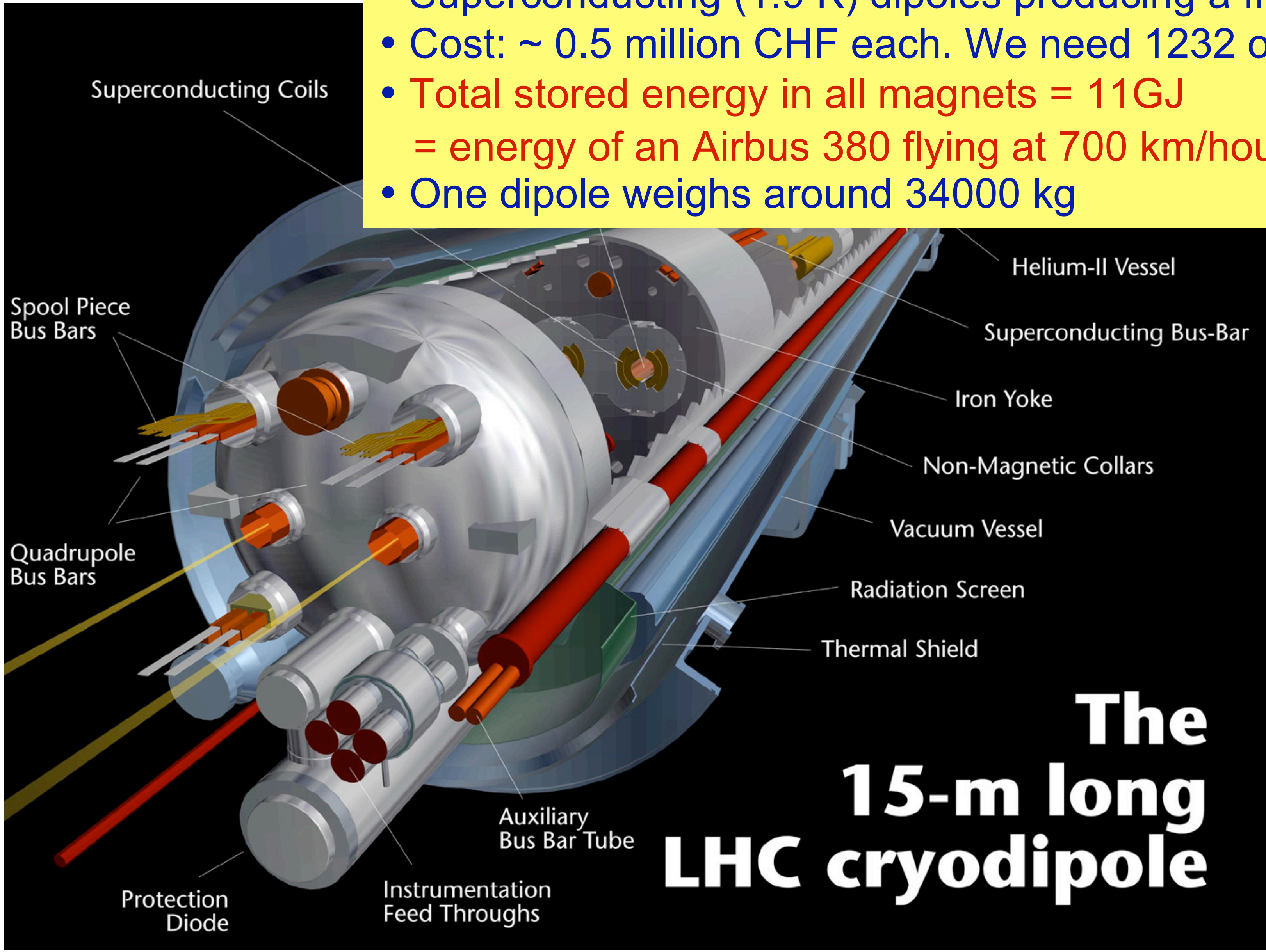
LHC is 100m underground
LHC is 27 km long
Magnet Temperature is 1.9 Kelvin = -271 Celsius
LHC has ~ 9000 magnets
LHC: 40 million proton-proton collisions per second
LHC: Luminosity 10-100 fb^{-1}/year (after start-up phase)



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

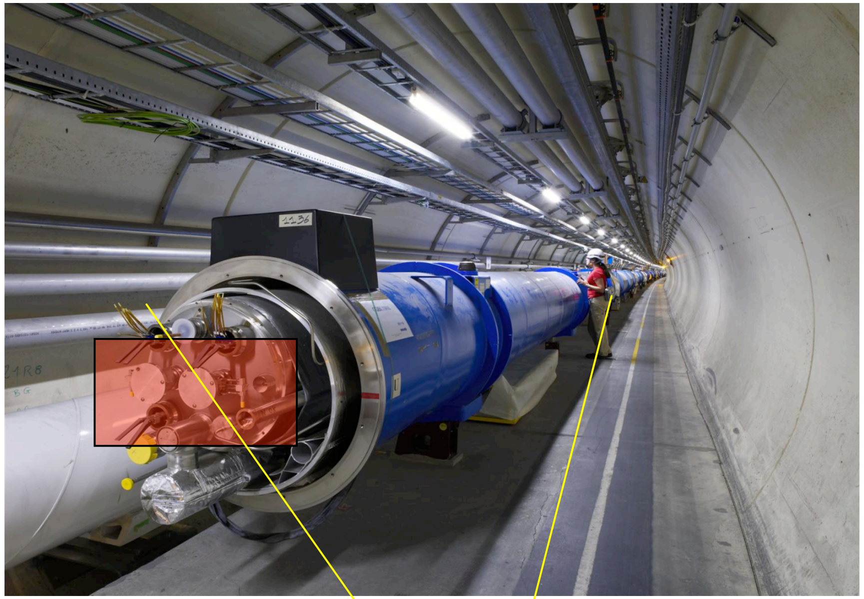
The Cryodipole Magnets

- 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.

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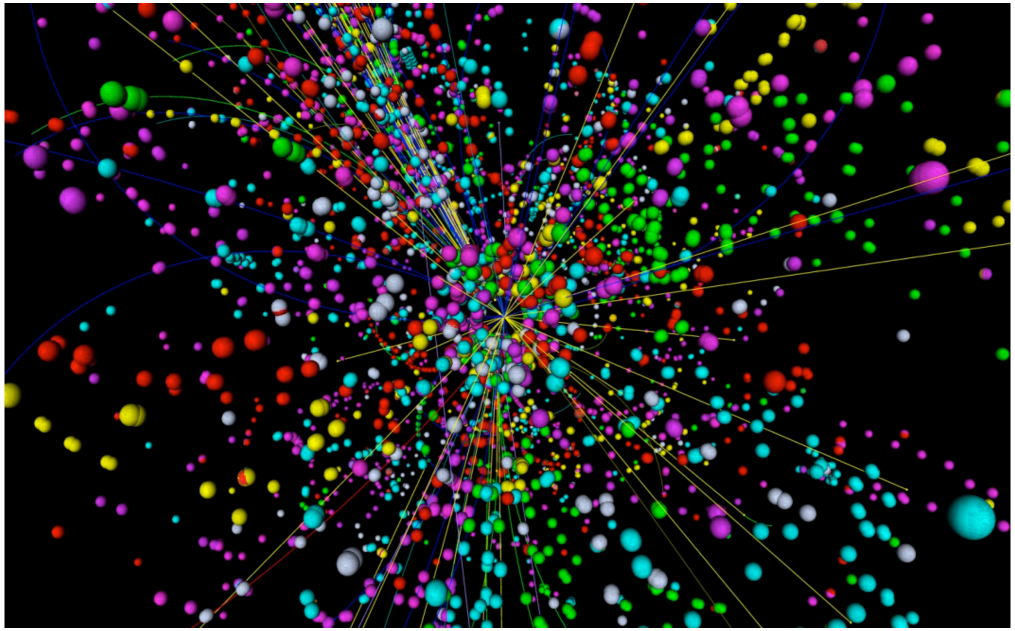
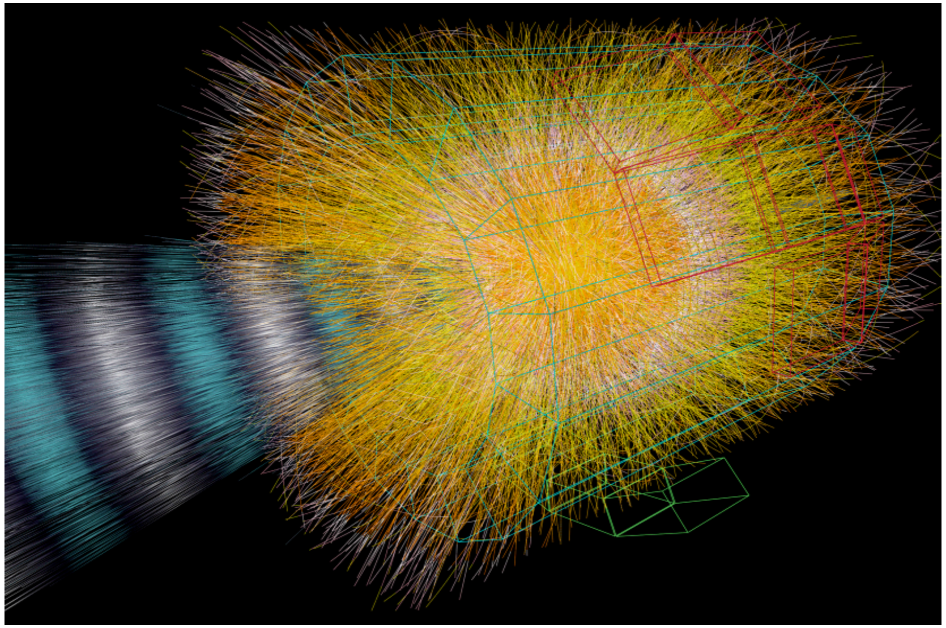
LHC facts

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.

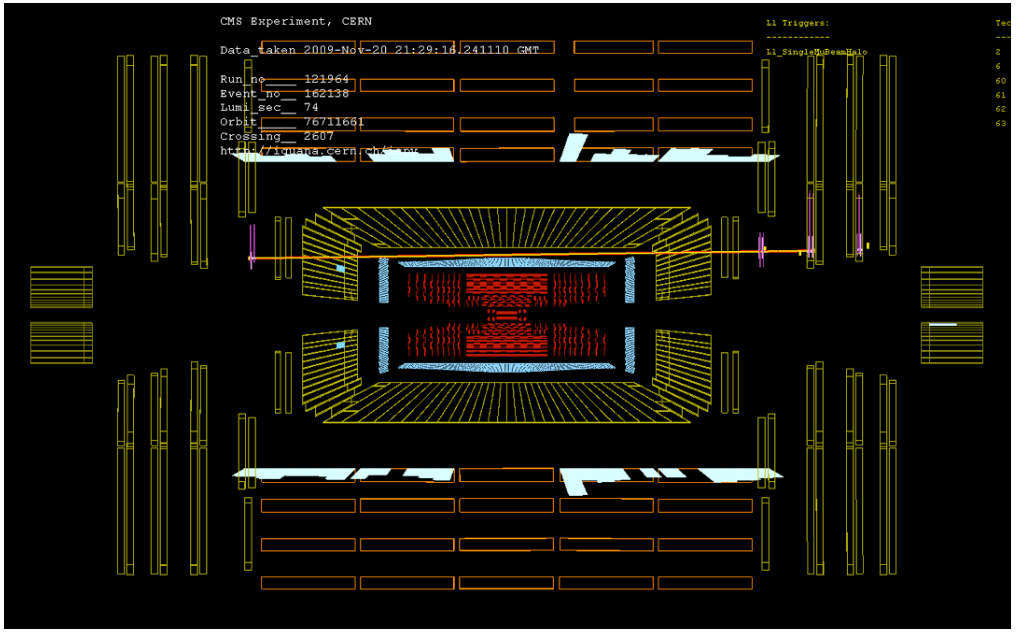
18

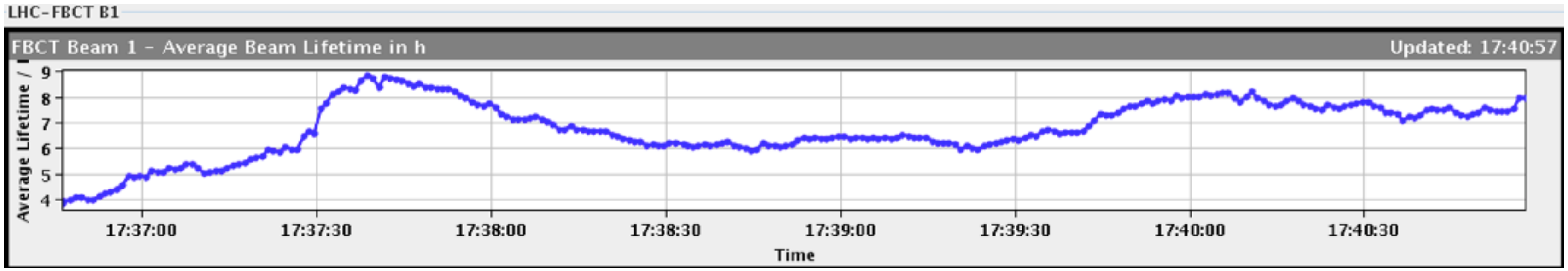
The LHC machine is fully installed and was ready to start operation with single beams on 10th September 2008, but it is now delayed until November 2009 after an incident that happened last year on 19th September 2008

Restart of the LHC November 2009

20/11/09: …A few hours after the startup of the machine

⇒ Keep beam 1 in the machine for over an hour…





The Grand Plan

- Essential 450 GeV commissioning
- Machine protection commissioning 1
- Experiments' magnets at 450 GeV
- 450 GeV collisions
- Ramp commissioning to 1.2 TeV
- Machine protection commissioning 1.5
- First collisions at 1.2 TeV
- System/beam commissioning | Machine protection commissioning 2
- 3.5 TeV beam & first collisions
- Full machine protection qualification
- Pilot physics

Beam 'safety'

Energy	'Safe'	Pretty Safe
450 GeV	1 e12	1 e11
1 TeV	2.5 e11	2.5 e10
3.5 TeV	3.0 e10	5 e9

5 TeV/Beam in 2010?

Exciting Times !! : Summary of the events

- November: Splashes in the experiments.. The beam is back!
- Friday November 20: First circulating beams
- Monday November 23: First collisions at 900 GeV (few 100 events/exp)

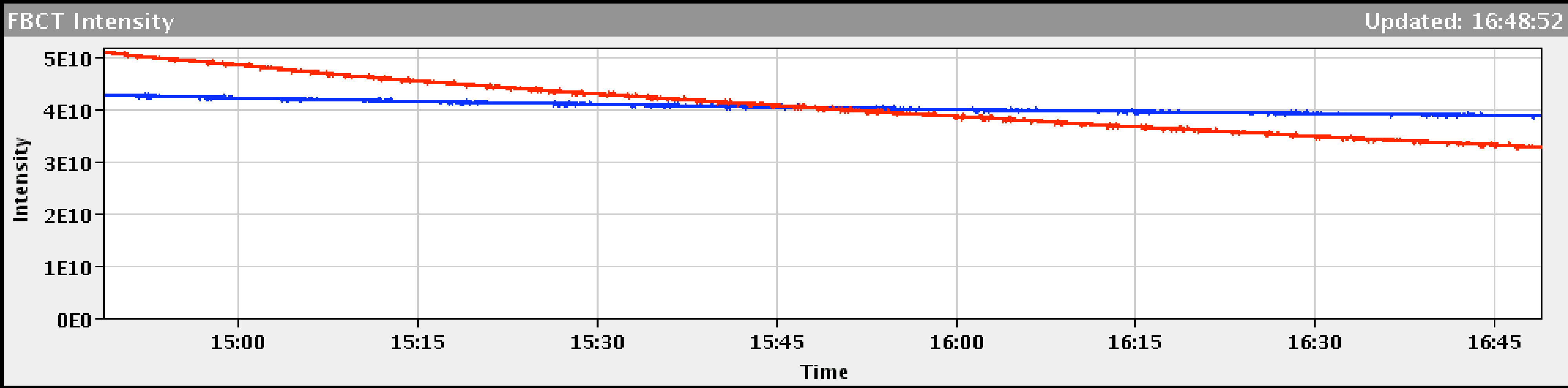
  ⇒The LHC became a collider
- Tuesday November 24: First acceleration from 450 GeV to 560 GeV

  ⇒The LHC became an accelerator
- Tuesday December 8: Acceleration to 1.18 TeV World Record!
- Monday December 14: 1.5 hrs of collisions at 2.36 TeV
- LHC will stop for 2009 today December 16 18:00 (GVA time)

  ⇒ Generally LHC came on line "easy" this year
- But still on a learning curve (occasional cryogenics problems etc…)

BEAM SETUP: STABLE BEAMS

Energy:	450 GeV	I(B1):	4.51e+10	I(B2):	3.71e+10



Comments 12-12-2009 14:09:39 :

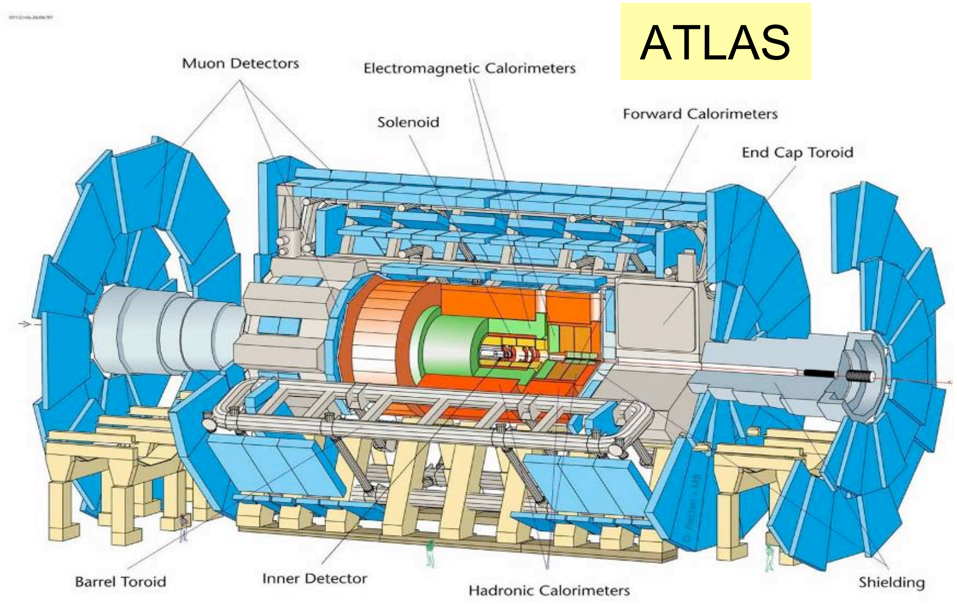
*** stable beams ***

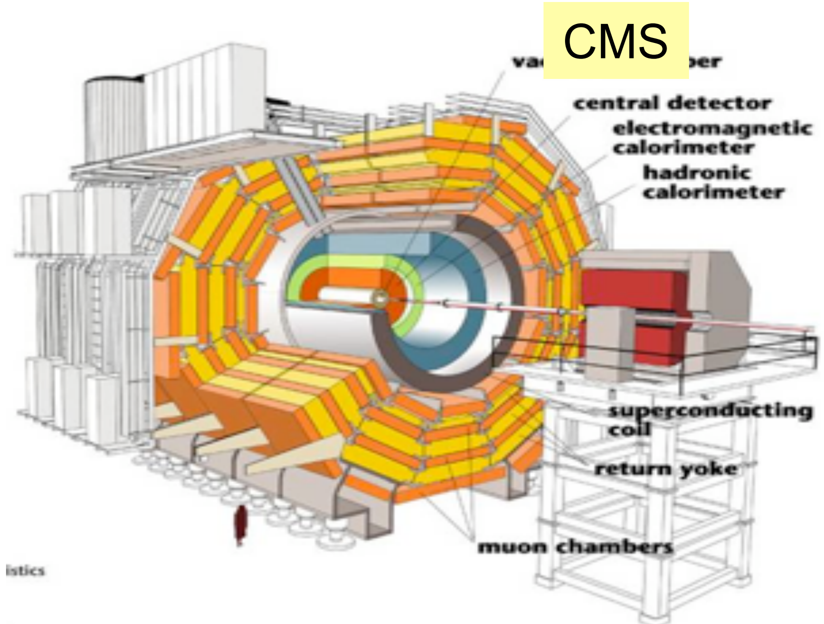
Stable beam for hours
16 bunches/beam
1.18 TeV/beam

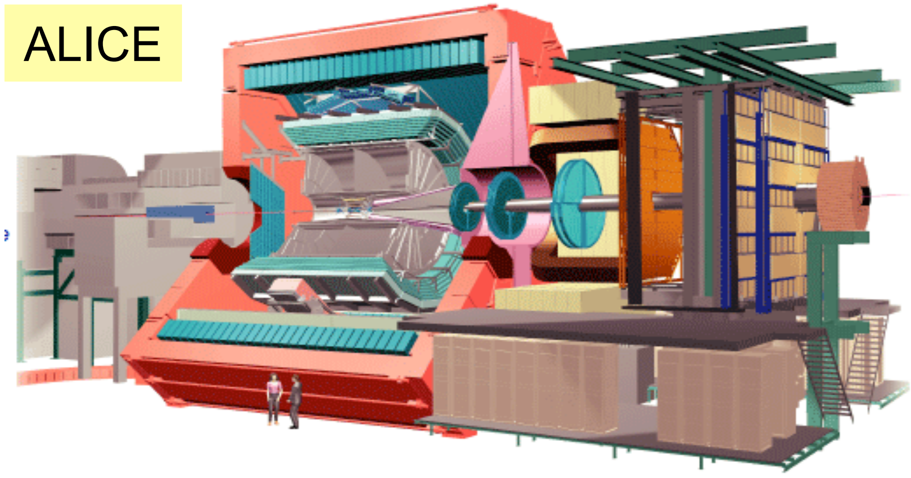
SMP Flags

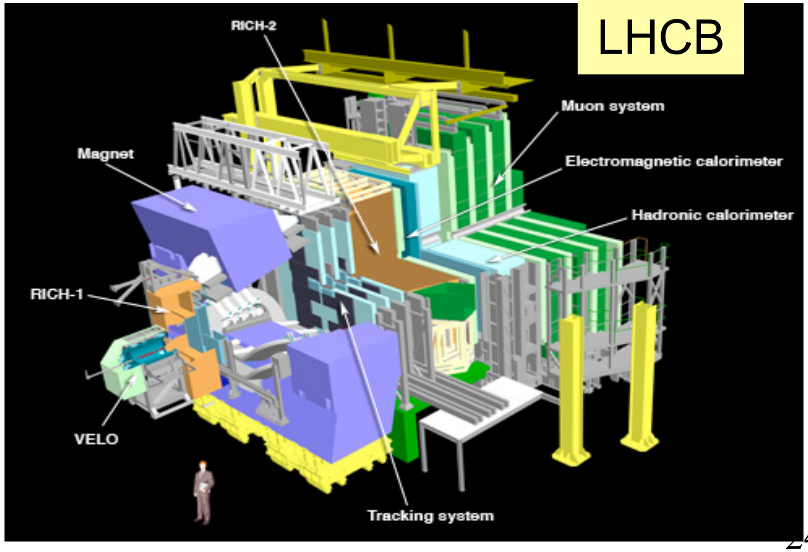
	Beam 1	Beam 2
Global Beam Permit	true	true
Setup Beam	true	true
Beam Presence	true	true
Moveable Devices Allowed In	true	true
Stable Beams	true	true

The Four Main LHC Experiments

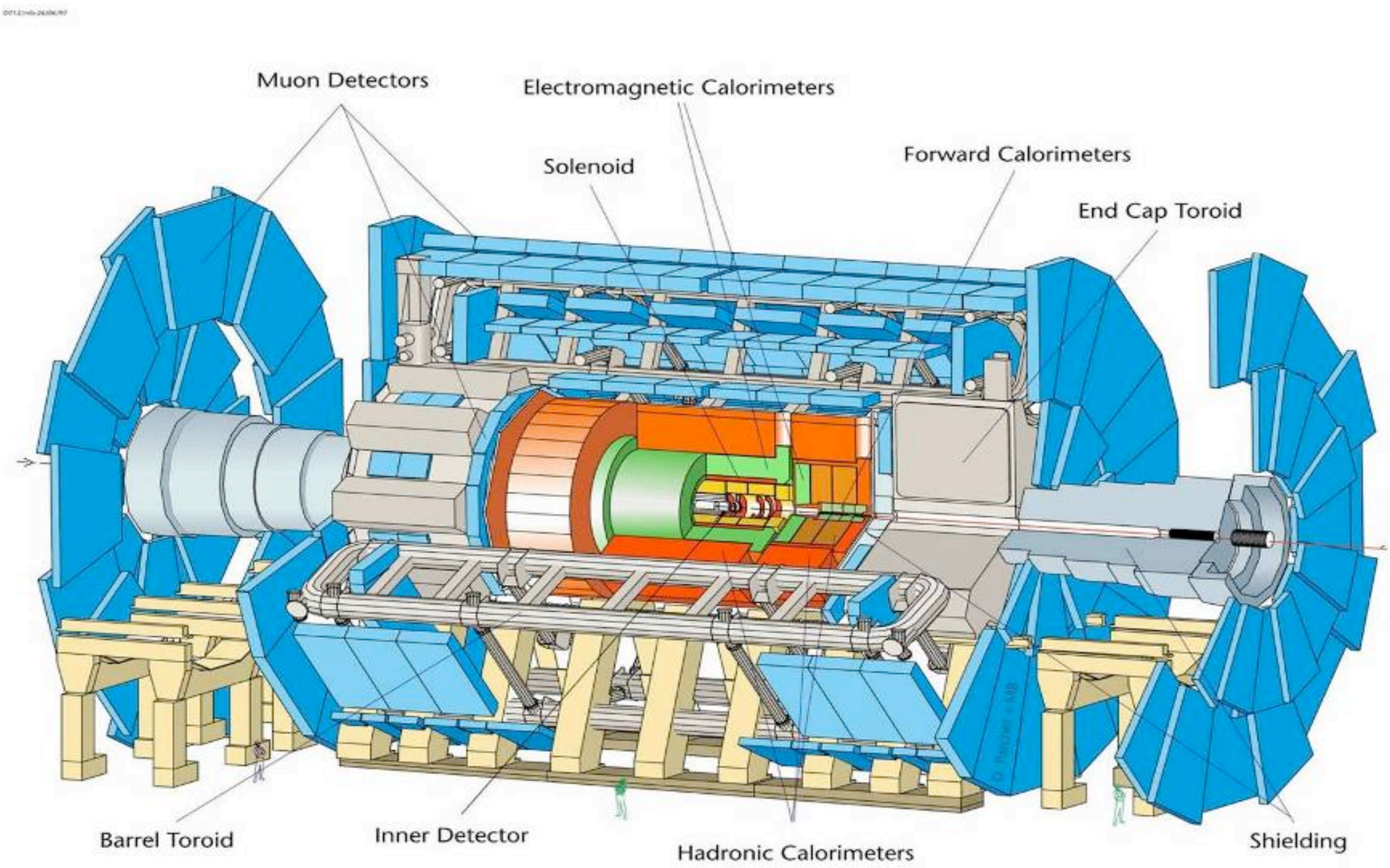






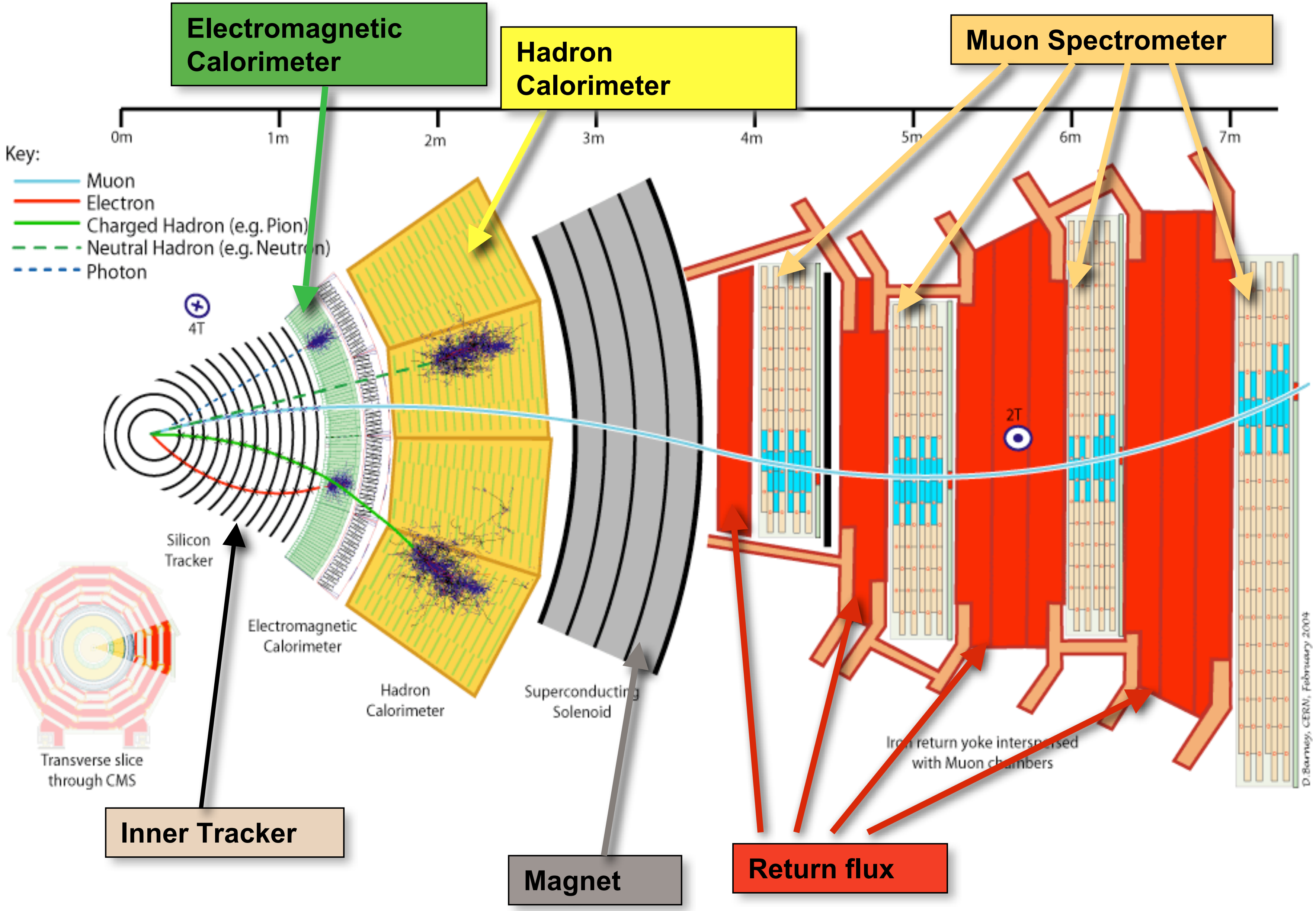


[redacted]



