The ATLAS and CMS Experiment

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Taller de Altas Energías 2010

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Lecture Plan

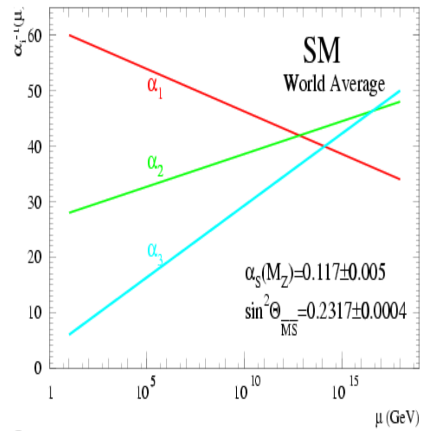
- Introduction
- The LHC Collider
  - Introduction to the LHC
- The experimental challenges at the LHC
  - The experimental solutions
- The “general purpose” experiments
  - The CMS experiment
  - The ATLAS experiment
- First performance results of the experiments
- First physics with the ATLAS and CMS experiments
  - QCD, B-physics
  - EWK/Searches and the outlook

Physics case for new High Energy Machines

Understand the mechanism Electroweak Symmetry Breaking

Discover physics beyond the Standard Model

Reminder: The Standard Model
- tells us how but not why
  3 flavour families? Mass spectra? Hierarchy?
- needs fine tuning of parameters to level of 10^{-30} !
- has no connection with gravity. Dark matter, energy?
- no unification of the forces at high energy

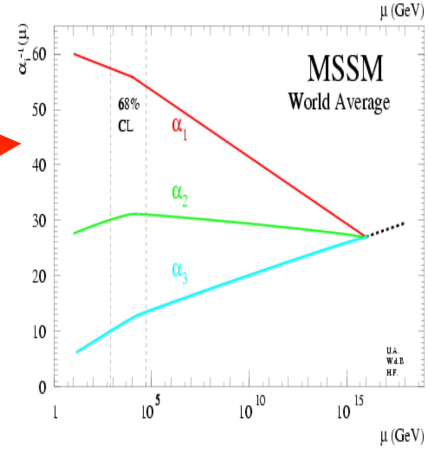


Most popular extensions these days

If a Higgs field exists:
- Supersymmetry
- Extra space dimensions

If there is no Higgs below ~ 700 GeV
- Strong electroweak symmetry breaking around 1 TeV

Other ideas: more gauge bosons/quark & lepton substructure, Little Higgs models, Technicolor…

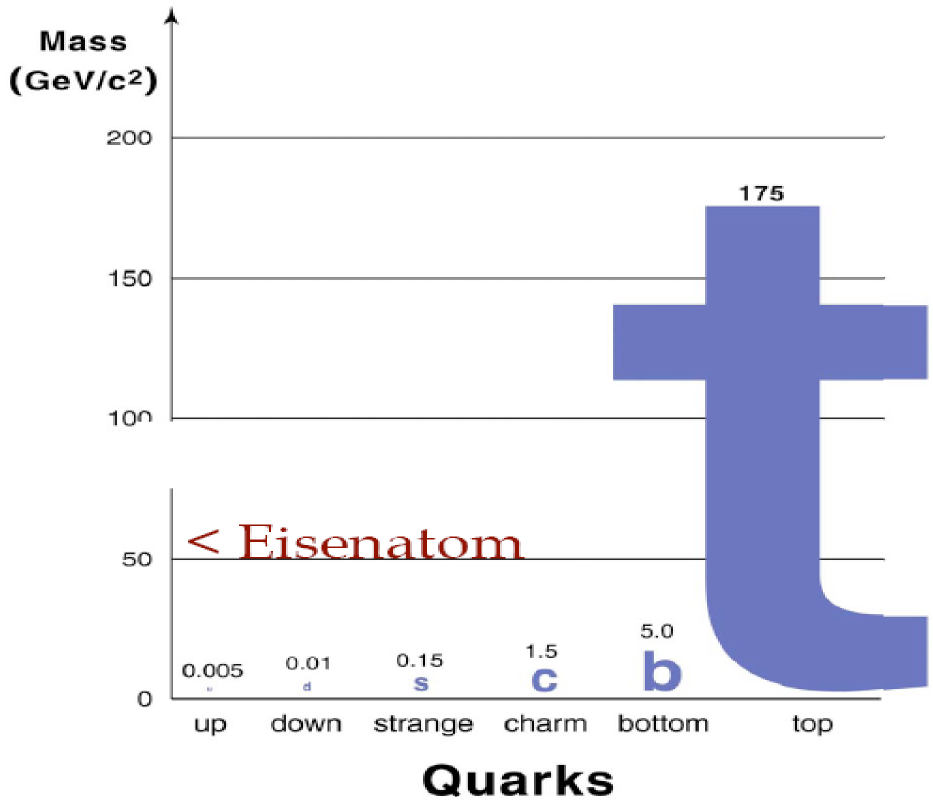


The Origin of Mass

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



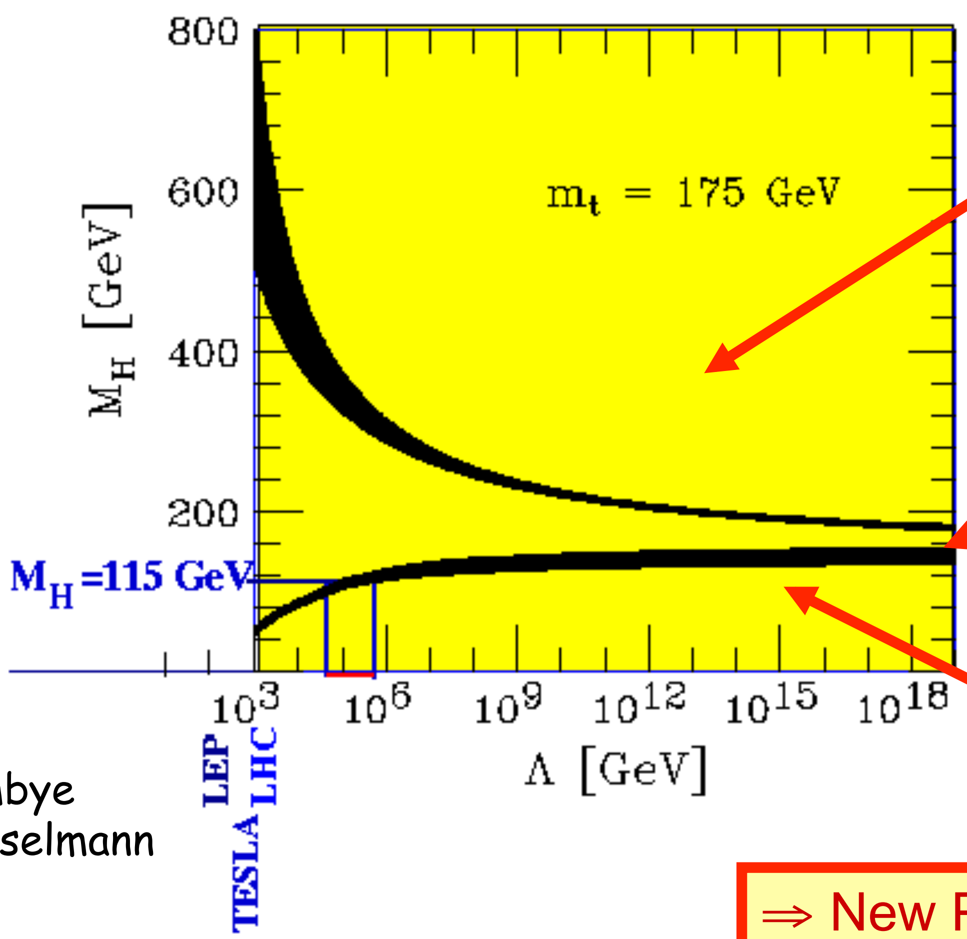
The Higgs (H) particle has been searched for since decades at accelerators, but not yet found…

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


Francois Englert

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 $\Lambda >> v = 246$ GeV

⇒ New Physics expected in O(TeV) range

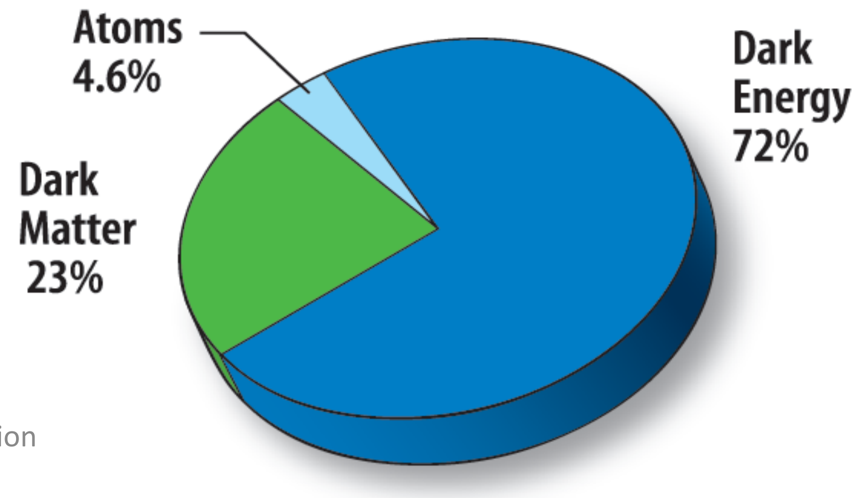
Dark Matter in the Universe

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

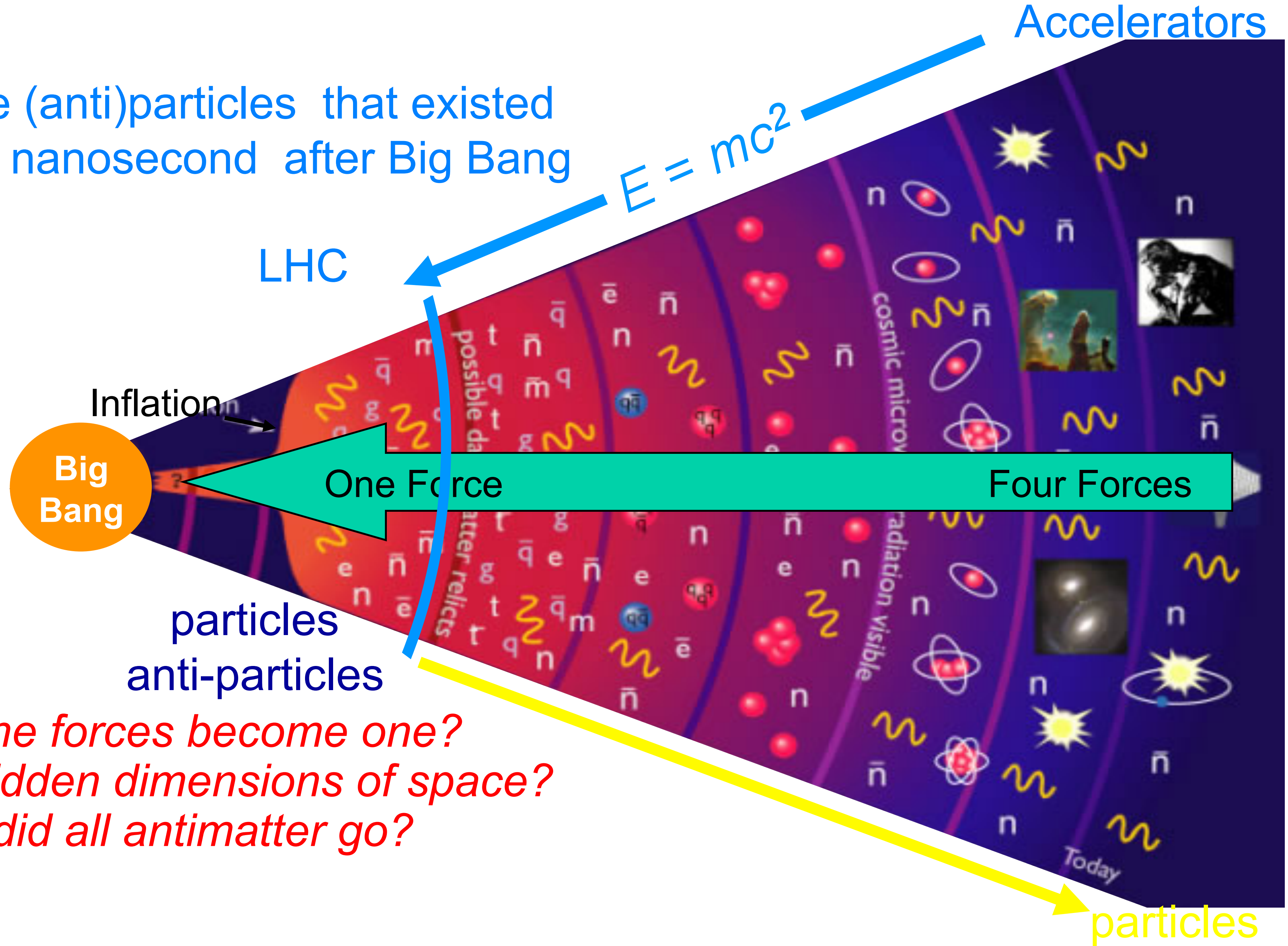
'Supersymmetric' particles ?

We shall look for them with the LHC

F. Zwicky 1898-1974

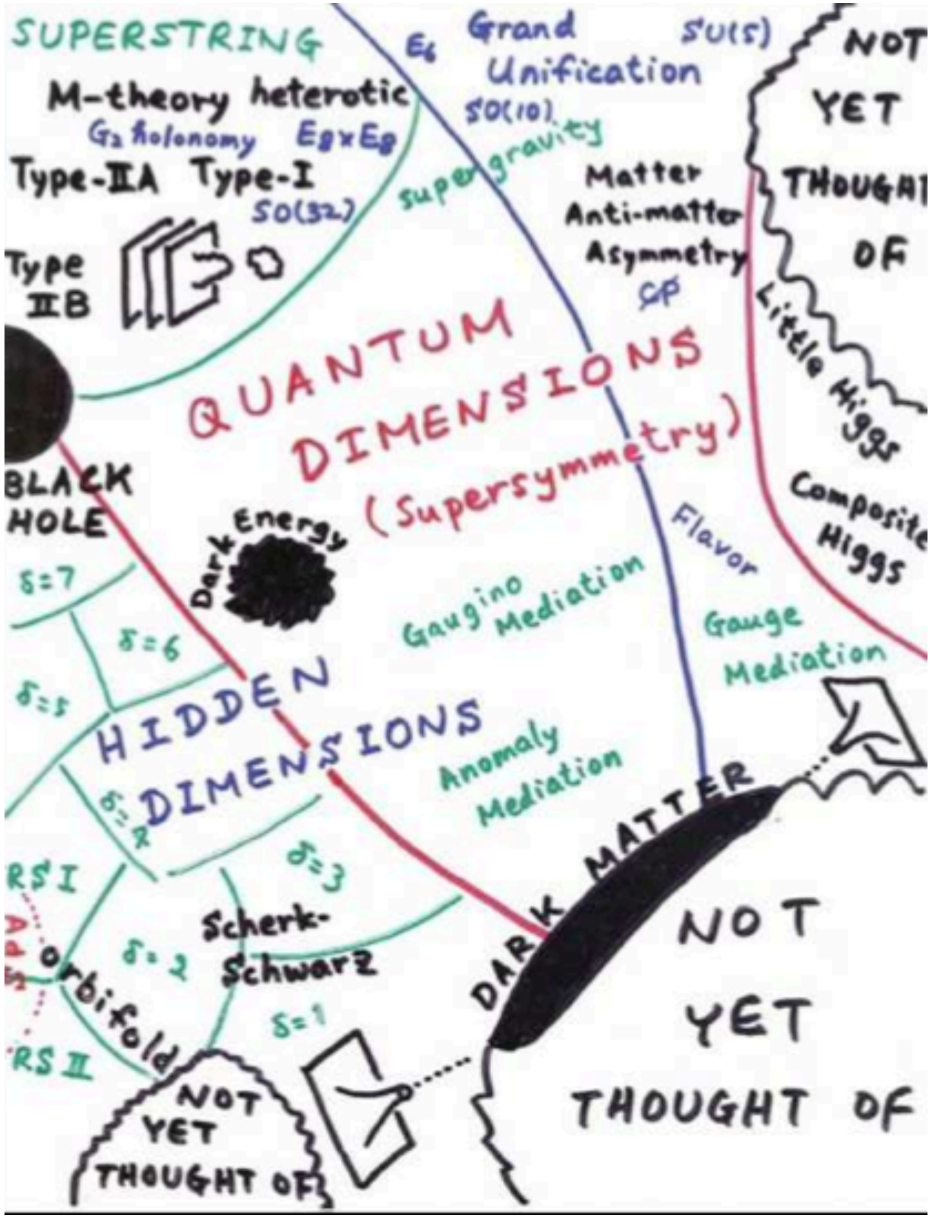


Create (anti)particles that existed
~0.001 nanosecond after Big Bang



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

Beyond the SM? Ask a Theorist

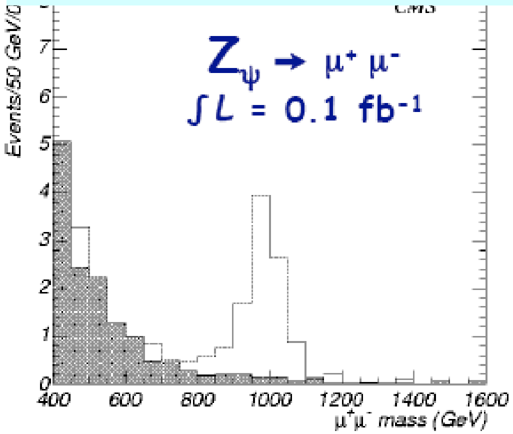


Or maybe not…☺

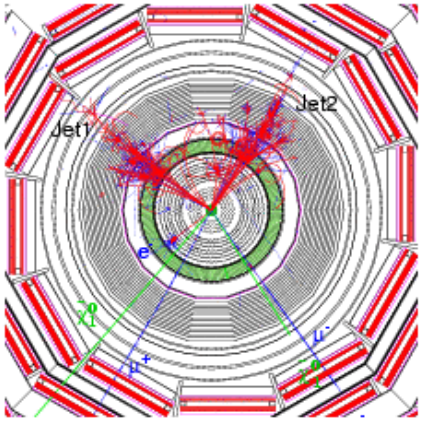
During the last 2-3 years we –LHC experimentalists- got more models to deal with than we needed…
Some theorists found it a challenge to invent a model with signatures difficult for the experiments:
heavy stable charged particles, hidden valley models, Quirks…

BSM Physics at the LHC: pp @ 7/14 TeV

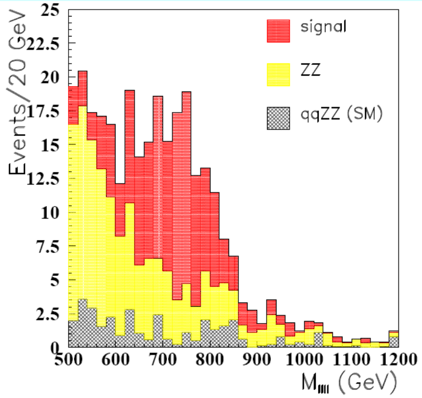
New Gauge Bosons?



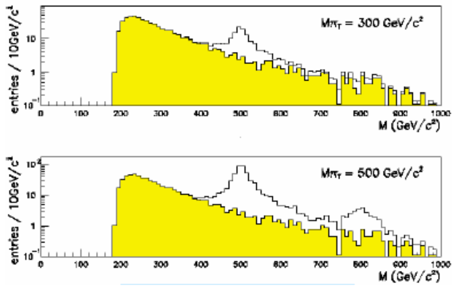
Supersymmetry



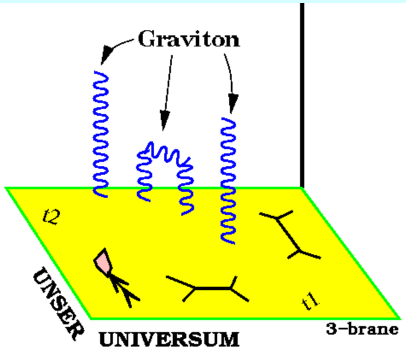
ZZ/WW resonances?



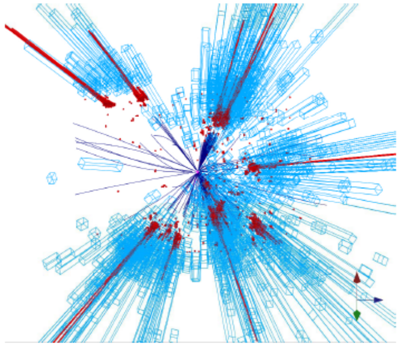
Technicolor?



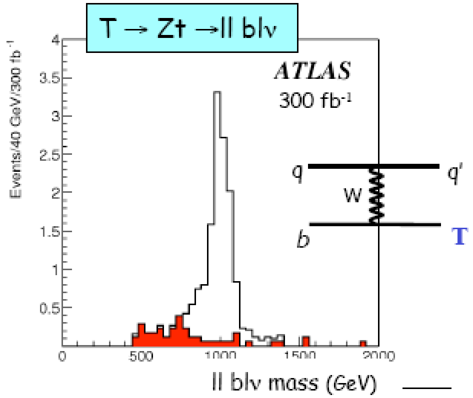
Extra Dimensions?



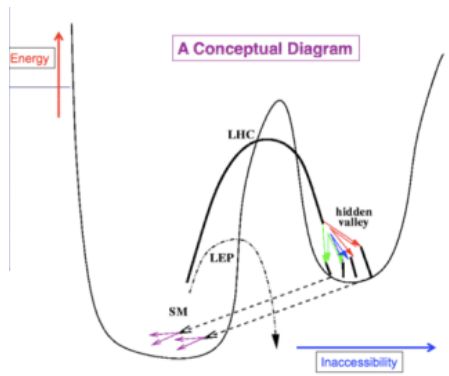
Black Holes???