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

Particles in the Detector



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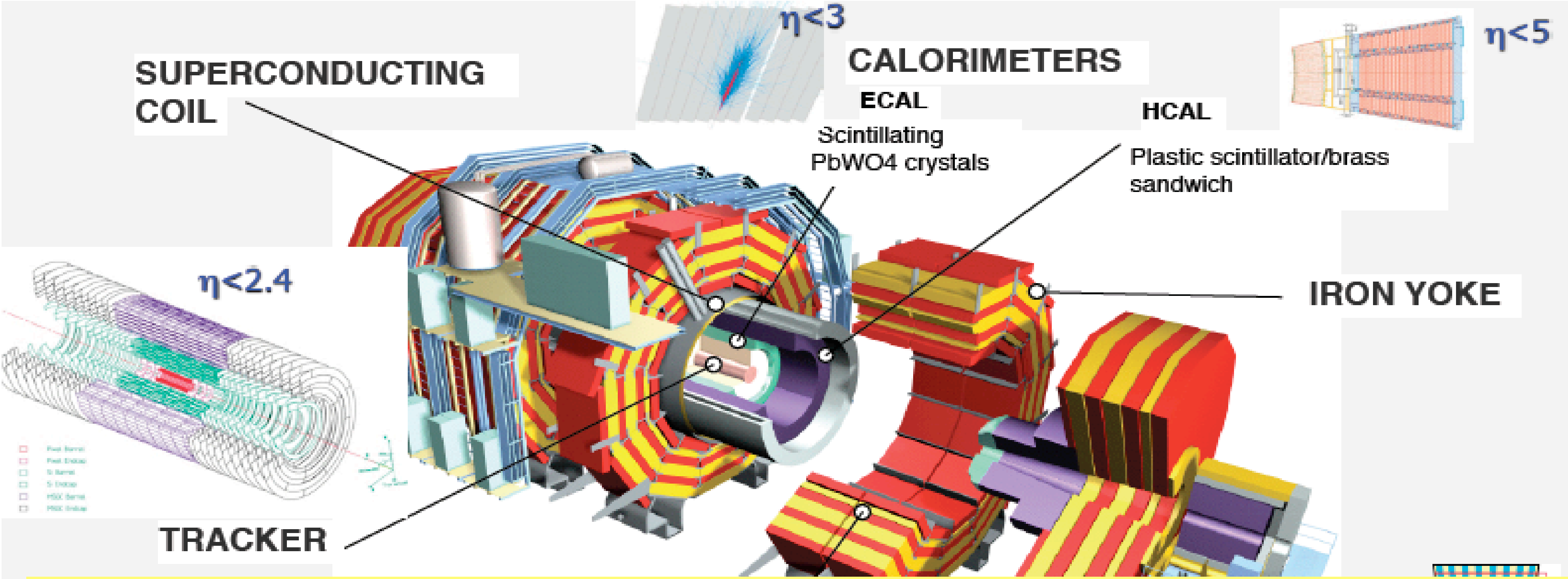
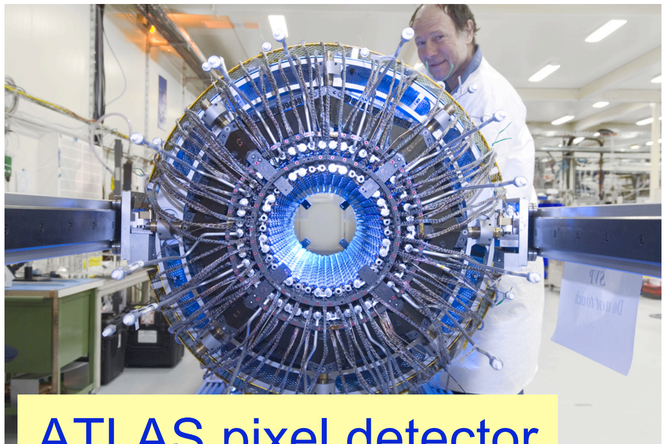
The Compact Muon Solenoid Experiment



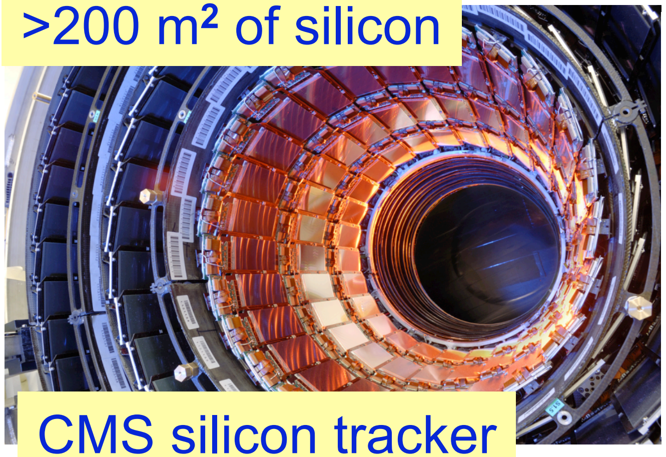
In total about
~100 000 000 electronic channels
Each channel checked
40 000 000 times per second (collision rate is 40 MHz)
An on-line trigger selects events and reduces the rate from 40MHz to 100 Hz
Amount of data of just one collisions
>1 500 000 Bytes

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

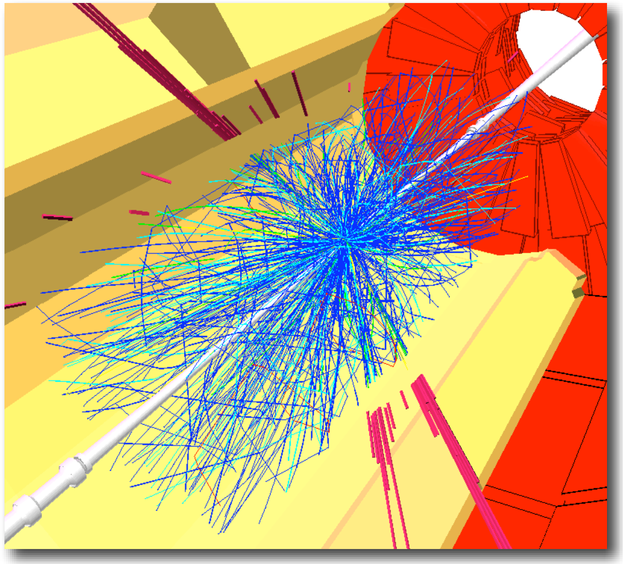

ATLAS pixel detector

>200 m² of silicon

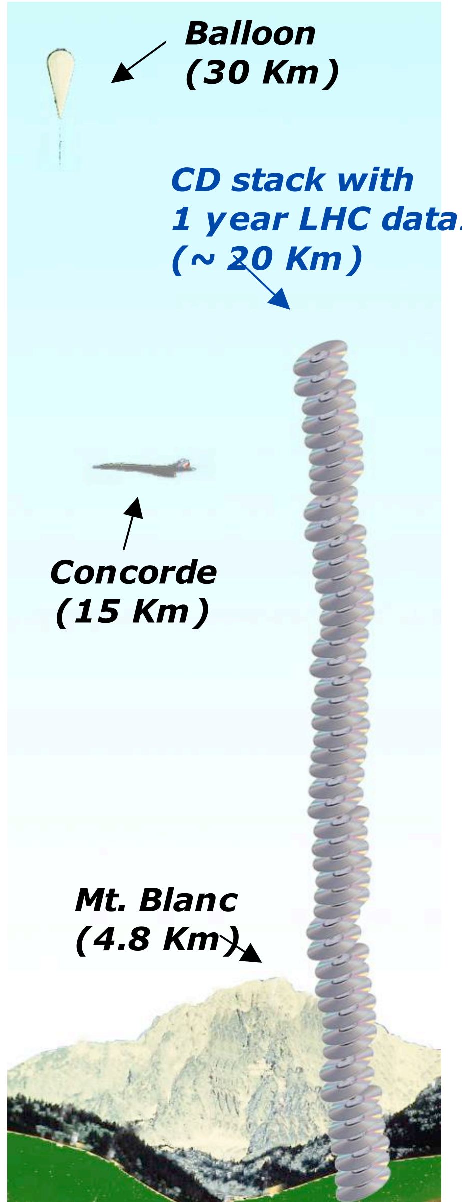

CMS silicon tracker

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...)

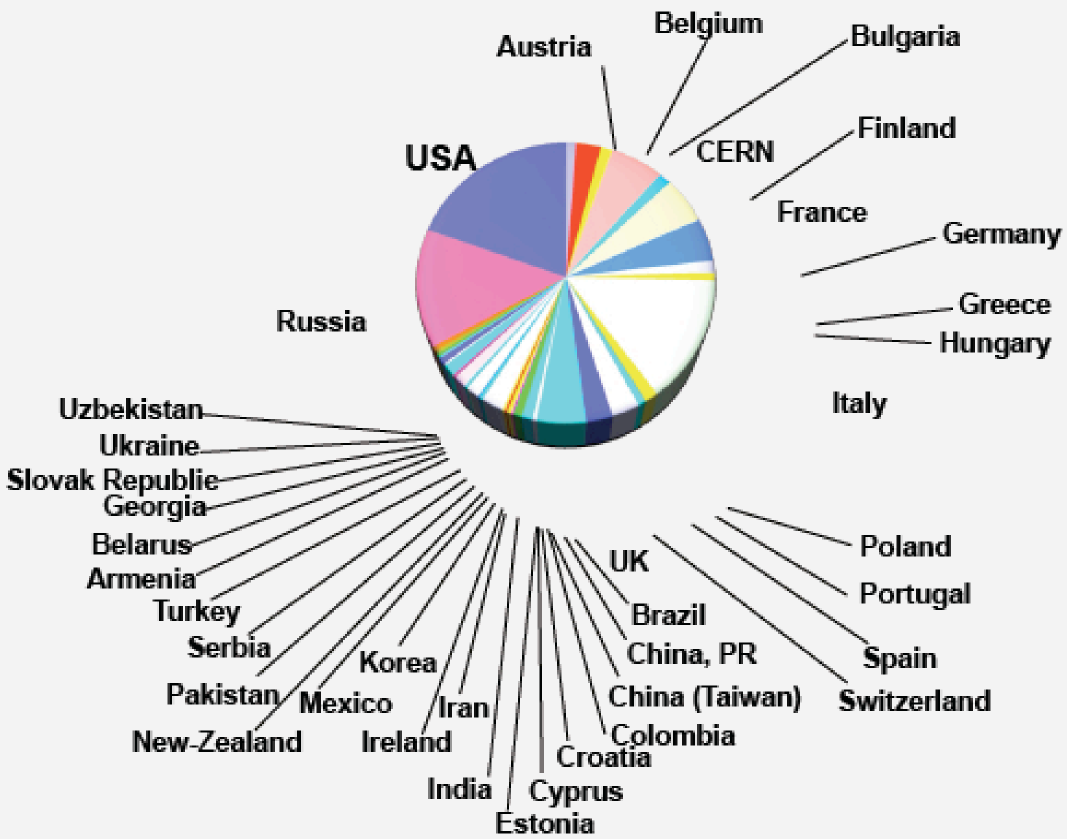
The CMS Collaboration

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



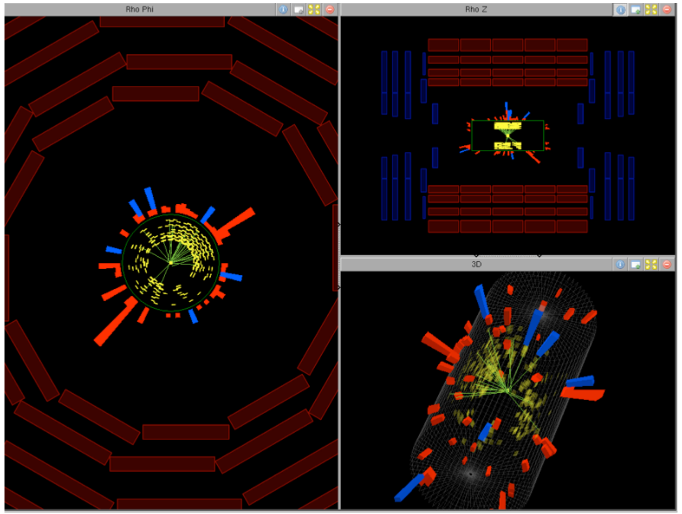
May, 04 2006/gm
http://cmsdoc.cern.ch/pictures/cmsorg/overview.html

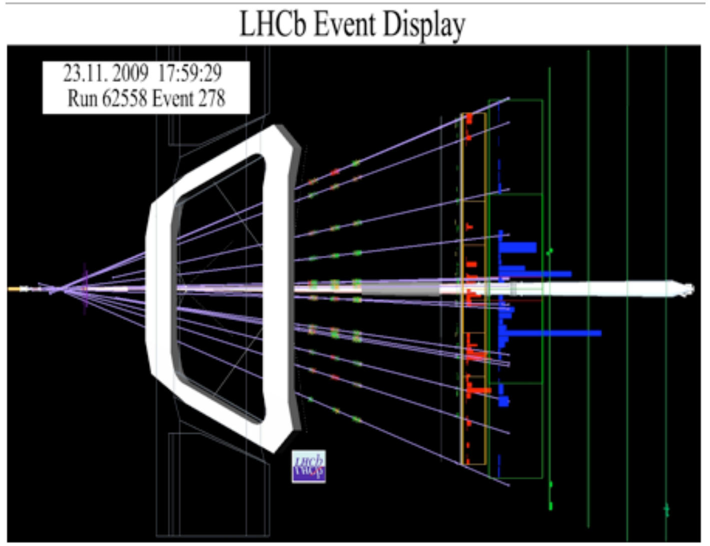
Now: 2900 Physicists 184 Institutions 38 countries

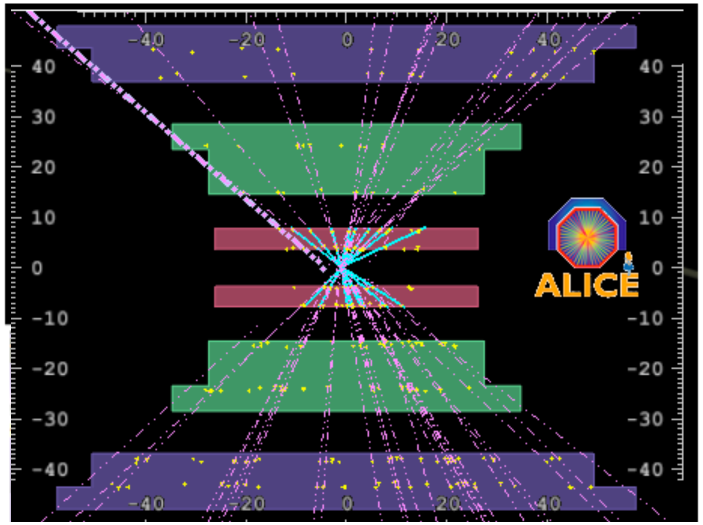
India is an important collaborator in CMS
$\Rightarrow$ detector, software/computing/physics…

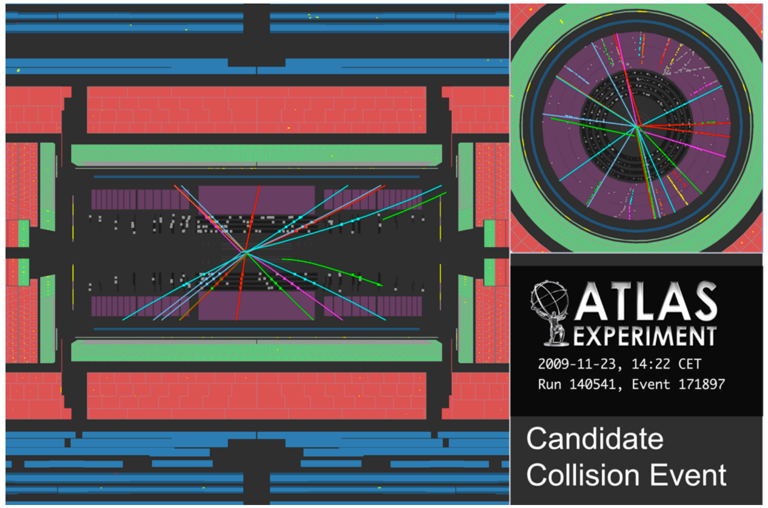
First Collisions in the Experiments

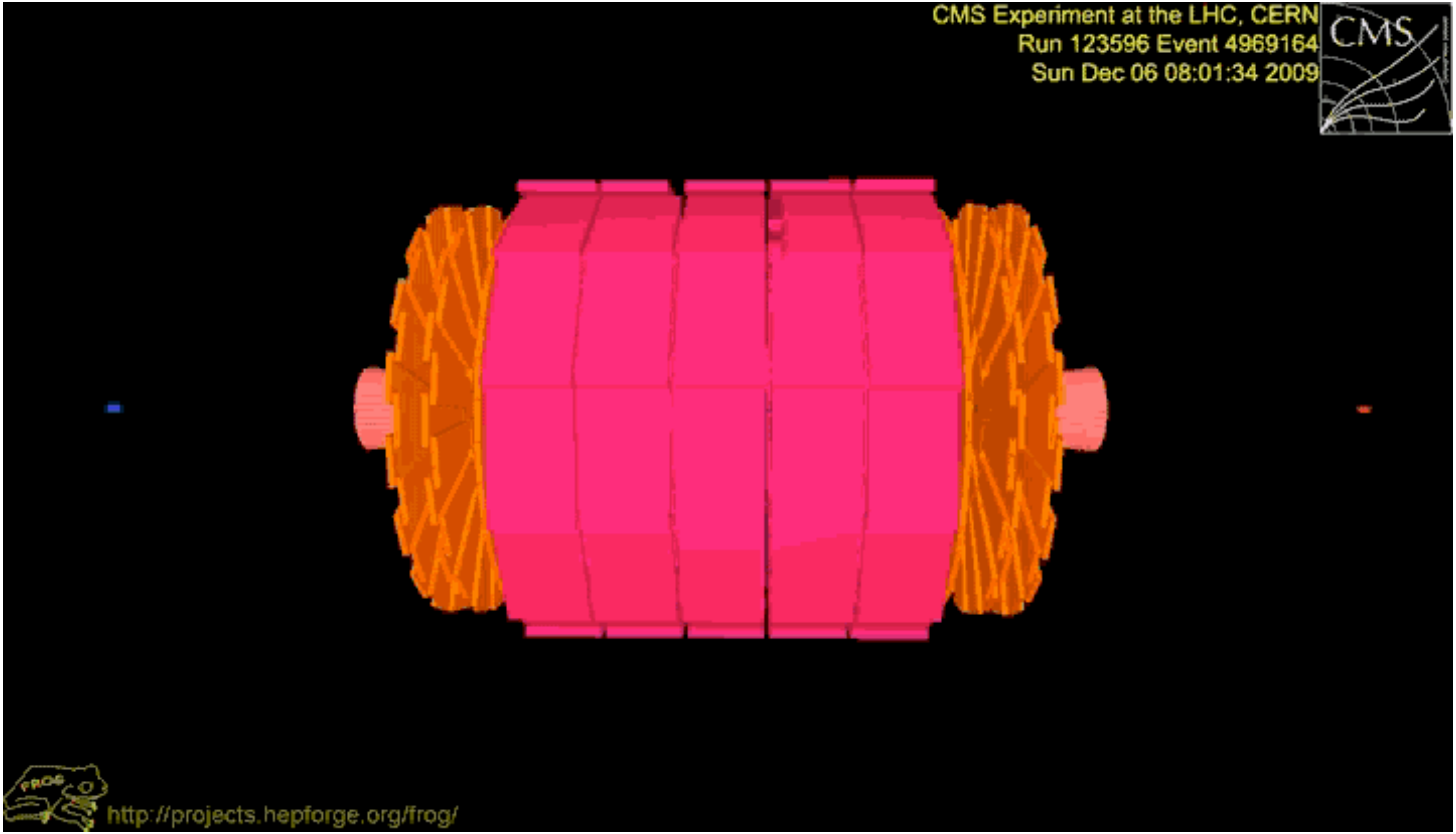
23/11 First 'trial' collisions in the experiments

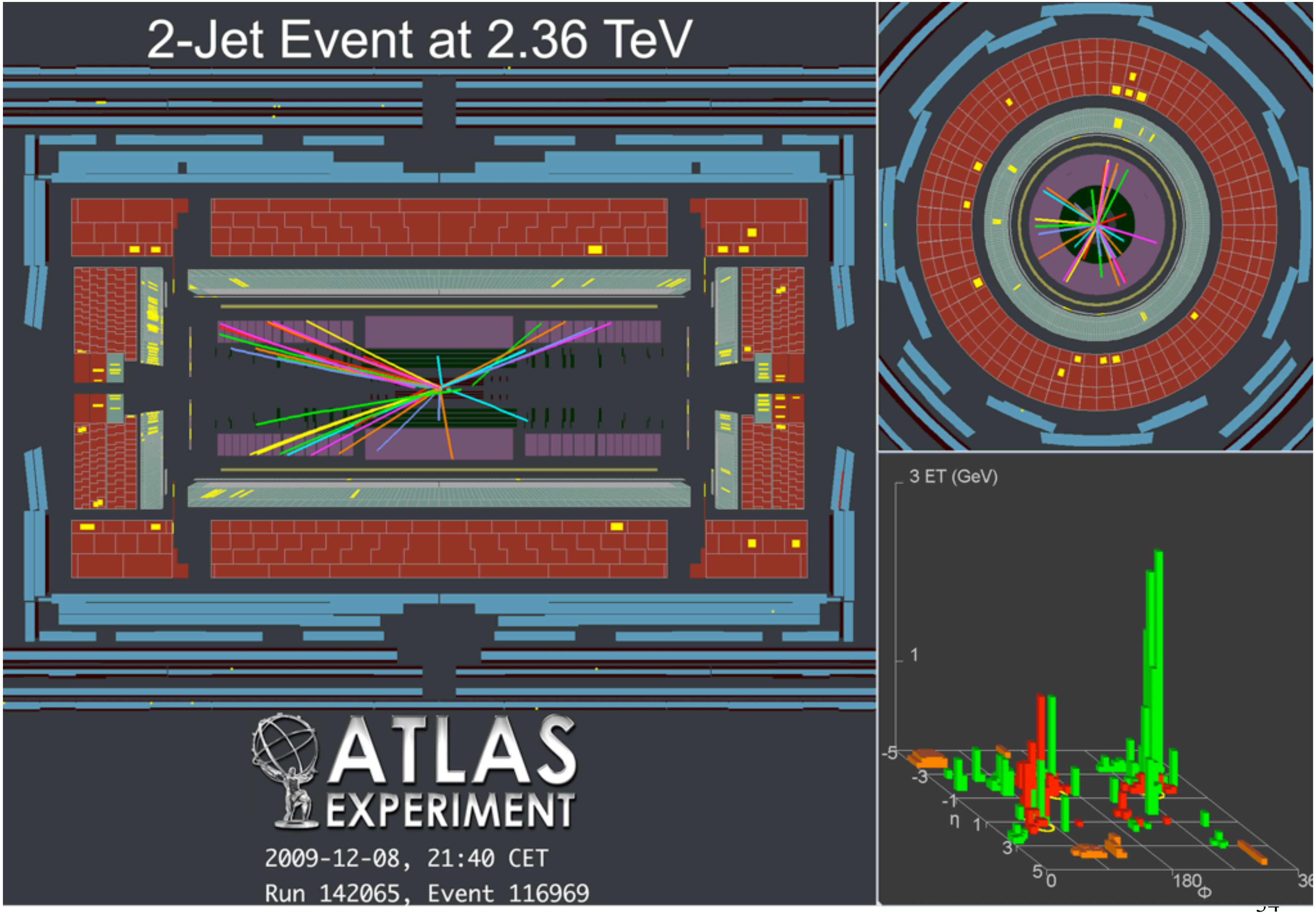






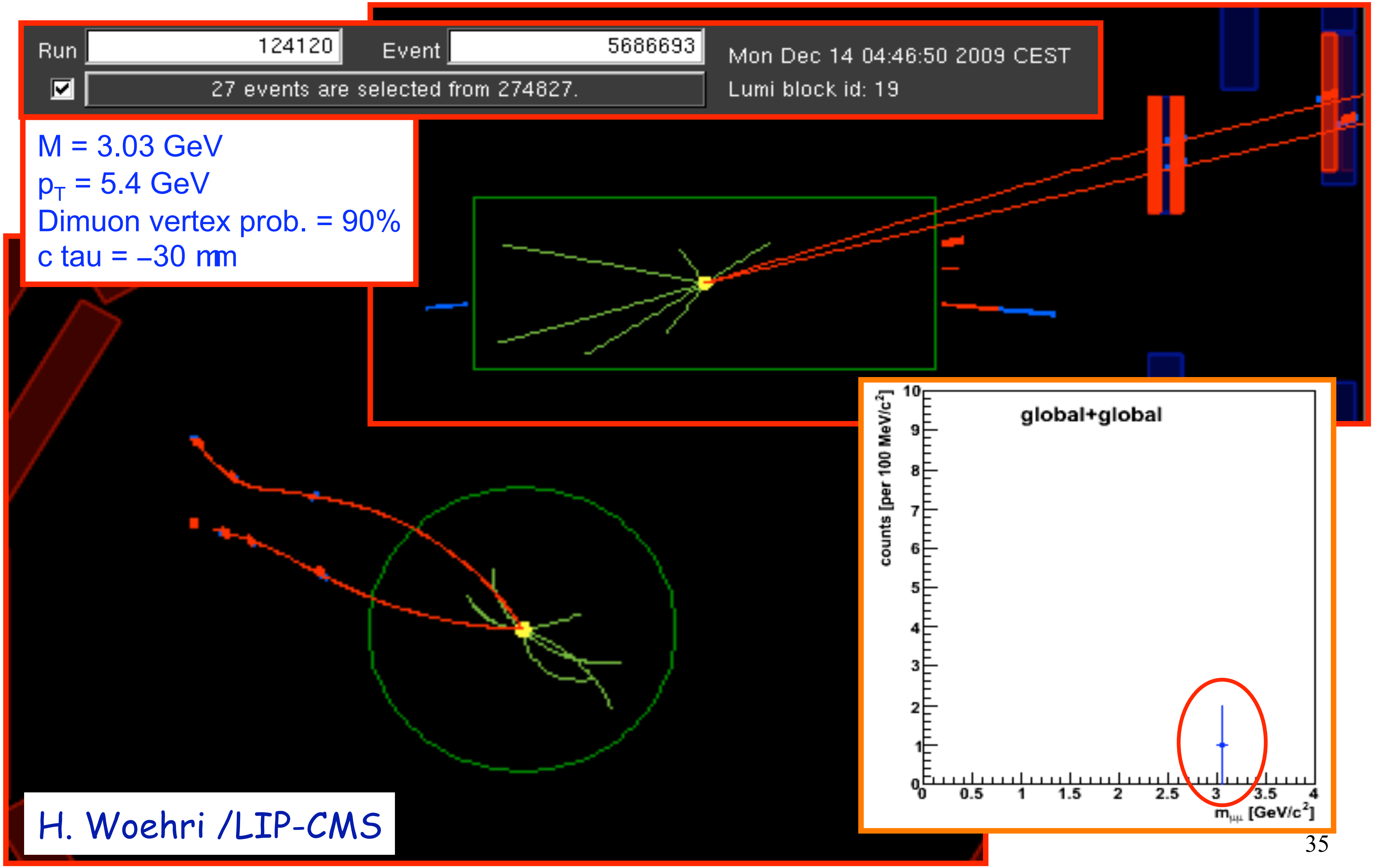



CMS Experiment at the LHC, CERN
Run 123596 Event 4969164
Sun Dec 06 08:01:34 2009
CMS
http://projects.hepforge.org/frog/


2-Jet Event at 2.36 TeV
ATLAS
EXPERIMENT
2009-12-08, 21:40 CET
Run 142065, Event 116969
3 ET (GeV)
1
η
180
Φ

CMS: Dimuon event at 2.36 TeV in CMS

M = 3.03 GeV
p_T = 5.4 GeV
Dimuon vertex prob. = 90%
c tau = –30 mm



H. Woehri /LIP-CMS

The LHC in 2010

Plugging in the numbers with a step in energy

Month	OP scenario	Max number bunch	Protons per bunch	Min beta*	Peak Lumi	Integrated	% nominal
1	Beam commissioning						
2	Pilot physics combined with commissioning	43	3×10^{10}	4	8.6×10^{29}	~200 nb^{-1}	
3		43	5×10^{10}	4	2.4×10^{30}	~1 pb^{-1}	
4		156	5×10^{10}	2	1.7×10^{31}	~9 pb^{-1}	2.5
5a	No crossing angle	156	7×10^{10}	2	3.4×10^{31}	~18 pb^{-1}	3.4
5b	No crossing angle – pushing bunch intensity	156	1×10^{11}	2	6.9×10^{31}	~36 pb^{-1}	4.8
6	Shift to higher energy: approx 4 weeks	Would aim for physics without crossing angle in the first instance with a gentle ramp back up in intensity					
7	4 – 5 TeV (5 TeV luminosity numbers quoted)	156	7×10^{10}	2	4.9×10^{31}	~26 pb^{-1}	3.4
8	50 ns – nominal Xing angle	144	7×10^{10}	2	4.4×10^{31}	~23 pb^{-1}	3.1
9	50 ns	288	7×10^{10}	2	8.8×10^{31}	~46 pb^{-1}	6.2
10	50 ns	432	7×10^{10}	2	1.3×10^{32}	~69 pb^{-1}	9.4
11	50 ns	432	9×10^{10}	2	2.1×10^{32}	~110 pb^{-1}	12

Energy:

Start with 3.5 TeV/beam

After few months

Increase to 5 TeV/beam?

Luminosity:

O(300) pb^{-1}

LHC Computing Grid project (LCG)

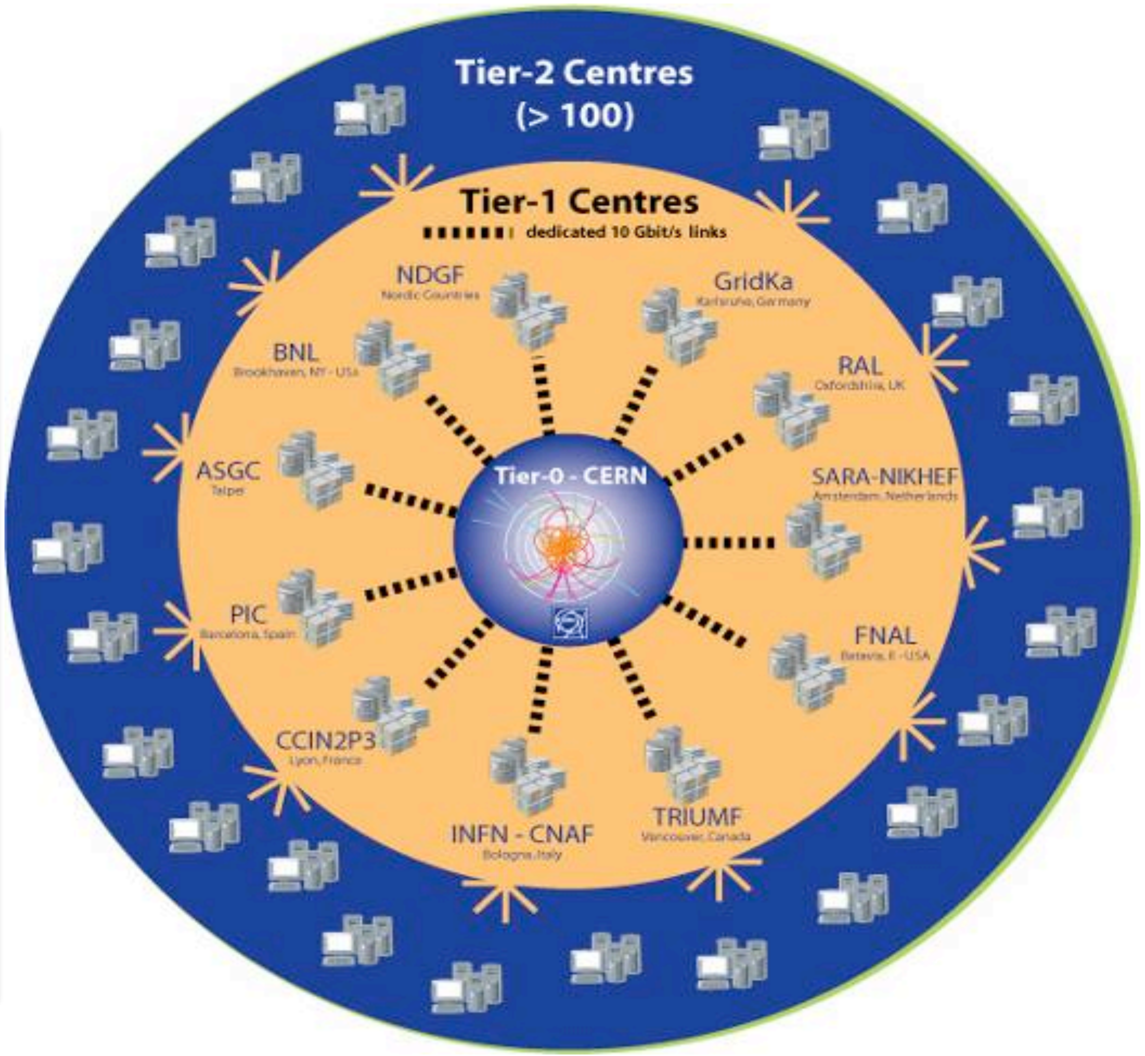
More than 140 computing centres
12 large centres for primary data management:
CERN (Tier-0)

Eleven Tier-1s

38 federations of smaller Tier-2 centres

India – BARC, TIFR, VECC

35 countries involved



The Science of the LHC

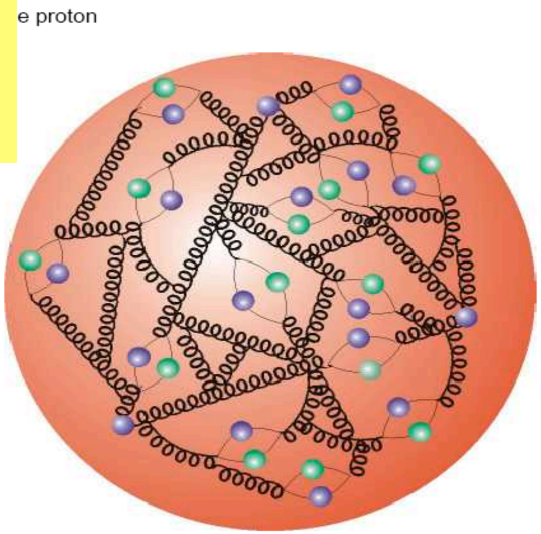
$\Longrightarrow$ Explore the new high energy regime: The Terascale

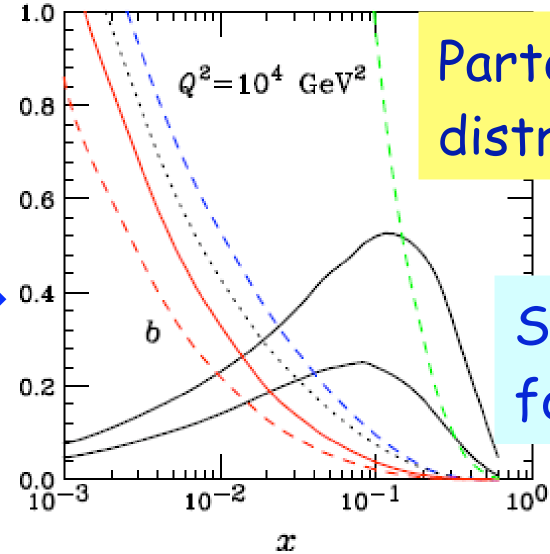
LHC Physics Program

- 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
- …

pp collisons : complications…

High parton density at low x

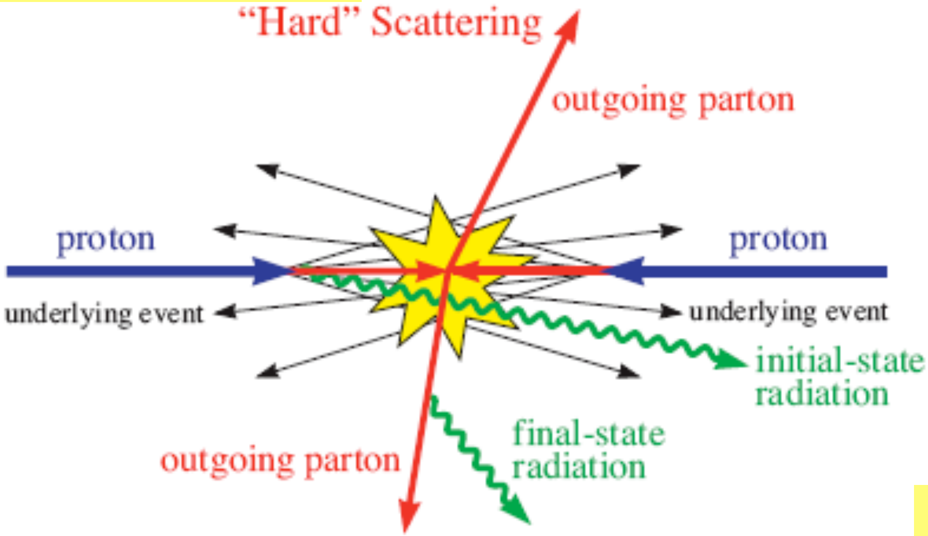




Parton distributions

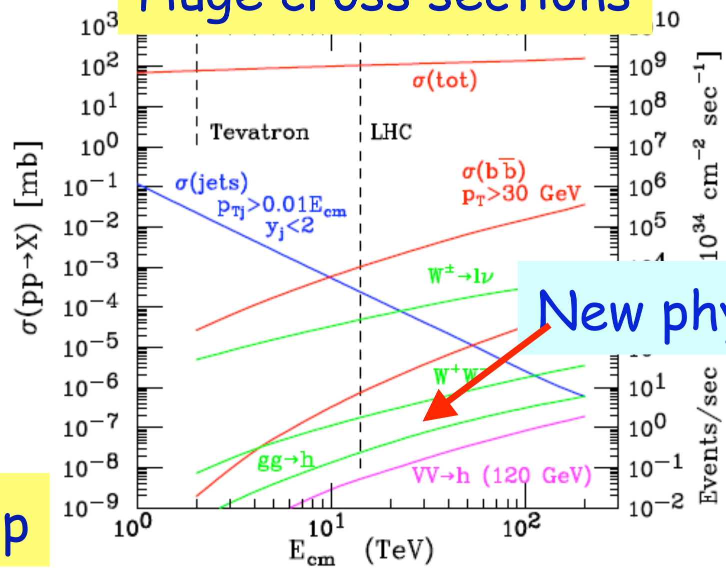
Strong role for HERA

Underlying event



Scattering cross sections for various SM processes:

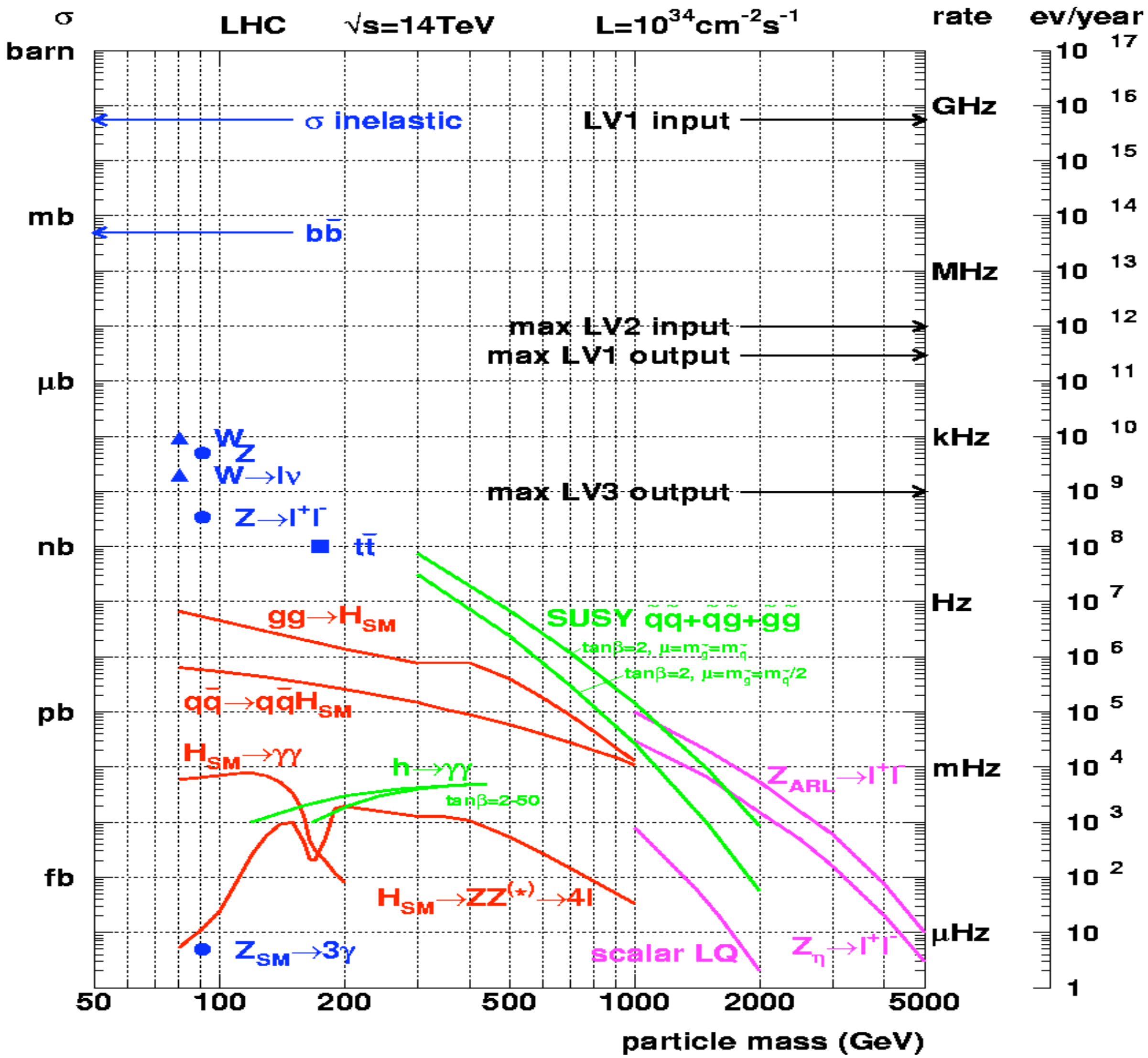
Huge cross sections



New physics ?

Pile-up

Cross Sections at the LHC



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

New Physics!!
This we want to keep!!

Event Rates for pp at √s=14 TeV

Process	Events/s	Events/
$W \to e\nu$	15	10^8
$Z \to ee$	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 $W \to \mu\nu, e\nu$ decays
- ~ 500 $Z \to \mu\nu, e\nu$ 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)

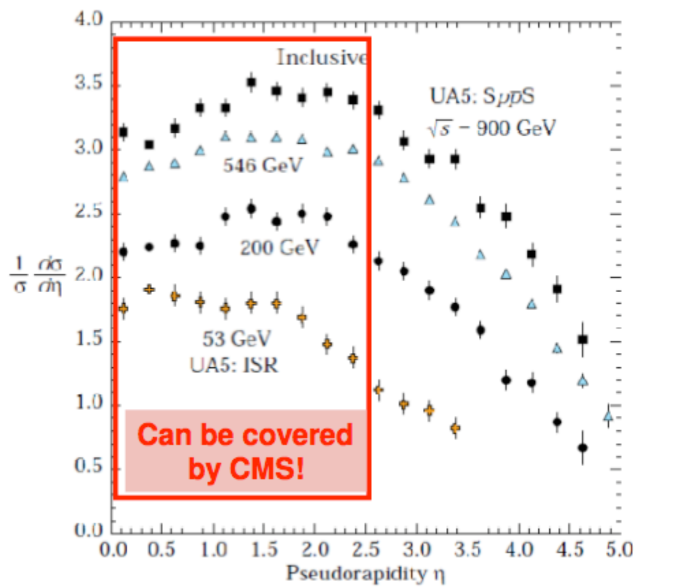
3 minutes: Record ~ 20K events/30Gbyte

Physics at 900 GeV?

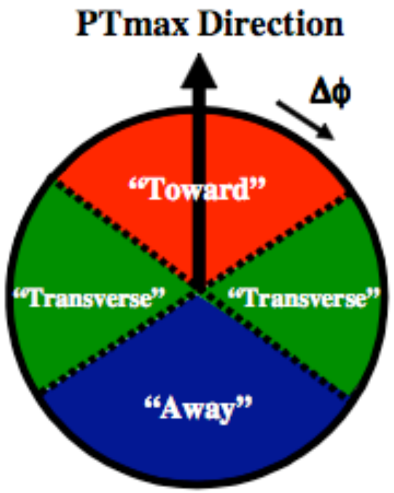
Above all: commissioning of the detectors with real collisions!

- Some, but not much, data exists from the SPPS (pulsed mode/ few μbarn^{-1})
- 1M events ~ 25 μbarns^{-1} (Sunday morning: CMS ~ 450 K in "physics")

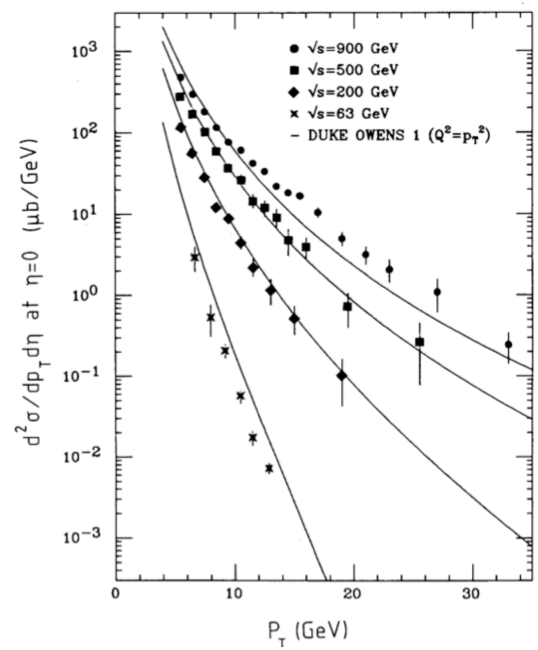
  $\Rightarrow$ Basically minimum bias and (mini)jet events
- Studies of soft interactions and underlying events with techniques that have been developed in the "90's and this decade: study energy dependence
- Commissioning of analysis objects: jets, leptons, photons, tracks, MET…



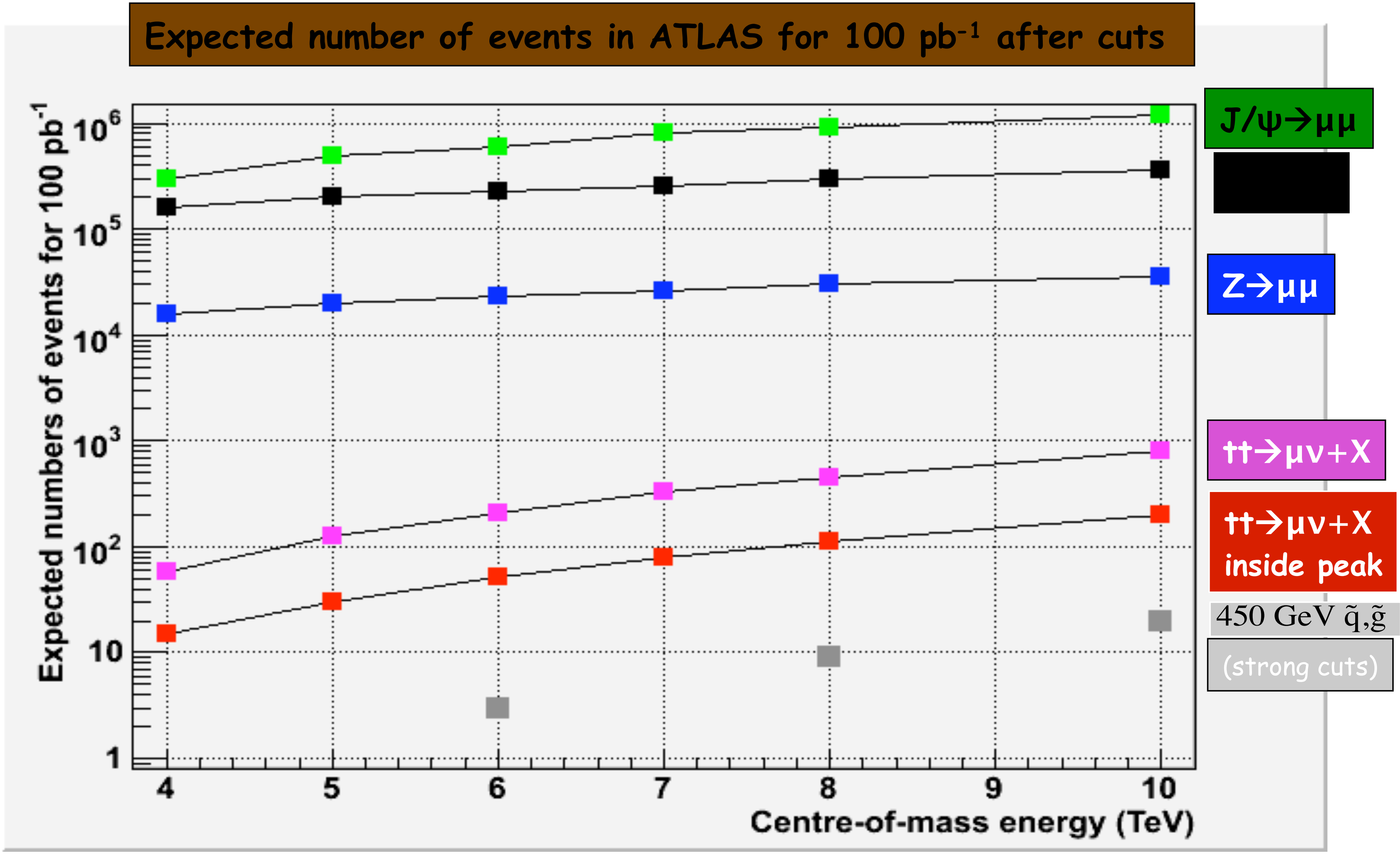
Ref: UA5, particle data book. Statistical errors only.



Underlying event

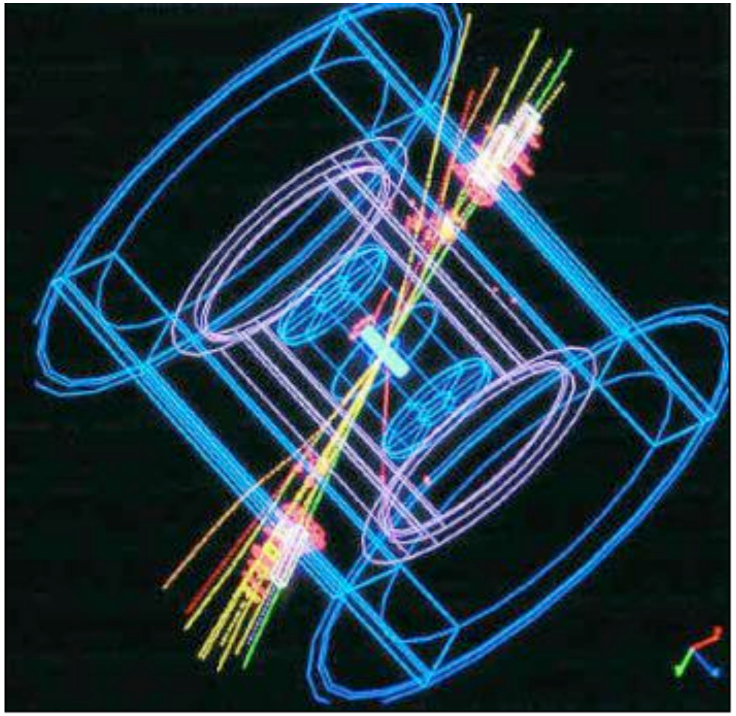


Preliminary



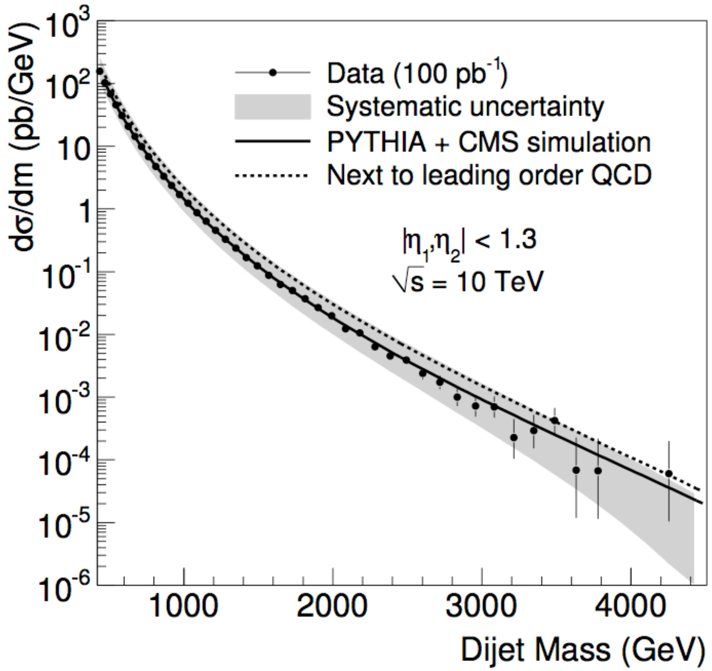
In the beginning "there will be QCD"

E.g. Jet Physics



Study of the strong force

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



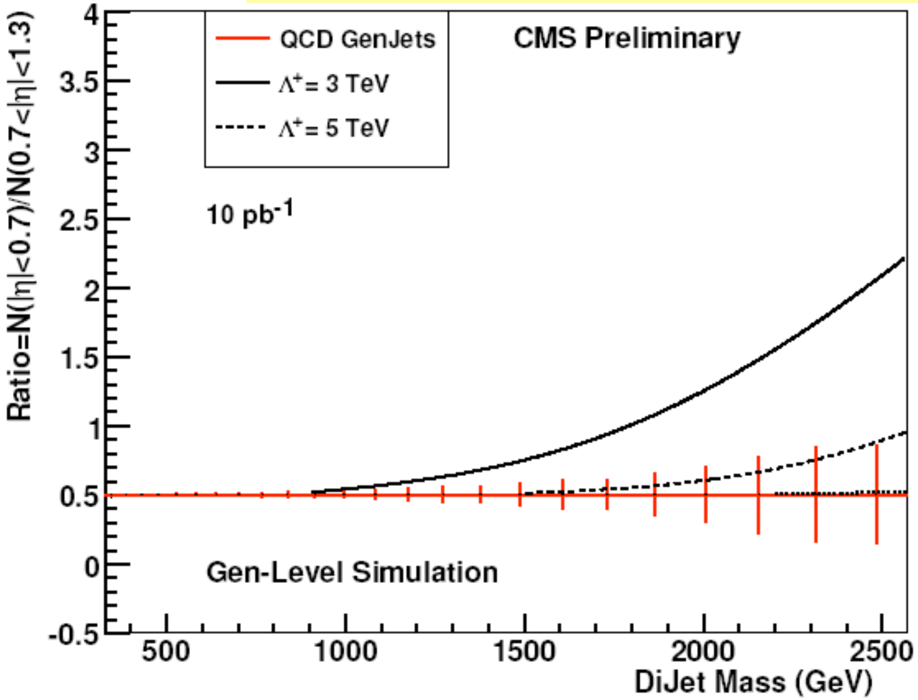
Understanding QCD at 10/14 TeV will be one of the first topics at the LHC

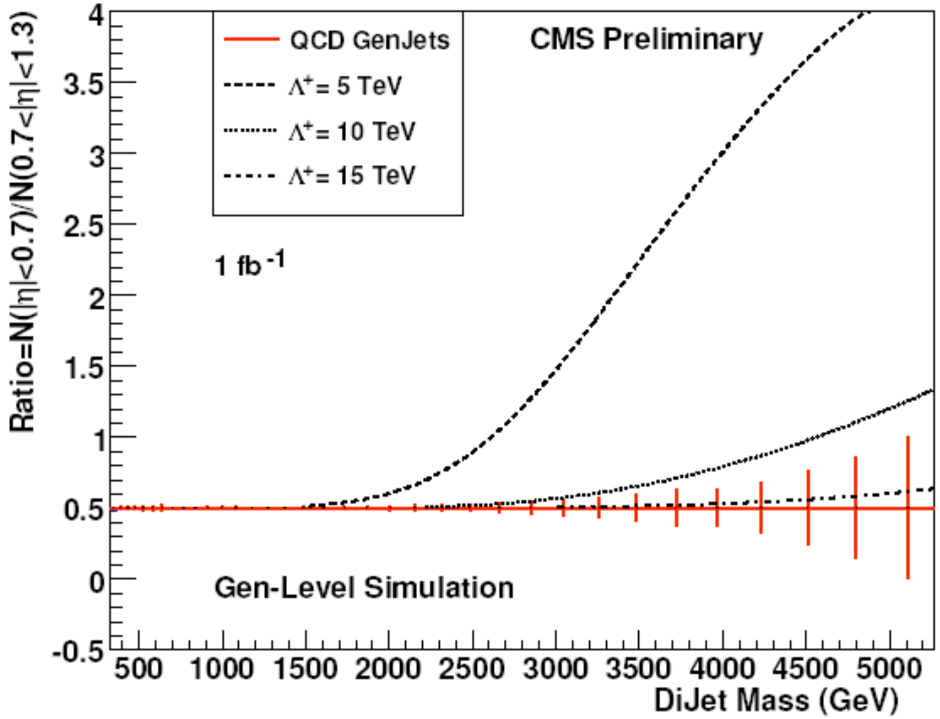
Precision measurements of the strong force QCD, New physics…

New Physics with Jets

Eg Contact Interactions

⇒ Using dijet event ratios in pseudorapidity η bins

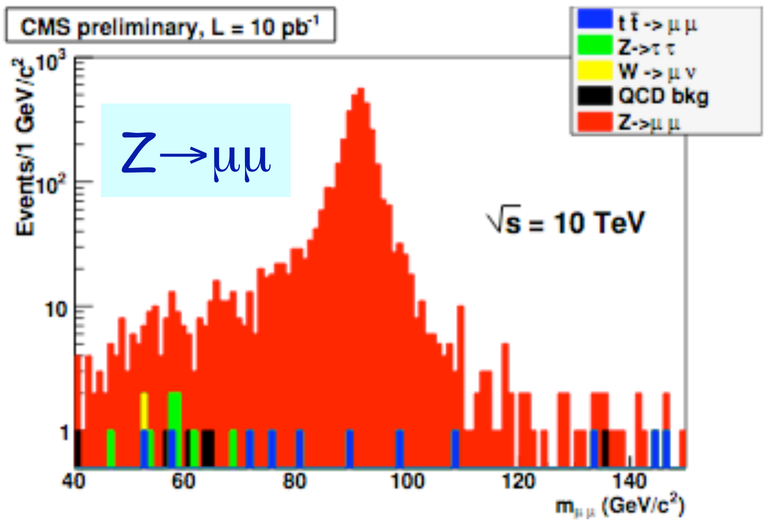


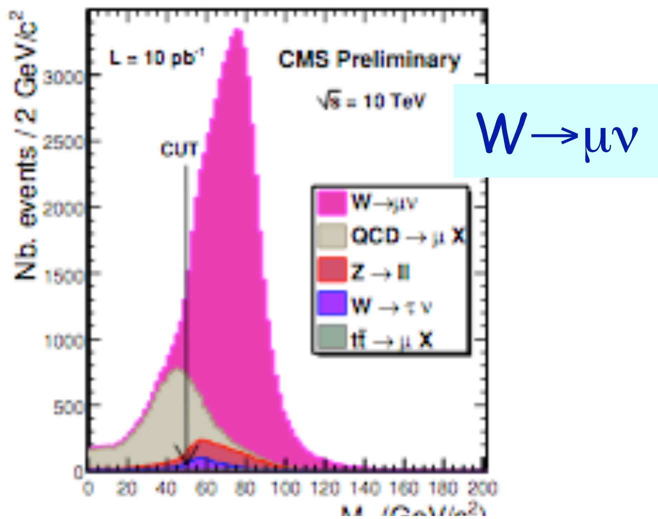


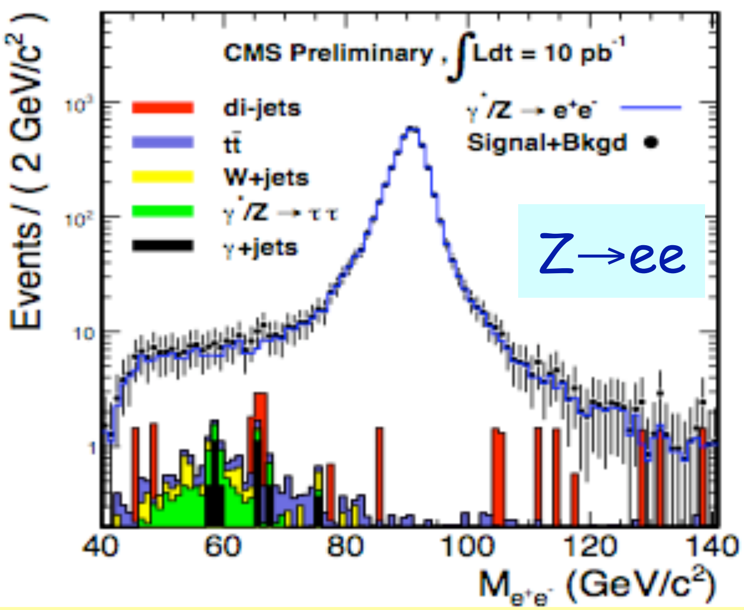
	Excluded Λ (TeV)			Discovered Λ (TeV)		
	10 pb^{-1}	100 pb^{-1}	1 fb^{-1}	10 pb^{-1}	100 pb^{-1}	1 fb^{-1}
DØ and PTDR η cuts	< 3.8	< 6.8	< 12.2	< 2.8	< 4.9	< 9.1
Optimized η cuts	< 5.3	< 8.3	< 12.5	< 4.1	< 6.8	< 9.9

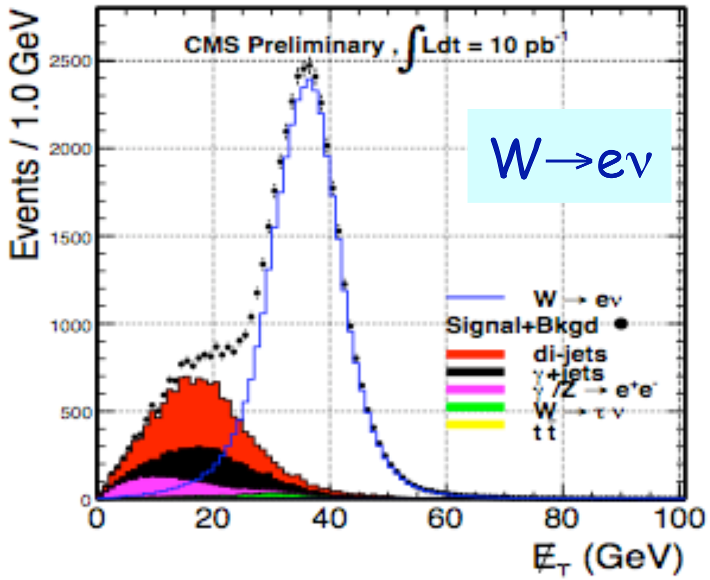
Already sensitivity with 10 pb^{-1}

Vector Boson Production





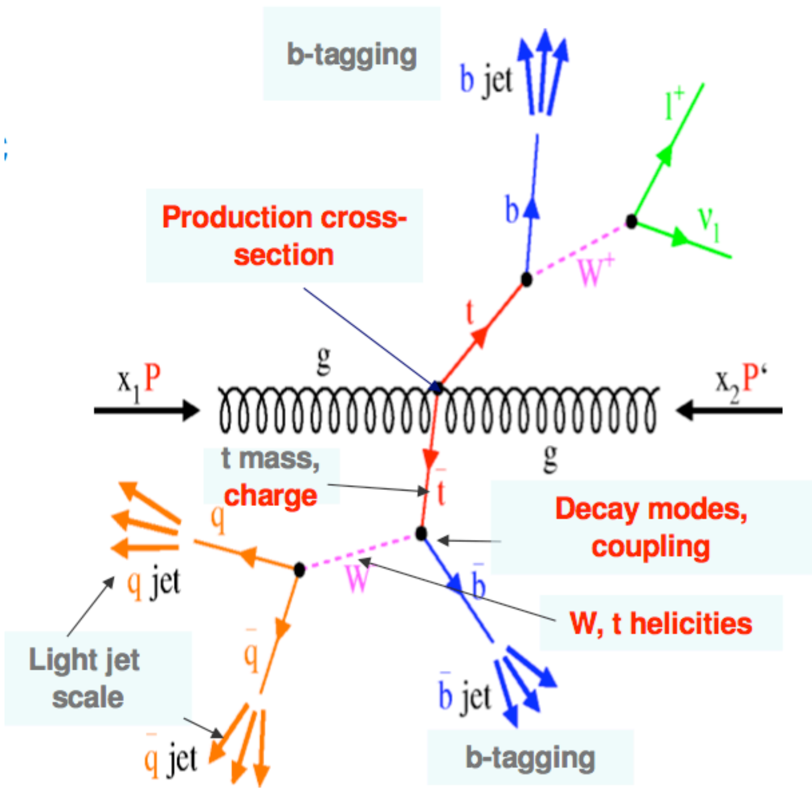


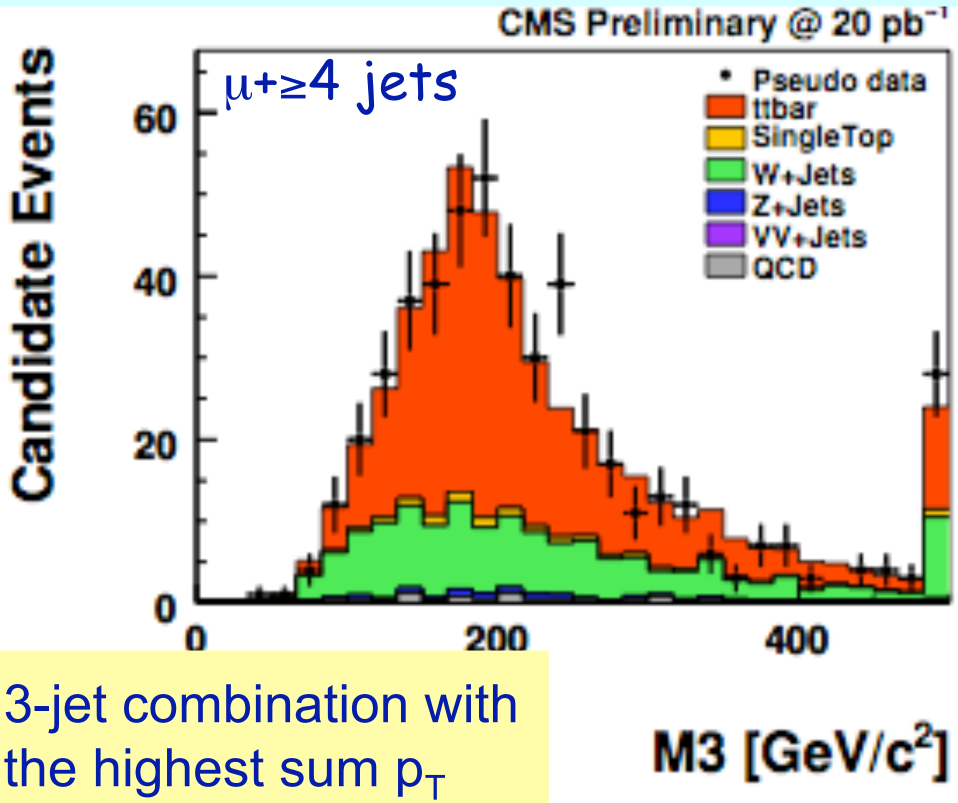


Good statistics at start-up. Important is V+jets for new physics searches

Top Quarks

Tevatron: O(10,000) top events ⇒ LHC: about 1 top event/minute at start up





3-jet combination with the highest sum p_T

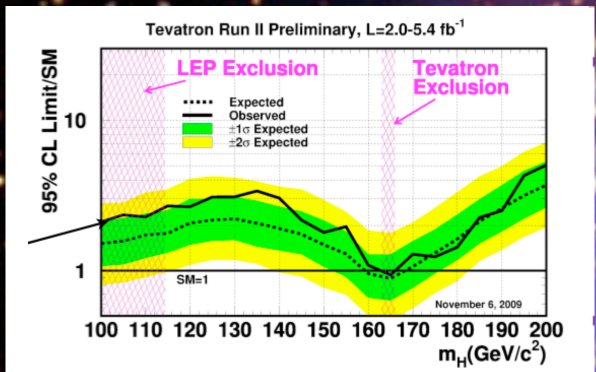
10-100 pb^{-1} (@ 10 TeV) needed for first top cross sections
~1 fb^{-1} or more for top properties: charge, mass, spin correlations, Wtb anomalous couplings, FCNC,..
Top production @ 10/14 TeV needs to be understood for new physics searches