Little Higgs?



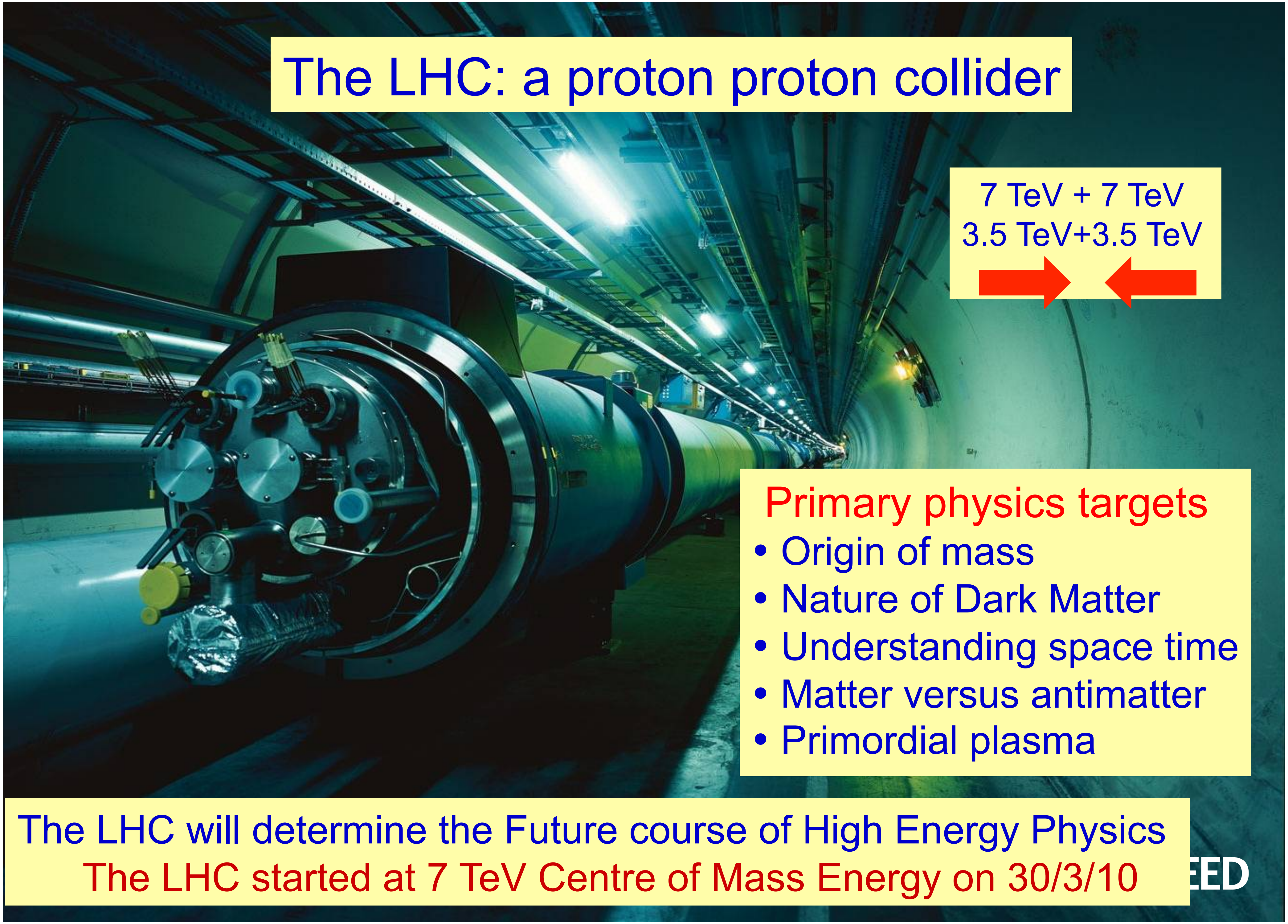
Hidden Valleys?



We do not know what is out there for us…
A large variety of possible signals. We have to be ready for that

The Large Hadron Collider LHC

The LHC: a proton proton collider



7 TeV + 7 TeV
3.5 TeV+3.5 TeV

Primary physics targets

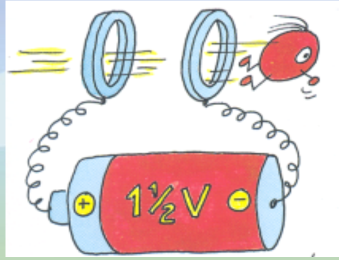
- Origin of mass
- Nature of Dark Matter
- Understanding space time
- Matter versus antimatter
- Primordial plasma

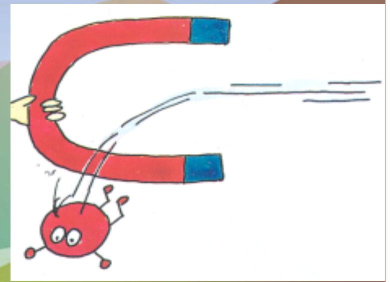
The LHC will determine the Future course of High Energy Physics

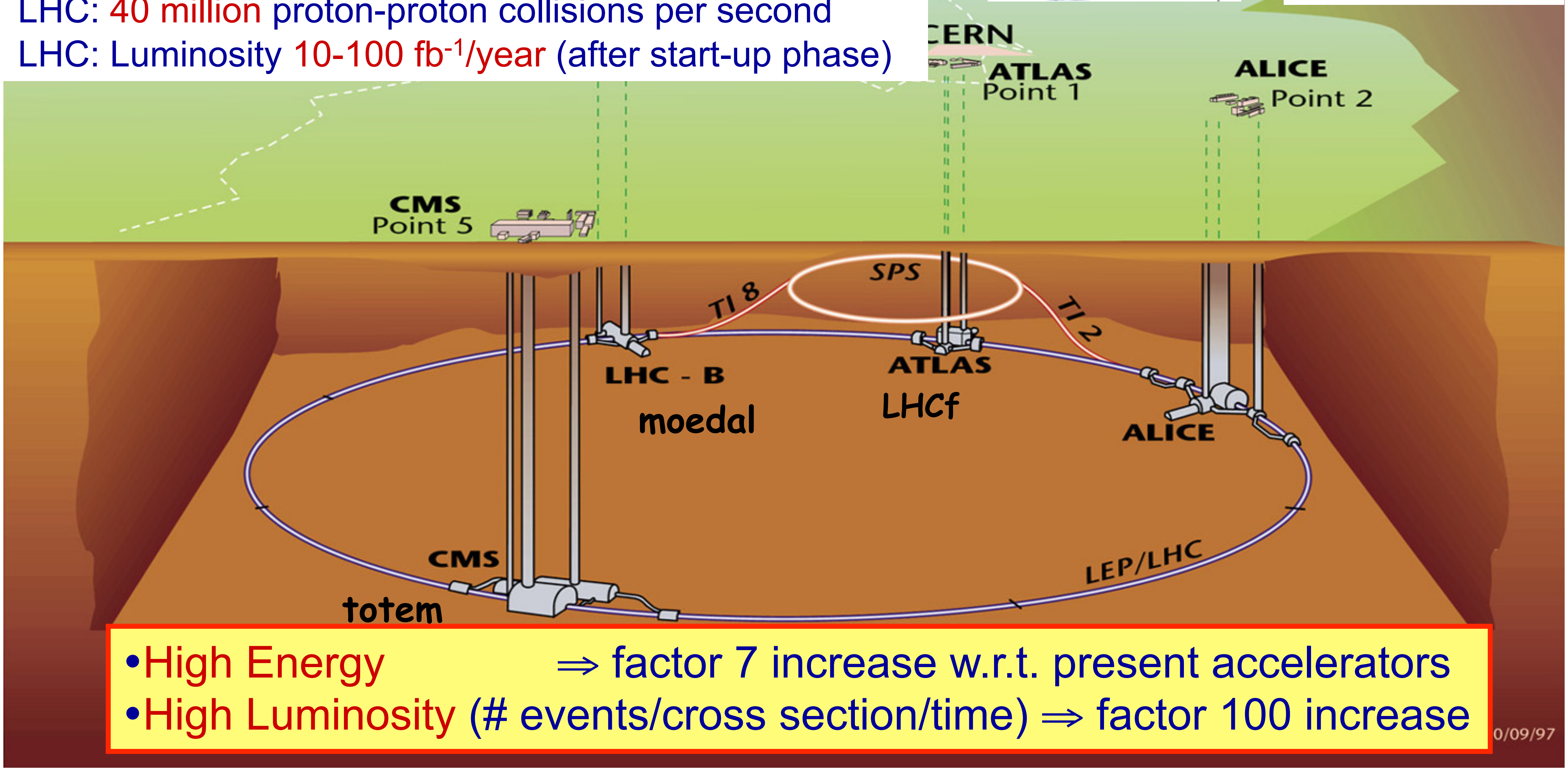
The LHC started at 7 TeV Centre of Mass Energy on 30/3/10

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)







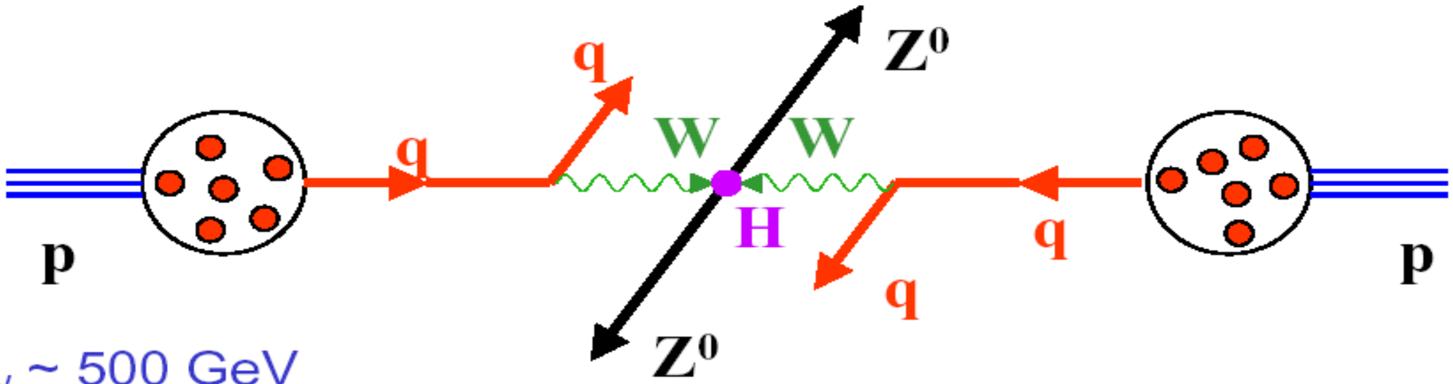
- High Energy ⇒ factor 7 increase w.r.t. present accelerators
- High Luminosity (# events/cross section/time) ⇒ factor 100 increase

Requirements for a New Collider

Example: Higgs particle production

Hadron colliders are broad-band exploratory machines

May need to study W_L-W_L scattering at a cm energy of ~ 1 TeV



⇨ E_W ~ 500 GeV

⇨ E_{quark} ~ 1 TeV

⇨ E_{proton} ~ 6 TeV

⇨ **pp collisions at 7 + 7 TeV** → **14 TeV collider**

→ $L \sim 10^{34}$ cm^{-2} s^{-1}

Event Rate = L.σ.BR

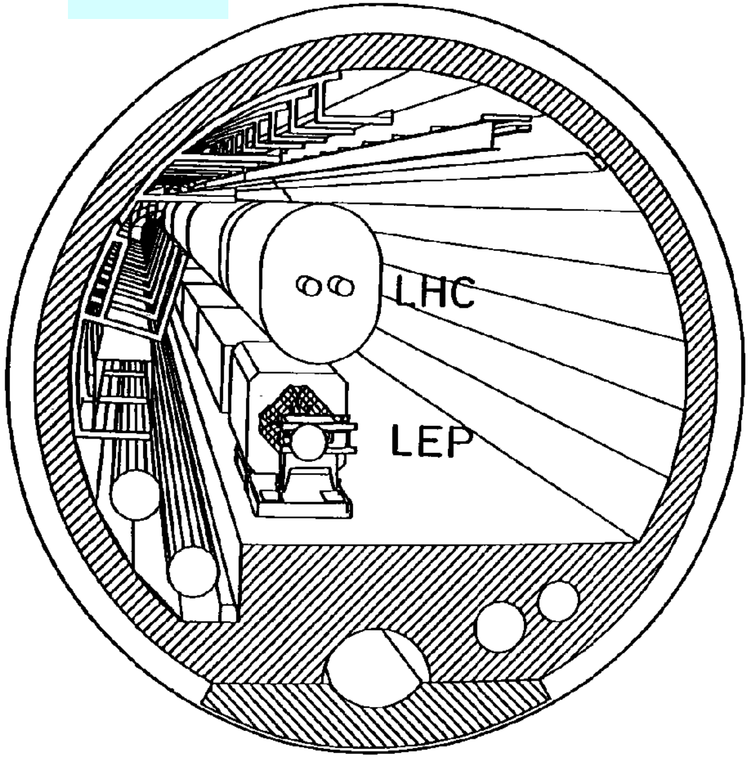
e.g. H(1 TeV) → ZZ → 2e+2μ or 4e or 4μ

For L ~10^{34} , Evts/yr = **10^{34}** $10^{-37}.10^{-3}.10^{7}$ ~ 10 /yr !!

The LHC: > 25 Years Already!

1984

ECFA 84/85
CERN 84-10
5 September 1984



LHC History

1982 : First studies for the LHC project

1983 : Z0/W discovered at SPS proton antiproton collider

1989 : Start of LEP operation (Z boson-factory)

1994 : Approval of the LHC by the CERN Council

1996 : Final decision to start the LHC construction

1996 : LEP operation > 80 GeV (W boson -factory)

2000 : Last year of LEP operation above 100 GeV

2002 : LEP equipment removed

2003 : Start of the LHC installation

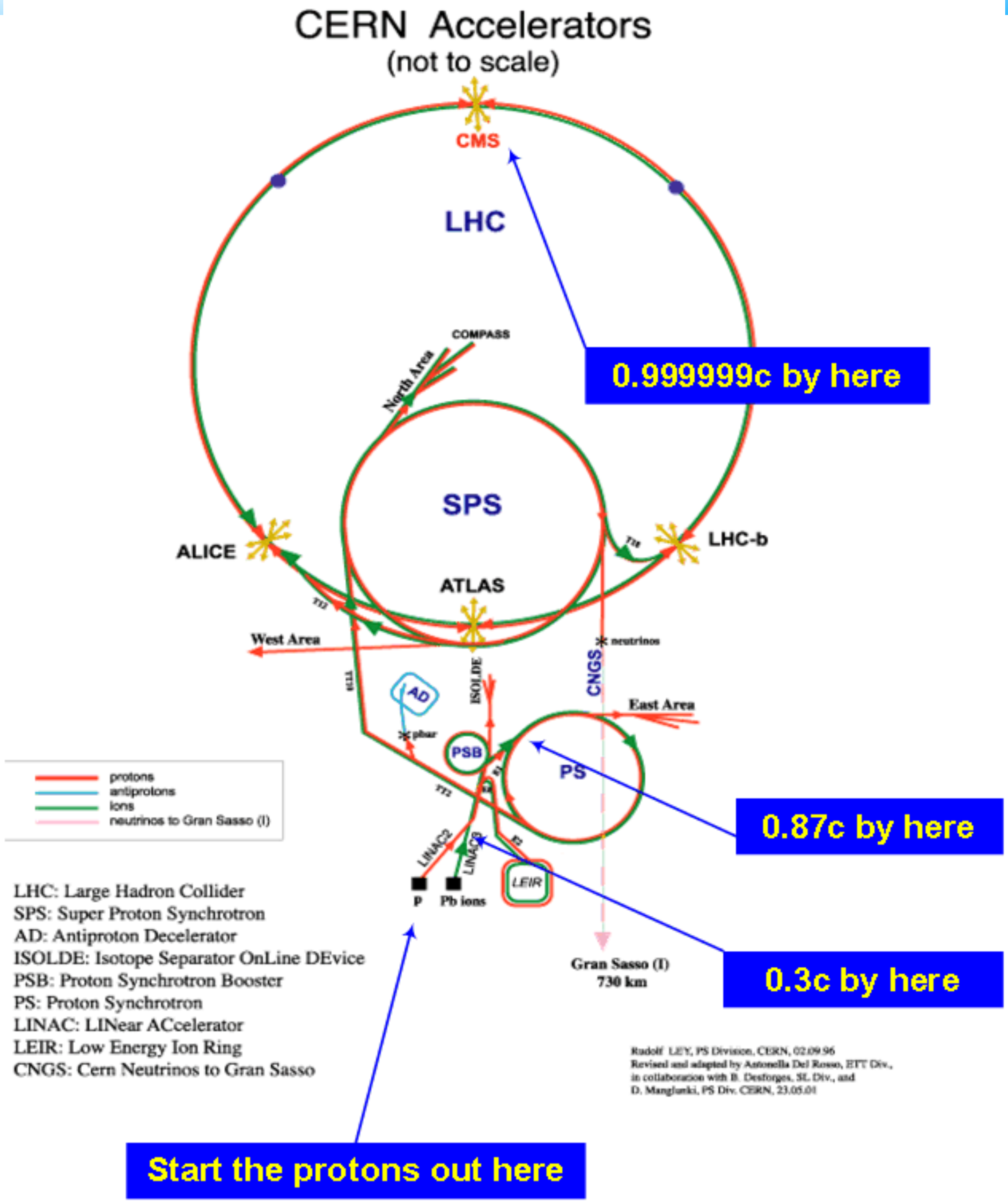
2005 : Start of LHC hardware commissioning

2008 : Expected LHC commissioning with beam

1984:	cms energy	10-18 TeV
	Luminosity	10^{31}-10^{33}cm^{-2}s^{-1}
1987:	cms energy	16 TeV
	Luminosity	10^{33}-10^{34}cm^{-2}s^{-1}
Final:	cms energy	14 TeV
	Luminosity	10^{33}-10^{34}cm^{-2}s^{-1}

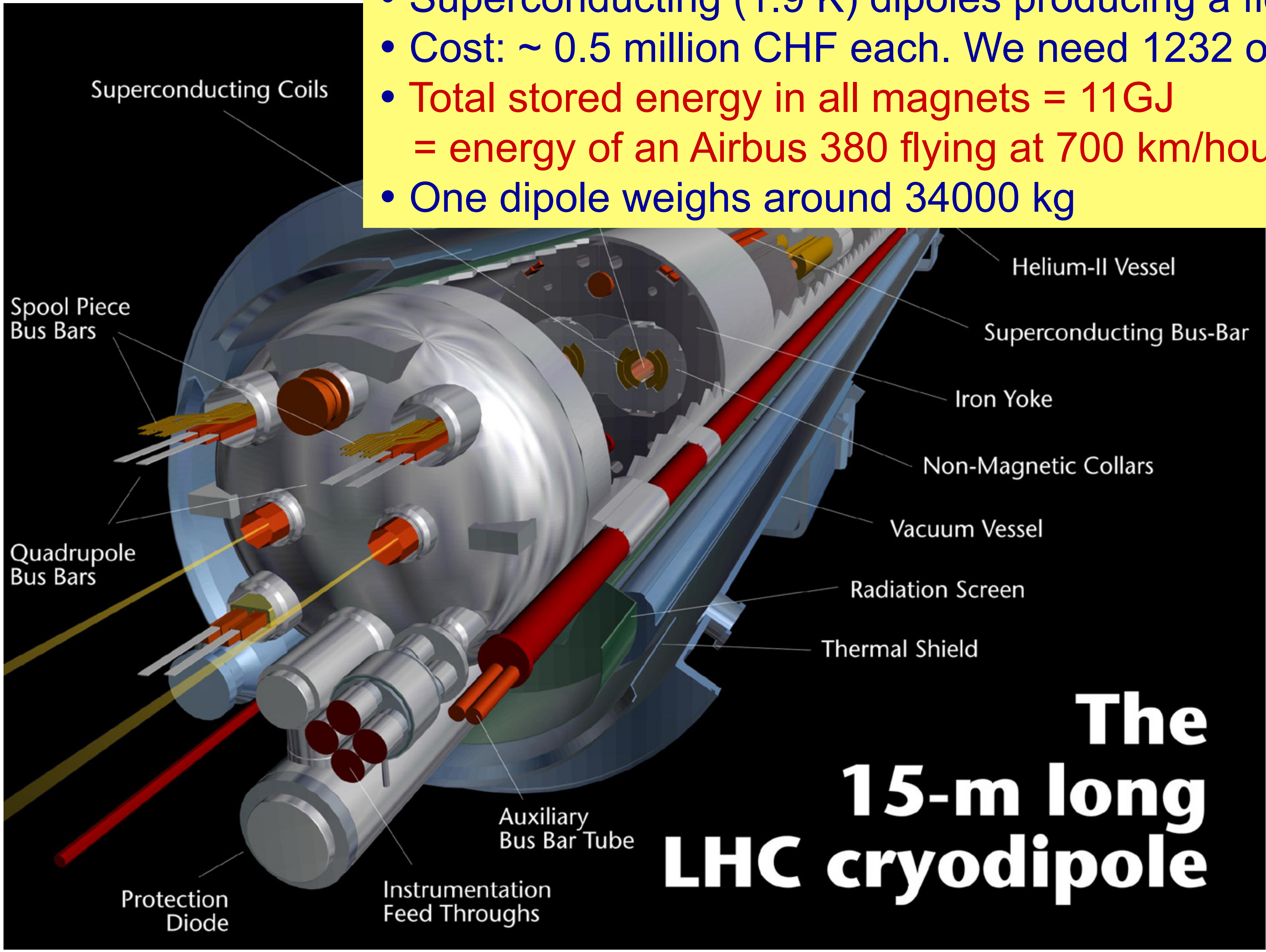
The Accelerator Scheme

Linac
↓
Booster
↓
PS
↓
SPS
↓
LHC



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



Energy in the Magnets/beam

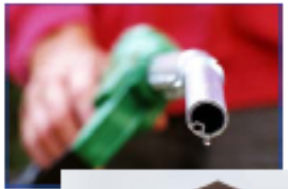
Comparison…

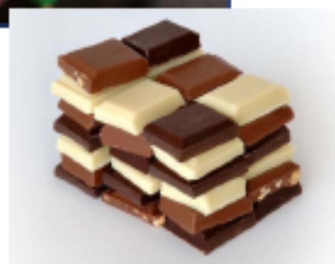
The energy of an A380 at 700 km/hour corresponds to the energy stored in the LHC magnet system :

Sufficient to heat up and melt 12 tons of Copper!!