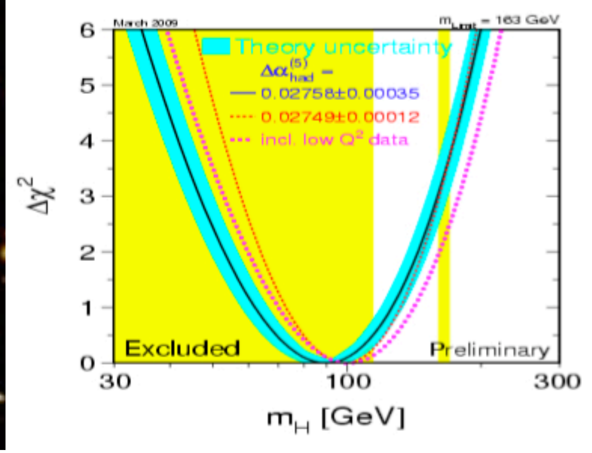
The Origin of Mass

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



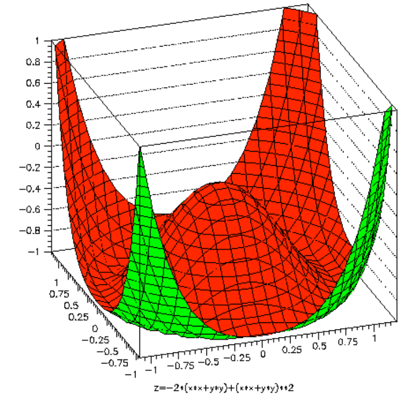


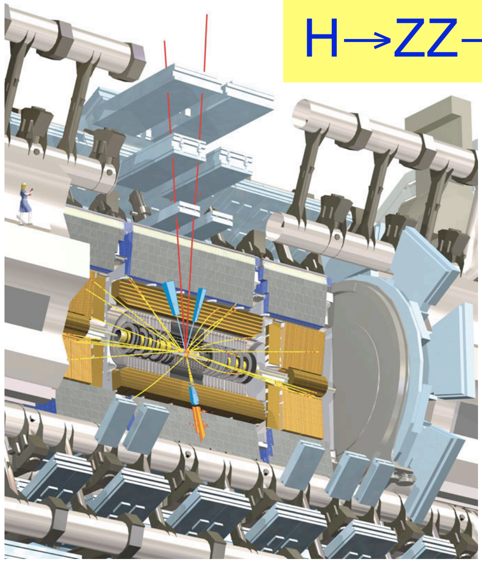
The key question: Where is the Higgs?

The Higgs Particle

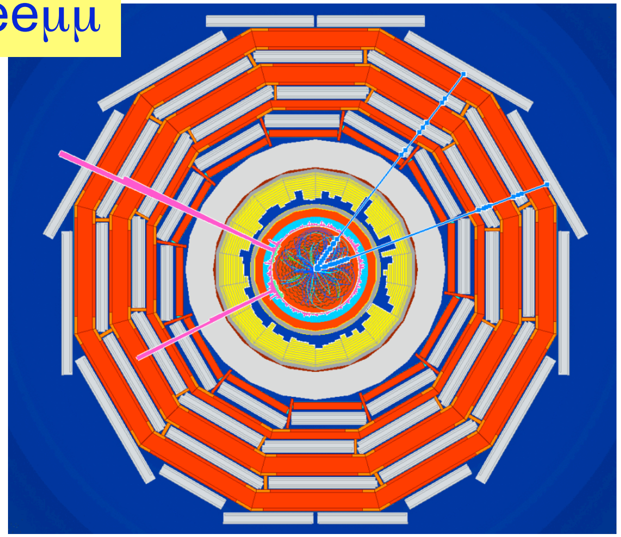
⇒ What is the origin of mass of the elementary particles?
Solution within the Standard Model: A scalar Higgs field

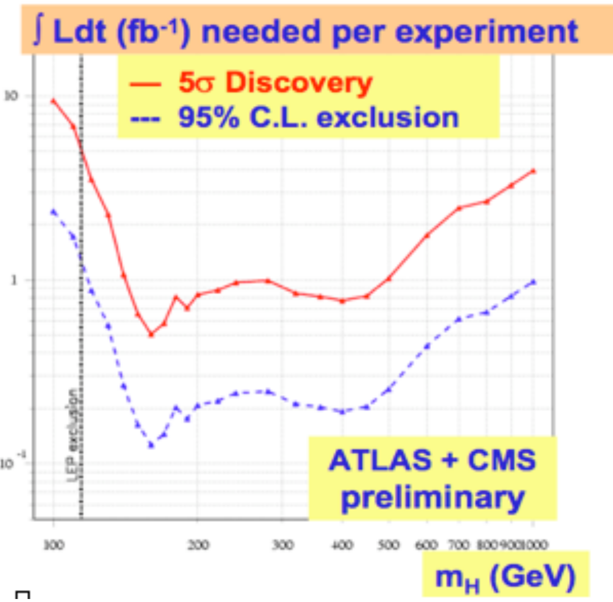
⇒ At least one new scalar particle should exist: The Higgs
The Higgs is the last missing particle in the Standard Model
One of the main missions of LHC: discover the Higgs





H→ZZ→eeμμ



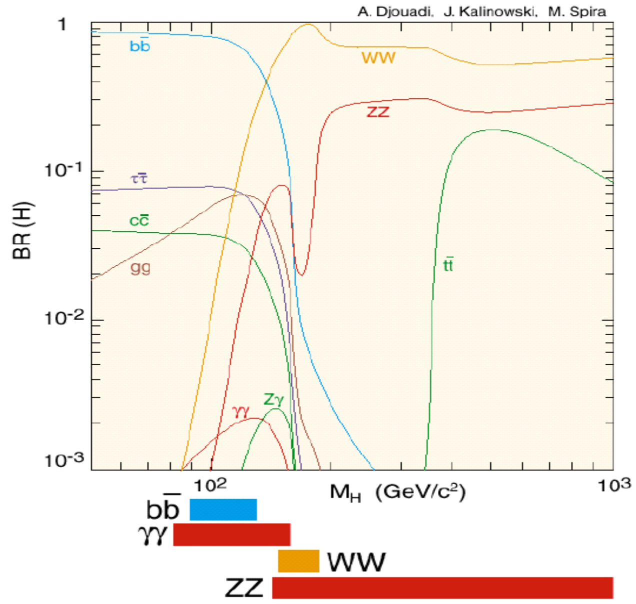


- If the Higgs exist: LHC will discover it after 2-3 years of operation
- If the Higgs does not exist: LHC should see other spectacular new effects

Higgs Boson Search Channels

Low mass $M_H \lesssim 200$ GeV

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



Intermediate mass
(200 GeV $\lesssim M_H \lesssim$ 700 GeV)

inclusive $H \rightarrow WW$
inclusive $H \rightarrow ZZ$

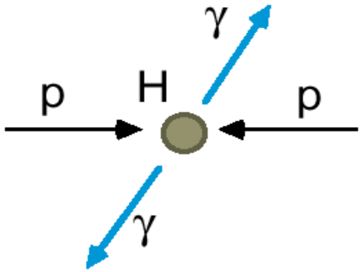
High mass ($M_H \gtrsim$ 700 GeV)

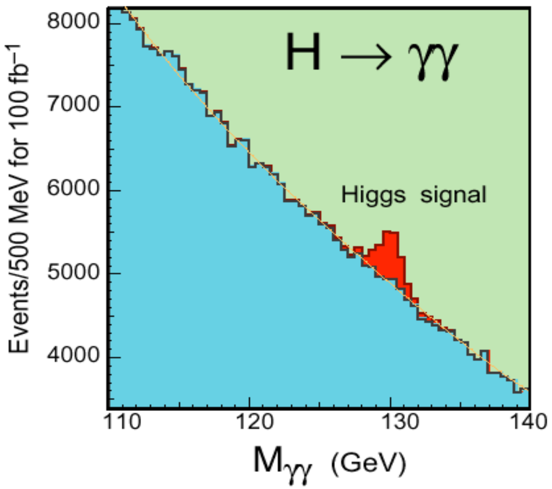
VBF $qqH \rightarrow ZZ \rightarrow \ell\ \ell\ \nu\ \nu$
VBF $qqH \rightarrow WW \rightarrow \ell\ \nu jj$

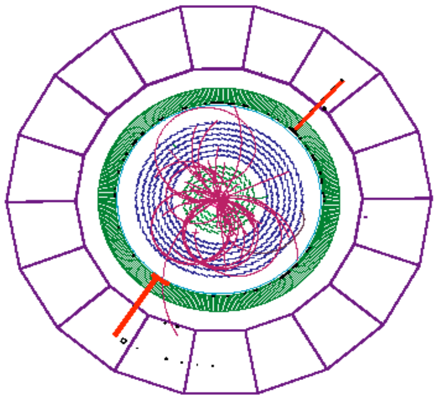
$H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4\ell$ are the only channels with a very good mass resolution ~1%

Higgs Boson Searches

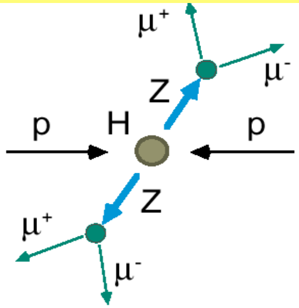
Low M_H < 140 GeV/c²

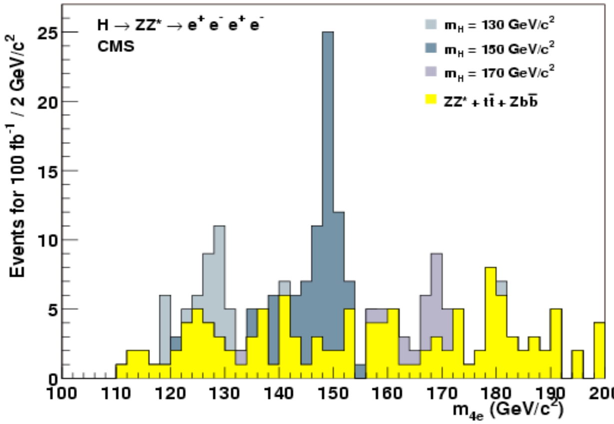




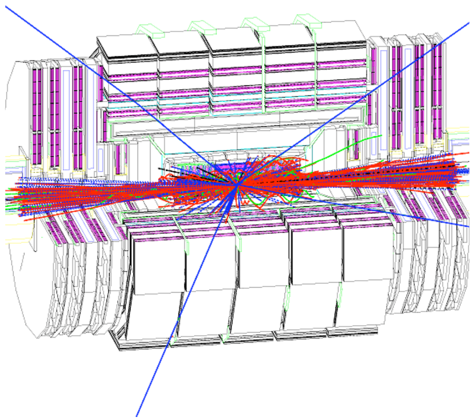


Medium 130<M_H<500 GeV/c²

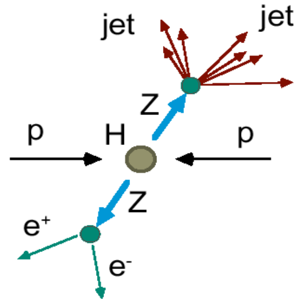


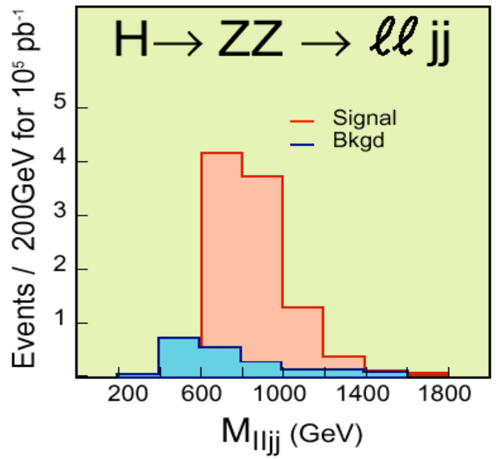


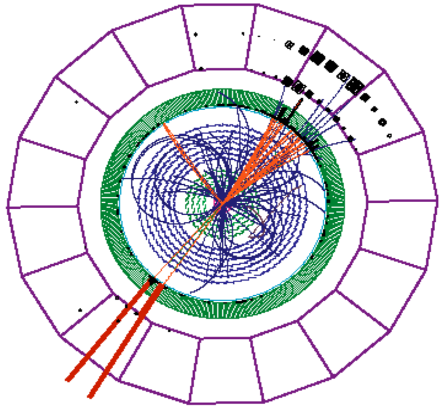
H (150 GeV) → Z⁰Z⁰* → 4μ



High M_H > ~500 GeV/c²

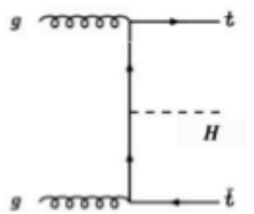


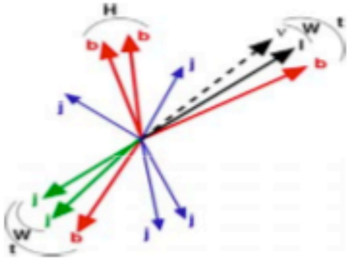


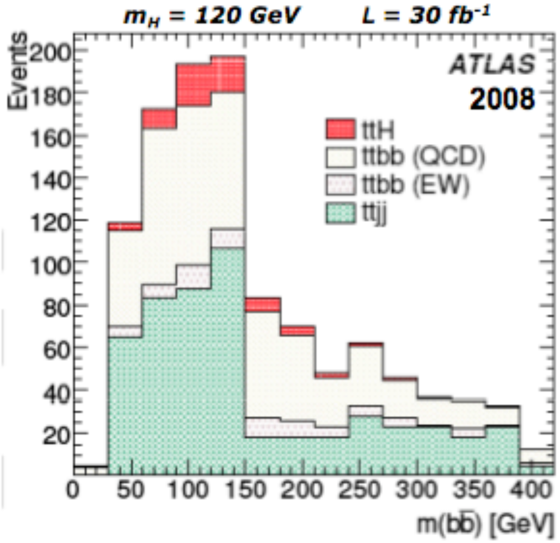


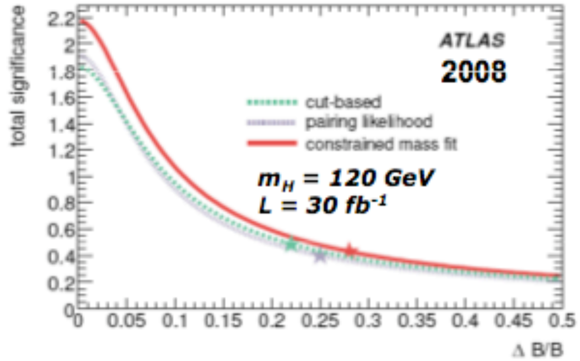
The Channel ttH with H→bb ⇒ R.I.P?

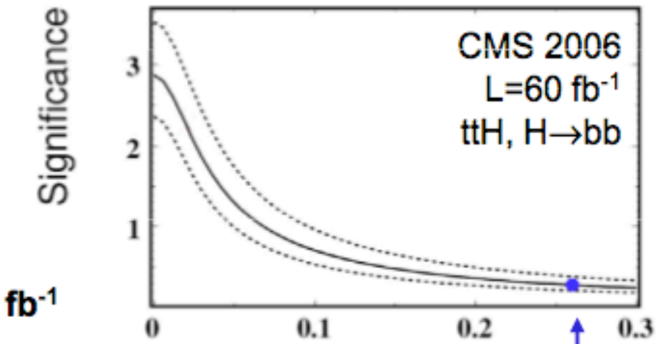
ttH is (was?) the best bet to see H→bb











dB

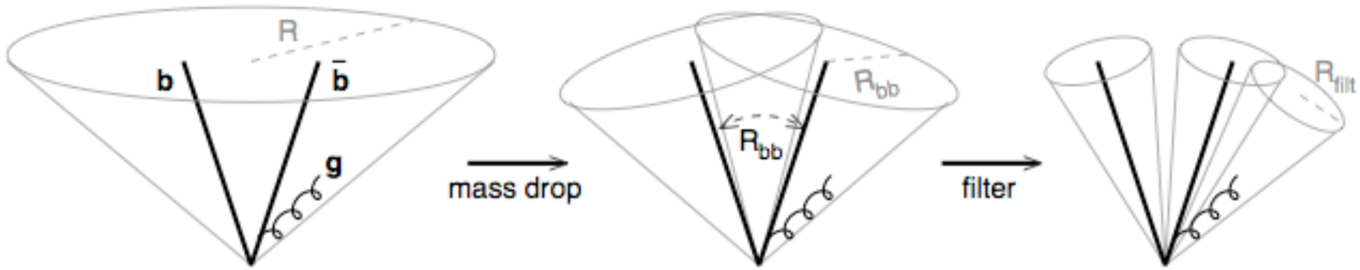
current estimate of background uncertainties

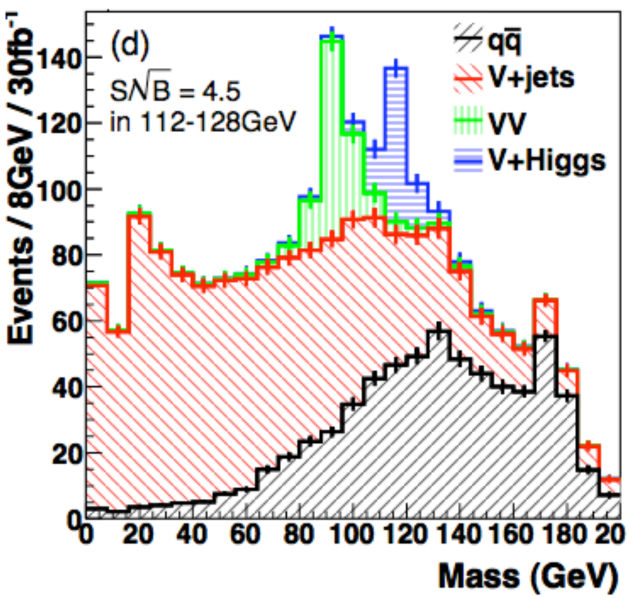
jet energy scale (3-10%)
jet energy resolution (10%)
b/c-tag efficiency (4%)
uds/g-tag efficiency (10%)
luminosity (3%)

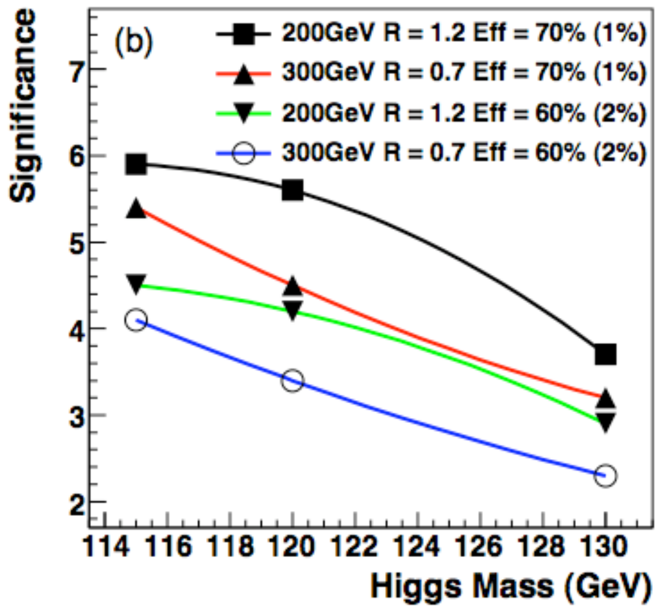
- **Early projections:** might be observable already at $L=30\ fb^{-1}$
- **CMS-2006 analysis:**
  - systematic error control at a percent level is needed—not feasible...
-
-

So is H→bb Hopeless? Maybe not…

- New idea from Butterworth et al. arXiv:0802.2470
- Use high P_T associated WH production with H→bb
- Use subjet analysis techniques & recover WH for O(30 fb^{-1})

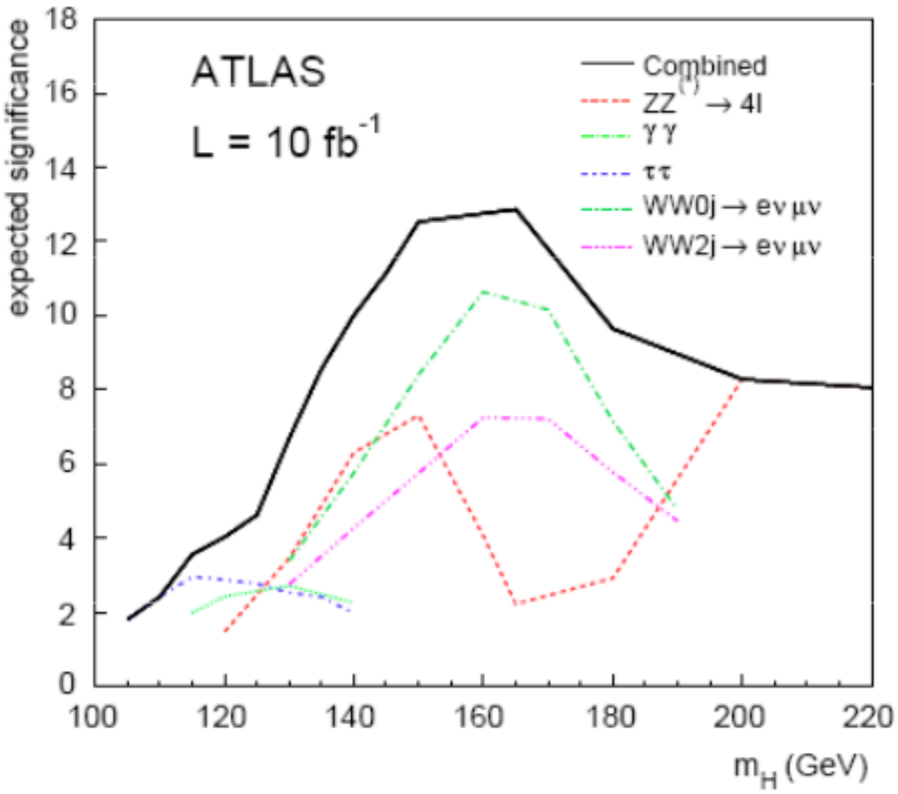


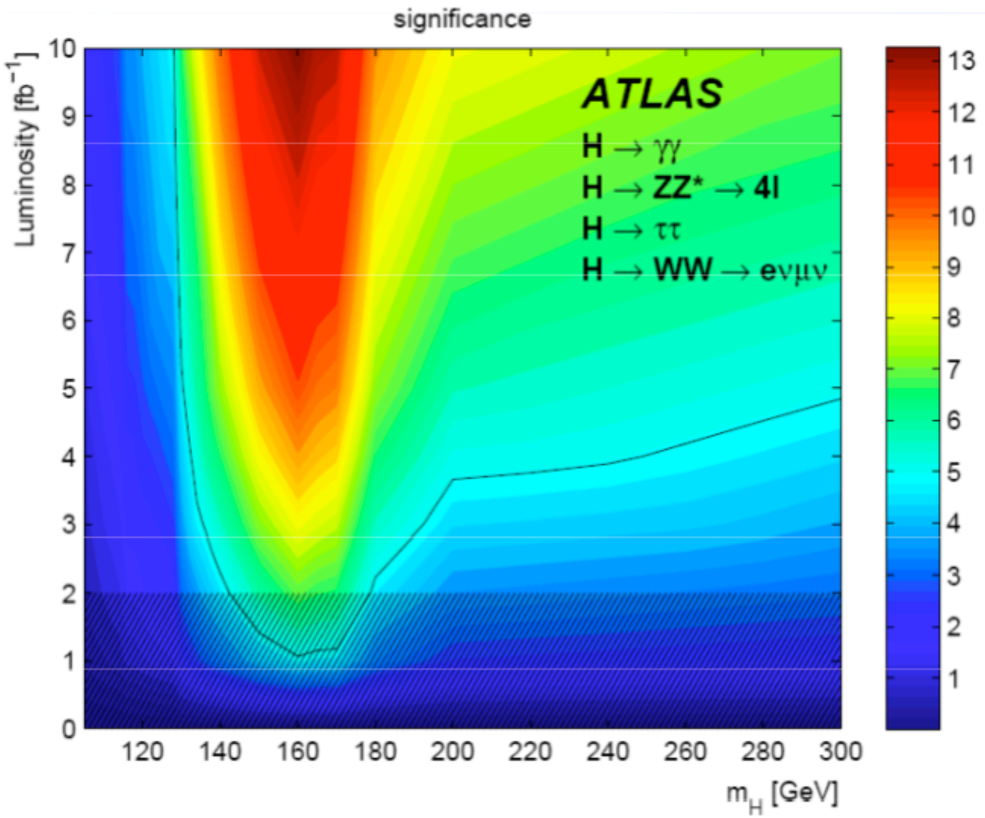




+Exclusive production

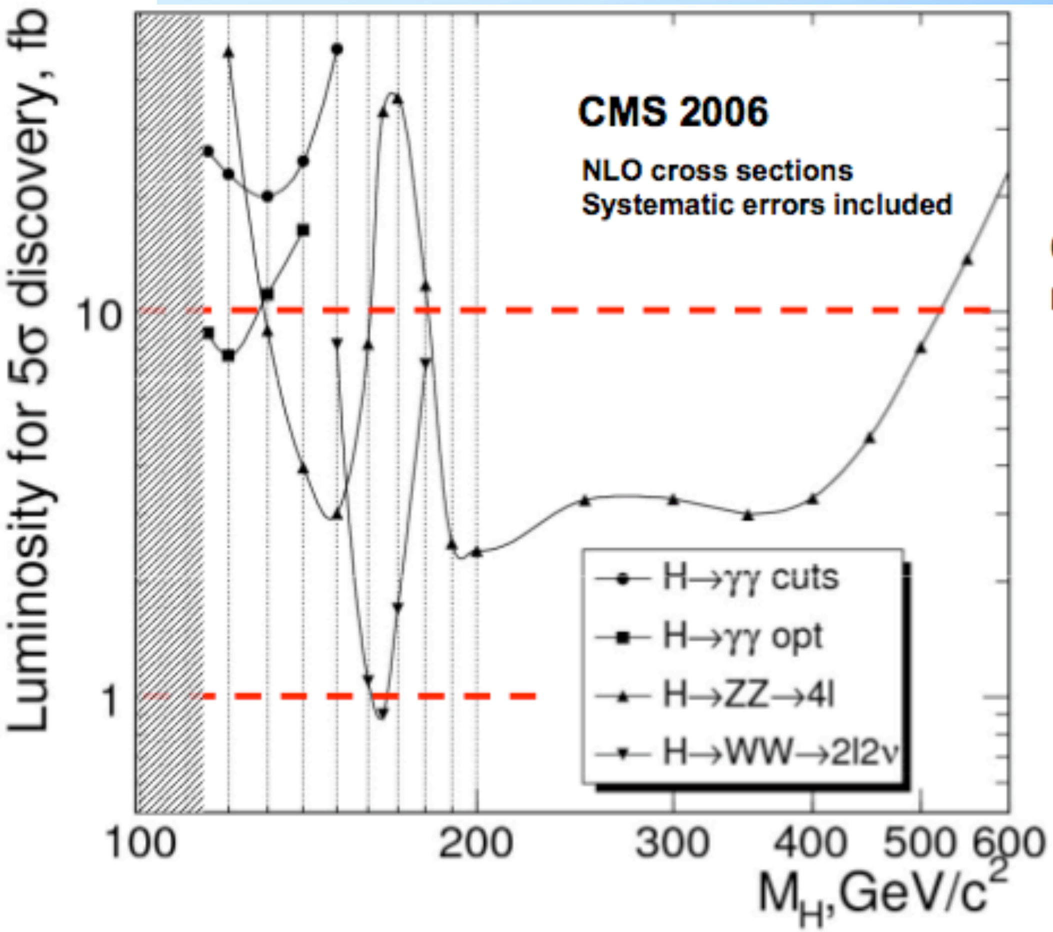
ATLAS Summary (Low Mass)





Higgs with mass less than 125 GeV needs more than 10 fb^{-1}

Higgs Summary



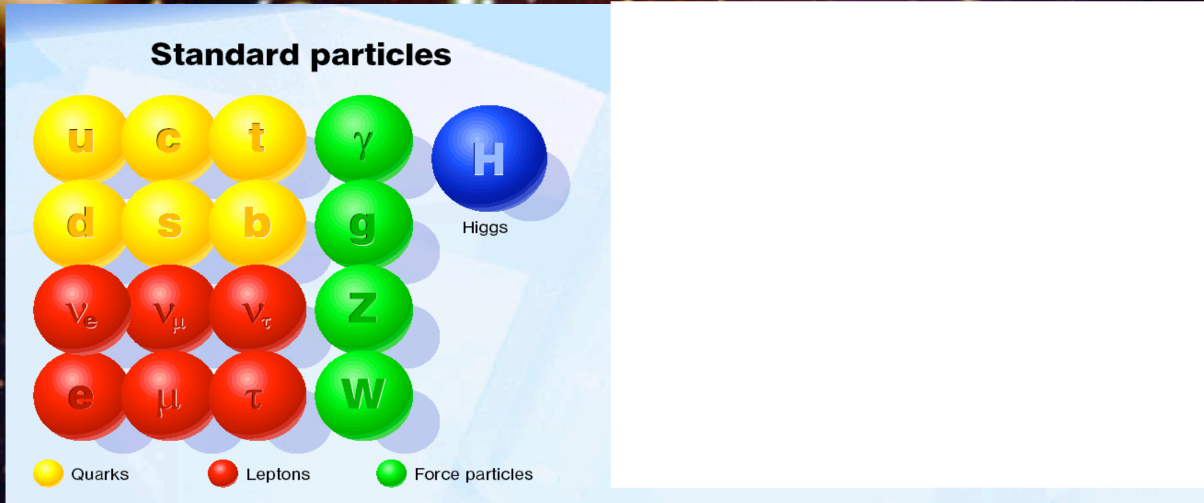
CMS and ATLAS different at low mass region, ~agree elsewhere

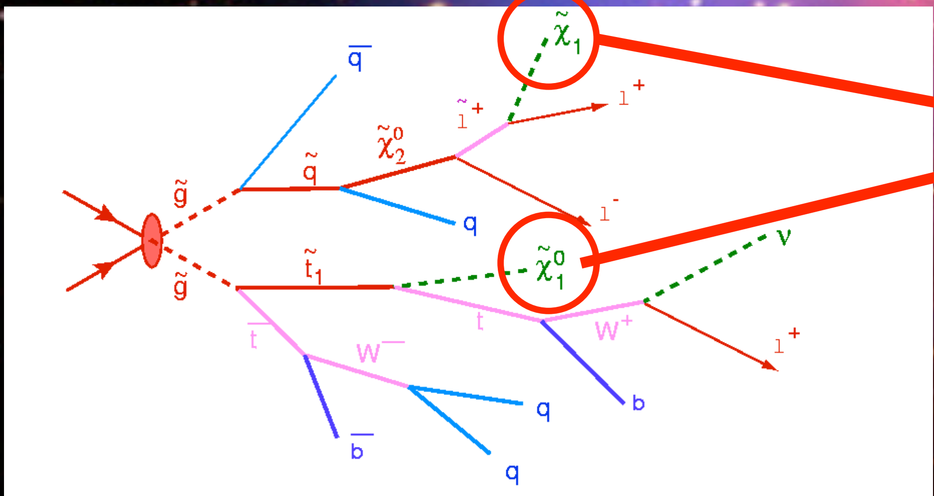
Benchmark luminosities:

– **$0.1\ fb^{-1}$:** exclusion limits will start carving into SM Higgs cross section
– **$1\ fb^{-1}$:** discoveries become possible if M_H~160-170 GeV
– **$10\ fb^{-1}$:** SM Higgs is discovered (or excluded) including low mass range (CMS)

Beyond the Higgs Particle

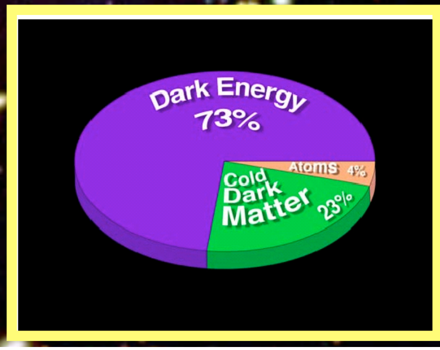
Supersymmetry: a new symmetry in Nature





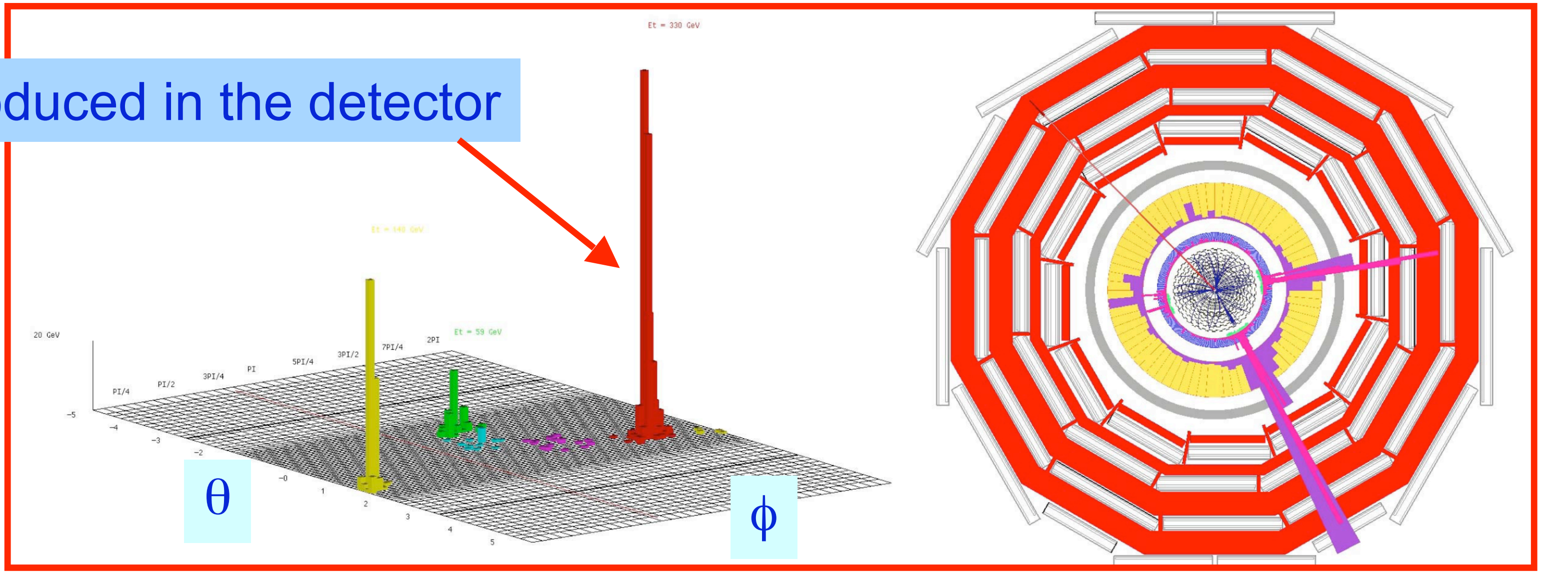
SUSY particle production at the LHC

Candidate particles for Dark Matter
⇒ Produce Dark Matter in the lab



Detecting Supersymmetric Particles

Energy produced in the detector



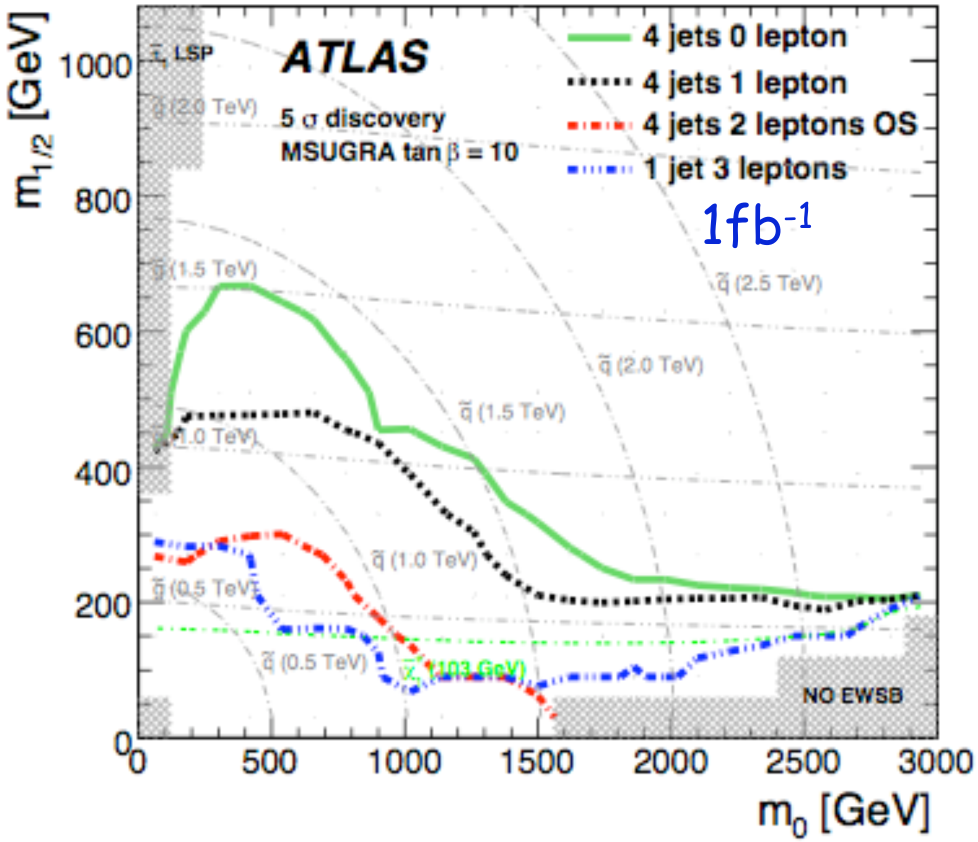
Supersymmetric particles decay and produce a cascade of jets, leptons and missing (transverse) energy due to escaping 'dark matter' particles

⇒ 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

Early SUSY Reach



minimal Supergravity (mSUGRA)

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

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?

arXiv:0808.4128

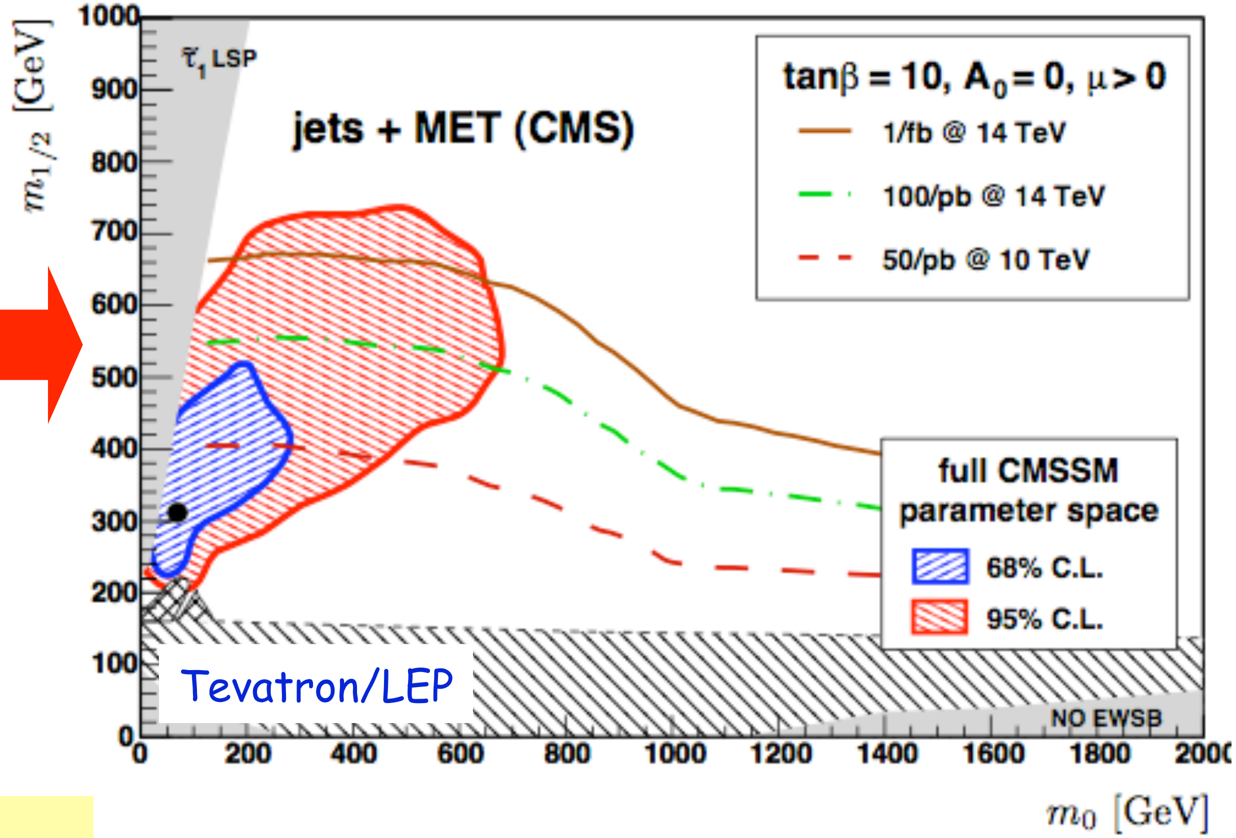
OB, R.Cavanaugh, A.De Roeck,
J.R.Ellis, H.~Flaecher, S.~Heineme
G.Isidor, K.A.Olive, P.Paradisi,
F.J.Ronga, G.Weiglein

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, M_{top}, g-2, BR(B→Xγ), relic density)

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

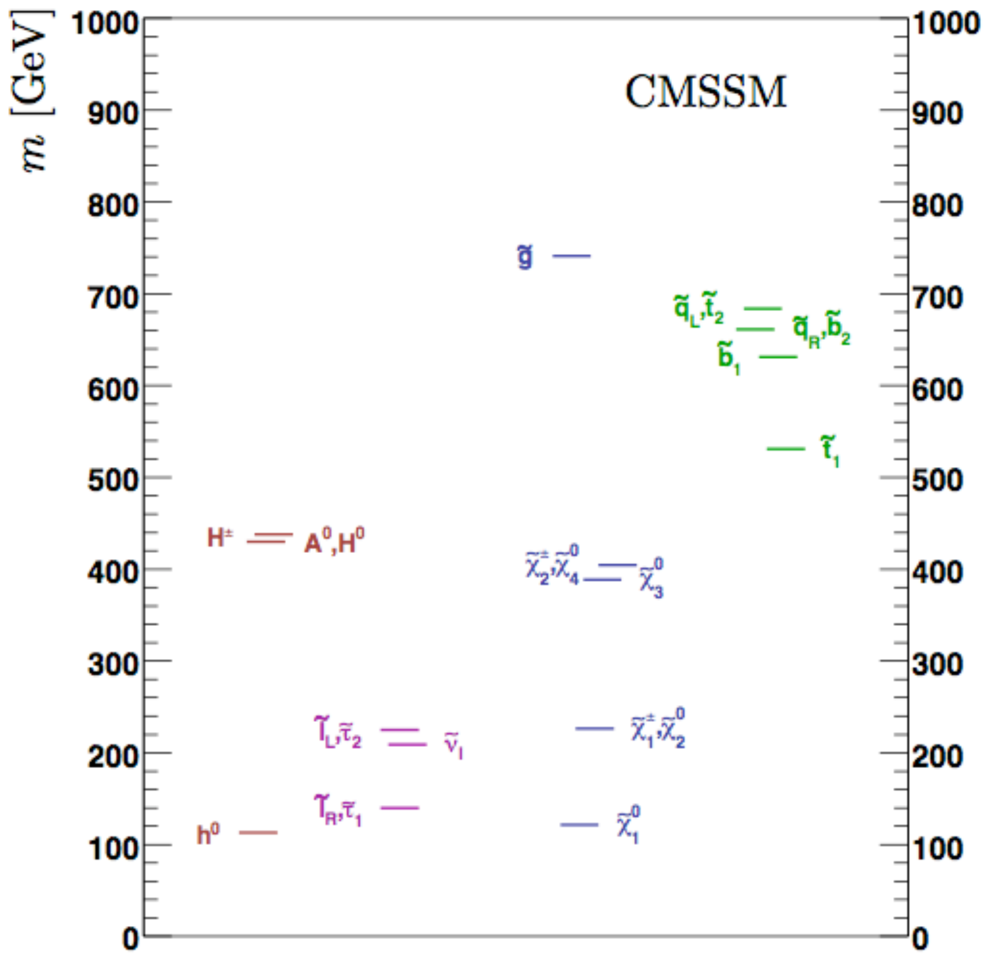
"LHC Weather Forecast"

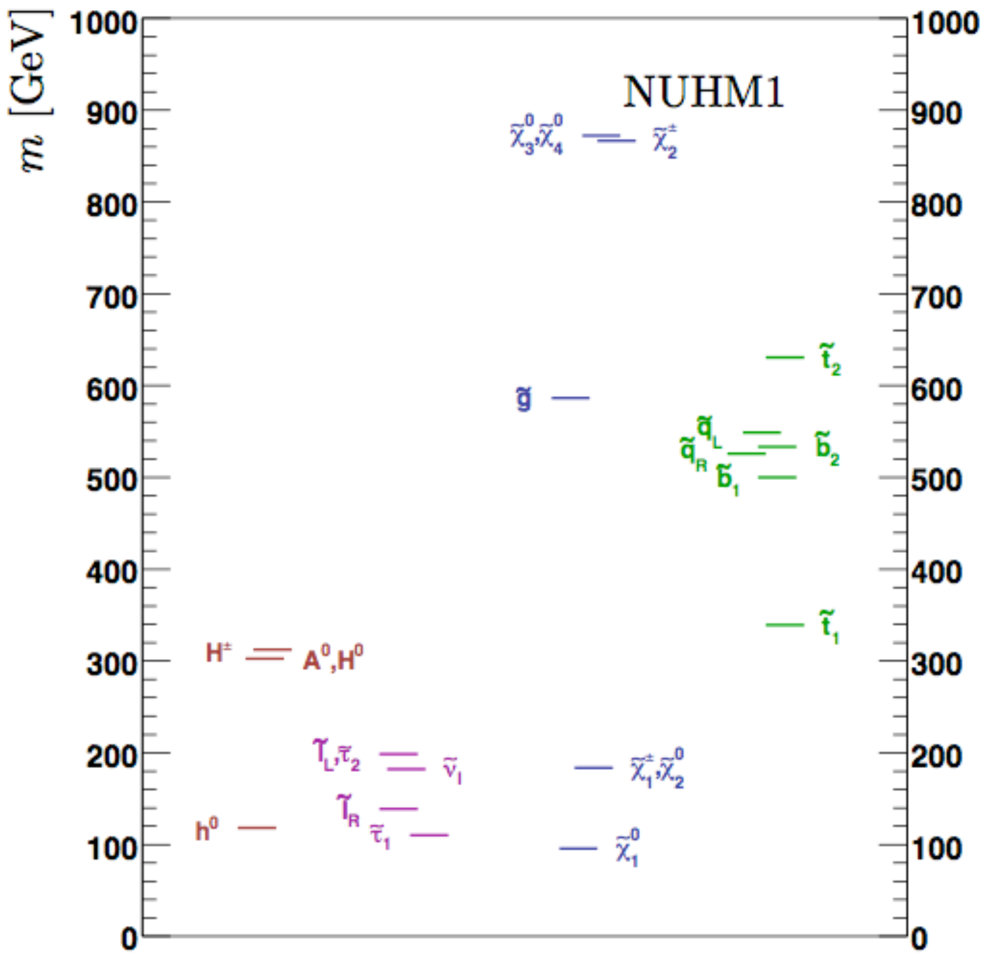


"CMSSM fit clearly favors low-mass SUSY - Evidence that a signal might show up very early?!"

SUSY Particle Spectrum

"best" point: Mass spectrum

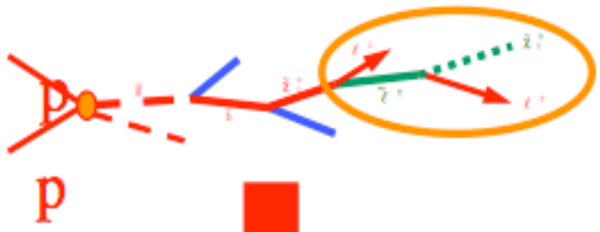


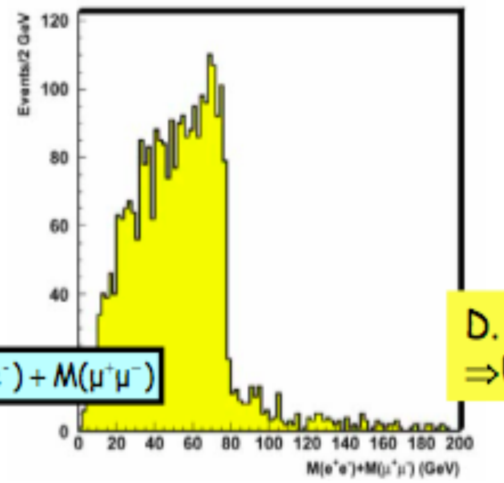


Sparticle Reconstruction

Mass precision for a favorable benchmark point at the LHC
LCC1~ SPS1a~ point B'

m_0=100 GeV
$m_{1/2}$= 250 GeV
A_0=-100
$\tan\beta$ = 10
sign(μ)=+



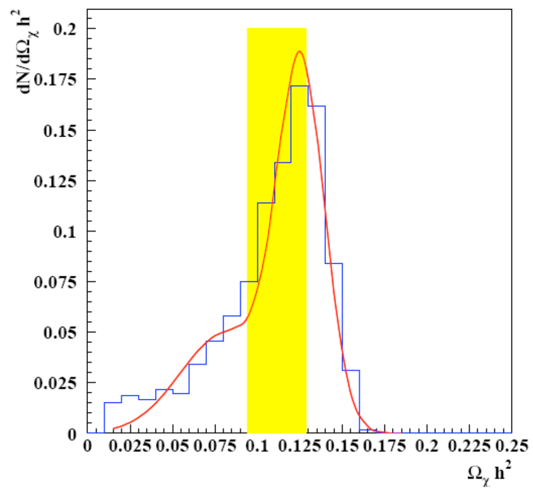


D. Miller et al
⇒Use shapes

hep-ph/0508198

GeV	LHC
$\Delta m_{\tilde{\chi}^0_1}$	4.8
$\Delta m_{\tilde{\chi}^0_2}$	4.7
$\Delta m_{\tilde{\chi}^0_4}$	5.1
$\Delta m_{\tilde{l}_R}$	4.8
$\Delta m_{\tilde{\ell}_L}$	5.0
$\Delta m_{\tilde{\tau}_1}$	5-8
$\Delta m_{\tilde{q}L}$	8.7
$\Delta m_{\tilde{q}R}$	7-12
$\Delta m_{\tilde{b}_1}$	7.5
$\Delta m_{\tilde{b}_2}$	7.9
$\Delta m_{\tilde{g}}$	8.0

Lightest neutralino → Dark Matter?
Fit SUSY model parameters to the measured SUSY particle masses to extract $\Omega_\chi h^2$ ⇒ O(10%)



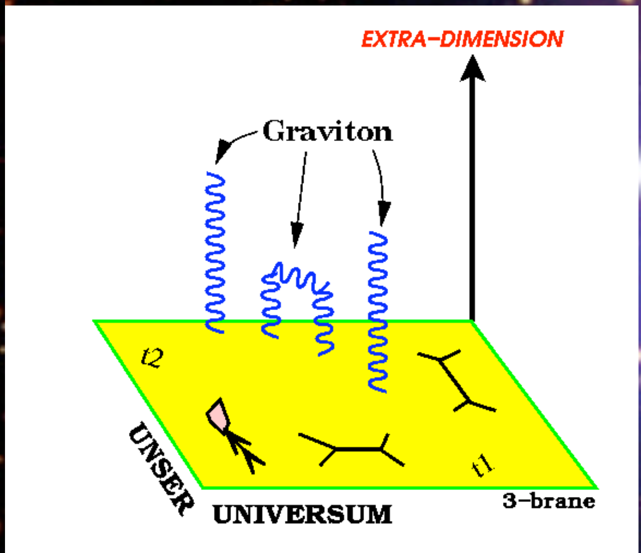
Beyond the Higgs Particle

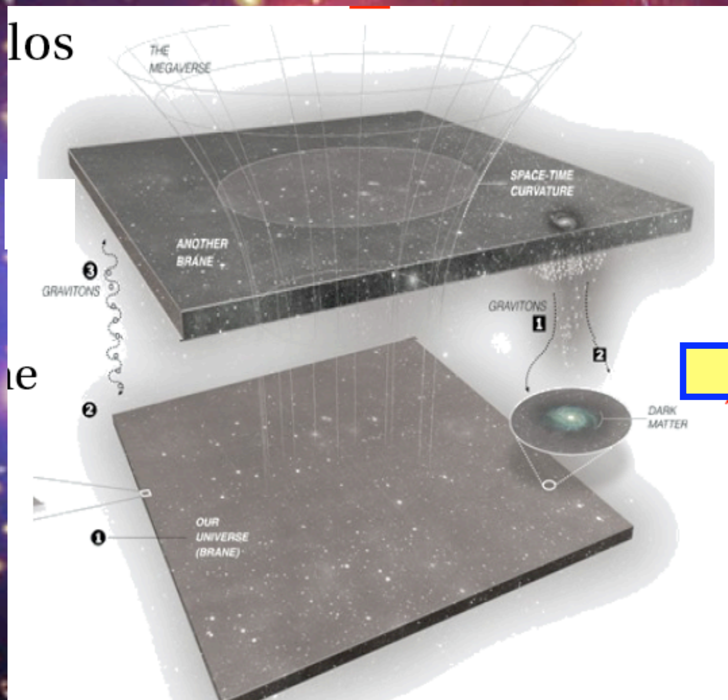
Extra Space Dimensions

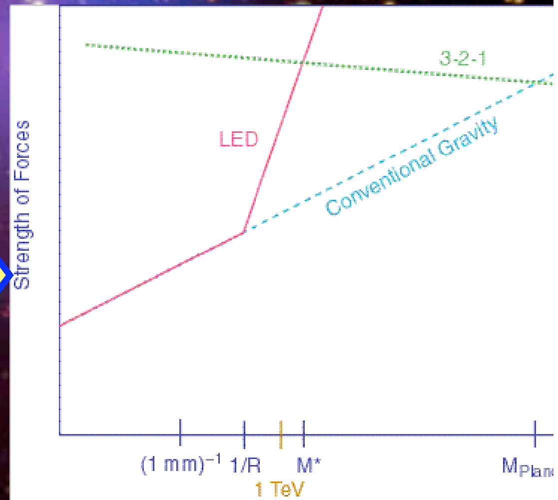
Problem:

$$m_{EW} = \frac{1}{(G_F \cdot \sqrt{2})^{\frac{1}{2}}} = 246\ \text{GeV}$$

$$M_{Pl} = \frac{1}{\sqrt{G_N}} = 1.2 \cdot 10^{19}\ \text{GeV}$$



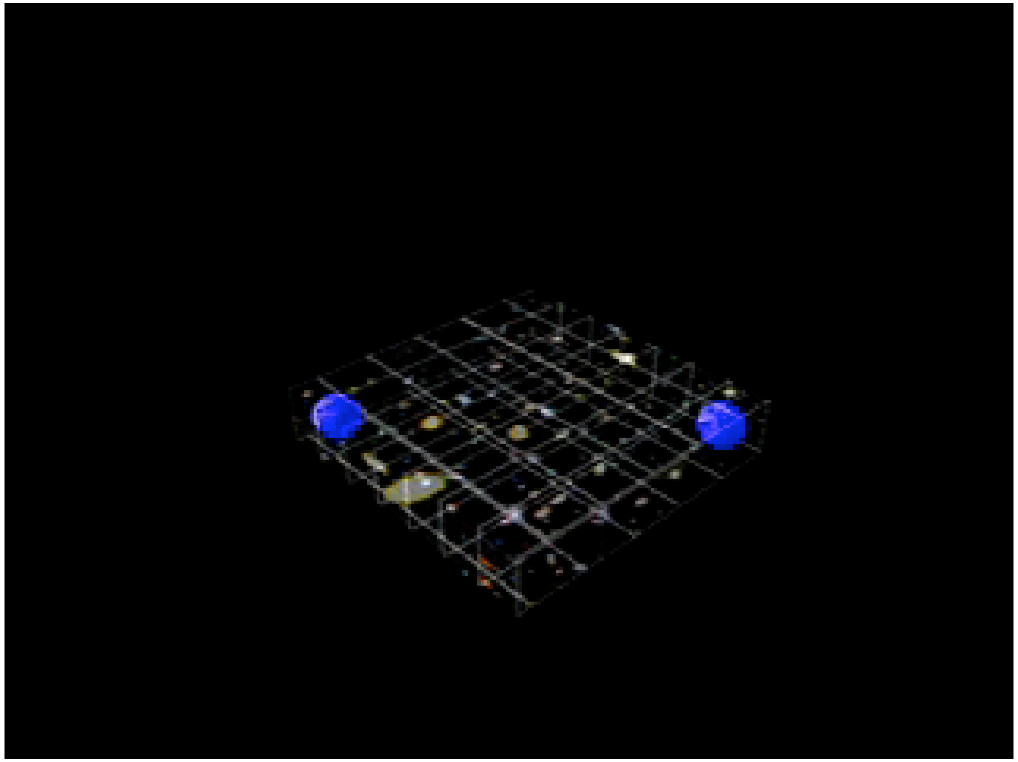


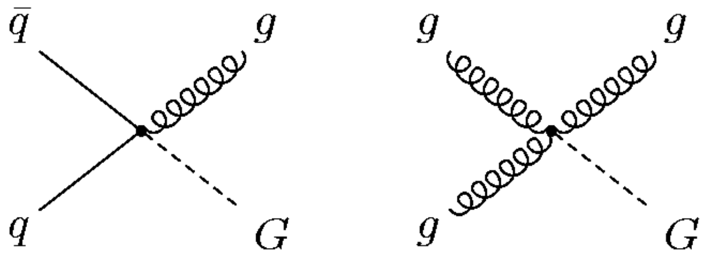


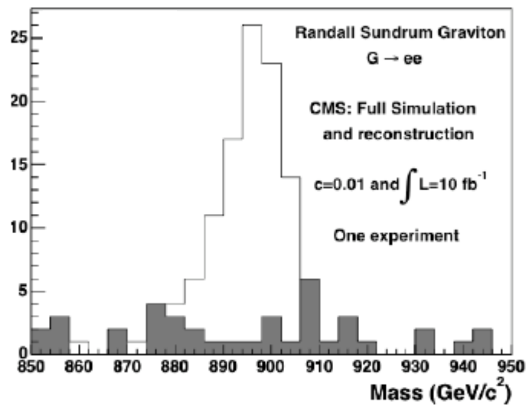
The Gravity force becomes strong!

Detecting Extra Dimensions at the LHC

Main detection modes at the experiments
- Large missing (transverse) energy
- Resonance production



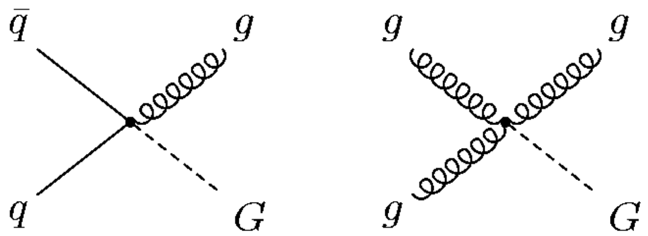




LHC can detect extra dimensions for scales up to 5 to 9 TeV

Large Extra Dimension signals at the LHC

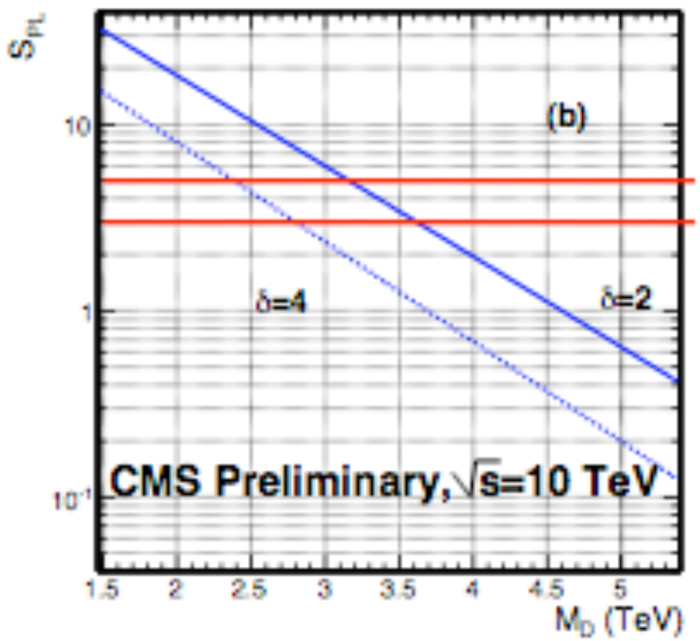
ADD: Arkani –Hamed, Dimopolous,Dvali

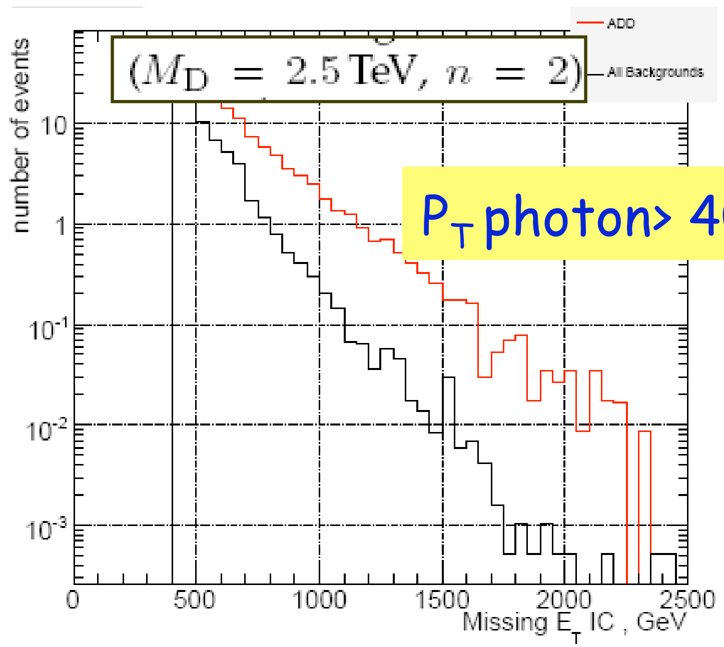


Graviton production!
Graviton escapes detection

Signal: single jet + large missing ET

Signal: single photon + large missing ET





$30fb^{-1}$

P_T photon> 400 GeV

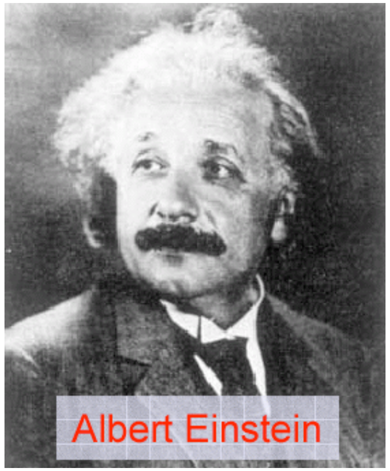
Test M_D to 2.5-3 TeV for 100 pb^{-1}
Test M_D to 7-9 TeV for 100 fb^{-1}

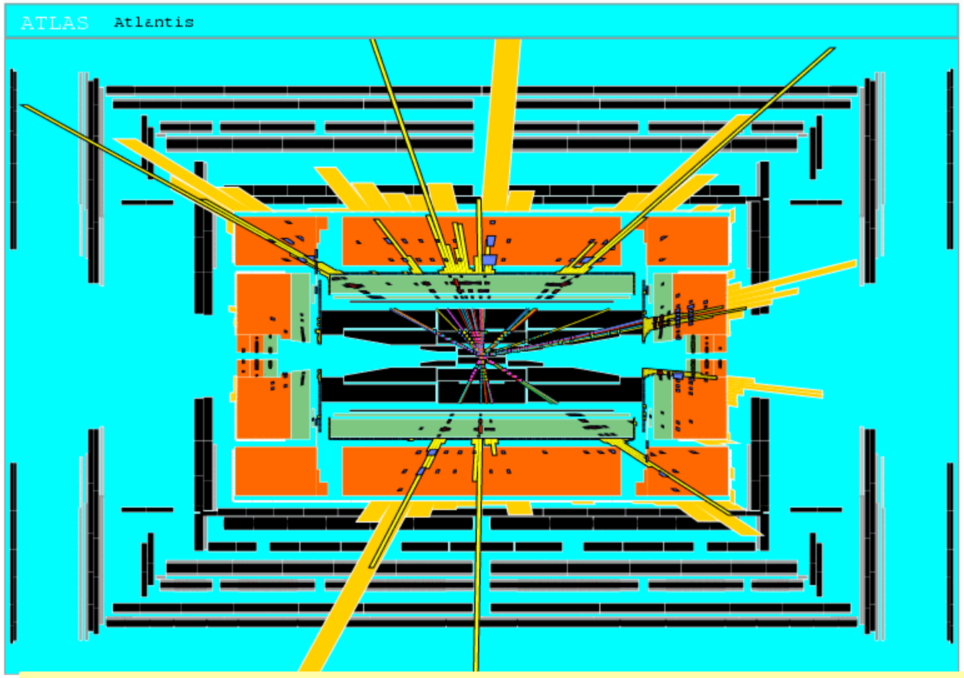
Test M_D to ~ 2 TeV for O(300) pb^{-1}
Test M_D to ~ 4 TeV for 100 fb^{-1}

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!