The energy stored in one LHC beam corresponds approximately to…

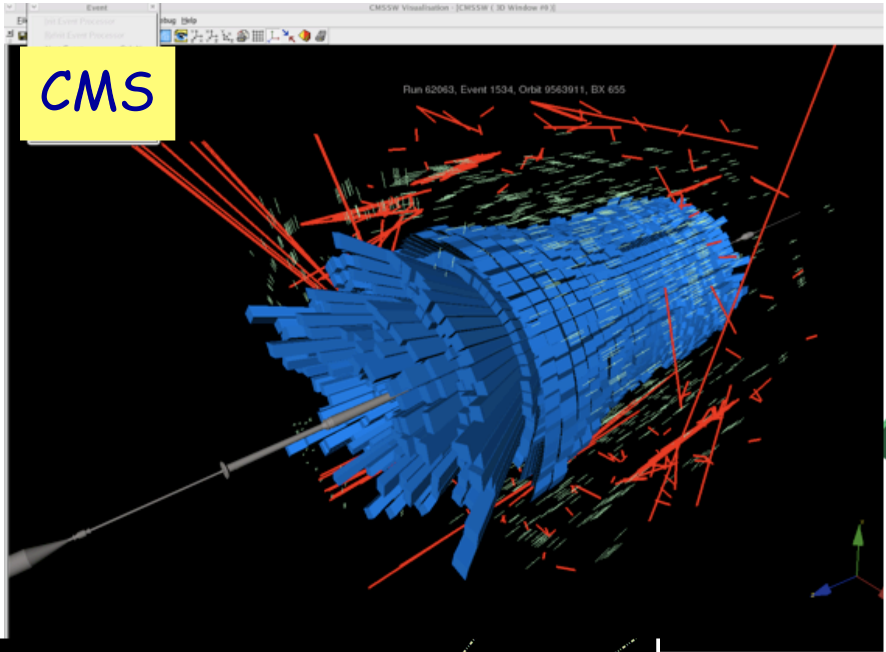
- 90 kg of TNT
- 8 litres of gasoline
- 15 kg of chocolate

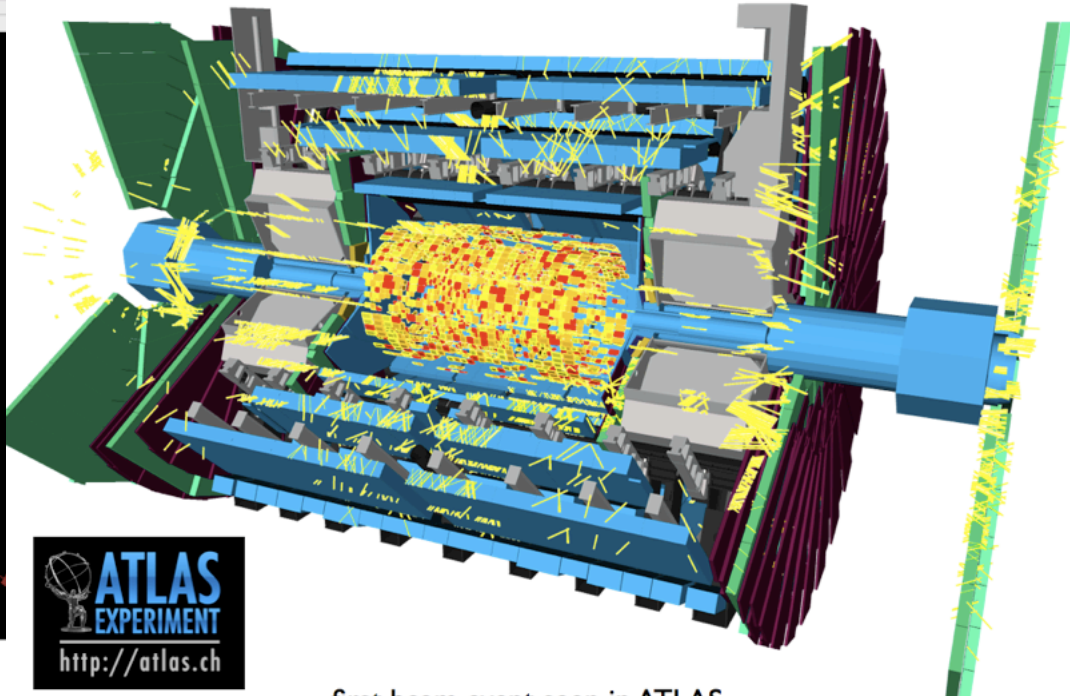


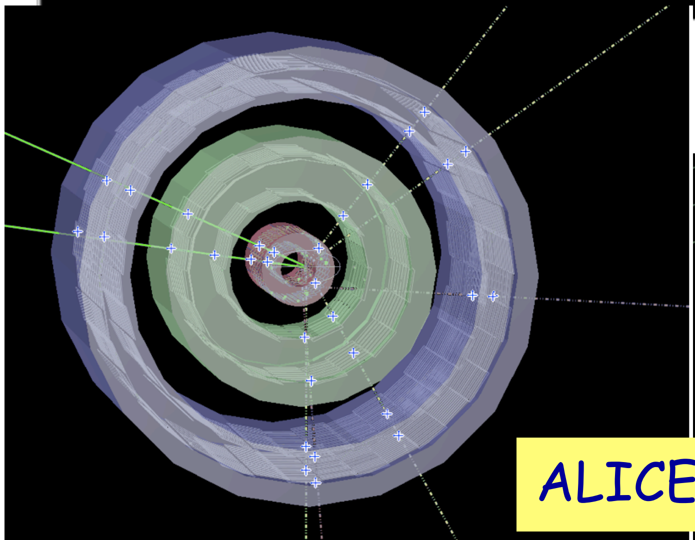


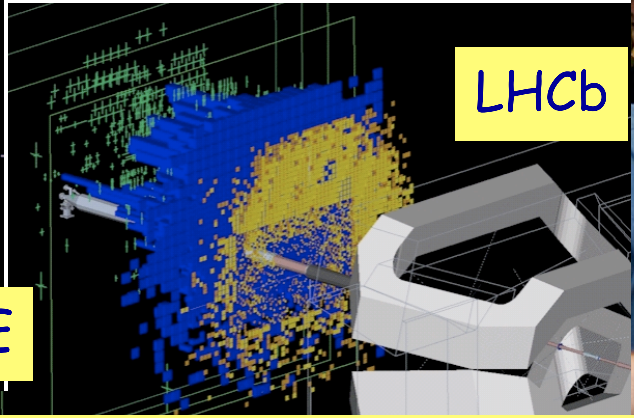
It's how ease the energy is released that matters most !!

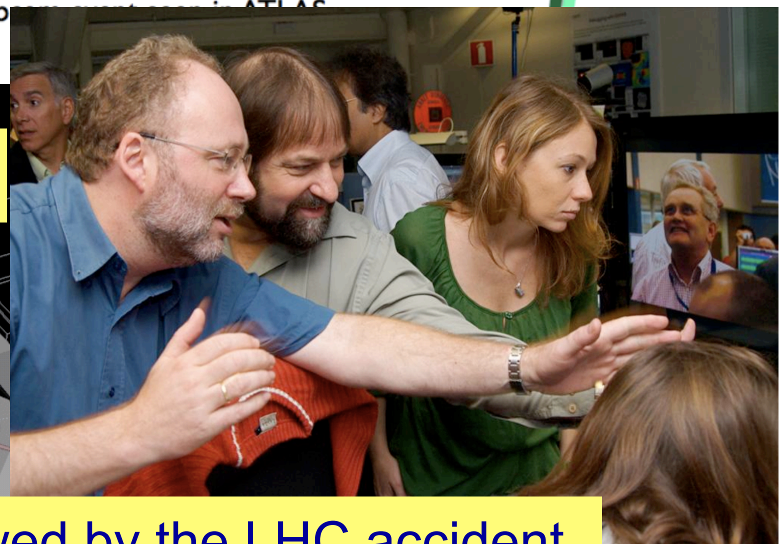
LHC Story: Beam Halo and Splashes on 10/9/08







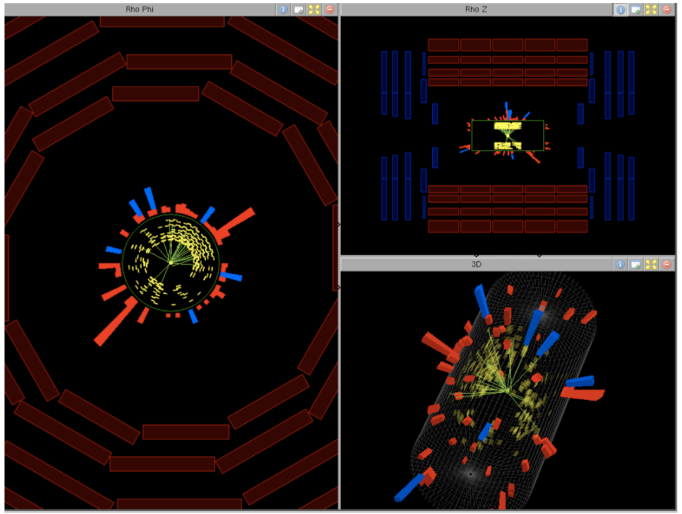


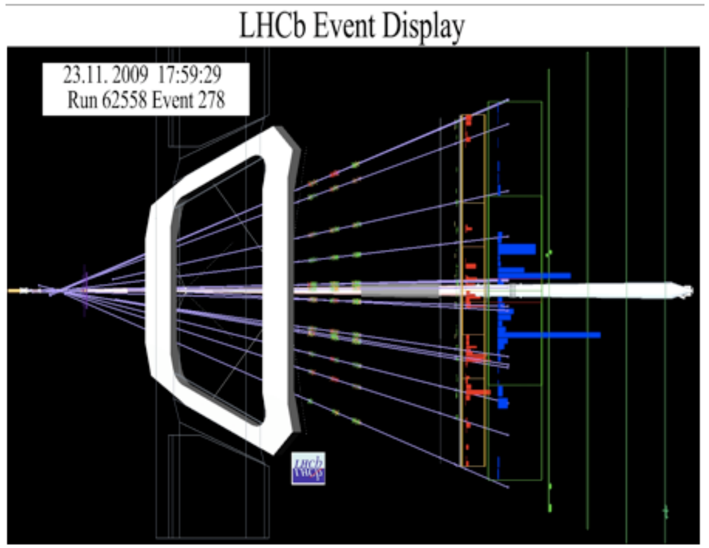


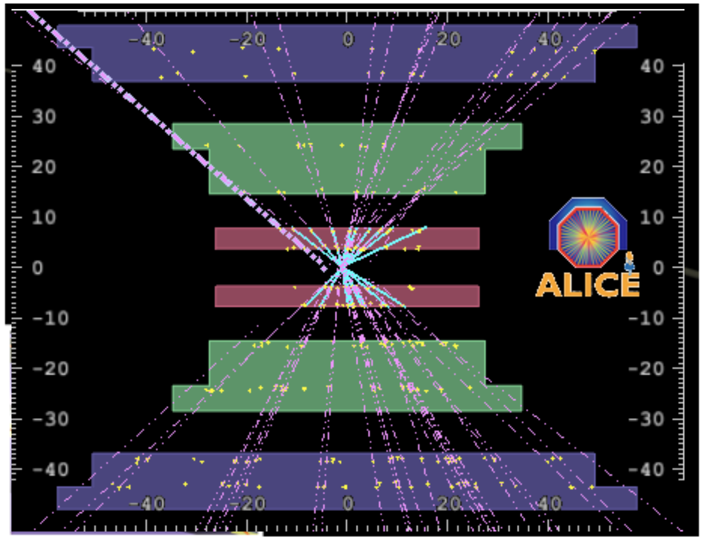
First LHC activity in the detectors in Sept. 2008, followed by the LHC accident

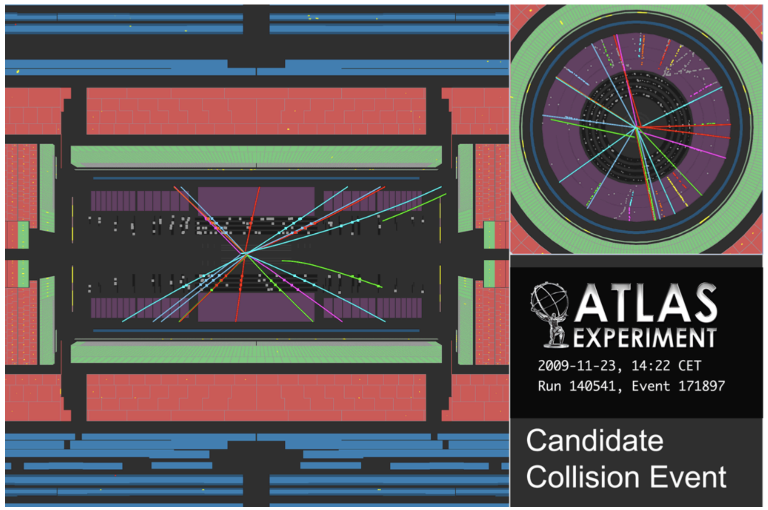
LHC Story: First Collisions in Nov. 2009

23/11 First ‘trial’ collisions in the experiments
A run with collisions at $\sqrt{s}$ = 900 GeV or 2.36 TeV in December 2009

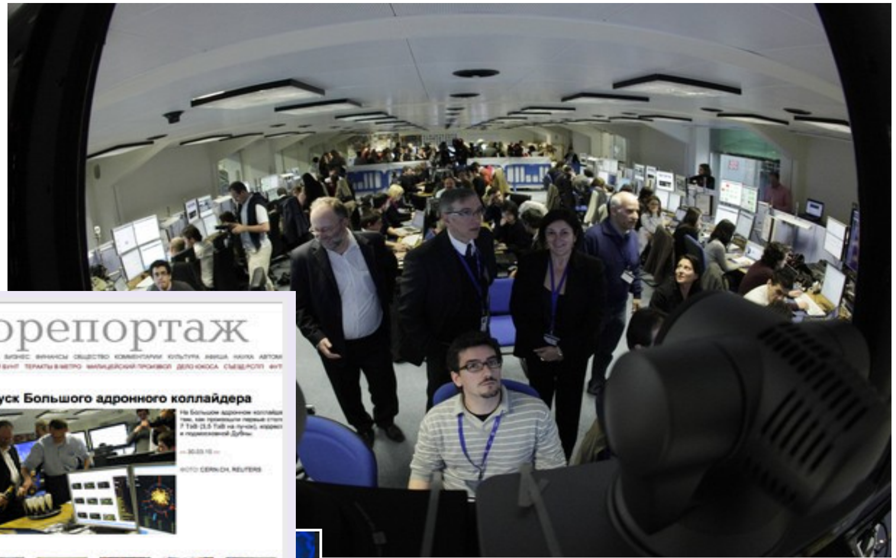






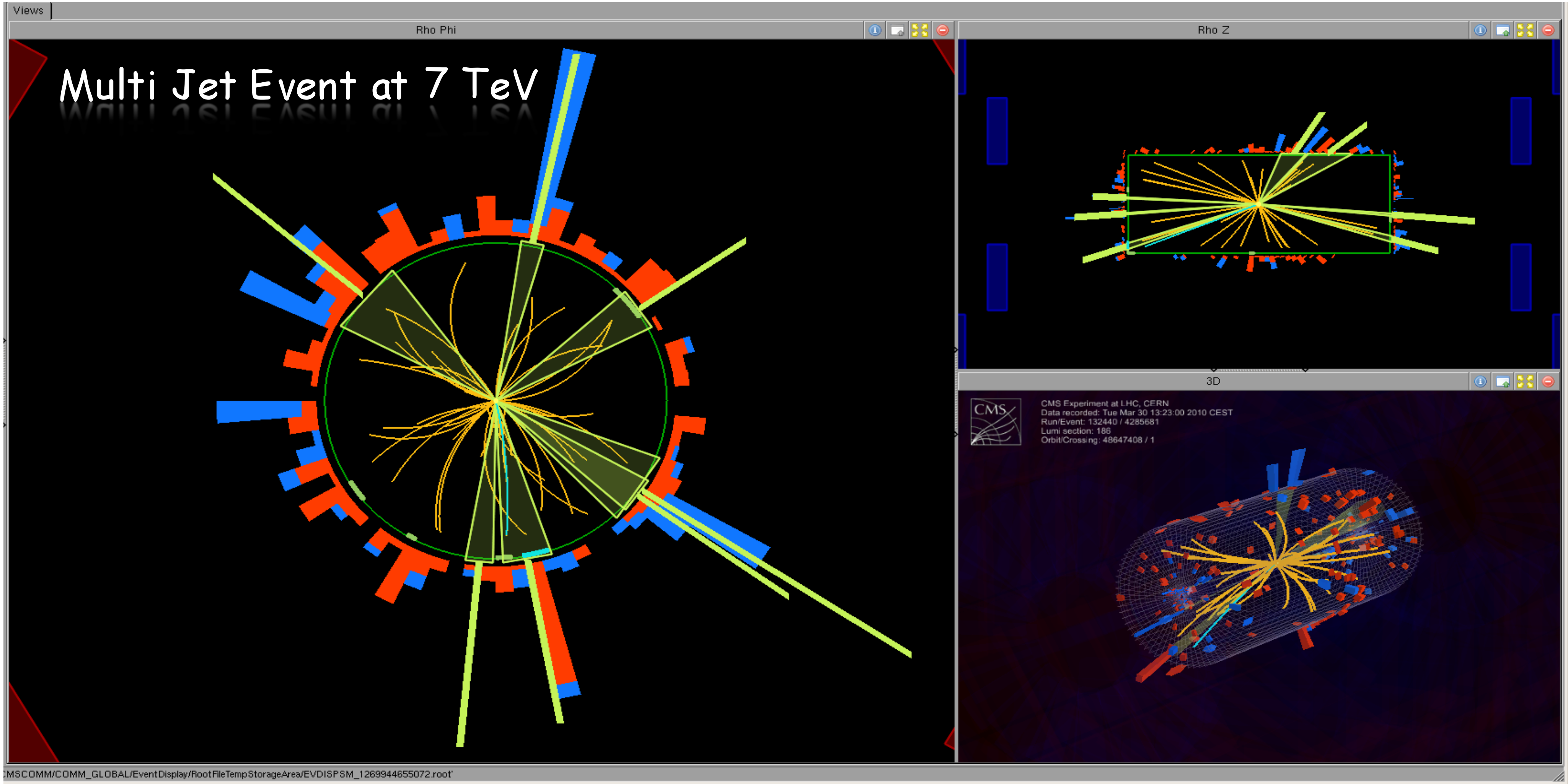


30/3/10: Experiments are waiting for 7 TeV…

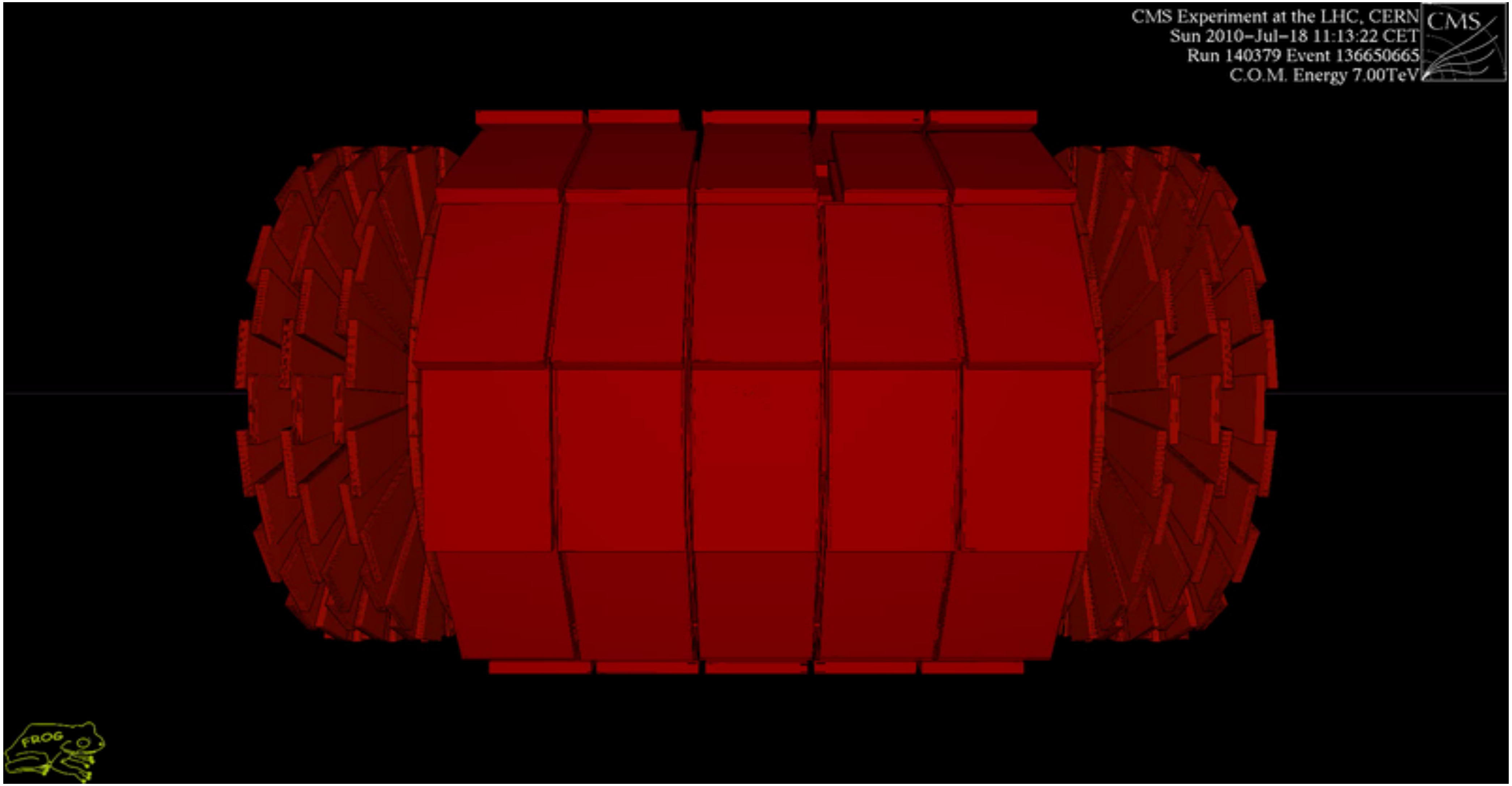


12:58
7 TeV collisions!!!

First Collisions at 7 TeV



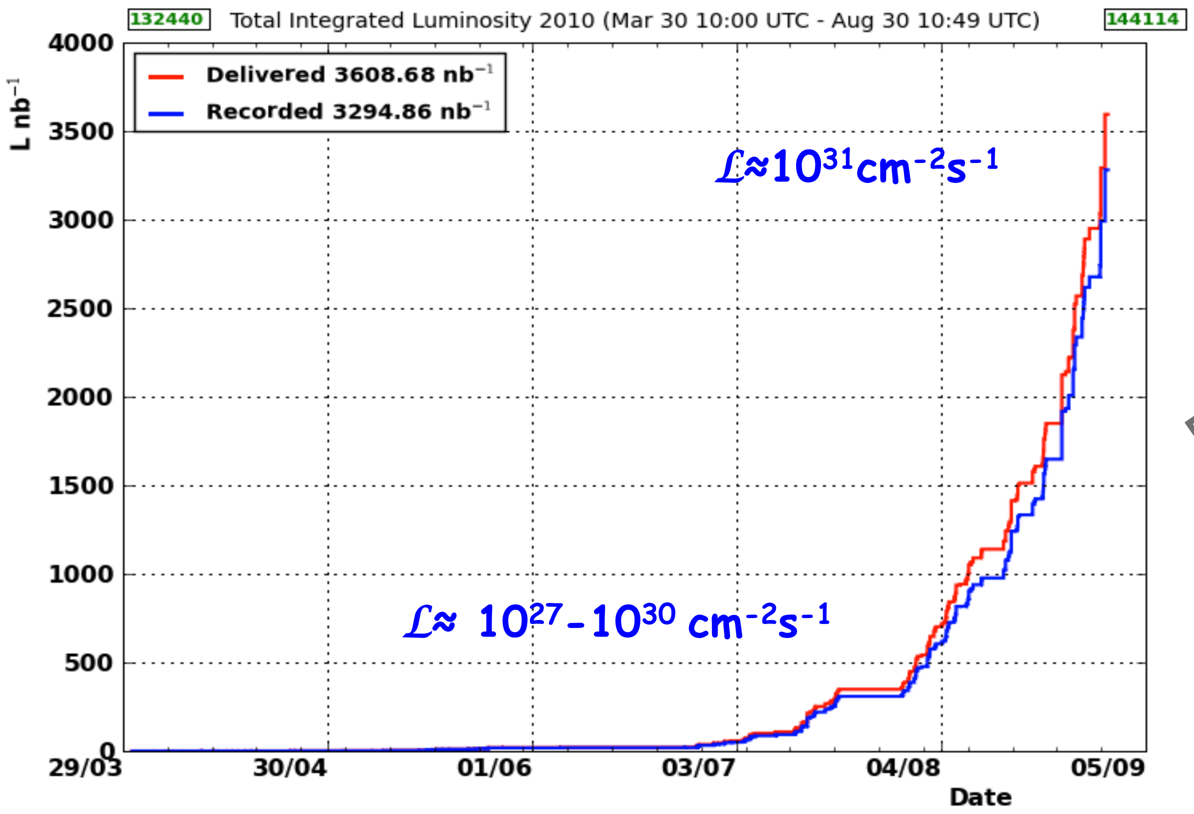
A Brave New World….


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

The Physics Program at LHC can begin!

Integrated Luminosity @ 7 TeV

CMS values   Similar ones for ATLAS



Since end of March (7 TeV):
3609 nb^{-1} delivered (*)
3295 nb^{-1} recorded
Data taking efficiency (~92%)

(*) Stable beams only

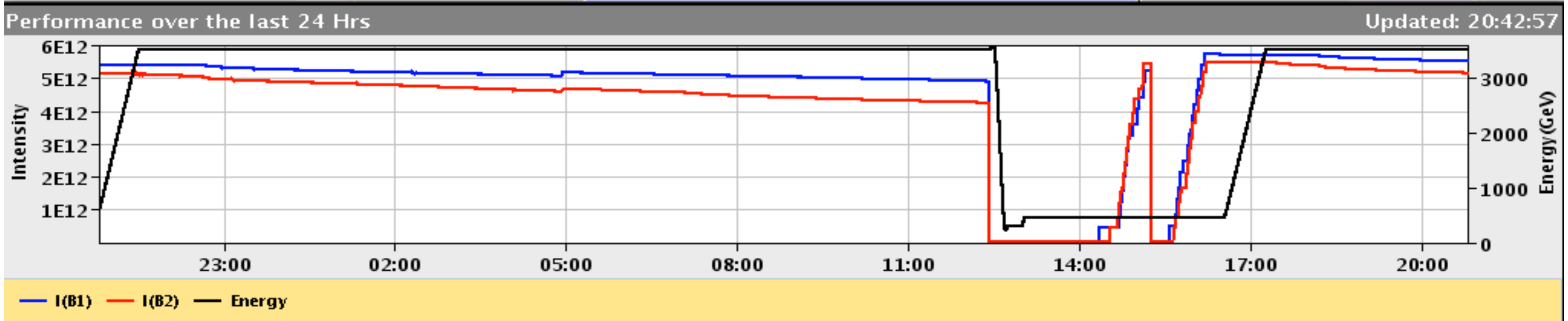
- Max Lumi now ~ $1.1 \cdot 10^{31} cm^{-2}s^{-1}$
- Aim for this year $10^{32} cm^{-2}s^{-1}$…

Last week's running…

24-Aug-2010 17:39:13 Fill #: 1301 Energy: 3500 GeV I(B1): 5.22e+12 I(B2): 4.94e+12

	ATLAS	ALICE	CMS	LHCb
Experiment Status	PHYSICS	NOT READY	STANDBY	PHYSICS
Instantaneous Lumi (ub.s)^-1	9.218	0.096	10.108	8.338
BRAN Luminosity (ub.s)^-1	8.636	0.104	7.896	7.029
Fill Lumiosity (nb)^-1	--	0.0	1.9	1.7
BKGD 1	0.047	0.015	19.608	0.188
BKGD 2	10.000	0.218	0.002	5.317
BKGD 3	17.000	0.005	0.003	0.098

LHCb VELO Position OUT Gap: 58.0 mm | STABLE BEAMS | TOTEM: STANDBY



$1 \cdot 10^{31}$ $cm^{-2}s^{-1}$ instantaneous luminosity reached!

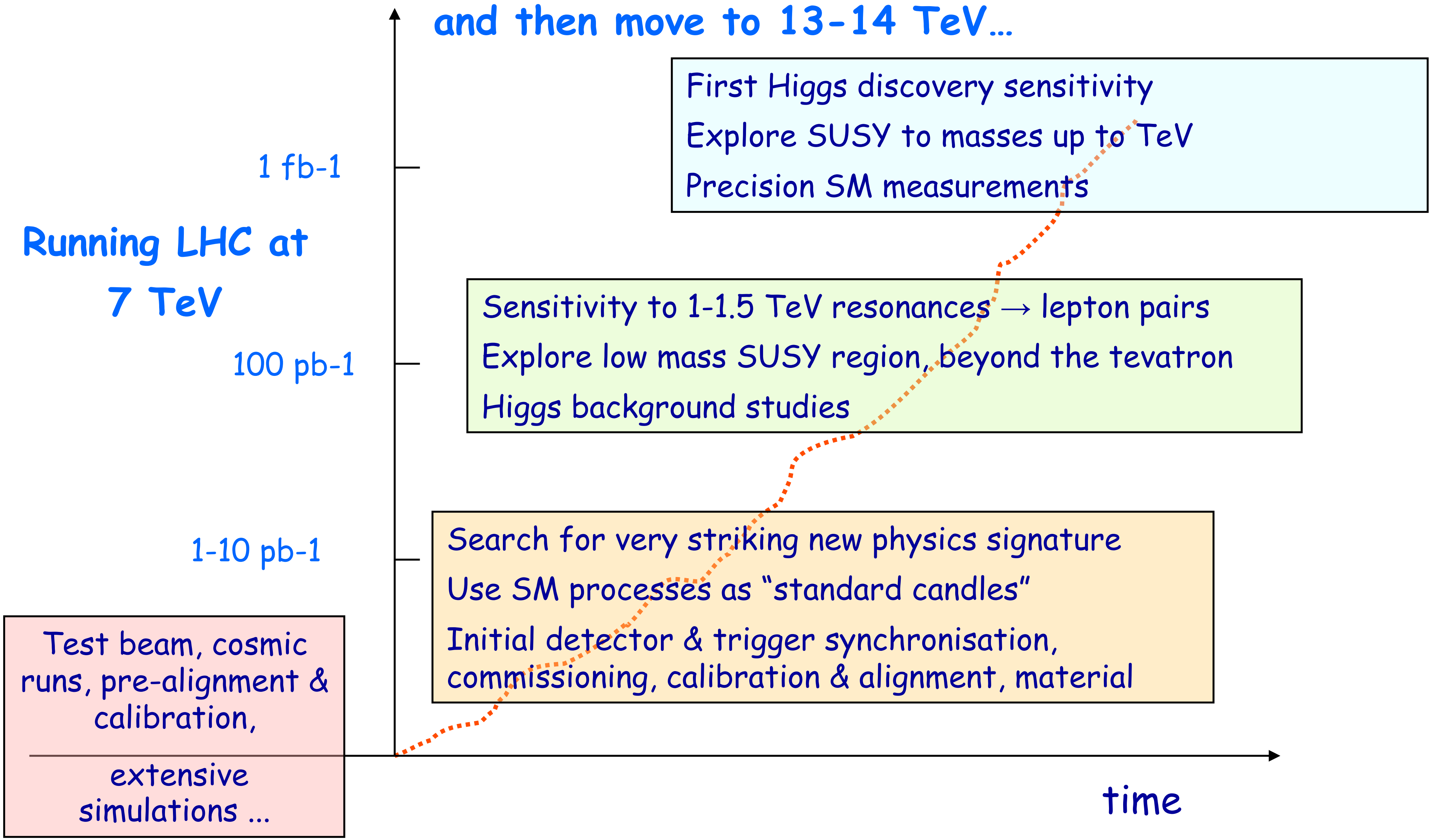
Only a factor 10 to go to the end-year goal.

⇒ Bunch trains! Getting > 300 colliding bunches in CMS/ATLAS

LHC Physics Program

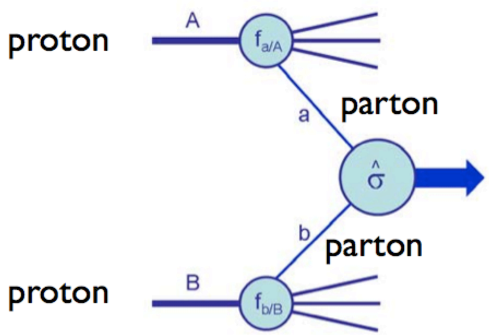
- Discover or exclude the Higgs in the mass region up to 1 TeV. Measure Higgs properties
- Discover Supersymmetric particles (if exist) up to 2-3 TeV
- Discover Extra Space Dimensions, if these are on the TeV scale, and black holes?
- Search other new phenomena (e.g. strong EWSB, new gauge bosons, Little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

Physics Roadmap for 2010-2011

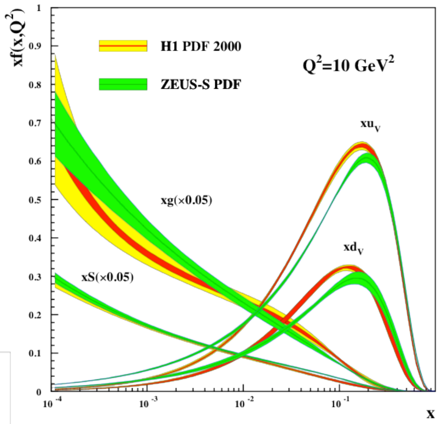


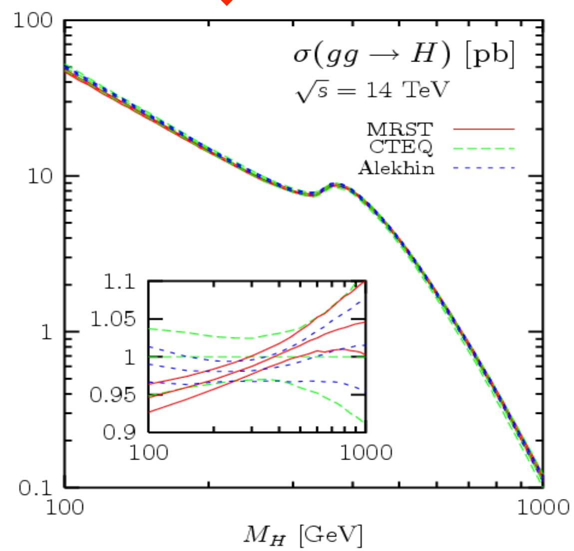
Proton-proton collisions and PDFs

Generic LHC Collision

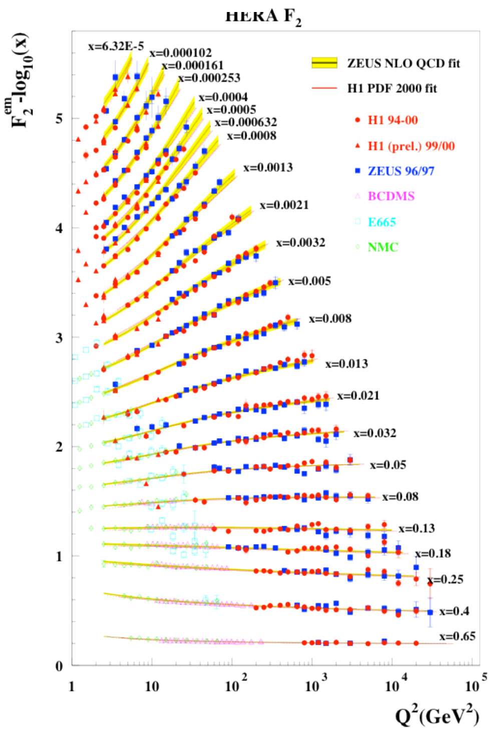


Parton Distribution Functions: the probability of finding a parton with momentum fraction x in the proton



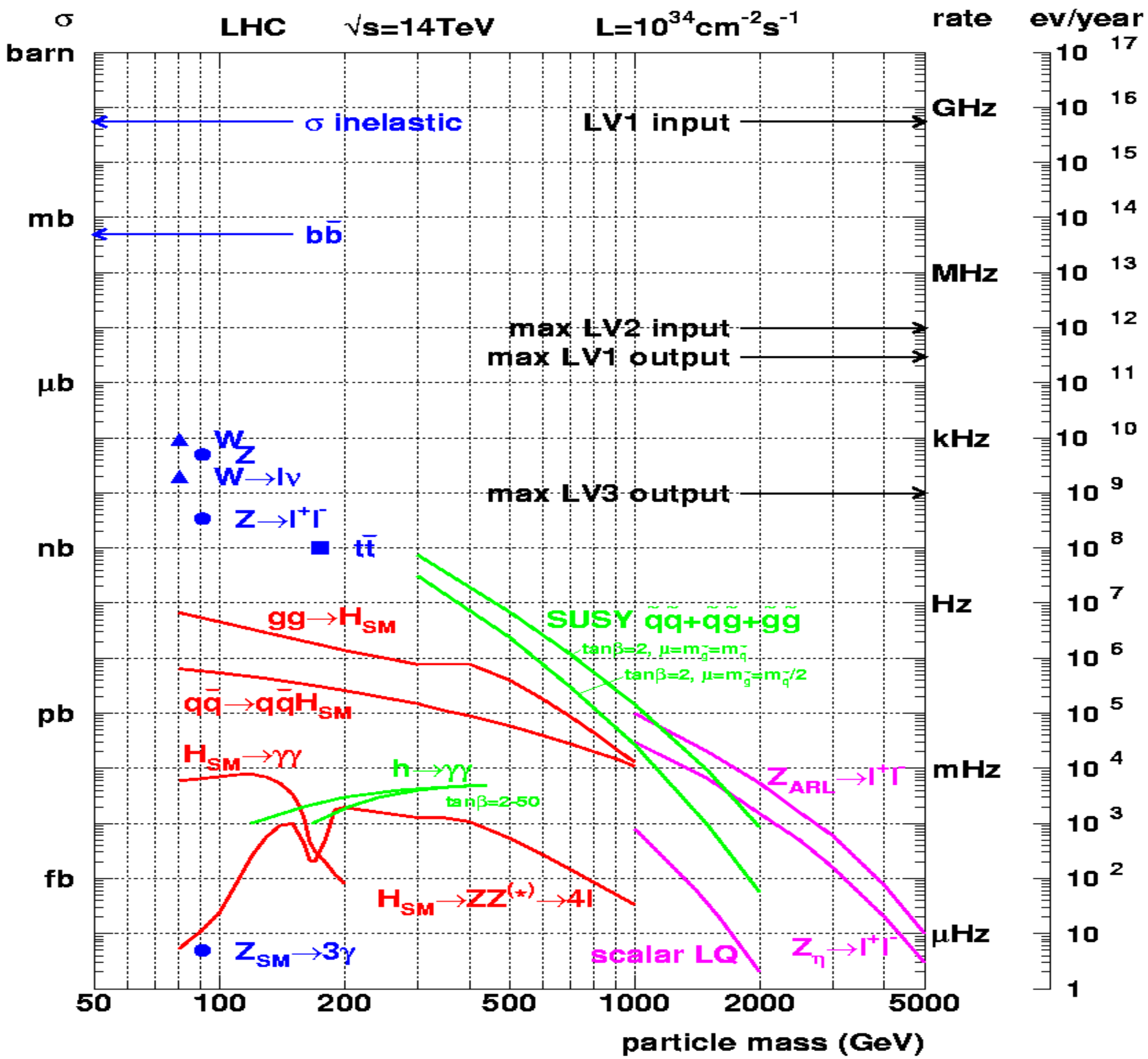


Structure function measurements eg from HERA



Simple spread of existing PDFs gives up to 10% uncertainty on Higgs cross section. Possible gain ~ factor of 2 with final HERA data (PDF4LHC)

Cross sections at the LHC



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

New Physics!!
This we want to keep!!

pp Interaction Rate

Table 2. Measurements of the total pp or $p\bar{p}$ cross-section for $\sqrt{s} \geq 546$ GeV and expectations for the LHC.

$\sqrt{s}$	Experiment	σ_{tot} [mb]
546 GeV	UA4	61.9 ± 1.5
	CDF	61.26 ± 0.93
1.8 TeV	CDF	80.03 ± 2.24
	E710	72.8 ± 3.1
	E811	71.42 ± 2.41
14 TeV	(extrapolation [10] to LHC)	$111.5 \pm 1.2^{+4.1}_{-2.1}$
	TOTEM	? ± 1

The total pp cross section at the LHC is about 100 mb.

unit: barn $1\ \text{b} = 10^{-28}\ \text{m}^2$

$$100\ \text{mb} = 10^{-29}\ \text{m}^2 = 10^{-25}\ \text{cm}^2$$

pp → anything (by strong int.)

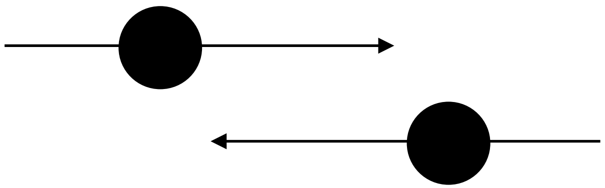
$$\text{Rate} = L\,\sigma = (10^{34}\ \text{cm}^{-2}\text{s}^{-1})(10^{-25}\ \text{cm}^2) = 10^9\ \text{s-1}$$

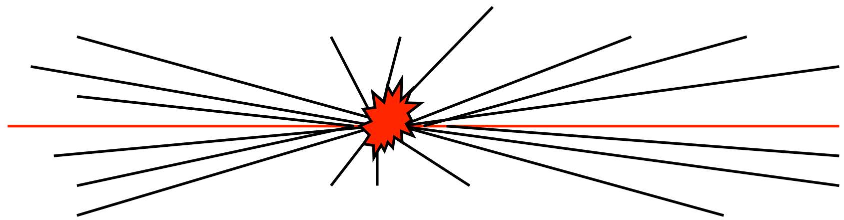
The pp interaction rate is about 1 GHz.