Quantum Back Holes

- Schwarzschild radius

Landsberg, Dimopoulos
Giddings, Thomas, Rizzo…

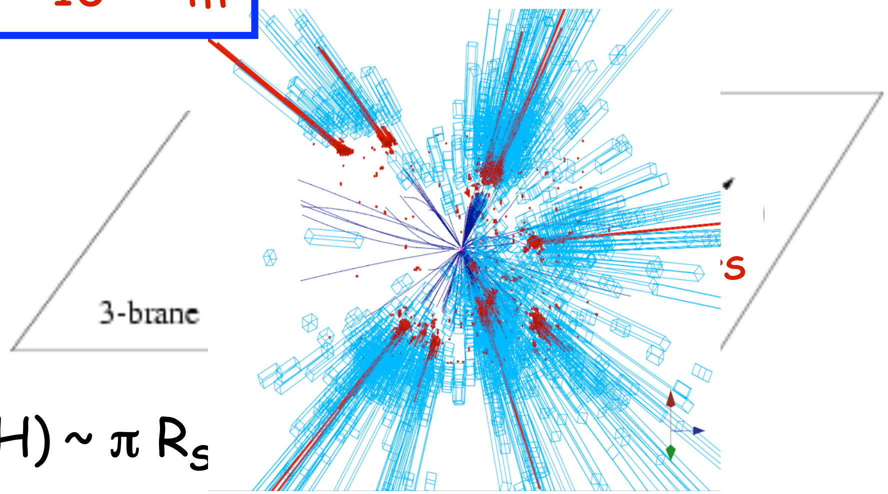
4-dim., $M_{gravity} = M_{Planck}$

$R_s \to \ll 10^{-35}$ m

4 + n-dim., $M_{gravity} = M_D \sim$ TeV

$R_s \to \sim 10^{-19}$ m

Since M_D is low, tiny black holes of $M_{BH} \sim$ TeV can be produced if partons ij with $\sqrt{s_{ij}} = M_{BH}$ pass at a distance smaller than R_S



- Large partonic cross-section : $\sigma(ij \to BH) \sim \pi R_S$
- $\sigma(pp \to BH)$ is in the range of 1 nb – 1 fb

e.g. For M_D ~1 TeV and n=3, produce 1 event/second at the LHC

- Black holes decay immediately by Hawking radiation (democratic evaporation) :

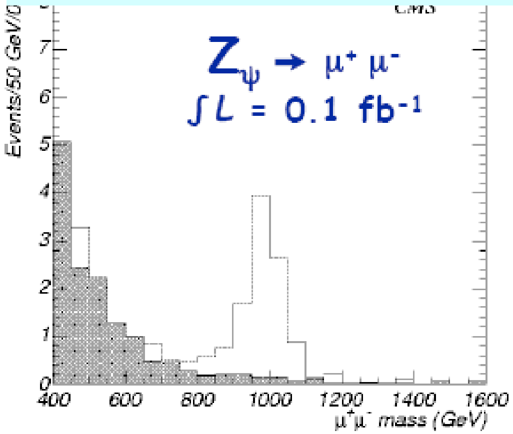
-- large multiplicity
-- small missing E
-- jets/leptons ~ 5

} expected signature (quite spectacular …)

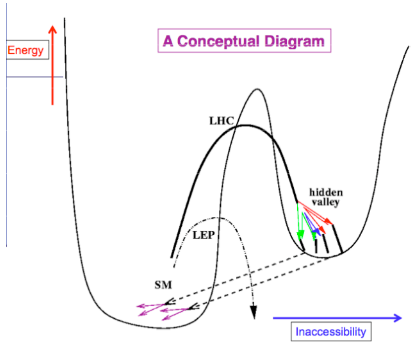
Black Holes Hunters at the LHC…

Other New Physics Scenarios at the LHC

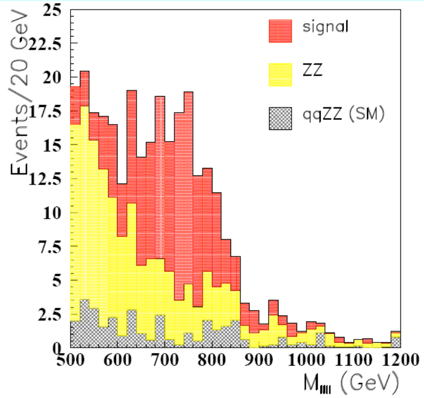
New Gauge Bosons?



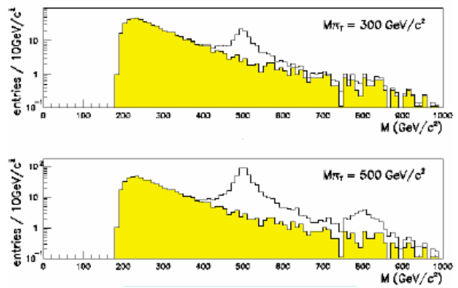
Hidden Valleys?



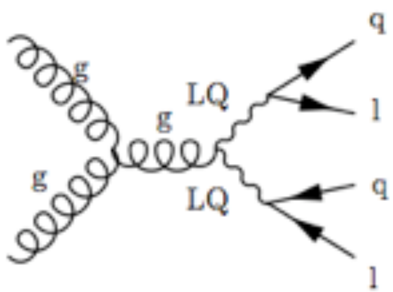
ZZ/WW resonances?



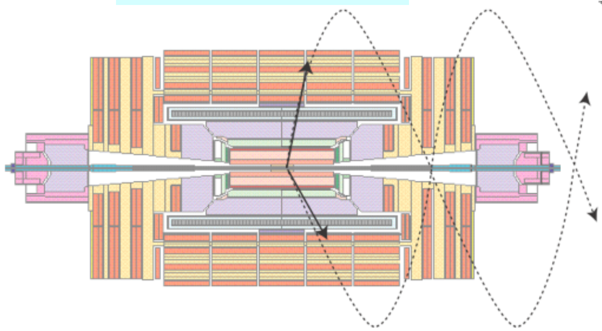
Technicolor?



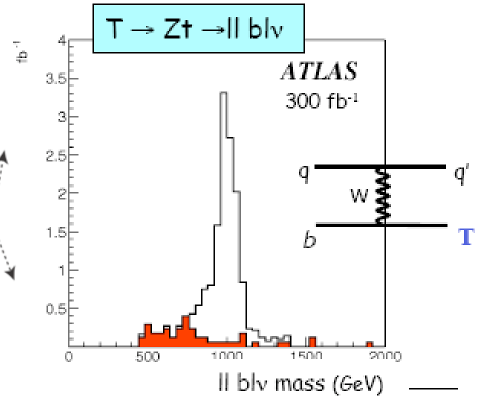
Leptoquarks?



Quirks???

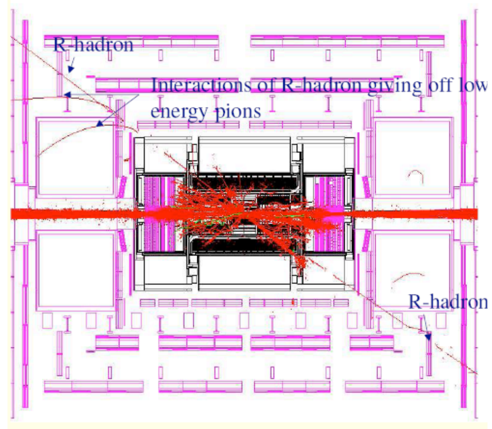


Little Higgs?



Split Susy?

PYTHIA R-hadron event from ATLSIM



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

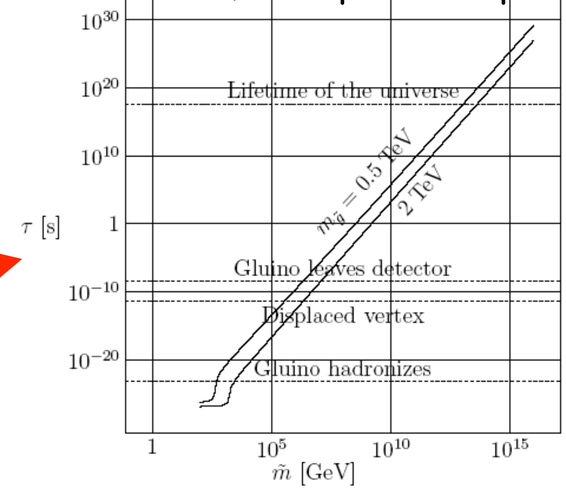
  eg. with the calorimeters of the experiments!

Gravitino Dark Matter and GMSB

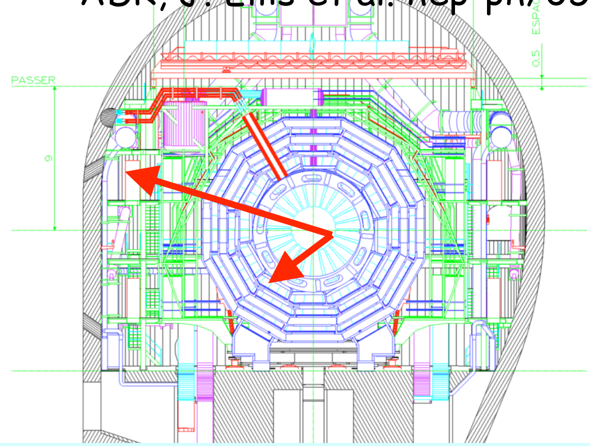
- In some models/phase space the gravitino is the LSP
- ⇒ NLSP (neutralino, stau lepton) can live 'long'
- ⇒ non-pointing photons

⇒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

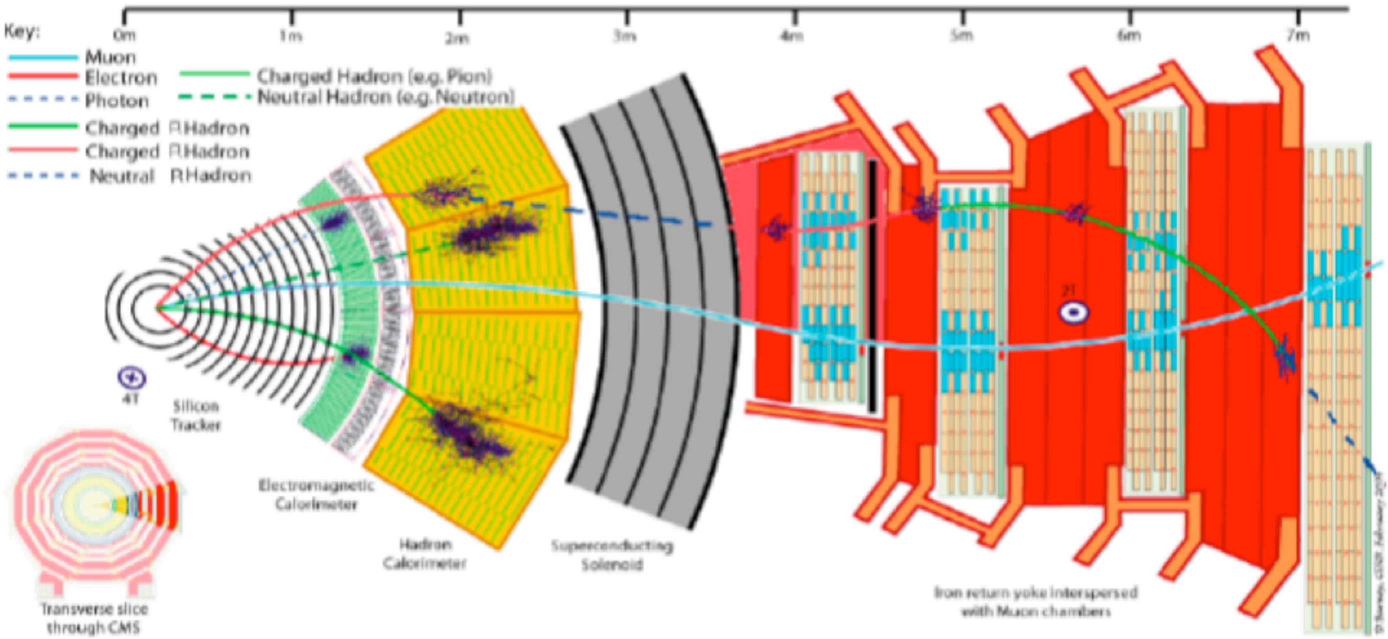


Also eg.
R. Barbieri

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

R-Hadrons Passing Through the Detector

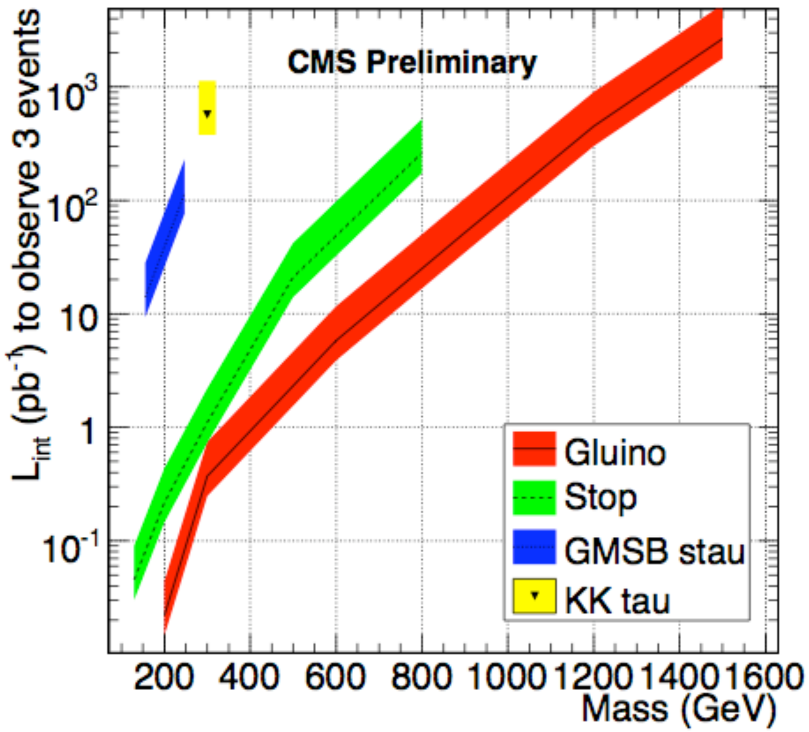
R-hadrons would have a mass of at least a few 100 GeV
- They 'sail' through the detector like a 'heavy muon'
- In certain (hadronization) models they may change charge on the way
- They also loose a lot of energy when passing the detector (dE/dx)



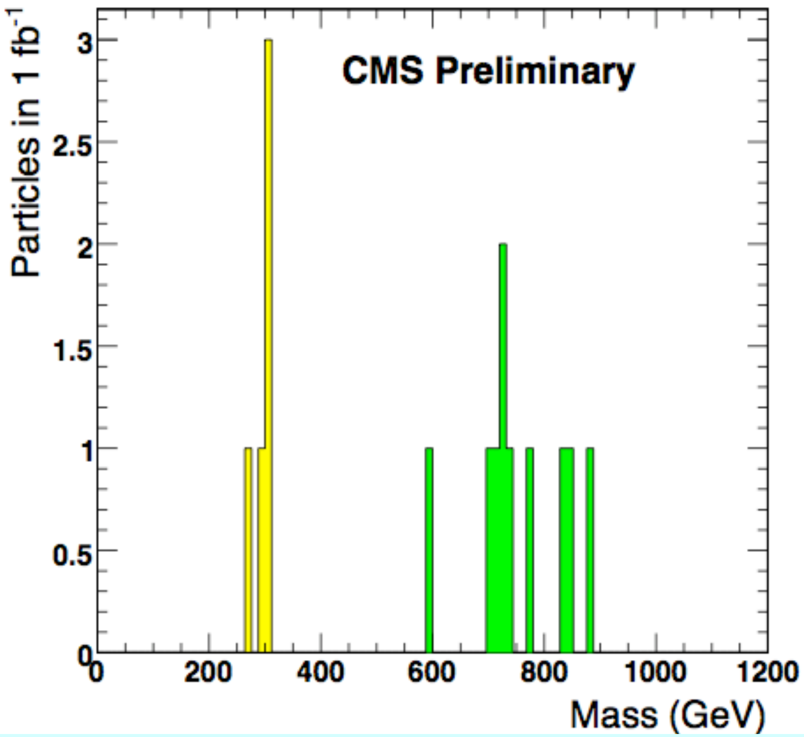
Weird signature!!

Heavy Stable Charged Particles

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

Stopped R-hadrons or Gluinos!

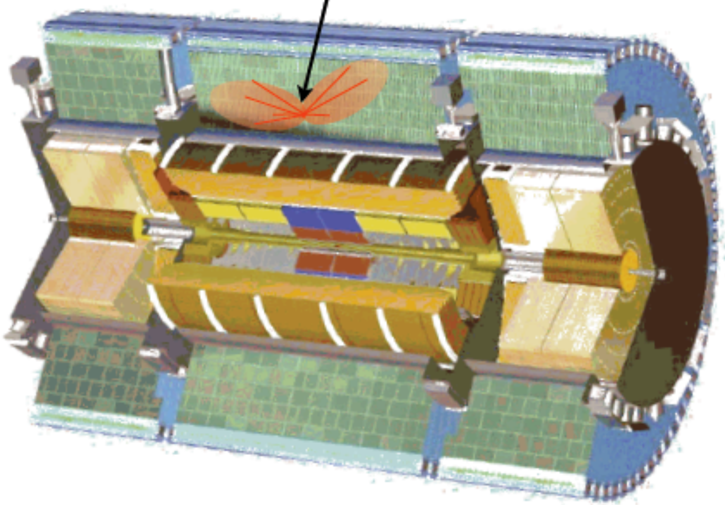
The R-hadrons may loose so much energy that they simply stop in the detector

Long Lived Gluinos

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

looking for stopped gluinos that later decay

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



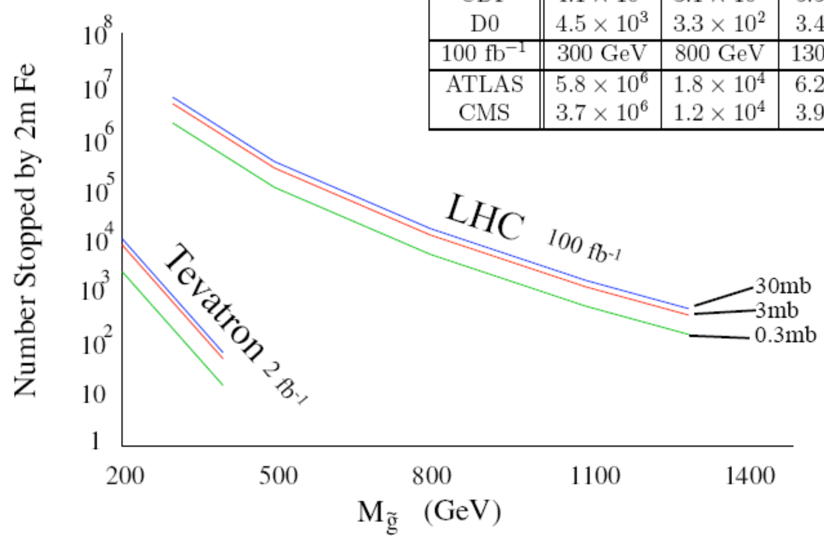
Uncorrelated with any beam crossing

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



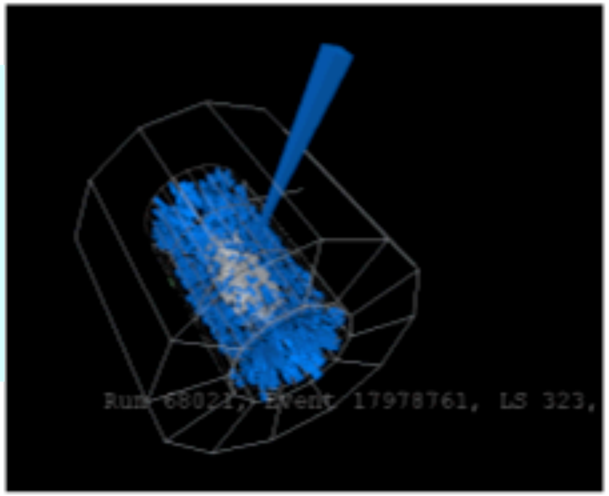
⇒ Special triggers needed, asynchronous with the bunch crossing

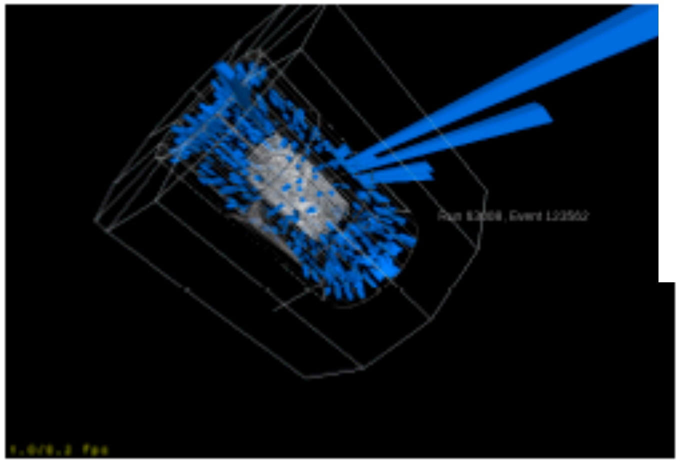
Stopped Gluinos

Studies in CMS with the 2008/2009 cosmic data:

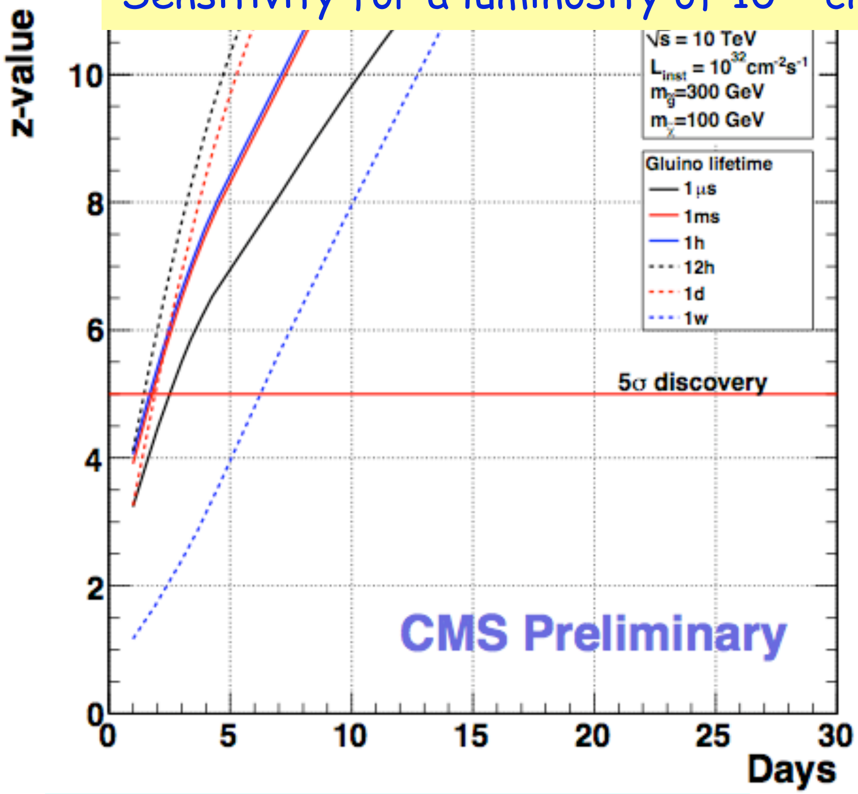
All events we find now are background and we can learn how to cut on them!

Find energy splashes with certain topology



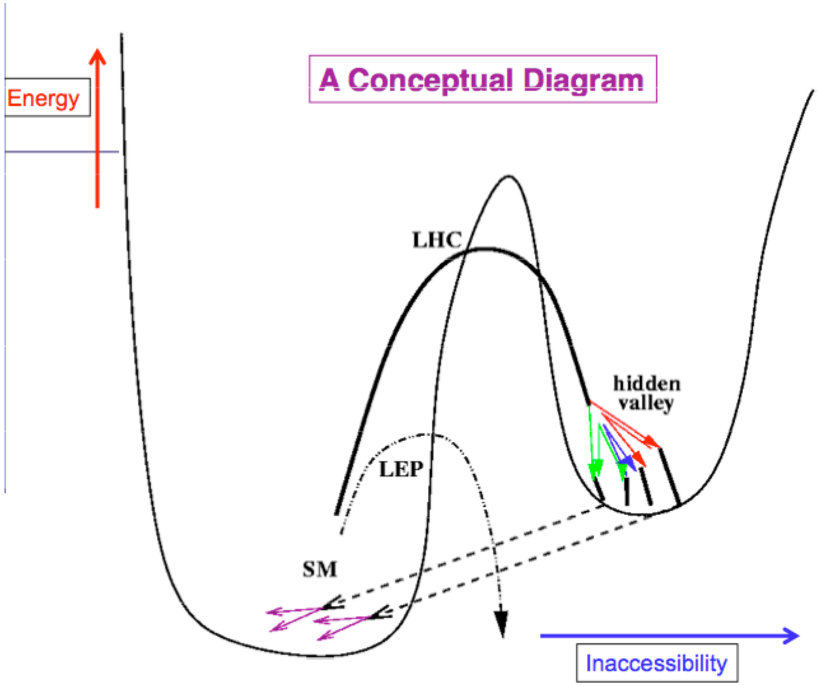


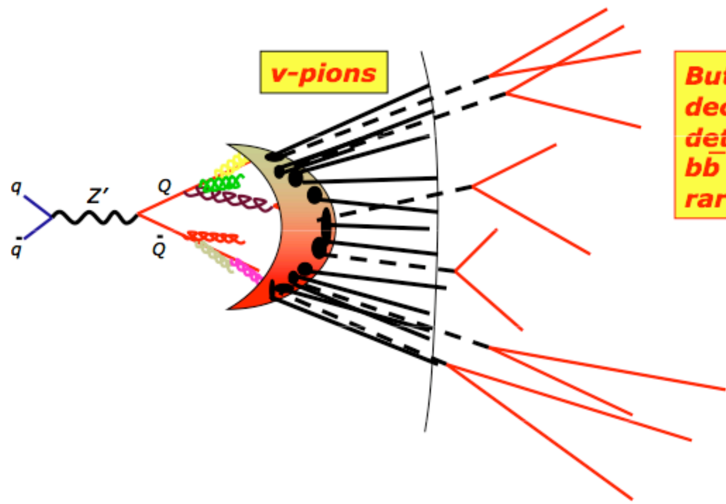
Sensitivity for a luminosity of 10^{32} $cm^{-2}s^{-1}$



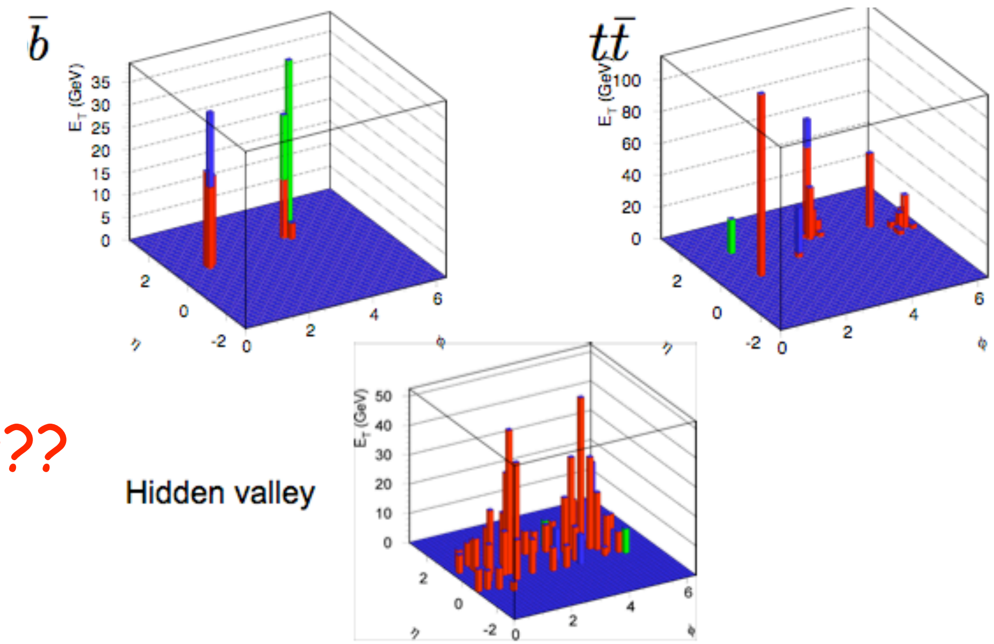
Discovery with only a few weeks running!

Hidden Valley Physics: New Signatures





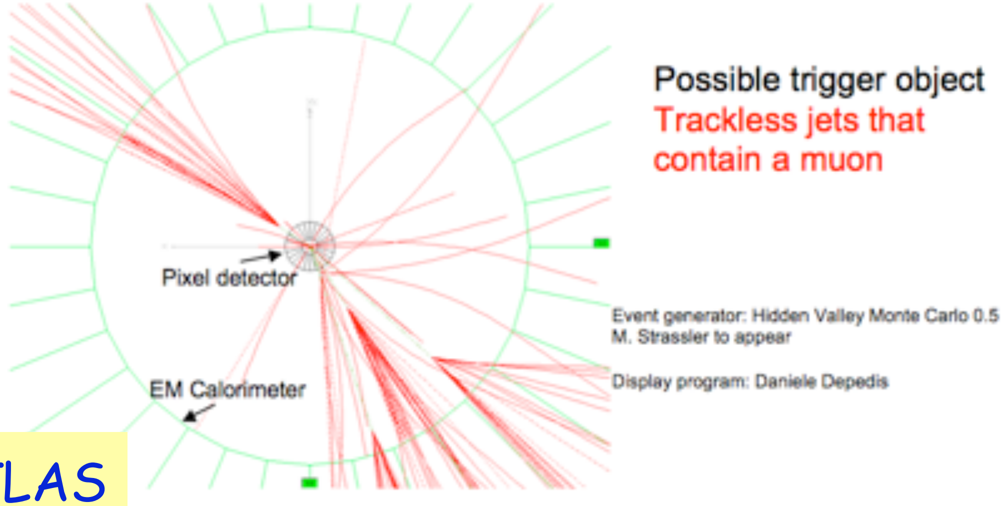
Will produce"Weird Jets" and a lot of secondary vertices



⇒ Difference with QCD jets??