Bunches in the LHC every 25 ns ⇒Bunch crossing rate = 40MHz
⇒ 25 events per bunch crossing at top luminosity

Proton-proton Collisions

Most interactions due to collisions at large distance between incoming protons where protons interact as " a whole "
→ small momentum transfer ($\Delta p \approx \hbar / \Delta x$)
→particles in final state have large longitudinal momentum but small
→transverse momentum (scattering at large angle is small)





$< p_T > \approx 500$ MeV of charged particles in final state

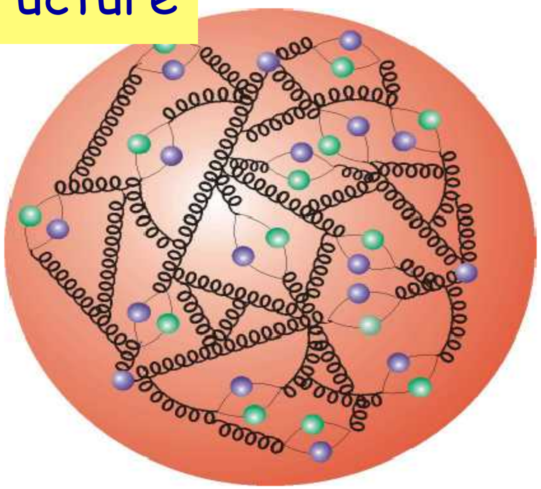
Most energy escapes down the beam pipe.

These are called soft events…

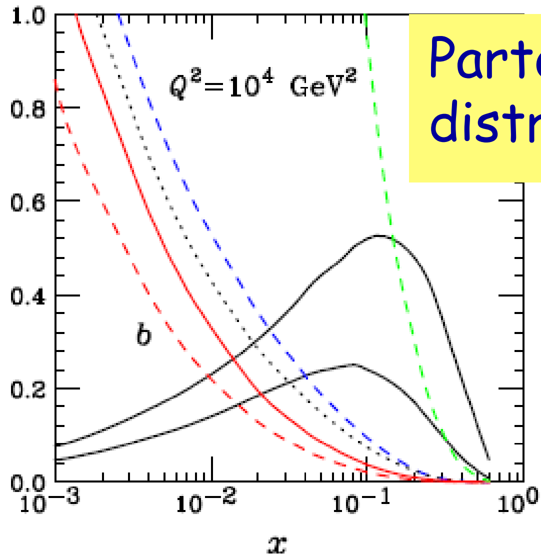
A minimum bias data event sample is dominated by soft events

Summary pp collisons : complications

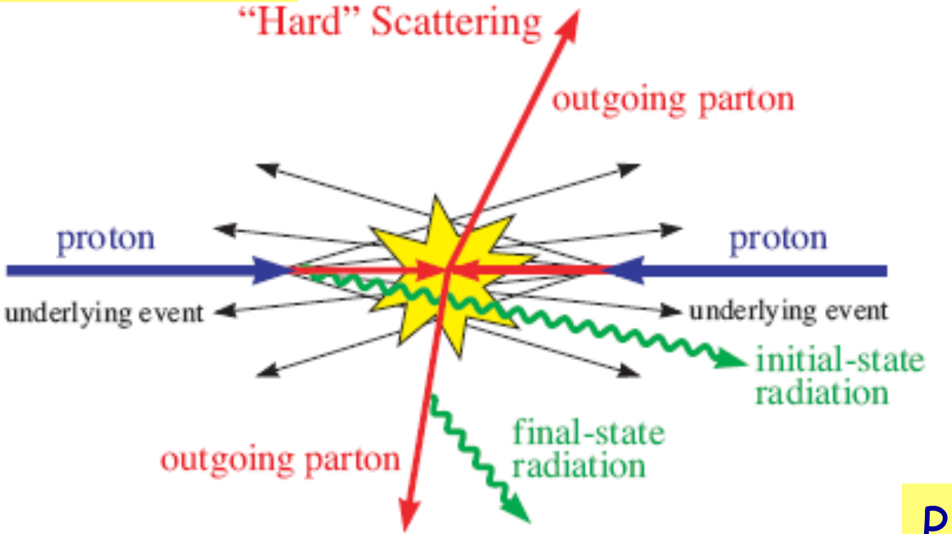
Protons have structure



Parton distributions

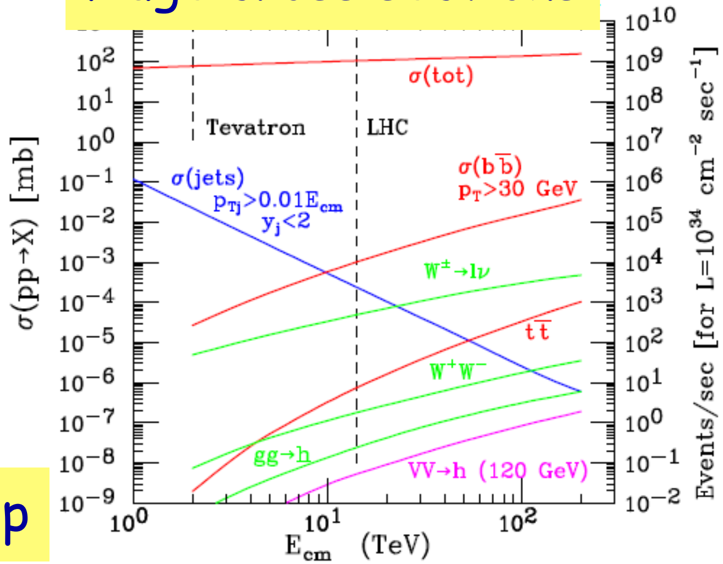


Underlying event



Scattering cross sections for various SM processes:

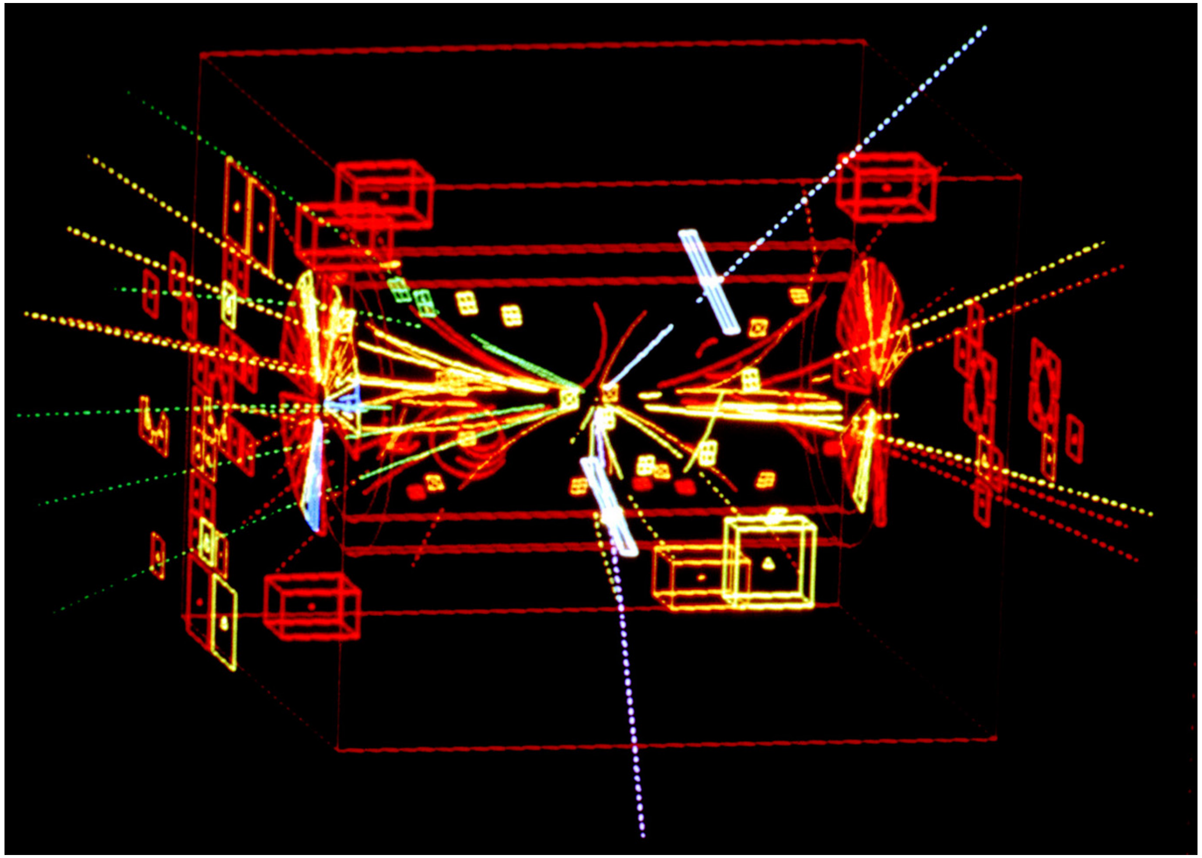
Huge cross sections



Pile-up

Proton –(anti) Proton Colliders
Discoveries are possible

Discovery of the Z and W bosons in UA1/UA2 (1983)



'Picture' of the first

$pp \rightarrow Z + X$

$\rightarrow e^+e^- + X$ -

event in the UA1 detector at the SppS, for a centre of mass energy (√s) = 630 GeV

(30/4/1983)

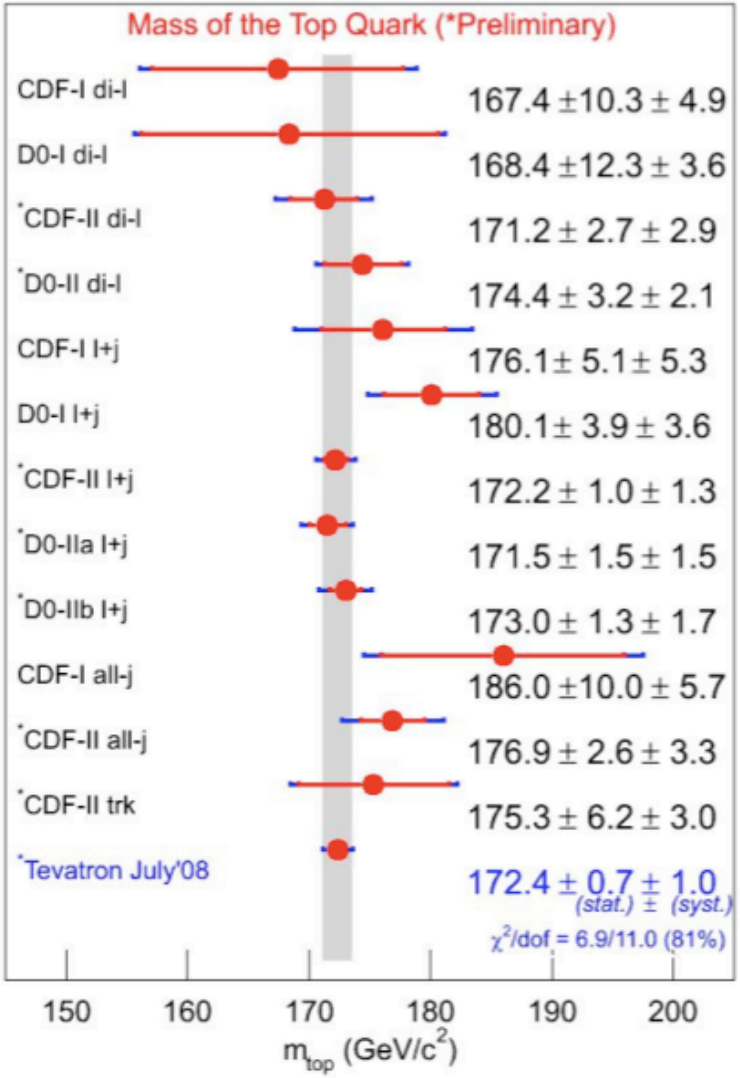
Success story of the SppS machine at CERN rebuilt from a fixed target machine to a collider

And the top quark in 1995, see later

Precision measurements @ proton colliders

2009

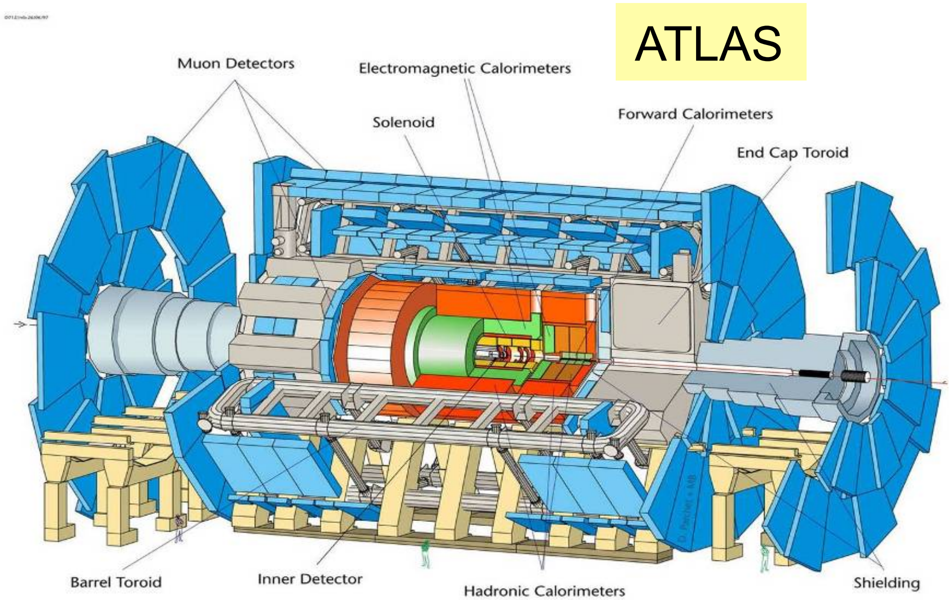
- Excellent results in each channel
  - Dilepton
  - Lepton+jets
  - All-hadronic
- Combine them to improve precision
  - Include Run-I results
  - Account for correlations
- Uncertainty: 1.2 GeV
  - Dominated by systematic uncertainties

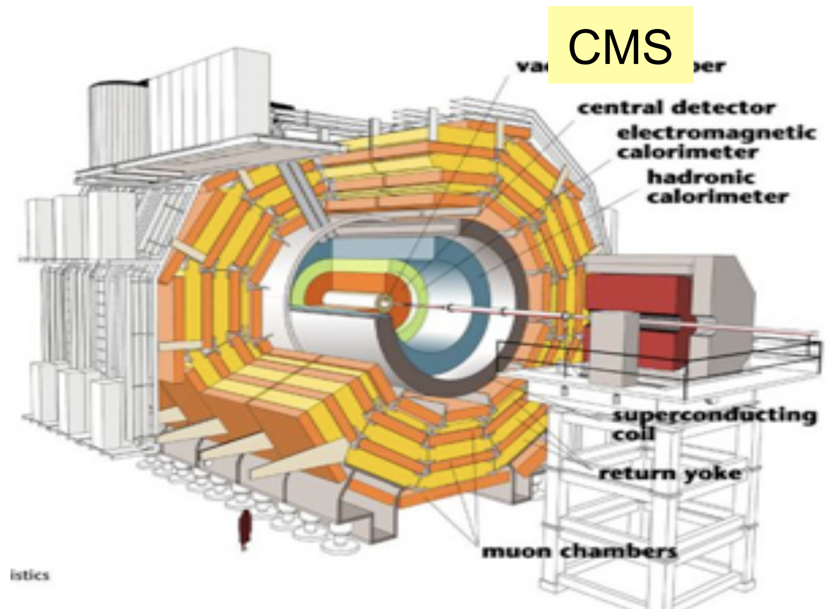


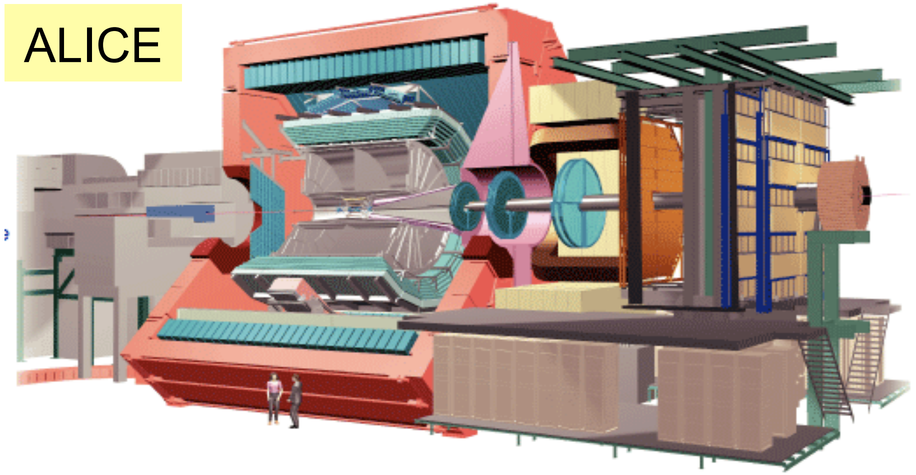
Tevatron p anti-p collider today

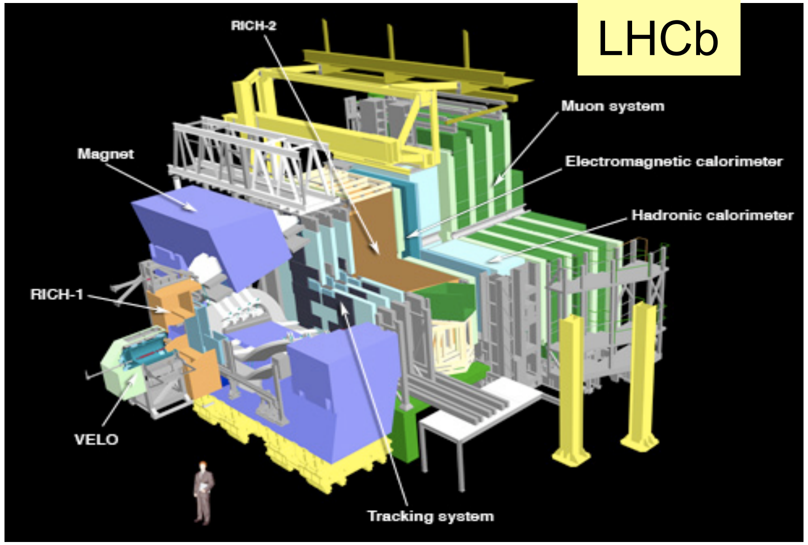
Experiments at the LHC

The Four Main LHC Experiments

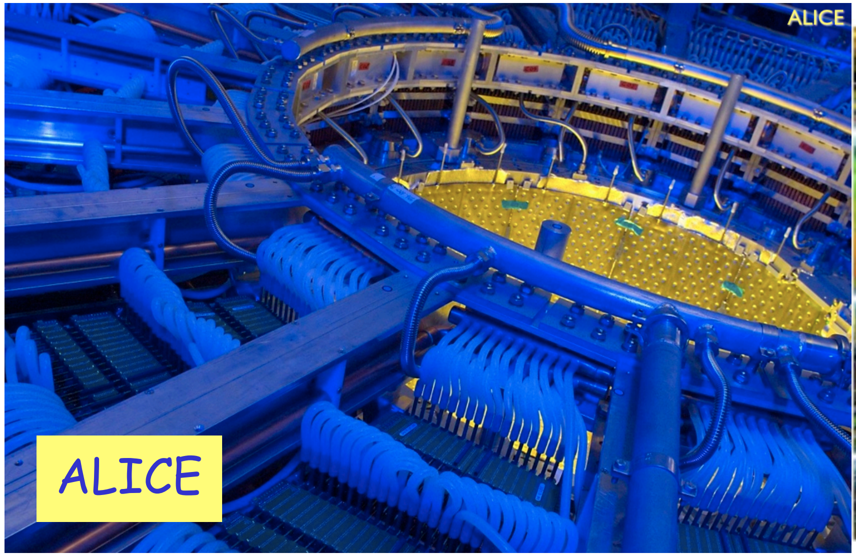


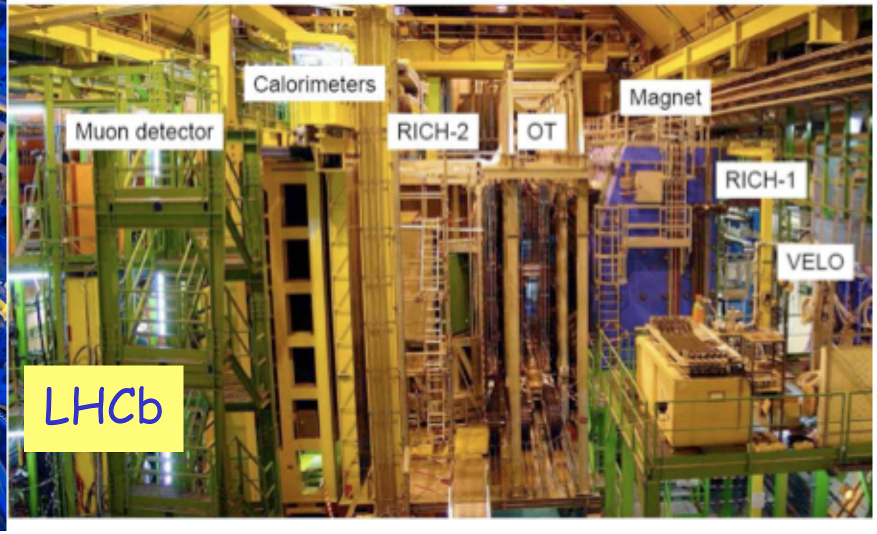


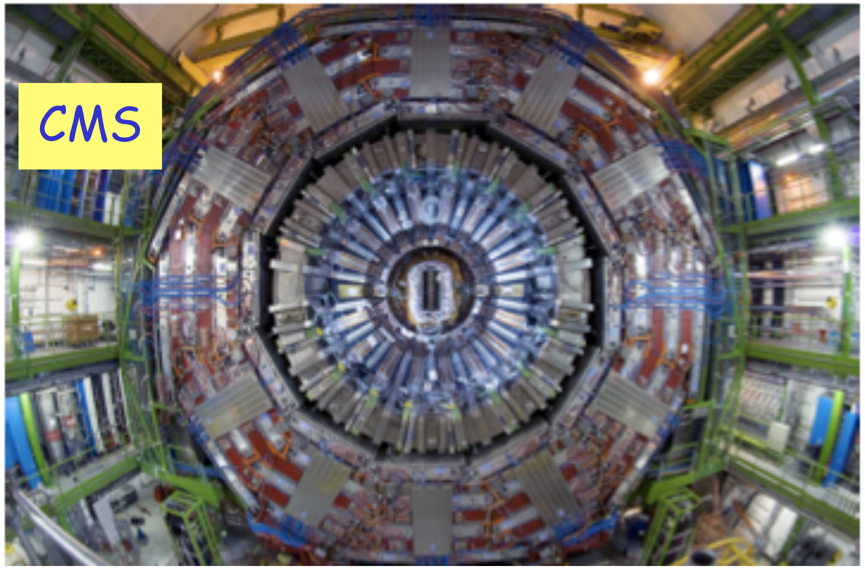


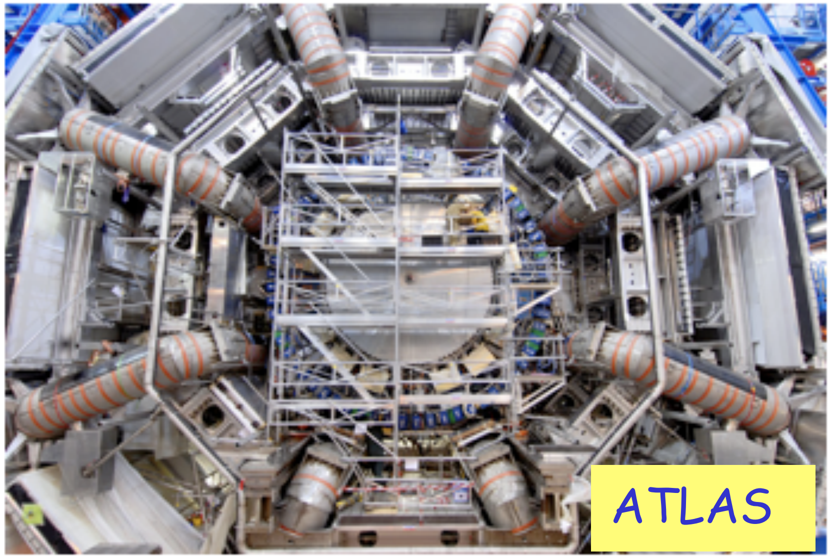


...and in real life..







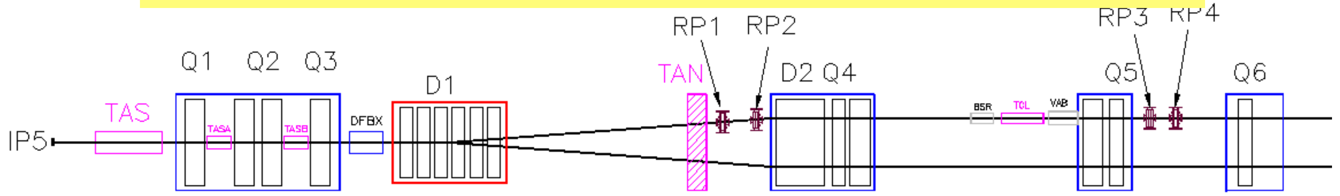


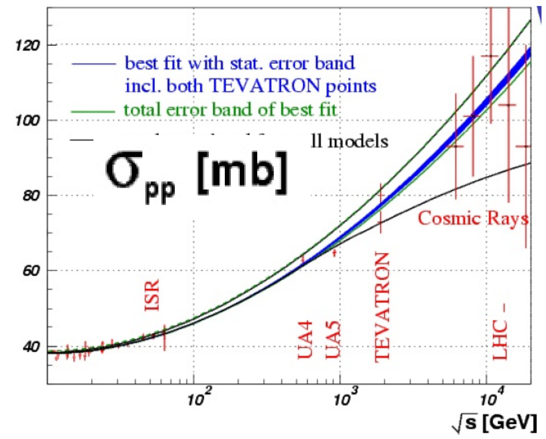
Eg..: ATLAS & CMS construction started >10 years ago

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

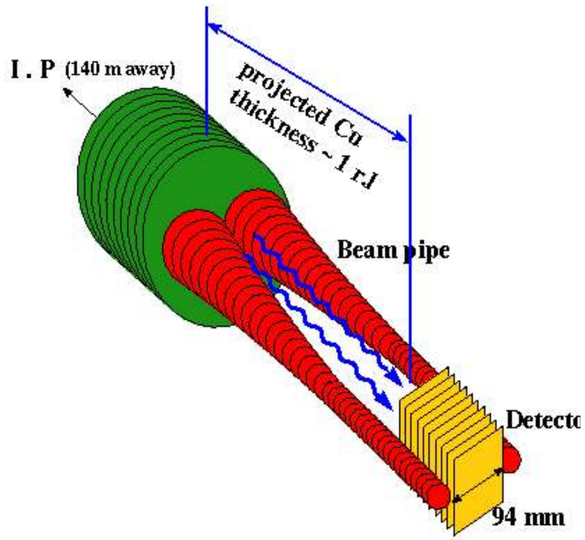
TOTal and Elastic cross section Measurement

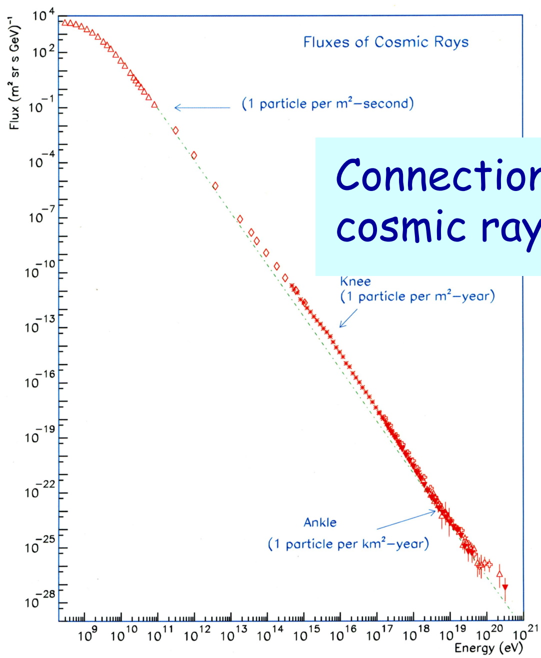




LHCf: measurement of photons and neutral pions in the very forward region of LHC

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

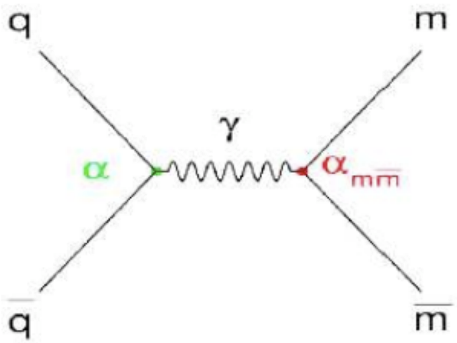




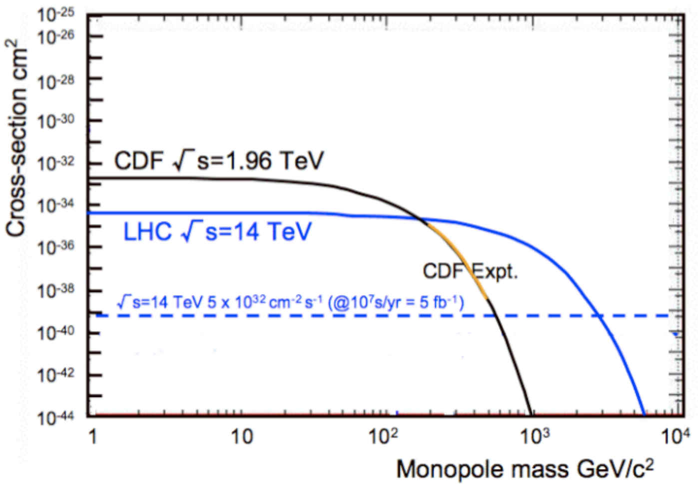
Connection with cosmic rays

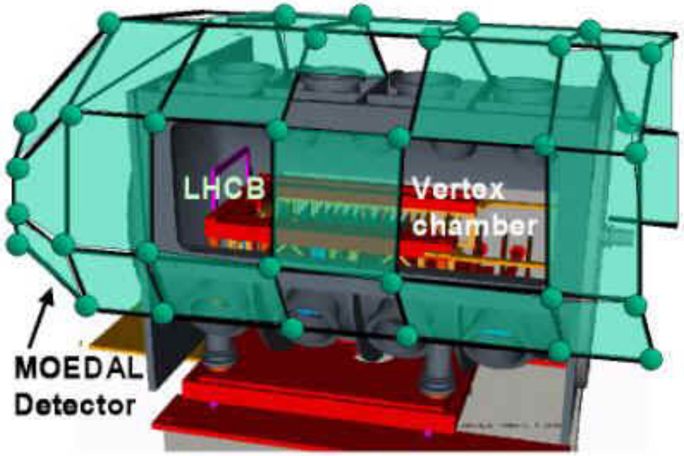
Moedal: MOnopole and Exotics Detector at the LHC

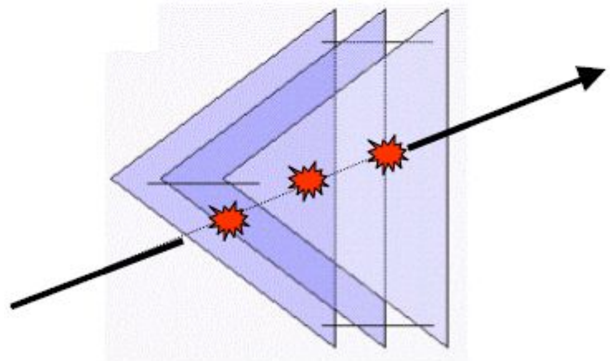
Heavy particles which carry “magnetic charge”
Could eg explain why particles have “integer electric charge”



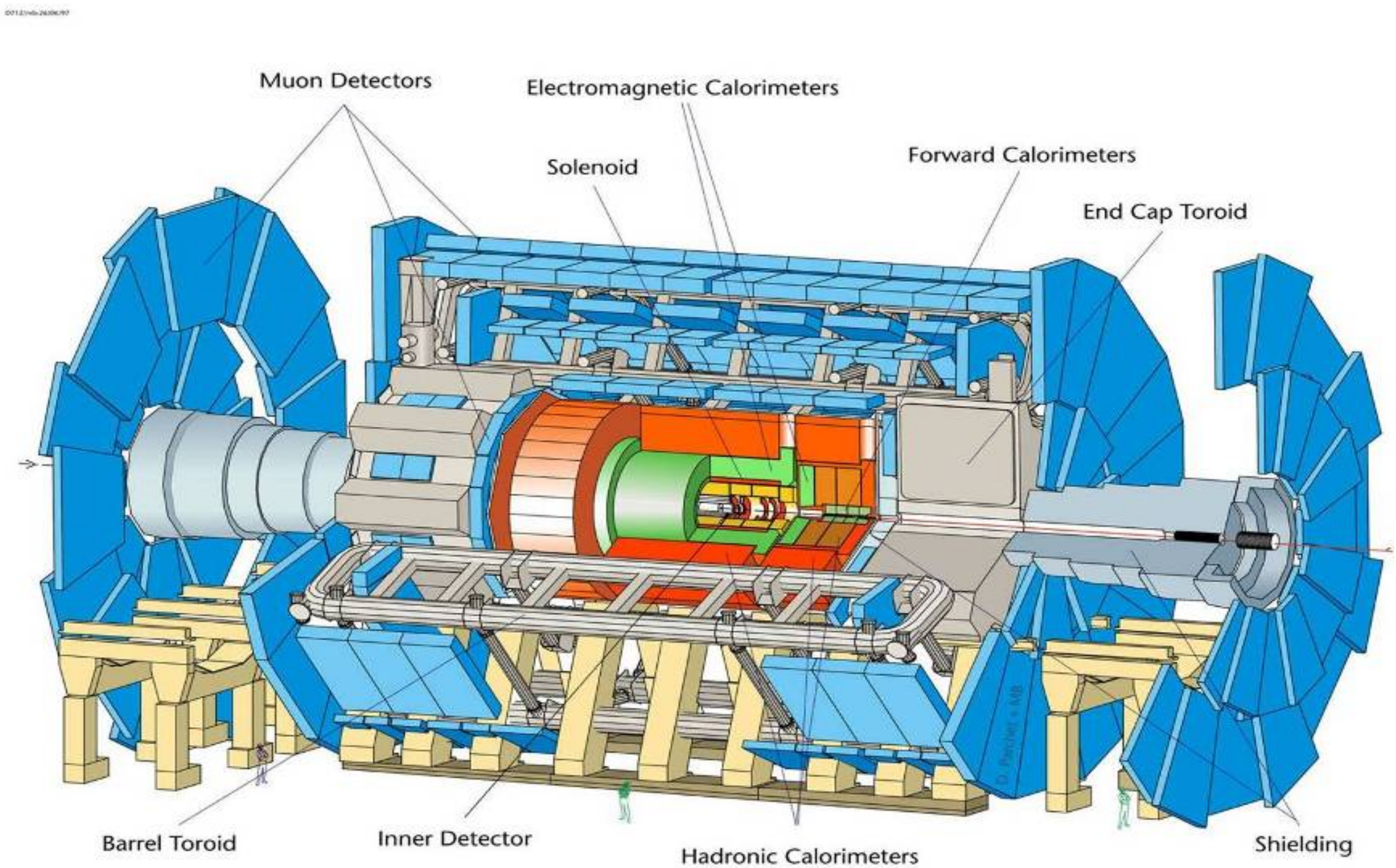
Direct Monopole production





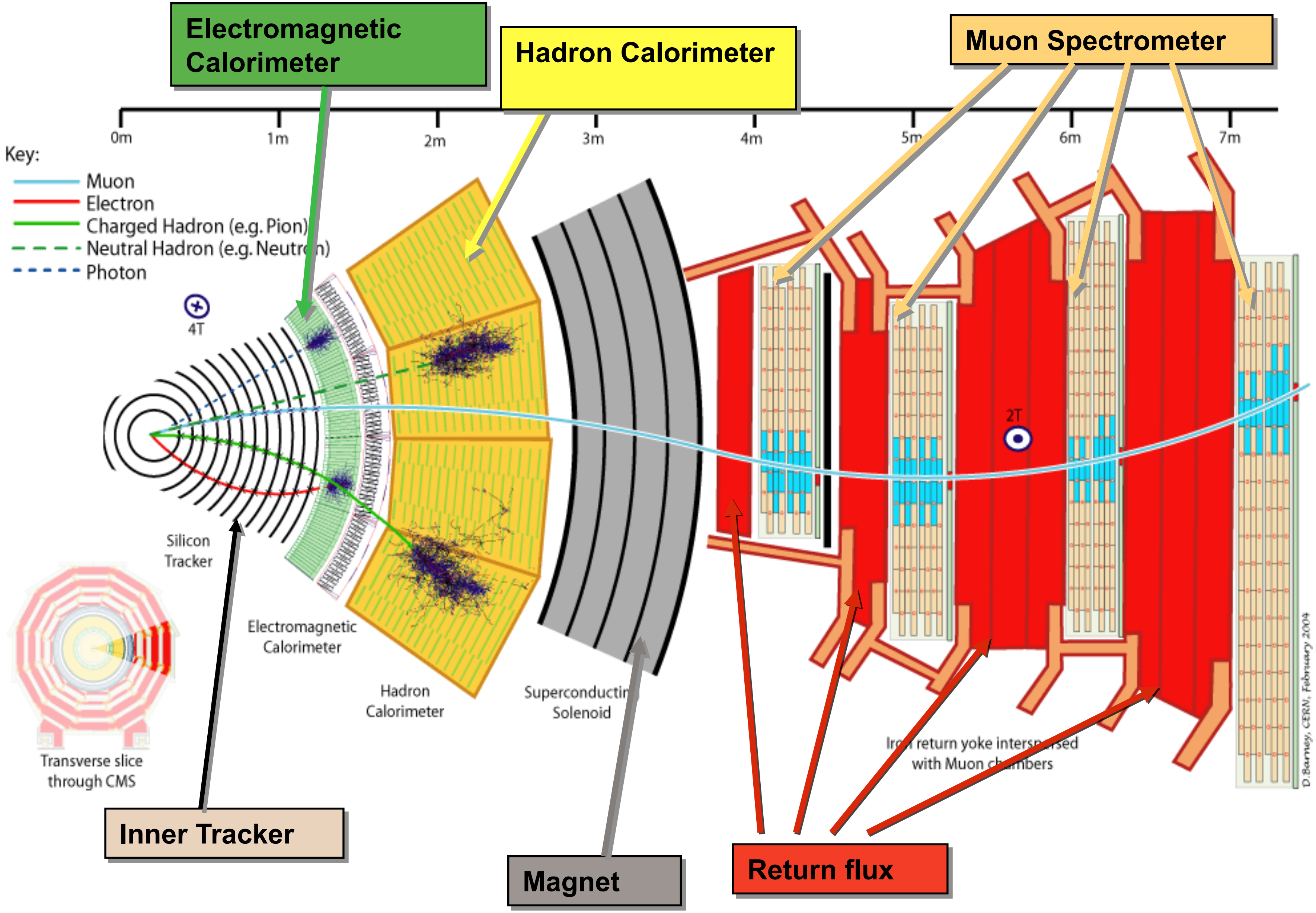


Remove the sheets after some running time and inspect for ‘holes’



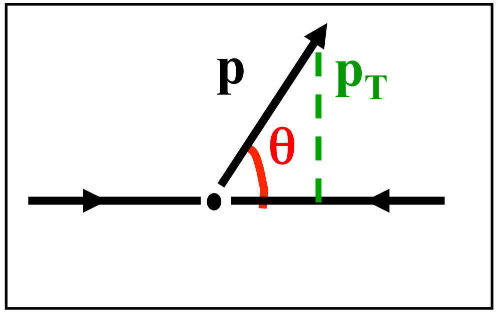
Length = 55 m Width = 32 m Height = 35 m but spatial precision ~ 100 μm

Particles in the Detector



Kinematic Variables for pp Scattering

- Transverse momentum, p_T and E_T=E sinθ
  - Particles that escape detection (0) have p_T=0
  - Visible transverse momentum =0
    - Very useful variable!



- Longitudinal momentum and energy, p_z and E
  - Particles that escape detection have large p_z
  - Visible p_z is not conserved
    - Not so useful variable
- Angle:
  - Polar angle θ is not Lorentz invariant
  - Rapidity: y
  - Pseudorapidity: η

$$y = \frac{1}{2}\ln\frac{E+p_z}{E-p_z}$$

For M=0

$$y = \eta = -\ln(\tan\frac{\theta}{2})$$

- Missing E_T and P_T: : Vectorial sum of all transverse momenta

Challenges for Experiments at the LHC

Challenges for ATLAS and CMS (early '90's)

- Detectors must survive for 10-20 years or so of operation
  - Radiation damage to materials and electronics components
  - Problem pervades whole experimental area (neutrons): NEW!
- Detectors must provide precise timing and be as fast as feasible
  - 25 ns is the time interval to consider: NEW!
- Detectors must have excellent spatial granularity
  - Need to minimise pile-up effects: NEW!
- Detectors must identify extremely rare events, mostly in real time
  - Lepton identification above huge QCD backgrounds (e.g. e/jet ratio at the LHC is ~ 10^{-5}, i.e. ~ 100 worse than at Tevatron)
  - Signal X-sections as low as 10^{-14} of total X-section: NEW!
  - Online rejection to be achieved is ~ 10^{7}: NEW!
  - Store huge data volumes to disk/tape (~ 10^{9} events of 1 Mbyte size per year: NEW!