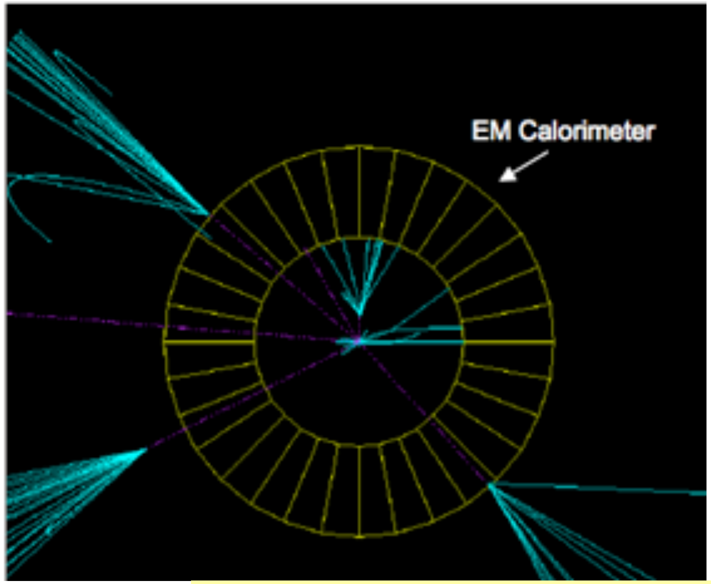
⇒ Study SM jet structure

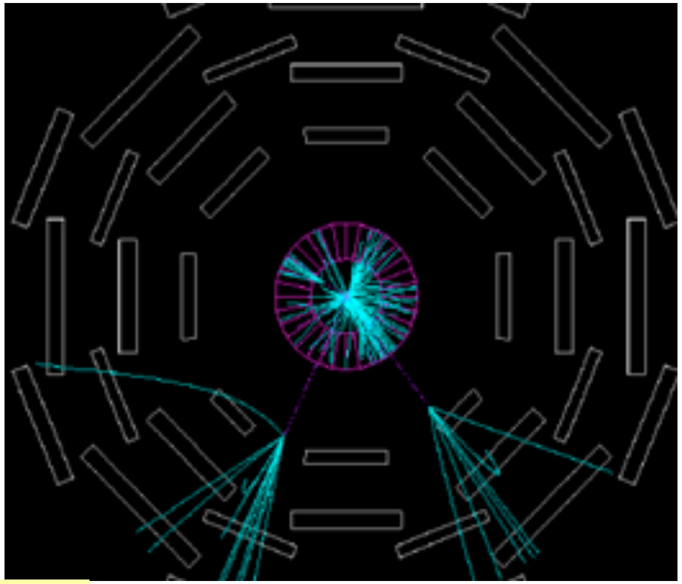
Hidden Valley Events



The experiments are not really prepared for this(*)
For example: Trigger problems for events with large displayed vertices

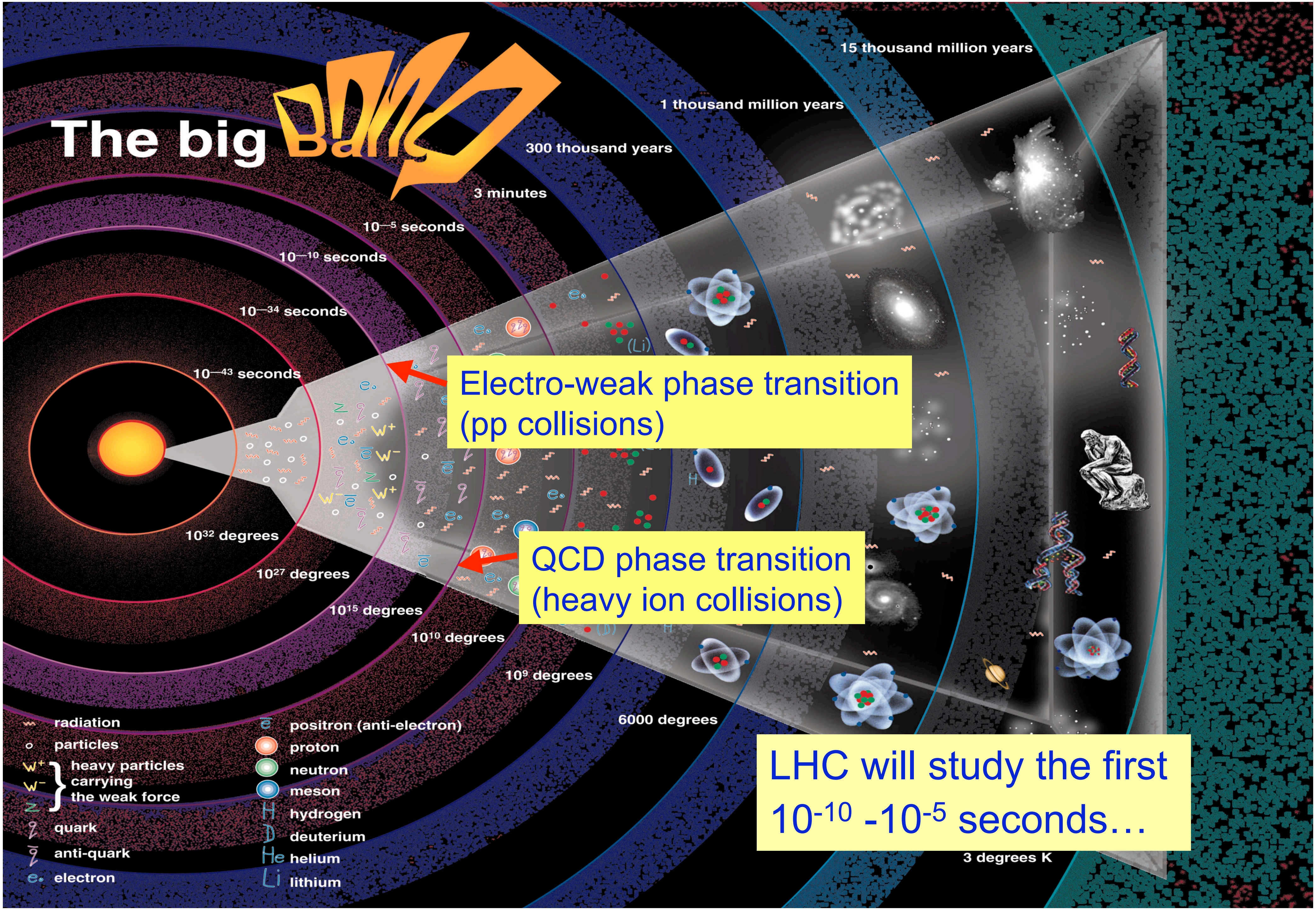
ATLAS





⇒Need special triggers

(*) except possibly LHCb



The big Bang
15 thousand million years
1 thousand million years
300 thousand years
3 minutes
10⁻⁵ seconds
10⁻¹⁰ seconds
10⁻³⁴ seconds
10⁻⁴³ seconds
10³² degrees
10²⁷ degrees
10¹⁵ degrees
10¹⁰ degrees
10⁹ degrees
6000 degrees
3 degrees K
Electro-weak phase transition (pp collisions)
QCD phase transition (heavy ion collisions)
LHC will study the first 10⁻¹⁰ -10⁻⁵ seconds…
radiation
particles
heavy particles carrying the weak force
quark
anti-quark
electron
positron (anti-electron)
proton
neutron
meson
hydrogen
deuterium
helium
lithium

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…?

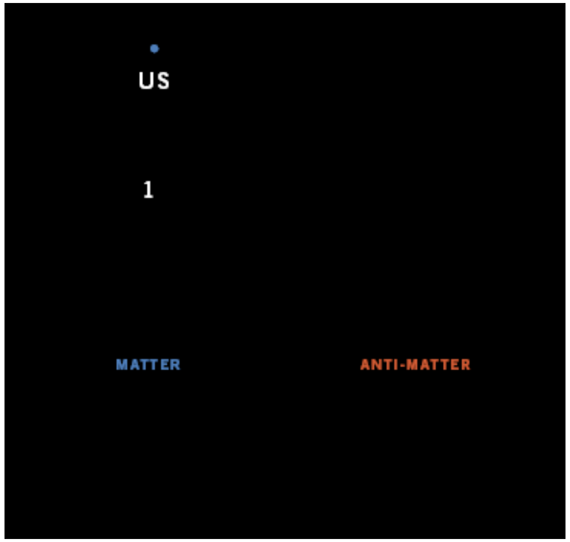
The LHC operates at an energy and precision that will take us far beyond our current understanding, into a new regime

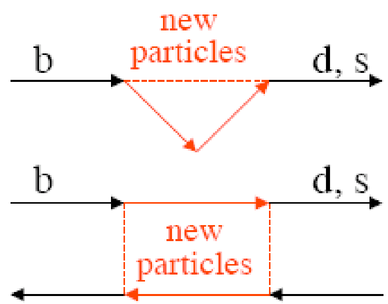
Machine and detectors are of an unprecedented scale and complexity. They have been completed in summer 2008.
The LHC has started successfully its operation this month!!.

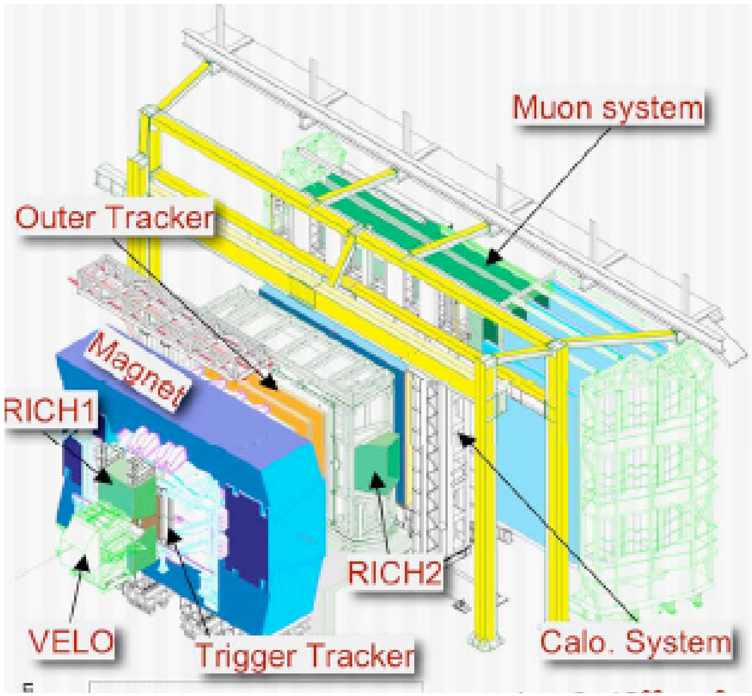
We are on the verge of a revolution in our understanding of the Universe and our place within it

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

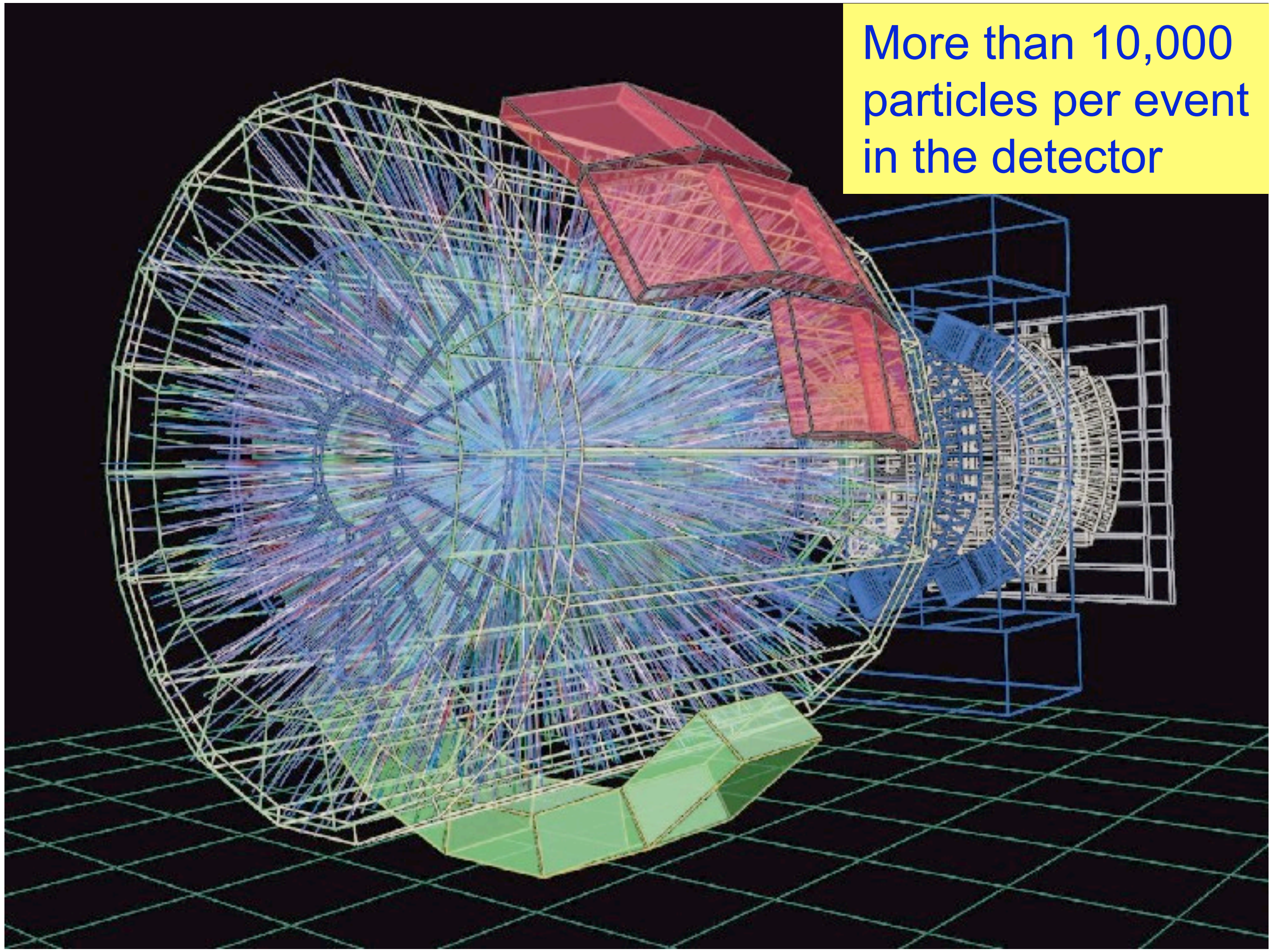




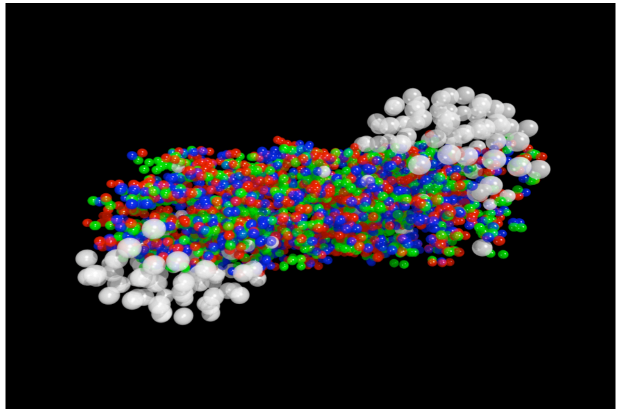


Primordial Plasma

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



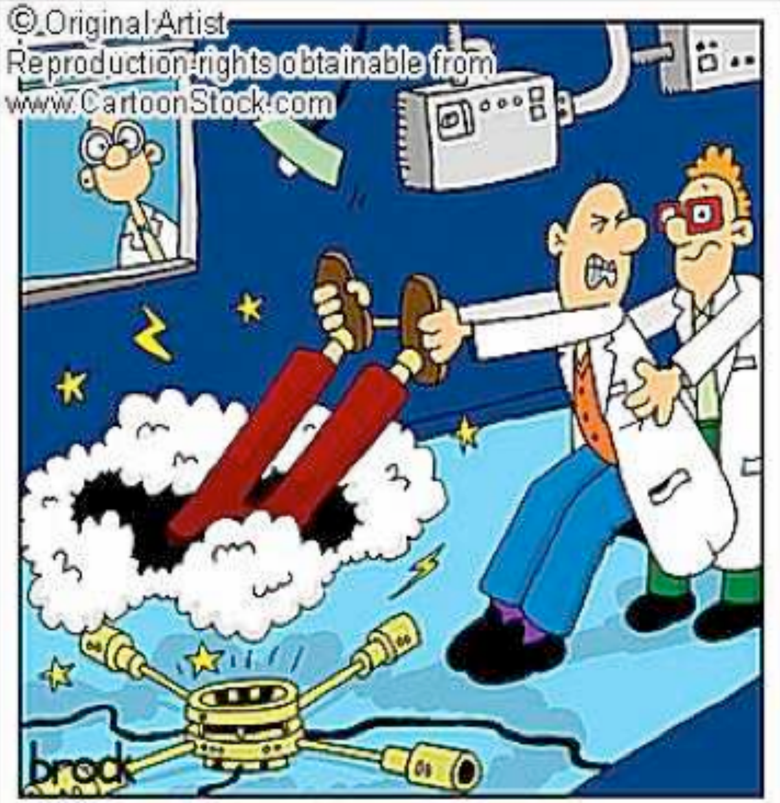
Study the phase transition of a state of quark gluon plasma created at the time of the early Universe to the baryonic matter we observe today

Quantum 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* LSAG, *http://arXiv.org/pdf/0806.3414*
  - Scientific Policy Committee Review, *http://indico.cern.ch/getFile.py/access?contribId=20&resId=0&materialId=0&confId=35065*
  - CERN public web page, *http://public.web.cern.ch/public/en/LHC/Safety-en.html*



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

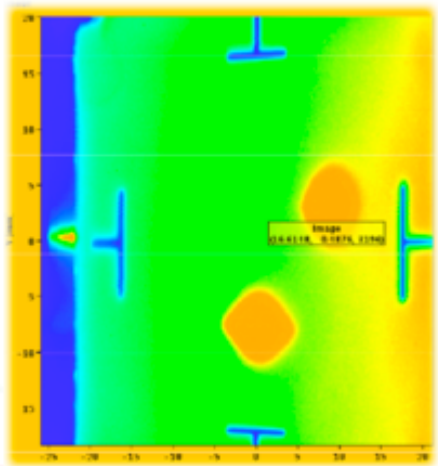
LHC Start-up in Fall 2007

September 10th

Despite the presence of an unbelievable crowd of people :

> 300 Journalist

- 10:30 : Beam 1 around the ring (in ~ 1 hour). Beam makes ~ 3 turns.
- 15:00 : Beam 2 around the ring, beam makes 3-4 turns.
- 22:00 : Beam 2 circulates for hundreds of turns…



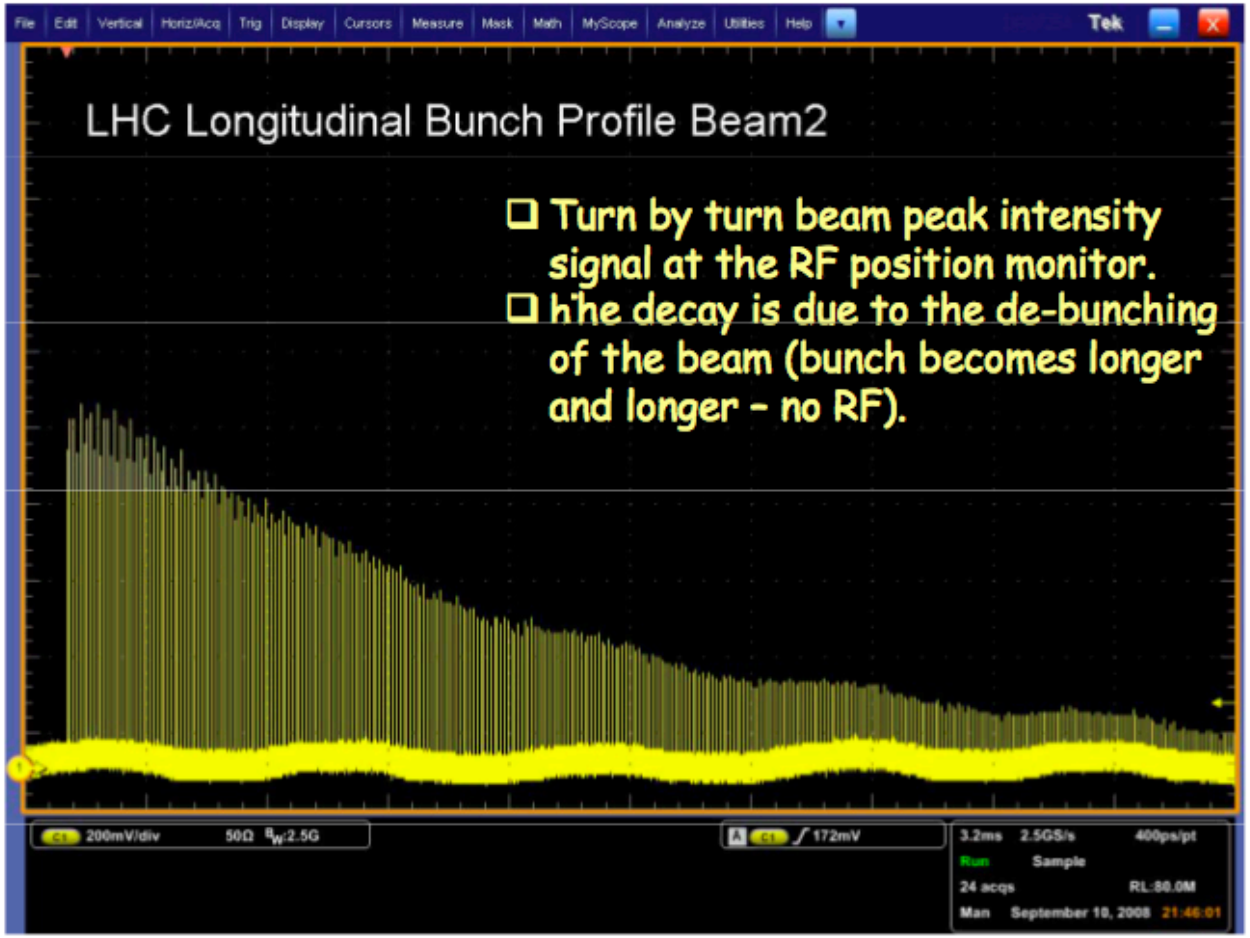
September 10th 2008

Circulating Beam

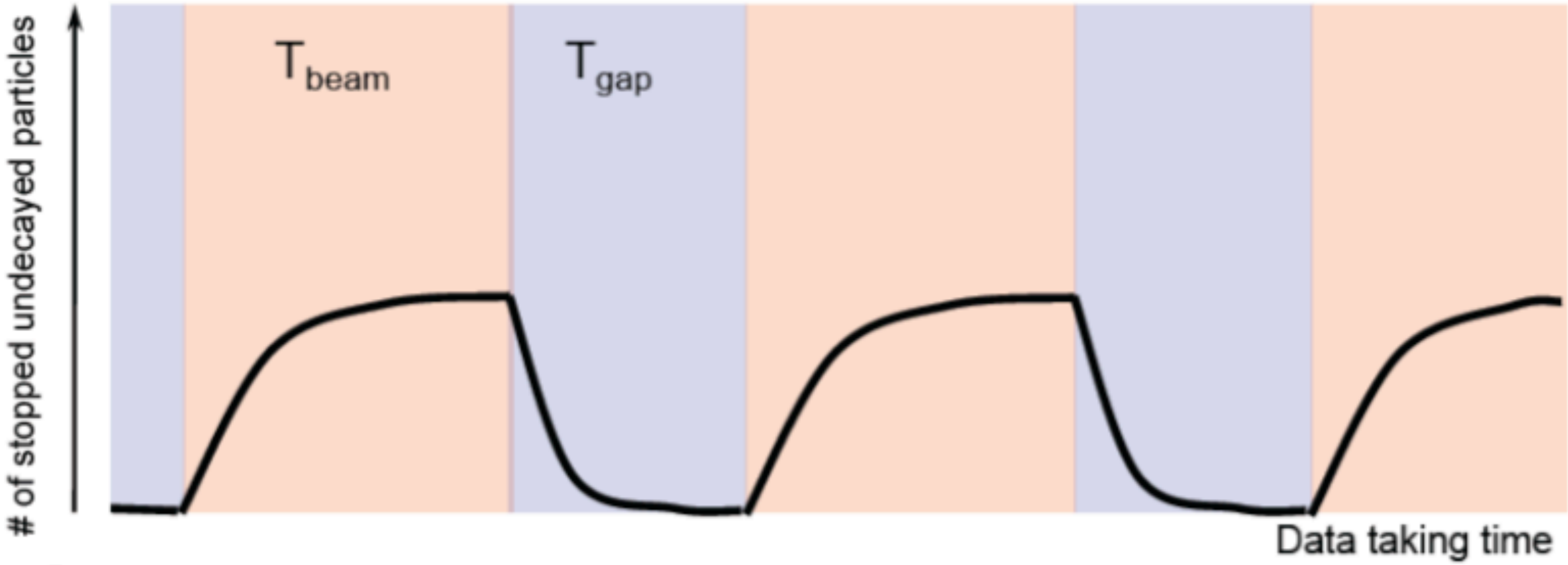
Beam 2 circulating – no RF

Evening of September 10th , after the crowds left :

Beam 2 makes hundreds of turns after some empirical correction (no RF)



Stopped gluinos



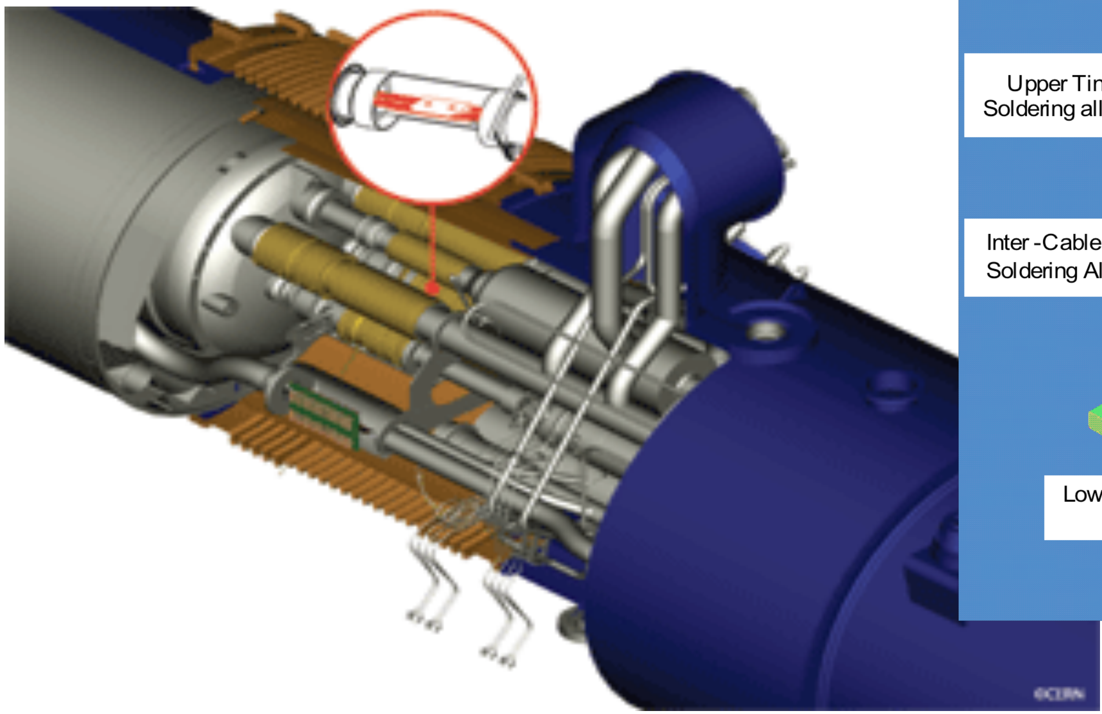
- Basic idea: R-hadrons can loose enough energy in the detector to stop somewhere inside (usually calorimeters)
- Sooner or later they must decay Eg when there is no beam!
- Trigger: (jet) && !(beam)
- Only possible backgrounds: cosmics and noise

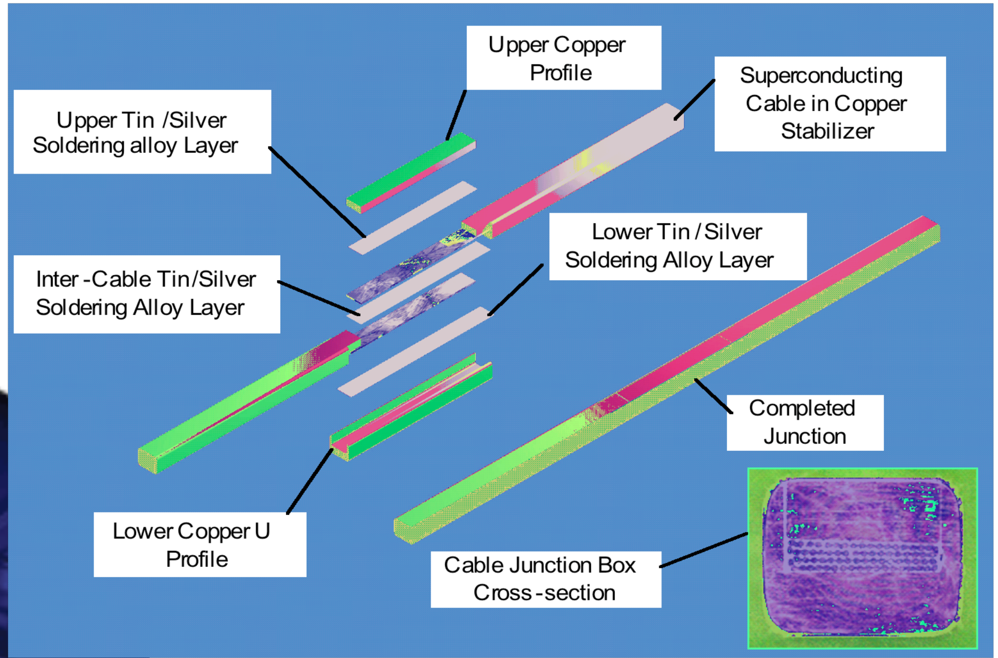
Can be studied in the experiments NOW with cosmic data

The Incident of September 19th

The LHC decided to use a few days of down-time due to a 'standard' power converter fault to finish work on missing powering tests in sector 3-4 (other sectors were tested to 5.5 TeV equivalent currents)

At 8.7 kA (corresponding to ~ 5.1 TeV), a resistive zone appeared in the superconducting busbar between quadrupole Q24 and the neighboring dipole (due to a bad welding 'splice')