D. Froidevaux

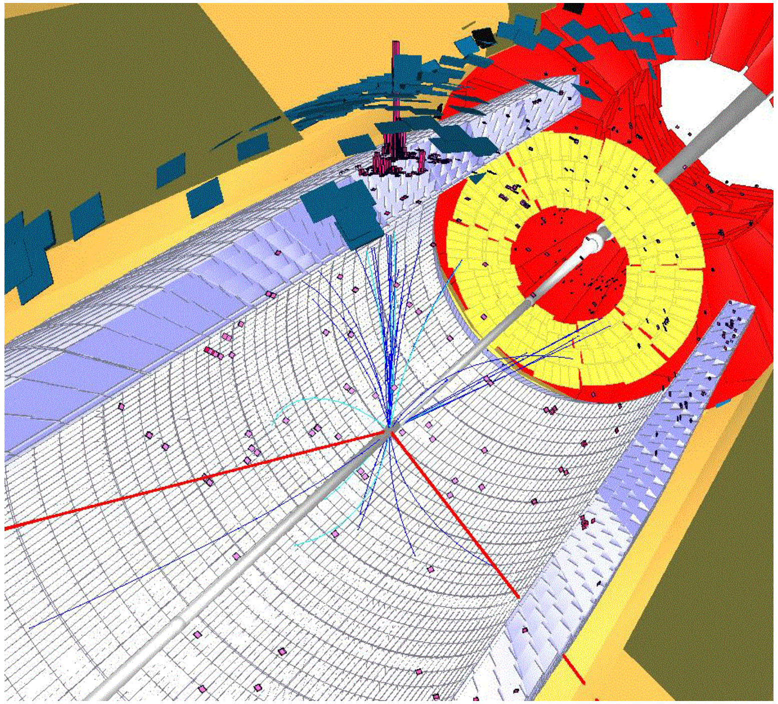
Challenges for ATLAS and CMS

- Detectors must measure and identify according to certain specs
  - Tracking and vertexing: ttH with H → bb
  - Electromagnetic calorimetry: H → γγ and H → ZZ → eeee
  - Muon spectrometer: H → ZZ → μμμμ
  - Missing transverse energy: supersymmetry, H → ττ
- Detectors must please
  - Collaboration: physics optimisation, technology choices
  - Funding agencies: affordable cost (originally set to 475 MCHF per experiment by CERN Council and management)
  - Young physicists who will provide the main thrust to the scientific output of the collaborations: how to minimise formal aspects? How to recognise individual contributions?

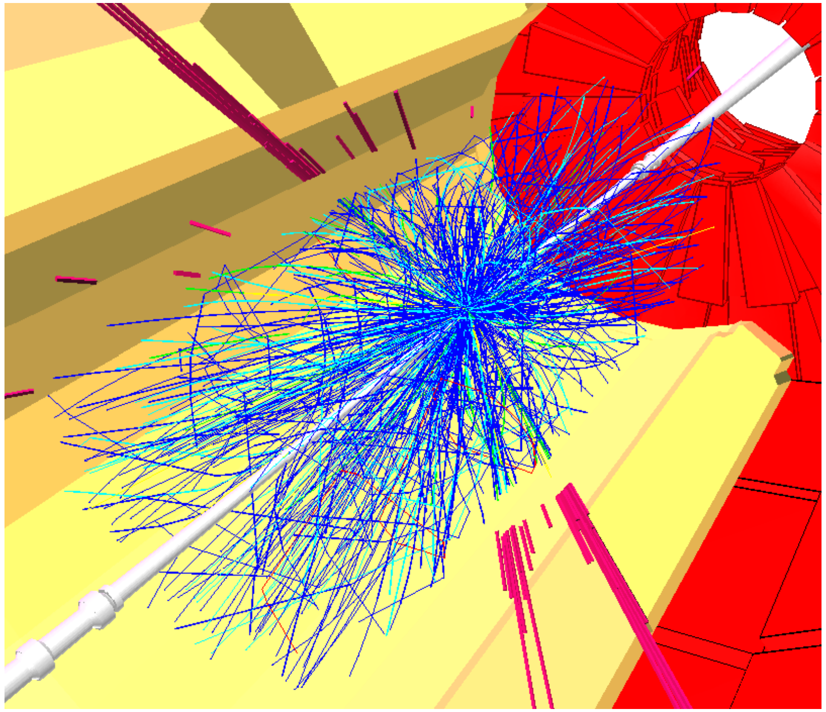
  - ATLAS and CMS : started in 1992… ⇒ 2008!!!

Pile-up at the LHC

Pile-up ⇒ additional -mostly soft- interactions per bunch crossing
Startup luminosity 2010/2011 ⇒ 2-4 events per bunch crossing
High luminosity $10^{34}cm^{-2}s^{-1}$ ⇒ ~25 events per bunch crossing
Luminosity upgrade > 2020 ⇒ >200 events per bunch crossing



SUSY event (no pileup)

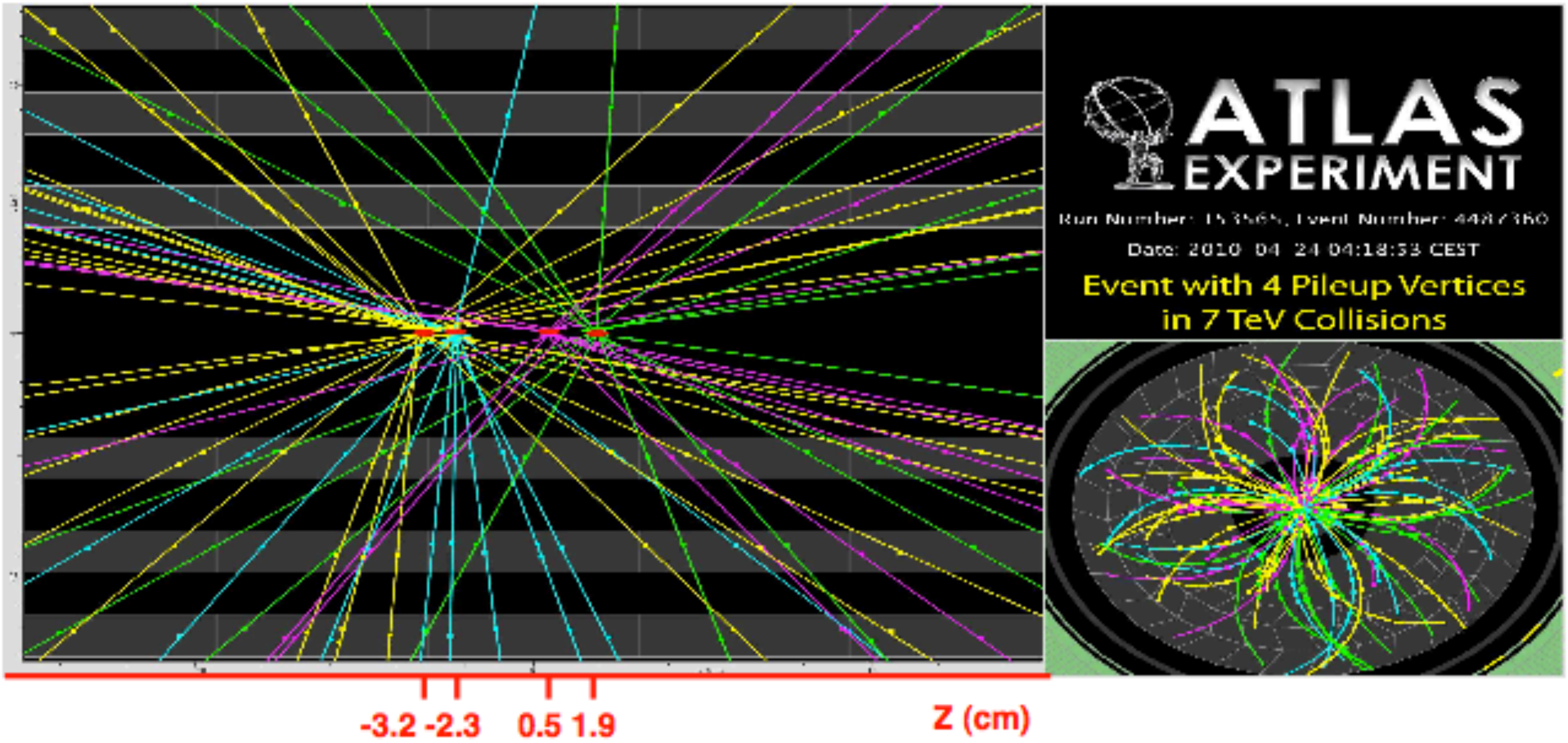


SUSY event ($10^{34}cm^{-2}s^{-1}$)

Pile-up at present

- **40% of event have > 1 pp interaction per crossing**
  - Example : 4 pp interactions in one bunch crossing

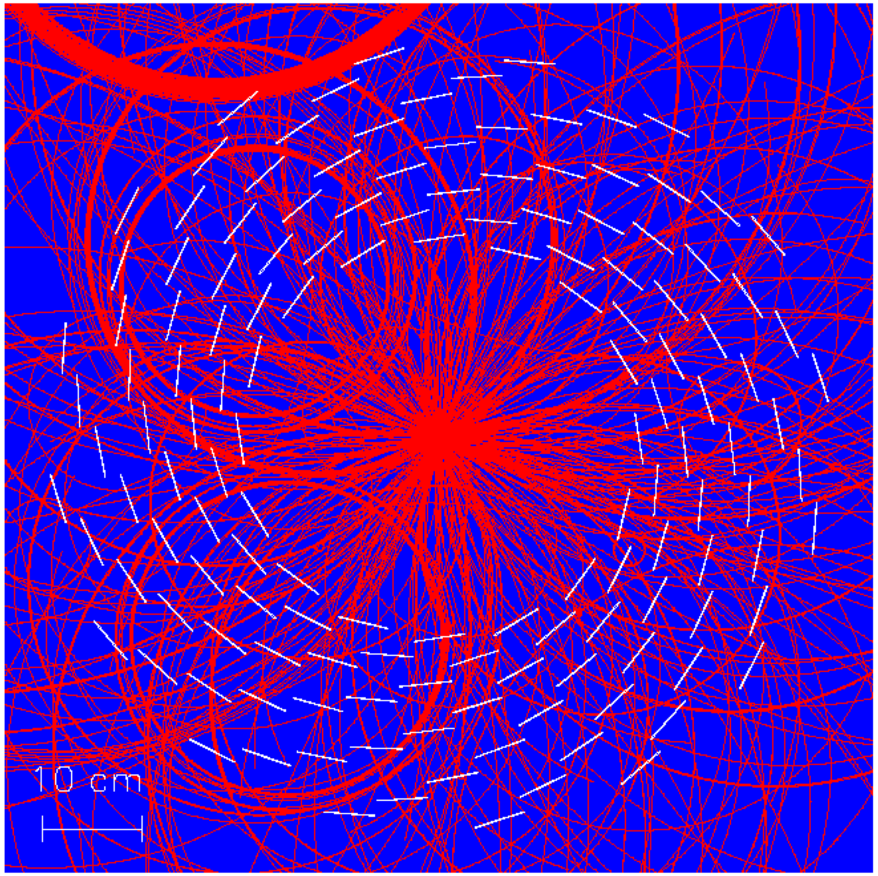
    ➔ 10-45 tracks p_T>150 MeV per vertex



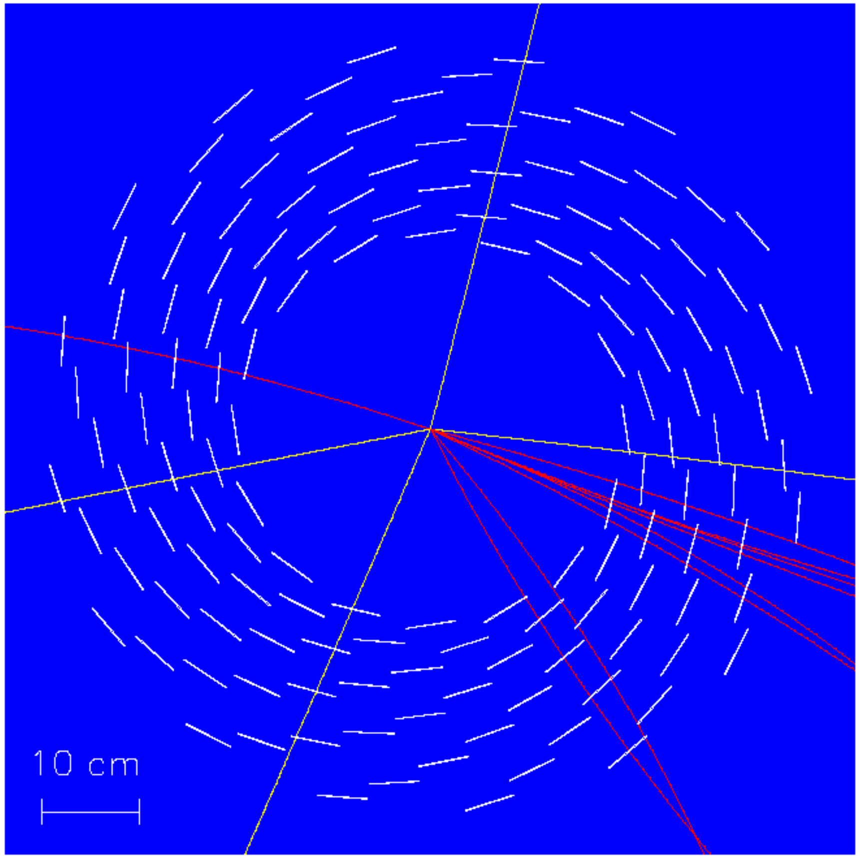
How to find the interesting signals

This event contains pp →H+X, with H→ZZ→μμμμ

X ~ 100 charged particles



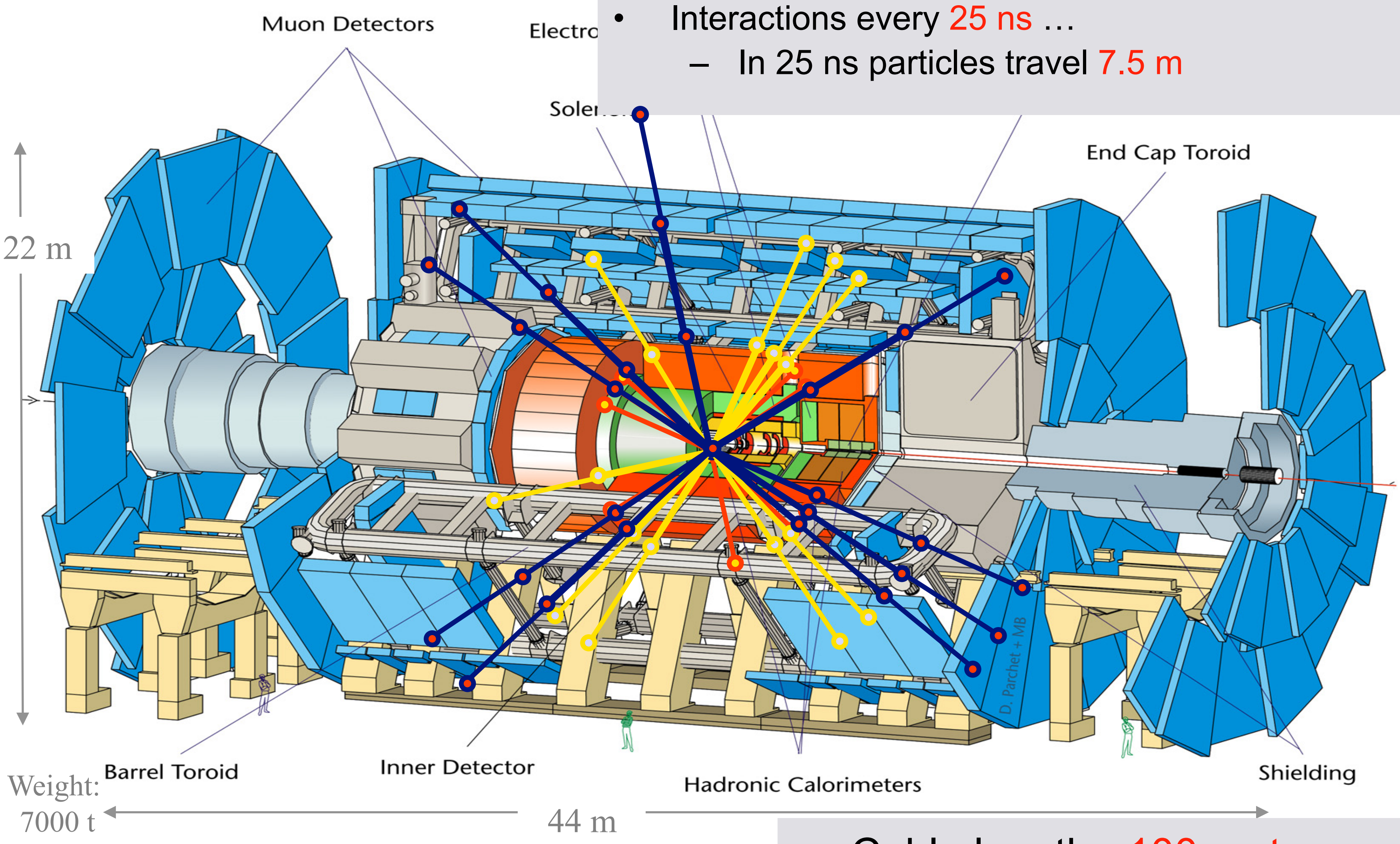
All tracks shown



Only tracks with transverse momentum > 2 GeV shown

The LHC: Environement

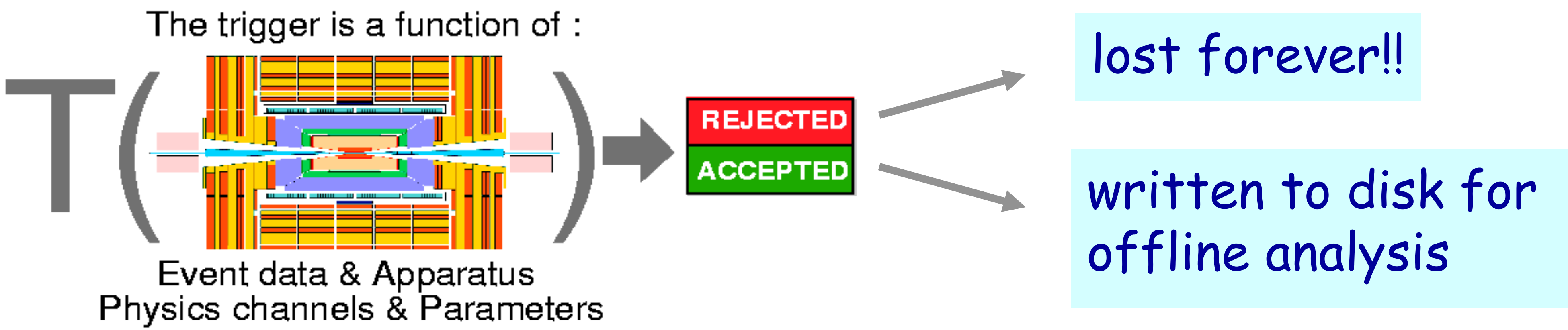
- Interactions every 25 ns …
  - In 25 ns particles travel 7.5 m



- Cable length ~100 meters …
  - In 25 ns signals travel 5 m

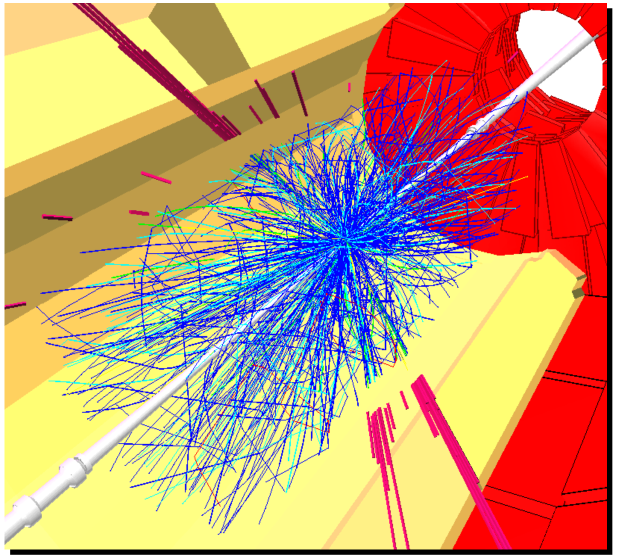
Event Filtering: the Trigger System

Collision rate is 40 MHz   Event size ~1 Mbyte
2007 technology (and budget) allows only to write 100 Hz of events to tape → need a factor ~10^7 online filtering!!

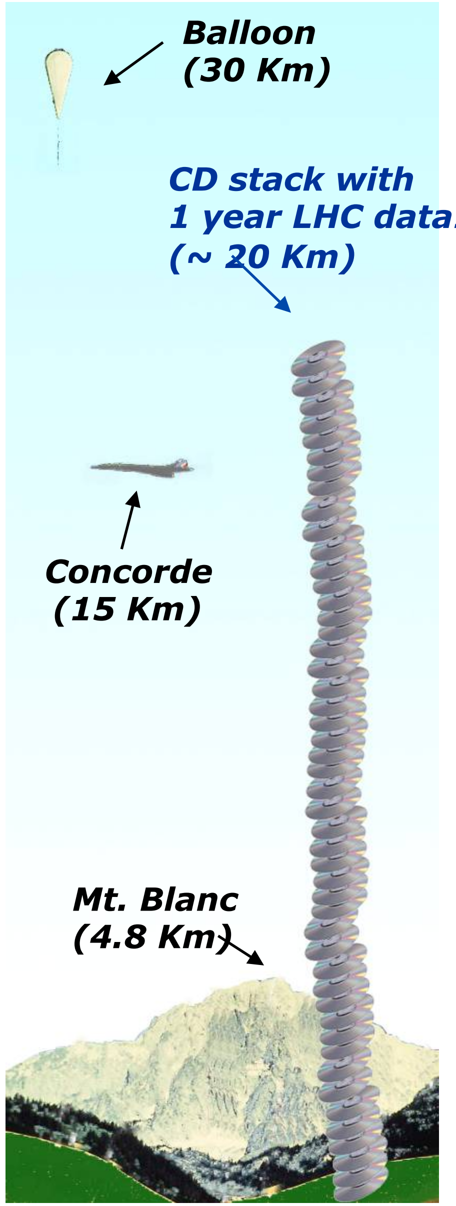


The event trigger is one of the biggest challenges at the LHC
⇒ Based on hard scattering signatures: jets, leptons, photons, missing Et,…

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...)