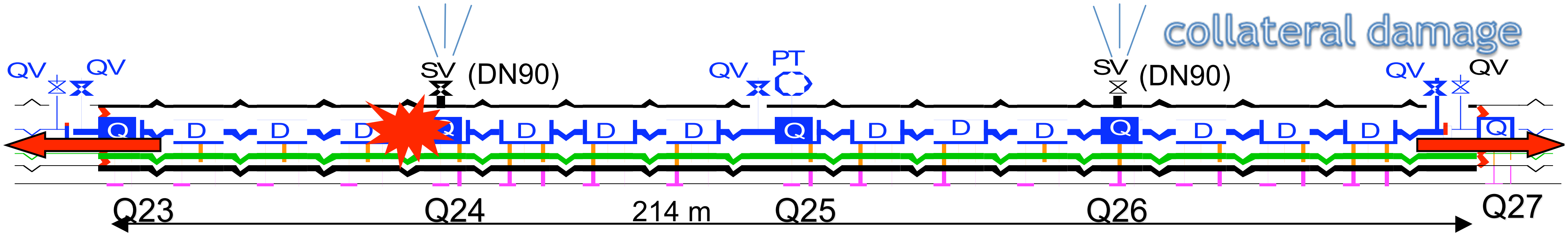


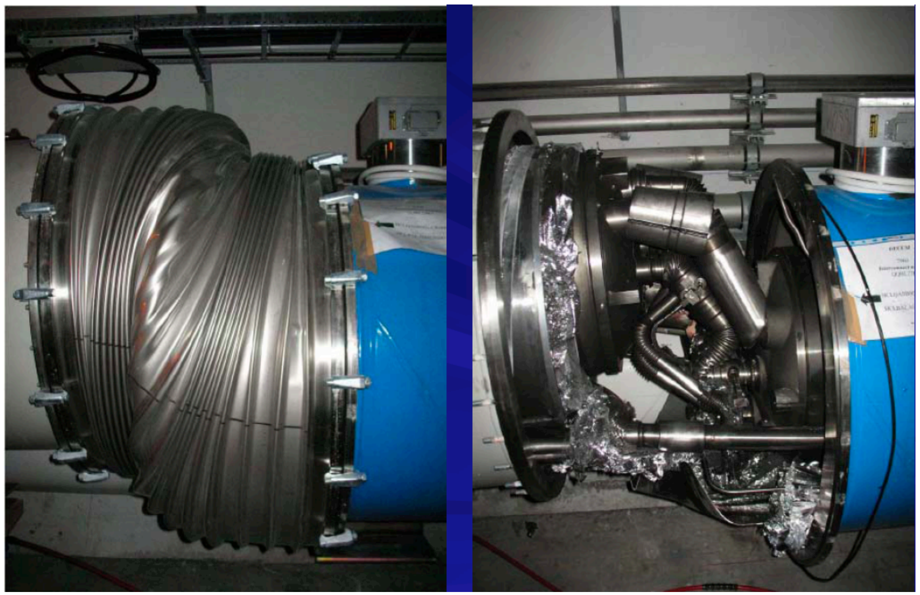


The Incident of September 19th

Most likely, an electrical arc developed, which punctured the Helium enclosure

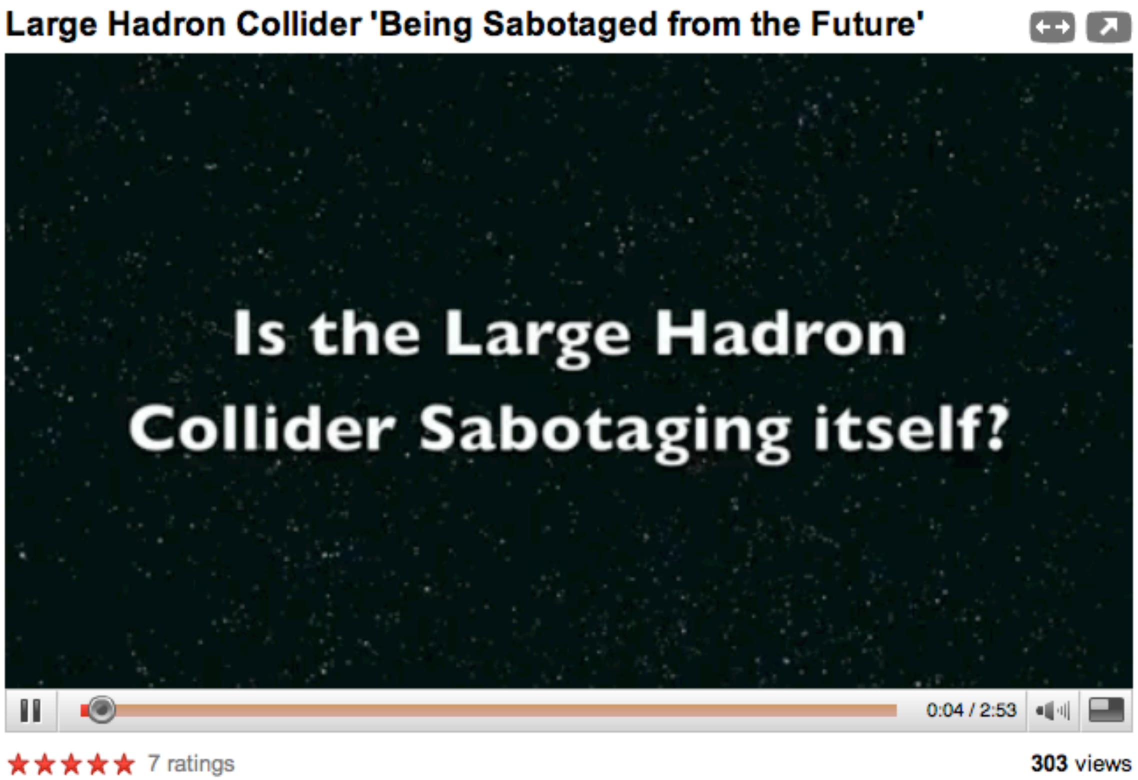
Large amounts of Helium gas were released into the insulating vacuum of the cryostat and a large pressure waves traveled along the accelerator both ways

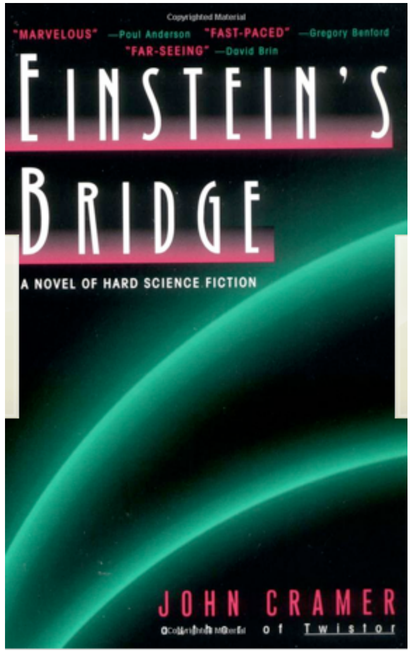




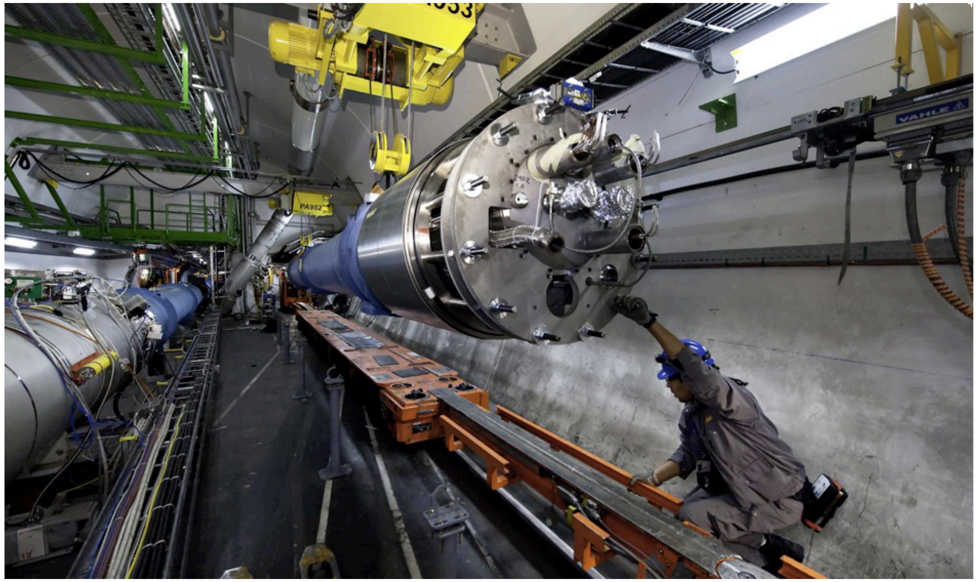
Science Fiction Speculation ☺

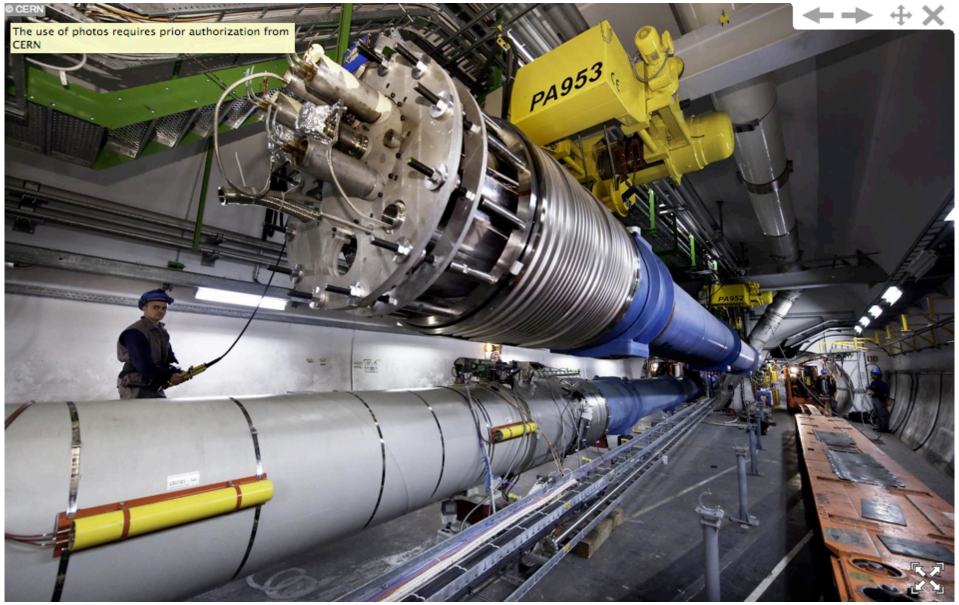
New on YouTube…





Maybe 'the future' does not want to LHC to start ☺
… as in the SF novel from '96 … on the SSC in the US

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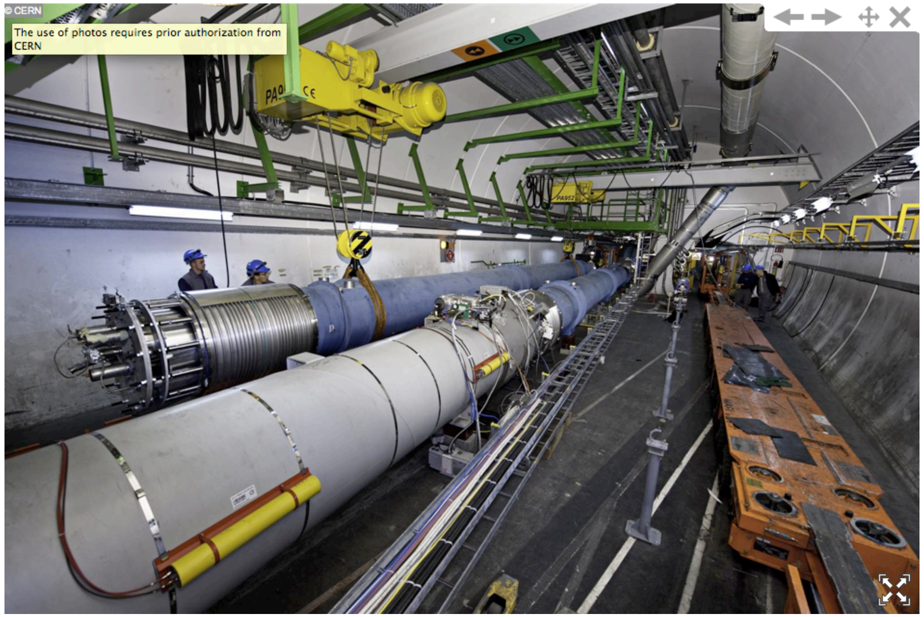
Use arrow keys for next and previous.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Lessons

M. Lamont September 2009

- The enhanced quality assurance introduced during sector 3-4 repair has revealed new facts concerning the copper bus bar in which the superconductor is embedded.
- The process of soldering the superconductor in the interconnecting high-current splices can cause discontinuity of the copper part of the bus-bars and voids which prevent contact between the super-conducting cable and the copper.

Danger occurs only in case of a quench

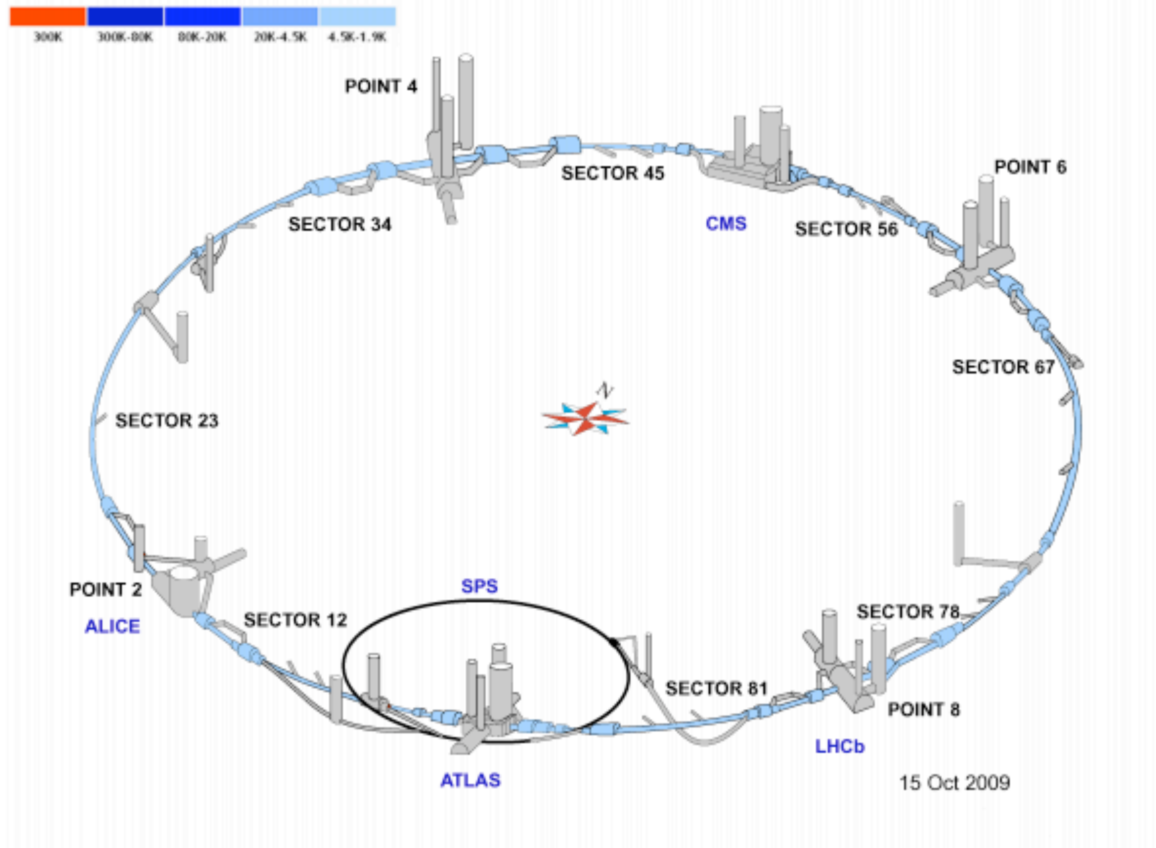
Plan for the first run (2009/2010)

- Operating at 3.5 TeV with a dipole energy extraction time of 50 s.
  - Simulations show that resistances of 120 micro-ohm are safe from thermal runaway under conservative assumed conditions of worst case conditions for the copper quality (RRR) and no cooling to the copper stabilizer from the gaseous helium

- Decision:
  - Operation initially at 3.5 TeV (energy extraction time of 50 s) with a safety factor or more than 2 for the worst stabilizers.

- Then operate at 4 – 5 TeV

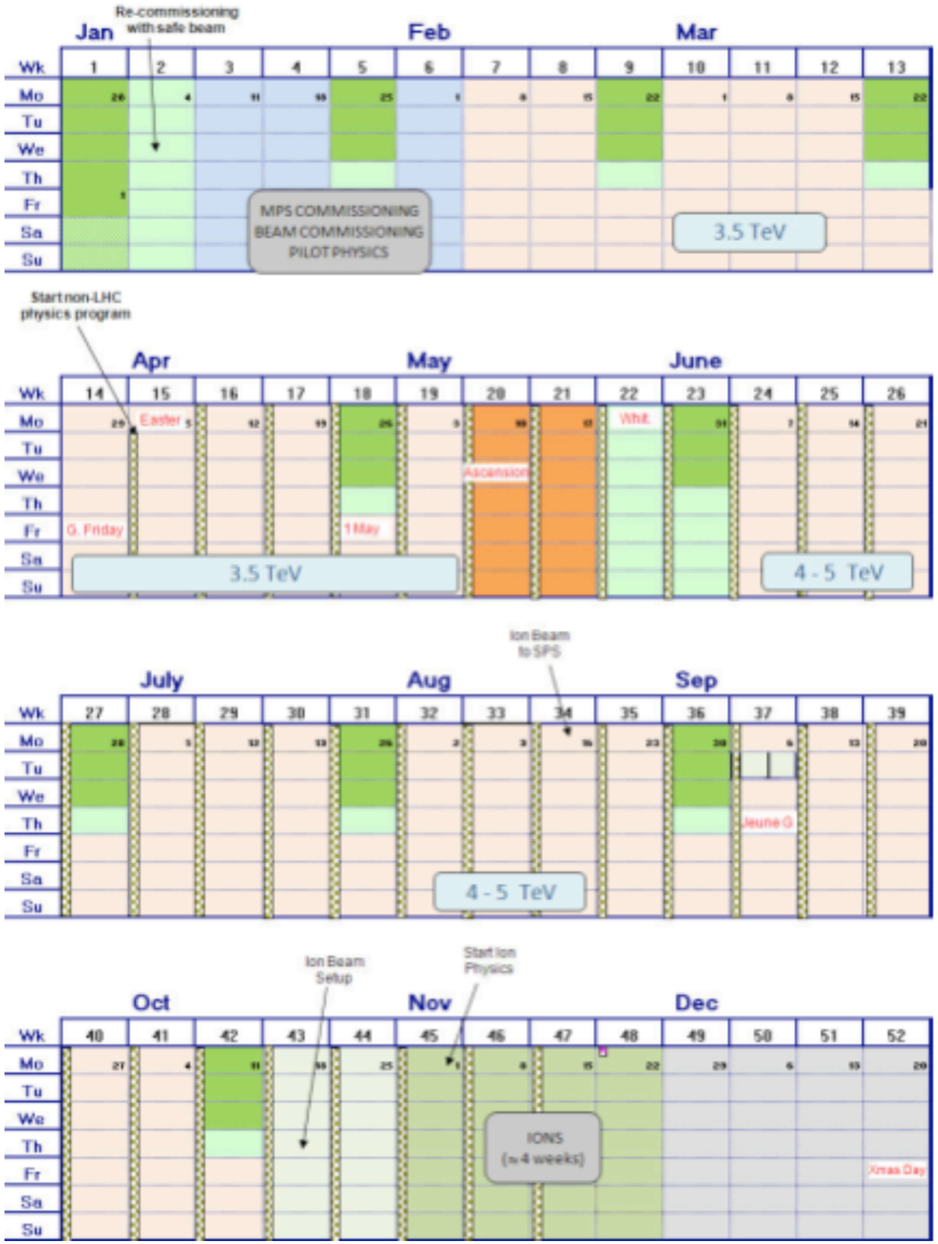
The LHC Today



LHC Cooldown Status

- Repairs are now completed
- Machine is cooled down again
- Plan to start again middle of November 2009

LHC run plan for 2010



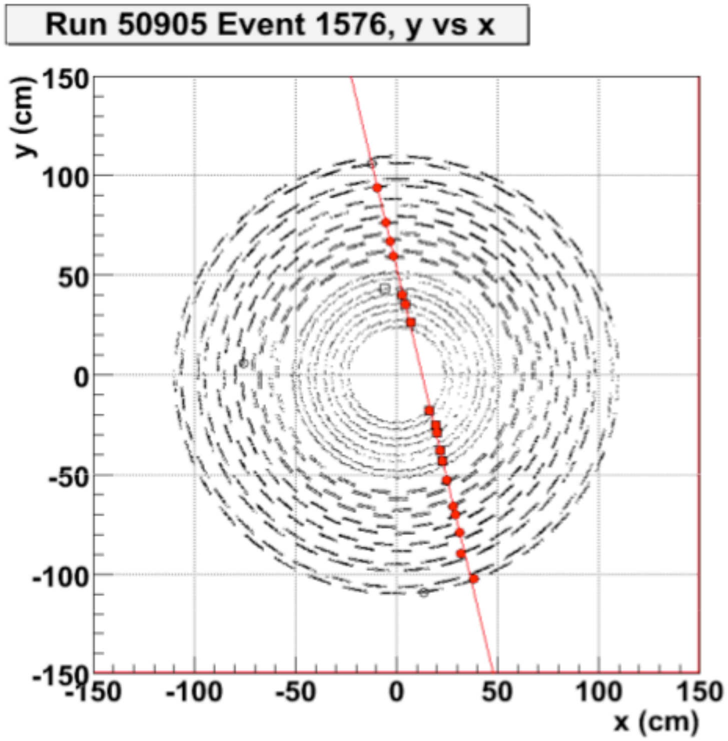
O(30)pb^{-1} at 7 TeV
O(200) pb^{-1} at 10 TeV

- **2009**:
  - 1 month commissioning
- **2010**:
  - 1 month pilot & commissioning
  - 3 month 3.5 TeV
  - 1 month step-up
  - 5 month 4 - 5 TeV
  - 1 month ions

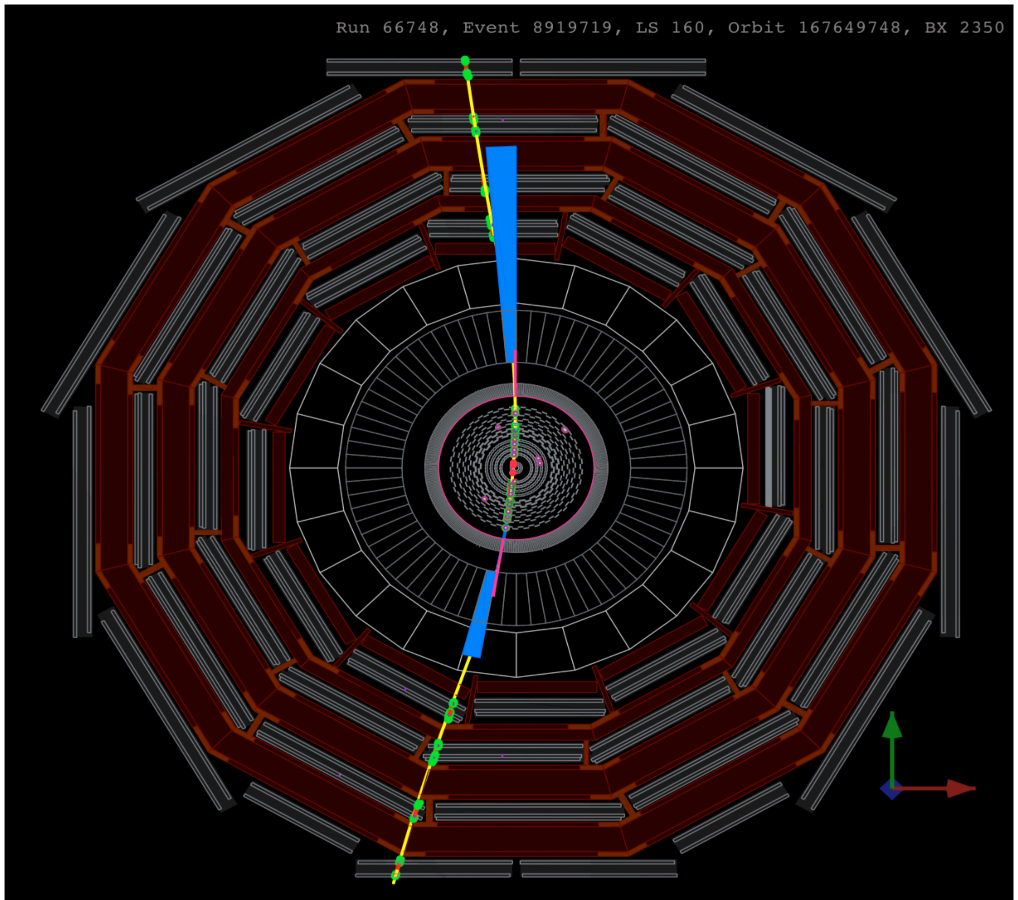
2011 ???

CMS Works! …
Example: Recorded Cosmic Muons

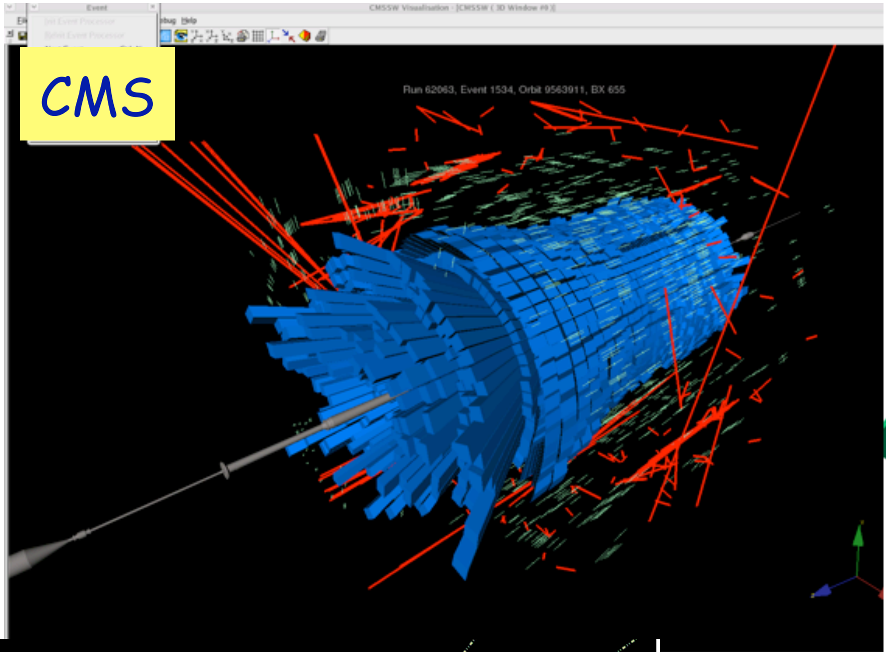
Cosmic muons recorded by the complete central tracker during the summer '08

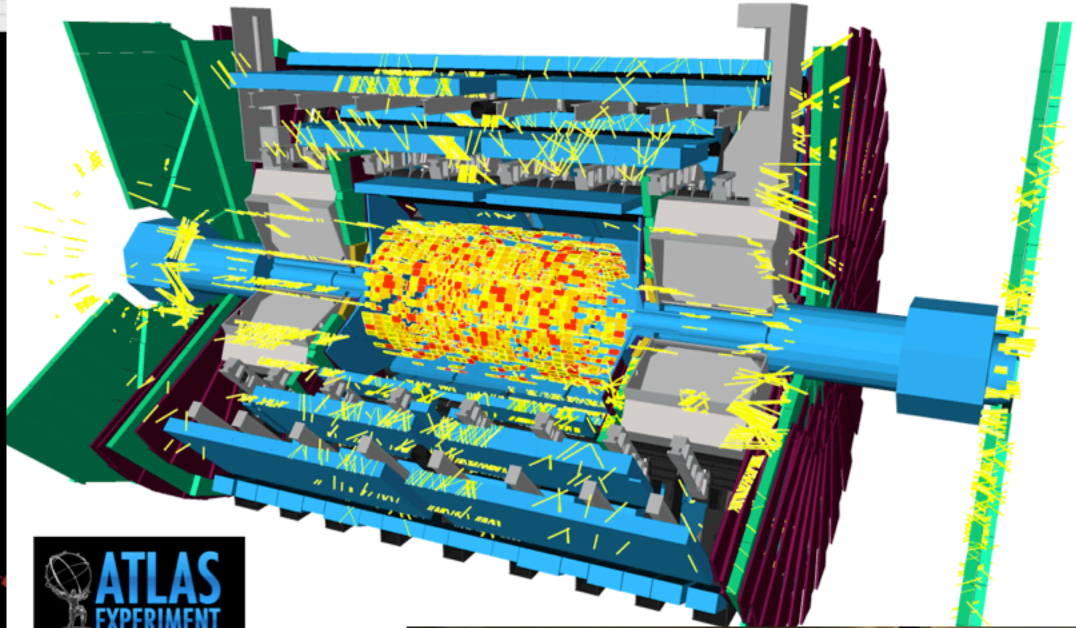


Cosmic muons recorded by CMS



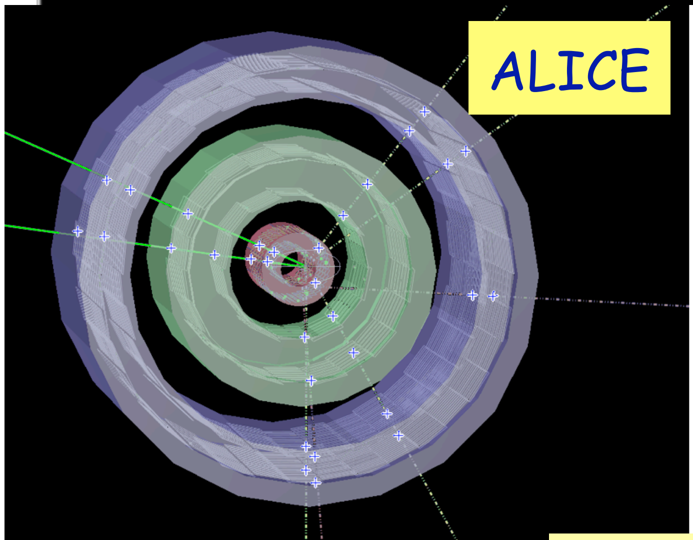
Beam Halo and Splashes on 10/9

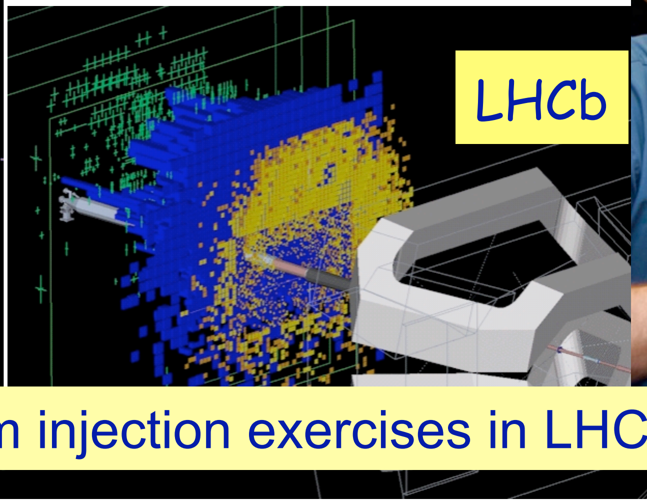




ATLAS EXPERIMENT
http://atlas.ch

first b





Beam injection exercises in LHC starting again tomorrow!

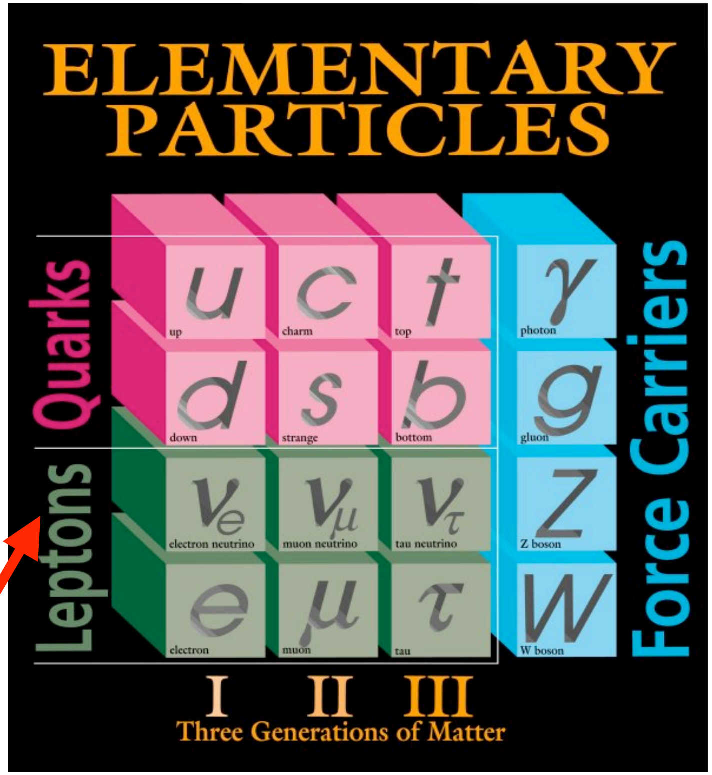
The Standard Model in Particle Physics

But not all questions solved:

Needs to be completed with eg a Higgs mechanisme/ particle
⇒ Electroweak Symmetry breaking

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