LHC Computing Grid project (LCG)

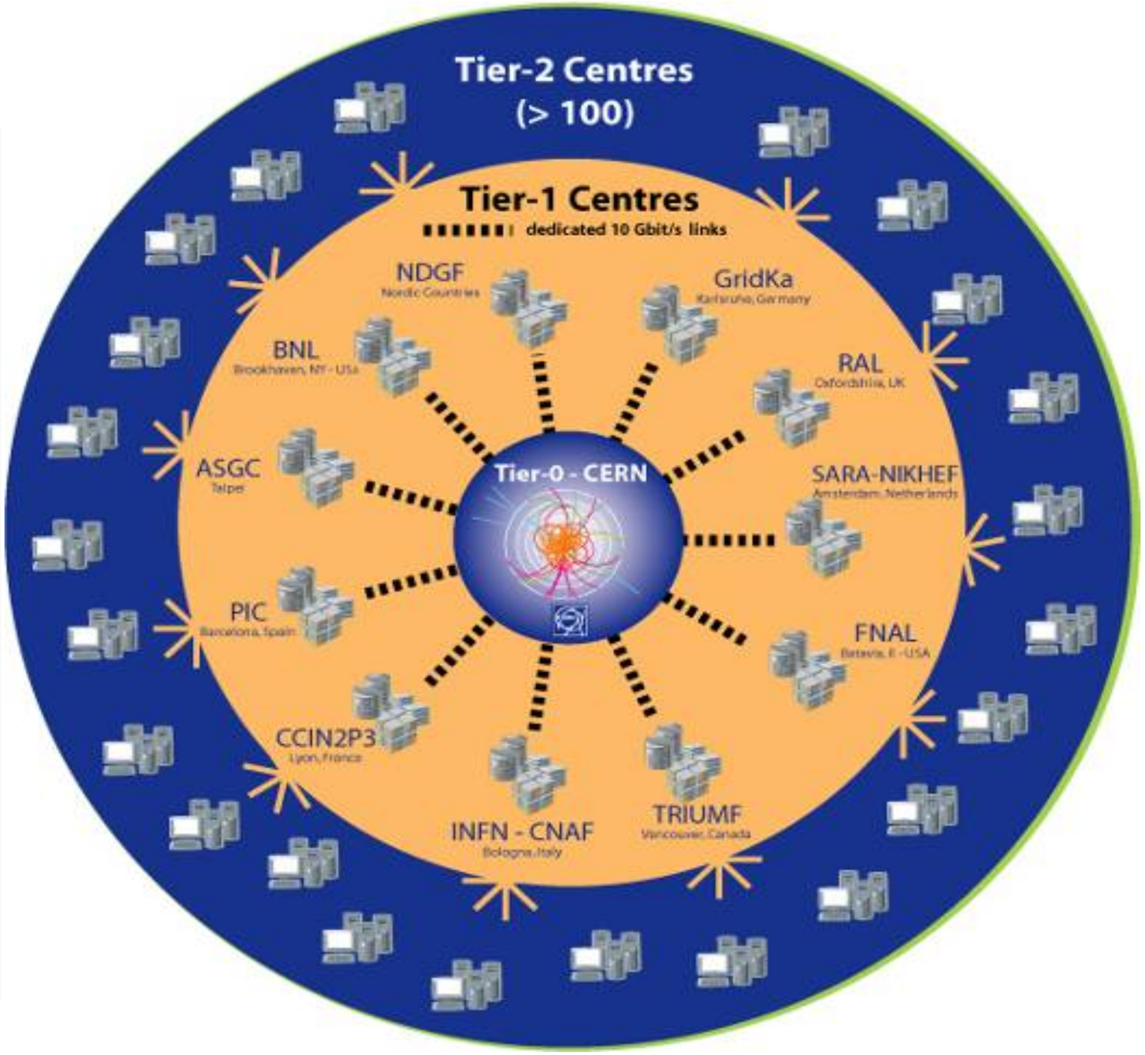
More than 140 computing centres
12 large centres for primary data management:
CERN (Tier-0)

Eleven Tier-1s

38 federations of smaller Tier-2 centres

India – BARC, TIFR, VECC

35 countries involved



Summary: Challenges

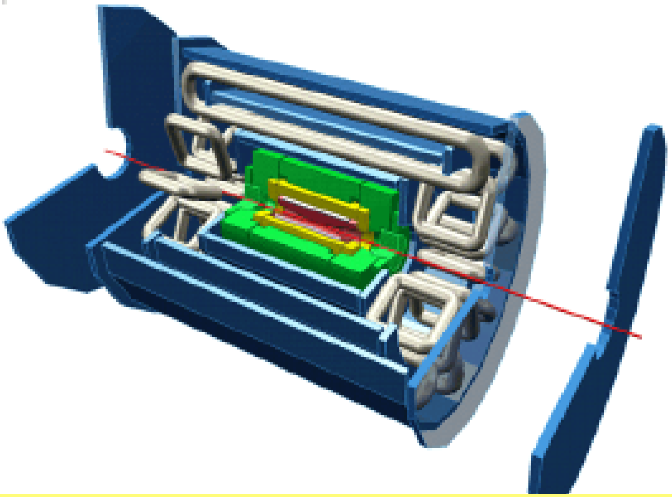
- High event rate and pile-up
  - High granularity: typically 10x more channels compared to present detectors
- Timing/synchronization of 10^8 channels is non trivial
- Event size (> 1 Mbyte)/Computing
  - Limit event rate to 100 Hz, use the Grid
- Trigger reduce event rate from 40MHz to 100 Hz
  - Multi-layered trigger system and pipelined electronics
- Detectors need excellent hermeticity (missing ET), lepton identification, B & Tau identification, jet measurements…
- Detectors must be radiation hard and reliable for ~ 10-20 years…

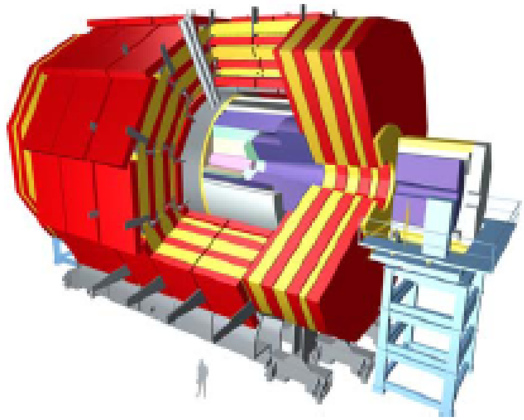
Can it be done?

ATLAS and CMS

General Purpose Detectors at the LHC

ATLAS A Toroidal LHC ApparatuS **CMS** Compact Muon Solenoid





In total about
- ~100 000 000 electronic channels

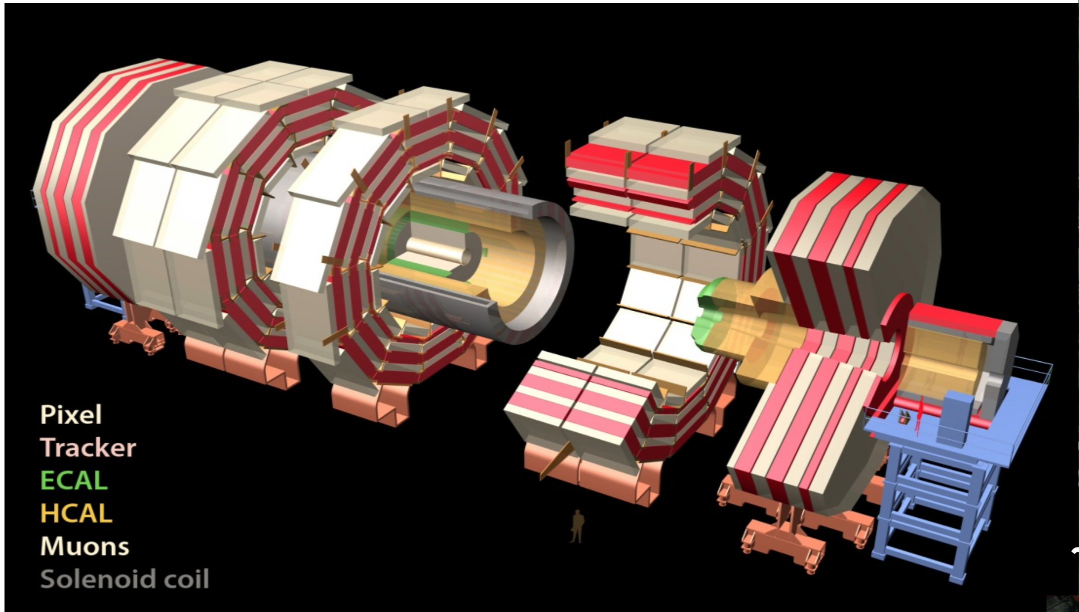
Each channel checked
- 40 000 000 times per second (collision rate is 40 MHz)

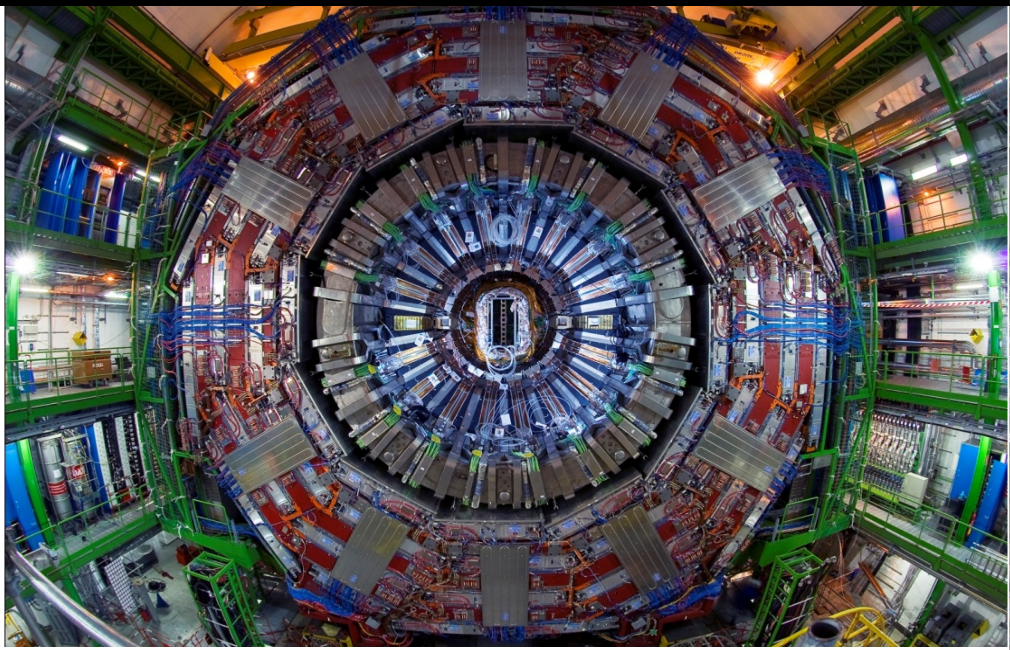
Amount of data of just one collisions
- >1 500 000 Bytes

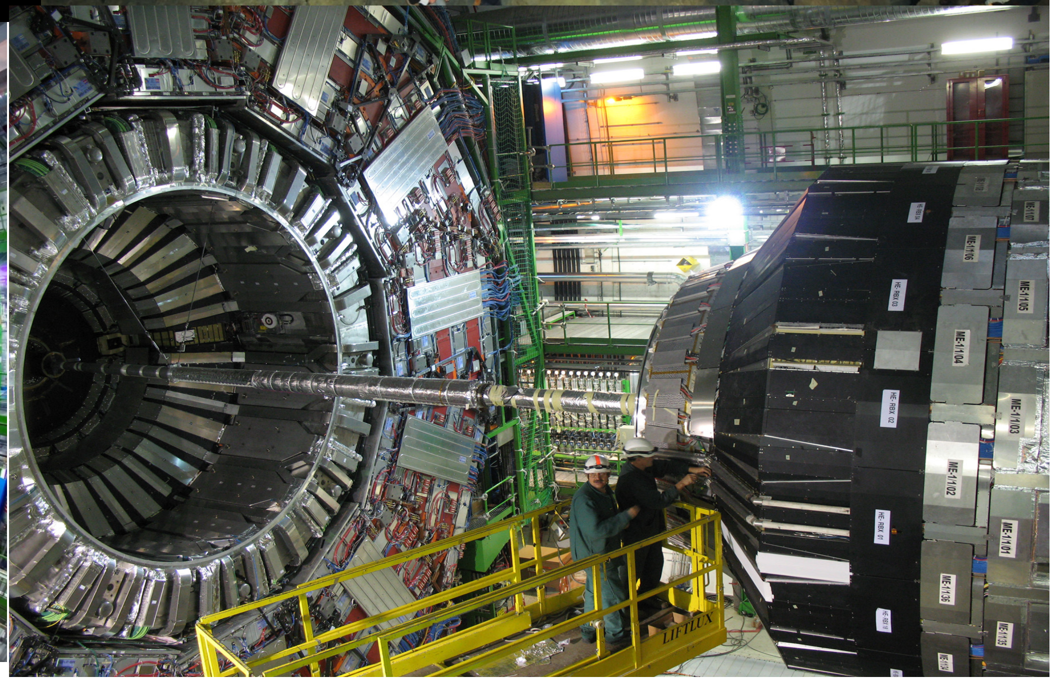
Trigger (online event selection)
- Reduce 40 MHz collision rate to ~100 Hz data recording rate

Readout to disk
- 100 collisions/sec ⇒ pentaBytes of data/year

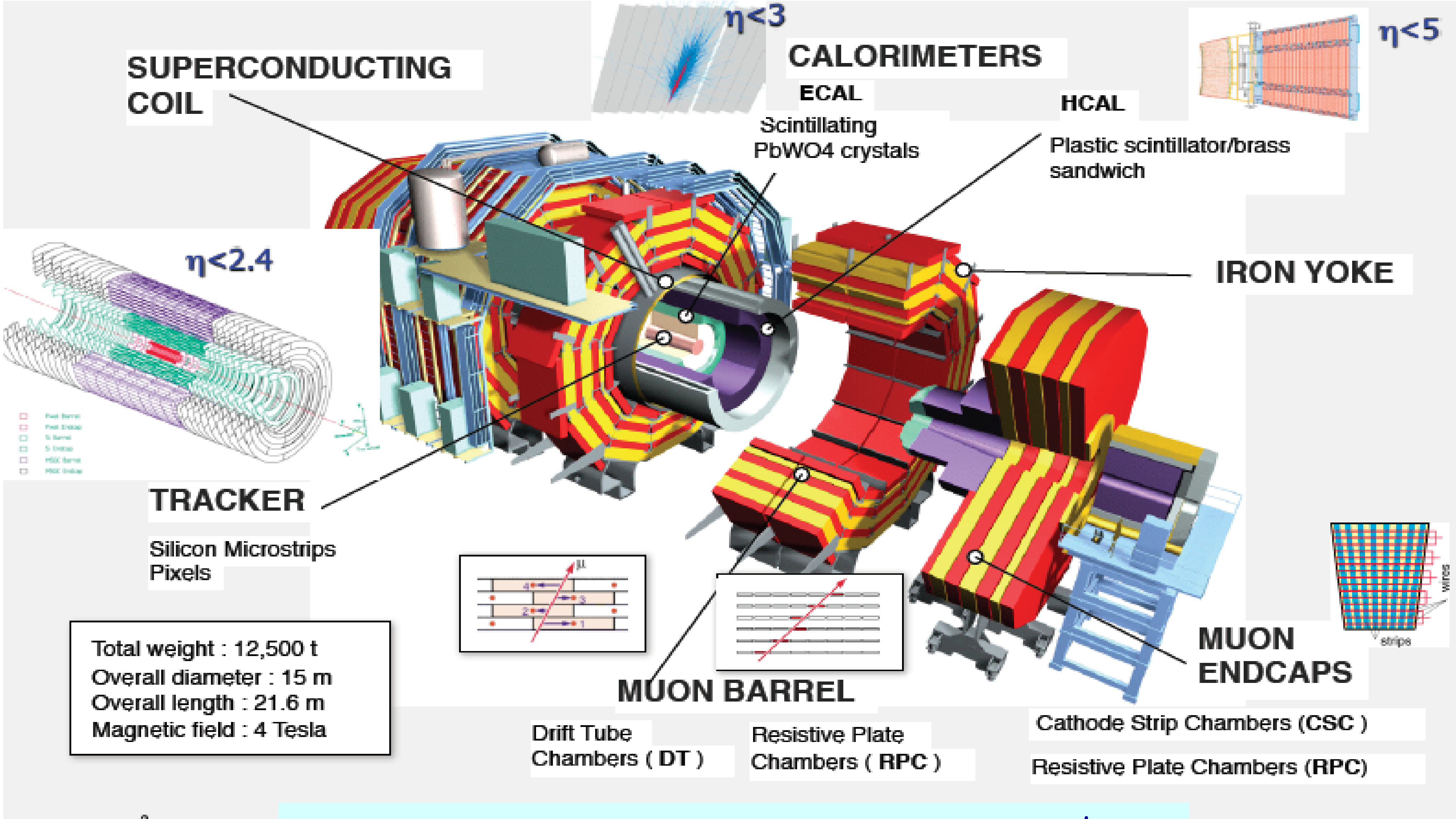
The CMS Collaboration: >3000 scientists and engineers, >700 students from 182 Institutions in 39 countries .







The Modular Design of CMS



Acceptance: Calorimetry $|\eta| < 5.0$ Tracking $|\eta| < 2.4$

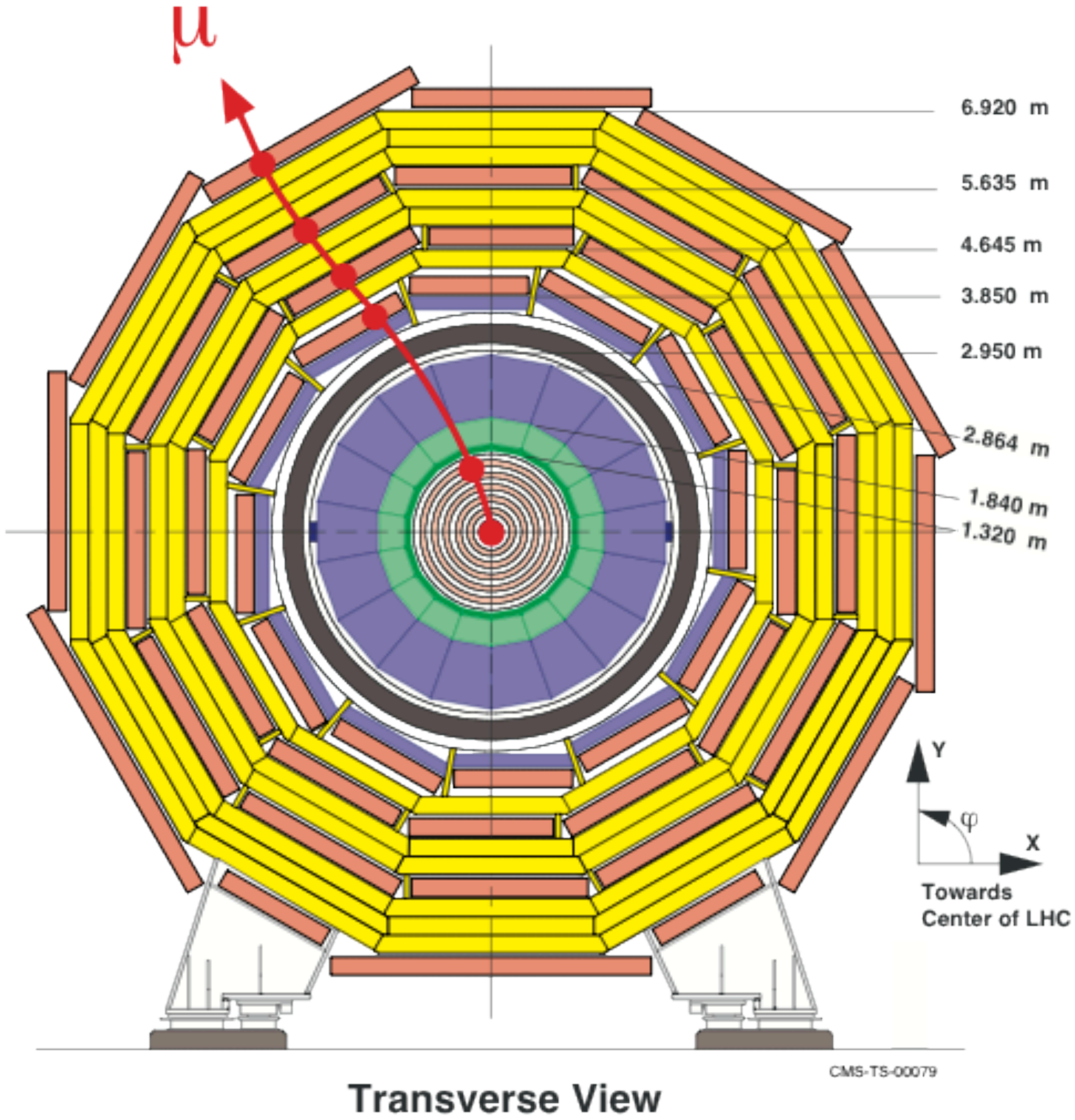
CMS Detector Design Priorities

Expression of Intent (EOI): Evian 1992

1. A robust and redundant Muon system
2. The best possible e/γ calorimeter consistent with 1.
3. A highly efficient Tracking system consistent with 1. and 2.
4. A hermetic calorimeter system.
5. A financially affordable detector.

Compact Muon Solenoid (CMS)

Letter of Intent (LOI): LHCC, TDR in 1994



Strong Field 4T

Compact design

Solenoid for Muon P_t trigger in transverse plane

Redundancy: 4 muon stations with 32 r-phi measurements

$\Delta P_t/P_t \sim 5\%$ @1TeV for reasonable space resolution of muon chambers (200μm)